

THE SUBTERRANEAN FAUNA OF BARROW ISLAND, NORTHWESTERN AUSTRALIA, AND ITS ENVIRONMENT

by

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I – INTRODUCTION

Rich subterranean faunas are associated with Tertiary limestones of the Cape Range peninsula and Barrow Island in northwestern Australia. The affinities of the terrestrial components largely lie with wet forest litter dwellers and they constitute a relictual mesic fauna in this now arid region (HUMPHREYS, 2000a). Many of the aquatic species have affinities with those occurring in anchialine caves on either side of the North Atlantic and they comprise a relictual Tethys fauna of Mesozoic age (*ibid.*). No work has been published specifically addressing the nature of the Barrow Island karst. This paper considers the nature of the subterranean ecosystems of Barrow Island and summarises the information available on the diverse subterranean fauna inhabiting the Island. Barrow Island contains an oilfield that has been in production for more than 30 years and thus stands in contrast to the relatively pristine Cape Range peninsula (HUMPHREYS, 2000a), the latter situation is, however, now rapidly changing (HAMILTON-SMITH *et al.*, 1998).

The obligate subterranean fauna of Barrow Island comprises inhabitants of air-filled (troglobites comprising the troglofauna) and water-filled voids (stygobites comprising the stygofauna). Although both the amount of sampling conducted on, and access to the fauna is rather limited, the island is known to contain a significant subterranean fauna comprising species known from

adjacent karst systems, as well as those apparently endemic to the Island.

II – METHODS

Barrow Island was visited on seven occasions between 1991 and 1999 to seek subterranean fauna (Table 1). The work has involved basic cave exploration and mapping, sampling cave and groundwater fauna and recording environmental attributes of the subterranean environment.

Bore logs were examined from a number of anode wells for information on the position of hidden caves and open conduits as indicated directly in the logs or suggested by the loss of circulation of the drilling fluid and/or the insertion of materials to regain circulation of the drilling fluid.

Temperature and relative humidity in caves were measured using a whirling hygrometer (Brannan, England). Soil water content of caves soils was determined gravimetrically using methods described elsewhere (HUMPHREYS *et al.*, 1989).

The water quality data are derived from environmental consultancies commissioned by the oil company, although some were measured by me using methodologies described elsewhere (WATTS and HUMPHREYS, 2000). Water column profiling was conducted by M. J. LAMBERT (IT Environmental) using a Data Sonde 4a multi-parameter water quality logger (parameter: Depth, temperature, pH, ORP, DO and TDS)

Table 1 - Field sampling cavities for subterranean fauna on Barrow Island.

From	To	Main focus	Notes
1.9.91	17.9.91	Terrestrial cave fauna	Cave fauna and environment
12.12.91	15.12.91	Terrestrial cave fauna	Establish litter traps
24.4.92	29.4.92	Terrestrial cave fauna	Recover traps
24.7.92	29.7.92	Terrestrial and aquatic cave fauna	Cave and bore sampling
20.11.92	2.12.92	Aquatic cave fauna	Bore sampling
19.10.98	25.10.98	Aquatic cave fauna	Stable isotope work
20.8.99	21.8.99	Aquatic cave fauna	Cave diving

Only four large caves open to the surface. Consequently, sampling of stygofauna largely depends on artificial access to the groundwater through old water wells and, predominantly, through the anode wells that form part of the corrosion protection system of the oil wells. In use some of these anode wells become extremely acidic and they vent chlorine and so they are only useful for sampling stygofauna before they are commissioned and after decommissioning. Whether the electrical field between the anode and oil (cathode) wells affects stygofauna is unknown.

Terrestrial fauna was mostly collected by hand after visual searching; moistened leaf litter or additional water was added on occasion to attract troglobitic fauna. Aquatic fauna was collected by hand-held sweep nets in the one cave providing access to the groundwater; elsewhere it was collected from boreholes using haul nets (250 or 350 μm mesh) or with baited traps, working according to the cray-pot principle.

II. 1 - Stable isotope analysis

Organisms' metabolism utilizes the isotopes of an element differentially. Such 'fractionation' of the isotopes of nitrogen ($^{15}\text{N}/^{14}\text{N}$) and carbon ($^{13}\text{C}/^{12}\text{C}$) occurs in broadly predictable ways such that consumers are typically enriched (are 'heavier') by about 3-5 ‰ in ^{15}N and 1-2 ‰ in ^{13}C relative to their food source (EHLERINGER *et al.*, 1986). Hence, stable isotope analysis (SIA) of nitrogen and carbon is a powerful tool to examine

food webs (PETERSON and FRY, 1987; LAJTHA and MICHENER, 1994) and technical advances have recently allowed it to become a routine method in ecosystem and other studies.

Ecological studies express the isotopic composition in terms of δ values which are the parts per thousand differences from a standard:

$$\delta X = [(R_{\text{sample}}/R_{\text{standard}}) - 1] \times 10^3,$$

where X is ^{13}C or ^{15}N and R is the corresponding ratio $^{13}\text{C}/^{12}\text{C}$ or $^{15}\text{N}/^{14}\text{N}$ and the standards respectively are the Pee Dee Belemnite and nitrogen gas in the atmosphere (PETERSON and FRY, 1987).

SIA was conducted on animals sampled at different distances from the Barrow Island Fault, mainly *Stygocaris stylifera* (Atyidae) and some *Haplolana pholeta* (Cirolanidae). Total carbon and nitrogen and the fractionation of $^{15}\text{N}/^{14}\text{N}$ and $^{13}\text{C}/^{12}\text{C}$ determinations ($\delta^{13}\text{C}$ ‰ and $\delta^{15}\text{N}$ ‰) were made by the Stable Isotope Laboratory, Centre for Ecosystem Management, Edith Cowan University, Western Australia.

A range of plant material and species has been used for stable isotope determinations on the Cape Range peninsula, which has a flora very similar to that of Barrow Island (KEIGHERY and GIBSON, 1993), and is located in a similar coastal karst. The $\delta^{13}\text{C}$ values for the C_3 and C_4 plants on the Cape Range peninsula (HUMPHREYS, 1999b) are within normal limits which have median values respectively of - 27‰ and - 11‰ (LAJTHA and MARSHALL, 1994). Similarly, the values of $\delta^{15}\text{N}$ for the C_3 and C_4 plants are

within normal bounds (PETERSON and FRY, 1987).

Statistical errors are given as \pm one standard deviation.

III - RESULTS AND DISCUSSION

III. 1 - Geology and geography

Barrow Island is situated 55 km off the Pilbara coast of Western Australia and lies just within the tropics ($20^{\circ}48'$ S, $115^{\circ}25'$ E) (Fig. 1). Although maritime, it is located in the arid zone that occupies much of Central and Western Australia.

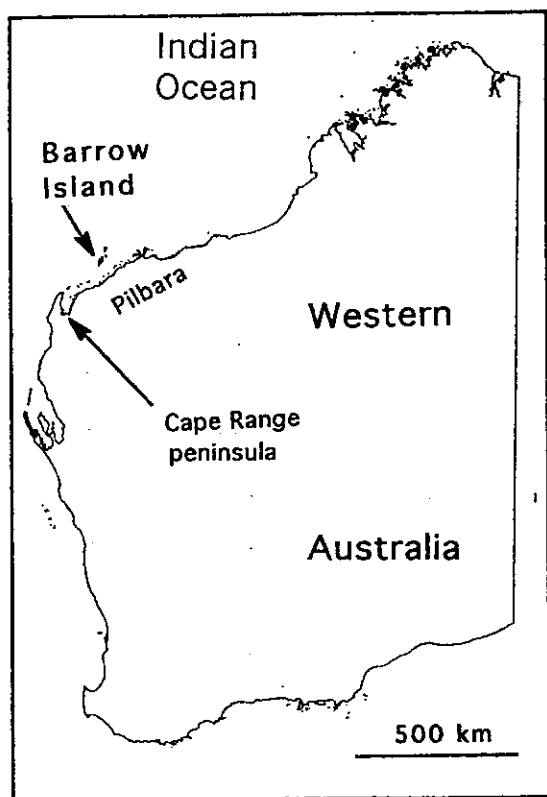


Fig. 1 - Regional setting of Barrow Island. North is at the top.

Barrow Island lies in the Carnarvon Basin, 170 km to the north-east of the Cape Range peninsula, which is bound to the east by the Precambrian Pilbara Craton that has been continuously emergent for more than 600×10^6 years. This regional setting is described more fully elsewhere (HUMPHREYS, 2000a, 2000b). Barrow Island lies on the North West Shelf and is separated from the mainland by a channel ca. 12 m

deep so that it would have been part of the mainland for most of the previous several million years before about 8000 BP owing to eustatic changes. Indeed, there are troglobitic (HARVEY and HUMPHREYS, 1995) and stygobitic species (ADAMS and HUMPHREYS, 1993) in common between the north-eastern coastal plain of the Cape Range peninsula and Barrow Island, and there are stygobites in common between Barrow Island and the mainland to the east, namely the Fortescue and Robe River alluvial fans (HUMPHREYS, 1999c, 2001b).

Barrow Island is about 12 x 27 km in extent and comprises Miocene marine limestones (McNamara and Kendrick, 1994) reaching a maximum altitude of 68 m. It represents the most northerly surface exposure of Miocene marine deposits in Australia and is one of a series of anticlines formed from Miocene and other limestones that extend southwards to Shark Bay, the principle exposure being Cape Range.

Superficial Pleistocene sediments mostly overlie the Miocene Poivre Formation, which is present from the east to the west of the island (MCNAMARA and KENDRICK, 1994). Sparse exposures of Giralia Calcarenite, of Upper Eocene age, are confined to the higher central region. The southern end of the island is low due to faulting—the Barrow Island Fault—while the northern end is low, largely owing to the plunge of the anticline.

While much of the limestone is hard, drilling reports and others (MCNAMARA and KENDRICK, 1994) show a complex lithology variously recording bands of clay (described as seams, sticky, dark brown, red, mustard), silt, sand (yellow, red, grey), gravel (bands, loose, small), rocks (large) and limestone (powdery, soft, hard, very hard, white, dark, grey, pink, yellow, greenish).

III. 2 - Karst

The Tertiary limestones of Barrow Island are karstic but, although 18 caves have been recorded (HUMPHREYS and VINE, 1991), only four large caves open to the surface, one of which reaches the water table. The latter, Ledge Cave (B1), also maintains sufficient humidity to be populated routinely by troglobites, albeit in sparse populations. Drill logs show that large caves occur above, at, and below the present water table, presumably resulting from karst development at times of lower sea level. Numerous cave-fill

deposits have been exposed by coastal erosion, especially in the more elevated coast to the north-west of the Island. The contained fossils show, in places, a pre-murid rodent fauna (A. BAYNES, personal communication, 2001) indicative of a date at least 4.5×10^6 years BP (FLANNERY *et al.*, 1992). Other deposits contain Pleistocene faunas (A. BAYNES, personal communication, 2001) and, together, these suggest that caves have been present throughout the last 4.5×10^6 years.

There are rock clefts on Barrow Island from which warm and humid air blows (e.g. B6) and which clearly communicate with much larger humid caverns where troglobitic fauna may be expected. In addition, drill logs for anode wells routinely record encountering small and large cavities, or indicators of them, such as lost circulation of drilling fluids. Some cavities are very large; for example, in 1967 drillers of oil well B 25 struck a large cavity at 45 m depth (ca - 42 m AHD) and the hole developed back to 37 m depth. The magnitude of the cave can be appreciated by the copious quantities of sealants added by the drillers in attempts to regain circulation (150 sacks cement, 110 lb [50 kg] cellulose, 1200 lb [544 kg] nut kernels, 800 lbs [363 kg] asbestos and 250 bags of mica). This well was markedly tidal and thus part of the anchialine system. In other places limestone is described as honeycombed with open cavities, a description that suggests it developed under phreatic conditions.

Tidal range is about three metres in J block (between wells J 46 and J 56: K. HALLETT, personal communication, 1998), comparable to the ocean tide of up to 3.0 m at Wapet Landing. This indicates only slight damping of the tidal movement more than one kilometre inland and suggests open conduit flow at depth. This is in contrast to the anchialine Bundera Sinkhole, 1.7 km inland on Cape Range peninsula, which had a tidal amplitude only ca 16% of the ocean tide (HUMPHREYS *et al.*, 1999). Together this evidence suggests the presence of well developed karst below the surface of Barrow Island and supports the general contention that most caves have no surface expression (CURL, 1966).

III. 3 – Vegetation

The vegetation of Barrow Island has closer affinities with that of the Cape Range peninsula than it does with the adjacent Pilbara coast. Although 213 species of plants have been recorded from Barrow Island the vegetation is over-

whelmingly dominated by tussock grasses of the genus *Triodia*. *Triodia wiseana* (Poaceae) predominates but this is replaced with *T. angusta* along the major drainage lines. This dominance by grasses is reflected in the termites in which 20 of the 25 species are grass harvesters (PERRY, 1972). *Erythrina vespertilio* (Papilionaceae) woodland overstorey occurs in several small patches and there are a few small stands of *Eucalyptus patellaris* (Myrtaceae). Tussock grasslands are ringed by a complex of coastal vegetation types. *Ficus* sp. are commonly associated with cave entrances but are also found widely scattered on the exposed limestones (BUCKLEY, 1983).

III. 4 - Cave climate

On Barrow Island troglobitic species occurred in caves with high relative humidity (R. H. = $97.6 \pm 0.89\%$, $n = 9$ v's 95.3 ± 1.50 ; $F_{1,7} = 8.723$, $P = 0.021$, angular transformation) at a mean temperature of $27.8^\circ \pm 0.27^\circ\text{C}$ ($n = 9$). The only cave reaching the groundwater is Ledge Cave (B1) within which the temperature and humidity were fairly uniform throughout, not differing significantly between areas. The mean temperature was $27.6 \pm 0.6^\circ\text{C}$ ($n = 11$) and the mean relative humidity was $>96\%$ throughout, approaching 100% in parts. The lower chamber of B1 had soil banks which contained 26.3% water, while the cracking soils higher in the chamber contained 23.1% soil water ($\text{g H}_2\text{O g}^{-1}$ soil). Cave soil in the upper chamber, remote from the water, contained $19 \pm 0.7\%$ ($n = 4$) soil water.

A similar association of a relictual rainforest leaf litter fauna with high relative humidity — and high moisture and organic carbon content in cave soils — has been reported in more detail in the cave systems of Cape Range (HUMPHREYS, 1993, 2000a). In Cape Range these troglobites were found in caves with $> 27\%$ soil water, below this level the proportion of caves with troglobites declined (HUMPHREYS, 1990).

Barrow Island lies within the world climatic area in which the average daily range in temperature exceeds the average monthly range (PETTERSEN, 1958). In consequence, there is a marked tropical winter effect (HOWARTH, 1980) on Barrow Island in which there is a strong outflow of water down the gradient in partial pressure of water vapour (EDNEY, 1977). The humidity in the depth of even the 'dry' caves is about 20-30% points greater than that of the surface even at a time when the caves are relatively

dry. Hence, within the cave there must be a buffering effect (capacitance) from stored water, either from a pool, as in B1, or from water stored in cave soils—an important store of water in Cape Range. Those caves that take the form of a choked sinkhole (B3 and B10) must extend in deeper voids to a water store in order to maintain high humidity. This contention is supported by the short-term (diurnal) fluctuations in the position of a marked cline in the carbon dioxide concentration within the sinkhole, apparently resulting from volumetric changes in a layer of high CO₂ concentration moving through breakdown in the sinkhole floor.

The outflow of moist air combined with thermal stratification, may result in the condensation of water in the upper reaches of a cave or near the entrance. For example, the condensation point is ca 27° C for deep air from B1 and ca 24° C from B10. This effect probably permits the presence of schizomids in the uppermost, otherwise dry part of cave B1.

III. 5 – Groundwater

The importance of groundwater ecosystems in Australia was overlooked as recently as 1998 (HATTON and EVANS, 1998) but it has now been accepted that groundwater ecosystems are a prime target for environmental managers. Current recommendations are that "Groundwater should be managed in such a way that when it comes to the surface, whether from natural seepages or from bores, it will not cause the established water quality objectives for these waters to be exceeded, nor compromise their designated environmental values. *An important exception is for the protection of underground aquatic ecosystems and their novel fauna. Little is known of the lifecycles and environmental requirements of these quite recently-discovered communities, and given their high conservation value, the groundwater upon which they depend should be given the highest level of protection*" [emphasis added] (ANZECC and ARMCANZ, 2000).

In this context, it needs to be stated that development of the Barrow Island oilfield occurred in the 1960's and thus predates modern environmental standards. Although the groundwater has been used both as a resource and as a sink, knowledge of the characteristics of the groundwater is scant. Barrow Island is presumed to

have a freshwater lens overlying saline water, such as occurs in Cape Range (ALLEN, 1993). The form of such a lens is determined by the interplay of the Ghyben—Herzberg principle (FORD and WILLIAMS, 1989), the transmissivity of the karst and the rainfall balance. In general, the principle states that where sea water is overlain by freshwater the depth of the saltwater interface will be 40 times as deep as the elevation of the freshwater lens above sea level. Hence, a unit drawdown of the freshwater through pumping will cause a cone of saltwater to rise 40 times as far towards the groundwater surface and, in consequence, such systems are especially vulnerable to saltwater intrusion (upconing).

Consultants have reported conflicting data from wells on Barrow Island that have prevented the plotting of groundwater contours until recently but which concluded that the "the water table is relatively flat and lies at or slightly above sea level" (WAPET, 1996). However, evidence can be drawn from the scant data available on the form and characteristics of the groundwater on the island. Although the horizontal resolution is poor, these data (Figure 2) suggest a typical island freshwater lens extending to at least 25 m below AHD (Australian Height Datum), lying over seawater. By application of the Ghyben-Herzberg principle (FORD and WILLIAMS, 1989), the freshwater lens could rise to at least 0.6 m above sea level. Recently interpreted groundwater elevation contours show it rising to 0.9 m above sealevel (suggesting a freshwater lens up to 36 m thick) and the elevation is greater than 0.5 m AHD (suggesting a freshwater lens up to 20 m thick) over about 15% of Barrow Island, entirely within the oilfield.

The relative influence of the marine system within the anchialine system, using for example, the $\delta^{14}\text{S}$ distribution (PETERSON and FRY, 1987), has not been investigated but it may be expected to decline with distance from the sea, often also a correlate of the thickness of the freshwater lens.

Anchialine system

The physicochemical profile of the groundwater on the periphery of the deep freshwater lens (Fig. 2) is given in Figure 3. Well M62 displays a marked halocline between the freshwater and underlying saline water at 6-8 m depth. The associated changes in DO, ORP and

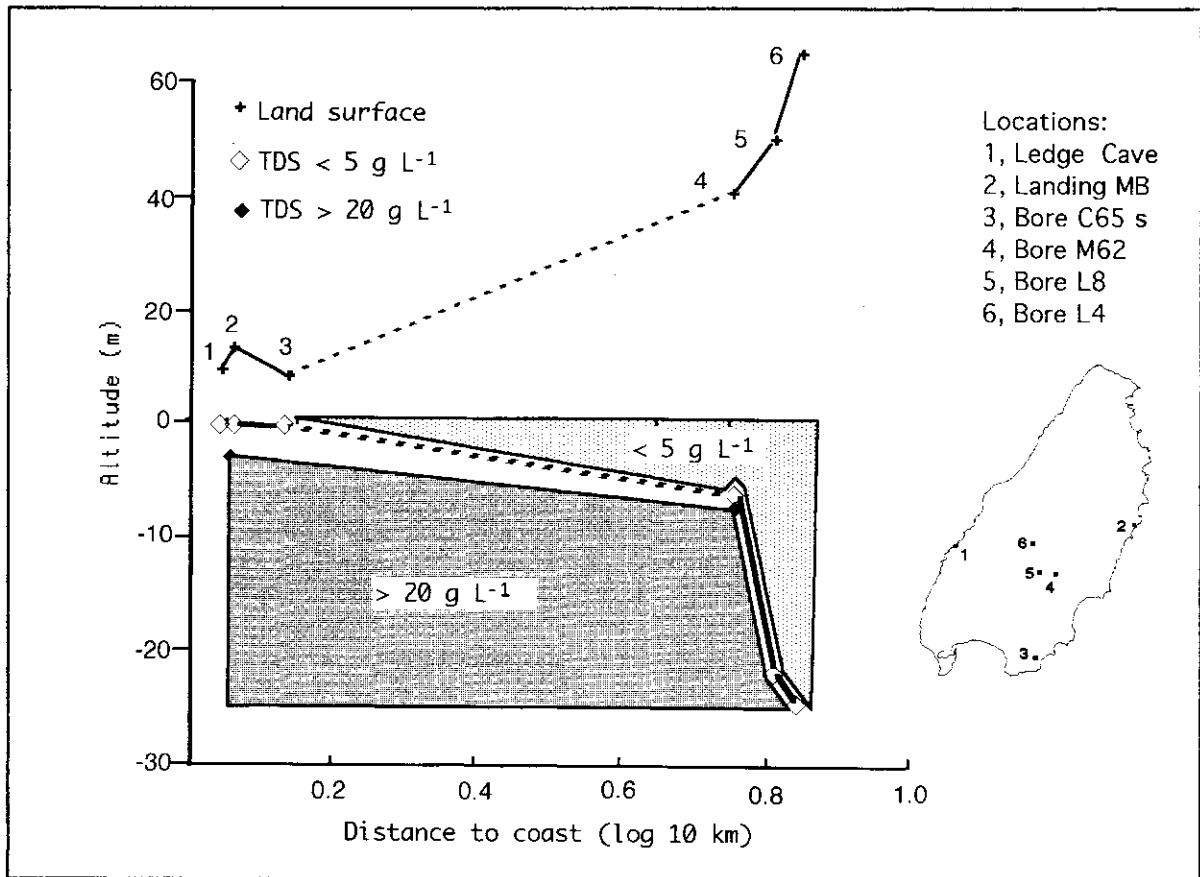


Fig. 2 - Reconstructed partial section of Barrow Island showing the landform, freshwater lens (light shading), seawater intrusion (dark shading) and the mixing zone between them (white). Note the doubling of the altitude scale below 0 m AHD. Points 1-3 my data; points 4-6 extracted and interpreted by me from the partial vertical profile data collected by M.J. Lambert. Map shows locations of the profiles. Refer to the groundwater elevation contours (Figure 5).

Table 2 - Mean water quality taken from data supplied by WAPET¹.

	Temperature °C	Salinity ppm	pH	DO mg L ⁻¹
Mean	30.3	6954	6.67	6.7
St.dev	2.29	7850	1.16	7.2
N	65	64	70	64
Min	19.3	54	2.2	0.02
Max	32.8	39600	8.7	45.7

¹While there are clearly erroneous values present in these data, seen in the range values, the mean values are in approximate accord with data taken by the author at some sites.

pH are typical of anchialine systems (Fig. 3). Note that below the halocline the water is suboxic with low ORP. This profile is similar to that found in Bundera Sinkhole on the Cape Range where bands

of hydrogen sulphide occur associated with a chemoautotrophic signature (HUMPHREYS, 1999b). The profiles of wells L4 and L8 (Fig. 3), which lie within the deep freshwater lens (Figure

2), extended to a water depth of ca 24 m but did not penetrate to water of near marine salinity that is presumed to underlie the lens. Both wells showed a thin freshwater layer overlying water of ca 4.5 mg L⁻¹ TDS at a depth of about 6 m, and below which the DO levels were low but the ORP values remained positive.

The groundwater in the Barrow Island karst thus forms a typical anchialine system, namely, stratified waters (Fig. 3), usually with a restricted exposure to open air, always with more or less extensive subterranean connections to the sea, and showing noticeable marine as well as terrestrial influences (STOCK *et al.*, 1986). The marine influence typically consists of an hypoxic layer of seawater (ca 33-36 g L⁻¹) beneath one or more layers of limnetic to polyhaline water (YAGER *et al.*, 1994). Below the density interface, such ecosystems often support a wide range of relict life forms (SKET, 1996) that comprise a community whose general structure is predictable from the Caribbean region, the Canary Islands and northwestern Australia (e.g. YAGER, 1994; YAGER and SCHRAM, 1986; HOLSINGER, 1989; DANIELOPOL, 1990; YAGER *et al.*, 1994; BALTANAS and DANIELOPOL, 1995; YAGER and HUMPHREYS, 1996; DANIELOPOL *et al.*, 1999; ILIFFE, 2000). Consequently the near coastal sections of the waterways grade from marine near the coast and at depth, to freshwater inland and near the surface, with a variable zone of mixing in between. Such anchialine systems are noted both for their relict faunas and their species richness (SKET, 1981, 1996) and are the subject of widespread conservation assessment (SKET, 1981; MACIOLEK, 1986; BROCK *et al.*, 1987; RIDGLEY and CHAI, 1990; MARTIN *et al.*, 1991; THOMAS *et al.*, 1991; ILIFFE, 1992; MARTIN *et al.*, 1992; THOMAS *et al.*, 1992; BAILEY-BROCK and BROCK, 1993). These issues are discussed more fully in HUMPHREYS (2000b).

Water quality

There appear to be no historic records of groundwater quality on Barrow Island but anecdotal information refers to water production wells becoming saline, being abandoned and additional wells being established further inland (K. HALLETT, personal communication, 1998; A. BURBIDGE, personal communication, — even-

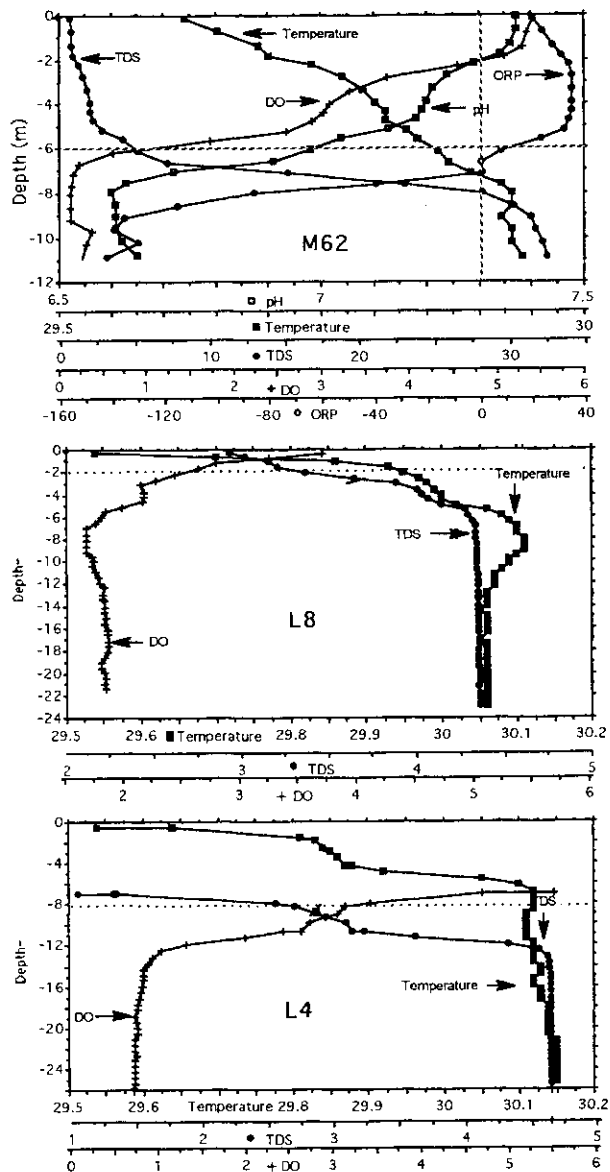


Fig. 3 - Physico-chemical profiles through the water column of three wells (M62, L8 and L4) on Barrow Island showing the change with depth in pH, temperature (°C), total dissolved solids (TDS, mg L⁻¹), dissolved oxygen (DO, mg L⁻¹), oxidation reduction potential or redox (ORP, mV). The scale for each parameter is shown below each figure and note that ORP may show both positive and negative values. The broken horizontal line denotes the depth at which the pH was 7.0 (data not shown in L8 and L4) and the broken vertical line, where applicable, denotes the position where the redox (ORP) potential is zero. The locations of the bores are shown in Figure 2 (inset). Raw data from M.J. LAMBERT.

tually a reverse osmosis plant was used to provide potable water. The intrusion of underlying saline

water into the freshwater lens is a common consequence of overdrawing bores in Ghyben-Herzberg systems.

Recent groundwater monitoring data collected for the oil company was examined and some additional measurements were made from the upper part of the groundwater in anode wells, and in the groundwater monitoring and remediation wells associated with the Terminal Tanks. The mean values are presented in Table 2. Water quality differed between samples taken from the Terminal Tanks, which are adjacent to the coast, and the samples taken from anode wells. Dissolved oxygen at the Terminal Tanks ($3.38 \pm 1.49 \text{ mg L}^{-1}$ DO, $n = 17$), was lower than in anode wells ($7.92 \pm 8.07 \text{ mg L}^{-1}$, $n = 47$; $F_{1,62} = 5.324$, $P = 0.026$), whereas the pH was higher at the Terminal Tanks (7.2 ± 0.50 , 17) than in anode wells (6.5 ± 1.29 , 50; $F_{1,65} = 5.032$, $P = 0.028$). The acidic water in the anode bores probably results from some having been in operation prior to sampling; under operating conditions the pH in the anode bores may rapidly drop to less than pH 2. Of 87 anode wells sampled in 1983 a number exhibited especially low pH values (mean 2.28 ± 0.53 , range 1.50-3.17, $n = 12$) but the remaining 75 wells were in the range pH 6.0 to 7.5 (K. HALLETT, personal communication, 2001). For comparison, ground water from the limestone karst of the Cape Range peninsula had a mean pH of 7.38 ± 0.44 (range 5.32-9.13, $n = 62$) (HUMPHREYS, 1994). In contrast, the mean salinity ($6954 \pm 7850 \text{ mg L}^{-1}$

TDS, $n = 64$) and temperature (30.3 ± 2.29 , $n = 65$) did not differ between the anode wells and those wells at the Terminal Tanks.

III. 6 - Distribution and biodiversity of the Barrow Island troglofauna

Troglofauna comprises obligate inhabitants of air-filled underground voids, including caves and mesovoids. The composition of the troglofauna of Barrow Island is given in Table 3 and the distributions shown in Figure 4. Two species of troglofauna have been formally described—three if the blindsnake proves to be a troglobite—from the Barrow Island karst and a number of other troglobitic taxa are present (*Nocticola* sp. nov., a scorpion and a philosciid isopod). The distributions shown probably reflect the limited number of caves providing access to the subterranean realm, as well as the few caves with suitable climatic conditions (see 'cave climate'), rather than the real distribution of the troglofauna. For example, *Draculoides bramstokeri* is widespread, being known from the northeast coastal plain of the Cape Range peninsula (HARVEY and HUMPHREYS, 1995) — with which Barrow Island would have been connected across a broad coastal plain prior to ca. 8000 BP (HUMPHREYS, 2000a)—as well as from several caves and anode bores on Barrow Island. However, in Ledge Cave *D. bramstokeri* occurs commonly at only a single location ($< 0.1 \text{ m}^2$) in the upper chamber.

Table 3 - The distribution of troglobitic species on Barrow Island. Prefix 6 denotes cave rather than borehole.

Species	Cave or borehole
<i>Draculoides bramstokeri</i> Harvey & Humphreys (Schizomida: Hubbardiidae)	6B1, 6B6, 6B10, B2, L2, WF7, WL4
^{1,4} <i>Speleostrophus nesiotetes</i> Hoffman (Diplopoda: Pachybolidae: Trigoniulinae)	6B1
<i>Nocticola</i> sp. nov. (Blattodea: Nocticolidae)	6B1
Oniscidea (Isopoda) indet.	6B1
^{2,4} Scorpion: new genus: family placing uncertain (see text)	6B1
³ <i>Ramphotyphlops longissimus</i> Aplin (Squamata: Typhlopidae)	borehole

¹ The first known troglobitic spiroboloid milliped. ² Has characters in common with both Urodacidae (endemic to Australia) and Heteroscorpionidae (endemic to Madagascar) (E. Volshank, personal communication, 2001). ³ Possibly the first known troglobitic reptile. ⁴ Genus known only from Barrow Island.

Speleostrophus nesiotetes, the world's first known troglobitic spiroboloid millipede (HOFFMAN, 1994), is known only from soil banks in a small lower chamber of Ledge Cave.

No specimens were seen when the chamber was last examined (1998) and it was recommended that this section of the cave be closed to human access. The blindsnake *Ramphotyphlops longissimus*

exhibits extreme slenderness of the body, very small eyes for its lineage and an almost total lack of external pigmentation, in addition to an unusual degree of flattening to the head (APLIN, 1998). Such attributes would be considered troglomorphies in many animal taxa. The only specimen (plus one that escaped) was taken from a well casing being withdrawn for servicing from the karst limestone. The diet is unknown but if it proves a cavernicolous lifestyle it would suggest that *R. longissimus* is the first troglobitic reptile to be described globally (DECU *et al.*, 1998).

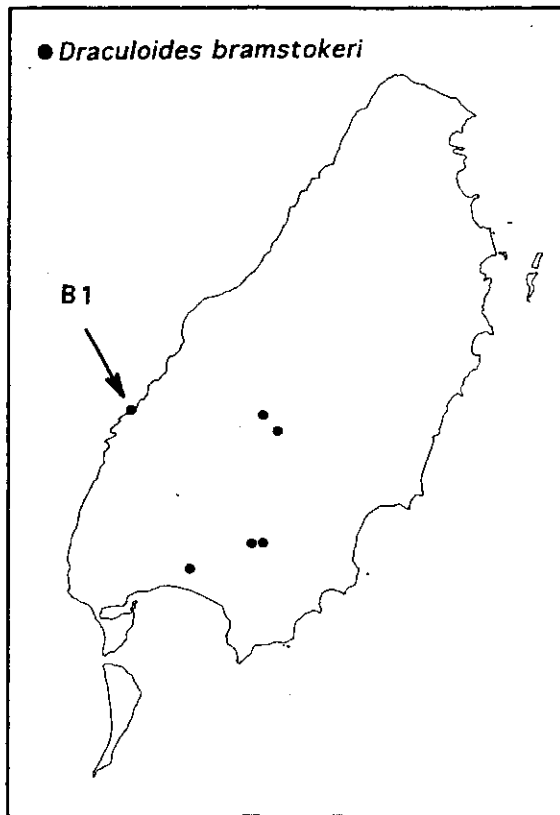


Fig. 4 - Distribution of troglobitic taxa on Barrow island. Points show the distribution of *Draculoides bramstokeri*. The remaining species are known only are from Ledge Cave (B1) on the west coast. North is at the top.

The scorpion is an unknown species in a new genus that shares morphological features of the families Urodacidae (species in the genus *Urodacus* and endemic to Australia) and Heteroscorpionidae (species in the genus *Heteroscorpion*, endemic to Madagascar). A recent revision of the superfamily Scorpionoidea (PRENDINI, 2000) highlighted as a future research priority, determining the phylogenetic positions of

Scorpionidae, Heteroscorpionidae and Urodacidae. This new species is likely to play a pivotal role in addressing that priority and will most likely see the family Heteroscorpionidae collapsed into the Urodacidae (the older of the two family names) (E. VOLSHANK, personal communication, 2001).

The finding of relict Gondwanan lineages in subterranean systems in northwestern Australia, some providing basal links, has precedents. The family Hyidae (Pseudoscorpionida), previously known from India and Madagascar, has been recorded from Cape Range (HARVEY, 1993). Among aquatic lineages phreatoicidan isopods (WILSON and KEABLE, 1999) and spelaeogriphaceans (POORE and HUMPHREYS, 1998) may be cited. Indeed, it was suggested that the atyid *Stygiocaris* may be closely related to the genus *Typhlopatsa* Holthius from Madagascar (HOLTHIUS, 1960).

III. 7 - Distribution and biodiversity of the Barrow Island stygofauna.

Stygofauna comprise obligate inhabitants of groundwater, including cave waters. The composition of the stygofauna of Barrow Island is given in Table 4 and the distributions shown in Fig. 5. The overall distribution of stygofauna probably reflects the distribution of access to the groundwater (Fig. 5a), which is largely confined to the area of access in the oilfield, rather than the actual distribution. As the few outlying sample points contain stygobionts, stygofauna is likely to be found throughout the Barrow Island karst. However, in contrast to the very restricted access to caves for sampling troglobites, sampling access to stygofauna sites is both widespread and common. Hence, the apparently restricted distribution of some taxa—some amphipods for example— to small parts of Barrow Island may reflect their actual distribution.

Twenty species of stygofauna have been formally described from the Barrow Island aquifer and a number of other taxa are present (Bathynellacea, Calanoidea, Ostracoda, Turbellaria) which have not been determined. Thus, there are at least 24 stygal species on Barrow Island. Were Barrow Island a single cavernous system, which is unknown, it would be firmly classed as a biodiversity 'hot spot' in a global context (CULVER and SKET, 1999) despite no meiofauna having been determined. Furthermore, it contains the second greatest number of stygal amphipods

described from any system (the most speciose being the Ethel Gorge calcrete on the Fortescue River (species described in BRADBURY, 2000). Given the low sampling effort and limited

taxonomic coverage of the species determinations, the overall diversity of the Barrow Island stygofauna is likely to increase markedly on further study.

Table 4 - The distribution of stygal species on Barrow Island. Prefix 6 denotes cave rather than borehole. Amphipod data are from Bradbury and Williams (1996a, 1996b), Bradbury (2002) and unpublished data. • denotes species known from the Cape Range peninsula. Type localities are denoted in bold. B1 is an anchialine cave, the remaining locations are boreholes, mostly anode wells.

Species	Borehole or cave 6B1
Amphipoda: Melitidae	
<i>Nedsia hulberti</i> Bradbury and Williams	6B1, MW15, MW17, W62Jw
<i>N. humphreysi</i> Bradbury and Williams	L4, L8
<i>N. straskraba</i> Bradbury and Williams	L8, L16
<i>N. chevronya</i> Bradbury	MW15
<i>N. stefania</i> Bradbury	L32J
<i>N. halleti</i> Bradbury	L32J
<i>N. urifimbriata</i> Bradbury and Williams	WK11
<i>N. fragilis</i> Bradbury and Williams	B2
<i>N. macrosculptilis</i> Bradbury and Williams	WC66
<i>N. sculptilis</i> Bradbury and Williams	WL8
<i>N. sculptilis</i> / <i>N. macrosculptilis</i>	L8, L4N, M13, M62
Amphipoda: Bogidiellidae	
<i>Bogidonma australis</i> Bradbury and Williams	L8
Amphipoda: Hadziidae	
<i>Liagoceradocus subthalassicus</i> Bradbury and Williams	6B1
Thermosbaenacea	
• <i>Halosbaena tulki</i> Poore and Humphreys	6B1, B2, C66, F11, G19, L4, L8, L16, M5N, M52, M62Q5
Isopoda: Cirolanidae	
• <i>Haptolana pholeta</i> Bruce and Humphreys	6B1, B2, 6B2, C66, L8, L16, M5
Decapoda: Atyidae	
• <i>Stygiocaris stylifera</i> Holthuis	6B1, B2, B2, C65S, E1, G19, L4, L8, L17, M5, M5N, M62, Q5, QQ5, WC66, X62JW
Copepoda: indet.	
	6B1, B18, B2, C65S, C66, E1, F41A, G19, K3N, L16, L17, L32J, L4, L5, L8, M52, MW13, Q5, X62JW
Calanoida: indet.	
	6B1
Harpacticoida: Ameiridae	
<i>Inermipes humphreysi</i> Lee and Huys ²	K3N
Cyclopoida: Cyclopidae	
• <i>Halicyclops longifurcatus</i> Pesce, De Laurentiis and Humphreys ³	K3N
<i>Diacyclops humphreysi</i> n. sp.	L8, MW7, M62, L32J, F11
• <i>Halicyclops rochai</i> De Laurentiis, Pesce and Humphreys ⁵	L8, F11, C77J, C65 deep south, M5N
⁴ <i>Alloccyclops</i> n. sp. Karanovic	Old batchplant bore
Syncarida: Bathynellacea	
<i>Atopobathynella</i> sp. nov.	B2, MW3 /SB8
Vertebrata: Perciformes: Gobioidei: Eleotridae	
• <i>Milyeringa veritas</i> Whitley	L8

¹Number of amphipod species in sympatry: 4, L8; 2, B1, MW15, L32J.

Some copepods are of uncertain stygal status: ²genus known only from Barrow Island; ³known only from anchialine systems; ⁴only record of genus from Australia, species clearly stygal; ⁵known only from bores and not hyporheic (Bou-Rouch) samples on Fortescue River alluvium on adjacent mainland.

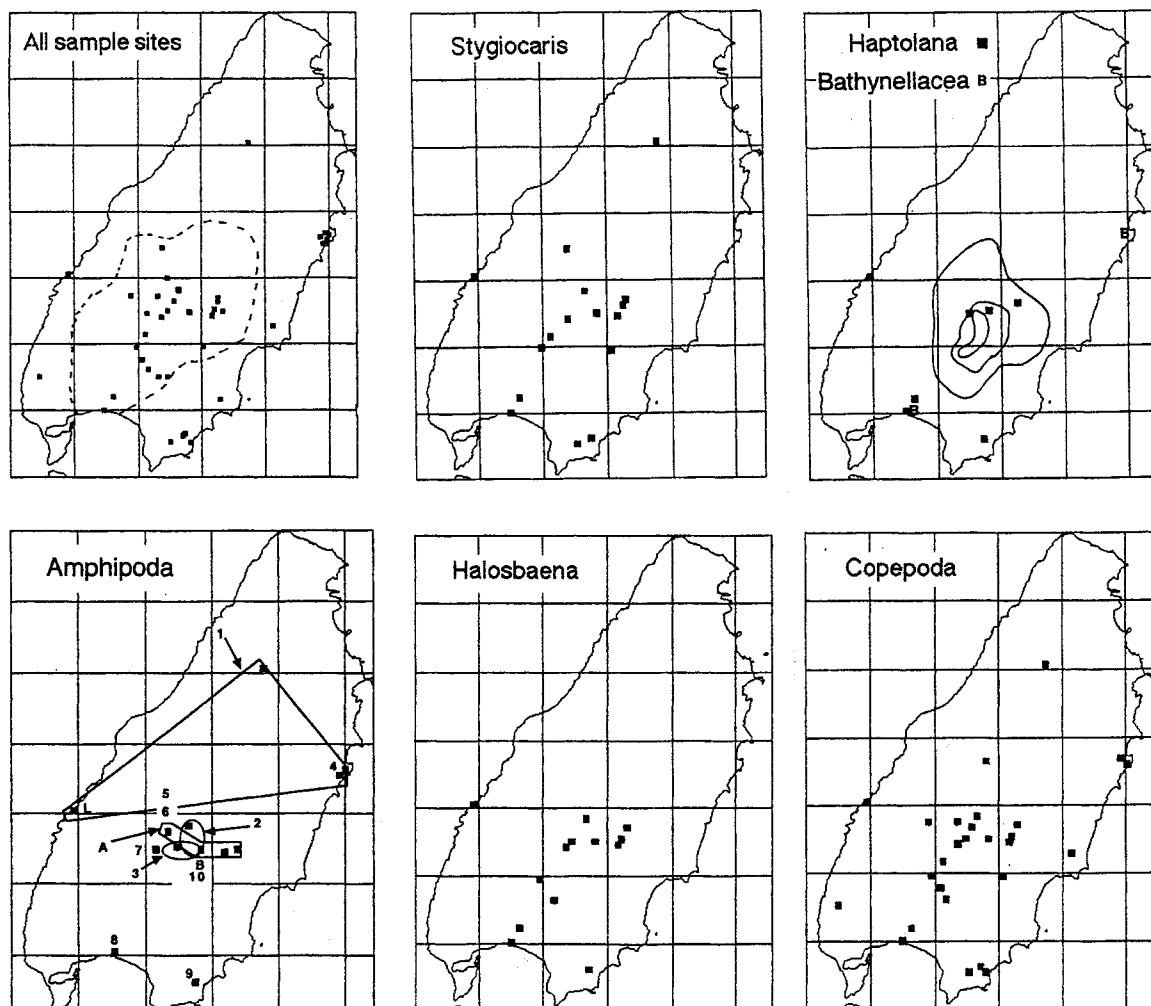


Fig. 5 - Distribution of the Barrow island stygofauna, groundwater elevation and oilfield. Upper left, sites sampled, the dashes enclose the distribution of 120 anode wells, each servicing several oilwells; upper middle, *Stygiocaris stylifera*; upper right, *Haptolana pholeta* and Bathynellacea, and the interpreted groundwater elevation contours of 0.5, 0.8 and 0.9 m AHD; lower middle, *Halosbaena tulki*; lower right, Copepoda; lower left, Amphipoda: 1, *Nedsia hulberti*; 2, *N. humphreysi*; 3, *N. straskraba*; 4, *Nedsia* n. sp.1; 5, *Nedsia* n. sp.2; 6, *Nedsia* n. sp.3; 7, *N. urifimbriata*; 8, *N. fragilis*; 9, *N. macrosculptilis*; 10, *N. sculptilis*; A, *N. sculptilis*/*N. macrosculptilis*; B, *Bogidomma australis*; L, *Liagoceradocus subthalassicus*. The inclusive distribution is shown of amphipods known from more than one location.

III. 8 – Chemoautotrophic energy production ?

In some groundwater ecosystems both petroleum (KUEHN and KOEHN, 1988; LONGLEY, 1981, 1992) and sulphides (SARBU and POPA, 1992; SARBU, 2000; SARBU *et al.* 1996) can be the source of chemoautotrophic energy production (POULSON and LAVOIE, 2000). These are, respectively, analogues of cold seep (ARP and FISHER, 1995; SCOTT and FISHER, 1995) and hydrothermal vent

(CHILDRESS and FISHER, 1992) ecosystems of the deep ocean. Chemoautotrophy has also been demonstrated in Frasassi Cave (SARBU *et al.*, 2000), and strongly indicated in anchialine systems (Pohlman *et al.*, 2000), including that of the anchialine Bundera Sinkhole 240 km southwest of Barrow Island (HUMPHREYS, 1999b). Anchialine (HUMPHREYS, 1999b) and cold seep communities (K. GLENN, Australian Geological Survey Organisation, personal communication, 1999) have been identified on the North West

Shelf and can be expected to be more widespread. In this context, it is worth noting that sulphide-oxidising mixotrophic *Thiothrix* and *Beggiatoa* bacteria, which may be primary producers using sulphide-based chemosynthesis (BRIGMON *et al.*, 1994; cf. KANE *et al.*, 1994), occur widely in anchialine, other groundwaters (YAGER, 1991; BRIGMON *et al.*, 1994; HUMPHREYS, 1999b)

and on deep-sea hydrothermal vents (BELKIN and JANNASCH, 1989). These processes could make the ecosystem independent of surface inputs. The downwards percolation of organic carbon fixed by photosynthesis at the surface is considered to be the typical energy source for subterranean faunas (POULSON and LAVOIE, 2000).

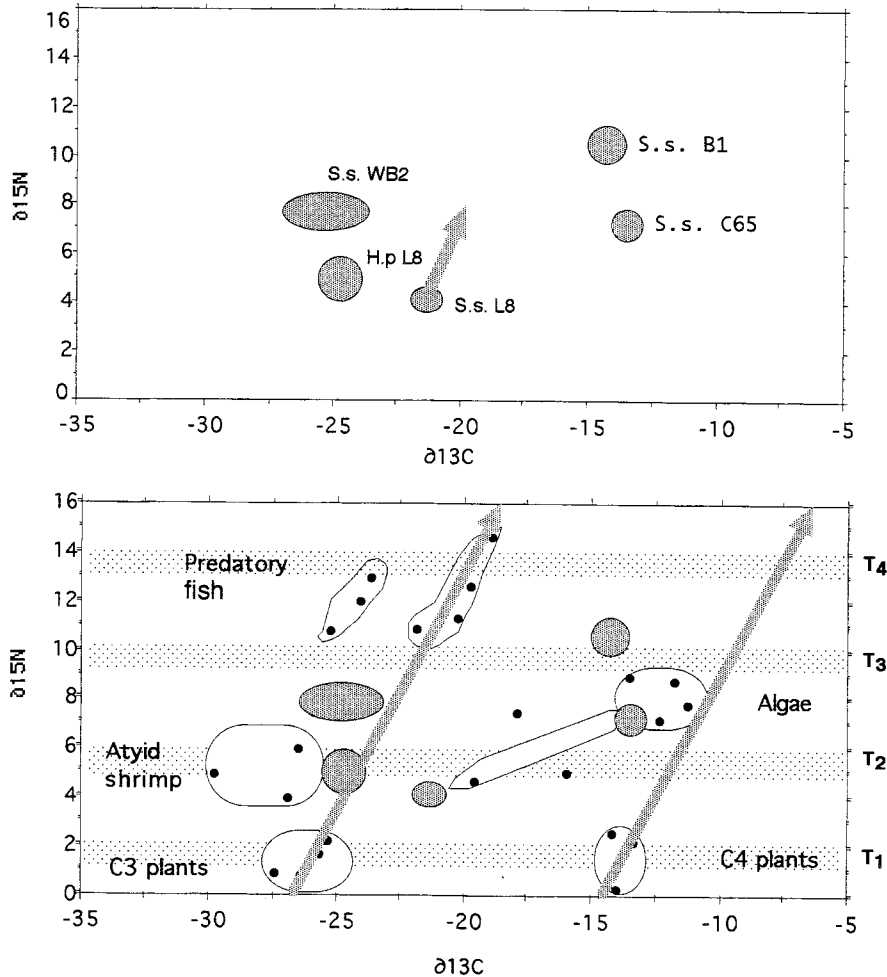


Fig. 6 - Stable isotope signatures ($\delta^{13}\text{C}$ ‰ and $\delta^{15}\text{N}$ ‰)— **a**, samples from various locations and species of stygofauna on Barrow Island. S. s.= *Stygiocaris stylifera* (Decapoda: Atyidae), H. p. = *Haptolana pholeta* (Isopoda: Cirolanidae); **b**, data above overlain by samples from the anchialine Bundera Sinkhole on the Cape Range peninsula, 250 km southwest of Barrow Island (from Humphreys, 1999b). In (a) the sloping arrow represent the expected trajectory of the trophic increment through one trophic level using 2 ‰ for ^{13}C and 4 ‰ for ^{15}N ; data for *H. pholeta*, a predator of *S. stylifera*, could be expected to be at the arrow tip. In (b) the arrows represent the trajectory of the hypothetical trophic increments in the stable isotope data from a basal food source derived from C3 (left arrow) and C4 plants (right arrow) — the shaded bars represent trophic levels T₁ to T₄ incremented by 4 ‰ $\delta^{15}\text{N}$ from a C₃ and C₄ plant base.

Hydrogen sulphide was encountered during drilling of some anode and oil wells on Barrow Island (e.g. 8 ppm at anode well E2), and some anode wells vent H_2S , which also emanates from

natural vents near the Barrow Island Fault (Fig. 1), depositing sulphur minerals at the surface. Geochemical fingerprinting of oil from seeps in the vicinity of the Barrow Island Fault are

consistent with the occurrence there of natural petroleum seeps (WAPET, 1996), but oil is also found in some anode wells remote from the fault, the origins of which are unknown.

Stable isotope analysis and trajectories

The widespread occurrence of sulphur bacteria generally in groundwater and the presence of H_2S , suggest that sulphur bacteria are likely to be involved in chemoautolithotrophy on Barrow Island. Chemosynthetic biomass has a stable isotope signature that is characteristically lighter (more negative $\delta^{13}C$) than photosynthetically derived carbon (CONWAY *et al.*, 1994) and this

should be amplified through the food chain (see HUMPHREYS, 1999b). Hence, chemoautotrophy resulting from sulphur bacteria should be detectable if it forms a significant proportion of the diet of the stygofauna (POHLMAN *et al.* 1997, 2000; HUMPHREYS, 1999b). If chemoautotrophy occurs in the groundwater ecosystem on Barrow Island, its influence on the stable isotope signature in the stygofauna is likely to be more marked nearer the Barrow Island Fault where H_2S is more abundant, and where most natural oil seeps may be expected.

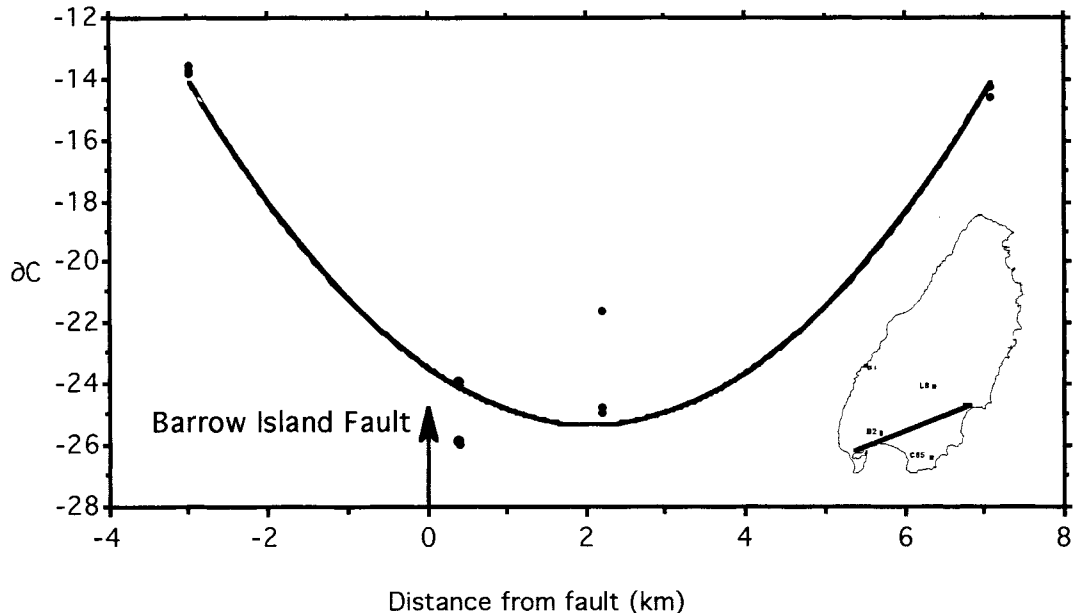


Fig. 7 - Plot of stable isotope values ($\delta^{13}C$ ‰) in *Stygiocaris styliifera* from groundwater at different locations north and south of the Barrow Island fault. A second order polynomial is plotted that is significant overall ($y = 0.44x^2 - 1.801x - 23.47$; $F_{2,16} = 76.511$, $P < 0.0001$) and in its components (x , $t = 9.186$, $P < 0.0001$; x^2 , $t = 12.369$, $P < 0.0001$). In similar analyses, neither the proportion of carbon or nitrogen in the samples, nor the $\delta^{14}N$ values were associated with distance from the fault line. Inset shows the location of the sample sites and the approximate position of the Barrow Island Fault.

In a pilot study, *Stygiocaris styliifera* (Atyidae) were collected from a number of bores at different distances from the fault on Barrow Island and the stable isotope signature determined (Figure 6). The $\delta^{13}C$ values decline towards the fault from both sides, yielding a highly significant second order polynomial relationship (Figure 7, caption), consistent with the hypothesis of chemoautotrophy associated with the fault line. The other variables measured— the proportion of carbon and nitrogen in the samples, and the stable isotope signature of nitrogen — were not associated in this way with the distance of the sample site from the

fault line. A better resolution with distance from the fault is needed and samples of the biofilms within the groundwater systems should be examined for direct evidence of chemo-autotrophic energy production.

A number of points in Figure 6a are worthy of comment. From a general understanding of stable isotope fractionation in food chains (CONWAY *et al.*, 1994; EHLERINGER *et al.*, 1986; LAJTHA and MICHENER, 1994), it seems that, trophically, the same species behaves differently at separate locations on Barrow Island. *S. styliifera* appears to have been feeding at

different parts of the food chain (T_2 , T_3 in Figure 6b in which the data are overlaid on the stable isotope signature from the Bundera Sinkhole; HUMPHREYS, 1999). The brush-shaped tuft of setae in the first two pereopods of atyids are used to brush the substrate while they feed (BAILEY-BROCK and BROCK, 1993), so they have a feeding apparatus well suited to harvesting biofilm. However, these stable isotope data suggest that, under some conditions, they may feed much further along the food chain, acting as consumers, even predators, for which they seem ill equipped, or through the decomposer route. This is consistent with the thesis that omnivory is an adaptation to subterranean life (a so called troglobiomorphy).

Secondly, the stable isotope signatures of different species in the same environment are discordant with that expected from a knowledge of their biology and of the expected trophic cascade. *Haptolana pholeta* is a known predator of *S. stylifera* (my unpublished data). Hence, the expected stable isotope signature would place the data to lie at the tip of the arrow in Figure 6a, indicating typical trophic amplification. Whereas, the data for *H. pholeta* are consistent with it feeding at trophic level T_2 , the same position as *S. stylifera*. Even more surprisingly *H. pholeta* has accumulated a $\delta^{13}\text{C}$ signature markedly different from *S. stylifera* and in the opposite direction expected due to trophic amplification. Namely, it has a lighter (more negative) $\delta^{13}\text{C}$ signature than *S. stylifera* at the same location rather than the expected heavier value. Furthermore, the $\delta^{13}\text{C}$ values are consistent with having been derived from C_4 plants in a predominantly C_3 environment (*Triodia*).

Examination of the stable isotopes of C and N in the Barrow Island stygal system suggest: 1, the data are consistent with the hypothesis that chemoautotrophy occurs associated with the Barrow Island Fault; 2, trophically, the stygofauna does not behave as expected from general principles either between or within sampling sites; and 3, the stable isotope signature of C appears to be discordant with local vegetation and raises questions as to the origin of the energy in the groundwater system. A significant research effort is needed to elucidate the surprisingly complex trophic biology suggested by these data to occur in this anchialine system. The most obvious target would be the partitioning of trophic ecology between the freshwater lens and the underlying seawater, as suggested for Bundera Sinkhole in

Cape Range (HUMPHREYS, 1999b), where some species, including *S. stylifera* and *Milveringa veritas*, occur both above and below the pycnocline. The data are consistent with the thesis that omnivory is a troglobiomorphic trait (RACOVITZA, 1907).

The above considerations, dealt with more fully elsewhere (HUMPHREYS, 1999b, 2000b; POULSON and LAVOIE, 2000), raises the possibility that the biological diversity seen in the Barrow Island stygofauna may, in part, be supported by, even dependent upon, the petroleum deposit itself. The issues raised above deserve to be fully and properly tested as this scientifically interesting question may have implications both for the operators of the oilfield and for the agencies tasked with conserving the fauna — the purification service provided by the groundwater ecosystem of a site may be degraded by common pump-and-treat remediation (HERMAN *et al.*, 2001).

III. 9 - History of groundwater use

Barrow Island was declared an A-class Reserve in 1910, the highest level of conservation protection in Western Australia, and since 1967 has been a producing oilfield. However, the high conservation values of its subterranean ecosystems, including the near surface groundwater, was not recognized until the early 1990's (HUMPHREYS, 1991, 1993; HUMPHREYS and VINE, 1991).

The groundwater of Barrow Island has been used both as a water resource and as a sink for produced water and its contents. In addition the subterranean system has received sustained accidental inputs of contaminants as a result of pipeline, storage tank and top-valve leaks and well stem fractures which variously add saline water, petroleum, antioxidants and other corrosion inhibitors, drilling fluids, etc. (WAPET, 1996). Disposal of produced water in the superficial karst has ceased and the collector pipes have been replaced and will lead to a central separator plant.

Oilfield exploitation results in ever increasing amounts of water requiring disposal. This 'produced water' — $2.4 \times 10^6 \text{ m}^3$ in 1996 — is saline (ca 40,000 - 45,000 mg L^{-1} TDS) and has an oil content of 100-2000 ppm (WAPET, 1996). Hence, the produced water has potentially injected up to several thousand tonnes of oil a year into the disposal sites, together with corrosion inhibitors added to the flowlines. In addition, it has the potential to disrupt the salinity stratification

present in the groundwater. Such stratification is an important characteristic of anchialine systems (HUMPHREYS, 1999b), such as on Barrow Island, and its disruption can be expected to impact on the anchialine ecosystem.

Initially, produced water was pumped to evaporation ponds or injected into the Cardabia Formation (at a depth about ca. 200 m) and, in places, into caves. Some was disposed in 'B Block Cave' (the identity of which is unknown) from 1968-1979, and in 'F Block caves' from 1987-1994. Since 1991 the disposal of produced water in caves has been prohibited and emphasis placed on transferring the reinjection of produced water from the Cardabia Formation to the Barrow Group (at a depth of ca. 1200 m) which lies below some of the oil reservoirs (WAPET, 1996).

III. 10 - Conservation

Two troglobites and 10 stygobites from Barrow Island are specially protected under the *Wildlife Conservation Act 1950-1979*, Western

Australia. They comprise nine species of crustaceans, one millipede, one micro-whipscorpion and a fish (Table 5). *Milyeringa veritas* is listed as vulnerable under the Commonwealth *Environment Protection and Biodiversity Conservation Act 1999*. Oilfield operations on Barrow Island have continued for more than 30 years. Despite this, the subterranean fauna, especially the stygofauna, is remarkably rich and this diversity is mostly from within the area most intensively drilled. Whether this comprises the full compliment of the subterranean species present prior to the establishment of the oilfield cannot be known owing to a lack of any information before 1992.

From knowledge of the Cape Range fauna, with which Barrow Island has some species in common, the cave eel, *Ophisternon candidum* Mees, could occur on Barrow Island. However, this species is unlikely to be sampled as direct access to the groundwater, generally lacking on Barrow Island, has been required for all sightings so far recorded (HUMPHREYS, 1999a, 2001a).

Table 5 - Specially protected subterranean fauna on Barrow Island (Department of Conservation and Land Management Declared Threatened Fauna: 4 July 2000). VU, vulnerable.

Fish	
<i>¹Milyeringa veritas</i> , Blind Gudgeon	VU
Millipedes	
<i>Speleostrophus nesiotus</i> , Barrow Island Millipede	VU
Chelicerates	
<i>Draculoides bramstockeri</i> , Barrow Island Draculoides	VU
Crustaceans	
<i>Bogidomma australis</i> , Barrow Island Bogidomma Amphipod	VU
<i>Liagoceradocus subthalassicus</i> , Barrow Island Liagoceradocus Amphipod	VU
<i>Nedsia fragilis</i>	VU
<i>Nedsia humphreysi</i>	VU
<i>Nedsia hurlberti</i>	VU
<i>Nedsia macrosculptilis</i>	VU
<i>Nedsia sculptilis</i>	VU
<i>Nedsia straskraba</i>	VU
<i>Nedsia urifimbriata</i>	VU

While there are undoubted impacts of oilfield operations on the subterranean fauna, their extent, duration and significance is unknown. However, there is limited evidence that some species do reinvade areas from which they were probably eliminated.

One *Draculoides bramstockeri* was recorded in cave F53 [karst number B6] in 1996, a cave that was used for the disposal of produced water

between 1987-1988 and was coated with a waxy residue and still smelled strongly of petroleum in 1999. Numerous dead specimens of this species have been recovered from a non-operational anode well, B2, and from L4.

It is presumed that stygofauna are eliminated from operational anode wells owing to the chlorine production and, frequently, the reduced pH. However, stygobionts have been collected from a

number of previously operational anode wells (B2, C66, E1, K3N and L4), including Bathynellacea, *Halicyclops longifurcatus*, *Inermipes humphreysi*, *Halosbaena tulki*, *Nedsia fragilis*, *N. humphreysi*, *Haptolana pholeta* and *Stygiocaris stylifera*.

Anchialine ecosystems are considered to be extraordinarily vulnerable to even slight organic pollution (ILIFFE *et al.*, 1984) by affecting the physico-chemical conditions, while being tolerant of a wide range of physico-chemical conditions (SKET, 1996; HUMPHREYS, 1999b). Nonetheless, SKET (1986) asserts "the extreme unsusceptibility of [*Niphargus hebereri*] against different unfavourable conditions in its environment (light, lack of oxygen, presence of H₂S, oil pollution ...)", and of the Thermosbaenacean *Monodella argentarii* which "may occur in environments with apparently quite unfavourable conditions (H₂S replacing O₂)". While these papers may appear contradictory, their differing emphasis (interpretation) could result from the extremely sharp gradients in physico-chemical conditions that may occur in anchialine habitats (see Fig. 3). Such gradients are associated, *inter alia*, with the interface between waters of differing salinity (HUMPHREYS, 1999b), typically between fresh and saline waters.

III. 11 - Decommissioning

When the oilfield on Barrow Island is abandoned, it is stressed that the anode wells (and other relatively shallow bores) could be decommissioned such that their integrity is retained suitable for sampling subterranean fauna. This would provide a unique opportunity to monitor the changes accompanying the closure of the oilfield, providing information of utility for operators and regulators on the effects of oilfield

development on groundwater ecosystems — globally, numerous oilfields occur in similar situations. Furthermore, it would provide a valuable window through which fundamental and applied research could be conducted on ecosystem and population processes, and on the maintenance of subterranean biodiversity in one the world's more diverse stygal systems. Such decommissioning would be contrary to established practice and policy and its implementation would need the involvement of numerous government agencies and petroleum company partners. Consequently its implementation would require considerable lead-time and early planning.

Acknowledgements. Fieldwork on Barrow Island was conducted with the assistance of Brian Vine, Ray Wood, Stefan Eberhard and Carl Close. Julianne Waldoock provided continual support in Perth. Keith Hallett conducted additional sampling in 1998-9 and imparted of his extensive knowledge of the groundwater. Numerous WAPET personnel or contractors in Perth and on Barrow Island provided assistance in many ways that made sampling possible in this remote and restricted location, especially Environmental Officers Stephan Fritz, Russell Lagdon and Kellie Pendoley. IT Environmental interpreted the groundwater elevation contours. Unpublished identifications of taxa were made by K. Schminke, (Bathynellacea), M.S. Harvey (Chelicerata), L.M. Roth (Blattodea), L.B. Holthuis (*Stygiocaris*), W. Lee and R. Huys (Copepoda: Harpacticoida, Ameiridae and Cyclopoida: Cyclopidae). Funding for field work was provided by Western Australian Petroleum Pty Ltd. (now Chevron Oil Pty Ltd.).

This paper is a contribution to DIVERSITAS-IBOY project, "Exploration and Conservation of Anchialine Faunas".

RESUME

Barrow Island est située au nord-ouest de la côte de l'Australie Occidentale et se compose d'un anticlinal de roches calcaires du Miocène. Elle a été le lieu de production de champ de pétrole durant plus de 30 années et produisait de l'eau en partie localisée dans le karst superficiel, des pratiques maintenant arrêtées. L'île renferme une lentille d'eau douce de type Ghyben-Herzberg, surmontant de l'eau salée à 7-8 m de profondeur, constituant un écosystème anchihaline de grande extension. La faune souterraine aquatique se compose d'au moins 27 espèces : un poisson Eleotridae, et des Crustacés appartenant aux Bathynellacea, Harpacticoida, Cyclopoida, Thermos-

baenacea, Isopoda (Cirolanidae), Decapoda (Atyidae), Amphipoda (Hadziidae, Bogidiellidae, Melitidae). Quatre espèces appartenant à la faune souterraine terrestre ont été décrites ainsi qu'un serpent aveugle d'apparence troglodiorphte et un Scorpion de position taxonomique incertaine car il présente des caractères de la famille des Urodacidae et de celle Heteroscorpionidae, familles respectivement endémiques de l'Australie et de Madagascar. La présence générale de bactéries sulfureuses et d'H₂S suggère que ces bactéries sont impliquées dans une production chimioautolithotrophe dans les eaux souterraines de l'île. Les résultats des mesures radioisotopiques de la stygofaune appuient l'hypothèse d'une production d'énergie par voie chimioautotrophe en relation avec

la faille de Barrow Island. Ceci confirme l'intérêt de la gestion et de la protection de la faune souterraine de Barrow Island.

ABSTRACT

Barrow Island lies on the North West Shelf of Western Australia and comprises an anticline of Miocene limestones. It has been a production oilfield for more than 30 years and produced water was, in part, disposed of into the superficial karst, a practice now stopped. The island contains a freshwater lens overlying saline water providing an extensive anchialine ecosystem. A summary of the cave and groundwater environments is given. The stygofauna comprises at least 24 species, a fish (Eleotridae), and crustaceans from the Bathynellacea, Harpacticoida, Cyclopoida, Thermosbaenacea, Isopoda (Cirrolanidae), Decapoda (Atyidae), Amphipoda (Hadziidae, Bogidiellidae, Melitidae). Four species of troglifauna have been formally described, as well as a blindsnake with apparent troglomorphies. A scorpion of uncertain family placement, with characters of the families Urodacidae and Heteroscorpionidae, respectively endemic to Australia and Madagascar. Evidence from stable isotope ratio analysis of stygofauna is consistent with the hypothesis that chemoautotrophic energy production may be associated with the Barrow Island Fault, confirmation of which would have implications for the management and conservation of the Barrow Island subterranean fauna.

REFERENCES

- ADAMS, M. and W. F. HUMPHREYS - 1993 - Patterns of genetic diversity within selected subterranean fauna of the Cape Range peninsula, Western Australia: systematic and biogeographic implications. **Rec. West. Austr. Mus., Suppl.**, 45, p. 145-164.
- ALLEN, A. D. - 1993 - Outline of the geology and hydrogeology of Cape Range, Carnarvon Basin, Western Australia. **Rec. West. Austr. Mus., Suppl.**, 45, p. 25-38.
- ANZECC and ARMCANZ - 2000 - *Australian and New Zealand Guidelines for Fresh and Marine Water Quality. National Water Quality Management Strategy*. Paper No 4. Australian and New Zealand Environment and Conservation Council & Agriculture and Resource Management Council of Australia and New Zealand, Canberra.
- APLIN, K. P. - 1998. - Three new blindsnakes (Squamata: Typhlopidae) from northwestern Australia. **Rec. West. Austr. Mus.**, 19, p. 1-12.
- ARP, A. J. and C. R. FISHER - 1995 - Introduction to the symposium: Life with sulfide. **Am. Zool.**, 35, p. 81-82.
- BAILEY-BROCK, J. H. and R. E. BROCK - 1993 - Feeding, reproduction, and sense organs of the Hawaiian anchialine shrimp *Halocaridina rubra* (Atyidae). **Pac. Sci.**, 47, p. 338-355.
- BALTANAS, A. and D. DANIELOPOL - 1995 - Cladistic analysis of *Danielopolina* species (Ostracoda: Thaumatoocyprididae) and the origin of anchialine fauna. **Mitt. Hamburg Zool. Mus. Inst.**, 92, p. 315-324.
- BELKIN, S. and H. W. JANNASCH - 1989 - Microbial mats at deep-sea hydrothermal vents: new observations. p. 16-21. *In: Microbial Mats: physiological ecology of benthic microbial communities* (Y. Cohen and E. Rosenberg eds), American Society for Microbiology, Washington.
- BRADBURY, J. H. - 2000 - Western Australian stygobiont amphipods (Crustacea: Paramelitidae) from the Mt Newman and Millstream regions. **Rec. West. Austr. Mus., Suppl.**, 60, p. 1-102.
- BRADBURY, J. H. - 2002 - Melitid amphipods of Barrow Island, Western Australia. Part II—recent discoveries. **Rec. West. Austr. Mus.**, 21, p. 83-103.
- BRADBURY, J. H. and W. D. WILLIAMS - 1996a - Freshwater amphipods from Barrow Island, Western Australia. **Rec. West. Austr. Mus.**, 48, p. 33-74.
- BRADBURY, J. H. and W. D. WILLIAMS - 1996b - Two new species of anchialine amphipod (Crustacea: Hadziidae: *Liagoceradocus*) from Western Australia. **Rec. West. Austr. Mus.**, 17, p. 395-409.
- BRIGMON, R. L., MARTIN, H. W., MORRIS, T. L., BITTON, G. and S. G. ZAM - 1994 - Biogeochemical ecology of *Thiothrix* spp. in underwater limestone caves. **Geomicrobiol. J.**, 12, p. 141-159.
- BROCK, R. E., NORRIS, J., ZEIMANN, D. and M. T. LEE - 1987 - Characteristics of water quality in anchialine pools of the Kona, Hawaii, coast. **Pac. Sci.**, 41, p. 200-208.
- BUCKLEY, R. C. - 1983 - The flora and vegetation of Barrow Island, Western Australia. **J. Roy. Soc. West. Austr.**, 66, p. 91-105.
- CHILDRESS, J. J. and C. R. FISHER - 1992 - The biology of hydrothermal vent animals: The physiology, biochemistry and autotrophic symbioses. **Oceanogr. Mar. Biol.**, 30, p. 337-442.

- CONWAY, N. M., KENNICUTT II M. C. and C. L. VAN DOVER - 1994 - Stable isotopes in the study of marine chemosynthetic-based ecosystems. p 158-186. In: K. Lajtha and R.H. Michener (eds). *Stable isotopes in ecology and environmental science*. Blackwell, Oxford.
- CULVER, D. C. and , B. SKET - 1999 - Hotspots of subterranean biodiversity in caves and wells. **J. Cave Karst Stud.**, 62, p. 11-17.
- CURL, R. - 1966 - Caves as a measure of karst. **J. Geol.**, 74, p. 798-830.
- DANIELOPOL, D. L. - 1990 - The origin of the anchialine cave fauna - the "deep sea" versus the "shallow water" hypothesis tested against the empirical evidence of the Thaumatoocyprididae (Ostracoda). **Bijdr. Dierk.**, 60, p. 137-143.
- DANIELOPOL, D. L., BALTANÁS, A. and W. F. HUMPHREYS - 2000 - *Danielopolina kornickeri* sp. n. (Ostracoda: Thaumatoocypridoidea) from a western Australian anchialine cave — morphology and evolution. **Zool. Scripta**, 29, p. 1-16.
- DECU, V., JUBERTHIE, C. and M. D ANDREI., - 1998 - Reptilia. p. 1245-1247. In: C. Juberthie and V. Decu (eds) *Encyclopædia Biospeologica II*. Société de Biospéologie, Moulis & Academie Roumaine, Bucarest. 1373 pp.
- EDNEY, E. B. - 1977 - *Water Balance in Land Arthropods*. Springer-Verlag, Berlin, Heidelberg, New York.
- EHLERINGER, J. R. , RUNDEL, P. W. and K. A. NAGY - 1986 - Stable isotopes in physiological ecology and food web research. **Trends Ecol. Evol.**, 1, p. 42-45.
- FLANNERY, T. F., RICH, T. H., TURNBULL, W. D. and E. L. LUNDELIUS - 1992 - The Macropodoidea (Marsupialia) of the Early Pliocene Hamilton Local Fauna, Victoria, Australia. **Fieldiana Geol.**, New Ser., 25, p. 1-36.
- FORD, D. C. and P. W. WILLIAMS - 1989 - *Karst Geomorphology and Hydrology*. Unwin Hyman, London. 601 pp.
- HAMILTON-SMITH, E., KIERNAN, K. and A SPATE. - 1998 - *Karst management considerations for the Cape Range karst province, Western Australia*. A report prepared for the Department of Environmental Protection, March 1998.
- HARVEY, M. S. - 1993 - The systematics of the Hyidae (Pseudoscorpionida). **Invert. Taxon.**, 7, p. 1-32.
- HARVEY, M. S. and W. F. HUMPHREYS - 1995 - Notes on the genus *Draculoides* Harvey (Schizomida: Hubbardiidae), with the description of a new troglobitic species. **Rec. West. Austr. Mus., Suppl.**, 52, p. 183-189.
- HATTON, T. and R EVANS - 1998 - Dependence of Ecosystems on Groundwater and its Significance to Australia. **Land and Water Resources Research and Development Corporation Occasional Paper 12/98**.
- HERMAN, J. S., CULVER, D. C. and J. SALZMAN - 2001 - Groundwater ecosystems and the service of water purification. **Stanford Environ. Law J.**, 20, p. 479-495.
- HOFFMAN, R. L. - 1994 - Studies on spiroboloid millipeds. XVIII. *Speleostrophus nesiotetes*, the first known troglobitic spiroboloid millipede, from Barrow Island, Western Australia (Diplopoda: Pachybolidae: Trigoniulinae). **Myriapodologia**, 3, p. 19-24.
- HOLSINGER, J. R. - 1989 - Preliminary zoogeographic analysis of five groups of crustaceans from anchialine caves in the West Indian region. **Proc. 10th Int. Congr. Speleology, Budapest**, 2, p. 25-26.
- HOLTHUIS, L. B. - 1960 - Two new species of atyid shrimps from subterranean waters of N.W. Australia (Decapoda Natantia). **Crustaceana**, 1, p. 47-57.
- HOWARTH, F. G. - 1980 - The zoogeography of specialized cave animals: a bioclimatic model. **Evolution**, 34, p. 394-406.
- HUMPHREYS, W. F. - 1990 - The biology of a troglobitic schizomid (Chelicerata: Arachnida) from caves in the semi-arid Cape Range, Western Australia. **Acta zool. Fenn.**, 190, p. 181-186.
- HUMPHREYS, W. F. - 1991 - Troglobites on Barrow Island, Western Australia.. **Western Caver**, 31, p. 11-14.
- HUMPHREYS, W. F. - 1993 - Stygofauna in semi-arid tropical Western Australia: a Tethyan connection? **Mém. Biospéol.**, 20, p. 111-116.
- HUMPHREYS, W. F. - 1994 - *The subterranean fauna of the Cape Range coastal plain, northwestern Australia*. Report to the Australian Heritage Commission and the Western Australian Heritage Committee. 202 pp. Unpublished.
- HUMPHREYS, W. F. - 1999a - The distribution of the Australian cave fishes. **Rec. West. Austr. Mus.**, 19, p. 469-472
- HUMPHREYS, W. F. - 1999b - Physico-chemical profile and energy fixation in Bundera Sinkhole, an anchialine remiped habitat in north-western Australia **J. Roy. Soc. West. Austr.**, 82, p. 89-98.

- HUMPHREYS, W. F. - 1999c - Relict stygofaunas living in sea salt, karst and calcrete habitats in arid northwestern Australia contain many ancient lineages. p. 219-227. *In*: W. Ponder and D. Lunney (eds). *The Other 99%. The Conservation and Biodiversity of Invertebrates*. Transactions of the Royal Zoological Society of New South Wales, Mosman 2088.
- HUMPHREYS, W. F. - 2000a - Chapter 30. The hypogean fauna of the Cape Range peninsula and Barrow Island, northwestern Australia. p. 581-601. *In*: H. Wilkens, D. C. Culver and W. F. Humphreys (eds). *Ecosystems of the World, vol. 30. Subterranean Ecosystems*. Elsevier, Amsterdam.
- HUMPHREYS, W.F. - 2000b - Karst wetlands biodiversity and continuity through major climatic change - an example from arid tropical Western Australia. p. 227-258. *In*: B. Gopal, W. J. Junk and J. A. Davis (eds). *Biodiversity in wetlands: assessment, function and conservation, volume 1*. Backhuys Publishers, Leiden.
- HUMPHREYS, W. F. - 2001a - *Milyeringa veritas* Whitley 1945 (Eleotridae), a remarkably versatile cave fish from the arid tropics of northwestern Australia. **Environ. Biol. Fish.**, 62, p. 297-313.
- HUMPHREYS, W. F. - 2001b - Groundwater calcrete aquifers in the Australian arid zone: the context to an unfolding plethora of stygal biodiversity. **Rec. West. Austr. Mus., Suppl.**, 64, p. 63-83.
- HUMPHREYS, W. F. and B. VINE - 1991 - *The caves of Barrow Island and their fauna*. A Report to West Australian Petroleum Pty Ltd. 22 pp.
- HUMPHREYS, W. F., ADAMS, M. and B. VINE - 1989 - The biology of *Schizomus vinei* (Chelicerata: Schizomida) in the caves of Cape Range, Western Australia. **J. Zool., Lond.**, 217, p. 177-201.
- HUMPHREYS, W. F., POOLE, A., EBERHARD, S. M. and D. WARREN - 1999 - Effects of research diving on the physico-chemical profile of Bundera Sinkhole, an anchialine remiped habitat at Cape Range, Western Australia. **J. Roy. Soc. West. Austr.**, 82, p. 99-108.
- ILIFFE, T. M. - 1992 - Anchialine cave biology. p. 614-636. *In*: A. I. Camacho (ed.). *The Natural History of Biospeleology*. Monografias Museo Nacional de Ciencias Naturales, Madrid.
- ILIFFE, T. M. - 2000 - Anchialine cave ecology. p. 59-76. *In*: H. Wilkens, D. C. Culver and W. F. Humphreys (eds). *Ecosystems of the World, vol. 30. Subterranean Ecosystems*. Elsevier, Amsterdam.
- ILIFFE, T. M., JICKELLS, T. D. and M. S. BREWER - 1984 - Organic pollution of an inland marine cave from Bermuda. **Mar. Environ. Res.**, 12, p. 173-189.
- KANE, T. C., SARBU, S. and B. K. KINKLE - 1994 - Chemoautotrophy: methodological approaches, geological implications, and a case study from Romania. p. 38-39. *In*: I. D. Sasowsky and M. V. Palmer (eds). *Breakthroughs in Karst Geomicrobiology and Redox Geochemistry Symposium*. Special Publication 1. Karst Waters Institute, Charles Town, WV.
- KEIGHERY, G. and N. GIBSON - 1993 - Biogeography and composition of the flora of the Cape Range peninsula, Western Australia. **Rec. West. Austr. Mus., Suppl.**, 45, p. 51-85.
- KUEHN, K. A. and R. D. KOEHN. - 1988 - A mycofloral survey of an artesian community within the Edwards Aquifer of Central Texas. **Mycologia**, 80, p. 646-652.
- LAJTHA, K. and R. H. MICHENER - 1994 - *Stable isotopes in ecology and environmental science*. Blackwell, Oxford.
- LONGLEY, G. - 1981 - The Edwards Aquifer: earth's most diverse groundwater ecosystem? **Intern. J. Speleol.**, 11, p. 123-128.
- LONGLEY, G. - 1992 - The subterranean aquatic ecosystem of the Balcones Fault Zone Edwards Aquifer in Texas - threats from overpumping. p. 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.
- MCNAMARA, K. J. and G. W. KENDRICK - 1994 - Cenozoic molluscs and echinoids of Barrow Island, Western Australia. **Rec. West. Austr. Mus., Suppl.**, 51, p. 1-50.
- MACIOLEK, J. A. - 1986 - Environmental features and biota of anchialine pools on Cape Kinau, Maui, Hawaii. **Stygologia**, 2, p. 119-129.
- MARTIN, L. H., EAKINS, K. E. and A. LOGAN - 1991 - Physical characteristics of the anchialine ponds of Bermuda. **Bull. Mar. Sci.**, 48, p. 125-136.
- MARTIN, L. H., LOGAN, A. and K. E. EAKINS - 1992 - Biotic characteristics of the anchialine ponds of Bermuda. **Bull. Mar. Sci.**, 50, p. 133-157.
- PERRY, D. H. - 1972 - Some notes on the termites (Isoptera) of Barrow Island and a check list

Lasionectes exleyi, sp. nov., the first remipede crustacean recorded from Australia and the Indian Ocean, with a key to the world species. **Invert. Taxon.**, 10, p. 171-187.

YAGER, J. and F. R. SCHRAM - 1986 - *Lasionectes entrichoma*, new genus, new species, (Crustacea: Remipedia) from anchialine caves in the Turks and Caicos, British West Indies. **Proc. Biol. Soc. Wash.**, 99, p. 65-70.

YAGER, J., SPOKANE, R. B., BOZANIC, J. E., WILLIAMS, D. W. and , E. BALADO - 1994 - An ecological comparison of two anchialine caves in Cuba with emphasis on water chemistry. p. 95-101. *Proceedings Second International Conference on Groundwater Ecology*. U.S. Environ. Prot. Agency & Am. Water Resources Assoc.

- of species. **West. Austr. Naturalist**, 12, p. 52-55.
- PETERSON, B. J. and B. FRY - 1987 - Stable isotopes in ecosystem studies. **Ann. Rev. Ecol. Systemat**, 18, p. 293-320.
- PETTERSSSEN, S. - 1958 - *Introduction to meteorology*. McGraw-Hill Book Company, New York.
- POHLMAN, J. W., CIFUENTES, L. A. and T. M. ILIFFE - 2000 - Food web dynamics and biogeochemistry of anchialine caves: a stable isotope approach. p. 345-357. *In* H. Wilkens, D. C. Culver and W. F. Humphreys (eds). *Ecosystems of the world, vol. 30. Subterranean ecosystems*. Elsevier, Amsterdam.
- POHLMAN, J. W., ILIFFE, T. M. and L. A. CIFUENTES - 1997 - A stable isotope study of organic cycling and the ecology of an anchialine cave ecosystem. **Mar. Ecol. Progress Ser.**, 155, p. 17-27.
- POORE, G. C. B. and W. F. HUMPHREYS - 1998 - First record of Spelaeogriphacea from Australasia: a new genus and species from an aquifer in the arid Pilbara of Western Australia. **Crustaceana**, 71, p. 721-742.
- POULSON, T. L. and K. H. LAVOIE - 2000 - The trophic basis of subsurface ecosystems. p. 231-249. *In*: H. Wilkens, D. C. Culver and W. F. Humphreys (eds). *Ecosystems of the world, vol. 30. Subterranean ecosystems*. Elsevier, Amsterdam.
- PRENDINI, L. - 2000 - Phylogeny and classification of the superfamily Scorpionoidea Latreille 1802 (Chelicerata, Scorpiones): an exemplar approach. **Cladistics**, 16, p. 1-78.
- RACOVITZA, E. G. - 1907 - Essai sur les problèmes biospéologiques. **Archiv. Zool. exp. gén.**, 6, p. 371-488.
- RIDGLEY, M. A. and D. K. CHAI - 1990 - Evaluating potential biotic benefits from conservation: anchialine ponds in Hawaii. **Environ. Prof.**, 12, p. 214-228.
- SARBU, S. M. - 2000 - Movile Cave: a chemoautotrophically based groundwater ecosystem. p. 319-343. *In*: H. Wilkens, D.C. Culver and W.F. Humphreys (eds). *Ecosystems of the world, vol. 30. Subterranean ecosystems*. Elsevier, Amsterdam.
- SARBU, S. M., GALDENZI, S., MENICHETTI, M. and G. GENTILE - 2000 - Geology and biology of Frasassi Caves in Central Italy: an ecological multidisciplinary study of a hypogenic underground karst system. p. 359-378. *In*: H. Wilkens, D. C. Culver and W. F. Humphreys (eds). *Ecosystems of the world, vol. 30. Subterranean ecosystems*. Elsevier, Amsterdam.
- SARBU, S. M., KANE, T.C. and B. K. KINKLE - 1996 - A chemoautotrophically based cave ecosystem. **Science**, 272, (5270), p. 1953.
- SARBU, S. M. and R. POPA - 1992 - A unique chemoautotrophically based cave ecosystem. p. 641-666. *In*: A.I. Camacho (Ed.), *The Natural History of Biospeleology*. Monografias Museo Nacional de Ciencias Naturales, Madrid.
- SCOTT, K. M. and C. R. FISHER - 1995 - Physiological ecology of sulfide metabolism in hydrothermal vent and cold seep vesicomyid clams and vestimentiferan tube worms. **Amer. Zool.**, 35, p. 102-111.
- SKET, B. - 1981 - Fauna of anchialine (coastal) cave waters, its origin and importance. **Proc. 8th Internat. Congr. Speleol.**, p. 646-647.
- SKET, B. - 1986 - Ecology of the mixohaline hypogean fauna along the Yugoslav coasts. **Stygologia**, 2, p. 317-337.
- SKET, B. - 1996 - The Ecology of anchihaline caves. **Trends Ecol. Evol.**, 11, p. 221-255.
- STOCK, J. H., ILIFFE, T. M. and WILLIAMS, D. - 1986 - The concept 'anchialine' reconsidered. **Stygologia**, 2, p. 90-92.
- THOMAS, M. L. H., EAKINS, K. E. and A. LOGAN - 1991 - Physical characteristics of the anchialine ponds of Bermuda. **Bull. Mar. Sci.**, 48, p. 125-136.
- THOMAS, M. L. H., LOGAN, A., EAKINS, K. E. and S. M. MATHERS - 1992 - Biotic characteristics of the anchialine ponds of Bermuda. **Bull. Mar. Sci.**, 50, p. 133-157.
- WAPET - 1996 - *Protection of Barrow island groundwater*. Report to the National Parks and Nature Conservation Authority 1996. Western Australian Petroleum Pty Ltd.
- WATTS, C. H. S. and W. F. HUMPHREYS - 2000 - Six new species of *Nirridessus* and *Tjirtudessus* (Dytiscidae; Coleoptera) from underground waters in Australia. **Rec. S. Austr. Mus.**, 33, p. 127-144.
- WILSON, G. D. F. and S. J. KEABLE - 1999 - new genus of phreatoicidan isopod (Crustacea) from the North Kimberley Region, Western Australia. **Zool. J. Linn. Soc., Lond.**, 126, p. 51-79.
- YAGER, J. - 1991 - The Remipedia (Crustacea): recent investigations of their biology and phylogeny. **Verh. Dtsch. Zool. Ges.**, 84, p. 261-269.
- YAGER, J. and W. F. HUMPHREYS - 1996 -