

## Stygofauna in the Pilbara region, north-west Western Australia: a review

S M Eberhard<sup>1</sup>, S A Halse<sup>1</sup> & W F Humphreys<sup>2</sup>

<sup>1</sup>Department of Conservation and Land Management, Science Division,  
PO Box 51, Wanneroo, WA 6065

<sup>2</sup>Western Australian Museum, Locked Bag 49, Welshpool DC, WA 6986  
✉ [stefane@calm.wa.gov.au](mailto:stefane@calm.wa.gov.au)

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### Abstract

North-west Western Australia appears to contain one of the world's more diverse subterranean faunas and this paper summarises published literature about stygofauna of the Pilbara region, within north-west Western Australia. To date, 332 occurrences of 78 species from approximately 223 sites have been recorded. The stygofaunal species occur in an array of different groundwater environments including porous, karstic and fractured-rock aquifers, springs and hyporheic habitats. Sampling coverage has been highly skewed in terms of areal coverage and the different types of groundwater environments represented – 96 % of sampled sites are bores or wells, while springs and hyporheic habitats have rarely been sampled. The higher-level systematic diversity of the region is quite comprehensive in global terms, but the species-level taxonomy of most groups is still incomplete. There appears to be significant regional endemism in the Pilbara stygofauna, including some relict freshwater lineages. Karstic aquifers, karst springs and porous alluvial aquifers contain high species richness. This review confirms that the Pilbara is an important region for subterranean biodiversity.

**Keywords:** stygofauna, Pilbara

### Introduction

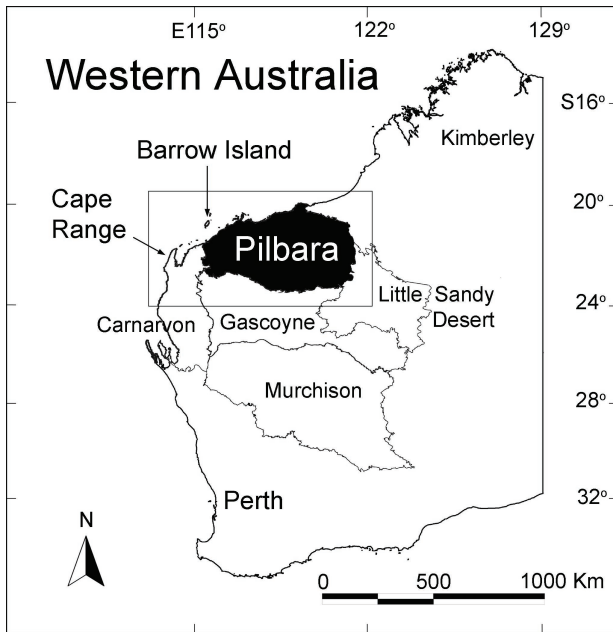
This paper reviews current information on stygofauna in the Pilbara region of north-west Western Australia by providing an updated list of taxa and making some comparisons with adjacent regions. Since the last synopsis of stygofauna in the Pilbara region (Humphreys 2000a), 11 papers describing 47 new species and seven new locality records from the Pilbara (*cf.* 23 described Pilbara species up to 2000 ) have been published. This suggests that the Pilbara region is important for subterranean biodiversity. The review is apposite because in recent years there has been some conflict between ecological water requirements for groundwater-dependent ecosystems, including stygofauna, and groundwater abstraction or mine dewatering (Water & Rivers Commission 1996; Johnson & Wright 2001; Playford 2001).

Despite its arid setting, north-west Western Australia appears to contain one of the world's more diverse subterranean faunas, dominated by crustaceans and including many relict obligate groundwater species with affinities to Tethys, and to Pangaea and its derived landmasses (Humphreys 1993ab, 1999a, 2001a; Knott 1993). This rich stygofauna was initially discovered in the anchialine groundwater system at Cape Range (Whitley 1945; Mees 1962; Humphreys & Adams 1991), subsequently on Barrow Island (Humphreys 2001b) and then in the Pilbara region (Poore & Humphreys 1998). As a consequence of earlier discovery and small land areas, the Cape Range (3,600 km<sup>2</sup>) and Barrow Island (324 km<sup>2</sup>) stygofaunas are reasonably well known and

taxonomically described, with a review and systematic lists in Humphreys (2000b). By contrast, since 2000 in the Pilbara region, descriptions have been published of Amphipoda (Bradbury 2000), Isopoda (Wilson 2003), Ostracoda (Karanovic & Marmonier 2002; Martens and Rossetti 2002; Karanovic 2003ab; Karanovic & Marmonier 2003; Karanovic 2005), Spelaeogriphacea (Poore & Humphreys 2003), and Copepoda (Karanovic 2004a; Karanovic 2006 in press). Taxonomic knowledge of Amphipoda has been augmented by molecular studies that investigated incongruence between morphology and molecular markers (Finston *et al.* 2004), and geographic patterns of genetic diversity (Finston and Johnson 2004). In addition, Pinder (2001) recorded undescribed species of phreodrilid oligochaetes, and there has been a substantial amount of recent collecting in the Pilbara region, results of which are unpublished. To the south of the Pilbara region, stygofauna have been discovered in the Murchison and Gascoyne regions (Humphreys 1999a; Watts and Humphreys 1999; Humphreys 2001a; Leys *et al.* 2003), and to the northeast, the Kimberley is proving to contain relictual lineages (Wilson & Ponder 1992), gondwanan relicts (Wilson & Keable 1999) and endemic taxa (Cho *et al.* 2005) (Figure 1).

### Description of the Pilbara region

The Pilbara IBRA (Interim Biogeographic Region of Australia) region (20–24° S and 115–122° E) covers an area of approximately 178,000 km<sup>2</sup> in the arid north-west of Western Australia (Environment Australia 2000). The Pilbara IBRA region coincides, more or less, with the emergent part of the Pilbara Craton and encompasses five major hydrographic basins, from largest, Ashburton River Basin, De Grey River Basin, Fortescue River Basin, Port Hedland Coast Basin and Onslow Coast Basin



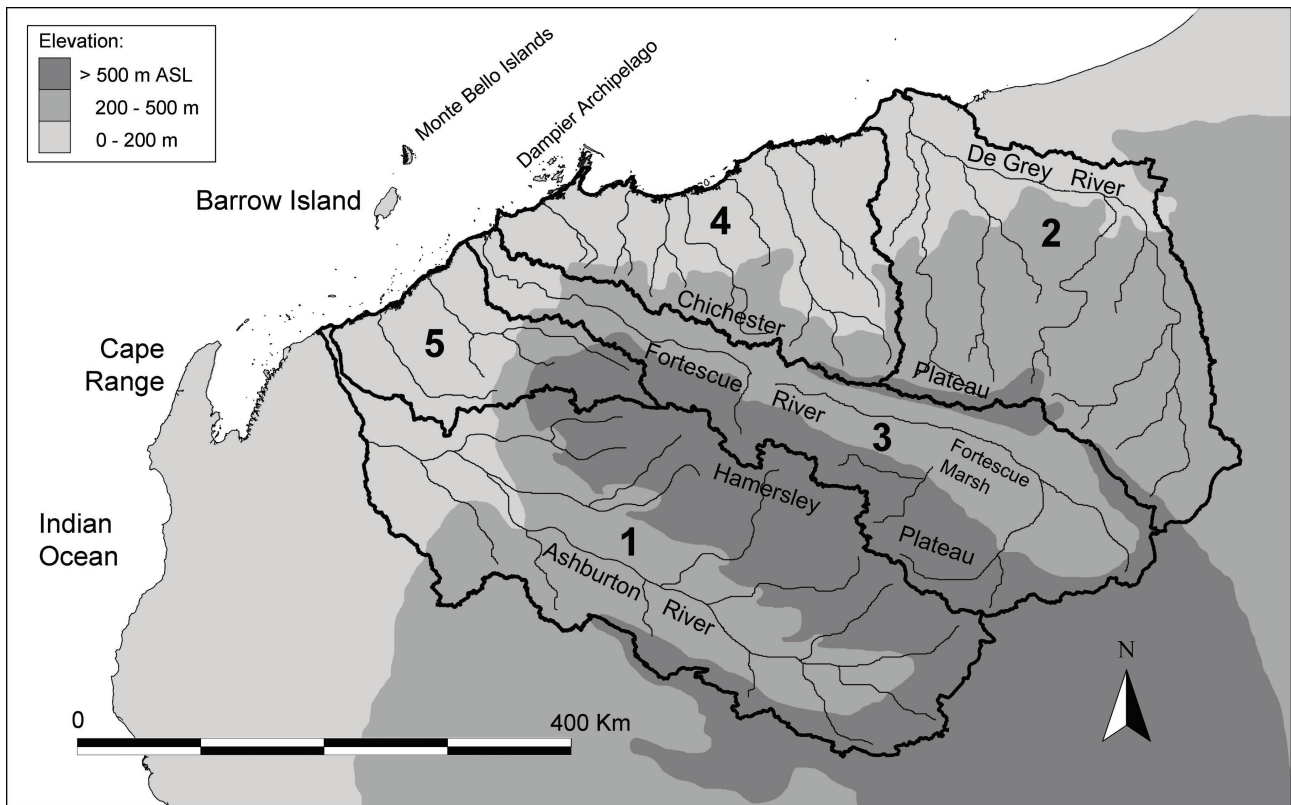
**Figure 1.** Western Australia showing the Pilbara IBRA region, and adjacent IBRA regions (Murchison, Carnarvon, Gascoyne, Little Sandy Desert), and other localities mentioned in the text (Cape Range, Barrow Island, Kimberley, Perth).

(Water and Rivers Commission 1996), although most of the Ashburton lies outside the IBRA region (Figures 1, 2). Because hydrography strongly influences the distribution of groundwater fauna, we are including the entire

Ashburton River Basin as part of the greater 'Pilbara region' (234, 886 km<sup>2</sup>), which is more or less synonymous with the 'Pilbara IBRA region'. Additionally, Barrow Island located 50 km off the Pilbara coast is part the Pilbara IBRA region, based on phytogeographic criteria, although geologically (along with Cape Range) it is part of the Northern Carnarvon (geologic) Basin (Hocking *et al.* 1987), so for the purposes of this review we are considering Barrow Island as separate from the Pilbara region.

**Climate and physiography**

The climate of the Pilbara region is Subtropical Dry, characterised by very low rainfall, high daytime temperature in summer and low winter minima (Gentili 1972). Mean annual rainfall across the region ranges between 200 and 350 mm (mostly in summer), with high inter-annual variation associated with irregular tropical cyclones. For example, Tropical Cyclone Monty deposited 200–400 mm rain over the Pilbara region in March 2004 (<http://www.bom.gov.au/weather/wa/cyclone/monty>) and consequent flooding removed major bridges on the Robe and Maitland Rivers. Annual pan evaporation varies from 3200 mm near the coast to > 4000 mm inland (Bureau of Meteorology 1977). Although palaeoclimatic data are sparse, it is clear that aridity was well established at Cape Range by the Pliocene 5.3–2 million years ago (Ma) (Wyrwoll 1993). The long-term cumulative trend towards increasing aridity reached peak intensity during the Last Glacial Maximum (Wyrwoll 1979; van der Kaars & De Deckker 2002).



**Figure 2.** Pilbara region showing physiographic features mentioned in the text including elevation (metres above sea level), river drainage systems, and the five major hydrographic basins, numbered from largest: (1) Ashburton River Basin, (2) De Grey River Basin, (3) Fortescue River Basin, (4) Port Hedland Coast Basin, (5) Onslow Coast Basin (after Water and Rivers Commission 1996).

Much of the Pilbara region is a very old landscape, with the Pilbara Craton having remained more or less continually emergent since the Proterozoic (> 545 Ma), bordered by marine environments (including the Tethys Sea) from the Devonian (410–354 Ma) until the fragmentation of Gondwana in the Cretaceous (141–65 Ma) (Cockbain & Hocking 1990). The major physiographic features of the Craton are the Hamersley Plateau, the Fortescue River, and the Chichester Plateau and Range (Figure 2). The Hamersley Plateau, which coincides with the Central Pilbara iron ore region and contains the Hamersley Range that reaches an elevation of 1250 m above sea level (asl), is drained by the Ashburton and Fortescue Rivers, which flow northwest to the Indian Ocean. The Chichester Plateau, of more subdued relief (618 m asl), is drained to the north by numerous rivers in the De Grey and Port Hedland hydrographic basins. The river drainage systems have deeply dissected the margins of the Hamersley and Chichester Plateaus, but then follow broad low-gradient valleys across extensive lowlands to wide coastal plains. Development of the river drainage systems commenced during the Late Cretaceous to Early Tertiary (Beard 1973, 1998; van de Graaff *et al.* 1977). The river valleys accumulated sediments during the Cainozoic (65–0 Ma), including alluvium, colluvium, calcrete and Robe Pisolite (channel iron deposits) (van de Graaff *et al.* 1977). The coastal plain, and present coast formed during the Quaternary, are composed of riverine plains, deltas, tidal flats, coastal dunes and limestone barriers, relic deltas and archipelago/ria shores (Beard 1975; Hickman 1983; Semeniuk 1996).

#### Groundwater habitats

Groundwater occurs throughout the Pilbara region in the Precambrian basement rocks, Phanerozoic sedimentary basins and Cainozoic deposits. It originates from direct rainfall recharge over outcropping basement rocks and from infiltration of rainfall and runoff through Cainozoic deposits, especially during periodic flooding (Davidson 1975; Water and Rivers Commission 1996). Aquifers have been classified into three types by Johnson & Wright (2001): (1) unconsolidated sedimentary aquifers; (2) chemically-deposited aquifers; and (3) fractured-rock aquifers. Unconsolidated sedimentary aquifers comprise Cainozoic valley and coastal plain alluvium and colluvium, whilst chemically-deposited aquifers consist of calcrete or pisolitic limonite formed within valley-fill sequences. Fractured rock aquifers occur in Proterozoic and Archaean sedimentary and volcanic rocks, including dolomite, sandstone, shale, chert, banded-iron formation and basalt.

The highest yielding aquifers are contained within the alluvial aquifers on the coastal plains and the valley-fill aquifers within the Fortescue Valley and Hamersley Range where sequences of alluvium/colluvium, Millstream Dolomite, calcrete and Robe Pisolite have saturated thicknesses generally between 10 to 30 m (Water and Rivers Commission 1996; Johnson & Wright 2001). Major aquifers also occur in Proterozoic dolomites (Wittenoom Dolomite and Carawine Dolomite) that have been karstified and contain cavernous zones (Barnett & Commander 1985). Aquifers in other hard rocks rely on fracturing and jointing which may be locally significant in the Brockman and Marra Mamba Iron Formations and

the Hardey Sandstone (Johnson and Wright 2001). Interfluvial areas contain low yielding aquifers owing to shallow regolith cover, as do coastal flatlands which have high silt-clay fractions and low permeability away from the river deltas (Davidson 1975). Granitic rocks usually contain low-yielding aquifers unless deeply weathered.

Different geology and aquifer types yield particular groundwater habitats. The unconsolidated sedimentary aquifers provide only interstitial habitats within the primary porosity of the clastic sediments. The chemically-deposited aquifers are characterised by secondary porosity with karstic voids in the calcrete and vuggy porosity in the pisolite (Johnson and Wright 2001). Secondary porosity is also developed in the basement rock aquifers in fractured and weathered zones or along bedding plane partings or joints. Across most of the Pilbara region, groundwater salinities are fresh (< 3000 mg L<sup>-1</sup> Total Dissolved Solids) but they may be locally saline where evapo-concentration occurs within internal drainage basins such as the Fortescue Marsh (Commander 1989) or even hypersaline on the coastline (Semeniuk 1996). Anchialine habitats are present in coastal areas such as the lower Fortescue River where there is a saltwater interface (Commander 1993). Other groundwater habitats include many springs and spring-brooks, and extensive hyporheic habitats developed in the alluvium of surface watercourses.

## Stygofauna

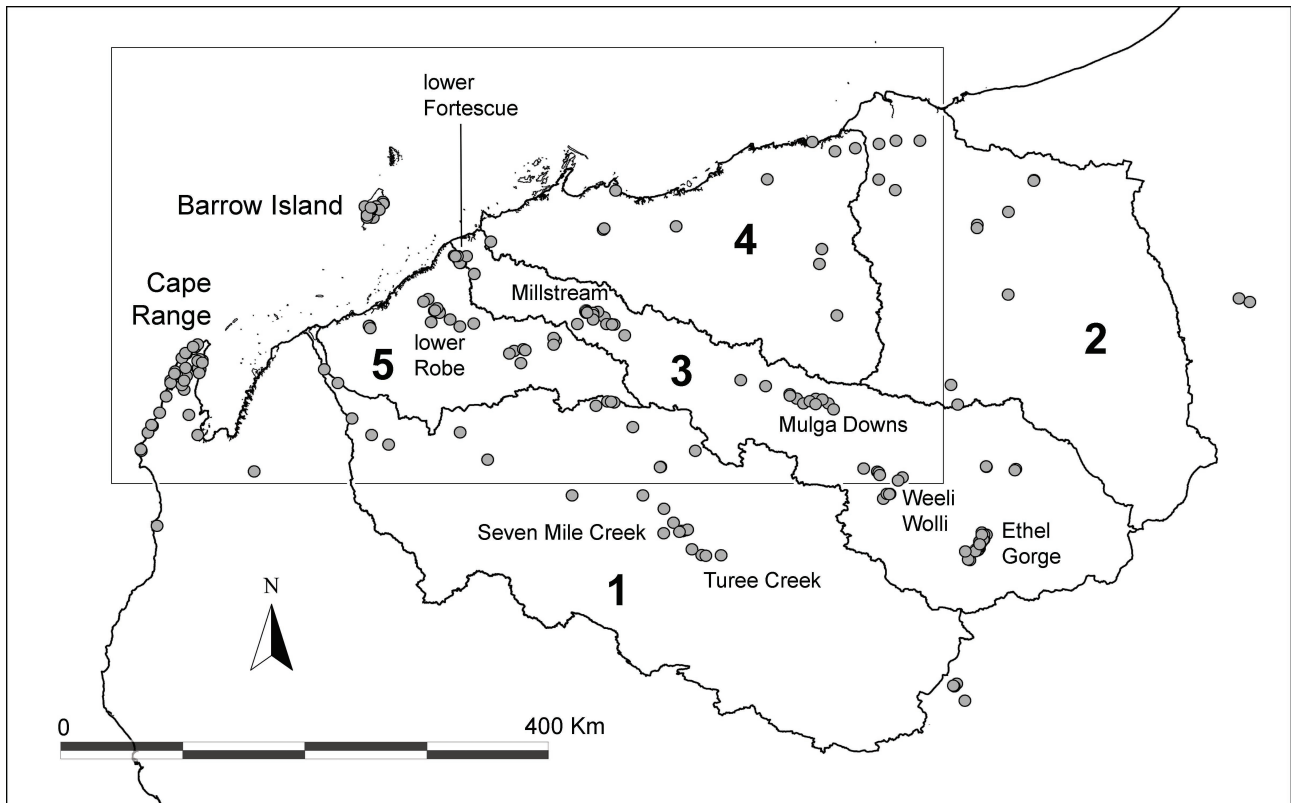
#### Sampling methods and coverage

As has been the case elsewhere in the world, sampling for stygofauna in the Pilbara has been constrained by the availability of suitable access points to groundwater. Most sampling to date has been undertaken in bores, of which there are > 3,700 (Allen 1997) associated with water supply and mine dewatering operations, and to a lesser extent in geotechnical drill holes, pastoral wells, springs, and the hyporheos. Of 223 sampled sites, 214 (96 %) were bores or wells while spring-brooks and springs (5 sites) and the hyporheos (4 sites), have been comparatively under-sampled. Sampling methods have consisted mostly of hauling a plankton net (250 or 350 µm mesh) through the water column in bores and wells, while springs and shallow hyporheic habitats have been sampled by modified 'kick sampling' (Halse *et al.* 2002), Bou Rouch pumping (Bou & Rouch 1967), or the Karaman-Chapuis method (Camacho 1992a). Sampling has mostly been of low intensity with one sampling method applied and a single sample from each site, although the borefields developed for water supply or mine dewatering have been sampled more than once.

#### Published records

Of 332 published records, more than one-half (56 %) lie in the Fortescue Basin (186 records), nearly one-third (31 %) in the Ashburton (52) and Onslow Coast (51) Basins, and the remaining 13 % in the De Grey (24) and Port Hedland Basins (19) (Figure 3). There are few published records from the upper catchments of the Ashburton, De Grey, and Port Hedland Basins. The clustered distribution of records reflects the concentration of sampling in aquifers with borefields or wells





**Figure 3.** Distribution of published stygofauna records of the Pilbara region and adjacent localities including Cape Range and Barrow Island. Sampled aquifers named in the text are shown, and the five major hydrographic basins (numbered as in Figure 2). Boxed area refers to Figure 5.

developed for water supply or mine dewatering, such as Ethel Gorge (68 records), Millstream (42), lower Robe (38), lower Fortescue (23), Mulga Downs (23), Weeli Wolli (14), Seven Mile Creek (13), and Turee Creek (6). Mulga Downs is the only location where concentrated sampling has occurred in pastoral wells, rather than a water supply or mine dewatering borefield.

### Systematics

Published literature records 78 species from the Pilbara belonging to 41 genera and 21 families (Table 1). This compares with 24 species (22 genera) and 25 species (15 genera) found at Cape Range and Barrow Island, respectively. Recorded diversities from Cape Range (63 records, > 30 sites) and Barrow Island (42 records, > 20 sites) are likely to approach actual diversities because considerable sampling and taxonomic effort has been applied to these areas over a number of years. For the size of the area, proportionately less effort has been applied to the Pilbara and the diversity in Table 1 may be a substantial under-estimate. For example, recent collecting suggests much greater diversity of ostracods and bathynellids than previously recognized (I Karanovic, pers. comm.; J-L Cho, pers. comm.).

Knowledge of the Pilbara stygofauna is at an early stage and as further taxonomic work is undertaken the number of species in the Pilbara will likely increase and the proportions of various faunal groups may change. Nonetheless, the synopsis of obligate groundwater species across the world by Botosaneanu (1986), which

recorded approximately 3,574 species belonging to 17 major taxonomic groups, makes a useful point of reference. To date, formally described representatives from only nine of the 17 major faunal groups have been recorded from groundwaters of the Pilbara region (Figure 4), although representatives (mostly undescribed) of six other major groups (Mollusca, Oligochaeta, Polychaeta, Rotifera, Nematoda, Turbellaria) are known to be present (M. Scanlon, J. Cocking, H. Barron, A. Pinder, J. McRae, unpublished data). Nearly three-quarters (73.8 %) of published records are Copepoda, followed by Ostracoda (12.7 %) and then Amphipoda (5.1 %), with all other groups included in the remaining 8.4 %. Groups that have not so far been recorded from the Pilbara are Remipedia and Coleoptera, both of which are present in adjacent regions, respectively at Cape Range (Yager & Humphreys 1996), and in the Gascoyne (Watts and Humphreys 2004) and Little Sandy Desert regions (M. Scanlon, J. Cocking, H. Barron, unpublished data).

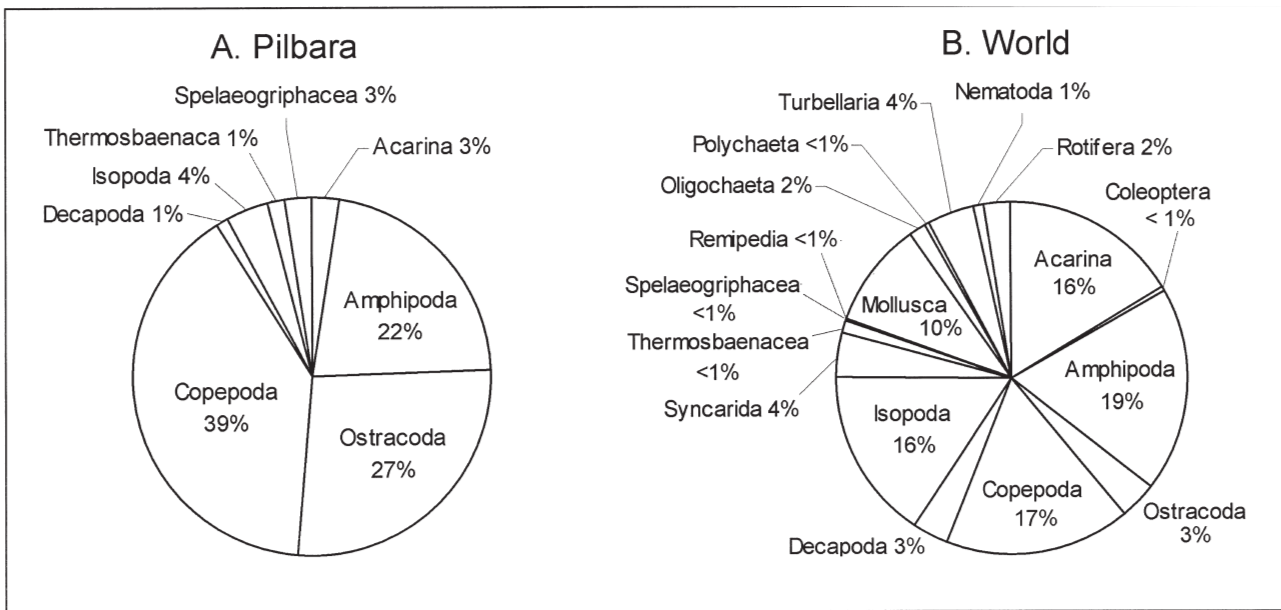
Several faunal groups that are poorly represented in the rest of the world appear to be relatively species-rich in the Pilbara: for example, the region supports two of the four known species of Spelaeogriphacea (Poore and Humphreys 2003). The Pilbara fauna also appears to be disproportionately rich in Ostracoda (27 % of Pilbara fauna cf. 3 % World) and Copepoda, (39 % cf. 17 %). The large number of species belonging to these two groups (Ostracoda: 18 species in eight genera; Copepoda: 31 species in 18 genera) partly reflects the focus of taxonomic effort but, nonetheless, the groups are clearly

Table 1

Systematic list of genera with the number of described stygal species in the Pilbara region, Cape Range and Barrow Island, and a cross reference number to the literature source. \*But see Finston *et al.* (2004) for molecular evidence that many of the species of *Chydaekata* are synonyms.

Higher Rank	Family	Genus	Pilbara	Cape Range	Barrow Island	Source
Acarina	Momonidae	<i>Hesperomomonina</i>	1			12
	Mideopsidae	<i>Tiramideopsis</i>	1			12
Polychaeta	Spionidae	<i>Prionospio</i>		1		35
	Syllidae	<i>Sphaerosyllis</i>		1		35
		<i>Typosyllis (Ehlersia)</i>		1		35
Amphipoda	Bogidiellidae	<i>Bogidomma</i>			1	2
	Hadziidae	<i>Hadzia</i>		1	1	3, 39
	Melitidae	<i>Nedsia</i>		1	10	1, 2, 5, 15
		<i>Norcapensis</i>		1		4
	Paramelitidae	<i>Chydaekata</i>	15			5, 10
		<i>Molina</i>	1			5
		<i>Pilbarus</i>	1			4
Bathynellacea	Parabathynellidae	<i>Atopobathynella</i>			1	14
Copepoda	Ameiridae	'Genus A'	2			38
		'Genus B'	1			38
		'Genus C'			1	38
		<i>Inermipes</i>			1	8
		<i>Nitokra</i>		1	1	24
		<i>Stygonitocrella</i>	3			38
		<i>Parapseudoleptomesochra</i>	1			38
	Canthocamptidae	<i>Elaphoidella</i>	1			38
	Cyclopidae	<i>Allocyclops</i>			1	21
		<i>Apocyclops</i>	1	1		29, 38
		<i>Diacyclops</i>	6	1	1	28, 38
		<i>Halicyclops</i>	2	2	2	26, 30, 38
		<i>Fierscyclops</i>	2			38
		<i>Mesocyclops</i>	2			16, 29, 38
		<i>Metacyclops</i>	2	1		22, 26, 29
		<i>Microcyclops</i>	1	1		26, 29
		'Genus D'	1			38
		<i>Thermocyclops</i>	1			38
		<i>Tropocyclops</i>	1			38
	Diosaccidae	<i>Schizopera</i>	2			38
	Ectinosomatidae	<i>Pseudectinosoma</i>	1			38
	Epacteriscidae	<i>Bunderia</i>		1		16
	Parastenocaridae	<i>Parastenocaris</i>	1			38
	Pseudocyclopiidae	<i>Stygocyclopiia</i>		1		17
	Speleophriidae	<i>Speleophria</i>		1		17
	Tetragonicipitidae	<i>Phyllopodopsyllus</i>		1	1	23
Decapoda	Atyidae	<i>Stygiocaris</i>	1	2	1	13, 15
Isopoda	Amphisopididae	<i>Pilbaraphreatoicus</i>	1			25
	Cirolanidae	<i>Haptolana</i>	1	1	1	7, 15, 34
	Tainisopidae	<i>Pygolabis</i>	1			36
Ostracoda	Candonidae	<i>Areacandona</i>	2			20
		<i>Deminutiocandona</i>	1			18
		<i>Humphreyscandona</i>	6			19
		<i>Meridiescandona</i>	2			18
		<i>Neocandona</i>	1			20
		<i>Notacandona</i>	2			19
		<i>Origocandona</i>	2			20
		<i>Pilbaracandona</i>	2			19
	Darwinulidae	<i>Vestalenula</i>	2			11, 27
	Limnocytheridae	<i>Limnocythere</i>	1			11
	Thaumatocyprididae	<i>Danielopolina</i>		1		9
Spelaeogriphacea	Spelaeogriphidae	<i>Mangkurtu</i>	2			32, 33
Remipedia	Speleonectidae	<i>Lasionectes</i>		1		37
Thermosbaenacea	Halosbaenidae	<i>Halosbaena</i>	1	1	1	15, 31, 34
Pisces	Eleotridae	<i>Milyeringa</i>		1	1	13
	Synbranchidae	<i>Ophisternon</i>		1		14
		No. described species	78	24	25	
		No. described genera	41	22	15	
		No. Families	21	16	11	

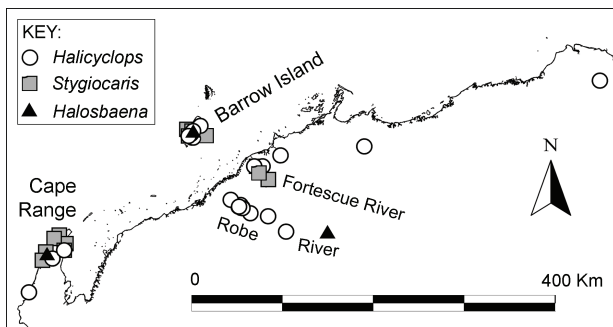
Table 1 sources: 1 (Barnard & Williams 1995), 2 (Bradbury & Williams 1996a), 3 (Bradbury & Williams 1996b), 4 (Bradbury & Williams 1997), 5 (Bradbury 2000), 6 (Bradbury 2002), 7 (Bruce and Humphreys 1993), 8 (Lee and Huys 2002), 9 (Danielopol *et al.* 2000a), 10 (Finston *et al.* 2004), 11 (Halse *et al.* 2002), 12 (Harvey 1998), 13 (Humphreys & Adams 1991), 14 (Humphreys 1999b), 15 (Humphreys 2001b), 16 (Jaume & Humphreys 2001), 17 (Jaume *et al.* 2001), 18 (Karanovic I. 2003b), 19 (Karanovic & Marmonier 2003), 20 (Karanovic I. 2005), 21 (Karanovic T. 2003), 22 (Karanovic 2004a), 23 (Karanovic *et al.* 2001), 24 (Karanovic & Pesce 2002), 25 (Knott & Halse 1999), 26 (Laurentis *et al.* 1999), 27 (Martens & Rossetti 2002), 28 (Pesce & Laurentis 1996), 29 (Pesce *et al.* 1996a), 30 (Pesce *et al.* 1996b), 31 (Poore & Humphreys 1992), 32 (Poore & Humphreys 1998), 33 (Poore & Humphreys 2003), 34 (Humphreys 2000a), 35 (Wilson & Humphreys 2001), 36 (Wilson 2003), 37 (Yager & Humphreys 1996), 38 (Karanovic 2006 in press), 39 (Sawicki *et al.* 2004).



**Figure 4.** Systematic composition of described stygofauna from the Pilbara region (A) compared with World Average (B) derived primarily from Botosaneanu (1986) as in Scarsbrook *et al.* (1998) and supplemented with data in Boutin (1998).

speciose in groundwaters of the Pilbara region. Copepoda are also speciose in the Murchison (31 species in 16 genera) (Karanovic 2004b) and Cape Range (11 species, 10 genera) (Table 1) whereas Ostracoda are less diverse in adjacent regions (Murchison: five species, one genus; Cape Range: one species).

A striking feature of the groundwater fauna in north-west Western Australia is the high proportion of species with marine Tethyan, Pangean and/or Gondwanan affinities (Humphreys 1993a, 2000b, Knott 1993). Most of the marine faunal elements recorded in the Pilbara region (atyid decapods, cirrolanid isopods, thermosbaenaceans, melitid amphipods, and the cyclopid copepods *Halicyclops* and *Apocyclops*) are shared at generic or supra-generic level with nearby Cape Range and Barrow Island. As noted by Humphreys (2001a), the marine elements appear to share a generalised distribution coinciding with the present coastal margins of the Northern Carnarvon Basin and the Pilbara Craton, with the greatest inland penetration (110 km, 300 m asl) by *Thermosbaenacea* in the Robe River valley (Figure 5).



**Figure 5.** Distribution of some marine and/or Tethyan elements shared between the Pilbara region, Cape Range and Barrow Island: *Halicyclops* (Cyclopidae), *Stygiocaris* (Atyidae), *Halsobaena* (Thermosbaenacea). Refer Figure 3 for area shown.

The Pilbara region differs from Cape Range and Barrow Island in the occurrence of several ancient freshwater lineages including paramelitid amphipods, tainisopid and phreatoicid isopods, momonid and mideopsid acarines, various copepod taxa, and ostracods: (Candonidae, Darwinulidae, Limnocytheridae), all of which appear to be absent from the younger Tertiary karst areas. To date, the only stygal freshwater lineage known from the Tertiary karsts is an undescribed species of phreodrilid oligochaete from Barrow Island (A. Pinder, pers. comm.); other phreodrilids (mostly undescribed) are recorded from groundwaters in the Pilbara and Murchison regions (Pinder 2001). Sixteen freshwater genera (59 % of total Pilbara genera) have to date been recorded only in the Pilbara region, including *Mangkurtu* (Spelaeogriphacea), *Pilbarophreatoicus* (Phreatoicoidea), *Pygolabis* (Tainisopidae), *Molina*, *Pilbarus* and *Chydaekata* (Parameletidae), 'Genus A', 'Genus B', (Ameiridae), 'Genus C' (Cyclopidae), and the eight genera of candonine ostracods (Table 1). While taxonomic knowledge of the Murchison and other adjacent regions is still incomplete, some distinct differences from the Pilbara region have already been noted (Humphreys 2001a). For example, both *Haloniscus* isopods (Taiti and Humphreys 2001) and dytiscid beetles (Watts and Humphreys 2004) seem to be absent from the Pilbara.

The richness of species recorded from individual aquifers in the Pilbara region appears roughly proportional to sampling effort: Ethel Gorge (31 species: 43 sites), Millstream (16: 24), Mulga Downs (11: 10), lower Fortescue (10: 10), lower Robe (9: 8), Weeli Wolli (7: 6), Seven Mile Creek (5: 7), Turee Creek (4: 5). The three aquifers with more than 10 species contain karstic calcrete and dolomite and the two richest aquifers contain comparatively high diversity, respectively, of paramelitid amphipods and candonine ostracods (15 species and 5 species, Ethel Gorge), and cyclopid copepods of the genus *Diacyclops* (5 species, Millstream).

## Discussion

Sampling coverage of the Pilbara region is skewed, in terms of both areal coverage (Figure 3) and the different types of groundwater habitats represented. This is partly a consequence of logistical constraints that have directed much of the sampling towards water supply borefields and mine dewatering sites, where access is afforded to many bores within a small area, although widely dispersed pastoral wells have also been sampled. However, even if the available bores had been randomly sampled, sampling would have been biased because bores and wells are concentrated in high-yield aquifers (mostly Cainozoic valleyfill sediments with calcrete and limonite, or Proterozoic carbonates). There are comparatively few bores or wells in low-yielding aquifers but meiofauna have been recorded from fractured igneous and sedimentary (ore-bearing) rocks (Eberhard 1998; Eberhard & Humphreys 1999). Sampling of springs, or the benthic and interstitial zones of spring-brooks and rivers has been too limited to draw general conclusions about the degree of faunal overlap and importance of groundwater-surface water ecotones but these habitats have also yielded stygofauna (*e.g.*, Poore & Humphreys 1998; Halse *et al.* 2002). Caves provided important access points for sampling stygofauna at Barrow Island and Cape Range, but in the Pilbara region only a handful of enterable caves are known at three locations (Millstream, Rippon Hills and Tongolola Creek) (Western Australian Speleological Group, pers. comm.). Nonetheless, the Pilbara region contains extensive karstic carbonates and we predict that karst springs will have rich stygobite faunas.

In evaluating the biodiversity of a region, comparisons are often made with endemism and species richness of other areas (*e.g.*, Storey *et al.* 1993; Horwitz 1997; Halse *et al.* 2000; Halse 2004; Pinder 2004). However, endemism is scale-dependent (*e.g.*, local endemism versus regional endemism) and assessment assumes a complete knowledge of species taxonomy and distribution. For most Pilbara taxa this knowledge is very incomplete. While many species appear to have localised distributions, recent sampling has shown some taxa are more widely distributed than published records suggest (J. Reeves, M. Scanlon, J. Cocking and H. Barron, unpublished data) and a molecular genetic study of amphipods by Finston and Johnson (2004) in the Fortescue and Ashburton River basins found evidence of genetic exchange within sub-catchments. Hence, we remain cautious in interpretation of local endemism patterns at this time. However in terms of regional endemism, the Pilbara region contains several major freshwater lineages (phreatoicid isopods, momonid and mideopsid acarines) that have not been recorded at Cape Range, Barrow Island or in the Murchison. Independently of endemism, the Pilbara region has comprehensive systematic diversity, with nearly all major stygofauna groups represented by published or unpublished records, including several higher-level systematic lineages that are phylogenetic relics (see Humphreys 2001a).

Valid comparison of species richness between regions is hindered because of differences in area, habitats, seasonality, taxonomic resolution, sampling methods and effort (*e.g.*, Horwitz 1997). Most assessments of

subterranean biodiversity focus on the comparative richness of stygobites because these species are permanently confined to subterranean habitats (see for example Knott 1993; Culver & Sket 2000; Humphreys 2000b). In groundwater environments that are more or less isolated from surface waters, such as occur at Cape Range, Barrow Island and in most of the Pilbara region, the stygofauna consists almost entirely of stygobites. In a review of world hotspots of subterranean biodiversity, which specifically excluded porous aquifers and interstitial species, Culver and Sket (2000) listed 20 individual caves, springs and karst wells that contained 20 or more stygobites and/or troglobites (obligate terrestrial subterranean species). The one Australian hotspot (Bayliss Cave in Queensland) included in the list supported exclusively troglobites, while Cabaret Cave at Yanchep near Perth (Figure 1), which contained > 40 aquatic species (Jasinska *et al.* 1996; Jasinska & Knott 2000), was not included because the majority of species are not strictly stygobitic (Culver and Sket 2000).

Outside of the Pilbara region, the highest published diversity of stygobites from an individual karst aquifer in Australia is 25 species from Barrow Island (Table 1, and Humphreys 2000b). Ignoring Ethel Gorge, where there is molecular evidence that many of the species of *Chydaekata* are not valid (Finston *et al.* 2004), the richest aquifer in the Pilbara region is Millstream with 16 species. The next richest location (12 species) is a calcrete aquifer (Lake Violet) in the Murchison (Watts and Humphreys 2003). Comparisons with eastern Australia are difficult, because of poor taxonomic resolution within most groups and limited sampling coverage of meiofauna, but the richest single karst area assemblages in the east appear to support  $\leq 10$  stygobites (Eberhard *et al.* 1991; Eberhard 1992, 1993; Eberhard & Spate 1995).

While most studies have focussed on stygobites in karst aquifers because of the speleological basis of much subterranean work (*e.g.*, Camacho 1992b), stygobites occur more widely in alluvial aquifers (see for example Dole-Olivier *et al.* 1994; Stanford *et al.* 1994; Ward & Voelz 1994; Danielopol *et al.* 2000b; Marmonier *et al.* 2000). Alluvial aquifers in the Rhone River Basin, France, hold greater stygobite richness than adjacent karst aquifers within the same drainage basin (Dole-Olivier *et al.* 1994). This situation appears to be mirrored in the Pilbara region where recent sampling using pump methods indicates that some alluvial aquifers in the lower Robe and lower Fortescue Rivers have very high richness, including > 20 stygobites collected from a single bore (M. Scanlon and J. Cocking, unpublished data). This richness exceeds that recorded from any single bore, well or cave in Australia, the previous richest site was Bundera Sinkhole at Cape Range with 12 species (Humphreys 1999a).

With the exception of large taxa such as fish, which are rare in Australian subterranean waters and worldwide tend to be restricted to karst (Proudlove 1997; Humphreys 1999b), stygofaunal elements from the Pilbara region and adjacent areas tend to colonise most groundwater environments, whether karst conduit or the benthic and interstitial zones of springs and spring-brooks. This applies to both meiofauna (copepods) and meso/macrofauna (amphipods, isopods, decapods). Taxa originally identified from karstic habitats at Cape Range



and Barrow Island (*Stygiocaris*, *Nedsia*, *Halosbaena*, *Haptolana*, *Halicyclops*, *Apocyclops*) were subsequently collected in alluvial river-aquifer systems on the Pilbara coastal plain (Humphreys 2001a). Humphreys (1993ab) suggested that the Cape Range and Barrow Island karsts were colonised by fauna which migrated either from the Pilbara Craton or the fringing Mesozoic deposits. Hence future sampling of Pilbara coastal margins and islands (e.g., Dampier Archipelago, Montebello Islands), particularly in anchialine habitats, may reveal the presence of other marine Tethyan and/or anchialine elements. Irrespective of future discoveries, this review confirms that within the already world-recognised subterranean fauna richness of north-west Western Australia, the Pilbara region is important for the conservation of subterranean biodiversity.

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## References

- Adams M and Humphreys W F 1993 Patterns of genetic diversity within selected subterranean fauna of the Cape Range peninsula, Western Australia: systematic and biogeographic implications. *Records of the Western Australian Museum Supplement* 45: 145–164.
- Allen A D 1997 Groundwater: the strategic resource – a geological perspective of groundwater occurrence and importance in Western Australia. *Western Australia Geological Survey, Report* 50, 61p.
- Barnard J L and Williams W D 1995 The taxonomy of Amphipoda (Crustacea) from Australian fresh waters. *Records of the Australian Museum* 47: 161–201.
- Barnett J C and Commander D P 1985 Hydrogeology of the Western Fortescue Valley, Pilbara region, Western Australia. *Western Australia Geological Survey Record* 1986/8.
- Beard J S 1973 The elucidation of palaeodrainage patterns in Western Australia through vegetation mapping. *Vegetation survey of Western Australia, Occasional Paper* 1.
- Beard J S 1975 The vegetation of the Pilbara area 1: 1 000 000 Vegetation Series Explanatory notes to Map Sheet 5 of Vegetation Survey of Western Australia. University of Western Australia Press, Perth.
- Beard J S 1998 Position and development history of the central watershed of the Western Shield, Western Australia. *Journal of the Royal Society of Western Australia* 81: 157–164.
- Botosaneanu L 1986 Stygofauna Mundi: A faunistic, distributional and ecological synthesis of the world fauna inhabiting subterranean waters (including the marine interstitial). Brill and Backhuys, Leiden.
- Bou C and Rouch R 1967 Un nouveau champ de recherches sur la faune aquatique souterraine. *C.R. Academy of Sciences Paris* 256: 369–370.
- Bradbury J H 2000 Western Australian stygobiont amphipods (Crustacea: Paramelitidae) from the Mt Newman and Millstream regions. *Records of the Western Australian Museum Supplement* 60: 1–102.
- Bradbury J H 2002 Melitid amphipods from Barrow island, Western Australia Part II – recent discoveries. *Records of the Western Australian Museum* 21: 83–103.
- Bradbury J H and Williams W D 1996a Freshwater amphipods from Barrow Island, Western Australia. *Records of the Australian Museum* 48: 33–74.
- Bradbury J H and Williams W D 1996b Two new species of anchialine amphipod (Crustacea: Hadziidae: *Liagocerodocus*) from Western Australia. *Records of the Western Australian Museum* 17: 395–409.
- Bradbury J H and Williams W D 1997 The amphipod (Crustacea) stygofauna of Australia: description of new taxa (Melitidae, Neoniphargidae, Paramelitidae), and a synopsis of known species. *Records of the Australian Museum* 49: 249–341.
- Bruce A J and Humphreys W F 1993 *Haptolana pholeta* sp. nov., the first subterranean flabelliferan isopod crustacean (Cirolanidae) from Australia. *Invertebrate Taxonomy* 7: 875–884.
- Bureau of Meteorology 1977 *Climatic Atlas of Australia*. Australian Government Publishing Service, Canberra.
- Camacho A I 1992a Sampling the subterranean biota cave (aquatic environment). In: *The natural history of biospeleology* (ed A I Camacho), Graficas Mar-Car, Spain, 135–168.
- Camacho A I 1992b *The natural history of biospeleology*. Graficas Mar-Car, Spain.
- Cho J-L, Park J-G and Humphreys W F 2005 A new genus and six new species of the Parabathynellidae (Bathynellacea, Syncarida) from the Kimberley Region, Western Australia. *Journal of Natural History* 39: 2225–2255.
- Cockbain A E and Hocking R M 1990 Phanerozoic. In: *Geology and Mineral Resources of Western Australia: Western Australia Geological Survey, Memoir* 3. Department of Mines, Perth, 750–755.
- Boutin, C 1998 Thermosbaenacea. In: *Encyclopaedia Biospeologica II* (eds C Juberthie and V Decu). Société de Biospéologie, Moulis – Bucarest, 877–888.
- Commander P D 1989 Hydrogeological map of Western Australia, 1: 2 500 000. Geological Survey of Western Australia, Perth.
- Commander P D 1993 Hydrogeology of the Fortescue River alluvium. Geological Survey of Western Australia Hydrogeology Report.
- Culver D C and Sket B 2000 Hotspots of subterranean biodiversity in caves and wells. *Journal of Cave and Karst Studies* 6: 11–17.
- Danielopol D L, Baltanas A and Humphreys W F 2000a *Danielopolina kornickeri* sp. n. (Ostracoda, Thaumatozoidoidea) from a Western Australian anchialine cave: morphology and evolution. *Zoologica Scripta* 29: 1–16.
- Danielopol D L, Popisil P, Dreher J, Mossbacher F, Torreiter P, Geiger-Kaiser M and Gunatillaka A 2000b A groundwater system in the Danube wetlands at Wien (Austria). In: *Ecosystems of the world Vol. 30 – Subterranean ecosystems* (eds H Wilkens, D C Culver and W F Humphreys). Elsevier, Amsterdam, 479–480.
- Davidson W A 1975 Hydrogeological reconnaissance of the northwest Pilbara region. *Western Australia Geological Survey Record*.
- Dole-Olivier M-J, Marmonier P and Creuzé des Châtelliers M 1994 Interstitial fauna associated with the alluvial floodplains of the Rhone River (France). In: *Groundwater ecology* (eds J Gibert, D L Danielopol and J A Stanford). Academic Press, San Diego, 314–345.
- Eberhard S 1992 The invertebrate cave fauna of Tasmania: ecology and conservation biology. MSc thesis, Zoology Department, University of Tasmania, Hobart.
- Eberhard S 1993 The invertebrate cave fauna of Wombeyan. In: *Wombeyan Karst Workshop, Wombeyan, Helictite*, 31(2): 45.
- Eberhard S 1998 Groundwater fauna in the West Angelis project area. *Western Australian Museum report to Ecologia Environmental Consultants*, Perth.
- Eberhard S, Richardson A M and Swain R 1991 The invertebrate cave fauna of Tasmania. Zoology Department, University of Tasmania, Hobart.
- Eberhard S M and Humphreys W F 1999 Stygofauna survey – Ore Body 23 (Newman) and Mine Area C. *Western*



- Australian Museum report prepared for BHP Iron Ore Pty Ltd, Perth.
- Eberhard S M and Spate A 1995 Cave invertebrate survey: toward an atlas of NSW cave fauna. Report prepared under the NSW Heritage Assistance Program.
- Environment Australia 2000 Revision of the Interim Biogeographic Regionalisation for Australia (IBRA) and development of version 5.1 – Summary report. Environment Australia, Canberra.
- Finston T L, Bradbury J H, Johnson M S and Knott B 2004 When morphology and molecular markers conflict: a case history of subterranean amphipods from the Pilbara, Western Australia. *Animal Biodiversity and Conservation* 27: 83–94.
- Finston T L and Johnson M S 2004 Geographic patterns of genetic diversity in subterranean amphipods of the Pilbara, Western Australia. *Marine and Freshwater Research* 55: 619–628.
- Gentilli J 1972 Australian climate patterns. Thomas Nelson and Sons.
- Halse S A, Lyons, M.N., Pinder, A.M. and Shiel, R.J. 2004 Biodiversity patterns and their conservation in wetlands of the Western Australian wheatbelt. *Records of the Western Australian Museum Supplement* 67: 337–364.
- Halse S A, Scanlon M D and Cocking J S 2002 Do springs provide a window to the groundwater fauna of the Australian arid zone? In: *Balancing the groundwater budget: Proceedings of the International Association of Hydrogeologists Symposium, Darwin, 2002* (ed. D Yinfoo). International Association of Hydrogeologists, Darwin (available on CD), 1–12.
- Halse S A, Shiel R J, Storey A W, Edward D H D, Lansbury I, Cale D J and Harvey M S 2000 Aquatic invertebrates and waterbirds of wetlands and rivers of the southern Carnarvon Basin, Western Australia. *Records of the Western Australian Museum, Supplement* 61: 217–265.
- Harvey M 1998 Unusual new water mites (Acari: Hydracarina) from Australia, Part 1. *Records of the Western Australian Museum* 19: 91–106.
- Hickman A H 1983 Geology of the Pilbara Block and its environs. *Geological Survey of Western Australia Bulletin* 127: 1–268.
- Hocking R M, Moors H T and van der Graaff W J E 1987 Geology of the Carnarvon Basin, Western Australia. *Geological Survey of Western Australia Bulletin* 133: 1–289.
- Horwitz P 1997 Comparative endemism and richness of the aquatic invertebrate fauna in peatlands and shrublands of far south-western Australia. *Memoirs of the Museum of Victoria* 56: 313–321.
- Humphreys W F 1993a Stygofauna in semi-arid tropical Western Australia: a Tethyan connection? *Memoire de Biospeleologie* 20: 111–116.
- 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* 45: 165–192.
- Humphreys W F 1999a Relict stygofaunas living in sea salt, karst and calcrete habitats in arid northwestern Australia contain many ancient lineages. In: *The other 99%. The conservation and biodiversity of invertebrates* (eds W Ponder and D Lunney). *Transactions of the Royal Zoological Society of New South Wales, Mosman*, 219–227.
- Humphreys W F 1999b The distribution of Australian cave fishes. *Records of the Western Australian Museum* 19: 469–472.
- Humphreys W F 2000a The Pilbara stygofauna: a synopsis. Unpublished report to the Water and Rivers Commission, Western Australia.
- Humphreys W F 2000b The hypogean fauna of the Cape Range peninsula and Barrow Island, northwestern Australia. In: *Ecosystems of the world Vol. 30 – Subterranean ecosystems* (eds H Wilkens, D C Culver and W F Humphreys). Elsevier, Amsterdam, 581–601.
- Humphreys W F 2001a Groundwater calcrete aquifers in the Australian arid zone: the context to an unfolding plethora of stygal biodiversity. *Records of the Western Australian Museum, Supplement* 64: 63–83.
- Humphreys W F 2001b The subterranean fauna of Barrow Island, Northwestern Australia, and its environment. *Mémoire de Biospéologie* 26: 108–127.
- 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.
- Jasinska E J and Knott B 2000 Root-driven faunas in cave water. In: *Ecosystems of the world Vol. 30 – Subterranean ecosystems* (eds H Wilkens, D C Culver and W F Humphreys). Elsevier, Amsterdam, 287–307.
- Jasinska E J, Knott B and McComb A J 1996 Root mats in groundwater: a fauna-rich cave habitat. *Journal of the North American Benthological Society* 15: 508–519.
- Jaume D and Humphreys W F 2001 A new genus of epacteriscid calanoid copepod from an anchialine sinkhole on northwestern Australia. *Journal of Crustacean Biology* 21: 157–169.
- Jaume D, Boxshall G A and Humphreys W F 2001 New stygobiont copepods (Calanoida; Misophrioida) from Bundera Sinkhole, an anchialine cenote in north-western Australia. *Zoological Journal of the Linnean Society* 133: 1–24.
- Johnson S L and Wright A H 2001 Central Pilbara groundwater study. Water and Rivers Commission, Perth.
- Karanovic I 2003a A new genus of Candoninae (Crustacea, Ostracoda, Candonidae) from the subterranean waters of southwestern Western Australia. *Records of the Western Australian Museum* 21: 315–332.
- Karanovic I 2003b Towards a revision of Candoninae (Crustacea: Ostracoda): description of two new genera from Australian groundwaters. *Species Diversity* 8: 353–383.
- Karanovic I 2005 Towards a revision of Candoninae (Crustacea: Ostracoda): Australian representatives of the subfamily, with descriptions of three new genera and seven new species. *New Zealand Journal of Marine and Freshwater Research* 39: 29–75.
- Karanovic I and Marmonier P 2002 On the genus *Candonopsis* (Crustacea: Ostracoda: Candoninae) in Australia, with a key to the world recent species. *Annale de Limnologie* 38: 199–240.
- Karanovic I and Marmonier P 2003 Three new genera and nine new species of the subfamily Candoninae (Crustacea: Ostracoda: Podocopida) from the Pilbara region (Western Australia). *Beaufortia* 53: 1–51.
- Karanovic T 2003 First representative of the genus *Allocyclops* Kiefer, 1932 (Crustacea, Copepoda) from the Australian subterranean waters. *Annale de Limnologie* 39: 141–149.
- Karanovic T 2004a The genus *Metacyclops* Kiefer in Australia (Crustacea: Copepoda: Cyclopoidea), with description of two new species. *Records of the Western Australian Museum* 22: 193–212.
- Karanovic T 2004b Subterranean Copepoda from arid Western Australia. *Crustaceana Monographs* 3: 1–366.
- Karanovic T 2006 in press Subterranean copepods (Crustacea, Copepoda) from the Pilbara Region in Western Australia. *Records of the Western Australian Museum Supplement* 70.
- Karanovic T and Pesce G L 2002 Copepods from groundwaters of Western Australia, VII. *Nitokra humphreysi* sp. nov. (Crustacea: Copepoda: Harpacticoida). *Hydrobiologia* 470: 5–12.
- Karanovic T, Pesce G L and Humphreys W F 2001 Copepods from groundwaters of Western Australia, V. *Phyllopodopsyllus wellsi* sp. nov. (Crustacea; Copepoda: Harpacticoida) with a key to world species. *Records of the Western Australian Museum* 20: 333–344.
- Knott B 1993 Stygofauna from Cape Range peninsula, Western Australia: Tethyan relicts. *Records of the Western Australian Museum Supplement* 45: 109–127.

- Knott B and Halse S A 1999 *Pilbarophreatoicus platyarthricus* n.gen., n.sp. (Isopoda: Phreatoicidae: Amphisopodidae) from the Pilbara region of Western Australia. Records of the Australian Museum 51: 33–42.
- Laurentiis P D, Pesce G L and Humphreys W F 1999 Copepods from ground waters of Western Australia. IV. Cyclopids from basin and craton aquifers (Crustacea: Copepoda: Cyclopidae). Records of the Western Australian Museum 19: 243–257.
- Lee W and Huys R 2002 A new genus of groundwater Ameiridae (Copepoda, Harpacticoida) from boreholes in Western Australia and the artificial status of *Stygonitocrella* Petkovski, 1976. Bulletin of the Natural History Museum, London (Zoology) 68: 39–50.
- Leys R, Watts C H S, Cooper S J B and Humphreys W F 2003 Evolution of subterranean diving beetles (Coleoptera: Dytiscidae: Hydroporini, Bidessini) in the arid zone of Australia. Evolution 57: 2819–2834.
- Marmonier P, Creuzé des Châtelliers M, Dole-Oliver M J, Plenet S and Gibert J 2000 Rhone groundwater systems. In: Ecosystems of the world Vol. 30 – Subterranean ecosystems (eds H Wilkens, D C Culver and W F Humphreys). Elsevier, Amsterdam, 481–512.
- Martens K and Rossetti G 2002 On the Darwinulidae (Crustacea, Ostracoda) from Oceania. Invertebrate Systematics 16: 195–208.
- 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.
- Pesce G L and Laurentiis P D 1996 Copepods from groundwaters of Western Australia, III. *Diacyclops humphreysi* n. sp., and comments on the *Diacyclops crassicaudis* – complex (Copepoda, Cyclopidae). Crustaceana 69: 524–531.
- Pesce G L, Laurentiis P D and Humphreys W F 1996a Copepods from groundwaters of Western Australia, I. The genera *Metacyclops*, *Mesocyclops*, *Microcyclops* and *Apocyclops* (Crustacea: Copepoda: Cyclopidae). Records of the Western Australian Museum 18: 77–85.
- Pesce G L, Laurentiis P D and Humphreys W F 1996b Copepods from groundwaters of Western Australia, II. The genus *Halicyclops* (Crustacea: Copepoda: Cyclopidae). Records of the Western Australian Museum 18: 77–85.
- Pinder A M 2001 Notes on the diversity and distribution of Australian Naididae and Phreodrilidae (Oligochaeta: Annelida). Hydrobiologia 463: 49–64.
- Pinder A M, Halse, S.A., McRae, J.M. and Shiel, R.J. 2004 Aquatic invertebrate assemblages of wetlands and rivers in the Wheatbelt region of Western Australia. Records of the Western Australian Museum Supplement 67: 7–37.
- Playford P E 2001 Subterranean Biotas in Western Australia. Report for the Environmental Protection Authority, Perth.
- 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.
- Poore G C B and Humphreys W F 1998 The first record of the Spelaogriphacea (Crustacea) from Australasia: a new genus and species from an aquifer in the arid Pilbara of Western Australia. Crustaceana 71: 721–742.
- Poore G C B and Humphreys W F 2003 Second species of *Mangkurtu* (Spelaogriphacea) from north-western Australia. Records of the Western Australian Museum: 67–74.
- Proudlove G S 1997 A synopsis of the hypogean fishes of the world. In: 12th International Congress of Speleology, La Chaax de Fonds, Switzerland, 351–354.
- Sawicki T R, Holsinger J R and Illite T M 2004 Four new species of the subterranean amphipod genus *Hadzia* (Hadziidae) from caves in the western Pacific, with a re-evaluation of the taxonomic status of the genus. Subterranean Biology 2: 65–90.
- Scarsbrook M R, Fenwick, G.D., Duggan, I.C., Haase, M. 2003 A guide to the groundwater invertebrates of New Zealand.
- Semeniuk V 1996 Coastal forms and Quaternary processes along the arid Pilbara coast of northwestern Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 123: 49–84.
- Stanford J A, Ward J V and Ellis B K 1994 Ecology of the alluvial aquifers of the Flathead River, Montana. In: Groundwater ecology (eds J Gibert, D L Danielopol and J A Stanford). Academic Press, San Diego, 367–390.
- Storey A W, Halse S A and Shiel R J 1993 Aquatic invertebrate fauna of the Two Peoples Bay area, southwestern Australia. Journal of the Royal Society of Western Australia 76: 25–32.
- Taiti S and Humphreys W F 2001 New aquatic Oniscidea (Crustacea: Isopoda) from groundwater calcretes of Western Australia. Records of the Western Australian Museum, Supplement 64: 133–151.
- van de Graaff W J E, Crowe R W A, Bunting J A and Jackson M J 1977 Relict early Cainozoic drainages in arid Western Australia. Zeitschrift für Geomorphologie 21: 379–400.
- van der Kaars S and De Deckker P 2002 A Late Quaternary pollen record from deep-sea core Fr10/95, GC17 offshore Cape Range Peninsula, northwestern Western Australia. Review of Palaeobotany and Palynology 120: 17–39.
- Ward J V and Voelz N J 1994 Groundwater fauna of the South Platte River System, Colorado. In: Groundwater ecology (eds J Gibert, D L Danielopol and J A Stanford). Academic Press, San Diego, 391–423.
- Water and Rivers Commission 1996 Pilbara region water resources review and development plan, summary report 4. Water and Rivers Commission, Perth.
- Watts C H S and Humphreys W F 1999 Three new genera and five new species of Dytiscidae (Coleoptera) from underground waters in Australia. Records of the South Australian Museum 32: 121–142.
- Watts C H S and Humphreys W F 2003 Twenty-five new Dytiscidae (Coleoptera) of the genus *Tjurtudessus* Watts and Humphreys, *Nirripirti* Watts and Humphreys and *Bidessoides* Regimbart, from underground waters in Australia. Records of the South Australian Museum 36: 135–187.
- Watts C H S and Humphreys W F 2004 Thirteen new Dytiscidae (Coleoptera) of the genus *Limbodessus* Guignot and *Nirripirti* Watts and Humphreys, from underground waters in Australia. Transactions of the Royal Society of South Australia in press.
- Whitley G P 1945 New sharks and fishes from Western Australia, Part 2. Australian Zoologist 11: 35–37.
- Wilson G D F 2003 A new genus of Tainisopidae fam. nov. (Crustacea: Isopoda) from the Pilbara, Western Australia. Zootaxa 245: 1–20.
- Wilson G D F and Ponder W F 1992 Extraordinary new subterranean sopods (Peracarida: Crustacea) from the Kimberley Region, Western Australia. Records of the Australian Museum 44: 279–298.
- Wilson G D F and Keable S J 1999 A new genus of phreatoicid isopod (Crustacea) from the north Kimberley Region, Western Australia. Zoological Journal of the Linnean Society 126: 51–79.
- Wilson R S and Humphreys W F 2001 *Prionospio thalanjii* sp. nov. (Polychaeta: Spionidae) from an anchialine cave, Cape Range, north-west Western Australia. Records of the Western Australian Museum, Supplement 64: 105–113.
- Wyrwoll K-H 1979 Late Quaternary climates of Western Australia: evidence and mechanisms. Journal of the Royal Society of Western Australia 62: 129–142.
- Wyrwoll K H 1993 An outline of Late Cenozoic palaeoclimatic events in the Cape Range region. Records of the Western Australian Museum Supplement 45: 39–50.
- Yager J and Humphreys W F 1996 *Lasionectes exleyi*, sp. nov., the first remipede crustacean recorded from Australia and the Indian Ocean, with a key to the world species. Invertebrate Taxonomy 10: 171–187.