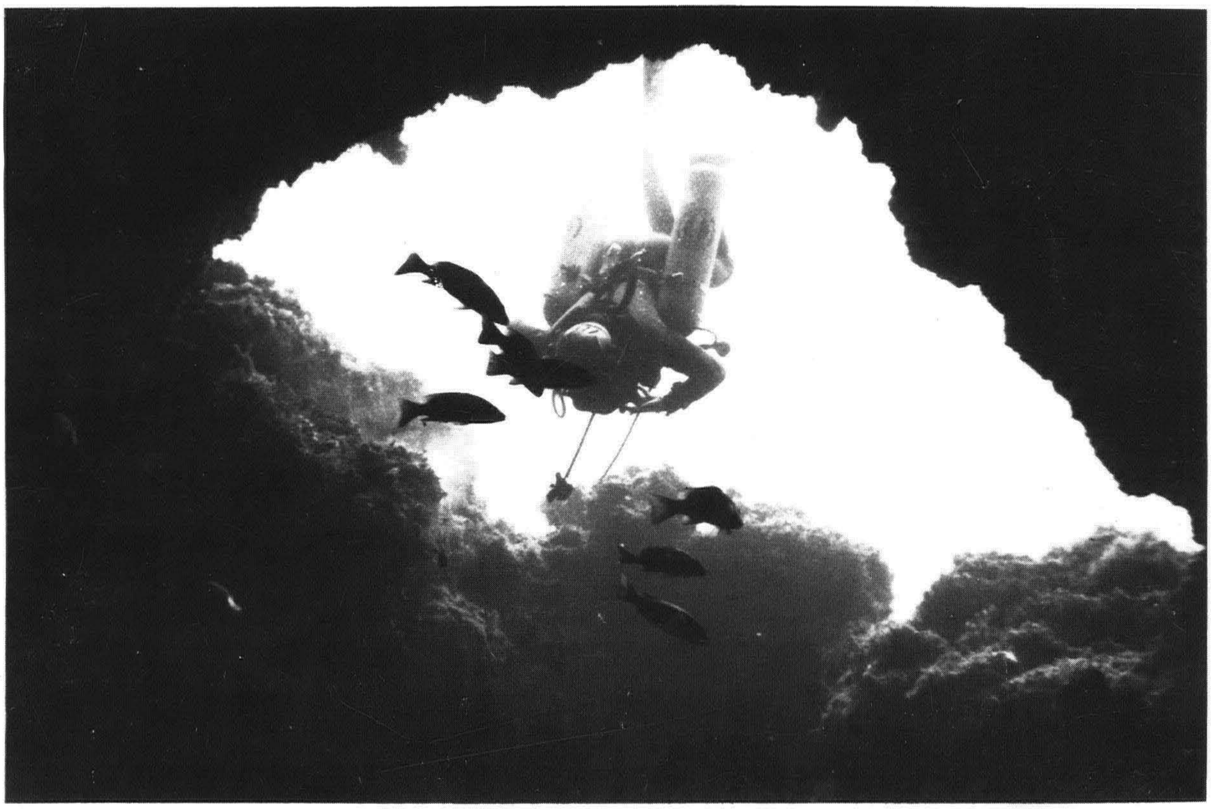
Cave Science

The Transactions of the British Cave Research Association

BCRA

Volume 11 Number 1 March 1984



Bahamas Blue Holes

1981-1982

BRITISH CAVE RESEARCH ASSOCIATION

NOTES FOR CONTRIBUTORS

Articles for publication in CAVE SCIENCE may cover any aspect of speleology and related sciences, such as geology, geomorphology, hydrology, chemistry, physics, archaeology and biology. Articles on technical matters such as caving techniques, equipment, diving, surveying, photography and documentation are also accepted for publication as well as expedition reports, historical and biographical studies.

These notes are intended to help authors to prepare their material in the most advantageous way so as to expedite publication and to reduce both their own and editorial labour. It saves a lot of time if the rules below are followed.

All material should be presented in as close a format as possible to that of CAVE SCIENCE. Text should be typed double-spaced on one side of the paper only. If typing is impractical, clear, neat handwriting is essential. Subheadings, sectional titles, etc., within an article should follow as far as possible the system used in CAVE SCIENCE. In any case, they should be clearly marked, and a system of primary, secondary and tertiary subheadings, if used, should be clearly indicated and double-checked before submission.

Abstract: All material should be accompanied by an abstract stating the essential results of the investigation for use by abstracting, library and other services.

References to previously published work should be given in the standard format used in CAVE SCIENCE. In the text the statement referred to should be followed by the relevant author's name and date (and page number, if appropriate) in brackets. Thus: (Bloggs, 1999, p. 99). All such references cited in the text should be given in full, in alphabetical order, at the end. Thus: Bloggs, B. 1999. The speleogenesis of Bloggs Hole. Bulletin X Caving Assoc. vol. 9, pp 99-199. Books should be cited by author, date, title, publisher and where published. Periodical titles should be abbreviated in World List of Scientific Periodicals format if possible.

Acknowledgments: Anyone who has given a grant or helped with the investigation, or the preparation of the article, should be acknowledged briefly. Contributors in Universities and other institutions are reminded that grants towards the cost of publication may be available and they should make appropriate enquiries as early as possible. Expedition budgets should include an element to help publication, and the editor should be informed at the time of submission.

Illustrations: Line diagrams and drawings must be in BLACK ink on either clean white paper or card, or on tracing paper or such materials as kodatrace. Anaemic grey ink and pencil will not reproduce! Illustrations should be designed to make maximum use of page space. If photo-reduction is contemplated all lines and letters must be large and thick enough to allow for their reduction. Letters must be done by stencil, letraset or similar methods, not handwritten. Diagrams should be numbered in sequence, Fig. 1, Fig. 2, etc., and referred to in the appropriate place in the text by inserting (Fig. 1) etc., in brackets. Captions should be typed on a separate sheet if they are not an inherent part of the diagram.

Photographs are welcome. They must be good clear black and white prints with sharp focus, and not too much contrast. Prints about 15 x 10 cm (6 x 4 inches) are best. Experienced authors may make up their complete photo pages (Plates) with captions printed or electro-typed in, but other authors should lightly pencil the photo number on the back, type the caption on a separate sheet and indicate in the text the point where the photo is referred to. Thus: (Photo 1) etc.

Copyright: If any text, diagrams or photos have been published elsewhere, it is up to the author to clear any copyright or acknowledgment matters.

Speleological expeditions have a moral obligation to produce reports (contractural in the cases of recipients of awards from the Ghar Parau Foundation). These should be concise and cover the results of the expedition as soon as possible after the return from overseas, so that later expeditions are informed for their planning. Personal anecdotes should be kept to a minimum, but useful advice such as location of food supplies, medical services, etc., should be included.

Authors may order reprints of their contribution for their own private use. The order must be notified to the Editor at the time of submission. Orders after publication cannot be accepted.

If you have any problems regarding your material, please consult the Editor in advance of submission. (Dr. T.D. Ford, Geology Department, University of Leicester, Leicester LE1 7RH. Phone 0533-554455, ext. 121, or 0533-715265).

ISSN 0263-760X

CAVE SCIENCE

TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION

Volume 11 Number 1 March 1984

CONTENTS

The Report of the 1981 and 1982 British Cave Diving Expeditions to Andros Island, Bahamas ... compiled by R. Palmer and other members of the expedition

Published by and obtainable from:
The British Cave Research Association, 30 Main Road,
Westonzoyland, Bridgwater, Somerset TA7 OEB

CAVE SCIENCE

Transactions British Cave Research Association. Vol 11, No.1, March 1984

REPORT OF THE 1981 & 1982 BRITISH CAVE DIVING EXPEDITIONS TO ANDROS ISLAND

Patron: H.R.H. The Duke of Kent

Compiled by R. J. Palmer and members of the Expeditions

INTRODUCTION

The Blue Holes of the Bahama Islands are some of the most extensive underwater cave systems known to man. Found throughout the island range, they lie beneath both land and sea. Where they open to the surface, they are known locally as "Blue Holes" or "boiling holes", the latter because of the strong tidally-related currents associated with many of them.

Exploration began in the 1960's, when a diver named George Benjamin took an interest in them. Benjamin, Latvian by birth but Canadian by adoption, was a photographic research chemist, with his own laboratories, and made a complete photographic record of his discoveries and explorations. His major work was a cataloguing of the ocean Blue Holes of Andros Island, the largest of the Bahamas group, and the island with one of the greatest concentrations of Blue Holes. His catalogue is included as a part of this report (Appendix III).

In 1966, Benjamin and his team began their explorations of Blue Holes in the South Bight of Andros. During the next five years they explored hundreds of metres of submarine cave passage, reaching depths of over 100 metres, and making the first discoveries of speleothems in the caves, proof of a period of emergence during their history. In this cave (SB*4 in App. III) later called "Benjamin's Blue Hole", a single penetration was made by Tom Mount and Ike Ikehara of over 600 m, at an average depth of 35 m, in 1970. Exploration at this site virtually halted after the death of one of its foremost explorers, Frank Martz, in 1971, but not before a complex of passages over a mile in extent had been explored.

Benjamin explored a considerable number of other entrances off the eastern coast of the island, including a cave called the "Hole in the Wall", an opening in the edge of the huge underwater cliff that parallels the east of Andros, and drops vertically for 2000 m into an oceanic trough called the "Tongue of the Ocean". Benjamin made several films about his explorations, the best known being "15,000 years Beneath the Sea", in 1970. That year he was joined by Jacques Cousteau and the crew of the Calypso, who filmed for their own series of underwater films, largely in the caves of the South Bight.

Explorations were made at the same period of some of the many inland Blue Holes of the island, some of which were descended for over 60 m. One of the main discoveries was of Stalactite Blue Hole by Archie Forfar, who tragically met his death a short time later while attempting a depth-record on air in the Tongue of the Ocean.

In 1979, Benjamin passed his notes to Robert Palmer and Martyn Farr of the Cave Diving Group of Great Britain. A study of these led to the formation of the first British Cave Diving Expedition to Andros, mounted in the summer of 1981. The expedition chose to work on the northern end of the island, an area not extensively worked by Benjamin's team, but an area with known Blue Holes, which were not only easily accessible but also known to be shallower than their southern counterparts. In view of the inexperience of the British divers in working at depth, this latter was an important factor.

THE BRITISH EXPEDITIONS

The 1981 and 1982 British Expeditions marked a new direction in British cave-diving; the organisation of major exploratory and scientific expeditions to explore caves that were completely water-filled, with no hope or aim of surfacing in air-filled passage.

A distinction has been made in U.S. cave diving between "sump divers" and "cave divers". Sump divers explore water-filled sections of "dry cave" in the primary hope of finding more dry cave beyond and are primarily cavers. Cave divers explore underwater systems (e.g. Florida springs) for their own intrinsic sake and could be counted as primarily divers. The Blue Holes expeditions definitely fall into the latter category, making cave diving an exploratory tool in its own right and not merely an additional technique of dry caving.

Because we were breaking new ground, in both individual and exploration terms, we went to considerable lengths to seek advice in such matters as deep diving, decompression and scientific technique from institutes like the Royal Navy research centre at HMS Vernon, the Society for Underwater Technology and the Institute of Oceanographic Sciences. New equipment was adapted or designed, notably by Geoff Attwood and Rodney Beaumont, who produced some outstanding light units. Spirotechnique UK Ltd came to an arrangement with the expeditions over the loan of much of the basic diving equipment, and the Royal Geographical Society's Expeditions Office provided much in the way of advice to an inexperienced leadership on the structure and logistics of expedition planning. In the Americas, help was forthcoming from the Miami-based Institute for Underwater Archeology whose Secretary, David Pincus, went considerably out of his way both in 1981 and 1982 to act as U.S. Liaison Officer.

With the official support of the Royal Geographical Society and Sports Council in 1981, H.R.H. The Duke of Kent was approached, and graciously agreed to act as Royal Patron, extending this Patronage for the 1982 Expedition.

In both years, the Bahamas National Trust, Bahamas Tourist Authorities, Bahamas Department of Agriculture and Fisheries, and Bahamasair assisted the Expeditions with logistics and transport in the field. Members of the Executive Committee of the Trust were especially outstanding in their selfless support of our work.

These Expeditions, like any other, were only possible because of such support in the Bahamas, U.K. and U.S.A. It is unfortunate that only those at the tip of the public pyramid receive credit openly for the countless hours of work that go into the success of a venture like this. The acknowledgements given later in this Report are made with our heartfelt gratitude and we hope that those mentioned, and all those others who were involved in both expeditions, have regarded their involvement as worthwhile.

EXPEDITION MEMBERS

1981:

Robert Palmer: Leader
Martyn Farr: Deputy Leader
Rod Beaumont: Equipment Officer
Dr George Warner: Biologist
Dr Mel Gascoyne: Hydrologist/Geologist
Simcha Gascoyne: Hydrologist
Sally Farr: Base organiser
Pamela Beaumont: Base organiser
Dr John Fish of the U.S. Geological Survey joined the team for several days to examine inland blue hole hydrology.

1982:

Robert Palmer: Leader
Martyn Farr: Deputy Leader
Robert Parker: Diver
Julian Walker: Diver
Dr Tony Boycott: Diver / Expedition doctor
Christopher Moore: Biologist
Anna Savary: Biological Assistant
Elizabeth Plummer: Scientific assistant
Sally Farr: Base organiser

Inland team:
Dr Christopher Smart: Hydrologist
Graham Proudlove: Biologist
Katherine Hall: Geologist
Ken Jones: Diver
Laurie Jones: Diver
Clark Shimeall: Boat Captain

David Pincus of the Institute of Underwater Archaeology acted as U.S. liaison officer for both the 1981 and 1982 expeditions.

THE 1981 BRITISH BLUE HOLES EXPEDITION

The eight person 1981 Expedition was mounted with considerable financial support from Comex-Houlder Ltd, in addition to support from the Royal Geographical Society, the British Sports Council and the Ghar Parau Foundation. It took its field base in the Forfar Field station at Stafford Creek, North Andros. The Centre, a field research station owned by International Field Studies of Columbus, Ohio, provided land transport in the form of a large Ford pickup truck, and ocean transport in a twin-outboard low draught twin-hulled pontoon boat. Compressor facilities, and 72/80 cubic foot air tanks belonging to the centre were used by the Expedition throughout, and the staff of the centre were of great assistance both in guiding us to sites and in day-to-day logistics.

During the period 3rd to 28th August, seven inland and six ocean Blue Holes were visited. These sites are described in detail elsewhere in the Report. In the oceanic sites, over 2000 metres of oceanic cave was explored, at depths ranging from 15 to 50 metres.

The exploratory diving was carried out by Martyn Farr and Robert Palmer, with the support of Rodney Beaumont. Rod was also equipment officer, a task he handled with great efficiency.

The scientific aspects of the expedition were handled by Dr George Warner of Reading University, Mel and Simcha Gascoyne of McMaster University, and Dr John Fish, from Miami, a hydrologist with the U.S. Geological Survey and ex-McMaster graduate.

George Warner, an extremely experienced marine biologist with much Caribbean experience, made basic faunal studies of the ocean and inland Blue Holes visited, using both photographic and physical collection techniques. Samples of inflowing and outflowing currents were taken at ocean sites, and returned to the U.K. for analysis at Reading University. Currents were monitored at Conch Sound One over a three-day period in 1981 with a Plessey Current Meter. Problems with freight prevented its use over a longer period.

Mel and Simcha Gascoyne between them carried out a programme of water analysis and uranium series dating of stalagmite samples collected from Conch Sound Blue Hole. All samples removed were already broken, and lying on the floor near their original site of growth.

Transport: Andros roads are in poor repair, and range from metalled two-lane roads to overgrown tracks, cleared about 1970 by bulldozer for forestry purposes. The main road between Forfar Field Station and Nicholls Town is in good repair, save for a seven-mile section immediately north of Stafford Creek. Movement inland, off the main roads, is difficult, and requires a sturdy vehicle, ideally with four wheel drive and a stout front bumper. A high-clearance chassis is a further asset. Navigation inland is difficult, our visits were to well-known cave openings, down tracks that were reasonably well-defined even yet. Most of the logging tracks are now overgrown and are more distinct from the air than from the ground. The absence of distinctive ground landmarks means that the navigator is reliant on accurate distance-measurement from a vehicle milometer, and it would be well worth the time for future explorers to make accurate maps from aerial photographs, and work out distances and compass bearings beforehand. Loss of position inland would be very dangerous, the roads form an interconnected maze, and aerial search would be necessary to find a team lost inland.

A further hazard to inland exploration is the thickness of the forest and the broken nature of the limestone underneath. Remote sites need paths cut to reach them and the shrubbery contains poison wood and poison ivy, to which some people have histamine allergies. Pyjamas are a serious recommendation.

Ocean travel necessitates the use of a shallow draught boat, the inner reef areas often having depths less than 0.5 metre at low tide. Local knowledge helps, though common sense and slow speeds would suffice in inflatable craft. None of the sites visited in 1981 stood in more than 1 metre of water at low tide.

Air transport in the islands is well-organised, though timetables are theoretical rather than practical. North Andros is well-served by Bahamasair , to airfields at Fresh Creek and San Andros. Bahamasair were of great help in 1981 in transporting freight from Nassau to Andros, free of charge.

Freight: Freight for the Expedition was sponsored by the Pacific Steam Navigation Company, though difficulties in Liverpool meant that the bulk of the freight did not arrive until the final week of the expedition. Fortunately this had little effect on the field programme, other than necessitating the purchase of extra guidelines and reducing the current monitoring programme. Return freight was a problem, the PSNC shipping all being one way. British Airways in Nassau helped considerably with this problem, and we are grateful to them.

SITES VISITED IN 1981

A brief description of sites visited in 1981 is given here. A more detailed description of the major sites is given elsewhere in this Report.

Ocean Sites:
Conch Sound (CS1): The major exploratory site of the Expedition. Almost 1000 m of passage was explored here, 700 m of it in a single large passage, containing many speleothems, at an average depth of 22 metres. No end was reached in this passage. A smaller series of passages were all explored to a conclusion near the entrance.
Conch Sound Two: 1.5 km south of CS1. A single rift passage, descending sharply to 39 m depth was explored for 200 m before becoming too objectively dangerous. An extremely strong current issued from this cave at full outflow, and the water was highly sulphurous.
Rat Cay Blue Hole: Explored to a total length of 600 m in two branching passages. Both of these closed down in areas of solutional breakdown. Average depth 15 m.
South Mastic Point: 1 km north of Rat Cay, a 20 m deep shaft (designated SM6 by George Benjamin) in a sandy area was descended, and a sand choked passage heading north noted. No further penetration possible.
Forfar Blue Hole: At Blue Hole Cay, off Stafford Creek. A rift system with associated surface collapse, and two entrances. Explored to a depth of 40 m where it became constricted.
Stafford Creek Blue Hole: Approx. 2 km up Stafford Creek, a silt-filled Blue Hole remnant, 10 m deep, surrounded by mangrove. A very hot layer at a depth of 3 to 6 m was encountered at this site.

Inland sites:
Uncle Charlie's Blue Hole: A 15 m deep entrance lake with a rift in the centre descending through silt/organic banks to a cave passage at 20 m depth. A final depth of 45 metres was reached, with passage development at 20 and 45 m depth.
Paul's Blue Hole: Descended to 55 m depth without sign of bottom. Reputed to contain stalactites at 45 m depth. Plumbed to a depth of 75 m.
Cousteau's Blue Hole: Descended to -40 m without sign of bottom. Walls deeply undercut, but no sign of passage.
Hourglass Lake: Double lake with hourglass shape. Blue Hole at south side undescended, but close to Paul's Blue Hole.
Goby Lake: Lake 6 m deep is possibly silt-filled remnant of Blue Hole. Contains freshwater eels, and goby fish.
Church's (De Souza's) Blue Hole: Silt bottom reached at -30. No horizontal development noticed.
Stalactite (Archie's) Blue Hole: Descended to silt banks at -45 m at sides, plumbed to -50 m at centre. Major stalactite development under ledges at 22 to 33 m depth, stopping abruptly at -33 m, where the halocline is encountered.

THE 1982 BRITISH BLUE HOLES EXPEDITION

The success of the 1981 Expedition, and the obvious potential for further discoveries beneath northern Andros prompted members of the 1981 Expedition to organise a further venture the following year, with the original intention of pressing on further in Conch Sound Blue

Hole, examining the Blue Holes of South Mastic Bay, which for logistical reasons could not be visited in 1981, and, if possible, examining some of the deeper Blue Holes further south, in the Mangrove Cay/South Bight areas worked by Benjamin in 1960-1973. It was hoped that the scientific programme might be expanded, and further biological and hydrological studies made in both the inland and oceanic Holes.

Once again, the Royal Geographical Society gave its support to the Expedition, a vital factor in the search for sponsorship, and H.R.H. The Duke of Kent graciously agreed to continue his Patronship for a further year. Many of the 1981 sponsors were willing to continue their involvement, notably Spirotechnique Ltd, who again made equipment available on a loan basis to the expedition. From the outset, the programme was more ambitious, with a team of fifteen in the field. The planned programme was split into three sections. A team of six would fly out in advance, and make a reconnaisance visit to the South Island, based on the M.V. Victoria, a 12 m trawl boat made available through the Miami-based Institute for Underwater Archaeology, whose Secretary, David Pincus, again took on the job of U.S. liaison officer. The boat was made available at no cost, on the understanding we would pay fuel costs, which were further reduced by David Pincus obtaining this at cost price in Miami. The second and third stages of the expedition would run simultaneously, with a five-person group basing themselves at the Forfar Field Station, and studying the biology and hydrology of the inland Holes, and the rest of the team working primarily on oceanic sites, basing themselves further north at Nicholls Town. There, through the assistance of the Bahamas Tourist Office in London, we had obtained two small self-catering villas for a service charge only, belonging to the Tradewind Villas group. These, though cramped, gave a reasonably comfortable standard of living that was slightly higher than the norm for caving expeditions which, considering the technical standard of the diving we were hoping to achieve, and the need for a high-standard of health, was perhaps no bad thing.

Despite the interest shown in the Expedition by the national press, by June 1982 the expedition was still far short of the financial support needed to ensure its success. As things were beginning to look bleak, an offer was made by John Gau productions for film rights, and the suggestion that BBC's "World About Us" series might be willing to put up a part of the financial backing for a film of the latter part of the Expedition's work, in the Conch Sound area. This meant that the Expedition was considerably more financially secure, but the agreement had still to be confirmed when the first members left for the Bahamas on July 16th. It was not until the base was set up in Nicholls Town that the film offer was confirmed, and the late re-adjustment to fitting in a film-crew, albeit a small one, caused a fair amount of friction within the team, despite the financial necessity of their involvement.

With much on-the-spot help in Nassau from members of the Bahamas National Trust, the 1982 Expedition got under way, sailing from Miami on July 17th, with a I.U.A. member, Clark Shimeall, as Captain. The freight was collected from Nassau and the M.V. Victoria anchored in Mangrove Cay bay on Tuesday, 20th July. There, a series of four Blue Holes were examined, and minor gear problems ironed out before a move further south, to Deep Creek, was made to examine Blue Holes with a peculiar coral ring around each cave, known as "Doughnut Holes". Local help from Stan and Dorothy Clarke showed us the sites concerned, and several dives were made there before the move to Nicholls Town and the start of the main work of the Expedition.

The team was based at Nicholls Town from the 3rd to 28th August, with the inland team based at Forfar from August 3rd to 14th. During that time, a total of six ocean sites were visited, and more than 1400 m of underwater cave passage was added to the earlier, South island total of 300 m, bringing the total new cave explored in 1982 to 1800 m. The maximum depth reached, in Forfar Blue Hole, was 63 m. A number of inland sites were examined further, with the only new discoveries of note being made in Ocean Hole, Nicholls Town. The inland team visited a total of 15 sites, making studies of the water chemistry and biology at each site.

At the close of the expedition, 3 members returned via Grand Bahama island, where they had the privilege of diving in the world's most extensive underwater cave, the eight-kilometre "Lucayan Caverns". This is a cave of a type as yet unknown on Andros, lying at the base of the freshwater lens, inland, with extensive horizontal development in a complex phreatic maze. The only Andros caves explored in 1981 and 1982 that have any similarity are Uncle Charlie's Blue Hole, Ocean Hole, and the dry cave system beneath Morgan's Bluff, north of Nicholls Town. This latter system lies approximately two to three metres above present sea level, and consists of a series of phreatic passages, very infilled with silt and guano deposits. Mindful of possible lung disorders, despite the official absence of histoplasmosis in the Bahamas, the divers in the team forbore exploration of these caves.

Transport 1982: Marine transport was on the M.V. "Victoria", captained by Clark Shimeall, with shallow-water Zodiac inflatable backup. The pontoons at Forfar Field Station were used to reach the ocean sites at Ray Cay and Forfar Blue Hole, and in the examination of "inland" sites in Stafford Creek, by the inland team. Land transport proved to be a greater problem than in 1981. Whilst the Forfar team again used I.F.S. vehicles, the team at Nicholls Town were less successful. Transport had been promised in Nassau by both the Bahamas Water Authority and Bahamas Power Authority, but on reaching Nicholls Town, it was obvious that this was not available. Tradewind Villas allowed use of their "rubbish pick-up", a not tremendously reliable vehicle which nevertheless gave good service on local drives to and from Conch Sound. The Nicholls Town District Commissioner made available the town truck, a better class of refuse vehicle, for long inland runs. Many problems were solved by Harry Treco, the local garage owner, who was more than generous with his time and help, and who on many occasions lent the expedition or film crew his own pickup truck, and his own services as guide. The expedition owes much of its eventual success to Harry Treco, and a special debt of gratitude is due.

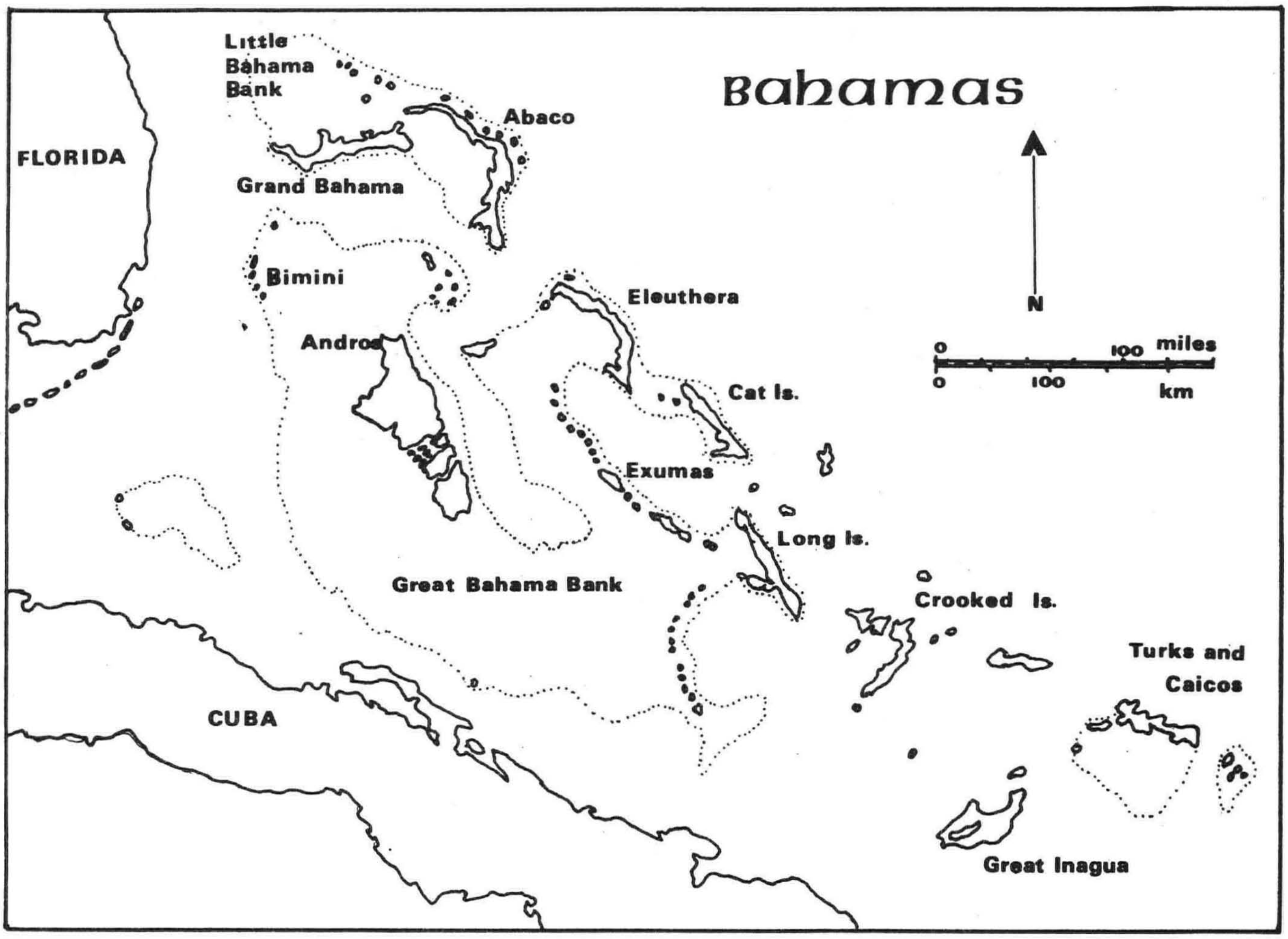
Freight: In 1982, freight sponsorship was obtained through Moonbridge Shippers, who had the freight ready for collection at their agents in Nassau, Container Services Ltd, when the expedition arrived. They were also able to provide a return service to London, and this help was greatly appreciated. The Bahamas National Trust were most helpful with their loan of a vehicle in Nassau to help move freight to the M.V. Victoria. Customs exemption on expedition freight was obtained on production of an official collection permit from the Department of Agriculture and Fisheries.

Film: A 55 minute documentary was made of the Expedition's work in Conch Sound Blue Hole, and other nearby Holes, for the BBC-2 "World About Us" series. This was made by John Gau Productions, under the field directorship of Duncan Gibbons. The film crew were Peter Scoones and Peter MacPherson (underwater cameramen), Chris Goodger (surface cameraman) and Chris Renty (sound recordist). The film had its first television screening in April 1983.

SITES VISITED IN 1982

A brief description of sites visited in 1982 is given here. A more detailed description of the major sites discovered or extended is given elsewhere in this report.

Ocean Sites:
Conch Sound One (CS1): The major exploratory site of the expedition. Almost 500 m of passage was added to the 1981 total, bringing the explored length of this cave to a little over 1500 metres. The main passage was extended to a point 1160 m from base, representing at the time of discovery the longest single penetration ever made in a submarine cave. The way on was lost at this point.
Conch Sound Two (CS2): Explored for 200 m in 1981, this cave was extended by a further 50 m.
South Mastic Bay One (SM1): A twin entrance led to two separate caves. SM1a, the main entrance, led to 230 m of passage at a depth of 50 m. SM1b was explored for a total of 100 m at a maximum depth of 30 m.
South Mastic Two (SM2): A collapsed entrance near shore. Impenetrable, with strong currents flowing between boulders choking the passage.
Forfar Blue Hole: This constricted Blue Hole, examined in 1981, was descended through further constrictions to a trunk passage at 63 m depth.
Mangrove Cay area (MC 31-33). Four ocean holes off the settlement of Moxey Town, on Mangrove Cay, were examined. The caves were aligned on a north-south slump fault, and may possibly be interconnected. The maximum penetration made was of 100 m, in site MC 33, to a depth of 40 m.
Kemps Bay area: Two ocean sites, known colloquially as "doughnut holes" were visited. One



was entered for a distance of 50 m to a depth of 30 m the other for 40 m to a depth of 40 m. Neither was pushed to a conclusion. At Mars Bay, a deep circular Blue Hole in the intertidal zone was descended for 61 m without reaching bottom.

Inland Sites: Uncle Charlie's Blue Hole: Near San Andros, explored to a depth of 45 m in 1981, Rift passages leading off at that depth were explored to choked conclusions.
Ocean Hole: Situated in a bluff overlooking Nicholls Town. A collapse opening in the top of the bluff contained a large water surface at sea level. Dived to a depth of 50 m, where a large passage was explored for 160 m to a boulder pile. The passage continues.

ACKNOWLEDGEMENTS

The success of the 1981 and 1982 Expeditions would have been impossible without generous assistance from a great number of individuals, organisations and sponsoring bodies. To them we owe a considerable debt of gratitude, and offer our sincerest thanks.

Financial Support: The Royal Geographical Society, The Royal Society, The World Expeditionary Association, The Sports Council, The Bahamas National Trust, The Ghar Parau Foundation, Rebbeck-Hunter Ltd., Wookey Hole Caves Ltd., Phoenix Insurance (Bristol) Ltd., Comex Houlder Diving Ltd.

Transport and Freight: Bahamasair, Moonbridge Shippers Ltd., Pacific Steam Navigation Co. Ltd., British Airways, Pan-American Airways, Container Terminals (Nassau) Ltd., H. Treco Esq., Institute of Underwater Archeology, Bahamas Water Authority, Bahamas National Trust, Nicholl's Town District Commissioner.

Diving Equipment: Spirotechnique Ltd., GUL Wetsuits Ltd., Wemlor Marine Ltd., George Benjamin, Troll Safety Eqpt., Small Hope Bay Lodge, International Field Studies, Apeks Marine Ltd., SOS Diving Eqpt., Tabata (UK) Ltd., North Cape Fabrics Ltd., Suunto Ltd., George Ibberson and Co. Ltd., Casio Watches Ltd., Dive-Care Systems, Sportsways, Michael Guy Esq., Undersea Services Ltd., Triumph Swimwear Ltd.

Surface and Scientific Equipment: Institute of Oceanographic Sciences Ltd., McMaster University, Reading University, U.S. Geological Survey in Miami, Professor J.D. Kramer, Professor D.C. Ford, Professor H.P. Schwartz, Ota Murdoch, Mark Luff, Rabone-Chesterman Ltd., Collins Publishers Ltd.

Medical Supplies: Roussel Laboratories Ltd., Parke Davis and Co. Ltd., Optrex Ltd., Lasonet Products Ltd., Johnson and Johnson Ltd., Jeyes Ltd., Goya International Ltd., Smith and Nephew Ltd.

Photographic Equipment: Agfa (UK) Ltd., Fuji Film Co. Ltd., Benjamin Film Laboratories, Wotan Lamps Ltd., Nikon (UK) Ltd., Greenway Marine Ltd., C.P.L. Ltd (Bristol)., Thorn Lighting Ltd., Polaroid (UK) Ltd.

Logistics and Support (UK): Nigel Winser, Oliver Lloyd, Admiral Sir John Rawlins, Dr. Nic Flemming, Les Sullivan, Mike Busitilli, Col. John Blashford-Snell, Geoff Attwood, Nigel and Caromay Gifford, Surgeon-Captain Ramsay Pearson, Bernard Parker, Pat Cronin, Peter and Jean Abbott, Zoe Hall, Bahamas Tourist Office, Chris Howes, Gordon Fielden, Ronnie Faux.

Logistics and Support in the Bahamas: Bahamas National Trust, Basil and Paula Kelly, Rod and Moira Attrill, Susan Holowesko, Jack A. Hayward, Dennis Williams, Jill Yager, International Field Studies Inc., Marylin Lisowski, Stan and Dorothy Clarke, Grace Green, Larry Smith, Colin Higgs, Cdr. Hugh Powlett, RN., Richard Hildyard, Tradewind Villas, Andros Beach Hotel, Harry Treco, Mike Guy, Bahamas Ministry of Tourism, Richard Farrington, Dick Birch.

Logistics and Support in the U.S.A: Bruce Wilson, David and Michael Pincus, Les Savage, and the Institute of Underwater Archeology.

The expedition owes a special debt to Dr. George Benjamin of Ontario, Canada, for his continual help and assistance during both expeditions, with advice and equipment. To him this report is respectfully dedicated.

CAVE SCIENCE

Transactions of the British Cave Research Association Vol.11, No.1, March 1984

OUTLINE GEOLOGY OF THE BAHAMA ISLANDS

R. J. Palmer

The Bahama Islands occupy an area of approximately 11,400 sq. km to the southeast of Florida, stretching in an extensive archipelago virtually to the islands of Cuba and Hispaniola to the south. There are 18 main islands, and over 700 smaller cays (islets), distributed on several "banks" which make up the main Bahama platform. Of these banks, the two largest are the Great Bahama Bank, which contains the islands of Andros, Exuma, New Providence, Eleuthera, Long and Cat, and the Little Bahama Bank, to the north, with Grand Bahama and Abacos.

The structural base for these islands is the Bahama platform, which covers an area of over 100,000 km^2. and which extends from 20°50' to 27°25' N and 72°37' to 80°32' W. This platform is sectioned into its various "banks" by deep oceanic troughs (Tongue of the Ocean, Exuma Sound) and is surrounded by steep oceanic dropoffs, including the Florida Straits, separating it from the American mainland, and the Old Bahama Channel, which separates it from the islands to the south (Fairbridge, 1975).

The entire block is composed of limestones, to a known depth of 4450 metres (Spencer, 1967), horizontally-bedded, and of shallow-water marine origin. The base of the platform lies at a depth of approximately 8000 metres and represents a shallow water zone of vigorous carbonate formation during immediate post-Pangean times (circa 200 million years ago). Tectonically-induced faulting at this time formed shallow basins (perhaps with a downthrow of only 20 metres or so) which dropped far enough to place them below the main zone of carbonate formation. The resultant growth of the higher banks has, in the intervening time, seen a relief of as much as 2000 metres developing between bank and basin.

The top of the banks are composed of shallow marine (oolitic), coral and aeolian limestones (often with calcrete crusts and paleosols) and living reefs, together with carbonate sands. The banks subside at a rate of about 1 cm per 250 years, but this is replaced by new carbonate deposits, maintaining surface stability in the area.

The entire region was greatly affected by glacio-eustatic sea-level changes in the Pleistocene, encouraging karst erosion, and creation of karst landforms. There are numerous caves and sinkholes, occasionally reaching depths of 100 m (this figure represents the estimated lowest sea-level known from Pleistocene times). Cavities, when only a metre or two deep, are known as "banana holes", holding soil and water, and "blue holes" when larger and deeper, from their colouration against the lighter waters of the surrounding reef, or inland forest.

The larger islands (Andros, Grand Bahama, Abaco etc.) have well-developed freshwater lenses beneath their surface, and it would appear that cavern development is still actively taking place within this phreas.

Higher surface landforms are largely formed from eolianite limestones, blown into dunes during periods of emergence, and later consolidated into rock. Such dune-rock consists of fine-grained skeletal sediments, fine, well-rounded oolite and shelly-ooid-peloid sediments of an intermediate grain size. A distinction can be made between these dune-chains, which form the backbone or eastern margins of many of the islands, and the relatively low areas of shallow-marine origin. The dunes also contain cave-development, possibly remnants of systems formed at higher sea-stands than the present. Dunes reach a maximum elevation of 67 metres on Cat Island, representing the highest point in the Bahamas.

DESCRIPTION OF ANDROS ISLAND

Andros is the largest of the Bahamian islands, with a land area of about 600,000 hectares. It is not so much a single island as a collection of islands, with three main land areas, North Andros and South Andros being separated by the low island of Mangrove Cay. The greatest dimensions of Andros as a unit are about 177 km (N-S) by 65 km (E-W).

The island is composed purely of limestone, in horizontal beds, all of which is of marine or eolian origin. Surface deposits divide generally into two, corresponding with the two distinct landforms of the island. The eastern coast is fringed inland by parallel eolian dunes, dating from a period of island exposure during the lower sea-levels of the Pleistocene, which reach a maximum height of 20 metres at Morgan's Bluff, north of Nicholl's Town. Behind these consolidated rock-dunes, the island is flat, rarely reaching more than 2-3 metres in height, and is composed of oolitic and coral limestones laid down in shallow seas during recent times. The geological history of the island is one of stability since the first sediments were lain down in the late Mesozoic. Limestone sediments have been accumulating since then, keeping pace with a slow subsidence (at present approximately 1 cm in 250 years) and are now known to be at least 4450 metres thick from test borings at Fresh Creek. Drilling was abandoned at this depth when some 2400 m of drill pipe was lost in a natural cavern ten metres high at a depth of approximately 3250 metres. Basement is thought to be at about 8000 metres.

To the immediate east of the island lies the 2000 metres deep "Tongue of the Ocean", an oceanic trough that separates the eastern part of the Great Bahama Bank (Containing the islands of Eleuthera, Cat, Long and the Exuma Cays) from the western section (Andros, Bimini, Berries). Edging this, a kilometre or so off the eastern coast of Andros, is a long barrier reef, one of the world's greatest. A shallow lagoon, generally only a metre or two deep, separates the reef from the island.

The western coast of Andros is virtually indistinguishable from the sea, a low and swampy coastline that turns in and out of innumerable tidal creeks, mangrove swamps, sand bars and mudbanks. Travel in this area is extremely difficult, and most of it is visited only by sponge fishermen and drug-runners, who use the confusing geography of the area as a cover for their nefarious activities. For the latter reason alone, great care is needed if venturing into the western coastal region or remote interior of the island.

From the coast, the very shallow seas continue into the western reaches of the Great Bahama Bank, which continues westwards for over 100 km and a maximum 7m depth before dropping away into the Florida Straits.

Inland, the island is heavily forested, with pine, mahogany and various hardwoods that prohibit easy travel. The north island was largely felled in the early 1970s by the Illinois Paper Co. who left a network of roads that are still useable, allowing access to much of the interior.

Settlement today is generally along the eastern coast, the main island sections are linked by air and ferry, and roads have been laid parallel with the coast down the length of the island (though still separated from linkage by the Bights). There are four main airfields, at San Andros, Fresh Creek (Andros Town), Mangrove Town, and Congo Town on South Andros.

Beneath the island lies a freshwater lens, or more accurately a series of lenses, locally influenced by tidal creek and coastline position. They reach thicknesses of up to 30 to 40 metres, depending on position and distance from the nearest marine influence. Considerable karst development has taken place during low sea-level stillstand, when glacial storage of ocean water lowered sea-levels by an estimated 100 metres below their present level. Whilst it is likely that cave development existed prior to this phase, the lowering of sea level contributed to vertical cavernous development within the island bedrock, and probably within other areas of the Great Bahama Bank, now obscured by the sea.

REFERENCES

Fairbridge, R.W. 1975. Encyclopoedia of Workd Regional Geology. (Bahamas in part 1, pp. 109-115. Dowden, Hutchison & Ross, Stroudsberg, Pennsylvania.

Spencer, M. 1967, Bahamas Deep Test. *Bull. Amer. Assoc. Petrol. Geol.* vol.51,pp.263-8.

M.S. Received December, 1983.

R.J.Palmer,
7, Lovell Avenue,
Oldland Common,
Bristol.

CAVE SCIENCE

Transactions British Cave Research Association. Vol.11, No.1, March 1984.

THE BLUE HOLES: DESCRIPTION AND STRUCTURE

Martyn Farr and Rob Palmer

Blue Holes are cavernous features of solutional origin found within the limestone bedrock of the Bahama islands, which have been reported from elsewhere in the Caribbean (notably Honduras, Yucatan and Turks and Caicos Islands). They are the result of phreatic development within the freshwater lenses of the islands and of further modification during periods of low sea-level. They appear to be divisible into two main sub-types:

a) Inland Blue Holes (cenotes). Circular, often deep shafts that bell out beneath the surface into a wider cavern. These frequently reach through the freshwater lens into the underlying salt-water. On Andros alone over 120 such sites have been noted, and of 78 holes depth-sounded on the island by the Bahamas Land Resource Survey, four exceeded 100 metres (the deepest being 110 m). All are water-filled today, though some are known to contain stalactites at depth. Few have evident horizontal cave development associated with them, though this could in many cases be obscured by massive sedimentation at their base.

b) Oceanic Blue Holes ("boiling holes"). Cave systems opening out on the surface, generally beneath sea-level, which contain horizontal and, usually, vertical development, often stretching for considerable distances. Most of these caves are subject to strong tidal currents, generally 2½ to 3 hours out of phase with tides at the surface, which flow in and out of the caves. Safest times of exploration are at "slack water", though this is of very few minutes duration, and, because of vagaries of wind and weather, not entirely predictable. The safest time for distance penetration is in the changeover from "suck" to "blow", approximately mid-way between high and low tide at the surface. Oceanic holes have been discovered off Andros that reach depths of other 100 metres, and lengths in excess of 1.5 km in extent. At the time of writing, no shallow inland system resembling the Lucayan Caverns of Grand Bahama Island has been discovered on Andros, though it is possible such caves exist within the lens. They would appear to be closer in relationship to ocean holes than the inland cenotes.

CONCH I BLUE HOLE SC 974.808

Conch I Blue Hole lies at the northern edge of Conch Sound a short distance from Nicholls Town. The large horseshoe-shaped depression is a well known feature locally, being sited about 70 metres offshore at a depth of two metres.

There are four large entrances and a number of smaller ones, several of which interconnect. A prominent feature of the entrance near the shore is an eight-metre-long boat. Below this, at a depth of six metres lies open passage trending both north and south. To the north an initially spacious route degenerates to a complex area of small bedding controlled passages. A considerable flow sweeps through through these, the area having been penetrated for a distance of 70 metres. Marine life is abundant and one of the larger chambers is occupied by a fine grotto of stalagmites.

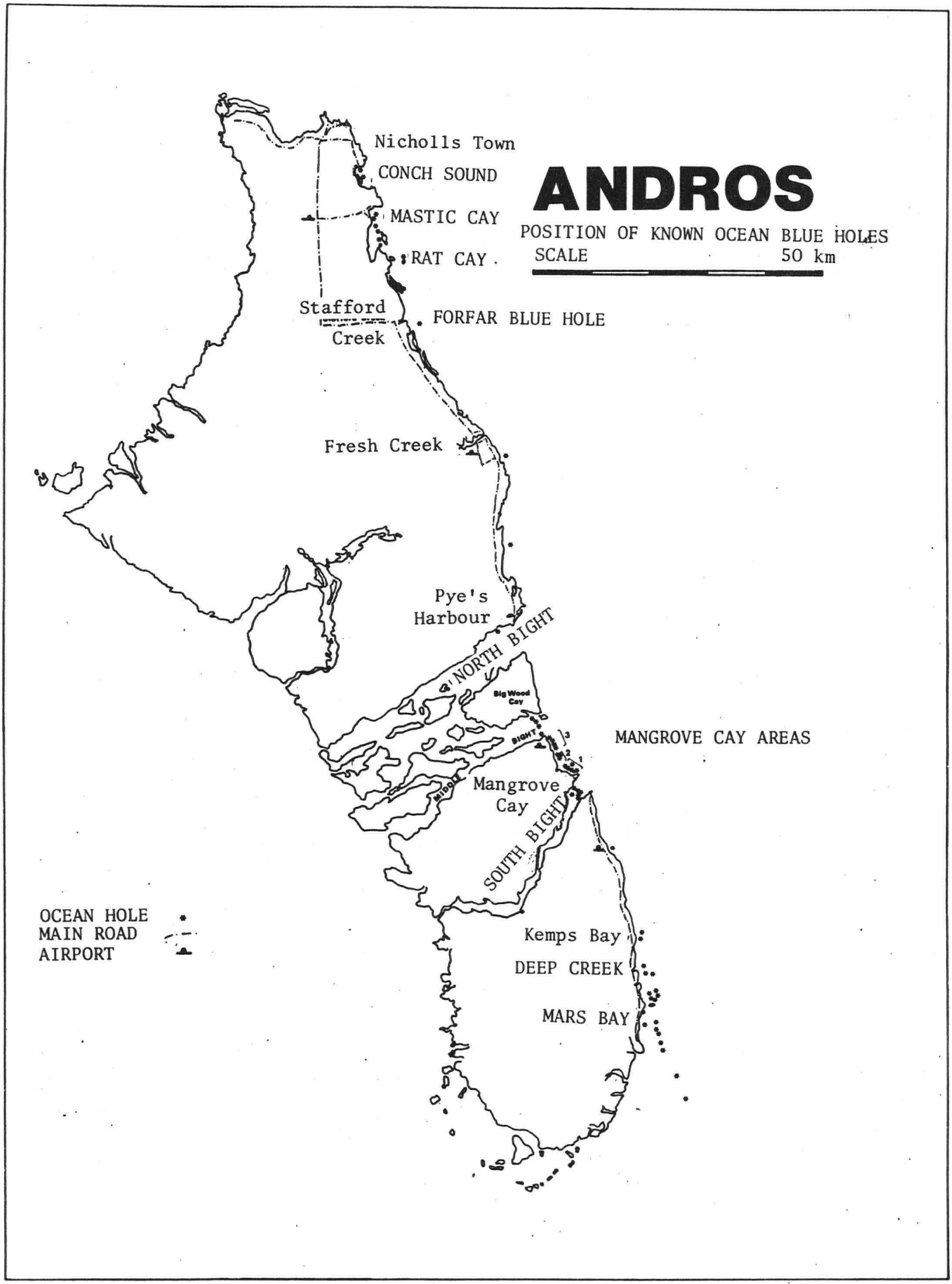
In the other direction the floor gradually shelves away to 20 metres, passing beneath two of the larger entrances. This leads down to the impressive five-metre-diameter South Passage, the site of the longest penetration on the island (Aug. 1982).

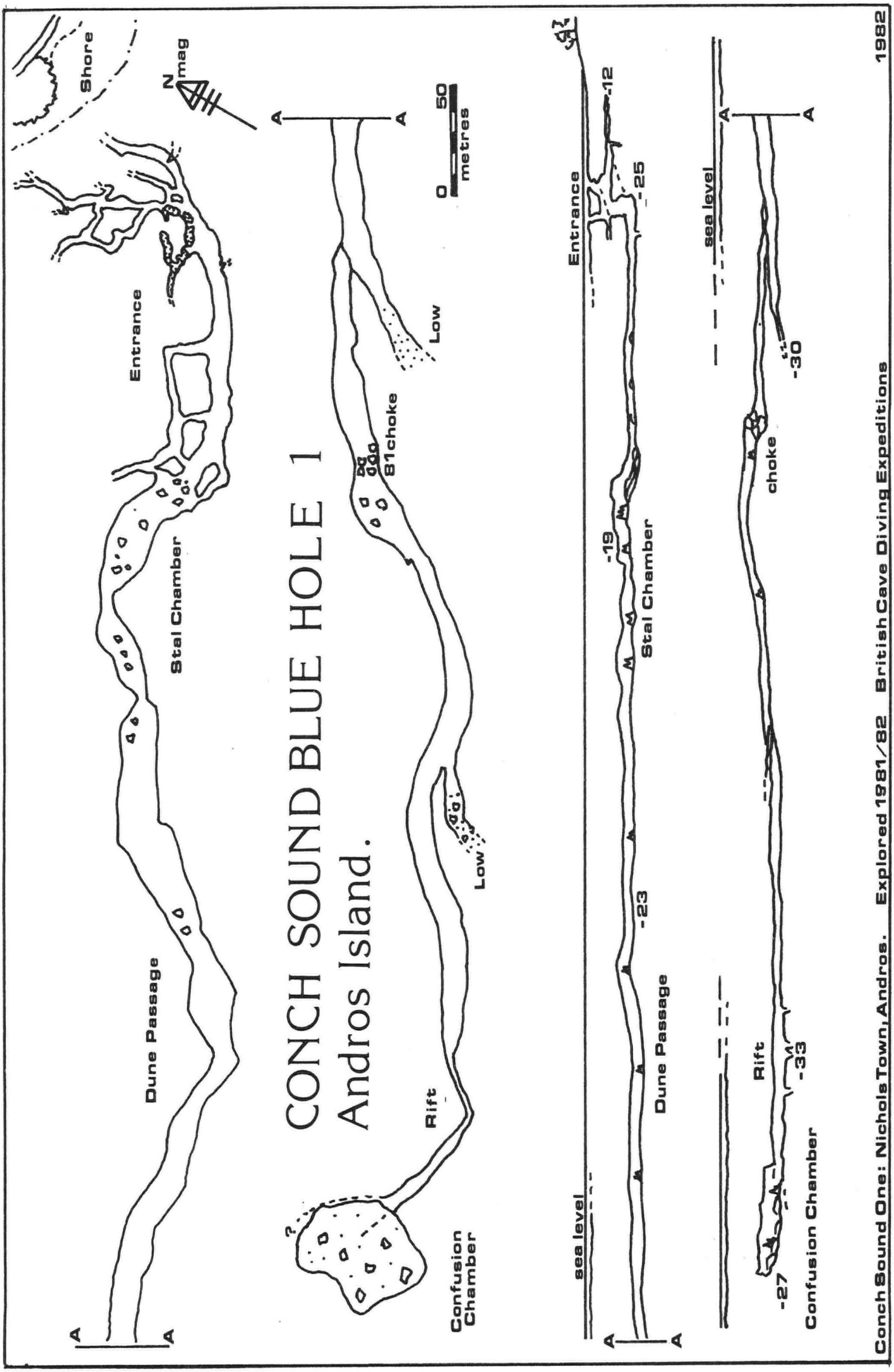
A wealth of marine life occupies the entrance passages, apart from the fish the most conspicuous being the hydroids, tube fans and sponges. Once in to the South Passage the proportions gradually begin to diminish and from a diving point of view present strong currents - recorded at three to four knots. On the walls and roof sponges and corals proliferate but life is conspicuously sparse on the floor over the next 90 - 100 metres. This consists of coarse silts and small friable rocks, shifting at the mercy of the current. Several side passages are to be found in this area, all oxbows looping back to the main passage.

At 130 metres from the entrance a substantial chamber is entered, generally less than three metres in height but over 18 metres in width. A fine grotto of stalagmites lies on the western side, a small indication of the wonders which lie ahead. As with all rock surfaces in the first 500 metres the stalagmites here are heavily encrusted with marine organisms.

Beyond this point the route involves frequent areas of breakdown, posing short ascents over large slabs. Odd patches of stalagmite are to be found over much of this sector but at 190 metres one of the finest decorated chambers is gained. The route passes directly through this amazing area and for the next 90 metres continues through a forest of stalagmites where the precise limits of the passage are difficult to establish. Pillars up to three to four metres length are frequent but by far the most common are the stalagmites. It is significant to note that stalactites are virtually absent.

Once beyond the grottos it is evident that the passage is much larger than hitherto while at 350 metres one starts in to a huge tunnel certainly over 15 metres in width and in all probability regularly over 20 metres. The floor consists of fine silts, undulating and well rippled like sand dunes in a desert. The 'Sahara' continues agrophobically to 450 metres where once more an 'island' of stalagmites breaks the monotony. Several more small grottos intermittently line the route to 550 metres providing useful landmarks. By this point there is a significant reduction in marine life; there are no hydroids, anemones or corals.


ANDROS
POSITION OF KNOWN OCEAN BLUE HOLES
SCALE
50 km
Nicholls Town
CONCH SOUND
MASTIC CAY
RAT CAY
Stafford Creek
FORFAR BLUE HOLE
Fresh Creek
Pye's Harbour
NORTH BIGHT
Big Wood Cay
MANGROVE CAY AREAS
3
2
1
MIDDLE BIGHT
Mangrove Cay
SOUTH BIGHT
Kemps Bay
DEEP CREEK
MARS BAY
OCEAN HOLE
MAIN ROAD
AIRPORT



Conch Sound One: Nichols Town, Andros. Explored 1981/82 British Cave Diving Expeditions 1982

Occasionally one may observe the odd crab, shrimp or snake eel but from this point on bare rock surfaces become increasingly prevalent.

By 600 metres the depth has reached 26 metres and at this point a junction is encountered. Directly ahead and attaining a depth of 28 metres is a 60-metre-long passage terminating at a low silted section. A high level passage from the junction is the way on, six metres wide but less than two metres high. The reduced proportions are short lived. In less than 20 metres the passage doubles in size and there are several other noteworthyfeatures. The cave is now seemingly devoid of life and the floor of the passage becomes progressively more of a jumble of block breakdown. At 700 metres several extremely large slabs pose a constriction (the limit reached in Aug. 1981) at a depth of 23 metres.

This is passed to give access to another very large ascending chamber. At the head of the slope the floor lies at 15 metres depth and the roof three metres above. This cavern is over 20 metres in width dominated by a now rare grotto of large pillars. The shallowing is temporary and shortly a descent gives a resumption of depths at around 25 metres.

At 805 metres there is a junction. The obvious route is directly ahead but this closes down somewhat intimidatingly at 823 metres. The main way on lies down to the right through a slightly constricted opening where the cave continues its south-westerly trend. By this point the depth has increased to 28 metres and the passage is never less than nine metres wide. Spacious proportions continue all the way to 915 metres where there is a sudden transformation in character. The next section is an awkward rift the floor of which reaches 34 metres. Narrow ledges at 29 metres provide the most paractical route,but at 936 metres one is forced down and the passage is substantially reduced in size.

As suddenly as it began the rift ends at 986 metres and, despite 30 metres depth, a spacious continuation is found. Shortly a vast breakdown chamber is reached - Confusion Chamber, which exceeds 46 metres by 37 metres. Huge blocks of limestone are scattered in all directions but the most striking feature of the place is the extent to which the rock surfaces are severely pitted and corroded, a complete contrast to the walls near to the entrance. A fine array of stalactites can be found here, as 'glassy' as the day the cave was flooded. A circumnavigation of the chamber has been made but the diver could locate no definite way on.

Surprisingly life was found to exist even as far from the entrance as Confusion Chamber. In a corner a couple of weak sea squirts were located and nearby a solitary cave fish *Lucifuga spelaeotes* was noted, to date the only sighting of this species in the network.

Over the two expeditions to Andros the total length of passage explored and surveyed in Conch I has been in excess of 1520 metres. It must certainly rate as one of the most interesting and challenging sites anywhere in the world.

CONCH 2 BLUE HOLE SC 972.791

Conch 2 Blue Hole is situated about 50 metres offshore directly across the bay from the major site Conch 1. The sea floor in the locality is less than two metres and the hole is particularly conspicuous during outflow. A strong upwelling of clear blue water produces a distinct 'mushrooming' effect that is evident over a considerable distance and best viewed from the air.

The entrance, which is less than two metres in diameter, lies at the western edge of a small oval-shaped depression at a depth of six metres. Observation and diving experiences revealed a strong flow at every stage of the tidal cycle, excepting a period of approximately 15 minutes at the reversal. Explorations at this site were potentially hazardous as there was considerable risk of being prematurely ejected from the entrance before the necessary decompression schedules were complete. Such an intense flow was experienced at no other site.

Another unusual characteristic of this cave was the quality of the outflow. On both expeditions a distinct sulphurous smell could be detected, a feature noted by earlier explorers.

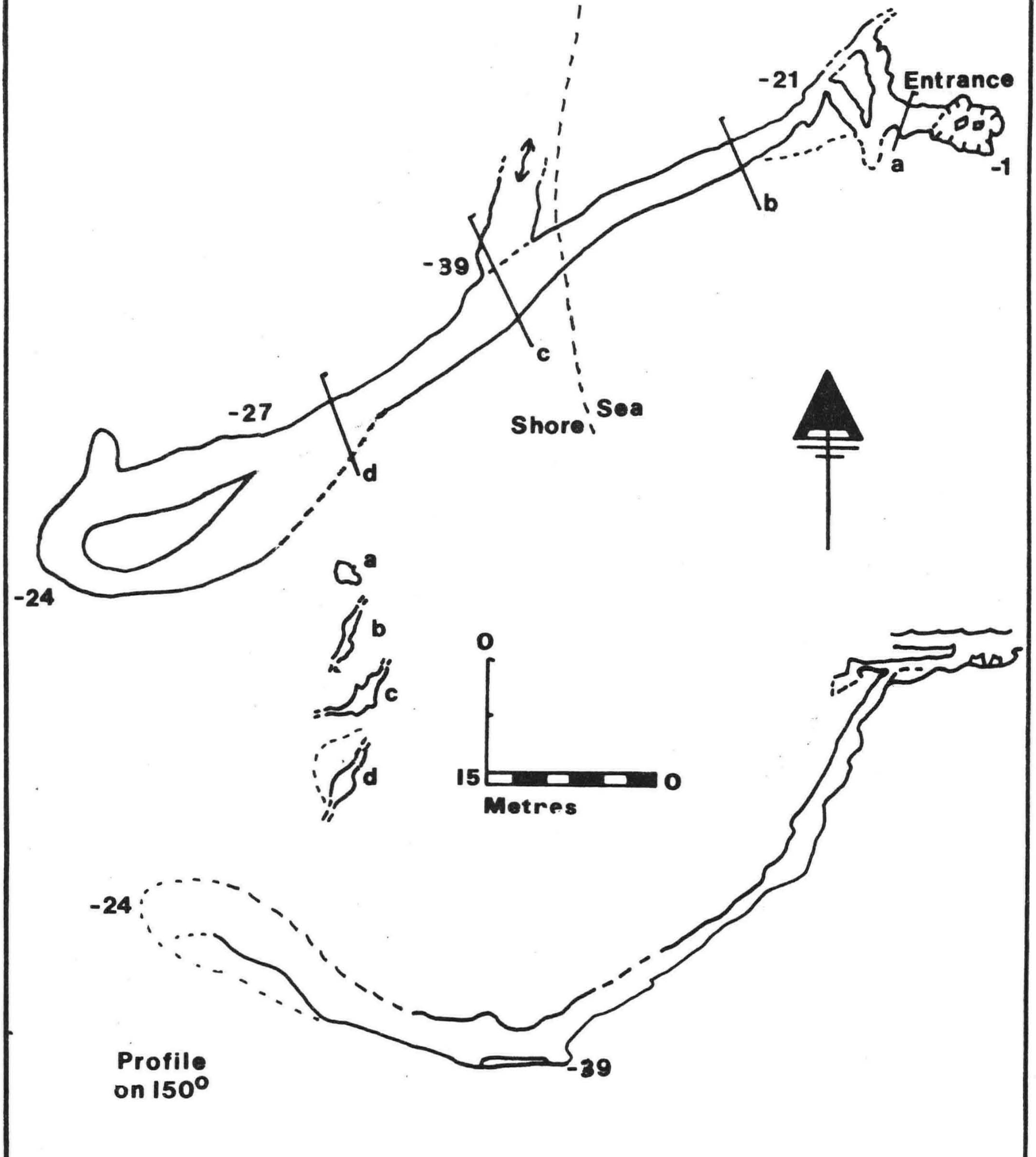
Proceeding from the entrance the rocks are coated with a strange creamy substance, best compared to cotton wool. Despite the apparent 'pollution' there was a profusion of fish life. Snappers and grunt for example swarmed beyond the limit of the daylight zone, while anemones were common to perhaps 45 metres. But beyond this point there was no marine life at all.

The cave descends at a steep angle for 60 metres at which point the depth reaches 25 metres. Here the passage assumes a more pleasant character - a comfortable half tube as opposed to the initial rift. The descent continues, more gradually, until at a distance of 120 metres the deepest point is gained. Here at 39 metres an area of bedding stretches off to either side; that to the north has been penetrated for five metres before the roof lowers to within 0.3 metres of the floor. Water emerging from the beddings has been observed to produce a very strange 'mixing effect'. Both passages emit a flow of clear water but at the convergence a shimmering mixing effect may be observed at a certain stage in the outflow. Visibility here is reduced to approximately 0.3 metres. This unusual characteristic has yet to be studied.

Beyond 120 metres the explored route ascends gradually into a large chamber with copious quantities of light silt. In 1981 exploration was terminated at 180 metres at a depth of 27 metres. The following year several more dives were made to this area but other than achieving a loop no significant extension was made. The way on, if at all negotiable, must surely be located in the vicinity of the maximum depth.

SOUTH MASTIC ONE BLUE HOLE (T.C.002723)

South Mastic One Blue Hole is the largest blue hole in the South Mastic Bay area, lying to the north of a small island approximately one kilometre offshore. There are two separate caves at this location and a 'natural arch' set about midway between the two on the sea bed.



CONCH SOUND BLUE HOLE: 2.
Conch Sound, Andros.

The largest cave starts as a huge inclined rift over 10 metres high by five metres wide. Over the next 40 metres the route continues large, descending gradually to 21 metres depth. A narrowing rift then leads for 20 metres to the head of a constricted shaft. This quickly opens out and leads down to 48 metres depth. At this point the floor comprises a bed of fossilised Conch shells and a low wide arch gives access to a spacious ascent. A large boulder-strewn chamber is entered 50 metres later, at a depth of 37 metres. The shallowing is but temporary, however, as immediately beyond the chamber the route once more descends steeply back to 47 metres, a depth it maintains to the boulder-choked termination, 220 metres from the entrance.

The second cave is considerably smaller than the first. Side-mounted cylinders are essential for its exploration which leads for over 100 metres to another boulder choke. As with the main cave strong currents are present and a normal distribution of marine life can be found throughout.

SOUTH MASTIC 6 BLUE HOLE (TC 021.674)

South Mastic 6 is the most southerly of a small group of blue holes lying in South Mastic bay. Access is by boat of shallow draught.

This site is an impressive shaft partially covered by a bridge-like roof at a depth of six metres. The hole is 20 metres deep but other than a large alcove extending to the north for 10 metres there are no further openings and no evidence of water movement. It would appear that S.M.6 is in the process of being infilled with sediment.

SOUTH MASTIC BLUE HOLE TWO (S.C.995727)

200 metres south of Mastic Bay pier, 30 metres offshore, a 3 m deep choked opening was examined. The blockage was impenetrable, but might be opened by a determined digging operation. A very strong current was observed, rocks moved in the entrance choke being sucked down into the cave. The same sulphurous taint as at Conch Sound Two was evident.

RAT CAY BLUE HOLE (TC 039.656)

Rat Cay Blue Hole lies several kilometres offshore from the mainland nearly halfway between Stafford Creek and Nicholls Town. It takes its name from the small island of Rat Cay which lies only 10 metres from the entrance.

Lying so far out to sea the clarity of the water at this site is almost unparallelled and a diverse marine life extends deep into the cave network.

The entrance lies at the northern side of a five metre deep pit in an area of otherwise shallow reef. The floor at the entrance lies at six metres and a spacious tunnel four metres wide by two metres high leads quickly to a narrow but easily descended pot. At the foot one must be wary of the corals which encrust all surfaces. These can exact a heavy toll on a misplaced hand or leg. Ahead the cave enters an area of bedding which becomes prohibitively low for conventional back-mounted sets 35 metres from the entrance.

Using side-mounted equipment an easy wriggle forward leads after a further 25 metres to a spacious continuation. Beyond this point the entire cave is bedding controlled, of ample proportions, and depths nowhere exceed 18 metres throughout the 700 metre complex.

A major junction is located 130 metres from the entrance. The larger passage trends directly ahead, due west, which can be followed along a spectacular, gently undulating route for 315 metres. At this point the cave splits up and passing an awkward squeeze gives access to a small chamber at 325 metres. Ahead all ways are prohibitively low.

The other route leading off from the junction commences in a low and silty manner but within 45 metres it assumes almost the proportions of those encountered in the Western Passage. At 90 metres from the junction a small pit is found in the floor, aligned upon a rift. This emits a strong current but is impossibly tight. The main route continues to a point 350 metres from the entrance where quite suddenly the passage closes down.

Marine life gradually diminishes with distance into the cave but even at 300 metres the odd lobster, snapper and snake eel may be encountered.

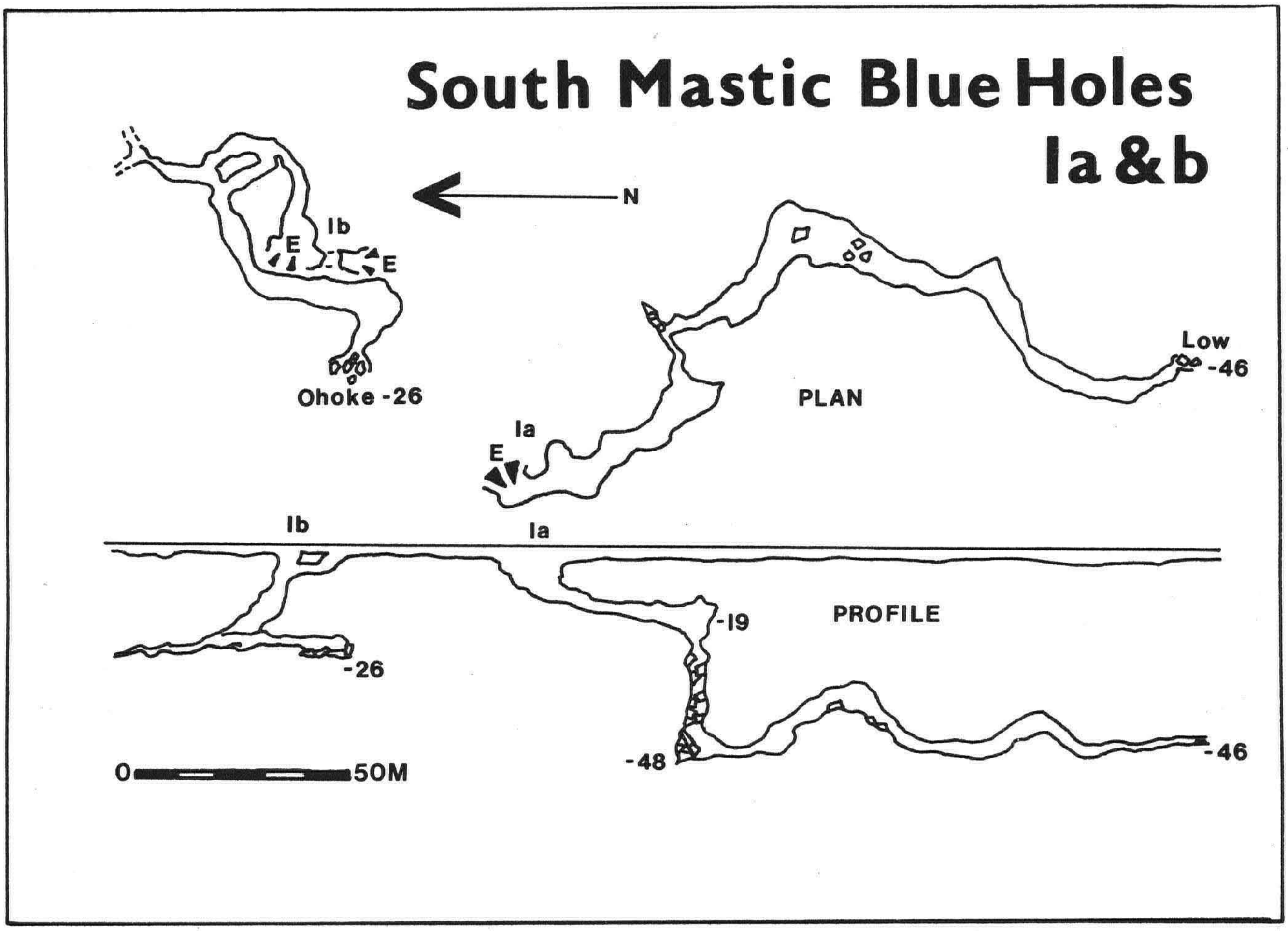
FORFAR BLUE HOLE (TC 053.571)

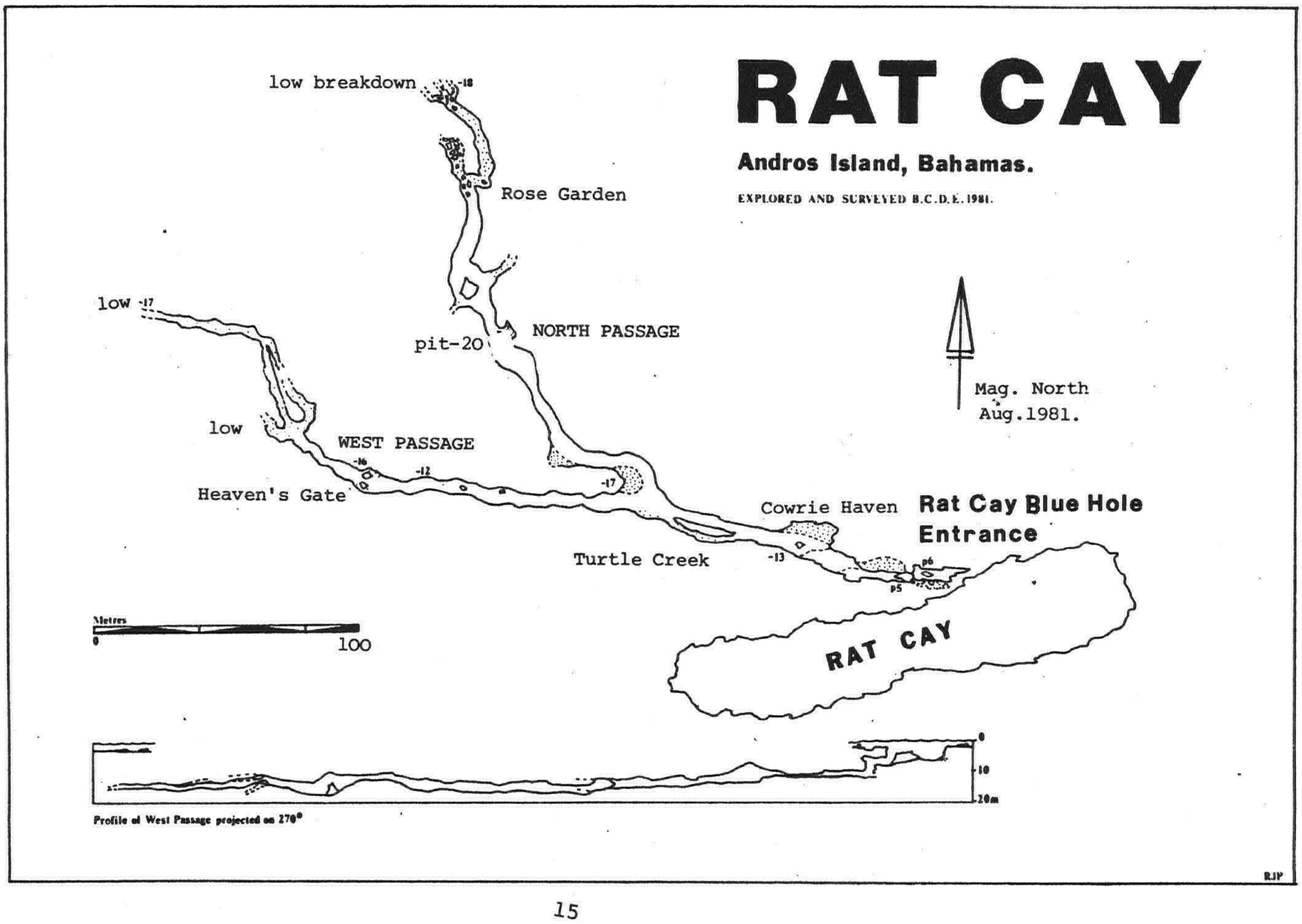
The Forfar Blue Hole lies approximately one kilometre offshore from the Forfar Field Study Centre at Stafford Creek. There are two interconnecting entrances a matter of 15 metres apart, situated less than 25 metres to the south of the small island known locally as Blue Hole Cay.

Previous explorers maintained that the site was too tight to enter but using normal British techniques, i.e. side-mounted sets,the low boulder-strewn entrances posed no difficulty.

A 25 metre dive connects the two openings via a small passage. Ten metres in from the entrance in the larger depression a substantial passage, two metres wide, is encountered trending away to the left, i.e. north. This quickly narrows in to a descending rift heading in a northwesterly direction. At 45 metres from the entrance, at a depth of 25 metres, the rift descends almost vertically. A tight squeeze at 38 metres depth gives access to a small chamber at 40 metres. Beyond a series of equally tight constrictions lead down to a depth of 60 metres where access is made to a large passage. Owing to extreme depth and the considerable difficulty of reaching this point the ongoing lead has yet to be explored.

Marine life is profuse, this being one of the oceanic sites where *Lucifuga spelaeotes* was found.


South Mastic Blue Holes
Ia &b
N
Ib
E
E
Ohoke -26
Ia
E
PLAN
Low
-46
Ib
Ia
PROFILE
-19
-26
-48
-46
0
50M


RAT CAY
Andros Island, Bahamas.
EXPLORED AND SURVEYED B.C.D.E. 1981.
low breakdown
-18
Rose Garden
low -17
NORTH PASSAGE
pit-20
Mag. North
Aug.1981.
low
WEST PASSAGE
-16
-12
-17
Heaven's Gate
Cowrie Haven
Rat Cay Blue Hole
Entrance
Turtle Creek
-13
p6
p5
Metres
0
100
RAT CAY
0
10
20m
Profile of West Passage projected on 270°
RJP

MANGROVE CAY AREA R. Palmer

The classification here follows that given by George Benjamin during his original explorations. This most northerly area of the Mangrove Cay area was his area 3. The four Blue Holes, from north to south, are numbered 1 to 4. M.C.31 is Mangrove Cay, area 3, no. 1.

M.C.31 T.B.288885
A large doline 60 m long by 30 m wide, with small passages at the northern end at a depth of -28 metres. These were investigated by Walker, and found to be tight and awkward, with much silt evident. Little current and very poor visibility.

M.C.32 T.B.289884
A rift entrance in 2 metres of water 300 metres southeast of 31. This was descended by Parker and Walker to a depth of -38 metres, which a north-south passage was entered. This narrowed down to the south, but was followed north for 50 metres, continuing open.

M.C.33 T.B.291883
On the same north-south joint as 32, and 300 metres southeast. An entrance under a ledge in three metres of water (divided by a large brain coral) entered a small chamber with a descending rift in the floor. At a depth of -32 metres, this entered a large north-south passage. To the north, a large chamber was entered after 50 metres, which the passage split into two. The right-hand (larger) branch was followed for a further 50 metres and a final 40 metre depth. In front, the passage continued open, up a sand slope, as a rift passage 3 m wide and 10 m high.

Walker and Parker explored a high level series at -20 m depth, which descended at its northern end to enter the left hand branch of the large chamber. Passages to the south became constricted at all levels. Much life was evident at this site, notably crustaceans.

M.C.34 T.B.292882
Unexplored on the 1982 Expedition. The entrance to this is on the same joint line as 32 and 33, 200 metres further southeast. Inside a slightly smaller entrance to 33 is a descending rift.

DOUGHNUT HOLES: Kemps Bay

Coral Hole
The first of the "Doughnut Holes descended. These holes are typified by an encircling coral "ring" around their entrance shafts. At this site, a 15 m long entrance rift, 3 m wide, was descended past ledges at -10 and -15 metres to a depth of -25 m. From there a narrow rift passage ran off at 250°, and this was followed by Walker and Palmer through several small chambers and narrow rifts (0.5 m wide in places) for 50 m to a final depth of -32 metres. There may be a larger continuation 10 metres below, access to which could be gained via one of several shafts in the floor of the passage. At the final point reached, a well-established colony of rose coral was discovered on the walls of the cave.

Giant Doughnut Hole
A large doline entrance 0.5 km south of Coral Hole, 30 m by 40 m in extent, and shallowest at its eastern end (-10 m) sloping down to a maximum -19 m to the west, where a small passage leads off. A few metres inside is a tight descending rift, dropping to -30 metres into a N-S passage. Parker and Walker followed this for approximately 40 metres to a squeeze at -38 metres depth. Beyond this, a larger descending continuation could be seen.

The coral ring at this site was breached on the seaward wide (east), probably by wave or storm action and a considerable amount of dead and broken coral had slumped in to the sides of the Hole. The floor of the Hole was of fine sand.

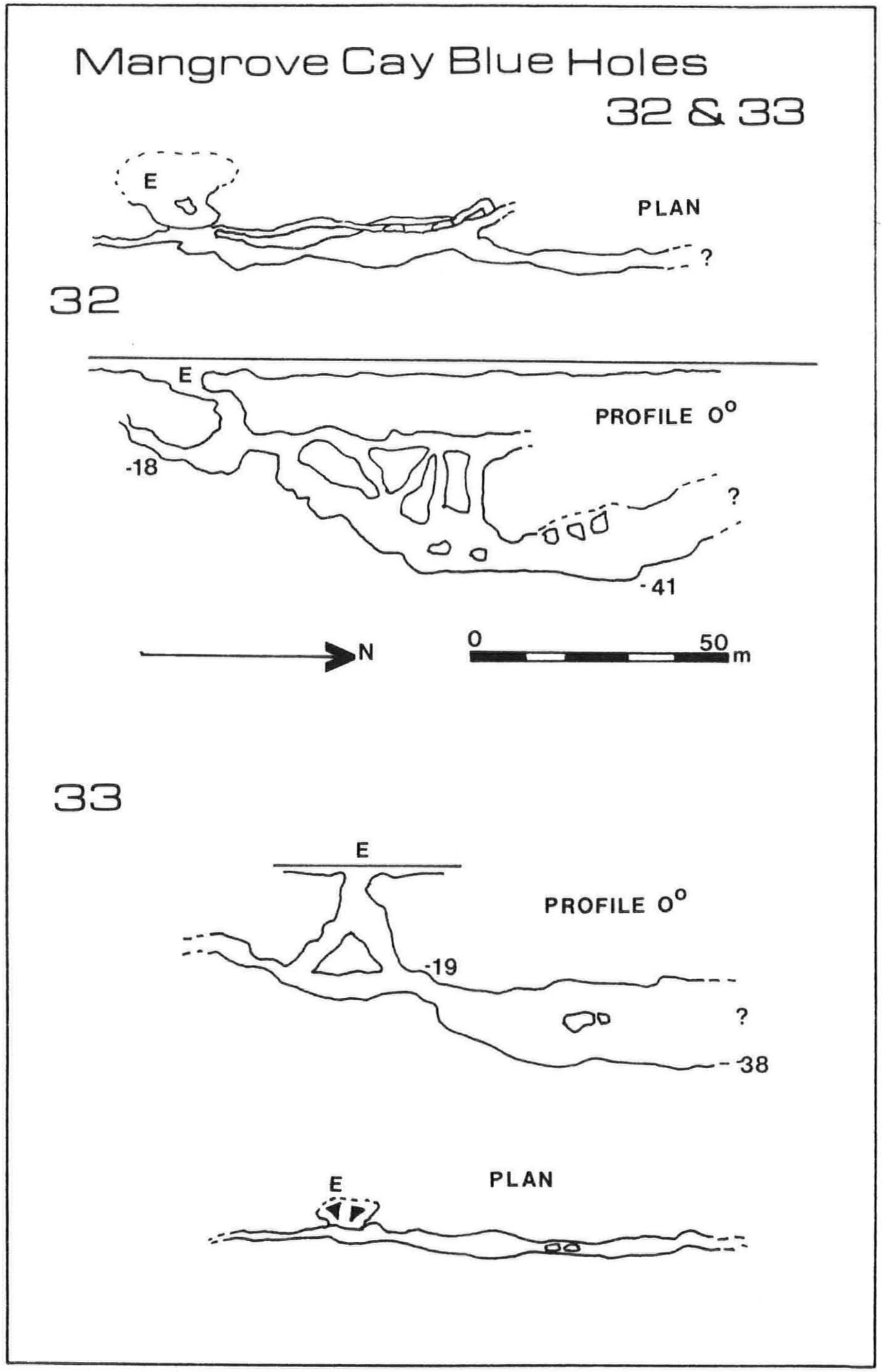
Mars Bay Blue Hole T.B.439417
On the south side of Mars Bay settlement, on South Andros, this Blue Hole is a 40 metre diameter shaft four metres from the beach, in an intertidal zone of flat sandy beach. The shaft opens out at 15 m depth into an underwater chamber in the classic manner of an 'inland' hole. A descent by Palmer and Parker in the centre of the shaft met a sand cone tip at -58 metres, and no true bottom was seen at the final exploration depth of 60 metres. A small shoal of jack-like fish were seen at this depth, and a profusion of white globular sponges hung from the walls at all depths.

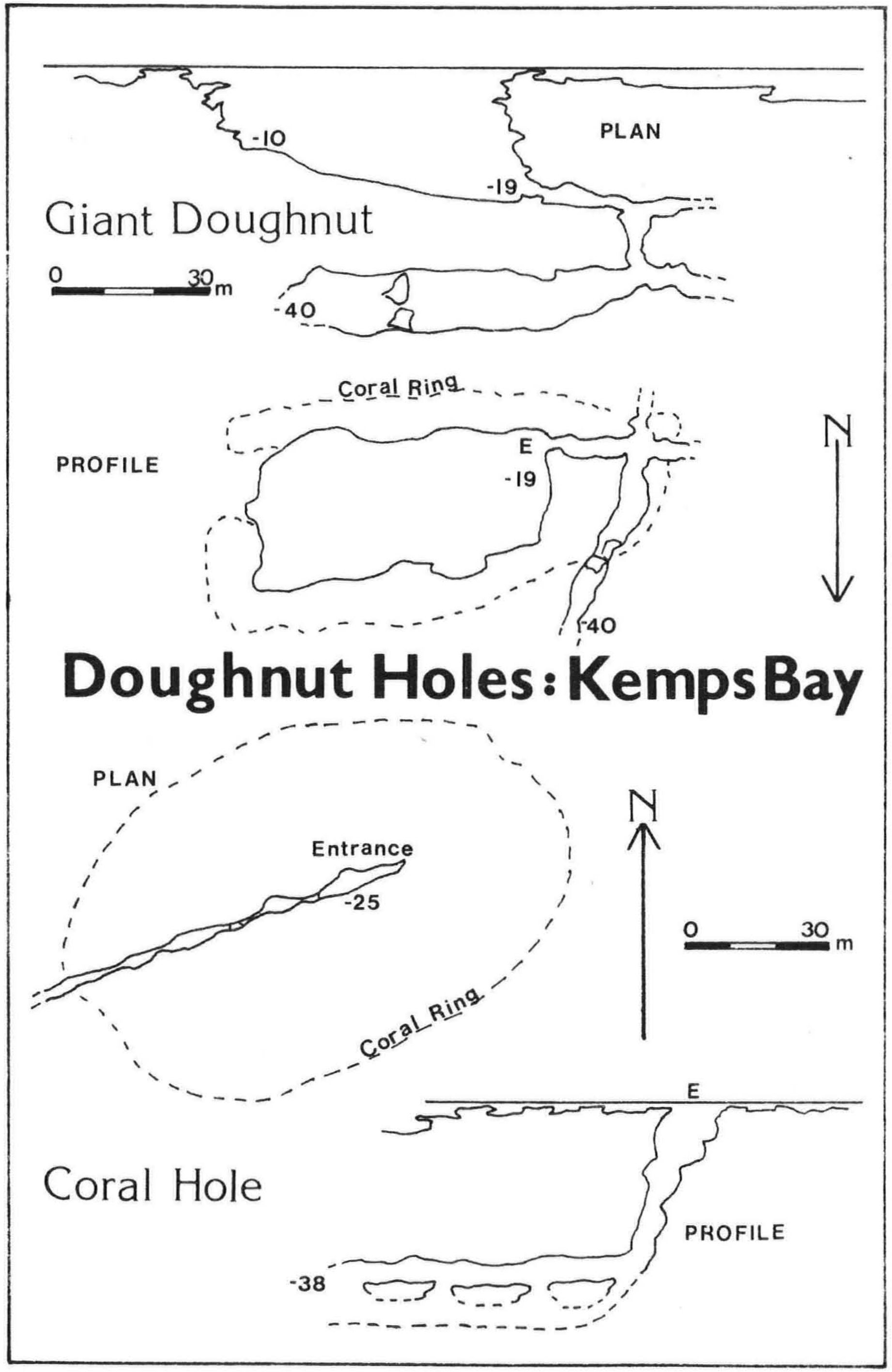
INLAND HOLE SITES

Uncle Charlie's Blue Hole (S.C.933806)

An inland hole approximately 4 km northeast of San Andros, reached by a short drive down a forestry track, the Blue Hole is a few metres to the north of the track at an obvious turning bay and is marked as a blue hole on the 1:25000 map.

The entrance to Uncle Charlie's is a lake approximately 50 metres in diameter, the water surface being surrounded by a 2 m high overhanging cliff. Exit from the water is easiest at the western end, up a short gully. Underwater, a sloping silt/rock floor is reached at -15 metres, with many small solutional tunnels a few centimetres in diameter in the walls. These contain a population of *Lucifuga spelaeotes* , the blind Bahaman cave fish. Numerous land crabs inhabit the base of the lake. In the centre, the silt banks slope down to a descending funnel, approximately 2 metres in diameter. A further descent, past loose walls of decaying organic material, brings one to the "sulphur layer" or halocline at a depth of approximately 14-15 metres. Passing through this unpleasant layer, rock-walled cave passage is entered at a depth of 20 metres where the clarity of the water increases dramatically, from about 1 metre in the sulphur layer to over 30 metres. At -20 metres, passages run off to


Mangrove Cay Blue Holes
32 & 33
32
E
PLAN
?
E
PROFILE 0°
-18
?
-41
N
0
50 m
33
E
PROFILE 0°
-19
?
-38
E
PLAN


Doughnut Holes: Kemps Bay
Giant Doughnut
PLAN
-10
-19
0
30 m
-40
Coral Ring
PROFILE
E
-19
-40
N
PLAN
Entrance
-25
Coral Ring
N
0
30 m
Coral Hole
E
PROFILE
-38

west and east, while the main shaft continues vertically to a final depth of 41 metres. At the deepest point large passages run off to east and west, ascending only to choke quickly in narrown, inclined rifts.

At the -22 metre level, the passage heading west was explored in 1981, and the end reached in a small chamber after 10 metres. This was found to contain the body of an American diver, missing for over three years, but previously unknown to the expedition. The diver was inadequately equipped for such a venture, having only one light, one air tank (though with octopus regulator rig) and no guideline. Copious quantities of fine silt line the floor, roof and walls of this passage, and it is presumed that the diver became disorientated in a silt-out caused by both his bubbles and movements and ran out of air before he could find his way out.

Two observations can be made here. Firstly, had he taken a line reel, it is unlikely that he would have died. Secondly, had he switched his light off, and waited for the sediment to settle a little, he may have been able to locate his exit. Neither good equipment nor open-water expertise are a substitute for cave-diving training or experience.

The diver's next-of-kin were located, following extensive enquiries, and were notified. It was decided to leave the remains undisturbed in the cave.

Ocean Hole (S.C.967846)

Half a kilometre northwest of Nicolls Town Hotel, a bluff overlooking the town is topped by a large collapse feature. This reaches base-water-level in two places. The first, where water-level is visible between boulders, is on the south side of the feature, underneath a large overhanging cliff some 12 metres high.

The second and considerably larger water surface is approximately 50 metres further north, where a short climb down a rock slope leads to a 40 x 20 metre lake. This is surrounded on three sides (NE, NW, SW) by 12 metre vertical cliffs, and on the 4th (SE) by a steep and rocky slope. Falling vegetation and rainwater run-off from the slopes ensures a high organic content in the water, and the "sulphur layer" commences at the surface. This is not a pleasant diving site, decompression having to be made within the sulphur layer.

Solo explorations, using a Wemler-Marine drysuit to reduce skin-contact with the sulphurous water as much as possible, revealed a steeply descending passage on the western side of the lake. This was descended to a depth of 48 metres, where a three-way junction was encountered. Low, wide passages led south and west, while a large, square-sectioned passage (6 m x 6 m) led due east. The walls of the passage were coated with a black peaty silt, which soaked up light, despite the exceptional clarity of the water at this depth (saltwater) and this gave the cave a very oppressive air. After 150 metres, reaching a maximum depth of 50 metres, a boulder pile was encountered, and the water again took on a slightly sulphurous taste. The boulders were ascended to -42 m where the line was tied off. Passage appeared to continue over the pile, which may lie beneath the first water surface in the surface collapse. In the cold water, alone and with few reference points in the dark and silt-lined cave, the diver experienced a strong attack of nitrogen narcosis, which soon cleared as he returned along the line and ascended.

This cave is of especial note, due to its proximity to the sea, its tidal variation of 15 cm, and the dense organic content of the top 20 metres of water. A curious layered effect is visible on initial descent, with certain of the denser layers exhibiting effects similar in shape to a galactic spiral. A deep incut in the surrounding cliffs at a height of approximately 3 metres may be indicative of a higher sea stance.

Stalactite Blue Hole (Archie's Blue Hole)

An inland hole 7 km north of Twin Lakes airstrip, up a distinctive track on the east side of the main access road. A short walk from the end of the track along a well defined path leads to a 75 metre diameter blue hole, with a wooden diving platform placed there in the early 1970's by Archie Forfar, the original discoverer of the Hole. The Blue Hole is 70 metres deep at its centre, and 50 metres deep at the base of the sides. Beneath a ledge at -23 metres, extending virtually round the diameter of the Hole, are very large and well-developed stalactites, which extend to the halocline at -33 metres.

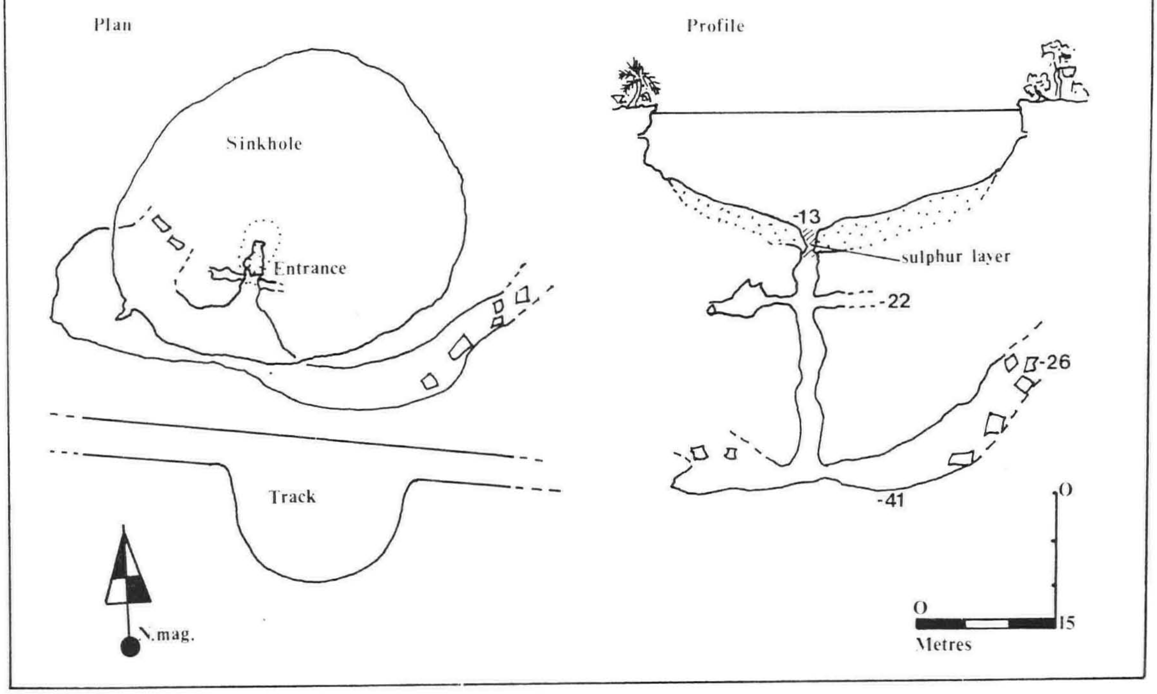
The halocline, as is usual in inland Holes on Andros, is marked by a layer of sulphurous water, and a curious growth on the end of one stalactite which extends into this layer may be the result of a chemical interaction with the material in the layer. The Blue Hole has a notable population of large gobies and land crabs.

Martyn Farr,
Tullyhona,
Pen-yr-Ale Lane,
Llangynidr,
Powys.

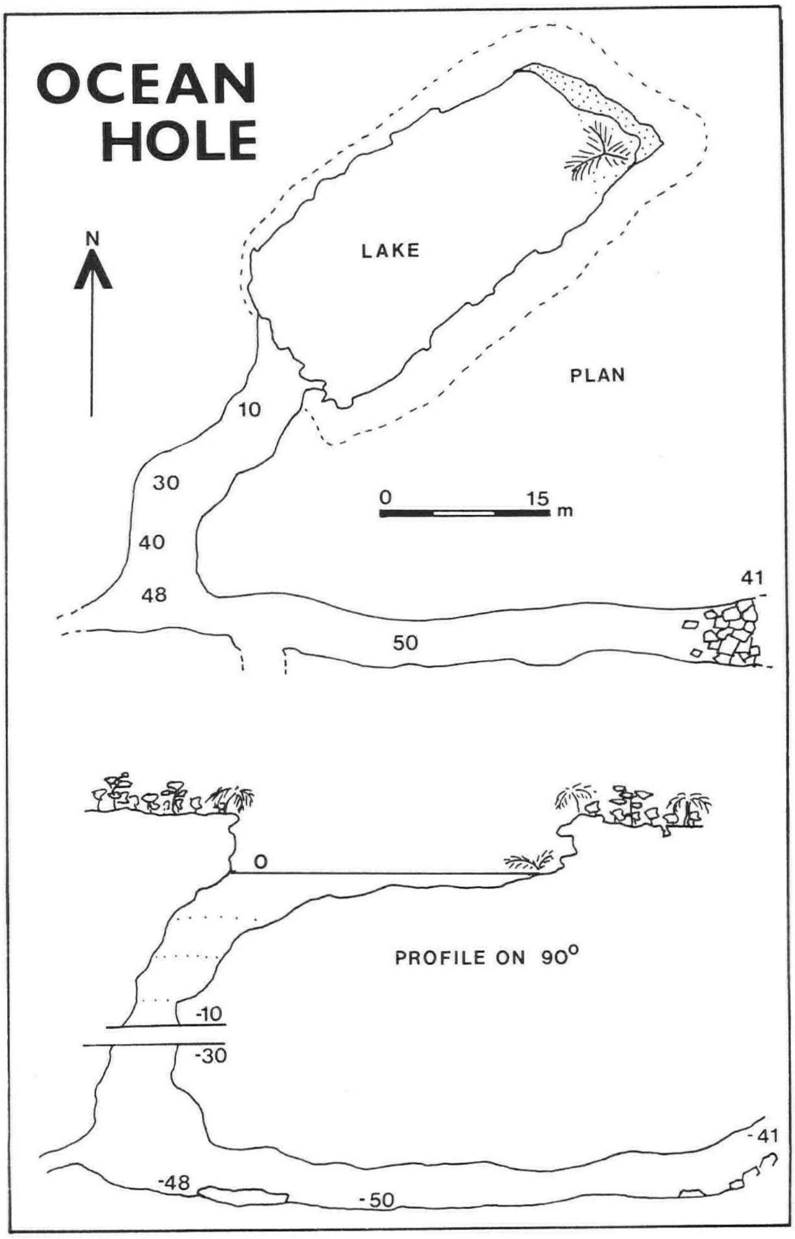
R.Palmer,
7 Lovell Avenue,
Oldland Common,
Bristol.

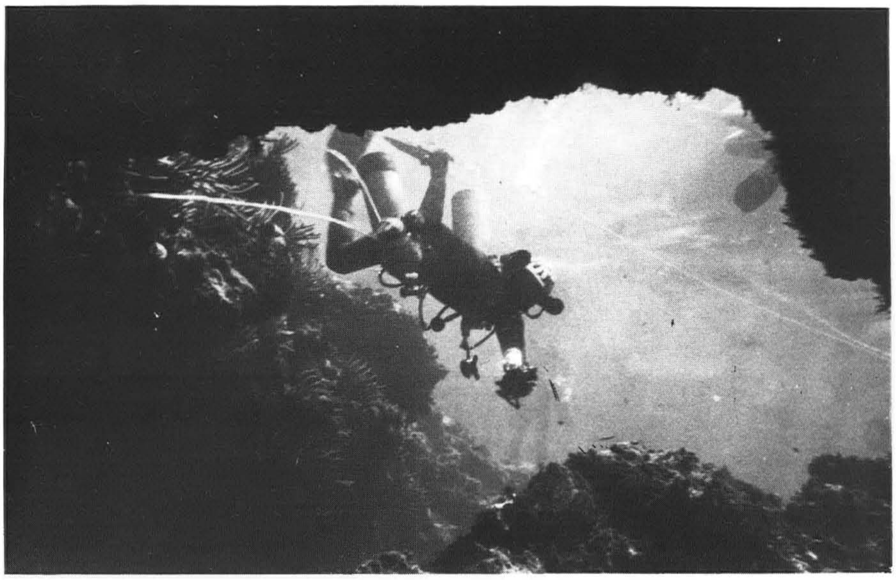
UNCLE CHARLIE'S BLUE HOLE

SAN ANDROS, ANDROS. Explored and Surveyed 1981 B.C.D.E.

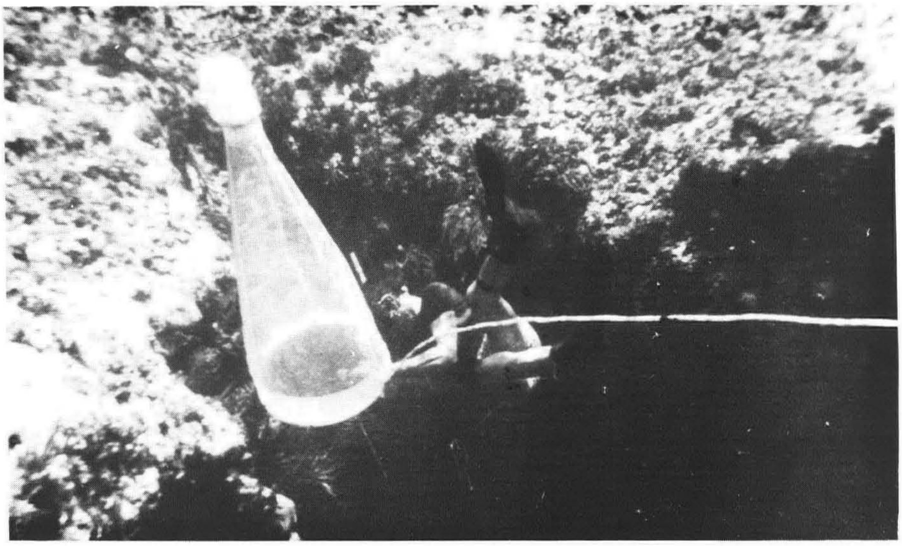


OCEAN HOLE

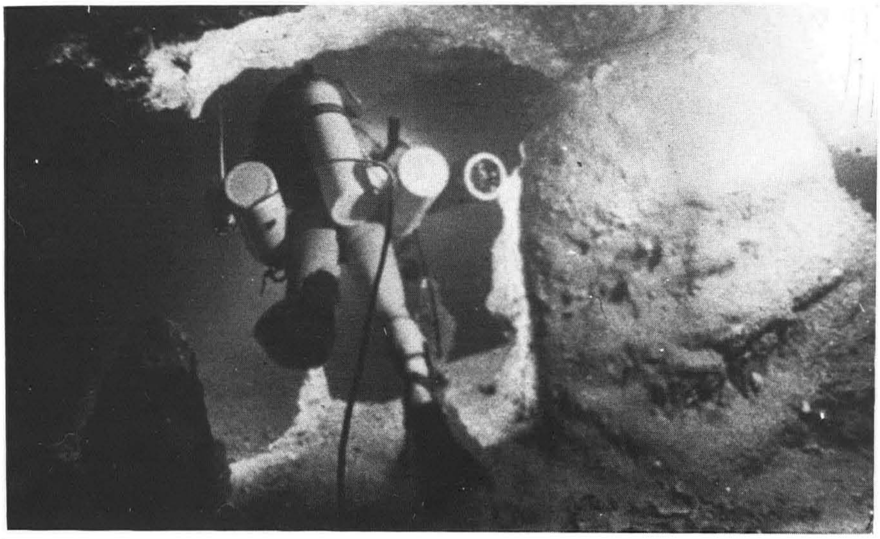




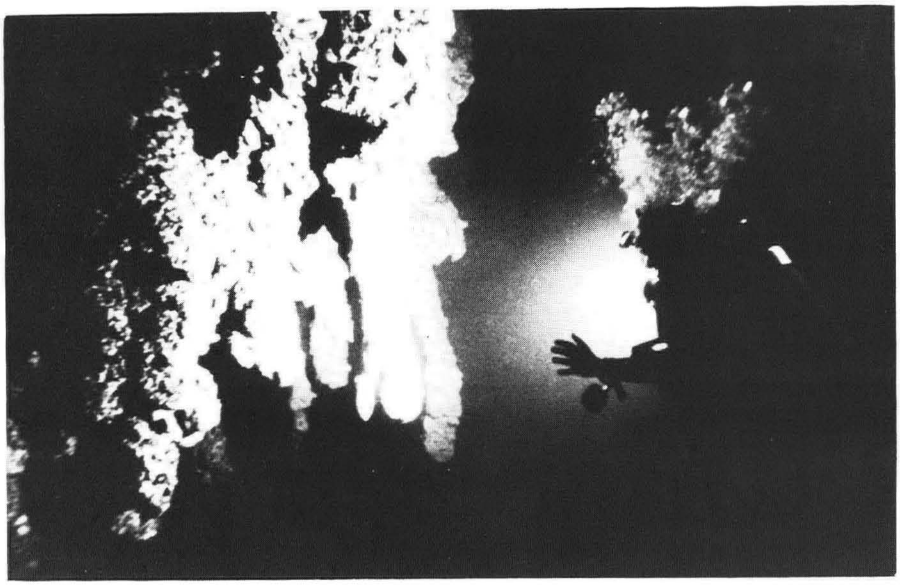
4. The entrance to Rat Cay Blue Hole (R.Palmer).



5. George Warner attaches a plankton net in the entrance to Rat Cay Blue Hole. The strength of the outward current is clearly visible (R.Palmer).



6. In the main chamber of Conch Sound One an expedition diver ferries in a spare tank of air for a long distance exploration dive. Large stalagmite bosses occur on each side (M.Farr).



1. Heavily corroded depositional features in Stalactite Blue Hole which may have formed from muds rather than pure calcite during a period of low sea level (M.Farr).

2. The entrance passage to Conch Sound Blue Hole One. The smooth walls and floor are the result of abrasive action by strong tidal currents (M.Farr).

3 In Stalactite Blue Hole the formations extend to the halocline at 30 m. The fresh/salt water interface is marked by a "sulphur layer", a chemical soup that is responsible for the lighter band on the wall behind the diver and at the tip of the stalactite (M.Farr).

7. Stalactite Blue Hole surrounded by lush vegetation with algal mats floating on the surface. The Blue Hole is 45 m deep and has stalactite formations at depths of 20-30m (R.Palmer).

BAHAMAS BLUE HOLES

8. A British Expedition diver in full exploratory gear, using side-mounted tanks and helmet-mounted lamps (R.Beaumont).

9. In the entrance shaft of Ocean Hole. The figure in the centre is standing in an undercut that may be a relic of a higher sea still-stand (A.Boycott).

CAVE SCIENCE

Transactions of the British Cave Research Association Vol.11, No.1 March 1984

THE HYDROLOGY OF THE INLAND BLUE HOLES, ANDROS ISLAND

C. C. Smart

ABSTRACT

Andros Island in the Bahamas contains numerous small lakes some of which are over 100 m in depth. A short programme of temperature and salinity profiling in these lakes suggests the presence of an extensive freshwater lens, thinning towards the coast and estuaries. A lake deeper than the thickness of the freshwater lens is defined as a "Blue Hole". These lakes are anoxic at depth and mixing is confined to the upper freshwater component. The interface between fresh and salt water may be a zone of intense solution, although geomorphic evidence suggests biologically enhanced erosion beneath photosynthetic mats. The blue holes probably developed by collapse of cavernous openings during times of low sea level when buoyant support was removed. There is little evidence for integrated conduit systems beneath much of the island, although long submarine caves have been explored, and some blue holes are tidal and exhibit conduits at depth. This suggests that tidal "pumping" may be the dominant driving force in developing the horizontal conduits explored by cave divers.

INTRODUCTION AND METHODS

The inland blue holes of Andros Island, Bahamas, are deep lakes of very small surface area. From the air, their deep blue colour makes them stand out clearly from the numerous shallow lakes and marshes of the island. The blue holes are broadly distributed on Andros, but concentrated towards the eastern edge of the Island (Fig. 1) Brackish water estuaries such as Stafford Creek run deep into the interior.

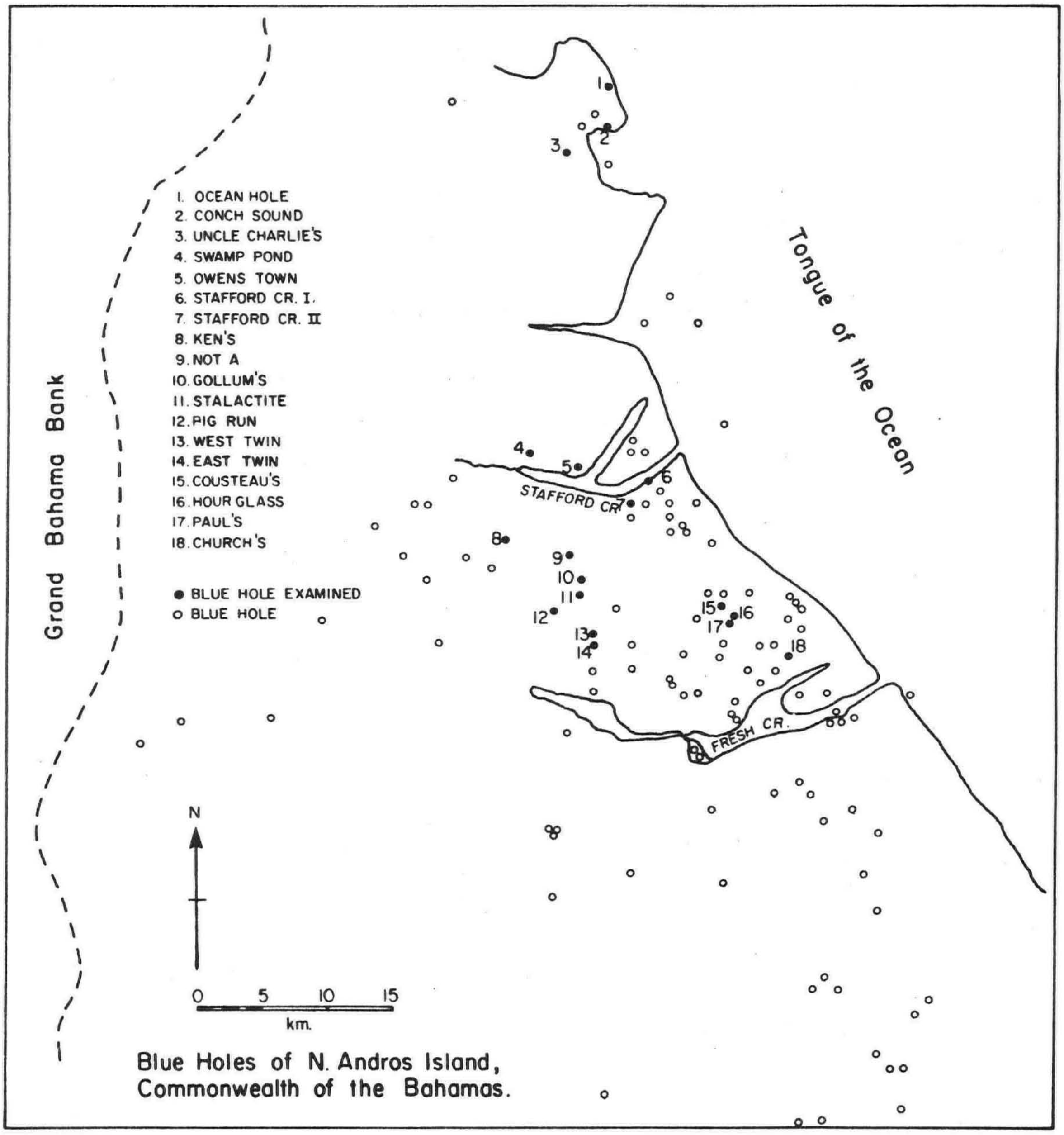


Fig.1. The distribution of Blue Holes on Andros Island compiled from 1:25ooo topographic maps. Many of these may not be true Blue Holes and others offshore may not be shown.

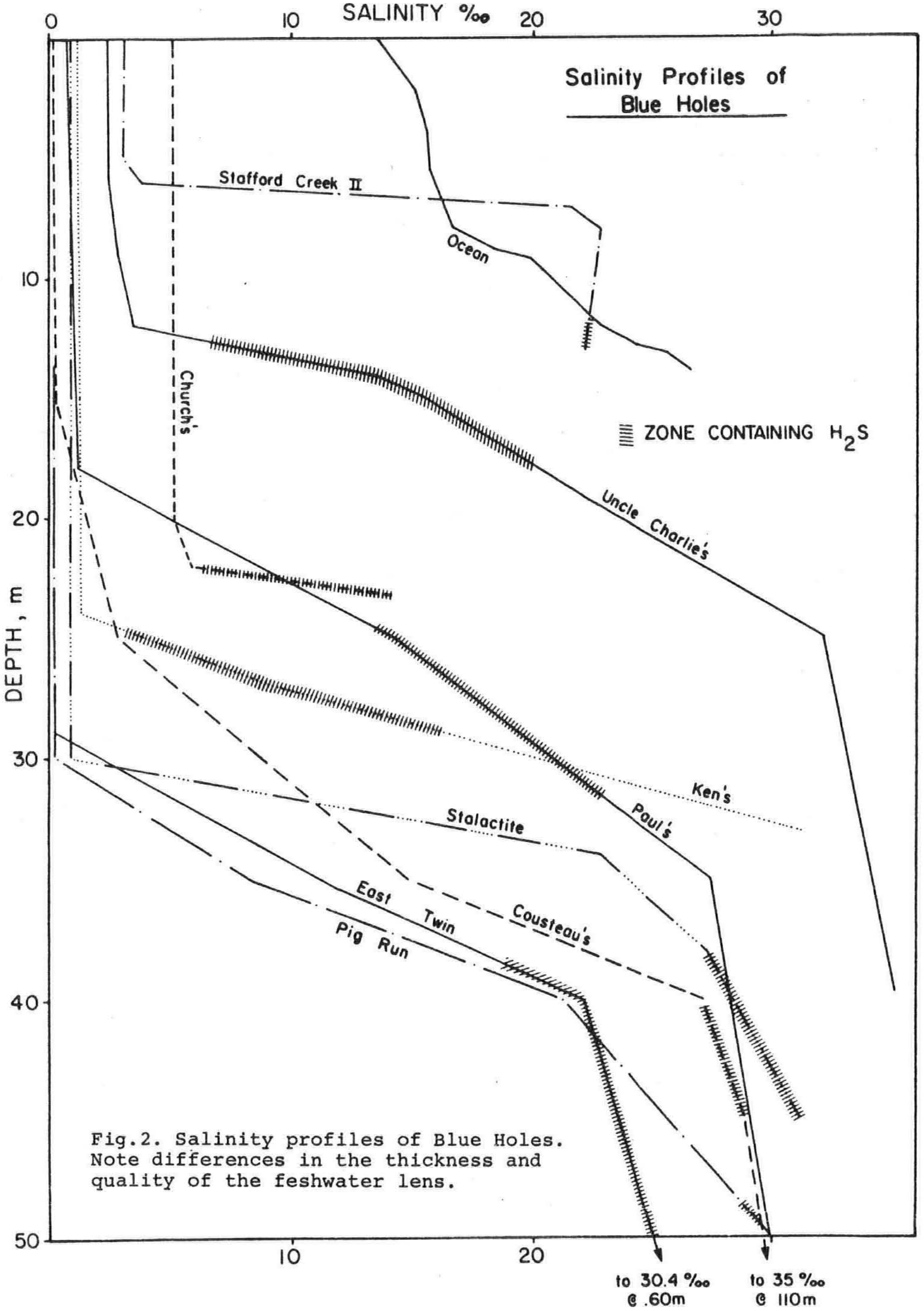


Fig.2. Salinity profiles of Blue Holes. Note differences in the thickness and quality of the feshwater lens.

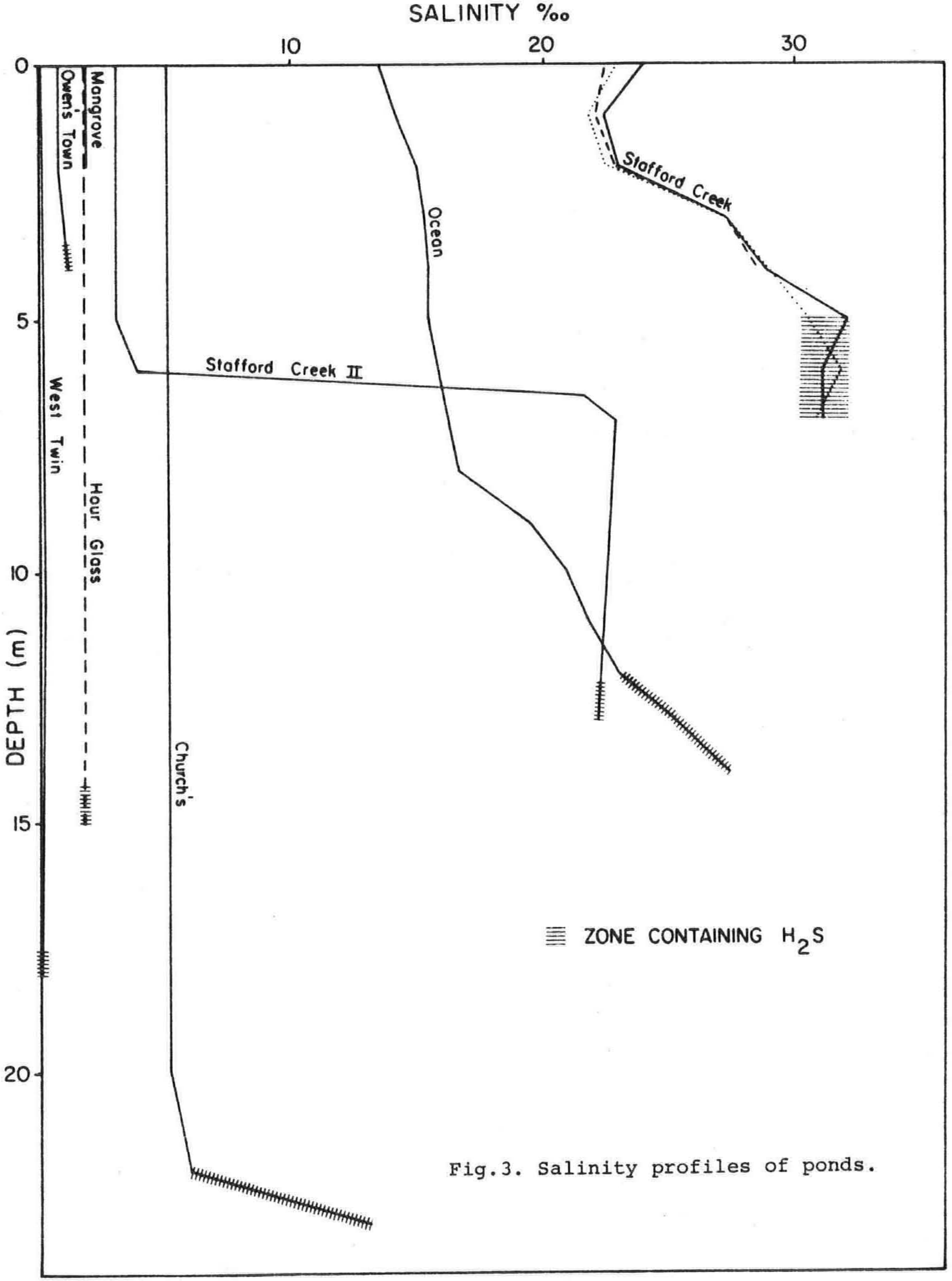


Fig.3. Salinity profiles of ponds.

The blue holes occur in all types of environment on Andros: pine barrens, swash, mangrove swamp and within lakes and estuaries. The logistic difficulties of travelling in many areas meant that only the more accessible sites were visited such as those near logging roads in the pine barrens.

At each site visited the depth was recorded along with descriptive information. The profile of temperature and conductivity was usually determined with a 15 m probe and a YSI-33 Salinity, Conductivity, Temperature meter. Samples below 15 m were obtained by a water sampler or direct sampling by diver.

A temperature/salinity profile of the Stafford Creek Estuary was conducted up to the limits of navigation.

RESULTS

The blue holes investigated are circular in plan and range from 30 to 250 m in diameter and varied from 2 m to 110 m in depth. There are no surface streams associated with the blue holes. The walls are usually vertical, but sloping sides occasionally lead down from the surface. Overhanging walls are reported at depth. The sides are irregular and pitted, except where angle of repose slopes occur. These are covered in coarse calcareous mud. Subaerial cliffs are rare, but are 15 m high at Ocean Hole. Surface relief on Andros is seldom more than 2 m a.s.l.

The water quality varies from clear to cloudy, but at great depth is very clear. Algal/bacterial mats occupy much of the sloping walls except in the more saline holes. The limestone beneath the mats is extremely weak and friable. In places spontaneous collapse of walls is occurring. Beneath overhangs and at great depth the limestone is hard and sharply etched. Stalactite Blue Hole contains "speleothems" at approximately 30 m depth.

The salinity profiles of the blue holes are low and uniform for a depth of from 5 to 31 metres. Below this there is a transition to saline water called the halocline. A blue hole was defined as a lake exhibiting a marked halocline. The salinity profiles for blue holes are shown in Fig. 2, those for ponds in Fig. 3. Stafford Creek II and Church's Blue Holes are intermediate features and are shown on both Figures.

The depth of freshwater was taken for the blue holes studied in central Andros and mapped to determine whether there was sufficient continuity between sites to define a freshwater lens (Fig. 4). The thickness of the freshwater lens at Church's Blue Hole was calculated assuming a complete mixing of two end-member types of salinity: 1.0‰ and 15‰ (see Discussion). Lens thickness was estimated as 15.4 m.

Maximum thickness of freshwater is 31 m. The data support the existence of a freshwater lens, although the thickness contours are very tentative.

The sampling locations in Stafford Creek estuary are shown on Fig. 4. The salinity profiles are shown in Fig. 5. The freshwater lens exists only in the narrow channel at the head of Stafford Creek. The remainder of the estuary was well-mixed because of strong wave and tide activity. However, there appears to be fresher water at the mouth of Riley Creek (Profile 8) than in the centre of the estuary (Profile 9). The very saline water of Stafford Creek Blue Hole (Profile C) is discharging into the estuary at profile 10.

Selected temperature profiles are shown in Fig. 6. East Twin Lake Blue Hole shows the typical double thermocline. The shallow one being daily, the deeper being seasonal. Slight increases with temperature occur occasionally at depth. This temperature inversion is most marked in Stafford Creek Blue Hole (Fig. 7). There is no fresh water here, it is the high salinity of the "hot layer" which maintains internal stability.

Water sampled from ponds and blue holes occasionally stank of H_2S (rotten eggs). The layers from which such samples came are marked in Figs. 2 and 3. Odorous samples come from the bottom of ponds, but from distinct levels in blue holes. Divers also reported marked one-two metre thick opaque maroon layers in blue holes. A similar phenomenon was observed at 6 m depth in Stafford Creek Blue Hole. These layers are bacterial plates probably of the purple sulphur bacteria (Thiorhodaceae). The optimal conditions for these bacteria are strictly defined (Wetzel 1975) which is why they occupy such narrow zones within the blue holes.

DISCUSSION

The salinity profiles of the blue holes create highly stable conditions. All chemical and physical exchange between fresh and salt water is then by diffusion and conduction, or by inclusion in strong overturning events in the freshwater "mixolimnion". Within chemically homogeneous zones, however, conditions are less stable, and the density changes caused by temperature differences may cause overturning. Overturning will allow surface and deep water to exchange. This exchange will decrease in frequency with depth. The surface zone will exchange perhaps every day, in response to diurnal temperature fluctuations. This "epilimnion" is also mixed by winds. The zone of annual or less frequent overturning is the "mixolimnion". Both zones are usually able to support conventional aquatic fauna and flora.

The perennial stability of the underlying saline water induces the condition of "meromixis". The lower "monimolimnion" is anoxic and abiotic which accounts for the clarity reported by divers. Very little oxygen diffuses down to the top of the monimolimnion, but energy is available to those bacteria which convert sulphate to sulphide. The dense bacterial plates found here demonstrate the sharp transition between oxygenated and anoxic water, where sulphate reduction is occurring.

The salinity profiles (Fig. 2 and 3) are probably correct to the halocline, some contamination occurring at lower levels due to sampling problems. However, most blue holes fit the pattern of meromixis, the H_2S zone occurring within the halocline and below the thermocline.

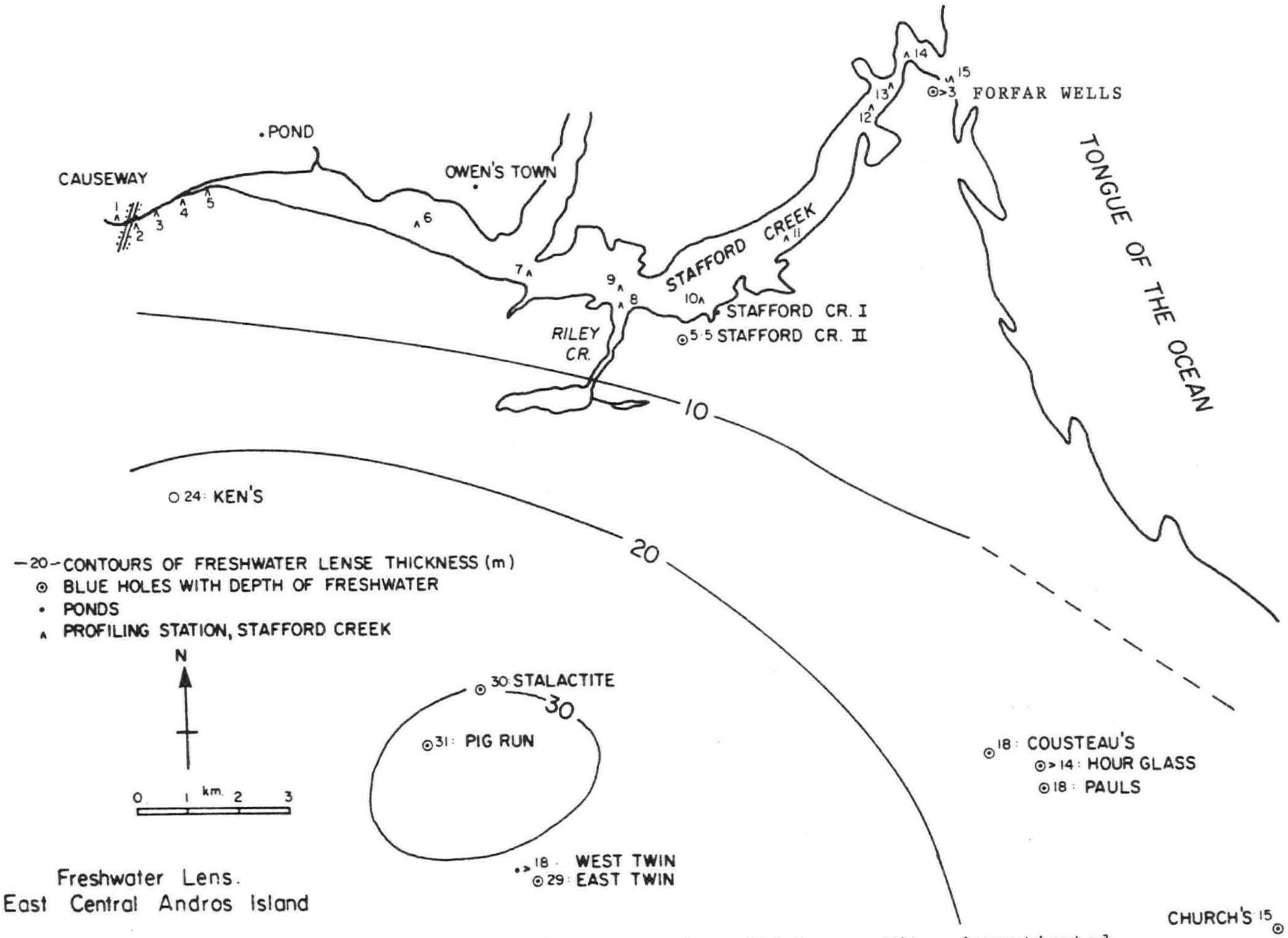


Fig.4. Approximate contours of freshwater lens thickness. Sites investigated in Stafford Creek estuary are also marked (see Fig.5 for results).

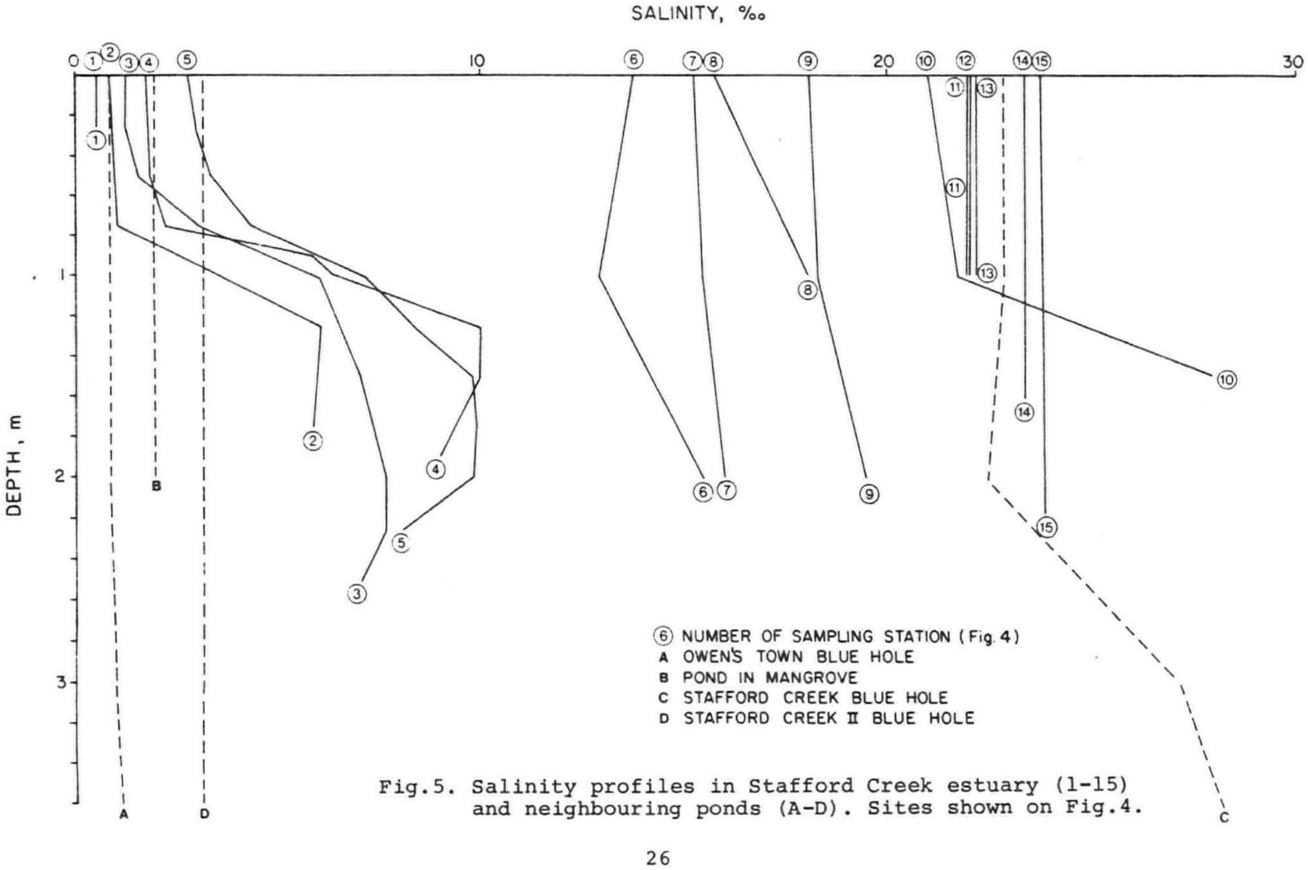


Fig.5. Salinity profiles in Stafford Creek estuary (1-15) and neighbouring ponds (A-D). Sites shown on Fig.4.

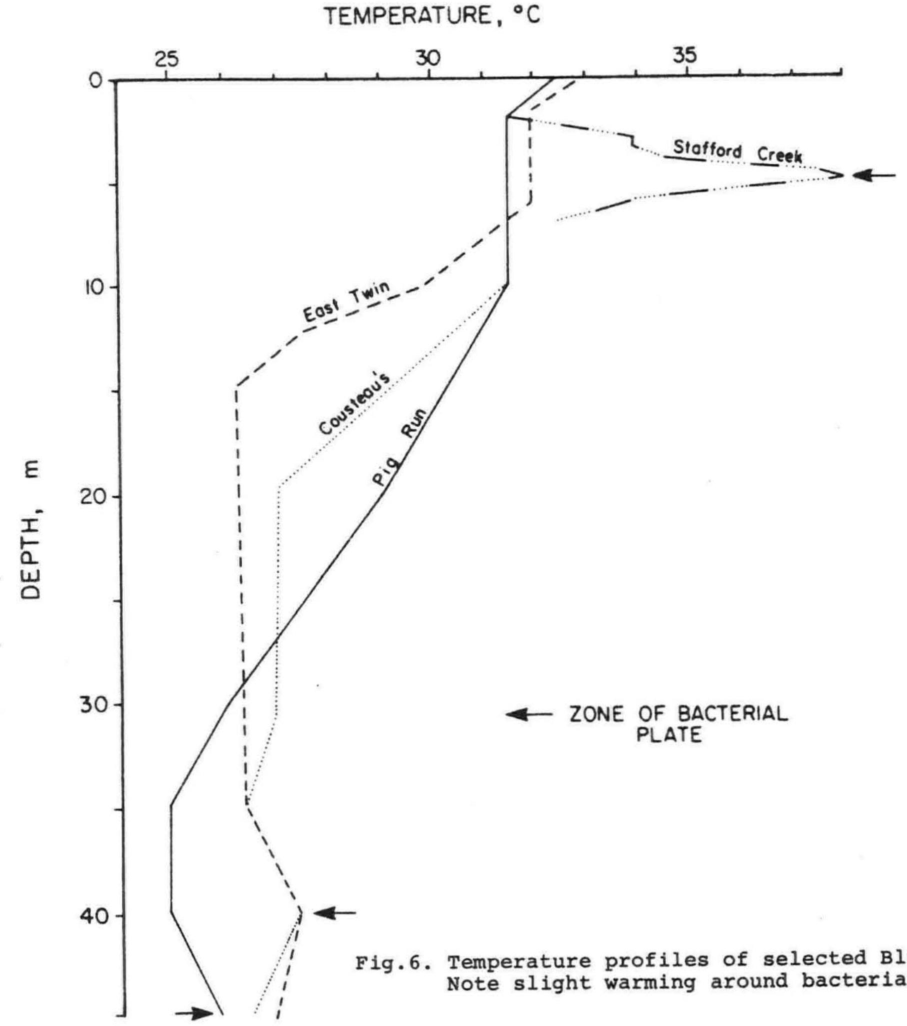


Fig.6. Temperature profiles of selected Blue Holes. Note slight warming around bacterial plates.

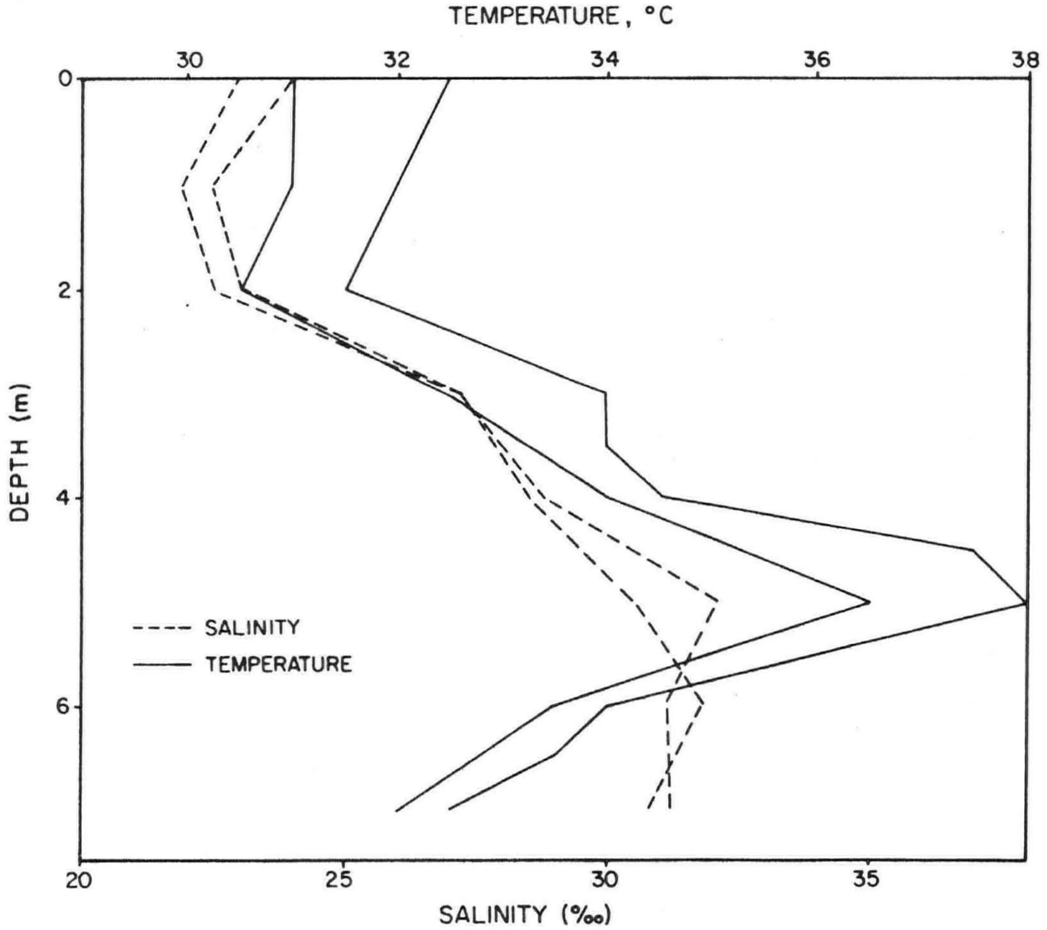


Fig.7. Temperature and salinity profiles of Stafford Creek Blue Hole.

There is a possible association between the bacterial plate and slight temperature inversions. This clearly occurs in Stafford Creek Blue Hole (Fig. 7). Here the strong stability of the water has allowed a bacterial plate to develop at 6 m depth. The origin of the stability is unclear; it may have been capture of estuarine saline water, purely biogenic, or caused by a saline spring. A combination of the former two processes is probably responsible. The high temperature at depth is caused by the absorbtion of solar radiation without subsequent heat dispersion by overturning (Wetzel, 1975).

Fig. 3 shows that even for entirely fresh blue holes some H_2S generation occurs in contact with the basal sediments.

Ocean, Uncle Charlie's, Stafford Creek II and Church's Blue Holes are all somewhat anomalous, having relatively high surface salinities. Both Ocean and Uncle Charlie's Blue Holes are tidal. The enhanced mixing is probably associated with tidal fluctuations. In addition, like Stafford Creek II, the halocline is very shallow which means it may be mixed by shallow instability. Church's Blue Hole is exceptionally well mixed. It also has the largest area of the blue holes studied (about 3 ha). This means that it will be more influenced by winds which may induce overturning and mixing. The basal salinity increase has possibly developed since the last overturning. The chemical homogeneity of the profile also means that the lake is susceptible to thermal instability, which will ensure continued homogeneity.

The sparse data obtained from the Stafford Creek Estuary (Fig. 4 and 5) suggest a double zonation. The lower, broad estuary is vertically mixed because it is shallow and strongly influenced by tides and waves. The profile up the narrow channel is increasingly strongly stratified, which can only occur where freshwater inflow occurs and mixing proceeds. A significant enhancement of the fresh groundwater resources of Andros Island could be gained if Stafford Creek were controlled at its mouth.

The apparent continuity across the aquifer of central Andros suggests a disperse rather than karst groundwater flow. In contrast, Uncle Charlie's, Ocean, and Conch Sound are tidal and have major karst conduits at depth. Karst development implies an organisation of water discharge along fractures, which develop into conduits. The present discharge of Conch Sound is brackish, becoming less saline further in at 1.15 km. A net mean efflux of 1.57 $m^3 s^{-1}$ was recorded in 1981. Conch Sound is therefore draining a reasonably large part of the freshwater lens.

Although flow data are not available from Stafford Creek, there is clearly a significant freshwater discharge from the estuary. The salinity of "Ocean Water" at Forfar Pier is 24-27‰, less than the global average of 35‰. Salinities of up to 46‰ occur on the west edge of Andros (Cloud, 1962). There may be a net west-east flow of saline water at depth beneath the island. At 100 m depth in Cousteau's Blue Hole salinity is 35‰. The low salinity of east coast water suggests that an aureole of brackish water exists on the narrow shelf of eastern Andros.

Back et al (1979) and Hanshaw and Back (1980) have described karst estuarine discharge on the Yucatan Peninsula, Mexico. They attribute the growth of estuarine features to the mixing of fresh and salt water. Back et al (1981) have demonstrated that this is most likely to occur underground where loss of CO_2 to the atmosphere is prevented. It is possible to develop phreatic caves at points of groundwater discharge. Thus the caves associated with blue holes may be presently developing.

The Yucatan peninsula is characterised by "cenotes" which are essentially sub-aerial blue holes. These are interpreted as collapse features formed in response to active solution at the water table. If the Andros blue holes are analogous, then sea level must have been considerably lower for their formation. If solution is occurring at depth in the aquifer, this need not be the case. The apparent lack of karstic continuity between blue holes suggests the blocking of any pre-existing karst by sedimentation. This is believed to have occurred in Florida (Back and Hanshaw, 1970).

The chemistry of the blue holes is complex because of the mixture of water types, and biological activity. The role of bacterial mats and plates is unclear. The contrast in the chemistry of recharge through a vadose zone and marshes has been demonstrated by Plummer et al (1976) for Bermuda. Fish (pers.comm.) has reported chlorinities higher than sea water at depth in the blue holes. The intense erosion beneath photosynthetic mats suggests locally very high PCO_2.

There appear to be no processes presently active at depths sufficient to develop the deeper blue holes. They must have formed in periods of lower sea level. A possible model of their origin is:

1. Development of cavernous porosity at both water table and halocline.
2. Fluctuating sea level enlarges the vertical extent of these features and reduces buoyant support favouring collapse.
3. Marine-fresh water sedimentation fills interconnecting karst conduits.
4. Solution continues at the approximate water table (± land surface) and at the halocline. Flow is disperse because of poorly developed karst system.

CONCLUSION

The blue holes of Andros Island are meromictic lakes of complex biology and chemistry. They provide cross-sections through a fresh water lens of up to 30 m thickness which thins towards estuaries and the sea. Discharge of fresh water occurs through caves and by diffuse seepage. The blue holes appear to reflect deep solution and collapse of limestone enhanced by sea-level fluctuations. At present they are generally non-karstic although karst horizons may be developing.

ACKNOWLEDGMENTS

I wish to thank D.C. Ford for financial assistance from his National Science and Engineering Research Council Operating Grant.

International Field Studies of Columbus, Ohio, helped in shipping equipment and in providing transport and accommodation. Thanks go to the staff of Forfar Field Station for their enthusiastic assistance. The hydrological team of Kitty Hall, Ken and Laurie Jones and Graham Proudlove provided continuous help, support and humour, often under trying circumstances. The data of Mel Gasgoyne and John Fish from Blue Holes '81 has been included in this report with their permission.

REFERENCES

Back, W. and Hanshaw, B.B., 1970. Comparison of chemical hydrogeology of the carbonate peninsulas of Florida and Yucatan. *Jour. Hydrology,* vol. 10, pp330-368.

Back, W., Hanshaw, B.B., Pyle, T.E., Plummer, L.N. and Weidie, A.E. 1979. Geochemical significance of groundwater discharge and carbonate solution to the formation of Caleta Xel Ha, Qintana Roo, Mexico. *Water Resources Research,* vol. 15, no. 6, pp1521-1535.

Back, W., Hanshaw, B.B., Van Driel, J.N., Ward, W. and Wexler, E.J. 1981. Chemical characterisation of cave, cove, caleta and karst creation in Qinta Roo. *Abstract with Programs, Annual Meeting Geol. Soc. Amer.,* Cincinnati, p400.

Cloud, P.E. 1962. *Environment of calcium carbonate deposition west of Andros Island, Bahamas.* U.S. Geol. Surv. Prof. Paper 350.

Hanshaw, B.B. and Back, W. 1980. Chemical mass-wasting of the northern Yucatan Peninsula by groundwater dissolution. *Geology,* vol. 8, pp222-224.

Klein, H. and Hull, J.E. 1975. *Biscayne Aquifer, south-east Florida.* U.S. Geol. Surv. Water Resource Investigation 78-107.

Plummer, L.N., Vacher, H.L., Mackenzie, F.T., Bricher, O.P. and Land, L.S. 1976. Hydrogeochemistry of Bermuda: a case history of groundwater diagenesis of biocalcarenites. *Geol. Soc. Am. Bull.,* vol. 87, pp1301-1316.

Wetzel, R.G. 1975. *Limnology.* W.B. Saunders, Philadelphia, 743pp.

M.S.Submitted October 1982.

C.C.Smart,
Department of Geography,
University of Saskatchewan,
Saskatoon,
Saskatchewan S7N OWO
Canada.

CAVE SCIENCE

Transactions British Cave Research Association. Vol. 11, No.1, March 1984.

ECOLOGICAL STUDIES IN THE MARINE BLUE HOLES OF ANDROS ISLAND, BAHAMAS

G. F. Warner and C. A. M. Moore

ABSTRACT

Seven blue hole sites were visited in 1981 and 1982 and two sites, Conch Sound 1 (CS1) and Rat Cay (RC), were studied in detail. About 85 species were collected of which 65 have so far been identified. Currents in CS1 were continuously recorded and showed a tidal periodicity two to three hours out of phase with oceanic tides. Short and long-term irregularities and evidence of long-term patterns were observed. Periods of either apparent net inflow or apparent net outflow were observed to persist for several days. Various methods were used to assess the organic matter entering and leaving the blue holes with the currents. Inflowing currents were found to contain more planktonic organisms and fresh algal detritus and had a higher concentration of particulate organic matter than outflowing currents which contained more faecal material and sand. Sessile communities of organisms within the blue holes had a characteristic appearance and were dominated by sponges or ahermatypic corals. Communities were rich and varied in entrance passages but became sparse at deeper penetrations. Community differences were associated with the location of the blue hole entrance (inshore/offshore) and with any sulphurous influences.

Blue Holes are the entrances to complex cave systems that lie beneath the islands of the Bahamas. Formed solutionally, they were exposed to aerial conditions during the low sea levels of the Pleistocene glaciations, and re-inundated as seas rose at the end of these phases.

The environment of a typical Andros marine blue hole is characterised by several special factors. Like other caves, they are dark inside, but their unique feature is the almost constant presence of strong currents closely related to tidal cycles. Additional features result from these currents. The inward or 'suck' current consists of surface water, often slightly turbid, containing plankton, detritus and silt, and having normal surface temperature, salinity and chemical composition. In contrast, the outward or 'blow' current is limpid, usually slightly cooler than the surface water, and may contain dissolved hydrogen sulphide. The absence of light limits photosynthetic organisms to the entrances of the blueholes and thus the main, or only, nutritive input for organisms within the caves comes with the suck current.

These unusual features result in an unusual ecology which it has been our privilege to study. Initial hypotheses were: (1) that new or unusual species, especially cave-adapted or deep water forms, might be discovered; (2) that the suck current contained more suspended organic matter than the blow current (the difference being due to feeding and sedimentation) and that this might influence the orientations of sessile suspension feeding organisms; (3) that the availability of food should decrease with distance from the entrance (again due to feeding and sedimentation) and therefore sparser communities should occur in the deeper reaches of the caves; (4) that those blueholes with a sulphurous blow should be azoic or contain a restricted fauna; and (5) that, although sites might differ in their faunal complements, there should be a recognisable bluehole fauna with certain characteristic species.

There has been little previous study of the fauna of marine blue holes. Dill (1977) referred to the strong tidal currents and noted the difference in turbidity between suck and blow. He also observed 'gorgonian corals and anemones ... encrusting the cave walls 350 m away from the entrance of one cave system at a depth of 50 m showing that the organic material derived in the surface is supporting biological activity far back inside the reef platform'. Gascoyne *et al.*(1979) noted the presence of annelids, fungal filaments, bivalve molluscs and bryozoans on stalagmites retrieved from a blue hole. Annelids were observed to have bored into the calcite cores of the stalagmites. Benjamin's (1970 film) general surveys of the blue holes of Andros showed that sponges, ahermatypic corals and anemones are common on the walls of the caves and that numerous fish occur near the entrances.

Our own work on both the 1981 (G.F.W.) and 1982 (C.A.M.M.) British Cave Diving Group Expeditions to Andros was concerned with testing the hypotheses listed above, and with compiling a species list. We have made progress on the hypotheses, but more work is required in all areas. On the species list, some identifications are still outstanding, and more collection of new material is required. This report is therefore a progress report and points the way for future work.

METHODS

Currents in Conch Sound 1

The speed and direction of currents at a penetration of about 20 m into the entrance passageway of CS1 were recorded automatically on magnetic tape at four minute intervals from 13.01 h, 26/8/81, to 14.01 h, 29/8/81, and at ten minute intervals from 12.20 h, 5/8/82, to 12.30 h, 20/8/82, using a Plessey Current Meter. The meter was suspended from the same point on the roof of the passageway during 1981 and 1982 and at all times was exposed to mainstream currents. Times of high and low tides were taken from tables supplied by A.U.T.E.C. (the Atlantic Undersea Test and Evaluation Centre) at Fresh Creek.

Suspended particulate material

Particulate organic carbon (POC) content of water samples collected in August 1981 were determined by two methods: (1) 4 litre water samples were filtered through Whatman GF/C filter papers soon after collection; the filters were then rinsed with 10% seawater formalin, stored individually in polythene bags and transported to the U.K. POC on the filters was measured in the laboratory, after rinsing with distilled water, by a wet oxidation method in which concentrated sulphuric acid and potassium dichromate were used to oxidise organic carbon, and excess dichromate titrated with ferrous sulphate; (2) 1.5 litre water samples were filtered through glass-fibre papers immediately after collection. The papers were then rinsed with a few ml of 0.3% sulphuric acid to remove inorganic carbon, air dried, and sealed in petri-dishes for transport to Canada. In the laboratory POC was measured using a Carbon/Sulphur Determinator (Leco Corp., Michigan).

In 1982 two coarse mesh plankton nets, each with a mouth diameter of 0.45 m, were used to sample the particulate material suspended in the suck and blow currents in CS1. 15 min samples were collected at 07.30 (suck), 12.30 (early blow) and 15.30 (late blow) on 19/8/82. At the end of each sampling period the nets were removed to the beach where the contents of the two 2 litre collecting bottles were vigorously stirred and 3 or 4 sub-samples removed from each in 30 ml tubes. A few ml of formaldehyde were then added to each of the tubes and the samples transported to the U.K. In the laboratory each sample was filtered through pre-weighed Whatman GF/D filters. These were then dried to constant weight and the dry weight of suspended particulate material determined.

Plankton sampling in 1981

Plankton was collected during the day between 11.00 a.m. and 3.00 p.m. using a 0.3 mm mesh net with a mouth diameter of 0.45 m. 15 min samples of suck and blow current were taken by setting the net in the blue hole entrance. Current speed in entrances was about 0.25 m sec^{-1}.

Plankton samples were fixed in sea water formalin and examined at Reading. Each sample was placed in a large petri dish marked on the bottom with a 2 cm grid. The area of the bottom of the dish was 144 cm^2. Samples were spread evenly within the dish and examined using a Wild M5 stereo microscope. Whole samples were first scanned at x12 and numbers of large animals (e.g. *Sagitta*, amphipods) recorded. Then two 4 cm^2 squares were selected at random and scanned at x50; numbers of all animals and objects were recorded. These numbers were added, then multiplied by 18 to give an estimate of total numbers in the sample. In cases where numbers of animals had been both counted and estimated the two figures were compared. It was found that x12 was inadequate for counting small animals such as ostracods and larvae, but that larger, less frequent animals such as cumaceans and amphipods were better counted by scanning the whole sample. The blow sample from BC was substantially larger than the others and was therefore placed in two petri dishes. Each dish was treated separately and the totals summed to give figures for the whole sample.

Sessile organisms

Estimates of the percentage cover of sessile organisms in CS1 and RC were made using photographic quadrats. A Nikonos III underwater camera with 28 mm lens, Nikonos close-up lens and flash was used, giving quadrats of 0.03 m^2. Each photograph was of a randomly selected area of floor, wall or roof. Colour slide film was used. Photographs were analysed by projecting slides onto a regular grid and recording whatever occurred at each point of intersection of the grid. The grid used gave about 100 intersections per slide. Results were converted to percentages to give estimates of cover of the various organisms. Where surfaces were obscured by hyroid canopies it was assumed that the covers of other organisms beneath the hydroids were the same as those observed on adjacent unobscured surfaces, and estimates were adjusted accordingly.

RESULTS AND DISCUSSION

Table 1 shows the species so far identified from collections made during 1981 and 1982. In the following sections we first describe relevant features of each Blue hole site which was visited by one or both of us, noting the characteristic sessile organisms. Second, we give details of the occurrence and distribution of mobile species. We then detail the quantitative measurements made on the currents, seston and sessile communities. And lastly we comment on the growth forms and orientations of passive suspension feeders. Site locations and detailed surveys of the cave systems are given by Palmer (1984, this volume). In the following account organisms will be referred to by genera unless more than one species of a single genus is listed in Table 1.

General descriptions of study sites

Conch Sound 1 (CS1) - Visited in 1981 and 1982. The depth of the surrounding sea bed is 1-2 m, the site is very near the shore and the surrounding water contains suspended sediment. A large, irregular entrance arena drops to about 10 m. The main passage is about 2 m high and 4-6 m wide and leads SW, dropping rapidly to 20-25 m then levelling out. At 150 m penetration the passage widens into the first stalagmite chamber at about 20-25 m depth. Current in the main passage was up to 0.5 m sec^{-1} (see below).

The surrounding area was sandy or silty with sea grass and algae. Growing on the upper parts of the walls of the arena were algae and a few hermatypic corals; lower down the sponges *Ulosa* and *Haliclona viridis* were common, with *Spirastrella* at the bases of the walls. Arc shells *Arca* were embedded amongst the sponges (Pl.1). Surfaces sheltered from the current were silty, sponges and ahermatypic corals were observed half buried in the silt (Plate 5) and siltation is evidently an important factor at this site.

Table 1. Species collected on 1981 and 1982 expeditions, and sites of collection. CS1 = Conch Sound 1, CS2 = Conch Sound 2, RC = Rat Cay, BC = Bluehole Cay, MB = Mangrove Bay, SCB = Stafford Creek Bluehole, DH = Doughnut Holes. Asterisks denote species captured in blow plankton samples.

FORAMINIFERA
2 spp to be identified
PORIFERA, DEMOSPONGIA
Haliclona viridis (Duchassaing & Michelotti) CS1, RC, BC.
Haliclona aquaeductus Schmidt CS1,RC,BC
Ulosa ruetzleri Wiedenmayer CS1,RC,MB
Spirastrella cunctatrix Schmidt CS1,RC
Timea mixta (Topsent) CS2, BC
Tethya crypta (de Laubenfels) CS1
Epipolasis lithophaga Wiedenmayer CS1,BC
Myriastra kallitetilla de Laubenfels CS1
Geodia neptuni (Sollas) CS1
Chondrilla nucula Schmidt RC,BC,MB
Chondrosia collectrix (Schmidt) CS1
PORIFERA, CALCAREA
Clathrina coriacea (Montagu) CS1,RC
16 spp to be identified.
COELENTERATA, HYDROZOA
Thyroscyphus ramosus Allman CS1,RC,BC
Sertularia of *turbinata* sens Vervoort BC
Lytocarpus philippinus (Kirchenpauer) RC,BC
Stylaster roseus (Pallas) RC, DH
COELENTERATA, ANTHOZOA
Telmatactis rufa Verrill CS1,RC
Diplactis bermudensis McMurrich CS2
Stoichactis helianthus (Ellis) MB
Diadumene sp BC
Pseudocorynactis caribbeorum Hartog MB
Phyllangia americana Milne-Edwards & Haime CS1,RC
Astrangia solitaria (Lesueur)CS1,RC,MB
Rhizosmilia maculata RC
PLATYHELMINTHES
Unidentified flatworm at BC
ANNELIDA, POLYCHAETA
Hermodice caruncuIata (Pallas) BC,CS1,MB
Chaetopterus sp.RC
4 spp to be identified
MOLLUSCA, GASTROPODA
* *Scissurella* of *crispata* Fleming RC
Petaloconchus mcgintyi Olsson & Harbison RC
* *Caecum antillarum* Carpenter RC
* *Caecum nitidum* Stimpson RC
Cypraea zebra L.RC,CS1,MB
Cymatium nicobaricum Röding RC
Cymatium pilare L.CS1
MOLLUSCA, BIVALVIA
Arca imbricata Bruguière RC,CS1
Barbatia cancellaria Lamarck CS1,RC
Barbatia domingensis Lamarck RC
Brachidontes citrina Röding RC
Brachidontes exustus L.SCB
Lithophaga nigra Orbigny CS1
Isognomon radiatus Anton RC
Lima scabra Born RC
CRUSTACEA, OSTRACODA
* *Amboleberis americana* (Muller)RC
* *Actinoseta chelisparsa* (Kornicker) RC
* *Asteropella monambon* (Kornicker)RC
* *Sarsiella 'carinata'* (Kornicker)RC
* *Skogsbergia lerneri* (Kornicker)RC
CRUSTACEA, COPEPODA
* *Peltidium* sp.nov.RC
CRUSTACEA, CIRRIPEDIA
Lithotrya dorsalis (Ellis) RC
CRUSTACEA,DECAPODA
Stenopus sp. CS1
Barbounia sp.RC
Synalpheus sp.RC
Panulirus argus (Latreille) CS1,RC
Panulirus guttatus (Latreille) CS1,RC
Scyllarides aequinoctialis (Lund) RC
Dromia erythropus (G.Edwards) BC, CS1
Dromidia antillensis Stimpson RC, BC
Stenorhynchus seticornis (Herbst) CS1,RC
Portunus vocans (A.Milne-Edwards) CS1
Carpilius corallinus (Herbst) RC
Micropanopeus nuttingi (Rathbun) RC
Heteractaea ceratopus (Stimpson) RC
Several spp. of *Amphipoda, *Isopoda and *Cumacea to be identified.
BRYOZOA
Steginoporella magnilabris (Busk) RC
Celleporaria sp. nov. RC
Crisia ramosa Harmer RC
ECHINODERMATA
Echinaster sentus (Say) BC
Ophiactis savignyi CS1
Holothuria parvula (Selenka) CS1
PISCES
Myrophis punctatus CS1, RC

The entrance to the main passage, especially the floor and walls, was fringed with a dense growth of the hydroid *Thyroscyphus* (Pl.3). Inside the passage common sponges on floor, walls and roof were *H.viridis*, *Haliclona aquaeductus* (Pl.2), *Spirastrella*, *Chondrosia* and the bright yellow *Clathrina*. Also common were the ahermatypic corals *Phyllangia* (Pl.2) and *Astrangia* , and the large anemone *Telmatactis* (Pl.4). Colonial ascidians were frequent. This sessile community appears to occupy almost 100% of the rock surface in the main passage, interspecific competition is probably intense.

In the first stalagmite chamber the increased diameter of the passage leads to greatly reduced current speed. The sessile community is much less dense (Pl.8) and composed mainly of sponges: a white species resembling *Clathrina* was common and *Myriastra* was collected here. A boulder collected from the entrance to the chamber had the arc shell *Barbatia cancellaria* and the boring date mussel *Lithophaga* associated.

Conch Sound 2 (CS2) - Visited in 1981 and 1982. Across the bay from CS1, the entrance is in shallow water 1-2 m deep close to shore. A small entrance arena about 3 m deep leads to a passage which slants steeply down. The current was stronger than in CS1 and in 1981, but not 1982, the blow was sulphurous.

The entrance arena was colonized by algae. In 1981 dense tufts of white filaments, probably bacterial, occurred around the entrance and grew thickly on the rocky walls of the passages throughout the explored system.

A collection made in 1981 at 10 m deep just beyond the entrance revealed the following restricted fauna: two species of sponge, *Timea* and another; the anemone *Diplactis* embedded in the *Timea* ; and some small tube-dwelling polychaetes.

Rat Cay (RC) - Visited in 1981 and 1982.
The entrance arena is about 6 m deep, 6 m wide and 15 m long and lies in water 1 - 2 m deep close to Rat Cay about 1 km offshore. The surrounding water is clear and appeared free of suspended silt. The entrance at one end of the arena leads into a vestibule with a sheltered cave above; the main passage descends a narrow vertical pot to about 10 m. Here it flattens into a bedding, descending gradually to about 15 m and opening into a larger passage at a penetration of about 40 m. The current is very strong in the pot and in parts of the bedding but slackens beyond as the passage widens.

Reef corals and gorgonians are common in the area surrounding the arena and on the upper parts of the walls of the arena. The sponge *Ulosa* was common on the lower parts of the walls and beneath overhangs. *Arca* occurred embedded amongst sponges (Fig. 1) and *Lima* was observed in crevices. Around the cave entrance were several colonies of the hydroid *Lytocarpus* (Pl.9).

Within the cave entrance the large hydroid *Thyroscyphus* was prominent, growing on boulders on the floor and on the rocky walls and roof and streaming in the current (Pl.3). Ahermatypic corals, especially *Phyllangia* , were abundant within the vestibule (Pl.2) and a single colony of the coral *Rhizosmilia* was found in the sheltered cave at the back, associated with sponges and colonial ascidians.

At the base of the pot the floor of the bedding was partly sand and partly a pavement of the coral *Phyllangia* . The roof of the bedding bore a rich and diverse community: numerous sponges, the corals *Phyllangia* and *Astrangia* the anemone *Telmatactis,* colonial ascidians, bryozoans and sabellid worms competed for space (Pl.4). The sheet-like bryozoan *Steganoporella* was common and a specimen was collected which had overgrown a 4 cm diameter lump of the sponge *Spirastrella* (the sponge was alive beneath). A boulder retrieved from the base of the pot contained various bivalves in crevices and was bored by the barnacle *Lithotrya.*

The rose coral *Stylaster* was collected from boulders at a penetration of about 300 m, depth 15 m.

Bluehole Cay (BC) (Forfar Blue Hole) - Visited in 1981. There are three small entrances within 25 m of each other, close to the Cay in water 1-2 m deep. The Cay lies about 500 m offshore. The surrounding water is fairly clear but not as clear as at RC. Entrance arenas are poorly developed or lacking. Only two entrances are large enough to be entered and are very cramped inside. There is an interconnecting passage and deeper passages. Currents were moderate.

The area surrounding the entrances is sandy with sea grass, algae and scattered coral clumps. Hydroids occurred around and within the entrances; inside, the sponge *Timea,* with embedded anemones *Diadumene,* was common encrusting the rocky walls. Various other sponges including *H.viridis* and *H.aquaeductus* were present but ahermatypic corals were not observed.

Stafford Creek Blue Hole (SCB) - Visited in 1981 . This is a shallow (7 m deep) silt-filled hole about 1 km up Stafford Creek. The surrounding area is 0.5-1m deep and the creek bed is silty with sea grass and algae. The surface water is brackish and cool but there is a very hot layer below about 2 m. A further cool layer occurs at about 4 m, below the hot layer. There was no current; the water was turbid.

Stands of mangrove were growing around the hole and their roots bore a sessile fauna of serpulid worms and the mussel *Brachidontes exustus.* Mats of algae grew on the muddy slopes leading into the hole but they stopped at the hot layer.

Mangrove Bay Blue Holes (MB) - Four holes visited in 1982 are aligned on a N/S fault about 200 m offshore and may be interconnected. The main reef in this area lies about 1.5 km offshore and shows signs of recent devastation (reputedly the effect of bleach application by lobster fishermen). Inshore and around the holes the shallow water covers a sandy bottom with few coral heads and limited fauna. Currents appeared similar to CS1.

The entrance arenas at three of the holes (2, 3 and 4) are slot-shaped depressions 3 - 5 m deep with corals *Astrangia,* gorgonians and sponges *Ulosa, Chondrilla* present around the sides and roofs of the passages, and abundant hydroids covering the floors. Specimens of *Stoichactis* were found only at hole 2.

The entrance arena to hole 1 was by contrast a wide (30 m diameter), deep (25 m) depression, heavily silted on three sides with a more vertical sparsely colonised rock wall on the fourth side. It was noticed that of the four holes in MB, hole 1 had less fish life associated with the entrance arena.

Kemps Bay Doughnut Holes (DH) - Two holes visited in 1982. These holes lie 2 - 3 km offshore. The water is 5 - 10 m deep with numerous coral heads supporting a diverse fauna. The entrance arenas are characterised by encircling 'doughnuts' of reef coral growth, especially *Acropora palmata* and *A. cervicornis,* the elk-horn and stag-horn corals. Within the 'doughnuts' funnel-shaped depressions, heavily silted, lead to the entrances in coral- and sponge-encrusted rock at 18-20 m. Crinoids and the rose coral *Stylaster* were common in these holes.

These holes were only briefly examined but appeared radically different, ecologically, to those holes studied more closely in the north of Andros.

Notes on mobile species.

ANNELIDA - The fire worm *Hermodice* was often seen wandering amongst sponges and corals in arenas and vestibules.

MOLLUSCA - Measled cowries *Cypraea* were frequent in vestibules and at short penetrations of main passages.

CRUSTACEA - Lobsters were frequent in crevices in entrance arenas and vestibules in CS1, RC and MB. Large specimens of *Panulirus argus.* occurred in the better lit areas whereas *P.guttatus* appeared to be more cryptic. Small individuals of the latter species were sometimes seen some distance back into the cave systems beyond the reach of daylight, creeping on the passage walls and roof.

Reef crabs such as the arrow crab *Stenorhynchus* (Pl.5) and the coral crab *Carpilius* occurred in arenas, vestibules and at short penetrations into main passages. In vestibules and deeper into main passages the sponge crabs *Dromia* and *Dromidia* were frequent. One from CS1 lacked a sponge case. One sponge case from *Dromia* and two from *Dromidia* were collected: the *Dromia* case was *Epipolasis* and the *Dromidia* cases were *Chondrilla* and unidentified. The swimming crab *Portunus* was collected in the 1st stalagmite chamber of CS1.

Shrimps were often seen on floors, walls and roofs of passages, but were rarely collected. *Stenopus* was retrieved from the 1st stalagmite chamber of CS1 and *Barbounia* from beyond the bedding in RC. Small crustaceans are probably plentiful in the passages since ostracods, harpacticoid copepods, amphipods, isopods and cumaceans were collected in blow plankton (see below).

ECHINODERMATA - The deposit feeding holothurian *Holothuria* was common in the first stalagmite chamber of CS1, creeping over the walls and floor. In the deeper passages of BC the starfish *Echinaster* was common.

VERTEBRATA - Fish were plentiful in entrance arenas and in sheltered parts of vestibules (Pl.6). They avoided places with strong currents and, with two exceptions mentioned below, were rarely seen more than a few metres back into main passages. Systematic identifications were not attempted but the fish appeared to be common reef species with snappers and grunts being plentiful.

On deep penetrations (300 m) into CS1 and RC in areas where soft sediment had accumulated in dunes on the floor, the snake eel *Myrophis* was frequently observed burrowing in the silt. A fish resembling the cave fish *Lucifuga spelaeotes* was occasionally observed, but never captured, in the deeper passages of RC and BC; this species was captured in fresh water in an inland hole (see Proudlove, 1984, this volume).

Turtle bones were found on the floor in the deeper passages of RC and CS2. Probably these reptiles had entered alive, with the suck current, and had been unable to find their way out.

Currents in CS1.

Table 2 shows the duration and peak speeds of the alternating suck and blow currents and the durations of each successive suck/blow cycle in CS1 during a two-day period in August 1981. The durations of the alternate suck and blow phases and successive suck/blow cycles vary considerably and without obvious pattern. Peak current speeds during blow phases were, however, consistently greater than during suck phases within the same cycle. Changes of current speed with time are shown in Fig.1, from which the following points should be noted: (1) current speeds were generally greatest when tabulated tides were at high or low extremes; (2) there was greater variation in the peak current speeds during suck phases than during blow phases; (3) if the area under each curve is proportional to the volume of water entering or leaving CS1 during that phase, then the total volume of water blown out during the two days of recording was greater than the total volume sucked in; i.e. there was an apparent net loss of water from the hole.

Table 2 Current cycles measured in CS1 in August 1981

day of month	time	direction	current		
			phase duration (mins)	peak speed (m.s.$^{-1}$)	cycle duration (mins)
26	14.37 - 20.59	suck	382	0.46	-
26-27	21.03 - 03.49	blow	406	0.53	788
27	03.53 - 08.37	suck	284	0.31	-
27	08.41 - 15.24	blow	403	0.53	687
27	15.27 - 22.05	suck	398	0.47	-
27-28	22.09 - 04.37	blow	388	0.50	786
28	04.41 - 09.49	suck	308	0.39	-
28	09.53 - 16.29	blow	396	0.54	764
28	16.33 - 22.37	suck	364	0.44	-
28-29	22.41 - 05.09	blow	388	0.53	752

Table 3 shows the duration and peak speeds of the alternating suck and blow currents and the duration of each successive suck/blow cycle in CS1 during a 14 day period in August 1982. Considerable variation can again be seen, but this time a pattern is evident.

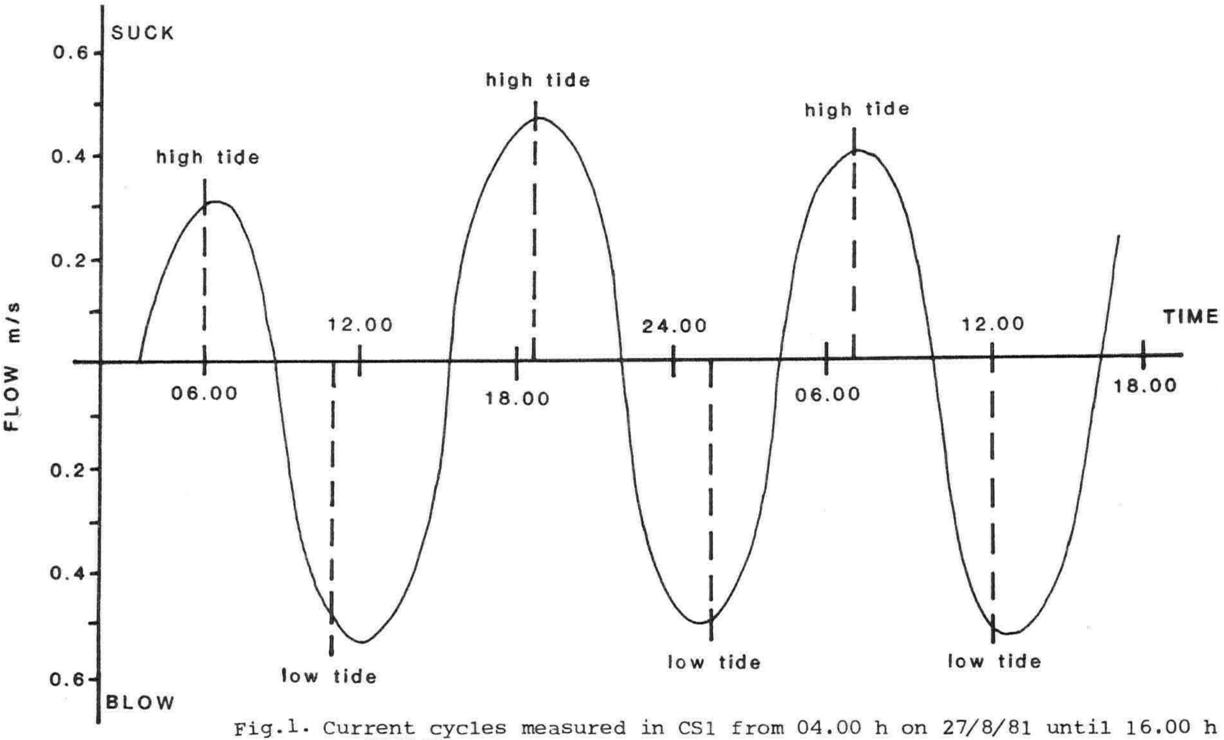


Fig.1. Current cycles measured in CS1 from 04.00 h on 27/8/81 until 16.00 h on 28/8/81.

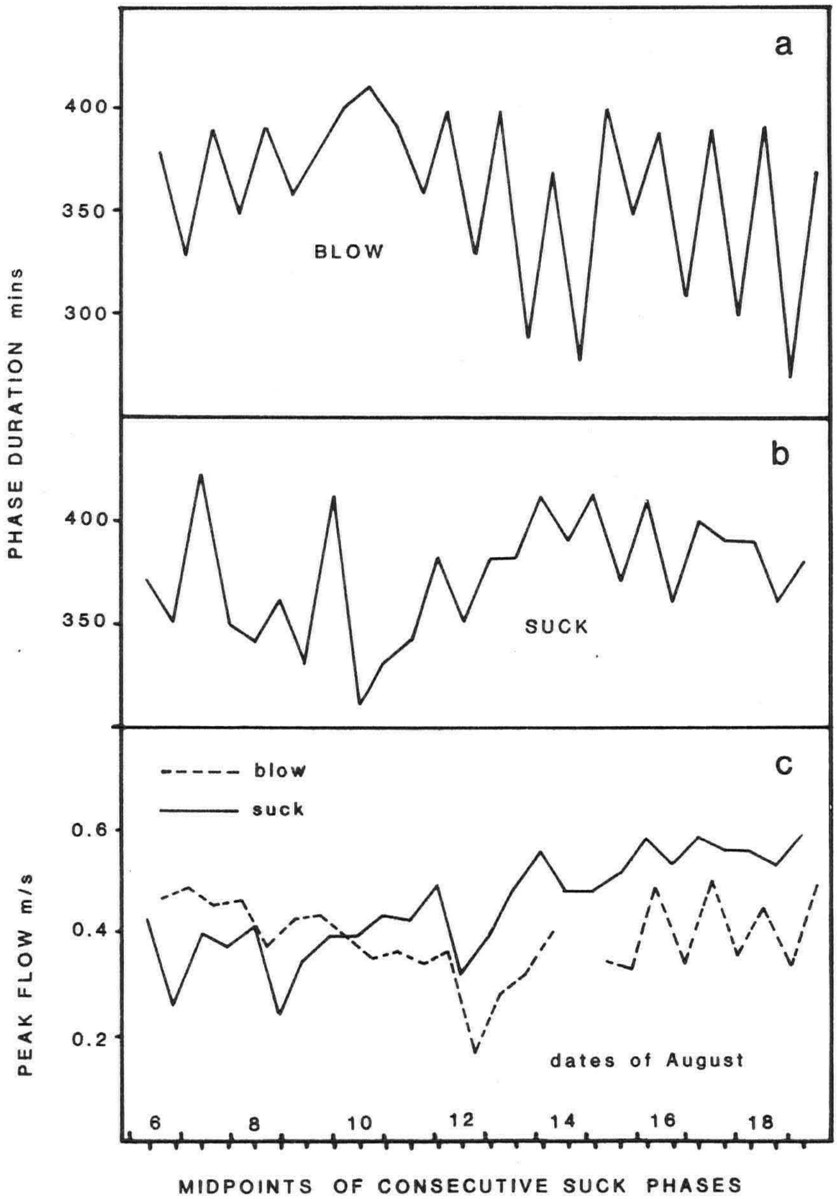


Fig.2. Long-term patterns in the currents in CS1 recorded between 6th and 19th August, 1982 (Table 3). (a) durations of consecutive blow phases, (b) durations of consecutive suck phases, (c) peak current speeds during consecutive phases of suck and blow. A change in pattern is evident on or about the 10th August.

Initially, from 6/8/82 until about 10/8/82, the duration of successive blow phases were alternately longer and then shorter (Fig.2a); following 10/8/82 the sequence reversed and successive blow phases became alternately shorter and then longer. A similar, but less clear pattern can be seen in the durations of successive suck phases (Fig.2b), and a pattern of suck/blow cycles: long then short, changing to short then long, is also evident (Table 3). Fig.2c shows that a change in the pattern of peak current speeds also occurs on 10/8/82. Before this date peak current speeds during blow phases were mostly greater than those during suck phases, but after 10/8/82 the pattern is reversed and peak current speeds were greater during the suck phases. Admiralty tide tables show that during August 1982 spring tides occurred on the 7th/8th and the 21st and neap tide on the 14th. Thus the observed pattern does not fit the spring/neap cycle.

Table 3

Current cycles measured in CS1 in August 1982.

day of month	time		current		
		direction	phase duration (mins)	peak speed (m.s.$^{-1}$)	cycle duration (mins)
6	05.50 - 12.00	suck	370	0.41	-
6	12.10 - 18.30	blow	380	0.45	750
6-7	18.40 - 00.30	suck	350	0.25	-
7	00.40 - 06.10	blow	330	0.47	680
7	06.20 - 13.20	suck	420	0.38	-
7	13.30 - 20.00	blow	390	0.44	810
7-8	20.10 - 02.00	suck	350	0.36	-
8	02.10 - 08.00	blow	350	0.45	700
8	08.10 - 13.50	suck	340	0.39	-
8	14.00 - 20.30	blow	390	0.36	730
8-9	20.40 - 02.40	suck	360	0.23	-
9	02.50 - 08.50	blow	360	0.41	720
9	09.00 - 14.30	suck	330	0.33	-
9	14.40 - 21.00	blow	380	0.42	710
9-10	21.10 - 03.00	suck	410	0.38	-
10	03.10 - 09.50	blow	400	0.38	810
10	10.00 - 15.10	suck	310	0.38	-
10	15.20 - 22.10	blow	410	0.34	720
10-11	22.20 - 02.50	suck	330	0.42	-
11	03.00 - 09.30	blow	390	0.35	720
11	09.40 - 15.20	suck	340	0.41	-
11	15.30 - 21.30	blow	360	0.33	700
11-12	21.40 - 04.00	suck	380	0.47	-
12	04.10 - 10.50	blow	400	0.35	780
12	11.00 - 16.50	suck	350	0.31	-
12	17.00 - 22.30	blow	330	0.16	680
12-13	22.40 - 05.00	suck	380	0.38	-
13	05.10 - 11.50	blow	400	0.27	780
13	12.00 - 18.20	suck	380	0.47	-
13	18.30 - 23.20	blow	290	0.31	670
13-14	23.30 - 06.20	suck	410	0.54	-
14	06.30 - 12.40	blow	370	0.39	780
14	12.50 - 19.20	suck	390	0.47	-
14-15	19.30 - 00.10	blow	280	-	670
15	00.20 - 07.10	suck	410	0.47	-
15	07.20 - 14.00	blow	400	0.33	810
15	14.10 - 20.20	suck	370	0.50	-
15-16	20.30 - 01.20	blow	350	0.32	720
16	01.30 - 08.20	suck	410	0.57	-
16	08.30 - 15.00	blow	390	0.47	800
16	15.10 - 21.10	suck	360	0.52	-
16-17	21.20 - 02.30	blow	310	0.33	670
17	02.40 - 09.20	suck	400	0.57	-
17	09.30 - 16.00	blow	390	0.48	790
17	16.10 - 22.40	suck	390	0.55	-
17-18	22.50 - 03.50	blow	300	0.35	690
18	04.00 - 10.30	suck	390	0.55	-
18	10.40 - 17.10	blow	390	0.43	780
18	17.20 - 23.20	suck	360	0.52	-
18-19	23.30 - 04.00	blow	270	0.33	630
19	04.10 - 10.30	suck	380	0.58	-
19	10.40 - 16.50	blow	370	0.48	750

The data collected during 1981 suggest that there was a net loss of water from CS1 during the recording period. Similarly the data collected in 1982 suggest that there was a net loss from the 6th to the 19th and a net gain from the 10th to the 10th (Fig.2). The fact that both net losses and net gains were recorded indicates that the differentials are not merely

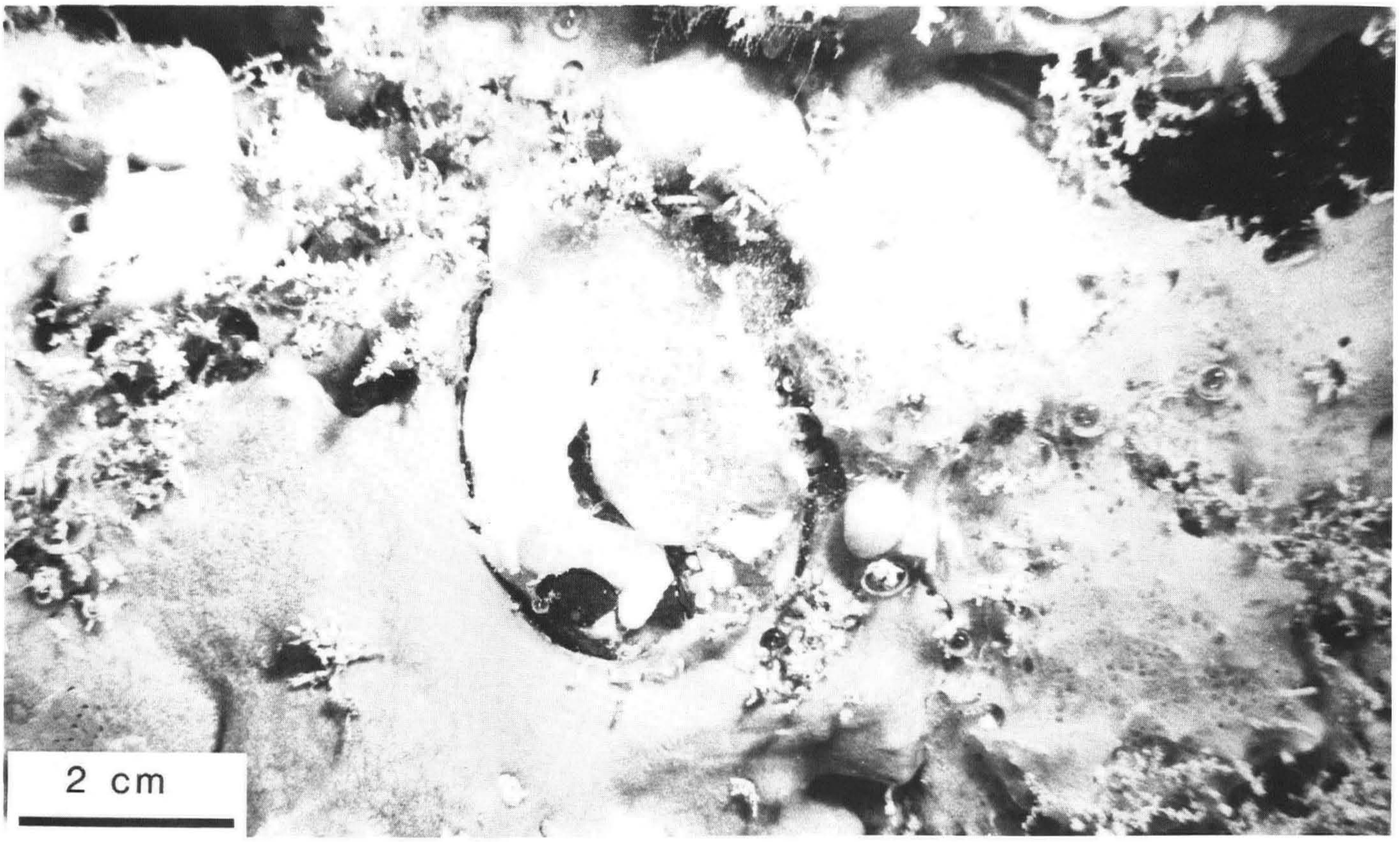


Plate 1. An arc shell *Arca* embedded amongst sponges. *Spirastrella* on the left and *Ulosa* on the right, beneath an overhang in the entrance area of CS1.

Plate 2. The coral *Phyllangia* and the sponge *Haliclona aquaeductus* growing on the wall of the main entrance passage in CS1. The sponge shows tassels streaming in the current.

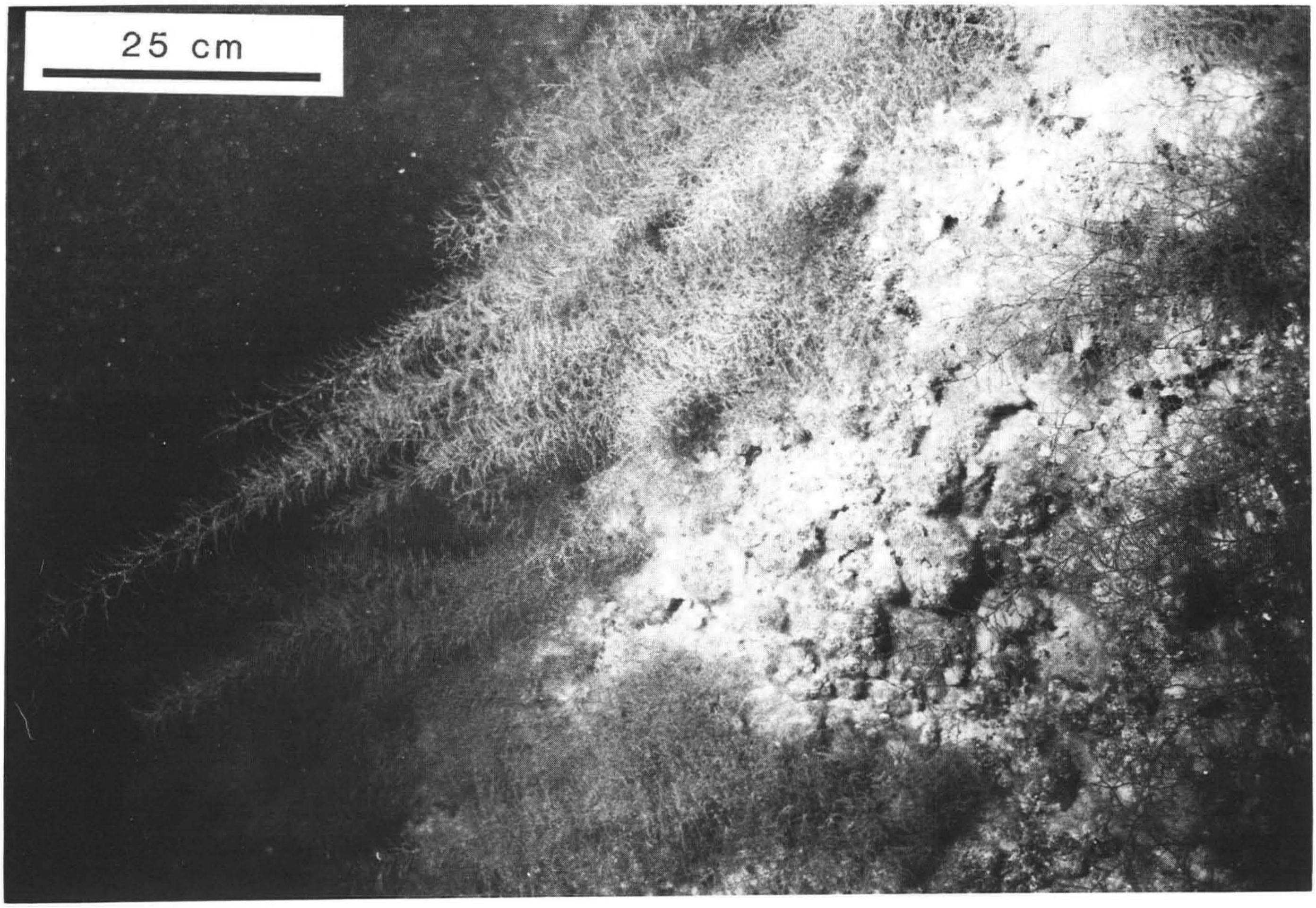


Plate 3. The wall of the entrance vestibule at RC during the suck phase showing encrusting corals and the hydroid *Thyroscyphus* streaming in the current.

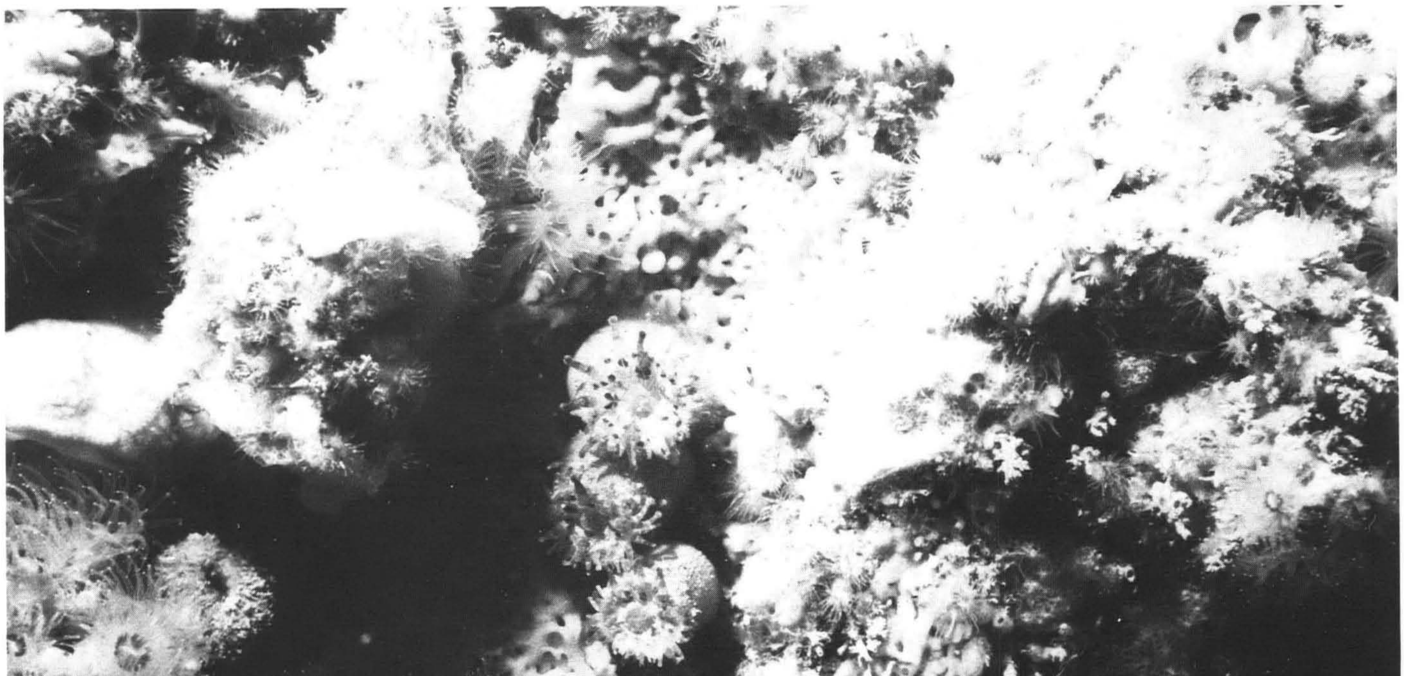


Plate 4. The diverse community on the roof of the bedding in RC. In the centre is a group of three anemones *Telmatactis* surrounded by a variety of sponges and corals.

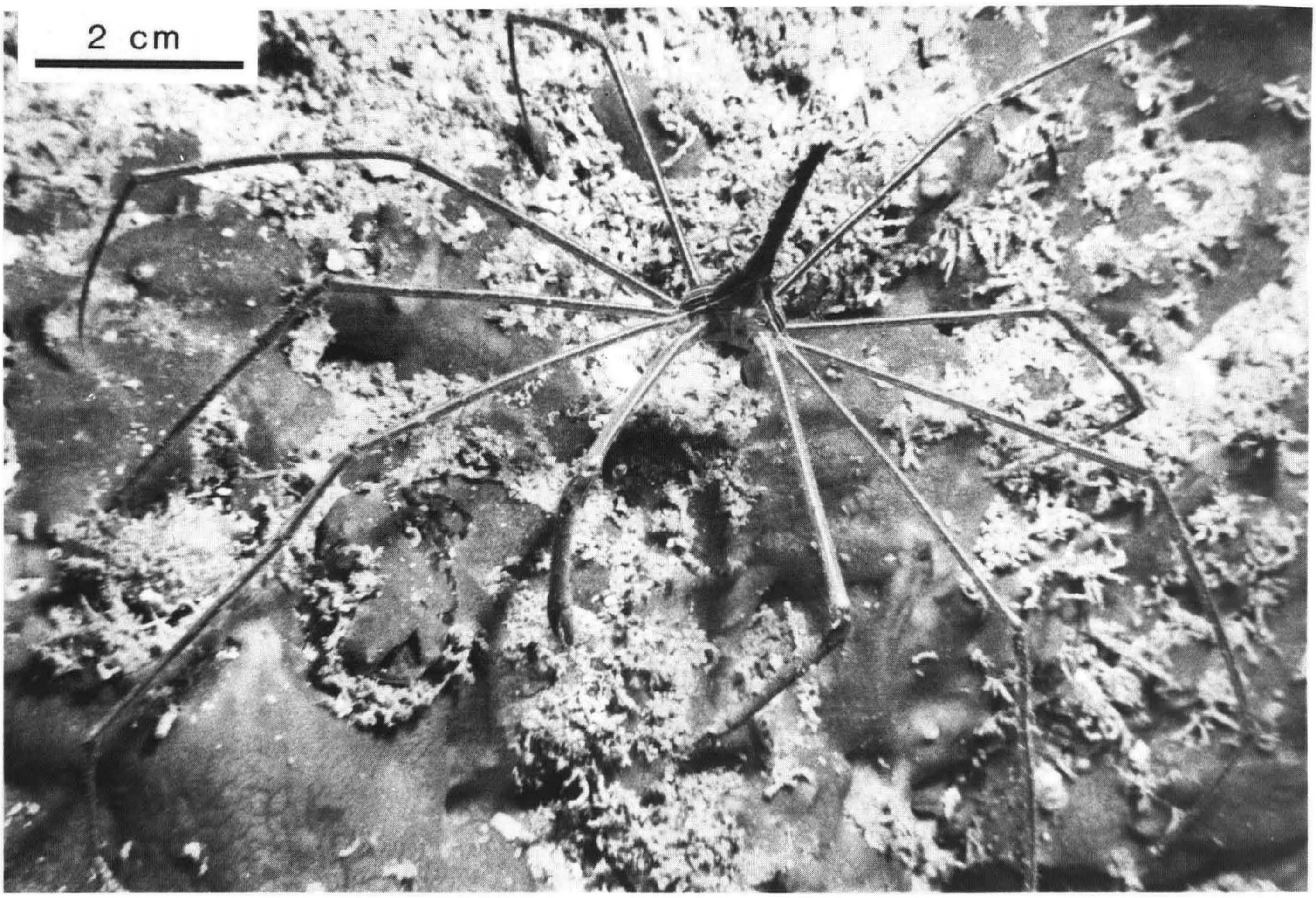


Plate 5. The arrow crab *Stenorhynchus* on the sponge *Spirastrella* in the entrance arena of CS1. Note the heavy silting of the sponge.

Plate 6. Grunts sheltering in a crevice in the vestibule of RC. In the absence of light the fish orientate their ventral sides to solid surfaces, hence in this crevice some swim upside down.

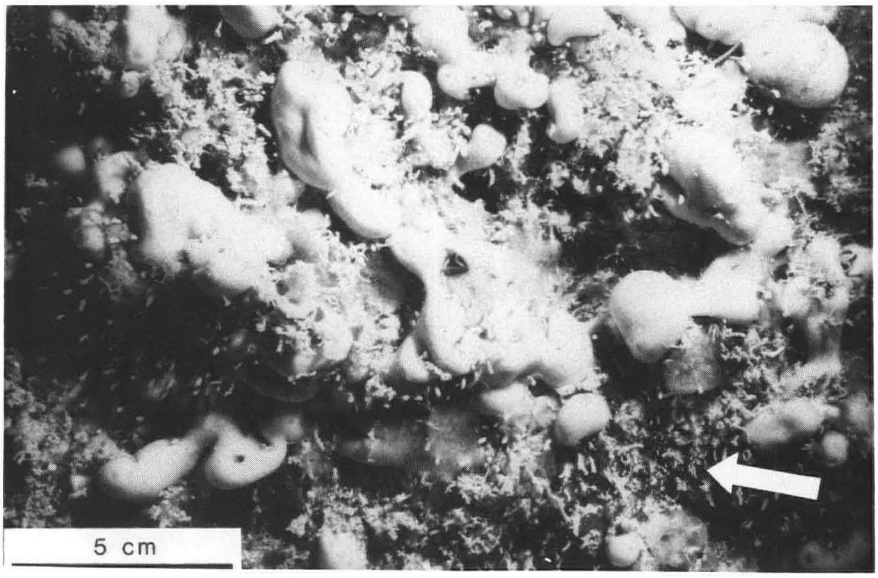


Plate 7. Photographic quadrat of a 0.03 m^2 area of wall in the entrance passage of CS1; sponges are prominent with some areas unidentifiable (arrow).

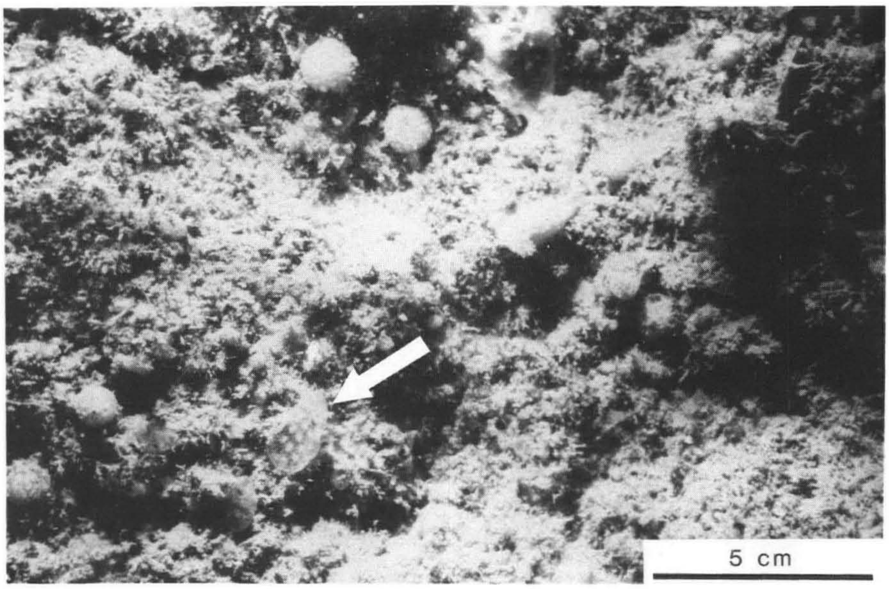


Plate 8. Photographic quadrat of a 0.03 m^2 area of the wall in CS1 at a penetration of 300 m; growth is sparse - only two round sponges can be seen at the top and an ascidian colony below (arrow).

Plate 9. A fan-shaped colony of the hydroid *Lytocarpus* orientated across the current on the wall of the vestibule at RC. The fan is dish-shaped with the concave side facing the entrance (below).

artifacts relating to the exact location of the current meter in the passageway. In 1981 the net loss of water was observed 2-3 days after the neap tide; in 1982, just after the neap tide, a net gain was observed. Thus net movements of water do not follow the spring/neap cycle. It is possible that the change in patters observed on 10/8/82 may have related to some unrecorded atmospheric condition.

These data are being analysed further to determine, (1) net volumes of water entering and leaving CS1 during a complete tidal cycle; and (2) exact temporal relationships between local tides and current speeds. Observations indicate that slack water in blue holes occurs within 2-3 h of tabulated high and low tides but that the relationship varies considerably.

Suspended particulate material

The particulate organic carbon (POC) concentrations of water samples collected from CS1, RC and BC were determined by two methods, a wet oxidation method, and analysis by a carbon/sulphur determinator (see Methods). The results are given in Tables 4 and 5.

Table 4

The concentration of particulate organic carbon, measured by wet oxidation, in samples of water collected from CS1, RC and BC.

site	date	current phase	sample volume	POC, mg l^{-1}
Conch Sound 1	18/8/81	mid-suck	4 l	1.50
"	"	mid-blow	"	0.48
Rat Cay	19/8/81	mid-suck	4 l	1.33
"	"	mid-blow	"	0.78
Blue Hole Cay	20/8/81	mid-suck	4 l	2.54
"	"	early-blow	"	2.89

Table 5

The concentration of particulate organic carbon, measured by a carbon/sulphur determinator, in samples of water collected from CS1, RC and BC.

site	date	current phase	sample volume, l	POC, mg l^{-1}
Conch Sound 1	18/8/81	mid-suck	1.5	0.54
"	"	mid-blow	"	0.42
"	23/8/81	late blow	"	0.32
Rat Cay	19/8/81	mid-suck	1.5	0.48
"	"	mid-blow	"	0.32
Blue Hole Cay	20/8/81	mid-suck	1.5	0.37
"	"	early blow	"	0.38

POC concentrations determined by the wet oxidation method were greater than those determined by the carbon/sulphur determinator and there is no clear explanation for the difference. Similar trends, however, are evident in bot sets of data. The POC concentrations during the middle of the suck phase in CS1 and RC were greater than those during the middle of the blow phase in those holes. The single sample collected during late blow at CS1 (Table 5) contained the least POC. At BC the POC concentration during the middle of the suck phase was similar to that during the early part of the blow phase.

These trends support the hypothesis that water sucked into blue holes contains more organic matter than water blown out. The relatively high concentration of POC in water leaving BC during early blow was probably caused by the presence of a high concentration of detrital material such as that found in the plankton sample taken at the same time (Table 7). Detritus is probably generated within the hole during the suck phase and is exported early in the blow phase, after which the POC concentration gradually diminishes, becoming least at the end of the blow phase.

Table 6

Mean dry weights (mg ± 95% confidence limits) of suspended particulate material (SPM) collected per litre of filtrate during 15 min plankton net samples in CS1. Asterisks denote significant difference ($p < 0.01$) established by t-test.

date	time	current phase	number of sub-samples	mean weight of SPM
19/8/82	07.30	mid-suck	7	82.3 ± 17.3
"	12.30	early blow	7	95.3 ± 21.7
"	15.30	late blow	8	**40.0 ± 11.0

The hypothesis is further supported by the data collected during 1982. Table 6 shows the mean weight of suspended particulate material (SPM) collected per litre of filtrate by 15 min plankton net samples in CS1. The weight of SPM during the mid-suck and early blow phases were similar, but significantly less SPM was filtered during the later part of the blow phase. It should be noted that these figures refer to mg SPM per litre of filtrate not per litre of water filtered. The overall concentration of SPM in the suck and blow currents cannot be calculated from these data because the plankton nets only filtered the larger particles, and estimates of the volume of water filtered by the nets are subject to considerable error.

Plankton

Five plankton samples collected in 1981 - a suck and early blow from BC and a suck and two blows from RC - were analysed in detail. The main results are shown in Table 7. Differences between sites, between suck and blow samples and between different stages of the blow phase can be seen. In contrast, the two blow samples from RC taken one week apart but at the same stage of the blow phase are very similar.

Table 7

Numbers of items frequently encountered in plankton samples taken in 1981. 'Biogenic Sand' includes pieces of echinoderm skeleton, pieces of serpulid worm tube and sections of erect bryozoan stem.

	10/8/81 BC mid suck	19/8/81 RC mid suck	20/8/81 BC early blow	12/8/81 RC mid blow	19/8/81 RC mid blow
sand	918	990	1386	2052	5472
biogenic sand	108	54	1008	576	558
algal filaments & fragments	2052	1098	1350	648	108
crustacean exuvia	234	252	360	738	414
ostracod valves	36	-	234	234	324
faecal pellets	162	72	14274	414	630
amorphous detrital aggregates	1602	288	3078	1746	1386
hydroid pieces	-	-	990	306	144
foraminiferans	36	54	288	180	216
tiny gastropods	-	36	72	162	162
ostracods	9	-	234	108	126
planktonic copepods	35	3420	7	90	72
harpacticoid copepods	-	-	162	36	-
cumaceans	3	-	46	8	23
amphipods	4	-	11	21	48
isopods	20	-	26	5	6
crustacean larvae	18	254	54	-	-

Differences between sites are clearly revealed by the two suck samples. The water entering BC contained more detrital material and a few small benthic crustaceans. At RC, however, planktonic crustaceans were much more abundant. These differences correlate with the local environments of the sites (see above).

Differences between suck and blow samples include an increase in the amount of sand of both indeterminate and biogenic origins in the blow, a decrease in the recognisable algal detritus in the blow but an increase of other detrital material, especially faecal pellets, a decrease in planktonic organisms, and an increase in small benthic organisms (see Table 1). The latter are presumably normally resident within the caves, the captured individuals having been blown out by the current.

The blow sample from BC differed from the two RC samples in that it contained vastly more detrital material, especially faecal pellets. The sample was taken about 1 h after the current reversal whereas the RC samples were taken 2-3 h after reversal. The relative scarcity of faecal pellets and detrital aggregates in the suck samples suggests that most of this detritus is generated within the blue holes and probably accumulates during the suck phase in places sheltered from the suck current. At reversal it is presumably resuspended by the blow current and exported from the caves early in the blow cycle.

Several items occurring sporadically in the samples are not shown in Table 7. Most of these were found in the BC blow sample and included several nereid worms, tiny anemones and ascidians. 180 planktonic larvaceans were found in the RC suck sample. Curiously, a few *Sagitta* were found in each blow sample but in neither of the suck samples.

Table 8

Mean percentage cover of sessile organisms near the entrance and at 300 m penetration into CS1, and near the entrance to RC, derived from photographic quadrats. n = 4 in CS1 (total quadrats = 24) and 2 in RC (total quadrats = 6). Allowance has been made for primary cover obscured by hydroids (see Methods).

	CS1 entrance			CS1 300 m			RC entrance		
	floor	walls	roof	floor	walls	roof	floor	walls	roof
Sand	66	-	-	20	-	-	63	-	-
unidentifiable	14	38	26	54	74	67	9	17	26
sponge	10	46	70	24	19	28	6	68	30
ahermatypic coral	2	7	1	-	-	-	22	15	40
colonial ascidian	8	9	3	2	1	2	-	-	4
yellow tubes	-	-	-	-	6	3	-	-	-
hydroid	23	1	-	-	-	-	46	36	4

Sessile communities

Table 8 shows results from photographic quadrats near the entrance and at a penetration of about 300 m in CS1 taken in 1982, and from near the entrance to RC in 1981. There was much variation between single quadrats but certain real trends are apparent.

First, there is a clear difference between the entrance passage and the deep penetration of CS1. The entrance passage is more diverse with hydroids and corals present, and there is much less unidentifiable surface. Unidentifiable surfaces in CS1 were apparently barren areas of rock covered by fine sediment; muddy tubes possibly belonging to amphipods or sabellids were frequently present projecting from the sediment (Pl.7). Thus there was much less cover of sessile organisms at the deep penetration (Pl.8); the only additional organism noted here was the 'yellow tubes', probably a species of sabellid worm. Likely reasons for the sparser epifauna at deep penetrations include a smaller amount of food in the water due to feeding and sedimentation nearer to the entrance, and a slower delivery of food in the slower current, due to the wider passage at this penetration.

The second trend is that there appears to be more coral and hydroid and less colonial ascidian in the entrance to RC than in the entrance to CS1. This difference may relate to the cleaner water entering RC with the suck current. Unidentifiable areas in RC appeared to be bare rock without sediment, but may have been colonised by foraminiferans or bryozoans.

Third, a comparison of floor, walls and roof shows, trivially, more sand on the floor. Otherwise, the only difference is that hydroids in the entrance passages (almost entirely *Thyroscyphus* in these photographs) appear to occur more commonly on the floor and walls than on the roof.

Growth forms and orientations

An initial hypothesis was that the availability of suspended food, especially planktonic organisms, would be greater in the suck current than in the blow current, and that the growth forms of fan-shaped passive suspension feeders such as gorgonians might be correlated with this. It was predicted on the basis of a hypothesis developed by Warner (1977, 1981) that these organisms might grow to form parabolic dishes orientated across the current and with the concave sides facing the blue hole entrance. Unfortunately, no gorgonians were found within the passages, but two fan-shaped organisms, the hydroid *Lytocarpus* and the hydrozoan coral *Stylaster* , were found and in both cases a dish-shaped growth form was observed with the concave side facing the entrance (Pl.9). One *Stylaster* colony 9 cm wide and 5 cm high collected at DH had a radius of curvature of about 6 cm.

Two other observations on growth forms are worth recording. First, the hydroid *Thyroscyphus* grows much longer in blue hole entrances than has been recorded elsewhere. We found colonies up to 75 cm long (Pl.3), compared to previous records of about 20 cm. Second, the sponge *Haliclona aquaeductus* was found to develop long tassels which streamed in the current (Pl.2). Digitations on this sponge in environments exposed to currents are mentioned by Wiedenmayer (1977).

CONCLUSIONS

Returning to the hypotheses listed in the Introduction, our work to date has clearly demonstrated that more suspended matter enters with the suck current than leaves with the blow, although early blow currents may contain large quantities of detritus. In nutritive terms the suck current is a much better source of food for suspension feeders than the blow current since most of the particles captured in the blow plankton were sand and low grade detritus whereas in the suck plankton fresh algal detritus and planktonic organisms were prominent. Chemical measurements of particulate organic carbon support this conclusion. Measurements made at different stages of the blow phase showed an apparent progressive reduction in suspended matter and nutritive value during the phase, with the late blow containing the least.

These findings correlate with the regrettably rather few observations made on fan-shaped suspension feeding organisms which were found to adopt a dish-shaped growth form with concave sides of dishes facing the blue hole entrance. It has been suggested that this growth form is more efficient than a flat fan at harvesting suspended particles from a unidirectional current (Warner, 1977, 1981). In the blue holes the current flows roughly equally in both directions but food particles come predominantly from one direction, from the entrance. The adoption of dish-shapes in these circumstances therefore indicates that trophic factors as well as hydrodynamic effects may be important in determining growth form.

Observations on the details of the currents in CS1 showed both short and long term irregularities, and evidence of long term patterns in which both apparent net outflow and, later, apparent net inflow were recorded. Unfortunately, records were not continued long enough to detect any regularity in these patterns, which did not appear to be phased to the spring/neap tidal cycle. Further analyses of these data are in hand.

None of the species identified so far from the marine parts of these cave systems (with the exception of the possible sighting of *Lucifuga spelaeotes* has turned out to be a special cave-adapted or deep water form. All are species which have previously been recorded from conventional marine habitats. The strong currents and the dispersal stages, especially larvae, of most marine species probably ensure that populations within blue hole systems do not become sufficiently reproductively isolated for cave-adapted species to evolve. Evolution of cave-adaptations is facilitated in fresh water systems because fresh water organisms tend to have limited dispersal. With regard to deep water species, it is possible that the environment, especially the relatively high temperature, is unsuitable: darkness, by itself, may be an insufficient condition to allow deep water species to flourish.

The sessile organisms on the cave walls formed a rich and varied community, thinning out at deeper penetrations. Some species were recorded sufficiently often to be regarded as characteristic of this community. They include the large hydroid *Thyroscyphus*, prominent around and just within blue hole entrances, the sponges *Ulosa*, *Spirastrella*, and the tasseled growth form of *Haliclona aquaeductus*, the ahermatypic corals *Phyllangia* and *Astrangia* and the anemone *Telmatactis*. However, the various holes differed in two respects, both of which affected the faunal composition. CS2, and other holes (G. Benjamin, pers.comm.) are sulphurous and this severely limits the fauna. Presumably the sulphurous outflow comes from the sulphurous layer at the interface between the fresh water lens of Andros and the underlying seawater (C. Smart, 1984, this volume). Variations in the depth of the fresh water lens, and hence of the sulphurous layer, due to weather conditions, might be expected to vary the sulphurous blow from these holes. This may explain the lack of sulphurous conditions in CS2 observed in 1982. Conversely it is possible that holes which are normally fully marine, occasionally become slightly sulphurous, perhaps after heavy rain. The presence of the sponge *Timea* in both CS2 and BC and the absence of corals in the latter lead us to suggest that BC may sometimes become slightly sulphurous.

The other variable is the environment surrounding the blue hole entrance. RC and DH lie further from the mainland of Andros than the other holes and both are surrounded by rich growths of reef corals. Both holes suck in silt-free oceanic water which, at RC, contains numerous planktonic organisms and little detritus. DH was visited very briefly but, with crinoids and *Stylaster*, appeared different from most other holes. In RC the growth of ahermatypic corals was particularly rich. Thus in addition to occasional sulphurous influence in some holes, there is probably an effect due to proximity of the shore or to offshore reef conditions.

Few observations were made of mobile animals. Sponge crabs and various shrimps were active in the dark passages by day; both are cryptic in reef environments by day but become active at night. The entrance arenas and vestibules appear to be important shelter sites for lobsters and fish. The latter, especially the snappers and grunts, probably disperse at night to feed on the surrounding shallow sea bed.

Our findings so far are encouraging, but point to the need for further work. More water and plankton sampling are required from a greater variety of holes, concentrating on contrast points such as suck, early blow and late blow. Also the extent to which the various holes are sulphurous should be investigated. Further studies are required on the currents: data for a complete lunar cycle should be obtained from two different holes concurrently to test for similarities of pattern. Additionally, the local tidal cycle should be directly monitored. Additional collections of organisms should be made, especially from deeper penetrations, and further observations of fan-shaped organisms are required. For analysing the sessile communities a larger sampling unit - perhaps a 1 m^2 quadrat - should be used since the photographic quadrats are too small and very time consuming to analyse.

ACKNOWLEDGEMENTS

We would like to thank Simcha Stroes-Gascoyne, a member of the 1981 Expedition, for her analysis of particulate organic carbon in water samples. We are very grateful to the Institute of Oceanographic Sciences for the loan of the Plessey current meter and to Dr. W.J. Gould for his help with the analysis of the data. We would also like to thank the following for help with the identifications: Dr. P.F.S. Cornelius (hydroids), Major K.W. England (anemones), G. Paterson and R.A. Armstrong (corals), Professor A. Graham (gastropod molluscs), Dr. R.J. Lincoln, Dr. R.W. Ingle, Dr. G.A. Boxshall and Dr. L.S. Kornicker (crustaceans), Dr. P.J. Hayward (bryozoans), A.M. Clark (echinoderms) and Dr. R.C. Robbins (fish).

Lastly, we are deeply grateful to the Royal Society for providing financial support for the biological study programme, and to 1981 & '82 expedition members for their help in providing materials for these studies.

REFERENCES

Benjamin, G.J. 1970. Diving into the blue holes of the Bahamas. *Nat. Geogr. Mag.*, vol. 138, pp346-363.

Benjamin, G.J. Andros Blue Hole Surveys (unpublished). (Copy held by Palmer).

Dill, R.F. 1977. The blue holes - geologically significant submerged sink holes and caves off British Honduras and Andros, Bahama Islands. *Proc. 3rd Int. Coral Reef Symp., Miami*, vol. 2, Geology, pp237-242.

Gascoyne, M., Benjamin, G.J., Schwarcz, H.P. & Ford, D.C. 1979. Sea-level lowering during the Illinoian glaciation: evidence from a Bahamian 'blue hole'. *Science*, vol. 205, pp805-808.

Warner, G.F. 1977. On the shapes of passive suspension feeders. pp567-576 in Keegan, B.F., O'Ceidigh, P. & Boaden, P.J.S., eds. *Biology of benthic organisms*. Pergamon, Oxford.

Warner, G.F. 1981. Species descriptions and ecological observations of black corals (Antipatharia) from Trinidad. *Bull. mar. Sci.*, vol. 31, pp147-163.

Wiedenmayer, F. 1977. Shallow water sponges of the western Bahamas. *Experientia*, suppl. 28, 287 pp, 43 pl.

M.S. Received October 1983

G.F. Warner & C.A.M. Moore
Zoology Department
University of Reading
Reading RG6 2AJ.

CAVE SCIENCE

Transactions of the British Cave Research Association Vol.11, No.1, March 1984

URANIUM-SERIES AGES OF SPELEOTHEMS FROM BAHAMAN BLUE HOLES AND THEIR SIGNIFICANCE

by M. Gascoyne

ABSTRACT

Twenty one $^{230}Th/^{234}U$ ages have been determined for nine speleothems from submerged and subaerial caves in the Bahamas, collected during the 1981 expedition. Ages range from 7 to >350 ky but only dates <100 ky are regarded as sufficiently accurate to correlate with Quaternary events. Clear evidence of a rise in sea level older than 47 ky is recorded in the calcite of one stalagmite.

The freshwater karstic origin of blue holes off the eastern coast of Andros Island was clearly demonstrated by the discovery of speleothems with a pure calcite core (Benjamin, 1970). Most speleothems are formed in a vadose environment by precipitation of calcite or aragonite from supersaturated groundwaters entering via the roof or walls of a cave. Deposits formed in underwater caves generally have a characteristic 'coraly' or knobbly appearance. Since the Bahama Banks are known to have been a relatively stable carbonate platform since Cretaceous times (Dietz et al, 1970), the discovery of speleothems below modern sea level was clear indication of the rise and fall of sea level in response to interglacial and glacial periods in the past. Glaciation of the northern hemisphere during Quaternary time was marked by ice accumulation and thickening on the continents which caused a corresponding drop in sea level roughly proportional to the intensity of the glaciation. At maximum glaciation, a drop of over 120 m is thought to have occurred (Shackleton and Opdyke, 1973) exhuming the entire Bahama platform and allowing cave formation and speleothem deposition processes to begin over a considerable vertical extent. Global warming caused sea level to rise and terminate karstic development so that most caves are now flooded and accessible only to divers.

The first attempt at dating speleothems recovered from such caves (Spalding and Mathews, 1972) gave support to this concept of speleothem formation by obtaining radiometric ages in agreement with ages of a low sea-stand determined from other locations. Subsequent workers (Harmon et al, 1978; Gascoyne et al, 1979) were also able to correlate ages of presently-submerged speleothems in Bermuda and the Bahamas, respectively, with palaeo-sealevel curves such as those determined by Shackleton and Opdyke (1973).

This study is a continuation of the work described by Gascoyne et al (1979) on the ages of speleothems in other parts of the Bahamas, specifically, the northeastern coast of Andros Island and from the Lucaya Caverns, Grand Bahama Island. Ages obtained by the $^{230}Th/^{234}U$ dating method are reported here and their significance is discussed in terms of minimum age of the caves, palaeo-sealevels and correlation to other palaeoclimatic records.

SAMPLE LOCATION AND ANALYTICAL METHODS

Of the marine blue holes visited by divers during the 1981 expedition, only Conch Sound No. 1 (CS1) contained any speleothems that were sufficiently well-preserved to merit sampling. Blue hole locations and descriptions can be found elsewhere in this volume. All the samples were already broken but lying close enough to other, unbroken speleothems so that their original depth and growth position could be established. One speleothem, which was collected from Conch Sound No. 2 (CS2) on an earlier visit by George Benjamin is also included here. Other speleothems were collected, by the author, from above sea-level caves in Morgan's Bluff on the north-eastern tip of Andros Island, and by George Benjamin from the entrance chamber of Lucaya Caverns. Usually, only stalagmites were sampled because (1) they were easy to recognise amongst lime-muds and marine carbonate growths on the cave floor and (2) characteristics of their morphology (e.g. thick, non-porous growth layers, stratigraphically superimposed on older layers) make them superior to other types of speleothem for age dating.

All speleothems were first sectioned down the long axis to determine the extent of marine carbonate replacement. The structure and texture of primary, freshwater calcite still present in the interior of most speleothems was then examined for evidence of boring by marine organisms such as annelids, fungal filaments, bryozoans, bivalves, etc. In preparation for analysis, calcite was chipped out of the central core, taking care not to incorporate any of the marine replacements. In the case of more heavily altered samples, the chips were rinsed in dilute nitric acid to remove adhering powder and unaltered calcite was hand-picked from the residue until sufficient sample was obtained for analysis.

The analytical techniques used to obtain $^{230}\mathrm{Th}/^{234}\mathrm{U}$ ages for these samples and theoretical aspects of the method are described by Gascoyne et al (1978). Briefly, the method involves dissolution of the calcite in acid, coprecipitation of U and Th by ferric hydroxide, re-solution and separation of U from Th using ion exchange resins, followed by preparation of thin sources for alpha spectrometry using standard plating techniques. The isotope radio-activity ratios $^{230}\mathrm{Th}/^{234}\mathrm{U}$ and $^{234}\mathrm{U}/^{238}\mathrm{U}$ are determined from α-spectra and radiometric ages are obtained by computerised solution of the age equation using appropriate values of the decay constants of $^{230}\mathrm{Th}$ and $^{234}\mathrm{U}$.

RESULTS

Speleothem locations, approximate depths below mean sea level, uranium concentrations, isotope activity ratios and calculated ages are given in Table 1. Quoted errors are ± 1σ, based on counting statistics. Chemical yields of Th and U are > 10% in all cases except where indicated. Assessments of the precision and accuracy of ages determined in the McMaster University laboratory are described in detail elsewhere (Gascoyne, 1980; Gascoyne et al, 1983).

TABLE 1 Speleothem locations, descriptions, isotopic data and $^{230}\mathrm{Th}/^{234}\mathrm{U}$ ages for samples from Bahaman caves

Speleothem	Description	Analysis No.	U conc^{n} (ppm)	$^{234}\mathrm{U}/^{238}\mathrm{U}$	$^{230}\mathrm{Th}/^{232}\mathrm{Th}$	$^{230}\mathrm{Th}/^{234}\mathrm{U}$	AGE ± 1σ (ky)
81048	80cm long sg from Conch Sound No.1 (with overgrowth)	base -1	0.19	0.980±0.042	> 1000	0.847±0.053	$206.5^{+49.2}_{-33.6}$
		middle -2	0.16	0.996±0.033	> 1000	0.691±0.036	$127.7^{+13.7}_{-12.1}$
81049	90cm long sg from CS1 with obvious overgrowth	base -1	0.19	1.065±0.056	197	0.680±0.043	$121.5^{+15.0}_{-13.2}$
		top -3	0.12	0.920±0.056	163	0.926±0.062	$331.4^{+164.2}_{-97.8}$
		near top -4	0.12	0.986±0.040	> 1000	0.972±0.062	> 350
		outer overgrowth -5	0.19	1.034±0.027	84	0.188±0.012	22.5 ± 1.6
		inner overgrowth -6	0.24	1.024±0.022	99	0.353±0.014	47.2 ± 2.4
81050	80cm long thick sg with dense white calcite core from CS1	base -1	0.21	1.030±0.042	59	0.324±0.029	$42.3^{+4.7}_{-4.5}$
		middle -2*	0.21	1.011±0.040	> 1000	0.326±0.030	$42.8^{+5.0}_{-4.7}$
		near top -4	0.19	1.043±0.034	11	0.356±0.016	$47.6^{+2.8}_{-2.7}$
81052	lower piece of 30cm heavily eroded sg from CS1	-1	0.31	1.035±0.019	110	0.836±0.040	$192.0^{+28.2}_{-22.4}$
81054	20cm long, chalky, layered sg from cave entrance in Morgan's Bluff	base -2*	0.16	1.074±0.044	25	0.368±0.021	$49.5^{+3.7}_{-3.5}$
81055	sc from cave entrance in Morgan's Bluff	inner layer (= oldest) -1	0.25	1.080±0.042	112	0.563±0.027	$88.6^{+6.7}_{-6.3}$
		outer layer (= youngest) -2	0.44	1.087±0.025	> 1000	0.063±0.006	7.0 ± 0.6
76017	20 cm sg with yellow single crystal core, from CS2 at -10m	base -1a	0.11	1.000±0.057	11	0.350±0.030	$46.7^{+5.1}_{-4.9}$
		base -1b (replicate)	0.11	1.022±0.057	126	0.379±0.030	$51.6^{+5.3}_{-5.0}$
		top -2	0.17	0.999±0.049	> 1000	0.386±0.024	$53.0^{+4.3}_{-4.2}$
78026	sg from entrance chamber pool, Lucaya Caverns	base -1	0.51	1.066±0.027	16	0.485±0.025	$71.5^{+5.3}_{-5.1}$
		top -4*	0.22	1.036±0.026	> 1000	0.464±0.029	$67.3^{+6.1}_{-5.7}$
78027	sg near to 78026	top -1	0.28	1.021±0.021	> 1000	0.408±0.023	$56.7^{+4.2}_{-4.0}$
		base -2	0.48	1.027±0.017	358	0.428±0.015	$60.4^{+2.8}_{-2.7}$

sc = stalactite
sg = stalagmite
* = U or Th yield was between 5 and 10%

DISCUSSION

1. Relationship between degree of alteration and age

Of the submerged speleothems examined, a full spectrum of alteration features were observed. These can be broadly classified as follows:

(i) solution of surface calcite layers with no encrustation or boring (e.g. 78026, 78027)

(ii) surface pitting (up to 0.5 cm deep) with minor boring and some encrustation by marine deposits (76016)

(iii) partial replacement of calcite with marine carbonate, extensive boring but original texture and growth layers still visible (81048, 81049, 81050, 81052)

(iv) total replacement of all original calcite by marine carbonate, no original texture preserved, only the overall morphology belies origin.

From the results in Table 1, it can be seen that there is a broad correlation between speleothem age and degree of alteration, although some samples (78026, 78027) were submerged in fresh to brackish water and therefore experienced surface dissolution rather than encrustation and replacement.

2. Effects of low uranium concentrations

Analysis of most of the Conch Sound 1 and 2 samples was complicated by low U concentrations in most speleothems (close to the practical limit of 0.1 ppm). Consequently, calculated ages generally have error limits in excess of ±10% and are more likely to be inaccurate because non-systematic errors become important at this level (e.g. contamination, reagent blank variations, etc.). Furthermore, low U concentrations make it increasingly difficult to resolve age ambiguities as seen in speleothem 81049. Here, a basal age of about 120 ky becomes questionable in view of the two determinations of $>$300 ky on stratigraphically younger material from the same deposit. Similarly, the apparently long period of growth of 81048 ($>$ 80 ky, top age not determined) becomes less credible when the large error limits are considered. Only when ages are less than 100 ky can error limits be seen to reduce to $< \pm$ 10% and some confidence in the results be expressed.

3. Speleogenetic significance of ages

Three of the six speleothems analysed contained sections dated at $>$160 ky (the previous age limit for submerged Bahaman speleothems, Gascoyne et al, 1979). If these are correct, and not simply due to recrystallisation or contamination as described above, then it can be inferred that the caves are at least 200 ky and possibly $>$ 300 ky, old. This is consistent with other studies in Quaternary chronology which indicate periods of glaciation, and, hence sea-level lowering, occurring since at least one million years ago. Since the older samples were taken from a depth of about 25m, then a maximum deposition rate for sedimentary carbonates in the Conch Sound area is 0.08m/ky. This reduces to 0.06m/ky if allowance is made for subsidence of the Bahama platform using a mean rate of 0.02m/ky (Mullins and Lynts, 1977). These calculations, however, assume that there has been no erosion in the area. This assumption is unrealistic because the Bahama platform has been exhumed for well over 50% of the time since speleothem formation due to sea level lowering during glacial or interstadial time. Carbonate deposition rates in the area, therefore, are probably greater than these calculations suggest.

4. Speleothems formed above modern sea level

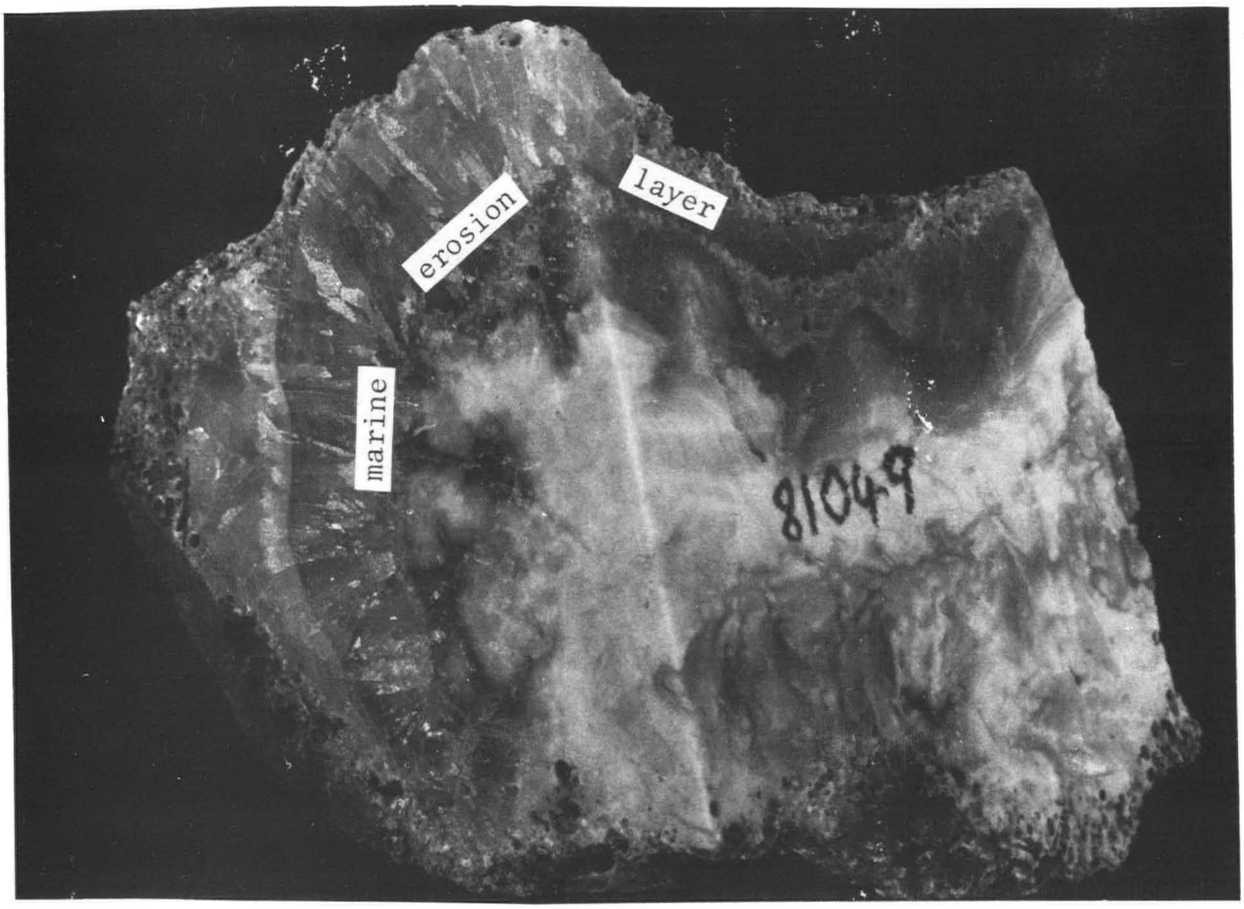
The speleothems from caves in Morgans Bluff were formed within 10 m above modern sea level. Sample 81054 contains several thin porous layers which may be due to periodic ponding of freshwater in the cave entrance. A similar porous horizon separates the inner and outer sections of 81055, but in both cases, no characteristic marine overgrowth features could be seen which might indicate that sea level had risen to above modern sea level since 90 ky. This evidence is in agreement with other palaeo-sea level records that show a generally lower sea level than present for this period. The inner core of 81055 (a roof pendant) shows evidence of re-solution, consistent with the possibility of occasional freshwater ponding during this time.

5. Speleothem growth periods and palaeoclimate

Correlation between speleothem growth frequency and palaeoclimate is more complex for sub-tropical areas, than for temporate Northern latitudes such as the Canadian Rockies (Harmon et al, 1977) and northwest England (Gascoyne et al, 1983). In these latter situations, abundant growth over some interval in the past was interpreted as a feature of warm climates where speleothem growth was aided by free-flowing groundwater and soil CO_2 production. Cold periods were accordingly marked by low or zero speleothem growth frequency. In environments such as the Bahamas where freezing conditions are not encountered, even during Northern hemisphere glaciations (see, for instance, CLIMAP 1976), periods of abundant growth cannot simply be related to temperature. Instead, it is more likely that they mark intervals of abundant rainfall. In a similar manner, the salt and carbonate beds formed in the now-desiccated North American lakes Lahontan and Bonneville (Broecker and Kaufman, 1965) and Searles (Peng et al, 1978) have been ascribed to pluvial intervals correlating closely with cooler periods in Quaternary time.

Ages for speleothems greater than 100 ky are unfortunately too imprecise and of insufficient frequency to allow determination of the timing of pluvial periods in the Bahamas. The fact that two ages lie close to the time of the last interglacial maximum ($\sim$ 125 ky), when most other evidence indicates a high sea stand at this time, demonstrates the probable inaccuracy of these ages.

More reliable, perhaps, is the period from about 90 to 40 ky during which seven different speleothems grew in four well-separated Bahaman caves. This suggests that a more humid climate than present prevailed over this interval, probably due to southward migration of rain-bearing winds, in response to cooler, interstadial conditions at higher latitudes.



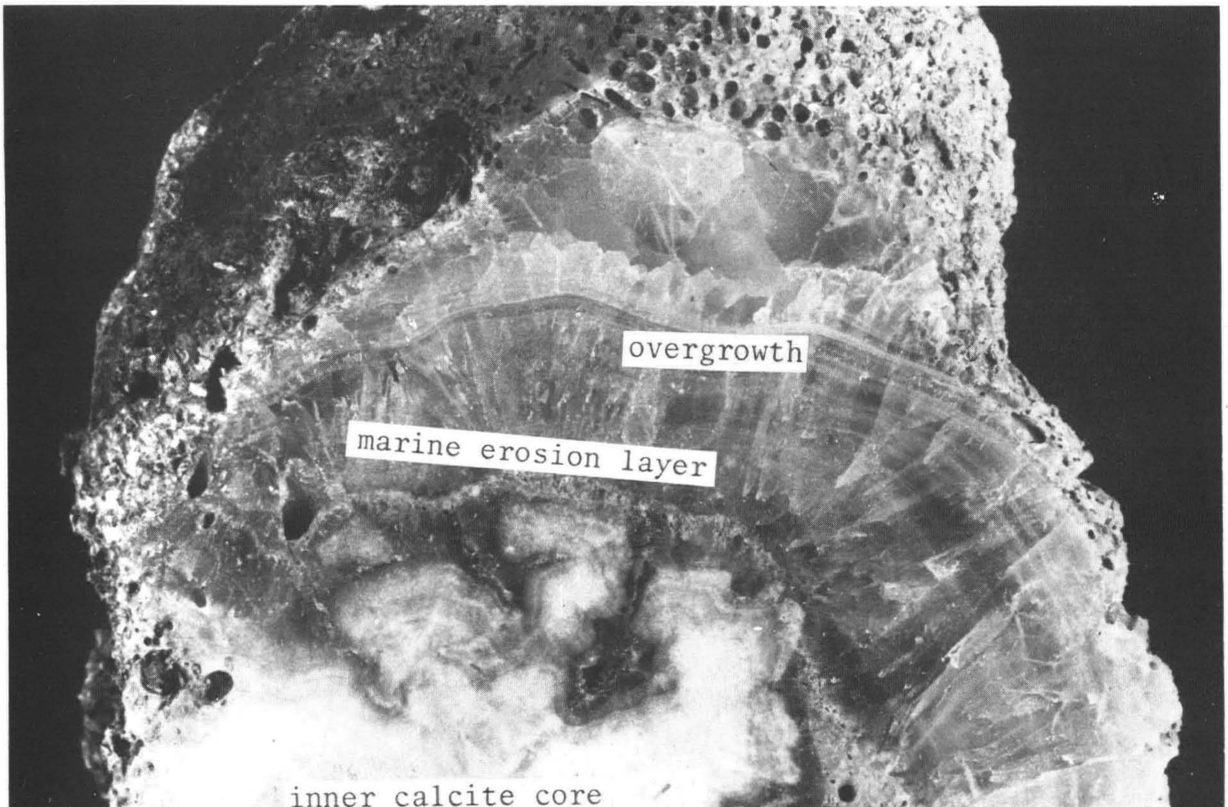


Plate 1. End and side view of a section of speleothem 81049 showing marine erosion layer separating inner milky brown calcite; core from outer clear-white overgrowth.

6. Marine erosion layers and sea level changes

The most striking part of this study of submerged speleothems was the discovery of an eroded and pitted horizon within the pure calcite of two speleothems, 81048 and 81049. The horizon is close to the edge of the speleothem in 81048 and is not easily seen, but in 81049, it is more clearly visible between 0.5 and 2 cm from the perimeter of the deposit. The horizon is more distinctive where a side overgrowth is well-developed, separating the yellow-brown opaque calcite core of the stalagmite body from the clear to white calcite of the overgrowth (Plate 1). The shallow pitting and general appearance of the horizon is similar to the exterior of the less altered speleothems (e.g. 76017) and is interpreted as an erosion surface caused by a short-duration marine transgression. Unfortunately, ages on either side of this horizon do not clearly pin-point the age of this event because the yellow-brown calcite may be as recent as 120 ky or as old as 330 ky (see above discussion). Calcite immediately above the horizon gives a minimum age for the sea level rise of 47 ky. Other palaeo-sea-level records date marine transgressions higher than -25 m relative to modern sea level at above 82 ky, 104 ky and 125 ky (see Dodge et al, 1983, for recent summary). Only more definitive ages on this speleothem or ages for the same horizon on other speleothems, if available, can better define which of these events (if any) were responsible.

CONCLUSIONS

This study has used the $^{230}Th/^{234}U$ age dating technique with variable success to date speleothems recovered from up to 25 m below modern sea level. Low uranium concentrations have hindered precise age determination of many samples older than 100 ky but several deposits have been found within the age range 90 to 40 ky. This is interpreted as indicating a relatively pluvial period during which sea level was generally lower than -20 m. The discovery of a marine erosion layer in the calcite of speleothems collected from about -20 m is proposed as evidence for a rise in sea level some time prior to 47 ky. Further evidence of palaeo-sea level fluctuations coupled with better age definition may be obtainable from other speleothems in submerged blue holes in the region.

ACKNOWLEDGMENTS

I wish to thank Rod Beaumont, Martin Farr and Rob Palmer for collecting speleothems for dating as part of the 1981 expedition, and Dr. George J. Benjamin of Toronto for providing speleothems from two areas in the Bahamas. Dr. Benjamin is also gratefully acknowledged for his enthusiasm for this work, and Professors Derek C. Ford and Henry P. Schwarcz of McMaster University, Hamilton, Ontario provided support and facilities for this research. Nicky Cesar is thanked for providing some analytical support.

REFERENCES

Benjamin, G.J. 1970. Diving into the Blue Holes of the Bahamas. *Nat. Geographic,* Vol. 138, pp347-363.

Broecker, W.S. and Kaufman, A. 1965. Radiocarbon chronology of Lake Lahontan and Lake Bonneville II. *Geol. Soc. Amer. Bull.,* Vol. 76, pp537-566.

CLIMAP Project Members. 1976. The surface of the Ice-Age Earth. *Science,* Vol. 191, pp1131-1137.

Dietz, R.S., Holden, J.C. and Sproll, W.P. 1970. Geotectonic evolution and subsidence of Bahama platform. *Geol. Soc. Amer. Bull.,* Vol. 81, pp1915-1928.

Dodge, R.E., Fairbanks, R.G., Benninger, L.K. and Maurrasse, F. 1983. Pleistocene sea levels from raised coral reefs of Haiti. *Science,* Vol. 219, pp1423-1425.

Gascoyne, M. 1980. Pleistocene climates determined from stable isotope and geochronologic studies of speleothem. Unpub. PhD thesis, McMaster Univ., Hamilton, Ontario, Canada.

Gascoyne, M., Schwarcz, H.P. and Ford, D.C. 1978. Uranium series dating and stable isotope studies of speleothems: Part I, Theory and Techniques. *Trans. Brit. Cave Res. Assoc.,* Vol. 5, (2), pp91-111.

Gascoyne, M., Benjamin, G.J., Schwarcz, H.P. and Ford, D.C. 1979. Sea-level lowering during the Illinoian glaciation: Evidence from a Bahama 'Blue Hole'. *Science,* Vol. 205, pp806-808.

Gascoyne, M., Schwarcz, H.P. and Ford, D.C. 1983. Uranium-series ages of speleothem from northwest England: Correlation with Quaternary climate. *Phil. Trans. Roy. Soc. Lond.,* Vol. B301, pp143-164.

Harmon, R.S., Ford, D.C. and Schwarcz, H.P. 1977. Interglacial chronology of the Rocky and MacKenzie Mountains based on 230Th/234U dating of calcite speleothems. *Can. J. Earth Sci.,* Vol. 14, pp2543-2552.

Harmon, R.S., Schwarcz, H.P. and Ford, D.C. 1978. Late Pleistocene sea level history of Bermuda. *Quat. Res.,* Vol. 9, pp205-218.

Mullins, H.T. and Lynts, G.W. 1977. Origin of the northwestern Bahama Platform: Review and interpretation. *Geol. Soc. Amer. Bull.,* Vol. 88, pp1447-1461.

Peng, T-H, Goddard, J.G. and Broecker, W.S. 1978. A direct comparison of ^{14}C and ^{230}Th ages at Searles Lake, California. *Quat. Res.,* Vol. 9, pp319-329.

Shackleton, N.D. and Opdyke, N.D. 1973. Oxygen isotope and paleomagnetic stratigraphy of equatorial Pacific core V28-238: Oxygen isotope temperatures and ice volumes on a 10^5 and 10^6 year scale. *Quat. Res.,* Vol. 3, pp39-55.

Spalding, R.F. and Mathews, T.D. 1972. Submerged stalagmites from caves in the Bahamas: Indicators of low sea stand. *Quat. Res.,* Vol. 2, pp470-472.

M.S.Received October 1983.

M.Gascoyne,
Atomic Energy of Canada Ltd.,
Pinawa, Manitoba, Canada.

CAVE SCIENCE

Transactions British Cave Research Association. Vol.11, No.1, March 1984.

CAVE DEVELOPMENT UNDER ANDROS ISLAND, BAHAMAS

R. Palmer and D. Williams

ABSTRACT

Available evidence suggests that cave development has occurred horizontally at or near to the base of existing or previously-existing freshwater lenses, along the halocline. Levels of such development are primarily controlled by glacio-eustatic changes in sea-level, and their resulting effect on lens position. Access to these caves can be gained where solutional enlargement of slump faulting intersects them, or where ahston collapse occurs.

Andros is the largest of the Bahaman islands, lying on the western side of the U-shaped Great Bahama Bank. Its surface rock to a depth of approximately 12 metres below mean sea level is composed of oolitic and ooliclastic limestones, and below that, to a depth of approximately 160 metres, of fossiliferous reef limestones. Beneath that, limestones continue to at least 5000 metres depth (Spencer 1966).

Development of caves within the upper limestones appears to have had two major controlling factors: (a) the position of a Ghyden-Hertzberg type freshwater lens and (b) slump faulting and associated fractures running parallel to the deep oceanic trough that borders the eastern coast of the island, the "Tongue of the Ocean".

Previous work on this subject (Benjamin 1970, Williams 1978) related the horizontal development of caves under the islands of the Bahamas to glacio-eustatic sea-level changes (sea-level fluctuation in response to glacial advance and retreat) and to still-stands of sea-level within those changes. Major horizontal cave passages have been thought to develop at or near to the level of the sea during periods of relative stability (still-stands) (Williams, 1979; Mylroie 1983). If this is the case, it would be reasonable to assume that such major horizontal passages are pointers to the level of the sea at the time they were formed. As sea levels are known to have fallen by as much as 120 metres below their present levels, in several stages (Mylroie, 1983) during the Pleistocene glaciations, it is possible that horizontal development took place during this period at depths of up to and possibly beyond 100 metres. (Fig.3).

A more precise picture is emerging that places the point of formation of major conduit passages as being at or near to the base level of the freshwater lens (Fig.1). Visual evidence of development at this level has been observed elsewhere in the Caribbean (Palmer, 1983) and in the Lucayan Caverns of Grand Bahama, now undergoing a secondary period of formation, where the halocline can be observed regularly throughout the system. On Andros, the exploration of such inland horizontal caves is still in its infancy, such development that can be presently observed is related to lower sea-level stances (Uncle Charlie's Blue Hole and Ocean Hole).

The freshwater/saline interface is generally regarded as a point of enhanced solution (Smart, this volume). The intermixing of two waters of different density, despite pre-saturation of each with $CaCO_3$, can produce a third water-type which still reacts aggressively with the surrounding rock. (Bögli 1971). Additionally, the presence of decaying organic material immediately above the halocline, prevented from sinking by greater density of the underlying salt-water (visible in most inland Blue Holes on Andros as a distinctive orange layer - the "sulphur layer"), might encourage removal of limestone at this level through bacterial reduction. A transitional zone of brackish water is evident at and near the halocline, becoming more diffuse with rapid replacement of freshwater as after heavy rainfall. Rapid recharge of the freshwater lens, at times of heavy rainfall, would enhance the mixing process at the halocline, encouraging limestone removal in solution.

Removal of saturated waters from the point of solution can take place in several ways. Rapid recharge of the lens would encourage not only intermixing with the saltwater beneath the island, but would create sideways movement within the lens, encouraging diffuse percolation into the sea. This could account partly for the aureole of brackish water that exists along the eastern coast of Andros Island (Smart, this volume).

Williams (1979) and Smart (this volume) suggest the presence of salt-water movement beneath the freshwater lens of the island. On Grand Bahama, Williams suggested that this movement is related to tidal time-variations on opposite sides of the island, together with a lag induced by the distance tides have to travel across the shallow banks that extend to the north of the island. This effectively creates a "head" of water on the northern side of Grand Bahama, and encourages a net north-south sub-lens tidal flow. This theory is equally valid on Andros, where conditions are similar, the net flow in this case being west to east. Such a sub-lens flow, with additional fresh/saline intermixing, would be sufficient to carry saturated waters beneath the island towards the sea. The general west-east flow could account for the greater occurrence of Blue Hole caves on the eastern side of the island of Andros, though a secondary factor may be involved here. Spontaneous circulation in the waters along the eastern coast, induced by density or temperature variation between the shallow coastal waters, with their less saline content, and the deeper, colder waters in the Tongue of the Ocean, would remove $CaCO_3$ saturated waters from the base of the lens more quickly, due to an increased flow and water exchange, than would slow sideways percolation within the lens itself.

Fluctuations in lens pressure, CO_2 and H_2S concentrations and water flow would create conditions suitable to the formation of solutional cavities at or near to the base of the lens, without the need for a developed opening to the surface or the sea. Though these cavities could remain isolated, water flow would encourage sideways migration along the base of the lens, where conditions continue to be most suitable for cavern development, and where their very growth will stimulate their role as conduit caves. Such development would be most likely to take place towards the outer edge of the lens, where water discharge is most pronounced but, where sub-lens flow is a controlling factor, could equally well occur towards the centre of the lens.

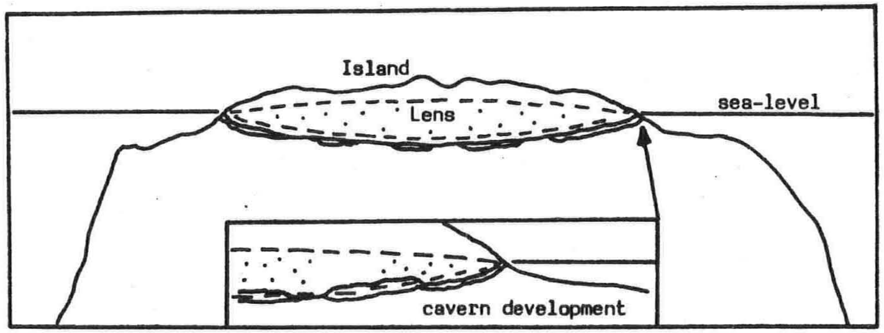
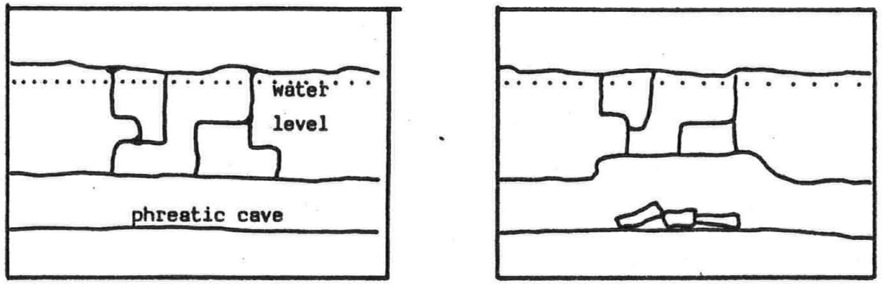
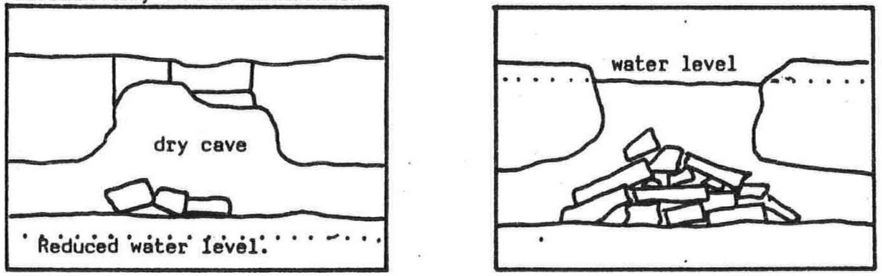


Fig. 1: Cavern devlopment position at the base of a freshwater lens



a) Phreatic development in horizontally-bedded limestones

b) Solutionally-induced roof collapse commences



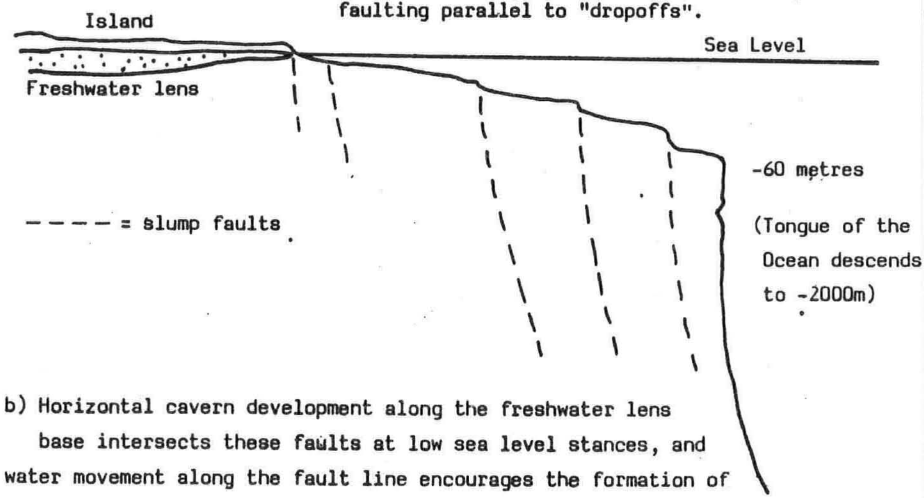
c) Further gravitational collapse with removal of water support.

d) Total collapse of roof, leading to entrance formation

Fig. 2. Aston development in a phreatic cave.

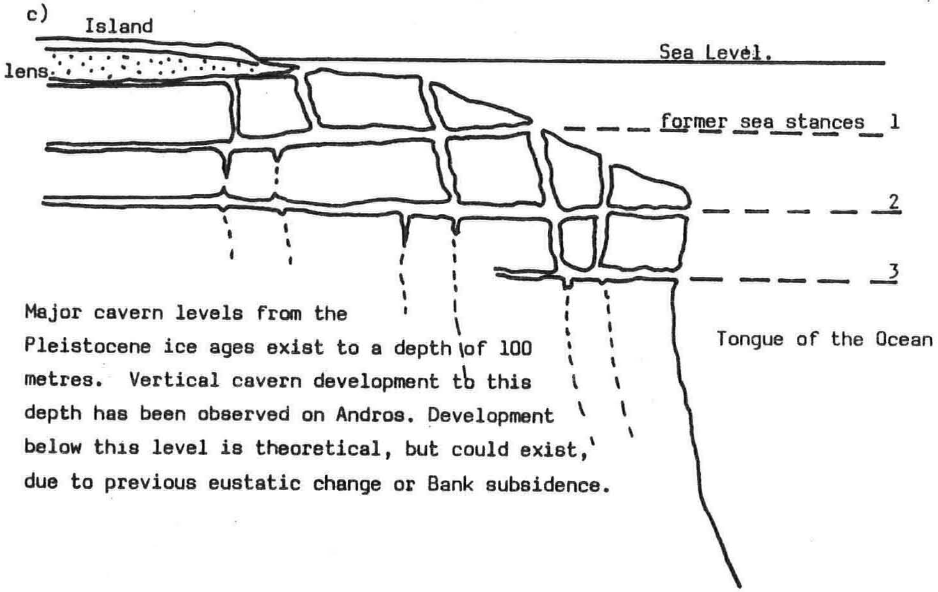
The upward migration of cave roof due to collapse of horizontally-bedded limestones, caused by a combination of solutional weakening and gravitationally induced breakdown during dry periods of low water levels.

a) Slumping of Bahama Banks into surrounding deep ocean induces slump faulting parallel to "dropoffs".



b) Horizontal cavern development along the freshwater lens base intersects these faults at low sea level stances, and water movement along the fault line encourages the formation of vertical cave passage along the line of fracture.

c)



Major cavern levels from the Pleistocene ice ages exist to a depth of 100 metres. Vertical cavern development to this depth has been observed on Andros. Development below this level is theoretical, but could exist, due to previous eustatic change or Bank subsidence.

Fig.3. FAULT DEVELOPMENT AND EFFECT ON CAVE FORMATION.

Caves migrating along the halocline would approach the surface as they near the edge of the lens. As they approach the eastern coast of Andros, such halocline conduits encounter slump faults, running parallel to the Tongue of the Ocean and the island coast. Vertical movement of water at the edge of the lens, due to tidal action and spontaneous circulation, together with outward pressures from freshwater within the lens, can enlarge these to give an open surface connection through vertical rift passage (e.g. Conch Sound Two, Forfar Blue Hole, Mangrove Cay 32-34) (Fig.3). Lateral development along such faults has been observed (e.g. Mangrove Cay 32-34).

During periods of low sea-level, the freshwater lens will migrate downwards, matching the level of the sea. Such fluctuation, together with increased vadose movement in the exposed bedrock between surface and new lens level would continue to enlarge inland shafts and joints which, with associated collapse in the horizontal bedding of the rock, would produce the deep inland Blue Holes, similar in shape to the "cenotes" of the Yucatan peninsula in Mexico. In some cases, as in Uncle Charlie's Blue Hole or Ocean Hole) these caves would appear to be associated with horizontal development at depth. Evidence for or against such association of development elsewhere is unfortunately obscured by thick sediments at the base of inland Holes.

The porous nature of the island bedrock and the lack of horizontal gradient makes it unlikely that horizontal cave passage above the altered lens level would play a major role in island drainage during periods of low sea-level. Such drainage at these times would be largely vertical through a well-developed system of micro-conduits from the surface to the new lens position. Where vertical conduits encountered open, air-filled passage, such vertical movement might be encouraged, providing an enlarging link between inactive and active horizontal development levels. These links would further develop as a result of water movement within the lens as it rose again, leading to an inter-related network of caves on two or more levels. During such periods of low sea level, conditions would be suitable for the development of speleothems in dry high-level cavern systems.

Where halocline conduits lie near the surface at the edge of a freshwater lens, stresses caused by repeated exposure and submergence on horizontal beds of limestone above the cave could lead to roof-collapse. The combined effect of solutionally-induced breakdown and gravitational forces when the roof is not hydraulically supported by water in dry conditions will encourage upward migration of the roof through collapse, leading to " aston " development (Jiminez 1967—aston collapse is the collapse of horizontally bedded limestones into phreatic cave beneath due to solutionally induced gravitational breakdown of the cave roof) which creates entrances where such breakdown reaches the surface (Fig. 2) e.g. Conch Sound One, Rat Cay, Mangrove Cay 31, Giant Doughnut Hole, where collapse of the cave roof opens into phreatic passages beneath. The large collapse chamber discovered at the end of Conch Sound One is a classic example of the early stages of aston formation.

The processes involved in cave formation beneath Andros and other Bahaman islands, outlined above, are many and varied, and much work remains to be done to establish which of these controlling factors are most important in the formation of these spectacular and curious underwater caves.

REFERENCES

Benjamin, G. 1970. Diving into the Blue Holes of the Bahamas. *Nat. Geog. Mag.*, September, pp.347-363.

Bögli, A. 1971. Corrosion by mixing of karst waters. *Trans Cave Research Grp G.B.* vol. 13, pp.109-114

Dill, R.F. 1977. *Geologically significant submerged sink holes and caves off British Honduras and Andros Island*. Proc. 3rd International Coral Reef Symposium. Rosenstiel Inst., Miami.

Jiminez, A.Nunez. 1967. *Clasificacion genetica de las Cuevas de Cuba*. Acad. ciencias de Cuba, Habana. 223pp.

Mylroie, J.E. 1982. *Karst geology and Pleistocene history of San Salvador Island*. Proc. 1st Symposium on the Geology of San Salvador Island.

Palmer, R.J. 1983. Caving potential of the Dominican Republic. *Caves and Caving, May*.

Smart, C.C. 1983. The hydrology of the inland Blue Holes, Andros Island. *Cave Sci.* (Trans. B.C.R.A.), vol.11. no 1.

Spencer, M. 1966. Bahamas deep test. *Bull. American Assn. Petroleum Geologists*, vol. 51, pp.263-268

Williams, D.W. 1979. Nature's reversing syphons. *Bahamas Naturalist*, winter, pp. 6-7.

Williams, D.W. 1982. Pers. comm. P.O. Box F-951, Freeport, Bahamas.

M.S. Received December 1983

R. Palmer,
7 Lovell Avenue,
Oldland Common,
Bristol.

D. Williams,
P.O. Box F-951,
Freeport,
Grand Bahama,
Bahama Islands.

CAVE SCIENCE

Transactions British Cave Research Association Vol.11, No.1, March 1984

PRELIMINARY OBSERVATIONS ON THE BIOLOGY OF INLAND BLUE HOLES, ANDROS ISLAND

Graham S. Proudlove

Abstract

Collections and observations of animal and plant life in inland (freshwater) Blue Holes were made during the 1982 British Cave Diving Expedition to Andros Island, Bahamas. Five different plant types were observed and although the biomass was very high, the species diversity was low. Similarly the diversity of animal species was low, only about a dozen species being seen or collected. It is suggested that the waters are too oligotrophic to support much life.

This brief report is based upon work carried out by Dr George Warner of the University of Reading in August 1981 and by the present author in August 1982.

In 1981 Warner was primarily concerned with the biology of marine Blue Holes and only limited observations were made inland. In 1982 the hydrological programme took up much of our time and man-power and biological observation was again limited.

The aims of both studies were similar, to collect and observe any plant and animal life found in inland Blue Holes. An extensive literature search has revealed that very little indeed is known about the biology of Inland Blue Holes so that any information collected is of value. In addition to recording all of the plant and animal life seen a special search was made for the Bahaman' blind cave dwelling fish which had previously been recorded from only one site on Andros (Warner and Stroes-Gascoyne, 1981). This species is known from several sites on three other islands (Anon. 1979).

As well as collecting and observing the biota it was hoped to collect some information on the chemical and physical limnology of inland Blue Holes. (Limnology is the integrated study of lakes taking into account the biology of the plants and animals present, as well as the chemistry, physics and morphology of the lakes). Smart (1984, this volume) gives information on the limnology of inland blue holes and his paper should be read in conjunction with this one.

This report is very much a preliminary one. A previous, even briefer, report has already been published (Palmer, 1982).

The team, base camp, and general planning.

The inland team comprised five people: Chris Smart responsible for the hydrology project; Kitty Hall, geologist and hydrological assistant; Ken and Laurie Jones, guides, divers, and assistants; and Graham Proudlove, responsible for freshwater biology and assistance to the hydrology project. The team was based at Forfar Field Centre at Stafford Creek, owned and run by International Field Studies of Columbus, Ohio, U.S.A.

Since so little is known about the inland Blue Holes of Andros Island the aims of the team were simple: to collect as much basic hydrological and biological data from as many sites as possible in the time available. Initially, accessible sites were located on 1:25000 maps so as to give as broad a coverage of the northern part of the island as possible. Eventually seventeen sites were visited and a trip up Stafford Creek by boat provided an opportunity to sample extensive open water.

Daily routine and problems encountered.

Each day the routine was similar; rise and breakfast at 0800, collect equipment required for the day and then drive to the sites decided upon the previous night. At each Blue Hole the hydrological measurements were taken before the water was entered so as to get an undisturbed record of the relevant parameters. Once this had been completed (taking usually one to two hours depending upon the site) Ken Jones and Graham Proudlove dived, Ken to collect further water samples for Chris, Graham to observe and collect animals and plants. On most days two or three sites were visited. The team returned to Forfar by 18.30 for an evening meal. The evening was spent on analysis and planning as well as "extra-curricular" activities.

The main problems encountered were distance, extremely bad road surfaces which restricted the speed at which the truck could be driven, overgrown tracks to Blue Holes which sometimes necessitated abandonment of the truck, and very thick and unfriendly vegetation. The drug smuggling trade prevalent on Andros also required us to abandon plans to visit some important sites in the centre of the island. Other smaller problems such as the water-sampler breaking and the complete omission of roads from one section of the map were easily overcome. All but two of the holes were visited, due in no small part to Chris' and Kens' driving abilities and Ken's knowledge of the remoter parts of the island. The presence of logging roads, rough tracks cut by workers harvesting the abundant pine trees, was an undoubted advantage; without them we would have had to walk to nearly every site, a daunting prospect with sampling and diving gear, and could have achieved much less. Taken as a whole the inland projects were very successful, especially given the limited time available and the difficult terrain. The diving especially was superb for those who were lucky enough to take part.

Location and description of the inland sites visited.

The location and a brief description of each of the inland sites visited in 1981 and 1982 are given below. The numbering system (1-19) is the same as that used in the reports following this introduction.

Following the name of each site is its grid reference, depth in metres (where known) and the dates on which it was visited.

1. Ocean Hole SC.967846 50 m 15th August 1982
A most unusual Blue Hole surrounded by large limestone cliffs. Unlike all of the other Blue Holes visited which were vertical flooded shafts, this site descended at an angle down to a depth of 50 m and a large horizontal passage. The first 20 m of water are very murky due to the presence of the sulphur layer at the surface. Lower down the water clarity was excellent. The hole is located in Nicholls Town and is only about 300 m from the sea.

2. Conch Sound Blue Hole.
This extensive marine site is adequately described elsewhere in this report.

3. Uncle Charlie's Blue Hole SC.934806 42 m 20th and 25th August, 1981, 15th Aug. 1982.
Although the top 15 m are very like any other Blue Hole this one has a large horizontal passage at 40 m depth. It is a most interesting site biologically having two species found nowhere else on the island. It is located 5 km from Nicholls Town near to the main road and can be easily reached by truck.

4. Swamp Blue Hole SC.905555 2 m 6th August 1982
Not really a Blue Hole, merely a pond in mangrove swamp. Situated 1 km from the northern shore of Stafford Creek, 3 km west of Owens Town. Reachable only by boat up Stafford Creek and then by foot.

5. Owens Town Blue Hole SC.948544 4 m 6th August 1983
Again merely a pond. Situated in dense pine barrens 1.5 km from the abandoned settlement of Owens Town. From here logging roads lead east and the hole is just at one side of the main road. Best reached by boat to Owens Town and then by foot.

6. Stafford Creek No. 1 Blue Hole TC.008529 7 m 10th August 1981, 9th August 1982
A most unusual Blue Hole having a very hot layer of water at 5 m depth, situated on the south bank of Stafford Creek, 5 km from its mouth. The entrance is under water and is surrounded on two sides by mangrove. Reachable only by boat.

7. Stafford Creek No. 2 Blue Hole SC.991513 13 m 9th August 1982
A comparatively shallow hole but showing the same characteristics as much deeper ones. Located in mangrove swamp 0.5 km from the southern shore of Stafford Creek, and about 1.5 km east of Riley Creek. Can be reached only by boat and foot.

8. Ken's Blue Hole SC.888484 73 m 8th August 1982
Named in honour of Ken Jones, our guide and diver extraordinaire. A deep and impressive hole with interesting sloping terraces at various depths, it contained a species of fish found normally in estuaries. Located 3 km from the nearest road down overgrown logging tracks!

9. Not a Blue Hole SC.937475 8th August 1982
Marked on the map as a Blue Hole, this is just a damp area of no interest.

10. Gollum's Blue Hole SC.949460 5 m 8th August 1982
A very shallow Blue Hole near to Ken's Blue Hole.

11. Stalactite Blue Hole SC.949444 45 m 22nd August 1981, 18th August, 1982.
A large hole containing massive stalactites at 30 m depth. A very impressive diving site! Land crabs seen on sandy ledge at 25 m. Located off the main road to Twin Lakes. Known also as Archie's Blue Hole.

12. Pig Run Blue Hole SC.959419 50 m 10th August 1982
Another deep Blue Hole situated 5 km from the nearest road. The logging trucks leading to the hole are so overgrown that it can only be reached on foot. Named after the many runs used by wild pigs.

13. West Twin Blue Hole SC.957407 8 m 11th August 1982
More resembling a large pond than a true Blue Hole. Located ½ km from the main road to Twin Lakes.

14. East Twin Blue Hole SC.959406 60 m 11th August 1982
A very deep hole with unusually murky water, probably due to large quantities of phytoplankton, 100 m from Twin Lakes road in pine barren.

15. Cousteau's Blue Hole TC.051431 110 m 21st August 1981, 7th August 1982
The deepest known Blue Hole on North Andros. It is located in dense pine barren to the west of the main Fresh Creek - Stafford Creek road, with very dark water.

16. Hour Glass Blue Hole TC.062429 15 m 21st August 1981, 12th August 1982
The entrance to this uninteresting Blue Hole is located under the water of an ordinary lake in the same pine barren area as Cousteau's.

17. Paul's Blue Hole TC.063423 75 m 21st August 1981
Found in same area as Hour Glass and Cousteau's. Reputed to contain stalactites at 45 m depth.

18. Church Blue Hole TC.105392 25 m 7th August 1982
The largest Blue Hole in area of any visited, surrounded by 5 - 10 m high cliffs. Very interesting limnologically because of its large surface area. Found in the same region of pine barren as Paul's Blue Hole, etc.

19. Goby Lake TC.044489(?) 4 m 21st August 1981, 13th August 1982.
The most biologically interesting of all sites visited. This is more like a pond than a Blue Hole but it is very rich in animal life. Located just off the rough road running parallel to the main road from Fresh Creek to Stafford Creek.

METHODS

Observations and collections were made whilst diving using SCUBA equipment modified for cave diving (see Palmer, 1982 for details). Whilst underwater, notes were made on an arm-mounted plastic slate and depths read from a standard depth gauge. Animals were all hand collected, either directly into tubes, or in a hand net. Samples of sediments and plant material were also collected.

Upon return to England most specimens were sent to experts for identification. Many have not yet been returned and others proved to be unidentifiable.

PLANTS IN INLAND BLUE HOLES

All of the inland Blue Holes visited contained some plants. Samples of four types were collected but because they were dried rather than preserved in alcohol it has not been possible to make a detailed identification. The plants fall into five main groups and these are briefly described below.

Blue-green algae (Cyanophyta). The most abundant freshwater plants, present in all Blue Holes and in road-side ditches, were blue-green algae (now usually thought of as colonial bacteria). All holes contained great masses of this plant, usually laid down in mats on horizontal and sloping surfaces. When disturbed, the material tended to float slowly to the surface suggesting a high gas content. In Ken's Blue Hole the mats were stratified suggesting that growth is discontinuous, probably occurring mainly in the summer months and reducing in the winter. In Cousteau's Blue Hole small red water mites were seen to enter the interior of the mats and the algae may be their main food source. The biomass of blue-green algae in most Blue Holes is enormous.

Charophytes. These were present only in Ken's Blue Hole and in East Twin Blue Hole, and only in discrete patches.

Green algae (Chlorophyta). Probably represented only by the genus *Cladophora*. Present in all holes but restricted to small patches.

Bryophyta. Again present only in two holes, Kens and East Twin. Found only down to a depth of 10 m. It is likely that the light levels, especially in the latter where a large amount of phytoplankton was present, were too low at greater depths to support growth.

Phytoplankton. From the surface to a depth of 15 m in East Twin Blue Hole the water was very cloudy and visibility was restricted to about two metres. This situation was in great contrast to that in all other holes where visibility was excellent. It is highly likely that a growth of planktonic algae was responsible for the bad visibility. No samples were collected.

General comments. Although there is a very high biomass of plant material in the blue holes (made up mainly of blue-green algae) there seem to be a very few species present. Some of the possible reasons for this low diversity are outlined in the discussion.

As with all other aspects of blue hole biology much remains to be done. More detailed collections with proper preservation are needed and it would be interesting to correlate the plant species present with chemical and physical features of the holes and with distance from the sea. Comparisons with the freshwater flora of other Caribbean islands would also be interesting.

ANIMAL LIFE IN THE BLUE HOLES

The animals collected from, and observed within, the inland holes are listed in Table 1.

Table 1. Animals collected from inland Blue Holes.

No.	Site	Animals present
1	Ocean Hole	Land crab larvae
3	Uncle Charlie's Blue Hole	*Sesarma angustipes* Decapoda:Grapsidae *Lucifuga spelaeotes* Teleostei:Bythitidae
6	Stafford Creek No. 1 Blue Hole	Copepoda (unidentified)
7	Stafford Creek No. 2 Blue Hole	*Lutjanus griseus* Teleostei:Lutjanidae
8	Kens Blue Hole	*Lutjanus griseus* Teleostei:Lutjanidae
11	Stalactite Blue Hole	Land crabs
15	Cousteau's Blue Hole	Red water mites (unidentified)
18	Church's Blue Hole	Fishes, crabs (unidentified)
19	Goby Lake	Fishes, copepoda (unidentified)

The most surprising sighting was of a grey snapper, *Lutjanus griseus* , in Ken's Blue Hole. This species is normally a resident of estuaries and can happily penetrate into freshwater (P. H. Greenwood, pers.comm.). Ken's Blue Hole is, as far as we were able to ascertain, completely isolated from any other water so how the fishes got there is a complete mystery. Three possible explanations spring to mind: (1) there is a cave passage from an estuary below the sulphur layer (the deepest point dived to); (2) the fishes were carried to their present position during a storm which can throw water great distances inland; (3) the fishes were placed there by man. I can make no judgement on this issue at present and leave the answer until further evidence is to hand.

The grapsid crab *Sesarma angustipes* and the cave dwelling fish *Lucifuga spelaeotes* were both found only in Uncle Charlie's Blue Hole. It is no surprise that this is the only known inland hole with horizontal passage development at depth. Fishes from 2 - 12 cm in length were observed and they were of various colours, from pink to black.

DISCUSSION

The most outstanding feature of inland Blue Holes as observed during the 1982 expedition was the relative paucity of animal and plant life. Even after taking into account the poor sampling programme and the short time available there still seem to be very few species present. There are two possible explanations for this:

(1) The chemical and physical conditions within the water bodies are not suitable for the growth and survival of many animal and plant species, i.e. the waters are too oligotrophic. With some fairly basic chemical analyses this possibility will be easily confirmed or refuted.

(3) The time since the development of the Blue Holes has been too short for many species to colonise them from elsewhere. This does not, however, seem to be a very likely explanation. The presence of a cave dwelling fish and a Grapsid crab in one hole means that animals can and have travelled onto Andros from elsewhere. However, the fact that most inland Blue Holes seem to be blind-bottomed may well make colonisation of them rather more difficult than would otherwise be the case.

Obviously a great deal remains to be learnt about the inland Blue Holes of Andros.

ACKNOWLEDGMENTS

I would like to thank the members of the 1982 Blue Holes Expedition for their help and encouragement, particularly Chris Smart , Kitty Hall and Ken and Laurie Jones who formed the inland team. To the staff of Forfar Field Station I also express my thanks for the hospitable surroundings they provided. Finally I thank Rob Palmer for giving me the opportunity to visit Andros Island.

REFERENCES

Anon. 1979. Cave Fish. *Bahamas Naturalist*. vol.4, no.2, p.22.

Palmer, R.J. 1982. Report of the 1982 British Blue Holes Expedition. *Jour. Soc. Underwater Technology*. Winter, 1982. pp.15-21.

Smart, C.C. 1984. The hydrology of the inland Blue Holes, Andros Island. *Cave Science*. Vol.11, No.1. 23-29

Warner, G. & Stroes-Gascoyne, S. 1981. Ecological report. In Palmer, R.J.(ed). Blue Holes '81. British Cave Diving Expedition. University of Reading. (available from R.J.Palmer or G.S.Proudlove)

M.S.Received 2nd March. 1984.

Graham S.Proudlove,
Zoology Dept.,
University of Manchester,
Manchester M13 9PL

APPENDIX I

BLUE HOLES 1982 EXPEDITION: MEDICAL REPORT

by A. Boycott, M.B., Ch.B.

The principles of providing medical care for overseas caving expeditions have been discussed adequately elsewhere, both in general terms (Standing, 1975; Illingworth, 1979, 1981) and in specific expedition reports (Standing, 1973; Buchan, 1976, 1982). There are also many reference books available (see bibliography). I do not propose to review the requirements for any caving expedition here, but will concentrate on the problems specific to diving.

Andros Island is subtropical, at sea level and fairly close to civilization. The nearest hospital is in Nassau, New Providence Island, and could be reached in under 24 hours. We were living luxuriously with adequate supplies of fresh water and food, so no nutritional problems were expected.

PREPARATION

It is usually safe to assume that members of a caving expedition are fit, and a pre-expedition medical was not considered necessary. All the divers had at some time passed the standard British Sub Aqua Club medical, and some a more rigorous commercial diving medical. A short questionnaire was sent to each member to obtain the following information:

Age   Blood Group   Allergies (especially to medicines)
Major illnesses in past
Current medical problems and medication

Every member was recommended to have a thorough dental check. This was especially important for the divers as compressed air can easily enter rotten or loose fillings and cause severe pain and damage to the tooth on surfacing.

The D.H.S.S. recommend typhoid, tetanus and polio immunisation for the Bahamas. To this we added human gamma globulin as protection against hepatitis.

Medical insurance of £50000 for each member was included in the expedition insurance.

Most of the equipment was already in my possession or begged from various pharmaceutical companies. See table for list of equipment taken.

MAIN PROBLEMS EXPECTED

General Trauma. The island consists of extremely sharp limestone, especially where it has been eroded by the sea. The vegetation is either mangrove swamps or dense pine forest, and the latter contains many poison ivy bushes, the leaves of which can cause painful acid burns. Any cuts would be slow to heal because of constant immersion in water.

Local Wildlife. Insect bites, especially from midges, were more of an annoyance than a health problem. There are poisonous snakes on Andros, but to my knowledge none were ever seen.

Sharks and barracuda were encountered from time to time while diving. The commonest shark seen was the Nurse shark *(Ginglymostoma cirratum)* one of which lived in the entrance to Rat Cay Blue Hole. These, in common with most other sharks, are not prone to attack humans if left alone and not attracted by spearfishing. Moray eels can deliver a severe bite. One was frequently seen in the entrance passages of Conch Sound I, but did not succeed in biting anyone.

The reefs and the cave walls are covered in coral which resulted in some nasty grazes. Fire coral *(Millepora)* also produces a mild burn, received by most of the divers at some time. Coral cuts are notoriously slow to heal and easily become infected. We found that mercurochrome 2% solution was an effective antiseptic.

Sea urchins, although mostly not poisonous, have spines that can puncture neoprene, break off easily, and are extremely difficult to remove.

Ear Problems. Divers frequently have problems with ears and sinuses. Diving necessitates equalising the pressure inside the inner ear and sinuses with that outside. Any blockage of the passages by infection can result in pain and damage to the ears. Despite repeated diving we had fewer problems than in the UK, probably because the Bahamian climate reduced the amount of upper respiratory tract infections.

Infection of the outer ear (Otitis externa) is very common in divers, especially in tropical waters. This probably starts with particles of sand or coral which irritate the outer ear canal; bacterial and fungus infection can easily follow. To prevent this the divers were advised to wash their ears out with fresh water and mild wax-dissolving ear drops (cerumol) after each dive. Despite this many people developed some infection which required ear syringing and treatment with antibiotic drops (audicort). This was the only medication we ran out of and I would advise any future expedition to take at least one 10 ml bottle per diver.

Decompression Sickness. This is potentially the most dangerous, if not the most likely medical problem that an expedition of our type could encounter. Most of the dives, especially the exploratory dives, required decompression, and we were diving repeatedly. The nearest recompression chamber was at the Atlantic Undersea Test and Evaluation Center (AUTEC) at Fresh Creek 100 miles south of our main diving site at Conch Sound I. The nearest alternative was probably in Miami. We were using standard U.S. Navy diving tables rigidly, and usually allowing an extra period of decompression as an added safety margin, and to allow for the fact that we were diving frequently.

I do not intend to write a detailed description of decompression sickness here. For a fuller description and decompression tables see books in the bibliography. Technically the term decompression sickness covers any medical problem occurring through a decrease of pressure on the body, and applies to mine workers, aircraft leaks and astronauts as well as divers resurfacing, i.e. burst lung, ear trauma, but is usually applied to problems caused by gas bubbles appearing in the body tissues. The amount of nitrogen dissolved in the tissues depends on the depth reached and the time at that depth and these must be taken into account when calculating decompression time and stops. However, cave dives are often complicated by not maintaining a standard depth and requiring repetitive dives; these factors must be taken into account in the calculations. We also had the added problem that in some of the dive sites, especially Conch Sound II, the prescribed depth for a decompression stop was in an area of the cave where the current was very strong, and it was conceivable that a decompressing diver could be thrown uncontrollably up to the surface by the current.

The susceptibility to decompression sickness varies between individuals and in the same individual from day to day. The following conditions make it more likely to occur:

Obesity
Unfitness
Dehydration
ageing
Exertion
Cold
Other injuries

The only one likely to apply to us was exertion. Being cold was not a problem except during the enforced inactivity decompressing at the end of a long dive. It is possible that some degree of acclimatization can happen on repetitive dives. However, decompression sickness can occur when the decompression tables are followed to the letter, and conversely not happen when they are ignored.

The only acceptable treatment for decompression sickness is rapid recompression to a depth below which symptoms disappear, and then slow decompression according to medical tables. It is possible to carry this out on site in water, but this is not normally recommended as there may not be enough air available and the condition of the victim cannot be adequately assessed and monitored, quite apart from problems with cold, weather, sharks, etc. Modern practice recommends oxygen recompression, as this is faster and more effective, and can more easily be used in the water. The recommended regime in this case uses 100% oxygen at a maximum depth of 9 metres for between 30 - 120 minutes, then ascend at the rate of 12 minutes per metre. We did not have any oxygen on site, however, and our only choice would be to move the victim to recompression facilities as fast as possible.

There is no known medical treatment which can stop or reduce bubble formation once it has occurred, but there is now a lot of evidence that certain drugs can reduce the severity of decompression sickness and also the incidence of permanent after effects. Two recent papers summarize the present state of knowledge (Bove, 1982; Catron and Flynn, 1982). The recommended treatment is aimed at reducing the damage caused by the bubbles, both directly any by over-reaction of the bodies inflammatory process. The most important aspect of this is replacement of the blood volume, with drugs to prevent further clotting and assist the bodies own defences. We were recommended to use the following regime while en route to a recompression chamber.

Dextran 40 500 ml over 8 hours intravenously
Dexamethasone 10 mg intravenously straight away, followed by 4 mg every 6 hours for up to 3 days.
Heparin 7500 International Units (IU) intravenously straight away, followed by 5000 IU every 6 hours.

Fortunately in the field all these precautions proved unnecessary. Any future expedition of this type would be well advised to obtain up to date advice from the Royal Naval Medical Service (see acknowledgements) and also to remember the following points:

We were diving at sea level, and the start of our dives was also the entrance to the caves. Any divers contemplating deep dives at underground sites should allow for the effects of altitude in calculating decompression times, and also consider the potential difficulty of evacuating a diver with decompression sickness from a cave.

Most commercial aircraft are pressurised to about 2000 m above sea level (0.8 atmospheres). Any diver should allow at least 24 hours after a decompression dive before flying.

CONCLUSIONS

The expedition was remarkably healthy and I had little medical work to do. Thankfully, no one developed any suspicion of decompression sickness. Apart from dealing with recurrent otitis externa, the most daunting medical task was the removal of a piece of glass from the foot of one of the film crew.

ACKNOWLEDGEMENTS

To all the drug companies which have supplied me with medicines for various expeditions in the last few years, and especially the following:

Janssen Pharmaceutical Ltd for Imodium
Labs for Applied Biology Ltd for Cerumol
Merck Sharp and Dohme Ltd for Decadron Shock Pack
Stiefel Labs (UK) Ltd for Lacticare

To Surgeon Captain R.R. Pearson, Submarine Flotilla Medical Officer, HMS Dolphin, Gosport, Hampshire,
for valuable advice on avoidance and treatment of decompression sickness.

A. Boycott, M.B., Ch.B.,
14 Walton Rise,
Westbury on Trym, Bristol, BS9 3EW

July, 1983

REFERENCES

Bove, A.A. 1982. The basis for drug therapy in decompression sickness. *Undersea Biomedical Research*, vol. 9, pp.91-111.

Buchan, J. 1976. Medical report on British New Guinea Expedition, 1975. *Trans. British Cave Research Assoc.* vol. 3, pp 238-242.

Buchan, J. 1982. Medical report Mulu '80 Expedition. *Cave Science*, vol. 9, pp 72-75.

Catron, P.W. & Flynn, E.T. 1982. Adjuvant drug therapy for decompression sickness: a review. *Undersea Biomedical Research*, vol. 9, pp.161-174

Illingworth, R.N. 1979. *Expedition Medicine, a Planning Guide*. Brathay Hall Trust, Cumbria.

Illingworth, R.N. 1981. Medical Equipment for Expeditions. *British Medical Journal*, vol. 282, p.202.

Standing, P.A. 1973. Medical Appendix in *Ghar Parau* by D.M.Judson, Cassell Ltd. London.

Standing, P.A. 1975. Medical Care on Caving Expeditions. *Trans. British Cave Research Assoc.* vol. 2, pp 99-105.

BIBLIOGRAPHY

Colbourne, M.J. 1980. *Preservation of personal health in warm climates*. Ross Institute of Tropical Hygiene, London.

Edholm, O.G. & Bacharach, A.L. 1965. *Exploration Medicine*. John Wright, Bristol.

Miles, S. & Mackay, E. 1976. *Underwater Medicine*. Granada Publishing, London.

Strauss, R.H. 1976. *Diving Medicine*. Grune & Stratton, New York.

U.S.Navy. 1974. *U.S.Navy Diving Manual*. U.S.Navy Dept., Washington, D.C.

List of Medical Supplies: Blue Holes Expedition 1982

Instruments

- Otoscope
- Ear Syringe
- Eye bath
- Syringes 6 x 2ml
- Needles 6 of each S G 21,23,25
- Assorted sutures & steristrips
- Scissors
- Artery forceps
- Forceps 1 pair each toothed & non-toothed
- Scalpel
- Thermometer
- Stethoscope
- Sphygmomanometer

Antibiotics

- Ambaxin tabs 20
- Erythromycin tabs 20
- Flagyl tabs 36
- Oxytetracycline tabs 20
- Septrin tabs 32
- Magnapen injection x 1

Antihistamines

- Piriton tabs 50
- Piriton injection x 4
- Sudafed tabs 30
- Dimotapp tabs 30
- Triludan tabs 10

Antiemetic

- Fentazin tabs 50
- Maxolon tabs 20
- Actal tabs 20

Anti Diarrhoeal

- Lomotil tabs 100
- Immodium caps 50

Analgesics

- Aspirin tabs 100
- Paracetamol tabs 100
- Panadeine Co tabs 20
- Temgesic sublingual tabs 20*
- Temgesic injection x 6 *
- Distalgesic tabs 50

Dressings

- Crepe Bandages 4" x 4
- Elastoplast 1 roll
- Sterile field dressings 2
- Melolin dressings 10cm sq x 10
- Gauze swabs 1 doz
- Safety pins 10
- Elastoplast dressings (Various) 1 box
- Triangular bandages 2
- Cavit (Temporary filling) 1
- Micropore tape 3 rolls
- Bactigras x 10
- Sofratulle x 10
- Savlon concentrate 100ml

Ear, Nose & Throat

- Audicort ear drops 3 x 10ml
- Cerumol ear drops 10 x 10 ml
- Clove Oil (For dental pain)
- Afrazine nasal spray 2
- Neo-cortef oint x 2
- Otrivine-anthistin drops 10ml

Eyes

- Chloromycetin oint x 3
- Amethocaine drops x 5
- Atropine drops x 3
- Neomycin drops x 2
- Fluoroscein strips x 6

Skin

- Daktarin oint x 3
- Trimovate oint x 1
- Anthisan oint x 3
- Savlon Cream x 2
- Lacticare cream x 3
- Calomine cream x 2
- Mercurochrome 2% lotion 100 ml
- Uvistat cream x 2

Intravenous & Emergency drugs

- Haemasol 2 x 500ml
- Giving sets x 2
- Venflon cannulae 1.2mm x 4
- Heparin injection
- Decadron shock pack 10 x 5ml
- Lignocaine 1% 30ml

Miscellaneous

- Puritabs x 48
- Dulcodos tabs 10
- Halcion tabs 10
- Prednisolone 5mg x 50
- Ventolin Inhaler x 1

* Note: Temgesic sublingual tabs and Temgesic injection have recently become available. This is a powerful painkiller, supposedly equivalent to morphine in strength, but it is not addictive, and not subject to the drug control laws in the U.K. or any other country, so far as I am aware. The dose is one or two tablets, allowed to dissolve under the tongue (NOT sucked or swallowed) every four hours as necessary.

APPENDIX II

CAVE DIVING EQUIPMENT AND TECHNIQUES ON THE BRITISH BLUE HOLES EXPEDITIONS 1981-1982

by Julian Walker

This section gives a detailed account of the equipment and techniques used in the exploration of Bahamian Blue Holes by members of the C.D.G. of Great Britain in 1981/82. It includes description of any innovations in British cave diving technique adopted to suit Bahamian conditions, and analyses faults found with these.

DIVING SUITS

Wet suits were necessary for thermal insulation in the warm Caribbean sea due to the length of dives and the strong, cool cave currents encountered on decompression. Protection was also required from the sharp coral and stinging hydroids found lining the walls of most caves.

The suits were individually fitted, one piece, 3 mm neoprene supplied by Gul. This one piece, made-to-measure design gave maximum insulation and comfort whilst the thin material maintained flexibility. An additional waistcoat-hood was found necessary on some lengthy dives. Front-zip and rear-zip suits were used, the former being easier to put on although not as warm or comfortable as the latter. Hard-soled wetsuit boots proved comfortable and durable in jet-fins and in walking over sharp, rough terrain to dive-sites.

The suits were made in individual colours to aid in the identification of divers below water, as well as above in photographs and film.

Drysuits found use in some inland holes where it was desirable to have the least contact possible with the green, murky water.

Thin, nylon, Wemlore membrane suits were used as these were light and comfortable, giving minimal thermal insulation in the warm water. The use of drysuits did not extend beyond this as the wetsuits described above proved ideal for all other situations.

AIR CYLINDERS AND HARNESSES

The system used by most divers was based on side-mounted cylinders. If enough air could not be carried using this method, then additional tanks were worn back-mounted, carried by hand (staged), or both.

The majority of tanks in use were aluminium 80 cu ft. Luxfer tanks bought in America. These were neutrally buoyant when full and therefore suitable for side-mounting and hand carrying. Also available were 6 Spirotechnique steel 105 cu ft. cylinders which were too heavy to be practicably side-mounted. A number of small, light, steel 72 cu ft. cylinders were also used, mainly for staging.

Side-mounted cylinders were worn on a Troll diving harness, which carried both cylinders, lead and main lamp. The cylinders were attached with stainless-steel bottle bands, either bolted to or threaded through the roller-buckle belt. The Troll harness provided padding for the heavy load and could be used in conjunction with shoulder straps if necessary. Attachment loops provided a useful way of carrying things such as line reels and decompression tables.

Twin back-mounted harnesses were normally used with the Luxfer tanks whilst each Spiro cylinder was fitted with its own back-pack. The Spiro harness had no waistbelt, only shoulder straps, making it easy to remove underwater. It could also be fitted to a number of cylinder sizes.

When hand carrying the heavy Spiro cylinders, it was necessary to attach a buoyancy aid to the harness. Adjustable Buoyancy Life Jackets (A.B.L.J.) were used with direct air feed from the tank to give an independent load with easily adjustable buoyancy. The other types of cylinder needed no such aid and were held at the neck by the pillar valve or by the hose of the attached demand valve.

Cross-flow pillar valves were used in all tanks. These have large taps which can be easily found underwater and can also be used as handles. It was found, however, that American pillar valve first-stage seats are smaller than their European counterparts. Our demand valve first-stage seats were therefore changed to fit the American cylinders. No trouble was found when using the converted demand valves on European pillar valves.

DEMAND VALVES

Each cylinder worn or carried by a diver had its own demand valve to guarantee against total air loss due to one valve failure. No manifolds were used, so it was not possible to breath air from a cylinder once its valve had failed. In addition, a variety of models were used by each diver to protect against possible manufacture or design faults in a new model.

Spirotechnique supplied the majority of demand valves used. The three models in use were the 40/10, 50/10 and Pro R. The 40/10 proved reliable, whilst the 50/10 and Pro R had the added complication of an airflow adjustor on the second-stage, for deep dives. This facility was seldom used, even on dives to 60 m. During the 1982 expedition, 8 out of the 9 new Spiro Pro R models taken failed, delivering bottle-pressure air to the second-stage. This was found to be due to incorrect parts assembled in our particular batch of first-stages. All the Spiro second-stages were easily cleaned whilst the diaphragm first-stages found on each model were not readily dismantled. A few Manta valves were also used, proving reliable and extremely simple. No tools are required to dismantle and reassemble either first or second-stages.

As up to four valves were worn at any one time, right and left-handed models were used to keep the mass of low-pressure hoses tidy. Colour coding was also needed to relate second-stages to their appropriate contents gauge.

Contents gauges on side-mounted and hand-held cylinders were tied around the neck of the cylinder, whilst those on back-mounted sets were tucked under an appropriate harness strap. Demand valve second-stages were either worn on neck straps or through the neck of the A.B.L.J.

Every valve was stripped, cleaned and tested before each dive to ensure correct functioning.

LIGHTING

High power lighting was necessary in the large clearwater passage. Main light duration had to be of the order of two hours with backup lighting lasting for up to 6½ hours, the maximum length of one dive.

No suitable main lights were commercially available, so a number of specifically designed units were manufactured. These consisted of a stack of rechargeable 'D' cells in a belt-mounted container with switch unit, and a sealed headlamp. Power output was either 20 Watt or 50 Watt, duration being 2½ hours or one hour respectively. A number of designs were tried, and impeccable maintenance was found to be necessary with all types to prevent flooding.

The main-lamp was used in conjunction with two 10 Watt Iodin torches, which have a rechargeable duration of one hour. Although large and heavy, these lamps proved robust and reliable.

Backup lighting was provided by two Aquaflashes with a reliable duration of 12 hours when used with rechargeable batteries.

All lighting was helmet mounted. This had the obvious advantages of keeping both hands free, making reserve lights easy to find and turn on, and providing light where you looked. However, this did lead to the tendency to shine your lights in a buddy's face, and in murky water it was not possible to avoid glare by holding the lights out to one side. The large assembly was also found to be clumsy in small spaces.

BUOYANCY CONTROL

The depth of dives combined with the number of cylinders in use necessitated some form of buoyancy control to assist in ascent and descent and to help maintain neutral buoyancy. A.B.L.J.'s were used in preference to other types of B.C. due to their versatility.

Yellow Spirotechnique and orange Fenzy jackets were supplied by Spirotechnique with direct air feed and an independent air cylinder. The Fenzy was found to be bulkier than the Spiro although it does have a greater lifting capacity. The small, independent air cylinder found on both jackets was often removed to reduce bulk, inflation then achieved by direct feed from one main cylinder. A pocket also found on both jackets was used to store such items as survey slates, spare decompression tables, spare knife and spare pencil.

SURVEY EQUIPMENT

Survey notes were taken as new passage was entered, using depth gauge and compass readings along a tagged line. A four-paged formica survey booklet was needed due to the length of passage often discovered. Both compass and depth gauge were wrist-mounted, the compass separate from watch and knife to avoid errors. Survey data was transferred to paper as soon as possible and surveys drawn on the same day whilst the cave was still fresh in the mind.

LINES AND LINE REELS

Thick 6 mm line was required in all ocean holes due to the strong tidal currents encountered. When securely belayed, the line could be used to pull on and was more resistant to abrasion. It was tagged at 10 m intervals with yellow and black tape. The yellow tag was always on the exit side of the black, showing a confused diver the way out. Yellow and black tagging replaced the original green-red code to protect the colour-blind. The 10 m interval was used as survey information.

Line reels were manufactured to hold 200 m of line. The reels were large, but this quantity of line was required to take full advantage of each exploration dive.

DECOMPRESSION

Nearly all dives required decompression stops before a return to surface could be made. All divers used U.S. Navy decompression tables, in conjunction with a watch and depth gauge, as these were suitable for the warm waters encountered. The tables were in the form of colour-printed plastic cards for underwater use and contained repeat dive tables in addition to the standard decompression tables. Depths were in feet, however, so as our European depth gauges were calibrated in metres a reliable conversion method was needed. Conversion tables could be written on a wrist slate or memorized.

Due to the lack of recompression facilities available, extra decompression was added by most divers. (The U.S. Navy dive tables are reputed to have a 4% failure rate). The diver was assumed to have spent the full duration of the dive at maximum depth, and as this was seldom the case nitrogen-absorption was thus exaggerated. In addition, five extra minutes could be added to bottom time and an extra short stop below that first scheduled included. All incidents were thus avoided, although frequent twinges were imagined by paranoic divers.

On occasion, a planned dive would exceed the standard U.S. dive tables. This meant resorting to the Extreme Exposure tables found in the U.S. Navy Diving Manual. These were copied on to a slate and left at the deepest anticipated stop on the way in.

In addition to the tables, some divers used decompression meters. Although these were useful to check calculations, they were not trusted enough to rely on independently.

AIR MANAGEMENT

All divers worked within the confines of the 'thirds' rule. That is, every cylinder used was breathed in succession until all were 2/3 full. The journey out could then be made breathing from each tank again. This guards against total failure of a full cylinder at maximum penetration, and leaves 1/3 in reserve for delays of any kind. In reality, the outward journey is normally faster than the inward, so the diver reaches the entrance with more than 1/3 remaining. This spare air could be used for decompression, although a decompression cylinder was usually left at the entrance in case the diver returned with depleted reserves.

On long dives, the technique of staging was used to enable a lead diver to gain maximum penetration. This involved airdumps at appropriate locations within the cave. Support divers would accompany the lead diver carrying extra tanks, the lead diver breathing from a hand-held cylinder. Wherever this was emptied, two similar tanks were left for the lead diver's outward journey, thus maintaining the thirds rule. Eventually, the lead diver would continue alone with full tanks, until having breathed 1/3 from each he returned via the airdumps. Empty cylinders could be swapped for full ones, and a safe exit made. Separate tanks were available for decompression.

Using the above technique, a penetration of 1100 m was made at a depth of 24 m. This involved the lead diver using 11 tanks with 4 support divers and taking 6¼ hours.

Julian Walker
23 Furness Road
Fallowfield
Manchester 14

MS received October 1983

APPENDIX III

OCEAN HOLE SITES ON ANDROS

George J. Benjamin

The original catalogue of ocean hole sites made by Dr George J. Benjamin from 1967 to 1972 (without additions from the 1981 and 1982 expeditions). Sites are catalogued from north to south. See page 10 for area map.

Code letters refer to the nearest landmark, e.g. MC21. MC stands for Mangrove Cay, 21 stands for the first Blue Hole in the second group.

Rating:
- = no interesting features found
* = worth exploring
** = good
*** = excellent site

CONCH SOUND AREA

CS1 ** Five openings, connected in a rotunda 60 to 80 feet down. Large tunnel leading south from main pit, explored for 300 ft. Strong current. Smaller passages lead north and west. The north passage reverses 30 min. later than the main current. Many fish. Occasionally smelly sulphurous water appears in main passage, especially in late summer and all life disappears for that period.

CS2 * Small cave. Sulphurous smell prevails throughout the year, and the opening is covered by a thick layer of algae typical of sulphur springs. At 20 ft the cave divides. The upper tunnel is much warmer than the lower one (in summer). No sulphur was detected in the lower part. The passages have been entered for 50 ft. Further penetration is possible.

SOUTH MASTIC POINT AREA

SM1 ** Opening 50 by 100 ft. To the east, deep ledges and arches blocked with sand. To the west, the entrance slopes down to 80 ft where a tunnel opens up. Powerful current - explored for 300 ft without finding end. Many side passages, ledges at different levels. As divers stir up mud, lifeline essential for safe return. Many fish, lobsters, shrimp and cowrie shells.

SM2 - Sulphur spring, 20 ft deep
SM3 - Spectacular sink hole. Deep blue in colour. Appears bottomless but is only 20 ft deep. No passages. Murky.
SM4 - Small cave under a ledge, 40 ft.
SM5 - Same as above.
SM6 - Chimneylike pit, 20 to 30 ft across, 80 ft deep. Current small, clarity moderate.

RAT CAY/STAFFORD CREEK AREA

RC1 ** Small Blue Hole at Rat Cay. Easily accessible by boat from Stafford C Creek or Mastic Point. Daylight pit 20 ft deep. Many passages. At west side a 20 ft pit leads into the lower system. All passages have been explored to the end, many reach 300 ft. Powerful currents detected at small cracks showing that large tunnels are not necessary for strong currents. Many fish, lobsters, colourful coral and anemones at entrance. Recommended for beginners since it contains the features of a big cave in miniature.
ST1* Two small openings, too narrow to enter. Most powerful current. During suction a peculiar whirlpool is often formed. Air is sucked into the cave in the centre of the current.
Hole in the Wall : Off Stafford Creek, in the edge of the dropoff, an opening in the top of the escarpment at 150 ft leads down to a lower opening in the wall itself at 200 ft depth.

OTHER NORTH ANDROS SITES

Andros Town 1 * Five miles south from Andros Town. Small entrance pit to 30 ft level. North passage leads into a sizeable room, 110 ft deep. Bottom is extremely muddy. Many fish, small current.
Youngs Town 1 ** Opening is some 30 ft across and 25 ft deep. Two passages at the beginning very tight - diver has to remove tanks to get through. Passages explored for 300 ft without finding end. Many fish, small current.
Mars Bay Sink Hole : Not explored.

MIDDLE BIGHT

North arm area
MB1 ** Small opening, vertical pit to 100 ft. Passages north and south. Strong current.
MB2 / MB3 / MB4 : Small openings, murky, not fully explored.
Shark Hole, North Bight ** Sink Hole 400 ft across, 200 ft deep. Murky, funnel-like. At 50 ft, vertical pit over 100 ft across. At 160 ft, a zone of liquid mud limits further descent.
Middle Bight Sink Hole - 25 ft deep, very clear.

Gibson Bay Sink Hole - 40 ft deep. Top clear, bottom liquid mud. Small passage at north end, probably leading to MB1.
Moxey Town Sink Hole - 30 ft deep, murky.

MANGROVE CAY AREA

a) North area 3. (4 blue holes).
MC31 - Large sink hole 150 by 200 ft. Murky. At the north end, slopes down to 80 ft, into a passage. Not explored.
MC32 * Opening 5 by 20 ft clear. 100 ft deep.
MC33 ** Opening is a narrow fissure leading into a pit, 110 ft deep. Passage to the north leads after 150 ft into a sizeable room. To the south is blocked after 50 ft. Not fully explored.
MC34 * Narrow fissure. At 60 ft a narrow passage leads north and south for short distances. Many fish, very clear.

b) Central area (3 blue holes). Area 2.
MC21 *** Semivertical pit, 20 by 30 ft to a ledge. Several passages. Vertical pit to 110 ft. South passage leads into a huge room 210 ft deep. After 400 ft there is a rockfall, passage explored for 600 ft without finding end. North passage leads after 100 ft into a sizeable room with warm water.
MC22 Small funnel of 20 ft depth.
MC23 * Opening 30 ft by 40 ft, 20 ft deep. Murky. Passage to the north entered for 100 ft. Small current. Many fish.

c) South area 1. (7 blue holes).
MC11 *** Small opening leads to pit at 30 ft. 170 ft deep. Moderately clear, strong current. At 100 ft there is a side passage with pillars resembling cave stalagmites. At bottom, several passages entered to a depth of 230 ft and to a distance of 300 ft from the main pit.
MC12 *** Large tunnel leading south from a funnel at 60 ft. A 10 ft by 30 ft pit opens some 200 ft inside. Have descended to 240 ft into a passage leading south. It is suspected the passage may connect with the lower system of MC11.
MC13 / MC14 - Small openings.
MC15 * Counterpart of MC12 but leading north. 80 ft deep. Murky.
MC16 ** Opening pit, 60 ft deep. Narrow fissure leads North and South. Passage is up to 5 ft wide and over 260 ft deep. Very clear. Strong current.
MC17 * Small opening with extremely strong current, which reverses up to 30 minutes later than other caves in this group. Very clear.

SOUTH BIGHT AREA

10 blue holes.
SB1 / SB3 * Small openings, most likely above the inner passages of SB2. No connections have been found. Entered for 100 ft to depth of 80 ft.
SB2 *** Opening 20 ft by 30 ft. Vertical pit 100 ft deep. South passage 140 ft deep. Entered for 400 ft. At 150 ft inside, a 100 ft high dome with stalactites. North passage 160 ft deep. At 400 ft inside, beautiful grotto with many stalagmites and stalactites, some 20 ft long. Passage has been entered for 800 ft.
SB4 *** Greatest of all Andros Blue Holes. Superb clarity. Strong current. At least 400 ft deep, over 1 mile of passages explored. The stalagmite grotto is 1000 ft inside the south passage,with an extension close to the north passage of SB2. No connection has been found.
SB5 * Narrow fissure, extremely strong current. At the depth of 120 ft, too tight to enter with tanks on. No bottom visible. Great possibilities.
SB6 / SB7 * Small openings, many fish. Entered for 50 ft.
SB8 / SB9 / SB10 Small water outlets, no passages found. Many fish.
Driggs Hill Sinkhole 40 ft deep. The system from SB5 to the sinkhole appears to be a part of a joint stretching for many miles from Gibson Cay in the north, past Congo Town in the south. The joint is best exposed a few hundred yards north from the sinkhole, with many small openings.

CONGO TOWN AREA (not fully surveyed)

CT1 * Upper level at 20 ft. Muddy. Passages south. Lower level, tight squeeze to 60 ft.

LONG BAY CAY AREA

LBC1 to LBC5 All small and murky. Not fully explored.
Victoria Point Sink Hole. Some 300 ft across. Spectacular appearance. Only 30 ft at deepest point. Murky.

DOUGHNUT AREA. EXTREME SOUTH ANDROS (not fully surveyed)

The character of these Blue Holes is different from those described before. From the air they look like huge doughnuts. They are circular coral patches with a Blue Hole in the middle. In this area, the deep water no longer follows the contour of the island at approx. 2 miles, as in the north, but is a distance of 5 to 10 miles. The chain of Blue Holes follows the deep water at the same distance (from the dropoff) as in the north, which is from 1 to 2 miles. As a result, some of the holes are almost 10 miles offshore.

Doughnut ** 300 ft across, 60 ft deep at the south end where small passages can be entered for a short distance. Moderate current. Poor visibility. (This is "Great Doughnut" of 82 report).
North Doughnut system * Six Blue Holes explored to 120 ft. Moderate visibility.
South Doughnut system * Five Blue Holes entered up to 120 ft. Clarity poor. Interesting Coral formations, many black urchins, especially in the roof of a dark passage. Many fish. Moderate currents.
Mars Bay Sink Hole. Not explored.

CAVE SCIENCE

The TRANSACTIONS OF THE BRITISH CAVE RESEARCH ASSOCIATION covers all aspects of speleological science, including geology, geomorphology, hydrology, chemistry, physics, archaeology and biology in their application to caves, as well as technological matters such as exploration, equipment, surveying, photography and documentation. Papers may be read at General Meetings held in various parts of Britain, but they may be submitted for publication without being read. Manuscripts should be sent to the Editor, Dr. T.D. Ford, Geology Department, University of Leicester, Leicester LE1 7RH, who will be pleased to advise in cases of doubt about the preparation of manuscripts. The Transactions is normally issued four times a year to paid-up members of the British Cave Research Association. Subscriptions are due on 1st January annually.

MEMBERS OF BCRA COUNCIL FOR 1984

President:	Dr. G.T. Jefferson, Zoology Dept., University College, PO Box 78, Cardiff CF1 1XL.
Chairman:	B.M. Ellis, 30 Main Road, Westonzoyland, Bridgwater, Somerset.
Dept. Chairman:	J.J. Rowland, Llywn yr Eos, Capel Bangor, Aberystwyth, Dyfed, SY23 3LR.
Secretary:	Dick Willis, Basement Flat, 56 Granby Hill, Clifton, Bristol BS8.
Membership Secretary:	David R. Stoddard, 23 Claremont Avenue, Bishopston, Bristol BS7 8JD.
Treasurer:	J.W. Dey, 16 Edge Hill Road, Sheffield S7 1SP.
Transactions Editor:	Dr. T.D. Ford, Department of Geology, The University, Leicester LE1 7RH.
Bulletin Editor:	J.S. Corrin, 55 Osborne Terrace, Bacup, Lancs OL13 8JY.
Librarian:	R. Poulson, 26 Ashley Road, Keyworth, Nottingham.
Foreign Secretary:	J.R. Middleton, 2 Broad Elms Close, Sheffield S11 9ST.
Conservation Officer:	D.M. Judson, Rowlands House, Summerseat, Bury, Lancs BL9 5NF.
Sales Officer:	B.M. Ellis, 30 Main Road, Westonzoyland, Bridgwater, Somerset.
Biological Recorder:	M.C. Day, 118 Whitmore Road, Harrow HA1 4AQ.
Archaeological Recorder:	Dr. J.D. Wilcock, 22 Kingsley Close, Stafford ST17 9BT.
Meetings Manager:	Dr. R.G. Picknett, 28 Potters Way, Laverstock, Salisbury, Wilts SP1 1PX.
Distribution Manager:	Sam Moore, Havencourt, The Parks, Aldington, Evesham.
Insurance Manager:	Geoff Wells, 39 Linden Road, Redland, Bristol BS6.
Advertising Manager:	Keith Plumb, 11 Copper Beech Way, Leighton Buzzard, Bedfordshire LU7 8BD.
Southern Club Representative:	Peter Robertson, 36 Tadfield Road, Romsey, Hants SO5 8AJ.
Co-opted Members:	
Special Projects Editor:	Dr. A.C. Waltham, 11 Selby Road, West Bridgford, Nottingham.
Equipment and Techniques Officer:	A. Eavis, Tides Reach, Redcliff Road, Hessle, N. Humberside HU13 OHA.

1984 SUBSCRIPTIONS

Members are respectfully reminded that their subscriptions for 1984 are due. The rates for the coming year (unchanged from 1983) are:

Full individual membership	£10.00
Joint membership (i.e. one set of publications)	£12.50
Member Club	£12.50

All payments should be sent to Membership Secretary, Dave Stoddard, 23 Claremont Avenue, Bishopston, Bristol BS7 8JD. Cheques made payable to 'British Cave Research Association'.