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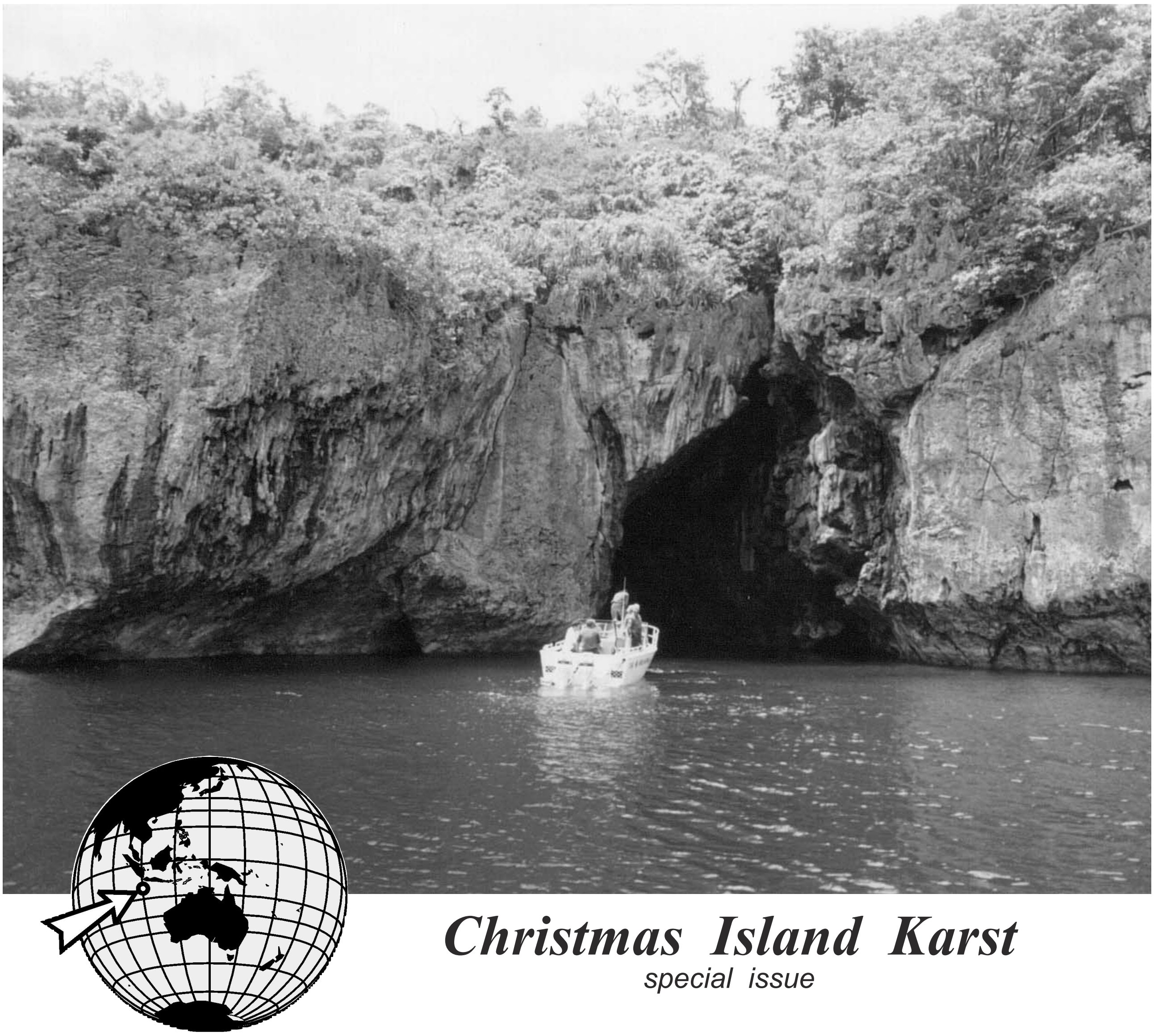
Helictite

Journal of Australasian Speleological Research



Christmas Island Karst

special issue

Helictite

Journal of Australasian Speleological Research

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Helictite was established in 1962 by Edward A. Lane and Aola M. Richards who were the foundation editors. It is intended to be wide ranging in scope from the scientific study of caves and their contents, to the history of caves and cave areas and the technical aspects of cave study and exploration. The territory covered is Australasia: Australia, New Zealand, the near Pacific Islands, Papua New Guinea and surrounding areas, Indonesia and Borneo.

In 1974 the Speleological Research Council agreed to support the Journal with financial assistance and in 1976 took over full responsibility for its production. From 1974 to 1997 the Journal was edited by Julia James assisted by other members of the Speleological Research Council Ltd. In 1998 Susan White and Ken Grimes took over as editors with Glenn Baddeley as Business manager.

In 2000 ownership was transferred to the Australian Speleological Federation, Inc. (ASF) and production is administrated by the Helictite Commission of the ASF.

The aim of the Helictite Commission of the Australian Speleological Federation is:
To publish the results of scientific studies in all fields of speleology in Helictite — Journal of Australasian Speleological Research and other publications.

Helictite

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Contents

Cover: The sea cliff that circles much of Christmas Island makes access difficult. The cave entrance, to Grimes Cave, is larger than most. Photo by K.G. Grimes.

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Editorial

Ken Grimes

This *Helictite* is a special issue on the karst of Christmas Island, in the Indian Ocean.

In March–April of 1998 a group of six karst scientists spent two and a half weeks on Christmas Island, doing a study of the biology, geology, hazards and general management of the island's caves and karst. This was done for Parks Australia North (now Environment Australia), to assist them in preparing a management plan for the National Park which now covers a large part of the island.

The team comprised Bill Humphreys and Stefan Eberhard, who studied the cave biology, Ken Grimes and Dan O'Toole, who looked at the geological hazards, and Andy Spate and Rauleigh Webb who looked at other hazards and cave and karst management in general. The study was arranged and coordinated on the island by Paul Meek of Parks Australia North.

In this issue we present four papers. An introductory paper by Paul Meek, previously of Parks Australia North, sets the scene with a discussion of the history and management of the caves and karst. A short note by Peter Barrett, who was geologist for the phosphate mining operation, presents the history of exploration for water supplies in the karst. The two main papers are based on the consultant's reports: Ken Grimes describes the physical karst features of the island, and Bill Humphreys and Stefan Eberhard describe the karst biology.

Helictite web page

Thanks to Glenn Baddeley, our business manager, *Helictite* now has a web page.
The URL is: http://home.mira.net/~gnb/helictite/

The site provides subscription information, a list of contact addresses, information for contributors, and contents and abstracts for recent issues. The last area will be expanded as time permits—we hope eventually to provide an index and abstracts for all issues of *Helictite*.

Helictite (2001) **37(2):** pp. 31-36.

The History of Christmas Island and the Management of its Karst Features.

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Abstract

Christmas Island is an external Territory of Australia. It hosts a diverse range of endemic and native terrestrial, subterranean and aquatic flora and fauna with Australian, Indo-Malesian and Pacific affinities. The Island has survived the impacts experienced on other tropical islands as a result of human settlement and is a highly valued ecological asset to Australia. The karst environment had been under-valued as an ecological entity until recently when extensive speleological surveys were conducted. These surveys were a part of broader attempts to prepare a management plan to conserve the values of the karst environment.

Introduction

Christmas Island is located in the Indian Ocean (10°25'S and 105°40'E) approximately 2,600 km west of Darwin and 360 km south of Java. The Island is volcanic in origin and has undergone a series of uplifts and subsidence during the last 80 million years. The geological setting of the Island is described in Grimes (this volume). Christmas Island covers an area of approximately 135,000 hectares of which 68% has been gazetted as Christmas Island National Park (Figure 1). The remaining tenure comprises the phosphate mine lease which is managed by Christmas Island Phosphates Ltd and the urban environment which is managed by the Christmas Island Shire Council and the Department of Transport and Local Government (Christmas Island Administration). Management of the karst environment is shared between Parks Australia North (PAN), Christmas Island Administration and the Christmas Island Shire Council; however the primary responsibility for conservation lies with Parks Australia North.

There are ninety–five known karst features including approximately 30 caves (Spate and Webb, 1998; Grimes, this volume). Until 1998, little was known about the Christmas Island cave ecosystem and biodiversity, with only a few species having been collected on an opportunistic basis (Harvey and West 1988; Short and Meek 2000). Many caves are used by Island residents for recreational pursuits and some are well known historic sites where Islanders took refuge from the Japanese invasion during the Second World War.

In 1997 an inexperienced group of local cavers narrowly escaped serious injury while exploring a cave. This incident raised concerns for public safety and the protection of the cave ecosystems. As a result, Parks Australia declared a moratorium prohibiting access into all caves until a survey could be undertaken to assess the risks to people and the threats to the cave ecosystem. In 1998, three consultancies were commissioned to assess the management of the caves and karst features (Spate and Webb, 1998), the fauna and flora of the caves (Humphreys and Eberhard, 1998) and the public risk concerns (O'Toole and Grimes, 1998). The intent was to use these reports to develop a Christmas Island Cave Management Plan balancing conservation with cave use. This is currently under consideration (Environment Australia, 2000). This issue of *Helictite* presents initial reports on the scientific aspects of the consultancies.

The Island Climate

Christmas Island experiences a tropical monsoonal weather pattern with a pronounced wet and dry season, although rain can fall in any month. December to April is generally recognised as the wet season with the highest rainfall during February to March and the dry season is August to October. Mean average rainfall is 2.1 metres per year and relative humidity maintains a fairly consistent 80-90%. The average temperature is 28^{o} Celsius and can drop to 22^{o} Celsius in the dry season.

Karst Vegetation

The terrestrial vegetation has been divided into three main groups (DuPuy 1988); primary rainforest, marginal rainforest and scrub forest. The vegetation has Indo-Malesian affinities with some species also being found in north-eastern Queensland (DuPuy 1988). The tallest trees occur over the deepest soils and flora species decrease in size and diversity where the limestone is closer to the surface. Primary rainforest on the deep soils is dominated by emergent trees to 50 m high including broad buttress species such as *Planchonella nitida*, *Syzygium nervosum*, *Tristiropsis acutangula* and *Inocarpus fagifer*. Marginal rainforest is a more open habitat with trees between 20-30 metres high growing along the lower terraces and dominated by species such as *Pisonia grandis*, *Gyrocarpus americanus* and *Erythrina variegata*. Scrub forest occurs on the lowest terraces and comprises a low structured (5-10 m) scrubby

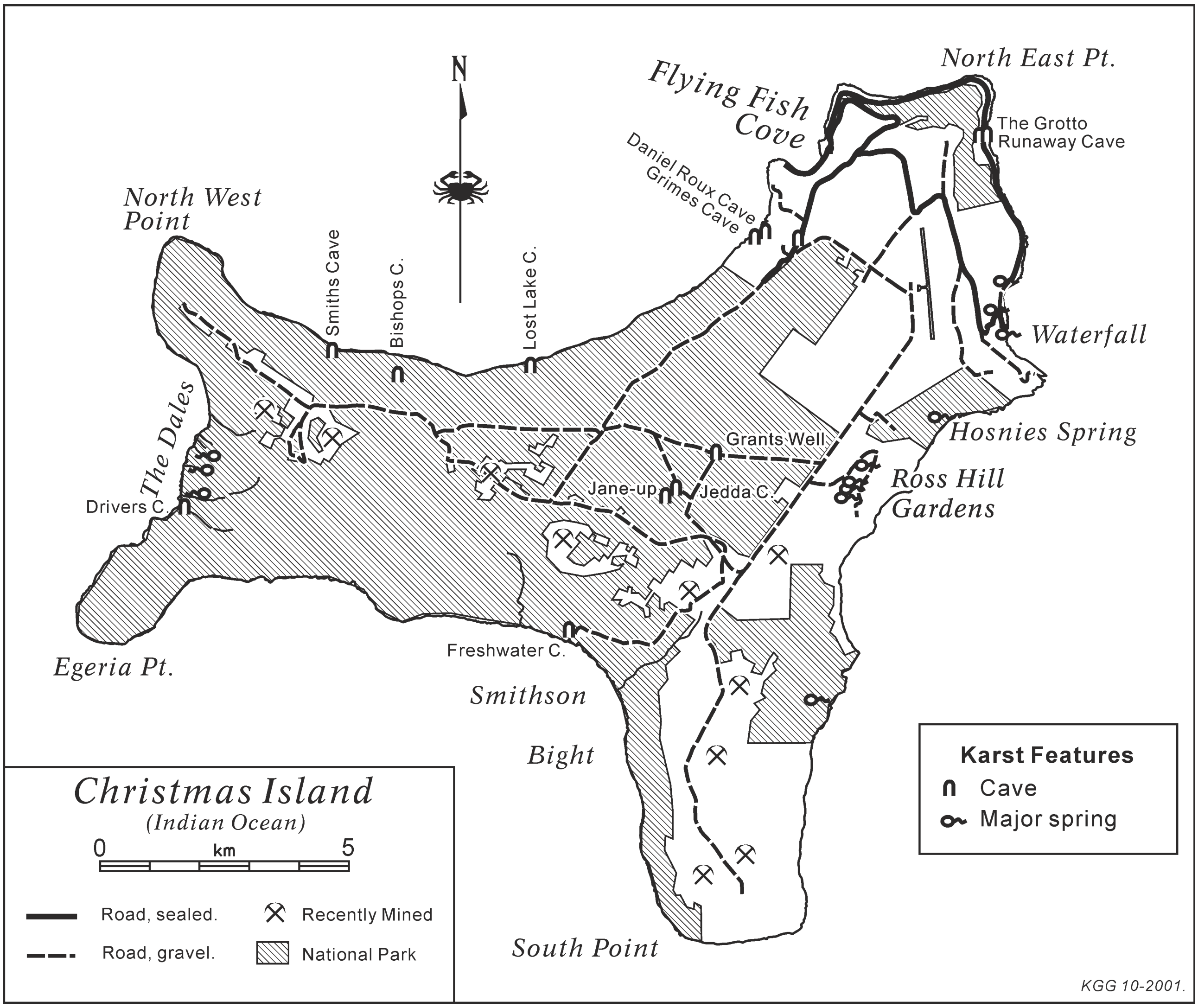

Figure 1: Locations on Christmas Island

understorey with spiny and scrambling shrub vines and the trees *Columbrina pedunculata*, *Celtis timorensis* and *Gyrocarpus americanus* which are mostly deciduous.

A fourth, localised, habitat type occurs around surface water and is the strong-hold of the Blue Crab *Cardisoma hirtipes*. The Dales, which are small surface stream valleys located on the western terraces, are dominated by the enormous *Inocarpus fagifer* or Tahitian chestnut. Another surface fresh water site occurs at the unique Hosnies Springs (RAMSAR site) where two species of coastal mangrove *Bruguiera gymnorhiza* and *B. sexangula* (DuPuy 1988) can be found in an area of less than one hectare .

Ecological Values

There are nine main terrestrial habitat types (after Environment Australia, in draft) excluding disturbed urban environments, which provide habitat for Island species: sea cliffs, terrace forest, shallow soil rainforest, limestone scree slopes and pinnacles, deeper plateau and terrace soil rainforest, mangrove forest, perennially wet areas, karst (caves) and mine fields.

These habitats contain a high number of endemic species: 17 endemic plants, five endemic reptiles, seven endemic land-birds, three species of endemic sea-birds, five endemic mammal species including two extinct rats and a shrew, twelve endemic cave fauna (Humphreys and Eberhard, this volume) and two endemic land crabs. The Island is famous for its twenty species of land crab in particular the Red Crab *Gecarcoidea natalis* and Robber Crab *Birgus latro.*

The modern Christmas Island ecosystem is unlike any other tropical Island in that land crabs dominate the terrestrial landscape which is now devoid of any native mammals. Red crabs play an integral role in the ecology of the Island biota as leaf decomposers, and seed and seedling consumers—a role which ultimately controls the species composition of the rainforest (Green 1993, 1997).

Owing to the small size of the Island, all endemic taxa are at risk of decline due to their limited distribution and vulnerability to major catastrophes. The island currently has seven threatened fauna, three listed as endangered and four as vulnerable under the *Environmental Protection and Biodiversity Conservation Act 1999*. Recovery Plans have been prepared for five of the flagship species although only two have been approved by the Minister for the Environment and Heritage (see http://www.biodiversity.environment.gov.au/wildlife/plans/recovery/index.html for further details). To ensure the protection of this unique flora and fauna, considerable work is required to update the number of threatened species and to facilitate their listing as rare or threatened and to develop recovery plans

History of Occupation

On Christmas Day in 1643 Captain William Mynors named Christmas Island while sailing past the Island on board the *Royal Mary*. However, the first detailed shore exploration was in 1887 by the crew of the *HMS Egeria*. The Island was later declared a part of the British Empire and settled in 1888 under a joint lease to George Clunies-Ross and John Murray. As there were no indigenous people on the Island, these pioneers shipped Malay workers to the Island from nearby Cocos Island. In the late 1890's mining leases were granted to the Christmas Island Phosphate Company and more Cocos Malays and Chinese workers were brought to the island to help establish the mining industry. Descendents of these early workers are still resident and have a long history of association with Christmas Island.

The only accessible point of landing on Christmas Island is in Flying Fish Cove on the North-Eastern end of the Island, known informally as the Dog's Head. Flying Fish Cove was established as the main settlement on the Island for the growing population although several camps were scattered throughout the Island for mine workers. As the population of the island grew and mining expanded through the 1900's, the demand for water for human consumption and mining increased and the first investigations to locate suitable subterranean supplies were undertaken.

In 1958 the administration of Christmas Island was handed over to the Commonwealth of Australia and the Island has been a Territory of Australia since. The population of the Island has fluctuated in size over the years from 1200–2500 depending on the availability of employment. The community is composed of Chinese–Malay (85%) and Australian–European (15%).

History of Cave and Karst Exploration

Exploration to locate phosphate resources was extensive across the Island and is still evident in some locations from the drill lines spaced throughout the Island landscape. The British Phosphate Commissioners (BPC) and the Phosphate Mining Company of Christmas Island (PMCI) also conducted surveys in the 1960-70's to establish a water supply for the wash screen at South Point (Barrett, this volume) and it was in these surveys that some caves were reported. In one case water tracing was conducted at Jedda Cave in an attempt to map the underground water flow. Domestic water is now supplied to households and businesses from Jedda Cave and Grants Well, with back up pumps at Ross Hill Gardens on the southern side of the Island. There are few detailed reports describing the early explorations of Christmas Island caves apart from some historical notes on archived Christmas Island Phosphate Ltd files.

Speleologist, Roy Bishop conducted many surveys across the Island in search of water throughout the 1950-60's and this search was continued by Mr David Powell in the 1960's. Many caves were discovered and some were named by, or after, these early explorers. Letters on old files refer to the naming of some caves. Lost Lake was named in the 1960's by a team of Islanders including Roy Bishop; his undated article describes their finding; *"At the 1500 foot mark* [450m] *... the next 300 ft. was all deep water, in fact an underground lake. It was a magnificent sight and one of the "romantics" in the party promptly names*[sic] *it "Lost Lake". The water was crystal clear, cold and drinkable, and the underwater torches picked out fantastic grottoes and limestone sculptures."* A letter dated 30 October 1969 by T.J. Kennedy, the Assistant Geologist for BPC, describes a cave exploration that was undertaken in October 1969 by a group of six. On the expedition he recorded a cave and named it Bishops Cave after Roy Bishop. During interviews between David Powell and this author in 1997 he revealed that Jane-up Cave was named after his daughter Jane. He later named Jedda Cave after his daughter Jeanna and son David although it has also been reported to have been named after Roy and David's wives Jeanne Powell and Daphne Bishop (Neale and Adams 1988).

Runaway Cave was so named as it was supposedly used by Island residents during the Second World War to hide from the Japanese. The best known, and most significant cave (Spate and Webb 1998) has a plaque on the entrance (Upper Daniel Roux Cave) indicating that it was named after Daniel John Roux, born Christmas Island 1957, died in Switzerland 1960 (aged 3.5 years).

In recent times other caves have been allocated colloquial names by those who have found and investigated them. Most have been allocated numbers in accordance with the Australian Speleological Federation (Spate and Webb, 1998). Recent finds of new caves by the local caving group had not been issued with numbers at the time of writing this paper.

Detailed Cave Surveys

The most significant speleological exploration was in 1987. This expedition (SEXI 1987) attempted to locate and map all of the Island's known caves (Brooks 1990). In the SEXI 1987 expedition, a scorpion was collected from Bishops Cave and sent to the Western Australian Museum by Mr. Neil Plumply. This specimen was misdirected until 1997 when it was found at the Perth Hospital. It was later identified as a blind scorpion *Liocheles polisorum (Ischnuridae*) which is the first record of a blind cave scorpion in Australia (Humphreys and Eberhard, this volume) and a significant record for the Island.

In November–December 1996, this author accompanied a water engineer/consultant (Tony Faukland) to inspect Lower Daniel Roux as a part of an ongoing consultancy to assess water flow and quality (Faukland, 1999). On this expedition the author collected a fresh water prawn in Daniel Roux Cave, later identified as *Macrobrachium microps*. This species is known to occur in New Ireland and West Samoa (Holthuis, 1978; Bruce and Iliffe, 1993) and is a significant range extension for the species (Short and Meek, 2000). On a later visit to survey and collect more species for identification, the author collected a fresh water fish that was confirmed to be the Brown gudgeon *Eleotris fusca* (Gerry Allen, pers. comm. 1998), thought to be extinct from the Island. This species was known to occur at the Waterfall Spring on the north-east coast (Allen and Steene 1988) but that habitat was destroyed by the construction of the Christmas Island Resort.

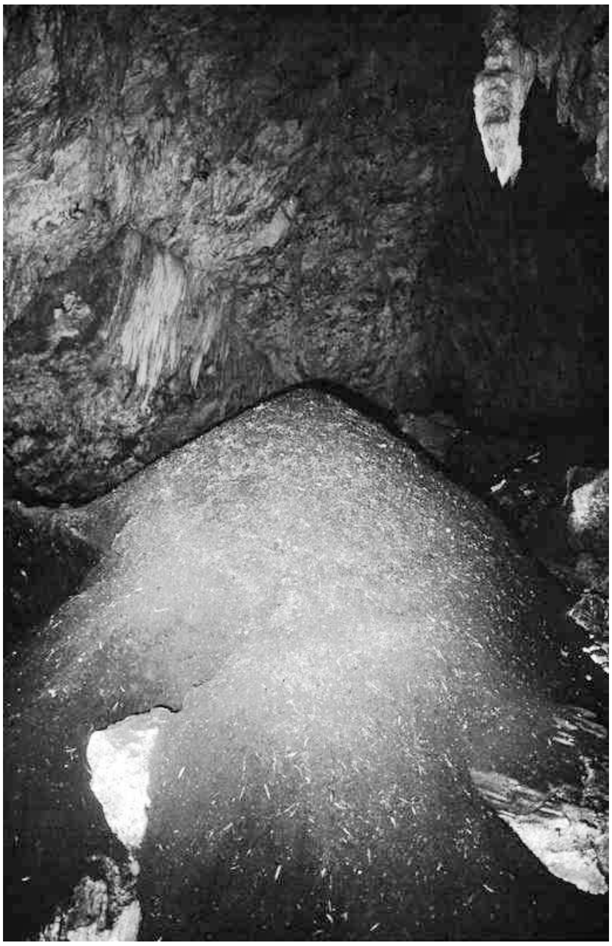

Figure 2: Guano mound of the Christmas Island Glossy Swiftlet in Upper Daniel Roux Cave.

In 1997 the author started a trapping study to determine the status of the Christmas Island Shrew *Crocidura attenuata trichura* (Meek 2000). Longworth traps and hair tubes were located in the first chamber of Upper Daniel Roux Cave in an attempt to detect mammal presence. The survey was unsuccessful in trapping mammals although a nest containing a litter of rodents (probably *Rattus rattus*) was recorded in a major Swiftlet guano mound (Figure 2). Several necrophagic and saprophagic arthropods were collected from traps and hair tubes including; beetles *Carcinops sp*, *Alphitobius laevigatus* and the ant cricket *Pachycondyla sp*. These samples were sent to the Western Australia Museum and Western Australian Department of Agriculture for taxonomic identification. Robber crabs *Birgus latro* and red crabs are consistently recorded in the twilight zone of the first chamber of Upper Daniel Roux Cave and are commonly found in most caves and karst features on the Island.

These early surveys provided the foundations for the 1998 consultancies, which provided the most detailed reports on the caves of Christmas Island (Spate and Webb, 1998; Humphreys and Eberhard, 1998; O'Toole and Grimes, 1998). They have improved our understanding and appreciation of the caves, their geology, geomorphology, scientific value, fauna and the level of risk posed by recreational use. Scientific aspects of these reports are summarised elsewhere in this volume by Humphreys and Eberhard (this volume), and Grimes (this volume). Some management aspects are summarised later in this paper.

The caves and cave fauna of Christmas Island are undoubtedly unique and biologically valuable both for Christmas Island and for the Australian natural estate. The caves host an array of endemic cave species (Humphreys and Eberhard, this volume) and the karst provides the foundation for a unique and diverse biota.

Current Management

Two Commonwealth Government agencies currently administer the caves on the Island. Parks Australia North manage the caves found within the National Park and the wildlife in all caves while Christmas Island Administration are responsible for all caves outside of the Park. At present there are no organised tours of Christmas Island caves although there are some diving tours into Thunderdome, Thundercliff and Lost Lake caves. The Grotto and Freshwater Cave are the most frequently visited by local people as swimming holes and social gathering destinations, particularly The Grotto.

The impact caused by human access into the caves is alarming and many features have been damaged and destroyed by vandalism. Pollution of the ecosystem is prevalent in many of the well visited caves (Freshwater, Daniel Roux and Runaway). Litter occurs in some of the caves frequented by residents and there is some deliberate dumping of construction rubbish. Damage to cave formations has occurred extensively in some caves due to poor caving skills and deliberate vandalism (Figure 3). Concerns over cave impacts resulted in all caves within the National Park and Crown lands being closed to the public in 1997 until a cave plan was prepared. This moratorium has continued beyond the original period of closure but is not enforced although access is discouraged.

The risk of injury or death to cave users is an issue that has been considered crucial to the Commonwealth and has been addressed by O'Toole and Grimes (1998) and risks are also discussed by Spate and Webb (1998). The consultants have recommended that most caves have signs placed at the entrances indicating the potential dangers and risks. Further, that some restrictions are placed on cave entry at some sites and that a permit system is put in place to restrict inexperienced cavers from entering some caves. Those authors also suggest that cavers should register their planned expeditions with local authorities as a safety net in case of emergency. O'Toole and Grimes (1998) and Spate and Webb (1998) both recommend caving codes for normal caving and sump diving to ensure some safety measures are being conveyed to users. The ongoing training of local cavers and the development of an on-island rescue capability was proposed.

One of the recommendations in both Spate and Webb (1998) and O'Toole and Grimes (1998) was that route marking should be done in some caves to limit human impacts and to avoid dangerous areas. This was undertaken in two caves by this author and Ranger Matt Hudson in 1998. Reflectors were used to mark a route throughout Runaway Cave including a new section not shown on the maps of Spate and Webb (1998). Routes were also marked in Upper Daniel Roux to deter cavers from walking across the rim-stone pools and other formations at the rear of the first cavern.

Future Management Concidirations

Spate and Webb (1998) state that the karst features specific to Christmas Island are of national significance. They note the distinctive morphology of the coastal caves such as Lost Lake Cave, the well developed "spongework" of Smiths Cave and others, and the speleothems now found below sea-level. Twenty-six species have been identified by Humphreys and Eberhard (this volume) as "significant or having unusual biogeographical, evolutionary or conservation attributes". Twelve endemic species are recorded. The richness of the troglomorphic species of the island is reported to be comparable to those of Mexico, Central America, South East Asia, Virginia and the central Pyrenees (Humphreys and Eberhard 1998, this volume). The caves continue to be threatened by human induced pressures and the Island needs a specific cave management plan which is separate to the Plan of Management for the Christmas Island National Park, that facilitates the implementation of the recommendations of the consultant reports. Such a plan will need to balance the needs of residents and the tourism industry as well as conservation objectives.

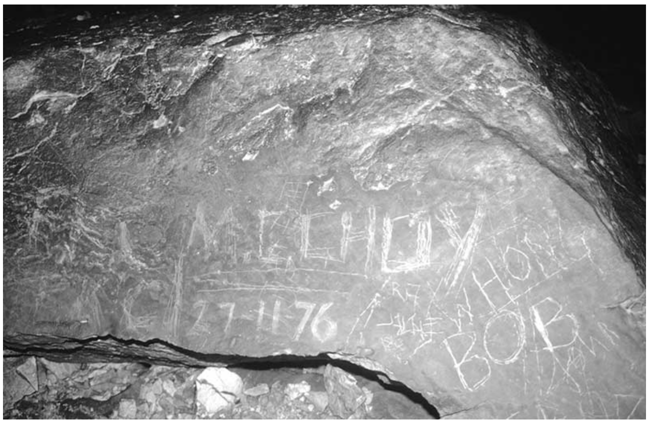

Figure 3: Vandalism by local residents in Runaway Cave.

The growing pressure to improve access for residents and visitors to the caves and the impacts caused by past cave use/abuse will need careful consideration. There are caves that could be developed to a limited extent to provide safe access; however development of show caves of the calibre seen on mainland Australia is not appropriate at this stage and the caves should remain "real caving experience" sites. Construction of major boardwalks and installation of lighting is also not recommended—the cost would be prohibitive and visitation is too low to warrant major development.

The local cave club should play a role in training residents and in assisting with management of the caves of Christmas Island. Cave conservation would also be improved by the appointment of a single governing agency to ensure appropriate and consistent measures are adopted for all caves. The continued use of the caves by residents and visitors should also be coordinated through the cave club to ensure people are aware of the caving code of conduct and to ensure safety measures are in place in the advent of an accident.

The Commonwealth's Cave Management Plan, which is currently being developed, will hopefully provide a strategy where cavers can continue to enjoy caving while also protecting the caves and the cave ecosystems from vandalism, development and pollution. Future monitoring and research in the caves needs to focus on comprehensive long term investigations to determine the species richness of subterranean fauna and the potential threats to these communities.

Acknowledgments

Thank you to Tony Faulkland for providing information on the caves in his study, and to Gerry Allen for identifying the fish specimen collected. Thanks to John Short for identifying the shrimp. I am indebted to Rauleigh Webb, Andy Spate, Bill Humphreys, Stephan Eberhard, Ken Grimes and Dan O'Toole for their professional input into the cave studies and for providing me with a good foundation for continued interest in speleology. Ken Grimes and Bill Humphreys provided valuable comments on this manuscript.

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Helictite (2001) **37(2):** 37-39

Searching for Water on Christmas Island

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Abstract

A hundred years of searching for underground water supplies for the settlement and mine operations on Christmas Island has involved digging wells, drilling, cave exploration and geophysics. Water has been extracted from wells, drill holes, springs and caves. The main production at present is from a set of cave streams on the plateau.

Introduction

Although it has a high rainfall, Christmas Island lacks permanent surface water. Nearly all rainfall goes quickly underground to join a karst drainage system. Thus the search for water supplies has been entirely for underground sources, and has included extensive cave exploration.

Early sources

Water for the 1891 Clunies Ross settlement on Christmas Island was first obtained from wells excavated at the base of the cliff behind Flying Fish Cove, and extracted by steam pumps at about 1000 litres/minute (l/m). Later the supply to the mining settlement at South Point was operating in 1916 from the Grants Well shaft and cave stream in the centre of the island. The Ross Hill Gardens springs were developed in the late 1920s as a dry season supplement to Grants Well.

As water requirements grew, water for the Settlement was initially pumped overland from the Waterfall springs via the Phosphate Hill workers quarters, and then a new pipeline laid around the shore terrace to the Settlement in 1934.

Concern by the Christmas Island Phosphate Company about large dry season flow variations in the main Grants Well source led to the first known scientific water investigations on the island, a program of ground electrical resistivity measurements, by M.S. Crosbie in 1941. Interim reports indicate that he believed that he had located subsurface water, but both Crosbie and his records disappeared in Singapore in 1941 during the Japanese occupation.

Post-war developments and cave exploration

After transfer of the mine to the British Phosphate Commissioners (BPC) in 1949, a Mr Dulfer was commissioned to carry out resistivity surveys at Grants Well, South Point and Phosphate Hill. Dulfer confirmed Crosbie's findings, and although it is believed that some drill testing for water was done, no confirmatory results have been located. Later test bores near Grants Well bottomed on basalt at 24 m, a depth closely matching Crosbie's and Dulfer's "water tables".

A power cable and electric pump were installed in Runaway Cave in the late 1950s or early 1960s, but pumping of the initially fresh water led to salt water contamination, and it was abandoned. The cable and switch board still remain.

From the mid 1950s to the early 1960s cave and sinkhole exploration continued, as described by Paul Meek elsewhere in this volume. In December 1962 resident speleologists David Powell, Ray Bishop and Les Smith located and named Jedda Cave to the southwest of Grants Well. This important new source gave a flow of 1700 l/m from an underground stream running on basalt at the base of the limestone. Jedda Cave, when developed and connected to the water distribution network, provided a reliable addition to the supplies for the increasing demands of a growing population. An additional flow came from nearby Jane-Up sinkhole. Several more were located in caves along the northern coastline, but these were technically too difficult or expensive to exploit.

A proposal for a phosphate washing plant convinced the BPC in 1966 to drill twenty seven test holes in the Central, South Point and Phosphate Hill areas, but only minor freshwater traces were found.

Australian Government exploration

In 1958 Christmas Island became an Australian Territory. Technical assistance was subsequently obtained from the Bureau of Mineral Resources, Geology and Geophysics (BMR) in Canberra, and under their guidance BPC staff carried out extensive ground magnetic and electrical resistivity profiling throughout 1967 and 1968. BMR geophysicists selected five drill sites at Drumsite, all of which proved to be dry. Of a further thirteen drill holes in the Central Area, two yielded minor water, but one, Water Bore 30, produced 3000 to 5000 l/m after development. However this technical success was short lived when, in late 1969 a new flow developed at the base of Jane-Up was confirmed as the same underground stream that supplied Water Bore 30. Pumping from one site was competing with the other. Regardless of source, this additional 1200 to 1500 l/m was an important factor in allowing establishment of the South Point phosphate washing plant.

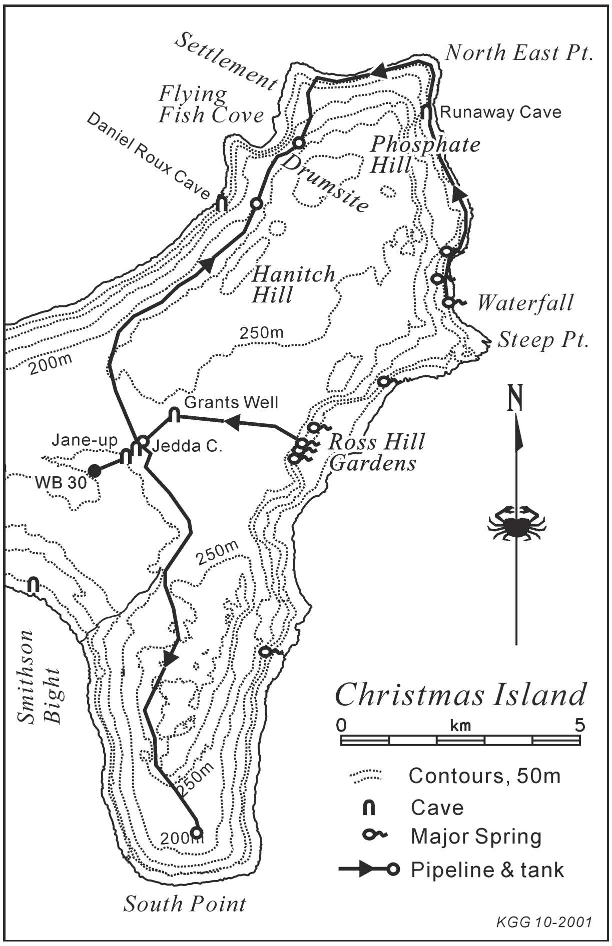

Figure 1: Water sources and pipelines

In the late 1960s, pumping from Ross Hill Gardens ceased, and the (mostly superannuated) pump station attendants were relocated.

Still with BMR guidance, a dry hole was drilled behind Ross Hill Gardens in late 1969, and a program of regular water flow and level measurements was carried out at all known sources until 1974, then intermittently until 1979.

More BMR magnetic and resistivity surveys in 1970/71 were the basis for targeting of seven holes above the Golf Course at Phosphate Hill in an unsuccessful attempt to trace the source of the Waterfall Springs. Further south, seven more holes then profiled the top of the subsurface basalt between Hanitch Hill and Ross Hill Gardens. Returning to the area of the “successful” Water Bore 30, thirteen holes encountered water, but although the field was systematically developed only 380 l/m was confirmed as a reliable wet season supplement.

A party from the BMR Engineering Geology Group led by Dr Ed Polak visited the island early in 1973 and conducted magnetic, resistivity, gravity and seismic surveys with more sensitive instruments in conjunction with the drilling of six stratigraphic calibration bores in the vicinity of Water Bore 30. This work, which provided information on the profile of the island’s volcanic core, the configuration of major volcanic dyke systems and the distribution of potentially water bearing caves and cavities in the cap limestone, was published as BMR Record 1976/100.

From 1973 to 1976 consistently high rainfall and a high groundwater availability from all sources precluded the need for exploration.

Dr. Polak’s group returned in 1976 to extend previous surveys, but apart from a stratigraphic bore at Ross Hill Gardens and an unsuccessful attempt to develop Water Bore 66 at Grants Well, the only other water program was the resumption of collection and pumping of water from Ross Hill gardens to Grants Well.

Attention then turned to the reliable but difficult to access 1500 l/m flow in Daniel Roux Cave below the Drumsite dryers complex where, after detailed engineering and feasibility work, the project was abandoned after a rock fall in the cave in 1978.

Later exploration

Plans by the Phosphate Mining Company of Christmas Island Ltd. (PMCI) to expand the phosphate washing plant led to an investigation and report from WLPU Consultants in 1982 recommending construction of a dam at Ross Hill Gardens to collect and store runoff from the springs there plus surplus flows from Grants Well – Jedda Cave, but this proposal did not proceed.

In 1985 P. Barrett, for PMCI, drilled seven small diameter water exploration holes on the lower terrace at Smithsons Bight, all of which intersected a fresh water lens above saline water and yielded between 110 and 170 l/m . Six similar holes drilled into basalt at Ross Hill Gardens found no significant flows.

By 1985 plans for the expanded phosphate washing plant were abandoned, and the existing plant closed


Figure 2: A captured spring at Ross Hill Gardens. (photo by K. Grimes)

down when mining ceased in 1989. Since resumption of mining in 1991, phosphate production has mainly been "B-grade" material for the Asian market.

The Present Situation

With the cessation of mining in 1989 the Commonwealth Government, through the local Administration, assumed responsibility for supply of water to the island community, and this activity is now the responsibility of local government.

Up to that time, the search for water on this limestone-capped seamount had continued for almost 100 years and utilized methods ranging from investigation and excavation of sinkholes and underground caves, through drilling and setting of bore casing up to 400mm diameter, to advanced geophysics.

However, in 1990 the Grants Well – Jedda cave system was still the mainstay of Christmas Island's water supply, but has been supplimented by the more recently-developed source at Daniel Roux Cave.

In the last decade, a network of piezometers has been installed to monitor groundwater levels and especially water quality given the potential for human contamination of the underground systems.

The conclusions from this lengthy and expensive program are that there are no significant perched water tables or confined aquifers on Christmas island, only seasonally charged underground streams flowing in limestone cave systems on or above a basalt floor, together with a fresh water density separation lens within the limestone at favourable locations at or near sea level around the margins of the island.

The proposed Christmas Island spaceport, if it proceeds, will need large quantities of water for each launch, and the 200 or so additional staff will also require domestic supplies.

Somehow, I doubt that the search for water on the island is over yet!

Karst Features of Christmas Island (Indian Ocean)

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Abstract

Christmas Island (in the Indian Ocean) is an uplifted, composite, reef-carbonate island with a volcanic core. The coast is mostly cliffed and rises steeply via a series of terraces to a central phosphate-blanketed plateau. In spite of the high rainfall, there is little surface water as drainage is underground and karstic. Water is initially stored in an epikarst aquifer, then follows the limestone/volcanic contact out to the island edge to emerge at major conduit springs. These springs are mostly at or below sea level, but some perched springs occur where the volcanic rocks appear at the surface. Caves occur at the present coast, as uplifted coastal caves, on the plateau, and there are a few pseudokarst caves. Cave development involves mixing zones between fresh and sea water in the coastal zone, and between vadose and phreatic waters perched on the volcanic rocks beneath the plateau. Cave locations and forms are controlled by the rock structure (especially jointing), the location of the volcanic contact, and the combination of uplift with present and past sea levels — which controls the location of the mixing zone.

Keywords: island karst, caves, tropical karst, Indian Ocean.

Introduction

Christmas Island is an isolated limestone-capped volcanic island in the eastern Indian Ocean, located about 350 km southwest of Java. It would be classed as an “Uplifted, Composite, Reef Carbonate Island” in the sense of Vacher (1997) or a “Carbonate Cover Island” verging on a “Composite Island” in the terminology of Mylroie & others (2001). The present island is the tip of a submerged seamount that rises 4.5 km from the ocean floor. The mainly-basaltic volcanic rocks that make up the core of the island are capped by a sequence of Tertiary limestones with some interbedded volcanics. These in turn are buried in part by a surface cover of phosphate-rich soils. The base of the phosphate cover is a pinnacled karst surface with strong local relief. There are many caves in the limestones. Most of the island’s drainage is underground and emerges in submarine springs, or at the coast from a series of springs and “sea caves” that extend back into extensive karst caves.

In March–April 1998 six speleologists studied the karst, its biology and its management for Parks Australia North. The results were presented as three unpublished reports (Coffey, 1998; Humphreys & Eberhard, 1998; Spate & Webb, 1998). This paper describes the geological setting, and the caves and karst features of the island. A subsequent paper is planned to discuss the concepts of cave genesis in more detail; however, some preliminary ideas on speleogenesis are presented here. Given the limited time and the management orientation of our field work, and a broken ankle half way through!, the data are restricted and I have supplemented them from a number of unpublished company reports and cave expedition reports. A paper on the karst biology of the island appears elsewhere in this issue (Humphreys & Eberhard, this volume). Meek (this volume) discusses the history of cave exploration and the management of the karst and Barrett (this volume) summarises the exploration for water. Some aspects of management are also discussed by Webb (1999).

The Island Environment

At latitude 10°30'S, the island has a tropical monsoonal climate, with the heat and humidity moderated by SE trade winds. WLPU Consultants (1982) reported average rainfalls ranging from 1905 mm to 2423 mm on different parts of the island. December to April are the wettest months, and August to October the driest. The rainfall is extremely variable: a minimum annual total of 899 mm was recorded in 1965 and a maximum of 3716 mm in 1978. The temperature is uniform throughout the year, with a maximum of 27 °C and a minimum of 22 °C. The relative humidity averages 87% with little variation throughout the year. Winds are from the southeast during the dry season, but from the northwest during the summer wet season—which is a time of strong swells. The island has a spring-tide range of about 1.8 m, which is at the high end of the microtidal range. Apart from clearings associated with the settlement and mining operations, the island is covered in rain forest. There is little agriculture.

Previous studies

The existing geological reports have a strong bias towards either the phosphate deposits or the offshore sea-floor geology, with less information on the limestone and little on the caves. Borissova (1994) summarises the offshore work and provides a map of the bathymetric contours of the seamont. The main onshore geological reports are by Trueman (1965), Rivereau (1965), Barrie (1967), and Barrett (1989). Woodroffe (1988) discussed the uplift history of the island. Bourrouilh-le Jan

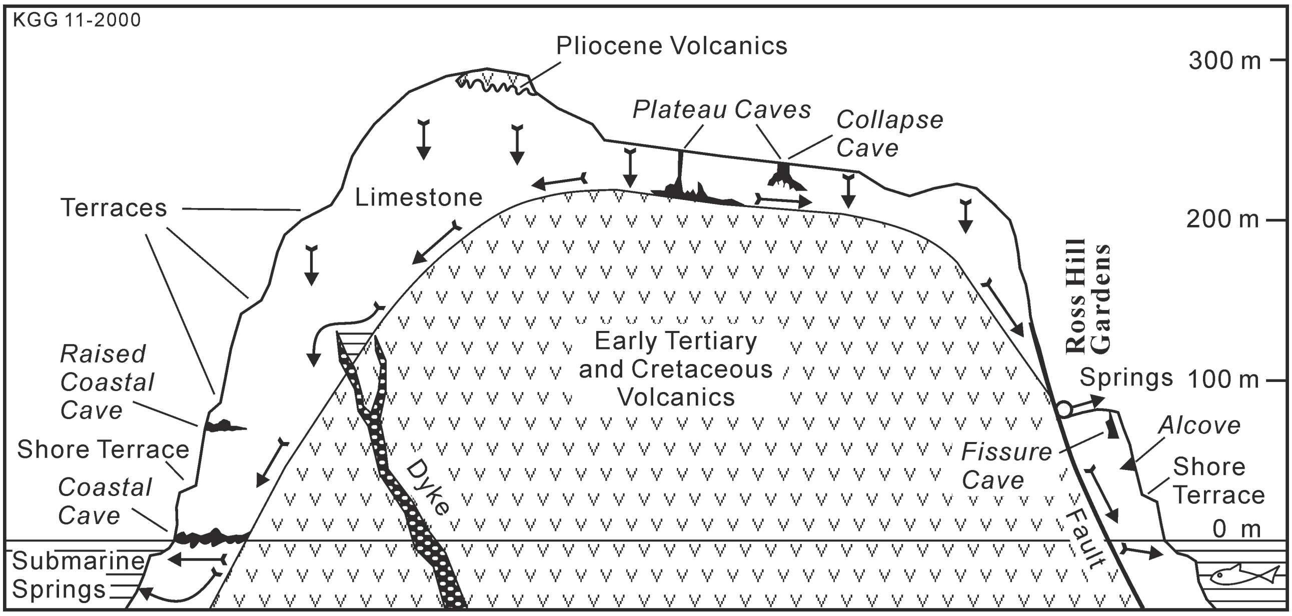

Figure 1: Diagrammatic cross-section of Christmas Island, showing volcanic core, limestone capping, water flow lines (arrows) and typical cave development. Vertical scale is exaggerated x10.

(1992) includes the island in her review of the high carbonate islands of the Pacific Ocean. Two geophysical surveys were carried out in the 1970s to assist in locating groundwater supplies (Polak, 1976, and Pettifer & Polak, 1979) and these provide some information on the karst drainage. The mining company, *Christmas Island Phosphates Ltd.,* holds a number of unpublished reports on the caves, springs and water-supply.

There is little published information about the karst and caves of the island. During the 1960s local speleologists, including David Powell, Roy Bishop and Les Smith, explored and mapped many of the caves as part of a search for water supplies for the settlement and mine (Meek, this volume; Barrett, this volume). A Western Australian Speleological Expedition to Christmas Island (SEXI) in August 1987 visited and mapped most of the known caves, but little was published (Brooks, 1990). R. Webb updated the earlier cave maps with additional information from the present study and presented them as an appendix to Spate & Webb (1998).

Geology

The island is the exposed cap of a seamount sitting on the Wharton Basin of the Indian Plate, which is moving northwards at 70-80 mm/year towards the Java Trench, into which it will sink in about 4 million years time (Borissova, 1994). The island is also rising at about 140 mm per thousand years (Woodroffe, 1988). The seamount is one of a number of old volcanoes formed in the late Cretaceous (starting about 80 Ma), but it had renewed volcanism and uplift in the Tertiary, and has been affected by the fluctuating sea levels of the Quaternary.

The submerged core of the island is composed of late Cretaceous to early Tertiary intermediate to basic volcanic rocks (basalts, andesites and trachybasalts) that resulted from normal intra-plate volcanism. This core is overlain by an interbedded sequence of limestones, volcanic rocks, and minor dolomites, with phosphate deposits forming a thick blanket over a deeply dissected epikarst surface. The stratigraphic sequence is shown in Table 1.

Table 1: Geological units

Late Quaternary (124 ka)	"Shore Terrace" limestones, and reworked phosphates.
Quaternary	Phosphate deposits (soils, talus and cemented material) and minor marine and beach deposits (limestones and phosphates) on the higher terraces.
Pliocene (3–5 Ma)	Localised volcanic rocks (mainly dykes and minor vents and tuffs).
Miocene – Pliocene?	Paleokarst deposits.
Late Oligocene to mid Miocene	"Upper Carbonate Series": the main limestone sequence.
Eocene (35–40 Ma)	Volcanic rocks (interbedded with limestones).
Eocene	"Lower Carbonate Series": limited outcrops of limestone.
Late Cretaceous – early Tertiary	The main, mostly submerged, basaltic volcanic structure.

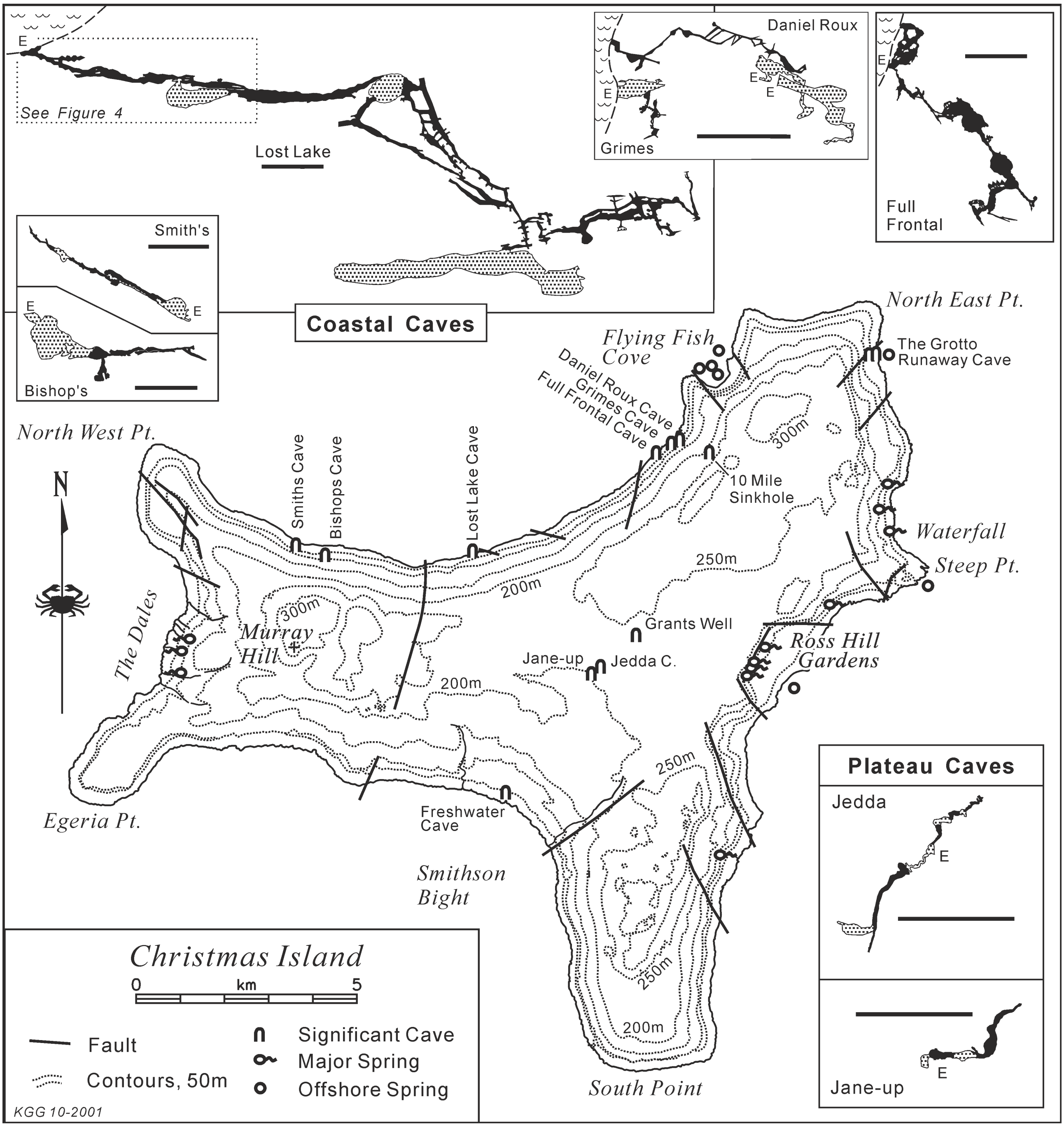

Figure 2: Location map and karst features of Christmas Island. For the cave maps: the scale bar in each map is 100 m; black is solution passage; collapse areas are shaded; "E" marks an entrance.

Numeric dating of the volcanic rocks is based on Borissova (1994) who cites an “in prep.” paper by Falloon & others that indicates firstly a reactivation of volcanism in the Eocene (35–40 Ma), when lavas similar to those formed in the Late Cretaceous were produced; and secondly a more recent, Pliocene, volcanic phase (3–5 Ma).

The main volcanic sequence (Cretaceous to early Tertiary)

The basal rocks of the island include andesite, basalt, trachybasalt, and volcanic glass, with a thin, irregular cover of pyroclastics at the top of the sequence. Younger Eocene basalts and tuffs are interbedded with the oldest limestones.

The main (mid Tertiary) carbonate series

The limestones tend to be relatively thin (20–30 m) in the centre of the island, but thicken towards the coast above the steep-dipping volcanic surface where they reach up to 250 m in thickness (Figure 1; Pettifer & Polak, 1979). Stratigraphically, there is a “Lower Carbonate Series” of Eocene age, which is seen only in one small area, and the main “Upper Carbonate Series” of late Oligocene to mid Miocene age.

The main limestone sequence also includes some dolomites. The limestones are dominantly micritic calcarenites (detrital sandy limestones with a matrix of lime mud). In Dunham's (1962) classification they would be wackstones and packstones. They are mostly hard, massive to thick-bedded rocks, with very little matrix porosity apart from joints. Dolomitisation and diagenetic alteration are more common on the plateau, beneath the phosphate cover (Kaulback, Appendix I in Barrie, 1967). Sporadic large corals (up to 0.7 m across) occur but fossils are generally fragmented and not readily recognisable. Kaulback reported occasional thin shelly or foraminiferal beds that have greater matrix porosity, but these were not seen in any of the caves inspected.

Pliocene volcanic rocks

Barrett (1989, and citing Baxter & Weeks (1984)), described a final phase of volcanic activity that accompanied faulting of the "Upper Carbonate Series" and resulted in the formation of minor volcanic vents and emplacement of dykes along slip-fault planes or fractures in the Murray Hill area. Borissova (1994) cites Falloon & others "in prep" as giving a Pliocene age (3-5 Ma) to this stage of volcanism. Some of these volcanic rocks are tuffs and other subaerial deposits that fill earlier (late Miocene?) karst depressions in the limestone (Barrett, 1989). This suggests that the island was at least partly emergent in the early Pliocene.

Paleokarst material

Locally, the limestones show an earlier generation of karstic solutional porosity. In some cases the solutional vugs have been partly lined or wholly refilled with sparry calcite. Brecciated zones and pockets were seen in several caves: Lost Lake (CI-7), Smiths (CI-9), Freshwater (CI-10) and Whip (CI-54). The breccias comprise angular clasts (from <1cm up to 0.5m blocks) of hard fine-grained limestone either in a similar hard fine-grained matrix, or else cemented by sparry calcite with a vuggy porosity remaining where the gaps between the clasts are incompletely filled. The breccias tend to occupy irregular areas rather than linear zones, so are probably paleokarst fills rather than fault breccias (see later discussion of paleokarst ages). Matching clasts were observed in CI-10, indicating minimum movement of the material. In CI-10 one area of breccia was capped by horizontally bedded material, then an irregular contact with a solid limestone roof, which suggests an old cave fill. This particular breccia matrix contained rounded sand grains that must have been introduced from the surface—possibly from a coastal (beach or dune) situation. The hard indurated character of the matrix and the occurrence of breccias in the ceilings of large collapse domes suggests a significant age; they are not part of the present cave systems and could date back to the low sea stands of the Pliocene and early Pleistocene, or even as far as the late Miocene period of low seas following deposition of the limestones (Figure 7).

Less common (found only in Lost Lake, CI-7), was a breccia of hard angular limestone clasts in a friable brown sandy mud. In CI-7 this was found in the rubble of each of the big collapse chambers of the entrance series and seemed to be derived from open(?) joints in the ceiling. This might be a more recent breccia, filling joints that have been enlarged by downward percolating waters.

Barrie (1967, p20) described both soft and consolidated oolitic and fragmentary phosphate material filling fractures and cavities in the limestones. Some of these show bedding (his figure 17) and contain fossil shells of "modern" land snails. The material appears to be reworked phosphate soil, cemented by phosphatic and calcareous material. As the cemented material is now exposed at the present surface it could be regarded as paleokarst material. Barrett (1989) also reported "vadose-zone fissures infilled with banded phosphorites and detrital rock phosphate and limestone fragments in a phosphatic or calcareous matrix".

The Phosphates

The phosphate deposits occur mainly on the plateau (primarily as unconsolidated "soil" material), but also are found as wedge-shaped relict beach deposits on the terraces, as fissure fills in a variety of settings and as enrichment of weathered volcanic rock. They are described in detail in Barrie (1967) and Barrett (1989). The material generally overlies an epikarst surface with a strong pinnacled relief. Average soil depths are commonly less than three metres, but locally range up to 80 m where fault or fissure infilling has occurred. The age is mainly Quaternary, but some deposits could date back to the late Pliocene.

The late Quaternary "Shore Terrace"

Quaternary limestones occur on the lowest terrace, known as the Shore Terrace. Most of the terrace is composed of bedded marine calcarenites, phosphatic pellet and pebble conglomerates and talus deposits derived from the inland cliffs (Woodroffe, 1988). Corals are common and occur in growth positions. The limestone is hard, and distinguished from the older limestones mainly by the more abundant fossil content. Some areas show a coarse vuggy porosity resulting from the moldic solution of fossil corals, others have only minor porosity and even less permeability. Woodroffe (1988) and Veeh (1985) refer to four U-series dates on corals from the Shore Terrace, giving a mean age of 124 ka BP, i.e. last interglacial age (oxygen isotope stage 5e).

Other Quaternary deposits

The main Quaternary marine sequence is that of the Shore Terrace (see above), but higher terraces are reported to have scattered outcrops of beach and marine deposits (Truman, 1965) and more may be hidden beneath the scree deposits. Barrett (1989) interprets

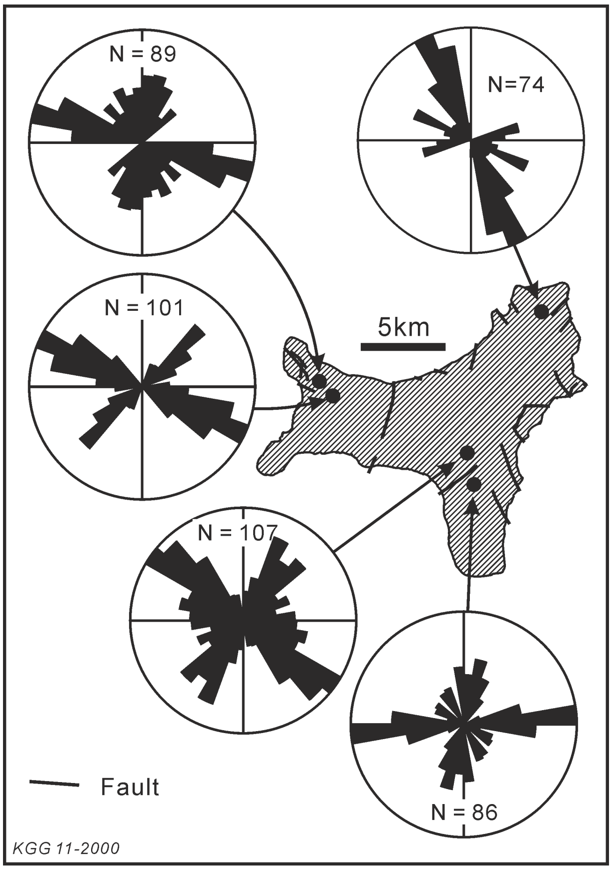

Figure 3: Rose diagrams showing trends of surface structures exposed in mined areas.

much of the phosphate material on the higher terraces as beach deposits. Scree deposits are common on many of the lower terraces, as is reworked phosphatic material (an oolitic or "pebble" phosphorite) derived from the plateau or higher terraces.

Structure

The limestones are typically hard and massive. Where bedding is visible it is generally flat-lying and thick, but in several places, particularly about the terraces, both depositional and slump-fault dips are reported (Barrie, 1967).

Polak (1976, p7) deduced from geophysical evidence a central volcanic caldera and three major rifts dividing the island into four blocks. These are hidden beneath the limestone capping. Barrett (1989), Barrie (1967) and Rivereau (1965) all mapped faults and lineaments, but there are significant differences between their maps (photo-interpretation and ground mapping are not easy on an island covered in rain forest!). Some of the faults divide the terraces into "piano-key" steps—the most obvious example is in the Ross Hill Gardens area (Figure 2).

Joints are the main structural influence on cave development directions and roof stability. Faults, bedding planes, porous beds, and volcanic dykes are less common but can provide local influences. The observed joints in the caves are typically vertical or steeply dipping, and spaced between 0.5 and 2 m. In a few places local sets of inclined joints may have influenced roof form (e.g. Freshwater Cave, CI-10, and one area in Lost Lake Cave, CI-7). In many cave chambers joints are not obvious, and any roof breakdown is via a mesh of irregular cracks; but in others, such as Lost Lake Cave, the joints have had a strong influence on the development of the big collapse chambers (see cross section in Figure 4). Tension joints can occur behind and parallel to major cliff faces, and subsequent mass movement of the outer blocks may form fissure caves (e.g. Runaway Cave, CI-2).

A detailed structural study of the island was not attempted. However, structural trends (joints?) in the exposed epikarst in several mined areas were analysed from air-photos on the assumption that if they affected the epikarst they would also have affected the caves at depth. Figure 3 shows these trends plotted as rose diagrams. There is significant variation in the directions of the surface structures over the island and even in local areas (compare the two rose diagrams from the southeast of the island which are from sites only 2 km apart). This probably explains the lack of obvious correlation with the mapped caves, which are all some distance from the surface sites.

The geophysical studies by Polak (1976) and Pettifer & Polak (1979) showed up a number of trends interpreted as possible faults and buried dykes; which might control karst cavern development and water flow directions. In the area of their detailed studies on the central plateau the dominant trend was to the north-east.

Pettifer & Polak (1979) estimated the thickness of the limestone on the plateau from resistivity probes (but the results were not clear-cut), and mapped the surface of the volcanics from a combination of resistivity and drill data. Over the central plateau the limestone is generally less than 30 m thick and basalt has been reported from the floors of two of the caves there. Towards the edge of the island the limestone is more than 250 m thick, and continues below sea level (Figure 1). The slope of the buried basalt surface at the island margins appears to be between 1 in 5 and 1 in 10.

General Geomorphology

The island is the top-most part of a seamount that rises 4500 m above the ocean floor. The exposed part of the island reaches a maximum of 361 m ASL. The outline of the major headlands and embayments of the island appears to be not the result of modern coastal erosion, nor of major landslides into deep water (as suggested by some early authors), but reflects the underwater topography of the submerged three-armed volcanic structure (Polak, 1976, see above). The coast is mostly cliffed and rises to a central plateau via a series of terraces and steep to gentle scarps. The central plateau is

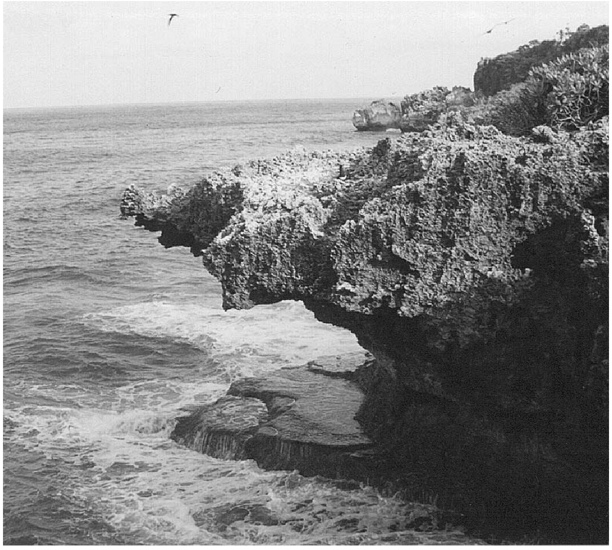

Photo 1: Sea cliff with undercut notch.

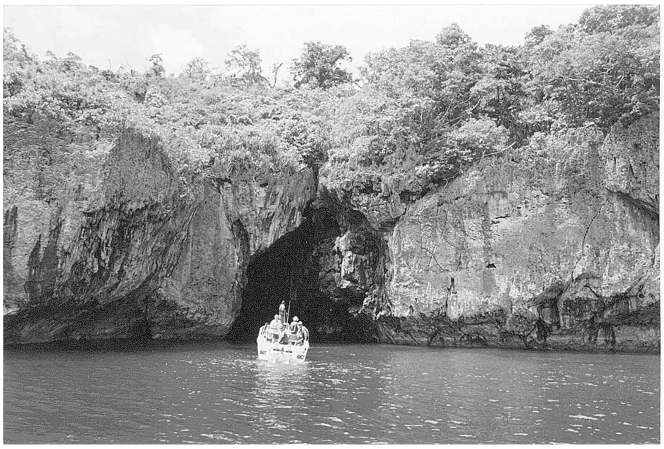

Photo 2: Coastal cliff and large sea entrance to Grimes Cave, CI-53.

slightly saucer shaped, with a southerly tilt, and has a general elevation of 180-240 m (Figure 2).

The sea cliff

The sea cliffs rise 3–40 m to the edge of the first terrace. The cliffs are nearly vertical and have a well-developed basal notch with many fissures and sea caves (Photos 1 & 2). Beaches are rare; being small pocket beaches of gravel or sand and are commonly backed by the sea cliff. Some sea caves are connected to extensive, partly-flooded, karst cave systems that run back beneath the Shore Terrace. The sea cliffs have been dissolved into a sharp and delicate fretwork of phytokarst (Photo 3).

The terraces

The terraces are a prominent feature of the island: with at least four on the north coast, two on the south coast and three on the upper plateau (Rivereau, 1965; Woodroffe, 1988). The terraces result from a combination of Quaternary uplift of the island and sea-level changes. They appear to be mainly erosional in origin, but there is local evidence for constructional features (raised phosphatic beach deposits and younger "reef" limestones on the Shore Terrace).

The lowest terrace, known as the *Shore Terrace*, extends right around the island, with the exception of a break at Flying Fish Cove. It is from 50 to 200 m wide and generally lies at an elevation between 10 and 30 m. Although partly erosional in origin it also has thick reef and other deposits of last interglacial age (124 ka). Woodroffe (1988) deduced an average rate of uplift of about 140 mm/ka since the last interglacial from the present elevation of the terrace and other evidence (Figure 8). The inner parts are covered by soil and talus from the inland cliff, but the outer margin consists of a band of jagged limestone pinnacles (phytokarst) and is cut by channels and fissures. In The Dales several streams have incised narrow ravines into the terrace (Photo 4). There are some spectacular blow-holes. The inland cliff, behind the Shore Terrace, has old wave-cut notches and caves in places.

The higher terraces are less well-defined. They are separated by small cliffs or slopes of rubble and soil. As with the Shore Terrace, the outer margins commonly have limestone pinnacles.

The plateau

The plateau is formed on limestone and phosphate "soil". The Pliocene volcanics are restricted to only a few small outcrops of weathered rock (e.g. Murray Hill). The surface of the plateau comprises shallow valleys

Photo 3: Coastal phytokarst is sharp and fragile.

and low hills, with ridges of limestone. There are also areas with karst depressions: collapse and subsidence dolines, and larger hollows (uvalas). The central plateau is somewhat depressed, and slopes away to the south-west. Several writers have suggested that the shape is that of an old coral atoll with lagoon, uplifted and tilted to the south-southwest. However, Bourrouilh-Le Jan (1989) argues that central hollows of this type may result from karstic solution.

Drainage

The island has a typical karst drainage system that is almost entirely underground, surface runoff being confined to the monsoon season (December–March) and to short spring-fed streams about the margin of the island. The underground drainage is discussed later.

Karst And Caves

Surface Karst

Surface karst features include:

- *Subsidence and collapse dolines* on the plateau surface, and on some terraces,
- *The Dales,* narrow ravines cut into the Shore Terrace.
- *Springs*, mostly near the island margins,
- *Tufa deposits* associated with springs and waterfalls,
- *Karren* (including phytokarst) on coastal and inland cliffs and outcrops,
- *Pinnacles* that developed at the soil-limestone contact but have been exposed by soil erosion or mining,
- *Coastal Notches* cut at the base of the sea cliff (see above).

Dolines: On the plateau surface medium-sized closed depressions appear to be fairly common—though difficult to see or map under the rainforest cover. Both collapse and soil-subsidence dolines occur, and some hollows might be solutional dolines. Some larger hollows form composite features, i.e. uvalas. Collapse dolines result from the collapse of the roof of a cave and some collapse dolines contain open entrances to caves (e.g. the combined collapse and subsidence doline that contains Jedda Cave, CI-5, which is 20 m across and about 8 m deep to the start of the cave). Collapse dolines also occur on the terraces and some connect to the coastal caves (e.g. the doline of Freshwater Cave, CI-10, Figure 6).

The Dales: These are narrow ravines cut into the Shore Terrace in the western part of the Island (Photo 4). The streams are spring-fed and rise at a volcanic outcrop only a short distance inland. They initially run in normal valleys, but become deep fissures close to the coast. Brooks (1990) suggested that The Dales might be karst gorges resulting from collapse of cave passages.

Photo 4: One of The Dales. Incised into the Shore Terrace. (Photo by R.Webb)

However, no relict cave features were seen, and the narrow, deep, cliffed sections may merely be the result of incision of surface streams into the terraces, following uplift (R. Webb, pers comm).

The springs are either from coastal caves or further inland from point sources or wide seepages, usually at the top of an impermeable bed of volcanic rock. Submarine springs have been reported down to depths of 200 m in Flying Fish Cove (Pettifer & Polak, 1979), and Barrett (1985) also reported underwater springs offshore from The Grotto, Steep Point and Ross Hill Gardens (see Figure 2). Many of the coastal caves have strong outflows of fresh water. See the section on karst drainage for more on the spring flows.

Tufa deposits are associated with the springs and waterfalls. Low tufa mounds are associated with some of the springs, and the rubble and soil below the springs have been cemented by tufa. In The Dales area, the waterfalls below the springs have large vertical tufa deposits.

Karren (and coastal phytokarst). Most of the exposed limestone surfaces on the island show intense rain pitting that produces 1-3 cm hollows separated by sharp edges. In the coastal areas, sea spray coupled with organic activity produces a particularly delicate and very sharp fretted phytokarst surface (Photo 3). Spate & Webb (1998, p. 9) noted features on the wave-cut platforms that they referred to as "paddy-field karren".

The pinnacles are widespread, and are strictly a type of subsoil karren. The pinnacle and pit surface, which is widespread beneath the phosphate soils, appears to be an epikarstic surface formed by solution at the soil-limestone contact. Where the pinnacles now occur at the surface, this is due to subsequent erosion of the soil or mining of the phosphate. Where freshly exposed, the pinnacles have smooth or vertically fluted surfaces, but with time they develop an irregular sharp pitted karren surface. Some pinnacles exposed in the mine areas were "floaters" that were not attached to the bedrock (Barrie, 1967). In recently mined areas the tops of the pinnacles have been removed or damaged beyond recognition and these areas are now dominated by fields of deep conical pits lying between polygonal ridges.

The Caves

Most of the caves are developed in the indurated Tertiary limestones; however a few are developed partly or wholly in the Quaternary Shore Terrace limestone, which is also hard, but has a vuggy porosity. Individual caves are summarised in Table 1.

Several types of cave are recognised:

- *Plateau caves:* small collapse chambers or horizontal stream passages,
- *Coastal caves:* horizontal partly-flooded systems running back from the sea,
- *Raised coastal caves* and *Alcoves:* older, uplifted, horizontal caves and alcoves found under the terraces or in old sea cliffs.
- *Sea caves:* small caves formed by wave action, as against solution.
- *Fissure caves:* vertical fissures parallel to a cliff face and formed by mass movement,
- *Collapse caves:* modifications of any of the above types,
- *A basalt cave:* Ten Mile Sinkhole (CI-14) appears to have been a pseudokarst system developed in basalt.

Photo 5: Stream passage with mud banks in a plateau cave (CI-5).

The Plateau Caves are of two types: (a) several small caves consist of simple vertical shafts or small mud-floored or rubble-filled chambers associated with collapse dolines (CI-12, 13, 28, 52) and (b) a larger, hydraulically connected, set of three stream caves: the Grants Well, Jedda, Jane-up group (CI-11, 5, 6). Of the simple caves, CI-52 is of interest in that it has ten solution-pipe entrances, all of which open into the roof of its single large collapse chamber (SEXI, 1987). The three stream caves have a vaguely meandering form that has been modified by collapse (see insets to Figure 2). Grants Well has a vertical shaft entrance, and several blind shafts in its roof. The other two caves have entrances in collapse dolines. In the case of Jane-up the entrance in the side of the doline leads to a high-level chamber that then drops to the main stream level. The plateau caves flood regularly and the walls and roof are very muddy, with the stream flowing between large mud-banks (Photo 5). In many places the speleothems on the roof of the stream passages are coated with mud with the exception of a short clean tip. Soft mud "stalagmites" with central drip holes have built up beneath these muddy stalactites at one place in Jedda Cave.

Foul air (CO_2) was encountered in the plateau stream caves during the study and may be due to the decay of organic material in the mud. Humphreys & Eberhard (1998 & this volume) measured values of 3% CO_2 and corresponding reductions of oxygen to 17%. The foul air has not been reported previously and may be a seasonal (wet season) phenomenon—this needs to be tested by regular sampling over the space of a year.

The Coastal Caves are horizontal, partly-flooded systems developed at or near present sea level. They are entered directly from the sea or from collapse dolines on the shore terrace (or higher) that lead down through collapse chambers and rubble slopes to the sea-level passages (e.g. CI-3, 8 & 9). Several of these caves can only be entered by swimming from a boat (e.g. CI-7, 20). Others have entrances that are completely submerged and only accessible to divers (e.g. CI-91). Most of the recorded caves with sea entrances are on the north and west coasts of the island. These coasts are sheltered from the prevailing SE swell that makes exploration difficult along the southern and eastern coastlines.

The part-flooded sections of the coastal caves are typically joint-controlled passages with strongly-developed coarse spongework sculpturing of the walls (Photo 6, Figure 4). Some passages are vertical fissures that extend to at least 18 m below sea level (Anon, 1971, p6). The maximum recorded depth is in CI-87 which is a totally submerged cave that has its entrance at a depth of -30m, and terminates at a depth of -50m (S. Eberhard, pers. comm.). Submerged (and partly resorbed) speleothems were seen down to at least 6 m depth in several caves (S. Eberhard & A.P. Spate, pers. comm., Photo 8). The water is tidal and varies from fresh to very salty (see later, page 54).

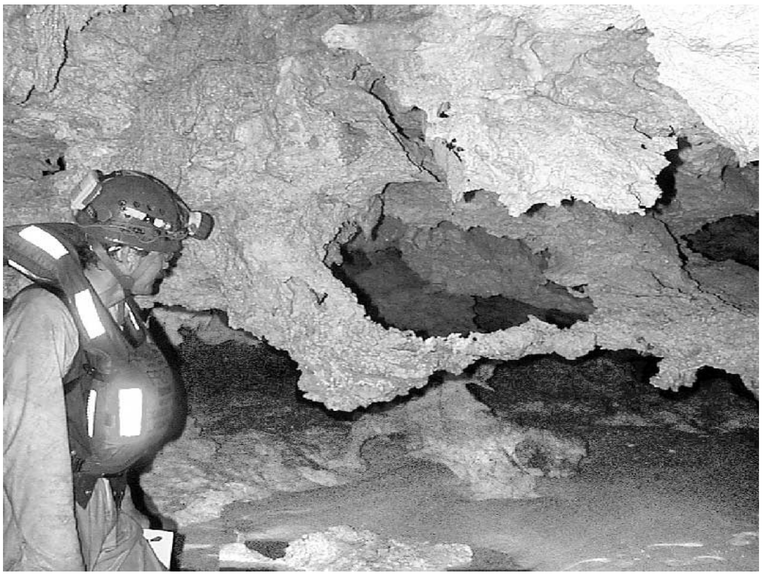

Photo 6: Spongework in a coastal cave (CI-20). A mixing corrosion effect. (Photo by R. Webb)

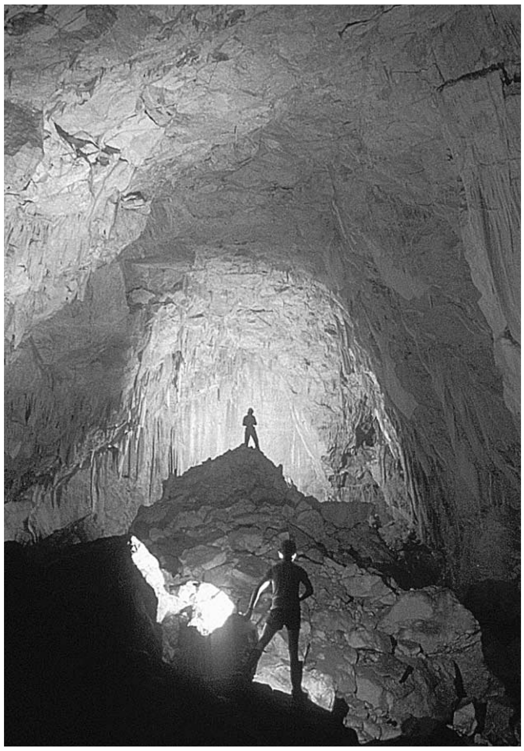

Photo 7: Large collapse chamber (CI-8). Note domed roof and rubble piles on floor. (Photo by R. Webb)

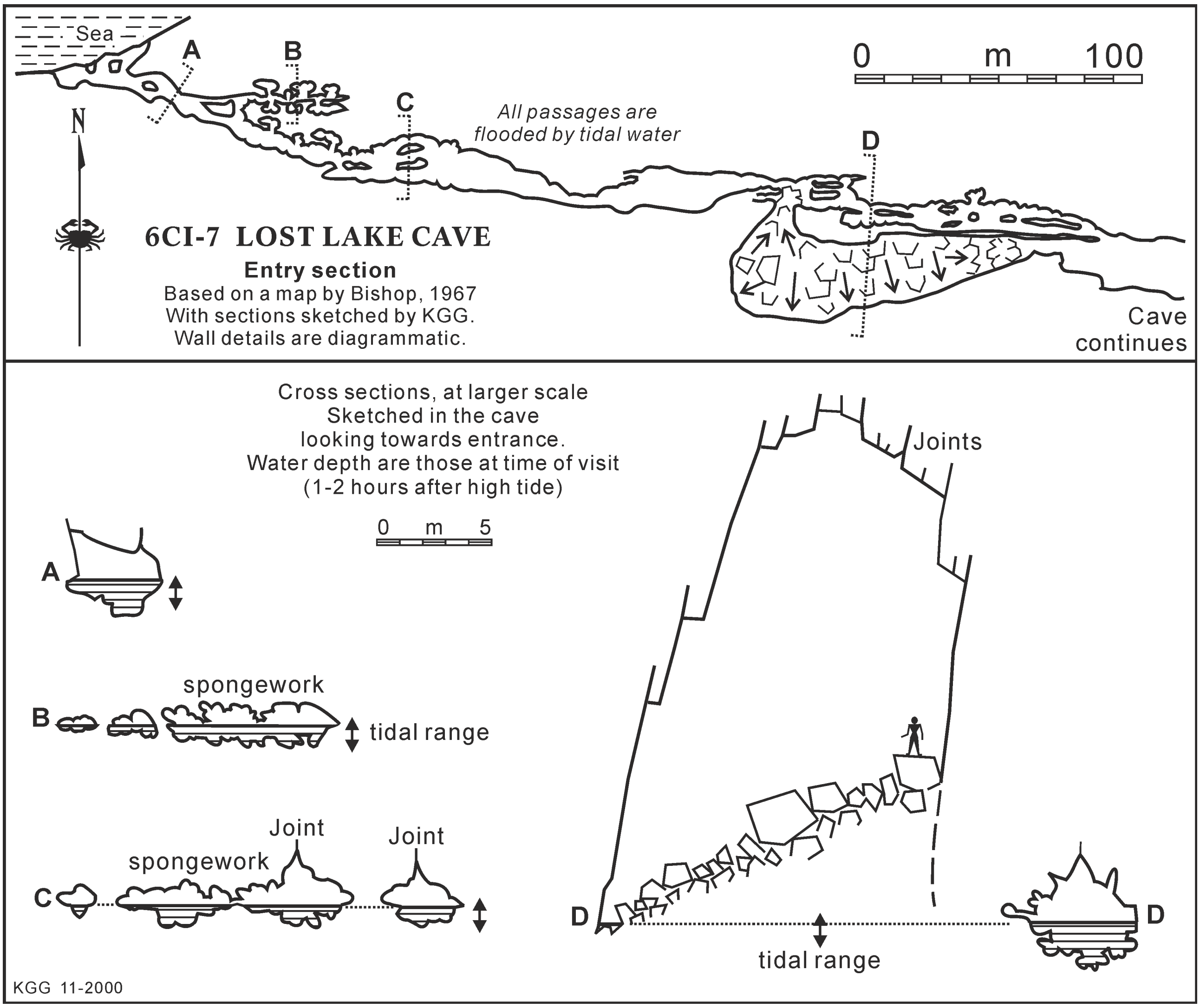

Figure 4: Map & cross-sections of part of a typical coastal cave (Entrance part of CI-7). Showing joint-controlled passages with phreatic spongework walls, and large collapse chambers. For full map see inset in Figure 2.

Table 2: Geologically Significant Caves on Christmas Island

Cave Number	Cave Name	Cave Type	Comments
6CI-1	The Grotto	Coastal	20m L chamber, plus submerged connection to the sea, and a reported connection to CI-54.
6CI-2	Runaway Cave	Fissure	120m L. Brackish water.
6CI-3	Lower Daniel Roux C	Coastal	560m L. Joint-controlled passages at sea-level and a collapsed inclined fissure connecting to surface.
6CI-5	Jedda Cave	Plateau	240m L, 22m D. Meandering stream passage with some collapse areas.
6CI-6	Jane-up Cave	Plateau	130m L. Meandering stream passage and collapse areas.
6CI-7	Lost Lake Cave	Coastal	3500m L. Major system of joint-controlled passages, spongework expansions, and large collapse domes.
6CI-8	Bishops Cave	Coastal	400m L. Large collapse dome and lower solutional passage.
6CI-9	Smiths Cave	Coastal	330m L. A single straight passage and collapse.
6CI-10	Freshwater Cave	Coastal + Collapse	About 700m L (rough estimate). Interconnected collapse chambers, some remains of original spongework.
6CI-11	Grants Well	Plateau	30m L, 26m D, Small stream passage with blind shafts above.
6CI-14	10 Mile Sinkhole	Pseudokarst ? in basalt	?m L, 56m D, Entrance filled in. See Appendix 1.
6CI-16	Strangler Cave	Coastal + Collapse	350m L.
6CI-19	The 19th Hole	Coastal + Collapse	>100m L, Collapse chambers. Saline water.
6CI-20	Full Frontal Cave	Coastal	>1560m L. Joint controlled passages with spongework expansions. Fresh water over salt.
6CI-31	Indian Cave	Alcove (Raised coastal)	Horizontal line of daylight chambers in cliff.
6CI-35 to 49	Alcoves along Smithson Bight	Alcove (Raised coastal)	All less than 40m L, in cliff.
6CI-50	Managers Alcove	? Fissure	50m L, Location uncertain.
6CI-52	10 entrances	Plateau	36m L, Lost. Single collapse chamber.
6CI-53	Grimes Cave	Coastal + Raised coastal	170m L, Large collapse entrance chamber. +4m level passages are “raised” coastal.
6CI-54	Whip Cave	Coastal + Collapse	100m L. Collapse chamber. Possible connection to CI-1
6CI-56	Upper Daniel Roux C	Raised coastal	160m L, 54m ASL in cliff. Large horizontal passage.
6CI-68	Wobble Cave	Alcove (Raised coastal)	
6CI-70	Boat Cave	Sea cave + Collapse	80m L. Single chamber.
6CI-87	Egeria Point Cave 1	Submerged Coastal	Entrance at -30m depth, Max depth -50m.
6CI-88	Egeria Point Cave 2	Submerged Coastal	Shallow entrance, possibly extensive.
6CI-90	Thunder Cliff Cave	Coastal	>100 m L.
6CI-91	Thunder Dome	Submerged Coastal	>50m L, about -14m depth.
6CI-92	Councillor Cave	Sea Cave	50m L.
6CI-93	Coconut Point Cave	Submerged Coastal	Shallow entrance, possibly extensive.

NOTES.
Cave Numbers follow the convention of the Australian Speleological Federation in which entrances are numbered rather than the cave (so some caves can have several numbered entrances).
L = total cave passage length,   D = depth.
Descriptions of CI-87 to CI-93 are based on information provided by S. Eberhard.

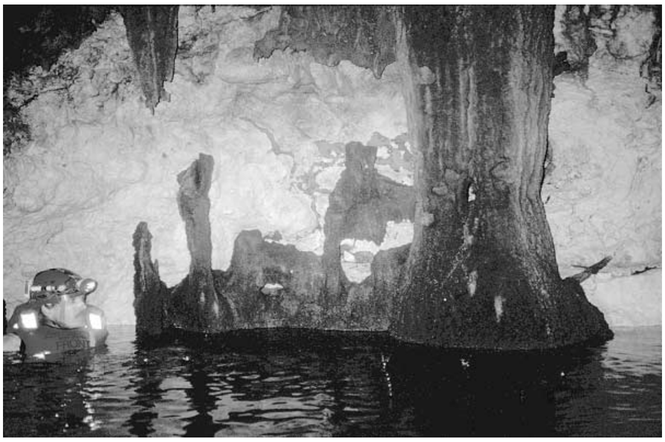

Photo 8: Brown, partly re-dissolved speleothems in Lost Lake Cave (CI-7) continue at least 6 m below sea level. (Photo A.P. Spate)

The larger chambers and higher sections of these caves are the result of roof collapse and development of collapse chambers. Some of these collapse chambers are quite large (Photo 7, Figure 4) e.g. a long collapse passage in Lost Lake Cave (CI-7), is 514 m long, 30 m wide and has a roof height from 5 to 20 m. Some of these collapse chambers have massive speleothem development—parts of which are cracked and rotated, indicating continuing solution and settlement of the rubble floor (Photo 11).

Raised Coastal Caves would have formed in a similar way to the present coastal caves, but at earlier stands of sea level, and have been uplifted out of the present zone of active solution. Thus they are no longer forming, apart from collapse modification and speleothem formation. Only a few examples are known, of which Upper Daniel Roux (CI-56) is the only sizable one. It has an elevation of 54 m ASL (Anon, 1971) and the entrance is half way up the cliff behind the Shore Terrace. This cave comprises a large horizontal passage with rubble floor and abundant dry speleothems. At the back it narrows down to several smaller, but also well-decorated chambers. Beneath the Shore Terrace, in the same area, the high-level passages of Grimes Cave (CI-53) are about 4 m ASL.

The Alcoves in the cliff behind the Shore Terrace on the east side of Smithson Bight may also be of this type. We did not visit them, but Brooks (1990, and notes in SEXI, 1987) reported a number of large entrances there that led only to short caves—the longest is 40 m. These have large inverted-V cross-sections (fault or joint controlled?) up to 20 m high. The entrances are reported to be generally about 10 m up from the base of the cliff, which would put them at about 50–60 m ASL. These caves contained old dry speleothems. Indian Cave (CI-31) is a horizontal line of shallow alcoves visible in the cliff above the Shore Terrace on the road to Waterfall (Photo 9). The nearby Wobble Cave (CI-68) is similar.

Sea Caves have formed in coastal cliffs by wave erosion. Most are small daylight chambers, but they may extend far enough to have a dark zone if following a line of weakness. On Christmas Island, where the coastal rocks are limestone, the dividing line between a sea cave and a karstic coastal cave can be difficult to draw. Thus the entrance chambers of many of the long coastal caves may have been partly formed or enlarged by wave action. "Pure" sea caves on the island could include Boat Cave (CI-70) and The Tunnel (CI-73); the former has been modified by collapse at the back, the latter appears to have developed by wave erosion along a pair of joints that run through a small headland.

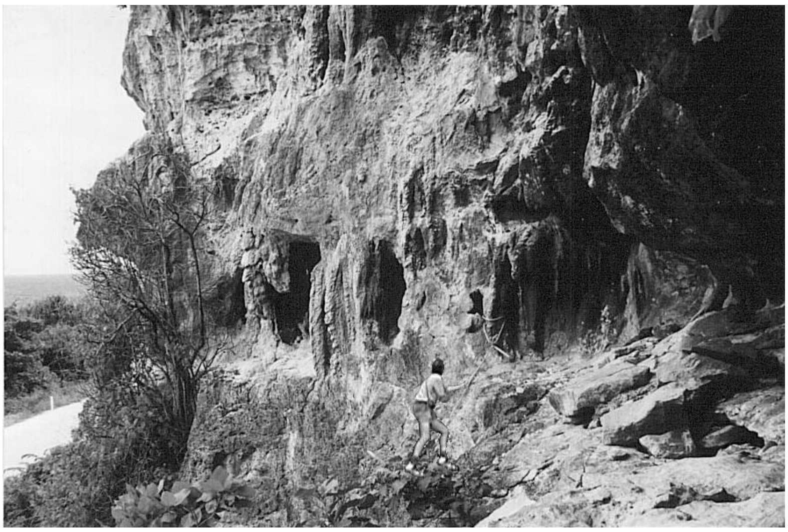

Photo 9: Indian Cave (CI-31). A line of alcoves in an old sea cliff, about 8 m above the Shore Terrace (in background).

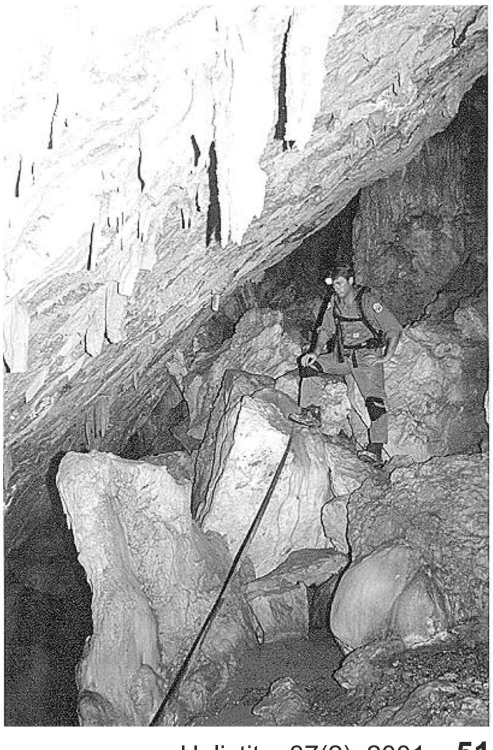

Photo 10: A fissure cave (Runaway Cave, CI-2). Note smooth planar hanging wall and rubble floor of foot-wall; and the power cable that runs to an abandoned water pump.

Photo 11: Rotated and subsiding speleothems in a large collapse dome. Mixing corrosion at sea level is undermining the base of the material. (photo by R. Webb)

Fissure Caves include Runaway Cave (CI-2) and possibly Managers Alcove (CI-50), though the latter was not located. Fissure caves form by the development of tension cracks behind and parallel to a cliff face, followed by outward mass movement of large slabs or blocks to open up a fissure. However solution would have played some part in their origin, so they are only partly pseudokarst. Most such fissures remain open to the sky, but if the outer block tilts back it can maintain a closed roof, or rubble falling from above can jam to form chockstones that roof the fissure. Runaway Cave is a single 100 m long fissure, 5 to 10 m wide, and from 4 to 15 m high (Figure 5). It runs behind the base of, and more-or-less parallel to, a high south-west trending cliff face; which in turn may be fault controlled. The outer, southeast, wall is generally a smooth sloping, overhung surface; the inner wall is less regular. The roof is composed of large jammed chockstones. The cave contains numerous large angular boulders and blocks up to 5 m across (Photo 10). Some of the rubble has a thin coating of grey sparry calcite and is cemented together; other parts are loose and unstable.

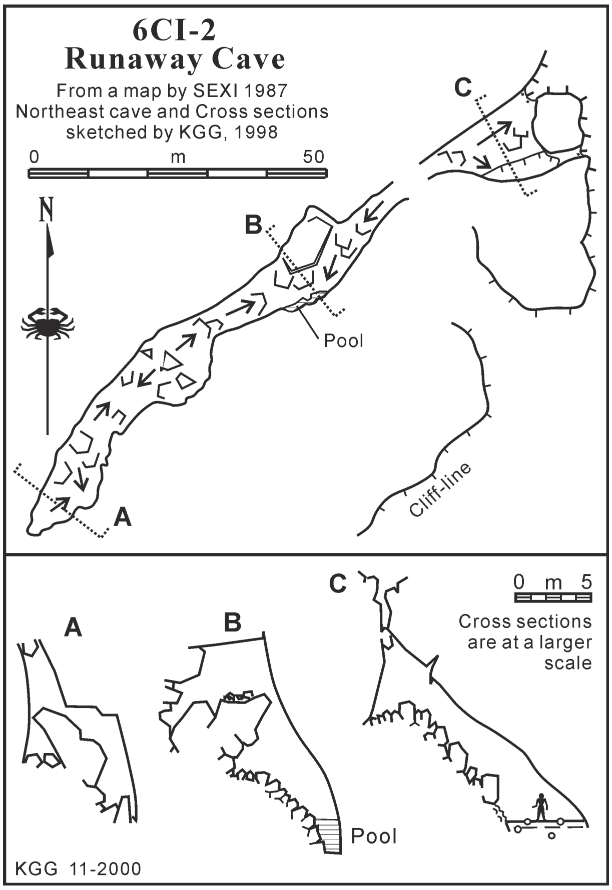

Figure 5: Map and sections of a typical fissure cave.

CI-50 was not entered (the entrance is in a vertical cliff and access requires a rope descent from above, and there is some confusion as to its location) so its interpretation is based on an inspection of the SEXI (1987) cave map. The map shows a short entrance passage running into the cliff that joins a passage running parallel to the cliff and a cross section shows that this has a high fissure form. A proper inspection would be needed to confirm my interpretation of this as being a mass-movement fissure cave.

Collapse caves are a modification of all the other types (Figure 6). Within any cave, collapse chambers can alternate with sections showing the original cave form; but some caves are now entirely collapse in character with nothing of the original form remaining (e.g. Nineteenth Hole, CI-19). In many cases the collapse has reached the surface to form entrance dolines. In some cases the collapse is old and the rubble has stabilised or is cemented by later calcite deposits (Photo 12). In others the process is still active and there is a real, but low, risk of spontaneous roof-fall at any time.

Local collapse areas or chambers occur in most caves. Caves that are dominated by collapse include: CI-2, CI-10, CI-19, CI-54, CI-55.

Basalt Cave: An unusual cave developed in basalt was once accessible from 10 Mile Sinkhole (CI-14), but the entrance has now been filled in and it is inaccessible. It was possibly formed by underground stream erosion of a joint or fault. The only description is in two memos to the mining company by D.A. Powell (circa 1967) and Anon (1971) which are reproduced in Appendix 1. The entrance was a solution hole passing through the limestone, but below that the walls were all of basalt, with upper sections showing tuff with interbedded volcanics. Powell reported that the cave was a linear system and 56 m deep. The direction seemed to be controlled by a fault or joint.

Karst Drainage

Early cave exploration was motivated by the need for water for the settlement and for the mine operations

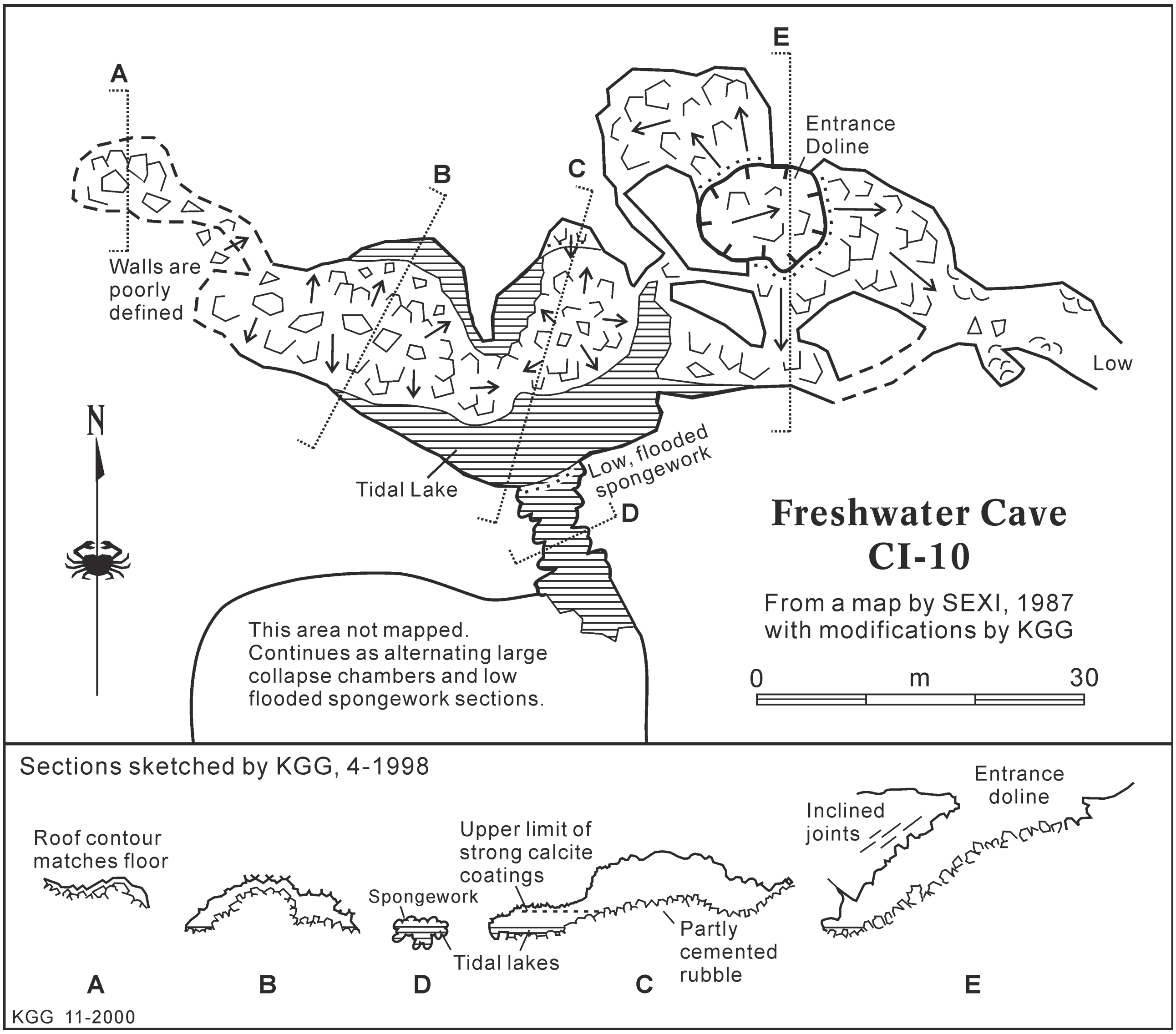

Figure 6: Map and sections of a typical collapse-dominated cave (northern part of CI-10).

(Barrett, this volume), as was an extensive program of geophysics and drilling on the plateau (Polak, 1976; Pettifer & Pollak, 1979 and Barrett, 1985). The latter program had little success and most of the present supply is pumped from conduit streams within the plateau caves (Grants Well – Jane-up system) and from springs at Waterfall and Ross Hill Gardens.

Pettifer & Polak (1979) calculated a water balance for the island, assuming a 70% loss of rainfall to evapotranspiration, which suggested that only about 5% of the rainfall is accounted for by the measured discharges from known sources; the remainder must be accounted for by coastal and offshore springs from the limestone or the limestone/volcanic contact and by infiltration into the volcanics. Four water analyses are listed in Polak (1976). Typically the waters have Total Dissolved Solids of 195–280 mg/l. The analysis from Grants Well was (in mg/l):

TDS 195 mg/l, Ca 64, Mg 2, Na 9, K <1,
HCO_3 212, SO_4 4, Cl 12, NO_3 <1, pH 8.0.

Plateau waters

Pettifer & Polak (1979) reported that the water table under the plateau is just above the limestone/basalt contact and fluctuates seasonally. However, Barrett (1985) concluded that significant water storage occurs in the epikarstic phosphate and soil zone above the limestone, and that the water moves down from there through fractures and solution holes in the limestone to the volcanic contact. From there it moves in conduits along the volcanic contact. Drilling has indicated that there is little water obtainable from the matrix porosity away from these isolated conduits. Barrett (1985) reported that the drainage channels intersected above the volcanics were narrow, fast flowing and were draining downslope without appreciable backing-up. The Grants Well – Jane-up system is the only significant conduit identified to date. A water tracing exercise, using salt, indicated a through-flow time of three hours from Grants Well to Jane-up, a distance of 1.3 km, i.e. 400 m/h (Anon, 1971).

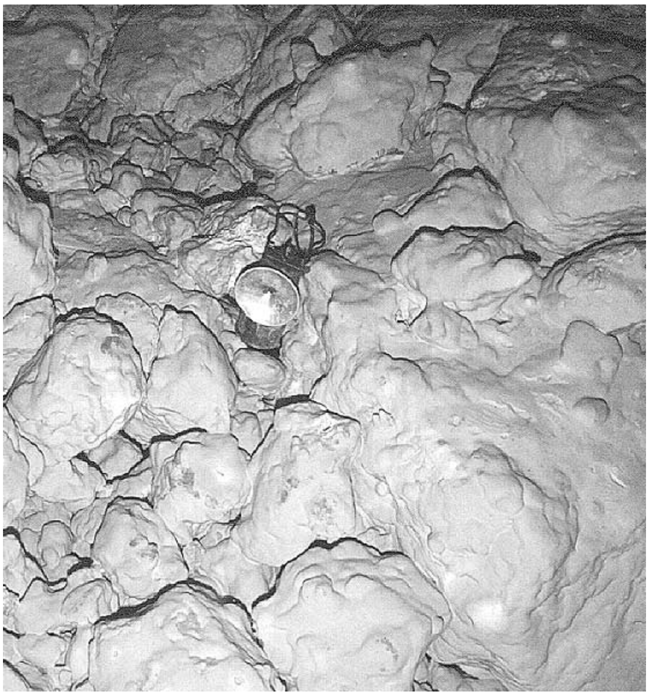

Photo 12: A rubble mound in the intertidal zone of CI-10 that is cemented and coated by calcite deposits.

From the plateau the water then flows outward and downward to the sea through karst conduits along the volcanic contact. This is evident from the common occurrence of springs or seepages where the contact of limestone and basalt is at or very near the ground surface.

Coastal waters

At the edge of the island the water table is at or just above sea level. In some caves the fresh water is floating as a lens above sea water, in others the two appear to have mixed to form a brackish water. In one cave (CI-20) we detected a metre or so of cool fresh to brackish water overlying warmer, but denser, salty water that had entered from the sea. In Lower Daniel Roux Cave (CI-3) fresh water enters as a spout from the roof, 'Watsons Gusher', at the inland end and flows out toward the sea. The inflow rate ranges from 15 to 30 l/s (Barrett, 1985). Only in the final chamber of this cave (which has an open underwater connection to the sea) was salt water encountered. A constriction in the passage inland from this appeared to be inhibiting mixing, though there is tidal influence on the levels throughout the cave. In Freshwater Cave (CI-10) the water was fresh, but still tidally influenced. The water in this cave differs from most others in that it is actively depositing calcite on the rubble piles in the intertidal zone (Photo 12), which suggests that it is saturated and has escaped mixing with sea water. This is unusual, as in most caves the main water body is obviously aggressive. However, Powell (c.1967) reported that on one occasion the water in CI-10 was brackish so some mixing must occur at times. In other caves (CI-2, 8, 9, 16 & 19) the water is brackish to quite salty both at the surface and deeper. See table 1 in Humphreys & Eberhard (1998), who measured electrical conductivities that were up to 34 mS/cm, nearly 70% that of sea water (50 mS/cm).

In the Smithson Bight area water-bore drilling located a freshwater lens, 4 m thick and at or slightly above mean sea level (Barrett, 1985 & pers. comm.). The thickness of this lens, compared to the thin or absent lenses in the caves, suggests that it is in matrix or fissure porosity, rather than conduits, so that the hydrological conductivity is lower and tidal mixing excluded to allow a thick fresh water lens to form.

Flow behaviour

Barrett (1985) analysed monthly flow rates in cave streams and springs over a six year period (1968–1973) and related these to rainfall. The cave stream in the Grants Well – Jane-up system on the plateau showed marked seasonal variations (0–120 l/s) and yearly average base-flows varied from 19 to 85 l/s. There was a lag in peak flow behind rainfall that averaged three months, but varied from one month (following a wet 'dry' season) to five months (following a long dry season). Thus the lag time was determined by the amount of water in storage in the epikarst aquifer at the start of the wet season, with conduit flow only increasing after the surface aquifer was recharged.

The springs at Ross Hill Gardens, at about 120 m ASL, had a behaviour intermediate between the plateau streams (at 200 m ASL) and the coastal springs (see below). Apart from Hudsons No 2 Spring, which appeared to be a conduit-fed overflow spring with intermittent large flows of short duration (0–130 l/s); the remainder were moderately steady with a seasonal range between 5–13 l/s. Their peak flow lagged two months behind the rainfall.

The coastal springs were monitored in two places, both 20 m ASL at the back of the Shore Terrace. These springs were relatively steady at 15–20 l/s at Waterfall and 6 l/s at The Dales.

Exposure of The Island

Karst development requires that the island be at least partly exposed above the sea, as does evolution of the island's indigenous flora and fauna (Humphreys & Eberhard, this volume). To determine the duration of exposure one approach is to compare uplift rates to past sea levels (Figure 7), but it is dangerous to extrapolate recent uplift rates too far back in time. However, Woodroffe (1988, p29) suggests that the uplift of Christmas Island could be related to a topographic bulge in the subducting plate as it approaches the Java Trough. In that model one might expect a fairly uniform and non-episodic uplift rate for the last 2 Ma at least. If one takes Woodroffe's (1988) estimates of the uplift of the Shore Terrace over the last 124 ka and extrapolates

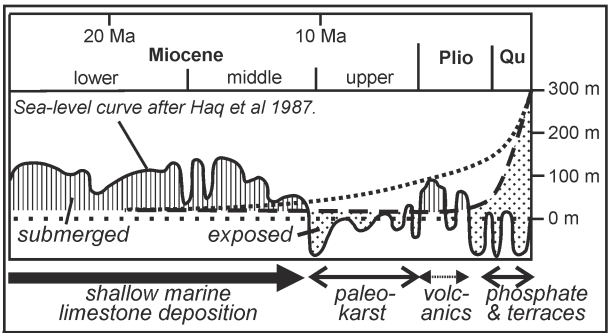

Figure 7: Past sea levels and uplift scenarios. Possible periods of exposure of the island can be estimated by comparing uplift rates to the global sea-level curve. Dotted and dashed lines are two versions of the elevation of Murray Hill through time. In the dashed version, uplift is concentrated in the last 2 Ma and the island may have been submerged for part of the Pliocene. In the dotted version, uplift is spread over a longer period, and the island may have been continually exposed for the last 10 Ma.

back through the Quaternary one finds that the highest point on the Island (Murray Hill, at 360 m) could have emerged between two and three million years ago and the upper part of the island would have been dry land since that time (dashed line in Figure 7).

Further back in time, the Pliocene volcanic rocks, dated at between 3 and 5 Ma, appear to have been subaerial (Barrett, 1989), which indicates that the highest part of the island was above the sea at that time also, and it is possible that parts of it may have remained above the high sea levels of the later Pliocene.

Even further back, at the end of the Mid Miocene (about 10 Ma) deposition of the main limestones ceased when global sea level dropped, and the limestone would have emerged for several million years and been subjected to karst solution. In the absence of reliable information on the vertical movements of the island during the late Tertiary it is difficult to say whether any of this exposed limestone would have remained above the high sea levels of the Pliocene, so we cannot be sure of the continuity of areas of dry land as far back as then. However, the lack of extensive Pliocene or Pleistocene limestone deposits suggests there was not extensive submergence of the island—or at least not for long periods of time.

Paleokarst

Karstic processes would have commenced acting on the limestones when their deposition ceased and they were exposed by the drop in global sea levels in the late Miocene. These low seas continued for several million years, and one would expect extensive cave and karst development to have occurred at that time, probably syngenetic with diagenetic induration of the limestones. The pockets of indurated breccias exposed in the walls of several of the present caves may be paleokarst cavity fills dating back to this Miocene period. Traces of the Miocene karst surface are preserved beneath the Pliocene volcanic deposits, which Barrett (1989) described as occupying “deep fissures and doline or sinkhole structures”.

Cave Genesis

Plateau Caves

The plateau caves appear to have formed in the “classical way” from water seeping vertically downward from the epikarst zone, and mixing with a perched water table just above the volcanic contact. Main cave development was at the contact. Collapse has modified the original solutional passages.

In detail: rain water would have accumulated initially in the epikarst zone of soft permeable soil cover, and much of its solution potential was expended in dissolving the upper surface of the limestone to form the pinnacled relief. The nearly saturated water then descended vertically (as vadose seepage) via isolated cracks, fissures and solution pipes which were enlarged only slowly. With time some of these formed vertical shafts, such as those seen in Grants Well (CI-11). The horizontal passages formed where downward seeping vadose water encountered the phreatic zone of the watertable perched on the volcanic surface. Mixing corrosion at this interface resulted in enhanced cavity development. In some cases isolated chambers formed, and were widened until their roof became unstable and started to collapse (e.g. CI-12, 13 & 52). Elsewhere, linear stream caves developed along concentrated flow lines (e.g. the Grants Well – Jane-up system; CI-11, 5 & 6). The direction of these stream passages was guided partly by the rock structure (joints and faults within the limestone, together with volcanic dykes) and possibly by the shape of the relatively impermeable volcanic surface.

Coastal caves

The development of the coastal caves will be discussed further in a future paper; a summary of my present ideas follows. As with the plateau caves, initial cavity development at depth was controlled by mixing corrosion. This occurred both at the contact between vertically descending vadose seepage water and the phreatic fresh-water lens and also at the contact between the fresh water and the underlying salt water—near the coast these two levels are very close together. The process is analogous with that in the development of flank margin caves in the Bahamas and caves at the volcanic interface at Bermuda (Mylroie & others, 1995; Mylroie & Carew, 2000; Mylroie & others, 2001). But it differs in that in the “soft-rock” eogenetic limestones of the Bahamas and Bermuda, the inter-granular matrix porosity produced a continuous groundwater body and lens so that cave development comprised interconnected irregular chambers; whereas on Christmas Island the hard, compact, limestones have a low matrix porosity and permeability and so the influence of joints and faults was much more important as inception planes in localising and directing initial cavern development. Once enlargement of a joint reached a critical size it would gain a competitive advantage over neighbouring joints and develop at their expense. These initial passages would have been narrow vertical fissures with relatively low hydrological conductivity and consequently a thick fresh-water lens. Where the enlarging passages made hydrological contact with the ocean, sea water could enter easily and tidal flushing and mixing effects would enhance the solution rate. The initial fissure passage would be widened rapidly by active spongework development and this widened zone would work back into the cave. The increased hydrological conductivity would result in a much thinner fresh-water lens and so the mixing effect would be concentrated on a narrow zone at the prevailing sea level. In some cases mixing has destroyed the freshwater lens entirely and we find only a brackish water zone. The expanded spongework zone would trigger instability and collapse chamber development.

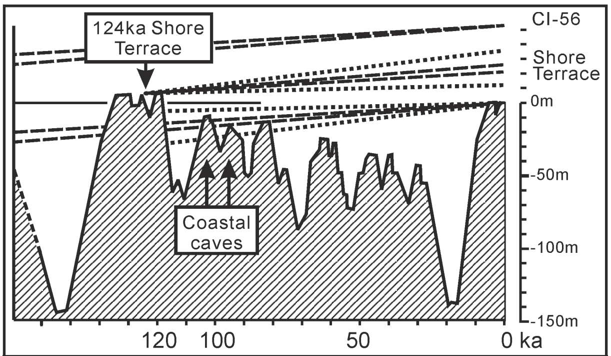

Figure 8: Deducing time of coastal cave formation from the interaction of uplift rates and past sea levels. The uplift rates (with error range dotted) are first deduced from the present elevations of the Shore Terrace, which formed 124 ka ago. That rate is then used to extrapolate back from the present elevation of the coastal and raised-coastal caves to intersect a past sea level—at which time they are deduced to have formed.

The timing of formation of the coastal caves can be deduced by comparing uplift rates to sea-level changes. The initial solution that produced the fissures and the submerged speleothems has intersected the limestones of the 124 ka Shore Terrace, so must be younger than that. The presence of submerged speleothems points to a period of draining of the passages when sea levels were lower during the last glacial period. If one takes Woodroffe's (1988) most likely uplift rates and compare them to sea level curves one finds that caves that formed at three high stands between 80 and 104 ka ago would have been brought up to present sea level after uplift, with the 101–104 ka high stand (isotope stage 5c) being the most likely (Figure 8). Since the rise of the post-glacial sea to reoccupy the fissures, mixing corrosion has been widening the passages at current sea level and developing the strong spongework morphology.

Uplifted Coastal Caves.

Upper Daniel Roux Cave (CI-56) lies at an elevation of 54 m ASL (Anon, 1971), and if we use Woodroffe's (1988) uplift rates (Figure 8) that could correspond to the high sea stand of an earlier interglacial about 330,000 years ago (isotope stage 9). The high-level passages of Grimes Cave (CI-53) are about 4 m ASL, but if we attempt to extrapolate this back to the old sea levels we find that, given the likely errors in both the uplift rates and the sea level curves, we cannot reliably distinguish this level from that of the modern sea level caves.

Collapse Chambers.

Collapse starts when a roof or wall becomes unstable: either because the rock is inherently weak as a consequence of its structure or composition, or where the walls have been undercut by solution or the roof span widened beyond a stable limit. Once collapse starts the cave may stope its way upwards towards the surface; rocks falling from the roof accumulate on the floor so both floor and roof rise with time (see cross-sections in Figure 6). Solution by water at the base of the rubble pile assists this process by undermining and lowering the rubble piles, and is responsible for the large collapse chambers (Figure 4, Photo 7). Continuing undermining and instability of the rubble piles is demonstrated by large cracked and rotated speleothems in some chambers (Photo 11). Eventually the upward migrating cavity may reach the surface and form a collapse doline.

Fissure Caves

Fissure Caves form by the development of tension cracks behind and parallel to a cliff face, followed by outward mass movement of large slabs or blocks to open up a fissure. Most such fissures remain open to the sky, but if the outer block tilts back it might maintain a closed roof, or rubble falling from above can jam to form chockstones that roof the fissure.

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Appendix 1: Descriptions of 10 Mile Sinkhole (CI-14).

This interesting pseudokarst cave is no longer accessible. Its location is shown on Figure 2.
The following are extracts from the two reports that give detailed descriptions.

Powell, D.A., no date (circa 1967): *Groundwater: Known Sources, Christmas Island.* Unpublished memo to E.Brennan, Geologist, Development Dept. Held in records of Christmas Island Phosphates. 5pp. See p2-3.

"10 Mile Sinkhole

Although this system is entered by a solution hole passing through limestone, the actual stream and its direction is controlled by the fault along which it flows. Measured in November 1960 by M.Parker and myself, it was estimated that some 8,000 g.p.h. [13 l/s] were going over the 'V' notch. Whether this was the complete flow would be hard to say, the cave floor is not of solid material and when the stream was blocked water could still be heard falling and passing below. The system was traced vertically down for 187' [55 m] until the water passed between a rock fall, appears to be a series of caverns and waterfalls lying along a fault. Walls of all caverns were basalt, upper sections showed tuff with interbedded volcanics, roof in one place was tuff, in the first cavern a collapse from the roof was limestone. In August 1965 the bottom of the solution hole had become choked by surface soil, this was dug out and access to the first cavern regained, water measured beginning of September and a flow of 770 g.p.h. [0.97 l/s] recorded, measured the following month and recorded as 600 g.p.h. [0.76 l/s]."

Anon, 1971: *Water Search - Christmas Island.* Unpublished report held in records of Christmas Island Phosphates. 9pp. See p6.

"10 Mile Sink Hole

The underground cave system is about 100' [30 m] below surface R.L. of approx 650' [195 m] and is encountered by a narrow sink hole, at the bottom of which surfaceous material is observed to overlie basalt. In this instance, the cave elongation is believed to be controlled by a fault in basalt, trending about 175°, and it is interesting to note the record that the system was traced down to a level 187' [55 m] below the surface R.L., and comprises a series of apparently well developed caverns in basalt, with a stream running throughout. The occurrence is of particular interest in that it shows clearly that water erosion of basalt along a fault has carved caverns and channels through that medium, and it should be compared against other locations, such as Jedda, where water erosion has penetrated at most five feet into the basalt, or Waterfall and Ross Hill Gardens, where water emerges at the contact, and has not eroded a channel into the basalt."

Helictite, (2001) **37(2):** 59-74.

Subterranean Fauna of Christmas Island, Indian Ocean

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Abstract

The subterranean environment of Christmas Island is diverse and includes freshwater, marine, anchialine, and terrestrial habitats. The cave fauna comprises swiftlets, and a diverse assemblage of invertebrates, both terrestrial and aquatic, which includes a number of rare and endemic species of high conservation significance. At least twelve species are probably restricted to subterranean habitats and are endemic to Christmas Island. Previously poorly known, the cave fauna of Christmas Island is a significant component of the island's biodiversity, and a significant cave fauna province in an international context. The cave fauna and habitats are sensitive to disturbance from a number of threatening processes, including pollution, deforestation, mining, feral species and human visitors.

Keywords: Island karst, biospeleology, stygofauna, troglobites, anchialine, scorpion, Procarididae

INTRODUCTION

As recently as 1995 Christmas Island (Indian Ocean) was considered to have no specialized subterranean fauna (Gray, 1995: 68), despite biological collections having been made since 1887 (especially Andrews et al., 1900). However, in 1996 a specimen of blind scorpion was recovered, collected by a speleologist in 1987. Subsequently in April 1998 we spent three weeks on Christmas Island, on behalf of Parks Australia North, to determine the affinities and significance of any subterranean fauna and the ensuing management implications. We sampled terrestrial, freshwater, and near-coastal salt water (anchialine) subterranean habitats which were accessed at boreholes, springs and 23 of the 42 caves recorded on Christmas Island, including all the major caves which are popular with visitors. This paper summarizes our findings which are reported fully elsewhere (Humphreys and Eberhard, 1998).

METHODS

Fauna was sampled by a variety of methods traditionally employed in caves and groundwater sites (Camacho, 1992; Pospisil, 1992). Terrestrial cave fauna was collected by means of visual searching, but guano samples were collected and examined for fauna in the laboratory.

Aquatic fauna was sampled by handnet following visual sighting, or by plankton nets of appropriate dimensions hauled through the water column with or without pre-baiting, and by the use of baited traps left in place overnight and working on the principle of cray pots. The entire stream flow was filtered through nets in cave streams and on spring outlets for 24 hours or more.

DEFINITIONS

It has been found useful to classify cave-dwelling animals according to their presumed degree of ecological/ evolutionary dependence on the cave environment. Many surface-dwelling forms enter caves by chance and while such ‘accidentals’ may survive for some time they do not reproduce underground. Trogloxenes spend part of their life cycle in caves, as for example, Glossy Cave Swiftlets roost and nest in caves but emerge to seek food outside. Swiftlet excreta may form the basis of distinct guano dwelling invertebrate communities, comprising guanophiles. Troglophiles are species found outside caves as well as inside caves, but they are able to complete their entire life cycle within caves. First level troglophiles are species known to occur in above ground (epigean) habitats, and second level troglophiles are species that have never been found outside caves but which display no obvious adaptations to cave life (Hamilton-Smith, 1971).

Troglobites are species which obligatorily spend their entire lives within caves (troglodytes are people inhabiting caves). Troglobites are highly specialized to life underground and they cannot survive on the surface for any length of time. They are of considerable interest to scientists because of their degree of specialization, and because they are frequently found to be relicts that have survived in underground refugia long after their surface dwelling ancestors have become extinct. However, this does not preclude active colonization of caves by their epigean ancestors (Rouch and Danielopol, 1987; Hoch and Howarth, 1999).

Troglobites display a number of characteristic convergent morphological traits. Amongst them, the reduction or loss of characters (regressive evolution), such as the loss of eyes, pigment, sclerotization and wings. This is complimented by the enhancement of other characters—elongate legs and antennae and other non-optic senses in arthropods and lateral line organs in fish—to compensate for the lack of visual sensory information. Collectively, these traits are referred to as troglomorphies.

It is convenient to distinguish those subterranean fauna restricted to water by the prefix stygo-, leading to the comparable terms stygoxene, stygophile, stygobite and stygofauna (following Gibert et al., 1994: 13), in contradistinction to troglobites, which are essentially terrestrial animals restricted to subterranean air-filled voids. The term troglobites is sometimes used in the broadest sense to encompass the obligate inhabitants of all hypogean environments.

RESULTS

The climate is tropical monsoonal (latitude c. 10°30'S) with a high rainfall (mean annual rainfall of 2109 mm) that supports rainforest throughout the 360 m high island. Further information is given in Grimes (2001).

Cave development

The basaltic core of Christmas Island is encased in a series of limestones dating from the Eocene to the Recent and eustatic changes have produced a series of marine terraces (see Grimes, 2001). Cave development is largely associated with the interface between the basalt and limestone, and between freshwater and seawater. Access to these caves is, respectively, from the plateau, and from the sea or the lower coastal terraces. Near the coast seawater intrudes beneath the freshwater within the karstic limestone, possibly penetrating to the basalt core, and so forming an anchialine collar around the island. The saltwater interface caves are strongly tidal. Owing to the mode of development of these caves (Grimes, 2001; for examples from the Bahamas see Mylroie et al., 1991; Vogel et al., 1990), and the predominantly lower sealevel stands during the Pleistocene (Chappell and Thom, 1977), these saltwater interface caves are likely to extend to at least 80 m below the present sea level, notwithstanding an uplift of the island of 12–30 m in the last 124 ka (Woodroffe, 1988; Veeh, 1985). Evidence of lower sea level is seen in speleothems originally formed subaerially but now drowned to a depth of 3 m in Thunder Dome Cave, and at least -6 and -5 m in Lost Lake Cave and Bishops Cave respectively. Scuba divers have reported caves and freshwater outflows up to 55 m depth off shore, whilst submarine springs (vruljas) have been reported at 200 m depth in Flying Fish Cove (Pettifer and Polak, 1979). Grimes (2001) addresses speleogenesis on Christmas Island.

Eight caves (CI- 1, 4, 7, 20, 53, 70, 73/74, 83: for names of caves see Table 1) have entrance openings directly into the sea. A further six caves (CI- 87, 88, 89, 91, 92, 93) are fully submerged, or almost entirely submerged, and can only be explored with SCUBA. At least 14 caves (CI- 1, 2, 3, 7, 8, 9, 10, 16, 19, 20, 53, 70, 89, 90) contain tidally influenced freshwater/anchialine habitats. The three plateau caves (CI- 5, 6, 11) contain non-tidal freshwater streams. Grimes (2001) discusses the karst drainage on Christmas Island in some depth.

Cave environment

The subterranean environments of Christmas Island are diverse and include both terrestrial and aquatic ecosystems, the latter comprising freshwater, marine, and anchialine habitats.

Cave temperatures on Christmas Island did not differ over the island (25.9±0.19°C, N=12) and were close to the mean annual surface temperature of 25.1°C , as expected. The cave humidities were nearly saturated (RH = 97.5±0.88%, N=14) and were similar in both coastal and plateau caves. Such warm and humid caves are a most suitable habitat for troglobitic fauna if the soils are moist. It has been found elsewhere in tropical caves that terrestrial cave fauna requires high humidity and/or moist cave soils (Queensland: Howarth, 1988; Cape Range: Humphreys, 1991; Kimberley: Humphreys, 1995). The north-west monsoon, that usually brings rain between December and April, had not commenced prior to our visit in April 1998 owing to the effect of the El Niño/Southern Oscillation; rainfall in the 14 months preceding sampling was only 55% of the annual average of 2109 mm. As a result cave soils were largely dry and cracked, a sign that the soil was too dry to support troglobitic fauna, at least in the voids large enough to be accessible by people: the macrocavernous spaces.

Carbon dioxide concentrations of 3% were recorded in Jedda Cave and Jane-up Cave on the plateau and were associated with a concomitant reduction in oxygen concentration, consistent with biogenic production of carbon dioxide. It is uncertain whether this reflects a flush of microbial activity following the onset of the rain, or is a normal, even a lower than normal, concentration of carbon dioxide in these caves. Cave fauna is commonly encountered in caves with much greater concentrations of carbon dioxide, and while Howarth and Stone (1990) claim that highly troglomorphic species are restricted to such areas in Far North Queensland, this association is not corroborated by observations elsewhere in Australia (W.F. Humphreys and S. Eberhard, unpublished).

The cave waters were all well oxygenated (dissolved oxygen >73% saturated) and the pH (7.65±0.41, N=13) did not differ either between plateau and coastal caves or between fresh and anchialine systems, no doubt reflecting the dominant influence of the limestone on the water chemistry. The conductivity of caves streams was in the range 0.51–0.94 mS cm^{-1} (0.66 ±0.154 mS cm^{-1}, N=6), whereas those caves affected by marine tides had a range of 5.54–34.4 mS cm^{-1} (22.8 ±12.17 mS cm^{-1}, N=7). These values are equivalent to salinities of about

Table 1. Summary of biological significance and vulnerability of caves on Christmas Island, including principal habitats and fauna present. This table is a synopsis of Appendix 3 in Humphreys and Eberhard (1998).

Cave number	Name	Type	Biology	Biological significance	Vulnerability to caver impacts
CI-1	The Grotto	Sea cave	Marine	?hydrological connection	Medium
		-	-	with CI-54 and CI-2.	-
CI-2	Runaway	Anchialine	Stygofauna	High	Low
CI-3	Daniel Roux (main)	Anchialine	Swiftlets, guano	Low/Medium	Low
CI-5	Jedda	Streamway	Troglobites	High	Medium
CI-6	Jane-up	Streamway	Troglobites	Medium (?high if wetter)	Medium
CI-7	Lost Lake	Anchialine	Marine & other?	Medium	Low
CI-8	Bishops	Aquatic	Troglobites	Medium	Low
CI-9	Smiths	Aquatic	Swiftlets, guano	Medium	Med/High
CI-10	Freshwater	Aquatic	Troglobites	Medium	Low
CI-11	Grants Well	Streamway	Aquatic fauna	Medium	Low
CI-16	Strangler	Roots, aquatic	Fauna	Medium	Low
CI-20	Full Frontal	Anchialine	Fauna	Medium	Low
CI-30	Swiftlet	-	Swiftlets, guano	? High	?
CI-31	Indian	Small cave	?	? Low	Low
CI-45	-	Alcove[1]	Guano	?	?
CI-50	Managers Alcove	-	Swiftlets, guano	? High	? High
CI-53	Grimes	Anchialine	Swiftlets	Medium: ?hydrological connection with CI-3	Low/Med
CI-54	-	Anchialine, roots	Stygofauna	High	Medium
CI-56	Daniel Roux (upper)	Terrestrial	Swiftlets, guano	High	High
CI-68	Wobble	Small cave	?	? Low	? Low
CI-70	Boat	Sea cave	Marine, ?anchialine	Medium	Low
CI-73	The Tunnel	Sea cave	Marine	Low	Low
CI-90	Thunder Cliff	Anchialine	Marine & other?	Medium	Low
CI-91	Thunder Dome	Sea cave	Marine	Medium	Low
CI-92	Councillor	Sea cave	Marine	Medium	Low

[1] R. Webb, pers. comm., 1998.

0.39 and 16.5 g L^{-1} TDS respectively (sea water c. 36 g L^{-1} TDS).

Major ion analyses of water from underground streams on the plateau are given in Polak (1976: 28, and plates 21–24). The water typically has total dissolved solids (TDS) of 195–280 mg L^{-1}—the analysis for Grants Well (mg L^{-1}) was TDS=195, Ca= 64, Mg= 2, Na= 9, K=<1, HCO_3 =212, SO_4= 4, Cl =12, NO_3 =<1, pH= 8.0. No major ion analysis is available for the anchialine systems, but experience elsewhere has shown that the composition largely results from the degree of mixing of the fresh and sea water (Humphreys, 1994, 1999; Yager and Humphreys, 1996).

Subterranean fauna

The cave fauna comprises swiftlets, and a diverse assemblage of invertebrates, both terrestrial and aquatic, which includes a number of rare and endemic species of high conservation significance. At least twelve new species are probably restricted to subterranean habitats and are endemic to Christmas Island. The habitual cave-dwelling fauna is summarized in Table 2 whilst a complete systematic listing of all fauna collected is given in Appendix 1. A synopsis of the fauna with significant or unusual biogeographical, evolutionary or conservation attributes is given in Table 3. Undoubtedly, many addition taxa remain to be found.

Troglofauna

The terrestrial fauna comprises six troglobites, plus a number of troglophiles, trogloxenes, guanophiles and accidentals (Table 2). Troglophiles include spiders (Pholcidae and Theridiidae), whip scorpions, millipedes, crabs, isopods, and springtails (Collembola). Despite the island's diverse crab fauna (Gray, 1995), only one species, Jackson's crab *Sesarma jacksoni* Balss was habitually found in the dark zone. Trogloxenic species include the glossy swiftlet *Collocalia esculenta natalis* Lister and the robber crab *Birgus latro* Linnaeus. Guanophiles (generally, species living on bat or bird excreta) include mites (Acarina), moths (Lepidoptera) and fly larvae (Diptera) that are associated with guano piles of the swiftlet. Accidentals included several crab species, plus snails, beetles, millipedes, and isopods.

A number of highly troglomorphic animals was found, such as the cockroach *Metanocticola christmasensis* Roth (Blattodea: Nocticolidae) which represents a genus endemic to Christmas Island and shows advanced troglomorphies (Roth 1999). Other troglobitic nocticolid species occur on mainland Australia, and elsewhere in

Table 2: Synopsis of the habitual cave-dwelling fauna of Christmas Island. The assessed cavernicolous status of the taxa is recorded as: Tx — trogloxene, Tp1 — first level troglophile, Tp2 — second level troglophile, Tb — troglobite, Gp — guanophile, Sb — stygobite including anchialine pool inhabitants, Sp — stygophile.

Terrestrial	**Aquatic**
Papuaphiloscia undescribed sp. Tp2	Microturbellaria. ?Sb
Metanocticola christmasensis Roth Tb	Aphanoneura. ?Sb
Blattellidae, ? undescribed gen. Tb	*Nerilla*, undescribed sp. Sp
Cocytocampa undescribed sp. 2 ?Tb	Enchytraeidae. ?Sb
Metrinura Mendes (sensu Smith), undescribed sp. ?Tb	*Antecaridina lauensis* (Edmondson). Sb
Liocheles polisorum Tb Scorpion (Plate 1)	Alpheidae ?Sb several species.
Charon gervaisi Harvey & West Tp1	*Procaris* undescribed sp. Sb (Plate 2)
Trochanteriidae, undescribed gen. Tb	*Macrobrachium microps* Holthuis, 1978. Sb
Pholcidae. indet. Tp2	*Parahippolyte* (?*P. uveae* Borradaile). ?Sb
Theridiidae indet. Tp	Ostracoda. Sb
Collembola. ?Tb	Copepoda. Sb
Acarina Indet. Tb by association.	Amphipoda. Sb
Acarina, indet. Gp	*Eleotris fusca* (Bloch & Scheider). Sp
Lepidoptera, indet. Gp	*Sesarma jacksoni* Balss. Sp
Diptera, indet. Gp	
Myrmecophilidae Tp (?inquilines)	
Collocalia esculenta natalis Lister, 1888. Tx	

southeast Asia. A second troglobitic cockroach of the family Blattellidae also represents an undescribed genus (L.M. Roth, pers. comm. 1998).

The first troglobitic scorpion recorded for Australia, *Liocheles polisorum* Volschenk, Locket and Harvey (Scorpionida: Ischnuridae) (Plate 1) was collected in Bishops Cave (CI-8) in 1987: we also recorded it from the 19th Hole (CI-19), but it is apparently rare. A species of troglobitic scorpion is now recorded from mainland Australia (Barrow Island: W.F. Humphreys, unpublished). Globally, outside Australia, only 14 species of blind scorpions are known, of which only one species occurs outside the New World tropics (11 in Mexico, one each in Equador and Sarawak). An epigean scorpion, *Hormurus australasiae* Fabricius has also been recorded from the island (in Gibson-Hill, 1947).

A new genus of troglobitic spider of the family Trochanteriidae (pers. comm., N. Platnick.) was recorded. An eyed species of the same genus is known from a cave on the Togian Islands, off Sulawesi. A parasitic mite (Acarina) occurs on the troglobitic trochanteriid which may, by association, be troglobitic.

The dipluran *Cocytocampa* sp. nov. 2 (Diplura: Campodeidae) collected has 39 articles in its antenna (maximum number in congeneric species is 30) and this may be a cave adaptation. The only other campodeid known from caves in Australia is not troglomorphic (Condé 1998) but two species of cave-adapted campodeids are known from the Australian region, from New Ireland and from Papua New Guinea.

The silverfish *Metrinura* Mendes (*sensu* Smith, 1998) collected is probably an undescribed species (male required) and represents a range extension for the genus from New Caledonia, the Northern Territory and Queensland (Smith, 1998). Of the six congeneric species, four species are probably soil dwelling and two species are from caves, at Chillagoe and from caves, now flooded, at Texas, Queensland (*M. russendenensis*). Species collected in caves in Australia tend to be longer and thinner or larger bodied on average than surface dwelling species but they do not show the degree of adaptation seen in North American and European troglobitic species (G. Smith, pers. comm., 1998). Members of the family characteristically lack eyes, are thin, often lack scales, and have reduced pigmentation and sclerotization, all of which are preadaptations to cave life.

The most commonly seen large arachnid in Christmas Island caves is the troglophilic whip scorpion, *Charon gervaisi* Harvey & West (Amblypygi: Charontidae). It occurs in the caves near the settlement such as Runaway (CI-2), 19th Hole (CI-19) and CI-54 but it was originally collected on the surface and is likely to have been an anthropogenic introduction from Java, only some 360 km away (Harvey and West, 1998). This opinion is

Plate 1: *Liocheles polisorum* (Scorpionida: Ischnuridae). The first blind scorpion known from Australia. Photo Stefan Eberhard, Western Australian Museum.

Table 3: Synopsis of fauna with significant or notable biogeographical, evolutionary or conservation attributes.

- A second species of *Nerilla* (Archiannelida: Nerillidae) from Australia.
- Subterranean forms of Aphanoneura (Annelida) are only known from Europe, west Africa and USA.
- *Microcystis* sp. (Pulmonata: Helicarionidae); unknown species of previously unrecorded group.
- *Myrmecodillo* n.sp. 1 (Isopoda: Armadillidae).
- *Myrmecodillo* n.sp. 2 (Isopoda: Armadillidae).
- *Papuaphiloscia* n.sp. (Isopoda: Philosciidae); first record of the genus for the Indian Ocean area.
- *Procaris* n. sp. (Decapoda: Caridea: Procarididae). A primitive, highly aberrant, family seemingly restricted to anchialine caves. Family known from four other species in two genera from Hawaii, Ascension Island and Bermuda. (Plate 2)
- Several species of Alpheidae (Decapoda: Caridea) in C-54. Only one species listed in the synopsis of the world's stygofauna, from an anchialine cave in Bermuda.
- *Macrobrachium microps* Holthuis, 1978 (Decapoda: Palaemoninae). Elsewhere known from New Ireland, Samoa and the Loyalty Islands.
- *Antecaridina lauensis* (Edmondson, 1935)(Decapoda: Atyidae). First record from Christmas Island of this widely distributed species.
- A new genus of troglobitic spider of the family Trochanteriidae (pers. comm., N. Platnick.) occurs in Jedda Cave (CI-5). An eyed species of the same genus is known from a cave on the Togian Islands, off Sulawesi!
- *Liocheles polisorum* (Scorpionida: Ischnuridae). The first blind scorpion known from Australia and the second outside the Americas where 12 species occur. (Plate 1)
- *Charon gervaisi* Harvey & West (Amblypygi: Charontidae). This new species will probably be found in Java.
- Diplopoda (Polyzoniida: Family Indet.) belonging to a small order of obscure millipedes known mainly from the western hemisphere.
- *Campodea* (*Indocampa*) sp. nov. (Diplura: Campodeidae). Possibly first troglomorphic campodeid from Australia.
- *Metrinura* (prob. n. sp.)(Thysanura: Nicoletiidae: Nicoletiinae). Range extension of the genus from New Caledonia and eastern Australia.
- *Metanocticola christmasensis* Roth (Blattodea: Nocticolidae). This is a new troglobitic genus.
- *Balta notulata* (Stoll) (Blattodea: Blattellidae). New record for Christmas Island.
- indet (Orthoptera: Grilloidea: Myrmecophilidae). An ancient family that live off the secretions of ants as inquilines in ant nests.
- *Cyphoderopsis* Carpenter 1917 (Collembola: Paronellidae) Springtail not recorded from Australia before.
- *Scleropages formosus* (Müller & Schlegel)(Teleostei: Osteoglossoidei: Osteoglossidae), Asian bony tongue. Almost certainly introduced. Listed on the IUCN Red List of threatened animals as vulnerable being an endemic of very restricted distribution, now threatened by overfishing.
- *Eleotris fusca* (Bloch & Scheider)(Perciformes: Gobioidei: Eleotridae), brown gudgeon. Pale forms seen in dark zone of cave.
- *Oreochromis* sp., tilapia. (Percoidei: Cichlidae). Introduced.
- *Poecilia reticulata* Peters (guppy) and *Xiphophorus maculatus* (Gunther) (swordtail). Introduced.
- (Cyprinodontiformes: Cyprinodontoidei: Poeciliidae). Introduced.
- *Collocalia esculenta natalis* Lister (Aves: Apodiformes: Apodidae), Christmas Island glossy swiftlet, endemic.

reinforced by the lack of sightings, during this survey, of specimens from caves in parts of the island further from the settlement. Two other species of *Charon* are found in tropical mainland Australia (Harvey and West, 1998) but neither is troglomorphic.

We recorded the trogloxenic (Tx) Christmas Island glossy swiftlet, *Collocalia esculenta natalis*, from Upper Daniel Roux Cave (CI-56); Smiths Cave (CI-9); Managers Alcove (CI-50); Grimes Cave (CI-53); Swiftlet Cave (CI-30). It appears to be restricted to nesting in caves. The subspecies is endemic to Christmas Island although many other subspecies and species occur in South-east Asia, Queensland and Pacific islands. The nests of *Collocalia* species in Southeast Asia and India are intensively harvested for the gourmet delicacy 'birds nest soup' (Nguyen Quang and Voisin, 1998), and there is anecdotal evidence which suggests that nests of Christmas Island swiftlets may have been harvested in the past (Brooks, 1990).

Stygofauna

About 12 stygobiontic species were recorded from Christmas Island, comprising more than seven species found in the anchialine systems, and more that six species from freshwater (Table 2).

Freshwater fauna

Flatworms (Platyhelminthes: Turbellaria: 'Microturbellaria' cf Schwank 1986) were recorded from freshwater streams in the plateau caves.

Crustaceans of the order Podocopa (Ostracoda) were widely collected from freshwater at underground streams and springs and from anchialine habitats.

The copepod *Bryocyclops* (*B.*) *muscicola* (Menzel, 1926)(Cyclopinidae: Copepoda) was collected from springs and underground streams. The species was known previously from Java and Sumatra from interstitial, cave and moss habitats. These collections expand the known habitat of the species to groundwater and anchialine systems and its range to Christmas Island. Harpacticoid copepods of the family Ameiridae are primarily marine forms but isolated representatives have secondarily invaded freshwater (Huys and Boxshall, 1991). *Nitocrella*/*Nitokra* complex (Harpacticoida: Ameiridae) was taken from groundwater, anchialine and freshwater spring habitats. A species of Canthocamptidae, the largest family of freshwater Harpacticoida (Huys and Boxshall, 1991), was taken from a gour pool. A species of Phyllognathopodidae was taken from a water bore.

Macrobrachium microps Holthuis, 1978 (Decapoda: Palaemoninae) appears to be restricted to caves, in contrast to the wide ranging *Macrobrachium lar* (Fabricius, 1798), also found on Christmas Island (Short and Meek, 2000).

The brown gudgeon, *Eleotris fusca* (Bloch & Scheider) (Perciformes: Eleotridae), is the only native freshwater fish known to penetrate into the dark zone of the cave systems—cave dwelling specimens display some degree of depigmentation.

A number of human introduced fish occur in freshwater of Christmas Island, including the asian bony tongue, *Scleropages formosus* (Müller & Schlegel), cichlid tilapia (*Oreochromis* sp.), the guppy (*Poecilia reticulata* Peters), mosquito fish (*Gambusia affinis* Baird & Girard), and swordtails (*Xiphophorus maculatus* (Gunther)). Some of these species have the potential to threaten native fauna, including fauna in anchialine systems (Allen, 1991; Ridgley and Chai, 1990).

Anchialine systems

Anchialine habitats are characterized by having fresh groundwater overlying seawater, usually with a restricted exposure to open air and always with more or less extensive subterranean connections to the sea. Many such systems in the tropics are renowned both for their relict faunas and their species richness (Sket, 1981, 1996)—at least ten new families of Crustacea have been described from them in recent years. Anchialine systems are considered to be vulnerable to even slight organic pollution (Iliffe et al., 1984; Notenboom et al., 1994). They are the focus of widespread conservation assessment (Sket, 1981; Maciolek, 1983, 1986; Brock et al., 1987; Ridgley and Chai, 1990; Thomas et al., 1991, 1992; Iliffe, 1992; Bailey-Brock and Brock, 1993) and public interest (*vide* Waikoloa Anchialine Pond Preservation Area Trust Fund in Hawai'i: Brock et al., 1987). Other than Christmas Island, the only other anchialine system reported in Australia is the Cape Range/Barrow Island area, the former being the only continental anchialine habitat reported for the southern hemisphere (Humphreys, 2000).

Access to the anchialine systems on Christmas Island is available in many of the coastal caves but logistical constraints meant that the system was sampled sparsely, predominantly in the settled part of the island. However, a significant anchialine fauna was recorded comprising a variety of Crustacea.

The stygobitic shrimp *Procaris* n. sp. (Decapoda: Procarididae) (Plate 2) occurred in anchialine waters together with alpheid, hippolytid and atyid shrimps. Only two species are described from the genus *Procaris*, *P. hawaiana* Holthuis, 1973, from Hawaii and *P. ascensionis* Chace and Manning, 1972 from Ascension Island in the South Atlantic; two undescibed species are known from Fiji (J. Short, pers. comm. 2000).

Nerilla sp. (Archiannelida: Nerillidae) were taken amongst tree roots in anchialine waters. The genus is free living and is cosmopolitan in marine systems.

Calanoid copepods were also collected from the anchialine system. Members of some of the most primitive families typically inhabit the near bottom hyperbenthic environment from where they have invaded anchialine habitats (Huys and Boxshall, 1991).

Other crustaceans in the anchialine system include podocopodid ostracods, cyclopinid copepods and harpacticoid copepods (Ameiridae).

DISCUSSION

Previously poorly known, the cave fauna has proved to be a significant component of the island's biodiversity and a significant cave fauna province in an international context. The cave fauna comprises swiftlets, and a diverse assemblage of invertebrates, both terrestrial and aquatic, which includes a number of rare and endemic species of high conservation significance. At least twelve species which are endemic to Christmas Island are probably restricted to subterranean habitats which ranks Christmas Island significant in terms of its subterranean fauna.

Christmas Island has, minimally, six stygal and six troglobitic species. The biodiversity of the subterranean fauna is most appropriately compared with that of islands and tropical systems elsewhere. Whilst Christmas Island is not in the most species-rich category of islands with respect to troglomorphic species (Table 4), it is already approaching the richness seen in entire, well researched, karst regions such as Mexico and Central America, Southeast Asia, Virginia and the Central Pyrenees. It was a poor year for collecting terrestrial cave fauna owing to the failure of the north-west monsoon that typically influences the area from December through April. Undoubtedly, further sampling of cave fauna will locate numerous additional cave dependent species, as typically found elsewhere (Humphreys and Eberhard, 1998: figure 2).

It is now appreciated that: 1, most caves do not have surface openings; 2, the vast bulk of subterranean voids comprise air and water filled spaces much too small for people to enter; 3, many species found in caves may be more numerous in the crevicular habitat, both within and without the traditional hypogean matrices; 4, many species found in these alternative habitats are not found in caves, and 5, that there is a continuum of hypogean spaces, both air and water filled, that merge, often imperceptibly, with epigean, lacustrine, riverine and marine systems (Humphreys and Eberhard, 1998). The preferred habitat of many terrestrial troglobites appears to be the smaller, so called, mesocavernous voids (0.1–20 centimetres) where the micro-climatic conditions tend to be more stable (Howarth, 1983).

The existence of extensive terrestrial and aquatic mesocavernous habitat on Christmas Island is likely given the high secondary porosity of the limestone, as evidenced by the characteristic honeycombed appearance of the rock surfaces both above and below ground. This extensive, and possibly continuous, sponge-like network provides a refuge for terrestrial fauna when environmental conditions in the larger cave passages are less suitable due to dryness for example. The extreme rarity of many of the troglobitic species—most are represented by single specimens despite intensive searching—and experience in other tropical karsts such as Cape Range (Humphreys 1991), support the contention that mesocaverns are the principal habitat of Christmas Island troglobites. For both terrestrial and aquatic fauna, the mesocaverns also provide underground dispersal routes between separate cave systems.

A number of factors are pertinent to the origins of the cave fauna. Namely, the period of time that the island has been above the sea level, the size of the island, likely routes of colonization, the proximity and size of other land masses, and the prevailing and intermittent winds and ocean currents, as well as the characteristics of the lineage in question. The main limestones were laid down in shallow water with fossil dates (Adams and Belford, 1974) from the Late Oligocene (26 Ma) to the Late Miocene (10 Ma). The existence of the terraces suggests the island was above sea level for much of the Quaternary. Grimes (2001) is confident that the island has been land for most of the Quaternary (2 Ma—evidence of uplift rates and the presence of the terraces), that it is reasonably likely to have been exposed continuously since the early or mid-Pliocene (3–5 Ma—evidence of volcanics), and there is a possibility that it may have been land since the late Miocene (10 Ma—last shallow water limestones).

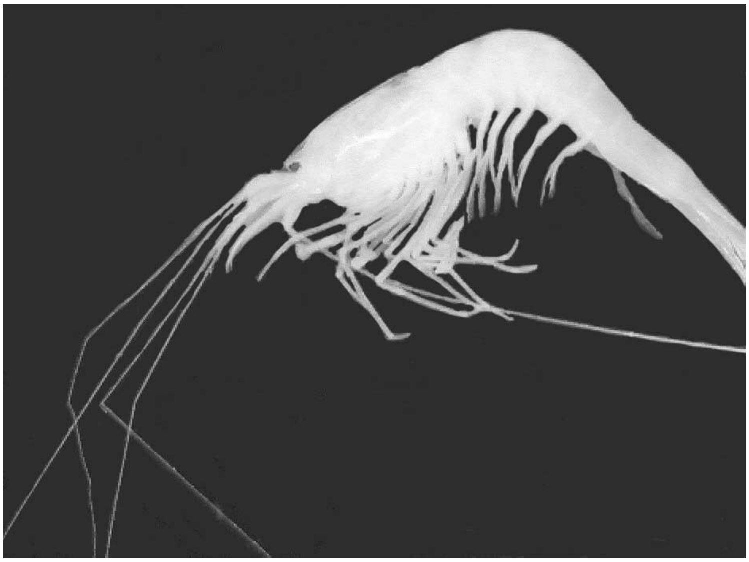

Plate 2: *Procaris* n. sp. (Decapoda: Caridea: Procarididae). A primitive, highly aberrant, family seemingly restricted to anchialine caves. Photo Stefan Eberhard, Western Australian Museum.

Table 4: Approximate numbers of recognized subterranean species from various islands and tropical locations.
Extracted from compilations in Juberthie and Decu (1994), and Deharveng and Bedos (2000). The figures in parentheses denote the percentage of all species that are troglobites. Australian sites are underlined and • denotes tropical locations.

Location	Troglobites	Stygobites	Total troglomorphic
Islands			
•Cuba	29	61	90
Bermuda	0	56	56
•Cape Range/Barrow I.[2]	33	22	55
Tenerife: Canary Islands (lava tubes)	34	11	45
•Galapagos: Ecuador	17	24	41
•Jamaica	25	14	39
Bahamas (numerous islands)	-	35	35
La Palma: Canary Islands[1]	19	2	21
Azores	16	-	16
Lanzarote: Canary Islands (lava tube)[1]	-	15	15
•Christmas Island[3]	6	6	12
Hierro: Canary Islands (lava tubes)[1]	8	1	9
Fuertoventura: Canary Islands[1]	1	5	6
Gomera: Canary Islands[1]	4	2	6
•Virgin Islands: Netherlands Antilles	-	4	4
•Mona Island: Netherlands Antilles	2	1	3
Gran Canaria: Canary Islands[1]	1	2	3
Karst regions			
•Mexico and Central America	0-14	0-10	-
•Southeast Asia	-	-	16-28
Virginia	-	-	14-21
Central Pyrenees	-	-	18-23
Caves	**-**	**-**	**-**
•Panama: Chilibrillo cave	-	-	3 (5)
•Ecuador: Jumandi cave	-	-	1(5)
•Venezuela: Serrania de San Luis	9	2	11(12)

[1]Mainly from lava tubes. [2]Cape Range is included for comparison and because it is isolated on a peninsula. [3]Provisional figure only.

Terrestrial and freshwater lineages are most likely to have been transported from the nearest land masses, the Indonesian archipelago, but freshwater species of marine origin may have invaded from the sea. Cave adapted terrestrial and freshwater invertebrates most likely will have arrived on the island as an epigean progenitor and will have evolved troglobitic adaptations *in situ* on Christmas Island and will thus be endemic to Christmas Island. By contrast only 16 taxa of plants, 3.9% of the total, are endemic to Christmas Island (Du Puy, 1993: 12), and probably none of the marine fauna (Berry, 1988). The vegetation on Christmas Island has predominantly Indo–Malesian affinities, with many species having distributions extending from Southeast Asia through Malaysia to Australia (northeast Queensland), New Guinea and into the Pacific islands. All species are tolerant of limestone and alkaline soils (Du Puy, 1993). However, it should be recognized that the species composition of the vegetation may have been influenced by the predation pressure of the land crabs on seeds and seedlings (Green et al., 1997), and this may bias the use of the flora as a model for colonization by terrestrial invertebrates. The fauna of tropical caves largely comprises lineages characteristic of forest floor leaf litter communities (Harvey et al., 1993; Humphreys, 1993; Deharveng and Bedos, 2000). The leaf litter on Christmas Island is sparse owing to its utilization by dense populations of land crabs of several species (Green, 1997). This intense competition for fallen leaves may be relevant to the colonization of the subterranean environment on Christmas Island and the subsequent onset of troglogenesis.

The marine fauna of Christmas Island largely comprises widespread Indo–west-Pacific taxa with representations of some western Indian Ocean species not typical of Australian waters. The species diversity of the marine fauna is not high, probably owing to the restricted habitat diversity (Berry, 1988). The anchialine fauna of Christmas Island will have invaded from the sea: Many anchialine lineages have widespread pantropical, or wider, distributions where suitable habitats are found.

The Procaridae is a primitive, highly aberrant, family which appears to be restricted to anchialine caves and has only one other representative, *Vetericaris chaceorum* Kensley & Williams, 1986, from Bermuda, which poses interesting questions concerning the distribution and dispersion of these faunas. Boxshall (1989) proposed that the mid-oceanic ridge islands form a continuous route of dispersal around the globe, however there is not a simple connection between the crevicular system of mid-oceanic ridges and hot spot islands such as Christmas Island. The occurrence of procaridid, alpheid, hippolytid and atyid shrimps in the same anchialine system on Christmas Island mirrors that on Bermuda where the same four families occur in the anchialine system on the island (Hart and Manning, 1981) which is renown for the diversity of its anchialine fauna. In addition *Procaris* has always been recorded with another ancient family, the Atyidae, wherever it is found (only known from Bermuda, Ascension Islands, Hawai'i and Christmas Island). These co-occurrences of two primitive and presumably ancient caridean families support the contention that crevicular habitats have served as faunal refuges for long periods of time (Kensley and Williams, 1986).

The cave fauna and habitats are sensitive to disturbance from a number of threatening processes, including pollution, deforestation, mining, feral species and human visitors (Meek, 2001). The sensitivity and vulnerability varies depending on the characteristics of the fauna and habitat, its distribution and the nature of the threatening process (Table 5). Public education, habitat protection and monitoring are recommended for managing human visitors. For other, external threatening processes, survey and assessment of impacts on subterranean biota is required (Humphreys and Eberhard, 1998).

Table 5: Summary of fauna habitat/association types, their occurrence, vulnerability to human visitors, and main external threatening processes.

Habitat/association	Occurrence	Vulnerability to human visitors	Main external threats
Glossy swiftlet	Restricted	High	Deforestation
Guano	Restricted	High	Deforestation
Tree roots	Restricted	High	Deforestation, mining
Freshwater pools	Restricted	High	Deforestation, pollution
Freshwater streams	Restricted	Medium	Deforestation, pollution, mining, water abstraction, feral species
Sediment banks	Restricted	Medium	Deforestation, pollution, mining
Organic material	Restricted	Medium	Deforestation
Anchialine	Widespread	Low	Pollution, water abstraction, feral species
Marine	Widespread	Low	Pollution
Entrance/twilight	Widespread	Low	Deforestation, mining
Wall association	Widespread	Low	Deforestation
Springs	Restricted	Low	Water abstraction, pollution, feral species
Deep zone	Widespread	Variable	Deforestation, pollution

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Appendix 1: Annotated Systematic Listing and Occurrence Records of Cave Fauna

The systematic listing largely follows the order and nomenclature of Botosaneanu (1986) and Harvey and Yen (1989). Occurrence records list the site and locality, or the cave name and/or number (eg. CI-54) as listed in Table 2. The assessed cavernicolous status of the taxa is recorded as: Ep – epigean, Tx – trogloxene, Tp1 – first level troglophile, Tp2 – second level troglophile, Tb – troglobite, Sb – stygobite including anchialine pool inhabitants, Gp – guanophile, Gb – guanobite. WAM refers to collections previously in the Western Australian Museum and ANIC refers to the Australian National Insect Collection, Canberra.

Phylum **Platyhelminthes —** Flatworms
Class **Turbellaria**
'Microturbellaria' cf Schwank 1986, ?Sb
Jane-up Well.

Phylum **Annelida**
Class **Polychaeta** det R. Wilson
Family **Syllidae**
Indet.
CI-54

Class **Archiannelida** det R. Wilson
Family **Nerillidae**
Nerilla sp.
CI-54

Class **Aphanoneura** det A. Pinder
Coastal water bore #1, Smithsons Bight area; Jane-up Well.

Class **Oligochaeta** det A. Pinder
Order **Haplotaxida**
Family **Enchytraeidae**
Coastal water bore #1, #2, Smithsons Bight area.

Family **Tubificidae**
Indet.
Freshwater Spring (CI-85).

Order **Opisthopora** (Earthworm)
Family Indet.
Indet.
Smiths Cave (CI-9).

Phylum **Mollusca** det S.M. Slack-Smith
Class **Gastropoda, Ep**
Sub-class **Prosobranchia**
Family **Truncatellidae**
Truncatella guerinii A. & J.B. Villa, 1841
Runaway Cave (CI-2); Smiths Cave (CI-9); 19th Hole (CI-19); CI-55.

Family **Cyclophoridae**
Leptopoma sp. (?*L. mouhoti* (Pfeiffer, 1861)
CI-55

Family **Assimineidae**
Assiminea sp. (?*A. andrewsiana* Smith,1900)
Grants Well (CI-11).

Sub-class **Pulmonata**
Family **Ellobiidae**
Pythia scarabaeus (Linnaeus, 1758)
Runaway Cave (CI-2); Jedda Cave (CI-5); 19th Hole (CI-19); CI-55.

Family **Vertiginidae**
Nesopupa (?*Insulipupa*) sp.
Coastal water bore #2.

Family **Subulinidae**
Subulina octona (Bruguiere, 1792)
Jedda Cave (CI-5); Strangler Cave (CI-16).

Subulina ?*octona* (Bruguiere, 1792)
Jedda Cave (CI-5). Anterior end of shell broken off.

?*Subulina* sp.
Strangler Cave (CI-16).

Lamellaxis gracilis (Hutton, 1834)
Jane-up Cave (CI-6).

?*Lamellaxis* sp.
Grants Well (CI-11).

Opeas ?*pumilum* (Pfeiffer, 1840)
Freshwater Spring (CI-85).

Family **Helicarionidae**
Microcystis sp.
Jane-up Cave (CI-6); CI-55.

?Family **Ferussaciidae**
Cecilioides sp
OR ?Family **Subulinidae**
Ochroderma sp. OR *Prosopeas* sp.
Freshwater Spring (CI-85).

Class **Bivalvia**
Family **Isognomonidae**
Isognomon ?*ephippium* (Linnaeus, 1758)
(CI-20).

Phylum **Crustacea**
Class **Ostracoda**
Order **Podocopa**
Jane-up Well; Jedda Cave (CI-5); Grants

Well (CI-11); CI-54; Henderson's Spring (CI-64); Hugh's Dale (CI-77); Freshwater Spring (CI-85).

Subclass **Copepoda**

Order **Calanoida** det. G.L. Pesce

Indet.

CI-54. Anchialine system.

Order **Cyclopoida**

Family **Cyclopinidae**

(CI-54). Anchialine cave

Bryocyclops (*Bryocyclops*) *muscicola* (Menzel, 1926)

Coastal water bore #1, #2, Smithsons Bight area; Jedda Cave (CI-5); Jane-up Well; Grants Well (CI-11); (CI-54); Hendersons Spring pumphouse outflow (CI-64).

Order **Harpacticoida**

Family **Ameiridae**

Nitocrella/*Nitokra* complex det. G.A. Boxshall

Coastal water bore #2; CI-54; Hendersons Spring (CI-64).

Nitokra cf. *spinipes* det. G.L. Pesce

Hendersons Spring (CI-64).

Family **Canthocamptidae** det. G.A. Boxshall

Indet.

Full Frontal Cave (CI-20).

Family **Phyllognathopodidae** det. G.A. Boxshall

Indet.

Coastal water bore #2, Smithsons Bight area.

Class **Isopoda**

Order **Oniscidea** det S. Taiti

Family **Armadillidae**

Myrmecodillo n. sp. 1 **Tx**

Jedda Cave (CI-5), Jane-up Cave (CI-6), Freshwater Cave (CI-10).

Myrmecodillo n. sp. 2 **Tx**

Coastal water bore #2, Smithsons Bight area.

Family **Eubelidae**

Elumoides monocellatus Taiti & Ferrara, 1983

Coastal water bore #2, Smithsons Bight area.

Family **Olibrinidae**

Olibrinus antennatus (Budde-Lund, 1902)
Full Frontal Cave (CI-20).

Family **Philosciidae**

Burmoniscus sp. (prob. *B. orientalis* Green, Ferrara & Taiti, 1990.
Hendersons Spring (CI-64).

Papuaphiloscia n. sp. **Tp2**
Jedda Cave (CI-5).

Class **Amphipoda**

Indet.
CI-54.

Class **Malacostraca**

Order **Decapoda**

Infraorder **Caridea**

Family **Procarididae** det. J. Short

Procaris (undescribed species), Sb Runaway Cave.

Family **Alpheidae** det. J. Short

?three species.
CI-54.

Family **Palaemoninae** det. J. Short

Macrobrachium, either *M. lar* or *M. microps*.
CI-54; Hendersons Spring (CI-64).

Macrobrachium microps Holthuis, 1978.
Freshwater Cave (CI-10).

Family **Atyidae** det. S. Choy

Antecaridina lauensis (Edmondson, 1935)

Family **Hippolytidae** det. J. Short

Parahippolyte (?*P. uveae* Borradaile, 1899).
Runaway Cave.

Infraorder **Anomura**

Family **Coenobitidae**

Birgus latro Linnaeus.
The robber crab, is nocturnal and they are occasionally found in the dark zone of caves on the plateau and especially down by the water in the small anchialine caves (e.g. CI-19 and CI-54).

Infraorder **Brachyura**

Several species of crab are found in the caves, all but Jackson's crab superficially.

Family **Gecarcinucidae**

Gecarcoidea natalis (Pocock, 1888), the red crab.
Diurnal and ubiquitous on the ground on Christmas Island is rarely found even in the twilight zone of caves.

Cardisoma hirtipes Dana, the blue crab.
Occurs around soaks associated with springs

at Ross Hill Gardens, The Dales and Waterfall.

Family **Grapsidae**

Sesarma jacksoni Balss, jackson's crab,
Lost Lake Cave (CI-7), Freshwater Cave (CI-10), Grimes Cave (CI-53), Full Frontal Cave (CI-20), Runaway Cave (CI-2), 19th Hole (CI-19) and Smiths Cave (CI-9).

Ptychognathus pusillus Heller, the freshwater crab.
Found in running freshwater at Dolly Beach and Waterfall spring, has not been encountered in subterranean streams.

Phylum **Chelicerata**
Class **Arachnida**
Order **Scorpionida**
Family **Ischnuridae**
Liocheles polisorum, Tb
Bishops Cave (CI-8), 19th Hole (CI-19).

Order **Araneae**
Family **Pholcidae**
Indet. **Tp2**
Runaway Cave (CI-2); Jedda Cave (CI-5); Jane-up Cave (CI-6); Bishops Cave (CI-8); Smiths Cave (CI-9); 19th Hole (CI-19); coastal water bore #2, Smithsons Bight area.

Family **Uloboridae** det. J.M. Waldock
Zosis sp., Ep
Smiths Cave (CI-9); Freshwater Cave (CI-10).

Family **Scytodidae** det. J.M. Waldock
Indet.
19th Hole (CI-19); CI-54.

Family **Theridiidae** det. J.M.Waldock
Indet. **Tp**
Smiths Cave (CI-9), Bishops Cave (CI-8).

Family **Oonopidae** det. J.M. Waldock
Opopaea sp. **Ep**
Hendersons Spring (CI-64).

Family **Gnaphosidae** det. R. Raven
Indet. **Tb**
Jedda Cave (CI-5).

Family **Heteropodidae** det. J.M. Waldock
Indet.
Smiths Cave (CI-9).

Order **Amblypygi**
Family **Charontidae**
Charon gervaisi Harvey & West 1998, Tp1
Runaway (CI-2); 19th Hole (CI-19); CI-54.

Order **Opilionida**
Family **Phalangodidae**
Indet., Tp1
Freshwater Cave (CI-10).

Order **Acarina** det. M.S. Harvey
Indet., Ectoparasite
From the plumage of a Glossy Cave Swiftlet.

Indet., Ep
Grants Well (CI-11).

Indet., Ep
Jedda Cave (CI-5).

Indet., Ep
Coastal water bore #2, Smithsons Bight area.

Indet., Gp
Grimes Cave (CI-53).

Indet., Commensal/parasite, possibly Tb by association.
Jedda Cave (CI-5), on troglobitic gnaphosid spider.

Phylum **Uniramia**
Class **Diplopoda**
Subclass **Penicillata**
Order **Polyxenida**
Indet.
Jedda Cave (CI-5); Jane-up Cave (CI-6); 19th Hole (CI-19).

Subclass **chilognatha**
Infraclass **Helminthomorpha**
Superorder **Anocheta**
Order **Spirobolida**
Family **Spirobolellidae** Brolemann, 1913 or **Pseudospirobolellidae** Brolemann, 1913
Indet.
Coastal water bore #2, Smithsons Bight area.

Superorder **merocheta**
Order **Polydesmida** det. W.S. Shear
Family **Paradoxosomatidae**
Subfamily **Paradoxosomatinae**
Tribe **Cnemodesmini**
Oxidus gracilis (C.L. Koch, 1847)
Smiths Cave (CI-9).

Superfamily **Polydesmidae**
Family **Haplodesmidae**
Cylindrodesmus hirsutus Pocock
Jedda Cave (CI-5); Jane-up Cave (CI-6).

Superorder **Ommatophora**
Order **Polyzoniida**
Family **Indet.**
19th Hole (CI-19).
Phylum **Uniramia**
Superclass **Hexapoda**
Class **Collembola**
Order **Collembola**
Indet.
Runaway Cave (CI-2); Jane-up Well; The Grotto (CI-1); Coastal water bore #1, Smithsons Bight area; Grants Well (CI-11), 19th Hole (CI-19); CI-54.

Family **Paronellidae** det. P.M. Greenslade
Cyphoderopsis Carpenter 1917, sp. indet..
Jedda Cave (CI-5).

Class **Diplura**
Order **Diplura**
Family **Campodeidae** det B. Condé
Cocytocampa sp. nov. 2, ?Tb

Order **Thysanura** det. G. Smith
Family **Nicoletiidae**
Subfamily **Nicoletiinae**
Metrinura Mendes (*sensu* Smith, 1998) Tb?
Jedda Cave (CI-5).

Class **Insecta**
Order **Blattodea** det L.M. Roth
Family **Nocticolidae**
Metanocticola christmasensis Roth 1998, Tb
Jedda Cave (CI-5); Jane-up Cave (CI-6).

Family **Blattellidae**
Gen. indet.
Freshwater Cave (CI-10).

Periplaneta americana L., Ep
Jedda Cave (CI-5); Smiths Cave (CI-9); Strangler Cave (CI-16); Upper Daniel Roux Cave (CI-56).

?New genus, Tb
Bishops Cave (CI-8).

Order **Orthoptera**
Superfamily **Grilloidea**
Grimes Cave (CI-53); Upper Daniel Roux Cave (CI-56).

Family **Myrmecophilidae**
Indet.

Order **Phthiraptera**
Suborder **Amblycera**
Family **Menoponidae**
Indet., Ectoparasite
From wing feathers of Glossy Cave Swiftlet.

Order **Hemiptera**
Suborder **Auchenorrhyncha**
Superfamily **Fulgoroidea**
Indet.
Grants Well (CI-11); 19th Hole (CI-19); CI-55.

Order **Coleoptera**
Family **Histeridae** det. ANIC
Carcinops sp., Gp
Upper Daniel Roux Cave (CI-56).

Family **Tenebrionidae** det. ANIC
Alphitobius laevigatus (Fabricius)., Gp
Upper Daniel Roux Cave (CI-56).

Order **Diptera**
Suborder **Nematocera**
Division **Culicomorpha**
Family **Culicidae** det. ANIC
Indet.
Strangler Cave (CI-16).

Family **Chironomidae** det. ANIC
Ablabesmyia notabilis type
Freshwater Spring (CI-85).

Polypedilum 'K3'
Freshwater Spring (CI-85).

Family **Ceratopogonidae** det. ANIC
Subfamily **Ceratopogonini**
Indet.
Freshwater Spring (CI-85).

Family **Simuliidae** det. ANIC
?*Austrosimulium* sp.
Freshwater Spring (CI-85).

Division **Bibionomorpha**
Family **Sciaridae** det. ANIC
?*Lycoriella* sp.
Jane-up Cave (CI-6).

Family **Mycetophilidae**
Indet., Tp1
Jane-up Cave (CI-6) and Jedda Cave (CI-5).

Suborder **Brachycera**
Division **Cyclorrhapha**
Family **Phoridae** det. ANIC
Indet.
Bishops Cave (CI-8).

Family ?**Drosophilidae** det. ANIC
Indet., Gp
Upper Daniel Roux Cave (CI-56).

Superfamily Chloropoidea
Family **Chloropidae** det. ANIC
Indet., Gp
Upper Daniel Roux Cave (CI-56).
Superfamily **Muscoidea**
Family ?**Fanniidae** det. ANIC
?*Fannia* sp.
19th Hole (CI-19).

Family **Muscidae** det. ANIC
Indet., Gp
Grimes Cave (CI-53); Upper Daniel Roux Cave (CI-56).

Order **Lepidoptera**
Family **Pyralidae** det. ANIC
Pyralinae or Epipaschiinae indet., Gp
Smiths Cave (CI-9).

Family **Tineidae** det. ANIC
Indet., Gb
Smiths Cave (CI-9); Upper Daniel Roux Cave (CI-56).

Order **Hymenoptera**
Family **Formicidae** det. ANIC
Subfamily **Formicinae**
Anoplolepis gracilipes (Smith)
Runaway Cave (CI-2).

Subfamily **Ponerinae**
Pachycondyla sp., Gp
Upper Daniel Roux Cave (CI-56).

Phylum **Chordata**
Subphylum **Vertebrata**
Class **Osteichthyes**
Infraclass **Teleostei**
Order **Perciformes**
Suborder **Gobioidei**
Family **Eleotridae**
Eleotris fusca (Bloch & Scheider), brown gudgeon, Tp1
Upper Daniel Roux Cave (CI-56).

Subclass **Aves**
Order **Apodiformes**
Family **Apodidae**
Collocalia esculenta natalis Lister, 1888.
Upper Daniel Roux Cave (CI-56); Smiths Cave (CI-9); Managers Alcove (CI-50); Grimes Cave (CI-53); Swiftlet Cave (CI-30).

BOOK REVIEW

KARST OF THE CENTRAL WEST CATCHMENT, NSW: RESOUCES, IMPACTS AND MANAGEMENT STRATEGIES.

Dunkley, J. & Dykes, P. (eds) 2001. *Karst of the Central West Catchment, NSW: Resouces, Impacts and Management Strategies.* Australian Speleological Federation Inc., Broadway, NSW. 103pp.

This is the first report from mainland Australia to comprehensively review karst on freehold lands in private ownership. A wide-ranging team of speleologists from New South Wales, who worked in conjunction with local landowners, were responsible for its development and publication. It certainly owes a great deal to chairpersons Chris Dunne and John Dunkley, and the thoroughness and keen observation of Peter Dykes as project officer deserves special mention. Although land management agencies have often given lip service to off-reserve conservation, this has generally only been acted upon in order to protect threatened species. Both vegetation associations and karsts, or other elements of geodiversity, have generally been ignored, and these receive full attention in this study. Thus, the study serves to highlight the potential value and importance of any such study.

The title provides an accurate short overview of the contents. It provides land managers, both public and private, with a fine background document and a clearly defined set of positive recommendations—one hopes that these will in due course be realised. Many other areas of Australia need an equivalent analysis that places the caves of a region properly in context.

The great Julian Tenison-Woods was probably the first to recognise that karst often displays distinctive vegetation associations, and this report is one of the very few to re-visit that phenomenon in temperate Australia. Six different associations were identified on the karst. One of these is an apparently relict association that appears to have survived only on the karst. Each of the others demonstrates at least some specific karst-related characteristics. The historical and geographic factors that have shaped each association are discussed and their implications for restoration and weed control spelled out.

The major strength of the report lies in this vegetation analysis. Although much of the original vegetation throughout the region has been eliminated or severely degraded, important relict associations remain on up to 20% of the karst outcrops. Four of these are very similar to associations that survive elsewhere in the region, but are often less degraded. Another (Cypress Pine woodland) is distinctive, and was only recorded from two karst areas, while another (Blackboy-Spinifex scrub) is only found on the Capertree Valley karst. This is the most distinctive and significant association recognised by the current study. The Spinifex (*Triodia scariosa)* is normally only found some 500 km to the west of the study area. Thus the study demonstrates something of the distinctive character of karst vegetation, and the role of karst in providing refugia.

The report also deals with issues of impacts upon the karst, and although local examples are used in this section, it also draws upon material from other regions. It chronicles impacts within the study area, but adds little other than a useful discussion of weed invasion processes in the way of new understandings.

A major defect of the study report is that it gives little other than passing notes on the methods adopted for field study. Given that a large number of observers were involved in data collection, there is no indication of what actions were taken to optimise consistency and comparability across all observational records. There is also a strange omission in that although the number of karst features identified is provided, there is no statement of the number of sites that were examined.

An extended discussion of the implications of the study includes 51 recommendations for action, all of which acknowledge and are congruent with current catchment management strategies. One hopes that these will be accepted and implemented in the foreseeable future, and that the continuing processes of degradation and weed invasion will be reversed.

Elery Hamilton-Smith, AM
Chair, IUCN/WCPA Task force on cave and karst protection.

Coming Events

International Association of Hydrogeologists

International Groundwater Conference

"BALANCIING THE GROUNDWATER BUDGET"

Darwin, Northern Territory, Australia
12 – 17 May 2002
Visit the web-site for up to date information.
http://www1.octa4.net.au/iahnt/conference.htm

The IAH is a scientific and educational organisation that has existed since 1956 to promote the study and knowledge of hydrogeological science.

Over 200 abstracts, from 27 countries, have been submitted. The conference involves 5 days of paper presentations, poster sessions, workshops, field excursions and social events.

The topics covered by each Conference Stream, and the approximate number of abstracts received for each topic, are briefly summarised below:

Conference Stream A:
1. Resource quantification / water balances in a range of environments
1.1. Large sedimentary basins - 16 abstracts
1.2. Karst - 18 abstracts
1.3. Fractured rocks - 12 abstracts
2. Use of isotopes and chemistry to quantify recharge, discharge and storage - 19 abstracts

Conference Stream B:
1. Modelling groundwater resources - 24 abstracts
2. Mapping / GIS - 6 abstracts
3. Groundwater / surface water interaction - 14 abstracts
4. Coastal / estuarine discharge processes - 14 abstracts
5. Artificial recharge - 9 abstracts

Conference Stream C:
1. Ecosystem dependence - 16 abstracts
2. Stygofauna - 6 abstracts
3. Quantifying tree water use - 5 abstracts
4. Salinisation - 9 abstracts
5. Overallocation - 5 abstracts
6. Sustainable Yield - 6 abstracts
7. Community involvement - 12 abstracts
8. Management plans - 9 abstracts

One of the mid-week day-tours will include a visit to the Berry Springs Nature Park, a small reserve around a large spring discharging from a dolomite aquifer.

One post-conference trip is to Katherine / Daly Basin. This is a three-day (two-night) bus tour, departing from Darwin on Saturday the 18th of May. The Daly Basin, situated approximately 300km south of Darwin, is a Lower Palaeozoic geological basin dominated by carbonate rocks which form regional fractured and cavernous aquifers. The landscape includes numerous karstic landforms characteristic of the wet / dry tropics, and many groundwater discharge points in the form of major springs.

Katherine is the regional centre, and will be the base for the tour. The trip will include visits to several springs (including Mataranka Hot Springs), a cave system showing evidence for a former groundwater regime, and a spectacular example of extensive tufa deposits downstream of a spring. Other local attractions will be visited, including a boat cruise on the famous Katherine Gorge.

Registration forms can be obtained from:
Convention Catalysts International
GPO Box 2541, Darwin, NT 0801
Telephone: (08) 89811875 Fax: (08) 89411639
E-mail: convention.catalysts@norgate.com.au

Information for Contributors to Helictite

Scope

Contributions from all fields of study related to speleology will be considered for publication. Suitable fields include Earth Sciences, Speleochemistry, Hydrology, Meteorology, Conservation, Biospeleology, History, Major Exploration (Expedition) Reports, Equipment and Techniques, Surveying and Cartography, Photography and Documentation. Comprehensive descriptive accounts of the exploration and morphology of individual caves will be welcomed, but simple trip reports and brief cave descriptions are not adequate. Papers overall should not exceed 20 printed pages in length. Contributors intending to write at greater length or requiring any advice on details of preparation are invited to correspond with the Editors. All manuscripts will be assessed by referees. "News and Views", "Short Notes" and "Letters to the Editor", expressing a personal view or giving a preliminary report of interesting findings, are welcomed, and will be given preference for speedy publication.

Manuscripts

Submitted manuscripts should initially be in printed form. Manuscripts should be typed, double spaced, on one side of the paper. Do not use multiple columns - this manuscript is for the editors and referees use and does not have to look like the final production.

The **title** should be upper case bold and the author's names and addresses should follow. A brief and explicit summary of the notable aspects of the paper, headed **abstract**, should precede the main text. **Acknowledgements** should be placed at the end of the text before the references.

Once authors have dealt with referees comments, they are requested to submit a copy of their final manuscript by email or on floppy disk as well as hard copy. Disks may be 3 ½" or 5 ¼" in either IBM or Macintosh format. If sending text as a word processing document (Microsoft Word etc.), please also send a copy as plain text on the same disk. Illustrations and tables are best sent in separate files, not embedded in the main document. Separate instructions concerning electronic layout are available from ken-grimes@h140.aone.net.au.

References

References should be listed alphabetically at the end of the manuscript and cited in the text by the author's name and the year of publication, e.g. "(Gray, 1973)". Where there is more than one reference to the same author in one year the letters a, b, c, etc. should be added. If there are more than two authors, they should all be named at the first citation and in the reference list, but the first name followed by et al. should be used in subsequent citations. References should be checked particularly carefully for accuracy. If journal titles are abbreviated, this should follow the "World List of Scientific Periodicals", which is available in most large libraries.

The following examples illustrate the style:

GRAY, M.R., 1973 Cavernicolous spiders from the Nullarbor Plain and south-west Australia. *J. Aust. ent. Soc.* **12:** 207-221.

VANDEL, A., 1965 *Biospeleology. The Biology of the Cavernicolous Animals.* Pergamon, London. pp. xxiv, 524.

WIGLEY, T.M.L. and WOOD, I.D., 1967 Meteorology of the Nullarbor Plain Caves. *In:* J.R. DUNKLEY and T.M.L. WIGLEY (eds), *Caves of the Nullarbor. A Review of Speleological Investigations in the Nullarbor Plain. Southern Australia*: 32-34. Speleological Research Council, Sydney.

Illustrations

For papers that have a geographical location we will provide a small location map in a standardised style (typically a map of Australia with a dot, rectangle or arrow—see recent issues for examples). Figures and photographs should not duplicate information in tables or other material. Photographs should be relevant to the text, and supplied as clear black and white prints with sharp focus. Figures should be supplied as Laser prints or drawn in Indian ink on white card, heavy paper or tracing material and lettered using stencils or stick-on lettering. Ink-jet prints should be enclosed in plastic to reduce the risk of water damage in transit. Most computer drawn documents and photographic images can also be handled. Please ask for additional instructions on file formats, pixel widths and photo "enhancements".

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Fold-outs or colour photographs and maps will be subject to negotiation, and the authors may be asked to make a contribution to the production costs.

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Units

The S.I. system (Australian Standard AS 1000) should be used unless citing historical data, in which case the original units should be quoted and appropriately rounded metric equivalents added; 100 feet (30 m) .

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Twenty free offprints of papers will be supplied after publication. Additional offprints can be arranged at the author's expense. The number required should be stated when submitting the final manuscript.

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