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# Karst Features of Christmas Island (Indian Ocean)

***Ken G. Grimes***

Regolith Mapping, PO Box 362, Hamilton, Vic. 3300, Australia.
ken-grimes@h140.aone.net.au

## 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 seamount. 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

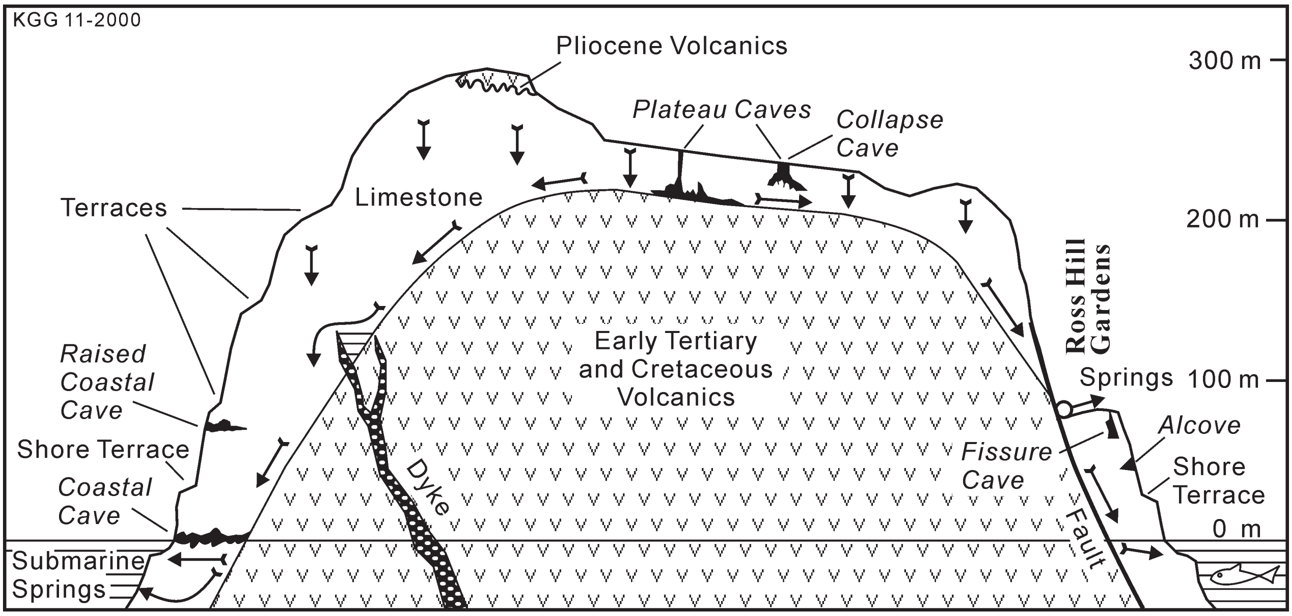

Figure 1: Diagrammatic cross-section of Christmas Island, showing volcanic core, limestone capping, water flow lines (arrows) and typical cave development. Vertical scale is exaggerated x10.

(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. |

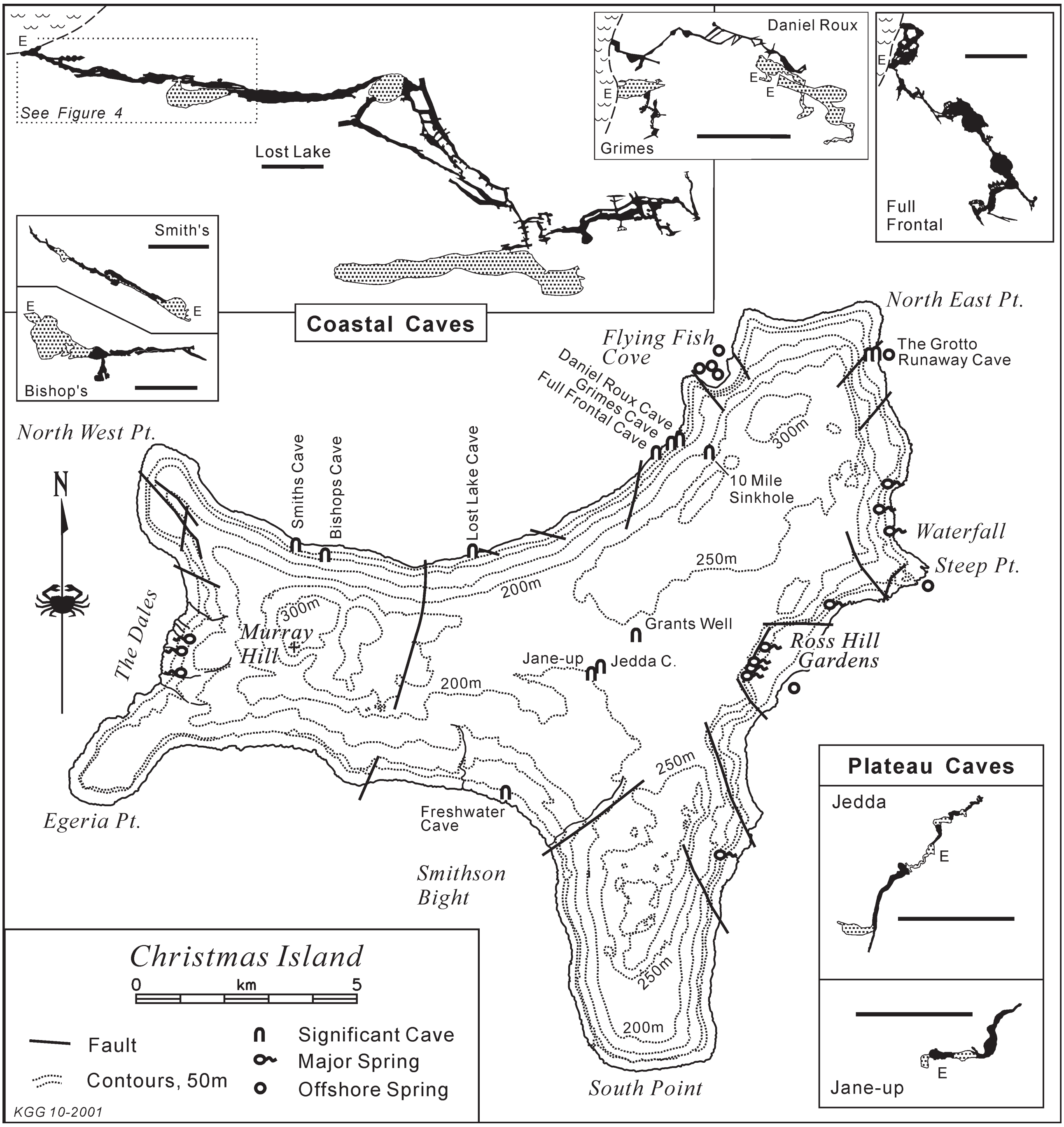

Figure 2: Location map and karst features of Christmas Island. For the cave maps: the scale bar in each map is 100 m; black is solution passage; collapse areas are shaded; "E" marks an entrance.

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

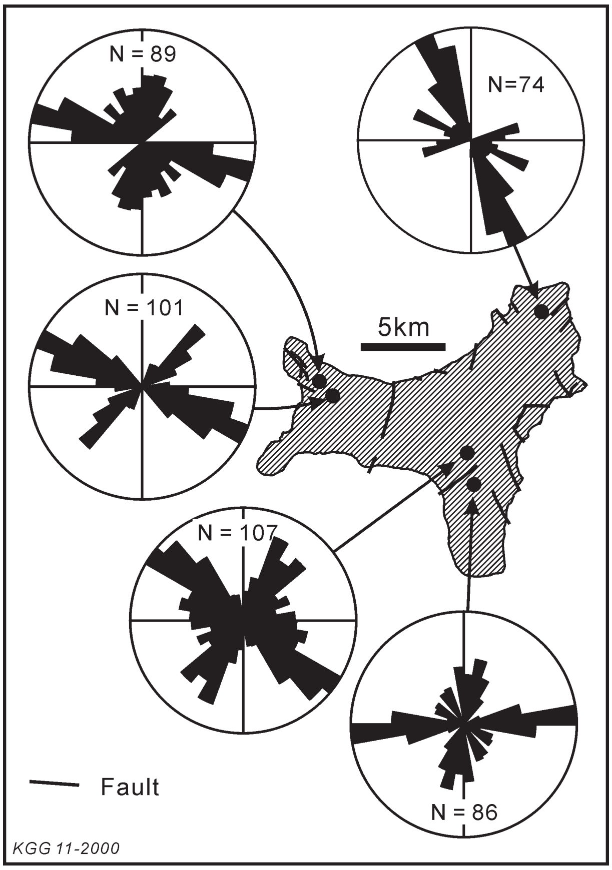

Figure 3: Rose diagrams showing trends of surface structures exposed in mined areas.

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. 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).


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

***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).

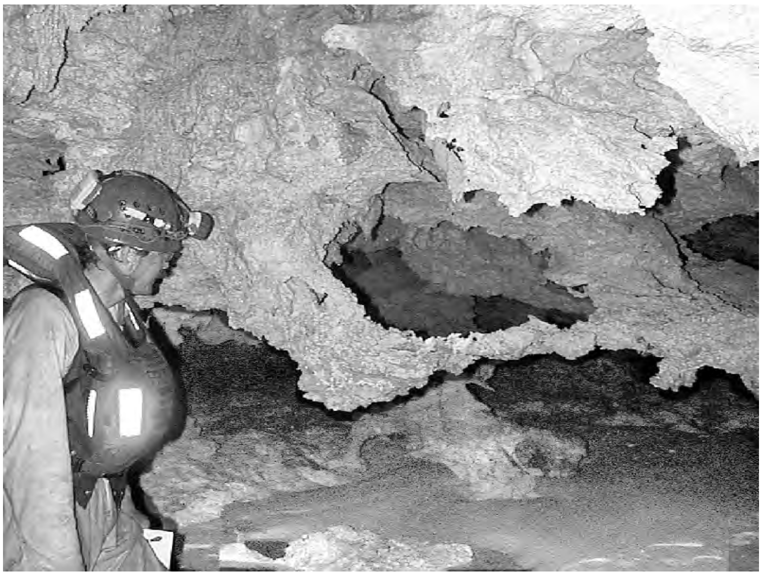

Photo 6: Spongework in a coastal cave (CI-20). A mixing corrosion effect. (Photo by R. Webb)

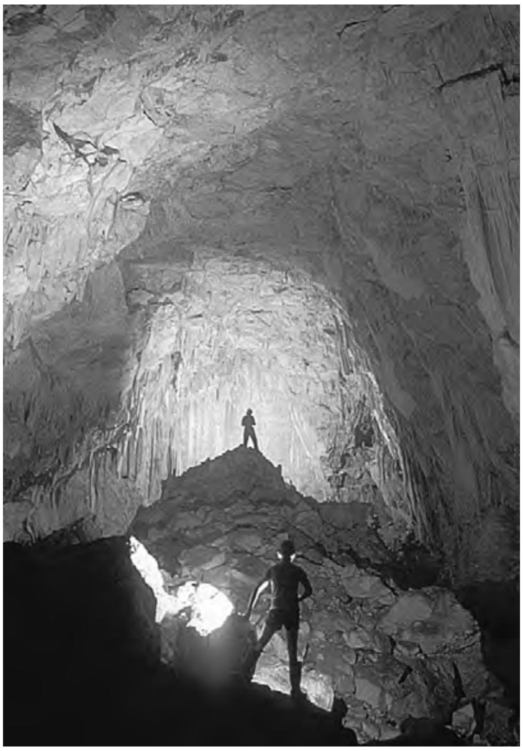

Photo 7: Large collapse chamber (CI-8). Note domed roof and rubble piles on floor. (Photo by R. Webb)

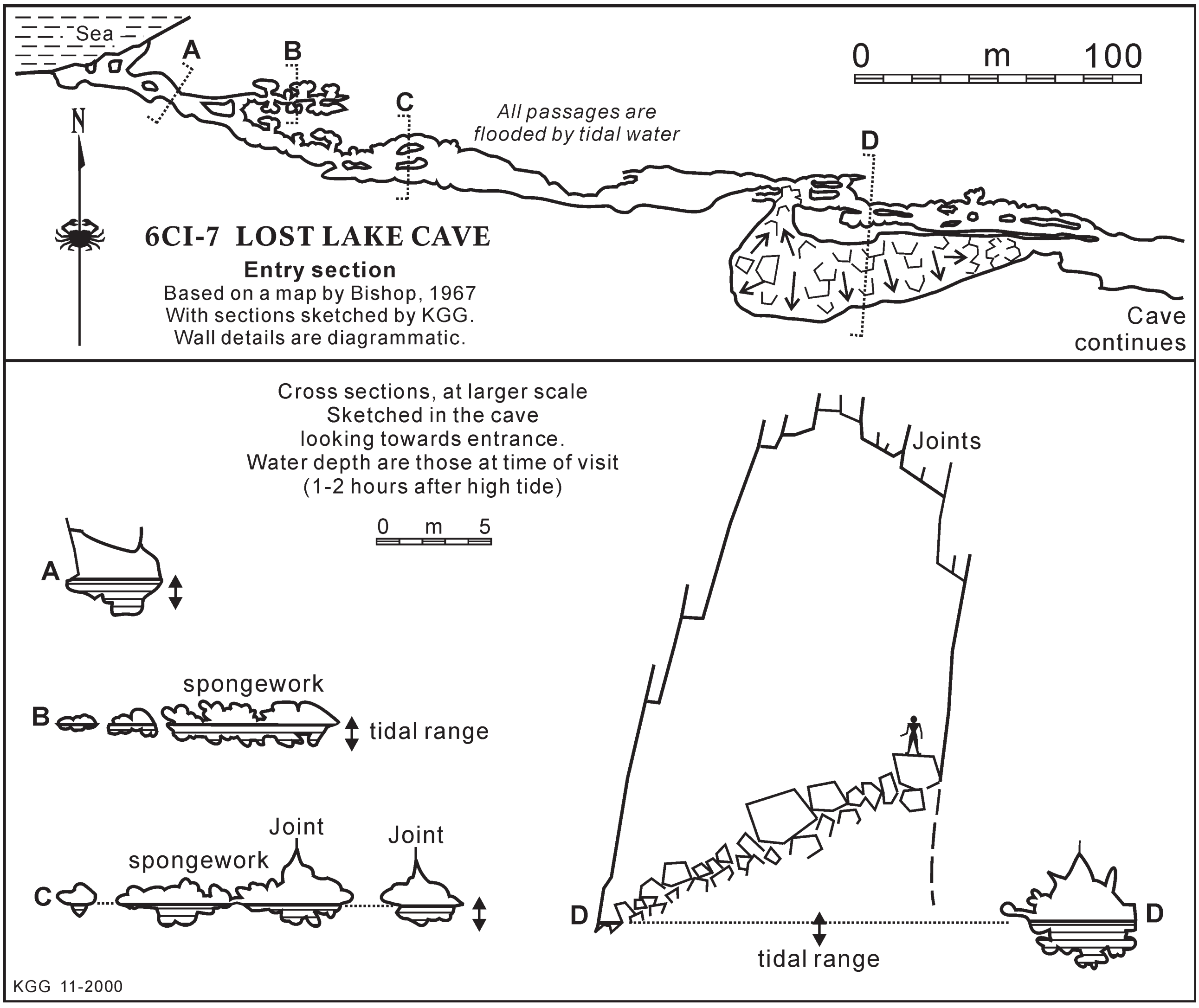

Figure 4: Map & cross-sections of part of a typical coastal cave (Entrance part of CI-7). Showing joint-controlled passages with phreatic spongework walls, and large collapse chambers. For full map see inset in Figure 2.

**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.

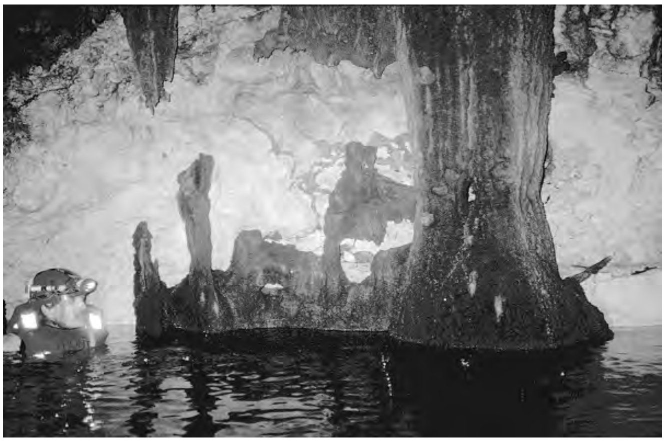

Photo 8: Brown, partly re-dissolved speleothems in Lost Lake Cave (CI-7) continue at least 6 m below sea level. (Photo A.P. Spate)

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.

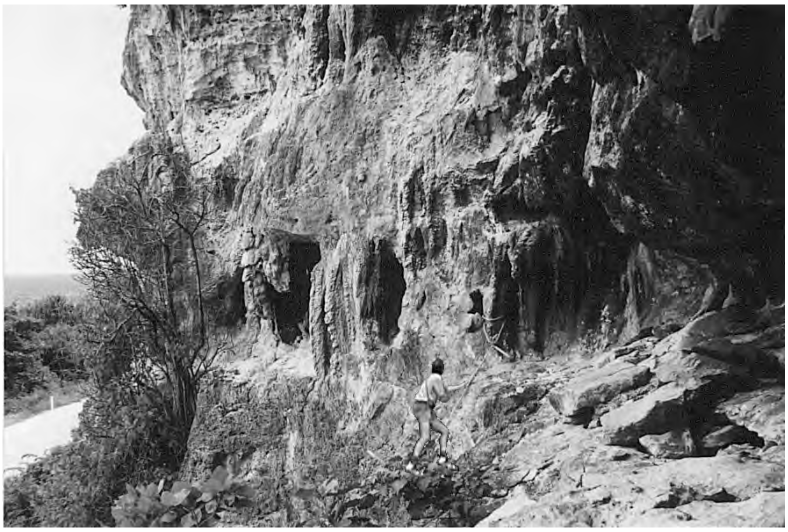

Photo 9: Indian Cave (CI-31). A line of alcoves in an old sea cliff, about 8 m above the Shore Terrace (in background).

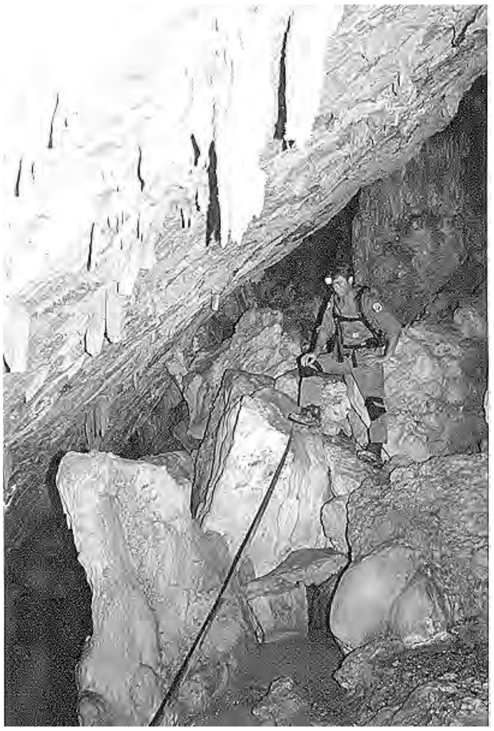

Photo 10: A fissure cave (Runaway Cave, CI-2). Note smooth planar hanging wall and rubble floor of foot-wall; and the power cable that runs to an abandoned water pump.

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.

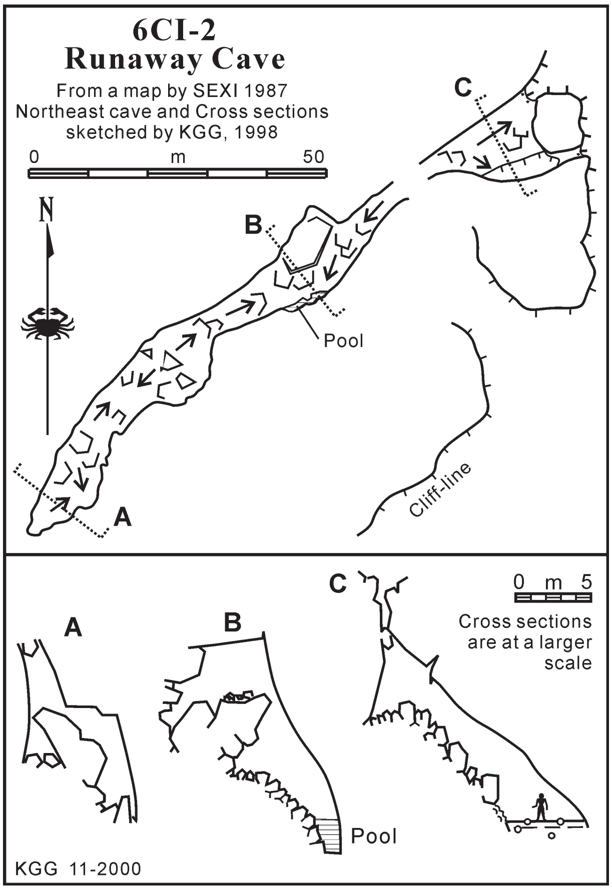

Figure 5: Map and sections of a typical fissure cave.

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

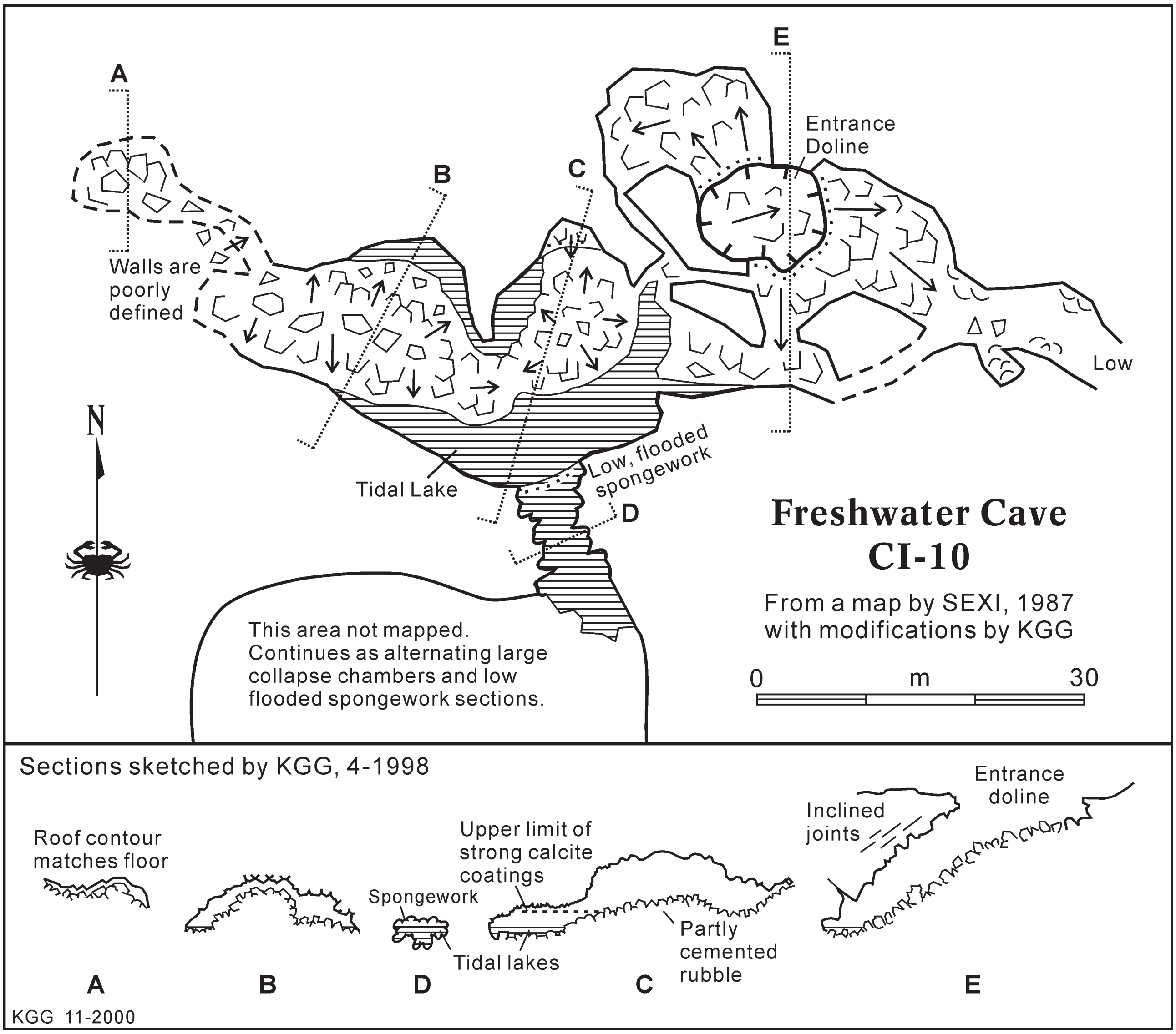

Figure 6: Map and sections of a typical collapse-dominated cave (northern part of CI-10).

(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).

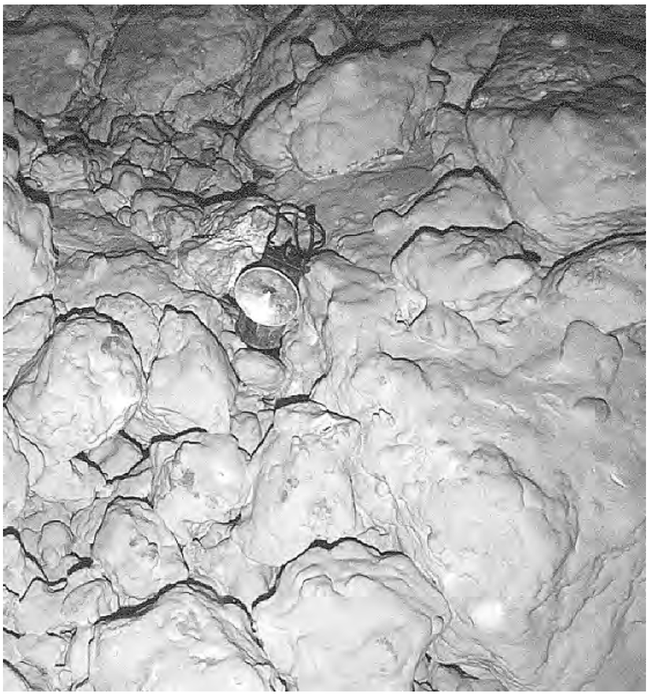

Photo 12: A rubble mound in the intertidal zone of CI-10 that is cemented and coated by calcite deposits.

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

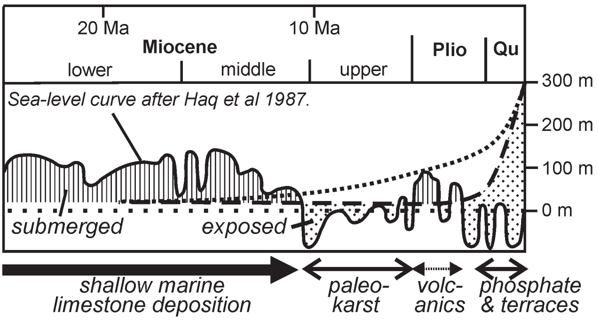

Figure 7: Past sea levels and uplift scenarios. Possible periods of exposure of the island can be estimated by comparing uplift rates to the global sea-level curve. Dotted and dashed lines are two versions of the elevation of Murray Hill through time. In the dashed version, uplift is concentrated in 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.

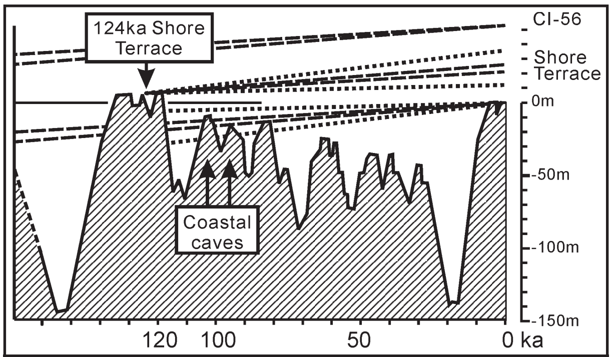

Figure 8: Deducing time of coastal cave formation from the interaction of uplift rates and past sea levels. The uplift rates (with error range dotted) are first deduced from the present elevations of the Shore Terrace, which formed 124 ka ago. That rate is then used to extrapolate back from the present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

## ACKNOWLEDGEMENTS

Parks Australia North (PAN, now Environment Australia) financed the field study, provided accommodation and logistic assistance in the field, and gave permission to publish this paper. Paul Meek, of PAN, was the main instigator in conceiving the study and getting it approved. My fellow members of the study team were Andy Spate, Rauleigh Webb, Bill Humphreys, Stefan Eberhard and Dan O'Toole. They and members of PAN are thanked for their assistance in helping me exit Lost Lake Cave after breaking my ankle! Peter Barrett of Christmas Island Phosphates gave access to company records and discussed the island geology and hydrology with me. The cave maps and other information compiled

by the early cave explorers on the island (e.g. Dave Powell and Ray Bishop) were invaluable, as were the maps and information compiled by members of the SEXI 87 expedition. Those maps were re-compiled by R.Webb for our use. The following provided critical comments on the manuscript as it developed: David Lowe, Bill Humphreys, and Armstrong Osborne. Andy Spate and Rauleigh Webb supplied some of the photographs; the remainder are my own. Grimes Cave (CI-53) has nothing to do with this author—the name dates back to the 1960s at least (e.g. Powell, c.1967).

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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."