Assesment of the Ecological Values and Management Options for Cave Use on Christmas Island

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A report prepared for Parks Australia North

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Western Australian Museum, Francis Street, Perth, Western Australia 6000

Cover photograph: The cave scorpion *Liocheles* sp. nov. Photo: Stefan Eberhard, W.A. Museum.

EXECUTIVE SUMMARY

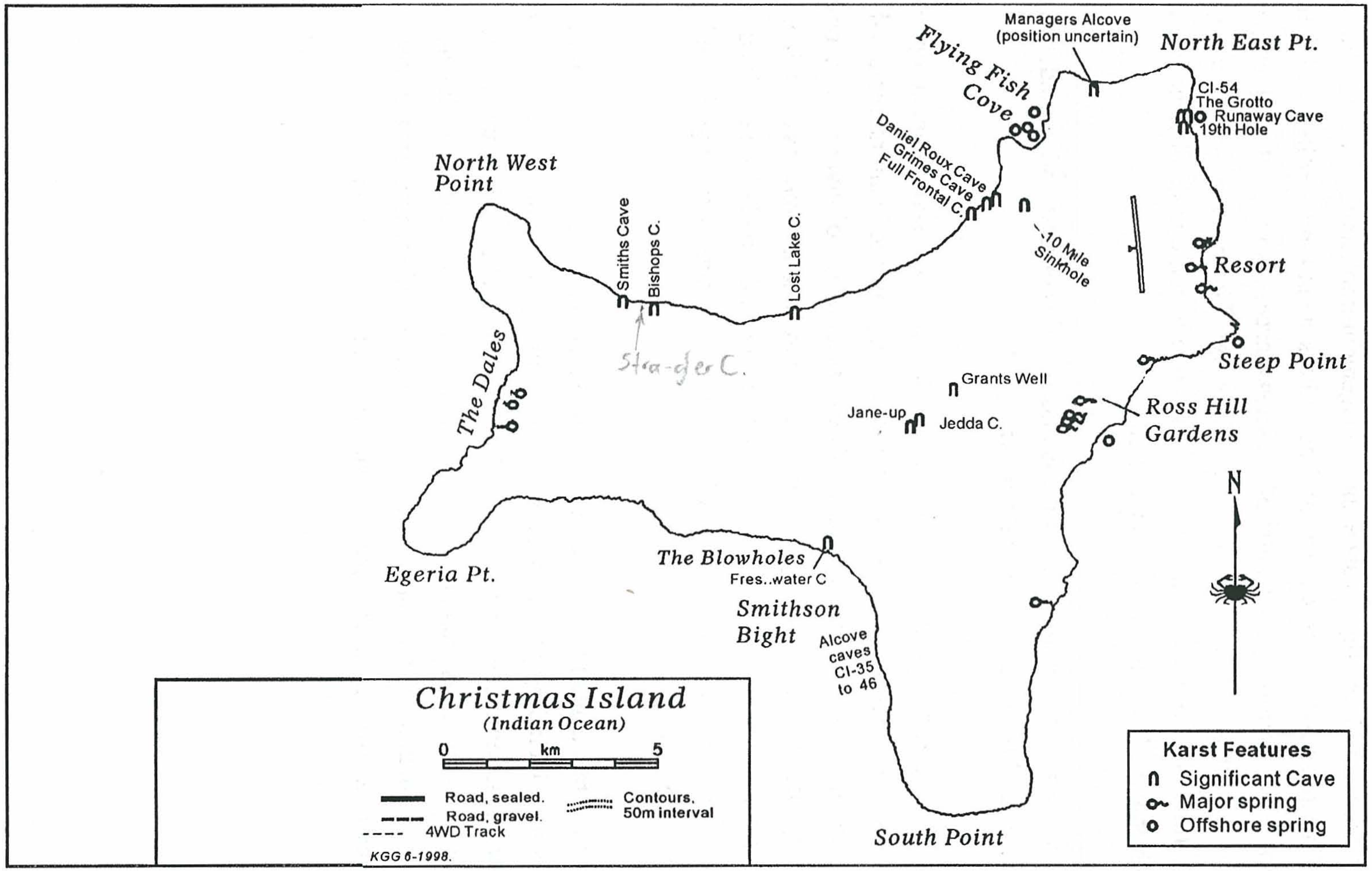
Following a brief from Parks Australia North, a survey was conducted to determine the existence, affinities, significance and management implications of any subterranean fauna on Christmas Island (Indian Ocean). The authors spent three weeks on Christmas Island in April 1998 examining a selection of the known access points to the subterranean environment such as caves, boreholes and springs. These were sampled using visual searching, trapping, haul netting and fixed nets, and some basic physico-chemical environmental parameters were measured.

The subterranean environment of Christmas Island is diverse and includes freshwater, marine, anchialine, and terrestrial habitats.

Previously poorly known, the cave fauna is shown 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 term of its subterranean fauna.

The cave fauna and habitats are sensitive to disturbance from a number of threatening processes, including pollution, deforestation, mining, and human visitors. Management recommendations are given for each of these threats. The major internal threat to cave fauna and habitats is human visitors. 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.

Figure 1: Map of Christmas Island showing the main locations referred to in the report. Drawn from a base map by K.G. Grimes.



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1. INTRODUCTION

This report has been prepared in response to a brief from Parks Australia North which reads as follows:

- survey the biota of accessible caves, bores and springs and report on endemic, native and introduced organisms;

- assess and rank each cave according to its biospeleological values on an international scale; and

- assess the health of, and record the impacts on the caves and habitat with reference to potential threatening processes.

The authors spend 18 and 21 days respectively on Christmas Island variously in the company of Messrs. Rauleigh Webb, Andy Spate, Ken Grimes and Dan O'Toole, who were working to their own briefs concerned, in pairs respectively, with karst management issues other than fauna, and issues of geotechnical stability and cave safety. We had close liaison with and assistance from personnel of Parks Australia North.

The time spent in the field permitted about half the known caves to be sampled. Owing to the close integration of caves and groundwater in karst terrains it was felt necessary to examine groundwater fauna, together with waters directly accessible from caves themselves, in order to obtain an adequate understanding of the subterranean communities.

Identification of the specimens collected is far from complete, as the description of new taxa is a long process. Nonetheless, the location of Christmas Island and the nature of its subterranean fauna is of sufficient interest to have attracted the cooperation of numerous taxonomic specialists (see Appendix 4 and Acknowledgments).

Technical terms used in the report are dealt with in a glossary (Appendix 1).

The report consists of six main sections:

- a background to biospeleology and methods;
- a review of threatening processes and impacts on cave fauna;
- a review of strategies in conservation;
- a description of habitats and cave communities on Christmas Island;
- the threatening processes and impacts on the cave fauna of Christmas Island; and
- cave management issues.

To this are added appendices comprising a glossary, photographs, a cave list and an annotated fauna list.

As well as addressing the fauna itself, we have reviewed pertinent literature to provide a background understanding to managers of the issues, knowledge and uncertainties surrounding subterranean fauna, its ecology, conservation and management.

2. ACKNOWLEDGMENTS

A broad scale survey of this type can only be bought to a successful conclusion with the help of numerous people over and above those principally involved. We acknowledge the support, discussions and information provided, on Christmas Island by Paul Meek, Holger Rumff , Peter Barrett, Bryan Edwards, Ron de Cruz, and Parks Australia North staff; in Perth by Julianne Waldock expedited the dispatch of specimens to specialists for determination, and numerous staff at the Western Australian Museum who discussed with us their knowledge of Christmas Island and its fauna.

Numerous specialists have contributed to or are still determining specific taxa:- Professor Geoff A. Boxshall FRS, The Natural History Museum, London (Copepoda); Dr John Bradbury, University of Adelaide (Amphipoda); Dr Satish C. Choy, Water Resources Technical Centre, Rocklea, Queensland (Atyidae); Professor Bruno Condé, Université de Nancy, France (Campodeidae); Dr D.L. Danielopol, Institut for Limnologie, Austrian Academy of Sciences (Ostracoda); Dr Christa Deeleman, Ossendrecht, The Netherlands (Pholcidae); Dr Penelope Greenslade,

CSIRO, Division of Entomology, Canberra (Collembola); David Morgan and Howard Gill, Murdoch University, Perth (Fish); Sue Morrison (fish) and Dr Mark S. Harvey, Western Australian Museum, Perth (Chelicerata); Dr Louis Kornicker, National Museum of Natural History, Washington, U.S.A. (Ostracoda); Dr Daniel Otte, The Academy of Natural Sciences of Philadelphia, USA (Gryllidae); Professor Giuseppe L. Pesce, University di l'Aquila Italy (Copepoda: Cyclopoidea); Dr Adrian Pinder, Department of Conservation and Land Management, Perth (vermes); Dr David C.F. Rentz, CSIRO, Division of Entomology, Canberra (Orthoptera); Dr Robert Raven, Queensland Museum; Dr L.M. Roth, Museum of Comparative Zoology, Harvard University, USA (Blattodea); Professor William A. Shear, Hampden-Sydney College, Virginia, USA (Diplopoda); Mr John W. Short, Queensland Museum, Brisbane (shrimps); Shirly M. Slack-Smith, Western Australian Museum, Perth (Mollusca); Dr Graeme Smith, Bayer Australia Ltd., Pymble NSW (Thysanura); Dr Stefano Taiti, Consiglio Nazionale delle Ricerche, Firenze, Italy (Isopoda); Ms Julianne Waldock, Western Australian Museum, Perth (Araneae and Myriapoda); Dr Robin Wilson, Museum of Victoria (Polychaeta) and the Identification Service, Australian National Insect Collection, CSIRO, Canberra (various).

3. SUBTERRANEAN FAUNA OF CHRISTMAS ISLAND

> 'Caves on Christmas Island do not appear to have any specially adapted cave dwellers (troglobites), but some organisms normally found on the outside ... do dwell in the dark interior' (Gray 1995: 68).

3.1 BACKGROUND

Subterranean faunas occur in both air- and water-filled underground voids. These voids are best developed and most integrated in karst systems which are themselves best developed in limestone owing to its often high solubility. In consequence, limestone karsts, especially if elevated and of Tertiary age, support the best developed subterranean communities in both aquatic and terrestrial ecosystems. The upper flanks of the Christmas Island seamount comprise Tertiary (and Quaternary) limestone karst.

3.1.1 Cave adaptations

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' (**Ac**) may survive for some time they do not reproduce underground. Trogloxenes (**Tx**) spend part of their life cycle in caves. For example, cave crickets (Rhaphidophoridae) and some bat species spend the day in caves and emerge at night to seek food, while Glossy Cave Swiftlets shelter and breed in caves. All are influential in transporting food energy into caves through their excreta and carcasses - bat and bird excreta may form the basis of distinct guano communities. Guanophiles (**Gp**) are invertebrates which dwell specifically on guano deposits while other cavernicoles exploit guano opportunistically (review Gnaspini and Trajano, in press).

Troglophiles (**Tp**) are species found outside caves as well as inside caves, but are able to complete their entire life cycle within caves. First level troglophiles (**Tp1**) are species known to occur in above ground (epigean) habitats, and second level troglophiles (**Tp2**) are species that have never been found outside caves but which display no obvious adaptations to cave life (Hamilton-Smith, 1971). The Australian fauna seems especially rich in forms that can be classified as second level troglophiles (e.g. Hamilton-Smith, 1967; Humphreys, 1995).

Troglobites (**Tb**) are species which obligatorily spend their entire lives within caves (troglodytes are people inhabiting caves). Troglobites are highly specialised 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 specialisation, and because they are frequently found to be relicts which have survived in underground refugia long after their surface dwelling ancestors have become extinct.

Troglobites display a number of characteristic convergent morphological traits. These include both the reduction or loss of characters (regressive evolution), such as the loss of eyes, pigment, sclerotization and wings, as well as 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 and these traits are variously thought to be adaptive to underground life or neutral (for full coverage see Culver, Kane and Fong, 1995; papers in Wilkens, Culver and Humphreys , in press). The degree of expression of troglomorphies may reflect different cave ecologies, the relative dependence of a species on the cave and the time since the lineage became isolated in a cave (Slaney and Weinstein, 1996). Such common features in a group of organisms in the same environment may be due to shared inheritance and/or shared environmental pressures. In contrast, similar trends among different organisms occupying disparate island-like habitats, such as caves, are more revealing about general evolutionary forces (Grant, 1998b), and it is in this latter context that troglomorphies are of most interest.

It is convenient to distinguish those subterranean fauna restricted to water with 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 fauna restricted to subterranean air-filled voids (the term troglobites is sometimes used *sensu lato* to encompass all hypogean environments). Such faunas are typically locally endemic — troglobites typically have more restricted ranges than do stygobites — and can be highly diverse (e.g. Holsinger, 1978; Holsinger and Culver, 1988; Bradbury and Williams, 1997a, 1997b; Humphreys, in press b).

3.1.2 Previous fauna collections

Fauna and flora collections, including invertebrates, were made from the time of the initial landings on Christmas Island and provide, especially Andrews (1900), a substantive base on which to observe qualitative changes to the biota. Principle amongst the early collections are those of the officers of H.M.S. Flying Fish (January 1887), J.J. Lister (September 1887), C.W. Andrews (August 1897 to May 1898, and 1908), W.F. Tweedie (August and September 1932), C.A. Gibson-Hall (September 1938 to November 1940), and T.G. Campbell (1964), who concentrated on target groups of likely applied significance. However, no substantive collection of cave animals has previously been available for examination. In 1987 an expedition from the Western Australian Speleological Group visited Christmas Island but the fauna collection made was recovered only recently when it was transferred to the Western Australian Museum (16/1/1996); only three specimens could be salvaged, a new species of scorpion collected by N. Plumley, 11 August, 1987 in Bishops Cave, and a louse and mites from the plumage of a Glossy Cave Swiftlet. P. Meek, of Parks Australia North, collected *Macrobrachium microps* and *Eliotris fuscus* from caves in 1996.

3.1.3 The nature of the epigean fauna

The fauna of tropical caves largely comprises lineages characteristic of forest floor leaf litter communities (Harvey et al., 1993; Humphreys, 1993; Deharveng, in press). The leaf litter on Christmas Island is sparse owing to its utilisation by dense populations of land crabs of several species. In studies of the effects of crabs on the vegetation of Christmas Island, Green (1994) found that 87% of the leaf litter fauna was made up of only three major taxa: pulmonate snails (42%), collembola (26%) and mites (19%: n=4751). The consumption of fallen leaves by crabs reduced the density of these invertebrates from about 3000 m^{-2} to 400 m^{-2}. This intense competition for fallen leaves may be relevant to the colonisation of the subterranean environment on Christmas Island and the subsequent onset of troglogenesis, the evolution of troglomorphies.

3.2 CLIMATE

The climate of Christmas Island is dealt with in detail elsewhere, with the rainfall being well covered by Falkland (1986). The climate is seasonal with the area coming under the influence of the north-west monsoon from December through April, when most rainfall is experienced, and the south-east trade winds for the rest of the year. The mean annual rainfall of 2109 mm masks the high variability that results from the impact of the El Niño/ Southern Oscillation (ENSO) on the island.

Rainfall in the 14 months preceding sampling was only 55% of the average owing to an ENSO event. This low rainfall was reflected in the caves by cracking cave soils — even at the end of the usual monsoon period — a sign elsewhere, that the soil is too dry to support troglobitic fauna (Cape Range, Kimberley; W.F. Humphreys, unpublished).

There were signs in some caves — especially Jane Up and Jedda, principally in the form of dead millipedes, *Cylindrodesmus hirsutus* — that the fauna has in the past been much more widespread through the caves. In other regions such relatively dry periods reduced the range of species recovered from the caves as the fauna tends to retreat into the finer crevices and voids inaccessible to people (Humphreys, 1991). This attribute is the basis of the artificial rewetting method used to collect fauna in caves otherwise temporarily unsuitable, a period which in some places may last several years (Humphreys, 1991; *ibid.*).

In consequence, for this reason alone, it is likely that a much more extensive troglobitic fauna occurs on Christmas Island than is recorded here. In addition, further collecting in known caves, as well as in yet unsampled or unfound caves, is likely to result in the collection of additional troglobitic species. Experience elsewhere has shown that additional collecting in known caves continues to yield additional species for prolonged periods, even in small caves such as C-15 in Cape Range (figure 2: although see Deharveng, in press).

3.3 METHODS

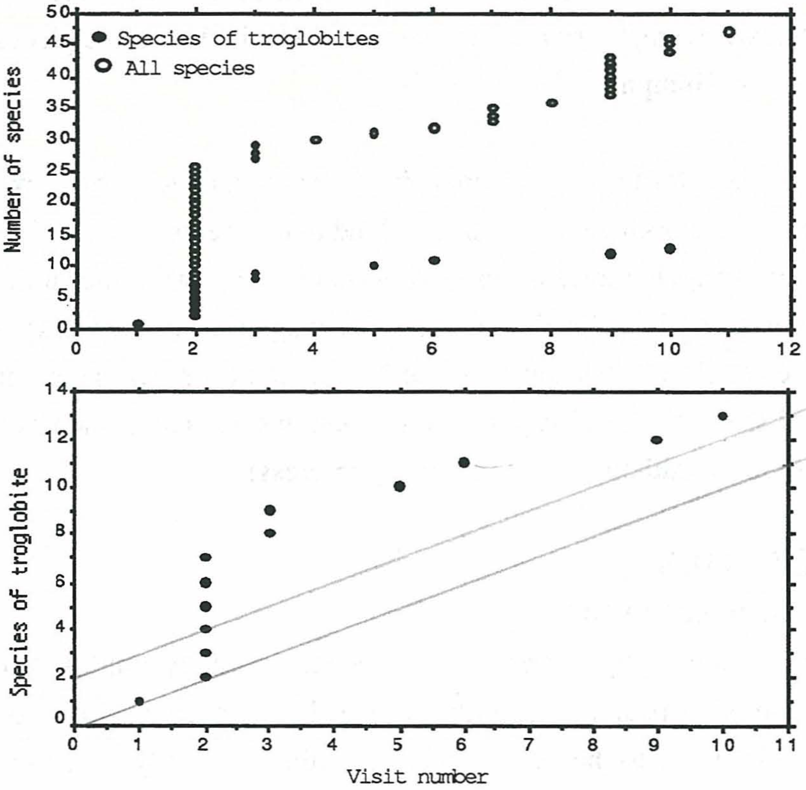
3.3.1 Fauna sampling

Fauna were sampled by a variety of methods traditionally employed in caves and groundwater sites (Camacho, 1992; Pospisil, 1992), but some methods, which require return visits to the sites — such as baiting — mostly were precluded by constraints of time. Visual searching was predominantly employed in caves and is the standard method used to find the sparse animals typically encountered there, at least away from guano piles. Guano samples were collected and examined for fauna in the laboratory.

Access to the groundwater was obtained through caves, springs and boreholes. It was sampled by handnet following visual sighting of fauna, 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 (photo.

A2.5) and on spring outlets for 24 hours or more. A net was held over the intertidal conduit outlet in Daniel Roux Cave briefly but its location low in the intertidal zone precluded long term sampling without custom designed fittings.

Figure 2: Cumulative number of new species found in a small cave, C-15, in Cape Range, Western Australia, by sampling visit. The sampling visits occurred between 16/6/1989 and 19/8/1997. The lower figure shows the detail of the troglobites alone (W.F. Humphreys, unpublished).



3.3.2 Physico-chemical

Relative humidity was determined using a whirling hygrometer (Brannon, England) and calculated from tables. Atmospheric oxygen and carbon dioxide concentrations were determined using air quality tubes connected to a sampling pump (Drägerwerk ag Lubeck — O_2 5-23% ISO 9001; CO_2 0.5-10% ISO 9001).

Physico-chemical parameters in the water were determined either *in situ* or on samples returned promptly to the laboratory using electronic instruments — pH using a WTW pH 320 meter with a SenTix 97T pH-combined electrode with integrated temperature sensor and redox probe and dissolved oxygen using a WTW Oxi 320 meter and a CellOx 325 oxygen sensor (Wissenschaftlich-Technische Werkstätten GmbH, Weilheim, Germany). Conductivity was measured with a TPS Model LC 84 conductivity meter (TPI Electronics, Springwood Queensland). All were calibrated as specified using the recommended standards.

Statistical errors are given in the form mean ±standard error, sample size unless otherwise specified.

3.4 SAMPLE SITES

3.4.1 Aquatic

Access to groundwater was more limited than expected from the literature. Most of the large number of groundwater exploration bores drilled on the island (Barrett, 1985; Falkland, 1986) are no longer present or their locations have been lost from the corporate knowledge. The few bores located (photo. A2.6) were sampled where possible but the two deep bores within the settlement that penetrate the saltwater interface could not be sampled — one is fitted with a swan neck and is used for storm water discharge from Silver City into the deep karst while the second, in Poon Saan, is fitted with multilevel piezometers (35 mm OD) which could not be sampled effectively (photo. A2.2).

Access to the groundwater was achieved on the plateau in the underground streams at Jane Up Cave, Jedda Cave and Grants Well and remotely at Water Bore 30—these are all on the same underground stream system (Barrett, 1985).

A series of five bores was recently established in the Smithsons Bight area to aid interpretation of the groundwater flow in the area that is considered to have the best prospects for groundwater supplies. Some of these large diameter bores penetrate below sealevel and some penetrate the saltwater interface but they are fitted with multilevel piezometers of 35 mm OD PVC tubing. These were sampled but these small diameters bores cannot be effectively sampled by the techniques available.

Access to the anchialine systems is available in many of the coastal caves but logistical constraints meant that the main sampling was undertaken at CI-54 (photo. A2.3), Runaway Cave (CI-2), The 19th Hole (CI-19), and Freshwater Cave (CI-10). Two water bores on the coastal plain along Smithsons Bight were located and sampled as these unslotted 150 mm diameter PVC bores offered the prospect of sampling the saltwater interface.

3.4.2 Terrestrial

The caves examined are detailed in the subsequent sections.

3.4.2.1 Guano Caves

Guano from the Christmas Island Glossy Swiftlet, has been reported from Swiftlet Cave (CI-30), an alcove (CI-45), Managers Alcove (CI-50), Grimes Cave (CI-53), Smiths Cave (CI-9) and the upper part of Daniel Roux Cave (CI-56: photo. A2.15). However, swiftlets are widespread on the island (Gibson-Hill, 1947a) and anecdotal evidence suggest other nesting sites on South Point [Smithsons Bight track] alcoves (Brooks, 1990).

3.5 CAVE ENVIRONMENT

Environmental parameters for various air and water variables are presented in table 1

3.5.1 Air

3.5.1.1 Temperature

Within caves the temperature varied according to the location of measurement (e.g. Jedda Cave; 25.2-26.1°C). Cave temperatures did not differ over the island (mean 25.9±0.19°C, 12) and was close to the mean annual surface temperature (MAST). Generally the temperature of deep cave environments approximates MAST, which at Christmas Island is 25.1°C (Meteorological Office, Christmas Island).

3.5.1.2 Relative humidity

The cave humidity was nearly saturated (mean RH% = 97.5±0.88, 14) and did not differ between coastal and plateau systems (P=0.49). The fauna of tropical caves is often dependent on high humidities (Humphreys et al., 1989; Humphreys and Collis, 1989) and the humidities recorded in Christmas Island caves are compatible with troglobitic fauna having tropical rainforest affinities.

Table 1: Physico-chemical parameters recorded from various caves (C) and springs (S) on Christmas Island. ch = chamber.

Location Date	Karst #	Note	DO $mg\ L^{-1}$	DO %	Cond. mS	[1]Temp. °C	pH	DB °C	RH %	CO_2 %	O_2 %	
Runaway C.	CI-2	Water	-	-	-	-	-	27.0	-	-	-	6/4/98
Runaway C.	CI-2	2 m depth	6.67	96.6	8.13	26.5	7.50	-	-	-	-	6/4/98
Runaway C.	CI-2	Surface	7.06	97.7	5.54	26.9	7.99	-	-	-	-	6/4/98
Jedda C.	CI-5	Up-stream in situ	6.10	-	0.56	25.4	7.10	25.2	-	-	-	29/3/98
Jedda C.	CI-5	Upper ch.	-	-	-	-	-	25.9	98	3	17	6/4/98
Jedda C.	CI-5	Mid-ch.	-	-	-	-	-	26.1	99	3	17	6/4/98
Jedda C.	CI-5	Upper big dome	-	-	-	-	-	25.7	99	3	17	6/4/98
Jedda C.	CI-5	Top troglobite ch.	-	-	-	-	-	25.9	98	3	17	6/4/98
Jane Up C.	CI-6	5 m below entrance	-	-	-	-	-	25.5	96	3	18	7/4/98
Jane Up C.	CI-6	1 m above stream	-	-	-	-	-	26.0	98	3	17	7/4/98
Bishops C.	CI-8	Top main ch.	-	-	-	-	-	26.2	99	[2]<0.5	20.0	9/4/98
Bishops C.	CI-8	Water	7.32	107	18.2	27.0	7.32	-	-	-	-	9/4/98
Smiths C.	CI-9	Upper ch.	-	-	-	-	-	26.8	97	-	-	3/4/98
Smiths C.	CI-9	Bottom, main ch.	-	-	-	-	-	24.4	99	-	-	3/4/98
Smiths C.	CI-9		6.18	85	33.2	28.5	7.48	-	-	-	-	3/4/98
Freshwater C.	CI-10	Top doline	-	-	-	-	-	29.2	87	-	-	2/4/98
Freshwater C.	CI-10	Bottom doline	-	-	-	-	-	27.2	96	-	-	2/4/98
Freshwater C.	CI-10	Twilight	-	-	-	-	-	26.8	100	-	-	2/4/98
Freshwater C.	CI-10	End twilight upper	-	-	-	-	-	26.9	99	-	-	2/4/98
Freshwater C.	CI-10	Water level	-	-	-	-	-	26.2	96	-	-	2/4/98
Freshwater C.	CI-10	Water	-	-	-	-	-	25.7	-	-	-	2/4/98
Freshwater C.	CI-10	Water sample	6.92	93.7	0.62	29.0	7.78	-	-	-	-	2/3/98
Strangler C.	CI-16	Upper twilight	-	-	-	-	-	25.6	98	-	-	9/4/98
Strangler C.	CI-16	Lower blind lead	-	-	-	-	-	25.6	100	0.5	19.5	9/4/98
Strangler C.	CI-16	Water	7.46	102	29.2	27.1	7.40	-	-	-	-	9/4/98
The 19th Hole	CI-19	Surface	6.6	94	31.2	27.0	7.60	-	-	-	-	5/4/98
The 19th Hole	CI-19	4.5 m depth	5.05	73	34.4	27.4	7.35	-	-	-	-	5/4/98
The 19th Hole	CI-19	At water level	-	-	-	-	-	-	-	2<0.5	-	14/4/98
Hendersons S.	CI-64		6.69	97.2	0.60	27.5	7.38	-	-	-	-	5/4/98
Hosnies S.	CI-75		6.64	93.2	0.94	26.5	8.46	-	-	-	-	5/4/98
Hughs Dale	CI-77		6.47	98.1	0.71	30.8	7.78	-	-	-	-	8/4/98
Andersons Dale	CI-78		6.36	97.6	0.51	30.7	8.34	-	-	-	-	8/4/98

[1] Temperature at which conductivity was measured. [2] Below detection limit.

3.5.1.3 Carbon dioxide and oxygen

Elevated levels of carbon dioxide were noticed in several caves through its physiological effect on cavers and its effect on naked flames. To distinguish between different causes of carbon dioxide concentration the level of oxygen and carbon dioxide was measured together. Elevated levels of carbon dioxide were seen only in caves on the plateau where it reached 3% of the composition of the cave air; this was matched by similar reduction in oxygen levels. Such replacement carbon dioxide typically results from biogenic oxygen consumption and resulting carbon dioxide production and this is most likely to result from the decay of organic matter in the cave and root respiration. However, in the cave sections large enough for cavers to enter, no large accumulations of organic matter were seen.

3.5.1.4 Conclusion

The cave atmospheres were quite compatible with the presence of troglobitic fauna. Troglobites do occur in high carbon dioxide levels and it has been suggested that they might even prosper under these conditions (Howarth, 1988; Howarth and Stone, 1990), although elevated carbon dioxide levels are certainly not a prerequisite (Humphreys, in press b).

3.5.2 Water

3.5.2.1 Conductivity

Freshwater, from the underground streams on the plateau (0.56 mS cm^{-1}) to their emergence of the springs close to the shoreline (0.69 ± 0.09 mS cm^{-1}, 4), did not exhibit any great changes in their conductivity. However, the mean conductivity in the coastal caves (20.1 ± 4.86 mS cm^{-1}, 8) was considerably greater ($Fs_{1,11} = 9.643$, $P=0.01$) and more variable (C.V.=25.8% and 68.5% respectively), as expected in an anchialine system.

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; Yager and Humphreys, 1996).

3.5.2.2 Dissolved oxygen

The mean DO level was 6.58 mg L^{-1} and did not differ between water types such as anchialine, underground streams and springs ($p=0.72$).

3.5.2.3 pH

The pH of the anchialine system (pH 7.55±0.08, 8; C.V.=3.0%) was lower and less variable than that from the freshwater systems (pH 7.81±0.26, 5; C.V.= 7.6%).

3.5.2.4 Conclusion

The physicochemical environment should not preclude stygofauna. Although limited data are available for the water quality, those measured are compatible with the presence of both freshwater and anchialine stygofauna (Humphreys, 1994; Yager and Humphreys, 1996; W.F. Humphreys, unpublished). Some of the latter are tolerant of a wide range of physicochemical conditions while being extremely sensitive to certain types of pollution.

3.6 DISCUSSION

3.6.1 Origins of the cave fauna

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, its size, likely colonisation routes, proximity of other land masses, prevailing and intermittent winds and ocean currents, and the characteristics of the lineage in question.

3.6.1.1 Age of the exposed landmass

There are a number of types of evidence that can be considered to determine the age of the land above sea level. These include the sea level curves, the date that phosphatisation occurred (>200 ka — Veeh, 1978, 1985) and rates of uplift of the island from the date of the shore terrace (c. 124 ka — Woodroffe, 1988; Veeh, 1985). There is evidence of volcanism in the Pliocene (range 3 to 5 Ma — Fallon et al., in prep. cited in Borissova, 1994) of a form suggesting subaerial deposition. The main limestones were laid down in shallow water with fossil dates (Adams and Belford, 1974) from the Late Oligocene (26 Ma).

K. Grimes (personal communication, 1998) reviewed this evidence to delimit the period when the island has been above sea level. The existence of the terraces suggests the island was above sea level for much of the Quaternary. He 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 Oliogocene (26 Ma — shallow water limestones).

3.6.1.2 Size

Owing to the steep submarine slopes on the island, the exposed landmass would never have been substantially larger but at times could have been both much smaller — even submerged— and fragmented, if, as suggested (Barrie, 1967), an atoll was present.

3.6.1.3 Source areas

The fauna colonising an island from a nearby mainland is the resultant of the combined filtering effects of, *inter alia*, biology, currents, distance, area and stochastic events (see Grant 1998a). The biological characteristics of most cave invertebrates, particularly troglobites, make it unlikely that they would have passed through these filters and have been transported between landmasses. Cave adapted 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).

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 although the isolating mechanisms normally proposed (Humphreys, in press b) may not be present on Christmas Island.

The present flora will be an integral, *inter alia*, of the effects of wind, oceanic and animal transport and will serve as a paradigm for the cave fauna. The vegetation on Christmas Island has predominantly Indo-Malesian affinities, with many species having distributions extending from Southeast Asia through Malesia 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 recognised 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 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.

Other than in a general sense, the affinities of the cave fauna on Christmas Island cannot be determined at this stage owing to the lack of phylogenetic information on the lineages present. In any case, the convergent morphologies that result from the development of the troglomorphies often make phylogenetic and historical biogeographic inference especially intractable in the absence of molecular data.

3.6.2 Identification of troglomorphies

Organisms inhabiting islands, in common with those inhabiting caves — and other island-like settings such as lakes, bogs and mountain tops — have a number of evolutionary responses in common. Compared with their mainland or epigean counterparts, there is a strong tendency to increased size, reduced dispersal ability (e.g. loss of wings), reduced clutch size and a concomitant increase in brood care and, possibly, at least for islands, a trend for broader ecological niches, increased hybridisation and enhanced morphological variation (Grant, 1998b). Hence, some apparent troglomorphies found on islands may be a result of changes to the lineage resulting from these trends prior to cave colonisation, rather than resulting from cave induced changes. However, a number of other troglomorphic characters are not also found to occur on island populations and these probably relate to the environmental attributes in caves that are not shared by islands *per se*. These include, reduction or loss of eyes and the concomitant enhancement of non-optic sense organs, elongation of appendages, and a reduction in the skeleton and body pigments.

Three types of eyeless species (Peck, 1994) may be expected on Christmas Island.

- Species introduced by people.

- Eyeless species in widespread eyeless lineages whose ancestors would have dispersed to Christmas Island in an eyeless condition.

- Eyeless (and reduced-eyed) species which have evolved from eyed-epigean relatives now living in Christmas Island.

- Eyeless (and reduced-eyed) species with no known ancestors on Christmas island, and which are probably relicts of an older or extinct fauna.

The first two can be distinguished from a general knowledge of the lineages to which the taxa belong. The latter two require a good knowledge of the epigean invertebrate fauna on Christmas Island, which generally is lacking.

3.6.3 Richness of the cave fauna compared with other oceanic islands.

Globally there are about 7725 species exclusively known from underground habitats (both troglobites and stygobites) belonging to 70 orders. Of these about 0.9% are vertebrates (fish and amphibians), 32% Crustacea, 32% Insecta, 20% Arachnida, 3% Myriapoda and 11% other classes (Juberthie, in press).

The richness of local faunas to some extent reflects the amount of biospeleological work conducted in an area and the intensity of taxonomic treatment. For example while many karst regions in North America have been the focus of generations of researchers and their graduate students, Cape Range, Western Australia, by contrast, has received sparse attention, and only within the past decade.

Tropical cave fauna are notable for the high proportion of non-troglobitic species inhabiting caves, in Southeast Asia ranging from 70-81% of all species (Deharveng, in press).

At the present stage of knowledge there seems, provisionally, to be at least six troglomorphic and six stygomorphic species known from Christmas Island (Table 3), a number that will certainly increase with further research. There is also a greater number of cave inhabiting species whose dependence on the caves is unknown at this stage. While this does not place Christmas Island in the most species rich category of islands with respect to troglomorphic species (table 2), 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.

3.7 CAVE FAUNA OF CHRISTMAS ISLAND

Collections of this type always run into problems of identification for various reasons, often due to the global lack of specialists working on a particular group — a number of pertinent ordinal level taxa have no, or at most one or two, currently active specialists worldwide many of whom are working well into retirement and nobody is being trained to fulfil their role. While specialists are sometimes prepared to work on the more interesting species — in terms of morphological adaptation to caves or distributional or phyletic relictual taxa (Humphreys, in press a) — more mundane species usually have to await major systematic revision of their lineage.

For this report most effort has been placed into trying to obtain information on those taxa most closely identified with caves, rather than species whose association with the caves is looser, even accidental.

An annotated listing of the currently established cave fauna of Christmas Island is given in appendix 4. Here we present a brief synopsis of the salient characteristics of

Table 2: Approximate numbers of recognized subterranean species from various islands. Extracted from compilations in Juberthie and Decu (1994), Deharveng, in press. ·tropical locations. The figures in brackets denote the percentage of all species that are troglobites. Australian sites are underlined.

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
[1]La Palma: Canary Islands	19	2	21
Azores	16	-	16
[1]Lanzarote: Canary Islands (lava tube)	-	15	15
·Christmas Island[3]	6	6	12
[1]Hierro: Canary Islands (lava tubes)	8	1	9
[1]Fuertoventura: Canary Islands	1	5	6
[1]Gomera: Canary Islands	4	2	6
·Virgin Islands: Netherlands Antilles	-	4	4
·Mona Island: Netherlands Antilles	2	1	3
[1]Gran Canaria: Canary Islands	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.

the cave fauna (table 3) and of fauna with significant or unusual biogeographical, evolutionary or conservation attributes (table 4). Numerous species are newly recorded on Christmas Island and at least 12 species and a (?two) genus new to science are recorded.

Table 3: Synopsis of the cave fauna of Christmas Island.

Terrestrial	**Aquatic**
Papuaphiloscia undescribed sp. Tp2	Microturbellaria. ?Sb
Nocticola-like undescribed gen. et sp. Tb (photo. A2.7)	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 undescribed sp. Tb Scorpion (photo A2.10)	Alpheidae ?Sb several species.
Charon undescribed sp. Harvey and West, in press. Tp1	*Procaris* undescribed sp. Sb
Gnaphosidae, undescribed sp. 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	
Diptera, indet. Gp	
Myrmecophilidae Tp (?inquilines)	
Collocalia esculenta natalis Lister, 1888. Tp1	

3.7.1 Terrestrial

A number of cave associated animals was recorded from Christmas Island. These comprise six troglobites, a number of troglophiles and three of more guanophiles (table 3). A number of species occur of uncertain cavernicolous association (Appendix 4). Undoubtedly, many addition taxa remain to be found.

3.7.2 Aquatic

About 12 stygobiontic species were recorded from Christmas Island but the extent of troglomorphies at this stage is largely unknown. These comprise more than seven species found in the anchialine systems, and more that six species from freshwater

Table 4: Synopsis of fauna with significant or unusual biogeographical, evolutionary or conservation attributes (from Appendix 4).

- A second species of *Nerilla* (Archiannelida: Nerillidae) from Australia.
- Subterranean forms of Aphanoneura (Annelida) are only 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. (photo. A2.14)
- *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. (photo A2.12)
- 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. (photo A2.11)
- indet. (Araneae: Gnaphosidae). Eyeless troglobitic spider of a family where only three other troglobitic species are known, from Cuba and the Galapagos.
- *Liocheles* sp. nov. (Scorpionida: Ischnuridae). The first blind scorpion known from Australia and the second outside the Americas where 12 species occur. (photo A2.10)
- *Charon* sp. nov. Harvey and West, in press (Amblypygi: Charontidae). This new species will probably be found in Java. (photo. A2.8)
- 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 Queensland .(photo A2.11)
- gen . et sp. nov. (Blattodea: Nocticolidae). This new troglobitic genus.
- *Balta notulata* (Stoll) (Blattodea: Blattellidae). New record for Christmas Island. (photo. A2.7)
- indet (Orthoptera: Grilloidea: Myrmecophilidae). An ancient family that live off the secretions of ants as inquilines in ant nests.
- *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) (Cyprinodontiformes: Cyprinodontoidei: Poeciliidae). Introduced.
- *Collocalia esculenta natalis* Lister (Aves: Apodiformes: Apodidae), Christmas Island glossy swiftlet. Cave inhabiting.

(Appendix 4). Undoubtedly, many addition taxa remain to be found, and the complexities of the anchialine system remain to be unravelled.

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* (photo. A2.12) is always recorded with another ancient family, the Atyidae, wherever it is found (only known from Bermuda, Ascension Islands, Hawai'i and Christmas Island).

The anchialine system on Christmas Island is of great significance and, owing to the location of the best known area, potentially vulnerable to future developments. The known number of anchialine sites on Christmas Island is small (cf. 520 anchialine ponds on Hawai'i of which 70% occur in 53 km of the Kona coast: Brock et al., 1987). Generally few anchialine systems have been identified in the southern hemisphere, of which only one, the Cape Range peninsula in Western Australia, is continental (see Iliffe, in press: fig. 1).

To provide appropriate management information the anchialine system needs to be examined in more detail to:
- provide additional or appropriate material for taxonomic work (very few specimens, often immature, were obtained in 1998),
- obtain a better representation of the diversity of the anchialine fauna,
- obtain some understanding of the physico-chemical conditions inhabited by the various species,
- determine whether the energy source is of marine, terrestrial, or, as found in some anchialine systems (Pohlman et al., 1997; Pohlman et al., in press) of chemoautotrophic origin.

4. GENERAL REVIEW OF THREATENING PROCESSES AND IMPACTS TO CAVE FAUNA

Owing to a paucity of earlier baseline data, and until recently a general lack of impact-related studies undertaken in Australia, it has proved difficult to quantify and predict precisely the effects of various human activities on cave fauna. Nevertheless, there are numerous examples where human activities have caused the local extinction of fauna, or where they have been seriously degraded or compromised. Many sites remain vulnerable to a range of threatening processes that include quarrying and flooding, land clearance (deforestation) and agricultural activities (crop-raising and stock raising) and forestry. The nexus between land clearance and agricultural activities is the most widespread and insidious threat on mainland Australia, affecting cave microclimates, nutrient inputs, hydrological regimes, and water-quality. A further threat to cave communities is direct disturbance caused by cave visitors, guano miners, cave management and research activities. In this general review they are commented upon here only briefly, having been extensively covered elsewhere (Hamilton-Smith and Eberhard, in press), and specific examples from Christmas Island are treated separately later (Section 7).

4.1 QUARRYING AND FLOODING

A number of caves, along with their resident fauna, have been obliterated through quarrying activities, whilst others have been inundated following the construction of water impoundments. One of these sites, Mt Etna, was the focus of a high-profile conservation campaign lasting 25 years that was finally settled in the law courts (Sprent, 1970; Hamilton-Smith and Champion, 1975; Bonyhardy, 1993), whilst another, Sellicks Hill Quarry Cave, was the subject of a parliamentary enquiry (Parliament of South Australia, 1995) and litigation, but the future of the site remains unresolved (Buswell, 1994).

A number of sites were lost before the importance of karst and cave communities was recognized beyond the speleological fraternity. Texas Caves in Queensland for example, was the type locality of an endemic troglobitic silverfish (Smith and Shipp, 1978) and other undescribed invertebrates, but they were inundated by waters of the Glenlyon Dam (Archer, 1978). Quarrying of karst has occurred, and is still occurring, at Flowery Gully in Tasmania, Lilydale in Victoria, Marulan in New South Wales, Cape Range in Western Australia, and elsewhere.

However, there have been a number of examples where cave fauna have been a contributory or major factor in determining land use decisions. For example, cave faunal values were a significant criterion in the decision to include Exit Cave within the boundaries of the World Heritage area in South-west Tasmania. Then in 1992, evidence of the deleterious impacts of quarrying upon this fauna was a major consideration in the decision to close the quarry concerned. Subterranean fauna are also a major factor in land use and environmental assessment in Cape Range (EPA, 1998; Hamilton-Smith et al. 1998; Planning Commission, 1998).

Many other limestone quarries are not known to have impacted upon caves (Gillieson 1989: 48-49), and there are large resources of non-cavernous limestones scattered throughout the country. Nevertheless, a number of highly significant karsts continue to be placed under considerable pressure for mining development, owing to their geographical proximity to population centres or the limestone quality, as well as other economic and political considerations. At the time of writing, a proposal for quarrying over part of the highly significant Cape Range karst has been approved by the Western Australian government. Further protection of this region, or any other cave faunal site, is hindered by the universal problem of inadequate recognition being accorded to invertebrate communities by political and administrative decision-makers (Hill and Michaelis, 1988).

4.2 LAND CLEARANCE AND AGRICULTURAL ACTIVITIES

Land clearance (deforestation), and agricultural activities (crop-raising and stock-

raising) and forestry are the most common and widespread threat facing karst biota in mainland Australia. The impacts resulting from these activities are often subtle and difficult to quantify because much of the degradation occurred long before any biota had been recorded. The impacts which potentially affect the biota include alteration to cave microclimates (including moisture and carbon dioxide), increased nutrient inputs, and changes to hydrological regimes and water quality, particularly sedimentation and pollutants (Hamilton-Smith and Eberhard, in press).
Most of the cave communities within New South Wales, Victoria, southwestern Western Australia and southeastern South Australia are likely to have undergone a marked alteration of composition or structure as a result of widespread land-clearance activities with their resultant wide range of environmental impacts. Of the approximately 120 karst areas in New South Wales and Victoria, some 60% have been subject to removal or major modification of their native vegetation cover (Eberhard and Spate 1995).

A decline in the numbers of cave-dwelling bats in New South Wales (Hall and Dunsmore, 1974) has been attributed, at least in part, to widespread clearance of forest foraging habitat. This has led to local extinction of guano-dependent invertebrates at the sites no longer used by bats. A 50% reduction in the species richness of the cave invertebrate fauna (Hamilton-Smith, 1968) followed the disappearance, between 1866 and 1895, of a large maternity colony of the large bent-wing bat, *Miniopterus schreibersii* (Kuhl, 1817) from Mount Widderin Cave in Victoria (Simpson and Hamilton-Smith, 1965).

A variety of hydrological impacts consequent upon deforestation, agricultural or other land-use activities threaten aquatic cave and groundwater communities, particularly the lowering of water tables (e.g. Jasinska and Knott, 1991), flow regime (e.g. Kiernan, 1988), sedimentation (e.g. Eberhard, 1995), nutrient enrichment (e.g. Thurgate 1995), and pollutants (eg. Aslin 1972). The extent of these impacts is best documented from studies undertaken in South Australia where water level in Sheathers Cave dropped by approximately one metre over a five-year period following the establishment of a pine plantation above the cave, whereas conversely, the level in the nearby Mount Burr Cave rose probably to the same extent, when the pine plantation above it was destroyed by wildfire (review in Grimes et al., 1995, p.

16). The protection of water resources in general, and karst groundwater resources in particular, is an acute problem within communities throughout Australia. Ignorance and disregard of the nature of karst hydrological systems have severely compromised water resources and subterranean fauna in some localities.

Impacts have been often caused by improper rubbish disposal in sinkholes, and poor management of pollutants (White, 1976). This is graphically illustrated by impacts on Town Cave, the initial water supply for Mount Gambier where the water in the cave was '. . . so deep as to give it, clear as it is, a deep sea-blue tint. ... The water is full of a cypris and cyclops, the shells of which seem to strew the bottom. There is also much conferva, a shrimp-like brachiopod and a minute paludina. . . ' (Woods, 1862: 359-360). The site later became a drain for the waste of the growing town, and today the water level is lower, with accumulations of silt and rubbish; the water is dirty and foul-smelling, and the aquatic community described by Woods has disappeared.

Nutrient enrichment may displace stygobiont communities and facilitate colonization of underground waters by epigean taxa (Eberhard, 1995; Kiernan 1988: 9-10; Malard, 1995). Eutrophication is the major threat to stromatolite colonies in karst lakes and cenotes in Western and South Australia (McNamara, 1997; Hallam and Thurgate, 1992; Thurgate, 1995).

4.3 HUMAN VISITORS

Direct impacts to cave communities have been caused by human visitors, including guano miners, cave managers and tourists, recreational cavers, and scientists. Mining of bat guano has long ceased in Australia, but during the last century large quantities were removed from caves throughout eastern Australia. Doubtless these operations caused major disturbance to resident bat populations at the time, as well as to the associated guano communities of invertebrates (Dwyer and Hamilton-Smith, 1965)

Traditionally, cave managers concerned with developing caves for tourism purposes have seen their conservation responsibility as being confined to the preservation and display of the most beautiful speleothems, and until recently, scant regard was given to the habitat requirements of the fauna. Climatic conditions are often changed and caves gated making them unsuitable for bats and thus cutting off the supply of guano. The metabolism of large numbers of human visitors affects cave microclimates by increasing carbon dioxide levels, moisture and temperature. Visitors also introduce lint, skin flakes, soil particles, food scraps, microflora, and fungi. These provide a rich food source which benefit some cavernicolous species but may also permit colonization by adventitious species. Some of these substances may be poisonous to fauna. The growth of algae, mosses and other vegetation near artificial lighting (termed *Lampenflora*) may also encourage colonization of the dark zone by invertebrates that are normally restricted to the twilight zone.

Other foreign materials that tend to accumulate in tourist caves include soot from carbide and other early combustible lighting sources, pitch from old electrical wiring seals, verdigris from scraps of electrical wiring or from coins placed in wishing wells, broken light globes, scrap metal and timber (Bonwick and Ellis, 1985). Old and disused timber left dumped in caves attracts cavernicolous species, and clean-up programs, although well-intentioned, can cause mortality to many individuals, and perturbation of the ecological balance established in the faunal community when the timber is removed.

Recreational caving activities have caused widespread and profound disruption to bat populations, as colonies that are repeatedly disturbed may abandon their cave sites and not return to them; even minor disturbances of bats at their over-wintering sites and maternity roosts may result in significant fatalities (Hamilton-Smith, 1970).

Floor-dwelling invertebrates in many caves are also widely under threat from recreational cavers who inadvertently trample them underfoot. A side effect of intensive trampling is the compaction of soft floor sediment that may render it less suitable as invertebrate habitat. For example, the residual invertebrate population in Mount Widderin Cave at Skipton in Victoria has been almost totally exterminated by opening of the cave to large visitor parties who have been allowed to trample and compact the total floor area (Hamilton-Smith, 1968; Spate and Hamilton-Smith, 1991). Similarly in Queensland, tours resulted in destruction of the root mat that had provided the habitat for planthoppers (Cixiidae and Meenoplidae).

Speleological activities such as digging can alter cave microclimates and the distribution of the fauna. There is one documented instance of a cave which when first dug into, contained a high relative humidity and many invertebrates. Shortly after opening of the entrance, the cave dried out and the fauna disappeared (Hamilton-Smith, 1970).

The final direct human threat to cave fauna concerns the activities of scientific researchers. At least part of the decline in numbers of cave-dwelling bats during the 1960s and 70s may be attributed to the pressure of specimen-collecting and banding programs (Hamilton-Smith, 1970). At the same time, although participants in the banding scheme took particular care to minimise the disturbance they caused, and this research yielded much useful information on the ecology of species (Simpson and Hamilton-Smith 1965), there were occasional negative impacts. More recently, concern has been expressed about the possibility that invertebrate specimens may be over-collected. Slaney and Weinstein (1995) found that continuous trapping over a one-month period in Rope Ladder Cave in Queensland caused a significant decline in numbers of invertebrate taxa and they recommended that the general ecology of organisms in a cave be investigated before any intensive sampling is carried out, and that, where possible, sampling with replacement should be used.

5. REVIEW OF STRATEGIES IN CONSERVATION

Human disturbance within caves has been identified as a major threat to the survival of cave dwelling populations (Spate and Hamilton-Smith 1991, Eberhard and Spate 1995, Richards and Hall 1996). Present understanding of the nature of karst landscapes emphasises the importance of the interrelationships between environmental conditions prevailing on the surface and those underground. We argue that this is fundamental to the development of effective strategies for the conservation of subterranean faunal communities. This approach may involve, for instance, the management of water- catchment areas which extend well beyond the geological boundaries of the karst outcrop. Aside from the highly publicised conservation campaigns which have been waged in attempts to conserve imminently threatened sites, the conservation strategies that have been applied in Australia to date include: legislative protection of threatened species and development of recovery plans for them; the protection of areas of sensitive habitat at individual cave sites; legislative recognition of endangered populations and communities, and key threatening processes; habitat restoration; the location of karstlands within National Parks and other protected or recognised areas; and community involvement and public awareness campaigns. Each of these strategies is discussed in turn below.

5.1 LEGISLATIVE PROTECTION

A number of cave dwelling species are protected under legislation in Australia. A person may not knowingly take, damage, or kill a protected species without a permit. The legislation potentially offers considerable security to listed species.

Many troglobitic species, because of their restricted range and vulnerability to extinction, satisfy the IUCN criteria as rare or threatened species. A number of invertebrate cave species are listed as threatened under the respective state legislations in Australia.

The greater part of Australia's invertebrate cave taxa remain undescribed, and are likely to remain so in the foreseeable future. The lack of adequate taxonomic knowledge will continue to be a major stumbling block in gaining protection for individual species. One solution is to seek protection of endangered populations or ecological communities, which is provided for under the Australian Endangered Species Protection Act 1992. Accordingly, a number of populations and communities of cave fauna have recently been nominated as endangered. In New South Wales, human visitors have been identified as the major threatening process to cave fauna (Eberhard and Spate 1995).

5.2 HABITAT PROTECTION AND HABITAT RESTORATION

The protection of areas of sensitive habitat within individual caves, coupled with an education program, has proved to be a pragmatic and successful conservation strategy which works much along the lines of a community recovery plan. Thus, in Mullamullang and Nurina Caves on the Nullarbor Plain, certain key habitat areas have been delineated with protective strings and signs that explain the reason for trying to exclude visitors from these areas (Poulter, 1991, 1994). Similarly in several Tasmanian caves, so-called substrate protection zones and fauna sanctuaries have been maintained by marking out pathways and no-go areas. This approach relies upon voluntary compliance by the caves visitors, and its relative efficacy will depend on a number of factors such as the accessibility and popularity of the site, the presence of a dedicated management authority, and the type of people who visit the cave (e.g. experienced cavers vs. casual visitors).

In some sensitive cave environments, the most effective strategy has been to severely curtail the number of visitors, or to exclude visitors entirely. Thus, in France, visitors are guided through replicas of the underground art sites at Lascaux cave, while at Niaux cave the number and size of visitor groups is severely restricted. At Anticline Cave in eastern Victoria, a major maternity site used by the horseshoe bat *Rhinolophus megaphyllus* had been abandoned, and the species was not seen in the area for a period of almost 20 years. Cavers took the initiative, with the support of the landowner, in restricting visits to the cave and as a result the population has been re-established (Hamilton-Smith, 1991).

For many years, the traditional approach adopted by land managers has been the construction of gates across cave entrances or within cave passages. Gates may be used to prohibit access entirely, or to strictly regulate visitor numbers through a permit/key system. However, some of the environmental problems involved with cave gating include:

- gates may interfere with bird or bat flight movements - gates may interfere, detrimentally, with the cave microclimate and natural cave processes such as airflow and water-flow patterns, light and nutrient inputs, and movements of fauna (eg. crabs and swiftlets on Christmas Island).

Exemplars from Australia will represent the numerous cases world wide. Many gates have been installed in Australia which inhibit — even though the spacing of vertical bars is wide enough — or entirely prohibit flight movements of bats. So-called 'bat friendly' gates may be constructed using horizontal bars with a certain minimum aperture. Particular gate specifications can also be expected to be required for the flight requirements of swiftlets. The smallest hole observed on Christmas Island to be used by the swiftlets was 45 cm, and other swiftlets will fly through spaces so narrow that they have to enter flying on their side (R. Johnstone, pers. comm., 1998). The importance of the configuration of the entrance is unknown.

At Naracoorte in South Australia a tunnel excavated to enable human access into a cave lacking a natural entrance allowed cave crickets to colonise the cave. The new entrance caused the cave atmosphere to dry out and previously active speleothems ceased growing and so the cave lost much of its tourist appeal. An air-tight door was installed which restored the microclimate and restarted speleothem growth but precluded the crickets whose life cycles depend upon movement into and out of cave entrances (Hamilton-Smith and Eberhard, in press).

Installation of gates on caves raises many problems unrelated specifically to fauna issues, and these are addressed by Spate and Webb (1998).

An alternative strategy to gating has been adopted at Bungonia in New South Wales, where a number of caves are closed annually by the National Parks and Wildlife Service during critical periods of the bat breeding season and winter torpidity. In this instance gates have not proved necessary to control access because of regular ranger patrols and the close proximity of the caves to a permanently manned ranger station. For most other caves however, this high level of surveillance is not possible. A similar example of seasonal preclusion of people from caves is given below with respect to the swiftlets at Chillagoe.

The importance of restoring previously damaged and degraded habitats is only now being realized. Both speleologists and tourism managers have been involved in aesthetic restoration (e.g, Bonwick and Ellis, 1985), and this clearly has some benefits in terms of habitat restoration. The experience at Waitomo in New Zealand clearly demonstrates the potential importance of restoration. In this instance, restoration of cave micro-climate conditions and revegetation in the stream catchment curtailed the demise of the glowworm population (Pugsley 1984). Restoration of climatic patterns or breaking-up of compacted floors are two examples where action is being taken at the time of writing, or might be taken, in

Australia. Rehabilitation of the former quarry at Ida Bay in Tasmania has been undertaken with a full recognition of the impacts upon fauna, and recovery of the aquatic fauna has occurred rapidly, including re-colonisation of a cave stream so badly polluted that the original fauna disappeared (Eberhard, 1995).

5.3 PROTECTED OR RECOGNISED AREAS

A number of important karst areas are located within National Parks or other conservation reserves, although, more often than not, their inclusion has been by fortuitous circumstance rather than deliberate intention. Consequently, some parts of the karst system, or its catchment, may not be included within the reserve boundaries. Such land protection is no panacea, and a range of other problems may arise, particularly in relation to fauna conservation. Lack of training for park managers in karst issues, combined with limited funding availability for karst-related conservation projects, is one of the more important (Hamilton-Smith and Eberhard, in press). Many caves in National Parks are under great pressure from large numbers of recreational visitors and in some parks this problem has been addressed by limiting access through institution of a permit system. Some caves have been closed entirely and enforcement of the closure sometimes requires the installation and maintenance of entrance gates which in turn may interfere with fauna and other natural processes as discussed above.

A great many significant karst and cave communities are located on privately-owned land, or they are located in areas of state forest subject to logging operations, especially in Tasmania. For karst-lands and cave communities under private ownership there is no legislative mechanism in place which specifically ensures their conservation, and many have already been seriously degraded. The key to any conservation program is essentially one of enhanced understanding through education and interpretation at all levels, and insufficient attention has yet been given to the involvement of private landowners as partners in conservation, particularly in respect to karst areas (Hamilton-Smith and Eberhard, in press).

The Register of the National Estate provides a mechanism for the recognition of areas containing important natural or cultural values. National Estate listing can be applied to sites anywhere regardless of the land tenure. The Cape Range karst in Western Australia has recently been listed provisionally, primarily on the basis of its subterranean faunal values. At the very least, such recognition can be used as a basis for further conservation action.

5.4 PUBLIC EDUCATION AND COMMUNITY INVOLVEMENT

It would appear that the future management and conservation of cave communities will rest both on a legislative footing and on better public recognition and understanding of the complexities of karst processes and karst environments (Eberhard and Spate, 1995). The adoption of Minimum Impact Caving Code (Australian Speleological Federation, 1997) practises by cavers is seen as a crucial component of the education process. This code goes along way towards detailing responsible caving practises although it is not directed specifically toward fauna conservation. Further information needs to be provided to cave visitors which is relevant in the local context, such as the recognition and avoidance of certain sensitive habitats and species. This awareness can be achieved through information leaflets, articles published in caving club newsletters, and public lectures for example. Another example is a pamphlet published by speleologists which has facilitated raising awareness of the plight of cave- dwelling bats in Victoria, and cooperation between the speleologists, a private landholder, and the state conservation department has enabled recovery of the Buchan population (Hamilton-Smith, 1991; Friends of Buchan Caves, 1993).

More generally, collaboration between cavers, academic researchers, and cave managers has proved to be a fertile starting point, from which there is a positive flow-on effect to the general public. The fostering of community involvement in the management of privately owned or lease-hold karstlands is seen as a crucial ingredient in the process. In New Zealand, protection of the catchment of the Glowworm Cave at Waitomo relied on cooperation between disparate parties including cavers, tourist operators, farmers, traditional Maori landowners, and the national conservation agency. The New Zealand experience has set an exemplary standard in community involvement, an approach to conservation which urgently needs to be forged in karstlands in Australia.

6. SUBTERRANEAN HABITATS AND CAVE COMMUNITIES ON CHRISTMAS ISLAND

6.1 AQUATIC

6.1.1 Groundwater

The karst landscape of Christmas Island means that surface water occurs only at a few springs at the limestone-basalt boundary, mostly on the shore terrace. Fresh groundwater is also limited and the essence of the hydrogeology of the island was captured perceptively by Andrews (1900: 9)

> "In several places on the east coast the shore terrace is composed largely of volcanic rocks, and since these hold up the water which elsewhere sinks through the porous limestone, the are several small brooks. These are never more than two or three hundred yards long, and rise from springs, welling out at or near the base of the inland cliff."

However, his prediction that groundwater would be easily extracted;

> "Wherever water is found to be held up by the volcanic rock, and since in many places this occurs at no great depth, borings will probably give an abundant supply without much difficulty." (Andrews, 1900: 18),

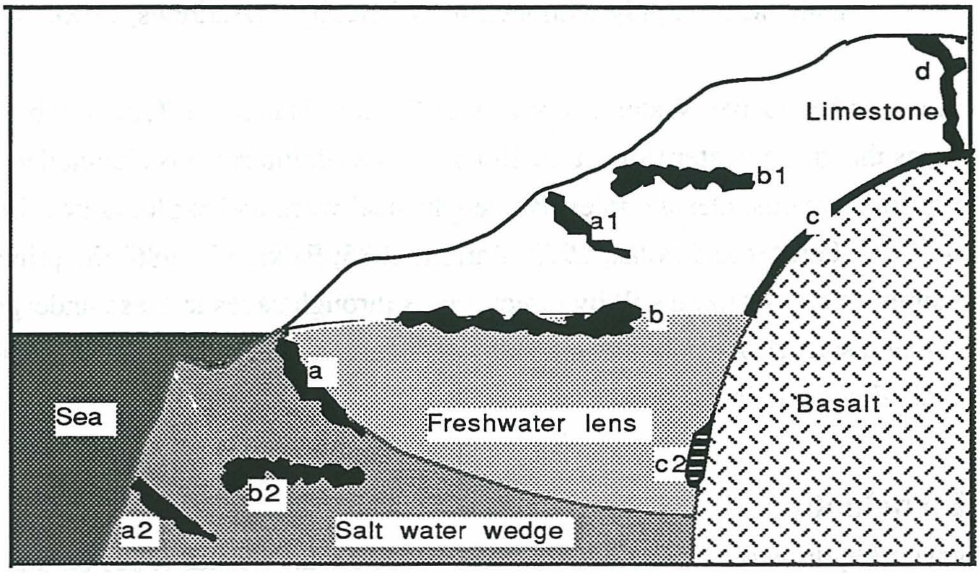
has proven to be elusive. Water has proven difficult to intercept effectively by drilling as the groundwater flow at the limestone-basalt interface is channelled in subterranean streams. Despite intensive geophysical work and exploratory drilling (Polak, 1976; Pettifer and Polak, 1979; Barrett, 1985; Falkland, 1986) the principle water supplies are obtained still by direct access through caves to these underground streams, and springs at the limestone/basalt interface. These remain the principle non-anchialine aquatic habitats

6.1.2 Anchialine

The general hydrogeological model for oceanic carbonate islands relies on the Ghyben-Herzberg principle; a fresh water lens floats on seawater that intrudes into the carbonates, so that locally a wedge of salt water intrudes under the fresh water contained in the limestone — a zone of mixing occurs between them, broadening towards the coast. This zone may be narrow (0.5 km on the coral island of Niue: Jacobson and Hill 1980) or quite broad (5 km in Cape Range; Martin, 1990).

The basaltic core of Christmas Island is encased in a series of limestones dating from the Eocene to the Recent (see figure in Grimes and O'Toole, 1998). Hence, the freshwater lens is likely to approximate a seawater wedge underlying freshwater and penetrating inland only until the basalt core is reached — there is as yet no confirmed freshwater lens within the basalt — and so forming an anchialine collar around the island (figure 3). The more extensive saltwater interface caves are tidal and, with the ebb and flow of the tide, exhibit marked changes in tidal height, the

Figure 3: Schematic section through Christmas Island to represent the known and hypothesised sites of cave development (shown in black) associated with the freshwater lens on a carbonate island on a basaltic core. The depth of the freshwater lens is greatly exaggerated to allow depiction of the basic thesis. The hypothesised lens associated caves are after Mylroie and Carew (1988), and the basalt associated caves (c) are interpreted from Barrie (1967: 41) connecting with sinkholes (d). Saltwater interface caves current (a) and at a former high sea level (a1), and air/water interface caves current (b) and at a higher sea level (b1). There should be an equivalent series of drowned caves a2, b2 and c2 representing the lower sea levels that have existed though most of the Pleistocene.



rate and direction of flow, as well as changing salinity, all of which would blur the distinct cave forming processes (fig. 3). Owing to the mode of development of these types of caves (e.g. 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), then 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 14-20 m in the last 124 ka (Woodroffe, 1988; Veeh, 1985). Evidence of lower sea level is seen in speleothems drowned to a depth of 3 m in Thunder Dome (CI-91: photo. A2.1), and at least -6 and -5 m in Lost Lake Cave and Bishops Cave respectively; submarine springs have been reported at 200 m depth in Flying Fish Cove (Pettifer and Polak, 1979).

Such fresh groundwater systems overlying seawater which have limited surface expression are termed anchialine habitats. Many such systems in the tropics support a distinctive, sometimes diverse, subterranean fauna. Hence, the presence of anchialine systems often substantially enhances the species richness of the subterranean fauna and they have become the focus of conservation effort. Such anchialine systems are noted both for their relict faunas, their species richness (Sket, 1981, 1996) and their extraordinary vulnerability to even slight organic pollution (Iliffe et al. 1984; Notenboom et al., 1994); they are the subject 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).

6.2 TERRESTRIAL

The air filled voids predominantly are associated with the drained parts of these cave systems and their associated sinkholes. However, it is likely that the fauna extends extensively into finer cracks and crevices whether or not associated with caves.

No longer can caves be considered as a separate biotope from the voids in the surrounding rock, as the voids inhabited by animals range in size from minute cavities a few millimetres in diameter through to large caverns tens of metres in extent. There is a continuum of void sizes, but 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.

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; 5) 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, submitted).

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. Tree roots emerge from the honeycomb network into cave passages, clearly indicating direct connections from the surface vegetation, soil and epikarstic zone, through the intervening rock mass and into deep cave passages. Similarly below the water table, the rocks are honeycombed with many small, interconnected phreatic tubes. 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.

The animals dwelling in caves can be broadly grouped into a number of distinct communities or associations, depending upon the microhabitats which they occupy (Chapman, 1993). Some species may be restricted to a single microhabitat, such as guano or tree roots, whilst others range across several habitat types. The habitat requirements of cave dwelling species can sometimes be defined at two broad levels of scale, namely macro-habitat and micro-habitat. Macro-habitats can be classified as either terrestrial or aquatic. Terrestrial macro-habitats can be further defined according to the different cave environmental zones, viz. entrance zone, twilight zone, transition zone, and deep zone. The degree of representation of different habitat types may be highly variable at the level of individual caves or cave passages. The types of habitats, and, communities or associations identified in the Christmas Island caves are briefly described below.

6.2.1 Entrance and twilight zone association

The entrance and twilight zone of caves usually contain a wide variety and abundance of invertebrates and is often an important site for bryophytes. This is partly due to the abundance of food supplies in the vicinity of the cave entrance, but also because cave entrances provide ideal shelter for many organisms. Thus, this association is composed of troglophilic species dwelling permanently within the entrance and twilight zone, as well as trogloxenic species seeking temporary shelter, and accidental species. The entrance and twilight zones may contain a variety of microhabitats including soil, plant litter, tree roots, and swiftlet guano for example.

6.2.2 Transition zone association

The transition zone may also contain a variety of microhabitats and abundant fauna where food supplies are still relatively plentiful. Pholcid spiders may be common in this zone, but they do not extend into the deep zone environment because of insufficient food supplies.

6.2.3 Deep zone association

The deep zone environment is characterised by relatively constant conditions and a low food supply. The microhabitats tend to be less diverse and more uniform, but plant litter, tree roots, sediment banks, and aquatic habitats are still present. The fauna is characteristically sparsely distributed, and often troglobitic.

6.2.4 Guano community

Bird or bat guano which accumulates in caves supports a specialised community of invertebrates which feed directly on the guano, or the microflora which grows on it. The guano represents a rich food source in the generally food-poor cave environment. The guano deposits can support enormous densities of small invertebrates which in turn attract other invertebrate predators. Some so-called *guanobites* are entirely dependent upon the regular input of fresh guano for their survival, whilst other so-called *guanophiles* exploit the resource on an opportunistic basis (Gnaspini and Trajano, in press).

Guano dwelling invertebrates play a crucial role in the underground ecology by facilitating decomposition of the guano, and thus recycling nutrients through the food web. So long as the supply of fresh guano is maintained through the presence of the birds or bats, then the guano community will continue to thrive, but if the birds or bats abandon the cave then the guano community will die out.

Because guano communities have a very localised distribution, on the floor beneath the roost or nest site, they are vulnerable to being inadvertently trampled underfoot. A side effect of intensive trampling is compaction of the soft guano deposits, which renders the substrate less suitable as invertebrate habitat, particularly for burrowing forms (Spate and Hamilton-Smith 1991). Many bat guano communities throughout New South Wales and Victoria for example, have been severely degraded, and in some cases almost obliterated, by the cumulative impact of trampling.

On Christmas Island, invertebrate guano communities are associated with colonies of the Glossy Swiftlet. The Christmas Island Pipstrelle Bat is not known to roost in caves, but instead roosts in the forest (Gray 1995). As expected, the guano communities comprise some species known only from this habitat. The communities have a highly disjunct and restricted distribution, they occur in only five caves known to contain swiftlets although it is likely that other sites exist. The guano communities in Daniel Roux Cave are especially vulnerable to human disturbance, either from direct trampling impacts, or disturbance to the swiftlets causing them to abandon the cave.

6.2.4.1 Summary

- Guano communities are very vulnerable to the impact of trampling by human visitors to caves.

- The guano communities in Christmas Island caves are dependent upon the continued presence of the swiftlets for their survival. The swiftlets in turn are vulnerable to human disturbance, as shown by their abandonment of the cave during 1984 (Gray, 1995).

- Swiftlet colonies and their associated guano communities are known from only five of the documented caves on Christmas Island, although they are likely to be found elsewhere.

- Daniel Roux Cave contains an outstanding example of a guano mound 2 m high (photo. A2.15), situated beneath an important swiftlet nesting site.

6.2.5 Tree root community

Tree roots which penetrate into air-filled or water-filled cave passages are a potential food source and habitat for invertebrates. Some invertebrate species are entirely restricted to tree root microhabitats, such as the planthopper bugs whose nymphal stages feed on root sap. Most of the terrestrial troglobites on Christmas Island, and some troglophiles as well, were almost invariably found in close association with tree roots. These taxa included millipedes, isopods, springtails, cockroaches, and silverfish. Submerged root mats on Christmas Island were found to contain minute crustaceans (Ostracoda and Copepoda). Submerged tree roots in south west Western Australia contain a diverse and specialised fauna (Jasinska et al. 1996).

Tree roots do not occur in all the Christmas Island caves, and where they do occur they tend to be localised and patchily distributed. They are fragile and vulnerable to breakage or trampling.

6.2.5.1 Summary

- Tree roots are an important and vulnerable invertebrate habitat.

6.2.6 Sediment banks community

Sediment banks, especially those subject to periodic flooding alongside streamways, are a potentially important invertebrate habitat. In many cave systems outside Christmas Island this habitat supports a diverse community of invertebrates because flooding deposits moisture and nutrients onto the sediment banks. If the sediment banks dry out however, then the fauna dies off, or migrates elsewhere. The plateau stream caves on Christmas Island contain good examples of sediment bank habitat although little fauna was collected here during the field survey. This may have been due to the unseasonally dry months preceding the survey which had caused the sediment banks to dry out, evident from their cracked surfaces. Dead millipedes were seen on these surfaces. Under wetter conditions, these banks may support more fauna.

6.2.6.1 Summary

- Sediment banks are a potentially important habitat which are vulnerable to trampling impacts.

6.2.7 Organic material

Plant material in the form of wood and leaves which falls into caves under gravity, or is carried in by water flow, is a food source and habitat for fauna. Wood carried in by humans may also be colonised by fauna, including troglobitic species. Often located on the cave floor, this habitat and its associated community are vulnerable to trampling impacts.

6.2.8 Wall association

The walls and ceiling of the dark zone are habitat for a number of wide ranging predatory and scavenging species, including spiders, whip-scorpions, scorpions and cockroaches.

6.2.9 Seepage-fed freshwater pool association

Pools fed by fresh seepage water, such as drips from stalactites, are a potential habitat for aquatic and terrestrial organisms. The pools may be permanent or ephemeral depending on rainfall events, and they may be excavated in bedrock, calcite (rimstone or gour pools), or unconsolidated sediments such as mudbanks. On first inspection these pools may appear to be devoid of life, but the water they contain will have brought with it organic material leached from the soil, and sometimes it may flush small organisms from the soil depositing them in the cave (Chapman, 1993). Some Collembola for example, specialise in exploiting the food resources associated with the surface of cave pools, and some aquatic species are known only from this habitat. The pools are vulnerable to trampling impacts, especially those pools occurring in soft sediments where they may be completely destroyed.

Examples of rimstone pools occur in the upper levels of Daniel Roux and Grimes Caves. At the time of this survey the pools in Daniel Roux were dry whilst those in Grimes were water-filled. No fauna was observed in the latter but it might still occur there, or in other sites.

6.3 Other habitats and associations

A number of species do not appear to be associated with specific microhabitats, instead they occur widely across a range of habitats and cave environmental zones as, for example, the non-troglobitic cockroaches.

A synopsis of the above habitats is presented in table 5.

6.3.1 Bats

Murray's Pipistrelle Bat *Pipistrellis tenuis* (Temminck, 1840) is found across Christmas Island, in plateau, terrace, and secondary growth forests. The bats are thought to roost in tree hollows in primary forest (Gray, 1995). No bats, or evidence of bat usage, were found in any of the Christmas Island caves.

6.3.2 Swiftlets

The Christmas Island Glossy Swiftlet *Collocalia esculenta natalis* is endemic to Christmas Island. A number of other species of *Collocalia* occur in the Indian

Ocean, South-east Asia and Queensland (Sibley and Monroe 1990). Most species of swiftlets nest in caves.

Table 5: Summary of fauna habitat/association types and their rated sensitivity.

Habitat/association	**Occurrence**	**Vulnerability to caver impacts**	**Main external threats**
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			
Sediment banks	Restricted	Medium	Deforestation, pollution,
mining			
Organic material	Restricted	Medium	Deforestation
Anchialine	Widespread	Low	Pollution, water abstraction
Marine	Widespread	Low	Pollution
Entrance/twilight	Widespread	Low	Deforestation, mining
Wall association	Widespread	Low	Deforestation
Springs	Restricted	Low	Water abstraction, pollution
Deep zone	Widespread	Variable	Deforestation, pollution

The biology of *C. esculenta natalis* appears to have been little studied and some consideration of the biology and management issues of related species is appropriate in considering management issues related to it.

6.3.2.1 Nests

C. esculenta natalis nests in colonies in several of the caves on Christmas Island where they build closely packed masses of cup-shaped nests high in the roof of the cave. Lichens and other fine threads are woven together, and cemented to the roof with saliva (Gray 1995). Guano - mostly insect exoskeletons - accumulates beneath the colonies and supports an assemblage of invertebrate species. Nests fall off the wall if the moisture content of the air falls below 70% relative humidity (Nguyen Quang et al. 1998). For this reason, amongst many, vegetation clearance should not occur in the vicinity of caves.

The nests of *Collocalia* species in South-east Asia and India, are intensively harvested for the gourmet delicacy 'birds nest soup' (Nguyen Quang et al., 1998). The Christmas Island swiftlets use smaller quantities of saliva to cement their nests than their congeneric relatives in South-east Asia. However, there is anecdotal evidence which suggests that nests of Christmas Island swiftlets may have been harvested on in the past. Brooks (1990) drew this conclusion after observing that the arrangement of poles lodged high in the roofs of caves occupied by swiftlets at South Point was similar to those used by bird nesters elsewhere.

6.3.2.2 Distribution

Gibson-Hill (1947a) recorded large numbers of swiftlets over the whole island where they were more common on shore terraces than the plateau. They were most numerous on the west side of South Point and least numerous along the coast from Egeria Point to West White Beach.

Swiftlets have been recorded from five of the caves on Christmas Island, namely Daniel Roux Cave, Smiths Cave, Managers Cave, Grimes Cave, and Swiftlet Cave. The colonies in Grimes Cave and Smiths Cave during April 1998 were small, numbering about 25 individuals at the latter site and only a handful at the former - the small quantities of guano here indicate that this is not a major nesting site. Daniel Roux Cave is clearly a major nesting site, containing several hundred individuals during April 1998. The large well developed guano mound (photo. A2.15) beneath this nesting site testifies to its high degree of usage by large numbers of birds over a long period of time.

At Chillagoe in Queensland, colonies of the White-rumped Swiftlet, *Collocalia spodiopygus chillagoensis*, occur in less than 10% of the circa 400 caves recorded in the region. The swiftlets build their nests in the dark zone, on smooth concave walls high above the cave floor. They roost in the caves each night of the year and breed there each wet season (October - March). The species is restricted to areas having caves and sufficient aerial insects for food (Tarburton, 1989).

The Fijian subspecies *C. spodygiopius spodygiopius* colonies tend to be in twilight situations (Tarburton, 1989). In Vietnam, most White-nest Swiftlet *Collocalia* *fuciphaga* colonies tend to occur in caves with wide openings, although swiftlets are able to fly through narrow cracks (see above).

6.3.2.3 Feeding

Glossy Swiftlets feed on the wing and flying ants are reported to make up a major portion of their diet (Gray 1995); in Vietnam, the diet of *C. maxima* is also predominantly Hymenoptera (Nguyen Quang 1996). Glossy Swiftlets are commonly seen outside the caves on Christmas Island, swooping through clearings and skimming the forest canopy capturing flying insects.

6.3.2.4 Breeding season

The breeding season for *C. esculenta natalis* has been reported from the beginning of September (earliest eggs seen 3 October) to the end of March (no young in nest after 14 April) with there being two peaks starting in October and January and with very few eggs are laid in November or early December (Gibson-Hill, 1947a). Note, however, that Gibson-Hill (ibid.) made his observations from September 1938 through November 1940, hence, no conclusion can be drawn of between year variation or the coincidence of the breeding season with the monsoon. Fresh egg shells observed beneath the nests in Daniel Roux Cave during April 1998 suggest that breeding on Christmas Island was occurring at this time but it is notable that the wet season had only just commenced, very late in this ENSO year.

Other species of *Collocalia* have a distinct breeding season, the commencement and duration of which is influenced by external climatic factors such as rainfall and wind, cave micro-climatic conditions, and human disturbance regimes (Giles 1936; Nguyen Quang 1992, 1994, 1996; Tarburton 1989). The timing of nest building and laying of the first clutch is frequently associated with the onset of the monsoon season, whilst nest harvesting activities have the effect of extending the breeding season as the birds will re-build their nests and lay further clutches. The survival rates for later clutches are usually lower however.

6.3.2.5 Disturbance

There are variable effects on swiftlets (*sensu lato*) reported. Extreme disturbance, such as nest harvesting, influenced breeding success in Singapore (Kang et al., 1990), Sarawak (Good 1993), and Vietnam (Nguyen Quang 1992; Nguyen Quang and Voison, 1998) and have resulted in declining yields of nests in exploited caves (Cranrook, 1984 in Kang et al., 1990) or the inability of the population to replace itself (Tarburton, 1987). Swiftlets at Chillagoe are rarely seen in caves during daylight from May to September and will not be disturbed by people, however, during the breeding season they sometimes knock eggs from their nests when disturbed by the close proximity of people to their nests, but egg loss is reduced if the nests are approached slowly and quietly and if the nests are not suddenly illuminated (Tarburton, 1989). Both eggs and chicks can endure hours without incubation and yet show no ill effect. Nevertheless, the Queensland National Parks and Wildlife Service does not allow cavers entry to swiftlet caves during the breeding season (L. Little pers. comm., 1998).

Upon entering a cave containing Christmas Island Glossy Swiftlets the birds are evidently disturbed as they leave their nests and fly about in an agitated manner. Just as bat colonies and other species of *Collocalia* swiftlets are susceptible to human disturbance, it is considered likely that the swiftlets on Christmas Island are also vulnerable to human disturbance. Gray (1995) reports that the swiftlet colony in Daniel Roux abandoned the site for a period around 1984, possibly because of the increasing number of visitors. This is the only cave containing swiftlets that is regularly visited on Christmas Island.

The relative importance of Daniel Roux Cave to the population of swiftlets on Christmas Island is unknown both because the number of swiftlets inhabiting Managers Cave and Swiftlet Cave is not known and because it is likely that many other caves, as yet undocumented, may be utilised by swiftlets. Viewed from a boat, there are numerous large cave entrances situated along relatively remote sections of the Christmas Island coastline, some of which may be suitable swiftlet sites. Brooks (1990) reports possible sites in the vicinity of South Point for example, and there are others located near North West Point. It would be desirable for management purposes, to establish the regional significance of Daniel Roux and other swiftlet caves in order that priority sites can be protected appropriately. This is especially desirable in the case of Daniel Roux given the inherent problems involved with protecting such an accessible and popular site.

In the interim, it is recommended that a precautionary approach be adopted towards the swiftlet colony in Daniel Roux. Options for protecting Daniel Roux range from total exclusion of visitors via a gate or fence (this would be difficult), to a 'token' barrier with explanatory sign requesting that visitors do not enter the cave to avoid disturbing the swiftlets. The latter measure could be promoted through a public awareness campaign in the local community. It is considered especially important to minimise disturbance during the breeding season. The evidence from Chillagoe (above) suggests that a better knowledge of their breeding biology would permit more rational management.

6.3.2.6 Summary

The Christmas Island Glossy Swiftlet is endemic to Christmas Island and apparently restricted to caves. Its management must be considered a key issue, yet its biology and distribution is poorly known. Being the only guano producer in caves on Christmas Island, guano communities are themselves dependent on its persistence.

Data from cave dwelling congeneric species suggest that the breeding success can be limited by human disturbance and by changed environments both outside and within the caves. However, evidence from Chillagoe suggests simple management measures can restrict disturbance.

6.3.2.7 Recommendations

6.3.2.7.1 Recommendation

Instal a sign, and perhaps a 'token' barrier, at entrance of Daniel Roux requesting visitors not to enter the cave to avoid disturbing the swiftlets, especially during the breeding season. Consider combining this with a public awareness program to the local community (eg. newspaper article, leaflet, seminars).

6.3.2.7.2 Recommendation

Monitor the colony in Daniel Roux Cave to determine breeding season and annual variations in abundance.

6.3.2.7.3 Recommendation

Assess the regional significance of Daniel Roux Cave to the Glossy Swiftlet. Assess swiftlet populations in Managers Cave, Swiftlet Cave and CI-45. Search for other swiftlet caves.

7. EXTERNAL THREATENING PROCESSES AND IMPACTS TO CAVE FAUNA ON CHRISTMAS ISLAND

7.1 EXTERNAL

7.1.1 Quarrying

There are three limestone quarries which are currently operational on Christmas Island. Two of these quarries are used for extracting softer grade rock (chalk pits) and are located near the airport and the rubbish tip. The other quarry, located near Taman Sweetland, is used for extracting hard rock for sand and aggregate. No caves are known to have been exposed by quarrying at these sites (B. Edwards pers. comm.).

7.1.1.1 Recommendation

Any quarrying operations should be preceded by assessment of cave and karst features and possible impacts, including 'downstream' impacts.

7.1.2 Phosphate mining

Amongst the most dramatic of the human impacts on the landscape of remote oceanic islands is the formation of a jagged 'moonscape' following the removal of the phosphate rock. The hydrology of such bare areas differs greatly from those covered by a thick canopy of tropical forest, and the ecological diversity and productivity of such areas are greatly reduced (Armstrong, 1992). Phosphate mining will clearly impact the subterranean ecology as well, by altering the infiltration rates of water, sediment and nutrients into the underlying voids and by removing the living tree roots which are a food source for cave invertebrates. The 'moonscape' areas worked for phosphate are extremely slow to recover, especially the older sites mined by hand because more of the phosphate was removed. Even after many years these sites still support only a rudimentary vegetation unless they are actively rehabilitated.

Rehabilitation after mining activities is minimal, with areas mined after 1975 having some rehabilitation work carried out (Parks Australia, pers. comm.).

To date, no cave systems have been explored which extend beneath phosphate mining areas on Christmas Island, although this does not mean that caves are absent from these areas. It is more than likely, given the highly cavernous nature of the karst and the large areas (*c.* 20% of the island) which have been subject to mining, that localised impacts have occurred to subterranean fauna directly beneath mined areas. It is anticipated that rehabilitation involving the re-establishment of natural soil and vegetation cover to mined areas will benefit the subterranean ecology.

The dust emitted from the phosphate driers has had an adverse effect on the environment, causing impacts to seabird nesting sites and siltation of the coral reef (Gray, 1995). The dust emissions have also caused impacts to nearby caves such as Daniel Roux. Deposits of dust have settled within the entrance overhang — where it is not washed away by rainfall — and has the effect of smothering the growth of the entrance and twilight zone flora which includes mosses and algae. This may affect animals which rely on these plants as a food source, although it is not known if this is specifically the case on Christmas Island. Some cave dwelling animals, such as rhaphidophorid crickets, are strongly dependant upon mosses and liverworts at cave entrances, however this particular group is absent from the Christmas Island cave fauna. In Cape Range highly troglomorphic millipedes of the genus *Stygiochiropus* feed on microfaunal films in such zones. A dust suppression programme is being implemented around the phosphate processing facilities.

7.1.2.1 Recommendations - none.

7.1.3 Deforestation

Deforestation for whatever purpose, including phosphate mining as discussed above, can be expected to impact the subterranean ecology by altering natural rates of water and nutrient infiltration, and by removing live tree roots which are a food source for cave invertebrates. On Christmas Island, the impacts of deforestation are likely to be confined to the karst immediately underlying the cleared land because surface water courses are largely absent and most of the rainwater percolates downward immediately upon contacting the karst surface. Elsewhere, in less porous karst terrains, the effects of deforestation may be more widespread as streams transport the effects considerable distances downstream from the point of disturbance. The effects observed in surface and underground streams as a result of deforestation include, *inter alia*, changes in flow regime, water chemistry, sediment and nutrient loads (Eberhard et al., 1996).

Approximately one fifth of the Island has been cleared for mining purposes, whilst rehabilitation after mining activities is minimal (Parks Australia, pers. comm.). In addition, much forest has been cleared for roads, railways, workshops, settlements and the airfield (Armstrong 1992).

A number of caves lie in or adjacent to cleared areas (Grants Well, 19th Hole, C-54, 10 Mile Sink) or, lying down slope and having freshwater outlets, are likely to be impacted from cleared areas (Daniel Roux, Grimes). 10 Mile Sink is now filled in but its proximity to the treatment plant could make it vulnerable to pollution relating to plant operations — as an underground stream may still be flowing beneath the filled doline this could impact on the Daniel Roux system (K. Grimes, pers comm. 1998). All of the remaining major cave systems presently known are situated beneath areas which currently retain a cover of native forest.

7.1.3.1 Recommendation

Forest clearance be preceded by a survey for karst features, caves and cave fauna both on site and in areas likely to receive subterranean drainage from the site.

7.1.4 Erosion

Areas cleared of vegetation, especially on hill slopes, are vulnerable to erosion. Eroded sediment may cause blockage of karst conduits and change the hydrology and characteristics of underground habitats, which may in turn affect the distribution of cave fauna. The high permeability of the karst surface and the poor development of permanent surface watercourses over much of Christmas Island limits the opportunity for transport of eroded sediments over long distances. Run-off from impervious surfaces, such as sealed roads, will enhance the concentration of water flows and the mobilisation of sediment during rainfall events. No cases of unnatural sedimentation were observed in any of the caves visited during this survey. However, two sites were identified which exemplify the potential for sediment-laden run-off from road surfaces to affect karst features. Where the vehicular track crosses the gully of Dale No. 1 there is an intermittent watercourse. When this watercourse becomes active after sufficiently heavy rainfall events then sediment from the gravel road surface might be transported into the karst system further downstream. Such a scenario is not considered an issue at this particular site because of the very intermittent nature of the watercourse (H. Rumff pers. comm.), but it might be relevant in other locations. Another site which could potentially receive run-off from a road surface is the cave CI 54, because the entrance is located in a depression just a few metres from the edge of the road.

7.1.4.1 Recommendation

To ensure that surface run-off from erodable or impervious surfaces does not enter caves or otherwise adversely affect karst features.

7.1.5 Agriculture

Plantation agriculture has never been of major importance on Christmas Island, although some vegetables and fruit continue to be grown on a small scale for local consumption (Armstrong 1992). Due to the limited agricultural developments on Christmas Island this is not considered to be a potential source of major disturbance to subterranean ecosystems. However, care should taken to minimise run-off of sediment, fertilisers, and biocides into karst drainage systems.

7.1.5.1 Recommendation

Avoid point source run-off entering underground drainage systems.

7.1.6 Tourist and commercial development and infrastructure

The economy of Christmas Island is fragile, being largely dependent on phosphate mining and tourism. As phosphate mining is phased out the further development of tourism and other facilities, such as the proposed rocket launching facility, will have an increasing impact on the subterranean ecology, both directly and owing to the development of the required infrastructure.

Factors that may especially impact on subterranean systems are:

1. The scarcity of potable water on Christmas Island is a perennial problem and considerable effort has been exerted in attempts to secure a more reliable supply. Water abstraction may entrain stygofauna, reduce their habitat and change the saltwater interface location and dynamics in the anchialine systems.

2. Nutrient enrichment and toxic leachates may result from refuse dumps, sewage and ornamental vegetation, especially from golf courses. These may adversely affect, at a distance (Pearce, 1996) subterranean fauna directly or change their competitive ability allowing the invasion of the hypogean spaces by epigean species (Notenboom et al., 1994; Malard, 1995).

3. Paving for car parks, roads, pads, etc. interferes with infiltration of water and nutrients.

7.1.6.1 Recommendation

The impact of developmental proposals on subterranean fauna and their habitats should be a criterion in environmental impact assessment.

The environmental impact assessment review should include people with appropriate karst expertise.

Any development should be preceded by survey of karst and cave features and potential impacts on the underground ecology.

7.2 INTERNAL

In-cave threatening processes to cave fauna on Christmas Island are concerned with human visitors to caves, and foreign materials transported underground by human visitors. Human visitors may cause direct disturbance to cave fauna, or cause degradation of fauna habitats. Materials such as wood placed in caves may alter nutrient supplies for cave fauna whilst other foreign materials may be poisonous to cave fauna.

7.2.1 Materials

A variety of materials have been installed or discarded within Christmas Island caves. Examples include the infrastructures associated with the water pumping stations in the plateau caves (photo. A2.4), climbing aids such as metal ladders and ropes, other infrastrucures and materials now discarded, and even rubbish dumped.

Wooden materials are a potential food source for cave fauna - a number of troglobitic species were found associated with pieces of discarded wood in Jedda Cave for instance. Although the wood may not have arrived underground by 'natural' means it should not necessarily be regarded as an undesirable pollutant unless it comprised timber treated with biocides. Wood is transported into certain parts of caves by natural processes of gravity and water flow, where it is utilised as a food source and habitat by cave dwelling organisms. Humanly transported wood may actually 'enhance' the cave ecology by providing a food source for fauna in the generally food-poor cave environment. As a potential pollutant wood is a relatively benign substance, and as a potential energy source it is relatively low in nutrients. Wood left in caves will eventually decompose although this process may take many years. Most cave organisms are generalists so they are able to exploit a range of food sources, and for many species the microflora associated with wood decomposition represents one of their natural food items.

The impact of wood upon cave ecology is not necessarily adverse, depending upon its location in the cave. Wood might be considered an undesirable pollutant when it occurs in large quantities, or where it occurs in places where it is unlikely to have arrived there by natural means, such as in low energy upper-level passages.

The question confronting cave managers is whether or not to remove old wood from caves. To do so abruptly might cause some upset to the cave ecology by removing the food source for populations which have come to depend on it over time. An alternative approach might be to remove the wood gradually, or to remove only a portion of the wood and leave some of it lying *in situ* for the fauna. The process of collecting and removing the wood can cause the death of quite a number of cave animals.

Structural materials placed in caves, especially metal structures, may release biocides (Spate et al. 1998). Examples on Christmas Island include disused structures in Runaway Cave, and the structures associated with the pumping stations in the plateau caves and old ladders in Daniel Roux. Given the hardness of the water problematic heavy metal contamination of freshwater is unlikely but corrosion in the anchialine systems may result in higher rates of release of heavy metals. Hence, in anchialine waters and above water lead, copper and other potentially biocidal fittings may be undesirable.

The pumping stations and associated infrastructures such as weirs in the plateau caves alter the flow regime by causing abrupt and regular changes in local water levels. However, the magnitude of these cyclical changes is small compared with the natural changes in flow in the cave and there are unlikely to be fauna related issues.

During low flow periods a major part of the stream flow is intercepted at Jedda Cave to supply the settlement and that fraction of the stygofauna in the water column will be entrained. The known stygofauna of these cave streams is limited to small organisms that are also likely to inhabit interstices and hence, on first principles, their removal by entrainment in the abstracted water is unlikely to jeopardise the survival of the species.

Some caves, such as Nineteenth Hole, contain rubbish of a type that is of aesthetic rather than biological import. However, certain types of rubbish, such as batteries, may release toxic leachates as they decompose.

7.2.1.1 Recommendation

The potential impact on the cave ecology should be considered before old wood is removed from caves. In cases where wood is to be removed, consider removing it gradually over a period of time, or leaving a portion of it *in situ*. When removing wood, take care not to kill or remove fauna as well. This can be achieved by searching the wood for animals and releasing them, or knocking the wood on the ground to dislodge them. This may also have the effect of dislodging wood fragments which can be left *in situ* to sustain the fauna.

7.2.1.2 Recommendation

Batteries and other potentially toxic rubbish should be removed from caves and management protocols established to minimise their reintroduction. Specially care should be taken to minimise the use of components containing potentially biocidal ingredients (treated timbers and galvanized metals for example), especially in anchialine systems and in structures in direct contact with cave soils.

7.2.2 Human visitors

Human visitors may be one of the most significant threats to cave fauna on Christmas Island. The most vulnerable cave fauna appears to be the swiftlet colonies, particularly the colony in Daniel Roux Cave because of its accessibility. The colony of swiftlets in Daniel Roux comprises many hundreds of individual nests and a significant guano mound with associated invertebrate fauna. The swiftlets evidently become disturbed when people enter the cave, flying around in an agitated manner. The location of Daniel Roux Cave is well known and it is easily accessible from the Settlement. It is reported that the swiftlet colony abandoned the cave in 1984, possibly as a result of frequent human disturbance (Gray, 1995).

7.2.2.1 Recommendation

Visitors be discouraged from entering Upper Daniel Roux Cave, perhaps by a low key barrier with explanatory sign as discussed in Section **.

Some cave dwelling invertebrates may be threatened by human visitors to caves. The most significant identified threat is trampling, especially where it causes degradation or destruction of habitat. The most sensitive and vulnerable invertebrate habitat is tree roots. Many of the troglobitic species were found in association with tree roots. Tree roots do not occur in all the Christmas Island caves, and where they do occur they tend to be localised and patchily distributed. They are fragile and vulnerable to breakage or trampling.

Other potentially sensitive habitats include deposits of organic material such as swiftlet guano, wood and leaf litter, and sediment banks.

7.2.2.2 Recommendation

Cave visitors be made aware of sensitive habitats and species, and how to avoid disturbing them.

7.2.3 Feral animals

A number of aquatic species have been introduced into the springs and water tanks on Christmas Island and they are prolific in some of the Dales and Ross Hill Gardens. They are a 'terrapin' and a number of fish including the swordtail (*Xiphophorus maculatus*), mosquito fish (*Gambusia affinis*), guppy (*Poecilia reticulata*), tilapia (*Oreochromis* sp.), and, presumably, the asian bony tongue (*Scleropages formosus*).

A number of these species are prolific breeders (Allen 1991) and are known to become pests of native fauna: guppies are likely to eliminate the native fauna when they enter natural fresh or brackish waters (G. Allen, pers. comm. 1993); tilapia because of its destructive behaviours (Allen 1991); and mosquito fish which often take over, crowding out the native species (Allen, 1991).

A number of these species are known to invade anchialine systems in Hawai'i (Ridgley and Chai, 1990) and Cape Range in Western Australia (W.F. Humphreys, unpublished) including *Gambusia* sp., *Poecilia* sp. and *Oreochromis* sp. (Ridgley and Chai, 1990). Predictions that feral fish locally contained in artificial ponds were likely to invade the anchialine system on the Cape Range peninsula, Western Australia (Humphreys, 1994), had been fulfilled by 1997 (Humphreys, W.F. unpublished) and the land management agency is attempting to eliminate this threat.

Invasion of the anchialine system is possible by direct invasion from freshwater habitats but is most likely by human agency.

7.2.3.1 Recommendation

Feral populations should be identified and eliminated where possible with greatest effort going to the areas most accessible to people and closest to the anchialine systems in the vicinity of Runaway Cave, especially the springs and tanks at Ross Hill Gardens.

8. CAVE MANAGEMENT ISSUES

8.1 CAVE SENSITIVITY

Virtually all caves contain sensitive features which, depending on the nature and intensity of the disturbance, will recover very slowly or not at all. Cave passages which lack active streams are particularly susceptible to damage because they are low energy environments where natural rates and magnitudes of change are limited (R. Eberhard, 1997). Even relatively robust caves will contain sensitive features which can be permanently degraded if visitors fail to observe appropriate codes of behaviour. It is therefore necessary to regard the majority of caves as highly sensitive places which can be rapidly and irrevocably degraded by inappropriate use. Some cave biota and habitats are very sensitive to human disturbance whilst others are relatively robust.

Cave sensitivity is defined here in terms of the potential for natural features and processes in caves to be degraded by human activities. Cave sensitivity will be influenced by a range of site-specific considerations, as defined by R. Eberhard (1997):

- the extent to which multiple sensitive features and processes are present;
- the potential (if any) for disturbed parameters to recover;
- the scope to protect sensitive features and processes through limited management intervention (eg. route delineation, cave hardening);
- the possibility that relatively minor impacts will accrue over time to produce more significant impacts of a cumulative kind;
- variations in both the sensitivity of particular parameters and their vulnerability to disturbance (i.e. the probability that they will actually be impacted given their

location within the cave);
- the potential to remedy some classes of impact after they have occurred;
- the extent of existing impacts.

A key element in the sensitivity analysis is the natural recovery potential of cave values following disturbance. One important characteristic of biological systems, compared with some non-biological systems, is their innate capacity for regeneration. Thus, damage to certain sensitive features will be permanent if the processes which formed them are no longer operative. This is usually the case with fossil speleothems, speleogens, sediments, palaeontological and archaeological features for example. Biological systems in contrast, have a degree of plasticity and resilience which enables them to respond and adapt to environmental changes, thus enhancing their recovery from impacts and promoting their continued survival. Many animals will actively avoid danger, and they can often respond to adverse conditions by migrating elsewhere. Populations of animals may experience severe decline during adverse periods, but they can also recover their former abundance when conditions improve. The continued propagation of natural biological systems is assured so long as the rates and magnitude of change do not exceed the capacity of the system to remain self-sustaining. If however, the limits of natural tolerance are exceeded then populations or species may be lost permanently.

Cavernicolous animals often have no other habitat and often are restricted to a single cave or karst area. If the cave environment changes beyond their capacity to adapt then the species will become extinct as migration is not an option. Cave restricted species are especially sensitive to environmental change.

A further level of complexity arises due to difficulties in predicting how natural systems will respond to disturbance, and this is perhaps most apparent in relation to cave ecosystems (R. Eberhard, 1997). In these circumstances, especially as even elementary dynamical information concerning troglobite populations is usually lacking, there may be a compelling argument for applying the *Precautionary Principle*.

These factors have important implications for the management of cave fauna with respect to direct human disturbance. In practical terms this means, for example, that destruction of cave biota by trampling in a particular site is unlikely to result in permanent ecological damage because of the ability of organisms to disperse and re-colonise the site from other areas once the disturbance ceases, assuming that the habitat and environmental conditions remain suitable. However, heavy trampling of cave soils may permanently degrade them and make them unsuitable for recolonization by the displaced fauna.

More so than human visitors to caves, a greater threat to cave communities and cave species are gross environmental disturbances which impinge on spatial scales encompassing entire karst catchment systems, or the entire distributional ranges of species, a range that may be much smaller than a catchment or karst region, even a single cave or part of a cave. Threatening processes acting on these scales have greater capacity to cause permanent ecological damage.

8.2 BIOLOGICAL SIGNIFICANCE AND VULNERABILITY OF CHRISTMAS ISLAND CAVES

Each cave has been ranked according to its apparent level of biological significance and perceived vulnerability (table 6). The significance ranking is based on the species and habitats recorded in the cave. The ranking categories are 'high/medium/low' and these are intended as a relative guide only. The vulnerability ranking assigned to each cave refers only to the vulnerability of biota and habitats with respect to human visitors. The ranking has been made on this basis because cave visitors are the most ubiquitous threat identified on Christmas Island, and have been identified as a high priority for management planning (Parks Australia pers. comm.). The impacts of human visitors on cave ecosystems are often subtle and difficult to predict because of the complexity of biological systems and the tendency for damage to be progressive and cumulative. The vulnerability ranking of each cave with respect to other external threats may vary depending on the nature of the threat, however, these impacts are often more clearly identifiable. The categories should not be regarded as rigid, but rather subject to change as further information is gathered and developments occur. They are intended as a relative guide only to assist management planning. It is emphasised that caves with a low vulnerability classification on biological criteria, may have a high vulnerability with respect to other values, and *vice-a-versa.*

8.3 SURVEY STATISTICS

Some 94 karst features are documented by Spate and Webb (1998). Less than one half (45%) of these karst features are caves, the remainder being alcoves, sinkholes, springs, and the Dales features. Of the 42 caves recorded, 23 (55%) were examined for fauna - these included all the major caves which are popular with visitors.

Fourteen (15%) of the karst features are springs including the Dales. Most of the springs are perennial although some flow only intermittently. All accessible bores were sampled for fauna and many of the springs.

Table 6. 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.

Cave #	Name	Type	Biology	Biological significance	Vulnerability to caver impacts
CI-1	The Grotto	Sea cave -	Marine -	?hydrological connection with CI-54 and CI-2.	Medium -
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.

Eight caves (CI- 1, 4, 7, 20, 53, 70, 73/74, 83) 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 are best explored with SCUBA equipment. 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. Only three caves (CI- 5, 6, 11) contain non-tidal freshwater streams.

There are likely to be a large number of caves on Christmas Island still to be explored. This is a consequence of the limited speleological investigations carried out to date, combined with the rugged and inaccessible nature of the terrain and coastline. Further exploration will undoubtedly reveal major new cave systems and associated subterranean fauna. Management planning needs to take this into account by assessing and protecting new discoveries as they come to light.

8.4 MANAGEMENT PRESCRIPTIONS

Perhaps the best strategy to protect cave fauna from caver impacts on Christmas Island involves the education of cave users, combined with habitat protection measures, and where necessary, restrictions on access. It is crucial to appreciate that any protective strategies put in place are a first step only and that ongoing monitoring, review and follow-up will be necessary. Thus, close and constant monitoring is required, together with a flexible and responsive management attitude because cave degradation is progressive, and may vary in space and time depending on natural events, and changes in cave usage patterns.

8.4.1. Protect cave fauna and habitats through education of cave users.

Cave users need to be made aware of sensitive fauna and habitats, and how to avoid disturbing them. This is part of Minimum Impact Caving practise, and is probably the most efficient way of curtailing general cave degradation. The information needs to be promoted assertively, and should be made available to all potential cave users. The cave users which are not affiliated with recognised speleological groups - such as school and outdoor groups, and casual visitors - are the priority community groups to target because they may lack cave awareness and caving experience. As for the in-cave protection measures adopted, the education program needs to be promoted on a continuing basis (eg. public presentations, posters, leaflets, published articles, media, etc.), and its efficacy closely monitored.

The Minimum Impact Caving Code of the Australian Speleological Federation (Australian Speleological Federation, 1995) goes a long way toward promoting conservation of cave fauna, however, there a number of caving techniques specifically relevant to fauna. The techniques are:

- Cave slowly.
- Be careful where you place your hands, feet and body, whilst looking out for small animals.
- Be aware of sensitive fauna and habitats, and avoid where possible:
  swiftlet colonies and guano deposits
  tree roots, sediment banks, organic material such as wood, leaf litter, carcasses, spiders webs.
- Avoid making loud noises or shining lights on animals.
- Do not leave any foreign material in caves including food scraps, human waste, batteries or carbide.

8.4.2 Protect invertebrate fauna and habitats by route marking to minimise trampling damage.

Habitat protection has been initiated in Jedda Cave with the installation of a string-line pathway and reflective markers to prevent trampling damage to sensitive tree root and mud bank habitat in the downstream chamber. Route markers or stringline pathways may need to be installed in other caves as the need arises. Route marking should be undertaken in 19th Hole to minimise trampling damage of soft floor sediments and litter deposits. Some other sites where habitat protection may be necessary are:

- other mud bank habitats in Jedda Cave;
- tree root and mud bank habitats in Jane Up Cave;
- other?

8.4.3 Fauna sanctuaries.

Some sensitive fauna or habitats may require strict regulation of visitor numbers, or total exclusion of cave visitors, to ensure their protection. Thus, fauna sanctuaries are designated 'no-go' areas for general cave visitors, although access may still be allowed for research, management, or other special purposes such as exploration, surveying, photography. Fauna sanctuaries may be delineated by a simple stringline barrier around the sensitive feature, or a stringline across the entrance of the passage containing the sensitive feature. An explanatory sign may also be installed. This form of protection relies on voluntary compliance by cave visitors, so appropriate behaviour can be encouraged through an education program. Where this method of protection is ineffective, or the biological feature especially sensitive, then installation of a gate may be necessary.

The only site identified on Christmas Island where a fauna sanctuary may be required is the swiftlet colony in Daniel Roux Cave.

8.4.4 Protect cave fauna and habitats through legislative protection where appropriate.

A number of cave dwelling species on Christmas Island are likely to satisfy the IUCN criteria for listing as threatened species. All of the troglobitic species, by virtue of their restricted distribution, satisfy the criteria for listing as rare species. All of these species remain undescribed at present, however they may be eligible for listing where appropriate voucher specimens exist.

The *Endangered Species Protection Act 1992* also allows for the listing of threatened populations, communities, and threatening processes. These categories may prove to be relevant on Christmas Island, for example, the swiftlets in Daniel Roux might qualify as an endangered population given that human disturbance was probably responsible for them abandoning the site for a period (Gray 1995).

8.4.5 Monitor human impacts on fauna and habitats.

Monitoring of fauna or habitats may be required to quantitatively assess impacts and undertake remedial actions. To measure impacts of human visitors on animal populations is not easy owing to the large natural variability in biological systems, and this is compounded by the extreme rarity of troglobitic species. Large numbers of sample units and intensive monitoring is required to obtain statistically valid results. In most cases, the required resources may not be available. An alternative approach to monitoring of animal populations is to monitor their habitat. With this approach, the condition of the habitat is monitored regularly and remedial actions taken if degradation reaches an unacceptable level. To give an example, the condition of tree roots and mud banks subject to trampling damage might be monitored by taking photographs at designated locations once a year. If a decline in habitat quality is detected then protective measures can be implemented.

The most sensitive cave dwelling fauna on Christmas Island are the swiftlets. The colony in Daniel Roux should be monitored on an annual basis at least. The condition of tree roots and soft floor sediments in other caves could be monitored on a casual basis. If excessive breakage of tree roots or compaction of soft floor sediments is occurring then protective actions are required.

8.4.6 Research

Research into the biology of cave species should be encouraged and supported because this will assist management of cave fauna.

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APPENDIX 1: GLOSSARY

anchialine (or anchihaline) — Anchialine habitats consist of bodies of haline waters, usually with a restricted exposure to open air, always with more or less extensive subterranean connections to the sea, and showing noticeable marine as well as terrestrial influences. They typically occur in volcanic or limestone bedrock.

cave — *Sensu lato* — underground void generally of a size sufficient for people to enter. However, the word means different things to different people. Cavers treat caves as natural holes large enough to enter — sometimes the term pothole is applied to vertical developments — or which extend to darkness. Archaeologists often use the term loosely to include rockshelters. In geomorphological terms, a cave is an opening of greater than 5-15 mm diameter or width, that is, a void of sufficient dimensions to allow turbulent rather than laminar flow of water (Ford and Williams, 1989). These differences are well reconciled by Howarth (1983: 370) "In both soluble and volcanic rocks, therefore, a complex of interconnected voids of varying sizes anastomoses throughout the rock in a great labyrinthine system. Within this system there is a continuum of various sized voids from the microscopic to the largest caverns. The existence of these voids, their size, depth, and extent, depends on the geological history of the area. From a biological perspective, this continuum can be divided into three size classes: microcavernous (< 0.1 cm), mesocavernous (0.1-20 cm) and macrocavernous (>20 cm)".

cavernicole — Species found in a cave *sensu lato* (value free)

cenote — Flooded collapse depressions on flat limestone plain - originally from Yucatan, Mexico.

crevicular — Pertaining to the finer cracks, crevices and spaces within rock matrix.

dark zone — Region of cave in perpetual total darkness.

decomposers — Any organism that feeds by degrading organic matter.

deep (zone) cave environment — Region of cave with constant temperature and near saturated humidity — the most troglomorphic species are often restricted to this region.

doline — Simple closed circular depression in karst area with subterranean drainage and commonly funnel shaped varying from a few to many metres in dimension.

entrance zone of cave — Area of cave where outside influences dominate both the physical and biological environment.

epigean — The surface environment as opposed to the subsurface (subterranean, hypogean) environment.

eutrophic — Pertaining to a large amount of available organic matter, high energy density or nutrient enrichment; in caves especially that provided by bat guano or flood debris.

foul air zone — Still air zone of cave, usually in depression or pot, with high humidity, and elevated carbon dioxide levels which may result from biogenic or physical effects (e.g. Howarth and Stone, 1990).

Ghyben-Herzberg principle — Expression of the relationship such that, in near coastal porous aquifers where fresh water overlays sea water, the depth below sea level of the fresh water/salt water interface is c. 40 times the height of the water table above sea level — hence a minor drawdown of the groundwater can lead to a major intrusion of sea water into an aquifer or by upconing.

guanobite — Species, that when in caves, inhabit exclusively bat guano deposits, and whose entire life cycle takes place in this substrate (Gnaspini and Trajano, in press).

guanophages — Species that feed directly on guano and animals that feed on microorganisms and fungi that grow on it (Gnaspini and Trajano, in press).

guanophile — Species that may inhabit and reproduce both in guano piles and in other substrates in the cave environment (Gnaspini and Trajano, in press).

guanoxene — A species feeding and/or reproducing in guano deposits but depending on other substrates in the cave to complete their life cycle (Gnaspini and Trajano, in press).

hypogean — The subsurface or subterranean environment as opposed to the surface (epigean) environment.

karst — Soluble rock landscape — terrain with distinctive hydrology and landforms arising from a combination of high rock solubility and well developed secondary porosity. The distinctive landforms above and below ground that are the hallmark of karst result from the solution of rock (mainly by carbonic acid) along pathways provided by the structure. The unusual features of the Kras (Karst in the period of the Austro-Hungarian empire) region on the Italo-Slovenian border became known as 'karst phenomena'. Such areas are characterized by sinking streams, caves, enclosed depressions, fluted rock outcrops and large springs (Ford and Williams, 1989).

lava tubes — Tubular caves within lava flows plus mechanical collapse of the roof in them (vulcanokarst).

MAST (or M.A.S.T.) — The mean annual surface temperature of a region — the expected temperature of the deep cave environment in the absence of significant geothermal heat or internal climatic effects.

mesocaverns — Underground voids in the size range 0.1-20 cm, especially in karst and volcanic substrates.

mesovoid shallow stratum — See superficial underground compartment.

mixohaline — Water with a salinity between 5 and 30 ppt under the Venice System (equivalent to 500 and 30,000 mg L^{-1} Total Dissolved Solids).

phreatic — That part of a cave system lying below the local groundwater table. cf. vadose.

pycnocline — More or less abrupt change in water density with depth — typically at halocline or thermocline in water column.

refuge (refugium, refugia) — A region in which certain types or suites of organisms are able to persist during a period in which most of the original geographic range becomes uninhabitable because of climatic change.

relics (*reliques* in French) — The last survivors of an ancient radiation.

relicts (*relictes* in French) — Population of organisms separated from a parent population by some vicariant event.

sinkhole — See doline.

speleothem — Secondary deposition in caves (commonly of calcite or aragonite) forming the cave decoration including stalagmites, stalactites, flowstone, draperies, straws, helictites etc. Also known as sinter or travertine.

stagnant air zone — See foul air zone.

stranding — The isolation inland of stygofauna owing to marine regression, especially following a period of marine transgression.

stygo- — Prefix referring to groundwater habitats (Gibert *et al.*, 1994: 13).

stygobiont — Animal inhabiting the various types of groundwater.

stygobite — Species that are specialised subterranean forms, obligatory hypogean. Some are widely distributed in all kinds of groundwater systems (both karst and alluvia), and sometimes they are found very close to the surface.

stygofauna — Fauna inhabiting the various types of groundwater. Numerous names are in use for subsets of this system mostly based on the habitat type (see e.g. Botosaneanu, 1986: especially the endpaper; Camacho, 1992; Gibert et al., 1994).

stygogenesis — The morphological, behavioural, physiological and other changes found in species or lineages as they populate groundwater or adapt to groundwater life.

stygophile — Organisms that seek out and exploit resources in the groundwater system (Stanford and Ward, 1993). In porous aquifers, stygophiles are subdivided into three categories; 1) the occasional hyporheos, (2) the amphibites, and (3) the permanent hyporheos. For more information see Gibert et al. (1994: 13).

stygoxen(es) — Organisms having no affinity for groundwater, but occur accidentally in caves or alluvial sediments.

stygomorphic — Pertaining to morphological, behavioural and physiological characters that are convergent in subterranean aquatic populations.

stygoxenes — Organisms that have no affinities with the groundwater systems, but occur accidentally in caves or alluvial sediments. Nevertheless, stygoxenes can influence processes in the groundwater ecosystems, for example, functioning either as predators or prey.

superficial underground compartment — The deep soil crevicular spaces as found in glacially fragmented zones. By origin the *mileau souterrain superficial* (MSS; Juberthie et al., 1980) also the mesovoid shallow stratum hence retaining the initials MSS.

transition zone of cave --- Region of cave between the twilight zone and the deep zone, where the environmental effects (e.g. temperature and humidity changes) from the surface are still felt. Extent of the transition zone is highly variable depending on the cave structure and changes in environmental conditions on the surface.

troglobite — Species which do not exist outside caves — but they may occur in the superficial underground compartment or in the upper hypogean zone.

troglobitization — See troglogenesis

troglogenesis — The morphological, behavioural, physiological and other changes found in species /lineages as they populate/adapt to cave hypogean life.
troglomorphic — See troglomorphy

troglomorphy — Pertaining to morphological, behavioural and physiological characters that are convergent in subterranean populations.

troglophile — Species able to live and reproduce underground as well as in the epigean domain.

troglos — Assemblage of organisms inhabiting underground voids, often restricted to the 'terrestrial' organisms in air filled voids.

trogloxene — Species that do not normally feed underground, but may enter caves actively (regular trogloxene) or passively (accidental trogloxene).

twilight zone of cave — Region of cave extending from the boundary of green vascular plants to total darkness — physical climate not stable.

APPENDIX 2: PHOTOGRAPHS 1 - 16

A2.1: Drowned stalagmites in Thunder Dome (CI-91). Photo: Stefan Eberhard.

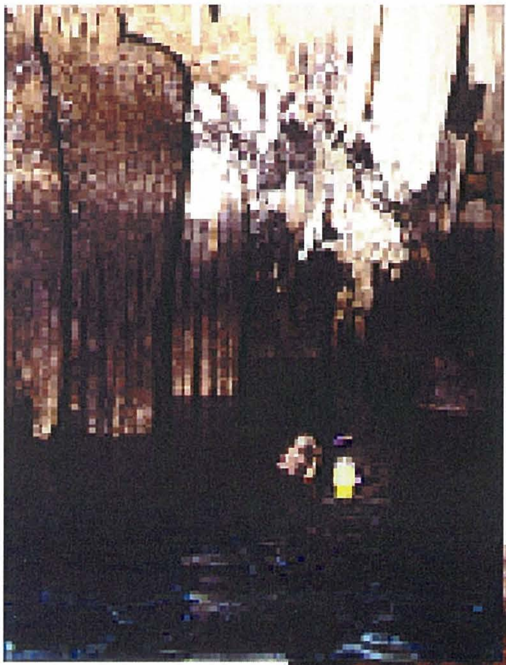
A2.2: Sampling from multilevel piezometers, Smithsons Bight area. Stefan Eberhard, W.A. Museum.

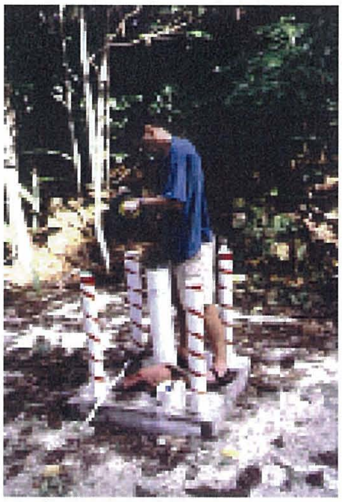
A2.3: Anchialine habitat in CI-54. Photo: Stefan Eberhard, W.A. Museum.

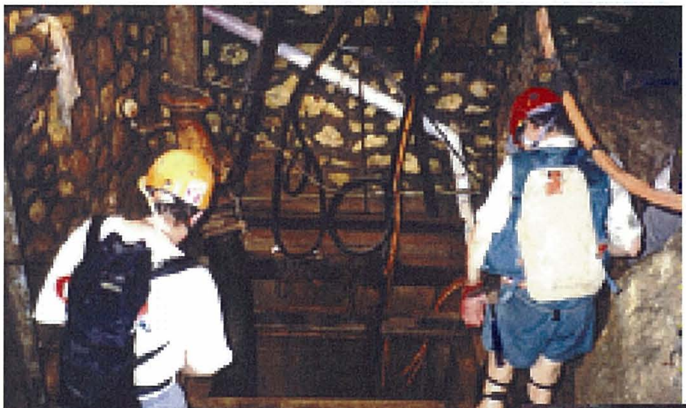
A2.4: Pump station infrastructure in Jedda Cave (CI-5). Photo: Bill Humphreys, W.A. Museum.

A2.5: Net (350 µm mesh) placed in the streamway of Jedda Cave for 24 hours to filter the major part of the stream flow upstream of the pumping station. Photo: Bill Humphreys, W.A. Museum.

A2.6: Abandoned water bore (WB30) in dense rainforest. Note the plate covering the bore hole on the concrete pad . The status of most of the old bore sites is unknown. Photo: Bill Humphreys, W.A. Museum.







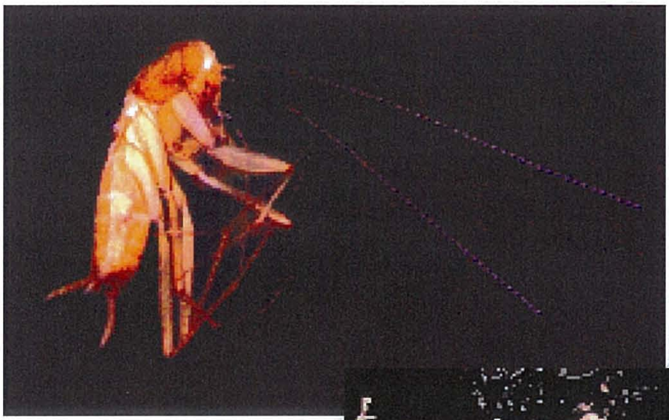
A2.7: Gen. et sp. nov. (Blattodea: Nocticolidae), Tb. Jedda Cave (CI-5). Preserved specimen. Photo: Stefan Eberhard, W.A. Museum.

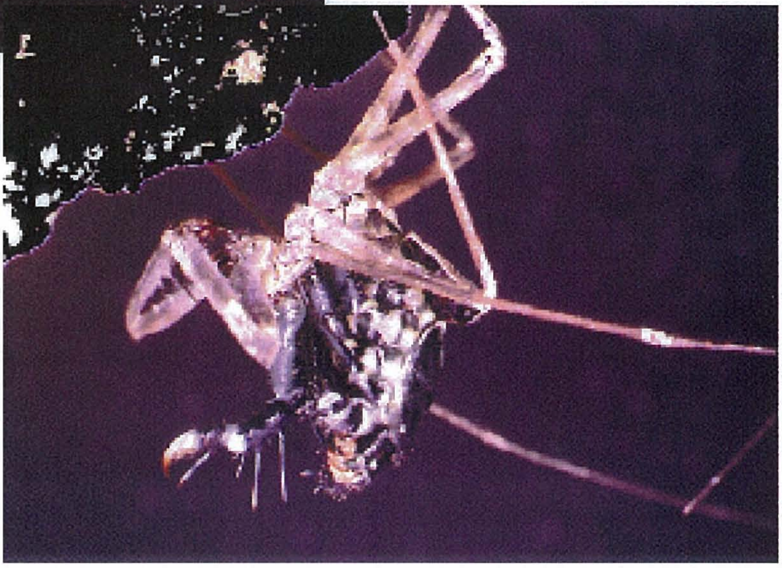
A2.8: *Charon* sp. nov. (Arachnida: Amblypygida: Charontidae). 19th Hole (CI-19). Died while moulting. Preserved specimen. Photo: Stefan Eberhard, W.A. Museum.

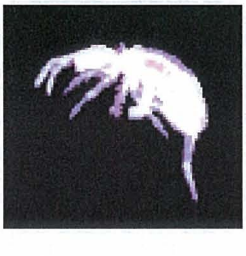
A2.9: Collembola. Jedda Cave (CI-5). Preserved specimen. Photo: Stefan Eberhard, W.A. Museum.

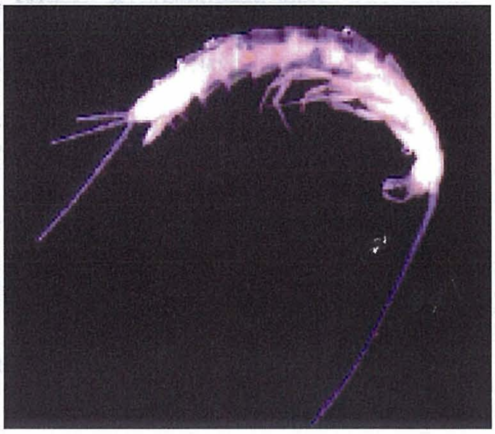
A2.10: *Liocheles* sp. nov. (Arachnida: Scorpionida), Tb. 19th Hole (CI-19). Female photographed in life. Photo: Stefan Eberhard, W.A. Museum.

A2.11: *Metrinura* sp. nov. (Thysanura) Tb? Jedda Cave (CI-5). Preserved specimen. Photo: Stefan Eberhard, W.A. Museum.









A2.13: *Antecaridina lauensis* (Edmondson, 1935) (Decapoda: Atyidae), An. 19th Hole (CI-19). Preserved specimen. Photo: Stefan Eberhard, W.A. Museum.

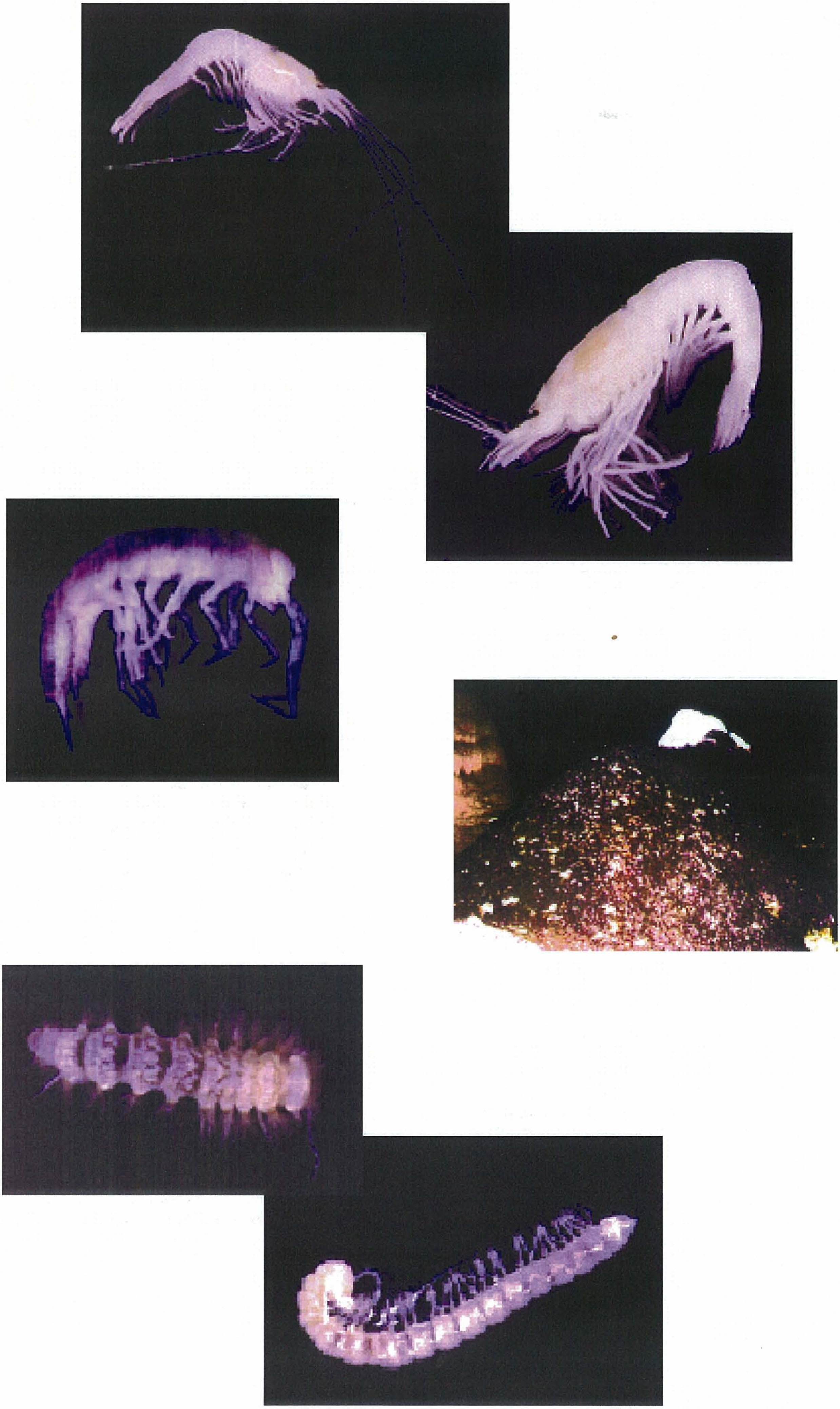
A2.12: *Procaris* sp. nov. (Decapoda: Procarididae), An. Runaway Cave (CI-2). Anchialine system. Preserved specimen. Photo: Stefan Eberhard, W.A. Museum.

A2.14: *Papuaphiloscia* n. sp. (Isopoda: Oniscoidea), Tb. Jedda Cave (CI-5). Preserved specimen. Photo: Stefan Eberhard, W.A. Museum.

A2.15: A large guano pile produced by the Glossy Cave Swiftlets in the upper part of Daniel Roux Cave. Such guano piles normally support a populous, sometime species rich, fauna of guanophilic animals. Photo: Stefan Eberhard, W.A. Museum.

A2.17: *Cylindrodesmus hirsutus* Pocock (Diplopoda: Polydesmida: Haplodesmidae), Tb . Jedda Cave (CI-5). Preserved specimen. Photo: Stefan Eberhard, W.A. Museum.

A2.16: Polyxenid millipede (BES 5849) (Diplopoda: Polyxenida: Polyxenidae). Jedda Cave (CI-5). Preserved specimen. Photo: Stefan Eberhard, W.A. Museum.



APPENDIX 3: CAVE LIST

A brief description of relevant biological features for each cave surveyed is given below, together with a ranked assessment of biological significance and vulnerability to human impacts. The data are also summarised in Table 5.

CI-1 The Grotto.
Sea cave entrance connecting with inland entrance and freshwater outflow system. Contains marine fish. Biologically important for its probable hydrological connection with CI-54 and CI-2. A popular site with visitors but the cave is a robust high energy environment. Vulnerability to caver impacts - Low.

CI-2 Runaway Cave.
Tidally influenced freshwater habitat overlying seawater. Important for anchialine habitat and associated aquatic fauna, hydrological relationships with CI-54 and C-I1. Contains tree roots and terrestrial fauna including whip scorpions. Cave is easily accessible and well known, but vulnerability of fauna to visitor impacts is not high.
Biological significance - Medium to High.
Vulnerability to caver impacts - Low

CI-3 Daniel Roux Cave (main).
Contains freshwater and anchialine habitats. Cave is well known and easily accessible - the lower levels are a generally robust high energy environment although mud bank habitats are also present.
Biological significance - Low to Medium.
Vulnerability to caver impacts - Low.

CI-4 Sea entrance to CI-3.

CI-5 Jedda Cave.
Plateau cave containing active streamway, sediment banks, wood, and tree roots. Cave is well known and easily accessible although access could be easily restricted by locking the entrance gate. The

lower streamway contains an upper level side passage with tree roots, sediment banks and a number of troglobitic species. This section of the cave is naturally well protected as it involves an arduous crawl in the streamway - the side passage has been trail-marked to prevent trampling damage. Troglobitic fauna also occurs on the sediment banks and old wood beside the stream and close to the entrance.

Biological significance - High.

Vulnerability to caver impacts - Medium.

CI-6 Jane Up Cave.

Plateau cave containing active streamway, sediment banks, tree roots, and troglobitic species. Cave is easily accessible, and there is some compaction of soft floor sediments and damage to tree roots.

Biological significance - Medium (possibly High at other times). Vulnerability to caver impacts - Medium.

CI-7 Lost Lake Cave.

Sea cave entrance with freshwater outflow and anchialine habitat. Contains marine biota. Cave is important for recreational caving and geomorphological values, but the biological components are considered resilient to caver impacts.

Biological significance - Medium.

Vulnerability to caver impacts - Low

CI-8 Bishops Cave.

Inland entrance leads to tidally influenced aquatic and anchialine habitats. Contains terrestrial fauna, including troglobites. Entrance is difficult to locate and not well known. Fauna and habitats in this cave are not considered threatened.

Biological significance - Medium.

Vulnerability to caver impacts - Low

CI-9 Smiths Cave.

Contains swiftlet colony and associated invertebrate guano community. Contains tidally influenced aquatic and anchialine habitat. Entrance is near to popular walking track but difficult to locate without prior knowledge of the location. The swiftlets and guano community are vulnerable to disturbance from cave visitors.

Biological significance - Medium.

Vulnerability to caver impacts - Medium to High.

CI-10 Freshwater Cave.

Inland entrance leads to tidally influenced freshwater habitat. Cave location is well known and a popular destination for visitors. Cave is biologically fairly robust, although the upper passages near the entrance contain tree roots and leaf litter deposits.

Biological significance - Medium.

Vulnerability to caver impacts - Low.

CI-11 Grants Well.

Plateau cave, contains freshwater stream habitat. Important for hydrological relationships with CI-5 and CI-6. Entrance location is well known, but unlikely to be visited often because vertical equipment is required.

Biological significance - Low

Vulnerability to caver impacts - Low

CI-12 and CI-13 Unnamed sinkholes. Not surveyed.

CI-14 10 Mile Sinkhole. Filled in. Not surveyed.

CI-15 Drivers Cave. Not surveyed.

CI-16 Strangler Cave.

Inland entrance leads to tidally influenced aquatic and anchialine habitat. Contains tree roots and terrestrial fauna. Cave is difficult to locate and not well known.

Biological significance - Medium.

Vulnerability to caver impacts - Low.

CI-17 and CI-18 Dolines. Not surveyed.

CI-19 The 19th Hole.

Inland entrance leads to tidally influenced anchialine habitat. Contains tree roots, plant litter and soft sediments; warm and humid environment. Contains aquatic and terrestrial fauna, including troglobites. Cave previously used for dumping rubbish. Entrance is easily located.

Biological significance - High.
Vulnerability to caver impacts - Medium.

CI-20 Full Frontal Cave.
Sea cave entrance leads into freshwater outflow system. Contains anchialine habitat, sediment banks, marine species. Entry is dependent on tides and swell conditions. Cave environment is robust.
Biological significance - Medium.
Vulnerability to caver impacts - Low.

CI-21 to CI-27 Sinkholes. Not surveyed.

CI-28 Brians Hole. Not surveyed.

CI-29 Petite Cave. Not surveyed.

CI-30 Swiftlet Cave.
Contains swiftlet colony, and potentially a significant site. Location uncertain, but near CI-3. Needs survey to assess swiftlets and vulnerability.
Biological significance - possibly High.
Vulnerability to caver impacts - probably High.

CI-31 Indian Cave.
Small cave with little or no dark zone environment. Entrance is well known and easily located. Not surveyed, but unlikely to be biologically important.
Biological significance - Low.
Vulnerability to caver impacts - Low.

CI-32 2nd entrance to CI-16.

CI-33 3rd entrance to CI-16.

CI-34 Safety Pin Cave. Not surveyed.

CI-35 to CI-44, and CI-46 Alcoves. Not surveyed.

CI-45 Alcove. Contains guano. Not surveyed.

CI-47 and CI-48 Sinkholes. Not surveyed.

CI-49 Alcove. Not surveyed.

CI-50 Managers Alcove.
Contains swiftlet colony and guano. Located on cliff near old Hospital. Potentially significant swiftlet site, which needs to be surveyed. Human access is made difficult by the need to abseil from top of cliff. Biological significance - possibly High.
Vulnerability to caver impacts - possibly Medium.

CI-51 Donald Duck Drain. Not surveyed.

CI-52 10 entrances. Not surveyed.

CI-53 Grimes Cave.
Sea cave entrance with freshwater outflow and upper level passages. Contains small swiftlet colony and freshwater pools.
Biological significance - Medium.
Vulnerability to caver impacts - Low to Medium.

CI-54 and CI-55 Unnamed. Not surveyed.

CI-56 Daniel Roux Cave (upper).
Contains large swiftlet colony and associated invertebrate guano community. Cave is easily accessible and well known. Swiftlet colony is very vulnerable to human disturbance - the colony abandoned the cave for a period in 1984, probably due to human disturbance (Gray 1995). The invertebrate guano community is sensitive to trampling impacts but remains viable so long as the swiftlets continue to occupy the site. Protective measures and monitoring of the swiftlet colony are considered desirable, as is a regional survey of other swiftlet caves. Biological significance - High.
Vulnerability to caver impacts - High

CI-57 Unnamed. Not surveyed.

CI-58 Hudsons Spring.

Intermittent freshwater outflow. Important for tufa deposit (CHECK). Not sampled because water absent.

Biological significance - Medium.

Vulnerability to impacts - Low.

CI-59 Pool and small spring. Not sampled.

Biological significance - Medium.

Vulnerability to impacts - Low.

CI-60 Dry Resurgence. Not sampled.

CI-61 Hewans Spring (piped).

Freshwater outflow diverted to pump house at CI-64. Contains aquatic fauna.

Biological significance - Medium.

Vulnerability to impacts - Low.

CI-62 Damp Creek Bed Resurgence. Not sampled.

CI-63 Active Surface Stream - Resurgence. Not sampled.

CI-64 Hendersons Spring (The Pump house).

Perennial freshwater outflow, includes water piped from CI-61, CI-65 and CI-66. Contains aquatic fauna.

Biological significance - Medium.

Vulnerability to impacts - Low.

CI-65 Spring (piped).

Freshwater outflow, piped to pump house at CI-64.

Biological significance - Medium.

Vulnerability to impacts - Low.

CI-66 Harrisons Spring (piped).

Freshwater outflow, piped to pump house at CI-64.
Biological significance - Medium.
Vulnerability to impacts - Low.

CI-67 Spring (abandoned). Not surveyed.

CI-68 Wobble Cave.
Small cave with little or no dark zone environment. Not surveyed, but unlikely to be biologically important.
Biological significance - Low.
Vulnerability to caver impacts - Low.

CI-69 Unallocated number.

CI-70 Boat Cave.
Sea cave entrance with freshwater outflow. Contains marine fauna, and possibly anchialine habitat. Popular dive site, but resilient to visitor impacts.
Biological significance - Medium.
Vulnerability to impacts - Low.

CI-71 Small cave near CI-10. Not surveyed.
CI-72 Doline. Not surveyed.

CI-73 and CI-74 The Tunnel.
Sea cave with entrances at both ends. Contains marine fauna. Popular dive site.
Biological significance - Low.
Vulnerability to impacts - Low

CI-75 Hosnies Spring.
Perennial freshwater outflow spring and surface stream. Important for tufa deposits and stand of freshwater mangroves (Gray 1995).
Biological significance - High.
Vulnerability to impacts - Medium.

CI-76 Dale No. 1.

Freshwater spring and surface stream. Important for tufa deposits and aquatic fauna. Soft stream bed is vulnerable to trampling although there is a warning sign in place.

Biological significance - High.

Vulnerability to impacts - Medium.

CI-77 Hughs Dale No. 2.

Perennial freshwater outflow spring and surface stream. Important for tufa deposits and aquatic fauna. Contains introduced fish.

Biological significance - High.

Vulnerability to impacts - Medium.

CI-78 Anderson Dale No. 2.

Perennial freshwater outflow spring and surface stream. Important for tufa deposits and aquatic fauna. Contains introduced fish.

Biological significance - High.

Vulnerability to impacts - Medium.

CI-79 Small cave near CI-78. Not surveyed.

CI-80 Rift and small cave near CI-79. Not surveyed.

CI-81 Sydneys Dale No. 6.

Freshwater spring and surface stream. Not sampled.

CI-82 and CI-83 Cave in Sydneys Dale.

Sea cave, transition zone environment only. Not sampled.

CI-84 Dale No. 7. Not surveyed.

CI-85 Freshwater Spring (at Resort).

Perennial outflow and surface stream, piped to the Resort. Contains aquatic fauna.

Biological significance - Medium.

Vulnerability to impacts - Low.

CI-86 Jones Spring. Not sampled.

CI-87 Egeria Point Cave 1.
Submarine cave. Entrance at approximately 30 metres depth with passage terminating at 50 metres depth. Contains marine fauna, and possibly freshwater outflow. Access by boat. Not surveyed.

CI-88 Egeria Point Cave 2.
Submarine cave. Entrance in shallow water leads into possibly extensive cave system. Access by boat. Not surveyed.

CI-89 West White Beach Efflux.
Sea cave entrance with freshwater outflow, possibly connected to CI-16. Access by boat. Not surveyed.

CI-90 Thunder Cliff Cave.
Sea cave entrance leads to freshwater outflow system. Contains terrestrial and aquatic habitats, and marine fauna. Popular dive site, access by boat.
Biological significance - Medium.
Vulnerability to impacts - Low

CI-91 Thunder Dome Cave.
Submarine cave with dark zone environment. Contains marine fauna, including species normally found in deeper water. Popular dive site, access by boat.
Biological significance - Medium.
Vulnerability to impacts - Low.

CI-92 Councillor Cave.
Sea cave, contains marine fauna. Popular dive site, access by boat.
Biological significance - Medium.
Vulnerability to impacts - Low.

CI-93 Coconut Point Cave.
Submarine cave. Entrance in shallow water leads into possibly extensive cave system. Access by boat. Not surveyed.

Dale No. 3. Not numbered.

Darling Dale No. 4. Not numbered.

APPENDIX 4: ANNOTATED SYSTEMATIC LISTING OF THE FAUNA COLLECTED IN 1998

Several pertinent records from other collections in the Western Australian Museum are included, as are a number of field observations.

The systematic listing largely follows the order and nomenclature of Botosaneanu (1986) and Harvey and Yen (1989). The references cited are given in the main reference list for the report. WAM refers to collections previously in the data base of the Western Australian Museum. The Pink House is the Christmas Island Environmental Research Station.

Studies of the new taxa are mostly in their early stages and the initial taxonomic and cavernicolous attributions may require revision.

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
ANIC: Australian National Insect Collection, Canberra.

SYSTEMATIC LIST

Phylum **PLATYHELMINTHES** — Flatworms

Class **TURBELLARIA**

'Microturbellaria' cf Schwank 1986

Microturbellara were recovered from freshwater at Jane Up Well. The absence of surface water on the plateau surface suggests that they will be widely present in the freshwater system and, of necessity, restricted to the groundwater. The majority of the turbellarian orders are combined, for practical purposes, under the term 'microturbellaria', a term which incorporates many morphological types and is systematically heterogeneous. Most subterranean microturbellaria are blind and colourless but then so are many epigean species and so these characters do not serve to distinguish subterranean forms (Schwank, 1986). Microturbellaria adhere to surfaces and preserve very poorly. They need to be examined *in vivo* by a systematist and as such targeted specialist collecting is required. They are poorly known globally and especially so in Asia. Nonetheless, they are important predators in stygal communities.

Phylum **ANNELIDA**

Class **POLYCHAETA** det R. Wilson

Family **SYLLIDAE**

Indet.

CI-54; baited net at 4 m depth in anchialine water. The Syllidae is a large and diverse family of creeping and burrowing polychaetes with diverse reproductive methods both sexual and asexual, ranging from broadcast of gametes in plankton swarms to intensive brood care. They are small and fragile and easily damaged during collecting. They are common in polyhaline waters such as estuaries (Day, 1967).

Class **ARCHIANNELIDA** det R. Wilson

Family **Nerillidae**

Nerilla sp.

CI-54; amongst tree roots in anchialine water. There are about 8 described species worldwide, at least some from interstitial and/or cave habitats (Gelder, 1974). One species, *Nerilla australis* Willis, 1951, is described from Australia, inhabiting a salt marsh in Westernport Bay, Victoria. The genus is free living and is cosmopolitan in marine systems, whereas other general are cave dwelling or inhabit the branchial chambers of freshwater decapod crustaceans (Willis, 1951).

Class **APHANONEURA** det A. Pinder

Coastal water bore #1, Smithsons Bight area; Jane Up Well. The Aphanoneura are now considered a separate clade of the Annelida and comprise two families, the Aphanoneura and Aeolosomatidae. Dumnicka and Juberthie (1994) only record subterranean forms from Europe, west Africa and USA.

Class **OLIGOCHAETA** det A. Pinder

Order **HAPLOTAXIDA**

Family **Enchytraeidae**

Coastal water bore #1, Smithsons Bight area; coastal water bore #2, Smithsons Bight area. Forest soils are usually teeming with enchytraeids and there are many of marine forms and quite a lot of freshwater forms (A. Pinder, pers. comm., 1998). Freshwater forms are known from Western Australia but none has been described. No subterranean forms are recorded by Dumnicka and Juberthie (1994) outside Europe and the Americas. Other than on marine species (Coates, 1990; Coates and Stacey, 1993), there has been virtually no work done on the whole family in Australia.

Family **Tubificidae**

Indet.

Freshwater Spring (CI-85). Widespread family inhabiting marine and freshwater habitats of great variety. About 48 marine species occur in Australia belonging to 13 mostly cosmopolitan genera (Erséus, 1990, 1993; Pinder in Davis and Christidis, 1997;). No subterranean forms are recorded by Dumnicka and Juberthie (1994) outside Europe and the Americas.

Order **OPISTHOPORA** (Earthworm)

Family Indet.

Indet.

Smiths Cave (CI-9).

Phylum **MOLLUSCA** det S.M. Slack-Smith

Snails thrive in limestone landscapes owing to the ready availability of calcium. On Christmas Island they were commonly found in the caves, often as shells but many live specimens as well.

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). Juvenile, just hatched.

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

?*Lamellaxis* sp.
Grants Well (CI-11). Juvenile, just hatched.

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

Family **Helicarionidae**
Microcystis sp.
Jane Up Cave (CI-6); CI-55. Unknown species of previously unrecorded group.

?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). Juveniles; but clustering habit consistent with this species which, however, is better known from mainland coasts. This crevice-dwelling mussel was found in small numbers intertidally in the

dark zone of Full Frontal Cave. The settling larvae are likely to seek dark entrances from which they would be carried into the cave where they would be sustained by nutrients transported by the ebb and flow of the tide.

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). This higher taxon was collected in a wide variety of habitats by haul net and filtering stream flows. It was collected from underground streams on the plateau in freshwater, in traps at 4 m depth in anchialine habitats in sea water.

Subclass **COPEPODA**

Order **CALANOIDA** det. G.L. Pesce

Indet.

CI-54. Anchialine system.

The Calanoida is a large order of planktonic copepods. 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).

Order **CYCLOPOIDA**

Cyclopoida is commonly regarded as a freshwater group, where it is the most successful order of copepods. However, the primary marine distribution of the plesiomorphic families, such as the Cyclopinidae, indicate that it was primitively a marine group (Huys and Boxshall, 1991: 407).

Family **Cyclopinidae**

(CI-54). Anchialine cave

Bryocyclops (Bryocyclops) muscicola (Menzel, 1926)

Coastal water bore #1, Smithsons Bight area; Coastal water bore

#2, Smithsons Bight area; Jedda Cave (CI-5); Jane Up Well; Grants Well (CI-11); (CI-54); Hendersons Spring pumphouse outflow (CI-64). This species was collected in a wide variety of habitats by haul net and filtering stream flows. It was collected from underground streams on the plateau in freshwater, down boreholes on the coastal plain, in traps at 4 m depth in anchialine habitats in sea water. 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.

Cyclopinids have secondarily invaded the sediments and become interstitial, have invaded freshwater via estuaries, but the number of freshwater forms is small (*ibid.*).

Order **Harpacticoida**

Harpacticoida is the dominant group of benthic copepods that have successfully exploited a wide variety of other habitats. Primitively a marine epibenthic group at least four families have independently invaded, and are mostly confined to, freshwater habitats.

Family **Ameiridae**

Nitocrella/Nitokra complex det. G.A. Boxshall

Coastal water bore #2; CI-54; Hendersons Spring (CI-64). Net over outlet for 24 hours. Collected from freshwater springs, near coastal bores and anchialine caves.

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

Hendersons Spring (CI-64). Freshwater.

The Ameiridae are primarily marine forms but isolated representatives have secondarily invaded freshwater (Huys and Boxshall, 1991).

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

Indet.

Full Frontal Cave (CI-20). Gour pool.

The Canthocamptidae is by far the largest family of freshwater Harpacticoida (Huys and Boxshall, 1991).

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

Indet.

Coastal water bore #2 Smithsons Bight area.

The plesiomorphic family Phyllognathopodidae comprised three genera, one of which inhabits unusual habitats such as the leaf pools of bromeliads and the pitchers of pitcher plants (Huys and Boxshall, 1991).

Class **ISOPODA**

Order **ONISCOIDEA** det S. Taiti

Family **Armadillidae**

Myrmecodillo n. sp. 1 **Tx**

Jedda Cave (CI-5), tree roots dark; Jane Up Cave (CI-6), tree roots dark; Freshwater Cave (CI-10).

Myrmecodillo n. sp. 2 **Tx**

Coastal water bore #2, Smithsons Bight area.

At present the genus *Myrmecodillo* includes seven species but at least 15 new species await description. The genus has an Indian and Pacific distribution from South Africa and Madagascar to Polynesia. The two new species from Christmas Island might be trogloxenous, as all the other species are common in forest litter (S. Taiti, pers. comm. 1998).

Family **Eubelidae**

Elumoides monocellatus Taiti & Ferrara, 1983

Coastal water bore #2, Smithsons Bight area. This species is widespread in the Indian and Pacific area, from the Seychelles to Polynesia (S. Taiti, pers. comm. 1998).

Family **Olibrinidae**

Olibrinus antennatus (Budde-Lund, 1902)

Full Frontal Cave (CI-20). *Olibrinus antennatus* is an amphibious species widely distributed along the coasts of the Indian Ocean and probably Japan. The family Olibrinidae was first recorded in Australia on Barrow Island (Dalens, 1993). Six of ten species come from shores of Indian Ocean, and the remaining species from Japan (3) and Hawaiian Is (1: *ibid.*).

Family **Philosciidae**

Burmoniscus sp. (prob. *B. orientalis* Green, Ferrara & Taiti, 1990.

Henderson's Spring (CI-64). Net over outlet for 24 hours. *B. orientalis* is widely distributed in Southeast Asia from Thailand to Indonesia.

Papuaphiloscia n. sp. **Tp2** (photo. A2.14)

Jedda Cave (CI-5), tree roots, dark zone. The genus *Papuaphiloscia* includes 10 species from southern China to Hawaii. The new species from Christmas Island represents the first record for the Indian Ocean area. All species are colourless and blind (only one with a reduced eye of a single ommatidium) and some are found in caves. However they are probably only troglophilic rather than troglobitic (S. Taiti, pers. comm. 1998).

Class **AMPHIPODA**

Indet.

CI-54. Anchialine system.

Class **MALACOSTRACA**

Order **DECAPODA**
Infraorder **CARIDEA**
Family **Procarididae** det. J. Short

Procaris (undescribed species) **Sb** (photo. A2.12)

Runaway Cave. Only two other species are known from the genus, *P. hawaiana* Holthuis, 1973, from Hawaii and *P. ascensionis* Chace and Manning, 1972 from Ascension Island in the south Atlantic. This is a primitive, highly aberrant, family appears to be restricted to anchialine caves and has only one other representative, *Vetericaris chaceorum* Kensley & Williams, 1986, from Bermuda. All species of Procarididae are sympatric with one or more species of atyid shrimps (Ascension I., Hawaiian archipelago, Bermuda and Christmas I.). 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).

Family **Alpheidae** det. J. Short

?three species.

CI-54. Anchialine system.

Only one species listed in the synopsis of the world's stygofauna (Botosaneanu, 1986), from an anchialine cave in Bermuda (Hart and Manning, 1981).

Family **Palaemoninae** det. J. Short

Macrobrachium, either *M. lar* or *M. microps*.

CI-54; Hendersons Spring (CI-64). Anchialine system and freshwater spring respectively.

M. lar is the most widespread *Macrobrachium* and occurs throughout much of the Indo-West Pacific. It is a usually epigeal and adults are generally found in freshwater rainforest streams. The larvae/early postlarvae appear to be tolerant of high salinities.

Macrobrachium microps Holthuis, 1978.

Freshwater Cave (CI-10). Few specimens are known of this species which was described from New Ireland and also known from Samoa and the Loyalty Islands. Also WAM: collected by P. Meeks, 1996).

Family **Atyidae** det. S. Choy

Antecaridina lauensis (Edmondson, 1935)(photo A2.11)

The species has a very wide distribution in anchialine waters ranging from Madagascar, the Red Sea and through to Fiji. As far as I am aware this is the first record from Christmas Island (S. Choy, pers. comm. 1998). Live specimens of this species range in colour, from almost colourless through orange to bright red. Red shrimps are tied in with mythology in some countries (eg. Fiji, Hawaii and the Philippines) and taboos have lead to their conservation (Choy, 1987). The family is cosmopolitan with many widely vicariant congeneric species (Holthuis, 1986).

Family **Hippolytidae** det. J. Short

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

Runaway Cave. *P. uveae* is widely distributed in anchialine pools from scattered localities between the Western Indian Ocean and Hawaii. Only one species listed in the synopsis of the world's stygofauna (Botosaneanu, 1986), from an intertidal sea cave in New Zealand.

Family **Palinuridae**

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**

Geograpsus grayi (H. Milne Edwards).

The little nipper, occurs throughout the island but was not found associated with caves.

Sesarma jacksoni Balss, jackson's crab,

originally described from the neighbourhood of Grimes Cave and it is most common along the NE shore terrace from Smith Point to Dolly Beach (Gibson-Hill, 1947b). Here it is recorded more widely including 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). Hence, it would appear that where low shore terraces do not exist, that the crabs utilize the lower parts of those caves connected to the sea; this crab readily enters buildings (George, 1978). Jackson's crabs are seen often deep in caves where no other fauna is seen.

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 sp. nov. **Tb** (photo A2.10)

Known from one specimen in each of Bishops Cave (CI-8: the first specimen was collected by N. Plumley, 11 August, 1987) and the 19th Hole (CI-19) where they were found walking on bare rock surfaces. This is the first blind scorpion known from Australia; globally only 14 blind scorpions are known, of which only two are known outside the New World tropics (11 in Mexico, one each in Equador, Sarawak and Christmas Island). An epigean scorpion, *Hormurus australasiae* Fabricius has also been recorded from the island (in Gibson-Hill, 1947a).

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. Found from twilight/ transition zone to deep cave habitats. This is a cosmopolitan family that is common and abundant in caves and ranging from twilight zone inhabitants to anopthalmic species in the deep zone, the latter principally in warmer climates (Ribera and Juberthie, 1994).

Family **Uloboridae** det. J.M. Waldock

Zosis sp.

Smiths Cave (CI-9); Freshwater Cave (CI-10). Found in doline and twilight zone.

Family **Scytodidae** det. J.M. Waldock

Indet.

19th Hole (CI-19), transition zone; CI-54, twilight zone.

Frequent occupiers of caves, principally in the tropics with several troglomorphic species (Ribera and Juberthie, 1994).

Family **Theridiidae** det. J.M.Waldock

Indet. **Tp**

Smiths Cave (CI-9), on web, transition zone; Bishops Cave (CI-8), on web, twilight zone. Frequently found in tropical, but rare in temperate, caves, they are mostly considered to be troglophiles (Ribera and Juberthie, 1994) but at least two troglobitic species are known from Cape Range, Western Australia (Harvey et al. 1993) and some from Tasmania (Eberhard et al. 1991).

Family **Oonopidae** det. J.M. Waldock

Opopaea sp. **Ep**

Hendersons Spring (CI-64), net over outlet for 24 hours. Tiny spiders common in tropical rainforest and tropical caves where they exhibit all degrees of troglomorphy (Ribera and Juberthie, 1994). The family is known from caves in Cape Range, Western Australia, where it is not troglomorphic, and where the genus *Opopaea* also occurs in the epigean fauna.

Family **Gnaphosidae** det. R. Raven

Indet. **Tb**

Jedda Cave (CI-5); dark zone with parasitic mites. Only three troglobitic gnaphosids are reported in Ribera and Juberthie (1994), from lava tubes in the Galapagos and a cave in Cuba.

Family **Heteropodidae** det. J.M. Waldock

Indet.

Smiths Cave (CI-9); twilight transition zone.

Family **Salticidae** det. J.M. Waldock

Plexippus? **Ep**

Pink House. No troglobitic salticids are known and, as they are the epitome of visual spiders, none is likely to be found.

Order **AMBLYPYGI**

Family **Charontidae**

Charon sp. nov. Harvey and West, in press. **tp1** (photo. A2.8)

Runaway (CI-2); 19th Hole (CI-19); CI-54 where it was seen in numbers. Note that all these sites are in the settled part of the island. The species is described from specimens collected from a woodpile in the settlement on Christmas Island and it is considered likely that the Christmas Island species will be found in Java, only some 360 km away (Harvey and West, in press). This is reinforced by the lack of sightings during this survey of specimens from caves in other parts of the island. Two species of *Charon* are found in tropical mainland Australia, one from sandstone caves in the Northern Territory, and an epigean species from Queensland (Harvey and West, in press), none is troglomorphic. A circum-tropical order in which all families have evolved cave dwelling species, some of which have reduced eyes (Weygoldt, 1994). Amblypygids seems to be limited to caves within 20° of latitude of the equator and their main prey is rhaphidophorid crickets (Deharveng, in press), which are not reported from Christmas Island.

Order **SCHIZOMIDA**

A single undetermined epigean species is known from Christmas Island (M.S. Harvey, pers. comm., 1998). Micro-whipscorpions are a circum-tropical order (Georgescu, 1994) and troglobitic species are found in some cave on continental Australia, especially in Cape Range (Harvey, 1992; Harvey and Humphreys, 1995).

Order **PSEUDOSCORPIONIDA**

Three species of pseudoscorpions are known from epigean habitats on Christmas Island [*Paratemnoides pococki* (With, 1907) (Atemnidae); *Metawithius* (*Metawithius*) *murrayi* (Pocock, 1900)(Withiidae); *Pseudochiridium clavigerum* (Thorell, 1889)

(Pseudochiridiidae) Harvey, 1985, 1991b] but to date none is known from caves. Pseudoscorpions are widely found in caves but in very sparse populations with species often being restricted to a single cave. Relict species may occur in caves and they sometimes exhibit extreme troglomorphies (Heurtault, 1994). They are most commonly known from caves outside the tropics but this may reflect collecting bias. Recently in mainland Australia many new cave dwelling species have been found (Harvey, 1991a; 1993).

Order **OPILIONIDA**

Family **Phalangodidae**

Indet. **Tp1**

Freshwater Cave (CI-10), twilight zone. The most speciose opilionid taxon with a worldwide distribution. Rambla and Juberthie (1994) reported that none were known to be troglobitic but there is one troglobitic species known from Cape Range, Western Australia.

Order **ACARINA** det. M.S. Harvey

Indet.

From the plumage of a Glossy Cave Swiftlet. N. Plumley, 17/8/1987.

Indet. **Ep**

Grants Well (CI-11).

Indet. **Ep**

Jedda Cave (CI-5), 24 hour filter on steam flow.

Indet. **Ep**

Coastal water bore #2, Smithsons Bight area.

Indet. **Gp**

Grimes Cave (CI-53), on swiftlet guano.

Indet. **Commensal/parasite, possibly Tb by association**

Jedda Cave (CI-5), on troglobitic gnaphosid spider.

Phylum **UNIRAMIA**

Class **CHILOPODA**

Order **SCOLOPENDRIDA**

Family **Scolopendridae** det. J. Waldock

Scolopendra subspinipes Leach **Ep.**

Pink House; this is one of the most frequently encountered scolopendrid species in the Indo-Australian region (Attems, 1930). It occurs in all subtropical and tropical lands save the Mediterranean (listed are: Japan, China, western Indonesia , Malay Peninsula, Burma, Thailand, India).

Order **SCUTIGERIDA**

None

These long legged centipedes, although not troglomorphic, are common in caves on continental Australia.

Class **DIPLOPODA**

Subclass **PENICILLATA**

Order **POLYXENIDA**

Indet. (photo. A2.16)

Jedda Cave (CI-5); Jane Up Cave (CI-6); 19th Hole (CI-19); Found from transition zone to deep cave habitats and associated with tree roots in dark zone. These 'bristly' millipedes are sometimes associated with ant nests and a species from Majorca is thought to be troglobitic (Mauries, 1994).

Subclass **CHILOGNATHA**

Infraclass **HELMINTHOMORPHA**

Superorder **ANOCHETA**

Order **SPIROBOLIDA**

Family **Spirobolellidae** Brolemann, 1913 or

Pseudospirobolellidae Brolemann, 1913

Indet.

Coastal water bore #2, Smithsons Bight area.

The first known troglobitic member of this order was described from Barrow Island, Western Australia (Hoffman, 1994).

Superorder **MEROCHETA**

Order **POLYDESMIDA** det. W.S. Shear

Family **Paradoxosomatidae**

Subfamily **Paradoxosomatinae**

Tribe **Cnemodesmini**

Oxidus gracilis (C.L. Koch, 1847)

Smiths Cave (CI-9). The genus contains four species (Japan, China, Korea, Riu Kiu Islands (one species now virtually cosmopolitan; Hoffman, 1979).

Superfamily **Polydesmidae**

Family **Haplodesmidae**

Cylindrodesmus hirsutus Pocock

Jedda Cave (CI-5); Jane Up Cave (CI-6). Genus contains about four species in the southwest Pacific region, also introduced into the West Indies, Panama, and South America; Hoffman, 1979).

Superorder **OMMATOPHORA**

Order **POLYZONIIDA**

Family **Indet.**

19th Hole (CI-19). A small order of obscure millipedes known mainly from the western hemisphere. The genera *Rhinotus* Cook, 1896, *Siphonoconus* Attems, 1930, *Bdellotus* Cook, 1895, and *Metriozonium* Attems, 1951, are known from Java.

Phylum **UNIRAMIA**

Superclass **HEXAPODA**

Class **COLLEMBOLA**

Order **COLLEMBOLA** (photo. A2.9)

Runaway Cave (CI-2); Jane Up Well; The Grotto (CI-1); Coastal water bore #1, Smithsons Bight area; Grants Well (CI-11), 24 hour filter on steam flow; 19th Hole (CI-19); CI-54, baited net -4 m seawater (?contaminant). Collembola were commonly collected in haul nets from bores but these represent epigean species that have fallen into the bore. Only a potentially cave-restricted species has been determined. *Homidia cingula* Börner, 1906, has been recorded from Christmas Island (Greenslade and Rodgers, 1998).

Family **Paronellidae** det. P.M. Greenslade

Cyphoderopsis Carpenter 1917, sp. indet..

Jedda Cave (CI-5). *Cyphoderopsis* has not been recorded for Australia before. The seven described species are from Ceylon, India, Formosa, Nepal and Malaysia.

Class **DIPLURA**

Order **DIPLURA**

Family **Campodeidae** det B. Condé

Cocytocampa sp. nov. 2

Adult female (ovigerous). Antenna with 39 articles (maximum number in congeneric species is 30 in *Cocytocampa* sp. nov. 1 (Condé, in press) and is possibly a cave adaptation. Only one campodeid is known from caves in Australia and that is not troglomorphic (Condé, in press). Two species of cave-adapted Campodeidae are known from the Australian region: from New Ireland and from Papua New Guinea (ibid.). Campodeids occur world wide and about 100 species are known to be troglomorphic (Bareth and Pagés, 1994). The Campodeidae from Australia are in need of global revision (Condé, in press).

The six known species of *Cocytocampa* are restricted to the central and western Pacific — Hawai'i (*perkinsi*), Solomon Islands and

New Ireland (*solomonis*), New Caledonia and Australia (*catalae,* sp. nov. 1, sp. nov. 2), Borneo (*s. borneensis* in Condé 1990) and Thailand (*eutrichoides* in Condé 1994).

Order **THYSANURA** det. G. Smith

Family **Nicoletiidae**

Subfamily **Nicoletiinae** — Jedda Cave (CI-5)

Metrinura Mendes (*sensu* Smith, 1998) **Tb?** (photo A2.11)

Probably an undescribed species (measurements outside range of known species: male required). Range extension of the genus from New Caledonia and Queensland (Smith, 1998). Of the six congeneric species, four species are soil dwelling and two species are from caves, at Chillagoe and from the now flooded caves at Texas, Queensland (*M. russendenensis*). Species collected in caves in Australia tend to be longer and thinner 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 and often lack scales and have reduced pigmentation and sclerotization, all readaptations to cave life. Indeed, c. 20% (n=77) of the species in this family, which is poorly known in the tropics, and three of eight genera are known only from caves, while half the genera contain cave restricted species. Those species recognised as troglobites are large for their lineage and have longer legs and palps (Mendes, 1994).

Class **INSECTA**

Order **BLATTODEA** det L.M. Roth

Family **Nocticolidae**

Gen . nov, sp. nov. **Tb** (photo. A2.7)

Jedda Cave (CI-5); Jane Up Cave (CI-6). New species group (L.M. Roth, pers. comm. 1998). This *Nocticola*-like species from Christmas Island shows advanced troglomorphies. Troglobitic cockroaches may show complete eye loss, the wings, tegmina and pigmentation are greatly reduced. The pulvilli (small cushions on the tarsi used to adhere to smooth surfaces) and also reduced or absent and the arolium(a small cushion between the claws) is also lost although the latter two features are sometimes absent in epigean species (Izquierdo and Oromí, 1994).

The genus *Nocticola* occurs widely in tropical Australia and a number are cave limited (Roth, 1995) including *N. flabella* Roth which is probably the most troglomorphic cockroach ever known (Roth, 1991) for its remarkable depigmentation and very slender appendages (Izquierdo and Oromí, 1994). Adult males of *Nocticola* may have fully developed tegmina and wings or their tegmina may be variably reduced and wings variously reduced or completely absent. Adult females are apterous. Epigean male *Nocticola* have wings but those from caves lack wings so that neither sex has great powers of dispersal. Males of *Nocticola brooksi* Roth and *N. flabella* that inhabit deep caves completely lack of eyes, whereas in *N. brooksi* that inhabit shallow caves or caves intermittently open to the light a few ommatidia are retained in adult males. Two groups of *Nocticola* are distinguished by the presence or absence of a male tergal gland (Roth, 1988). All Western Australian species are troglobites and belong to the *simoni*-species group (tergal gland absent) found also in Queensland, the Philippines, Vietnam, Ethiopia, South Africa and Madagascar. The *ueno*-species group (tergal gland present) is known only from Queensland and the Ryukyu Islands.

Family **Blattellidae**

Gen. indet.

Freshwater Cave (CI-10)

Periplaneta americana L. **Ep**

Jedda Cave (CI-5); Smiths Cave (CI-9); Strangler Cave (CI-16);

Daniel Roux Cave Upper (CI-56). *P. americana* is common in high energy caves in many parts of the world, such as bat guano caves (Cuba) and where sewage percolation has occurred (Canary Islands and Galapagos) (Izquierdo and Oromí, 1994).

Periplaneta australasiae (Fabr.) **Ep**
Pink House, to light.

Balta notulata (Stoll) **Ep**
Pink House, to light. This is a very widely distributed species. Apparently new record for Christmas Island; known from the Chagos Islands in the Indian Ocean. The largest Australian genus (42 spp.: Rentz, 1991)

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

Order **ORTHOPTERA**
Superfamily **Grilloidea**
Grimes Cave (CI-53); Daniel Roux Cave (CI-56).
Family **Myrmecophilidae**
These 'ant crickets' are small, apterous flattened, reduced eyed crickets that live off the secretions of ants as inquilines in ant nests. Each egg is about one third the size of the female. Their mode of travel from nest to nest is unknown. Two genera and 42 species are known globally. The world-wide distribution of *Myrmecophilus* suggest an ancient origin for the family (Rentz, 1991).

Order **PHTHIRAPTERA**
Suborder **Amblycera**
Family **Menoponidae**
Indet.
From wing feathers of Glossy Cave Swiftlet: N. Plumley,

17/8/1987.

Order **HEMIPTERA**

Suborder **Auchenorrhyncha**

Superfamily **Fulgoroidea**

Grants Well (CI-11); 19th Hole (CI-19); CI-55. Planthopper nymphs were commonly encountered living on tree roots in caves on Christmas Island. All were epigean species with eyes and adults were not encountered.

Plant hoppers comprise one of the more diverse groups found in the caves of the Australian tropics including the fulgoroid families Cixiidae (especially the genus *Solonaima;* Hoch, 1988; Hoch and Howarth, 1989a, 1989b, 1989c) and Meenoplidae (especially the genus *Phaconeura;* Hoch, 1990, 1993). Indeed by 1989 North Queensland alone had the highest known concentration of cave-adapted Fulgoroidea in the world (Hoch and Asche, 1989). They are sometimes attended by ants (Humphreys, in press).

Order **COLEOPTERA**

Family **Histeridae** det. ANIC

Carcinops sp. **Gp**

Daniel Roux Cave, upper (CI-56). Collected from swiftlet guano where these beetles, both as larvae and adults, feed on tineid moth larvae.

Family **Tenebrionidae** det. ANIC

Alphitobius laevigatus (Fabricius). **Gp**

Daniel Roux Cave, upper (CI-56). Collected from swiftlet guano. This species — one of the mealworms or flour beetles — is a serious pest of stored products. Tenebrionids are mostly scavengers that rarely feed on material of animal origin (Lawrence and Britton, 1991).

Order **DIPTERA**

Suborder **Nematocera**

Division **Culicomorpha**

Family **Culicidae** det. ANIC

Indet.

Strangler Cave (CI-16). Adult.

Family **Chironomidae** det. ANIC

Ablabesmyia notabilis type

Freshwater Spring (CI-85). Taken in nets filtering stream flow. This is a very common predatory larva throughout the world.

Polypedilum 'K3'

Freshwater Spring (CI-85). Taken in nets filtering stream flow. A cosmopolitan genus (Colless and McAlpine, 1991).

Family **Ceratopogonidae** det. ANIC

Subfamily **Ceratopogonini**

Indet.

Freshwater Spring (CI-85). Taken in nets filtering stream flow. These biting midges usually have predatory or blood-sucking habits.

Family **Simuliidae** det. ANIC

?*Austrosimulium* sp.

Freshwater Spring (CI-85). Taken in nets filtering stream flow. Black flies are a cosmopolitan family of biting flies. Some *Austrosimulium* sp. are vicious pests of humans and stock and this genus may have an 'Antarctic' pattern of distribution with congeneric relations in Australia and New Zealand (Colless and McAlpine, 1991).

Division **Bibionomorpha**

Family **Sciaridae** det. ANIC

?*Lycoriella* sp.

Jane Up Cave (CI-6). Adult.

Family **Mycetophilidae**

Indet. **Tp1**

Jane Up Cave (CI-6) and Jedda (CI-5). The characteristic mucilaginous threads of the larvae of these fungus gnats were seen occasionally in the plateau caves. This family are commonly encountered in the dark zone of caves worldwide, but they are not commonly troglobitic (Colless and McAlpine, 1991).

Suborder **Brachycera**

Division **Cyclorrhapha**

Family **Phoridae** det. ANIC

Indet.

Bishops Cave (CI-8). Adult. An aberrant family of small to minute flies displaying a wide variety of trophic habits.

Family ?**Drosophilidae** det. ANIC

Indet. **Gp**

Daniel Roux Upper Cave (CI-56). Larvae in swiftlet guano pile. (photo. A2.15).

Superfamily Chloropoidea

Family **Chloropidae** det. ANIC

Indet. **Gp**

Daniel Roux Upper Cave (CI-56). In swiftlet guano. Members of this family are found in a wide variety of habitats with diverse trophic relationships. Many are egg predators, parasites or hyperparasites (Colless and McAlpine, 1991).

Superfamily **Muscoidea**

Family ?**Fanniidae** det. ANIC

?*Fannia* sp.

19th Hole (CI-19). Larvae taken in baited stygofauna traps. A family poorly represented in Australia (11 species in 3 genera), but includes the relatively innocuous (Colless and McAlpine, 1991) lesser housefly *Fannia canicularis*.

Family **Muscidae** det. ANIC

Indet. **Gp**

Grimes Cave (CI-53); Daniel Roux Upper Cave (CI-56). Larvae in swiftlet guano.

Order **LEPIDOPTERA**

Family **Pyralidae** det. ANIC

Pyralinae or Epipaschiinae indet. **Gp**

Smiths Cave (CI-9). Larvae and adults in swiftlet guano. Some species are pests of stored cereals.

Family **Tineidae** det. ANIC

Indet. **Gb**

Smiths Cave (CI-9); Daniel Roux Upper Cave (CI-56). Larvae and adults in swiftlet guano.

Twenty species of tineid moths are known to have permanent cave-dwelling populations and their larvae feed mainly on bat- and bird-guano. Eleven of these species are known only from caves, many showing elongate antenna and one showing atypical eye reduction (Robinson, 1980), possible troglomorphies.

Order **HYMENOPTERA**

Family **Formicidae** det. ANIC

Subfamily **Formicinae**

Anoplolepis gracilipes (Smith)

Runaway Cave (CI-2).

Subfamily **Ponerinae**

Pachycondyla sp.

Daniel Roux Upper Cave (CI-56). On swiftlet guano. 'Ant crickets'

(Grilloidea: Myrmecophilidae) were taken from the same guano piles.

The Ponerinae is an exceptionally species rich subfamily in Australia.

Ants commonly enter caves but are rarely adapted for cave life. An undescribed *Paratrechina* sp. attends planthoppers in northern Australia (Humphreys, 1998), and it "seems likely that this is one of the few ants known that is especially adapted for cave life" (S. Shattuck, pers. comm. 1995).

Phylum **CHORDATA**

Subphylum **VERTEBRATA**

Class **OSTEICHTHYES**

Marine fishes and other marine organisms commonly occur in the entrance and twilight zone of coastal caves, and some species penetrate into the dark zone. Seven species have been recorded from freshwater environments on Christmas Island, all except one of which are probably introduced. Only one species, the native Brown Gudgeon, has been recorded from caves. The freshwater species are listed below. WAM denotes specimens in the collection of the Western Australian Museum.

Infraclass **TELEOSTEI**

Suborder **OSTEOGLOSSOIDEI**

Family **Osteoglossidae**

Scleropages formosus (Müller & Schlegel), asian bony tongue.

Has been recorded from an unspecified locality on Christmas Island (WAM). *S. formosus,* a mouth brooder, is found wildly in Bangka, Borneo, Malaya, Sumatra and Thailand and is listed on the IUCN Red List of threatened animals as vulnerable being an endemic of very restricted distribution, now threatened by overfishing. The bony-tongued fishes are an ancient, widespread, and specialised group which is considered to consist of primary freshwater fishes

- having remained in freshwaters throughout their history. Only eight osteoglossid species exist today and they are confined to Africa, South America, South-East Asia, Australia, and New Guinea; two species (not *S. formosus*) are known from mainland Australia. These scattered and broken distributions of a few relic species represent the remnants of the range of a once more numerous group (Merrick, 1984). Given the biogeography of the group it has presumably been introduced to Christmas Island.

Order **PERCIFORMES**

Suborder **GOBIOIDEI**

Family **Eleotridae**

Eleotris fusca (Bloch & Scheider), brown gudgeon.

Occurs in Daniel Roux Cave (CI-56)(WAM: collected by P. Meeks, 1996) and was seen during the survey possibly only in CI-54 but no other caves, in the dark zone. Cave dwelling specimens display some degree of depigmentation. The species is native to Christmas Island. Gudgeons are cosmopolitan and include both marine and fluviatile forms. Most of the 300 species in the Family occur in tropical freshwaters but the largest single group of freshwater species occurs in Australia (Merrick, 1984). *Eleotris fusca* is distributed in East Africa and the high volcanic islands of Oceania where it inhabits estuaries and the lower sections of freshwater streams (Allen, 1991).

Suborder **PERCOIDEI**

Family **Cichlidae**

Oreochromis sp., tilapia.

Recorded from Ross Hill Pond (WAM; ?CI-59). It is native to freshwaters of eastern Africa but has been widely introduced to other parts of the world for food. In some countries it is regarded as a pest because of its prolific breeding habits, and destructive behaviours (Allen 1991).

Order **CYPRINODONTIFORMES**

Suborder **CYPRINODONTOIDEI**

Family **Poeciliidae**

Poecilia reticulata Peters, guppy.

Recorded from Ross Hill Pond (WAM;?CI-59). It is native to the Americas and was probably introduced for mosquito control. It is considered a pest to native fauna because of its prolific breeding habits (Allen 1991); when they enter natural fresh or brackish waters they are likely to eliminate the native fauna (G. Allen, pers. comm. 1993).

Gambusia affinis Baird & Girard, mosquito fish.

Recorded from the swamp above Darling Dale Falls (WAM) and during this survey, *Gambusia* sp. was recorded from similar habitat above Hughs Dale waterfall (CI-77). These specimens, and the earlier material, may possibly be referrable to *G. holbrooki* (Howard Gill, pers. comm., 1998). The genus is native to freshwaters of North America and probably was introduced to Christmas Island possibly to help control mosquitoes, as it feeds on their aquatic larvae and pupae. It is a prolific breeder and often takes over, crowding out the native species (Allen, 1991).

Xiphophorus maculatus (Gunther), swordtail.

Occurs in Ross Hill Pond (WAM; ?CI-59). It is native to freshwaters of Central America and a popular aquarium fish, the probably route of its introduction to Christmas Island.

Subclass **REPTILIA**

'Terrapins' occur in the tank at Ross Hill Gardens (P. Meek, pers. comm. 1998) but they have not been identified.

Subclass **AVES**

Order **APODIFORMES**

Family **Apodidae**

Collocalia esculenta natalis Lister, 1888.

Daniel Roux Upper Cave (CI-56); Smiths Cave (CI-9); Managers Alcove (CI-50); Grimes Cave (CI-53); Swiftlet Cave (CI-30). The Christmas Island glossy swiftlet was recorded large numbers of swiftlets over whole island where they were more common on shore terraces than the plateau (Gibson-Hill, 1947c). They were most numerous on the west side of South Point and least numerous along the coast from Egeria Point to West White Beach. The subspecies is endemic to Christmas Island although many other subspecies and species occur in South-east Asia, Queensland and Pacific islands. The species is treated extensively in the main text of the report.