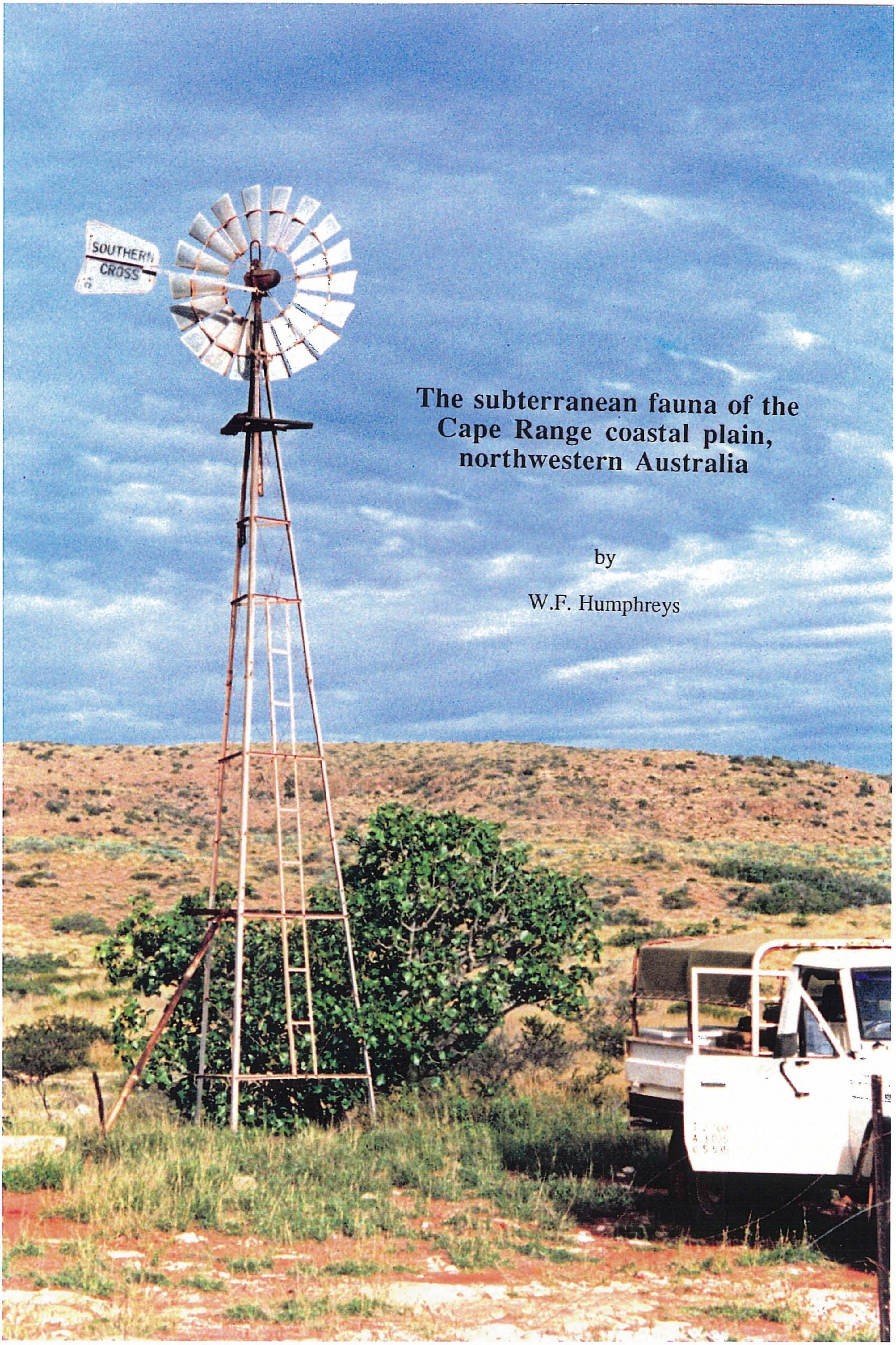
# The subterranean fauna of the Cape Range coastal plain, northwestern Australia

by

W.F. Humphreys



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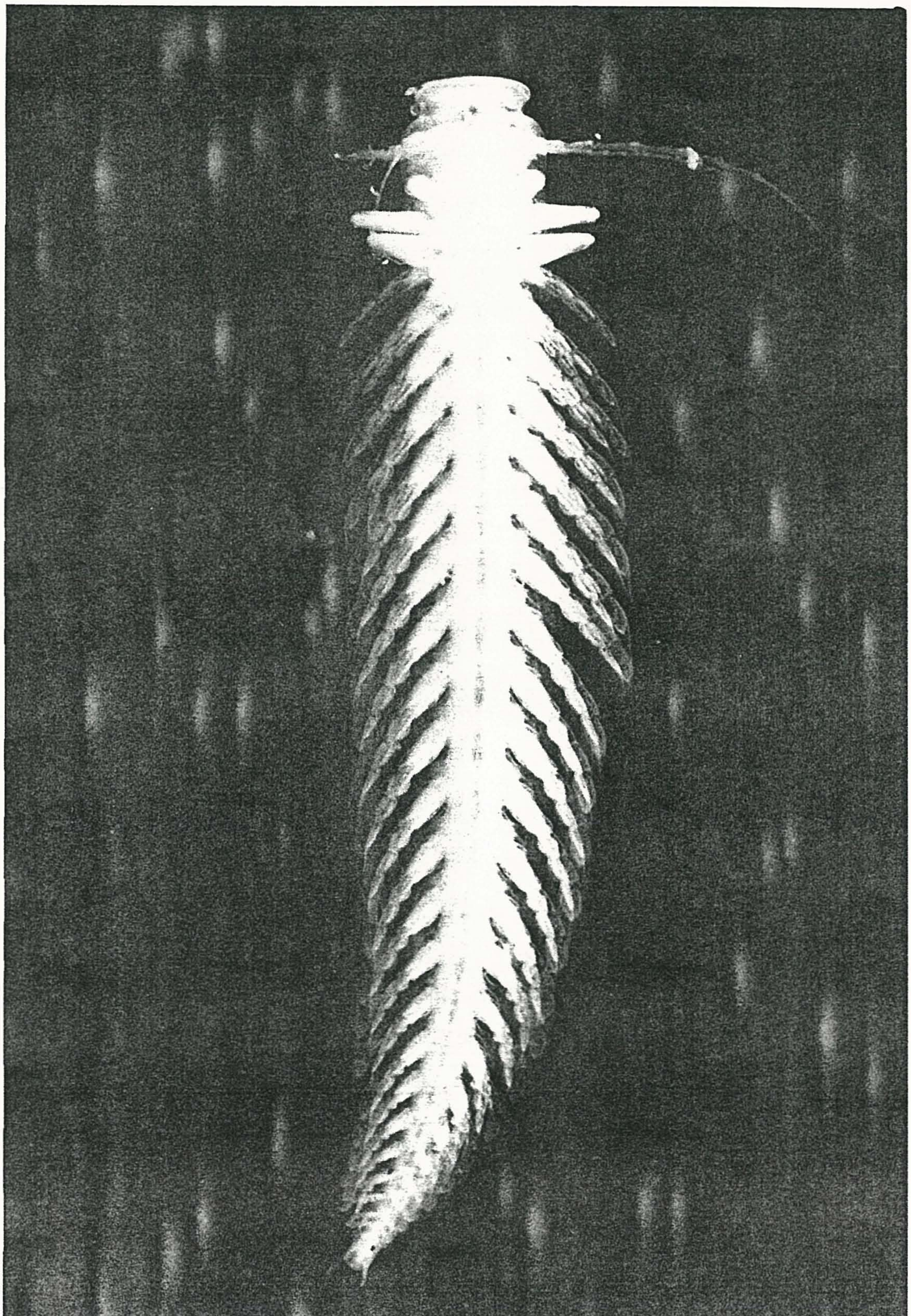

# The subterranean fauna of the Cape Range coastal plain, northwestern Australia

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A Report prepared under the National Estate Grants Program, a Commonwealth -financed grants scheme administered by the Australian Heritage Commission (Federal Government) and the Heritage Council of Western Australia (State Government).

**Front cover:** Five Mile Well, on the northwestern coastal plain of the Cape Range peninsula (21° 51' S; 113° 52' E), allows access to the subterranean aquatic fauna. It contains atyid shrimps (*Stygiocaris stylifera* Holthuis, 1960), thermosbaenaceans (*Halosbaena tulki*, Poore & Humphreys, 1992), Bind Cave Gudgeons (*Milyeringa veritas* Whitely, 1945), and calanoid and harpacticoid copepods.

**Frontispiece:** Remipedia from an inland seawater (anchialine) cave on the Cape Range peninsula— a new class of Crustacea for the southern hemisphere which is elsewhere known only from anchialine caves in the Caribbean area and Lanzarote in the Canary Islands. The inhabitants of such caves (stygofauna) typically lack eyes and are colourless. Body length *c.* 23 mm.

# Contents

## Acknowledgements

This work on the coastal plain of the Cape Range peninsula would not have been possible without the cooperation of numerous people and agencies, many being acknowledged specifically below.

Darren Brooks provided me with vital support and information in the field while Julianne Waldock and Caroline Lawrence fulfilled the same role in the laboratory, the latter often in a voluntary capacity. Ken Cameron of Exmouth provided information on coastal caves and cave eels while Brian Vine and Ray Wood assisted me on occasion in a voluntary capacity on Barrow Island.

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Hemiptera: Meenopliidae (H. Hoch, Universität Hamburg, Germany); Opilionida: Phalangodidae (G. Hunt, Australian Museum, Sydney); Ostracoda (D.L. Danielopol, Austrian Academy of Sciences and A. Baltanas, University of Madrid); Polychaeta: Syllidae (G. Hartmann-Schröder, Zoologisches Museum der Universität Hamburg, Germany); Remipedia (J. Yager, Antioch College, Ohio); *Stygiochiropus* (W.A. Shear, Hampden-Sydney College, Virginia); *Stygiocaris* (L.B. Holthuis, Rijksmuseum van Natuurlijke Historie, The Netherlands); Syncarida (H.K. Schminke, Universität Oldenburg, Germany); terrestrial isopods (H. Dalens, Université Paul Sabatier, Toulouse, France).

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The work was funded by the Western Australian Museum, the Western Australian Water Authority, the National Estate Grants Scheme and the W.H. Butler Trust.

# Summary

The coastal plain of the Cape Range peninsula in northwestern Australia contains an underground fauna of great antiquity that is endemic to the peninsula (and partly to Barrow Island). During 1993 the composition of the fauna and its extent were surveyed by sampling all available access points to the subterranean waters. In addition the water quality was sampled using both routine water analysis at 95 sites and detailed examination for contaminants made in the vicinity of Exmouth.

Cavernous karst to a depth of *c.* 100 m covers much of the Cape Range peninsula from the top of range to below sea level. There are isolated perched water tables in Cape Range at an altitude of *c.* 190 m that contain separate populations of an amphipod congeneric with one in the coastal water table. A fresh water lens underlies Cape Range reaching *c.* 10 m ASL and overlying salt water; these are separated by a zone of brackish water which is progressively thinner away from the coast. The fresh water lens is afaunate but the brackish and salt waters contain a relict tethyan sea community of great antiquity. Some elements of the community are found on Barrow Island but is otherwise confined to Cape Range.

The fauna comprises at least eleven species—the cave fish *Milyeringa veritas* and *Ophisternon candidum*, the atyid shrimps *Stygiocaris lancifera* and *S. stylifera*, the thermosbaenacean *Halosbaena tulki*, an ostracod *Danielopolina* sp. nov., a cirolanid isopod *Haptolana pholeta*, at least two species in an undescribed genus of melitid amphipods and an undescribed member of the class Remipedia. A number of other species are known from the sampling sites but their affinities and their association with the stygofauna are as yet unknown.

The stygofauna is primarily a relict group of taxa derived from the Tethys Sea. It includes a number of higher level taxonomic groups unknown elsewhere in the southern hemisphere including the genera *Danielopolina* (Ostracoda) and *Haptolana* (Isopoda), the order Thermosbaenacea (*Halosbaena tulki* ) and the class Remipedia (Crustacea). The prospects are good of finding additional taxa currently known only from either side of the Atlantic Ocean.

The typical Cape Range stygofauna is restricted to the peninsula (and partly to Barrow Island)—the two species of cave fish, the remipede, *Stygiocaris lancifera* and *Danielopolina* sp. nov. are unknown off the peninsula.

The terrestrial cave fauna from the coastal plain is distinct from that of Cape Range and

includes a number of undescribed taxa, especially myriapods (*Stygiochiropus* sp. nov.) and chelicerates (*Draculoides* sp. nov. (Schizomida), *Hyella* sp. (Pseudoscorpionida) and hahniid spiders. Some of the taxa are also found on Barrow Island.

In summary the Cape Range peninsula contains a great diversity of both terrestrial and aquatic animals that are especially adapted for subterranean life. The fauna is endemic to the peninsula (and partly to Barrow Island). The stygofauna is of ancient origin, its closest known affinities often lying with taxa living on either side of the Atlantic Ocean. The terrestrial fauna has characteristics typical of those now found in humid forests on the eastern seaboard of Australia—they are considered to survive the current aridity only because they have adapted to a subterranean life.

Blind Gudgeon, *M. veritas*, is now known from 18 locations (up from 11) and the Blind Cave Eel, *O. candidum*, from 11 locations (up from 6). The population of *M. veritas* in Kubura Well was *c*. 50 of which about 20% would be seen at any one time. In general, where crude capture data are available for specific sites, there seem to be similar numbers of fish present today as in historic times. There is a suggestion that *M. veritas* may grow fast but the sparse data are ambiguous.

The food of the blind cave fishes was examined from museum collections. *O. candidum* eats both the specialised stygofauna and the fauna found in open pools, as well as opportunistically on things falling into the water. *M. veritas* feeds primarily on animals falling into the water (mainly cockroaches and terrestrial isopods).

*Stygiocaris stylifera* was usually found in sparse populations but, where adequate food was available, could occur in substantial numbers (up to 314 $m^{-2}$). All populations of *Stygiocaris* had markedly bimodal population structures the cause of which is unknown (it may be associated with seasonal breeding).

Many of the stygofauna were recovered also from the water production borefield, including the Blind Gudgeon *M. veritas*. Pumping from the production borefield when fully developed will directly destroy >30,000 'shrimps' per year.

The stygofauna was not recovered inland of the saltwater interface. Owing to the superposition of many changes in this region, it is not known whether this results from a change in water quality or from a change in the pore size—there is some evidence supporting the former.

The characteristics of the water in which the stygofauna are found vary widely, from brackish to almost full seawater, the characteristics in common being carbonate waters of moderate alkalinity.

There is some evidence of anthropogenic contamination of the groundwater in the vicinity of Exmouth but at this stage gross pollution of the groundwater has been prevented mainly because, being a purpose built town (to support military facilities), deep sewers were installed when the town was built in 1964. However, considerable contamination may yet occur from past activities owing to the uncontained refuse dumps lying over the ground water and the dumping of petroleum products on the ground.

Potential and real hazards to the stygofauna are discussed and recommendations made to limit these impacts, especially by emphasizing the karstic nature of the landscape and the consequences that flow from this which need to be addressed in the early stages of planning.

To emphasize the wholeness of the system and to protect its integrity the entire peninsula should be included in the Register of the National Estate which alone, or together with the Ningaloo Marine Park, is deserving of World Heritage Listing.

## Preamble

This project has met the three aims:

1. To determine the extent, characteristics and environment of the subterranean aquatic fauna on the Cape Range peninsula—this is covered in chapters 2-7 covering the fauna, its distribution and biology, and the characteristics of the water.

2. To document the wells and bores on the Cape Range peninsula which permit access to the subterranean fauna—this is covered variously in the chapter *Habitat* in the Appendices A (*Sites visited*), E (*Descriptions of stygofauna sites etc.*) and F (*Photographs of the subterranean realm: fauna and access*).

3. To identify the conservation needs required to protect the National Estate significance of the subterranean ecosystem—the National Estate significance is covered in the section of Biogeography and the requirements to protect it are encompassed in the chapter *National Estate significance, conservation and recommendations*.

## Glossary

*Anchialine* — Inland waters affected by marine tides indicating subterranean connection.

*Bore* — see well.

*C-* — letter allocated by the Australian Speleological Federation (ASF) to prefix numbers allocated to caves and other karst features in the Cape Range karst province (see Matthews 1985).

*Contamination* — to change the water quality so as to produce a noticeable change in its characteristics (Australian Water Resources Council 1992).

*Piezometer* — used loosely for any pipe inserted vertically into the ground to observe the water.

*Pollution* — state of contamination for which the water quality has deteriorated to a point where the ability of the water to support or maintain the existing or potential beneficial uses is diminished (Australian Water Resources Council 1992), in this case where it affects the potential viability of the stygofauna populations and hence threatens to reduce the biodiversity of Australia and hence its National Estate significance.

*Stygobite* — true groundwater inhabitants, absent in surface waters, which are adapted to or specialized to the subterranean environment.

*Stygofauna* — the stygobiont fauna.

*Stygophiles* — epigean organisms that occur in both surface and ground waters without adaptation to subterranean life.

*Stygoxens* — typical epigean organisms found rarely and at random in ground waters.

*Troglobite* — obligatory inhabitant of cave, usually with troglomorphies.

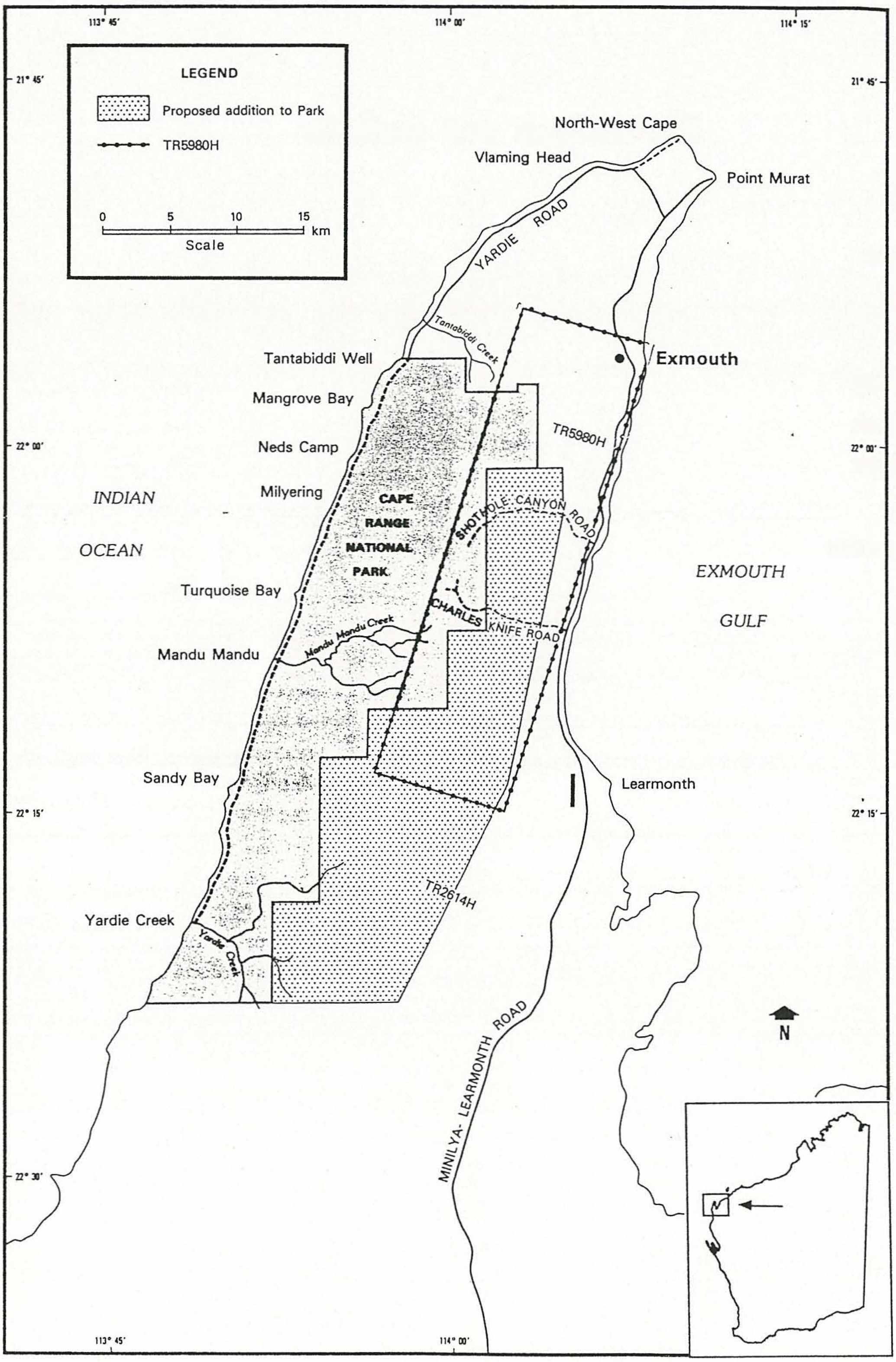
*Troglofauna* — the troglobitic fauna.

*Troglomorphy (stygomorphy)*— characteristic morphologies found in troglobites (stygobites), often considered adaptive, such as loss of body pigment, reduction or loss of eyes, hypertrophy of non-optic sense organs and relative lengthening of appendages. Physiological changes also occur and these include reduction of metabolic rate, reduction in egg numbers associated with increased size and an increased ability to fast.

*Well* — well and wellfield are now accepted internationally as meaning both small and large diameter holes independent of the means of construction. In this report the terms bore and well are retained to help distinguish the many sites. The wells are mostly old pastoral wells (pre-1964; the term is also used locally for traditional watering places such as Kubura Well which is a cave), whereas the bores are mostly recent water supply and water exploration bores (post-1964).

# Introduction and methods

The Cape Range peninsula showing its location in Western Australia, Cape Range National Park and the Temporary Reserve for Limestone (TR5980H)— from CALM 1987.



## Introduction

The Cape Range peninsula contains a remarkable subterranean fauna in the composition of which are echoes of orogenic and eustatic events, climatic change, and of past connections with other parts of Australia, eastern Gondwana and even Pangaea (Humphreys 1993b, in press b). The fauna shows both high diversity and generic and specific endemicity (papers in Humphreys 1993a). The fauna includes both aquatic and terrestrial components of very different origins. The terrestrial cave fauna is derived from the litter communities of wet forests, both tropical and temperate (Humphreys in press a; Harvey *et al.* 1993). The aquatic community is derived (Humphreys in press b; Knott 1993) from the ancient Tethys Sea that separated the continents of Gondwana and Laurasia and which persisted from the Triassic until the late Eocene (200-40 Ma; Smith and Briden 1977).

In consequence the affinities of the fauna are both diverse and often distant. It is the site of very great vicariance with the only know locations of the crustacean Order Thermosbaenacea in the southern hemisphere and, outside the Caribbean area and Lanzarote in the Canary Islands, the only know location of the Class Remipedia. Congeneric species may be known only from the Canary Islands and West Indies (*Halosbaena*; Thermosbaenacea; Poore and Humphreys 1992), or from Cuba and the Horn of Africa (*Haptolana*, Cirolanidae; Bruce and Humphreys 1993). Amongst the cavernicolous arachnids and myriapods several groups have their closest relatives in northern Australia, others have affinities with western Gondwana, while others clearly representatives of a southern fauna (Harvey *et al.* 1993). This indicates a temporal series of invasions into the caves from periods when the peninsula was blanketed by northern tropical rainforests and, later, southern temperate rainforests (Truswell 1990).

The two faunas have, for the most part, been considered to be separated in space, with the terrestrial component occupying caves in Cape Range, a 300 m high anticline which forms the spine of the peninsula, and the aquatic fauna occupying the coastal plain fringing Cape Range (Humphreys and Adams 1991; Poore and Humphreys 1992). Recent work has shown that elements of the Cape Range fauna reach the coastal plain (Humphreys and Shear 1993) or that related fauna occur in caves on the coastal plain (Harvey *et al.* 1993; Harvey and Humphreys in press; W.F.Humphreys unpublished).

Lack of access to water in the range and to caves (*sensu stricto*) on the coast constitutes the main problem in examining the distribution of the terrestrial and aquatic components of the fauna. While there are many caves in the range (>300), and many access points to underground water on the coastal plain (>100), there are known only four caves with water in the range (C-18, 64, 103 and 163) and only two caves in the coastal plain suitable for terrestrial fauna (C-215 and 452).

While the terrestrial component of this fauna has been examined to some extent (Vine *et al.* 1988; Humphreys *et al.* 1989; Humphreys and Collis 1990; Humphreys 1990; Humphreys 1991a,b; Humphreys and Shear 1993; Adams and Humphreys 1993; Humphreys 1993b, in press a), detailed work on the subterranean aquatic fauna has been lacking (Humphreys and Adams 1991; Poore and Humphreys 1992; Humphreys in press b; Bruce and Humphreys 1993; Knott 1993). It is the purpose of this study to delineate the distribution of the coastal fauna of the area, its limits and composition. Of necessity this means that the work is primarily concerned with specialised subterranean aquatic animals (stygofauna) as documented above (*ibid.*) and in various other publications and unpublished reports (Humphreys 1989; Humphreys *et al.* 1990; Humphreys 1990; Humphreys 1991a; Humphreys 1991d; Humphreys 1991e; Humphreys and Vine 1991; Humphreys 1991d).

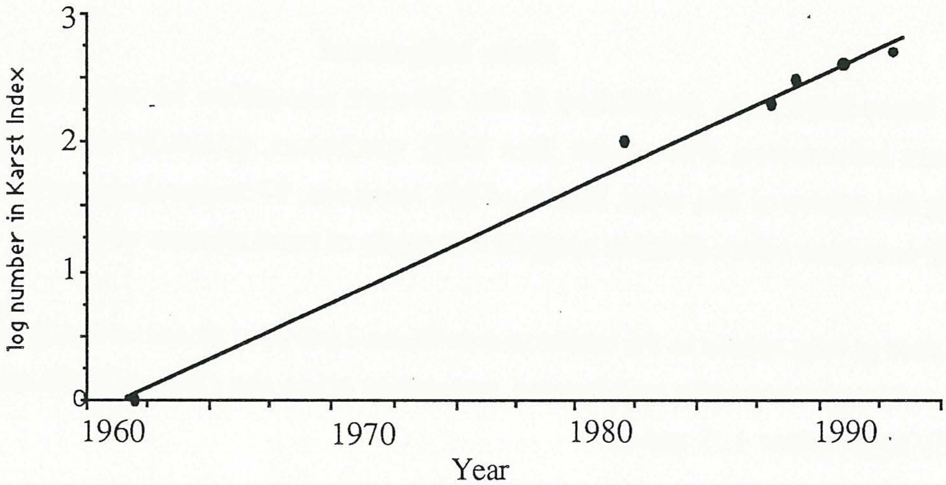
## Access

Knowledge of access points to the underground results from the cumulative efforts of large numbers of people (Humphreys 1991c, W.F. Humphreys unpublished; R.D. Brooks, pers. comm.). Some of the access points were constructed early this century as pastoral wells, often built on or near traditional watering points knowledge of which probably extends to 33,000 years BP (Morse 1993). The history of the formal work on the karst index up to 1989 (to C-362) was given in the introduction to the karst index to Cape Range (Humphreys 1991c); the index is currently at C-523 (R.D. Brooks, pers. comm.).

Compilation of the Karst Index for Cape Range was *ad hoc* up until *c*. 1980 when a series of Exmouth residents have sequentially taken on the task. From 1980-1986 B. Vine sorted out the previously reported but untagged and poorly located caves resulting from chance finds and a number of exploration trips by individuals, speleological clubs and the Western Australian Museum. M. East covered the period from *c*. 1986 until *c*. 1990, including the two major expeditions from the Western Australian Museum. Since 1990 R.D. Brooks has been the principle organiser of the index and has control of the tagging — most caves in the index are now tagged, a process that has been invaluable for the genetic studies (Humphreys and Shear 1993; Humphreys and Adams 1991; Adams and Humphreys 1993) and will continue to be so despite the availability of the Global Positioning System.

Sampling points on the coastal plain were only allocated karst index numbers (C-) if they were of karst significance; no bores or piezometers were numbered — the majority of sampling points. Notwithstanding this the rate of accumulation of new features in the karst index for Cape Range (Figure 1) is such that may hundreds of new access points are likely to be discovered. This rapid increase in the number of known access points to the subterranean world in both the Cape Range and the coastal plain means that the sampling conducted to date must be inevitably incomplete and further detail will be added from both additional locations and new sampling techniques. These undoubtedly will expand the geographic range of the fauna as well as the faunistic richness — one taxon not yet found on Cape Range but expected because it occurs on Barrow Island is *Atopobathynella* sp. nov. (Syncarida: Bathynellacea).

**Figure 1:** Regression of the number of features (log Y) in the Karst Index for Cape Range and the year of sampling (X); $r^2 = 0.99$, $Y = 0.088X - 173$.




## Methods

### Sampling

<u>Fauna</u> Bores were sampled for fauna using a plankton net with a 125 µm mesh and of a size suitable for the bore, the nets ranged from 30 mm to 180 mm in diameter. Wells were sampled by hand nets (125 µm mesh) and by Cvetkov (1968) phreatobiological nets (300 mm diameter; 125 µm mesh). Samples were variously taken through the entire water column and from various depths within the water column. Pumped water from bores was filtered through the same nets suspended in a bucket of water to buffer the water pressure. The volume sampled was read from the attached meter or by calculation from the duration of sampling and the time taken to fill the bucket.

<u>Water</u>. Water samples were collected by hand directly into the sampling containers, or transferred from bottles lowered into bore holes. Procedures followed the protocols

established by the Water Authority of Western Australia and, for microbiological samples, those established for such sampling by the State Health Laboratory (revised 1993). On collection all water samples were immediately placed in a refrigerator and transported by air to the analytical laboratories cooled to about $4^oC$. Where direct measurements were not made the salinity (total soluble salt: TSS mg $L^{-1}$) was estimated from the electrical conductivity (EC; $\mu S\ cm^{-1}$) as TSS = 5.4 EC + 90).

### Analyses

Microbiological analysis was conducted by the Water Examination Laboratory of the State Health Laboratory Services using their standard procedures. Comprehensive water analysis was conducted by the Scientific Services Branch of the Water Authority of Western Australia using their established procedures. Organic analyses were conducted by commercial analytical laboratories as specified in the results.

### Data lodgement

Data bases have been established in the Western Australian Museum containing the relevant information about more than 2000 specimens, primarily of fauna, obtained during the course of this work, details of 261 locations, 97 comprehensive water samples and 20 locations where detailed analysis was made of contaminants of water.

Key sites giving access to the subterranean fauna have been documented by description, map and/or photography and located accurately using the Global Positioning System (GPS)(Appendices 1, 5 and 6).

# Subterranean fauna

## Introduction

The fauna of the Cape Range peninsula has been covered extensively up to 1992 in Humphreys (1993a). Elements of the subterranean coastal aquatic fauna are addressed in Whitley (1945), Holthuis (1960), Mees (1962), Humphreys and Adams (1991), Poore and Humphreys (1992), Adams and Humphreys (1993), Bruce and Humphreys (1993), Harvey *et al.* (1993), Humphreys (1993a, b), Knott (1993) and Slack-Smith (1993).

## Aquatic fauna

The Cape range peninsula has a stygofauna known for *c.* 30 years which comprises the atyid shrimps *Stygiocaris lancifera* and *S. stylifera*, sympatric over part of their range (Holthuis 1960; Humphreys and Adams 1991; Adams and Humphreys 1993) and the only vertebrate troglobites in Australasia. These are the Blind Gudgeon, *Milyeringa veritas* and the Cave Eel, *Ophisternon candidum*; worldwide only 56 species of fish are known to be authentic troglobites and in only eight instances do two species co-occur under sympatry (Thinès and Proudlove 1986). They are illustrated in Appendix F.

In the last decade, especially since 1988, the stygofauna of the Cape Range peninsula has been found to be more diverse and to have unexpected affinities. These include both an Order (Thermosbaenacea) and a Class (Remipedia) previously unknown in the southern hemisphere and with known relatives only in caves of some Caribbean islands and Lanzarote in the Canary islands (Table 1).

**Table 1:** The composition of the stygofauna of the north west of Western Australia. About half of this fauna has been found since 1991. CRp = Cape Range peninsula, BI = Barrow Island.

| Major taxon | Genus and species | Locality |
|---|---|---|
| Pisces: Perciformes: Eleotridae | *Milyeringa veritas* Whitley | CRp |
| Pisces: Synbranchiformes | *Ophisternon candidum* (Mees) | CRp |
| Decapoda: Atyidae | *Stygiocaris lancifera* Holthuis | CRp |
| Decapoda: Atyidae | *Stygiocaris stylifera* Holthuis | CRp, BI |
| Isopoda: Cirolanidae | *Haptolana pholeta* Bruce & Humphreys | CRp, BI |
| Thermosbaenacea | *Halosbaena tulki* Poore & Humphreys | CRp |
| Amphipoda: Melitidae* | New genus, 2 species | CRp, BI |
| Ostracoda: Halocyprida | *Danielopolina* sp. nov. | CRp |
| Amphipoda | ? | BI |
| Syncarida: Bathynellacea | *Atopobathynella sp. nov.* | BI |
| Copepoda: Harpacticoida | ? | CRp |
| Copepoda: Cyclopoida | ? | CRp, BI |
| Remipedia: Nectiopoda | ? | CRp |
| Turbellaria | ? | CRp |

* sensu Bousfield 1973

In addition other genera of similar distribution have been found - the ostracod genus *Danielopolina* (Thaumatocyprididae: Halocyprida; Danielopol, pers. comm.) which has in addition species from the Galapagos Islands and the abyssal Atlantic Ocean off Brazil, and a cirolanid isopod of the genus *Haptolana* known only from the Horn of Africa and Cuba (Bruce and Humphreys 1993).

This fauna is represented on Barrow Island by *Stygiocaris stylifera* , *Haptolana pholeta*, *Halosbaena tulki*, two species of amphipod including a melitid (W.D. Williams, pers. comm.), ostracods and cyclopoid and harpacticoid copepods.

**The affinities of the stygofauna**

The stygofauna of the Cape Range peninsula (Table 2) has mainly Tethyan affinities (Humphreys in press b; Knott 1993) in that the related taxa occupy tropical regions that would have been underwater prior to the sea level changes of the Miocene and thus correspond with the concept of Tethyan relicts given by Newman (1991). Only two of the described (or being described) taxa do not fit happily with these critera — *Milyeringa veritas* has unknown affinities, and the syncarid *Atopobathynella* sp. nov. (H.K. Schminke, pers. comm.; Parabathynellidae, Bathynellacea) known only from Barrow Island and which is clearly Gondwanian, being known otherwise only from southeastern Australia, New Zealand and Chile.

*Ophisternon candidum* (Mees)

The Blind Eel, *Ophisternon candidum,* belongs to a circum-tropical genus mainly of fresh water and comprises six species. Their distribution is vicariant with species in northern Australia (*candidum* and *gutturale*), India to the Philippines (*bengalense*), West Africa - Guinea to the Niger delta (*afrum*), the Caribbean fringe (*aenigmaticum*), and in Mexican caves (*infernale*).

*Milyeringa veritas* Whitely

Eleotridids are widespread in shallow marine through brackish to fresh waters of tropical and subtropical zones, particularly of the Indo-Pacific region (Nelson 1984). The genus *Milyeringa* (Perciformes: Eleotrididae) is monospecific and endemic to the area and *M. veritas* is eyeless with the brain being visible through the brain case. The affinities of the genus *Milyeringa* remain to be elucidated (see discussion in Knott 1993).

*Stygiocaris* spp. Holthuis

*Stygiocaris lancifera* and *S. stylifera* were described from the same location (Holthuis 1960) and subsequent work has confirmed their sympatry on the Cape Range peninsula using protein electrophoresis (Humphreys and Adams 1991 and unpublished). *S. stylifera* was found in 1992 in anchialine systems on Barrow Island and the identity confirmed by L.B. Holthuis and by protein electrophoresis (Adams and Humphreys 1993).

*Stygiocaris* belongs to the *Typhlatya* series of species which have a Tethyan disjunct range encompassing the Caribbean, the western Balkans, Madagascar, Western Australia and parts of the Indo-west Pacific. The closest relative of *Stygiocaris* is *Typhlopatsa* of Madagascar and Banarescu (1990) considers their disjunct range a consequence of their ancestors being in a southern arm of the Tethys which separated the two mainlands then much closer.

**Table 2:** The affinities of genera from the stygofauna of north west of Western Australia. T= Tethyan distribution, G= Gondwanan distribution.

| Taxon | Genus | Tethyan? | Affinities |
|---|---|---|---|
| **Crustacea** | | | |
| Thermosbaenacea | *Halosbaena* | T | West Indies, Columbia, Canary Is (Poore and Humphreys 1992) |
| Amphipoda: Melitidae* | New genus | T | (Knott 1993) |
| Isopoda: Cirolanidae | *Haptolana* | T | Cuba, Somalia (Bruce and Humphreys 1993) |
| Decapoda: Atyidae | *Stygiocaris* | T | Madagascar (Banarescu 1990) |
| Ostracoda: Halocyprida | *Danielopolina* | T | West Indies, Canary Is, Galapagos, Atlantic abyssal |
| Remipedia: Nectiopoda | ? | T | West Indies, Canary Is |
| **Pisces** | | | |
| Perciformes: Eleotridae | *Milyeringa* | - | - |
| Synbranchiformes | *Ophisternon* | ? | Circum tropical (Mexican caves) |
| Syncarida: Bathynellacea | *Atopobathynella* | G | SE Australia, New Zealand, Chile |

*Haptolana pholeta* Bruce and Humphreys

The cirolanid isopod *Haptolana pholeta* Bruce and Humphreys, 1993 occurs in the anchialine system occupied by *Stygiocaris stylifera* on both the Cape Range peninsula and Barrow Island; *Haptolana* is known elsewhere only from Somalia and Cuba (Messana and Chelazzi 1984; Messana 1988). Cirolanids are present in subterranean waters of the Caribbean area, circum- Mediterranean and the Horn of Africa, a distribution suggesting a Tethyan marine origin with dispersal and isolation due to marine regressions (Kensley and Schotte 1989). Hence, they have a similar pattern of distribution to the Thermosbaenacea although the more heroic hypotheses about their origin (tectonic plate riders) havFe not been invoked, perhaps due to the uncertainty about their generic status (Messana and Chelazzi 1984; Messana 1988).

Halosbaena tulki Poore and Humphreys

The thermosbaenacean *Halosbaena tulki* occurs in the anchialine system occupied by *Stygiocaris lancifera* on the Cape Range peninsula and Barrow Island. *Halosbaena* is known elsewhere only from Caribbean islands, the Atlantic coast of Columbia and the Canary Islands (Poore and Humphreys 1992). Thermosbaenaceans are present in subterranean waters of the circum-Caribbean and Mediterranean areas and their associated islands, from Somalia and Cambodia (Table 3). Hence, they have a disjunct Tethyan distribution pattern similar to the cirolanids. However, owing to the distribution of species within genera, more varied and heroic hypotheses (e.g. tectonic plate riders) about their origin have been invoked.

**Table 3:** Distribution of the families (after Monod and Cals 1988) and genera of Thermosbaenacea.

| Family | Genus | Distribution |
|---|---|---|
| Thermosbaenidae | | |
| | *Thermosbaena* | Tunisia |
| Monodellidae | | |
| | *Monodella* | Land to north and east Mediterranean, Morocco, Somalia, West Indies, Texas. |
| Halosbaenidae | | |
| | *Limnosbaena* | Bosnia |
| | *Theosbaena* | Cambodia |
| | *Halosbaena* | Caribbean islands, Canary Islands, Columbia, Western Australia |
| | *Tulumella* | Bahamas, Mexico |

Melitid amphipods

A new genus (W.D. Williams, pers comm. 1992) in the Superfamily Melitoidae occurs with separate species in the stygofauna of the coastal plain and in caves at >150 m altitude in Cape Range and which were probably separated during the uplift of the Cape Range anticline (Humphreys 1993b). Within the range there is substantial genetic discontinuity between different cave areas indicative of isolated populations (Humphreys and Adams 1991; Adams and Humphreys 1993). The melitids are primarily a marine group found mainly in tropical and south-temperate regions. Those from the Range belong to a new genus within the *Eriopisa-Psammogammarus-Victoriopisa* complex (Knott 1993). Eriopisids are primitive melitids, and their present disjunct distribution suggests a Tethyan ancestry (Knott 1993). Melitids are possibly ancestral to the hadziids (Barnard and Barnard 1983), almost all of which are blind stygobionts with a Tethyan distribution (Knott 1993).

Remipedia

The first remipede, *Speleonectes lucayensis* Yager, was discovered in 1979 in an anchialine cave in the Bahamas (Yager 1981). Nine species have been described (two in preparation) representing six genera (five are monotypic) and two families (Table 4) from anchialine caves on island and coastal areas of the North Atlantic and Caribbean (Yager 1991) from 10-30o S. Until the discovery in northwestern Australia all but members of the genus *Speleonectes* were confined to the Bahamas (Yager 1991) — the remipede from the Cape Range peninsula is not *Speleonectes*.

**Table 4**: Extant remipedes of the world. Yager (pers. comm. 1993) is describing a species from Cuba, one of the three known locations for *Haptolana*. The Class is otherwise known from the Carboniferous.

| Family | Species | Location |
|---|---|---|
| Godzilliidae | *Godzilliognomus frondosus* Yager, 1989 | Bahamas |
| Godzilliidae | *Godzillius robustus* Schram, Yager & Emerson, 1986 | West Indies |
| Godzilliidae | *Pleomothra apletocheles* Yager, 1989 | Bahamas |
| Speleonectidae | *Cryptocorynetes haptodiscus* Yager, 1987 | Bahamas |
| Speleonectidae | *Lasionectes entrichoma* Yager & Schram, 1986 | Turks and Caicos, West Indies. |
| Speleonectidae | *Speleonectes benjamini* Yager, 1987 | Bahamas |
| Speleonectidae | *Speleonectes lucayensis* Yager, 1981 | Bahamas |
| Speleonectidae | *Speleonectes tulumensis* Yager, 1987 | Yucatan Peninsula, Mexico. |
| Speleonectidae | *Speleonectes ondinae* (Garcia-Valdecasas) | Lanzarote, Canary Islands |
| Speleonectidae | ?*Lasionectes* (not *Speleonectes* ) | Northwestern Australia |

Remipedes are typically found in communities consisting almost entirely of stygobiont crustacea. They are typically associated with thermosbaenaceans, hadziid amphipods, ostracods, cirolanid isopods, mysids and caridean shrimp. In addition, huge filamentous colonial sulphur bacteria of the *Beggiatoa-Thiothrix* are common in anchialine caves (Yager 1991) — the Australian habitat fits this description.

Ostracoda

While a number of ostracods were taken a single distinctive specimen is attributable to the genus *Danielopolina* which has as interesting a biogeography as the other Tethyan relicts. It was taken in a deep anchialine cave by divers in the same location as the remipede. The genus has the same general distribution as the other Tethyan relicts (Caribbean area and Lanzarote in the Canary Islands), but is known in addition from the Galapagos Islands and from an abyssal species in the Atlantic Ocean off Brazil.

Mollusca

The gastropod *Iravadia* (*Iravadia*) sp. (Family Iravadiidae) from brackish water in Bundera sinkhole (C-28: Slack-Smith 1993) may represent the first marine/estuarine stygophile recorded from the region (Knott 1993).

## Associated fauna

Many taxa were collected from superficial waters that do not form part of the stygofauna but represent taxa normally found in transient water bodies. In general these have not been identified beyond high level taxonomic groups (Table 5).

**Table 5.** High level taxonomic groupings of taxa collected in open water bodies that do not comprise part of the stygofauna. The references denote the source of determinations other than the authors. [1]Status ambiguous (*cf.* Knott 1993; Slack-Smith 1993).

| Taxon | Notes | Authority |
|---|---|---|
| Protista (sundry) | *Euplotes* sp.; *Paramecium* sp. | Knott 1993 |
| Rotatoria | | |
| Turbellaria | | |
| Nematoda | | |
| Polychaeta | Syllidae (two species) | G. Hartmann-Schröder, pers. comm. |
| Oligochaeta | | |
| Mollusca | *Iravadia* (*Iravadia*) sp. ?*I. ornata*[1] | Slack-Smith 1993 |
| Ostracoda | | |
| Amphipoda | | |
| Acarina | | |
| Ephemeroptera | - | |
| Trichoptera | | |
| Odonata | | |
| Hemiptera | | |
| Diptera: Chironomidae | *Chironomus* (*Kiefferulus*) *intertinctus* | Knott 1993 |
| Coleoptera | | |
| Pisces: Poeciliidae | [2]*Poecilia reticulata* Peters 1859 [Guppies!] | |

[2] Found in an overflow pool in the borefield supplying Kailis Fisheries (conductivity 335 mS $m^{-1}$) and in the tank at Upper Bulbarli Well (conductivity 110 mS $m^{-1}$). The former is maintained as a stock watering point and the guppies were reportedly introduced to control mosquitos at the recommendation of the W.A. Water Authority (G. Passmore; pers comm.). The guppies clearly thrive under these conditions and the population density is immense. As the pool is on a natural drainage line flooding could potentially spread the population. However, they are most likely to be spread by people. If they enter natural freshwater or brackish waters they are likely to eliminate the native fauna (G. Allen, pers. comm. 1993).

## Terrestrial fauna

The terrestrial troglobitic fauna of the North West Cape peninsula has been discovered only recently (e.g. Vine *et al.* 1988; Harvey 1988, 1991, 1992, 1993; Harvey*et al.* 1993; Humphreys 1989, 1990, 1991 a-e, 1993 a,b, in press a; Humphreys *et al.* 1989; Humphreys and Shear 1993; Roth 1991; Shear 1992; Dalens 1992; Adams and Humphreys 1993; Deeleman-Reinhold 1993; Hoch 1993; Millidge 1993; Sturm and Smith 1993; Moore and Humphreys in press). The troglobite fauna is rich, with at least 30 troglobitic species from many orders (in Humphreys 1993a). They belong to the Chelicerata (Pseudoscorpionida, Schizomida, Araneae, Opiliones), Crustacea (Isopoda), Diplopoda (Polydesmida, Polyzoniida, Spirobolida) and the Insecta (Blattaria, Hemiptera, Orthoptera). In addition there are many species not obviously troglomorphic but whose presence in this arid region is probably dependent on the subterranean habitat (Table 6).

The affinities of the terrestrial troglobitic fauna lie with the litter fauna of closed moist forests, both temperate and tropical, that are today typically found on the eastern seaboard of Australia (Harvey *et al.* 1993; Humphreys 1993b). It is considered to be a relictual fauna isolated from similar taxa by the onset of aridity in the late Miocene or early Pliocene (Humphreys 1993b). It contains some very ancient elements of clearly eastern Gondwanan affinities (e.g. *Hyella*; Harvey 1993).

When the project was proposed no significant terrestrial troglobitic fauna was known from the coastal plain of the Cape Range peninsula, although one cave was known (C-215) in the foothills where elements of the Cape Range terrestrial fauna met the coastal aquatic fauna (Poore and Humphreys 1992). Since that time, partly as a result of this project and partly due to related work, both on the Cape Range peninsula and on Barrow Island, we have started to uncover a distinct terrestrial troglobite fauna on the coastal plain. As elements of these are likely to interact with the stygofauna, they have been examined where found and some comment is made on them.

**Table 6.** Terrestrial troglobitic fauna known from the coastal plain of Cape Range peninsula. Thise marked * exhibit extreme troglomorphies; the remainder are possibly restricted to cave environments.

| | | |
|---|---|---|
| | CHELICERATA | |
| Schizomida | | **Draculoides vinei* (Harvey) |
| | | **Draculoides* sp. nov. |
| Pseudoscorpionida | Hyidae | **Hyella* sp. |
| Pseudoscorpionida | Chthoniidae | *Austrochthonius easti* Harvey |
| Pseudoscorpionida | Cheiridiidae | |
| Opilionida | Phalangodidae | *Gen? |
| Araneae | Hahniidae | *Gen? |
| Araneae | Desidae | *Forsterina* sp. |
| Araneae | Pholcidae | *Trichocyclus septentrionalus* Deeleman-Reinhold |
| Araneae | | Gallieniellidae |
| | MYRIAPODA | |
| Diplopoda | Paradoxosomatidae | **Stygiochiropus communis* Humphreys and Shear |
| | | **Stygiochiropus* sp. |
| | INSECTA | |
| Diplura | Japygidae | |
| Thysanura | Nicoletiidae: Atelurinae | |
| Coleoptera | Curculionidae: Brachycerinae (s. lat): | |
| | Polydrosinae | *Myllocerus* sp. |
| Hemiptera | Meenopliidae | **Phaconeura proserpina* Hoch |
| | CRUSTACEA | |
| Isopoda | Philosciidae | |

Some genera present in Cape Range are found as separate species on the coastal plain, namely *Draculoides, Stygiochiropus* and ?*Hyella*. Other taxa are known only from the coastal plain, such as the spider family Hahniidae and the meenopliid *Phaconeura proserpina* Hoch. *Hyella humphreysi*, endemic to the Cape Range peninsula, is the most extremely cave adapted pseudoscorpion in Australia the affinities of which lie with Gondwana; it is included in a subfamily known only from southern India, northwestern Australia and Madagascar (Harvey 1993).

The polydesmid millipede genus *Stygiochiropus* (Paradoxosomatidae) is endemic to the peninsula and includes three species (Humphreys and Shear 1993) which are all highly modified for cave existence.

*Draculoides* sp. nov. is one of several taxa known both from the Cape Range peninsula and Barrow Island, including terrestrial (*Nocticola* sp. and *Phaconura* sp.) and aquatic (*Stygiocaris stylifera*, *Haptolana pholeta* and *Halosbaena tulki* ) species, all apparently endemic to the Cape Range Formation.

## Diversity

The Cape Range peninsula comprises *c.* 0.07% of Western Australia but it has a high species density and exceptional endemism (papers in Humphreys 1993a). In addition the peninsula contain *c.* 6.5% of the specialist underground fauna known from the worlds tropics: 477 terrestrial, 115 freshwater and 57 anchialine water species have been described (S.B. Peck, pers. comm. 1992).

## Prospects

On both sides of the Atlantic thermosbaenaceans co-occur with other relictual crustacea (remipedes, cephalocarids and spelaeogriphaceans: Newman 1991), as well as cyclopoid copepods, mysids (*Stygiomysis*), isopods (microparasellids and stenasellines) and amphipods (*Hadzia* and *Psammogammarus* also found in the Indo-Pacific part of Tethys: Schram 1986). This association led to the search specifically for remipedes which are themselves associated with thermosbaenaceans, hadziid amphipods, ostracods, cirolanid isopods, mysids and caridean shrimp.

Some of these associated taxa have already been found on the Cape Range peninsula (ostracods, cirolanid isopods) in addition to the thermosbaenaceans and remipedes. As only a single deep anchialine cave has been examined, and that only briefly, the prospects are good for finding some of the other taxa elsewhere associated with these taxa.

# Geographical distributions of the stygofauna

## Introduction

Only two primary sources deal with the distribution of the stygofauna on the Cape Range peninsula (Mees 1962; Humphreys and Adams 1991). In 1959 Mees (1962) collected widely along the west coast of the peninsula but found stygofauna only in Milyering (C-24), Kudamurra (C-25) and Tantabiddi (C-26) Wells and recorded *Milyeringa veritas*, *Ophisternon candidum* and *Stygiocaris* spp., although only *O. candidum* was found in Tantabiddi Well. Humphreys and Adams (1991) bought up to date the more extensive distributional data but recorded no further taxa on the coastal plain.

This section describes the geographical distribution of those elements of the stygofauna that are recognisable at this stage at some lower taxonomic level, hence it excludes groups such as copepods, turbellaria, rotifers, ciliates etc.

It has been hypothesised that the stygofauna of the Cape Range peninsula, because of its apparent age, must have dispersed from older geological formations through limestone deposits on the North West Shelf at times of lower sea level (Humphreys 1993b, in press b). The presence of *Stygiocaris stylifera* , *Haptolana pholeta* and *Halosbaena tulki* on Barrow Island, together with terrestrial troglobite *Draculoides* (Chelicerata: Schizomida), a genus otherwise known only from the Cape Range peninsula, demonstrates the viability of the dispersal route and supports the hypothesis.

An alternative view has been expressed that, as a major component of the stygofauna is likely to have originated in fresh water (Knott 1993) and as the Ashburton River once flowed past North West Cape (Wyrwoll *et al.* 1993) its catchment would likely contain representatives of the Cape Range stygofauna (Humphreys 1993b, in press b; Knott 1993). A connection between these areas is supported by the presence on Cape Range of a relict population of Mill Stream Palms, *Livistona alfredii,* otherwise known only from the Pilbara, including the Ashburton system (Humphreys *et al.* 1990).

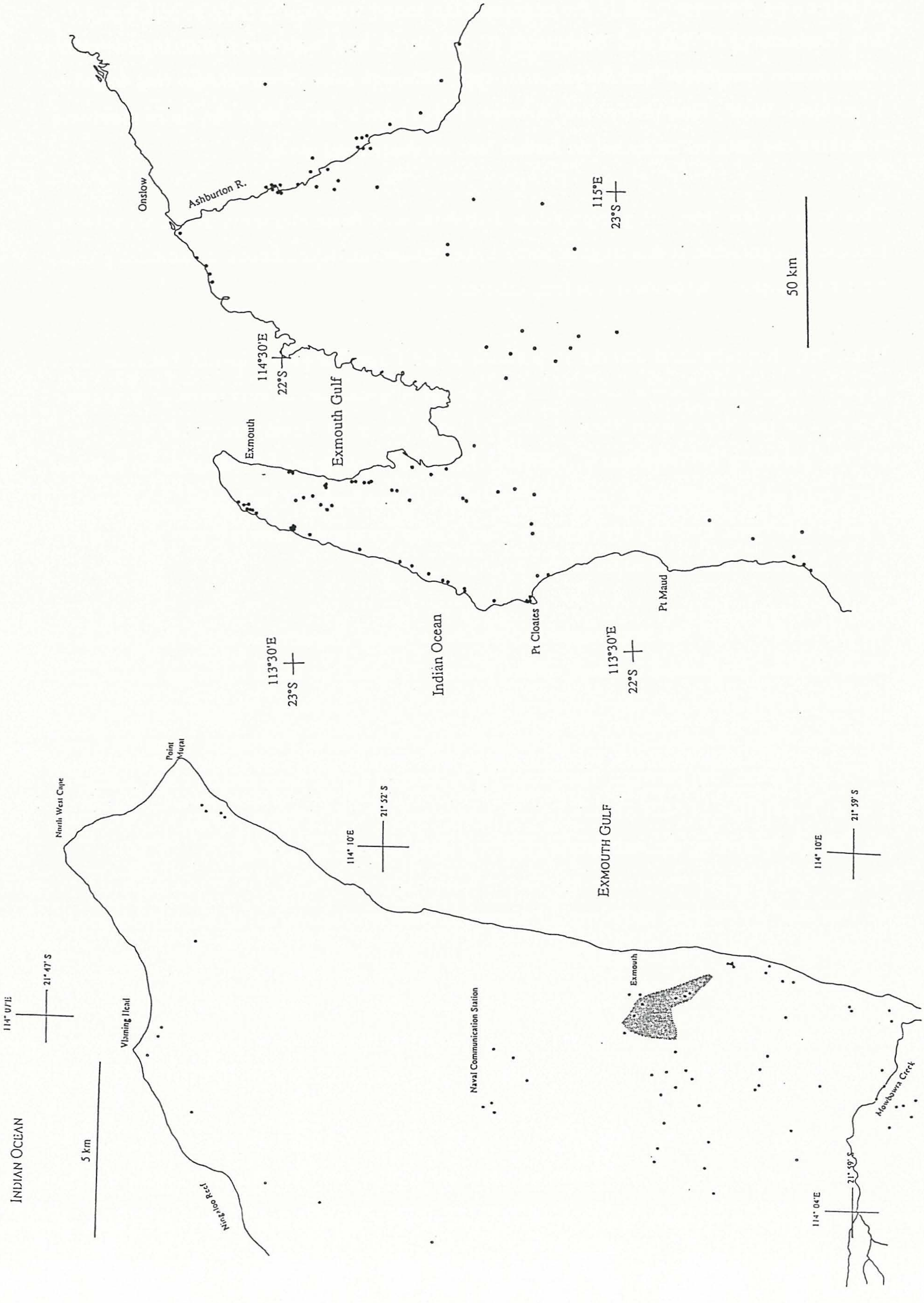
To this end, as well as sampling all known or newly discovered access points to the stygofauna on the Cape Range peninsula, the limits of the distribution of the stygofauna were determined by sampling forays into areas of the same geological formation, such as around Rough and Giralia Ranges, as well as southwards of the peninsula as well as due east in the Ashburton River basin, and (Figure 2, Appendix A).

### Vertebrates

#### *Ophisternon candidum*

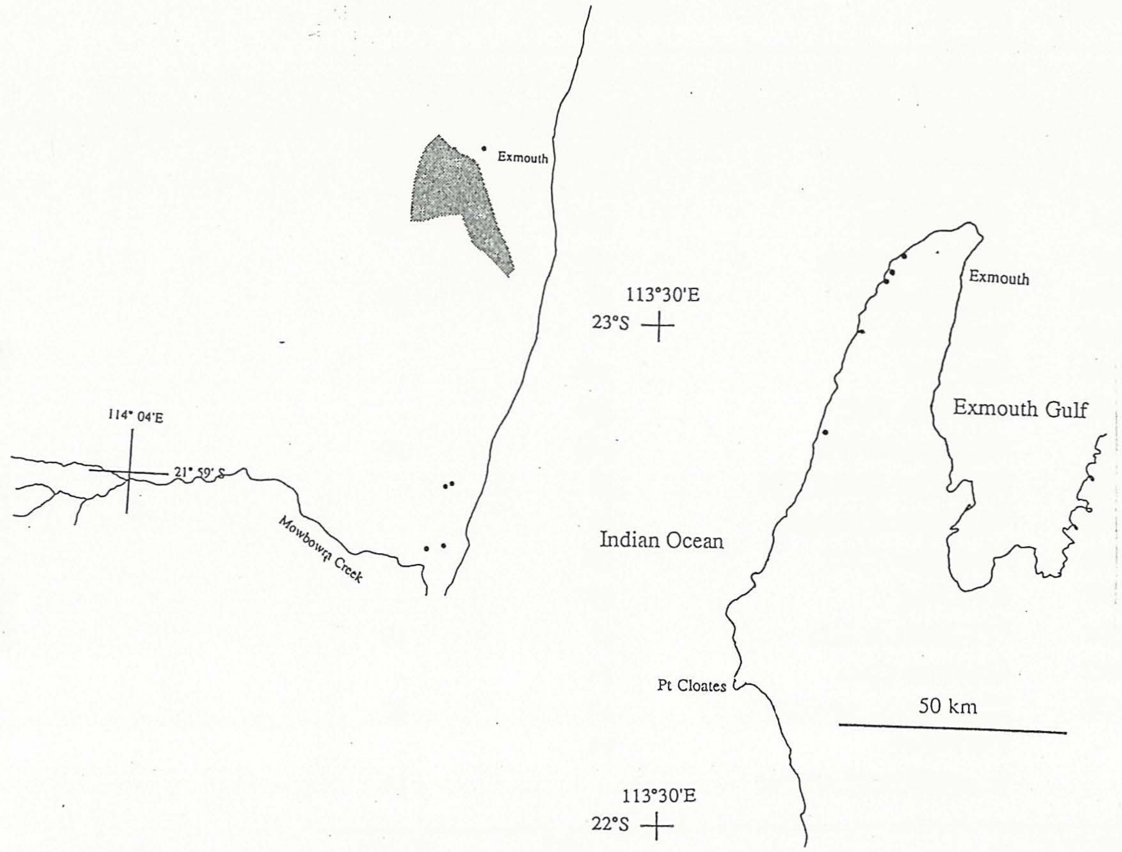
In addition to the sites previously recorded (Humphreys and Adams 1991) some earlier

**Figure 2:** Map of the Cape Range peninsula and its hinterland showing the location of the 185 stygofauna samples collected from the 261 sites examined in 1993. The second map shows an enlargement of the area around Exmouth between Mowbowra Creek and North West Cape.



records have been found in the American Museum of Natural History (AMNH). Together with two additional sites where *O. candidum* has been observed there are now 11 locations known to have be inhabited by the eel in recent times, of which eight are currently inhabited (Table 6; Figure 3). There is a record of an eel inhabiting for several days a recently excavated, 4 m deep, well to the south of Yardie Creek (Allen 1982) and, while the location is unknown, it would be at least 16 km south of other known sites.

**Figure 3:** The distribution of *Ophisternon candidum* which is restricted to the Cape Range peninsula. The enlargement shows the area around Exmouth. Note there is an unlocated record to the south of Yardie Creek.




*O. candidum* was recorded in 1969 by the AMNH expedition at two locations from where they have not subsequently been reported, despite frequent sampling, namely Pilgramunna Well (C- 274) and Dozer Cave (C- 23). The latter is very badly silted from site restoration work(!), however *O. candidum* has been reported from C-105 nearby.

The sites are primarily rock holes and small caves that were traditional watering places, or in adjacent hand dug wells that are in a poor state of repair (see section on well descriptions). While most of these sites have been (C-24, C-26, C-361, C-414), are currently used (C-25), or are equipped (C-27) for water supply, several sites have not obviously been used for water supply (C-23, C-105, C-495).

The most pristine site is New Mowbowra Cave at the extreme south-eastern limit of the distribution of *O. candidum*; the cave has a very small access and was entered for the first recorded time in 1993; two *O. candidum* were seen there. This cave, being 0.45 km from the sea, is the closest known stygofauna site to the coast.

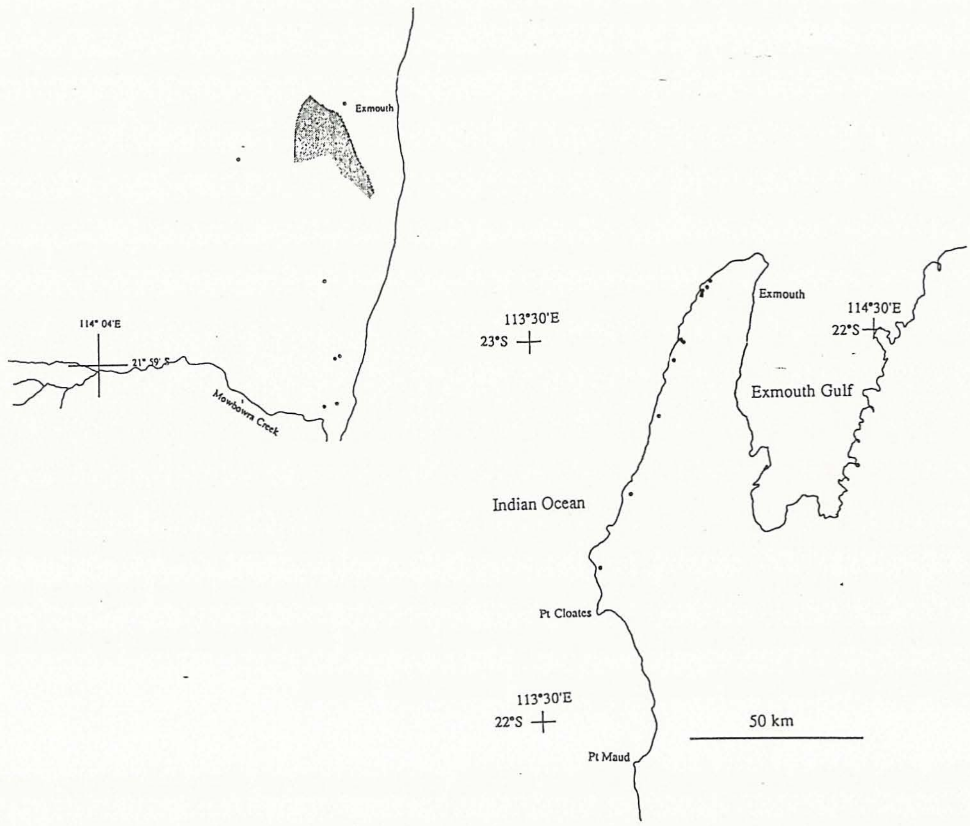
**Table 6**: The known occurrence of the blind cave fish on the Cape Range peninsula. The figures in brackets is the number of sites recorded in Humphreys and Adams (1991). a= 1993; b= recorded in Humphreys and Adams (1991); [c] from field notes of American Museum of Natural History; Station 60, 5 April 1969; [d] Samples (WAM: P.5863.001) were collected from Neds Well in 1963 but it has not contained water since at least 1987. [e] new well south of Yardie Creek (Allen 1982).

| Number | Name | *Milyeringa* | *Ophisternon* |
|---|---|---|---|
| C-23 | Dozer Cave | 1[bc] | 1[c] |
| C-24 | Milyering Well | 1[ab] | 1[ab] |
| C-25 | Kudamurra Well | 1[ab] | 1[ab] |
| C-26 | Tantabiddi Well | - | 1[b] |
| C-27 | Kubura Well | 1[ab] | 1[ab] |
| C-28 | Bundera Sinkhole | 1[ab] | - |
| C-105 | Gnamma Hole | 1[a] | 1[b] |
| C-149 | Tulki Well | 1[b] | - |
| C-215 | Unnamed | 1[ab] | - |
| C-273 | Five Mile Well | 1[ab] | - |
| C-274 | Pilgramunna Well | 1[ab] | 1[c] |
| C-282 | Neds Well 1963 C-282 | 1[d] | - |
| C-332 | Tantabiddi Rockholes | 1[a] | - |
| C-361 | Mowbowra Well | 1[b] | 1[b] |
| C-362 | Javis Well | 1[ab] | - |
| C-414 | Wobiri Rock Hole | 1[a] | 1[a] |
| C-452 | Camerons Cave | 1[a] | - |
| C-495 | New Mowbowra Cave | 1[a] | 1[a] |
| - | WAWA 44 | 1[a] | - |
| | ?south of Yardie Creek | | 1[e] |
| Total sites | | 18 (11) | 11 (6) |

### *Milyeringa veritas*

In addition to the 11 sites previously recorded (Humphreys and Adams 1991), *M. veritas* has been observed or collected at an additional six sites, making 18 in all (Table 6; Figure 4). The population at Neds Well is no longer present as the well has been dry since at least 1987; it is located in the water supply borefield of the Harold E. Holt Naval Communications Station which draws a separate water supply from Exmouth and in which a number of bores have dried up or become too saline for effective water treatment (see Humphreys and Adams 1991).

**Figure 4:** The distribution of *Milyeringa veritas* which is restricted to the Cape Range peninsula. The enlargement shows the area around Exmouth.




The geographic range of *M. veritas* has barely been increased by the additional records but the nature of the habitat known to be suitable for them was expanded by the recovery of a specimen from the Exmouth water supply borefield in a *c.* 40 m deep production bore, 4 km from the coast. Previously the record furthest from the coast was 1.6 km at C-215. It would seem that the populations can utilise the brackish water until the freshwater/seawater transition if suitable voids are available and this record possibly doubles the habitat area likely to be occupied by the fish.

No suitable method is known to trap *M. veritas* and, save for two individuals, those caught were first seen and then taken by hand net; one was taken in a stygofauna trap and one in a plankton net haul. This is not surprising for these sluggish fish (Knott 1993) have well developed avoidance behaviour, moving slowly away from mild disturbance, especially by moving below overhangs, but they also exhibit rapid and sustained escape behaviour, even leaping out of the water.

The sites occupied by *M. veritas* are similar to those inhabited by *O. candidum*, with the addition of deep bores. The most pristine sites are New Mowbowra Cave and C-215.

## Crustacea

### *Stygiocaris* spp.

Two species of atyid shrimps occur as stygofauna on the Cape Range peninsula, *Stygiocaris lancifera* and *S. stylifera* described from sympatric populations in Kudamurra Well (C-26). Morphological differences between the two species *S. lancifera* and *S. stylifera* are small (Holthuis 1960) and the characters by which they can be distinguished ambiguous (Williams 1964: 104) which led some to doubt the validity of the two species (Knott 1993). Electrophoretic examination supported the occurrence of the two species but not their sympatry (Humphreys and Adams 1991), but sympatry has subsequently been confirmed (Adams and Humphreys 1993).

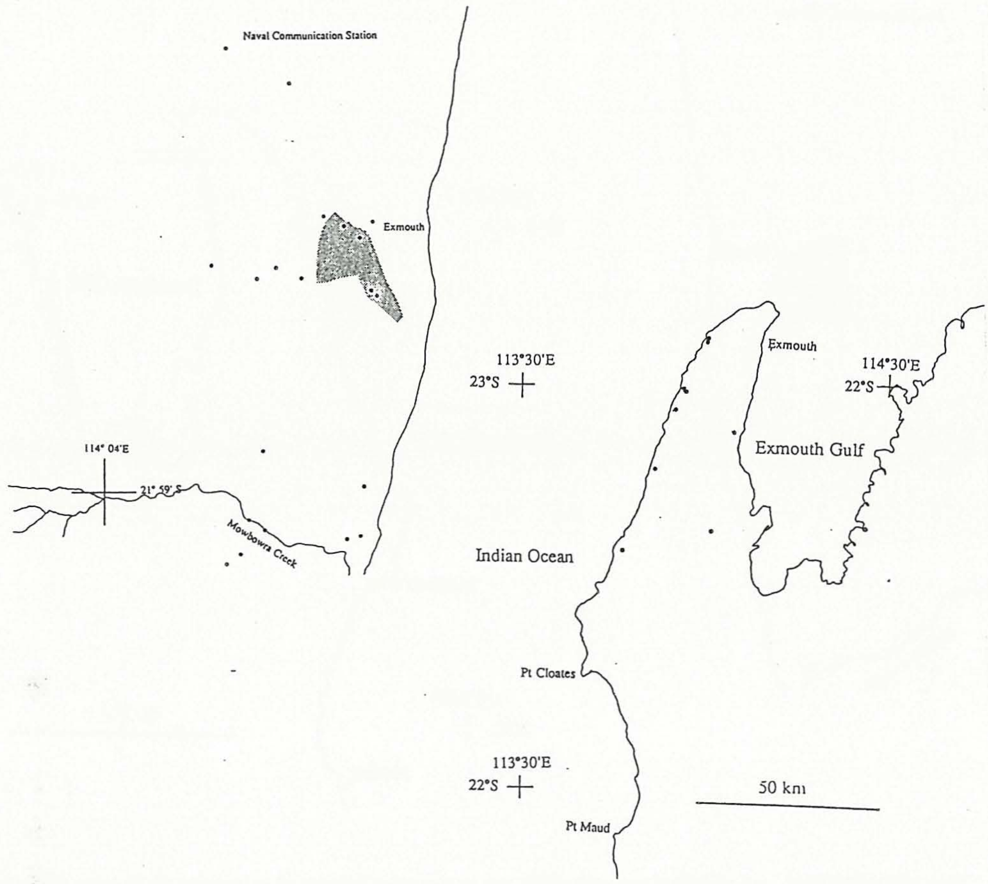
Previously recorded from 10 sites, *Stygiocaris* spp. are now known from 31 sites with major extensions of range inland and southwards on the east coast. *S. lancifera* is known from six sites and *S. stylifera* from 24 sites, of which they are sympatric at two sites. *S. stylifera* is found (Figure 5) on the north-west and east coasts (and Barrow Island) and *S. lancifera* on the west coast (Humphreys and Adams 1991) with both species occurring in sympatry in C-25 and 'near Milyering' (Holthuis 1960).

Save for the initial samples (Holthuis 1960), collections of *Stygiocaris* at any one site have been modest but where they occur in sympatry the smaller *S. lancifera* outnumbers *S. stylifera* by an order of magnitude (Humphreys and Adams 1991). In consequence numerically small samples may fail to record their sympatry and so it is not clear whether both species occur in sympatry through the greater part of their range.

*S. stylifera* has been identified from the south-west coast for the first time (C-28) suggestive of sympatry throughout their range. *Stygiocaris* have been recorded on the west coast south of C-28 at Javis Well (C-362; Humphreys and Adams 1991) but it is of undetermined species. *S. stylifera* does occur 26 km east of C-28 at Billy Wells, a population that is itself 30 km from the next closest population to the north (Figure 5). If they are not in sympatry throughout their range then there must be two zones where the species abut or overlap, one to the north-west of the peninsula, and another near Yardie Creek.

The locations from which *Stygiocaris* has been recorded are similar to those inhabited by the fish and, in addition, they are widely taken in both shallow and deep bores throughout the borefields. The shrimps clearly occupy widely the stygal habitat on the peninsula (and Barrow Island for *S. stylifera*).

**Figure 5:** The distribution of *Stygiocaris* spp. on the Cape Range peninsula. *Stygiocaris stylifera* is also found on Barrow Island. The enlargement shows the area around Exmouth.




### *Halosbaena tulki*

Originally described from a sparse population at a single location (C-215), *H. tulki* is now known to be a widespread member of the stygofauna, occurring at 23 sites on the Cape Range peninsula (Figure 6; and eight sites on Barrow Island). The sites occupied are similar to those inhabited by *Stygiocaris* spp.

Some populations are extremely dense with up to 100 individuals being taken from shallow bores by a single haul of a small plankton net. They have been taken no closer than 1.3 km from the sea shore on the Cape Range peninsula but are known from a deep anchialine cave on Barrow Island within 100 m of the sea cliffs.

### *Haptolana pholeta*

*Haptolana pholeta* has the smallest range of any of the more common stygofauna on the Cape Range peninsula being known from only eight locations (Figure 7), all on the north-east coast and five from sites on Barrow Island 160 km to the north-east. On the peninsula it has only been taken from bores more than 2 km from the sea in the lower

**Figure 6:** The distribution of *Halosbaena tulki* on the Cape Range peninsula. It is also found on Barrow Island. The enlargement shows the area around Exmouth.

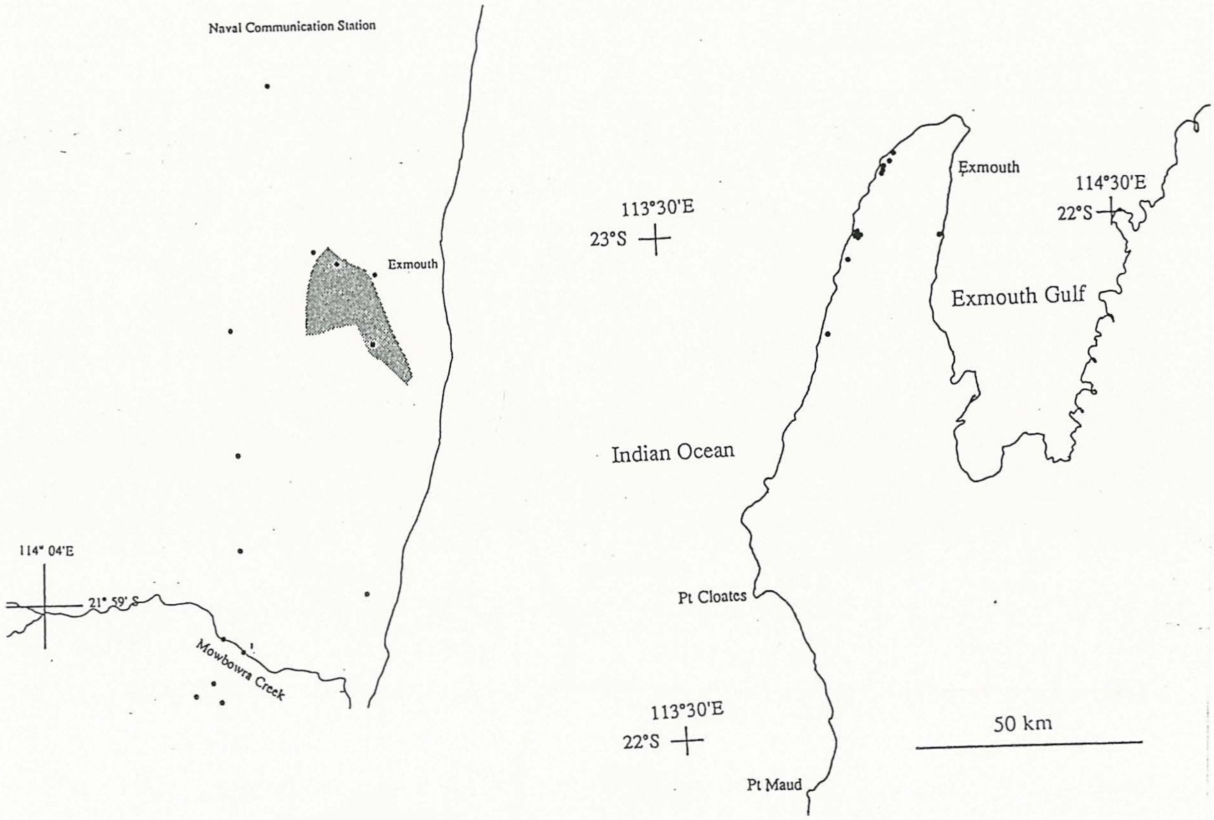
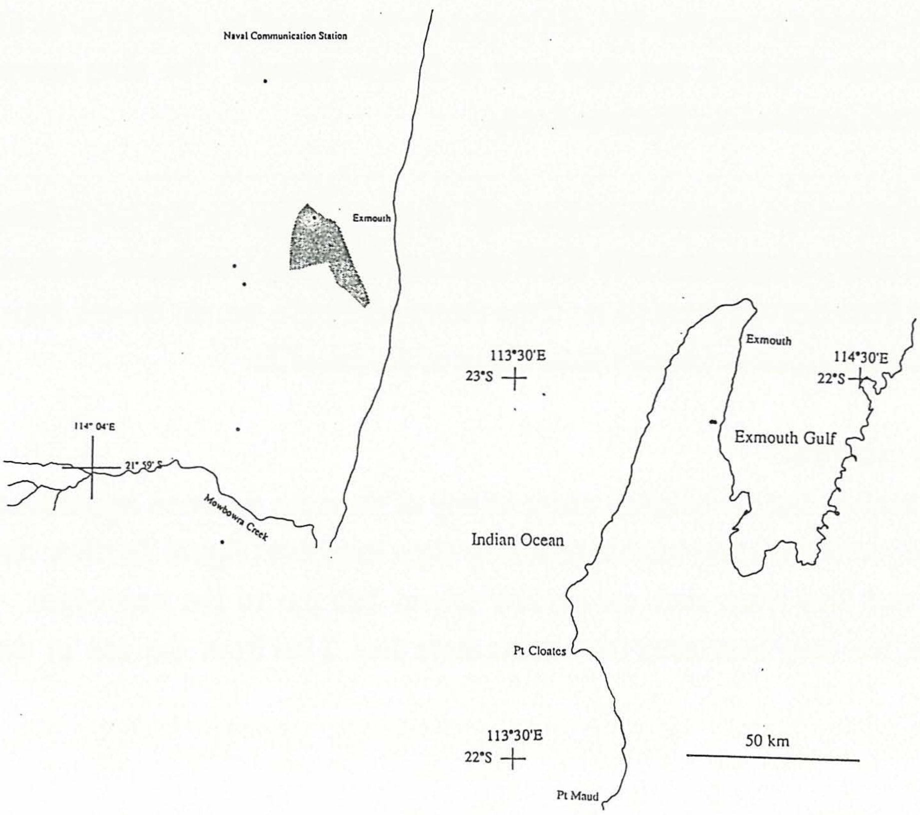



**Figure 7:** The distribution of *Haptolana pholeta* on the Cape Range peninsula. It is also found on Barrow Island. The enlargement shows the area around Exmouth.



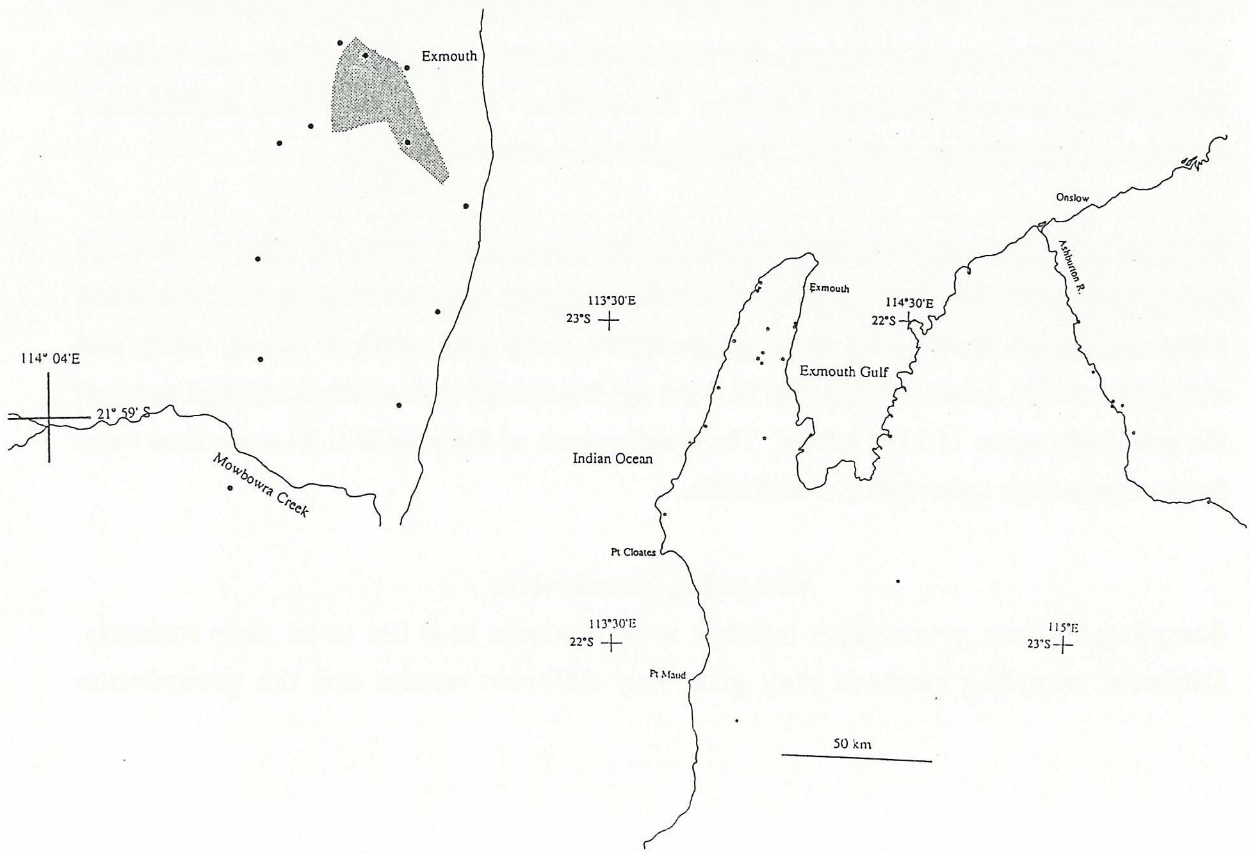
foothills of Cape Range and from no open habitat. On Barrow Island also it has been taken from bores and a single anchialine cave less than 100 m from sea cliffs.

## Melitid amphipods

Two taxa are known of an undescribed genus of melitid amphipods. One species occurs in the four caves known to contain standing water in Cape Range proper (Humphreys and Adams 1991; Knott 1993), namely C-18, C-64; C-103 and C-163 and at altitudes of >160 m ASL. There is morphological evidence of only one species (Knott 1993) but the high degree of allozyme variation indicates that there is no gene flow between the populations and the existence of more than one taxon (Humphreys and Adams 1991; Adams and Humphreys 1993). It has been argued that they became isolated from their congeners on the coastal plain during the uplift of the Cape Range anticline during the Tertiary (Humphreys 1993b).

Another species within the same genus (W.D. Williams, pers. comm.) occurs in the coastal plain groundwater of the Cape Range peninsula and similar forms occur both to the north and south of the Cape Range peninsula (Figure 8). This is the only member of the stygofauna known to occur off the peninsula (excluding Barrow island) but it is not known at this stage whether this entire distribution comprises one or more species.

**Figure 8:** The distribution of melitid amphipods on the Cape Range peninsula and its hinterland. They are also found on Barrow Island. The enlargement shows the area around Exmouth.



On the Cape Range peninsula they are found within 100 m of the sea shore in piezometers and in gravel beds associated with freshwater soaks, and up to 12 km from sea at Billy Wells. Off the peninsula they are found up to 110 km from the sea on the Ashburton River. They are found in rock-holes, shallow wells, bores (up to 100 m deep), and gravel banks; none have been taken from caves.

### Remipedia

Remipedes were collected at a single location (C-28) by divers in a deep anchialine cave. This is the only deep anchialine system able to be sampled but remipedes can be expected to occur throughout the deep anchialine water of the peninsula.

### Ostracoda

Several taxa of ostracods were collected from a range of habitats including rockholes, superficial and deep anchialine caves, piezometers, bores and wells from the coast to Cape Range and along the course of the Ashburton River. A single specimen of the genus *Danielopolina* was collected from deep anchialine water in C-28 by cave divers. They are being examined by Dr D.L. Danielopol, Limnological Institute, Austrian Academy of Sciences. The distributions of the taxa will be examined when further taxonomic information is available.

### Copepoda

Copepods, not unexpectedly, were the most widespread and most collected higher taxon. Owing to the lack of suitable taxonomic specialists they are not dealt with in detail, although various groups are being examined by specialists (Harpacticoidea - Dr R. Huys, The Natural History Museum, London; Calanoidea - Dr T.E. Bowman, Smithsonian Institution, Washington and Dr A. Fosshagen, University of Bergen).

Copepods were collected from 67 sites during the program of which 55 were on the Cape Range peninsula (from caves and soaks in Cape Range and the coastal plain, including deep anchialine caves, and from piezometers, deep and shallow bores, wells and rockholes on the coastal plain) and 12 from the hinterland both to the north and south of the peninsula up to 110 km inland. The distributions of the taxa will be examined when further taxonomic information is available.

## Sampling constraints

Sampling shallow groundwater habitats is problematic as it has to be done remotely. Different sampling methods may give very different results and the groundwater community may show small scale spatial (10 m) and temporal (several days) variation (Hakenkamp and Palmer 1992).

In general, few individuals were taken at any sampling point during this study, a procedure considered prudent owing to the unknown status of the fauna at the start of the field work. Most of the sampling sites were inaccessible, down deep bores, and even some of the wells were unsafe to enter; as such most of the sampling was remote, using traps and haul nets. In addition the characteristics of even those sites directly accessible varied widely from deep anchialine caves accessible on by divers, shallow flowing tidal water in caves, rockholes, wells with water from centimeters to tens of meters deep; even the bores varied from 2.5 cm piezometric bores to 33 cm exploration bores with water from $10^{-2}$ to $10^{2}$ m deep and at as variable a distance underground. Such heterogeneity of sampling sites precluded quantitative sampling of the fauna and the remote sampling method necessarily used prevented rigorous qualitative sampling. This latter effect needs to be examined further to see if it will have produced serious bias into the distributional data.

Sampling bores by haul net would be unlikely, as shown from observation of their behaviour, to catch these species having rapid escape reactions (*M. veritas*, *O. candidum*, *Stygiocaris* spp., *H. pholeta* and the remipedes). In addition some of these taxa could not be trapped (*M. veritas*, *O. candidum* and, probably, the remipedes) and so they would be unlikely ever to be sampled in deep bores. Indeed, throughout the study only one *M. veritas* (very small) was taken by haul net, that in a deep bore, and one was caught in a trap set in a rockhole.

This suggests that the absence of the fish and remipedes from deep bores cannot be taken as evidence that they are absent. Indeed, as the crustacean fauna tends to be strongly associated with the *O. candidum* but not *M. veritas,* although the fish are associated (Table 7), it is likely that the presence of the crustacean stygobionts indicates conditions suitable for the fish — in the case of *Stygiocaris,* that the void spaces would be sufficiently large, a consequence of *M. veritas* having overlapping size range with *Stygiocaris*. Therefore, it is possible that *M. veritas* is present wherever large *Stygiocaris* are found, but not necessarily *O. candidum,* the smallest known of which does not nearly overlap in size with *Stygiocaris*.

## Community

Constraints imposed by the sampling regime, discussed above, also impinge on the interpretation of the community structure. Analysis of the species assemblage is complicated by the inability to define its bounds and the data analysed include all site where, of the species included, one or more members was sampled; in addition, to exclude the statistical noise resulting from the clear absence of the 'community' elsewhere, only sites on the Cape Range peninsula were included.

Some taxa are strongly associated with each other (Table 7) while others exhibit strong, but not significant, negative associations. This is seen in the dendrograms constructed with and without the inclusion of ostracods and copepods (Figure 9 and 10 respectively). The core community is clearly made up of the two common crustaceans (*H. tulki* and *Stygiocaris*) and the two cave fish (*M. veritas* and *O. candidum*). The melitid amphipod(s) is, on general distributional criteria, not part of the core stygofauna but the position of the cirolanid isopod (*H. pholeta*) is more ambiguous. It was rarely taken on the peninsula and never at open sites on the coastal plain: it was once taken at a site inhabited by one of the species of cave fish, *M. veritas* in a deep bore (WAWA#44). Analysis of the food (see section 'Biology') of the two species of fish suggests that *O. candidum* may have a greater dependence on the stygofauna of than *M. veritas*—this is not supported by associations in Figure 9.

**Table 7:** Spearman's rank correlation on the association between a taxon and the number of other species of stygofauna a sites having one or more species. The statistic is *z* corrected for ties.

| | *H. t.* | *Sty.* | *M. v.* | *O. c.* | *H. p.* |
|---|---|---|---|---|---|
| *Halosbaena tulki* | • | 1.78 | -0.47 | 1.20 | 0.94 |
| *Stygiocaris* spp. | | • | -1.20 | 0.88 | 0.33 |
| *Milyeringa veritas* | | | • | 2.69 | -1.68 |
| *Ophisternon candidum* | | | | • | -1.39 |
| *Haptolana pholeta* | | | | | • |

**Figure 9:** Dendrogram of community structure for sites on the Cape Range peninsula only based on Spearman's rank correlation corrected for tied values.

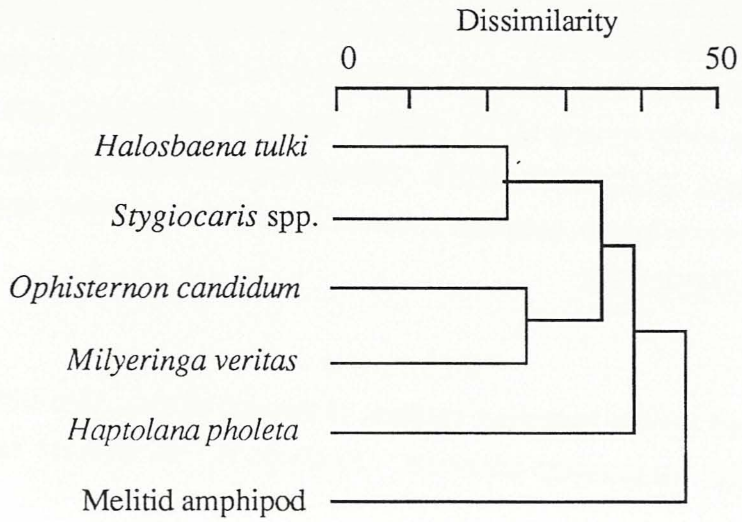
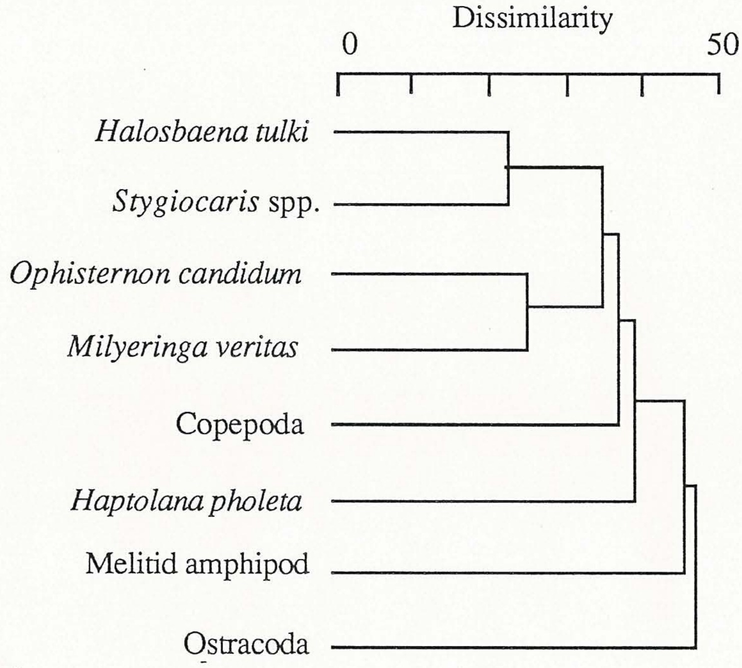


**Figure 10**: Dendrogram of community structure for sites on the Cape Range peninsula only based on Spearman's rank correlation corrected for tied values.



# Biology of the stygofauna

## Biology: Introduction

Owing to the inaccessibility of the fauna, because of its subterranean habitat, there are few locations where direct observation can be made of the animals. The following observations are made from a few accessible sites and from chance observations.

## Numbers of cave fish in Kubura Well

The numbers of *Milyering veritas* in Kubura Well were twice estimated by dilution sampling. At each sampling as many fish as possible were caught by hand net on a number of occasions over several days, removed from the water and retained in a separate container until the end of that sampling period. The number of fish in the cave was estimated from the regression of the number known to be alive (KTBA) at each sampling— the greater of, the cumulative number caught at time $t_i$ plus the number seen at time $t_i$, and the KTBA at any previous time.

In addition I examine the data collected irregularly over many months Mr K. Cameron made irregular observations over many months in Kubura Well; he was interested in *O. candidum* but later counted *M. veritas*.

Kubura Well (C-27) is a misnomer, as it a cave. The cave is fenced and locked and fitted with a permanent ladder and water pump for irrigating the Exmouth sports grounds. It is rarely used for that purpose now but the pump is maintained. The emergent part of the cave is entered through an artificially enlarged hole in the roof and leads to a pool. The cave continues underwater as a broad, low sloping passage before opening into a large but fully submerged chamber to a depth of 11 m. No additional leads were found by cave divers.

The first estimate by dilution sampling of the number of *Milyeringa veritas* in Kubura Well was 48.4 calculated from the intercept of the regression of the number known to be alive (KTBA) on the order of sampling (Figure 11: KTBA = 1.685 - 1.396 log Order, $r^2 = 0.989$, $F_{s\ 1,7} = 620$, $P<0.001$).

The second estimate by dilution sampling of the number of *Milyeringa veritas* in Kubura Well was 34.2 calculated from the intercept of the regression of the number known to be alive (KTBA) on the order of sampling (Figure 12: KTBA = 1.534 - 0.716 log Order, $r^2 = 0.858$, $F_{s\ 1,6} = 36.1$, $P=0.001$).

**Figure 11:** Dilution sampling to estimate the population of *Milyeringa veritas* in Kubura Well ending on 19 June 1993. The regression of the number known to be alive (KTBA) on the order of sampling is shown together with the 95% confidence intervals of the true mean Y.

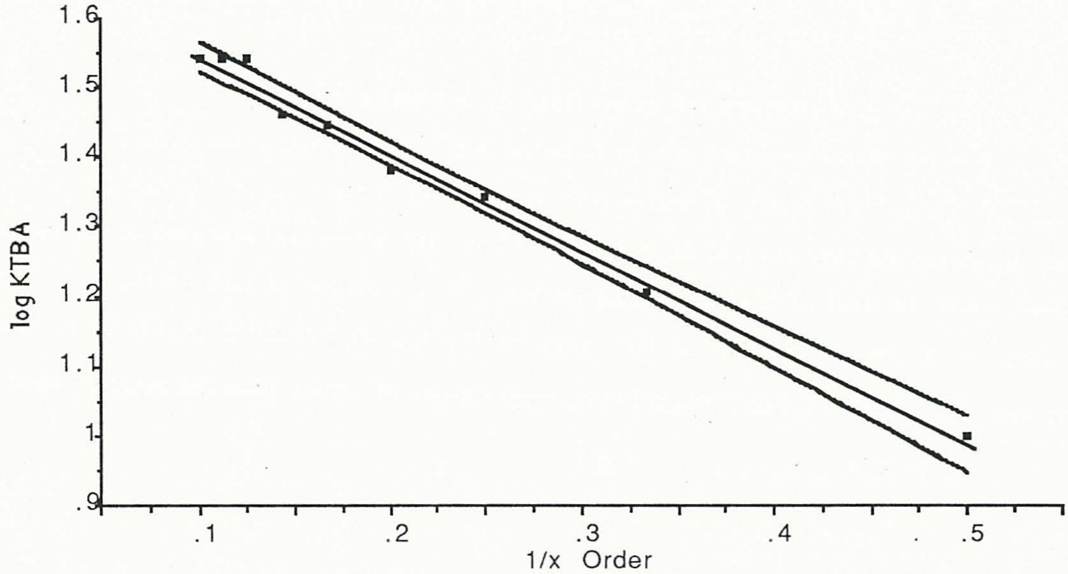
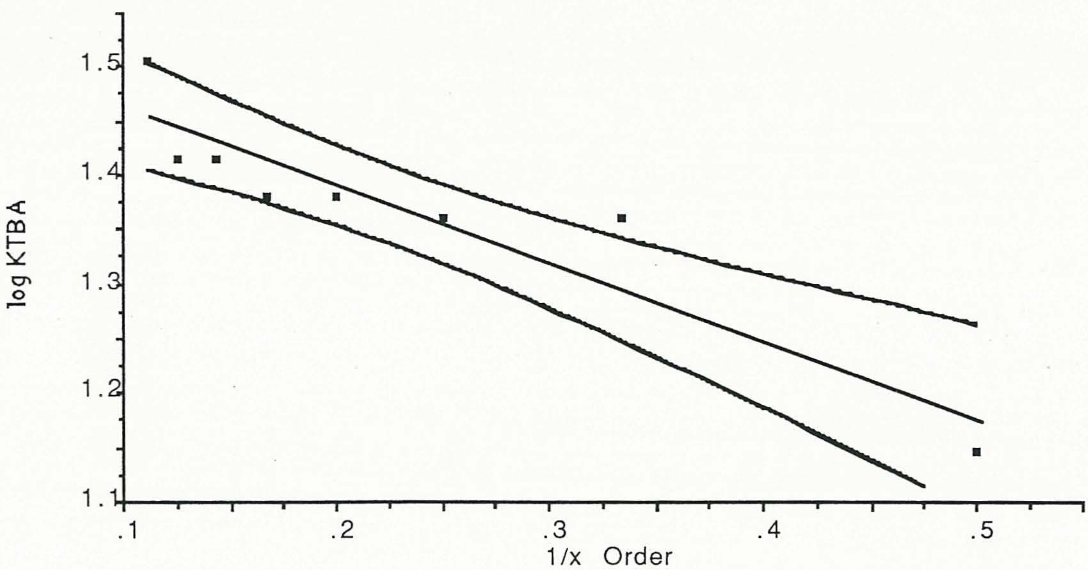



**Figure 12:** Dilution sampling to estimate the population of *Milyeringa veritas* in Kubura Well ending on 31 July 1993. The regression of the number known to be alive (KTBA) on the order of sampling is shown together with the 95% confidence intervals of the true mean Y.




The numbers in July need adjusting upwards by nine fish that were unavailable at the second estimate, being used in growth studies. Thus the estimated 48.4 fish in June compares with 43.2 fish in July, estimates with overlapping confidence intervals (Table 7).

## Discussion

The two estimates of the number of *M. veritas* in Kubura Well gave similar results of about 45 fish in the cave. The numbers seen and caught on each occasion during these

**Table 7:** The estimated population of *Milyeringa veritas* in Kubura Well on two occasions in 1992. The 95% confidence intervals are those for the estimated number of fish at X = 0.

| Sample | Mean | Confidence intervals lower | upper |
|---|---|---|---|
| June | 48.4 | 44.9 | 52.2 |
| July | 34.2 | 28.6 | 40.8 |
| July corrected[1] | 43.2 | 37.6 | 49.8 |

[1] Corrected by adding the nine fish that had been removed from the system.

estimates were between 16-18% of the estimated number in the cave (Table 8). From 4-20 *M. veritas* (mean 11.6) were recorded in an independent and long series of observations in Kubura Well leading up to the population estimates, namely 24% of the number subsequently estimated to be in the cave (Table 9). Similar numbers are seen in other large caves. For example, 18 *M. veritas* were seen in New Mowbowra Cave on 4 August 1993. In 1969 the AMNH collected fish on the Cape Range peninsula and the data sheets show that they collected 43 fish from five localities on the west coast and 20 fish from two localities on the east coast (respectively 8.6 and 10 fish per site), figures quite comparable to those found today at a single sampling time.

**Table 8:** The number of *M. veritas* seen or caught during successive sampling occasions when those caught were removed from the system in Kubura Well.

| Sample | Mean | s | N | Range | % estimate |
|---|---|---|---|---|---|
| June | 8.8 | 3.36 | 10 | 3-15 | 18 |
| July | 7.11 | 3.62 | 9 | 3-13 | 16 |

**Table 9:** The number of *M. veritas* seen on successive observations during which they were not removed. (Date from K. Cameron).

| Species | Period | Mean | s | N | Range | % estimated |
|---|---|---|---|---|---|---|
| *M. veritas* | 1/9/92-27/5/93 | 11.6 | 4.1 | 34 | 4-20 | 24 |
| *O. candidum* | 1/9/92-1/8/93 | 0.81 | 0.65 | 53 | 0-3 | - |

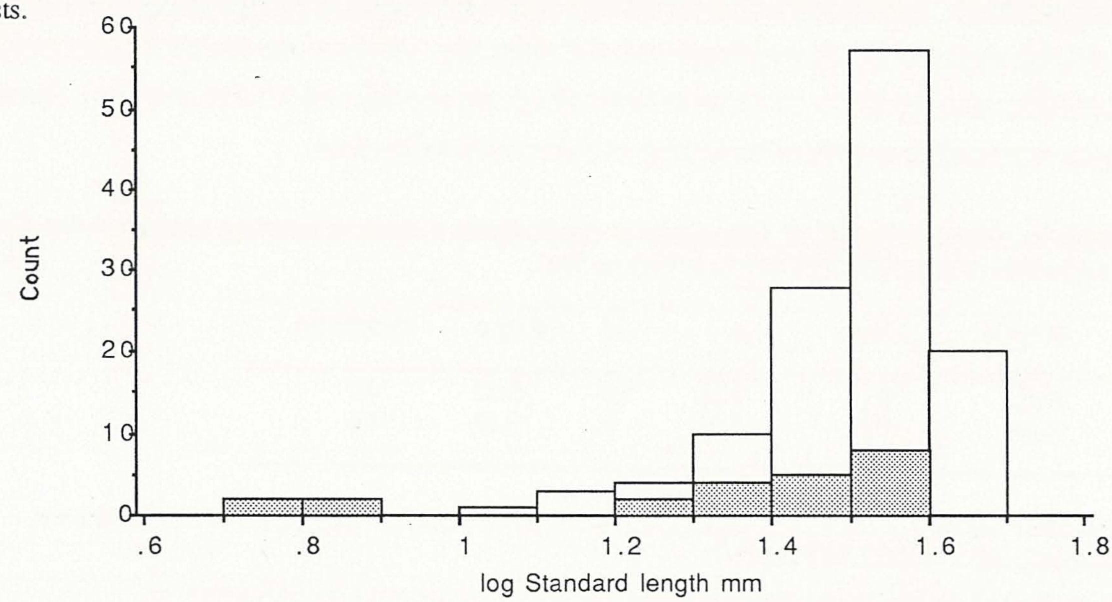
Cave divers report that Kubura Well cave slopes underwater from the open pool and leads to an adjacent large underwater cave from which there are no major leads. Consequently, on sampling, although some fish may not be visible in the open pool, many may be in the deeper water or the adjacent chamber. However, there is likely to be only very restricted interchange, via small crevices, with other large voids in the vicinity, as attested to by the effectiveness, over several days, of the dilution sampling. Hence, it is probable that the population sampled represents that normally inhabiting Kubura Well.

Although the populations of *M. veritas* are not panmictic throughout the Cape Range peninsula (Humphreys and Adams 1991), slow interchange between populations in adjacent voids is apparent as the populations in Kubura Well do not differ (Nei's genetic distance 0.0; *ibid.*) from those in Mowbowra Well, 7.6 km to the south.

### Size

The standard length (mm) of *M. veritas* varied from 5-57 mm and those collected from the east coast were bigger in every respect from those from elsewhere except that the meristic variables do not differ between areas (Figure 13). For example the mean standard length of fish from the west coast was 32.8 mm (s=7.9, 125) compared with a mean elsewhere of 24.6 mm (s= 10.4, 23; $Fs_{1,146}$= 18.67, P<0.001). This agrees with the samples examined from AMNH for prey (see below).

**Figure 13:** Frequency distribution of standard lengths of *M. veritas* examined from the collections. Unshaded are fish from the west coast whilst the stippled bars denote fish from the northwest and east coasts.




*Ophisternon candidum*

*O. candidum* was never trapped and in consequence is known only from open locations such as caves and wells but not from bores. It was normally seen as single individuals and then only briefly as they are sensitive to disturbance and move away (from ?light or ?vibration) either by swimming away or by descending into the faecal pellet ooze that covers the substrate in many areas.

The long series of observations by K. Cameron in C-27 showed that a mode of one individual *O. candidum* was seen in the cave (range 0-3). This is in accord with observations made in other locations; on only several occasions were they seen in pairs (C-

27, C-495) and on only one occasion were three individuals seen at the same time (C-27).

## Behaviour

*M. veritas* often hangs more or less motionless in the water or perches on rock ledges for long periods. When the water is disturbed the fish may swim directly to investigate the disturbance, gradually distance itself from the area, or swim to the bottom and moves behind obstacles, especially to move beneath ledges.

Despite the sluggish nature of these fish (Knott 1993) they show strong escape behaviour from a net, are strong swimmers for short distances and can even leap from the water. If stranded they can flip their bodies into the air.

When offered food they frequently ignore it and will allow tubificid worms to move over them without overt response—they often move to lie over the worms and may eventually eat them.

*O. candidum* is a pencil thin fish that moves eel-like mostly close to the substrate or within the faecal pellet ooze covering much of the substrate. They are not vigorous swimmers.

## Growth

On 30 June 1993 six *M. veritas* were isolated from the main pool in Kubura Well by fly netting dug into the substrate. The fish were measured (standard length) and blotted dry and weighed to 1 mg. The fish were recaptured after 28 and 42 days, identified by their relative size and remeasured. At the start they covered the length range of 21-44 mm and the weight range of 150-1780 mg. The smallest fish was missing at both remeasurements.

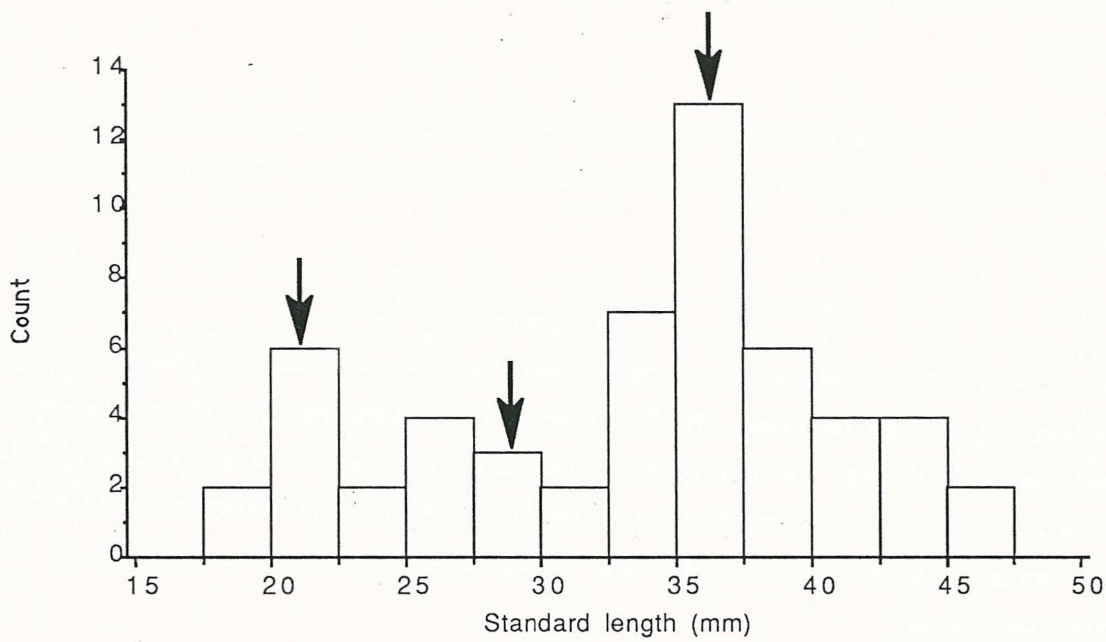
The fish grew at a rate of 0.6 mm per month (95% limits 0.2-1.0 mm) but during this time lost weight indicating that their conditions may not have been adequate (Table 8); the retaining pool prevented the fish moving into the deeper water and hence to the next chamber.

The smallest size of *M. veritas* were seen in the cave in January 1993 (K. Cameron, pers. comm.) and with the measured growth rates a fish 10 mm long in January should reach about 13 mm in July (range 11-16). There is no cohort in Figure 14 corresponding to that suggested by this growth rate but such small fish would unlikely to have been sampled by the method used to catch them, hand netting after visual identification. Nonetheless several cohorts are apparently represented in Figure 14. On this assumption then the apparent movement of the 'peaks' is in close accord with the growth in size projected from the measured growth rate and the upper peak would represent fish of 3+ years.

**Table 8**: The change in standard length and 'blotted dry' weight of *M. veritas* isolated in Kubura Well over 28 and 42 days in 1993.

| | Change in length (mm) | | Change in weight (mg) | |
|---|---|---|---|---|
| | 28 d | 42 d | 28 d | 42 d |
| Mean | 0.30 | 0.84 | -46 | -44 |
| s | 0.45 | 0.64 | 32 | 39 |
| N | 5 | 5 | 5 | 5 |

**Figure 14:** The pooled size class distribution of *Milyeringa veritas* from Kubura Well in 1993. The arrows show the projected movement of the lower 'cohort' over successive years at the measured growth rate.

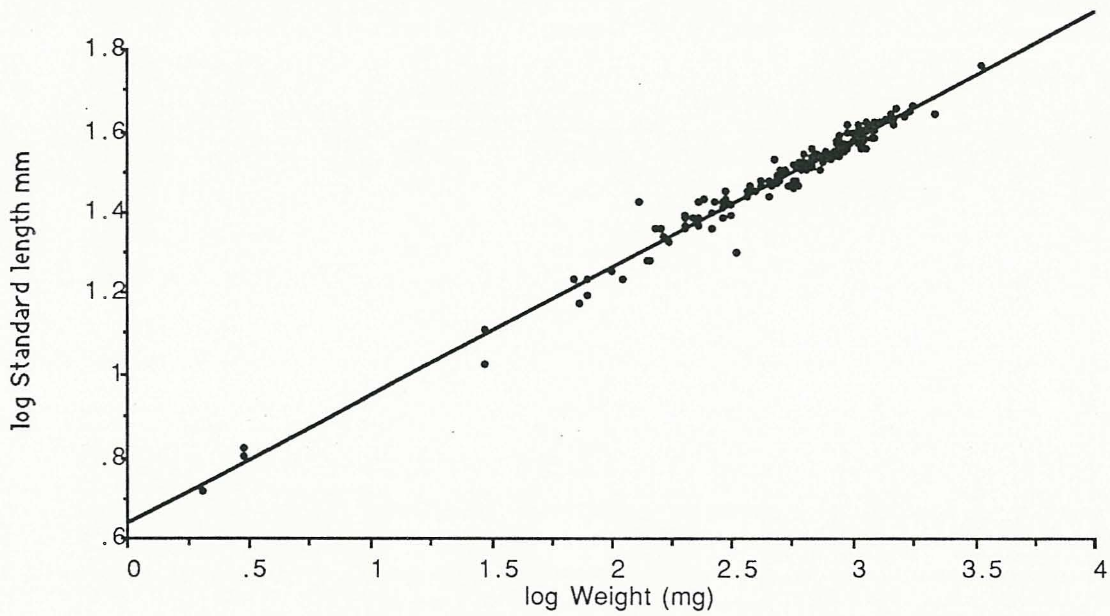



Annual, even seasonal, breeding cycles are unusual in cave animals and would, perhaps, be even less expected in the tropics — what could be the cue to seasonal breeding in *M. veritas* suggested by the 'cohorts' in Figure 14? It has been shown that *M. veritas* is seemingly less a part of the characteristic stygal community of the Cape Range peninsula, gaining, as it does, most of its food directly from animals inhabiting terrestrial habitats. As such it may be expected to respond closely to changes in this food resource. Rainfall is especially unpredictable in this arid area (Humphreys *et al.* 1989) and so a seasonal influx of particulate organic matter is unlikely to serve as a cue for breeding. The air in this arid tropical area becomes exceptionally dry and hot in summer (frequently >40°C) but cave temperature and humidity are well buffered. I suggest that, after the cool and humid winter, more invertebrates seek refuge in the cave from the desiccating surface environment thus providing a flush of food to which *M. veritas* responds by breeding. Detailed work on the fish is required, well beyond the scope of this study.

### *M. veritas* morphometrics

Eight continuous and four meristic measurements were taken from the *M. veritas* (N=151) held in the collections of the Western Australian Museum in order to examine the data for fluctuating assymetry (Leary and Allendorf 1989) and the allometric growth relationships. The linear measurements were made by means of dial calipers and the blotted-dry weights on an electronic balance. No correction is available to examine the effect of preservation on these variables but examination of the relationships indicates that the specimens of variable age and preservation methods gave comparable results (e.g. Figure 15).

**Figure 15:** Example of regression of measurements [(log Standard length (mm) on log Weight (mg)] on *M. veritas* showing the good correspondence between data from disparate sources.




The linear measurements were regressed on the scaled weight (log both) and tested for significant departure from a slope of 1.0 expected if the two values vary similarly. The analysis (Table 9) provides a consistent interpretation that as they grow the fish become relatively more massive. As the fish get bigger and relative to weight the standard length (L1; the slope of the regression being significantly >1.0 or <1.0 for those measurement), snout-vent length (L2), the jaw (L3) and tail lengths (L1-L2) were shorter and the jaw was narrower (W1), and the tail deeper (D2). Similarly, with growth the branchial area becomes narrower, deeper and longer. In summary *M. veritas* becomes relatively shorter and deeper with growth.

Examining all linear measurements against each other showed significant departure from a slope of 1.0 in most of the tests. The three most marked departures below a slope of 1.0 are of regressions of tail length (L1-L2) on anterior body parts, becoming relatively shorter than W1, D1 and D2. The three most marked departures above a slope of 1.0 are of regressions of anterior body parts on jaw length (L3) and showing that the jaw length becomes relatively shorter with size than L4, D1 and D2.

**Table 9:** The slope of the relationship between linear measurements and weight (cubed root weight; log both) in *M. veritas* and linear measurements against each other showing only significant results in the latter. The probability (P) is for significant departure from an allometric growth factor of 1.0. N= 148 to 151.

| x | y | b | S.E. b | P |
|---|---|---|---|---|
| Weight | L1 | 0.943 | 0.011 | <0.05 |
| Weight | L2 | 0.953 | 0.014 | <0.05 |
| Weight | L3 | 0.896 | 0.015 | <0.05 |
| Weight | L4 | 1.016 | 0.02 | N.S. |
| Weight | L1-L2 | 0.931 | 0.026 | <0.05 |
| Weight | D1 | 1.026 | 0.017 | N.S. |
| Weight | D2 | 1.042 | 0.02 | N.S. |
| Weight | W1 | 0.974 | 0.028 | N.S. |
| Weight | W2 | 0.964 | 0.016 | <0.05 |
| L1 | L3 | 0.944 | 0.014 | <0.05 |
| L1 | L4 | 1.064 | 0.021 | <0.05 |
| L1 | D1 | 1.061 | 0.023 | <0.05 |
| L1 | D2 | 1.085 | 0.023 | <0.05 |
| L2 | L3 | 0.924 | 0.017 | <0.05 |
| L2 | L4 | 1.048 | 0.021 | <0.05 |
| L2 | D2 | 1.064 | 0.024 | <0.05 |
| L3 | L4 | 1.087 | 0.028 | <0.05 |
| L3 | D1 | 1.099 | 0.027 | <0.05 |
| L3 | D2 | 1.127 | 0.025 | <0.05 |
| L3 | W2 | 1.045 | 0.021 | <0.05 |
| L4 | W1 | 0.910 | 0.032 | <0.05 |
| L4 | W2 | 0.914 | 0.019 | <0.05 |
| L4 | L1-L2 | 0.869 | 0.030 | <0.05 |
| D1 | W1 | 0.932 | 0.027 | <0.05 |
| D1 | W2 | 0.904 | 0.021 | <0.05 |
| D1 | L1-L2 | 0.872 | 0.029 | <0.05 |
| D2 | W1 | 0.904 | 0.028 | <0.05 |
| D2 | W2 | 0.895 | 0.018 | <0.05 |
| D2 | L1-L2 | 0.851 | 0.029 | <0.05 |
| W1 | W2 | 0.902 | 0.025 | <0.05 |
| W1 | L1-L2 | 0.847 | 0.036 | <0.05 |
| W2 | L1-L2 | 0.927 | 0.031 | <0.05 |

## Food of the blind cave fishes

(in association with M.N. Feinberg of The American Museum of Natural History)

### Methods

To elucidate the prey of the blind cave fish the gut contents of existing collections have been examined. The intestines were either dissected out and later examined by flushing the contents, or the flushing was conducted *in situ* on intestines longitudinally incised. The contents were identified to whatever level practicable depending on the state of digestion. As no details are available of the treatment of the specimens prior to preservation, no attempt is made to quantify feeding rates.

The gut contents were examined of all available specimens of *Ophisternon candidum* save the Holotype namely, Paratype P4918 Tantabiddy Well (C-26), Yardie Creek Station, collected A.M. Douglas and G.F. Mees, 17/5/1960; P5813; Tantabiddy Well (C-26), Yardie Creek Station, collected A.M. Douglas, 22/7/1963; P7716; North West Cape area, collected R. Gredling, 1963-4.

The stomach contents of a large series of *Milyeringa veritas* in the collection of the American Museum of Natural History were extracted by MNF and examined in Perth. Material came from:- AMNH 45497 which included specimens collected by Nelson, Butler and Rosen from the west side of the Cape Range peninsula between Yardie Station and Yardie Creek on the afternoon of 2 April 1969; AMNH 48568 which included specimens collected by Nelson, Butler and Rosen from the east side of Cape Range peninsula from Neds Well to Mowbowra Creek on the morning of 5 April 1969.

### Results and discussion

***Ophisternon candidum***

Members of the stygofauna were found in the midgut of P5813, namely thermosbaenaceans (*Halosbaena tulki* Poore and Humphreys) and atyid shrimps (*Stygiocaris* sp.); sand grains to 1.2 mm diameter were also recovered. The hindgut of the same individual yielded only terrestrial taxa or taxa terrestrial as adults namely, slaters (Isopoda: Philosciidae) and dragonfly (Odonata) and dipteran larvae (Table 10). No contents were found in P4918 or P7716.

The habitat characteristics of the taxa suggests two feeding episodes in the first (hindgut) of which the eel foraged in an open cave habitat on a non-cave aquatic fauna (Odonata and Diptera larvae) as well cryptic species accidentally in the water (philosciid isopod). During the subsequent feeding episode the eel foraged solely on the specialised subterranean aquatic (stygo-) fauna comprising sediment foraging species (*Halosbaena* and *Stygiocaris* ).

**Table 10.** The gut contents of *Ophisternon candidum* in the collections of the Western Australian Museum.

| Location | Identification | ID number |
|---|---|---|
| Midgut: | Thermosbaenacea, *Halosbaena tulki* | BES: 820 |
| Midgut: | Atyidae: *Stygiocaris* sp. | BES: 821 |
| Midgut: | Atyidae: *Stygiocaris* sp. | BES: 822 |
| Midgut: | Thermosbaenacea, *Halosbaena tulki* | BES: 823 |
| Midgut: | Thermosbaenacea, *Halosbaena tulki* | BES: 824 |
| Midgut: | Thermosbaenacea, *Halosbaena tulki* | BES: 825 |
| Midgut: | Sand to 1.2 mm diameter and residue | BES: 826 |
| Hindgut: | Isopoda: Philosciidae | BES: 817 |
| Hindgut: | Odonata, larva | BES: 818 |
| Hindgut: | Unidentified | BES: 819 |
| Hindgut: | Diptera, larva | BES: 856 |

No shrimps were taken from Tantabiddy Well (C-26) in the original collections (Mees 1962) or subsequently (Humphreys and Adams 1991; W.F. Humphreys, unpublished) although both *S. lancifera* and *S. stylifera* occur in an adjacent well (C-25, Kudamurra Well; Mees 1962; W.F. Humphreys and M. Adams, unpublished 1991). *Halosbaena* has not been collected from C-26 (Poore and Humphreys 1992; W.F. Humphreys, unpublished)—hence, these gut contents constitute the only records of *Stygiocaris* and *Halosbaena* from C-26.

The distribution of the genus *Ophisternon* has been described as Gondwanan (Rosen and Greenwood 1976) but a recent interpretation considered both the genus *Ophisternon* and the family Synbranchidae to have a Tethyan distribution (Banarescu 1990: 203). The latter interpretation would accord with that of the stygofauna of the Cape Range peninsula and hence of the prey items (Humphreys 1993b, in press b; Knott 1993). Indeed, there is known only a single element in the stygofauna of the Cape Range peninsula (and Barrow Island) that is clearly Gondwanan, a syncarid crustacean of the genus *Atopobathynella* (Parabathynellidae, Bathynellacea) (W.F. Humphreys, unpublished).

### *Milyeringa veritas*

*Milyeringa* included specialised members of the stygofauna (*Stygiocaris* sp.) in its diet, the aquatic larvae of terrestrial species (caddis larvae) and terrestrial species accidentally in the water (slaters, ants and cockroaches)(Table 11). The identifiable contents were predominantly (77%) terrestrial species that had presumably fallen into the water and, at most, only 10% were specialised members of the stygofauna.

**Table 11:** The gut contents of *Milyeringa veritas* from the the collection of the American Museum of Natural History.

| Side of peninsula | West | | East | |
|---|---|---|---|---|
| AMNH number (N) | 45497 (N=23) | | 48568 (N=16) | |
| Contents | Prey N(%) | Fish N(%) | Prey N(%) | Fish N(%) |
| No contents | - | 8 (31) | - | 4 (21) |
| Cockroaches | 1 (5) | 1 (4) | 9 (53) | 7 (37) |
| Isopods (slaters) | 14 (64) | 12 (46) | 2 (12) | 2 (11) |
| *Stygiocaris* (shrimps) | 1 (5) | 1 (4) | 1 (6) | 1 (5) |
| Crustacea (probably *Stygiocaris*) | 1 (5) | 1 (4) | 1 (6) | 1 (5) |
| Trichopteran larvae | 1 (5) | 1 (4) | 2 (12) | 2 (11) |
| Ants | 4 (18) | 1 (4) | 0 (0) | 0 (0) |
| Unidentified insect parts | - | 1 (4) | 0 (0) | 0 (0) |
| Vermes? | 0 (0) | 0 (0) | 1 (6) | 2 (11) |
| Total | 22 | 26 | 17 | 19 |

*Milyeringa* on the west coast ate predominantly terrestrial isopods (*Buddelundia* sp.), while those on the east coast fed mainly on cockroaches (Table 12); this distribution of prey items differs between coasts ($\chi^2c$ = 12.13, P<0.001). Despite these differences the source of the food was predominantly from outside the water body, of terrestrial origin (Table 12).

**Table 12.** Distribution of prey types between the east and west coast populations of *M. veritas*.

| Group | West | East |
|---|---|---|
| Insects | 4 | 10 |
| Crustacea | 16 | 4 |
| Aquatic | 4 | 3 |
| Terrestrial | 16 | 11 |

Gudgeons examined for prey were larger on the west coast (38.5 ±3.99 mm, n=26) than on the east coast (30.6 ±5.47 mm, n=19; $Fs_{1,43}$ = 28.75, P<0.001), as were those in which prey was found (38.6 ±4.39 mm and 31.2 ±5.69 mm respectively; $Fs_{1,31}$ = 17.5, P<0.001).

Prey size was converted to common units (body length, mm) using empirically derived relationships - isopod length (mm) = 2.8 carapace width (mm) - 0.04 ($r^2$ =0.89, P 0.017); cockroach length (mm) = 3.9 head capsule width (mm) +1.5. The mean head capsule width of the cockroaches was 1.3 ±0.16 mm (n=8) giving an estimated overall body length of 5 mm (by regression). The mean carapace width of the isopods was 2.9

±1.71 mm (n=6) giving an estimated overall length = 8.1 mm (by regression). Hence, the bigger west coast fish were associated with bigger food items (isopods). However, as terrestrial crustacea generally have an energy density only about 70% that of terrestrial insects (from Cummins and Wuycheck 1971), then the seeming advantage in food size may not confer an energetic advantage.

### Associated fauna in the field

The fish share their habitat with a large number of stygofaunal elements, many of which were not represented in their stomach contents (Table 13). The smallest taxa, such as copepods and ostracods, are probably outside the size range of prey items, which for *M. veritas* is known to include the length range of *c.* 2.8-14 mm, and for *O. candidum* 3 mm (*Halosbaena*) to an estimated 8 mm (Odonata). No fish samples were collected from known remiped habitat, although they do occur sympatrically. The melitid amphipods are sympatric with *M. veritas* (at locations C-24, 25,105, 274 and 362; W.F. Humphreys, unpublished) and abundant in the stygal habitat but, despite being in the known size range of prey for both species of fish, they are not obviously represented in the gut contents.

**Table 13.** Stygofauna associated with the two sympatric cave fish on the Cape Range peninsula. √ = is known from the same areas; + = found in the gut contents; - no record.

| | *M. veritas* | *O. candidum* |
|---|---|---|
| *Stygiocaris lancifera* Holthuis | + | +[1] |
| *S. stylifera* Holthuis | √ | +[1] |
| *Halosbaena tulki* Poore and Humphreys | √ | + |
| *Haptolana pholeta* Bruce and Humphreys | √ | - |
| Remipedia | √ | - |
| Melitid amphipod gen. nov. sp. nov. | √ | √ |
| Calanoid copepods | √ | √ |
| Harpacticoid copepods | √ | √ |
| Ostracoda | √ | √ |

[1] The species of *Stygiocaris* in *O. candidum* from C-26 is not known; immediately to the north of C-26 *S. stylifera* and *S. lancifera* are sympatric, while to the south only *S. lancifera* is known.

## Discussion

The prey identified is consistent with the behaviour of the fish. *O. candidum* inhabits the surface of, and burrows into, the faecal ooze characteristic of crustacea rich stygal habitats. All the prey items identified are bottom dwellers or, are hydrophilic (isopods) and would sink to the bottom when they fell into the water. In contrast *M. veritas* moves widely through the water column, often hovering in mid- to surface waters where prey with hydrophobic integuments, such as cockroaches, would be encountered when they fell into the water.

The locations sampled for *M. veritas* include flooded sinkholes, small rock pools, shallow open caves in the coastal limestones, old wells (hand-excavated and lined with wood or cement), deep anchialine caves and deep bores. From these samples the food of *M. veritas* comprised predominantly terrestrial taxa (79%) that have presumably fallen into the water; both the isopods and cockroaches are plentiful in some of the sampling locations as these cryptic taxa shelter there from the hot arid climate. However, there are populations of gudgeon known from caves (e.g. C-215, C-452) where such accidental food is unlikely to occur as the water is reached only at some horizontal distance from the entrance, or from 50 m deep bores. However, both these habitats contain rich stygofauna.

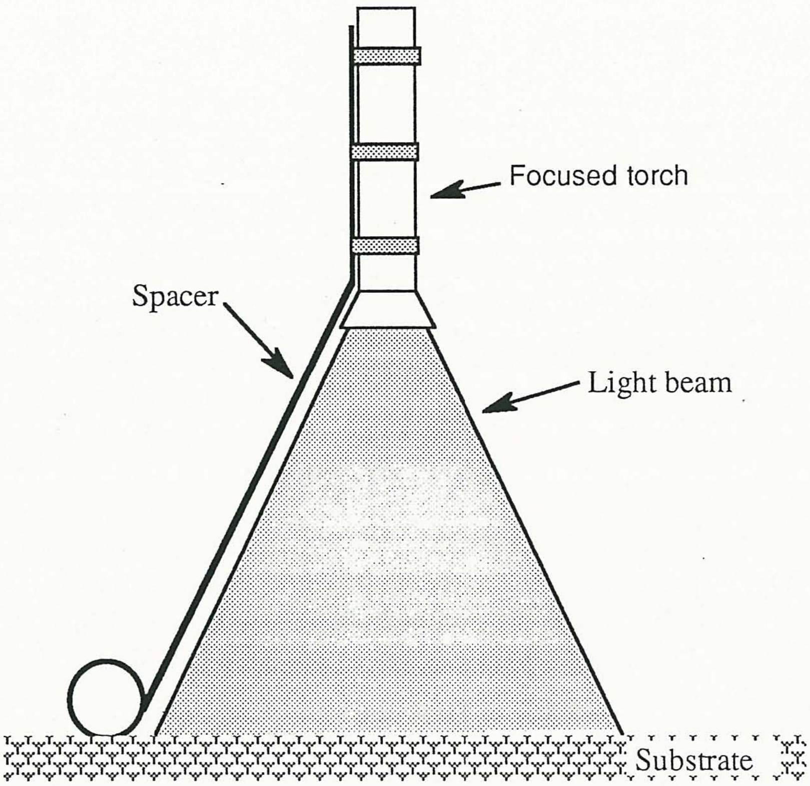
Both species of troglobitic fish are clearly opportunistic in their feeding, able to take accidental inputs of energy. The eel forages on the specialised subterranean inhabitants and the gudgeons must have this ability, although rarely recorded in these samples, because it inhabits some locations, such as C-215 and deep bores, essentially closed to accidentals. The gudgeons are capable of taking large and energy rich prey such as cockroaches, while the eels includes prey of minute size (*Halosbaena tulki* is <2 mm in total length; Poore and Humphreys 1992).

## *Stygiocaris* spp.

### Numbers

The numbers of *Stygiocaris* in Kubura Well was estimated by means of a 'light quadrat' (Figure 16). A small torch with good focussing capability was attached to a spacer wire. In use the wire was lowered into the water until it touched the substrate but remained outside the field of focus of the torch which was itself out of the water; this resulted in minimal disturbance to the substrate and to the shrimps. All shrimps seen on the substrate within the beam of the torch were counted. Owing to the fine focus of the torch the edge decisions were of a similar order of problem to those with standard wire quadrats. The quadrat used was of area 0.01 $m^2$. Owing to the nature of the sediment only the peripheral section of the pool could be sampled (the edge plus areas around 'stepping stones') and so no samples were taken at depth; divers reported seeing shrimps throughout the water column of this and other caves. The minimum population of the cave, including only the peripheral area of the pool, was several thousands of individuals.

**Figure 16**: The 'light quadrat' used to obtain estimates of the numbers of *Stygiocaris* in Kubura Well.




The mean population density of *Stygiocaris* in Kubura Well was 138 $m^2$ (95% C.I. 90-198, N = 52). The populations were nearly three times greater ($Fs_{1,50}$ = 86.9, P<0.001) on silt and faecal pellet ooze substrate (mean 314, 95% C.I. 232-418, N = 30) than on the neighbouring rock or coarse sand (mean 11, 95% C.I. 0-27, N = 22; statistics reconverted from log [x+1] transformed data). The population size may have been artificially raised as the cave had been baited on occasion over the previous several months in an attempt to attract the cave eel, *O. candidum*. (K. Cameron, pers. comm.).

### Size class structure and morphometrics

Two measurements of the carapace were made on *Stygiocaris* spp. (Figure 17) to examine their growth pattern. The size class structure of the *Stygiocaris* collections is shown in Figure 18. There is clear bimodality in the overall data (N=348) which is present also in the components parts—*S. stylifera* from both the Cape Range peninsula (N=317) and Barrow Island (N=145), and *S. lancifera* (N=31). The cause of the bimodality is unclear at this stage and further subdivision of the data (final diagram in Figure 19) indicates that polymodality may be present — further analysis is unwarranted due to the origin of the data. Owing to the hint of seasonal breeding in *M. veritas* (see above) it may be relevant that nearly all sampling of *Stygiocaris* was conducted during the winter months so that if seasonal breeding does occurs in *Stygiocaris* the intermediate size classes could have been missed consistently and so imparting an artificial bimodality to the data. Resolution of this observation would require regular and long term monitoring of some populations. The polymodality apparent in the pooled data (lower Figure 19) suggests that bigger samples may also uncover more structure in the local size class distributions.

**Figure 17:** Diagram showing the measurements taken on the carapace of *Stygiocaris* spp.

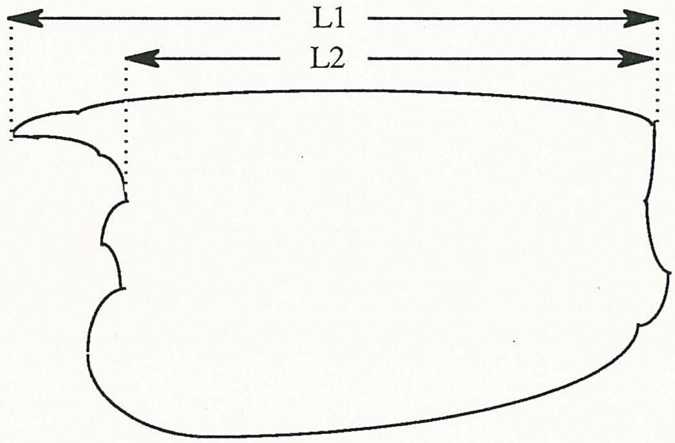
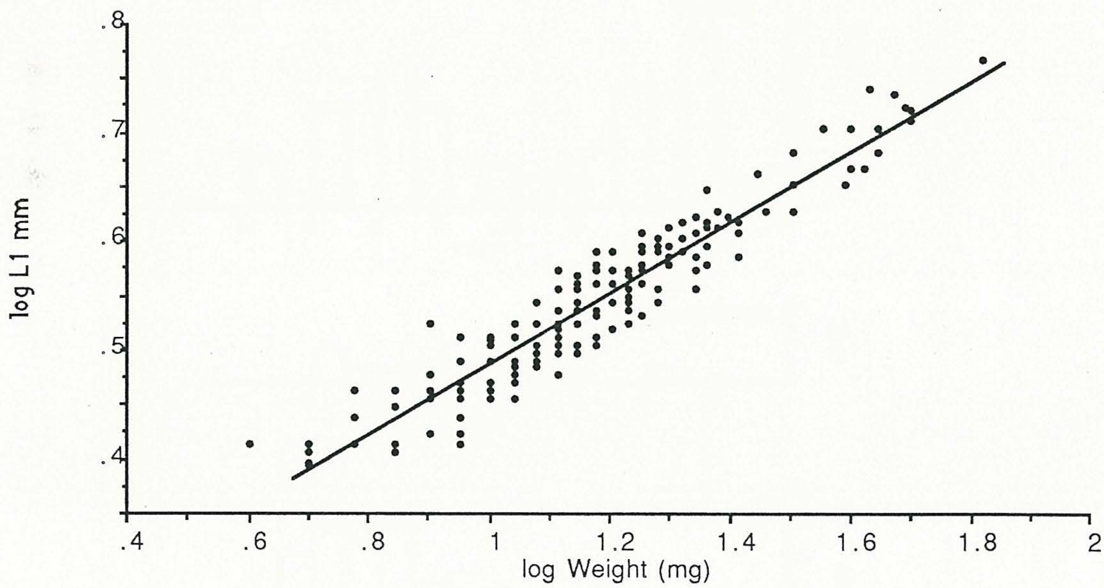



**Figure 18**: Regression of L1 (mm) on weight (mg) in *Stygiocaris* spp.: log L1 = 0.16 + 0.326 log weight (mg: $r^2$ =0.90, $Fs_{1,167}$ = 1428, P<0.001).




## Survivorship

A first approximation of shrimp survivorship was derived from the haul net samples from the Water Authority bore field, this in order to counter the selectivity of samples from other areas which were mainly by hand net or traps. As no growth data are available for the shrimps, the data are purely descriptive of artificial size classes. The numbers in each size class (Figure 20) indicate that *c*. 7% of the young survive until they are half grown and that 2% of the young survive to the largest size class. This apparent survival rate is high but many cave invertebrates have evolved strategies with a high investment in young and thus high survivorship (see Culver 1982: 37 ff.).

**Figure 19:** The size class distribution of *Stygiocaris* spp. from various parts of the Cape Range peninsula and Barrow Island.

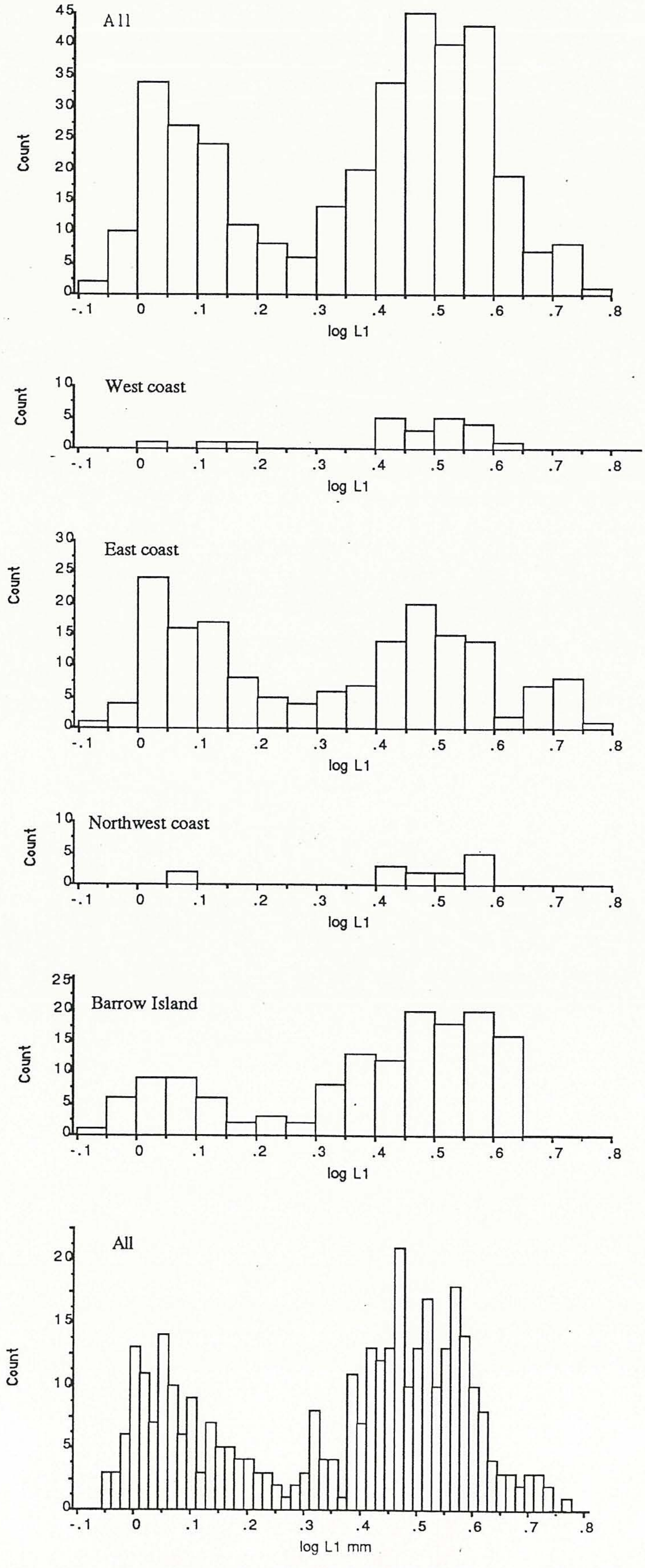
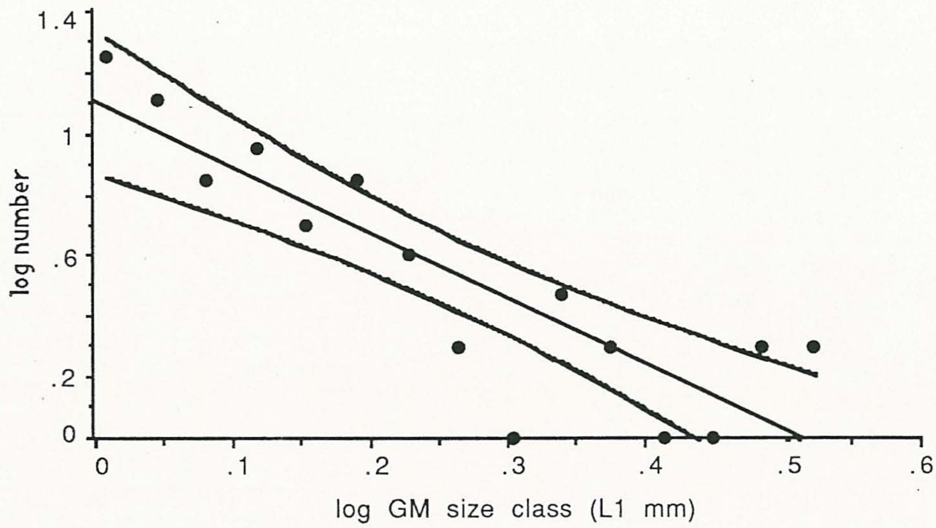


**Figure 20:** Regression of number of *Stygiocaris stylifera* (Y) on size class (geometric mean L1) in the Water Authority Exmouth bore field (log Y = -2.16 log GM size class + 1.11; $r^2 = 0.93$; $Fs_{1,13} = 38.88$, $P<0.001$). The 95% confidence intervals are for the true mean Y.




The eggs of *Stygiocaris stylifera* are cemented to the pleopods of females and, as in other atyids, presumably are carried until they hatch as either zoeal larvae or young adults—there is no obvious advantage for larval stages of inhabitants of restricted subterranean waters. No zoea have been collected despite intensive haul netting so they probably hatch as young adults; the smallest measured had a carapace length of 0.88 mm. The eggs of *S. stylifera* measure *c.* 0.6 x 0.54 mm, not exceptionally large for an atyid (see Bruce 1992: 563) but not dissimilar in estimated volume (0.10 $mm^3$) to that of the smallest eggs of *Caridina denticulata* Roux (0.11 $mm^3$) which has direct development (estimated from data of Shen cited in Bruce 1992).

## The effect of borefield pumping on the stygofauna

Pumping from the borefield has the potential to (a) eliminate fauna by direct mortality, (b) enhance the stygofauna owing to the increase in the movement of organic matter through the area, or (c) open up channels otherwise closed by sediments. These points are addressed in the sections that follow.

### Direct mortality

The surface outlets of five production bores were sampled by passing water from the bleeder valves through a 200 µm net (placed in a bucket to reduce damage to animals). The samples were taken for known periods of time and at known rates of flow and the total water output was read from the meter on the pipeline. From these data the minimum numbers of individuals per unit volume of water was calculated from examination of the whole, or fragments of, animals collected in the net (Table 14). A mean of 0.18

individuals $kL^{-1}$ was collected and this comprised 0.14 $kL^{-1}$ 'shrimps' (*Stygiocaris stylifera* and *Halosbaena tulki*) and 0.05 $k^{-1}$ copepods.

**Table 14:** The number of individual stygofauna collected in a 200 μm nets sampling water from the pumps in the WAWA Exmouth borefield.

| Date | Pumped kL | Sampled kL | Sampled % | [1]Shrimps | Copepods | Shrimps $kL^{-1}$ | Copepods $kL^{-1}$ | Individuals $kL^{-1}$ | WAWA Bore # |
|---|---|---|---|---|---|---|---|---|---|
| 23/6/93 | 113.1 | 28.00 | 25 | 1 | 0 | 0.036 | 0.000 | 0.036 | 10 |
| 23/6/93 | 166.4 | 11.40 | 7 | 1 | 0 | 0.088 | 0.000 | 0.088 | 17 |
| 22/6/93 | 67.0 | 7.40 | 11 | 3 | 0 | 0.405 | 0.000 | 0.405 | 43 |
| 4/8/93 | 105.8 | 27.36 | 26 | 1 | 0 | 0.037 | 0.000 | 0.037 | 18 |
| 3/8/93 | 70.8 | 8.67 | 12 | 1 | 2 | 0.115 | 0.231 | 0.346 | 44 |
| Mean | | | 16 | | | 0.136 | 0.046 | 0.182 | |
| Standard deviation | | | 8.6 | | | 0.154 | 0.103 | 0.179 | |
| N | | | 5 | | | 5 | 5 | 5 | |

The Water Authority borefield has 42 bores with an average pumping rate of 100.3 kL $d^{-1}$ (s= 25.0, n =42) and a potential pumping rate of up to 4211 kL $d^{-1}$ (calculated from WAWA data). The proposed expansion of the borefield, together with private extraction, would extract 1852 ML $a^{-1}$ which would result in an absolute minimum removal rate is *c.* $30 \times 10^5$ $a^{-1}$ 'shrimps' and *c.* $7 \times 10^4$ $a^{-1}$ copepods.

## Pumping *per se*

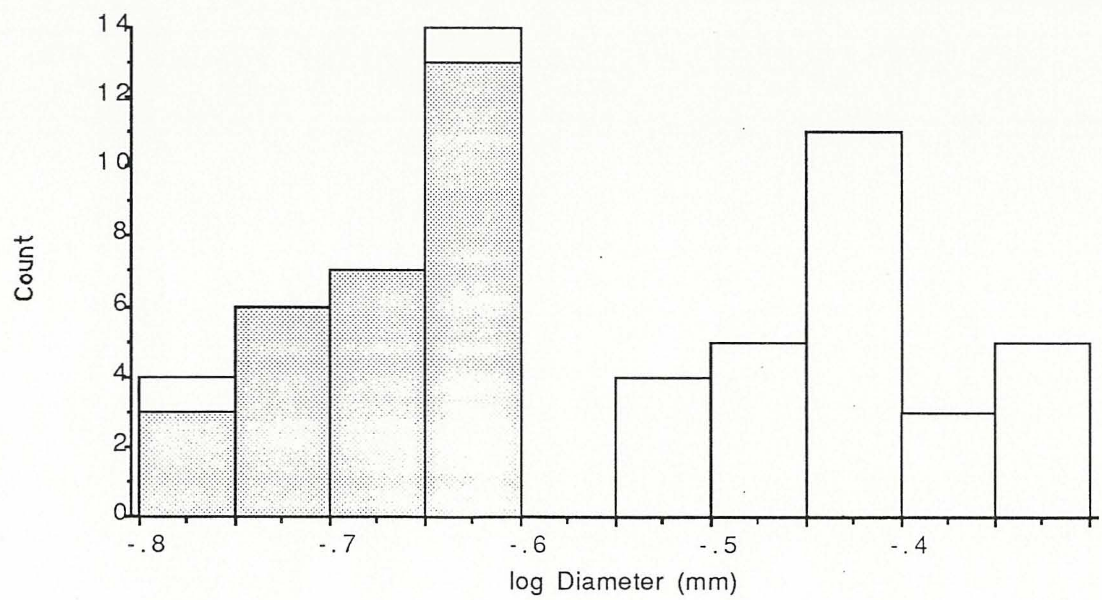
Some production bores at the southern end of the Water Authority borefield have never been used and these provide the basis from which to compare pumped and non-pumped bores of the same type and in similar locations. The species composition was similar in both sets of bores (Table 15) but there was a difference in the proportion of the different taxa between the used and unused bores ($\chi^2_{3c}$ = 80, P<0.001). However, within certain ecological sub-sets the proportions of the different taxa did not differ between treatments — large predators (*H. pholeta*) to large prey (*S. stylifera*) did not differ ($\chi^2_{1c}$ = 0.17, P= 0.56), both taxa inhabiting the water column, nor did those taxa principally inhabiting the faecal pellet ooze (*H. tulki* and copepods ($\chi^2_{1c}$ = 0.02, P= 0.99). The latter difference may be expected as the nature of the faecal pellet ooze varies substantially between different locations (Figure 21) which accumulate from bottom feeders such as the melitid amphipod, *Stygiocaris* and *Halosbaena*.

**Table 15:** The proportion (% across) of taxa taken in bores of various usage histories in the Water Authority borefield. The sample sizes are given in the row and column totals.

| Bore | Status | *Stygiocaris* | *Halosbaena* | *Haptolana* | Amphipod | Copepod | N |
|---|---|---|---|---|---|---|---|
| BOA | Never used | 43 | 29 | 0 | 0 | 29 | 7 |
| BOB | Never used | 0 | 20 | 20 | 0 | 60 | 25 |
| BOC | Never used | 4 | 56 | 0 | 0 | 40 | 25 |
| BOD | Never used | 0 | 0 | 0 | 14 | 86 | 7 |
| BOE | Never used | 10 | 10 | 0 | 0 | 80 | 10 |
| BOF | Never used | 2 | 54 | 0 | 0 | 44 | 41 |
| WAWA#44 | Production | 59 | 16 | 3 | 0 | 22 | 134 |
| WAWA#7 | Production | 0 | 0 | 0 | 0 | 0 | 0 |
| WAWA#10 | Production | 33 | 0 | 0 | 67 | 0 | 3 |
| | N | 86 | 65 | 9 | 3 | 89 | 252 |

The aggregation of fine material into larger faecal pellets by stygofauna is thought to be an important and beneficial process which prevents the clogging of the matrix (Danielopol 1984). The filling of sediments with fine particulate matter is a natural process that clogs the sediments and forces the system towards an equilibrium phase by increasing its entropy (Bloom 1969) — this process occurs especially in areas where there is a high load of fine sediments and little flow. For the sediments to maintain their porosity (hence their capacity to transmit water) the system must be steadily disturbed. Danielopol (1984) argues that the groundwater fauna, by pelletizing the silty sediments, represents a biological disturbance which helps to maintain the circulation of water and organic matter within the groundwater system.

**Figure 21:** Size class frequency distributions of faecal pellets from Kubura Well (light stipples; mean 0.37 ±0.069 mm, N= 30, range 0.16-0.48) and water production bore BOC (shaded; mean 0.21 ±0.026 mm, N= 29, range 0.16-0.25: Anova—Fs $_{1,57}$ = 132.94, P<0.0001.) on 25/5/93; two values in each site overlap in the class 0.250 and 0.275 mm).



Three bores in the Water Authority borefield were shut down and the pumps and outlet pipes removed for maintenance during the study, two specifically to monitor changes following shutdown. WAWA#44 had been shut down for 16 days before the pump was drawn and sampling commenced; no trend in the samples was apparent over the subsequent nine days (Table 16).

**Table 16**: Sampled fauna from production bore WAWA#44 that had been pumping until 16 days prior to the first sampling.

| Date | *Stygiocaris* | *Halosbaena* | *M. veritas* | *Haptolana* | Copepods | Turbellaria | Sum[1] |
|---|---|---|---|---|---|---|---|
| 13/5/93 | 24 | 0 | 1 | 0 | 1 | 0 | 25 |
| 16/5/93 | 16 | 7 | 0 | 1 | 15 | 100+ | 24 |
| 18/5/93 | 10 | 5 | 0 | 0 | 0 | 0 | 15 |
| 21/5/93 | 22 | 2 | 0 | 2 | 1 | 0 | 26 |
| 22/5/93 | 7 | 7 | 0 | 1 | 13 | 0 | 15 |

[1] Sum of first four columns only

WAWA#7 and WAWA#10 were closed down and the pumps drawn immediately in order to examine the effect of not pumping on the stygofauna. Over the next three weeks WAWA#7 yielded no stygofauna whereas WAWA#10 produced one crustacean per day for the first three days (*Stygiocaris* and melitid amphipods) and then no further fauna when sampled up to 19 days later. Clearly the bores differ considerably one from the other and their is inadequate information to suggest a reason for this difference.

At times the bores are managed such that the stygofauna will locally be lost, at least temporarily — bore WAWA#8 was air blasted and acid cleaned on 29/6/93 and the next day the water was pH 5.3 (and contained no stygofauna), 1.6 pH units less than any other groundwater sample recorded on the Cape Range peninsula.

# Habitat of the stygofauna

## Climate

The climate (Vine *et al.* 1988; Humphreys *et al.* 1989) and palaeoclimate (Wyrwoll 1993) of the Cape Range peninsula have recently been covered comprehensively and it is considered here only as required to understand the habitat setting of the stygofauna.

The Cape Range peninsula is hot and semi-arid and the rainfall (Exmouth average annual is 250 mm: 1967-1992) is highly unpredictable between both seasons and years (Figure 22: Humphreys *et al.* 1989); the actual rainfall was from 84-569 mm $a^{-1}$ (Allen 1989). Annual evapo-transpiration exceeds precipitation by an order of magnitude. The effect of this low rainfall is exacerbated at the surface because water rapidly percolates through the karst surface. In consequence, little surface flow occurs except after exceptional rainfall or where the karst landscape is buried beneath superficial deposits, such as found in areas of the coastal plain.

While the effect on the freshwater lens of this variability in rainfall will largely be buffered, in the Exmouth area water extraction (public, private [*c.* 1300 ML $a^{-1}$], and military) is causing a trend for both lower water levels [and hence a much thinner freshwater lens] and increasing salinity (Halpern *et al.* 1992).

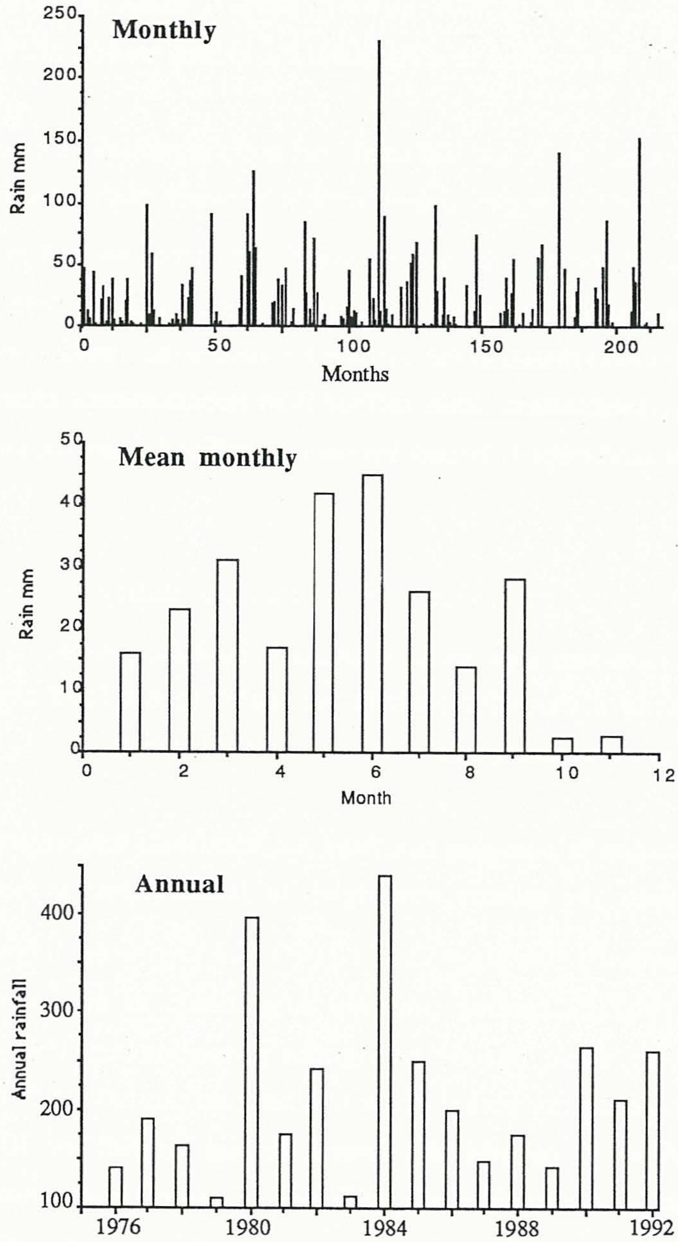
The seasonal variation in pumping rate from the borefields may impose seasonal variation on the water supply; the salinity was higher in January than in August 1991 (1143 v's 1059 mg $L^{-1}$; paired t-test, $t_{38}$= 2.371, P=0.023; working from data in Table 4.2, Halpern *et al.* 1992), a finding possibly attributable to the greater pumping rate in summer. However, these data are ambiguous as the January 1991 sample was taken at the end of a particularly dry period (there had been no rainfall for five month and only 124 mm in the previous 12 months, the lowest annual rainfall for 10 years), whereas the sample in August was taken following 207 mm of rain in the six months from February to July.

### Karst system

This subject has been covered recently (Wyrwoll *et al.* 1993; Allen 1993) and it is considered here only as required to understand the habitat setting of the stygofauna.

The geomorphology of the region is dominated by a series of anticlines expressed at the surface in the Cape, Rough and Giralia Ranges (van de Graaff *et al.* 1980). Geologically the area is dominated by the Cape Range Group, a sequence of marine Tertiary, mainly carbonate, sediments spanning the Late Oligocene to Middle ( ? Late ) Miocene. It

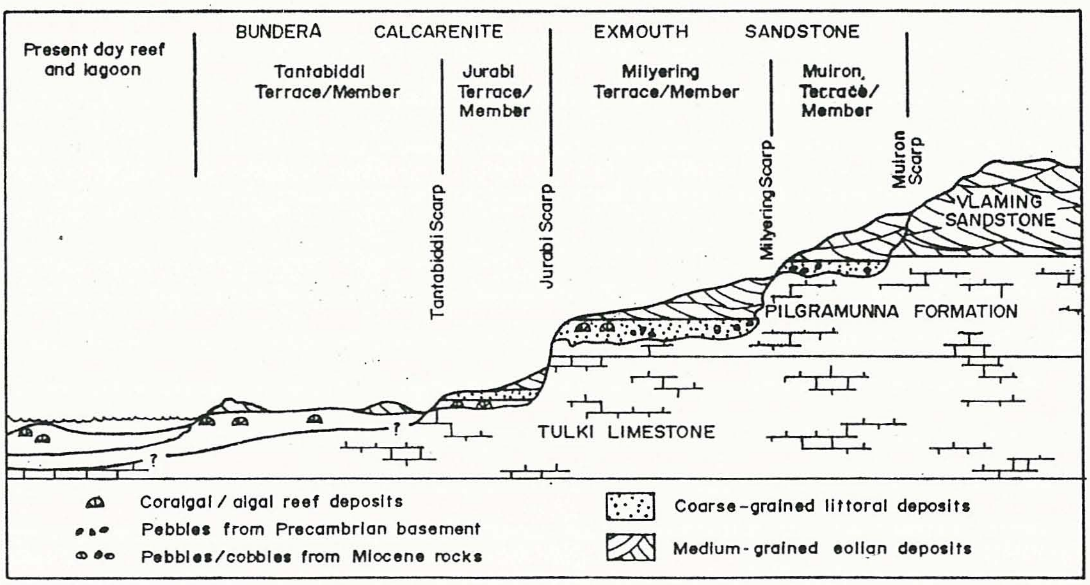
**Figure 22:** Rainfall (mm) at Learmonth on the east coast of the Cape Range peninsula from 1975 to 1993 — monthly, mean monthly and annual.



comprises the Mandu, Tulki and Trealla Limestone and the Pilgramunna Formation, with the latter confined to the western side of the Cape Range anticline (Hocking *et al.* 1987). The presence of the relatively pure and permeable Trealla and Tulki Limestones overlying relatively impermeable Mandu Limestone is a major factor predisposing the area to karst development (Allen 1993).

A series of well-preserved wave-cut erosion terraces occur on the west coast and record the uplift of the anticline (Figure 23: van de Graaff *et al.* 1976). These were long considered to be a Pleistocene phenomenon and hence that the uplift of the area occurred during the Quaternary (*ibid.*). Recent fossil evidence indicates that the Jurabi Terrace is not younger than late Pliocene and hence that the uplift of the range was essentially completed by this time (Wyrwoll *et al.* 1993). This would mean that all Quaternary coastal deposition along the western Cape Range would be located on or seaward of the present Tantabiddi Scarp (van de Graaff *et al.* 1976; Kendrick *et al.* 1991; Wyrwoll *et al.* 1993).

**Figure 23**: Uplifted coral reef complexes fringing the western flank of the Cape Range structure (after van der Graaff *et al.* 1976).



The Jurabi Terrace, although overlain with more recent littoral deposits, is cut directly into the cavernous Tulki Limestone. However, only one cave (C-215) is known to have developed in the Tulki Limestone on the coastal plain. Where the lithography of other coastal caves is known they have developed in Bundera Calcarenite (C-28) or in old coral reef facies (Milyering); there is no information about the other caves.

The Tantabiddi Terrace forms a continuous coastal plain, up to 5 km wide, along the north-eastern and western sides of the Cape Range. The deposit represents a former fringing reef and associated lagoonal environment, analogous in some respects to the modern Ningaloo lagoon and inshore reefs (Wyrwoll *et al.* 1993). The sediments on the coastal plain range from about 5 m in thickness on the western side of the range to 10 m in the east (Allen 1993). Most of the coastal wells and bores are on the Jurabi or Tantabiddi Terraces.

## Coastal karst

The coastal zone in karst areas is defined by the inland limit of marine tidal influences (Guilcher 1988). As found in porous, emerged coral islands (Jacobson and Hill 1980), tidal influence on the Cape Range peninsula extends far inland, at least 1.6 km (C-28).

Limestone dissolution is accelerated by the mixing of fresh and marine water at the halocline (mixture corrosion; Bolgi 1964). Oxidation of organic matter by bacterial processes in the halocline further enhancing limestone dissolution (Mylroie and Balcerzak 1992) and thus the mixing zone is a major horizon of karst cave development (Ford and Williams 1989). Because the freshwater lens floats on the salt water this mixing zone has, during Quaternary glacio-eustatic changes, repeatedly migrated through the limestone by up to >100 m vertically — this changed the focus of limestone dissolution and the sites of coastal karst development, as well as the extent of the vadose zone (Ford and Williams 1989). While the highly porous nature of coral encourages diffuse infiltration and hence inhibits karst development and only when dense crystalline limestones form the coast are the features are more clearly karstic (Ford and Williams 1989). Hence we may expect that karstic development will be minimal in the superficial deposits of the terraces but that when the dense crystalline Tulki Limestone is in contact with the mixing zone that caves should be well developed.

The sea has been at its present level only 8% of the past 240 ka and was at -20 to -50 m for *c.* 46% of this time, and as low as -130 m (Ford and Williams 1989: 498). As many karst landforms have developed during the 10 000 years of the Holocene there would have been plenty of time in the Quaternary to produce karst down to -130 m (*ibid.*). In consequence drowned karst is normal in all carbonate coasts, except those subject to very rapid tectonic uplift, and may be expected on the Cape Range peninsula which has been tectonically stable since the Pliocene (Wyrwoll *et al.* 1993).

Hence, there should be a substantial drowned karst on the coastal plain with submerged speleothems and drowned stream passages. This should be especially so on the west coast where a thin layer of Quaternary deposits overlies often cavernous Tulki Limestone. Only one substantial drowned cave is known (C-28) but there are submerged speleothems in other caves (C-27, C-215).

## Hydrogeology

### Aquifer

The sparse information on the aquifer as a whole indicates that a low (to *c.* 10 m ASL) groundwater mound occurs beneath Cape Range and is separated from the regional water table of the Carnarvon Basin by a groundwater col in the vicinity of Yardie Creek (Allen 1993).

The regional water table occurs within a heterogeneous aquifer formed by the limestones of the Cape Range Group, all of which are in hydraulic continuity. The groundwater in the Mandu Limestone is inferred to occur in joints and some minor permeable interbeds, whereas the groundwater occurs in permeable beds and karst–developed solution openings and cave systems in the Tulki Limestone and Pliocene–Recent sediments (Allen 1993).

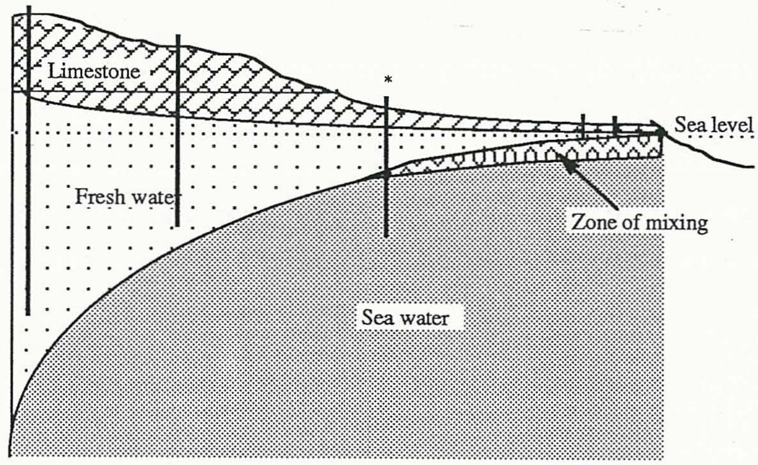
Much of the fresh water from the aquifer must escape through the seabed in the near shore zone. The existence of submarine springs (*vruljas*) in karst terrains is well recognised and have been reported, but not confirmed, from both coasts of the Cape Range peninsula. This implies confined pipe flow at depth and their location must reflect the position of springs during lower sea levels.

A synopsis of the groundwater, as it was then understood to effect the stygofauna, was given by Humphreys and Adams (1991). The only area where any detail can be added to the hydrogeology of the peninsula is in the Exmouth area owing to the concentration there of bores associated with the Exmouth Water Supply which is run by the Western Australian Water Authority (WAWA) — these include the deeper production bores and a number of deep water supply exploration bores up to 7 km inland. This information is incorporated in the discussion that follows.

## Background

The general hydrogeological model for oceanic islands has been applied to the ground water of Cape Range peninsula (Allen 1993). In this model, following the Ghyben-Herzberg principle, a fresh water lens overlies salt water. In essence, a wedge of salt water pushes under the fresh water contained in the limestone (Figure 24). The greater the transmissivity the limestone and the more arid the area (or the greater the withdrawal of water for human use) the greater the distance inland the wedge should penetrate. Indeed, in the Exmouth area the fresh water-salt water transition is, at *c*. 5 km (Martin 1990), exceptionally far inland (*cf.* 0.5 km on the coral island of Niue: Jacobson and Hill 1980).

**Figure 24:** Stylised section through coastal plain and foothills of the Cape Range peninsula showing the saltwater wedge pushing up the fresh water lens and the zone of mixing narrowing inland. The short bores (thick vertical lines) represent production bores and the long bores the exploration bores one of which (*) penetrated the salt water interface.




The thin layer of fresh groundwater on the coastal plain overlies seawater but there is a broad zone of diffusion 10-20 m thick which partly results from tidal oscillations (O'Driscoll 1963; Forth 1972, 1973; Martin 1990; this zone of diffusion has been considered to be 10-20 m thick [*ibid.*], but it is clearly much thicker than that even 5 km from the sea [Figure 28]). Consequently, the thin layer of fresh groundwater may not be detected if the well has been operating or if the sample is taken too far below the water table.

In caves as far as from 1.5-1.6 km from the coast (C-28, C-215, C-452) mass flow of water under tidal influence is seen. It is not known how far inland the tidal influence reaches but, as the one cave that is known to reach sea level in the cavernous Tulki Limestone (C-215 on the west coast) is tidal, open conduits may be expected to reach further inland. In the Exmouth area the inland limit to the saltwater interface appears to be controlled by the presence below the water table of solution cavities and channels (Martin 990) and in the WAWA borefield these highly transmissive karstic features allow the groundwater levels to be influenced by tides up to 3.5 km from the coast (Forth 1973).

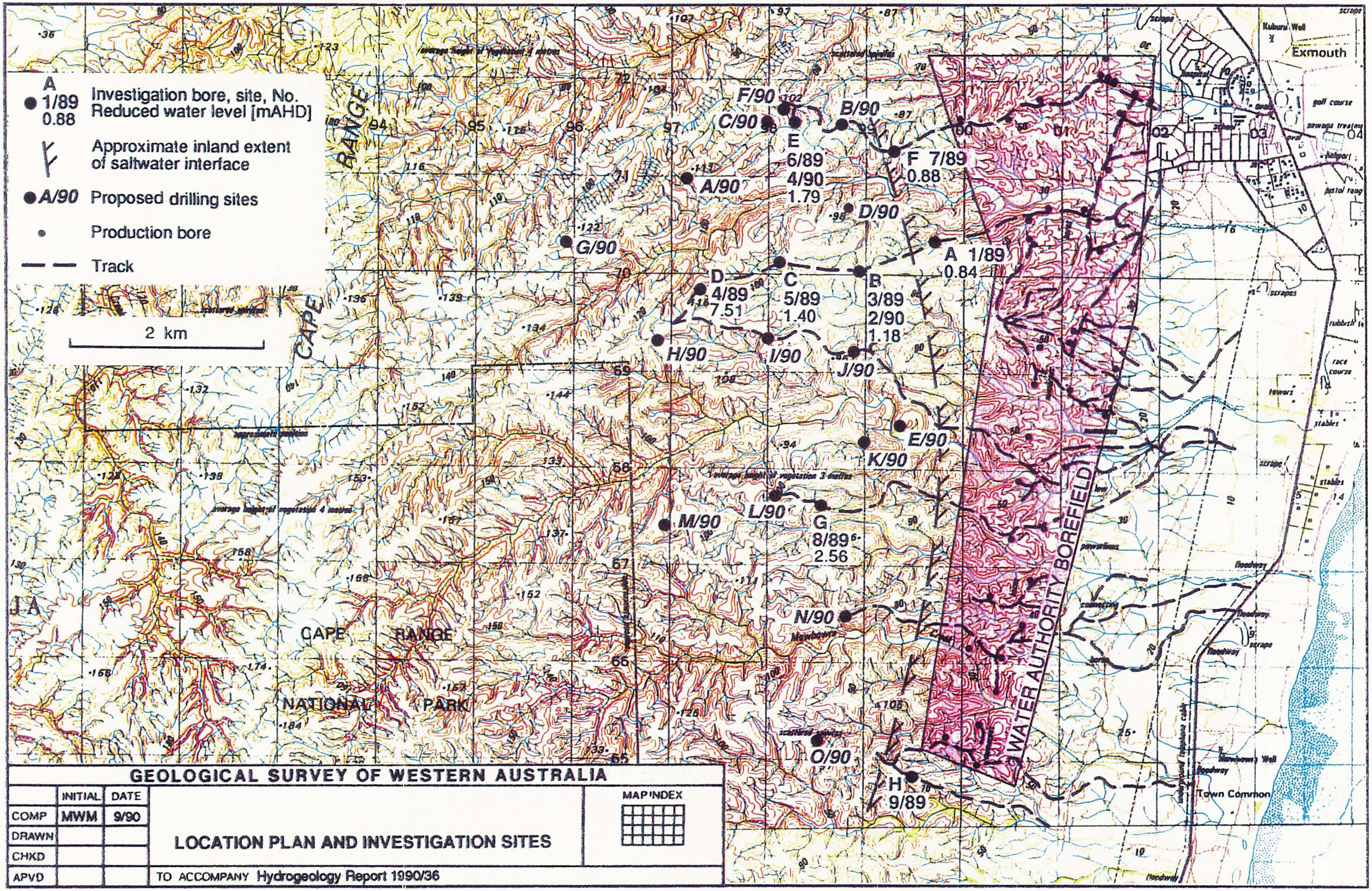
Further inland on the east coast, at least in the vicinity of the Exmouth bore field, the lateral hydraulic transmissivity varies widely (10-1000 m $d^{-1}$: Forth 1973), indicative, at the upper level, of the cavernous nature of the limestone. Inland from this borefield the transmissivity decreases with the hydraulic gradient increasing from the borefield ($1.7 \times 10^{-4}$; Forth 1972), westwards through $3.2 \times 10^{-4}$, and to $6.8 \times 10^{-3}$ where the marly part of the Mandu Limestone occurs (Martin 1990). In neither of the two latter areas has stygofauna been recovered, although *Stygiocaris* sp. were taken from a water exploration bore (N1) of the same series, but just east of the inferred boundary of the salt water interface (Figure 25). To the east of this boundary and almost to the coast, an area that encompasses the active borefield, a wide range of stygofauna was taken (Table 17).

**Table 17:** Stygofauna recovered from production bores in the Exmouth bore field run by the Western Australian Water Authority.

| Taxon | WAWA bore number |
|---|---|
| Turbellaria | 44 |
| Copepoda | 44, 46 |
| Ostracoda | 44, 47 |
| melitid amphipod | 10, 17, 46, 47 |
| *Haptolana pholeta* | 18, 44, 47 |
| *Halosbaena tulki* | 44, 46, 47 |
| *Stygiocaris* sp. | 10, 43, 44, 47, N1 |
| *Milyeringa veritas* | 44 |

To the south of the Exmouth bore field there are a number of bores that were drilled for production but never used — these contain a wide range of stygofauna (Table 18). Hence, the difference between the afaunate western area (exploration bores) and the faunate eastern area (production bores), is not simply a consequence of one set having been regularly pumped while the other has been only test pumped. Hence, it appears that a substrate transmissivity less than about 2720 $m^2$ $d^{-1}$ is unsuitable for stygofauna. This relationship is depicted in Figure 26 on which the distribution of the stygofauna is given.

**Figure 25** (overleaf): The estimated location of the salt-fresh water transition (saltwater interface) which lies just to the west of the Exmouth borefield. From Martin (1990) with permission of the Director of the Geological Survey of Western Australia.



A 1/89 0.88 Investigation bore, site, No. Reduced water level [mAHD]
Approximate inland extent of saltwater interface
A/90 Proposed drilling sites
Production bore
Track
2 km
CAPE RANGE
CAPE RANGE NATIONAL PARK
WATER AUTHORITY BOREFIELD
Exmouth
Town Common
F/90
C/90
B/90
E 6/89 4/90 1.79
F 7/89 0.88
A/90
D/90
G/90
A 1/89 0.84
D 4/89 7.51
C 5/89 1.40
B 3/89 2/90 1.18
H/90
I/90
J/90
E/90
K/90
L/90
G 8/89 2.56
M/90
N/90
O/90
H 9/89
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
INITIAL DATE
COMP MWM 9/90
DRAWN
CHKD
APVD
LOCATION PLAN AND INVESTIGATION SITES
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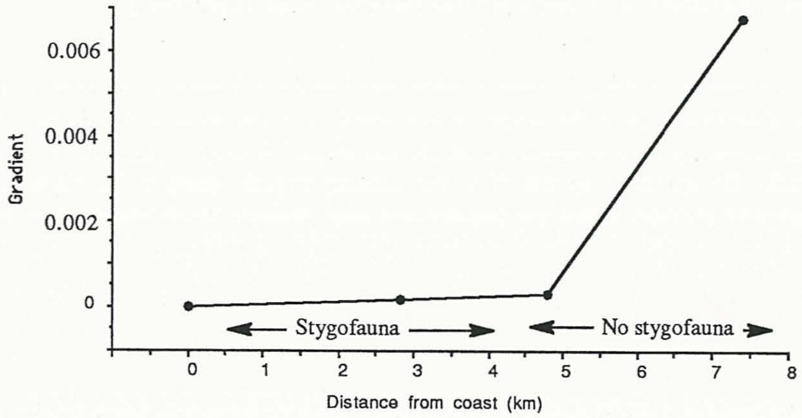
**Table 18:** Stygofauna recovered from never used production bores in the Exmouth bore field run by the Western Australian Water Authority.

| Taxon | Bore (my code, Appendix 2) |
|---|---|
| *Stygiocaris* sp., | BOA, BOC, BOE, BOF |
| Copepoda | BOA, BOB, BOC, BOD, BOE, BOF |
| *Halosbaena tulki* | BOA, BOB, BOC, BOE, BOF |
| *Haptolana pholeta* | BOB |
| Melitid amphipod | BOD |

**Figure 26:** Change in gradient of the water table on the east coast of the Cape Range peninsula, near Exmouth, and the distribution of the stygofauna.




## A model for population interaction

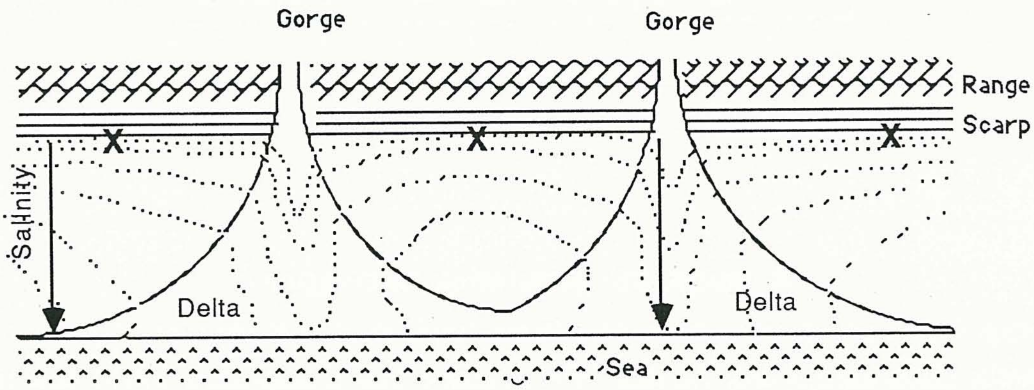
The stygofaunal populations occur as a linear band on or near the coastal plain of the peninsula (Humphreys and Adams 1991, Adams and Humphreys 1993) and these populations are genetically fragmented (*ibid.*). Hence, the potential zones of contact between these fragmented populations which will allow maintenance of gene flow between adjacent areas are important areas for the conservation of the fauna. Below I consider the nature of the coastal plain in this context.

The stygofauna was previously thought to be restricted to the near coastal part of the Cape Range peninsula and below the Jurabi scarp, but abutting the Tulki Limestone at C-215 (Humphreys and Adams 1991: Fig. 1). As such the model for the aquatic environment was developed for a thin layer of fresh to brackish water overlying sea water (*ibid.*).

In the model (Figure 27) there is a general gradient of increasing salinity towards the coast on which is superimposed the mass transfer of fresh ground water draining from the gorges. Hence, on the gorge (drainage) lines fresh water pushes towards the coast, whereas between the gorges the fresh groundwater is pushed closer to the foothills by the salt water wedge). The successful pastoral wells and bores are on these drainage lines, while between them water is absent or saline (Sofoulis 1951). This could result in interfluvial salinity barriers to the dispersal of the coastal fauna, indeed all the known faunal sites prior to 1993 were on these drainage lines.

The model suggests that the areas likely to be critical for conservation (areas where the coastal plain populations interact) are the interfluvial areas in the foothills. The significance of this model is that is directed attention away from the coast to areas where stygofauna was then unknown, a move that has proved most rewarding.

**Figure 27:** Schematic diagram of the scarp and coastal plain of the peninsula. The general form of the isohalines (.........) was determined from the evidence discussed in Humphreys and Adams (1991). The wells, hence the coastal fauna, are known mainly from the fan shaped drainage areas below the gorges in Cape Range. **X** marks the narrow corridor of lower salinity hypothesised to be close to or in the foothills of Cape Range and through which the populations may connect (from Humphreys and Adams 1991: Fig. 8).




While this model then was contraindicated by the distributional data (Humphreys and Adams 1991), the present study has shown that the stygofauna is present in the foothills and the coastal plain in both fluvial and interfluvial areas. For example most of the Exmouth town site bores with fauna are in interfluvial areas of the coastal plain and foothills. A few of the Exmouth bore field bores with stygofauna are interfluvial or on minor drainage lines (most of the bores sampled are on drainage lines).

There are constraints on the gene flow of at least some elements of the stygofauna (Humphreys and Adams 1991; Adams and Humphreys 1993) resulting in regional differences between populations. The nature of the differences suggest that the populations do not occur beneath Cape Range but rather extend linearly around the peninsula on the coastal plain (Humphreys and Adams 1991). Hence, the model indicates that the critical areas for the fauna to remain in continuity along the coast would be between the gorges in the foothills of the range; the loss of these contact zones would result in further genetic fragmentation of the stygofauna (Humphreys and Adams 1991).

In this context it is important to appreciate that the stygofauna would have extended widely across the extensive North West Shelf during times of lower sea level and hence much of the last 240 ka (Table 19). That this occurred is supported by the presence of several members of the stygofauna on Barrow Island which lies 160 km to the north-east on the North West Shelf (namely *Stygiocaris stylifera*, *Haptolana pholeta* and *Halosbaena tulki*). Hence, the stygofauna is currently almost as severely constrained in area as at any time during the last 240 ka. This means that the current genetic fragmentation of the populations is being exacerbated by small geographical range and low population size. The stygofauna must be considered relatively vulnerable from a palaeobiogeographic perspective alone.

**Table 19**: The proportion (%) of time sea level (m) was at or above a given level (relative to present sea level) over the last 240 ka (extracted from Figure 10.16: Ford and Williams 1989).

| Sea level | % time |
|---|---|
| 0 | 0 |
| -20 | 16 |
| -40 | 48 |
| -60 | 72 |
| -80 | 82 |
| -100 | 90 |
| -120 | 96 |
| -140 | 100 |

## Present condition

Owing to the bore sampling programme the stygofauna is now known to occur in the interfluvial areas of both the coastal plain and the eastern foothills of Cape Range. While there are no comparable sampling points on the west coast there seems little reason to doubt the existence there of a similar pattern of distribution. Although the freshwater mound is considered to be far removed from the west coast (Allen 1993), there is no hard evidence to support this.

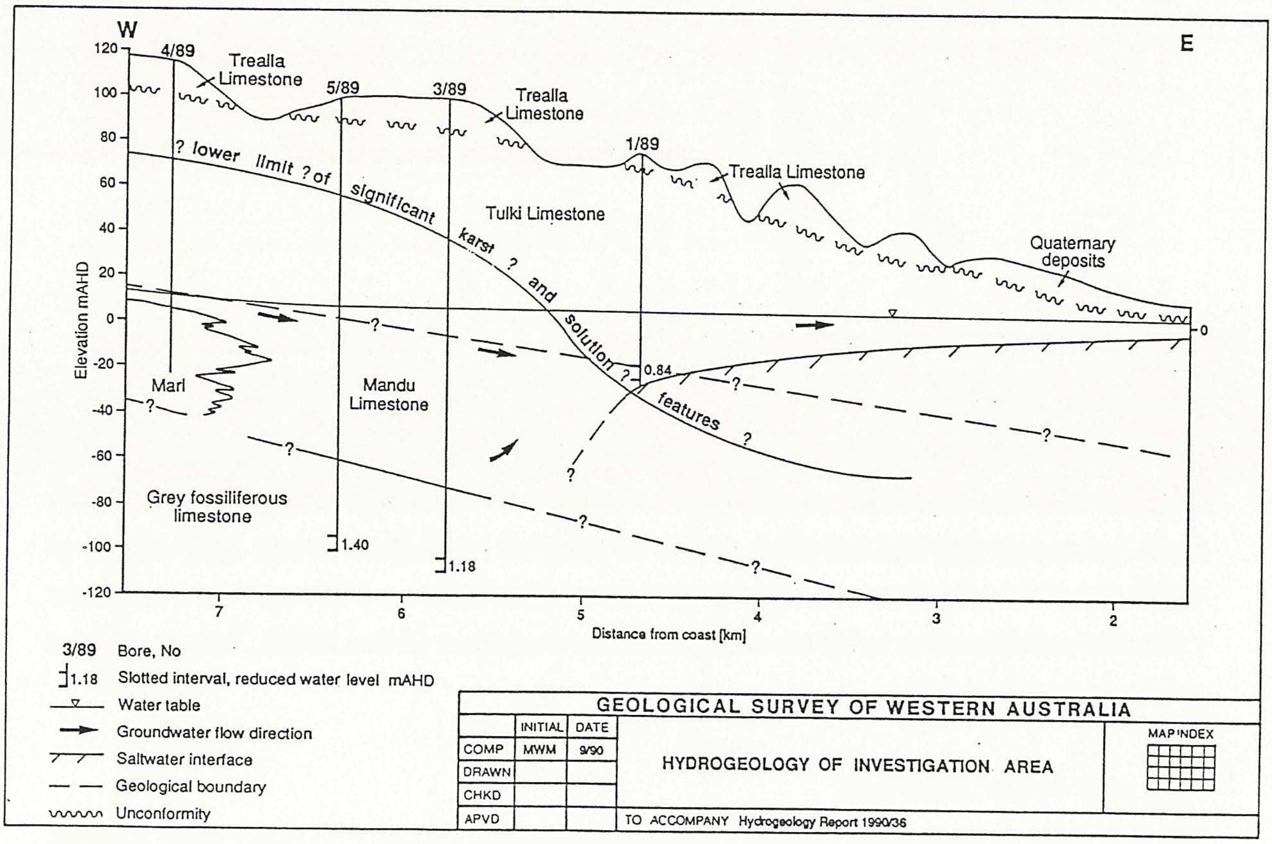
## The salt water interface

On both sides of the Atlantic Ocean thermosbaenaceans co-occur with many other relictual crustacea at the level of genera, families, orders and classes (Shram 1986; Newman

1991). The finding of Mystacocarida (Newman 1991), as well as Thermosbaenacea (Poore and Humphreys 1992) in Western Australia is indicative of poor sampling of stygofauna in Australia and suggested that further work may reveal some of these other relictual taxa (Poore and Humphreys 1992). The discovery of cirolanid isopods on Barrow Island was the first such find (Bruce and Humphreys 1993) to which this study adds the ostracod genus *Danielopolina* as well as the Class Remipedia.

Some of this relictual fauna is found only below the halocline in anchialine water and considerable efforts were made to sample this habitat. Several of the exploration wells to the west of the Exmouth bore field penetrated the saltwater interface (Figure 24 ) but they have been backfilled with gravel to the salt water interface and then sealed with cement. The drilling of such exploration wells opens unique and short-lived opportunities to sample this habitat to gain some understanding of the nature and distribution of the fauna. Such temporary holes have been effectively sampled on Barrow Island.

**Figure 28:** Hydrogeological section through the WAWA borefield at Exmouth and the exploration area to the west (from Martin 1990 with permission of the Director of the Geological Survey of Western Australia).



To sample the habitat where remipedes should be found cave diving was employed in an attempt to reach and sample the halocline in anchialine caves. None of the caves dived (C-23, C-27, C-28, C-105, C-215, C-452, C-495) could be penetrated to any depth or distance except for C-28 in which the divers (A. A. Poole and D. Warren) went through the halocline to a depth of 28 m.

As predicted (Poore and Humphreys 1992; Humphreys 1993b, in press b) this cave contained additional relict fauna of tethyan affinities and previously unknown in the southern hemisphere. These are Remipedia (?genus but not *Speleonectes* (J. Yager and W.F. Humphreys, unpublished) which is the only genus known outside the Bahamas) and the thaumatocypridid ostracod *Danielopolina* sp.

These findings, together with the thermosbaenacean *Halosbaena*, make it likely that additional relict taxa, elsewhere associated with this fauna, will be found on the Cape Range peninsula. These include cephalocarids, and spelaeogriphaceans (Newman 1991), as well as cyclopoid copepods, mysids (*Stygiomysis*), isopods (microparasellids and stenasellines) and amphipods (*Hadzia* and *Psammogammarus* are found in the Indo-Pacific part of Tethys: Schram 1986).

**Groundwater in Cape Range proper**

Standing water occurs in only four of the several hundred caves known in Cape Range and occurs at an altitude of *c.* 190 m, well above the hypothesised height of the fresh water lens beneath Cape Range (Humphreys 1993b). Electrophoretic data from the Cape Range amphipods indicate that this was once a continuous water mass from the Pliocene until it became fragmented in the early Pleistocene (Humphreys 1993b). The longevity of the water body, as indicated by the contained fauna, suggests that, contrary to other opinion (Allen 1993), there is a permanent perched water table in Cape Range.

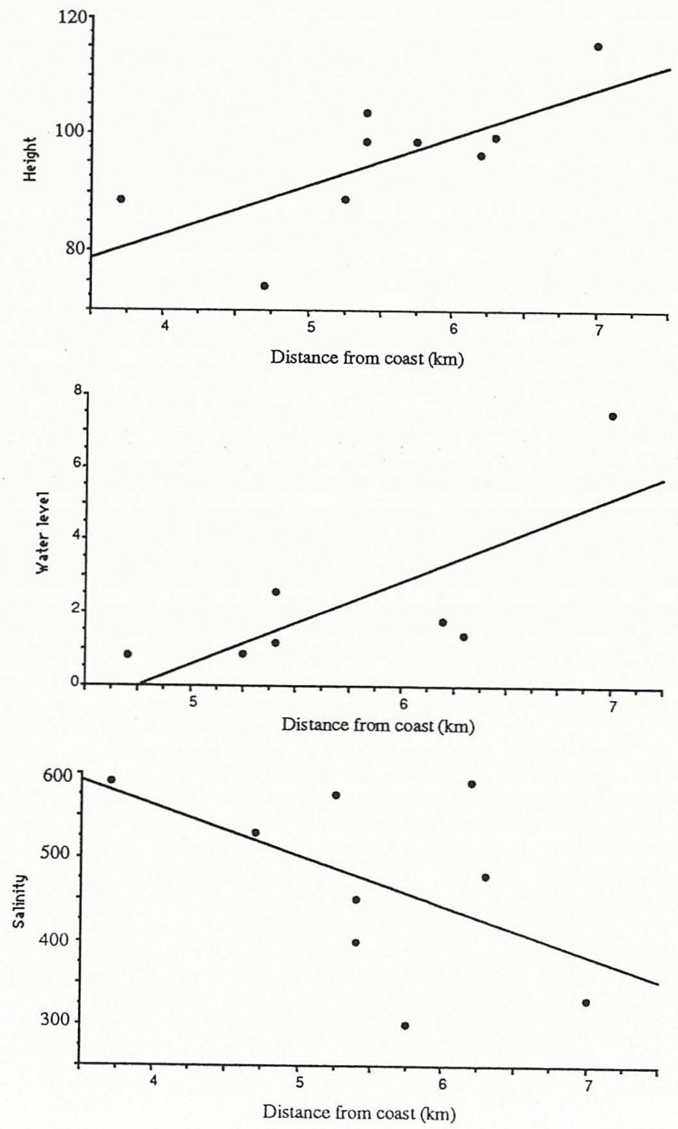
A perched water table will not be influenced by overuse or contamination of the near coastal aquifer or the fresh water lens beneath Cape Range. However, it is especially vulnerable to quarrying in the range and could be drained regionally if a major conduit was intersected by quarrying activity. Such draining could eliminate stygofauna in Cape Range and would compromise the environment required by the unique relict rainforest troglobitic fauna in the caves as this is dependent on water (both soil water and atmospheric humidity: Humphreys 1990, 1991b, 1991c).

**The Exmouth area**

The land mass buffering the ground water from external influences increases with increasing distance from the coast such that at the western most occurrence of the stygofauna the water table is more than 100 m below the ground surface in both the Exmouth area (Figure 29) and to the south of Cape Range in Billy Wells.

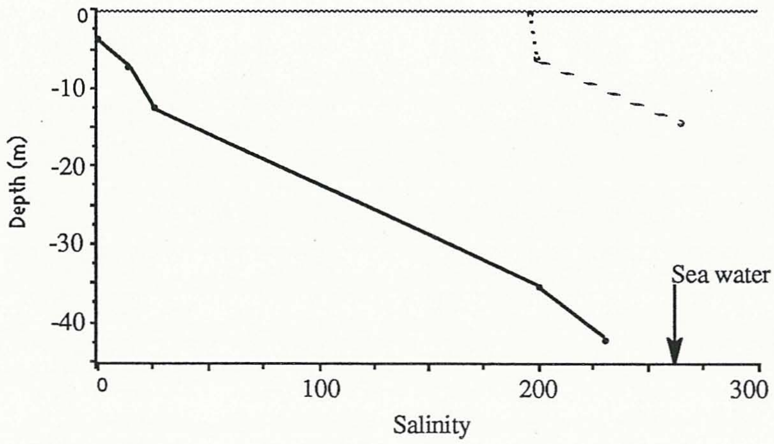
The altitude of the water surface increases with distance from the coast such that it reaches an altitude of >7 m (Figure 29). Applying the Ghyben-Herzberg principle and assuming hydrostatic equilibrium this implies a freshwater lens exceeding 250 m in depth. This change is reflected by the apparent lower mixing of sea water with the fresh water with distance from the sea (Figure 29).

**Figure 29:** Changes through the Exmouth bore field with distance from the coast — upper, altitude (m) of the bore openings (fauna is found up to 100 m below the ground surface); middle, altitude (m AHD) of the surface of the water table; lower, salinity (mg $L^{-1}$) of the water table (drawn from data in Martin 1990).



Although groundwater on the west coast is generally more saline (Humphreys and Adams 1991; Allan 1993) and the halocline is closer to sea level, the sparse data available indicate that the gradient of increased salinity with depth is similar in both areas (Figure 30).

**Figure 30:** The approximate change in salinity (mg $L^{-1}$ x $10^{-2}$) with depth in cave C-28 (·········) on the coastal plain 1.6 km from the east coast (my data) and in exploration bore 12/87 (____) in the foothills of Cape Range, 3.0 km from the east coast (data from WAWA).




## Consequences of the hydrogeology for the fauna

Despite repeated trapping and haul netting through considerable depths of water no stygofauna has been found to the west of the fresh water/salt water transition in the Exmouth area. This absence was at first thought to be a consequence of the treatment of the exploration bores [if saline water was encountered the bore was sealed with a cement plug before inserting casings - the slotted section of the casings was gravel packed and the remaining annulus backfilled with drill cuttings (Martin 1990)]. However, a similar bore (N1 [7/89]) to the east of the transition zone contains stygofauna.

Interpretation of this area is complicated by the apparent near coincidence of several interrelated factors in the vicinity of the transition zone.

1. The stygofauna is not present to the west of the transition zone.
2. The transmissivity of the limestone decreases abruptly.
3. The altitude of the water table increases sharply and hence the thickness of the freshwater lens.
4. The lower limit of karst development in the Tulki Limestone rises above the water table (Figure 28).
5. The base of the cavernous Tulki Limestone rises above sea level (Figure 28) so that the water table is in the marly Mandu Limestone.

One hypothesis consistent with this evidence is that the fauna is absent west of the transition zone owing to the lack voids in the limestone of sufficient dimension to support the fauna and that those voids present are clogged owing to the marly nature of the limestone. This would be consistent with the situation in Cape Range itself — there, water tables in karstic Tulki Limestone perch on the Mandu Limestone and where gorges cut through the Tulki Limestone and into the Mandu Limestone the amphipods inhabiting the water exhibit major genetic discontinuity (Humphreys and Adams 1991; Adams and Humphreys 1993).

However, close examination of the occurrence of the various species of stygofauna in relation to the water quality suggests a different interpretation. A summary of the range of salinity in the ground water on the Cape Range peninsula, in the bores west of the fresh water/salt water transition and that occupied by the stygofauna is given in Table 19. The mean salinity of water from which any taxon of stygofauna was collected from the coastal plain was mostly an order of magnitude greater than that found in the bores penetrating the fresh water lens (Bores 5/89 and 3/89; Figure 28). Indeed, with one exception, even the ranges do not overlap, the exception being a *Stygiocaris* collected in an unused bore and for which there is no evidence it was collected in the thin freshwater layer.

**Table 19:** The salinity (mg $L^{-1}$; derived from conductivity) of coastal groundwater from which the various taxa of stygofauna were collected, the water on the Cape Range peninsula generally (this study) and from the fresh water lens beneath Cape Range (data from WAWA). [1]One sample (C-23) excluded as no *M. veritas* were seen in 1993 after major inflow of silt laden water).

| Parameter | Mean | Min. | Max. | N |
|---|---|---|---|---|
| Cape Range peninsula | 4642 | 279 | 25470 | 62 |
| Ostracoda | 6710 | 684 | 17910 | 7 |
| Copepoda | 4091 | 511 | 19530 | 48 |
| *Haptolana pholeta* | 1652 | 630 | 2952 | 6 |
| *Halosbaena tulki* | 2358 | 511 | 6840 | 19 |
| *Stygiocaris* spp. | 2553 | 349 | 16290 | 25 |
| *Ophisternon candidum* | 3179 | 711 | 6840 | 8 |
| *Milyeringa veritas*[1] | 7438 | 711 | 25470 | 19 |
| Melitid sp. 1 from coastal plain | 3218 | 630 | 9270 | 19 |
| Melitid sp. 2 from Cape Range | 456 | 441 | 484 | 3 |
| Melitids off Cape Range peninsula | 1650 | 630 | 3681 | 6 |
| No melitids, off Cape Range peninsula | 3760 | 166 | 13212 | 29 |
| Bore 5/89: 16-103 m | 350 | 120 | 470 | 5 |
| Bore 3/89: 9-112 m | 243 | 210 | 280 | 6 |

*Stygiocaris* have not been observed directly swimming in water below 1224 mg $L^{-1}$ (C-215) or otherwise associated with water below 711 mg $L^{-1}$. [The depth at which samples were taken in bores is usually ambiguous — the mean depth of the halocline in those bores and wells that were profiled was 0.26 m (s= 0.08, n= 11; range 0.18-0.40 m) and below which the salinity increased by an average factor of 1.32 (s= 0.38). The water sample of low salinity containing the *Stygiocaris* was a superficial sample taken before the halocline profiles were examined.]

The melitid amphipods are a possible exception to this general statement because the Cape Range species occurs in much fresher water than that of the coastal plain. As it is the only taxon of the peninsula stygofauna occurring in areas adjacent to the Cape Range peninsula (both south and north), the taxon is treated separately in Table 19. Again it was not collected from water within the range of salinities found in the freshwater lens beneath Cape Range although such waters were present in the area.

In conclusion, the evidence would suggest that the fauna is not one of 'a freshwater oasis beneath an arid land surface' (Knott 1993) but of brackish-saltwater. The freshwater lens beneath Cape Range appears to be afaunate, not because it is inaccessible to the stygofauna (insufficient voids) but because the stygofauna cannot utilise fresh water. This conclusion, like that of the distributional model (above) is counterintuitive and is at variance with most previous work.

For example Mees (1962) considered that the fauna evolved during the Tertiary or Pleistocene in caverns in what are now the hills and colonised the coastal plain over the last 5000 years when fresh water entered the coastal following a fall in sea level.

However, Humphreys (in press b) recognised the Cape Range stygofauna to have its origins in the Tethys Sea, which argument was extended by Knott (1993). The fauna could have originated in Greater Tethys, undergone vicariance by seafloor spreading and subsequently colonised the Cape Range carbonates from geologically older areas (e.g. Pilbara Craton) across the North West Shelf at times of lower sea level (Humphreys and Adams 1991; Poore and Humphreys 1992; explicitly in Humphreys 1993b).

*In situ* evolution of the stygofauna has been variously rejected and advocated. It was discounted — on the coast because the high degree of troglomorphy found was not consistent with the young age of the platforms (Humphreys and Adams 1991), a youthfulness now challenged (Wyrwoll *et al.* 1993), and on Cape Range because of a lack of taxa common to the two areas (Humphreys and Adams 1991). However, the palaeogeographical evidence of the Pilbara Craton to the northeast of the Cape Range peninsula indicates that environments suitable for colonisation by stygofauna to have been widespread in northwestern Australia, ever since the Mesozoic (see Humphreys 1993b, in press b). It was advocated as colonisation by stygofauna, from the extensive marine embayments (Humphreys 1993b, in press b), that could have occurred *in situ* and contemporaneous with the formation of the limestone (Knott 1993) by adaptive shift (Howarth 1973, 1981). However, for this hypothesis to be supported then either one species only colonised what are now the higher altitudes of Cape Range (the Cape Range melitid amphipod; unlikely given the occurrence of elements of the stygofauna on Barrow Island), or the remainder have become extinct.

Knott (1993) envisaged early *in situ* invasion by melitid amphipods and thermosbaenaceans of stygal habitats on Cape Range peninsula (when originally described it was unclear whether *Halosbaena tulki* was rightly a member of the Cape Range fauna or part of the stygofauna of the coastal plain [Poore and Humphreys 1992] but subsequent work has shown it to belong to the latter [Humphreys in press b, unpublished]) with a subsequent invasion by the two species of fish and atyid shrimps probably from fresh waters of the early Ashburton river system, then adjacent to North West Cape. This hypothesis is not supported (this study) as widespread sampling has produced no evidence for either fish or atyids in the Ashburton River catchment, whereas the eropisid amphipods (but not thermosbaenaceans) are widespread through the catchment and elsewhere.

As the competing hypotheses concerning the origin of the stygofauna of the Cape Range peninsula, and of the relictual tethyan stygofauna generally, have very varied time frames (Triassic and Jurassic [Cals and Boutin 1985], Mesozoic [Wilkens *et al.* 1986] or Miocene-Pliocene or earlier [Bowman and Iliffe 1986] with respective times of 225-160, 136-65 and 30-0.01 Ma) and are well replicated geographically and systematically, then they are good subjects for biogeographical interpretation using both cladistic and DNA techniques.

## Summary

Cavernous karst to a depth of *c.* 100 m covers much of the Cape Range peninsula from the top of range to below sea level. There are isolated perched water tables in Cape Range at an altitude of *c.* 190 m that contain separate populations of an amphipod congeneric with one in the coastal water table. A fresh water lens underlies Cape Range reaching *c.* 10 m ASL and overlying salt water; these are separated by a zone of brackish water which is progressively thinner away from the coast. The fresh water lens is afaunate but the

brackish and salt waters contain a relict tethyan sea community of great antiquity. Some elements of the community are found on Barrow Island but is otherwise confined to Cape Range.

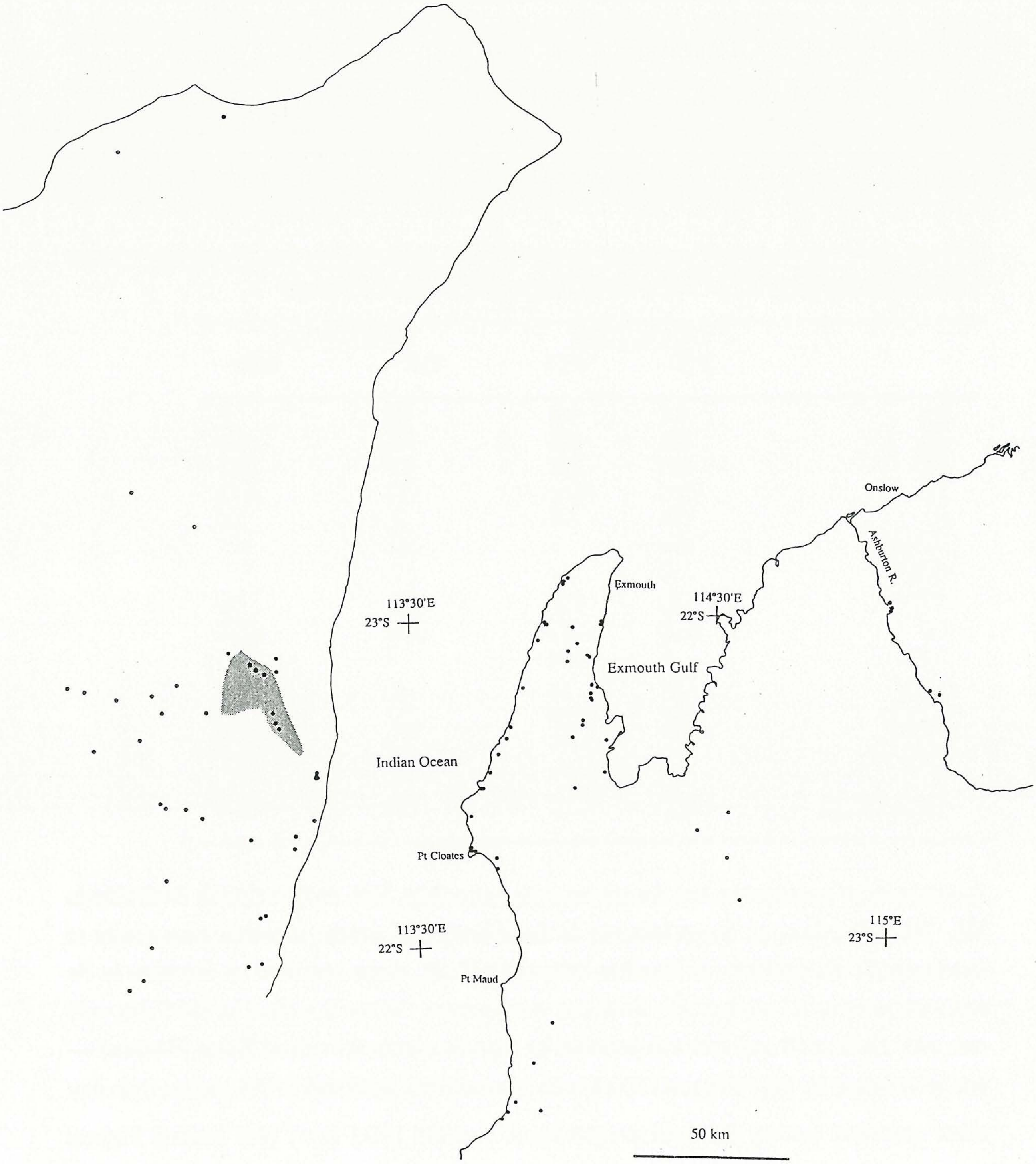
# Chapter 6

## Subterranean waters: characteristics and fauna

## Subterranean waters: physico-chemical characteristics

Ninety-seven water samples were taken from the 94 localities shown in Figure 31 and in Appendix B. The chemical constituents were analysed using standard methods and the site specific data presented in Appendix C.

**Figure 31:** Sites on the Cape Range peninsula and its hinterland from which water samples were taken. The sites are detailed in Appendix B.



## Water quality

### Historical changes

Water from Milyering Well and Tantabiddi Well (the type localities of *Milyeringa veritas* and *Ophisternon candidum* respectively) was analysed comprehensively in 1959 (Mees 1962). The same wells were included in the sampling in 1993 and they are compared in Table 20 where comparable data are available.

In Milyering Well only five parameters varied by more than 10% between the analyses 34 years apart (Table 20) — K and NO3 had increased 23 and 32% respectively while PO4 was reduced to 15%. The major changes are probably interrelated, there having been an increase in Fe (>250%, presumably from anthropogenic sources) and a reduction in Al (to 0.7%); this has probably resulted from the increase in Fe causing the precipitation of alums.

**Table 20:** Comparison of the chemical constituents in the water of Milyering Well and Tantabiddi Well in 1959 (Mees 1962) and 1996. *values for 1993 adjusted from elemental values.

| | Milyering Well | | Tantabiddi Well | |
|---|---|---|---|---|
| | 1959 | 1993 | 1959 | 1993 |
| pH | 7.1 | 7.4 | 7.5 | 8 |
| Ca | 126 | 130 | 113 | 150 |
| Mg | 188 | 170 | 141 | 210 |
| Na | 1414 | 1440 | 999 | 1590 |
| K | 53 | 65 | 36 | 70 |
| HCO3 | 316 | • | 336 | • |
| CO3 | 0 | • | 0 | • |
| SO4 | 358 | 345 | 240 | 85 |
| Cl | 2550 | 2800 | 1810 | 2600 |
| NO3 | 3 | 3.95 | 3 | 34.8 |
| SiO2 | 11 | 11 | 15 | 17.5 |
| *Fe2O3 | <0.1 | 0.25 | <0.1 | 1.29 |
| *Al2O3 | 10 | 0.07 | 5 | 0.45 |
| *PO4 | 0.2 | 0.03 | 0.4 | 8.9 |
| Total hardness | 1089 | 1010 | 862 | 1240 |

In contrast, all parameters bar the pH vary by more than 10% in Tantabiddi Well (Table 20). There has been an major increase in the salinity and related seawater parameters at this location. In addition, as found in Milyering Well, there has been an increase in Fe and reduction in Al presumably from the same cause. When sampled in 1993 the well was very shallow (8 cm) and was polluted by organic matter (two dead Zebra Finches) — this is reflected by the NH3 and NO2 levels (respectively 89% and 670% greater than any other recorded during the field programme), and the NO3 level (the second highest recorded — the highest being a similarly polluted bore in Exmouth town site).

Comparison of the temporally disjunct data from these two wells reveal three important points pertinent to the groundwaters around the Cape Range peninsula. Firstly, as epitomized by the water in Milyering Well, long term stability in the water quality is possible despite the site being opened to the air. Secondly, these small watering points are easily degraded to a serious degree by small scale inputs owing to the small body of water and the slow turnover. Finally, even seemingly benign activities, such as adding iron piping to the water, can lead to complex changes in the characteristics of the water — both wells showing such apparent effects with a reduction in Al resulting from an increase in Fe.

## Rainwater

Rainfall falling on Exmouth (and presumably Cape Range) contains many fewer solutes than many other coastal localities (comparison is made with sites in the Sydney area: Table 21) and in consequence water entering the limestone from the surface is relatively pure — groundwater around the coast is solute rich owing to marine input.

**Table 21**: Rainwater parameters for Exmouth and three Sydney, New South Wales, sites (Sydney data from Acworth and Jankowski 1993).

| Parameter | Exmouth | Banksmeadow | Kensington | Moore Park |
|---|---|---|---|---|
| pH | 6.5 | 6.3 | 5.5 | 5.9 |
| Conductivity mS $cm^{-1}$ | 1.0 | 10.3 | 8.1 | 4.5 |
| Na | 0.5 | 11.8 | 10.5 | 5.7 |
| K | 0.4 | 3.1 | 1.2 | 0.8 |
| Ca | 0.4 | 3.7 | 1.6 | 1.3 |
| Mg | 0.2 | 1.9 | 1.3 | 0.7 |
| Cl | 0 | 21.4 | 18.4 | 9.3 |
| SO4 | 1 | 10.3 | 7.3 | 4.5 |

## Status of the water table

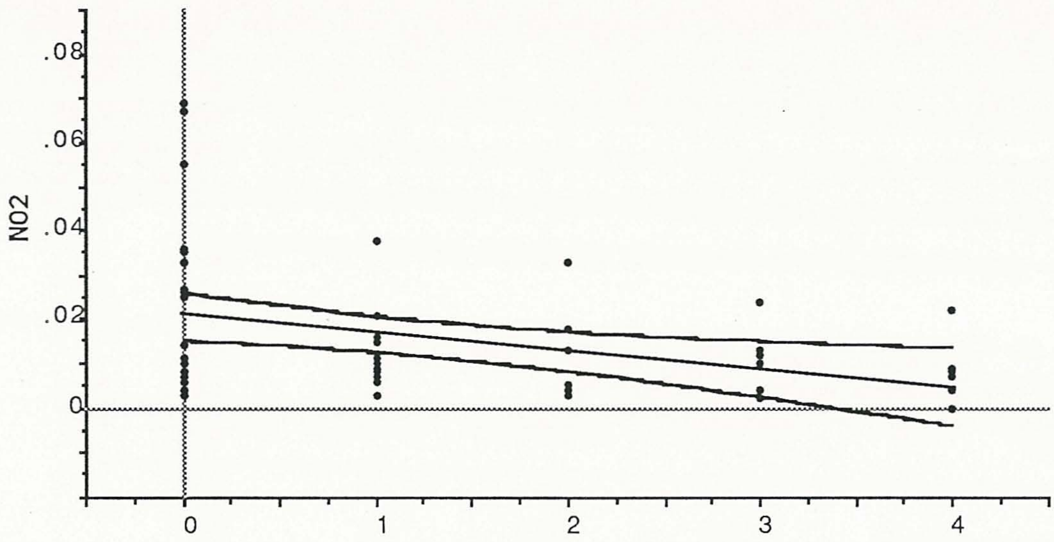
Tidal effects reach far inland and indicate that open conduits are common and widespread in the coastal limestone. This free movement of water would mask any changes in the water table and so the drying up of wells on the peninsula (Humphreys and Adams 1991) is most likely to be attributable to silting of the wells rather than to changes in the water table itself. Whilst the quality of the water on the west coast has not changed substantially (see above), there has nevertheless been a substantial change in water quality associated with the borefields on the east coast. These effects can mostly be seen in the increased salinity of the superficial groundwaters implying a thinning of the less saline surface layer (see Chapter on habitat).

## Nutrients

### Nitrite

Sites containing core stygofauna species have substantially lower nitrite levels (log mean, s.e., n — 0.004, 0.001, 36) than do those from which such fauna is absent (0.01, 0.002, 26: $Fs_{1,60}$ 9.998, P<0.003). This effect is strongly realised (Figure 32) when nitrite is regressed on the number of stygofauna species ($NO_2$ =0.021 - 0.004; $Fs_{1,60}$ 7.774, P=0.007).

**Figure 32:** Nitrite concentration regressed on number of stygofauna species for water samples collected only from the Cape Range peninsula. The 95% confidence intervals of the true mean Y are shown.




### Nitrate

Most of the samples 59% (n=97) contained <2 mg $L^{-1}$ NO3-N, the concentration generally found in water beneath grassland and forest (Hallberg 1989). An additional 31% of the samples exceeded 3 mg $L^{-1}$ NO3-N which is often considered to be indicative of contamination by human activities (Hallberg 1989). There is clear indication of nitrate enrichment in samples from the Exmouth town site as those from inhabited parts of the site had nitrate concentrations 2.5 times greater (4.5 mg $L^{-1}$ NO3-N) than those from uninhabited areas (1.8 mg $L^{-1}$ NO3-N; Fs1,21 = 6.513, P=0.019). Most of the samples exceeding 3 mg $L^{-1}$ NO3-N were from town sites or closely associated with sheep watering and *vice versa* for those with less than 1 mg $L^{-1}$ NO3-N.

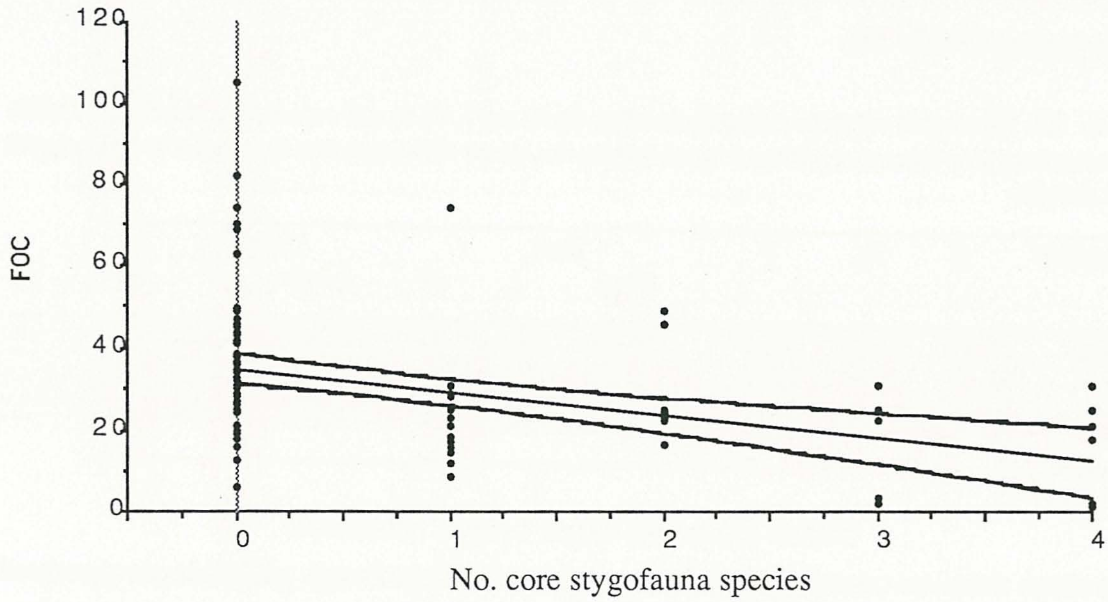
## Phosphorus

The water samples contained concentrations of total dissolved phosphorous (TP) of between 0.6 μg $L^{-1}$ to 119000 μg $L^{-1}$. Samples with <10 μg $L^{-1}$ TP will be oligotrophic while those with >20 μg $L^{-1}$ TP will be eutrophic (Vollenweider 1976); these accounted respectively for 8% and 65% of the samples taken. Were these waters in the light they may be expected exhibit the characteristics of eutrophic waters.

## Filterable organic carbon

Filterable organic carbon is greater in the hinterland of the Cape Range peninsula (mean, s.e., n — 37.3, 3.33, 34) than on the peninsula itself (26.7, 1.93, 64; $Fs_{1,96} = 8.75$, P=0.004). Overall on the peninsula FOC is greater in the absence (mean, s.e., n — 32.7, 2.73, 27) than in the presence (21.5, 2.42, 36) of core stygofauna ($Fs_{1,61} = 11.55$, P=0.003) and FOC is inversely related to the number of core stygofauna species present at the sample site ($Fs_{1,61} = 29.35$, P<0.001; log FOC = 1.52 - 0.14 x No. species) (Figure **33**).

**Figure 33:** Filterable organic carbon (mg $L^{-1}$) regressed on the number of species of core stygofauna present at the sample site (FOC = 35.0 - 5.76 x No species; $Fs_{1,95} = 20.53$, P<0.001). The 95% confidence intervals of the true mean Y are shown.




While it is tempting to consider this relationship to result from the removal of organic carbon from the water by the feeding of the stygofauna, it is notable that two important faunal caves (Camerons Cave and New Mowbowra Cave) had FOC levels with the four highest levels recorded in any water sample.

### Manganese

Manganese concentration exceeded the WHO drinking water limit 0.1 mg Mn $L^{-1}$ in 13% of the samples. The second highest level was in one of the four caves in the range containing amphipods (C-18, 1.4 mg $L^{-1}$) and another in a pristine cave on the coast (C-495, 0.15 mg $L^{-1}$).

### Turbidity

The only species distributed in relation to turbidity was *Milyeringa veritas*; water with *M. veritas* on the Cape Range peninsula was on average about half as turbid ([log (n+1)] mean, s.e., n — 0.64, 0.10, 19) as water without *M. veritas* (1.09, 0.10, 44; $Fs_{1,61}$ = 6.77, P=0.012).

## Water extraction

There is some evidence that water extraction itself causes some loss of water quality. The water was examined from wells in the WAWA borefield *sensu stricto* that had been bored and put into production in contrast to those bored but never equipped. Three parameters differed significantly in concentration, namely colour, SO4 and NO2 each of which was greater in those bores that had been long in production than in those bores never equipped for pumping (Table 22).

**Table 22**: Nitrite and sulphate concentration (log (x+1) mg $L^{-1}$) in and colour of water from WAWA Exmouth borefield bores that had been in production compared with those that have never been equipped with pumps.

| Parameter | df | Fs | P | Used | | | Unused | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Mean | s | N | Mean | s | N |
| Colour | 1,15 | 9.076 | 0.009 | 0.672 | 0.47 | 8 | 0.153 | 0.190 | 9 |
| $SO_4$ | 1,15 | 5.538 | 0.033 | 1.878 | 0.75 | 8 | 1.231 | 0.323 | 9 |
| $NO_2$ | 1,15 | 16.128 | 0.001 | 0.008 | 0.004 | 8 | 0.002 | 0.001 | 9 |

## Water from the Cape Range peninsula

The mean chemical constituents of the water from the Cape Range peninsula are presented in Table 23 with rainwater (from Exmouth) and seawater (from Learmonth jetty) for comparison.

### Water constituents and the fauna

The range of characteristics of the waters occupied by each taxon is given in Appendix D and the range of water occupied is further depicted in the triangular diagrams in Figure

34. Most of the fauna is clearly capable of adapting to quite varied conditions, being absent only in extremely fresh water (see the discussion in the section on Habitat).

**Table 23:** Analysis of the water from all sites on Cape Range peninsula *sensu stricto* (n=62), with rainwater (from Exmouth) and seawater (from Learmonth) for comparison. For definitions and units see Appendix C.

| Parameter | Rain | Sea | Mean | SE | Max | Min | CV |
|---|---|---|---|---|---|---|---|
| pH | 6.47 | 8.1 | 7.38 | 0.06 | 5.32 | 9.13 | 6 |
| Turbidity | 1.2 | 1.6 | 29.4 | 7.15 | 0.6 | 270 | 191 |
| Colour | 21 | 1 | 5.18 | 1.02 | 0 | 36 | 155 |
| Conductivity | 1 | 4950 | 843 | 139 | 35 | 4700 | 130 |
| TFS | 20 | 36500 | 5387.9 | 893.7 | 250 | 26500 | 131 |
| TFS-$CO_2$ | 15 | 36500 | 5238.4 | 895.9 | 210 | 26500 | 135 |
| Fe | 0 | 0 | 3.74 | 1.74 | 0 | 100 | 367 |
| Mn | 0 | 0 | 0.52 | 0.45 | 0 | 28 | 690 |
| Al | 0.015 | 0.092 | 0.22 | 0.07 | 0.01 | 4.4 | 263 |
| Na | 0.5 | 12000 | 1503 | 277 | 40 | 7780 | 145 |
| K | 0.4 | 540 | 57.9 | 10.8 | 2 | 310 | 147 |
| Ca | 0.4 | 420 | 146.0 | 11.7 | 15 | 420 | 63 |
| Mg | 0.2 | 140 | 177.1 | 30.6 | 3.4 | 940 | 136 |
| Hardness | 2 | 1630 | 1089.4 | 151.4 | 50 | 4840 | 109 |
| Alkalinity | 0.06 | 2.1 | 4.93 | 0.23 | 0.6 | 10.4 | 36 |
| Cl | 0 | 20250 | 2706.7 | 512.6 | 54 | 15050 | 148 |
| $SO_4$ | 1 | 3000 | 452.4 | 96.9 | 2 | 4500 | 169 |
| Si | 0 | 0 | 18.1 | 1.45 | 3.3 | 83 | 63 |
| FOC | 5.8 | 12.5 | 26.4 | 1.96 | 1 | 82 | 58 |
| TP | 0.045 | 0.028 | 2.03 | 1.92 | 0.006 | 119 | 745 |
| FRP | 0.011 | 0.008 | 0.24 | 0.18 | 0 | 11 | 591 |
| TKN | 0.09 | 0.054 | 1.71 | 1.08 | 0 | 67 | 499 |
| $NO_2$ | 0.004 | 0.003 | 0.02 | 0.007 | 0 | 0.46 | 257 |
| $NO_3$ | 0.028 | 0.019 | 2.88 | 0.86 | 0.003 | 52 | 236 |
| $NH_3$ | 0.02 | 0.003 | 0.21 | 0.09 | 0 | 5 | 355 |

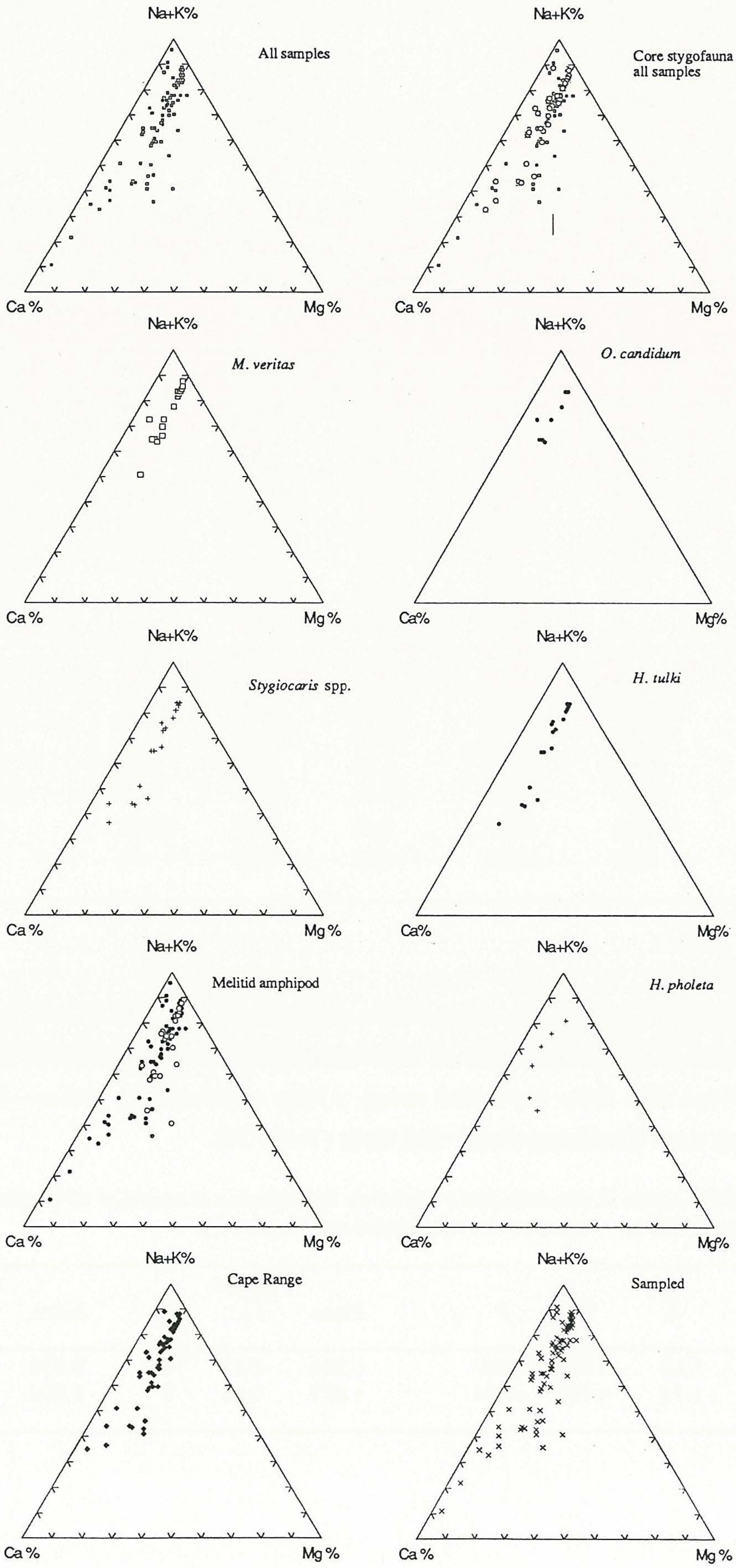
## Halocline

The deep halocline is known to have been reached only in C-28 (see below). However, superficial and weak stratification of the water column does occur superficially in most of the locations that were examined using a long conductivity probe—few consistent differences were found associated with these (Table 24).

**Table 24**: Differences in elements above and below the halocline at a number of locations in the northeast of the Cape Range peninsula— values are for transformed data (log (x+1)).

| Parameter | | | | Above | | | Below | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | df | Fs | P | Mean | S.D. | N | Mean | S.D. | N | |
| K | 1,15 | 4.859 | 0.043 | 0.556 | 0.15 | 3 | 0.828 | 0.2 | 14 | < |
| Ca | 1,15 | 4.794 | 0.044 | 1.697 | 0.04 | 3 | 1.892 | 0.149 | 14 | < |

**Figure 34:** Trilinear plots (Na+K, Ca and Mg) of waters from the Cape Range peninsula including various subsets of the data— all samples, core stygofauna (circles) overlying all samples (small squares), *Milyeringa veritas* sites, *Ophisternon candidum* sites, *Stygiocaris* spp. sites, *Halosbaena tulki* sites, melitid amphipod sites, *Haptolana pholeta* sites, sites on Cape Range peninsula *sensu stricto* and sites sampled for stygofauna.



## Deep anchialine caves inhabited by remipedes

Inland marine (anchialine) caves have served as biological refugia and often contain unique assemblages of taxonomically significant relict populations known only from a single system. The waters of such systems, in the absence of photosynthesis, characteristically have very depleted levels of dissolved oxygen. Under such conditions even low levels of organic pollution can produce anoxic conditions and may consequently result in the extinction of entire species (Iliffe *et al.* 1984).

Access could be gained to only one deep anchialine cave (C-28), one that is 1.6 km inland. Divers penetrated to a water depth of 34 m and collected remipedes (at depths from 20 to 30.5 m) and *Danielopolina* sp. (Ostracoda). The cenote opens through Bundera Calcarenite (it is the type section) of Late Pleistocene age (Wyrwoll *et al.* 1993) in the Tantabiddi Terrace. Although the lithology at the maximum known depth of 34 m is unknown, it could well be Tulki Limestone as the platforms generally are cut into this limestone.

Water in the sinkhole is tidal but the temporal lag and amplitude damping relative to the local coastal semi-diurnal tidal range of about 1.3 m is unknown.

The cave has not been surveyed. The open pool is about 9 x 18 m and from one side of which a steeply inclined slot descends. At a depth of *c.* 13 m there is a restricted entrance slot (*c.* 10 m wide and 1-2 m high) and the cave reaches a depth of 34 m. A thermocline occurs at a depth of 8 m and another at 13 m at which point the whispy suspension in the water ceases. The cave destabilized after the initial two dives but had returned to *c.* 90% of its original state after 5 days (A. Poole, pers. comm.).

The cave had a strong halocline and thermocline and water samples were taken from the open surface of the sinkhole, and immediately above and below the thermocline (Figure 35; Appendix Dm).

The open pool is more brackish than almost any other location sampled on the Cape Range peninsula and reaches full seawater below the halocline (Table 25). The exact relationship of the thermocline and the halocline is unknown at present and detailed sampling is required of this important location. However, the water column, with its halocline and temperature inversion, is of marginal stability (Table 26) and the water appears to form convection cells when disturbed by the exhaust air from the SCUBA and in the process forming at depth patches of warm and cooler water.

**Figure 35:** Schematic section of C-28 with the thermocline indicated by shading of increased density. The sketch is drawn from information provided by A.A. Poole and the total water depth is 34 m.

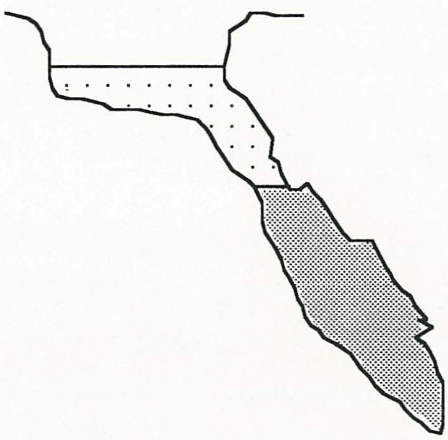


**Table 25**: Locations of three water samples taken in the sinkhole. Note that the temperature inversion may be stabilized by the increasing density with depth.

| Location | Depth *c.* m | Conductivity mS $cm^{-1}$ | Temperature $^{o}C$ | Water sample |
|---|---|---|---|---|
| Main pool | 0.2 | 33.7 | 22 | WAM 91 |
| Above thermocline | 6 | 30.9 | 21 | WAM 90 |
| Below thermocline | 14 | 49.8 | 27 | WAM 89 |

**Table 26**: Data examining the contribution of temperature and salinity to the stability of the water column through the thermocline in C-28.

| Parameter | Surface | Above halocline | Below halocline |
|---|---|---|---|
| Depth (m) | 0.2 | 6 | 14 |
| Temperature (oC) | 22 | 21 | 27 |
| Density pure water | 0.99741 | 0.99766 | 0.99614 |
| Contained salt (g L-1) | 19.829 | 19.593 | 26.438 |
| Density | 1017.237 | 1017.255 | 1022.574 |
| Relative density pure water | 1 | 1.00025 | 0.99847 |
| Relative density water + salt | 1 | 1.00002 | 1.00525 |

Near surface water in the cenote is thick with algae below which there is a zone of massive globular structures (probably bacterial films) and then a zone of huge filamentous structures — these are probably colonial sulphur bacteria and ones of the *Beggiatoa-Thiothrix* group are common in anchialine caves containing remipedes (Yager 1991).

# Chapter 7

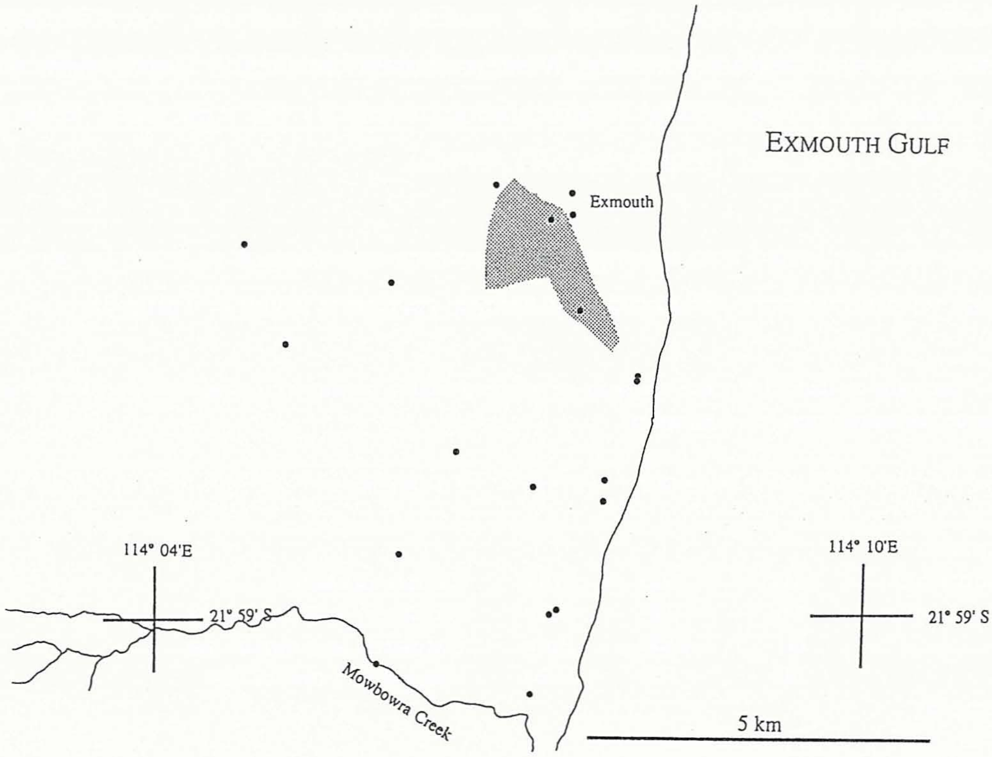
# Core water samples

## Examination for possible anthropogenic contamination of the groundwater

### Introduction

The prime focus of human activity on the Cape Range peninsula is around the Exmouth town site, its facilities and associated small holdings, and the VLF Naval Communications Facility, Harold E. Holt. In addition there are several foci of activity at camp sites at Vlaming Head and at the former Yardie Creek Homestead on the west side of the peninsula opposite Exmouth. To supplement the general water sampling conducted during this programme, 20 locations in the region of Exmouth town (Figure 36) were sampled to determine the level of anthropogenic contamination of the groundwater; this is the area where most sighting have been made of the cave eel *O. candidum*. and from where most species of the stygofauna have been collected.

**Figure 36:** Map showing the location of the twenty water samples taken to examine for possible anthropogenic contamination of the groundwater.




### Sampling strategy

The sampling sites were chosen to represent a range of likely anthropogenic contamination of the groundwater from, at the one extreme, virgin groundwater upstream of likely contamination, through a graded series to, at the other extreme, piezometers in a former landfill site (Figure 36; Table 27). All the sites were <6 km from Exmouth being the only area on the peninsula where samples could be taken to represent such a graded risk.

**Table 27**: Description of core water sample sites ranked in order of the perceived likely increase in anthropogenic contamination.

| Rank | Description |
|---|---|
| 1 | Deep unused bores in the foothills of Cape Range |
| 2 | Deep production bores in the foothills of Cape Range |
| 3 | Natural unused caves on coastal plain |
| 4 | Unused domestic bores in Exmouth town site |
| 5 | Open caves and piezometers on coastal plain |
| 6 | Used caves and wells (Mowbowra Well has junk in it) |

## Methods

In addition to the general water sampling regime, the 20 core sites were examined for microbiological, heavy metal and petrochemical contamination (organochlorine and organophosphorus pesticides and total hydrocarbons). Water sampling methods followed the protocols of the respective analytical laboratories and the determination generally following APHA (1985). Heavy metals were determined by the Western Australian Water Authority laboratories, as were all routine water analyses, microbiological determinations were conducted by the Western Australian Health Department water laboratory, and the petrochemical determinations made by the Analytical Reference Laboratory (W.A.) Pty. Ltd. (Report No ARL/4446).

All samples were collected into appropriate containers and shipped to Perth by air on ice for analysis within 24 hours. The complete sample routine is given in Table 28.

**Table 28**: Samples collected for the analysis of general water quality (all samples) and for potential anthropogenic contamination (core samples).

| Analysis | ID | Size (ml) | Type | Treatment |
|---|---|---|---|---|
| **All samples** | | | | |
| Major components | M1 | 500 | Poly | Air-free unfiltered |
| Major components | M2 | 125 | Poly | Unfiltered to 5 mm of top |
| Nutrients | N1 | 1000 | Poly | Unfiltered to 5 mm of top |
| Nutrients | N2 | 125 | Poly | Filtered to 5 mm of top |
| **Core samples** | | | | |
| Heavy metals | From samples above | | | |
| Mercury | HG | 125 | Glass | With reagents |
| Organics | H | 2000 | Glass | Special: Analytical Reference Laboratory |
| Microbiology FIRST | Biol | 125 | Glass | Special: Health Department Water Laboratory |

## Microbiology

Microbiological analysis was conducted primarily to detect sewage contamination. Hence, general heterotrophic bacterial counts were taken as a control against bacteria associated with anthropogenic sources (thermotolerant coliforms, faecal streptococcus) with specific isolates to confirm identity. The basic microbiological data are presented in Table 29. Heterotrophic plate counts at 22°C commonly reflect general bacteria in the environment whilst the HPC 35°C is commonly taken to reflect general bacteria of human or animals origin.

**Table 29**: Microbiological data. cfu = colony forming units. HPC = the heterotrophic plate count at 22°C and 35°C (cfu $ml^{-1}$). For total coliforms, thermotolerant coliforms and faecal streptococcus = cfu 100 $ml^{-1}$.

| Sample Number | Site | Rank | Thermo-tolerant coliforms | Faecal strepts | *E. coli* | Total coliforms | HPC 35 | HPC 22 | *Salmonella* |
|---|---|---|---|---|---|---|---|---|---|
| 12BOE | | 1 | 0 | 0 | 0 | 0 | 2300 | 2800 | - |
| 18 | S3 | 1 | 0 | 0 | 0 | 0 | 5300 | 9000 | - |
| 19 | N4 | 1 | 0 | 0 | 0 | 0 | 21000 | 23900 | - |
| 27 | Rifle range | 5 | 0 | 0 | 0 | 0 | 4000 | 3800 | - |
| 28 | C-361 | 6 | 0 | 18 | 0 | 2500 | 25300 | 17100 | - |
| 29 | C-105 | 5 | 2 | 30 | 1 | 2 | 230 | 240 | - |
| 30 | C-440 | 6 | 31 | 240 | 1 | 60000 | 110000 | 110000 | *oranienburg* |
| 31 | C-452 | 3 | 0 | 0 | 0 | 0 | 20000 | 29000 | |
| 32 | Marina North | 5 | 0 | 0 | 0 | 0 | 2300 | 3400 | |
| 45 | C-27 | 6 | 2 | 0 | 1 | 200 | 150 | 206 | *S.* + Arizonae |
| 46 | WAWA 44 | 2 | 2 | 0 | 0 | 4 | 9000 | 8300 | - |
| 47 | C-413 | 6 | 42 | 72 | 1 | 480 | 16000 | 7700 | *fremantle* |
| 49 | C-23 | 6 | 26 | 104 | 1 | 320 | 6000 | 7600 | - |
| 50 | WAWA 47 | 2 | 0 | 8 | 0 | 0 | 160 | 200 | - |
| 51 | WAWA 28 | 2 | 0 | 24 | 0 | 0 | 11000 | 4100 | - |
| 52 | E6 | 4 | 40 | 0 | 0 | 200 | 44000 | 31000 | |
| 55 | E1 | 4 | 0 | 0 | 0 | 700 | 35000 | 22000 | *bahrenfeld* |
| 56 | E4 | 4 | 0 | 0 | 0 | 14 | 330000 | 510000 | |
| 57 | E3 | 4 | 0 | 0 | 0 | 10 | 600000 | 910000 | - |
| 58 | Marina B | 5 | 0 | 280 | 0 | 0 | 710000 | 990000 | *fremantle* |

Isolates

*Salmonella* belonging to three serotypes were isolated from 5 samples (25%): *viz. S. fremantle* (x2), *S. oranienburg* and *S. bahrenfeld*. Arizonae were isolated from one sample (5%), coincident with *Salmonella*. *Escherischia coli* were isolated from 5 samples (25%) of which three (60%) were coincident with *Salmonella*.

Anthropogenic?

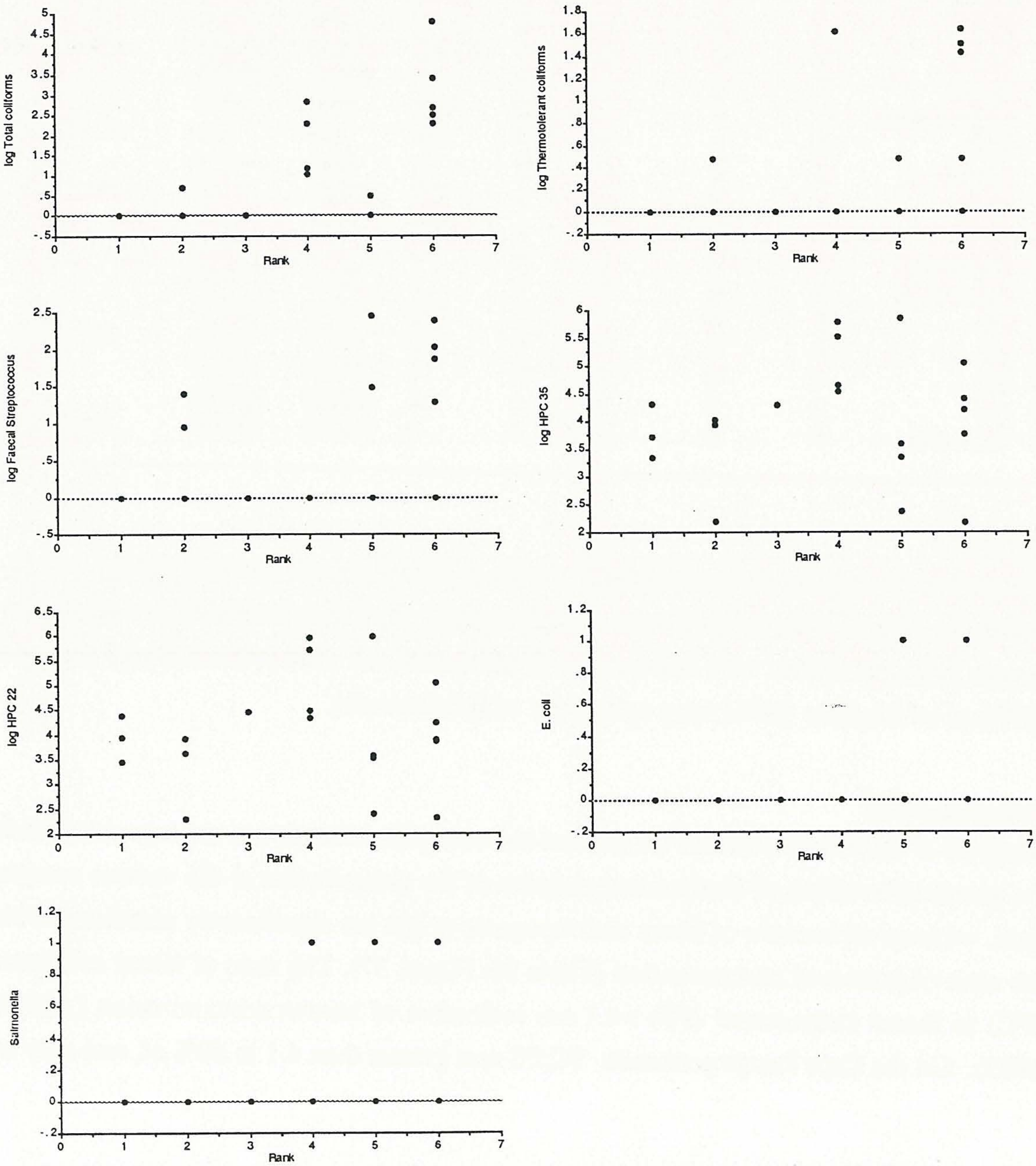
Analysis of the data shows that the general heterotrophic bacteria are not associated with the perceived ranking of likely contamination of the groundwater at the various sample sites, whereas all bacteria of likely anthropogenic origin are significantly associated with the rank of perceived contamination (Table 30; Figure 37). The ratio of faecal coliforms (FC) to faecal streptococci (FS) >4.1 are indicative of human contamination (APHA 1985). On the Cape Range peninsula TC/FS was greater than 4.1 in 60% of, and only in

**Table 30:** Non-parametric correlation between the microbiological data (Table 29) and the rank of the likely exposure of the groundwater to anthropogenic contamination. *P* is the probability determined using Kendall's rank correlation with correction for tied values.

| **Parameter** | **Units** | ***P*** |
|---|---|---|
| Total coliforms | cfu† 100 ml-1 | <0.001 |
| Thermotolerant coliforms | cfu 100 ml-1 | 0.008 |
| Faecal streps | cfu 100 ml-1 | 0.012 |
| *E. coli* | ± | <0.001 |
| *Salmonella* | ±††† | 0.006 |
| ††HPC 22°C | cfu ml-1 | 0.89 |
| ††HPC 35°C | cfu ml-1 | 0.60 |

†cfu = colony forming units.†† HPC = Heterotrophic Plate Count at 22°C and 35°C.
††† Presence/ absence data.

**Figure 37:** The relationship between the microbiological data and the rank of the likely exposure of the groundwater to anthropogenic contamination. From top to bottom, left column — total coliforms, faecal streptococcus, HPC 22 and *Salmonella*; right column — thermotolerant coliforms, HPC 35 and *E. coli.*



locations of rank 6; all these sites being open shallow wells (C-361, C-413 and C-440). This finding contrasts with the contamination of sources of many different types (bores, open and capped wells etc.) on San Salvador Island, Bahamas (Mylroie and Balcerzak 1992) and supports the validity of the prior subjective ranking of the sampled locations.

### Organochlorine and organophosphorus pesticides and total hydrocarbons

#### Pesticides

Dieldrin was detected in one sample (0.004 μg $L^{-1}$), in a shallow bore in the grounds of a low budget tourist accommodation in central Exmouth; concentrations in all other samples were below the limit of detection (<0.001μg $L^{-1}$). No other common organochlorine pesticides were detected (<0.001 μg $L^{-1}$). No common organophosphorus pesticides were detected (limit of detection for chlorpyrifos = 0.001 μg $L^{-1}$).

#### Petroleum hydrocarbons

No petroleum hydrocarbons were detected in the water samples at the limits of detection shown in Table 31.

**Table 31:** The limits of detection of the method used to examine for hydrocarbons of various size.

| Hydrocarbon size | C6-9 | C10-14 | C15-28 | C29-36 |
|---|---|---|---|---|
| Limits of detection (mg $L^{-1}$) | 0.01 | 0.01 | 0.02 | 0.02 |

#### Heavy metals

Some non-essential metals present a great risk to aquatic evironments and human health (e.g. Hg, Cd, As, Sn; Plenet *et al.* 1992). Mean heavy metal concentration in the water samples was below both Australian and EEC guidelines for drinking water. However, samples from a piezometer had a cadmium (and chromium) concentration four (3) times the recommended levels for drinking water and 20 (13.6) times the next highest level recorded. The piezometer, in a proposed marina site, is on a now disused refuse tip for Exmouth—this seems to be a case of groundwater contamination from the tip.

Zinc concentration (Table 32) exceeded guidelines (x1.8) in WAWA 47 but overall 55% of samples had zinc concentrations >0.1 mg $L^{-1}$ (n=11) and these were found throughout the core sample area — a common factor was that zinc contamination was likely either from galvanized pipes (Mowbowra Well, older production bores, test bores) or was located over a refuse tip (marina piezometer). In addition all the samples from PVC lined and never equipped domestic bores in the Exmouth town site had concentrations >0.2 mg $L^{-1}$ (n=4), probably elevated owing to the ubiquitous use of galvanized iron on roofs.

**Table 32:** Correlation between the level of parameters in the core water samples and the estimated rank exposure of the sample site to sources of contamination. MDL = Minimum detectable level; if not specified then all samples were greater than MDL. *P* is the probability determined using Kendall's rank correlation with correction for tied values. * ?anthropogenic. (-) denotes negative association. ± presence or absence.

| Parameter | Units | MDL | *P* |
|---|---|---|---|
| pH | | - | 0.65 |
| Turbidity | NTU | - | 0.97 |
| Colour | TCU | 1 | <0.001 |
| Conductivity at 25oC | mS m-1 | - | 0.018 |
| Total filterable solids | mg L-1 | | 0.024 |
| Total filterable solids-CO2 | mg L-1 | | 0.030 |
| Iron (unfiltered) | mg L-1 | 0.05 | 0.83 |
| Manganese (unfiltered) | mg L-1 | 0.04 | 0.81 |
| Aluminium (unfiltered) | mg L-1 | | 0.89 |
| Sodium | mg L-1 | | 0.021 |
| Potassium | mg L-1 | | 0.006 |
| Calcium | mg L-1 | | 0.105 |
| Magnesium | mg L-1 | | 0.047 |
| Hardness as CaCO3 | mg L-1 | | 0.051 |
| Alkalinity | meq L-1 | | 0.62 |
| Chloride | mg L-1 | | 0.015 |
| Sulphate | mg L-1 | | 0.111 |
| Silica (as SiO2) | mg L-1 | | 0.83 |
| Filterable organic carbon | mg L-1 | | 0.52 |
| Total phosphorus | mg L-1 | | 0.67 |
| Free reactive phosphorus | mg L-1 | 0.002 | 0.86 |
| Total Kjeldahl nitrogen | mg L-1 | | 0.079 |
| Nitrite as nitrogen | mg L-1 | 0.002 | 0.332 |
| Nitrate as nitrogen | mg L-1 | 0.002 | 0.67 |
| Ammonia as nitrogen | mg L-1 | 0.005 | 0.55 |
| *Arsenic | mg L-1 | 0.002 | 0.002 |
| *Cadmium | mg L-1 | 0.0001 | 0.19 |
| *Chromium | mg L-1 | 0.002 | 0.080 |
| *Lead | mg L-1 | 0.002 | 0.36 |
| *Mercury | mg L-1 | 0.0005 | |
| *Selenium | mg L-1 | 0.003 | 0.44 |
| *Zinc | mg L-1 | 0.02 | 0.029 (-) |
| *Total coliforms | cfu 100 ml-1 | | <0.001 |
| *Thermotolerant coliforms | cfu 100 ml-1 | | 0.008 |
| *Faecal streps | cfu 100 ml-1 | | 0.012 |
| *HPC35 | cfu ml-1 | | 0.60 |
| *HPC22 | cfu ml-1 | | 0.89 |
| **E. coli* | ± | | <0.001 |
| **Salmonella* | ± | | 0.006 |

*Considered anthropogenic. Combining all the analyses shows a strong relationship (Kendall's tau =3.416; P <0.0001) between the probability (above) and whether or not the parameter is considered anthropogenic.

### Nutrients and others

There was no obvious nutrient enrichment of the groundwater that could be considered anthropogenic. Those parameters with probabilities at or approaching significance can all be attributed to being closer to the sea (Na, K, Mg, hardness and chloride) or to the sites being more open and therefore more organic material falling into them (colour, TFS and TKN).

## Discussion

This analysis of the groundwater quality suggests, as does the presence of the stygofauna itself, that the groundwater on the peninsula is still in good condition. The levels of anthropogenic contaminants in the water itself are generally not high but it may be expected that concentrations of contaminants in the stygofauna may be very much greater than has been measured from the water samples, owing to the bioaccumulation in body tissue through the food chain (Ernst 1980; Plenet *et al.* 1992). In addition sediment loads of some contaminants may be high and these would have a large effect on the sediment processing taxa such as *Stygiocaris* and *Halosbaena.*

The location where dieldrin was found is adjacent to a house and was possibly contaminated as a result of pest control operations on the house; this bore contained both copepods and melitid amphipods but lacked the Stygiocaris present in adjacent sites.

Most sightings of *Ophisternon candidum* on the west coast have been at sites of categories 5 and 6 (Table 27) that are directly associated with the perceived and demonstrated degree of anthropogenic contamination ($t = 0.388$; $P = 0.015$). In contrast *Haptolana pholeta* is negatively associated with the level of perceived contamination ($t = -0.288$; $P = 0.076$), occurring as it does away from the coast. As such different elements of the fauna will be influenced by contamination differentially depending on their own distribution and the location and movement of contaminants.

The movement of contaminants in aquifers is complex (Gibert 1990). Contaminants disperse both laterally and downstream in underground water but the latter is much more rapid and the advance may be locally heterogeneous (Freeze and Cherry 1979). On the coastal plain itself, where the tidal influence is high, movement of contaminants will occur, not only towards the sea but parallel to the coast, especially in areas of open conduits.

# Chapter 8

## National Estate significance, conservation and recommendations

## National Estate significance, conservation and recommendations

### National Estate significance of the stygofauna

The significance of the stygofauna (and the coastal troglobites) to the National Estate lies in the unique and rich faunas and by their being known nowhere but parts of the Cape Range Formation (Cape Range peninsula and Barrow Island). The fauna is a major component of the biodiversity of Australia, especially at the higher taxonomic level.

The Cape Range peninsula has a high species density and exceptional endemism (papers in Humphreys 1993a)—of the described specialist underground fauna known from the worlds tropics, *c.* 6.5% are known only from this area comprising 0.07% of Western Australia.

The significance is further enhanced because in its composition are echoes of local eustatic events, climatic change, and of past connections with other parts of Australia, eastern Gondwana and even Pangea. The fauna contains the only evidence of closed forest, both temperate and tropical, since the Miocene when the Cape Range limestones were laid down.

The very ancient fauna from the Tethys Sea is known in the southern hemisphere only from northwestern Australia.

The importance is further enhanced by a unique combination of terrestrial and aquatic communities and by the more or less pristine state of the area.

The significance is enhanced by the inclusion of many higher order taxa (genera, orders and classes) found nowhere else in Australia — or even the southern hemisphere — and by the close affinity of some aquatic taxa with other subterranean species on the other side of the world—on either side of the North Atlantic. This imparts an international flavour to the **world heritage significance** of the fauna as the three sites— Bundera Cenote on the Cape Range peninsula, the blue holes in the Bahamas and Jameos del Agua marine lava cave on Lanzarote in the Canary Islands— hold the key to the history of the disjunct cave faunas in the area of the former Tethys Sea.

### Land tenure

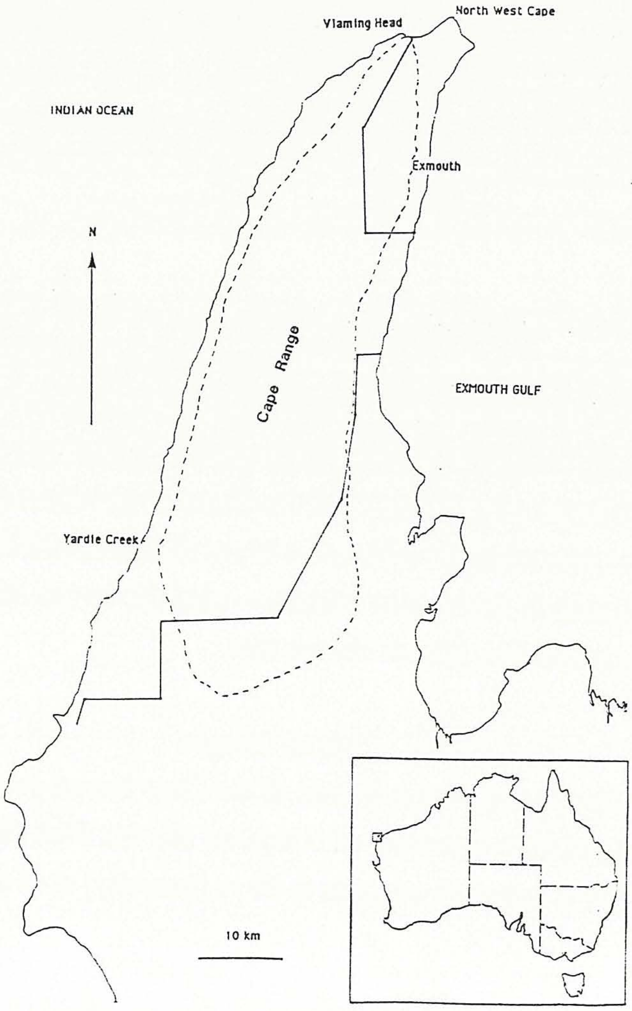
The area covered by the stygofauna typical of the Cape Range peninsula includes —
Cape Range National Park and parts of Ningaloo Marine Park (the landward limit of the Ningaloo Marine Park variously extends to 40 m [laterally] above high water mark except

where it abuts the Cape Range National Park (HWM), Commonwealth land associated with the live firing range south of Yardie Creek [?HWM or LWM], the jointly managed Jurabi Coastal Park (HWM) and Prohibited Area A [the VLF transmitters; LWM]). Commonwealth land (Naval Communication Base Harold E. Holt [Areas A, B and C], Learmonth Airforce Base, the Solar Observatory and the live firing range and adjoining land south of Yardie Creek). Pastoral stations (Exmouth Gulf and Ningaloo; the fauna is probably present on parts of Bullara Station as the location Billy Wells on Exmouth Gulf Station is only 2 km north of the boundary). The tourist facilities at the former Yardie Creek Homestead and the Vlaming Head Lighthouse, and Kailis Fisheries (two sites).

## Register of the National Estate

Much of the Cape Range peninsula has been included in the Register of the National Estate (Figure 38). Of the areas not included that in the northeast comprises mainly the Naval Communications Base and Exmouth town site, and that to the south is pastoral stations. Should the northeastern part of the peninsula be included in the Register of the National Estate then all locations (except for Billy Wells) of the stygofauna (excluding amphipods) would lie on land included within the Register of the National Estate.

**Figure 38:** The area included in the Register of the National Estate lies to the west of the continuous line.



The registration includes one listing for — *Cape Range National Park and surrounds* (registered 21/3/78) significant for *Representative of western and eastern coastal plains. Due to combination of summer and winter rains floristic elements represent all three botanical provinces of Western Australia. Endangered species, Brush-tailed Rock Wallaby occur. Large number of diverse reptilian species, Freshwater cave of palaeontological significance. Scenic beauty of canyons.*

In addition there are two current nominations — one dated 3/8/92, for *Cape Range geological site*, is entirely contained within the area of the current National Estate Registration, whilst the second, dated 5/8/92, for *Cape Range and adjacent coastal plain* serves to extend the area already listed to include the north-eastern sector of the Cape Range peninsula, a nomination fully supported by the findings of this study.

## Cape Range National Park

The current extent of the Cape Range National Park is a hotchpotch of compromise. Recommendations that the National Park be extended to include most of the physiographical unit—which would indeed make it an unusual national park— were endorsed by cabinet in 1975 but this endorsement was rescinded by Cabinet in 1979. The competing claims for land use relate partly to pastoral and tourist interests but the main debate is likely to be related to the essence of the range itself and its structure — high grade limestone, karst, petroleum, scenery, water and wilderness. Overlying all land use proposals is a Temporary Reserve for Limestone (*TR5980H*) lying mostly within Cape Range National Park and its proposed extensions; this reserve includes most of the known highly cavernous part of Cape Range.

The proposals to extend Cape Range National Park were made in complete ignorance of the existence and significance of the troglobitic and most of the stygo-fauna, and with sparse knowledge of the cavernous nature of Cape Range. The subterranean fauna is more significant that the surface fauna which, while having a high species density, for the most part represents a concentration of species well represented in other areas. As such the additional information recently available (the subterranean fauna) represents a quantum jump in the known importance of the area and argues strongly that the Cabinet endorsement of 1975 should be reaffirmed.

## Status of the cave fishes

The status of the cave fishes of the Cape Range peninsula was extracted from *The action plan for Australian freshwater fishes* (Wager and Jackson 1993).

*Ophisternon candidum*

A poorly known species on the Threatened Fauna list under the Conservation and Land Management (CALM) Act 1984.

Ranked 21 on the recovery action priority (ranked 16 when costs are taken into account, estimated to be $187,000).

Categorised as of indeterminate status in the Australian Society for Fish Biology Threatened Species List (Jackson 1992) and the IUCN Threatened Australian Freshwater Fish List (IUCN 1990).

*Milyeringa veritas*

Not categorised in Wager and Jackson (1993) but it is on the Threatened Fauna list under the Conservation and Land Management (CALM) Act 1984, which, with *O. candidum*, are the only fish species listed under the Western Australian Act.

Categorised as of restricted status in the Australian Society for Fish Biology Threatened Species List (Jackson 1992) but is not included in the IUCN Threatened Australian Freshwater Fish List (IUCN 1990).

### Additional comments from the current work

Most species of fish in Australia have become threatened through a limited number of processes (Table 33)—while many of these are unlikely to impinge on the cave fish, some classes of disturbance could have widespread impact—these are considered below.

**Table 33**: The distribution (%, n=148) of classes of threatening processes believed to be currently impinging on Australian native freshwater fish species (extracted from Wager and Jackson 1993).

| Class of disturbance | % |
|---|---|
| Regulation or modification of flow | 11 |
| Geomorphic alteration | 36 |
| Water quality | 3 |
| Introduced exotic species | 36 |
| Introduced native species | 3 |
| Overfishing | 3 |
| Loss of genetic diversity | 7 |

Modification of water flow could potentially impinge on the populations in and downstream of borefields. Current plans to extend the Exmouth borefield southwards could affect the entire known populations on the eastern side of the peninsula. A concomitant development of borefields on the western side of the peninsula, to satisfy tourist developments already proposed, would affect the entire global distribution of the cave fish.

Geomorphic alteration is most likely to result from quarrying activities (proposed) and infilling of subterranean cavities with silt as is happening around Dozer Cave (C-23) owing to surface changes and poor land management.

Changes to water quality is potentially the most wide ranging threat to the stygofauna as a whole, as is the case worldwide—this is discussed at length in the report.

Introduced species are unlikely to be a hazard to the cave fish except in the open locations.

Overfishing could quickly deplete the cave fish populations if they aroused the interest, albeit illegal, of aquarists.

Loss of genetic diversity would result if one section of the population was eliminated (see Humphreys and Adams 1991; Adams and Humphreys 1993).

### Perceived threats to the National Estate significance of the stygofauna

### Background

Recognition (Marmonier *et al.* 1993) of the biodiversity inherent in the fauna and flora of groundwaters, their vulnerability to groundwater contamination, their functional role and their potential utility to hydrogeological investigations remains, in practice, unrecognized in Australia. In a recent (1993) conference entitled *Aquifers at risk: towards a national groundwater quality perspective* (AGSO 1993), none of the 41 paper presented mention the natural biota of aquifers (one [Evans and Bauld 1993] mentions future consideration), this despite the rich faunas present around the world in some shallow (in Australia — Humphreys 1993b, this report; Knott 1993) and deep aquifers (in USA — Longley 1981, 1992). Neither is it recognised in the *National water quality management strategy — draft guidelines for groundwater protection* (Australian Water Resources Council 1992).

In Australia examination of this stygofauna has barely begun despite it being an important component of biodiversity, its utility in monitoring the spatial limits to groundwaters (Humphreys 1993b) and, owing to its sensitivity to changes in water quality, their health (Ward *et al.* 1992). Changes to the water table (overuse, pollution and flooding) are the prime cause (48%) of troglobitic fauna becoming vulnerable through human activities (see Humphreys 1993b).

Stygofauna is easily damaged by contaminants and in many inhabited areas it has been lost from the groundwater. The presence of a diverse stygofauna below central Exmouth is a tribute to the town having been deep sewered from the start, a factor attributable to its late development (1960's) and by it having been established to support a military facility. The town has gradually diversified and its main function is now as a centre for tourism. With the large reduction in the military establishment the town is evermore dependent on the civilian economy and there is a concerted effort to diversify and expand the tourist and other facilities on the peninsula.

The habitat of the stygofauna of the Cape Range peninsula is relatively secure owing to the low intensity human usage of the area and part being already in a National Park. Nonetheless, significant areas of potential threat already exist both in the short term and the long term. In addition proposals to increase considerably the human impact on the area, to establish lime kilns and the likely further participation of the area in petroleum exploration and production all need to take into consideration at the earliest stage of planning the unique and vulnerable stygofaunal habitat.

## Groundwater contamination

"Once ... aquifers are polluted ... they will almost always remain polluted" (Keary 1993).

"Only very recently has the existence of groundwater animals .. on this continent [America] been recognised to represent a largely unappreciated reservoir of biodiversity" (Ward *et al.* 1992).

### Petroleum

Groundwater contamination by manufactured organic chemicals is widespread in Australia. In Western Australia severe contamination of the groundwater has occurred from leaking storage tanks situated both above and below ground (Davis *et al.* 1993) , with bulk storage facilities being implicated, especially petrol stations of which 20% show evidence of leakage both nationally and within Western Australia [Harwood 1991, pers. comm. and Barber 1991, pers. comm. cited in Knight 1993: 115]). The threat is both from non-aqueous phase liquid, as well as dissolved petroleum compounds which are mobile when dissolved in groundwater (Davis *et al.* 1993). Such threats are especially severe in unconfined shallow aquifers below soils of low organic matter and clay content (Notenboom and van Gestel 1992; Davis *et al.* 1993), such as those on the Cape Range peninsula, and groundwater fauna are especially vulnerable (Marmonier*et al.* 1993).

Petroleum is the most likely major contaminant on the Cape Range peninsula as bulk storage facilities are found in Exmouth, the military areas, camping grounds, and at Learmonth. Not only is this a widespread threat, it is exacerbated by the hot salty environment accelerating corrosion of the bulk storage facilities. Many bulk storage facilities have no secondary containment to prevent contamination of groundwater. In addition the dumping in low lying areas of waste petroleum has been practiced by both civil and military authorities.

Oil entering karst systems, while being invisible, is persistent (Charles 1991) as there is no photic and little microbial action and, as it evaporates in confined spaces, it may accumulate to toxic levels in the caverns. Some cave systems have animals, such as remipedes, which are halocline specialists which are lost when the halocline breaks down such as would result from the disposal of saline waste water into the superficial karst. Hence it is undesirable that either pure saline water or oil contaminated water be disposed of into the superficial karst and the World Conservation Monitoring Centre has warned against such practices (Pearce and Pain 1991). Any petroleum resource development in the region should not rely on disposing of waste products into the superficial karst.

**Refuse dumps**

Landfill refuse dumps slowly break down yielding a toxic cocktail including heavy metals, petrochemicals and nutrients. Whether or not the dumps are lined artificially the ultimate fate of this is to percolate downwards. Even dumps using natural clays as the impermeable barrier are not exempt as the leachate may change the characteristics of the clay and so breaks down the barrier. In areas of superficial groundwater below soils of low organic matter and clay content (Notenboom and van Gestel 1992), such as those on the Cape Range peninsula, the toxic leachate will reach the groundwater and may spread through the open conduits.

Landfill sites in Exmouth are routinely burnt, a procedure which reduces bulk but will accelerate the mobilisation of the waste and enhance the richness of the chemical cocktail.

**Limestone extraction**

Most of the eastern side of the Cape Range peninsula is a Temporary Reserve for Limestone (TR5980H) under the control of the Minister for Mines. There are specific proposals to extract large quantities of limestone in the head of Mowbowra Creek and to produce lime within the confines of the developed quarry. Three factors relevant to the heritage values are discussed below — the physical loss of or damage to caves, drainage of the water table and contamination of the water table.

The northern part of the range has been little explored for caves but it is known that the process of speciation in the endemic millipede genus *Stygiochiropus* has progressed much more (to full species) in this area than in more southerly parts of the range (Humphreys and Shear 1992). As this pattern of speciation is mirrored in other species in the more southerly parts of the range (Adams and Humphreys 1993), it is likely also to be a general occurrence in the northern parts. Hence the concentration of endemic species is likely to be greatest in the northern areas of the range. This needs to be considered in the evaluation of proposals that will lead to the physical removal of, or damage to caves in the area.

Several populations of melitid amphipods inhabit the caves in Cape Range at an altitude of >150 m (Humphreys and Adams 1991). They have been long isolated from their coastal and the several populations are themselves genetically isolated from each other (Adams and Humphreys 1993; Humphreys 1993b, in press b). This indicates the presence of a perched water table in Cape Range, probably lying on the Mandu Limestone. Owing to the open conduits within the water table (Humphreys and Adams 1991) any quarrying activities that penetrated to this water table would be likely to drain it, as in the geotechnical drainage of engineering works. Draining the system would not only eliminate the habitat of the Cape Range amphipod, present there for many millions of years (Humphreys 1993b), it would reduce the humidity of caves, the maintenance of which is critical for the terrestrial component of the troglobitic fauna (Humphreys 1991b), itself a relict fauna from humid forests (Harvey *et al* 1993; Humphreys 1993b).

## Lime production

Lime doubles in volume when wetted and is highly alkaline — as such the chance of accidental loss is high and the consequences potentially severe. Lime (CaO) mixed with water produces calcium hydroxide (CaOH) which occupies twice the volume. CaOH is a moderate alkali which would decrease the hydrogen ion concentration of the water from *c.* pH 7.4 to *c.* pH 12 which would make it unsuitable for occupation by the stygofauna. On mixing with groundwater it would absorb $CO_2$ and precipitate as $CaCO_3$ or, in already calcium saturated karstic groundwater, would precipitate directly. This precipitation would clog the major conduits, upset the delicate balance in the porosity of the superficial aquifer and hence the hydrogeology. The escape of lime to the groundwater would, by soaking up the carbonic and humic acids on which karstification depends, put a complete brake upon the very dynamics of cave formation (in karstic groundwater at pH 7.4 the dissolved inorganic carbon exists almost entirely as $HCO_3^-$ and the water is saturated with calcium, ideal conditions for mixing corrosion to occur), a process that conditions the water suitable for the stygofauna. The extent of this gross damage would depend primarily on the incidence of major conduits in the limestone.

Lime contaminated water percolating through the vadose (above water) limestone would completely alter the dynamics of speleothem formation and flocculate the clay beds that are important to the survival of both the stygo and troglofauna.

A current proposal lies in the catchment of Mowbowra Creek, the lower reaches of which contains the town common and one of two prime sites for the fully protected Blind Cave Eel (*Ophisternon candidum*) as well as the Blind Gudgeon, (*Milyeringa veritas*) and the atyiid shrimps (*Stygiocaris* spp.), all fully protected.

### Groundwater extraction

Groundwater on the coastal plain is near sea level and is recharged by water from higher regions in Cape Range. As such the extraction of groundwater from the foothills of Cape Range or from the coastal plain will not influence the water in the perched water tables.

In contrast, extraction will influence the groundwater at and near sea level and so influence the habitat of the stygofauna. The upwards trend in salinities with time in almost half of the WAWA bores has been attributed to water extraction from the borefield (Halpern *et al*. 1992) and the trend for salinities to decrease from north to south in the borefield has been attributed to the extraction from private and military bores to the north (*ibid.*).

Coning in the water table around production bores results in upward movement of the salt water interface below a thinning layer of fresh water. In addition it changes the flow characteristics of the water with an inward radial flow replacing a primarily unidirectional flow towards the coast. This is especially significant in the Exmouth areas as the groundwater throughflow is insufficient to support the current extraction rate of 12000-1300 ML $a^{-1}$ (Halpern *et al.* 1992). While this has the trivial effect of increasing salinity through coning and sea water intrusion, it may influence the stygofauna in more subtle ways. The stygofauna is dependent on energy entering the system from upstream sources, probably mainly as particulate organic matter (POM). Instead of a gradient of POM declining towards the coast, it should be replaced by a gradient declining towards the borefield. Hence there could be an impact on the distribution of the fauna as well as their abundance owing to the pumping of POM from the groundwater and direct loss of individuals with their contained energy.

### Marina

Proposals to build a marina in Exmouth which will extend inland about 500 m from the coast and as such impinge on areas inhabited by stygofauna. If the seawater level was maintained during marina excavation the effect of the marina should be limited to an inland progression of 500 m of the saltwater wedge.

Open conduits are present in the limestone to the north and south of the marina site and reach some depth as determined by cave divers. If the site is dewatered during construction, interception of these conduits would drain the groundwater over a large area — seawater intrusion would occur on rewatering over a much wider area than if dewatering had not been used. This is a general problem for any project bringing seawater inland and is most likely to affect *O. candidum* as this species seems to be most closely tied to the coastal strip.

### Wastewater

Wastewater from the sewage works in Exmouth is used to irrigate public areas such as ovals and parks and serves to reduce water extraction. Irrigation with wastewater is implicitly a form of groundwater recharge which will therefore affect groundwater quality potentially increasing the loadings of nutrients, nitrates and bacteria (Dillon and Schrale 1993).

In Exmouth levels of these parameters showed no significant differences between water samples collected from sites close to or further from areas where wastewater irrigation is used. This is to be expected given the small scale of the operation in Exmouth. However, should the practice become both more intensive and widespread owing to major development projects then this avenue of contamination may need to be addressed.

## Conservation

C-28 (Bundera Cenote), in the Commonwealth area south of Yardie Creek, is the only known access to the unique stygofauna inhabiting deep anchialine waters. It is the only known location of the crustacean class Remipedia outside the North Atlantic and Caribbean and of the ostracod genus *Danielopolina* in the Southern Hemisphere. Many other taxa may be expected to occur in this system as the known fauna is associated with a rich relictual crustacean fauna wherever it occurs. For example, with thermosbaenaceans*, hadziid amphipods, ostracods*, cirolanid isopods*, mysids and caridean shrimp, some (*) already known from the Cape Range peninsula. As already successfully predicted (Poore and Humphreys 1992), the prospects are good of finding additional relictual taxa on the peninsula.

*Ophisternon candidum* occupies the very habitat where people will have greatest impact. However, although it has been recorded from 11 locations, access is precarious and those five (see below) that are in good condition should receive full protection.

Access is limited because most sampling locations are in a state of decay. The identity of one is unknown (Allen 1982); Dozer Cave (C-23) is being silted up owing to runoff from a rehabilitated(!) gravel pit and the nearby Gnamma Hole (C-105) is likely to be affected so; a major resort development is planned at Babjarrimannos which will abut Wobiri Rock Hole (C-414); Mowbowra Well (C-361) is slowly being filled with rubbish is in danger of collapse as the original wooden lining has been used by termites; Pilgramunna Well (C -274) is unprotected and was dry in 1993.

The more secure sites are Milyering Well (C-24) which is well preserved and protected by a heavy steel grill but it is unused and not maintained — the entrance to Milyering cave (C -172), a traditional water place 40 m away is obstructed by a *Ficus*; Kudamurra Well (C -25) has been in continuous use for many years to supply water to a major camp site and is in good repair and fitted with a marine ply cover — Kudamurra Cave, a traditional watering place in a small rock hole, lies 20 m to the north; Tantabiddy Well (C-26) is an enlarged natural hole lined with corrugated iron, uncovered unused and not maintained. Kubura Well (C-27) in Exmouth town site is fenced, covered with a locked grill and has a permanent motor — formerly used to water town facilities it is now maintained but rarely used for irrigation; New Mowbowra Cave (C-495) is a natural cave with a very tight entrance dropping into the water — first entered 1992.

## Recommendations

### General

1. In Australia stygofauna are barely known — as they are an important component of biodiversity and useful indicators of groundwater health a concerted study of stygofauna should be undertaken in Australia.

### Specific

2. Secondary containment should be required on all bulk storage facilities on the peninsula to prevent groundwater contamination; this should be designed to prevent both lateral and vertical migration of spilled fluids.

3. The disposal of waste oil by military and civilian authorities into the general environment should cease.

4. Lime production over the superficial aquifer poses a real threat to both the karstification processes and to the stygofauna.

5. The location and management of refuse sites should be reevaluated with consideration given to the long term management to prevent leachates reaching the groundwater.

6. The landfill sites should be protected from burning.

7. The location, condition and secondary containment of petroleum bulk storage facilities should be reviewed and remedial action taken where necessary.

8. C-28 (Bundera Cenote) should be given maximum protection to protect the deep cave anchialine fauna.

9. Irrigation from waste water should be recognised as a potential contaminant of the groundwater.

10. Consultants for all development proposals need to be briefed at the earliest stage to consider in detail the implications to the project of the karstic landforms and the stygofauna, and of the project to the fauna.

11. The limited access points for *Ophisternon candidum* should be protected and, where practicable, maintained.

12. Many of the 'wells' were traditional watering places and are themselves worthy of heritage listing (detailed consideration is outside the scope of this report).

13. Examples of the deep wells dug for pastoralists early this century are worthy of heritage listing (especially Mowbowra Well and Milyering Well).

**Consultants' briefs**

Consultants for all development proposals need to be briefed to consider in detail the implications to the project of the karstic landforms and the stygofauna, and of the project to the fauna. This needs be considered at an early stage for, if the issue is to be addressed adequately, it may have major financial implications to the project.

There is consistent failure of development projects to take cognizance of the implications of karstic landforms and stygofauna as, for example, a recent major report on tourist development on the Cape Range peninsula (Jones *et al.* 1993). This failed to consider the implications with respect of water movement in the ground (p. 25), disposal of saline waste water from desalination plants (p. 23) and effluent and solid waste treatment (p. 25). In addition the consultants considered that it was adequate to line such sites with HDPE; HDPE has a limited life so it does not prevent contamination of the groundwater but simply delays its occurrence. As such active site management, at least over many decades, may be required to remove the leachate from the landfill areas, the cost being incurred by the local community.

**Specific inclusion in the Register of the National Estate for sites currently outside NE areas** (for locations see Table 34) **or in need of special status** (1).

1. Bundera Cenote (C-28): unique anchialine fauna.
2. Kubura Well (C-27): major access point to diverse stygofauna on east coast.
3. Camerons Cave ( C-452): unique coastal cave with troglo- and stygo-fauna.
4. New Mowbowra Cave (C-495): access to unique stygofauna on east coast.
5. Mowbowra Well (C-361): access to unique stygofauna, historic site (pastoral well).
6. Kudamurra (Palms) Well (C-25): type locality of *Stygiocaris lancifera* and *S. stylifera*; only place they are known to be in sympatry.
7. Breakdown Maze (C-111): type and only locality of *Stygiocaris sympatricus* Humphreys and Shear; only place where *S. communis* known to be in sympatry with congenor.
8. Loop Cave (C-222): type and only locality of *Stygiocaris isolatus* Humphreys and Shear.
9. Wobiri Rockhole (C-414): access to unique stygofauna on west coast.

**Table 34**: Coordinates of specific locations recommended for inclusion in the Register of the National Estate — the accuracy of the locations has been degraded to the nearest minute.

| | Karst Index No | Latitude | Longitude |
|---|---|---|---|
| 1 | C-25 | 21o 54' S | 113° 49' E |
| 2 | C-27 | 21o 56' S | 114° 08' E |
| 3 | C-28 | 22o 25' S | 113° 46' E |
| 4 | C-111 | 21o 55' S | 114° 00' E |
| 5 | C-222 | 21o 56' S | 114° 06' E |
| 6 | C-361 | 22o 00' S | 114° 07' E |
| 7 | C-414 | 21o 50' S | 114° 04' E |
| 8 | C-452 | 21o 58' S | 114° 07' E |
| 9 | C-495 | 22o 00' S | 114° 07' E |

# References

### Including those in the Appendices


Acworth, I. and Jankowski, J. 1993. Hydrogeochemical zonation of groundwater in the Botany Sands aquifer, Sydney. *AGSO Journal of Australian Geology and Geophysics* **14**: 193-199.

Adams, M. and Humphreys, W.F. 1993. Patterns of genetic diversity within selected subterranean fauna of th Cape Range peninsula, Western Australia: systematic and biogeographic implications. *Records of the Western Australian Museum,* Supplement No. **45**: 145-164.

AGSO. 1993. Aquifers at risk: towards a national groundwater quality perspective. *AGSO Journal of Australian Geology and Geophysics* **14**: 99-318.

Allen, A.D. 1993. Outline of the geology and hydrogeology of Cape Range, Carnarvon Basin, Western Australia. *Records of the Western Australian Museum*, Supplement No. **45**: 25-38.

Allen, G.R. 1982. *Inland Fishes of Western Australia.* Western Australian Museum, Perth.

Allen, G.R. 1989. *Freshwater Fishes of Australia.* T.F.H. Publications, Inc. Neptune City, New Jersey

Amano, H. and Kasai, A. 1988. The measurement of radon in closed air using the liquid scintillation techniques. *Radiation Protection Dosimetry* **22**: 193-195.

Amano, H., Kasai, A. and Matsunaga, T. 1985. Simultaneous measurement of Rn and its progeny in cave air by liquid scintillation techniques and a-ray spectrometry. *Health Physics* **49**: 509-511.

American Public Health Association (APHA), American Water Works Association, and Water Pollution Control Federation. 1985. *Standard methods for the examination of water and waste water*, 16th edition. American Public Health Association, Washington, D.C.

Australian Water Resources Council. 1992. *National water quality management strategy — draft guidelines for groundwater protection.* Australian Water Resources Council, Melbourne.

Banarescu , P. 1990. *Zoogeography of Fresh Waters. Volume 1. General Distribution and Dispersal of Freshwater Animals.* AULA-Verlag, Weisbaden.

Barnard, J.L. and Barnard, C.M. 1983. *Freshwater Amphipoda of the World. I Evolutionary Patterns.* Hayfield Associates, Virginia, USA.

Bloom, A. 1969. *The surface of the earth.* Prentice Hall Inc., Englewood Cliffs, New Jersey.

Bolgi, A. 1964. Mischungskorrosion: ein Beitrag zum Verkarstungsproblem. *Erdkunde* **18**: 83-92.

Bousfield, E.L. 1973. *Shallow-water gammaridean Amphipoda of New England.* Cornell University Press, Ithaca.

Bowman, T.E. and Iliffe, T.M. 1986. *Halosbaena fortunata*, a new thermsobaenacean crustacean from the Jameos del Agua marine lava cave, Lanzarote, Canary Islands. *Stygologia* **2**: 84-89.

Bruce, A.J. 1992. *Pycnisia raptor*, a new genus and species of predatory troglobic shrimp (Crustacea: Decapoda: Atyidae) from Northern Australia. *Invertebrate Taxonomy* **6**: 553-566.

Bruce, N.L. and Humphreys, W.F. 1993. *Haptolana pholeta* sp. nov., the first subterranean flabelliferan isopod crustacean (Cirolanidae) from Australia. *Invertebrate Taxonomy* **7**: 875-884.

CALM. 1987. Parks and reserves of the Cape Range peninsula. Part 1: Cape Range National Park draft management plan: 1987-1997. Department of Conservation and Land Management, Perth.

Cals, P. and Boutin, C. 1985. Découverte au Cambodge, domaine ancien de la Tethys orientale, d'un nouveau 'fossil vivant' *Theosbaena cambodjiana* n.g., n.sp. (Crustacea, Thermosbaenacea). *Comptes Rendus Hebdomadaire des Séances de l'Académie des Sciences, Paris, série D*, **300** (8): 337-340.

Carter, T. 1903. The exploration of the North-West Cape: Part I. *The Emu* **3**: 30-38.

Carter, V. 1987. *No sundays in the bush: an english jackeroo in Western Australia 1887-1889*. Lothian Publishing Company, Melbourne.

Charles, D. 1991. Squeezing the deserts dry. *New Scientist* No. 1786: 22-26.

Culver, D.C. 1982. *Cave life evolution and ecology*. Harvard University Press, Cambridge, Massachusetts & London, England.

Cummins, K.W. and Wuycheck, J.C. 1971. Caloric equivalents for investigations in ecological energetics. *Mitteilungen Internationale Vereinigung für Theoretische und Angewandte Limnologie* No. 18.

Cvetkov, L. 1968. Un filet phréatobiologique. *Bulgarska Akademiya na Naukite, Otdeleniye za Biologichni Nauki, Zoologicheski Institut si Muzey, Izvestiya* **27**: 215-218.

Dalens, H. 1992. Oniscidea (Crustacea, Isopoda) from caves of Cape Range in Western Australia. *I*. The genus *Buddelundia*. *Records of the Western Australian Museum* **16**: 87-102.

Danielopol, D.L. 1984. Ecological investigations on the alluvial sediments of the Danube in the Vienna area — a phreatobiological project. *Verhandlungen, Internationale Vereinigung fuer Theoretische und Angewandt e Limnologie* **22**: 1755-1761.

Davis, G.B., Johnston, C.D., Thierrin, J., Power, T.R. and Patterson, B.M. 1993. Characterising the distribution of dissolved and residual NAPL petroleum hydrocarbons in unconfined aquifers to effect remediation. *AGSO Journal of Australian Geology and Geophysics* **14**: 243-248*AGSO*

Deeleman-Reinhold, C.L. 1993. *Trichocyclus septentrionalis* n. sp. a new species of cave dwelling pholcid spider from northwestern Australia (Araneae: Pholcidae). *Records of the Western Australian Museum* **16**: 323-329.

Dillon, P.J. and Schrale, G. 1993. Wastewater irrigation and groundwater quality protection. *Journal of Australian Geology and Geophysics* **14**: 259-262.

Eheman, C., Carson, B., Rifenburg, J. and Hofman, D. 1991. Occupational exposure to radon daughters in Mammoth Cave National Park. *Health Physics* **60**: 831-835.

Ellis, B.M. 1976. Cave surveys. Pp. 1-10 *in* T.D. Ford and C.H.D. Cullingford (Eds). *The science of speleology*. Academic Press, London.

Ernst, W. 1980. Effects of pesticides and related organic compounds in the sea. *Helgolander Wissenschaftliche Meeresuntersuchungen* **33**: 301-12.

Evans, W.R. and Bauld, J. 1993. Towards an Australian groundwater quality assessment program. *AGSO Journal of Australian Geology and Geophysics* **14**: 307-311.

Ford, D.C. and Williams, P.W. 1989. *Karst geomorphology and hydrology*. Unwin Hyman, London.

Forth, J. R. 1972. *Exmouth water supply*. Survey Record 1972/16. Geological Survey of Western Australia, Perth

Forth, J. R. 1973. Exmouth water supply. pp. 11-15. *Geological Survey of Western Australia, Annual Report 1972*.

Freeze, R.A. and Cherry, J.A. 1979. *Groundwater*. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Gibert, J. 1990. Behavior of aquifers concerning contaminants: differential permeability and importance of the different purification processes. *Water Science and Technology* **22**: 101-108.

Guilcher, A. 1988. *Coral reef geomorphology*. Wiley, Chichester .

Hakenkamp, C.C. and Palmer, M.A. 1992. Problems associated with quantitative sampling of shallow groundwater invertebrates. Pp. 101-110 *in* J.A. Stanford and J.J. Simons (eds). *Proceedings of the First International Conference on Groundwater Ecology*. American Water Resources Association, Bethesda, Maryland.

Hallberg, G.R. 1989. Nitrate in groundwater in the United States. 35-74 *in* Follett, R.F. (ed.). *Nitrogen management in groundwater protection*. Developments in Agriculture and Managed Forest Ecology 21. Elsevier, Amsterdam.

Halpern, Glick and Maunsell Pty Ltd. 1992. *Exmouth water supply:water services and levels of service assessment*. 3 vols. Halpern, Glick and Maunsell Pty Ltd., Water Authority of Western Australia.

Harvey, M.S. 1988. A new troglobitic schizomid from Cape Range, Western Australia (Chelicerata: Schizomida). *Records of the Western Australian Museum* **14**: 15-20.

Harvey, M.S. 1991. The cavernicolous pseudoscorpions (Chelicerata: Pseudoscorpionida) of Cape Range, Western Australia. *Records of the Western Australian Museum* **15**: 487-502.

Harvey, M.S. 1992. The Schizomida (Chelicerata) of Australia. *Invertebrate Taxonomy* **6**: 77-129.

Harvey, M.S., 1993. The systematics of the Hyidae (Pseudoscorpionida). *Invertebrate Taxonomy* **7**: 1-32.

Harvey, M.S., Gray, M.R., Hunt, G.S. and Lee, D.C. 1993. The cavernicolous Arachnida and Myriapoda of Cape Range, Western Australia. *Records of the Western Australian Museum*, Supplement No. **45**: 129-144.

Harvey, M.S. and Humphreys, W.F. in press. A new troglobitic schizomid from Cape Range. *Records of the Western Australian Museum*, Supplement No.

Hoch, H. 1993. A new troglobitic planthopper species (Homoptera: Fulgoroidea: Meenoplidae) from Western Australia. *Records of the Western Australian Museum* **16**: 393-398.

Hocking, R.M, Moors, H.T. and van de Graaff, W.J.E. 1987. Geology of the Carnarvon Basin, Western Australia. *Geological Survey of Western Australia, Bulletin* **133**: 1-289.

Holthuis L.B. 1960. Two new species of Atydid shrimps from subterranean waters of N.W. Australia (Decapoda Natantia). *Crustaceana* **1**: 47-57.

Howarth, F.G. 1973. The cavernicolous fauna of Hawaiian lava tubes. I. Introduction. *Pacific Insects* **15**: 139-151.

Howarth, F.G. 1981. Non-relictual terrestrial troglobites in the tropics: Hawaiian caves. *Proceedings of the 8th International Congress of Speleology* **2**: 539-541.

Humphreys, W.F. 1989. *The status of relict cave fauna of Cape Range, Western Australia, especially the Schizomida*. Unpublished report to the Australian National Parks and Wildlife Service, Canberra. 104 pp.

Humphreys, W. F. 1990. The biology of a troglobitic schizomid (Chelicerata: Arachnida) from caves in the semi-arid Cape Range, Western Australia. *Acta zoologica Fennica* **190**: 181-186.

Humphreys, W. F. 1991a. Biological research into the Cape Range karst area, North West Cape peninsula, Western Australia. Pp 6-14 *in* Brooks, S. (Ed.). *Cave Leeuwin - Proceedings of the 18th Biennial Conference of the Australian Speleological Federation Inc., Margaret River, Western Australia. 30 December 1990-5 January 1991.* Australian Speleological Federation Inc., Nedlands, Western Australia. 113 pp.

Humphreys, W. F. 1991b. Experimental re-establishment of pulse-driven populations in a terrestrial troglobite community. *Journal of Animal Ecology* **60**: 609-623.

Humphreys, W.F. 1991c. *Survey of caves in Cape Range, North West Cape peninsula, Western Australia.* Unpublished report to the Australian Heritage Commission and the Western Australian Heritage Committee. 178 pp.

Humphreys, W.F. 1991d. Troglobites on Barrow Island, Western Australia. *The Western Caver* **31**:11-14.

Humphreys, W.F. 1991e. *The Cave fauna of Cape Range: specific analyses.* Unpublished report to the Australian National Parks and Wildlife Service, Canberra. 132 pp.

Humphreys, W.F. (Ed.). 1993a. **The biogeography of Cape Range, Western Australia.** *Records of the Western Australian Museum,* Supplement No. **45**: 1-248.

Humphreys, W.F. 1993b. The significance of the subterranean fauna in biogeographical reconstruction: examples from Cape Range peninsula, Western Australia. *Records of the Western Australian Museum,* Supplement No. **45:** 165-192.

Humphreys, W.F. in press a. Cave fauna in semi-arid tropical Western Australia: a diverse relict wet-forest litter fauna. *Mémoires de Biospéologie* .

Humphreys, W.F. in press b. Stygofauna in semi-arid tropical Western Australia: a Tethyan connection? *Mémoires de Biospéologie* .

Humphreys, W. F. and Adams, M. 1991. The subterranean aquatic fauna of the North West Cape peninsula, Western Australia. *Records of the Western Australian Museum* **15***:* 383-411.

Humphreys, W.F., Adams, M. and Vine, B. 1989. The biology of *Schizomus vinei* (Chelicerata: Schizomida) in the caves of Cape Range, Western Australia. *Journal of Zoology, London* **217**: 177-201.

Humphreys, W.F., Brooks, R. D. and Vine, B. 1990. Rediscovery of the palm *Livistona alfredii* on the North West Cape Peninsula. *Records of the Western Australian Museum* **14**: 647-650.

Humphreys, W.F. and Collis, G. 1990. Water loss and respiration of cave arthropods from Cape Range, Western Australia. *Comparative Biochemistry and Physiology* **95A**: 101-107.

Humphreys, W.F. and Shear, W.A. 1993. Troglobitic millipedes (Diplopoda: Paradoxosomatidae) from semi-arid Cape Range, Western Australia - systematics and biology. *Invertebrate Taxonomy* **7**: 173-195.

Humphreys, W.F. and Vine, B. 1991. *The caves of Barrow island and their fauna.* Unpublished report to West Australian Petroleum Pty Ltd.

Iliffe, T.M., Jickells, T.D. and Brewer, M.S. 1984. Organic pollution of an inland marine cave from Bermuda. *Marine Environmental Research* **12**: 173-189.

IUCN. 1990. 1990. *IUCN Red list of threatened animals.* IUCN World Conservation Monitoring Centre, Cambridge.

Jackson, P.D. 1992. Australian threatened fishes—1992 Supplement. *Australian Society for Fish Biology Newsletter* **22**(2): 19-24.

Jacobson, G. and Hill, P.J. 1980. Hydrogeology of a raised coral atoll, Niue Island, South Pacific. *Journal of Australian Geology and Geophysics* **5**: 271-278.

Jones Lang Wootton. 1993. *North West Cape Tourism Development Study* prepared for the Department of Resources Development, Perth.

Keary, J.B. 1993. National groundwater protection guidelines for Australia. *Journal of Australian Geology and Geophysics* **14**: 303-306.

Kendrick, G.W., Wyrwoll, K-H, and Szabo, B.J. 1991. Pliocene - Pleistocene coastal events and history along the western margin of Australia. *Quaternary Science Reviews* **10**: 419-439.

Kensley, B. and Schotte, M. 1989. *Guide to the marine isopod crustaceans of the Caribbean.* Smithsonian Institution, Washington, D.C.

Knight, M.J. 1993. Organic chemical contamination of groundwater in Australia — an overview to 1993. *AGSO Journal of Australian Geology and Geophysics* **14**: 107-122.

Knott, B. 1993. Stygofauna from Cape Range peninsula, Western Australia: Tethyan relicts. *Records of the Western Australian Museum,* Supplement No. **45**: 109-127.

Leary, R.F. and Allendorf, F.W. 1989. Fluctuating assymetry as an indicator of stress: implications for conservation biology. *Trends in Ecology and Evolution* **4**: 214-217.

Longley, G. 1981. The Edwards Aquifer: earth's most diverse groundwater ecosystem? *International Journal of Speleology* **11**: 123-128.

Longley, G. 1992. The subterranean aquatic ecosystem of the Balcones Fault Zone Edwards Aquifer in Texas - threats from overpumping. Pp. 291-300 *in* J.A. Stanford and J.J. Simons (eds). *Proceedings of the First International Conference on Groundwater Ecology.* American Water Resources Association, Bethesda, Maryland.

Lyons, R.G. 1992. Radon hazard in caves: a monitoring and management strategy. *Helictite* **30**(2): 33-40.

Marmonier, P., Vervier, P., Gibert, J. and Dole-Olivier, M-J. 1993. Biodiversity in ground waters. *Trends in Ecology and Evolution* **8**: 392-395.

Martin, M.W. 1990. *Exmouth town water supply investigation report and recommendations for future work.* Hydrogeology Report No 1990/36. Western Australian Geological Survey, Perth. Unpublished.

Matthews, P.G. 1985. *Australian karst index 1985.* Australian Speleological Federation Inc., Broadway, New South Wales.

Mees, G.F. 1962. The subterranean fauna of Yardie Creek station, North West Cape, Western Australia. *Journal of the Royal Society of Western Australia* **45**: 24-32.

Messana, G. 1988. Stygobitic isopods of East Africa. *Biogeographica* **14**: 113-124.

Messana, G. and Chelazzi, L. 1984. The fauna of subterranean waters of East Africa, and particularly of Somalia. *Stygologia* **2**: 339-351.

Millidge, A.F. 1993. Three new species of the spider family Linyphiidae from Australia (Araneae). *Records of the Western Australian Museum* **16**: 211-219.

Monod, T. and Cals, P. 1988. Systématique et évolution des Thermosbénacés (Arthropodes, Crustacés), d'après l'ordonnance des structures épidermiques superficielles. *Comptes Rendus de l'Académie des Sciences, Paris* **306** (Série III): 99-108.

Moore, B.P. and Humphreys, W.F. in press. Australie. Pp XXX-XXX *in* C. Juberthie and V. Decu (eds). *Encyclopedia Biospeleologica.* Laboratoire souterrain du CNRS, Moulis, France.

Morse, K. 1993. Who can see the sea? Prehistoric Aboriginal occupation of the Cape Range peninsula. *Records of the Western Australian Museum,* Supplement No. **45**: 227-242.

Moyle, P.B. and Cech, J.J. 1982. *Fishes: an introduction to ichthyology.* Prentice-Hall, Inc., New Jersey.

Mylroie, J.E. and Balcerzak, W.J. 1992. Interaction of microbiology and karst processes in Quaternary carbonate island aquifers. Pp. 37-46 *in* J.A. Stanford and J.J. Simons (eds). *Proceedings of the First International Conference on Groundwater Ecology*. American Water Resources Association, Bethesda, Maryland.

Nelson, J.S. 1984. *Fishes of the World.* Second edition. Wiley-Interscience, New York.

Newman, W.A. 1991. Origins of southern hemisphere endemism, especially among marine crustacea. *Memoires of the Queensland Museum* **31**: 51-76.

Notenboom, J. and van Gestel, K. 1992. Assessment of toxicological effects of pesticides on groundwater organisms. Pp. 311-317 *in* J.A. Stanford and J.J. Simons (eds). *Proceedings of the First International Conference on Groundwater Ecology*. American Water Resources Association, Bethesda, Maryland.

O'Driscoll, E.P. 1963. Report on groundwater prospects Exmouth township. *Western Australia Geological Survey Hydrogeology Report No.46* (unpublished).

Pearce, F. and Pain, S. 1991. Oil from Kuwait still pumping into the desert. *New Scientist* No. 1794: 6.

Plenet, S. Marmonier, P., Gibert, J., Stanford, J.A., Bodergat, A-M. and Schmidt, C.M. 1992. Groundwater hazard evaluation: a perspective for the use of interstitial and benthic invertebrates as sentinels of aquifer metallic contamination. Pp. 319-329 *in* J.A. Stanford and J.J. Simons (eds). *Proceedings of the First International Conference on Groundwater Ecology*. American Water Resources Association, Bethesda, Maryland.

Poore, G.C.B. and Humphreys, W.F. 1992. First record of Thermosbaenacea (Crustacea) from the Southern Hemisphere: a new species from a cave in tropical Western Australia. *Invertebrate Taxonomy* **6**: 719-725.

Rathe, G. 1990. *The wreck of the barque* Stefano *off the North West Cape of Australia in 1875.* Hesperian Press, Carlisle, Western Australia.

Rosen, D.E. and Greenwood, P.H. 1976. A fourth neotropical species of synbranchid eel and the phylogeny and systematics of synbranchiform fishes. *Bulletin of the American Museum of Natural History* **157**: 1-70.

Roth, L.M. 1991. A new cave-dwelling cockroach from Western Australia (Blattaria: Nocticolidae). *Records of the Western Australian Museum* **15**: 17-21.

Schram, F.R. 1986. *Crustacea.* Oxford University Press, Oxford.

Shear, W. A. 1992. A new genus and two new species of millipedes from Cape Range, Western Australia (Diplopoda, Polydesmida, Paradoxosomatidae). *Records of the Western Australian Museum* **15**: 777-784.

Slack-Smith, S.M. 1993. The non-marine molluscs of the Cape Range peninsula, Western Australia. *Records of the Western Australian Museum,* Supplement No. **45**: 87-107.

Schminke, H.K. 1986. Syncarida. Pp 389-404 *in* L. Botosaneanu (ed.). *Stygofauna Mundi. A Faunistic, Distributional, and Ecological Synthesis of the World Fauna inhabiting Subterranean Waters.* E.J. Brill/Dr.W.Backhuys, Leiden.

Schram, F.R., Yager, J. and Emerson, M.J. 1986. Remipedia. Part 1. Systematics. *San Diego Society of Natural History Memoir* **15**: 1-60.

Sofoulis, J. 1951. Notes on water supply, Exmouth Gulf area. pp. 70-71. *Geolological Survey of Western Australia, Annual Report 1949.*

Sturm, H. and Smith, G.B. 1993. New bristle tails (Meinertellidae, Machiloidea, Archaeognatha, Insecta) from Australia. *Journal of the Australian Entomological Society* **32**: 233-240.

Thinès, G. and Proudlove, G. 1986. Pisces. Pp 709-733 *in* L. Botosaneanu (ed.). *Stygofauna Mundi. A Faunistic, Distributional, and Ecological Synthesis of the World Fauna inhabiting Subterranean Waters.* E.J. Brill/Dr.W.Backhuys, Leiden.

Toyne, P. 1993. Keynote address: aquifers at risk. *AGSO Journal of Australian Geology and Geophysics* **14**: 101-105.

Truswell, E.M. 1990. Australian Rainforest: the 100 million year record. Pp. 7-22 *in* L.J. Webb and J. Kikkawa (eds). *Australian Tropical Rainforest, Science - Values - Meaning.* CSIRO, Melbourne.

van de Graaff, W.J.E., Denman, P.D. and Hocking, R.M. 1976. Emerged Pleistocene marine terraces on Cape Range, Western Australia. *Western Australia Geological Survey*, Annual Report **1975**: 62-70.

van de Graaff, W.J.E., Denman, P.D., Hocking, R.M. and Baxter, J.L. 1980. *Yanrey-Ningaloo, Western Australia - 1: 250,000 geological series explanatory notes.* Western Australia Geological Survey, Perth.

Vine, B., Knott, B. and Humphreys, W.F. 1988. Observations on the environment and biology of *Schizomus vinei* (Chelicerata: Schizomida) from Cape Range, Western Australia. *Records of the Western Australian Museum* **14**: 21-34.

Vollenweider, R.A. 1976. Advances in defining critical loading levels for phosphorous in lake eutrophication. *Memorie, Istituto Italiano di Idriobiologia* **33**: 53-83.

Wager, R. and Jackson, P. 1993. *The action plan for Australian freshwater fishes.* Australian Nature Conservation Agency, Canberra.

Ward, J.V., Voelz, N.J. and Marmonier, P. 1992. Groundwater faunas at riverine sites receiving treated sewage effluent. Pp. 351-364 *in* J.A. Stanford and J.J. Simons (eds). *Proceedings of the First International Conference on Groundwater Ecology*. American Water Resources Association, Bethesda, Maryland.

Whitley, G. P. 1945. New sharks and fishes from Western Australia. Part 2. *Australian Zoologist* **11**: 35-37.

Wilkens, H. Parzefall, J. and Iliffe, T.M. 1986. Origin and age of the marine stygofauna of Lanzarote, Canary Islands. *Mitteilungen Hamburgisches Zoologische Museum und Institut* **83**: 223-230.

Williams, W.D. 1964. Subterranean freshwater prawns (Crustacea: Decapoda: Atyidae) in Australia. *Australian Journal of Marine and Freshwater Research* **15**: 93-106.

Wyrwoll, K-H. 1993. An outline of Late Cenozoic palaeoclimatic events in the Cape Range region. *Records of the Western Australian Museum,* Supplement No. **45**: 39-50.

Wyrwoll, K-H., Kendrick, G.W. and Long, J.A. 1993. The geomorphology and Late Cenozoic geological evolution of the Cape Range - Exmouth Gulf region. *Records of the Western Australian Museum*, Supplement No. **45**:1-23.

Yager, J. 1981. Remipedia, a new class of crustacean from a marine cave in the Bahamas. *Journal of Crustacean Biology* **1**: 328-333.

Yager, J. 1991. The Remipedia (Crustacea): recent investigations of their biology and phylogeny. *Verhandlungen, Deutsche Zoologische Gesellschaft* **84**: 261-269.

# Appendices

**Appendix A:** Sites visited during the field programme.

**Appendix B**: Location, names and major stygofauna associated with 98 water samples at 95 sample locations on or near the Cape Range peninsula.

**Appendix C**: Site specific data from routine water analysis of 98 samples from 95 subterranean systems on and near the Cape Range peninsula.

**Appendix D**: Physico-chemical characteristics of water inhabited by various taxa of stygofauna.

**Appendix E**: Descriptions of the main wells through which access to the stygofauna is facilitated on the Cape Range peninsula.

**Appendix F**: Surveys and photographs of access points to the stygofauna on the coastal plain of the Cape Range peninsula.

**Appendix G**: Radon in caves.

# Appendix A

## Sites visted during the field program

## Appendix A: Glossary

1— Name or description ( O=Onslow trip; GB= Giralia-Bullara trip)

2—Karst Index number

3—Description etc

4—Sampled for fauna

5—Water sample number

6—Conductivity (mS $cm^{-1}$)

7—Temperature of water ($^{o}C$)

8—Decimal latitude (degraded)

9— Decimal longitude (degraded)

**Appendix A:** Sites visted during the field program (n=260). See facing page for key.

| Name | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| Gnamma Hole | C-105 | Cave | √ | 29 | 1.33 | 29.8 | 21.98 | 114.12 |
| Planet Fisheries old well | | well | √ | | 26.80 | 27.3 | 22.20 | 114.07 |
| Woolcott Well | C-462 | well | √ | 4 | 2.25 | 29.4 | 22.22 | 114.06 |
| Guppy Pool: Tank overflow pool | | | | | 3.35 | 20.5 | 22.12 | 114.06 |
| Rifle Range bore | | | √ | 27 | 5.39 | 30.0 | 22.03 | 114.11 |
| Camel Well | | | | | | | 22.03 | 114.11 |
| Harbour piezometer B | | | √ | 58 | 19.90 | 26.9 | 21.95 | 114.13 |
| Harbour piezometer A | | | √ | | 53.50 | 25.4 | 21.95 | 114.13 |
| Harbour piezometer D | | | √ | | 16.10 | 28.7 | 21.95 | 114.14 |
| Piezometer near Camerons Cave | | | | | | | 21.97 | 114.12 |
| Camerons Cave | C-452 | Cave | √ | 31 | | | 21.97 | 114.12 |
| Qualing Pool | C-488 | Soak | √ | | | | 21.02 | 114.12 |
| BOA unused WAWA bore | | WAWA bore | √ | 10 | | | 22.00 | 114.09 |
| BOB unused WAWA bore | | WAWA bore | √ | | | | 22.00 | 114.10 |
| BOC unused WAWA bore | | WAWA bore | √ | 11 | | | 22.00 | 114.10 |
| BOD unused WAWA bore | | WAWA bore | √ | | | | 21.99 | 114.10 |
| BOE unused WAWA bore | | WAWA bore | √ | 12 | | | 21.99 | 114.10 |
| BOF unused WAWA bore | | | √ | | | | 21.99 | 114.10 |
| Pebble mound mouse | | | | | | | 21.99 | 114.10 |
| Oil dump in gravel pit | | | | | | | 21.97 | 114.13 |
| BOG unused WAWA 28 | | WAWA bore | √ | 51 | | | 21.96 | 114.11 |
| BOH unused WAWA bore | | WAWA bore | √ | | | | 21.95 | 114.08 |
| Bore 18 Cave | C-498 | Cave | | | | | 21.94 | 114.10 |
| Bore 43 Cave | C-499 | Cave | | | | | 21.94 | 114.10 |
| WAWA 44 production out | | WAWA bore | √ | 46 | | | 21.94 | 114.10 |
| Mowbowra Well | C-361 | Well | √ | 28 | 3.17 | 26.6 | 21.99 | 114.12 |
| New Mowbowra Cave | C-495 | Cave | √ | 60 | 2.10 | 29.0 | 21.99 | 114.12 |
| Salt water bore A | | Old bore | √ | | 11.60 | 29.3 | 21.82 | 114.14 |
| Salt water bore B | | Shothole | √ | 1 | 43.40 | 27.9 | 21.82 | 114.09 |
| | C-167 | Cave | | | | | 22.15 | 114.00 |
| | C-126 | Cave | | | | | 22.15 | 114.00 |
| | C-118 | Cave | | | | | 22.16 | 113.99 |
| Learmonth gravel pit bore | | Bore | √ | 2 | 9.80 | 28.7 | 22.26 | 114.07 |
| Nabalgee Well | | Well | √ | 3 | | | 22.26 | 114.07 |
| Woolcott Well | | Well | √ | | | | 22.22 | 114.06 |
| North West Seafoods Bore | | Bore | | | | | 22.20 | 114.05 |
| Ned's Well | C-282 | Well | | | | | 21.89 | 114.11 |
| Area B#2: Harold E. Holt | | Bore | √ | 5 | | | 21.90 | 114.11 |
| Area B#3: Harold E. Holt | | Bore | √ | | | | 21.90 | 114.11 |
| Quarry Harold E. Holt Area B | | | | | | | 21.90 | 114.11 |
| Area B#27: Harold E. Holt | | Bore | √ | 6 | | | 21.89 | 114.09 |
| Area B#20: Harold E. Holt | | Bore | √ | | | | 21.89 | 114.09 |
| Area B#6: Harold E. Holt | | Bore | √ | | | | 21.90 | 114.10 |
| Area B#21: Harold E. Holt | | Bore | √ | | | | 21.89 | 114.09 |
| Area A#AA1: Harold E. Holt | | Bore | √ | | 59.80 | 28.3 | 21.83 | 114.17 |
| Area A#AA2: Harold E. Holt | | Bore | √ | | 1.07 | 27.8 | 21.83 | 114.17 |
| Area A#AA3: Harold E. Holt | | Bore | √ | | 19.10 | 27.9 | 21.82 | 114.18 |
| Area A#AA4: Harold E. Holt | | Bore | √ | | 51.00 | 26.7 | 21.82 | 114.18 |
| Area C:#1 | | Bore | √ | | | | 22.34 | 114.04 |
| Area C:#2 | | Bore | √ | | | | 22.34 | 114.04 |
| Area C:#3 | | Bore | √ | 7 | | | 22.34 | 114.03 |
| North trial N1: test bore | | WAWA test bore | √ | 96 | 2.97 | 28.7 | 21.94 | 114.09 |
| North trial N2: B/90 | | WAWA test bore | √ | 95 | 0.90 | 30.1 | 21.93 | 114.08 |
| North trial N3: E4/90) | | WAWA test bore | √ | | | | 22.34 | 114.03 |
| North trial N4: test bore | | WAWA test bore | √ | 19 | | | 22.34 | 114.03 |
| 14 Fyfe Street Exmouth | | Rainwater | | 8 | | | 21.93 | 114.12 |
| Mowbowra Cave | C-136 | | | | | | 21.99 | 114.12 |
| South trial S1: 1/89 site A | | WAWA test bore | √ | 9 | | | 21.94 | 114.10 |

| Name | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| South trial S2: also BOH; 3/89 | | WAWA test bore | √ | | | | 21.95 | 114.09 |
| South trial S3: 2/90 | | WAWA test bore | √ | 18 | | | 21.95 | 114.09 |
| South trial S4: 5/89 | | WAWA test bore | √ | | | | 21.95 | 114.08 |
| South trial S5: 5/89 | | WAWA test bore | √ | | | | 21.95 | 114.08 |
| South trial S6: 4/89 | | WAWA test bore | √ | | | | 21.95 | 114.07 |
| Rockshelter | | | | | | | 21.95 | 114.08 |
| Trial Harbour, North piezometer | | piezometer | √ | 32 | 11.80 | 29.0 | 21.95 | 114.14 |
| BOJ: | | WAWA test bore | √ | | | | 21.99 | 114.09 |
| BOK: | | Dry | √ | | | | 21.99 | 114.10 |
| WAWA road extension BHP trail | | waypoint | | | | | 21.97 | 114.08 |
| WAWA road extension BHP trail | | trial blast | | | | | 21.97 | 114.06 |
| WAWA road extension BHP trail | | air blast holes | | | | | 21.97 | 114.09 |
| WAWA road extension BHP trail | | concrete filled bore | | | | | | 21.97 |
| 114.09 | | | | | | | | |
| WAWA road extension BHP trail | | concrete filled bore | | | | | | 21.97 |
| 114.09 | | | | | | | | |
| Cashen Well (Ex. Gulf Stn.) | | well | √ | 14 | 0.99 | 23.9 | 22.48 | 114.10 |
| Home Well (Ex. Gulf Stn.) | | well: not GPS | √ | 13 | 9.16 | 28.7 | 22.38 | 114.11 |
| Billy Well 3: | | bore | √ | 15 | 2.13 | 29.4 | 22.38 | 114.02 |
| Billy Well 2: | | bore dry | | | | | 22.38 | 114.02 |
| Billy Well 1 | | bore working | | | | | 22.38 | 114.01 |
| Wagetti Well | | Well not GPS | √ | 16 | 3.76 | 28.8 | 22.33 | 114.05 |
| Main Roads Bore | | Bore | √ | | 18.30 | 28.7 | 22.38 | 114.06 |
| Qualing Pool | C-488 | Soak | √ | | | | 22.02 | 114.12 |
| Mandu Mandu Bore | | not GPS | | | | | 22.15 | 113.88 |
| Milyering Well | C-24 | not GPS | √ | 24 | 9.75 | 25.8 | 22.02 | 113.93 |
| Milyering Quaters Bore #1 | | not GPS | √ | | | | 22.03 | 113.93 |
| Milyering Quaters Bore #2 | | not GPS | √ | | | | 22.03 | 113.93 |
| Upper Bulbarli Well | W1 | | √ | 33 | 1.13 | 23.6 | 23.50 | 113.77 |
| Bulbarli Well | W2 | | √ | 34 | 2.52 | 23.3 | 23.53 | 113.76 |
| Waroora Well | W3 | | √ | 35 | 14.20 | 19.6 | 23.49 | 113.79 |
| Quarry (Wapet) | | | | | | | 23.51 | 113.89 |
| Wapet Artesian Bore#1 | W4 | | √ | 36 | 13.60 | | 23.51 | 113.92 |
| Wapet Artesian Bore#2 | W5 | | √ | 37 | 13.40 | 57.7 | 24.27 | 113.90 |
| Corbett Well | W6 | | √ | 38 | | | 23.24 | 113.92 |
| Old Well in abandoned airstrip | | | | | | | 21.98 | 114.11 |
| Ningaloo Homestead Well | W7 | | √ | 39 | 7.14 | 22.8 | 22.70 | 113.68 |
| Javis Well (W8) | C-362 | | √ | 40 | 11.20 | 22.6 | 22.60 | 113.69 |
| Lighthouse Well | W9 | | √ | 41 | 13.10 | 22.5 | 22.69 | 113.68 |
| Perth Hill well (unnamed) | W10 | | √ | 42 | 4.38 | 26.2 | 22.71 | 113.69 |
| 10 Mile Well | W11 | | √ | 43 | 8.76 | 25.9 | 22.78 | 113.77 |
| 4 Mile Well | W12 | | √ | 44 | 15.50 | 25.8 | 22.73 | 113.76 |
| Pilgramunna Well | C-274 | | √ | 20 | 14.90 | | 22.19 | 113.87 |
| Tulki Well | C-149 | | √ | 21 | 8.63 | 24.4 | 22.09 | 113.90 |
| Five Mile Well | C-273 | | √ | 22 | 8.18 | 26.2 | 21.85 | 113.87 |
| Palms Well (Kudamurra) | C-25 | | √ | 23 | 4.99 | 28.2 | 21.89 | 113.82 |
| | C-215 | | √ | 25 | 2.19 | | 22.03 | 113.93 |
| Wanderers Delight | C-163 | | √ | 26 | | | 22.15 | 114.00 |
| Horack's Well | C-440 | | √ | 30 | 2.84 | 23.6 | 21.97 | 114.13 |
| Kubura Well | C-27 | | √ | 45 | | | 21.93 | 114.13 |
| Amphipod Well | C-413 | | √ | 47 | 4.15 | 27.9 | 21.97 | 114.13 |
| Wapet (Learmonth) Jetty | | sea water | | 48 | | | 22.21 | 114.10 |
| Dozer Cave | C-23 | | √ | 49 | 1.16 | 24.5 | 21.98 | 114.12 |
| WAWA 47 | | | √ | 50 | | | 21.98 | 114.10 |
| Exmouth Town Bore E6 | E6 | | √ | 52 | 2.47 | 28.4 | 21.94 | 114.13 |
| Exmouth Town Bore E5 | E5 | | √ | 53 | | | 21.94 | 114.13 |
| Exmouth Town Bore E7 | E7 | | √ | 54 | 16.40 | 27.4 | 21.94 | 114.13 |
| Exmouth Town Bore E1 | E1 | | √ | 55 | 4.99 | | 21.93 | 114.12 |
| Exmouth Town Bore E4 | E4 | | √ | 56 | 6.15 | 27.6 | 21.93 | 114.12 |

| Name | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| Exmouth Town Bore E3 | E3 | | √ | 57 | 1.76 | 25.8 | 21.93 | 114.13 |
| Exmouth Town Bore E2 | E2 | | √ | 86 | 5.82 | | 21.93 | 114.12 |
| Exmouth Town Bore E9 | E9 | | √ | | 1.21 | 25.9 | 21.93 | 114.12 |
| Racecourse Bore E8 | E8 | | √ | | | | 21.96 | 114.13 |
| WAWA 46A | | Bore never used | √ | 59 | | | 21.96 | 114.10 |
| WAWA 46B | | Bore never used | √ | 61 | 2.36 | 28.2 | 21.96 | 114.10 |
| WAWA 11 | | Blocked | √ | | | | 21.94 | 114.11 |
| O1 | O1 | Main Road bore | √ | | 17.40 | 26.9 | 22.57 | 114.01 |
| O2 | O2 | Main Road bore | √ | | 22.30 | 27.8 | 22.62 | 114.02 |
| Bullara Home Bore | | | | | | | 22.65 | 114.17 |
| Beavan Well | | | | | 5.90 | | 22.70 | 114.32 |
| O3 Minga Bore | O3 | | √ | | 3.45 | 30.0 | 22.90 | 114.78 |
| Sheila Well | | | | | | | 22.90 | 114.93 |
| O4 Jane Well | O4 | | √ | | 1.44 | 26.5 | 22.79 | 114.97 |
| Main Roads well | | | | | | | 22.72 | 114.98 |
| O5 Osborne Well | O5 | | √ | | 10.86 | 29.2 | 22.57 | 114.99 |
| Ryan Well | | | | | | | 22.47 | 115.03 |
| Cronks Well | | | | | | | 22.44 | 115.01 |
| O6 Home Well (Koordarrie hst) | O6 | | √ | | 2.35 | 27.7 | 22.30 | 115.04 |
| O7 Sixteen Mile Well | O7 | | √ | | 10.20 | 26.3 | 22.79 | 115.97 |
| O8 Centipede Well | O8 | | √ | | 7.80 | 26.2 | 22.17 | 115.02 |
| O9 Warralee Well | O9 | | √ | | 7.90 | 27.7 | 22.11 | 115.04 |
| O10 Cunuloo Well | O10 | | √ | | 11.10 | 26.3 | 22.05 | 115.02 |
| O11 Picul Well | O11 | | √ | | 5.90 | 24.1 | 22.01 | 115.03 |
| O12 River Well | O12 | | √ | | 1.05 | 25.4 | 22.00 | 115.03 |
| O13 Unnamed nr Ashburton Bridge | O13 | | √ | 62 | | | 21.97 | 115.03 |
| O14 Gravel bank of Ashburton | O14 | | √ | | 0.19 | 23.4 | 21.98 | 115.04 |
| O15 Shearing Shed Well | O15 | | √ | | 1.03 | 28.3 | 21.99 | 115.05 |
| O16 Old House well | O16 | | √ | 63 | 2.61 | 27.4 | 22.00 | 115.05 |
| O17 Four Mile Well | O17 | | √ | | 3.53 | 28.7 | 22.05 | 115.06 |
| O18 Urama Well | O18 | | √ | | 2.21 | 29.3 | 22.09 | 115.09 |
| O19 Geebera Well | O19 | | √ | | 24.30 | 28.0 | 22.10 | 115.13 |
| O20 Success Well | O20 | | √ | | | | 22.23 | 115.20 |
| O21 Cave Well | O21 | | √ | 65 | | | 22.25 | 115.19 |
| O22 old bore | O22 | | √ | | | | 22.01 | 115.05 |
| O23 Balchara Well | O23 | | | 64 | 20.40 | | 22.23 | 115.06 |
| O24 Dobi's Bore | O24 | | √ | | 1.00 | 30.0 | 22.24 | 115.15 |
| O25 8 year old unused bore | O25 | | √ | | 9.32 | 30.8 | 22.26 | 115.20 |
| O26 Mount Well | O26 | | √ | | 3.88 | 29.1 | 22.36 | 115.24 |
| O27 last Government Well 1953 | O27 | | √ | | 0.60 | 27.5 | 22.48 | 115.38 |
| O28 Bob's Well | O28 | | √ | | 2.53 | 25.0 | 22.48 | 115.38 |
| O29 Nannutarra Roadhouse Bore | O29 | | √ | | 1.43 | 30.1 | 22.55 | 115.51 |
| O30 Mark's Spring | O30 | | √ | | 4.21 | 27.4 | 21.97 | 115.35 |
| O31 New Freshwater Well | O31 | | √ | | | | 21.73 | 114.91 |
| O32 Urala Stn house well | O32 | | √ | | 6.88 | | 21.77 | 114.82 |
| O33 Peter's Well | O33 | | √ | | 3.67 | | 21.78 | 114.81 |
| O34 Concrete Well | O34 | | √ | | 6.80 | 22.1 | 21.80 | 114.77 |
| O35 Whittackers Well | O35 | | √ | | | | 21.80 | 114.73 |
| O36 Nanyarra Well | O36 | | √ | | 6.65 | 28.1 | 22.17 | 115.12 |
| O37 Jaminu Well | O37 | | √ | | 2.34 | 28.2 | 22.26 | 115.16 |
| O38 Old Outcamp Well | O38 | | √ | | 3.69 | 29.8 | 22.26 | 115.11 |
| O39 Number 8 Well | O39 | | √ | | 13.88 | 26.9 | 22.97 | 114.54 |
| O40 Number 3 Outcamp Well | O40 | Bore | √ | | 1.76 | 28.0 | 22.81 | 114.48 |
| O41 Jubilee Well | O41 | | √ | | 3.44 | 25.3 | 22.60 | 114.21 |
| South Well (Ex G Stn) | | | | | 6.83 | 22.3 | 22.44 | 114.08 |
| C-502 | | | | | | | 21.88 | 114.05 |
| C-501: main pool | | | √ | 17 | | | 21.88 | 114.06 |
| Tantabiddy Well | C-26 | | √ | 98 | 8.06 | 22.3 | 21.94 | 113.96 |
| WAWA 17 | | | √ | | | | 21.94 | 114.11 |

| Name | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| Trealla Tank | | | | | 2.10 | | 22.19 | 114.06 |
| Loop Cave | C-222 | | | | | | 21.94 | 114.10 |
| Yardie Creek Head Pool | | | √ | 67 | 4.78 | | 22.33 | 113.82 |
| Rock Hole north of Yardie Creek | C-510 | | √ | 68 | 39.10 | | 22.28 | 113.84 |
| Tantabiddi Rockholes | C-332 | | √ | 69 | 33.70 | | 21.92 | 113.98 |
| North West Seafoods | C-474 | | √ | 70 | 25.30 | | 22.20 | 114.07 |
| WAWA 10 | | | √ | 71 | 1.86 | 27.9 | 21.94 | 114.11 |
| WAWA 7 | | | √ | 72 | 2.45 | 27.5 | 21.93 | 114.11 |
| Qualing Pool | C-488 | | √ | 73 | 5.04 | 25.2 | 22.02 | 114.12 |
| Qualing Pool itself | C-488 | | | 74 | 3.80 | 25.2 | 22.02 | 114.12 |
| | C-503 | | | | | | 21.99 | 114.04 |
| | C-504 | | | | | | 21.98 | 114.02 |
| Wires for survey pole | | | | | | | 21.99 | 114.04 |
| Base F Geological Survey | | | | | | | 21.99 | 114.03 |
| GB1 Artesian Well | GB1 | Active | √ | 77 | 7.85 | 27.1 | 22.67 | 114.41 |
| GB2 Number 5 Well | GB2 | Active | √ | 78 | 13.36 | 22.4 | 22.62 | 114.45 |
| GB3 Number 7 Well | GB3 | Active | √ | | 5.67 | 26.7 | 22.68 | 114.49 |
| GB4 Number 8 Bore | GB4 | Active | √ | 79 | 4.12 | 29.0 | 22.75 | 114.51 |
| GB5 Howards Well | GB5 | Active | √ | | 12.23 | 28.4 | 22.72 | 114.57 |
| Fergies Well | | Equipped | | | | | 22.82 | 114.53 |
| GB6 Collins Well | GB6 | Active | √ | 80 | 7.95 | 27.1 | 22.89 | 114.55 |
| GB7 Bullvalley Well | GB7 | Active | √ | | 11.80 | 27.0 | 22.86 | 114.51 |
| GB7b New Bore near west tank | GB7b | New bore | | | | | 22.70 | 114.23 |
| GB7c West Tank | GB7c | Abandoned | | | | | 22.69 | 114.26 |
| GB8 Bullara House Well | GB8 | Active | √ | | 3.84 | 26.3 | 22.68 | 114.04 |
| GB9 Johnsons Well | GB9 | Active | √ | | 11.31 | 26.5 | 22.76 | 114.03 |
| GB10 Next White Ant Bore | GB10 | New bore | √ | | 10.98 | 25.5 | 22.71 | 113.92 |
| GB11 Artesian Bore (?Ampol) | GB11 | Not flowing | √ | | 19.23 | 25.4 | 22.71 | 113.88 |
| GB12 Main Roads Bore | GB12 | | √ | 81 | 7.39 | 29.6 | 22.53 | 114.02 |
| WAWA 8 | | Production bore | √ | 66 | 3.18 | 28.0 | 21.93 | 114.10 |
| River gravel section with soil horison | | | | | | | | 21.94 |
| 114.11 | | | | | | | | |
| Shothole Tunnel | C-64 | | √ | 75 | 0.78 | | 22.04 | 114.02 |
| Dry Swallett | C-18 | | √ | 76 | | | 22.09 | 113.99 |
| BOL: 8/89G | | WAWA trial | √ | | 0.75 | 27.8 | 21.97 | 114.08 |
| Lighthouse bore | | Unused | √ | 82 | 0.91 | 26.0 | 21.81 | 114.11 |
| Hunter's Access bore | | Production | √ | | 30.61 | 27.2 | 21.81 | 114.11 |
| Wobiri Rockhole | C-414 | | √ | | 32.10 | 28.6 | 21.84 | 114.07 |
| Cave north C-99 | | Rockshelter | | | | | 21.84 | 114.08 |
| | C-99 | Rockshelter | | | | | 21.84 | 114.08 |
| Tantabiddi Bore | | Production | √ | | 14.40 | 27.1 | 21.91 | 113.98 |
| Chugori Rockhole | C-461 | | | | | | 21.86 | 114.03 |
| Wotafinpool? lower pool | C-505 | | √ | 83 | | | 22.08 | 114.02 |
| Wotafinpool? upper pool | C-505 | | √ | 84 | | | 22.08 | 114.02 |
| Lacustrine deposit fossil leaves | | | | | | | 22.08 | 114.02 |
| Tantabiddi Rockholes: west | | | √ | | 31.40 | 21.9 | 21.92 | 113.98 |
| Pool adjacent piezometer B | | Pool | | | 60.10 | 23.7 | 21.95 | 114.13 |
| Pool adjacent piezometer A | | Pool | | | 88.60 | 26.4 | 21.95 | 114.13 |
| Ashbuton River at lower bridge | | | | | 0.24 | 20.1 | 0.00 | 0.00 |
| Barkatangee Well | | | | | 17.40 | | 0.00 | 0.00 |
| Lighthouse: west tank pipe 1 | | | √ | | 9.90 | 26.4 | 21.81 | 114.11 |
| Lighthouse: west tank pipe 2 | | | √ | | 4.71 | 26.8 | 21.81 | 114.11 |
| Lighthouse: east tank | | | | | 8.95 | 17.7 | 21.81 | 114.11 |
| Rockshelter nr C-99: hole 1 | | Rockshelter | | | 0.66 | 19.2 | 21.84 | 114.08 |
| Rockshelter nr C-99: hole 2 | | Rockshelter | | | 0.98 | 19.7 | 21.84 | 114.08 |
| Rockshelter nr C-99: hole 3 | | Rockshelter | | | 0.87 | 20.2 | 21.84 | 114.08 |
| Rockshelter nr C-99: hole 4 | | Rockshelter | | | 0.90 | 18.6 | 21.84 | 114.08 |
| Rockshelter nr C-99: hole 5 | | Rockshelter | | | 2.41 | 18.0 | 21.84 | 114.08 |
| Rockshelter nr C-99: hole 6 | | Rockshelter | | | 1.58 | 17.0 | 21.84 | 114.08 |

| Name | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| Rockshelter nr C-99: hole 7 | | Rockshelter | | | 0.78 | | 21.84 | 114.08 |
| Rockshelter nr C-99: hole 8 | | Rockshelter | | | 0.95 | 16.4 | 21.84 | 114.08 |
| Tantabiddi Rockholes: east | | Solution hole | √ | | 30.50 | 22.2 | 21.92 | 113.98 |
| Tantabiddi Rockholes: central | | Solution hole | | | 27.40 | 19.8 | 21.92 | 113.98 |
| Kailis West bore 1 | | Abandoned | √ | | 2.10 | 28.9 | 22.12 | 114.06 |
| Kailis South bore 1 | | Production | √ | 92 | | | 22.12 | 114.06 |
| Kailis Tank east | | Tank | | | | | 22.12 | 114.06 |
| Kailis West bore 2 | | Production | √ | 85 | 3.22 | 28.3 | 22.12 | 114.06 |
| Bundera Cenote | C-28 | Cenote top | √ | 91 | 33.70 | 22.1 | 22.41 | 113.77 |
| A1 | | Rockhole | √ | | 22.80 | 24.0 | 22.45 | 113.75 |
| A2 | | Rockhole | | | | | 22.47 | 113.74 |
| A3 | C-506 | Rockhole | √ | 87 | 36.50 | 25.5 | 22.47 | 113.74 |
| A4 | | Rockhole | | | | | 22.52 | 113.72 |
| A5 | | Rockhole | √ | | | | 22.52 | 113.72 |
| A6 | C-507 | Rockhole | √ | 88 | 26.10 | | 22.52 | 113.72 |
| A7 | | Bore: | | | 7.50 | 21.2 | 22.55 | 113.71 |
| | C-508 | Blank doline | | | | | 22.53 | 113.72 |
| | C-509 | Shelter | | | | | 22.48 | 113.74 |
| A9 | | Rockhole dry | | | | | 22.51 | 113.72 |
| Bundera Cenote | | Cenote bottom | √ | 89 | 49.80 | | 22.41 | 113.77 |
| Bundera Cenote | | Cenote middle | √ | 90 | 30.90 | | 22.41 | 113.77 |
| Kailis South bore 1 | | Production | √ | 93 | 2.92 | | 22.12 | 114.06 |
| Chicken farm | | Bore | | 97 | 5.49 | 30.1 | | |
| WAWA 25 | | Production | √ | 94 | 1.94 | 28.2 | | |
| WAWA 18 | | | √ | | | | 21.94 | 114.10 |
| WAWA 43 | | | √ | | | | 21.94 | 114.10 |
| Near C-162 | | | √ | | | | 22.15 | 114.00 |

# Appendix B

## Location, names and major associated stygofauna at 95 water sample locations on or near the Cape Range peninsula

## Glossary - Appendix B

| Locations | Parameters | |
|---|---|---|
| B. - Bore | OS Temp. | Temperature ($^{o}C$) measured in field |
| W. - Well | OS Cond. | Conductivity measured in field (mS $m^{-1}$) |
| C. - Cave | Cond. | Conductivity in lab (mS $m^{-1}$) |
| pz. Piezometer | Cop | Copepoda |
| Hsd - Homestead | Ost | Ostracoda |
| | H t | *Halosbaena tulki* |
| | Amp. | Melitid amphipod |
| | Hap. | *Haptolana pholeta* |
| | Sty. | *Stygiocaris* sp. |
| | Mv | *Milyeringa veritas* |
| | Oc | *Ophisternon candidum* |
| | South | Decimal latitude |
| | East | Decimal longitude |
| | CRP | On the Cape Range peninsula |

**Appendix B:** Location, names and major associated stygofauna at 96 sample locations on or near the Cape Range peninsula. See facing page for glossary.

| # | Name | OS Temp. | OS Cond. | Cond. | Cop. | Ost. | H t | Amp. | Hap. | Sty. | Mv | Oc | South decimal | East decimal | CRP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | SW B. B | 27.9 | 4340 | 3600 | 1 | | | | | | | | 21.82 | 114.09 | 1 |
| 2 | Learmonth gravel pit | 28.7 | 980 | 790 | | | | | | | | | 21.82 | 114.09 | 1 |
| 3 | Nabalgee W. | | | 980 | 1 | | | | | | | | 22.26 | 114.07 | 1 |
| 4 | Woolcott W. | 29.4 | 220 | 195 | 1 | | | | | | | | 22.26 | 114.07 | 1 |
| 5 | Area B#2 | | | 375 | 1 | | 1 | | 1 | 1 | | | 22.22 | 114.06 | 1 |
| 6 | Area B#27 | | | 48 | | | | | | 1 | | | 21.89 | 114.11 | 1 |
| 7 | Area C:#3 | | | 120 | 1 | | | | | | | | 21.89 | 114.09 | 1 |
| 8 | Rainwater | | | 1 | | | | | | | | | 22.33 | 114.03 | 0 |
| 9 | S1 | | | 80 | | | | | | | | | 21.93 | 114.12 | 1 |
| 10 | BOA | | | 78 | 1 | | 1 | | | 1 | | | 21.94 | 114.10 | 1 |
| 11 | BOC | | | 110 | 1 | | 1 | | | 1 | | | 22.00 | 114.09 | 1 |
| 12 | BOE | | | 92 | 1 | | 1 | | | 1 | | | 22.00 | 114.10 | 1 |
| 13 | Home W. | 28.7 | 920 | 920 | | | | | | | | | 21.99 | 114.10 | 0 |
| 14 | Cashen W. | 23.9 | 100 | 97 | 1 | | | | | | | | 22.38 | 114.11 | 0 |
| 15 | Billy W. 3 | 29.4 | 210 | 210 | 1 | | | 1 | | 1 | | | 22.48 | 114.10 | 1 |
| 16 | Wagetti W. | 28.8 | 380 | 365 | | | | | | | | | 22.38 | 114.02 | 0 |
| 17 | C-501 | | | 90 | | | | | | | | | 22.32 | 114.05 | 0 |
| 18 | S3 | | | 63 | | | | | | | | | 21.88 | 114.06 | 0 |
| 19 | N4 | | | 84 | | | | | | | | | 21.95 | 114.09 | 0 |
| 20 | Pilgramunna W. | | 1490 | 1250 | 1 | | 1 | 1 | | 1 | 1 | | 22.34 | 114.03 | 1 |
| 21 | Tulki W. | 24.4 | 860 | 810 | 1 | | 1 | 1 | | 1 | 1 | | 22.19 | 113.87 | 1 |
| 22 | Five Mile W. | 26.2 | 820 | 760 | 1 | | 1 | | | 1 | 1 | | 22.09 | 113.90 | 1 |
| 23 | Kudamurra W. | 28.2 | 500 | 460 | 1 | | 1 | 1 | | 1 | 1 | 1 | 21.85 | 113.87 | 1 |
| 24 | Milyering W. | 25.8 | 980 | 910 | 1 | | 1 | | | 1 | 1 | 1 | 21.89 | 113.82 | 1 |
| 25 | C-215 | | 220 | 210 | 1 | | 1 | | | 1 | 1 | | 22.01 | 113.93 | 1 |
| 26 | Wanderers Delight | | | 65 | | | | | | | | | 22.02 | 113.93 | 1 |
| 27 | Rifle Range B. | 30.0 | 540 | 480 | 1 | 1 | 1 | 1 | | | | | 22.15 | 114.00 | 1 |
| 28 | Mowbowra W. | 26.6 | 320 | 245 | 1 | | | | | 1 | 1 | 1 | 22.03 | 114.11 | 1 |
| 29 | Gnamma Hole | 29.8 | 130 | 115 | 1 | | 1 | 1 | | 1 | 1 | 1 | 21.99 | 114.12 | 1 |
| 30 | Horack's W. | 23.6 | 280 | 135 | | | | | | | | | 21.98 | 114.12 | 1 |
| 31 | Camerons C. | | | 225 | 1 | | | | | | 1 | | 21.96 | 114.13 | 1 |
| 32 | Marina, north pz. | 29.0 | 1180 | 900 | | | | | | | | | 21.97 | 114.13 | 1 |
| 33 | Upper Bulbarli W. | 23.6 | 110 | 110 | | | | | | | | | 21.95 | 114.14 | 0 |
| 34 | Bulbarli W. | 23.3 | 250 | 235 | | | | | | | | | 23.50 | 113.77 | 0 |
| 35 | Waroora W. | 19.6 | 1420 | 1250 | 1 | 1 | | | | | | | 23.53 | 113.76 | 0 |
| 36 | Wapet AB#1 | | 1360 | 1250 | | | | | | | | | 23.46 | 113.79 | 0 |
| 37 | Wapet AB#2 | 57.7 | 1340 | 1250 | | | | | | | | | 23.51 | 113.92 | 0 |
| 38 | Corbett W. | | | 900 | | | | 1 | | | | | 24.27 | 113.90 | 0 |
| 39 | Ningaloo Hsd W. | 22.8 | 710 | 660 | | | | | | | | | 23.24 | 113.92 | 0 |
| 40 | Javis W. | 22.6 | 1120 | 960 | 1 | | | 1 | | | 1 | | 22.70 | 113.68 | 0 |
| 41 | Lighthouse W. | 22.5 | 1310 | 1100 | | | | | | | | | 22.60 | 113.69 | 0 |
| 42 | Perth Hill W. | 26.2 | 440 | 415 | | | | | | | | | 22.69 | 113.68 | 0 |
| 43 | 10 Mile W. | 25.9 | 880 | 820 | | | | | | | | | 22.71 | 113.69 | 0 |
| 44 | 4 Mile W. | 25.8 | 1550 | 1350 | | | | | | | | | 22.78 | 113.77 | 0 |
| 45 | Kubura W. | | | 485 | | | 1 | | | 1 | 1 | 1 | 22.73 | 113.76 | 1 |
| 46 | WAWA 44 | | | 115 | 1 | | 1 | | 1 | 1 | 1 | | 21.93 | 114.13 | 1 |
| 47 | Amphipod W. C-413 | 27.9 | 420 | 375 | 1 | | | 1 | | | | | 21.97 | 114.13 | 1 |
| 48 | Sea water | | | 4950 | | | | | | | | | 21.97 | 114.13 | 0 |
| 49 | Bulldozer C. | 24.5 | 120 | 35 | 1 | | | | | | 1 | | 22.21 | 114.09 | 1 |
| 50 | WAWA 47 | | | 100 | | | 1 | 1 | 1 | 1 | | | 21.98 | 114.12 | 1 |
| 51 | BOG | | | 195 | | | | | | | | | 21.98 | 114.10 | 1 |

| # | Name | OS Temp. | OS Cond. | Cond. | Cop. | Ost. | H t | Amp. | Hap. | Sty. | Mv | Oc | South decimal | East decimal | CRP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 52 | E6 | 28.4 | 250 | 235 | 1 | | | | | 1 | | | 21.96 | 114.11 | 1 |
| 53 | E5 | | | 460 | 1 | | 1 | 1 | | 1 | | | 21.95 | 114.13 | 1 |
| 54 | E7 | 27.4 | 1640 | 1750 | | | | | | | | | 21.94 | 114.13 | 1 |
| 55 | E1 | | 500 | 500 | 1 | | 1 | 1 | | | | | 21.94 | 114.13 | 1 |
| 56 | E4 | 27.6 | 620 | 560 | 1 | | | | | 1 | | | 21.93 | 114.12 | 1 |
| 57 | E3 | 25.8 | 180 | 215 | 1 | | | 1 | | | | | 21.93 | 114.12 | 1 |
| 58 | Marina pz. B | 26.9 | 1990 | 3250 | | | | | | | | | 21.93 | 114.13 | 1 |
| 59 | Marina pz. B | | | 145 | 1 | | | 1 | | | | | 21.95 | 114.14 | 1 |
| 60 | WAWA 46A | 29.0 | 210 | 210 | 1 | | 1 | | | 1 | | | 21.96 | 114.12 | 1 |
| 61 | New Mowbowra C. | 28.2 | 240 | 210 | | | | | | 1 | 1 | 1 | 21.99 | 114.12 | 1 |
| 62 | WAWA 46B | | | 135 | | | | | | | | | 21.96 | 114.10 | 1 |
| 63 | O13 Unnamed | 27.4 | 260 | 250 | | | | 1 | | | | | 21.97 | 115.03 | 0 |
| 64 | O16 Old House W. | | 2040 | 1700 | | | | 1 | | | | | 22.00 | 115.05 | 0 |
| 65 | O23 Balchara W. | | | 1250 | 1 | | | 1 | | | | | 22.23 | 115.06 | 0 |
| 66 | WAWA 8 | 28.0 | 320 | 700 | | | | | | | | | 22.25 | 115.19 | 1 |
| 67 | Yardie Creek pool | | 480 | 445 | | | | | | | | | 21.93 | 114.10 | 1 |
| 68 | C-510 | | 3910 | 3300 | 1 | 1 | | 1 | | | | | 22.33 | 113.82 | 1 |
| 69 | Tantabiddi Rockholes | | 3370 | 2850 | 1 | | | 1 | | | 1 | | 22.28 | 113.84 | 1 |
| 70 | NW Seafoods old W. | | 2530 | 2100 | | | | | | | | | 21.92 | 113.98 | 1 |
| 71 | WAWA 10 | 27.9 | 190 | 165 | | | | 1 | | 1 | | | 22.20 | 114.07 | 1 |
| 72 | WAWA 7 | 27.5 | 250 | 210 | | | | | | | | | 21.94 | 114.11 | 1 |
| 73 | Qualing Pool soak | 25.2 | 500 | 630 | 1 | | | 1 | | | | | 21.93 | 114.11 | 1 |
| 74 | Qualing Pool C-488 | 25.2 | 380 | 820 | | | | | | | | | 22.02 | 114.12 | 1 |
| 75 | Shothole Tunnel C-64 | | 80 | 73 | | | | 1 | | | | | 22.01 | 114.11 | 0 |
| 76 | Dry Swallett C-18 | | | 65 | 1 | | | 1 | | | | | 22.04 | 114.01 | 0 |
| 77 | GB1 Artesian W. | 27.1 | 780 | 700 | 1 | | | | | | | | 22.09 | 114.00 | 0 |
| 78 | GB2 Number 5 W. | 22.4 | 1340 | 1200 | | | | | | | | | 22.67 | 114.41 | 0 |
| 79 | GB4 Number 8 B. | 29.0 | 410 | 375 | 1 | | | | | | | | 22.62 | 114.45 | 0 |
| 80 | GB6 Collins W. | 27.1 | 800 | 710 | | | | | | | | | 22.75 | 114.51 | 0 |
| 81 | GB12 | 29.6 | 740 | 630 | | | | | | | | | 22.89 | 114.55 | 0 |
| 82 | Lighthouse B. | 26.0 | 90 | 165 | | | | | | | | | 22.53 | 114.02 | 0 |
| 83 | C-505, lower pool | | | 110 | 1 | 1 | | | | | | | 21.81 | 114.11 | 0 |
| 84 | C-505, upper pool | | | 115 | 1 | 1 | | | | | | | 22.08 | 114.02 | 0 |
| 85 | Kailis west B. 2 | 28.3 | 320 | 325 | 1 | 1 | | | 1 | | | | 22.08 | 114.02 | 1 |
| 86 | E2 | | 580 | 530 | 1 | | 1 | 1 | 1 | 1 | | | 22.12 | 114.06 | 1 |
| 87 | A3 C-506 | 25.5 | 3650 | 3250 | 1 | | | | | | 1 | | 21.93 | 114.12 | 1 |
| 88 | A6 C-507 | | 2610 | 2250 | | | | | | | 1 | | 22.47 | 113.74 | 1 |
| 89 | C-28 | | 4980 | 4700 | | | | | | | 1 | | 22.51 | 113.71 | 1 |
| 90 | C-28 | | 3090 | 3050 | | | | | | | 1 | | 22.41 | 113.76 | 1 |
| 91 | C-28 | 22.1 | 3370 | 3000 | 1 | 1 | | | | 1 | 1 | | 22.41 | 113.76 | 1 |
| 92 | Kailis South B. 1 | | | 290 | 1 | | | | 1 | 1 | 1 | | 22.41 | 113.77 | 1 |
| 93 | Kailis South B. 1 | | 290 | 290 | | | | | | | 1 | | 22.12 | 114.06 | 1 |
| 94 | WAWA 25 | 28.2 | 190 | 215 | | | | | | | | | 22.12 | 114.06 | 1 |
| 95 | N2 | 30.1 | 90 | 94 | | | | | | | | | 21.93 | 114.08 | 0 |
| 96 | N1 | 28.7 | 300 | 340 | | | | 1 | | 1 | 1 | | 21.93 | 114.08 | 1 |
| 97 | Chicken farm | 30.1 | 550 | 630 | | | | | | | | | 21.94 | 114.09 | 1 |
| 98 | Tantabiddi Well | | | 900 | 1 | 1 | | | | | 1 | 1 | 21.94 | 113.96 | 1 |

# Appendix C

## Raw data from routine water analysis of 98 samples from subterranean systems on and near the Cape Range peninsula

# Glossary

**T = Type of location**

| | |
|---|---|
| AB | Artesian bore |
| AW | Active well |
| B | Bore |
| C | Cave |
| P | Piezometer |
| PB | Production bore |
| R | Rainwater |
| RH | Rock Hole |
| S | Soak |
| SH | Shothole |
| SW | Sea water |
| TB | Test bore |
| W | Well |

**Parameters**

| Key | Units[1] | Detection limit |
|---|---|---|
| Turb - Turbidity | NTU | |
| Col. - Colour | TCU | 1 |
| Cond. - Conductivity at 25°C | $mS\ m^{-1}$ | |
| TFS - Total filterable solids | Sum | |
| TFS- - TFS minus $CO_2$ | | |
| Fe - Unfiltered | | 0.05 |
| Mn - Unfiltered | | 0.04 |
| Al | | |
| Na | | |
| K | | |
| Ca | | |
| Mg | | |
| Hard. - Hardness as $CaCO_3$ | | |
| Alk. - Alkalinity | | |
| Cl | | |
| $SO_4$ | | |
| Si - as $SiO_2$ | | |
| FOC - Filterable organic carbon | | |
| TP - Total phosphorous | | |
| FRP - Free reactive phosphorous | | 0.002 |
| TKN - Total Kjeldahl nitrogen | | |
| $NO_2$ - Nitrite as nitrogen | | 0.002 |
| $NO_3$ - Nitrate as nitrogen | | 0.002 |
| $NH_3$ - Ammonia as nitrogen | | 0.005 |
| S - Fauna sample | | |
| CRP - On Cape Range peninsula | | |

[1]All units are in $mg\ L^{-1}$ unless otherwise stated.

**Appendix C:** Raw data from routine water analysis of 98 samples from subterranean systems on and near the Cape Range peninsula. For glossary see facing page.

| # | T | pH | Turb. | Col. | Cond. | TFS | TFS- | Fe | Mn | Al | Na | K | Ca | Mg | Hard. | Alk. | Cl | SO4 | Si | FOC | TP | FRP | TKN | NO2 | NO3 | NH3 | S | CRP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | SH | 7.26 | 120.0 | 3 | 3600 | 24000 | 24000 | 1.40 | 0.00 | 0.480 | 7490 | 280.0 | 360 | 840 | 4360 | 5.1 | 12950 | 1800 | 8.4 | 26.0 | 0.105 | 0.006 | 0.110 | 0.003 | 1.70 | 0.044 | 1 | 1 |
| 2 | B | 7.60 | 2.2 | 3 | 790 | 4900 | 4700 | 0.00 | 0.00 | 0.048 | 1370 | 28.0 | 140 | 120 | 850 | 7.1 | 2250 | 400 | 48.0 | 36.0 | 0.013 | 0.007 | 0.040 | 0.003 | 9.55 | 0.016 | 1 | 1 |
| 3 | W | 7.76 | 1.4 | 12 | 980 | 5850 | 5050 | 0.00 | 0.00 | 0.084 | 1630 | 55.0 | 190 | 180 | 1200 | 6.1 | 3000 | 285 | 34.0 | 30.0 | 0.710 | 0.670 | 0.400 | 0.035 | 5.05 | 0.084 | 1 | 1 |
| 4 | W | 7.02 | 0.9 | 2 | 195 | 1350 | 1150 | 0.00 | 0.00 | 0.043 | 200 | 4.4 | 170 | 24 | 510 | 6.3 | 395 | 43 | 27.0 | 33.0 | 0.006 | 0.019 | 0.000 | 0.004 | 3.70 | 0.006 | 1 | 1 |
| 5 | B | 7.54 | 35.0 | 2 | 375 | 2150 | 2050 | 4.80 | 0.35 | 0.024 | 580 | 20.0 | 70 | 75 | 500 | 3.9 | 1000 | 95 | 10.0 | 22.0 | 0.096 | 0.004 | 3.000 | 0.012 | 0.59 | 3.000 | 1 | 1 |
| 6 | B | 7.79 | 1.0 | 2 | 48 | 370 | 290 | 0.50 | 0.00 | 0.040 | 40 | 2.8 | 48 | 6 | 140 | 2.6 | 54 | 9 | 7.5 | 16.5 | 0.079 | 0.071 | 0.220 | 0.004 | 2.59 | 0.015 | 1 | 1 |
| 7 | B | 7.40 | 30.0 | 1 | 120 | 930 | 740 | 6.00 | 0.15 | 0.030 | 100 | 3.4 | 90 | 46 | 410 | 6.3 | 190 | 24 | 17.5 | 31.0 | 0.041 | 0.004 | 0.160 | 0.004 | 0.32 | 0.018 | 1 | 1 |
| 8 | R | 6.47 | 1.2 | 21 | 1 | 20 | 15 | 0.00 | 0.00 | 0.015 | 1 | 0.4 | 0 | 0 | 2 | 0.1 | 0 | 1 | 0.0 | 5.8 | 0.045 | 0.011 | 0.090 | 0.004 | 0.03 | 0.020 | 0 | 0 |
| 9 | B | 7.48 | 4.4 | 0 | 80 | 610 | 480 | 0.75 | 0.00 | 0.087 | 60 | 2.8 | 60 | 30 | 270 | 4.3 | 110 | 13 | 14.5 | 24.0 | 0.050 | 0.011 | 1.000 | 0.003 | 2.05 | 0.011 | 1 | 1 |
| 10 | PB | 7.09 | 21.0 | 0 | 78 | 610 | 480 | 0.10 | 0.05 | 0.082 | 55 | 3.0 | 85 | 16 | 280 | 4.3 | 100 | 14 | 13.5 | 25.0 | 0.019 | 0.004 | 0.100 | 0.003 | 0.69 | 0.013 | 1 | 1 |
| 11 | PB | 7.13 | 3.6 | 0 | 110 | 790 | 640 | 0.08 | 0.00 | 0.030 | 90 | 4.0 | 90 | 30 | 340 | 4.7 | 185 | 22 | 15.0 | 25.0 | 0.007 | 0.005 | 0.050 | 0.002 | 1.55 | 0.000 | 1 | 1 |
| 12 | PB | 7.24 | 28.0 | 0 | 92 | 700 | 560 | 0.17 | 0.00 | 0.195 | 75 | 2.8 | 75 | 28 | 300 | 4.6 | 140 | 18 | 14.0 | 24.0 | 0.038 | 0.011 | 0.060 | 0.003 | 2.15 | 0.000 | 1 | 1 |
| 13 | W | 7.23 | 1.2 | 0 | 920 | 5550 | 5350 | 0.00 | 0.00 | 0.089 | 1330 | 30.0 | 310 | 230 | 1690 | 6.8 | 2900 | 235 | 56.0 | 30.0 | 0.008 | 0.000 | 0.230 | 0.008 | 0.90 | 0.005 | 1 | 0 |
| 14 | W | 8.17 | 0.9 | 3 | 97 | 700 | 580 | 0.00 | 0.00 | 0.068 | 65 | 15.0 | 80 | 26 | 310 | 3.7 | 175 | 28 | 26.0 | 19.0 | 0.245 | 0.240 | 0.245 | 0.030 | 3.80 | 0.105 | 1 | 0 |
| 15 | B | 7.28 | 48.0 | 0 | 210 | 1400 | 1250 | 36.00 | 0.50 | 0.485 | 240 | 5.0 | 120 | 55 | 520 | 5.1 | 485 | 61 | 18.5 | 29.0 | 0.078 | 0.004 | 0.400 | 0.014 | 0.40 | 0.073 | 1 | 1 |
| 16 | W | 7.26 | 2.3 | 2 | 365 | 2400 | 2150 | 0.00 | 0.00 | 0.060 | 490 | 12.0 | 120 | 95 | 680 | 7.4 | 900 | 85 | 53.0 | 63.0 | 0.014 | 0.000 | 0.275 | 0.032 | 9.30 | 0.064 | 0 | 0 |
| 17 | C | 8.20 | 0.7 | 10 | 90 | 740 | 600 | 0.00 | 0.00 | 0.026 | 70 | 9.0 | 100 | 12 | 290 | 4.7 | 120 | 24 | 20.0 | 41.0 | 0.115 | 0.002 | 0.490 | 0.036 | 3.55 | 0.062 | 0 | 0 |
| 18 | TB | 7.53 | 3.4 | 1 | 63 | 560 | 440 | 0.30 | 0.35 | 0.090 | 40 | 3.4 | 46 | 30 | 240 | 3.9 | 72 | 14 | 16.0 | 45.0 | 0.048 | 0.023 | 0.125 | 0.005 | 0.36 | 0.105 | 1 | 0 |
| 19 | TB | 7.44 | 9.9 | 0 | 84 | 660 | 550 | 0.11 | 0.00 | 0.087 | 75 | 1.4 | 55 | 32 | 270 | 3.8 | 135 | 21 | 15.0 | 43.0 | 0.038 | 0.013 | 0.110 | 0.007 | 0.68 | 0.016 | 1 | 0 |
| 20 | W | 7.50 | 1.7 | 2 | 1250 | 7700 | 7550 | 0.09 | 0.00 | 0.155 | 2230 | 80.0 | 160 | 270 | 1500 | 4.1 | 4100 | 540 | 14.5 | 1.7 | 0.026 | 0.012 | 0.260 | 0.004 | 3.70 | 0.058 | 1 | 1 |
| 21 | W | 7.62 | 0.6 | 0 | 810 | 4750 | 4600 | 0.00 | 0.00 | 0.039 | 1330 | 46.0 | 120 | 170 | 970 | 4.7 | 2400 | 320 | 13.5 | 1.4 | 0.019 | 0.010 | 0.200 | 0.004 | 5.90 | 0.052 | 1 | 1 |
| 22 | W | 7.41 | 2.5 | 4 | 760 | 4600 | 4350 | 0.45 | 0.45 | 0.046 | 1230 | 55.0 | 120 | 160 | 950 | 8.2 | 2200 | 310 | 14.5 | 1.8 | 0.095 | 0.044 | 1.700 | 0.010 | 0.08 | 0.195 | 1 | 1 |
| 23 | W | 7.16 | 1.0 | 1 | 460 | 2700 | 2550 | 0.18 | 0.18 | 0.067 | 680 | 24.0 | 100 | 100 | 660 | 6.1 | 1250 | 160 | 15.0 | 1.0 | 0.042 | 0.006 | 0.650 | 0.000 | 4.25 | 0.022 | 1 | 1 |
| 24 | W | 7.40 | 1.2 | 1 | 910 | 5250 | 5100 | 0.00 | 0.00 | 0.038 | 1440 | 65.0 | 130 | 170 | 1010 | 4.9 | 2800 | 345 | 11.0 | 1.1 | 0.011 | 0.006 | 0.071 | 0.000 | 3.95 | 0.006 | 1 | 1 |
| 25 | C | 7.48 | 14.0 | 8 | 210 | 1250 | 1100 | 0.07 | 0.07 | 0.125 | 250 | 9.0 | 80 | 50 | 410 | 4.3 | 500 | 61 | 9.5 | 3.1 | 0.055 | 0.004 | 0.465 | 0.024 | 1.85 | 0.063 | 1 | 1 |
| 26 | C | 7.85 | 1.7 | 1 | 65 | 490 | 390 | 0.00 | 0.00 | 0.079 | 44 | 1.8 | 80 | 5 | 220 | 3.3 | 93 | 9 | 12.0 | 20.0 | 0.225 | 0.165 | 0.180 | 0.008 | 0.78 | 0.007 | 1 | 1 |
| 27 | B | 7.18 | 4.0 | 0 | 480 | 2950 | 2800 | 0.09 | 0.00 | 0.036 | 750 | 20.0 | 150 | 80 | 700 | 6.4 | 1300 | 155 | 27.0 | 49.0 | 0.017 | 0.005 | 0.057 | 0.033 | 4.05 | 0.035 | 1 | 1 |
| 28 | W | 7.56 | 9.0 | 34 | 245 | 1600 | 1400 | 0.15 | 0.00 | 0.071 | 290 | 9.0 | 110 | 55 | 490 | 6.1 | 580 | 55 | 18.0 | 46.0 | 0.029 | 0.008 | 0.730 | 0.013 | 0.14 | 0.026 | 1 | 1 |
| 29 | C | 7.42 | 4.4 | 4 | 115 | 710 | 640 | 0.10 | 0.08 | 0.073 | 140 | 5.0 | 55 | 22 | 220 | 2.3 | 255 | 31 | 10.5 | 21.0 | 0.026 | 0.010 | 0.067 | 0.008 | 0.08 | 0.010 | 1 | 1 |
| 30 | W | 7.28 | 15.0 | 25 | 135 | 830 | 770 | 0.30 | 0.15 | 0.240 | 140 | 18.0 | 75 | 34 | 320 | 2.2 | 350 | 7 | 11.5 | 29.0 | 0.035 | 0.013 | 1.200 | 0.069 | 0.83 | 0.175 | 1 | 1 |
| 31 | C | 7.43 | 1.0 | 3 | 225 | 1400 | 1300 | 0.00 | 0.00 | 0.041 | 280 | 9.0 | 80 | 46 | 390 | 3.0 | 540 | 63 | 15.0 | 74.0 | 0.185 | 0.125 | 0.069 | 0.038 | 1.65 | 0.115 | 1 | 1 |
| 32 | P | 7.54 | 39.0 | 3 | 900 | 5500 | 5350 | 2.80 | 0.00 | 0.028 | 1560 | 90.0 | 150 | 180 | 1110 | 4.2 | 2800 | 385 | 6.5 | 29.0 | 0.041 | 0.008 | 0.265 | 0.003 | 0.02 | 0.011 | 1 | 1 |
| 33 | W | 7.74 | 1.0 | 3 | 110 | 740 | 640 | 0.00 | 0.00 | 0.028 | 120 | 26.0 | 28 | 24 | 170 | 3.4 | 175 | 43 | 10.0 | 42.0 | 0.087 | 0.023 | 0.074 | 0.046 | 2.40 | 0.024 | 1 | 0 |
| 34 | W | 7.76 | 0.7 | 8 | 235 | 1450 | 1350 | 0.00 | 0.00 | 0.031 | 350 | 34.0 | 42 | 48 | 300 | 3.8 | 540 | 150 | 4.0 | 28.0 | 0.042 | 0.016 | 0.175 | 0.084 | 2.50 | 0.021 | 1 | 0 |
| 35 | W | 7.58 | 0.5 | 6 | 1250 | 7750 | 7600 | 0.00 | 0.00 | 0.024 | 2200 | 90.0 | 190 | 240 | 1480 | 4.0 | 4000 | 650 | 10.5 | 35.0 | 0.043 | 0.023 | 0.125 | 0.105 | 8.55 | 0.076 | 1 | 0 |

| # | T | pH | Turb. | Col. | Cond. | TFS | TFS- | Fe | Mn | Al | Na | K | Ca | Mg | Hard. | Alk. | Cl | SO4 | Si | FOC | TP | FRP | TKN | NO2 | NO3 | NH3 | S | CRP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 36 | AB | 6.98 | 24.0 | 0 | 1250 | 7950 | 7900 | 0.95 | 0.07 | 0.041 | 2520 | 65.0 | 190 | 60 | 730 | 3.0 | 3550 | 1300 | 23.0 | 37.0 | 0.380 | 0.340 | 5.950 | 0.000 | 0.02 | 5.550 | 1 | 0 |
| 37 | AB | 6.90 | 28.0 | 0 | 1250 | 8100 | 800 | 1.20 | 0.06 | 0.036 | 2420 | 65.0 | 300 | 100 | 1140 | 3.4 | 3650 | 1250 | 25.0 | 28.0 | 0.034 | 0.008 | 5.250 | 0.000 | 0.00 | 5.250 | 1 | 0 |
| 38 | W | 7.39 | 1.9 | 1 | 900 | 5350 | 5250 | 0.00 | 0.00 | 0.049 | 1100 | 28.0 | 300 | 340 | 2140 | 4.7 | 3000 | 135 | 29.0 | 28.0 | 0.027 | 0.000 | 0.063 | 0.185 | 16.50 | 0.009 | 1 | 0 |
| 39 | W | 7.83 | 1.0 | 11 | 660 | 3950 | 3850 | 0.12 | 0.00 | 0.165 | 1120 | 60.0 | 65 | 150 | 770 | 2.9 | 1950 | 255 | 9.3 | 49.0 | 0.062 | 0.026 | 0.190 | 0.095 | 7.20 | 0.009 | 1 | 0 |
| 40 | W | 7.62 | 3.7 | 3 | 960 | 6000 | 5850 | 0.06 | 0.00 | 0.220 | 1600 | 140.0 | 120 | 210 | 1150 | 4.9 | 2950 | 425 | 16.0 | 28.0 | 0.088 | 0.063 | 0.100 | 0.185 | 31.50 | 0.005 | 1 | 0 |
| 41 | W | 7.99 | 1.1 | 6 | 1100 | 6900 | 6700 | 0.00 | 0.00 | 0.045 | 1960 | 80.0 | 110 | 240 | 1260 | 6.4 | 3550 | 440 | 8.7 | 45.0 | 0.050 | 0.015 | 0.220 | 0.055 | 2.85 | 0.009 | 1 | 0 |
| 42 | W | 7.66 | 1.0 | 5 | 415 | 2600 | 2450 | 0.00 | 0.00 | 0.082 | 610 | 42.0 | 55 | 120 | 620 | 5.1 | 1000 | 175 | 10.5 | 50.0 | 0.038 | 0.016 | 5.400 | 0.012 | 29.50 | 0.140 | 1 | 0 |
| 43 | W | 7.16 | 0.8 | 28 | 820 | 6400 | 6300 | 0.00 | 0.00 | 0.063 | 850 | 180.0 | 660 | 340 | 3040 | 3.8 | 1500 | 2400 | 57.0 | 47.0 | 0.032 | 0.025 | 0.840 | 0.110 | 18.00 | 0.009 | 1 | 0 |
| 44 | W | 7.67 | 4.8 | 5 | 1350 | 8150 | 8050 | 0.60 | 0.00 | 0.061 | 2350 | 95.0 | 120 | 260 | 1390 | 3.6 | 4200 | 780 | 14.5 | 31.0 | 0.063 | 0.016 | 0.076 | 0.060 | 12.00 | 0.003 | 1 | 0 |
| 45 | W | 7.02 | 1.0 | 2 | 485 | 3000 | 2800 | 0.00 | 0.00 | 0.018 | 700 | 22.0 | 170 | 100 | 850 | 6.4 | 1300 | 190 | 23.0 | 31.0 | 0.038 | 0.019 | 0.210 | 0.009 | 4.25 | 0.030 | 1 | 1 |
| 46 | PB | 7.33 | 1.4 | 2 | 115 | 790 | 660 | 0.05 | 0.00 | 0.022 | 110 | 5.0 | 80 | 30 | 330 | 4.2 | 200 | 27 | 15.0 | 25.0 | 0.110 | 0.091 | 0.070 | 0.022 | 1.80 | 0.006 | 1 | 1 |
| 47 | W | 7.83 | 2.4 | 20 | 375 | 2150 | 2050 | 0.07 | 0.00 | 0.100 | 570 | 26.0 | 70 | 75 | 480 | 3.1 | 960 | 190 | 16.0 | 17.5 | 0.445 | 0.350 | 0.335 | 0.007 | 0.84 | 0.009 | 1 | 1 |
| 48 | SW | 8.10 | 1.6 | 1 | 4950 | 36500 | 36500 | 0.00 | 0.00 | 0.092 | 12000 | 540.0 | 420 | 140 | 1630 | 2.1 | 20250 | 3000 | 0.0 | 12.5 | 0.028 | 0.008 | 0.054 | 0.003 | 0.02 | 0.003 | 0 | 0 |
| 49 | C | 8.02 | 16.0 | 13 | 35 | 250 | 210 | 0.60 | 0.00 | 0.230 | 48 | 2.0 | 15 | 3 | 50 | 1.6 | 54 | 7 | 6.4 | 8.7 | 0.042 | 0.007 | 0.980 | 0.006 | 0.14 | 0.010 | 1 | 1 |
| 50 | PB | 7.35 | 3.5 | 2 | 100 | 660 | 540 | 0.14 | 0.00 | 0.115 | 80 | 2.6 | 65 | 32 | 300 | 4.0 | 165 | 14 | 14.0 | 17.5 | 0.018 | 0.003 | 0.200 | 0.007 | 1.35 | 0.100 | 1 | 1 |
| 51 | PB | 7.53 | 100.0 | 2 | 195 | 1100 | 1000 | 24.00 | 0.90 | 0.175 | 260 | 10.0 | 46 | 44 | 300 | 3.4 | 490 | 2 | 3.3 | 14.5 | 0.140 | 0.000 | 9.200 | 0.009 | 0.06 | 5.000 | 1 | 1 |
| 52 | B | 7.82 | 1.5 | 4 | 235 | 1450 | 1300 | 0.55 | 0.00 | 0.060 | 360 | 14.0 | 55 | 46 | 330 | 4.4 | 500 | 135 | 18.5 | 18.5 | 0.120 | 0.020 | 0.370 | 0.006 | 3.15 | 0.072 | 1 | 1 |
| 53 | B | 7.04 | 9.0 | 0 | 460 | 2750 | 2550 | 0.25 | 0.00 | 0.094 | 660 | 17.0 | 150 | 90 | 740 | 5.9 | 1200 | 170 | 18.5 | 23.0 | 0.020 | 0.003 | 0.155 | 0.005 | 3.80 | 0.043 | 1 | 1 |
| 54 | B | 6.94 | 24.0 | 3 | 1750 | 11500 | 11500 | 0.50 | 0.00 | 0.140 | 3340 | 44.0 | 320 | 300 | 2040 | 8.9 | 5650 | 1000 | 26.0 | 37.0 | 0.125 | 0.044 | 0.335 | 0.055 | 52.00 | 0.175 | 1 | 1 |
| 55 | B | 7.06 | 95.0 | 4 | 500 | 3350 | 3200 | 1.20 | 0.05 | 0.350 | 710 | 18.0 | 160 | 100 | 820 | 5.4 | 145 | 1800 | 18.5 | 22.0 | 0.091 | 0.040 | 0.270 | 0.018 | 2.45 | 0.070 | 1 | 1 |
| 56 | B | 7.05 | 26.0 | 2 | 560 | 3500 | 3250 | 0.55 | 0.00 | 0.245 | 930 | 22.0 | 150 | 90 | 740 | 8.2 | 1400 | 280 | 23.0 | 32.0 | 0.060 | 0.011 | 0.415 | 0.069 | 2.40 | 0.265 | 1 | 1 |
| 57 | B | 7.05 | 2.5 | 5 | 215 | 1600 | 1300 | 0.12 | 0.00 | 0.021 | 250 | 18.0 | 110 | 70 | 560 | 10.4 | 320 | 70 | 38.0 | 41.0 | 0.120 | 0.072 | 0.550 | 0.460 | 5.15 | 0.155 | 1 | 1 |
| 58 | P | 7.26 | 190.0 | 10 | 3250 | 22000 | 22000 | 4.60 | 0.10 | 1.200 | 6850 | 300.0 | 290 | 680 | 3500 | 3.5 | 11950 | 1550 | 6.9 | 15.5 | 1.450 | 0.690 | 1.400 | 0.025 | 6.55 | 0.170 | 0 | 1 |
| 59 | P | 7.24 | 2.6 | 3 | 145 | 950 | 810 | 0.13 | 0.00 | 0.062 | 160 | 8.0 | 75 | 38 | 340 | 4.6 | 280 | 36 | 13.5 | 25.0 | 0.020 | 0.020 | 0.075 | 0.015 | 2.05 | 0.022 | 0 | 1 |
| 60 | PB | 7.13 | 7.0 | 9 | 210 | 1350 | 1150 | 1.60 | 0.05 | 0.410 | 260 | 8.0 | 100 | 44 | 430 | 5.6 | 455 | 49 | 14.5 | 31.0 | 0.105 | 0.032 | 0.320 | 0.013 | 0.09 | 0.062 | 1 | 1 |
| 61 | C | 7.10 | 75.0 | 3 | 210 | 1500 | 1300 | 0.80 | 0.15 | 0.180 | 260 | 11.0 | 100 | 46 | 450 | 7.2 | 445 | 2 | 25.0 | 82.0 | 0.068 | 0.017 | 4.200 | 0.006 | 0.53 | 0.420 | 1 | 1 |
| 62 | PB | 8.19 | 4.4 | 5 | 135 | 1100 | 920 | 0.09 | 0.00 | 0.096 | 180 | 14.0 | 40 | 40 | 260 | 6.0 | 205 | 79 | 23.0 | 69.0 | 0.220 | 0.210 | 0.130 | 0.011 | 0.49 | 0.000 | 1 | 1 |
| 63 | W | 7.58 | 2.5 | 7 | 250 | 1950 | 1650 | 0.13 | 0.00 | 0.100 | 350 | 15.0 | 75 | 75 | 500 | 9.7 | 365 | 220 | 37.0 | 105.0 | 0.047 | 0.031 | 0.120 | 0.020 | 1.05 | 0.000 | 1 | 0 |
| 64 | W | 6.87 | 4.4 | 0 | 1700 | 11000 | 11000 | 0.08 | 0.00 | 0.130 | 1400 | 75.0 | 1070 | 1020 | 6870 | 5.2 | 5700 | 1150 | 75.0 | 70.0 | 0.015 | 0.010 | 0.052 | 0.020 | 5.75 | 0.000 | 1 | 0 |
| 65 | W | 7.87 | 1.6 | 1 | 1250 | 7750 | 7550 | 0.11 | 0.00 | 0.098 | 2220 | 110.0 | 130 | 250 | 1330 | 5.9 | 3600 | 870 | 39.0 | 74.0 | 0.041 | 0.036 | 0.105 | 0.023 | 0.62 | 0.000 | 1 | 0 |
| 66 | PB | 5.32 | 260.0 | 36 | 700 | 6450 | 6450 | 100.00 | 28.00 | 0.900 | 1790 | 6.0 | 170 | 60 | 650 | 0.6 | 0 | 4500 | 83.0 | 17.0 | 119.000 | 11.000 | 67.000 | 0.011 | 0.70 | 1.000 | 1 | 1 |
| 67 | S | 7.44 | 0.8 | 3 | 445 | 2550 | 2400 | 0.00 | 0.00 | 0.022 | 620 | 22.0 | 110 | 80 | 590 | 4.9 | 1200 | 105 | 18.0 | 44.0 | 0.007 | 0.007 | 0.095 | 0.033 | 0.38 | 0.000 | 1 | 1 |
| 68 | RH | 7.27 | 1.1 | 1 | 3300 | 21500 | 21500 | 0.00 | 0.00 | 0.074 | 6580 | 230.0 | 300 | 640 | 3370 | 3.9 | 12350 | 1300 | 19.0 | 27.0 | 0.019 | 0.014 | 0.017 | 0.027 | 0.84 | 0.000 | 1 | 1 |
| 69 | RH | 7.38 | 5.3 | 2 | 2850 | 19000 | 18500 | 0.06 | 0.00 | 0.600 | 5770 | 210.0 | 240 | 640 | 3260 | 4.7 | 10450 | 1100 | 18.0 | 29.0 | 0.032 | 0.022 | 0.105 | 0.008 | 0.09 | 0.000 | 1 | 1 |
| 70 | W | 8.08 | 43.0 | 19 | 2100 | 13000 | 13000 | 0.45 | 0.05 | 0.245 | 3640 | 100.0 | 420 | 420 | 2770 | 6.6 | 7050 | 960 | 19.0 | 36.0 | 0.670 | 0.670 | 0.920 | 0.067 | 0.97 | 0.115 | 1 | 1 |
| 71 | PB | 7.33 | 110.0 | 5 | 165 | 1000 | 890 | 12.00 | 0.30 | 0.066 | 170 | 6.0 | 75 | 38 | 340 | 4.0 | 365 | 38 | 12.5 | 24.0 | 0.120 | 0.045 | 0.550 | 0.036 | 0.93 | 0.049 | 1 | 1 |
| 72 | PB | 7.39 | 30.0 | 1 | 210 | 1250 | 1150 | 4.00 | 0.25 | 0.150 | 250 | 8.5 | 75 | 46 | 380 | 4.2 | 490 | 57 | 14.5 | 26.0 | 0.140 | 0.039 | 0.180 | 0.026 | 1.65 | 0.023 | 1 | 1 |
| 73 | S | 7.85 | 270.0 | 12 | 630 | 3900 | 3650 | 12.00 | 0.08 | 4.400 | 950 | 40.0 | 200 | 130 | 1010 | 7.6 | 1800 | 220 | 13.5 | 32.0 | 0.425 | 0.025 | 3.850 | 0.036 | 0.10 | 0.063 | 1 | 1 |
| 74 | S | 9.13 | 5.0 | 27 | 820 | 4650 | 4550 | 0.08 | 0.00 | 0.037 | 1310 | 55.0 | 65 | 150 | 800 | 3.7 | 2500 | 310 | 13.0 | 25.0 | 0.012 | 0.011 | 0.470 | 0.004 | 0.00 | 0.011 | 1 | 1 |

| # | T | pH | Turb. | Col. | Cond. | TFS | TFS- | Fe | Mn | Al | Na | K | Ca | Mg | Hard. | Alk. | Cl | SO4 | Si | FOC | TP | FRP | TKN | NO2 | NO3 | NH3 | S | CRP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 75 | C | 7.68 | 4.5 | 4 | 73 | 530 | 420 | 0.00 | 0.00 | 0.069 | 44 | 1.6 | 80 | 11 | 240 | 3.7 | 100 | 14 | 13.5 | 16.0 | 0.012 | 0.011 | 0.030 | 0.026 | 0.94 | 0.019 | 1 | 0 |
| 76 | C | 7.77 | 37.0 | 23 | 65 | 650 | 500 | 3.00 | 1.40 | 0.600 | 18 | 4.2 | 180 | 6 | 460 | 4.9 | 49 | 7 | 16.5 | 32.0 | 0.068 | 0.006 | 2.800 | 0.011 | 0.03 | 1.100 | 1 | 0 |
| 77 | AW | 7.72 | 2.1 | 1 | 700 | 4450 | 4200 | 0.15 | 0.00 | 0.063 | 1150 | 60.0 | 85 | 160 | 880 | 8.3 | 1950 | 340 | 101.0 | 39.0 | 0.014 | - | 0.100 | 0.415 | 6.05 | - | 1 | 0 |
| 78 | AW | 7.54 | 0.9 | 4 | 1200 | 7850 | 7550 | 0.09 | 0.00 | 0.031 | 2220 | 140.0 | 75 | 200 | 1020 | 9.5 | 3550 | 730 | 85.0 | 46.0 | 0.018 | - | 0.029 | 1.000 | 31.50 | 0.007 | 1 | 0 |
| 79 | AW | 7.42 | 1.0 | 0 | 375 | 2400 | 2200 | 0.00 | 0.00 | 0.035 | 520 | 44.0 | 85 | 100 | 620 | 5.7 | 900 | 160 | 91.0 | 30.0 | 0.010 | - | 0.092 | 0.980 | 16.50 | - | 1 | 0 |
| 80 | AW | 7.30 | 1.0 | 2 | 710 | 4400 | 4200 | 0.00 | 0.00 | 0.024 | 1020 | 70.0 | 130 | 190 | 1120 | 6.5 | 2000 | 270 | 100.0 | 34.0 | 0.020 | - | 0.072 | 0.980 | 23.00 | 0.135 | 1 | 0 |
| 81 | B | 7.96 | 12.0 | 10 | 630 | 3650 | 3500 | 0.85 | 0.10 | 0.370 | 920 | 22.0 | 130 | 130 | 880 | 4.7 | 1750 | 295 | 24.0 | 33.0 | 0.390 | - | 1.850 | 0.155 | 0.28 | 0.510 | 1 | 0 |
| 82 | PB | 7.27 | 25.0 | 2 | 165 | 1050 | 900 | 0.50 | 0.00 | 0.120 | 190 | 11.0 | 95 | 24 | 330 | 4.5 | 335 | 35 | 18.5 | 21.0 | 0.105 | 0.014 | 1.250 | 0.042 | 1.40 | 0.295 | 1 | 0 |
| 83 | S | 8.07 | 0.6 | 2 | 110 | 760 | 630 | 0.00 | 0.00 | 0.008 | 85 | 2.2 | 110 | 16 | 330 | 4.5 | 180 | 24 | 19.0 | 21.0 | 0.008 | 0.008 | 0.080 | 0.029 | 1.30 | 0.053 | 1 | 0 |
| 84 | S | 6.93 | 3.1 | 2 | 115 | 980 | 730 | 0.00 | 0.00 | 0.025 | 60 | 1.8 | 210 | 11 | 570 | 8.2 | 125 | 9 | 23.0 | 19.0 | 0.008 | 0.008 | 0.110 | 0.000 | 0.00 | 0.000 | 1 | 0 |
| 85 | PB | 6.97 | 0.7 | 2 | 325 | 2000 | 1850 | 0.13 | 0.00 | 0.088 | 390 | 100.0 | 150 | 46 | 560 | 5.8 | 790 | 86 | 27.0 | 28.0 | 0.010 | 0.010 | 0.072 | 0.003 | 1.40 | 0.007 | 1 | 1 |
| 86 | PB | 6.95 | 70.0 | 1 | 530 | 3300 | 3150 | 0.17 | 0.00 | 0.165 | 740 | 180.0 | 200 | 100 | 910 | 6.2 | 1450 | 195 | 19.5 | 25.0 | 0.013 | 0.012 | 0.110 | 0.004 | 2.55 | 0.011 | 1 | 1 |
| 87 | RH | 7.31 | 2.0 | 1 | 3250 | 22000 | 21500 | 0.50 | 0.00 | 0.074 | 6560 | 260.0 | 290 | 790 | 3950 | 3.6 | 11950 | 1600 | 10.5 | 23.0 | 0.015 | 0.015 | 0.185 | 0.021 | 1.30 | 0.076 | 1 | 1 |
| 88 | RH | 7.45 | 1.1 | 1 | 2250 | 14500 | 14500 | 0.00 | 0.00 | 0.057 | 4250 | 210.0 | 280 | 530 | 2850 | 4.0 | 7500 | 1400 | 16.5 | 23.0 | 0.009 | 0.009 | 0.385 | 0.010 | 1.70 | 0.130 | 1 | 1 |
| 89 | C | 7.27 | 1.2 | 0 | 4700 | 26500 | 26500 | 0.00 | 0.00 | 0.059 | 7780 | 310.0 | 390 | 940 | 4840 | 2.5 | 15050 | 1950 | 5.8 | 11.5 | 0.019 | 0.019 | 0.041 | 0.007 | 0.05 | 0.017 | 1 | 1 |
| 90 | C | 7.44 | 0.7 | 2 | 3050 | 20000 | 20000 | 0.00 | 0.00 | 0.038 | 6010 | 200.0 | 280 | 710 | 3620 | 4.4 | 11150 | 1450 | 12.0 | 17.0 | 0.020 | 0.014 | 0.175 | 0.003 | 0.01 | 0.024 | 1 | 1 |
| 91 | C | 8.08 | 1.7 | 2 | 3000 | 20000 | 20000 | 0.14 | 0.00 | 0.079 | 6090 | 210.0 | 290 | 720 | 3680 | 4.4 | 10750 | 1500 | 16.0 | 14.5 | 0.023 | 0.012 | 0.360 | 0.010 | 1.65 | 0.355 | 1 | 1 |
| 92 | PB | 7.18 | 31.0 | 5 | 290 | 1800 | 1600 | 6.00 | 0.00 | 0.053 | 350 | 8.0 | 160 | 42 | 560 | 5.7 | 700 | 73 | 26.0 | 31.0 | 0.015 | 0.003 | 0.175 | 0.009 | 1.55 | 0.048 | 1 | 1 |
| 93 | PB | 7.21 | 34.0 | 0 | 290 | 1800 | 1650 | 6.00 | 0.00 | 0.013 | 360 | 8.0 | 160 | 42 | 570 | 5.6 | 700 | 75 | 26.0 | 31.0 | 0.014 | 0.003 | 0.170 | 0.010 | 1.60 | 0.032 | 1 | 1 |
| 94 | PB | 7.31 | 2.3 | 0 | 215 | 1300 | 1150 | 0.35 | 0.00 | 0.018 | 260 | 8.0 | 85 | 48 | 410 | 4.6 | 490 | 61 | 15.5 | 25.0 | 0.006 | 0.005 | 0.057 | 0.016 | 1.70 | 0.051 | 1 | 1 |
| 95 | TB | 7.57 | 7.5 | 1 | 94 | 650 | 560 | 2.40 | 0.40 | 0.220 | 95 | 3.4 | 46 | 38 | 270 | 3.2 | 170 | 35 | 22.0 | 20.0 | 0.048 | 0.035 | 0.088 | 0.000 | 0.01 | 0.000 | 1 | 0 |
| 96 | TB | 7.46 | 2.9 | 1 | 340 | 1900 | 1800 | 0.35 | 0.00 | 0.094 | 480 | 9.0 | 95 | 60 | 480 | 2.7 | 970 | 36 | 15.5 | 21.0 | 0.035 | 0.020 | 0.500 | 0.007 | 1.35 | 0.036 | 1 | 1 |
| 97 | B | 7.05 | 0.6 | 1 | 630 | 3750 | 3550 | 0.40 | 0.00 | 0.280 | 910 | 24.0 | 190 | 130 | 1010 | 6.0 | 1750 | 215 | 21.0 | 38.0 | 0.010 | 0.010 | 0.110 | 0.033 | 14.00 | 0.135 | 0 | 1 |
| 98 | W | 8.00 | 3.5 | 80 | 900 | 5700 | 5400 | 0.90 | 0.35 | 0.240 | 1590 | 70 | 150 | 210 | 1240 | 11.1 | 2600 | 85 | 17.5 | 48 | 2.90 | 2.80 | 18.5 | 6.70 | 34.8 | 10.5 | 1 | 1 |

# Appendix D

## Chemical characteristics of water inhabited by various taxa of stygofauna

The following pages characterize the chemical composition of the water inhabited by the various taxa of stygofauna found on the Cape Range peninsula and, in the case of some more widely distributed taxa (melitid amphipods, copepods and ostracods), of the area sampled in 1993. They are discussed in the main body of the report.

### Contents

Appendix D2

**Appendix Da**: Water analysis for the sites inhabited by *Ophisternon candidum* (n= 8).

| Parameter | Mean | SE | Min | Max | CV |
|---|---|---|---|---|---|
| pH | 7.40 | 0.11 | 7.02 | 8.00 | 4 |
| Turbidity | 12.1 | 9.03 | 1 | 75 | 211 |
| Colour | 15.9 | 9.98 | 1 | 80 | 178 |
| Conductivity | 572 | 143 | 115 | 1250 | 71 |
| TFS | 3520 | 864 | 710 | 7700 | 69 |
| TFS-$CO_2$ | 3343 | 858 | 640 | 7550 | 73 |
| Fe | 0.28 | 0.13 | 0 | 0.9 | 129 |
| Mn | 0.10 | 0.05 | 0 | 0.35 | 133 |
| Al | 0.11 | 0.03 | 0.02 | 0.24 | 74 |
| Na | 916 | 267 | 140 | 2230 | 82 |
| K | 35.7 | 10.8 | 5 | 80 | 86 |
| Ca | 121.9 | 13.5 | 55 | 170 | 31 |
| Mg | 121.6 | 30.8 | 22 | 270 | 72 |
| Hardness | 802 | 151.6 | 220 | 1500 | 54 |
| Alkalinity | 6.03 | 0.91 | 2.3 | 11.1 | 43 |
| Cl | 1666 | 483 | 255 | 4100 | 82 |
| $SO_4$ | 176 | 64.9 | 2 | 540 | 104 |
| Si | 16.8 | 1.84 | 10.5 | 25 | 31 |
| FOC | 29.0 | 10.2 | 1 | 82 | 100 |
| TP | 0.392 | 0.358 | 0.011 | 2.90 | 258 |
| FRP | 0.36 | 0.35 | 0.006 | 2.8 | 274 |
| TKN | 3.09 | 2.26 | 0.07 | 18.5 | 207 |
| $NO_2$ | 0.84 | 0.84 | 0 | 6.7 | 290 |
| $NO_3$ | 6.46 | 4.10 | 0.08 | 34.8 | 108 |
| $NH_3$ | 1.38 | 1.30 | 0.006 | 10.5 | 266 |

**Appendix Db:** Water analysis for the sites inhabited by *Milyeringa veritas* (n= 20).

| Parameter | Mean | SE | Min | Max | CV |
|---|---|---|---|---|---|
| pH | 7.45 | 0.06 | 7.02 | 8.08 | 3 |
| Turbidity | 3.83 | 1.00 | 0.6 | 16 | 116 |
| Colour | 4.7 | 1.7 | 0 | 34 | 162 |
| Conductivity | 1295 | 307 | 35 | 4700 | 106 |
| TFS | 8168 | 1930 | 250 | 26500 | 106 |
| TFS-$CO_2$ | 8013 | 1927 | 210 | 26500 | 107 |
| Fe | 0.20 | 0.08 | 0 | 1.6 | 185 |
| Mn | 0.04 | 0.02 | 0 | 0.45 | 256 |
| Al | 0.12 | 0.03 | 0.02 | 0.6 | 119 |
| Na | 2352 | 589 | 48 | 7780 | 112 |
| K | 94.0 | 22.7 | 2 | 310 | 108 |
| Ca | 161 | 22.3 | 15 | 390 | 62 |
| Mg | 288 | 68.7 | 3.4 | 940 | 107 |
| Hardness | 1580 | 336 | 50 | 4840 | 95 |
| Alkalinity | 4.5 | 0.34 | 1.6 | 8.2 | 34 |
| Cl | 4321 | 1088 | 54 | 15050 | 113 |
| $SO_4$ | 579 | 145 | 7 | 1950 | 112 |
| Si | 13.8 | 0.9 | 2.8 | 23 | 29 |
| FOC | 19.6 | 4.1 | 1 | 74 | 93 |
| TP | 0.05 | 0.01 | 0.009 | 0.185 | 91 |
| FRP | 0.026 | 0.007 | .004 | .13 | 121 |
| TKN | 0.36 | 0.09 | 0.04 | 1.7 | 113 |
| $NO_2$ | 0.02 | 0.009 | 0 | 0.19 | 202 |
| $NO_3$ | 3.2 | 1.54 | 0.02 | 31.5 | 215 |
| $NH_3$ | 0.06 | 0.02 | 0 | 0.36 | 135 |

**Appendix Dc:** Water analysis for the sites inhabited by *Stygiocaris* spp. (n= 25).

| Parameter | Mean | SE | Min | Max | CV |
|---|---|---|---|---|---|
| pH | 7.35 | 0.06 | 6.85 | 8.08 | 4 |
| Turbidity | 17.3 | 5.2 | 1 | 110 | 151 |
| Colour | 3.6 | 1.4 | 0 | 34 | 190 |
| Conductivity | 456 | 121 | 48 | 3000 | 133 |
| TFS | 2859 | 793 | 370 | 20000 | 139 |
| TFS-$CO_2$ | 2716 | 798 | 290 | 20000 | 147 |
| Fe | 2.6 | 1.5 | 0 | 36 | 292 |
| Mn | 0.06 | 0.03 | 0 | 0.5 | 207 |
| Al | 0.11 | 0.02 | 0.02 | 0.49 | 102 |
| Na | 735 | 246 | 40 | 6090 | 168 |
| K | 31.2 | 10.6 | 3 | 210 | 171 |
| Ca | 113 | 10.9 | 48 | 290 | 48 |
| Mg | 97.6 | 28.5 | 6 | 720 | 146 |
| Hardness | 681 | 139 | 140 | 3680 | 102 |
| Alkalinity | 4.8 | 0.26 | 2.3 | 8.2 | 28 |
| Cl | 1332 | 437 | 54 | 10750 | 164 |
| $SO_4$ | 178 | 61 | 9 | 1500 | 172 |
| Si | 15.5 | 0.9 | 7.5 | 26 | 29 |
| FOC | 20.4 | 2.3 | 1 | 46 | 56 |
| TP | 0.05 | 0.007 | 0.007 | 0.12 | 77 |
| FRP | 0.02 | 0.004 | 0.003 | 0.091 | 128 |
| TKN | 0.39 | 0.12 | 0.05 | 3 | 149 |
| $NO_2$ | 0.012 | 0.003 | 0 | 0.069 | 126 |
| $NO_3$ | 2.1 | 0.31 | 0 | 0.07 | 126 |
| $NH_3$ | 0.18 | 0.12 | 0 | 3 | 336 |

**Appendix Dd:** Water analysis for the sites inhabited by *Halosbaena tulki* (n= 19).

| Parameter | Mean | SE | Min | Max | CV |
|---|---|---|---|---|---|
| pH | 7.3 | 0.05 | 6.95 | 7.62 | 3 |
| Turbidity | 15.8 | 5.9 | 0.6 | 95 | 164 |
| Colour | 1.9 | 0.5 | 0 | 8 | 108 |
| Conductivity | 420 | 75 | 78 | 1250 | 78 |
| TFS | 2577 | 450 | 610 | 7700 | 76 |
| TFS-$CO_2$ | 2427 | 446 | 480 | 7550 | 80 |
| Fe | 0.43 | 0.25 | 0 | 4.8 | 257 |
| Mn | 0.07 | 0.03 | 0 | 0.45 | 197 |
| Al | 0.09 | 0.02 | 0.02 | 0.35 | 89 |
| Na | 632 | 135 | 55 | 2230 | 93 |
| K | 31 | 10 | 3 | 180 | 138 |
| Ca | 112 | 9.7 | 55 | 200 | 38 |
| Mg | 87 | 15 | 16 | 270 | 76 |
| Hardness | 638 | 79 | 220 | 1500 | 54 |
| Alkalinity | 5.0 | 0.3 | 2.3 | 8.2 | 26 |
| Cl | 1104 | 254 | 100 | 4100 | 100 |
| $SO_4$ | 237 | 93 | 14 | 1800 | 171 |
| Si | 15 | 1 | 10 | 27 | 29 |
| FOC | 18 | 3 | 1 | 49 | 72 |
| TP | 0.04 | 0.008 | 0.007 | 0.11 | 82 |
| FRP | 0.016 | 0.005 | 0.003 | 0.091 | 132 |
| TKN | 0.41 | 0.17 | 0.05 | 3 | 179 |
| $NO_2$ | 0.01 | 0.002 | 0 | 0.03 | 94 |
| $NO_3$ | 2.47 | 0.37 | 0.08 | 5.9 | 65 |
| $NH_3$ | 0.20 | 0.16 | 0 | 3 | 346 |

**Appendix De:** Water analysis for the sites inhabited by *Haptolana pholeta* (n= 6).

| Parameter | Mean | SE | Min | Max | CV |
|---|---|---|---|---|---|
| pH | 7.22 | 0.06 | 6.95 | 7.54 | 3 |
| Turbidity | 23.6 | 11.2 | 0.7 | 70 | 116 |
| Colour | 2.3 | 0.6 | 1 | 5 | 59 |
| Conductivity | 289 | 67 | 100 | 530 | 56 |
| TFS | 1783 | 397 | 660 | 3300 | 55 |
| TFS-$CO_2$ | 1642 | 394 | 540 | 3150 | 59 |
| Fe | 1.9 | 1.1 | 0.05 | 6 | 146 |
| Mn | 0.06 | 0.06 | 0 | 0.35 | 245 |
| Al | 0.08 | 0.02 | 0.02 | 0.17 | 72 |
| Na | 375 | 105 | 80 | 740 | 69 |
| K | 53 | 30 | 2.6 | 180 | 138 |
| Ca | 121 | 23 | 65 | 200 | 47 |
| Mg | 54.1 | 11.3 | 30 | 100 | 51 |
| Hardness | 527 | 89 | 300 | 910 | 42 |
| Alkalinity | 4.97 | 0.43 | 3.9 | 6.2 | 21 |
| Cl | 718 | 200 | 165 | 1450 | 68 |
| $SO_4$ | 82 | 26 | 14 | 195 | 79 |
| Si | 18.6 | 2.8 | 10 | 27 | 37 |
| FOC | 24.8 | 1.9 | 17.5 | 31 | 19 |
| TP | 0.04 | 0.02 | 0.01 | 0.11 | 106 |
| FRP | 0.02 | 0.01 | 0.003 | 0.091 | 169 |
| TKN | 0.60 | 0.48 | 0.07 | 3 | 194 |
| $NO_2$ | 0.01 | 0.003 | 0.003 | 0.022 | 73 |
| $NO_3$ | 1.54 | 0.26 | 0.59 | 2.55 | 42 |
| $NH_3$ | 0.53 | 0.49 | 0.006 | 3 | 229 |

**Appendix Df:** Water analysis for the sites inhabited by melitid amphipods in Cape Range *sensu stricto* (n= 3).

| Parameter | Mean | SE | Min | Max | CV |
|---|---|---|---|---|---|
| pH | 7.77 | 0.05 | 7.68 | 7.85 | 1 |
| Turbidity | 14.4 | 11.3 | 1.7 | 37 | 136 |
| Colour | 9.33 | 6.89 | 1 | 23 | 128 |
| Conductivity | 67.7 | 2.67 | 65 | 73 | 7 |
| TFS-$CO_2$ | 436.7 | 32.8 | 390 | 500 | 13 |
| Fe | 1.0 | 1 | 0 | 3 | 173 |
| Mn | 0.47 | 0.47 | 0 | 1.4 | 173 |
| Al | 0.25 | 0.18 | 0.069 | 0.6 | 122 |
| Na | 35.3 | 8.67 | 18 | 44 | 42 |
| K | 2.53 | 0.84 | 1.6 | 4.2 | 57 |
| Ca | 113.3 | 33.33 | 80 | 180 | 51 |
| Mg | 7.33 | 1.86 | 5 | 11 | 44 |
| Hardness | 306.7 | 76.9 | 220 | 460 | 43 |
| Alkalinity | 3.97 | 0.48 | 3.3 | 4.9 | 21 |
| Cl | 80.7 | 16.0 | 49 | 100 | 34 |
| $SO_4$ | 10.0 | 2.08 | 7 | 14 | 35 |
| Si | 14.0 | 1.32 | 12 | 16.5 | 16.4 |
| FOC | 22.67 | 4.8 | 16 | 32 | 36.7 |
| TP | 0.10 | 0.06 | 0.012 | 0.225 | 109 |
| FRP | 0.061 | 0.052 | 0.006 | 0.165 | 149 |
| TKN | 1.000 | 0.90 | 0.03 | 2.8 | 155 |
| $NO_2$ | 0.015 | 0.006 | 0.008 | 0.026 | 64 |
| $NO_3$ | 0.58 | 0.28 | 0.003 | 0.94 | 83 |
| $NH_3$ | 0.38 | 0.36 | 0.007 | 1.1 | 167 |
| TFS | 556.7 | 48.1 | 490 | 650 | 15 |

**Appendix Dg:** Water analysis for the sites inhabited by melitid amphipods on the coastal plain of, and the hinterland to, the Cape Range peninsula (n=19).

| Parameter | Mean | SE | Min | Max | CV |
|---|---|---|---|---|---|
| pH | 7.38 | 0.07 | 6.87 | 7.87 | 4 |
| Turbidity | 37.3 | 15.2 | 1.6 | 270 | 177 |
| Colour | 3.79 | 1.13 | 0 | 20 | 130 |
| Conductivity | 579.2 | 105.1 | 100 | 1700 | 79 |
| TFS | 3621.6 | 658.1 | 660 | 11000 | 79 |
| TFS-$CO_2$ | 3462.6 | 663.7 | 540 | 11000 | 84 |
| Fe | 4.96 | 2.25 | 0 | 36 | 198 |
| Mn | 0.094 | 0.054 | 0 | 0.9 | 250 |
| Al | 0.35 | 0.23 | 0.02 | 4.4 | 286 |
| Na | 823.2 | 157.3 | 80 | 2230 | 83 |
| K | 46.2 | 11.9 | 2.6 | 180 | 112 |
| Ca | 180.3 | 51.3 | 46 | 1070 | 124 |
| Mg | 165.2 | 51.8 | 32 | 1020 | 136.7 |
| Hardness | 1124.2 | 337.7 | 300 | 6870 | 131 |
| Alkalinity | 5.53 | 0.45 | 3.1 | 10.4 | 35 |
| Cl | 1685.8 | 361.3 | 165 | 5700 | 93 |
| $SO_4$ | 260.5 | 69.9 | 2 | 1150 | 117 |
| Si | 23.0 | 3.71 | 3.3 | 75 | 70 |
| FOC | 34.96 | 5.59 | 1.7 | 105 | 70 |
| TP | 0.09 | 0.03 | 0.013 | 0.445 | 142 |
| FRP | 0.037 | 0.018 | 0 | 0.35 | 213 |
| TKN | 0.875 | 0.502 | 0.052 | 9.2 | 250 |
| $NO_2$ | 0.057 | 0.026 | 0.003 | 0.46 | 198 |
| $NO_3$ | 4.31 | 1.74 | 0.022 | 31.5 | 176 |
| $NH_3$ | 0.30 | 0.26 | 0 | 5 | 380 |

**Appendix Dh:** Water analysis at three depths in C-28 (n=1 at each depth).

| Parameter | W 91 | W 90 | W 89 |
|---|---|---|---|
| Depth (m) | 0.2 | 6 | 14 |
| Temperature (°C) | 22 | 21 | 27 |
| pH | 8.08 | 7.44 | 7.27 |
| Turbidity | 1.7 | 0.7 | 1.2 |
| Colour | 2 | 2 | 0 |
| Conductivity | 3000 | 3050 | 4700 |
| TFS | 20000 | 20000 | 26500 |
| TFS-$CO_2$ | 20000 | 20000 | 26500 |
| Fe | 0.14 | 0 | 0 |
| Mn | 0 | 0 | 0 |
| Al | 0.079 | 0.038 | 0.059 |
| Na | 6090 | 6010 | 7780 |
| K | 210 | 200 | 310 |
| Ca | 290 | 280 | 390 |
| Mg | 720 | 710 | 940 |
| Hardness | 3680 | 3620 | 4840 |
| Alkalinity | 4.4 | 4.4 | 2.5 |
| Cl | 10750 | 11150 | 15050 |
| $SO_4$ | 1500 | 1450 | 1950 |
| Si | 16 | 12 | 5.8 |
| FOC | 14.5 | 17 | 11.5 |
| TP | 0.023 | 0.02 | 0.019 |
| FRP | 0.012 | 0.014 | 0.019 |
| TKN | 0.36 | 0.175 | 0.041 |
| $NO_2$ | 0.01 | 0.003 | 0.007 |
| $NO_3$ | 1.65 | 0.015 | 0.054 |
| $NH_3$ | 0.355 | 0.024 | 0.017 |

**Appendix Di:** Water analysis for the sites inhabited by Ostracoda (n= 7).

| Parameter | Mean | SE | Min | Max | CV |
|---|---|---|---|---|---|
| pH | 7.44 | 0.18 | 6.93 | 8.08 | 7 |
| Turbidity | 1.67 | .52 | 0.5 | 4 | 82 |
| Colour | 2.14 | 0.71 | 0 | 6 | 87 |
| Conductivity | 1226 | 519 | 110 | 3300 | 112 |
| TFS | 7991 | 3413 | 760 | 21500 | 113 |
| TFS-$CO_2$ | 7873 | 3445 | 630 | 21500 | 116 |
| Fe | 0.051 | 0.025 | 0 | 0.14 | 128 |
| Mn | 0 | 0 | 0 | 0 | 0 |
| Al | 0.048 | 0.012 | 0.008 | 0.088 | 67 |
| Na | 2308 | 1076 | 60 | 6580 | 123 |
| K | 93.4 | 36.0 | 1.8 | 230 | 102 |
| Ca | 200 | 27.3 | 110 | 300 | 36 |
| Mg | 250 | 115 | 11 | 720 | 122 |
| Hardness | 1527 | 535 | 330 | 3680 | 93 |
| Alkalinity | 5.31 | 0.6 | 3.9 | 8.2 | 30 |
| Cl | 4214 | 1965 | 125 | 12350 | 123 |
| $SO_4$ | 532 | 240 | 9 | 1500 | 119 |
| Si | 20.2 | 2.26 | 10.5 | 27 | 30 |
| FOC | 27.6 | 4.37 | 14.5 | 49 | 42 |
| TP | 0.018 | 0.005 | 0.008 | 0.04 | 68 |
| FRP | 0.011 | 0.002 | 0.005 | 0.023 | 51 |
| TKN | 0.117 | 0.043 | 0.017 | 0.36 | 96 |
| $NO_2$ | 0.03 | 0.014 | 0 | 0.105 | 121 |
| $NO_3$ | 2.54 | 1.11 | 0 | 8.55 | 115 |
| $NH_3$ | 0.08 | 0.05 | 0 | 0.36 | 169 |

**Appendix Dj:** Water analysis for the sites inhabited by Copepoda (n= 50).

| Parameter | Mean | SE | Min | Max | CV |
|---|---|---|---|---|---|
| pH | 7.45 | 0.06 | 6.93 | 9.13 | 5 |
| Turbidity | 20.0 | 6.17 | 0.5 | 270 | 218 |
| Colour | 4.76 | 1.01 | 0 | 34 | 151 |
| Conductivity | 713 | 128 | 35 | 3600 | 127 |
| TFS | 4574 | 847.7 | 250 | 24000 | 131 |
| TFS-$CO_2$ | 4395 | 846.0 | 210 | 24000 | 136 |
| Fe | 1.72 | 0.77 | 0 | 36 | 316 |
| Mn | 0.068 | 0.031 | 0 | 1.4 | 323 |
| Al | 0.21 | 0.088 | 0.008 | 4.4 | 296 |
| Na | 1248 | 265 | 18 | 7490 | 150 |
| K | 54.4 | 10.4 | 1.8 | 280 | 135 |
| Ca | 137.7 | 9.92 | 15 | 360 | 51 |
| Mg | 152.0 | 29.1 | 3.4 | 840 | 135 |
| Hardness | 966 | 140.3 | 50 | 4360 | 103 |
| Alkalinity | 5.24 | 0.23 | 1.6 | 10.4 | 31 |
| Cl | 2227 | 478 | 49 | 12950 | 152 |
| $SO_4$ | 334.3 | 68.3 | 7 | 1800 | 144 |
| Si | 20.97 | 2.42 | 6.4 | 101 | 82 |
| FOC | 26.23 | 2.09 | 1 | 74 | 56 |
| TP | 0.078 | 0.018 | 0.006 | 0.71 | 163 |
| FRP | 0.045 | 0.016 | 0.003 | 0.67 | 249 |
| TKN | 0.44 | 0.11 | 0 | 3.85 | 177 |
| $NO_2$ | 0.055 | 0.023 | 0 | 0.98 | 290 |
| $NO_3$ | 2.95 | 0.71 | 0 | 31.5 | 169 |
| $NH_3$ | 0.14 | 0.07 | 0 | 3 | 334 |

**Appendix Dk:** Water analysis for the sites inhabited by harpacticoid copepods(n= 25).

| Parameter | Mean | SE | Min | Max | CV |
|---|---|---|---|---|---|
| pH | 7.46 | 0.09 | 6.93 | 9.13 | 6 |
| Turbidity | 23.1 | 11.4 | 0.6 | 270 | 247 |
| Colour | 6.04 | 1.75 | 0 | 34 | 144 |
| Conductivity | 1103 | 223 | 115 | 3600 | 101 |
| TFS | 7073 | 1501 | 980 | 24000 | 106 |
| TFS-$CO_2$ | 6867 | 1501 | 730 | 24000 | 109 |
| Fe | 1.23 | 0.56 | 0 | 12 | 228 |
| Mn | 0.03 | 0.02 | 0 | 0.45 | 308 |
| Al | 0.29 | 0.17 | 0.013 | 4.4 | 301 |
| Na | 2022 | 472 | 60 | 7490 | 117 |
| K | 82.0 | 17.4 | 1.8 | 280 | 106 |
| Ca | 170.6 | 15.1 | 65 | 360 | 44 |
| Mg | 235.4 | 52.2 | 11 | 840 | 111 |
| Hardness | 1389 | 246.9 | 410 | 4360 | 89 |
| Alkalinity | 5.44 | 0.30 | 3.1 | 8.2 | 27 |
| Cl | 3668 | 846.8 | 125 | 12950 | 115 |
| $SO_4$ | 466.5 | 107.1 | 9 | 1800 | 115 |
| Si | 17.7 | 1.37 | 6.5 | 34 | 39 |
| FOC | 21.7 | 2.57 | 1 | 46 | 59 |
| TP | 0.094 | 0.034 | 0.006 | 0.71 | 183 |
| FRP | 0.05 | 0.03 | 0.003 | 0.67 | 267 |
| TKN | 0.46 | 0.16 | 0 | 3.85 | 172 |
| $NO_2$ | 0.020 | 0.008 | 0 | 0.185 | 189 |
| $NO_3$ | 3.12 | 1.23 | 0 | 31.5 | 198 |
| $NH_3$ | 0.059 | 0.017 | 0 | 0.355 | 149 |

**Appendix Dl:** Water analysis for the sites inhabited by calanoid copepods (n= 39).

| Parameter | Mean | SE | Min | Max | CV |
|---|---|---|---|---|---|
| pH | 7.40 | 0.05 | 6.95 | 8.17 | 4 |
| Turbidity | 20.1 | 7.37 | 0.5 | 270 | 229 |
| Colour | 3.80 | 0.84 | 0 | 23 | 137 |
| Conductivity | 595.4 | 129.1 | 35 | 3300 | 135 |
| TFS | 3820 | 853 | 250 | 22000 | 139 |
| TFS-$CO_2$ | 3649 | 846 | 210 | 21500 | 145 |
| Fe | 1.92 | 0.97 | 0 | 36 | 317 |
| Mn | 0.076 | 0.038 | 0 | 1.4 | 316 |
| Al | 0.24 | 0.11 | 0.008 | 4.4 | 287 |
| Na | 1012 | 264 | 18 | 6580 | 163 |
| K | 46.7 | 10.8 | 2 | 260 | 145 |
| Ca | 126.4 | 9.99 | 15 | 300 | 49 |
| Mg | 126.0 | 28.5 | 3.4 | 790 | 141 |
| Hardness | 830.5 | 137.0 | 50 | 3950 | 103 |
| Alkalinity | 5.07 | 0.27 | 1.6 | 10.4 | 33 |
| Cl | 1817 | 487.7 | 49 | 12350 | 168 |
| $SO_4$ | 280 | 70 | 7 | 1800 | 159 |
| Si | 21.2 | 3.00 | 6.4 | 101 | 88 |
| FOC | 25.2 | 2.19 | 1 | 74 | 54 |
| TP | 0.072 | 0.016 | 0.006 | 0.45 | 139 |
| FRP | 0.036 | 0.011 | 0.003 | 0.35 | 195 |
| TKN | 0.44 | 0.14 | 0 | 3.85 | 192 |
| $NO_2$ | 0.068 | 0.029 | 0 | 0.98 | 266 |
| $NO_3$ | 3.39 | 0.88 | 0.033 | 31.5 | 162 |
| $NH_3$ | 0.16 | 0.08 | 0 | 3 | 332 |

**Appendix Dm:** Water analysis for samples taken at three depths in Bundera cenote (C-28).

| Parameter | W 91 | W 90 | W 89 |
|---|---|---|---|
| Depth (m) | 0.2 | 6 | 14 |
| Temperature (°C) | 22 | 21 | 27 |
| pH | 8.08 | 7.44 | 7.27 |
| Turbidity | 1.7 | 0.7 | 1.2 |
| Colour | 2 | 2 | 0 |
| Conductivity | 3000 | 3050 | 4700 |
| TFS | 20000 | 20000 | 26500 |
| TFS-CO2 | 20000 | 20000 | 26500 |
| Fe | 0.14 | 0 | 0 |
| Mn | 0 | 0 | 0 |
| Al | 0.079 | 0.038 | 0.059 |
| Na | 6090 | 6010 | 7780 |
| K | 210 | 200 | 310 |
| Ca | 290 | 280 | 390 |
| Mg | 720 | 710 | 940 |
| Hardness | 3680 | 3620 | 4840 |
| Alkalinity | 4.4 | 4.4 | 2.5 |
| Cl | 10750 | 11150 | 15050 |
| SO4 | 1500 | 1450 | 1950 |
| Si | 16 | 12 | 5.8 |
| FOC | 14.5 | 17 | 11.5 |
| TP | 0.023 | 0.02 | 0.019 |
| FRP | 0.012 | 0.014 | 0.019 |
| TKN | 0.36 | 0.175 | 0.041 |
| NO2 | 0.01 | 0.003 | 0.007 |
| NO3 | 1.65 | 0.015 | 0.054 |
| NH3 | 0.355 | 0.024 | 0.017 |

# Appendix E

## Descriptions of the main wells through which access to the stygofauna is facilitated on the Cape Range peninsula

Appendix E2

**Appendix E**: Descriptions of the main wells through which access to the stygofauna is facilitated on the Cape Range peninsula. To preserve some of the locations the coordinates are given only to the nearest minute of latitude and longitude — a data base containing more precise locations is maintained at the Western Australian Museum. Only wells within the main area of the Cape Range peninsula stygofauna are given here; many more wells and bores were recorded and the information is held in the Western Australian Museum.

| | |
|---|---|
| ***Index #*** | C-18 |
| *Name* | Dry Swallett |
| *Coordinates* | 22o 05' S; 114o 00' E |
| *Type* | Sinkhole |
| *Area around* | Scrub over spinifex |
| *Working gear* | - |
| *Top* | - |
| *Lining* | - |
| *Depth to water (m)* | 50 |
| *Water depth m* | *c.* 0.2 |
| *Fauna* | Melitid amphipod sp. 2 and large terrestrial troglobite fauna |
| *Notes* | In Cape Range. Water sometimes inaccessible under gravel and sand. Surveyed |

| | |
|---|---|
| ***Index #*** | C-23 |
| *Name* | Dozer Cave |
| *Coordinates* | 21o 59' S; 114o 07' " E |
| *Type* | Collapsed chamber |
| *Area around* | Gravel quarry in coastal dunes |
| *Working gear* | - |
| *Top* | *c.*12 m across collapse |
| *Lining* | Gravel |
| *Depth to water (m)* | 6 |
| *Water depth m* | 3 |
| *Fauna* | *Milyeringa veritas*, *Ophisternon candidum*; none seen since gross siltation started |
| *Notes* | Cave opened by a bulldozer in a gravel quarry and probably linked to C-105, which is 60 m away. Gross siltation resulting from erosion of 'landscaped' but unvegetated disused gravel pit |

| | |
|---|---|
| ***Index #*** | C-24 |
| *Name* | Milyering Well |
| *Coordinates* | 22o 01' S; 113o 56' E |
| *Type* | Well |
| *Area around* | Small concrete banded tank 3 m west in good condition and two troughs. C-172 (Milyering Cave ) 15 m to east. Old fencelines |
| *Working gear* | No headgear windmill leg bases around well |
| *Top* | 0.1 m high covered by heavy steel grill |
| *Lining* | Circular, concrete lined at top (0.8 m) then through coral rock |
| *Depth to water (m)* | 3 |
| *Water depth m* | 0.5 |
| *Fauna* | *M. veritas* (type locality),*O. candidum* (original report only; Mees 1962), *Halosbaena tulki*, *Stygiocaris lancifera*, ostracods |
| *Notes* | Mill was in place in 1959 (photo in Mees 1962) |

| | |
|---|---|
| ***Index #*** | C-25 |
| *Name* | Kudamurra (Palms) Well |
| *Coordinates* | 21o 53' S; 114o 01' E |
| *Type* | Well |
| *Area around* | Tank and trough 40 m to east all functioning providing "fresh water to all sites of the caravan park |
| *Working gear* | Was motor driven, now windmill, functioning. Polypipe feeds to tank |
| *Top* | Marine ply on top |
| *Lining* | Concrete, circular to bottom |
| *Depth to water (m)* | 1.8 |
| *Water depth m* | 0.3 |
| *Fauna* | *M. veritas, O. candidum, S. lancifera* (type locality), *Stygiocaris stylifera* (type locality), *H. tulki*, amphipods |
| *Notes* | Faint inscription on concrete lip '?-11-69' |

| | |
|---|---|
| ***Index #*** | C-26 |
| *Name* | Tantabiddi Well |
| *Coordinates* | 21o 56' S; 113o 58' E |
| *Type* | Hole just inland of coastal sand dunes |
| *Area around* | Old fence lines. Old tank base to east at 4 m, concrete filled drums next to water. Old drum sunk down hole |
| *Working gear* | Old mill legs only, 0.1 m high |
| *Top* | Flush, uncovered natural hole enlarged with retaining wall 5 m diameter. Railway track laid on top |
| *Lining* | Corrugated iron |
| *Depth to water (m)* | 1.5 |
| *Water depth m* | 0.08 m deep in 1x1 m hole |
| *Fauna* | *O. candidum* (type locality), *H. tulki* (from *O. candidum* guts only), ostracods |
| *Notes* | Baler shell; concrete block with date 1978. Birds drink here (2 dead Zebra Finches in water, mosquitoes and bad smell when sampled in 1993) |

| | |
|---|---|
| ***Index #*** | C-27 |
| *Name* | Kubura Well |
| *Coordinates* | 21o 56' S; 114o 08' E |
| *Type* | Natural cave, entrance enlarged |
| *Area around* | Locked fence |
| *Working gear* | Fixed ladder with irrigation pump on platform |
| *Top* | Locked grill |
| *Lining* | - |
| *Depth to water (m)* | *c.* 5 |
| *Water depth m* | *c.* 4 |
| *Fauna* | *M. veritas*, S. *stylifera, O. candidum, H. tulki* |
| *Notes* | Baler shell; used for irrigation for many years by Exmouth Shire. Waste plumbing materials (copper, bronze, plastic and concrete) in water.Calcite rafts form on water. Sulphurous mud |

| | |
|---|---|
| ***Index #*** | C-28 |
| *Name* | Bundera Sinkhole (South Yardie Cenote) |
| *Coordinates* | 22o 25' S; 113o 46' E |
| *Type* | Water filled sinkhole (cenote) |
| *Area around* | The cenote is about 18x 9 m; vehicular track alongside |
| *Working gear* | - |
| *Top* | - |
| *Lining* | Bundera Calcarenite (type section) |
| *Depth to water (m)* | 7.5, tidal |
| *Water depth m* | 32 |
| *Fauna* | *M. veritas*, *Iravadia* sp. (Gastropoda), *Danielopolina* sp. nov. (Ostracoda), Remipedia |
| *Notes* | Profuse algal growth; massive bacterial colonies above thermo -halocline |

| | |
|---|---|
| ***Index #*** | C-64 |
| *Name* | Shot-Hole Tunnel |
| *Coordinates* | 22o 03' S; 114o 01' E |
| *Type* | Outflow cave in Cape Range |
| *Area around* | Side of gorge |
| *Working gear* | - |
| *Top* | - |
| *Lining* | - |
| *Depth to water (m)* | - |
| *Water depth m* | <1 |
| *Fauna* | Melitid amphipod sp. 2 and large terrestrial troglobite fauna |
| *Notes* | A horizontally developed low cave in the side of a gorge. Surveyed at 318 m long. Flowing water and sump |

| | |
|---|---|
| ***Index #*** | C-103 |
| *Name* | Trionomo Cave |
| *Coordinates* | 22o 07' S; 113o 59' E |
| *Type* | Extensive cave in Cape Range |
| *Area around* | - |
| *Working gear* | - |
| *Top* | - |
| *Lining* | - |
| *Depth to water (m)* | 55.6 |
| *Water depth m* | <0.3 |
| *Fauna* | Melitid amphipod sp. 2 and large terrestrial troglobite fauna |
| *Notes* | Surveyed |

| | |
|---|---|
| ***Index #*** | C-105 |
| *Name* | The Gnamma Hole |
| *Coordinates* | 21o 59' S; 114o 07' E |
| *Type* | Small hole opening into dome of water-filled cave |
| *Area around* | Gravel pit |
| *Working gear* | - |
| *Top* | - |
| *Lining* | - |
| *Depth to water (m)* | c. 15 |
| *Water depth m* | c. 4 |
| *Fauna* | *O. candidum*, *M. veritas*, *S. stylifera*, *H. tulki* , troglobitic Meenoplidae (Hemiptera) |
| *Notes* | - |

| | |
|---|---|
| ***Index #*** | C-149 |
| *Name* | Tulki Well |
| *Coordinates* | 22o 06' S; 113o 54' E |
| *Type* | Well |
| *Area around* | Remains of concrete lined tanks; two troughs. Tank was cemented, then blocked and then concrete poured between |
| *Working gear* | - |
| *Top* | 0.1 m above ground covered by flat iron sheets |
| *Lining* | Circular 1.3 m diameter, lined to 0.8 m in concrete then none below (loose sandy conglomerate) |
| *Depth to water (m)* | 4.4 |
| *Water depth m* | 0.3, clear |
| *Fauna* | *M. veritas*, *Stygiocaris lancifera*, *H. tulki*, amphipods |
| *Notes* | Two crevices leading away *c.* 5m. Wind vane lying adjacent |
| with | 'Southern Cross' |

| | |
|---|---|
| ***Index #*** | C-163 |
| *Name* | Wanderers Delight |
| *Coordinates* | 22o 09' S; 114o 00' E |
| *Type* | Cave in Cape Range |
| *Area around* | - |
| *Working gear* | - |
| *Top* | - |
| *Lining* | Tulki Limestone |
| *Depth to water (m)* | c. 45 |
| *Water depth m* | >2 in parts |
| *Fauna* | Melitid amphipod sp. 2 and large terrestrial troglobite fauna |
| *Notes* | partly surveyed; > 5000 m surveyed passage |

| | |
|---|---|
| ***Index #*** | C-172 |
| *Name* | Milyering Cave |
| *Coordinates* | 22o 01' S; 113o 56' E |
| *Type* | Cave |
| *Area around* | *c.* 40 m SE of Milyering Well (C-24) |
| *Working gear* | - |
| *Top* | - |
| *Lining* | - |
| *Depth to water (m)* | - |
| *Water depth m* | - |
| *Fauna* | - |
| *Notes* | Baler shell |

| | |
|---|---|
| ***Index #*** | C-215 |
| *Name* | Unnamed |
| *Coordinates* | 22o 02' S; 113o 56' E |
| *Type* | Sink-hole under fig tree. Limestone, side of minor gorge |
| *Area around* | Beneath *Ficus* surrounded by spinifex |
| *Working gear* | - |
| *Top* | - |
| *Lining* | - |
| *Depth to water (m)* | 23.8 |
| *Water depth m* | *M. veritas*, *Stygiocaris* sp., *H. tulki* (type locality) and large terrestrial troglobite fauna including *Phaconeura proserpina* (Meenoplidae, Hemiptera) (type locality) |
| *Fauna* | - |
| *Notes* | Descend through several chambers to the water table; can follow stream passage for about 40 m which then sumps. In Milyering Terrace cut into foothills of Cape Range |

| | |
|---|---|
| ***Index #*** | C-273 |
| *Name* | 5 Mile Well |
| *Coordinates* | 21o 51' S; 114o 04' E |
| *Type* | Well |
| *Area around* | Tank stand base only (rest piled together); old yard and filled in trough; PVC piping leading away |
| *Working gear* | - |
| *Top* | Not covered |
| *Lining* | Square, concrete lined; originally timber lined part way down |
| *Depth to water (m)* | 9.8 |
| *Water depth m* | 0.4 |
| *Fauna* | *M. veritas, S. stylifera, H. tulki* |
| *Notes* | Close to Cape Range scarp |

| | |
|---|---|
| ***Index #*** | C-274 |
| *Name* | Pilgramunna Well |
| *Coordinates* | 22o 12' S; 113o 52' E |
| *Type* | Well, circular |
| *Area around* | No tanks, old concrete tank stand 3 m north. Short water trough and some metal yard posts. |
| *Working gear* | No |
| *Top* | Flush with surface; covered by iron sheet and old timbers |
| *Lining* | Circular, lined with coarse concrete to bottom. 1 m diameter |
| *Depth to water (m)* | 7.9 |
| *Water depth m* | 0.5 clean |
| *Fauna* | *O. candidum, M. veritas, Stygiocaris* sp., *H. tulki* |
| *Notes* | No rubbish |

| | |
|---|---|
| ***Index #*** | C-275 |
| *Name* | South Yardie (Bundera) Well |
| *Coordinates* | 22o 25' S; 113o 46' E |
| *Type* | Well |
| *Area around* | Pipes to old style tank in place; bolted metal not lined with concrete; decrepit |
| *Working gear* | Windmill (no blades) and pipe (very corroded) in place |
| *Top* | - |
| *Lining* | Concrete lined for top 3 m then through conglomerite |
| *Depth to water (m)* | 13 |
| *Water depth m* | Dry (had water in 1983; B. Vine pers comm.) |
| *Fauna* | - |
| *Notes* | Close to Cape Range scarp |

| | |
|---|---|
| ***Index #*** | C-282 |
| *Name* | Neds Well |
| *Coordinates* | 21o 54' S; 114o 07' E |
| *Type* | Old abandoned rectangular (1.2 x 1.2m) well |
| *Area around* | 4m to west is old tank; steel framed, concrete lined, large mullock heap adjacent |
| *Working gear* | Stumps of steel mill stand still in place and old windlass |
| *Top* | Flush with surface |
| *Lining* | Timber, rotten |
| *Depth to water (m)* | 9 |
| *Water depth m* | No water; had water in 1969 |
| *Fauna* | Melitid amphipod sp. 1 in 1960's none in 1980's or 1990's. |
| *Notes* | Timberwork falling in, dangerous. Sampled by the American Museum of Natural History in 1969 |

| | |
|---|---|
| ***Index #*** | C-332 |
| *Name* | Tantabiddi Rockholes |
| *Coordinates* | 21o 55' S; 113o 59' E |
| *Type* | Rockholes |
| *Area around* | Seven rockholes ranging from very small to about 2.5 m diameter |
| *Working gear* | - |
| *Top* | - |
| *Lining* | - |
| *Depth to water (m)* | Brackish water *c.* 1 m below the level of the surrounding country |
| *Water depth m* | - |
| *Fauna* | *M. veritas* ; *Grandidierella* sp. nov (Amphipoda: Aoridae) |
| *Notes* | Depressed area about 3-400 m south of Tantabiddi Beach |

| | |
|---|---|
| ***Index #*** | C-361 |
| *Name* | Mowbowra Well |
| *Coordinates* | 22o 00' S; 114o 07' E |
| *Type* | Well |
| *Area around* | Broken, steel-farmed, concrete lined tank 4 m to south |
| *Working gear* | Mill stand in place |
| *Top* | Flush with surface covered with corrugated iron sheet. Dug through conglomerate (1.2 x 0.9 m) |
| *Lining* | Top one metre lined with logs |
| *Depth to water (m)* | 8.1 m |
| *Water depth m* | 0.1 m, clear |
| *Fauna* | *M. veritas*, *O. candidum*, *S. stylifera* (none recently) |
| *Notes* | Rubbish accumulating recently (1989-1991) including old timbers |

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|---|---|
| ***Index #*** | C-362 |
| *Name* | Javis Well |
| *Coordinates* | 22o 36' S; 113o 41' E |
| *Type* | Well and bore |
| *Area around* | Adjacent to bore with mill which feeds new tank |
| *Working gear* | - |
| *Top* | Surrounding wall *c.* 0.4 m above ground level. Covered with timbers |
| *Lining* | Circular, concrete lined half way and then bellies out |
| *Depth to water (m)* | 8.1 |
| *Water depth m* | 0.15-0.4 m. Odorous and contaminated with animal waste. Muddy |
| *Fauna* | *M. veritas* (none recently), amphipods, syllid polychaetes |
| *Notes* | - |

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|---|---|
| ***Index #*** | C-413 |
| *Name* | Amphipod Well |
| *Coordinates* | 21o 56 S; 114o 08' E |
| *Type* | Well |
| *Area around* | Car breakers yard then a horse paddock |
| *Working gear* | None |
| *Top* | Covered by loose iron sheets |
| *Lining* | None |
| *Depth to water (m)* | *c.* 3 |
| *Water depth m* | *c.* 0.2 |
| *Fauna* | Melitid amphipod sp. 1 (first recorded occurrence after Neds Well) |
| *Notes* | - |

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|---|---|
| ***Index #*** | C-414 |
| *Name* | Wobiri Rock Hole |
| *Coordinates* | 21o 50' S; 114o 04' E |
| *Type* | Natural cave |
| *Area around* | Vehicular track to cave |
| *Working gear* | Steel pipe into cave |
| *Top* | - |
| *Lining* | None |
| *Depth to water (m)* | *c.* 3 |
| *Water depth m* | <0.5, tidal |
| *Fauna* | *O. candidum*, *M. veritas*, syllid polychaetes, ostracods |
| *Notes* | Long used for pumping water |

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|---|---|
| ***Index #*** | C-440 |
| *Name* | Horaks Well |
| *Coordinates* | 21o 58' S; 114o 08' E |
| *Type* | Well |
| *Area around* | Horse paddock |
| *Working gear* | Mill |
| *Top* | ?Traction engine fly wheel laid across |
| *Lining* | None |
| *Depth to water (m)* | *c.* 2 |
| *Water depth m* | <0.2 |
| *Fauna* | No stygofauna |
| *Notes* | Went saline shortly after construction |

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|---|---|
| ***Index #*** | C-452 |
| *Name* | Camerons Cave |
| *Coordinates* | 21o 58' S; 114o 07' E |
| *Type* | Natural cave opening from doline |
| *Area around* | Scrub |
| *Working gear* | - |
| *Top* | - |
| *Lining* | - |
| *Depth to water (m)* | - |
| *Water depth m* | > 2, tidal |
| *Fauna* | *M. veritas* and some terrestrial troglobites including *Draculoides* sp. nov. (Schizomida), *Hyella* sp. (Pseudoscorpionida), *Stygiochiropus* sp. (Diplopoda:Paradoxosomatidae), spiders, meenoplids |
| *Notes* | Condensation near entrance from outflowing air |

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|---|---|
| ***Index #*** | C-462 |
| *Name* | Woolcott Well |
| *Coordinates* | 22o 13' S; 114o 04' E |
| *Type* | Rotten tank which holds water |
| *Area around* | |
| *Working gear* | Mill, diesel pump (Southern Cross) |
| *Top* | 0.62 |
| *Lining* | Concrete |
| *Depth to water (m)* | 55+ deep, clear; bells out below lining |
| *Water depth m* | 5+ |
| *Fauna* | None seen (save multitudes of exotic cockroaches) |
| *Notes* | - |

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|---|---|
| ***Index #*** | C-495 |
| *Name* | New Mowbowra Cave |
| *Coordinates* | 22o 00' S; 114o 07' E |
| *Type* | Rocky ground, scrub |
| *Area around* | None |
| *Working gear* | - |
| *Top* | - |
| *Lining* | - |
| *Depth to water (m)* | 5 |
| *Water depth m* | *c.* 3.5 |
| *Fauna* | *M. veritas, O. candidum, Stygiocaris stylifera*, copepoda |
| *Notes* | Tight entrance through dog- legged solution pipe, drops into water. Dark silty floor |

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|---|---|
| ***Index #*** | C-507 |
| *Name* | 22o 31' S; 113o 43' E |
| *Coordinates* | Rockholes on both sides of the track |
| *Type* | - |
| *Area around* | - |
| *Working gear* | - |
| *Top* | - |
| *Lining* | - |
| *Depth to water (m)* | - |
| *Water depth m* | 1.3 (in tagged hole) |
| *Fauna* | *M. veritas* |
| *Notes* | Series of rockholes on coastal plain |

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|---|---|
| ***Index #*** | C-510 |
| *Name* | South Ranger rock hole |
| *Coordinates* | 22o 17' S; 113o 50' E |
| *Type* | Small rockhole |
| *Area around* | Vehicular track leading to rockhole |
| *Working gear* | Used to be a mill there |
| *Top* | - |
| *Lining* | - |
| *Depth to water (m)* | - |
| *Water depth m* | - |
| *Fauna* | *M. veritas* (swimming in sun) |
| *Notes* | Opposite the old southern rangers camp |

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|---|---|
| ***Index #*** | - |
| *Name* | Billy Well #3 |
| *Coordinates* | 22o 23' S; 114o 01' E |
| *Type* | Bore, steel in concrete pad |
| *Area around* | Low scrub over spinifex |
| *Working gear* | - |
| *Top* | Concrete pad 0.2 m thick with which bore is flush |
| *Lining* | Steel |
| *Depth to water (m)* | *c.* 100 m |
| *Water depth m* | - |
| *Fauna* | *Stygiocaris stylifera* , amphopods |
| *Notes* | Water supply source for Rough Range No. 1 oil well, the first oil strike in Australia. Billy Well#1 with steel quad frame over top, diesel |

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|---|---|
| ***Index #*** | - |
| *Name* | Cashens Well |
| *Coordinates* | 22o 29' S; 114o 06' E |
| *Type* | Well |
| *Area around* | Remains of water tanks and concrete pads |
| *Working gear* | None; pipe in well still hanging down centre |
| *Top* | Open 0.7 m above surrounding |
| *Lining* | Concrete, unlined at bottom |
| *Depth to water (m)* | 7 |
| *Water depth m* | 0.7 |
| *Fauna* | No stygofauna |
| *Notes* | Poor water supply but good quality |

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|---|---|
| ***Index #*** | - |
| *Name* | Wogatti Well |
| *Coordinates* | 22o 20' S; 114o 03' E |
| *Type* | Well |
| *Area around* | Fence line with two troughs in paddock |
| *Working gear* | Mill over well active |
| *Top* | 0.9 m timber covered |
| *Lining* | Concrete to bottom |
| *Depth to water (m)* | 33 |
| *Water depth m* | 1.8 |
| *Fauna* | No stygofauna |
| *Notes* | Mill braced with fencing wire |

| | |
|---|---|
| ***Index #*** | - |
| *Name* | Planet Fisheries (2 km W) |
| *Coordinates* | 22o 12' S; 114o 04' E |
| *Type* | Well |
| *Area around* | Barbed wire fence surrounds |
| *Working gear* | No mill but mill pipe still in place extending into mud at base |
| *Top* | Chalked on "Deliver to Ross Fisheries, Learmonth", not covered, surround projects 0.3 m above ground |
| *Lining* | Concrete lining (double at top, single further down then timber lined) with ladder fitted inside to full depth; ladder collapsed 1993 |
| *Depth to water (m)* | *c.* 20 |
| *Water depth m* | 0.2 m deep, deep sulphurous mud |
| *Fauna* | No stygofauna |
| *Notes* | - |

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|---|---|
| ***Index #*** | |
| *Name* | Corbett Well |
| *Coordinates* | 23o 15' S; 113o 55' E |
| *Type* | Well |
| *Area around* | Old concrete tank nearby adjacent to new fibreglass tank |
| *Working gear* | Southern Crosss 10' active over well filling fibreglass tank |
| *Top* | 0.4 m above ground, uncovered |
| *Lining* | Circular |
| *Depth to water (m)* | 20 |
| *Water depth m* | 1.5 m clear |
| *Fauna* | Amphipod |
| *Notes* | Several swallow nests on ledges in wall |

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|---|---|
| ***Index #*** | - |
| *Name* | Nabalgee |
| *Coordinates* | 22o 16' S; 114o 04' E |
| *Type* | Well |
| *Area around* | Three tanks; 2 concreted, one cable stressed prefabricated *c.* 1.5m high; two troughs, yards and roofed area |
| *Working gear* | Headgear and fan (defunct); new bore, pump and tank close by |
| *Top* | - |
| *Lining* | Circular, concrete lined |
| *Depth to water (m)* | *c.* 16 m |
| *Water depth m* | 2 m; surface oily, otherwise clean |
| *Fauna* | None |
| *Notes* | Two planks just above water |

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|---|---|
| ***Index #*** | - |
| *Name* | South Yardie Well |
| *Coordinates* | - |
| *Type* | Rock Hole |
| *Area around* | - |
| *Working gear* | - |
| *Top* | - |
| *Lining* | - |
| *Depth to water (m)* | - |
| *Water depth m* | - |
| *Fauna* | *M. veritas* in 1983-4 (B. Vine, pers. com.) |
| *Notes* | To the west of the main track |

| | |
|---|---|
| ***Index #*** | - |
| *Name* | 4-Mile Well |
| *Coordinates* | 22o 03'S; 115o 04' E |
| *Type* | Well and bore |
| *Area around* | Adjacent to new bore and two concrete tanks, one decrepit and the other leaking badly, fence around mill and well |
| *Working gear* | Bore has Southern Cross 10' mill active pumping to tank, well disused. Millframe still stands over old well |
| *Top* | Covered by termite eaten timbers |
| *Lining* | Concrete at top, rest unlined |
| *Depth to water (m)* | *c.* 30 |
| *Water depth m* | 0.04, not salty, foul taste |
| *Fauna* | No stygofauna |
| *Notes* | Well pumping continuously into uncovered and badly leaking tank to preserve dynamic equilibrium |

# Appendix F

## Photographs of the subterranean realm—fauna and access

Photographs are arranged as below unless otherwise indicated.

| | |
|---|---|
| a | b |
| c | d |
| e | f |
| g | h |

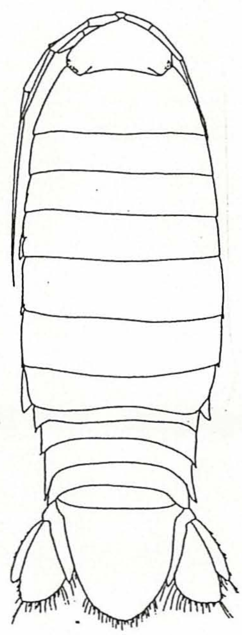
**Photographs**— W.F. Humphreys unless specified.

**Plate 1: Fauna—aquatic species**

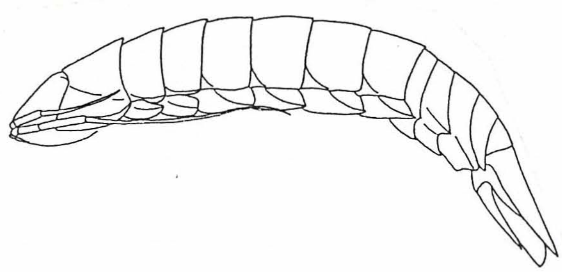
Remipedia (Nectiopoda: Speleonectidae). The photograph (a) is of the species from C-28 (body length *c.* 20 mm., photo— D. Elford) whilst the line drawing (b) is of *Speleonectes ondinae* (Garcia-Valdecasas) from the Canary Islands, which belongs to the same family. Drawing by D. Williams from Schram *et al.* (1986). (c, d) *Halosbaena tulki* Poore & Humphreys (Thermosbaenacea)—the young are brooded in a pouch which develops in the dorsal carapace. Body length 1.5 mm. Photo—W.F. Humphreys; line drawing G. Poore. (e) *Haptolana pholeta* Bruce & Humphreys (Isopoda: Cirolanidae). Body length 4.8 mm. Line drawing—N.L. Bruce. (f) *Hexabathynella halophila* Schminke, 1972 a form similar to *Atopobathynella* sp. nov. (Syncarida: Bathynellăcea) which is known from Barrow Island and is expected on the Cape Range peninsula. Body length *c.*1 mm. From Schminke (1986). (g) Amphipoda: Melitidae (New genus, 2+ species). This genus is found in both Cape Range *sensu stricto* and as a separate species on the coastal plain. Photo— W.F. Humphreys. (h) *Stygiocaris* sp. Holthuis (Decapoda: Atyidae). Photo— W.F. Humphreys. (i) *Milyeringa veritas* Whitley (Pisces: Perciformes: Eleotridae). Photo— G. Allen. (j, k) *Ophisternon candidum* (Mees) (Pisces: Synbranchiformes). Photos— G. Allen.

b

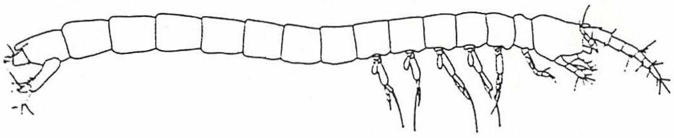
e



e



f



Appendix F3

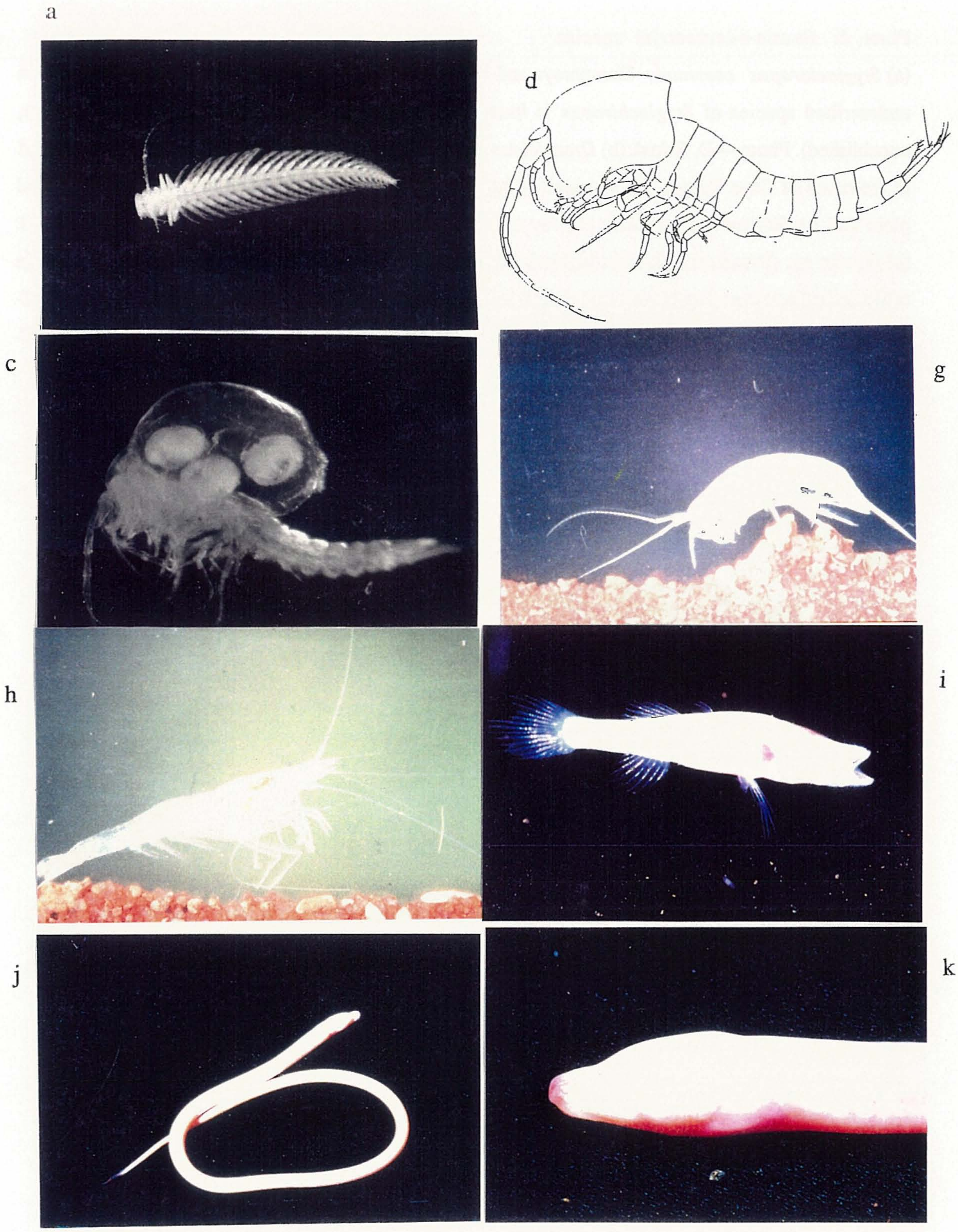


**Plate 2: Fauna—terrestrial species**

(a) *Stygiochiropus communis* Humphreys and Shear is widespread in the caves of Cape Range. An undescribed species of *Stygiochiropus* is found in C-452 on the coastal plain (W.F. Humphreys, unpublished). Photo— D. Elford. (b) *Draculoides vinei* (Harvey) (Schizomida: Chelicerata) is widespread in the caves of Cape Range. An undescribed species of *Draculoides* is found in C-452 on the coastal plain and on Barrow Island (M.S. Harvey and W.F. Humphreys, unpublished). Photo— D. Elford. (c) *Hyella* sp. (Pseudoscorpionida: Hyidae) from C-452. Photo— D. Elford. (d) Ctenidae: Araneae (undescribed genus and species) is widespread in the caves of Cape Range. A similar spider is found in C-452 on the coastal plain. Photo—P. Mead-Hunter. (e) An eyeless spider (Araneae: Hahniidae) from C-452. Photo— D. Elford.

Appendix F5

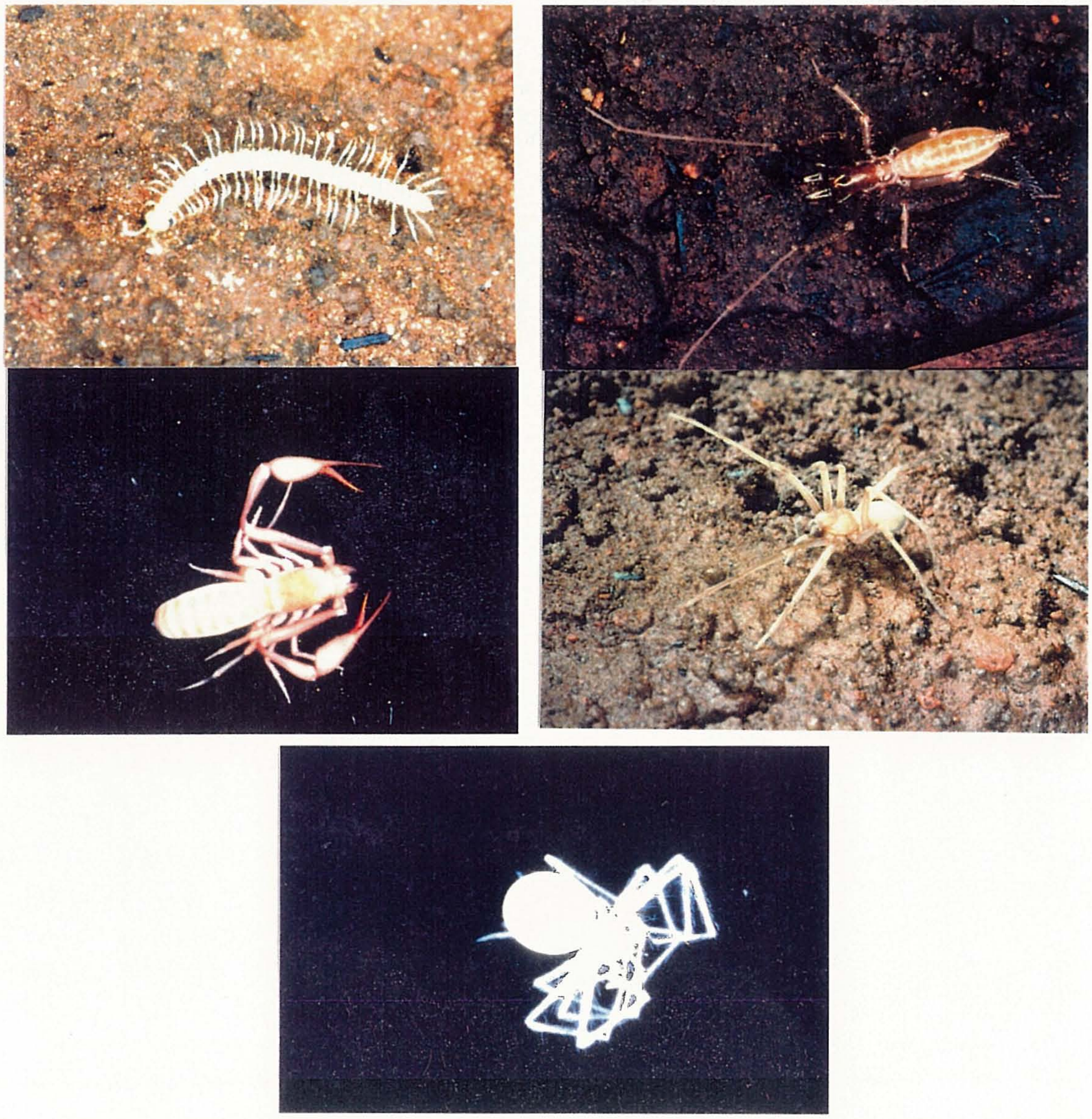


**Plate 3: Equipment—windmills and bores**

(a) Typical head gear of wind mills and (b) concrete tank and structure, House Well, Exmouth Gulf Station. Cashen Well, Exmouth Gulf Station; (c) the ovoid shape, for digging economy, appears in a number of wells on the Cape Range peninsula; (d) bucket and remains of windlass with detail (e). (f) A *No. 1* switching device on an abandoned *Aermotor Company* mill mechanism in Old Onslow; (g) detail of upper part of device—in use a counterweight worked against a float (baulk of timber) in the adjacent tank to move the wind vane parallel or perpendicular to the wind fan to switch the pump off and on respectively.

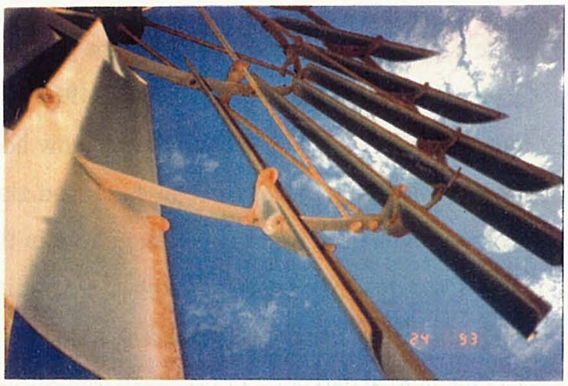
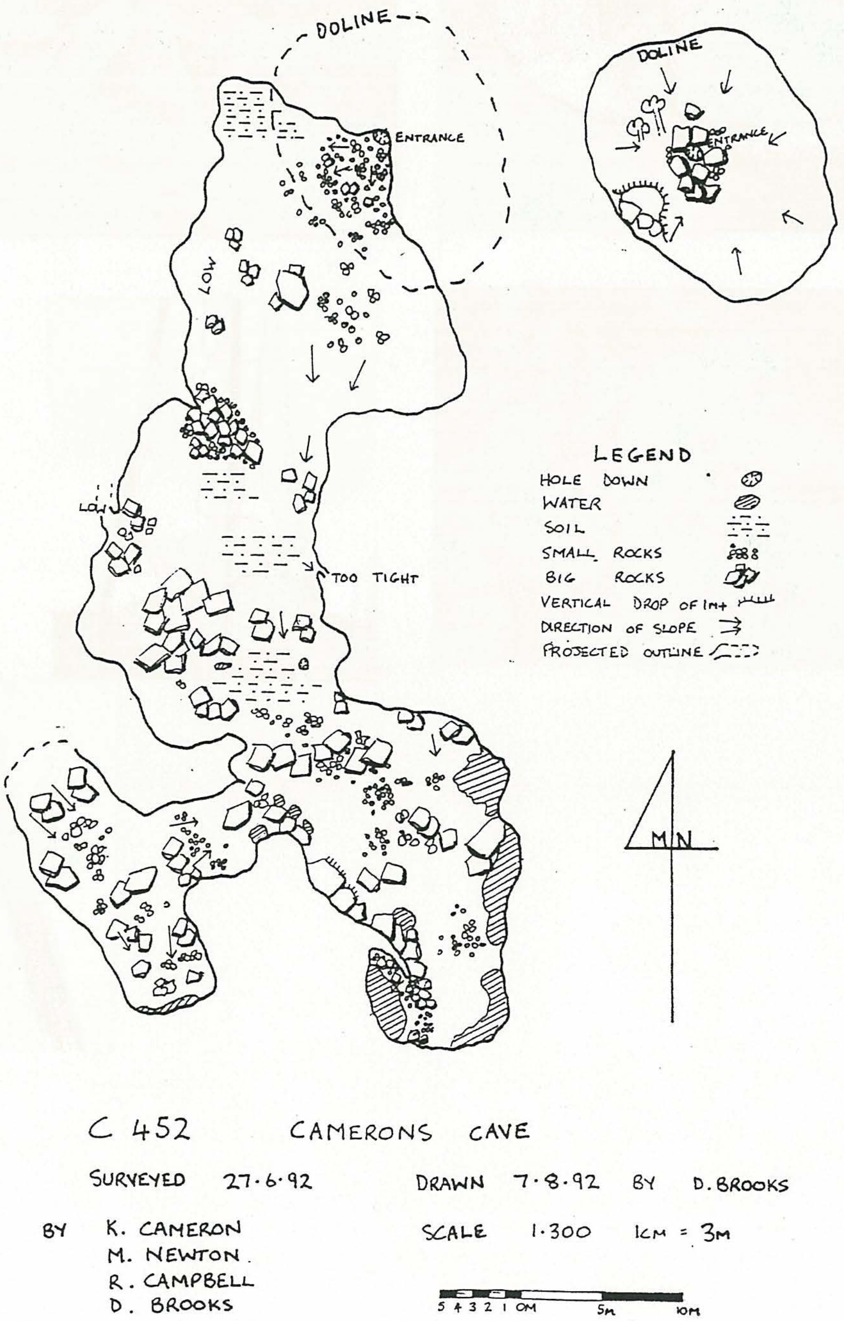


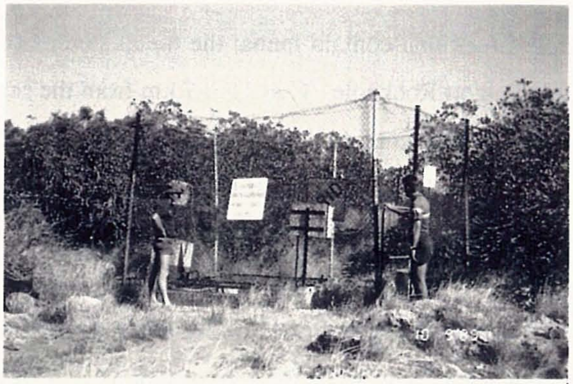
**Plate 4: Caves and bores**

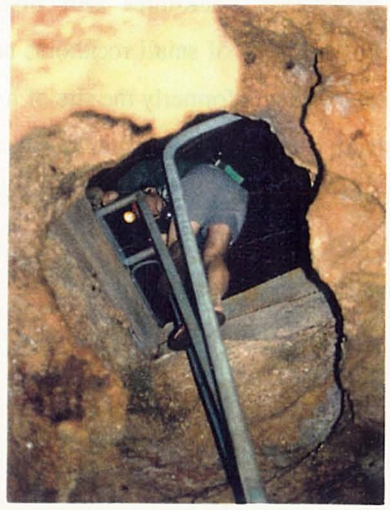
Kubura Well (C-27)—(a) Fence and grill protecting entrance ladder (b) which leads to a machine platform which pumps from the pool occupying one side of the cave (c). (d) New Mowbowra Cave (C-495)—the entrance gives access straight into the water in which root mats hang. (e) This unequipped shallow bore (white: lower left) in an Exmouth garden is the best site known to collect *Halosbaena tulki* and also yielded *Draculoides* sp. (micro-whipscorpions). (f) Sampling from a deep water exploration bore in the foothills of Cape Range. (g) The entrance to Camerons Cave (C-452) near Exmouth—it contains numerous baler shells (h): often deeply embedded in debris) indicative of use as a traditional watering place despite the water being accessible only by a tortuous low crawl in total darkness for 60 m. Below: survey

rons Cave.



Appendix F9





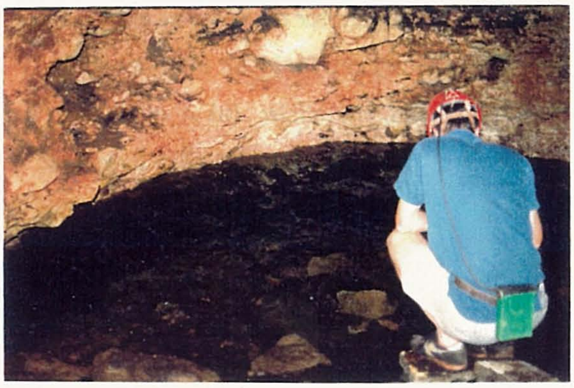



**Plate 5: Bores, rockholes and historical wells**

(a) One of a series of small rockholes north of Yardie Creek that contain fauna; the metal stumps (b) indicate that it was formerly the site of a windmill. (c) Chugori Rockhole (C-461), 0.7 km from the sea, is tidal and is one of the few sites known to contain *Ophisternon candidum* —the site is contiguous with a proposed major resort development at Babjarrimannos and is the northern most location known for the stygofauna. Billy Well 3 (d), Exmouth Gulf Station was bored to supply water for Rough Range No. 1 Oil Well, the first oil strike in Australia and is now open through the plug (e)—this is the most remote and deepest (*c*. 100 m) location of the stygofauna. (f) Wapet Artesian Bore No. 2—Waroora Station. Such profligate waste from artesian bores allowed to flow unchecked (some for a century or more; Toyne 1993) until they are exhausted is an example of the widespread disregard for the value of groundwater in Australia (Toyne 1993). A number of historical wells in the region could be maintained in good condition with little effort: (g) Road Board Well, Twitchen Road, Barradale; (h) A remote but fully equipped well on the banks of Pepingee Creek, a tributary of the Ashburton River— it was the last Government Well ever dug (1953: D. Forrest, pers. comm.).

Appendix F11

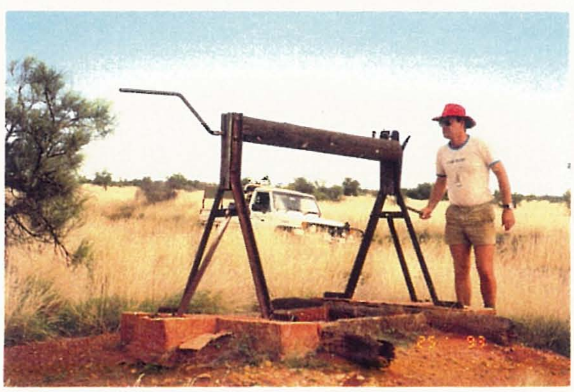
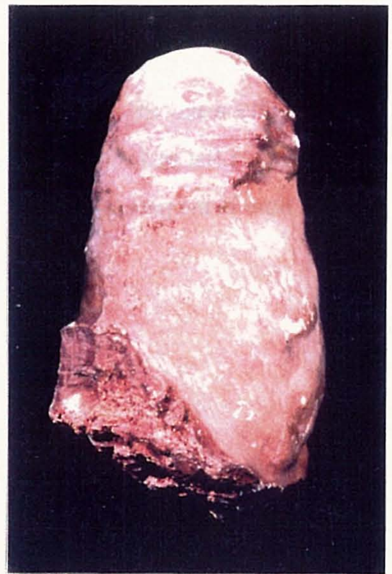
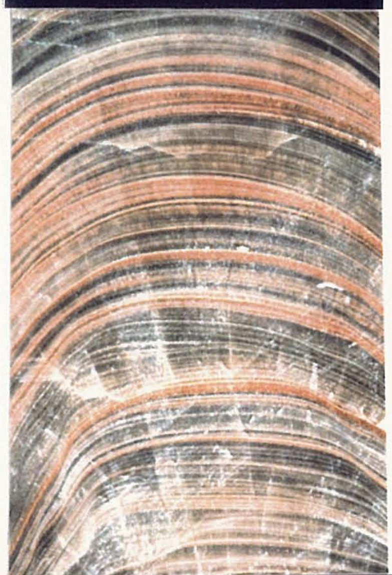


**Plate 6: Miscellaneous**

(a) Containers required for a full water sample. Speleothem, such as stalagmites (b), if well structured (c) contain a detailed record (d) of past climates in their banding and can be dated— this sample grew about 10 cm in 100,000 years. (e) Former gravel pit around the Gnamma Hole (C-105: on ridge beyond the vehicle) and Dozer Cave (C-23: beyond the person— it is an anthropogenic cave; this 'restored' pit has a large catchment draining to C-23— the heavy sediment load carried is evident from the erosion gullies in the foreground. (f) Cave divers tackle C-23 but sediment fills the leads.

Appendix F13





# Appendix F14

**Plate 7: Water in Cape Range**

Rockshelter (C-501) on the north western side of Cape Range with a series of mound springs (a) producing good quality water (b: Appendix 3, sample 17) and associated cyanobacteria (c). One mound spring was covered by a flat rock. (d) Tufa deposit in a gorge in eastern Cape Range—evidence of much greater freshwater flow in the past (e) and containing a good vegetation record (f).

# Appendix F15

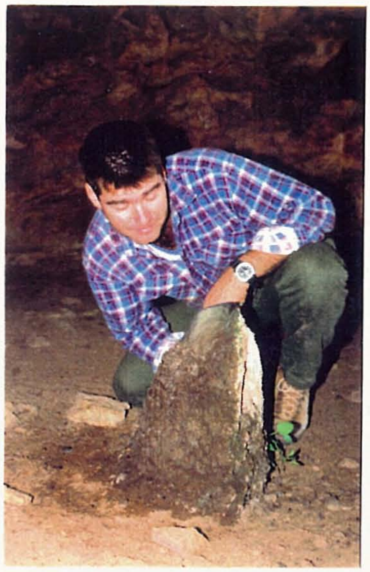
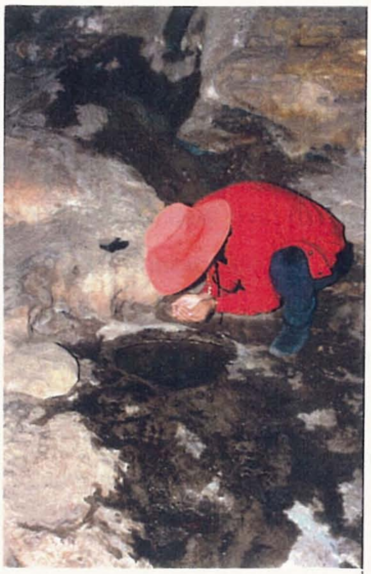
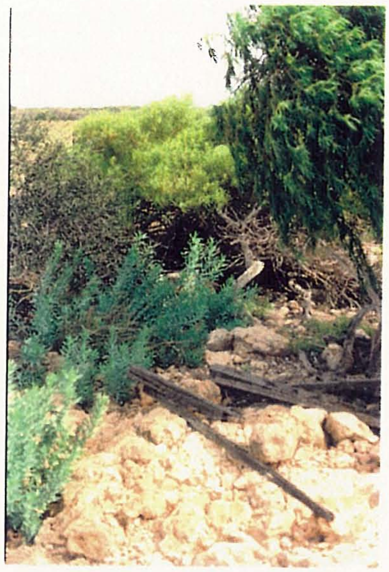



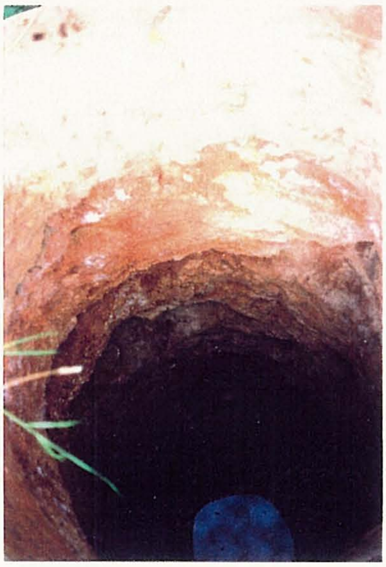


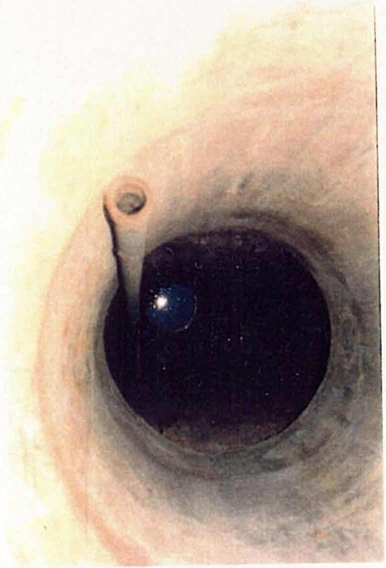
**Plate 8: Wells—west coast**

(a) The location of Milyering Well (C-24) on the coastal plain which is the type locality of *Milyeringa veritas* and (b) the entrance to the adjacent Milyering Cave (C-172)—many historical wells were dug adjacent to such traditional watering places. The circular well (c) is cut through coral rock and is unlined except for the concreted upper 0.8 m. (d) Javis Well (C-362), Ningaloo Station—the well is immediately to the right of the windmill which is pumping from bore; there is no control mechanism on the mill which is pumping into a leaking tank. The remain of an old tank are in front of the vehicle. The well is dug through cemented marine rubble and is lined (e) only at the top. (f) The location of Pilgramunna Well (C-274: behind vehicle) on the western coastal plain near the scarp of Cape Range with old yards and tank stands—the well is lined with coarse concrete (g).

Appendix F17







# Appendix F18

**Plate 9: Wells—west coast**

(a) 5-Mile Well (C-273) is square and concrete lined (b); originally it had a timber lining part way down. (c) Kudamurra (Palms) Well (C-25) provides water to a caravan park—the well is concrete lined and in good condition (d); it is the type locality of *Stygiocaris lancifera* Holthuis and *S. stylifera* Holthuis. (e) Tantabiddi Well (C-26) is a traditional watering place with a drum inserted in the base (f) to reduce silting. It is the type locality of *Ophisternon candidum*.

Appendix F19

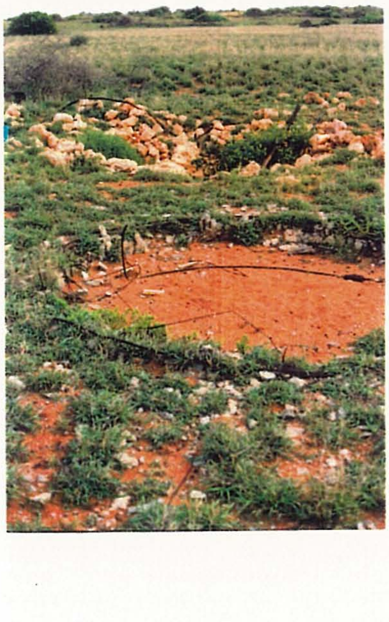


**Plate 10: Wells—east coast**

(a) Neds Well (C-282), in the prohibited area, the first recorded site of the coastal melitid amphipod; the well has long been dry and is in danger of collapse (b). (c) Bundegi (Cape) Well to the north of Exmouth is a timber lined well (d) in good repair but which has been dry for many years. A Bundegi Well is referred to in Rathe (1990) but it is not known whether this refers to a traditional well or to a deep well already present in 1875 as the present Bundegi Well is 2.0 km inland whereas in 1903 "the only wells ... [were] close to the beach" (Carter 1903: 31)— if it was present in 1875 it would have been constructed by mariners (?whalers) as it predates pastoral settlement of the Cape Range peninsula (Carter 1987).

Appendix F21



# Appendix G

# Radon in caves

Appendix G2

## Radon in caves

Radon ($^{222}Rn$) is a decay product of Uranium and is a gas which through inhalation may provide a significant internal radiation dose—as such it is a potential health hazard to those exposed. Recognition is quite recent that concentrations of radon can accumulate in domestic housing to dangerous levels and as such considerable effort has been made to establish the methods and monitor for radon (Amano et *al.* 1985; Amano and Kasai 1988). Uranium is usually present in limestone—it is one basis for the dating of speleothems—and the recognition that radon accumulates in caves is more recent (Eheman *et al.* 1991; Lyons 1992) and hence that cavers , and especially cave workers who spend substantial periods underground, may be at risk (its impact on troglobitic animals has not been considered).

During the 1993 field season a pilot survey of caves was conducted using five monitors supplied by the Australian Radiation Laboratory, Victoria. Three were placed in deep caves in Cape Range proper and inhabited by troglobites, and two were placed in the shallow caves on the coastal plain, those inhabited by stygofauna, and close to Exmouth.

The results (Table G1) show that one cave in the range and one in the coastal plain exceeded 1000 Bq $m^{-3}$, the level likely to be set as the guideline value for caves in Australia (B.M. Hartley, pers. comm. 1994). The highest level may be of concern if people spend considerable time in the area (E. McWilliams, pers. comm. 1993).

**Table G1**: Doses calculated from radon monitors placed for 3-6 months in five caves on the Cape Range peninsula.

| Cave | Latitude | Longitude | Gamma dose $\mu Sv\ a^{-1}$ | Radon Dose Bq $m^{-3}$ |
|---|---|---|---|---|
| C-118: unnamed | 22o 09' S; | 113o 59' E | 490 | 510 |
| C-126: unnamed | 22o 09' S; | 114o 00' E | 111 | 220 |
| C-167: unnamed | 22o 09' S; | 114o 00' E | 240 | 1450 |
| C-495: New Mowbowra Cave | 22o 00' S; | 114o 07' E | 857 | 1050 |
| *C-452: Camerons Cave | 21o 58' S; | 114o 07' E | 257 | 51 |