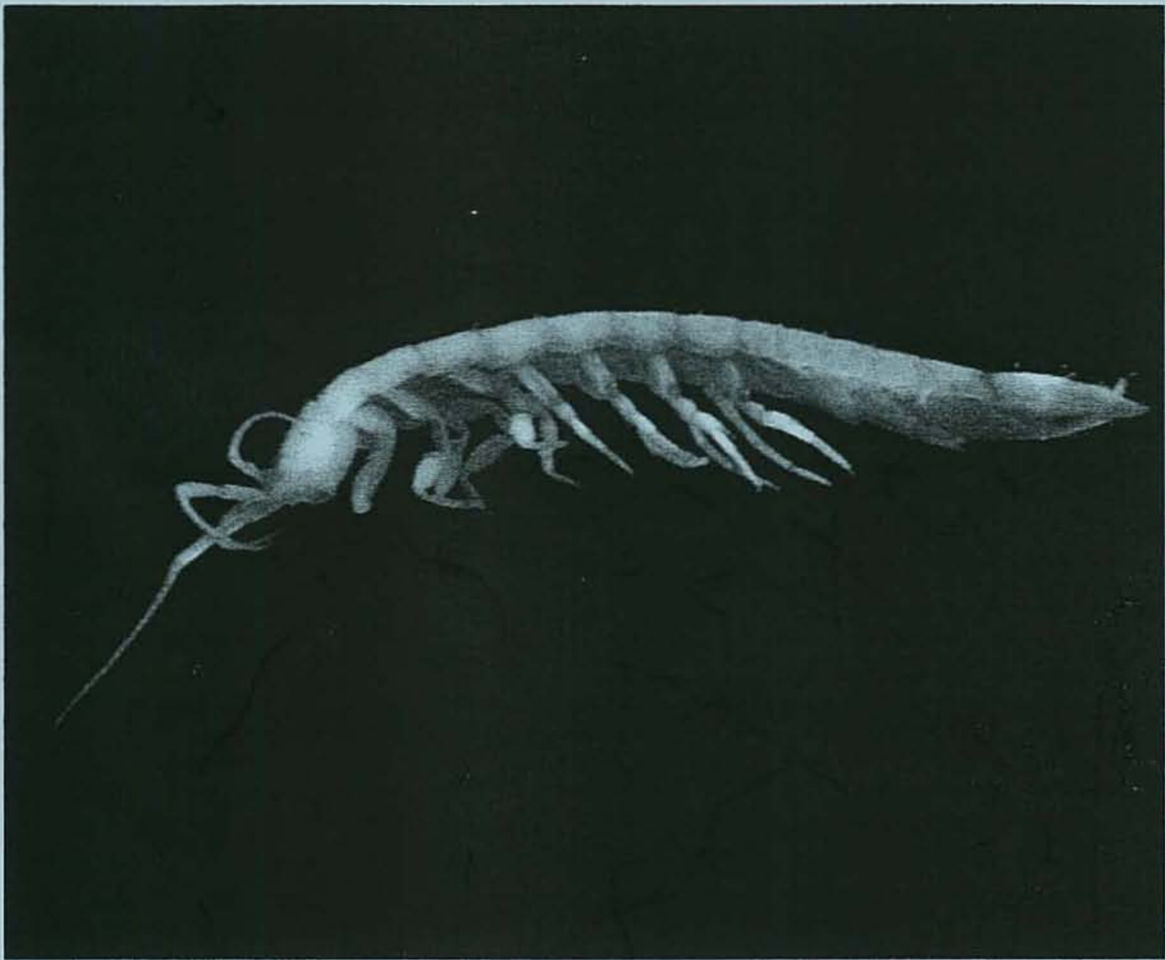
The Pilbara stygofauna: a synopsis



A report to the Water and Rivers Commission

W.F. Humphreys

Western Australian Museum of Natural Science

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Cover: Unnamed family of flabelliferan isopods from Weeli Wolli bore BH32s, Pilbara. Male. Image: Dr G.D.F. Wilson, Australian Museum.

Summary

The report outlines the distribution and nature of stygofauna (obligate groundwater dependent animals) in the Pilbara and adjacent coastal regions (principally Cape Range and Barrow Island) of Western Australia.

The fauna of the coastal area is principally derived from marine ancestors and has Tethyan affinities; it is typical of the Cape Range/Barrow Island fauna

The fauna of the Pilbara plateau, an area that has been above the sea for hundreds of millions of years, has ancient freshwater affinities. While each aquifer examined to date contains a separate fauna, there are regional differences with the Western Fortescue Plain differing from the remainder of the Pilbara.

The Pilbara stygofauna is distinct from that found in the Kimberley and the Yilgarn.

The stygofauna is an important component of the biodiversity in the Pilbara, is of clear continental significance, and is substantially diverse in an international context.

While many aquifers have yet to be examined, several stygofaunas have been identified that may be at risk from water abstraction or dewatering.

Sustained research needs to be initiated on the impact of water abstraction on the stygofauna of the Pilbara to permit informed management of these important ecosystems.

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1. Introduction

In a global context the groundwater fauna of Australia (along with that of Africa) is especially poorly known (Marmonier et al. 1997). Nonetheless, Australia, especially the northwestern part, unexpectedly (Humphreys 1993a) has become the focus of attention of stygobiologists and systematists (Wilson and Keable 1999; Wilson and Johnson 1999; Bradbury and Williams 1996a, 1996b, 1997a, 1997b; Pesce et al. 1996a, 1996b; Pesce and De Laurentiis 1996; De Laurentiis et al. 1999) on account of the diverse obligate groundwater fauna (stygofauna) that is being found in the region. They include a number of higher order taxa variously new to science (undescribed family of flabelliferan Isopoda: Wilson and Ponder 1992), new to the southern hemisphere (Thermosbaenacea: Poore and Humphreys 1992; Remipedia: Yager and Humphreys 1996; *Danielopolina*: Danielopol et al. 2000; Jaume and Humphreys in press), or new to Australia (Spelaeogriphacea: Poore and Humphreys 1998). Many of these occur in near coastal and anchialine waters and are interpreted as comprising a relictual tethyan fauna of which several lineages have congeneric species known elsewhere only from subterranean waters on either side of the North Atlantic — the northern Caribbean region and the Canary Islands (Humphreys 1993a, 1999; in press a).

Areas presently land that have ever been covered by the sea, even as far back as the Mesozoic, often contains communities of obligate subterranean aquatic species of formerly marine lineages 'stranded' inland by marine recession (Stock 1980: Boutin and Coineau 1990; Notenboom 1991; Holsinger 1994), particularly in karstic areas, and this is especially notable in areas that have undergone substantial orogenesis (Messouli et al. 1991; Boutin 1993). While such areas occur in Australia (orogenic: Humphreys 1993b; stranded: Bradbury and Eberhard in press), large parts of Australia have not been inundated by the sea since at least the Palaeozoic (Figure 1), including the Pilbara and Yilgarn Cratons of Western Australia and their associated orogens that collectively may conveniently be referred to as the Western Shield (Beard 1998). These regions of Precambrian rocks are covered only by a thin regolith and seem, on first principles, to proffer poor prospect for the exploration of stygal biodiversity.

2. Background

In response to the finding of diverse stygal communities (groundwater fauna) in the Pilbara (Poore and Humphreys 1998; Humphreys 1998a, 1999a, 1999b; Eberhard and Humphreys 1999, Eberhard 1998) — a truly continental area of Australia with a (presumably) freshwater history extending though several geological eras — the Water and Rivers Commission requested a report on the fauna of the Pilbara with the following scope:

• Report on the extent, locations and findings of previous surveys and investigations on subterranean fauna.

• Report on the limitations of previous surveys and/or other factors that may influence the validity or significance of conclusions that can be drawn from the reported surveys.

• Provide an assessment of the local, regional and international significance of the recorded fauna, including a description of any limitations to the assessment of their significance.

Since that time a significant stygofauna has been found in the Yilgarn (Humphreys 1998a, 1998b, 1999b; Watts and Humphreys 1999, in press).

3. Methods

Sampling was conducted variously using 200-350 μm mesh haul nets or traps (micro-cray pots) down bores (water abstraction, mineral exploration, geotechnical) and pastoral wells but some sampling was undertaken in river gravels using a Bou-Rouch pump and by the Karaman-Chappuis method (Pospisil 1992).

3.1 Proviso

The data comprise those specimens sampled from groundwater that are included in the BES data base of the Western Australian Museum of Natural Science (MONS) to 15 February 2000. The data base is continually being modified as the collections are examined in greater detail and as new taxonomic information becomes available. Data from Hamersley Iron Pty Ltd does not include the distribution of sites sampled if no groundwater fauna was obtained. Any other samples that may have been obtained by commercial interests have not been made available for this study.

The Cape Range area has been dealt with extensively in scientific papers, environmental assessments, and policy documents and will not be discussed in detail here (e.g. Bradbury and Williams 1996a, 1996b,1997a,1997b; Danielopol, Baltanás and Humphreys 2000; De Laurentiis, Pesce and Humphreys 1999; Hamilton-Smith and Eberhard in press; Humphreys 1993a, 1993b, 1993c, 1999a, in press a, in press c (papers in), in press d; Jaume and Humphreys in press; Karst Waters Institute 1998; Environmental Protection Authority 1998; Morton, Short and Barker 1995; Pesce, De Laurentiis and Humphreys 1996a, 1996b; Pesce and De Laurentiis 1996; Poore and Humphreys 1992; Yager and Humphreys 1996; Kojan et al. 1995; Hamilton-Smith et al. 1996).

4. Extent, locations and findings of previous surveys and investigations on subterranean fauna.

4.1 *Springs and spring brooks*

The current work does not consider fauna taken from springs and spring brooks, while recognizing that stygal species may sometimes occur in such situations (Botosaneanu 1998b), especially flushed out after heavy rainfall (Rouch and Carlier 1985). This general distinction between the fauna of springs and groundwater is recognized in the discipline of crenobiology for the study of springs and spring brooks (Botosaneanu,1998a). It is pertinent to note that while stygofauna are generally taken to invade from the surface, the presence of eyeless lineages of some surface crustaceans suggests that they may have been derived from stygal species, for example in the phreatoicid genus *Crenoicus* (Isopoda: G.D.F. Wilson, pers. comm. cited in Botosaneanu 1998b), and in some of Australian melitid and crangonyctoid amphipods (J.H. Bradbury, pers. comm. 1996).

In general, the fauna of springs and spring brooks, while it may be distinct from that of other surface waters (Lindegaard et al 1998), and even be relictual (Ito 1998), has little on common with the groundwater fauna. Mound springs in the Australian arid zone often harbour relictual, locally endemic taxa (see Knott and Jasinska 1998), whereas those closer to permanent rivers have faunas partly in common (Ponder 1995).

In the Pilbara, the fauna of the Millstream pools (L. Charlton, pers. comm. 1998) has no known elements in common with the aquifer — which contains a rich stygofauna (Poore and Humphreys 1998; W.F. Humphreys, unpublished) — supplying the pools themselves. Nonetheless, stygal species may be generally associated with areas of groundwater discharge (*Pilbarophreatoicus* sp. nov. in the Western Fortescue Plain), be flushed from springs (*Crenisopus acinifer* in the Kimberley: W.F. Humphreys, unpublished; Wilson and Keable 1999), and even occur in ephemeral water courses (for example *Pilbarophreatoicus platyarthricus* in the Robe catchment: Knott and Halse 1999).

4.2 *Western Australia*

A synopsis of the sites sampled for stygofauna within Western Australia, the distribution of all fauna from groundwater and the distribution of macrofauna from aquifers is presented in Figures 2-4.

4.3 *Pilbara* (sensu lato)

The distribution of stygofauna sampling sites in the Pilbara and immediately surrounding areas is given in Figure 5 together with the distribution of the larger elements of the stygofauna (that is excluding Syncarida, Ostracoda and/or Copepoda and other meiofauna; exclusion of sites containing only the latter groups of meiofauna does not substantially affect the overall pattern of distribution of stygofauna in the Pilbara, or in Western Australia as a whole). These data are repeated in Figures 6-9 at a scale allowing the detail of the sampling locations and intensity to be seen.

Stygofauna was initially found on the Western Shield in the calcrete aquifers of the Western Fortescue Plain and it has clear gondwanan affinities (Poore and Humphreys 1998; Harvey 1998). This site contains Spelaeogriphacea, an order previously only known living a caves in South Africa and Brazil (Poore and Humphreys 1998). The associated stygofauna includes Oligochaeta: Phreodrilidae (generally with a cool climate Gondwanan distribution: A. Pinder, pers. comm., 1997); Gastropoda: new hydrobioid (W.F. Ponder, pers. comm., 1997); Syncarida; Copepoda: Cyclopoidea (2+ species);

Copepoda: Harpacticoidea; Ostracoda (3+ species); Isopoda: Phreatoicidea (cf. *Hyperoedesipus*, Wilson and Johnson 1999); Amphipoda: Crangonyctoidea (gen. nov. J. H. Bradbury, pers. comm. 1999 plus other families and species); Acari: *Tiramideopsis* (genus previously known only from India: Harvey 1998). This aquifer is isolated by a water gap downstream and a groundwater divide upstream (ibid.). Downstream the fauna is related to the Cape Range/Barrow Island anchialine fauna (Humphreys 1999a) having tethyan affinities (see Introduction). Upstream the fauna differs at the closest point sampled (at Mulga Downs, the calcrete deposit second removed upstream on the Fortescue River). Near Newman on the Upper Fortescue a rich stygofauna occurs in calcrete adjacent to Orebody 23 (Eberhard and Humphreys 1999) comprising numerous taxa of amphipods (14 species of a new genus of crangonyctoids not known from Millstream and Ceinidae: J.H. Bradbury, personal communication), a second clade (G.D.F. Wilson, pers. comm. 1998) of an undescribed family of flabelliferan isopods (Wilson and Ponder 1992) known from locations that encompass much of the Devonian Reef system in the Kimberley (Humphreys 1995; Limestone Billy Hills, W.F. Humphreys, unpublished; Ningbing Range, S.M. Eberhard, unpublished).

All other calcrete areas in the Pilbara that have been sampled for stygofauna (Table 1) and for elements of which specialist taxonomic examination has occurred, including the upper reaches of the next major drainage basin to the south, the Ashburton River, may be characterised by the presence of the flabelliferan isopod — a very distinctive stygal animal uncharacteristically robust and opaque — represented by a different taxon at all sites so far investigated in the Pilbara (G.D.F. Wilson, pers. comm. 1998). In addition, all sites contain diverse amphipods, ostracods (especially Candoninae), copepods (especially Cyclopoidea).

Table 1: Specific differences between sites on the Pilbara craton.

Pilbarophreatoicus platyarthricus	Upper Robe	Knott and Halse 1999
Pilbarophreatoicus sp. nov.	[1]Millstream	G.D.F. Wilson, pers. comm.
Flabelliferan isopod a	Newman	G.D.F. Wilson, pers. comm.
Flabelliferan isopod b	Weeli Wolli	G.D.F. Wilson, pers. comm.
Flabelliferan isopod c	Hardey R.	G.D.F. Wilson, pers. comm.
Amphipoda	Newman	J.H. Bradbury, pers. comm.
	Mid Fortescue	J.H. Bradbury, pers. comm.
	W. Fortescue Plain	J.H. Bradbury, pers. comm.
Ostracoda		

[1]Note that the Robe River was captured by the Fortescue River at the end of the Pleistocene or Holocene (Barnett and Commander, 1985), so that these drainages have not long been separated.

Thus, the Pilbara appears to have three types of stygal assemblage. 1, the coastal plain comprising alluvial fan aquifers of the lower Robe and Fortescue Rivers which has a tethyan community characterised by *Stygiocaris* (Atyidae), *Haptolana* (Cirolanidae) and *Halosbaena* (Thermosbaenacea), elements of which intrude to an altitude of 300 m on the Robe River, the approximate level of the Late Eocene high sea level on the Yilgarn (G.W. Kendrick, pers. comm. 1999). 2, the Western Fortescue Plain characterized by Spelaeogriphacea. 3, sites upstream of the Western Fortescue Plain and the upper Ashburton catchment characterised by the undescribed higher taxon of flabelliferan isopods. Each area also has an array of Amphipoda families, Ostracoda, Copepoda, Syncarida (Bathynellacea) and Oligochaeta (Phreodrilidae) which have yet to be worked in any detail.

5. Limitations of previous surveys and/or other factors that may influence the validity or significance of conclusions that can be drawn from the reported surveys.

5.1 *Coverage*

Most sampling of stygofauna has been conducted by MONS since 1997 to gain a regional overview of the nature of the stygofaunal assemblages. Sampling has largely been of low intensity with a single sample and single sampling method at each site. Cape Range, Barrow Island, the Western Fortescue Plain and the Newman area have been sampled more intensively and in these areas some sites were visited more than once and sampled using two or more methods. Experience at the more intensively sampled sites suggests that if stygofauna area sampled on a single sampling occasion, then it stands proxy for a much more diverse fauna.

5.2 *Identification*

While the nature of the fauna can be determined from the convergent morphology (stygomorphies: Humphreys in press b) characteristic of stygal species, the stygofauna of Western Australia is largely unknown and predominantly undescribed, being newly found species or higher taxa. Few specialists are available to determine and describe the fauna and most specimens have been described most expeditiously by specialist taxonomists located interstate or overseas. The taxonomy of key groups, for which no institutional taxonomist is available, may need to be funded; some funded projects are already in train.

It is important to clarify taxonomic relationships to establish the diversity of the fauna and the likely significance of potential impacts. For example, if a taxon is represented by a single species throughout the aquifer then localized drawdown effects are unlikely to have significant impact, but if different species occur with limited distributions within a discrete calcrete unit then the impact in terms of loss of biodiversity may be significant.

Owing to their size, and hence the likelihood that they have less ability to migrate, the larger species (macro-invertebrates) have been the focus of most attention as indicators of any geographically restricted distributions, but Copepoda and Ostracoda have been examined to some degree.

5.3 *Habitat patchiness*

The dispersion of stygofauna within a karstic or fissured aquifer, as opposed to an alluvial aquifer, will be patchy and confined to the zones of conduit or fissure development. Stygofauna will only be detected when drill holes directly penetrate the natural cavities, which may be narrowly delimited by lineations, joints, or other structural features. Thus, there is a degree of chance involved which is dependent upon the drill hole intersecting a natural cavity containing stygofauna. However, in highly karstic areas which typically have open conduit flow, such as the Tertiary limestones of the Cape Range/Barrow Island karst and the groundwater calcrete aquifers, experience shows that there is a high probability of detecting stygofauna, in largely undisturbed systems, if suitable collecting and extraction methods are used intensively by suitably trained biologists. For example, stygofauna have been detected by MONS in 10 of 12 calcrete aquifers (83%). Of the two in which stygofauna was not found, one has been drawn down excessively and the other was sampled only at sites (pastoral bores) that provided no stygofauna throughout the region (Yilgarn) despite it being found widely in narrow drillholes (Watts and Humphreys in press).

In fractured rock systems, however, both the mesovoid volume and the continuity of the voids is probably low and both would contribute to a low probability of sampling stygofauna should it be present. The hydrology of fractured rock aquifers is poorly understood and is the focus of current research effort.

The inherent patchiness of stygofauna habitat can result in sampling anomalies, where stygofauna may not be detected even though it is present nearby. In the absence of dedicated sampling bores, intensive and repeated sampling of a large number and types of bores is required to be reasonably confident that an apparent absence of stygofauna is real. In some localities however, stygofauna appears to be genuinely absent in apparently suitable calcrete habitats. In the Millstream aquifer, for instance, the distribution of the spelaeogriphacean *Mangkurtu mityula* appears to be confined to a limited area of the calcrete aquifer, and absent from contiguous areas despite apparently similar bore age and construction, hydrogeology and sampling effort (Figure 10). Thus, stygofauna cannot be assumed to occur throughout the range of potential habitat (Poore and Humphreys 1998). Similar findings have been made in the calcrete near Newman on the upper Fortescue. There numerous species of amphipod appear to have rather restricted distributions within the body of the calcrete.

Additional sampling in the Newman area considerably increased the number of stygofauna sites in that region (Eberhard and Humphreys 1999). The calcrete and neighbouring alluvial and fractured rock aquifers, associated with the confluence of several creeks with the upper Fortescue River near Newman, were sampled for stygofauna at 79 locations. Stygofauna were recovered from 43 bores and included bathynellids, phreatoicid and flabelliferan isopods, amphipods, copepods and ostracods. One family of amphipods from this auifer has been examined in detail and this has revealed 13 undescribed species in a new genus (J.H. Bradbury pers. comm. 1999).

Hints that stygofauna may occur in fractured rock aquifers (Eberhard 1998; Eberhard and Humphreys 1999) have been reinforced by samples from Hamersley Iron Pty Ltd (S. Anstee, pers. comm. 1999) and from the Perth region (W.F. Humphreys and H. Hahn, unpublished 1999). Neither, the veracity of these reports nor the affinities of the faunas have yet been examined.

5.4 *Bore construction*

The construction characteristics of a bore will influence the chance of detecting stygofauna, should it be present in an area, by affecting its movement into the bore. This includes whether the bore is cased, slotted and/or packed, the type and dimensions of the slotting and of the packing material, whether the bore penetrates a natural voids in the host rock or sediment, the position and extent of slotting with respect to the water table, whether the bore has been developed, contamination by drilling fluids, the time interval since drilling, the casing material and whether the casing is capped at the top or the bottom (dealt with more fully in Eberhard and Humphreys 1999).

5.5 *Access type*

Pastoral bores rarely yield stygofauna in some situations although they may be abundant in nearby narrow bores tapping the same groundwater (Watts and Humphreys in press). Direct access to groundwater in dark caves is the preferred method, as fast moving taxa are rarely sampled from boreholes (e.g. fish, Humphreys submitted; remipedes, Humphreys 1999). However, no such access is known outside the Tertiary limestones of

Cape Range/Barrow Island.

5.6 Distinct faunas

Despite the above limitations and the patchy and largely not intensive coverage of the stygofaunal sampling in the Pilbara, nonetheless the conclusions that can be drawn from the sampling can be examined independently using a number of separate taxonomic lineages. The few lineages that have been examined to date in any depth (amphipods, flabelliferan isopods, ostracods) confirm that the different areas sampled contain distinct faunas (J.H. Bradbury, pers. comm. 1999; G.D.F. Wilson, pers. comm. 1999; P. Marmonier, pers. comm. 1999). Similar work in the Yilgarn, which has a regionally distinct stygofauna, also shows that each calcrete body in the palaeodrainage system contains a unique fauna (Humphreys 1999a, 1999b, submitted; Watts and Humphreys 1999, in press). Hence, in all areas examined on the Western Shield adjacent but discrete calcrete bodies contain unique faunas. The number of discrete calcrete bodies in Western Australia and the Pilbara can be seen in Figures 11 and 12. The fauna in fractured rock aquifers, should it prove to be distinct from those in calcrete aquifers, is of unknown affinities.

6. Assessment of the local, regional and international significance of the recorded fauna, including a description of any limitations to the assessment of their significance.

An overall assessment of the significance of the stygofauna of the Pilbara is to some extent hampered by the lack of detailed taxonomic and systematic work on the bulk of the material now in collections. There is, nonetheless, sufficient information to make broad statements about the significance of the Pilbara stygofauna with confidence. These statements are made in respect of the fauna on the 'Western Shield' proper, rather than of the near coastal fauna which has a different origin; this fauna has been widely covered elsewhere and the global significance of which is recognized (e.g. Poore and Humphreys 1992, 1998; Yager and Humphreys 1996; Bradbury and Williams 1997a, 1997b; Karst Waters Institute 1998; Wilson and Johnson 1999; Wilson and Keable 1999; Jaume and Humphreys in press; Humphreys 1999, in press a; in press c, in press d; Danielopol et al. 2000).

The importance of a fauna can be measured in a number of ways. Firstly, by the overall species diversity (biodiversity), by the number of species endemic to the area in question, by the number of higher level taxa (genera, families) endemic to the area, or by the number of higher level taxa that occur there and not elsewhere within a certain region (Pilbara, Western Australia, Australia, Southern Hemisphere). Secondly, how does this diversity compare with faunas in similar ecosystems elsewhere, and what is the intrinsic significance of the fauna and its setting in respect of the general question of the evolution of stygofauna and of specific lineages.

The first question is covered to the extent now possible in the following sections on Local and Regional Significance which shows the fauna is endemic at a higher taxonomic level and diverse. The second question is treated in the section International Significance.

6.1 *Local significance*

The Pilbara stygofauna has high species richness both within particular sites (Millstream, Newman) and an exceptional between site diversity. The full significance of this will only be understood when many more areas have been sampled. Sufficient here to say that stygofauna globally are considered to have quite widespread species compared to troglobites (obligate inhabitants of subterranean air-filled voids: Poulson and Levoie in press). Notwithstanding, as in the Yilgarn (Watts and Humphreys 1999, in press), stygofauna of the Pilbara appears quite circumscribed in distribution.

The local significance is established by the wide diversity and uniqueness of the fauna. For example, the 13 undescribed species from just one of three families of stygal amphipods apparently restricted to the Newman area may be compared with the total of 46 species of stygal amphipods formerly described from all other habitats throughout Australia (Bradbury and Williams 1997b: Table 1 plus *Nedsia urifimbriata* Bradbury and Williams 1997b). Numerous new genera have or will be described from Millstream and Newman including amphipods, ostracods, isopods and Spelaeogriphacea.

6.2 *Regional significance*

The Pilbara stygofauna is complex; while the local aquifers contain their own species, this is overlain by several regionally recognizable faunal assemblages. 1, the coastal plain with its 'tethyan' assemblage; 2, the Western Fortescue Plain characterized by Spelaeogriphacea. 3, sites upstream of the Western Fortescue Plain and the upper Ashburton catchment characterized by flabelliferan isopods. Each also having a diverse array of stygal species from other families.

The Pilbara stygofauna also differs from the apparently much less diverse (Humphreys 1999a) Kimberley stygofauna (it contains different isopods (Wilson and Keable 1999; Wilson and Johnson 1999). The Pilbara stygofauna is also distinct from that of the Yilgarn which is characterized by Dytiscidae (Coleoptera), bathynellid syncarids (Humphreys 1999b; Watts and Humphreys 1999, in press) and, in saline waters, oniscoid isopods.

The particular biogeographic importance of the Pilbara has been recognized elsewhere and arid zone refugia identified (Morton et al. 1995). To this recognition must be added the groundwater ecosystem as an important reservoir of biodiversity, often of relictual lineages (Poore and Humphreys 1998; Humphreys 1999; Knott and Halse 1999; Wilson and Johnson 1999; Wilson and Keable 1999).

6.3 *International significance*

The Pilbara stygofauna is of international relevance for the connections already established between it and the fauna of Gondwana (e.g. Ostracoda: Candoninae (P. Marmonier, pers. comm.), Phreatoicidea, *Tiramideopsis*, Phreodrilidae), and even Pangaea (e.g. Spelaeogriphacea, Syncarida), for its diversity, which is high on a global scale, and for its occurrence in an arid region. Furthermore, the presence of such a rich stygofauna central to an area where the normal mechanisms of isolation (eustatic stranding etc.; reviewed in Humphreys 1999a, in press a, submitted) have not operated since at least the Palaeozoic (Figure 1), suggest interesting questions of global significance concerning the origin and evolution of such faunas.

6.3.1 Species richness

It is often difficult to make direct comparison between the species richness of stygobitic faunas because the distinction is often not made between organisms with various life styles (stygoxene, stygophile, stygobite: *sensu* Gibert et al. 1994) that may be sampled from groundwater habitats. For example, in a study that included meiofauna along the altitudinal zonation (2900 m) along the length (560 km) of the South Platte River, Colorado, Ward and Voelz identified 213 taxa of which 89 came from phreatic habitats (42%). Of the hypogean species found in the Flathead River, Montana, only about eight of the 80 species (10 %) were stygobites. Similarly, the diverse root mat communities found in cave streams of southwestern Australia contain few stygobites (Jasinska et al. 1996).

The biodiversity of the Pilbara stygofauna is most appropriately compared with that of tropical systems elsewhere. The most biodiverse subterranean fauna of Southeast Asia is in Thailand from where 18 species of stygofauna are known (Deharveng and Bedos in press). Four caves in Southeast Asia had an average of three species (range 1-7 species) of stygal crustaceans (caves with six stygal species are considered to be biodiversity hotspots: Vermeulen and Whitten 1999), while a cave in each of France and China had respectively two and five species of stygal crustacea (Deharveng and Bedos in press). The best studied tropical karsts are in Mexico and central America and where each karst system has between 0 and 10 stygal species in their macrofauna (Peck and Finston 1993).

6.3.2 Amphipods

Although the amphipods of the Pilbara are poorly known, they are, as yet, the best known component of this recently identified stygofauna in the Pilbara. Australia is recognized a centre of amphipod evolution (Barnard and Karaman 1984). Taking into consideration the accumulation over time of described species of stygal amphipods from Australia (Figure 14) and the rate of new finds from calcrete aquifers (Watts and Humphreys 1999, in press) — 8 genera and15 species have just been tentatively identified associated with Hamersley Iron Pty Ltd samples (J.H. Bradbury pers. comm. 28/2/2000) of which 7-8 genera in three families come from the Ashburton catchment — the total number of stygal species is likely to be substantial.

Of the world's subterranean amphipod fauna 77% (573 species in 17 families) are found in the central and southern Europe-Mediterranean and the eastern and southern North America-West Indian regions (Ward et al., in press), a region comprising more than 44 countries, giving an average number of c. 13 species per country. While this undoubtedly can partly be attributed to similar geological and geographical factors, these areas have also been the subject of intensive work on their stygofaunas for more than 100 years. To date Australia has about 10% of this number of species comprising seven families of stygal amphipods. About 60 species of stygal amphipod are currently described from Australia and a total of more than 120 species are estimated to be informally recognized (J.H. Bradbury, pers. comm. 2000). About half (29) of the already described Australian stygal amphipods come from the Pilbara area.

Generally, the species richness of the stygofauna is likely to be under estimated if the assessment is made using techniques solely dependent on morphology. This is because, whereas stygal lineages may undergo evolution manifest in physiological and molecular changes, they may exhibit little morphological change (Boutin and Coineau in press). In consequence, subterranean faunas may contain numerous cryptic species, the presence of which is most easily revealed by molecular methods (e.g. for troglobites see Humphreys and Shear 1993; Humphreys and Adams, submitted).

It is clear from this analysis that the amphipod fauna of the Pilbara region is exceptionally diverse in both an Australian and international context. Areas with speciose higher stygal taxa tend to have a high degree of stygal diversity overall (papers in Botosaneanu 1986; Juberthie and Decu, 1986, 1994). Hence, the overall diversity of the stygofauna of the Pilbara is also likely to be of great significance in both an Australian and an international context.

7. The potential geographic extent/distribution of stygofauna in various systems.

Current understanding of the distribution of stygofauna in the Pilbara leads to a number of tentative conclusions:

13. The Pilbara stygofauna is restricted to the Pilbara.

14. There are distinct regional stygofaunas within the Pilbara.

15. Each calcrete aquifer has a distinct fauna.

16. Available stygofauna sampling of part of an aquifer cannot be extrapolated to the whole aquifer, as shown by sampling in the Western Fortescue Plain and the Newman area (Figure 13).

17. All undisturbed calcrete aquifers are likely to contain a significant and unique stygofauna.

8. Aquifers that are unsurveyed or undersurveyed (with priorities for further investigation).

The only groundwater calcrete aquifers that have been examined more than superficially are the Western Fortescue Plain and at Newman on the Fortescue (Table 2). The characteristics of aquifers (Bakalowicz 1994; Creuzé des Châtelliers et al. 1994), and their contained stygal assemblages, change, inter alia, depending on whether they are at efflux or influx zones with surface water, and with the depth and distances from these regions (e.g. Strayer 1994; Dole-Olivier et al. 1994; Pospisil 1994). Hence, all the aquifers in the Pilbara are undersurveyed and many remain entirely unexamined; the latter include Noreena Downs, Mulga Downs, Mt Florance, Fortescue Marsh, Cane River, Lake Waukarlcarly and Cuncudgene Hill.

Several major calcrete aquifers need to be examined thoroughly and drilling may be required in at least some of them to provide adequate sampling sites. They are, in approximate order of priority, Weeli Wolli, Yandicoogina, Turee Creek, Noreena Downs, Lake Waukarlcarly and Cuncudgene Hill. The alluvial aquifers at the Cane, De Grey and Yule Rivers need sampling. A full investigation of the Fortescue River (South Branch) should be undertaken to assess whether the considerable drawdown has affected stygofauna (none is known from this site).

Table 2: Groundwater aquifers with economic potential associated with calcrete, dolomite and valley fills in the Pilbara that were identified by Forrest and Coleman (1996); I have added the Western Fortescue Plain on the basis of Barnett (1981) and Barnett and Commander (1985), and the Cape Range Group. Cape Range and Barrow Island comprise Tertiary Limestones (Allen 1993; McNamara and Kendrick 1994), whereas coastal limestones occur on Legendre Island (Kojan 1994) and the Monte Bello Islands. Those aquifers in italics have not been examined for stygofauna.

Calcrete	Wittenoom Dolomite	[1]Valley Fill	Cape Range Group
Wyloo	*Wyloo*	*Wyloo*	Cape Range
Edmund	*Mt Bruce*	*Mt Bruce*	Barrow Island
[2]*Turee Creek*	[2]*Turee Creek*	Turee Creek	Robe Alluvium
Mt Egerton	*Roy Hill*	-	
Newman	Newman	Newman	
Collier	-	-	
W. Fortescue Plain	W. Fortescue Plain	W. Fortescue Plain	

[1] Valley Fill comprised alluvium and colluvium as well as Robe Pisolite and calcrete that occurs in thick valley fill sequences. [2] Barely examined.

There is some indication that fractured rock aquifers may contain stygofauna (Eberhard and Humphreys 1999; S. Anstee, pers. comm. 1999). However, as this is not established, the nature of such aquifers is not understood, and the affinities of any contained fauna unknown, no specific recommendations can be made. In general, however, this issue needs to be addressed to establish the existence, affinities and spatial extent of any stygofaunal assemblages in fracture rock aquifers.

8.1 *Other calcareous substrates*

Other than the Tertiary limestones of the coastal region (especially Cape Range with Trealla — also at Yarraloola — Tulki and Mandu Limestones, and Barrow Island with the Poivre Formation) and the groundwater calcretes on the Western Shield, there are extensive regions of other calcareous rocks in the Pilbara. These include the Wittenoom Dolomite, the Devil Creek Formation, the Cheyne Springs Formation and the Duck Creek Dolomite.

Cavities in carbonate rocks occur throughout Fortescue Valley, the valleys of the Hamersley range and the Oakover Valley where superficial Cainozoic deposits overlie dolomite (Forrest and Coleman 1996). There are both geotechnical and water resource implications associated with these cavities, but they also have implications for stygofauna, and they deserve investigation. Poore and Humphreys (1998) suggested that these karstic systems may have permitted the persistence of the more ancient stygofaunal lineages through geological eras.

9. Aquifers/stygofauna potentially at risk from water abstraction or mining.

The study area encompasses all or part of six surface drainage basins, namely, the Ashburton River Basin (706), Onslow Coast River Basin (707), Fortescue River Basin (708), Port Hedland Coast River Basin (709), DeGrey River Basin (710), Sandy Desert Basin (025). The region contains a number of public and industry developed water abstraction schemes (Figure 15).

The main factor likely to impinge on aquifers in the Pilbara is the abstraction of water associated with the extraction and processing of minerals and the change in water quality associated with these processes. Mineralogically the study area is divided into three regions. The coast and offshore areas of the Carnarvon Basin and North West Shelf contain industrial (limestone) and energy minerals (petroleum and uranium). On the Pilbara proper the mineralogy separates between north of the Chichester Range (gold, base metals, and alloying and speciality metals), while to the south of the Fortescue are found base metals (iron) as far south as Mt Olympus (gold).

A large number of separate aquifers is recognized by Forrest and Coleman (1996: Section 4), between about 8 and 14 in each drainage unit. Many of these are in deposits that are likely to support stygofauna (Valley Fill aquifers, Calcrete aquifers and Pisolite aquifers), while other are probably less likely to sustain stygofauna owing to the sparse voids in the formation (e.g. Morrissey Metamorphic, Brockman, Marra Mamba, Hardey, Mafic Volcanic Rocks, Undifferentiated. Proterozoic Rocks, Felsic Volcanic Rocks, Granitic Rocks, Greenstone Rocks).

9.1 *Water abstraction*

The impact of sustainable water abstraction on stygofauna in the Pilbara is entirely unknown. Aquifers used for water abstraction in the Pilbara (Newman) and the Yilgarn (Austin Downs, Lake Violet) that have not been drawn down excessively do support stygofauna. Conversely, sites where drawndown was well beyond what might be expected through long term climatic fluctuations, have not yielded stygofauna (Fortescue River, South Branch and Pillara in the Kimberley).

Stygofauna are known to be sensitive to quite subtle changes in hydrological conditions (Ordish 1976; Richoux and Reygrobellet 1986) and it must be expected that water abstraction has an impact on the stygofauna of the Western Shield. However, no aquifers have been studied to address these questions prior to the commencement of water abstraction and so the impact remains unknown. Calcrete aquifers often have waters exhibiting marked salinity stratification (e.g. Watts and Humphreys in press). In such cases excessive pumping may cause the upconing of salt water and this may damage calcrete aquifers and is likely to affect profoundly the stygofauna.

Sustained research at the Ph.D./post-doctorate level is required to address the impact of sustainable water abstraction on the stygofauna of calcrete aquifers with the longer term objective of addressing the management issues.

9.1.1 Aquifers/stygofauna at risk from water abstraction

From excessive drawdown: Fortescue River (South Branch), Hardey River.

From general water abstraction (flagged on account of lack of information on hydrology): Barrow Island.

The situation in unsurveyed areas is unknown.

9.2 *Mine dewatering*

Mine dewatering may result in drawdown well in excess of that expected from long term climatic fluctuations. While the aerial extent of such drawdown in fractured rock aquifers may be quite modest, dewatering that impacts directly or indirectly on karst is likely to have a much wider spatial extent. Because groundwater calcrete aquifers are typically thin (10-30 m), drawdown below the calcrete, even below the karstic part of it, may be expected to impact markedly on stygal populations.

9.2.1 Aquifers/stygofauna at risk from dewatering

Any stygofaunal assemblage is potentially at risk from dewatering. At the very lease, assessment of the risk directly attributable to the loss of habitat by dewatering requires a knowledge of the distribution of the species within the aquifer and the drawdown model of the proposed dewatering. Clearly at risk is the Fortescue at Newman (proposed Orebody 23). Drawdown can have effects other than habitat loss; for example by changing flow paths affecting energy (food) resources, and by salinity changes resulting from the evaporation of water from open pits following mine closure.

9.3 *Limestone mining*

Limestone is a major focus of attention in the Tertiary landscape of the Carnarvon Basin, particularly on the Cape Range peninsula. The extent of limestone mining from calcretes in the Pilbara is unknown but it is being increasingly mined in the Yilgarn for construction and process purposes. As well as removing habitat, limestone mining diverts drainage and can have very serious impact on stygofauna through opening or closing communication with the surface, through pollution caused by mining operations and, especially, by siltation (Vermeulen and Whitten 1999). There are documented cases in Australia of siltation resulting from limestone quarries adversely affecting subterranean fauna (Gillieson 1997; Hamilton-Smith and Eberhard in press).

9.4 *Petroleum*

The main risk to stygofauna resulting from petroleum exploration results from contaminating the aquifer with drilling muds, petroleum and produced water, and toxic gasses, some issues of which are discussed by Goodbar (1998) and BLM (undated). In karst areas surface spills often enter the groundwater through the karst surface and the results of bore fractures may spread through the karst conduits. On Barrow Island the disposal of production water and its contained oil into the superficial karst over decades — a practice recently stopped — would have introduced many thousands of tonnes of oil into the superficial aquifer, the fate of which is unknown.

9.5 *Dams*

Dams are a recognized environmental hazard for pools (Forrest and Coleman 1996), and they need to be considered as a potential threat to stygofauna. Firstly, because siltation within the impoundment will silt up any suitable habitat for macrofauna. Secondly, diverting water flow may lower recharge, change groundwater distribution, and permit the encroachment of salinity from the lateral parts of valleys and from the sea.

A number of the possible dam sites (DS) identified in Forrest and Coleman (1996: Appendix 3) could have a significant impact on known areas of stygofaunal diversity. Among them are DS123 and DS124 which could impact on the Western Fortescue Plain aquifer. The alluvial aquifers on the De Grey River may be impacted especially as the greater De Grey catchment has numerous major dam sites (e.g. DS158, Yarrie Station; DS85, Marble Bar; DS54, Doolena Gap; DS88, North Pole). DS114 may affect the aquifer near Onslow.

9.6 *Salinity*

The saline waters that intrude between and beneath the plumes of freshwater flowing onto the coastal plain from the Pilbara establish as complex interdigitation of low and high salinity ground water (see Forrest and Coleman 1996: Figures 4.1 and 4.2). Interfaces between fresh and saline waters appear to support a more diverse stygofauna (Perth Basin, W.F. Humphreys, unpublished; Cape Range, Humphreys in press a), or else a different stygofauna (Watts and Humphreys in press) from the surrounding areas. In the Pilbara region such varied salinity occurs in the lower Robe and the lower Fortescue alluvia, both of which support a diverse and populous stygofauna (Humphreys 1999a; W.F. Humphreys, submitted). Similar areas of complex salinity are associated with the lower Ashburton, Cane, Yule, Turner, Shaw and DeGrey Rivers (see Forrest and Coleman 1996: Figures 4.1 and 4.2).

Changes to the volume of groundwater recharge resulting from the interception of drainage upstream, either by barrages or water abstraction, is likely to change the location and extent of these zones of high gradients in salinity.

10. Conclusions

The stygofauna of the Pilbara, Western Australia, has been sparsely sampled and these samples are predominantly from groundwater calcrete aquifers that lie in the palaeodrainage channels on the Pilbara craton and its associated orogens. The fauna has mostly yet to be described formally but it is rich by world standards and distinct from those in the surrounding regions (Carnarvon Basin, Yilgarn, Kimberley), that is, it is endemic to the Pilbara, often at a higher taxonomic level. The fauna in each calcrete area sampled is distinct. Infilling of the sampling distribution is required in conjunction with additional taxonomic work using both morphometric and molecular methods to improve substantially understanding of the regional variation in the fauna as well as of the implications of direct and indirect anthropogenic impacts. The complete lack of information on the functioning of the groundwater calcrete ecosystem needs to be addressed if informed management of these system is to be implemented.

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12. GLOSSARY

anchialine (or anchihaline) • Anchialine habitats consist of bodies of haline waters, usually with a restricted exposure to open air, always with more or less extensive subterranean connections to the sea, and showing noticeable marine as well as terrestrial influences (Stock et al., 1986). They typically occur in volcanic or limestone bedrock.

biodiversity • the total biological diversity of an area, simply measured as species richness but often incorporating a measure of higher order taxonomic diversity or molecular diversity.

calcrete • Carbonate deposits that form in the soil or in the vicinity of the groundwater table as a result of the evaporation of soilwater or groundwater respectively. Groundwater calcretes form in arid climates (annual rainfall less than 200 mm) with high potential evaporation (more than 3000 mm per year: Mann and Horwitz, 1979).

craton • Part of the Earth's crust little deformed for a prolonged period (shield region).

dewatering • removal of water from a volume of ground, usually to facilitate mining or construction — unsustainable water abstraction may result in dewatering.

endemic • occurring only within a specified area.

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

macrocavernous • Underground voids > 20 cm, especially caves and underground passages in karst and volcanic substrates.

meiofauna • Assemblage of animals that pass through a 500 μm sieve but are retained by a 40 μm sieve, often interstitial; prefix meio-, hence meiobenthic.

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

refuge (refugium, refugia) • A region in which certain types or suites of organisms are able to persist during a period in which most of their original geographic range becomes uninhabitable because of climatic change (Morton et al., 1995).

relics (reliques in French) • The last survivors of an ancient radiation (Newman, 1991).

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

Schiner-Racovitza system • Classification of hypogean animals on ecological grounds into troglobites, troglophiles and trogloxenes (Schiner, 1854; Racovitza, 1907).

species richness • the number of species in an area, one measure of biodiversity.

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

stygal • See stygo-

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

stygobiont • Animal inhabiting the various types of groundwater.

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

stygofauna • Fauna inhabiting the various types of groundwater. Numerous names are in use for subsets of this system mostly based on the habitat type (see Humphreys in press b).

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

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

stygoxenes • Organisms that have no affinities with the groundwater systems, but occur accidentally in caves or alluvial sediments (Stanford and Ward, 1993). Nevertheless, stygoxenes can influence processes in the groundwater ecosystems – for example, by functioning either as predators or prey.

Tethys • The ocean that came into existence only after the Mesozoic fragmentation of the Triassic Pangaea (Por, 1986), when it became a seaway separating the continents of Gondwana and Laurasia, and it persisted from the Triassic until the late Eocene (that is, from 200 million to 40 million years ago).

troglo- • Prefix for subterranean terrestrial and aquatic systems, now more commonly restricted to terrestrial systems, being replaced by "stygo-" for aquatic systems.

troglobite • Species which do not exist outside caves (Schiner, 1854); they may, however, occur in the superficial underground compartment or in the upper hypogean zone.

troglomorphic • Pertaining to morphological, behavioural and physiological characters that are convergent in subterranean populations (Christiansen, 1962).

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

trogloxene • Species that do not normally feed underground, but may enter caves actively (regular trogloxene) or passively (accidental trogloxene)(Racovitza, 1907)

13. Figure captions

Figure 1: The current outline of Australia superimposed on the areas continually emergent since the Palaeozoic. 1. Cape Range; 2. Pilbara; 3. Kimberley. Derived from data in BMR Palaeogeographic Group (1990).

Figure 2: Western Australia: the general distribution of sampling sites for stygofauna.

Figure 3: Western Australia: the general distribution of stygofauna in Western Australia.

Figure 4: **Western Australia**: the general distribution of the larger stygofauna in Western Australia (excluding Bathynellacea, Ostracoda and Copepoda) .

Figure 5: Pilbara, distribution of stygofauna and sampling sites: red, all stygofauna (excluding Copepoda, Ostracoda and Syncarida); green, sites sampled for stygofauna. This map and those following include all area examined in Pilbara: there are no data east of the Newman area.

Figure 6: Western Pilbara, distribution of stygofauna and sampling sites: red, all stygofauna (excluding Copepoda, Ostracoda and Syncarida); green, sites sampled for stygofauna.

Figure 7: Eastern Pilbara, distribution of stygofauna and sampling sites: red, all stygofauna (excluding Copepoda, Ostracoda and Syncarida); green, sites sampled for stygofauna.

Figure 8: North West Shelf, distribution of stygofauna and sampling sites: red, all stygofauna (excluding Copepoda, Ostracoda and Syncarida); green, sites sampled for stygofauna.

Figure 9: Cape Range, distribution of stygofauna and sampling sites: red, all stygofauna (excluding Copepoda, Ostracoda and Syncarida); green, sites sampled for stygofauna.

Figure 10: Western Fortescue Plain aquifer (based on Barnett and Commander, 1985) showing sampling locations (triangles in upper map: circles denote multiple sampling points at Palm Springs and Millstream), and the distribution of selected stygofauna taxa in the aquifer of the Western Fortescue Plain. The groundwater divide between the Fortescue and Robe River drainages is denoted by a broken line.

Figure 11: The distribution of groundwater calcrete aquifers in Western Australia. Modern and palaeo- drainage (respectively continuous and dashed lines) and calcrete areas (black) are shown. Derived from data in Geological Survey (1989, 1990), drawn by Julianne Waldock on a base map provided by Philip Commander. Inset: general distribution of groundwater calcretes in mainland Australia, adapted from Mann and Horwitz (1979). 1, Fortescue River; 2, Robe River; 3, Hardey River; 4, Ashburton River; 5, Barrow Island; 6, Cape Range; 7, Millstream; 8, Devonian reef system between the 8's; 9, Ningbing Range, an outlier of 8.

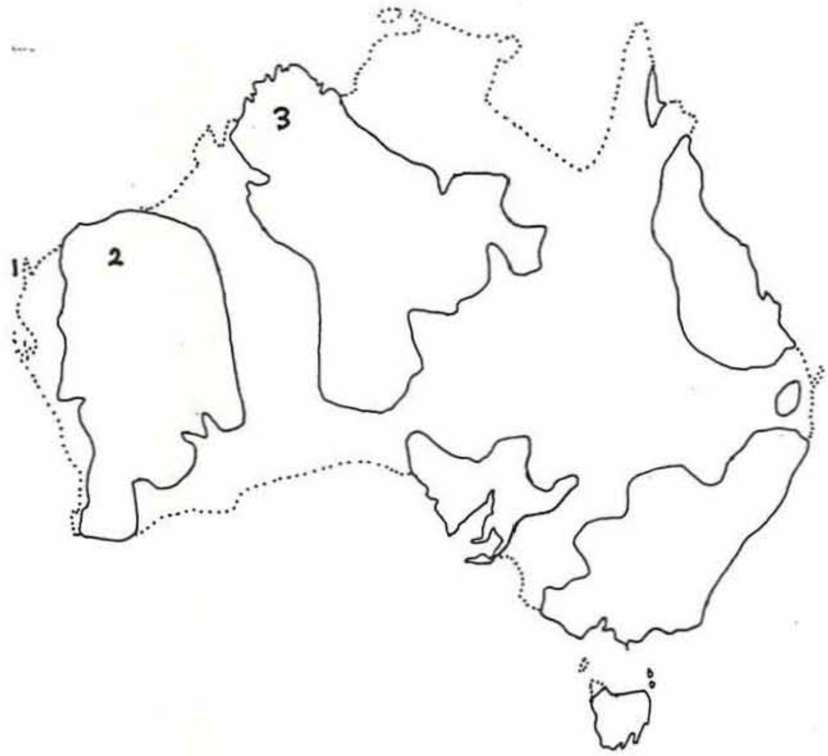
Figure 12: : The distribution of groundwater calcrete aquifers in the Pilbara (deep yellow: Geological Survey 1989).

Figure 13: Calcrete aquifer at the junction of the Fortescue River with Homestead, Warrawanda and Shovelanna Creeks near Newman. The dotted line represents the limits to the drawdown model for a proposed mining operation involving dewatering (from BHP with permission). Each dot represents the location of a new species of crangonyctoid amphipod.

Figure 14: The accumulation over time of stygal amphipod species described or in MS from Australia (Bradbury and Williams 1997; J.H. Bradbury, pers. comm. 2000; Bradbury and Eberhard in press). More than twice this number of stygal amphipod species are estimated already to be in collections (J.H. Bradbury, pers. comm. 2000).

Figure 15: Pilbara region groundwater and surface water schemes. Water and Rivers Commission; with permission.

Figure 1



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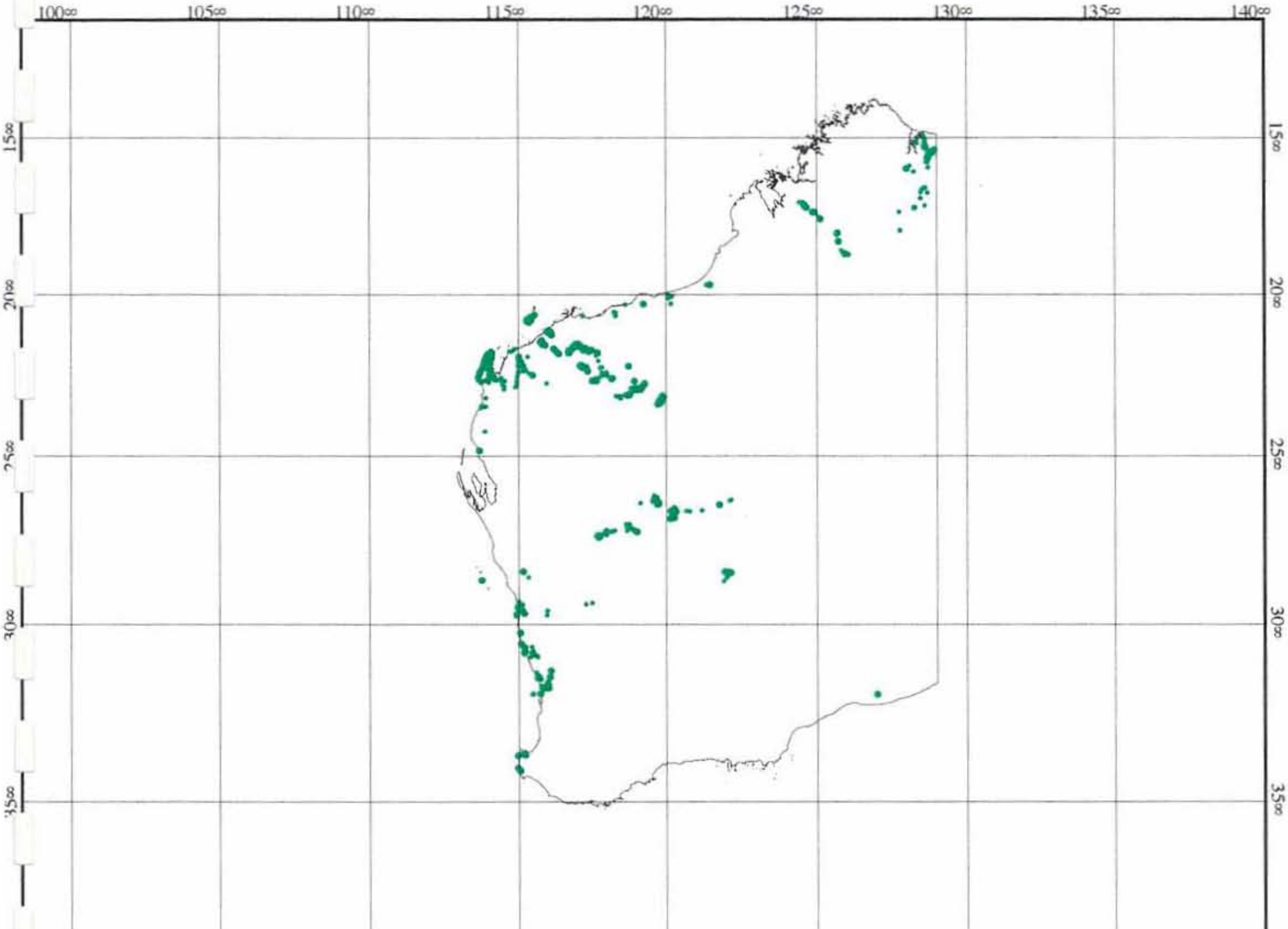

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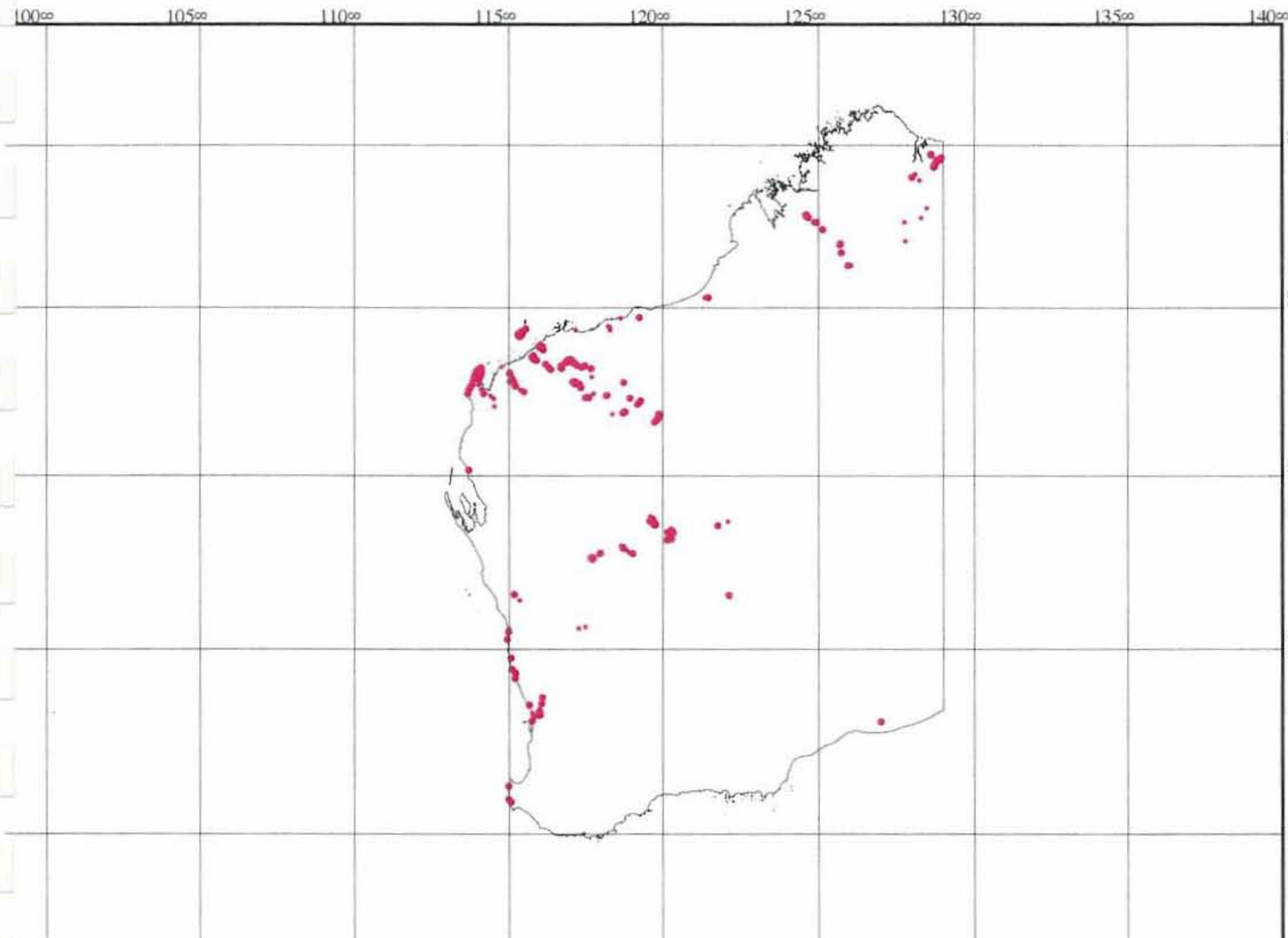

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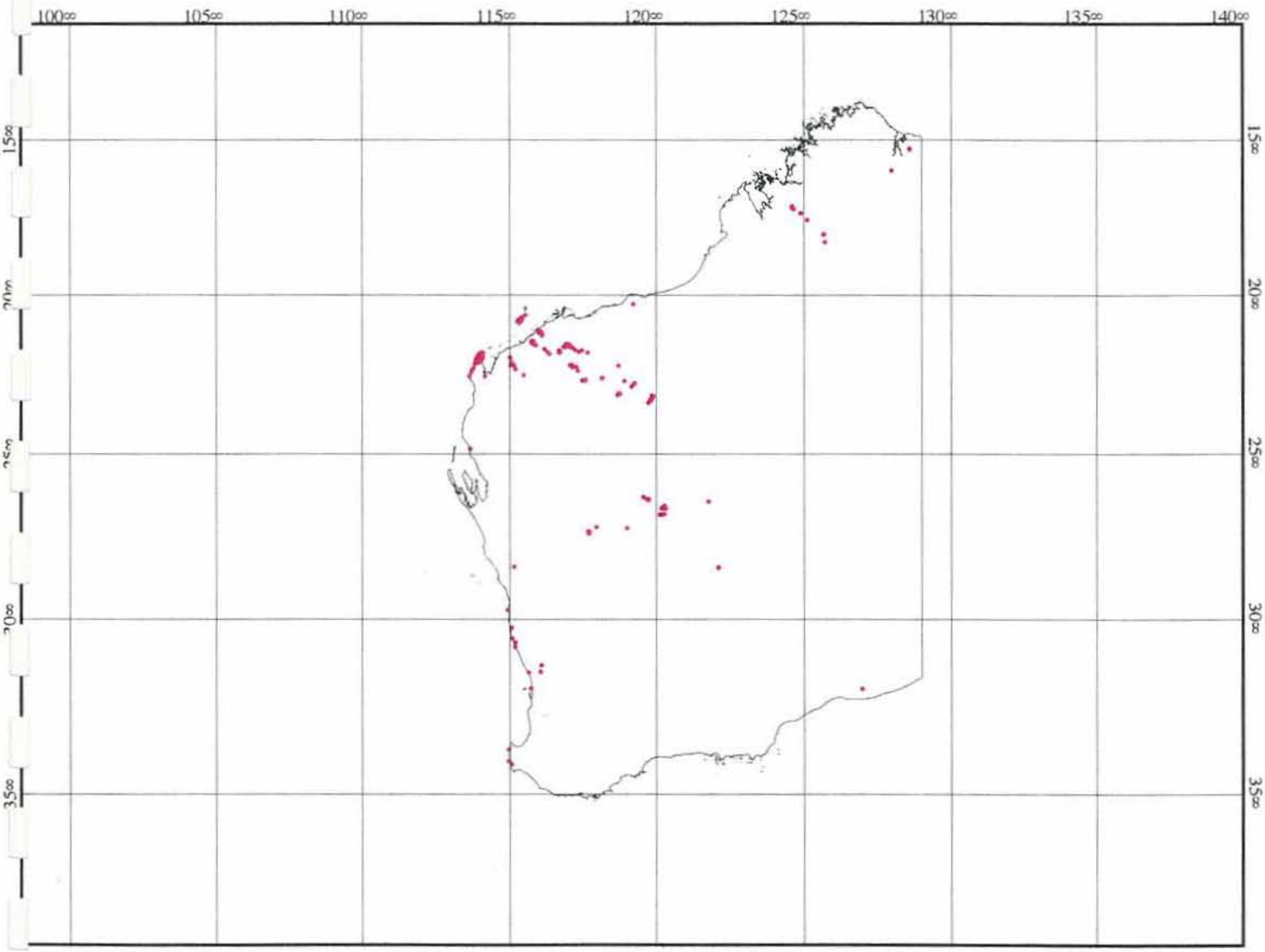

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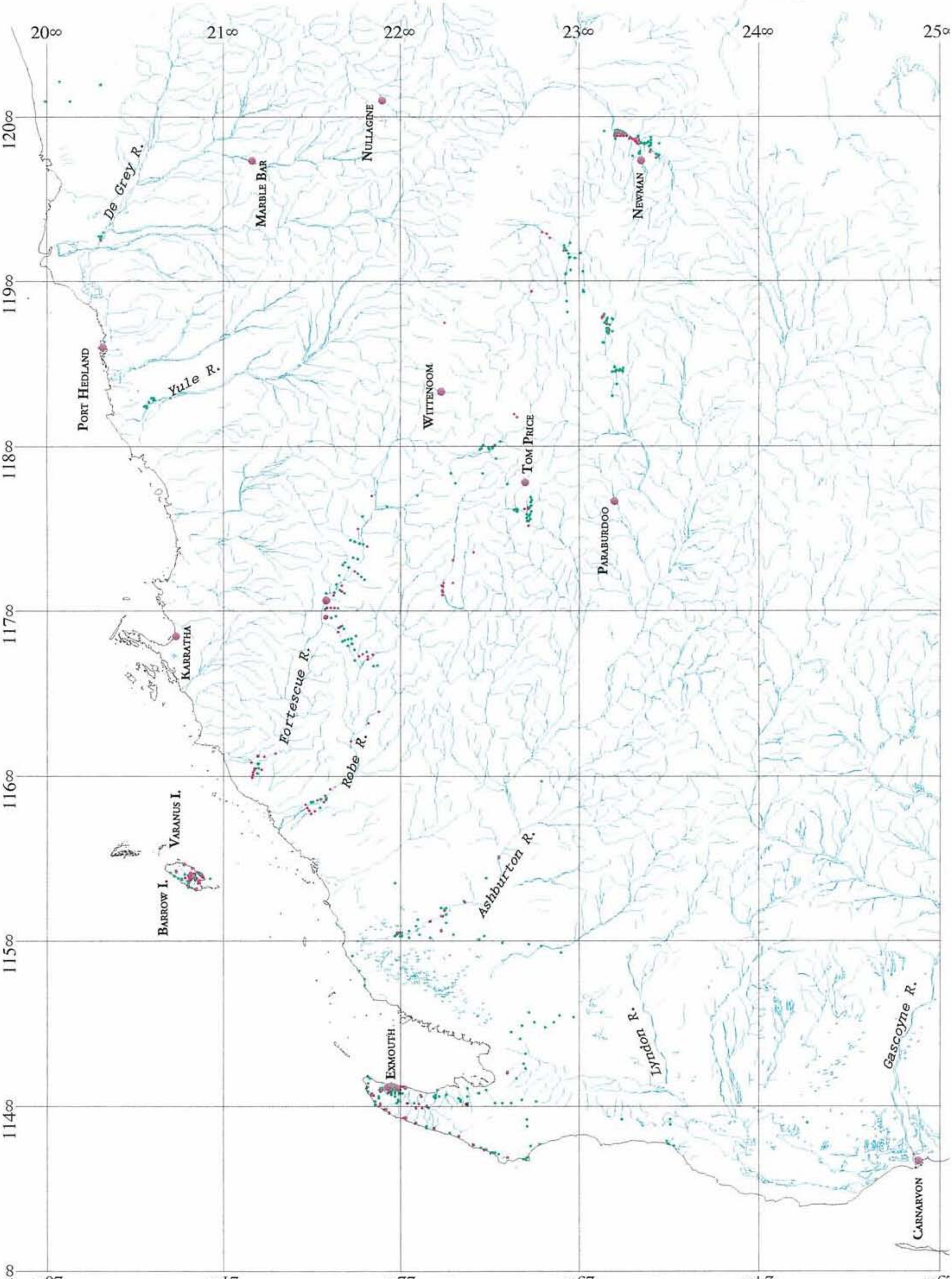
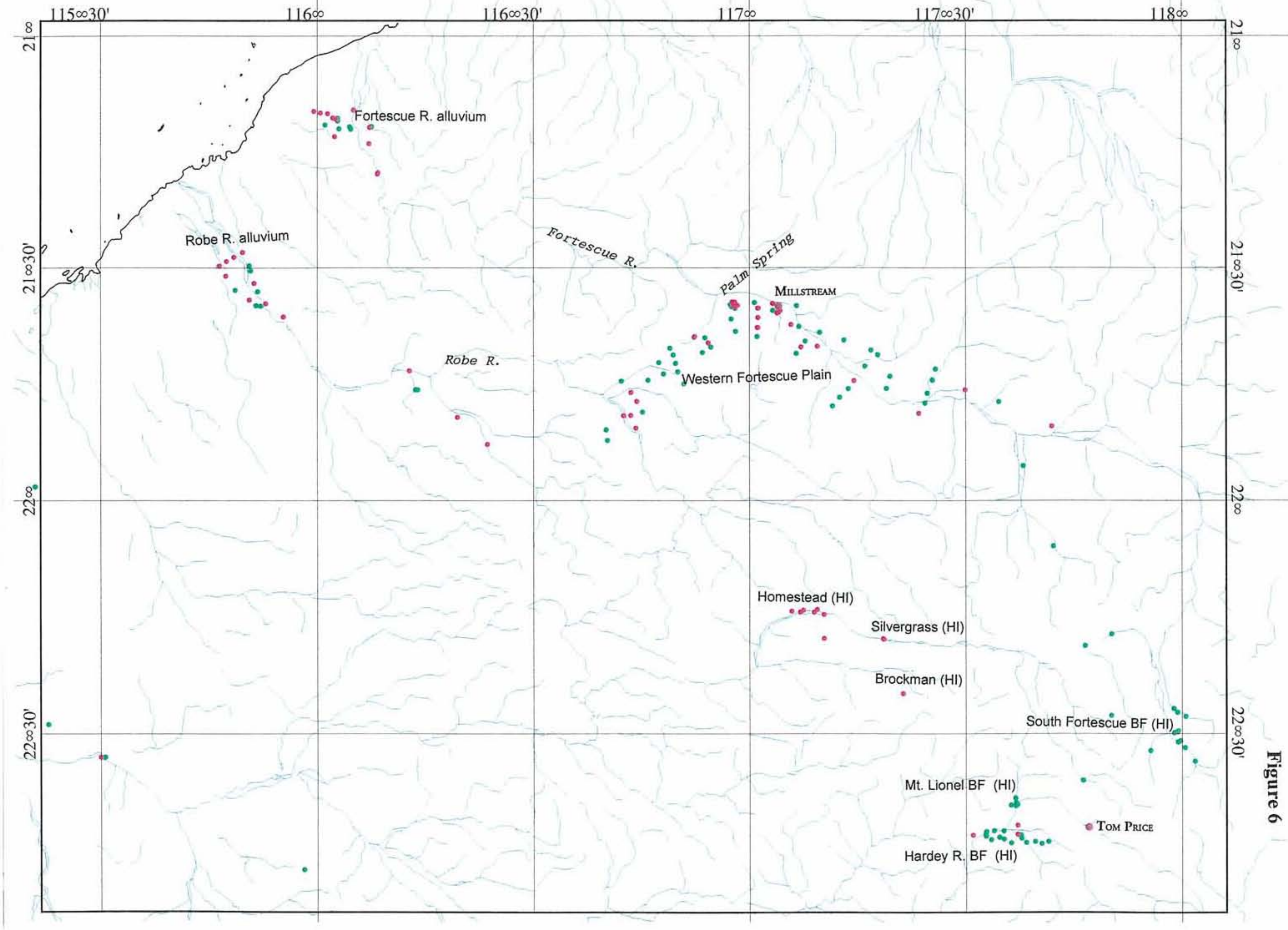


Port Hedland
Marble Bar
Nullagine
Newman
Wittenoom
Tom Price
Paraburdoo
Karratha
Varanus I.
Barrow I.
Exmouth
Carnarvon
De Grey R.
Yule R.
Fortescue R.
Robe R.
Ashburton R.
Lyndon R.
Gascoyne R.
20∞
21∞
22∞
23∞
24∞
120∞
119∞
118∞
117∞
116∞
115∞
114∞



115∞30'
116∞
116∞30'
117∞
117∞30'
118∞
21∞
21∞30'
22∞
22∞30'
Fortescue R. alluvium
Robe R. alluvium
Fortescue R.
Palm Spring
Millstream
Robe R.
Western Fortescue Plain
Homestead (HI)
Silvergrass (HI)
Brockman (HI)
South Fortescue BF (HI)
Mt. Lionel BF (HI)
Tom Price
Hardey R. BF (HI)

Figure 6

Figure 7

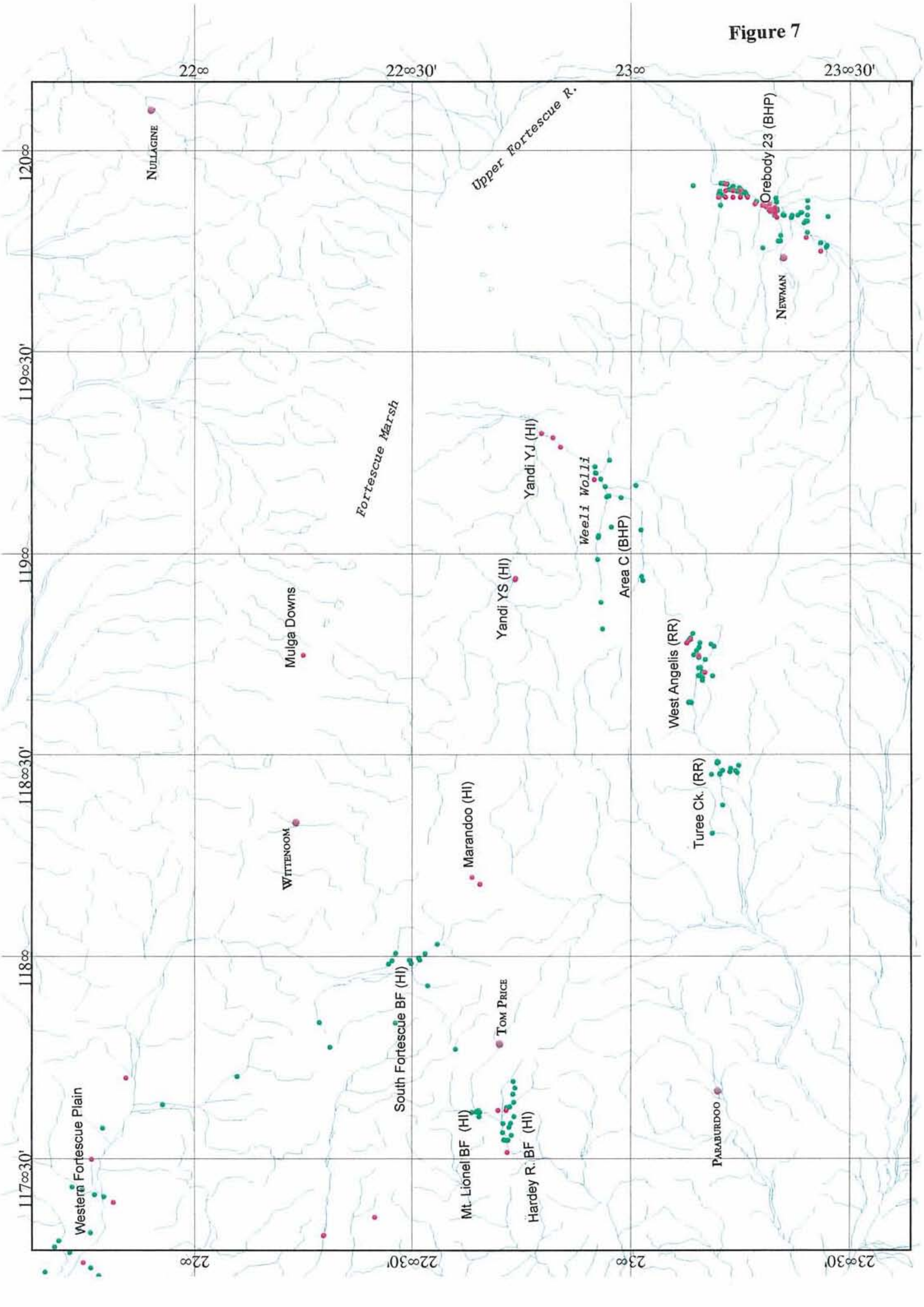
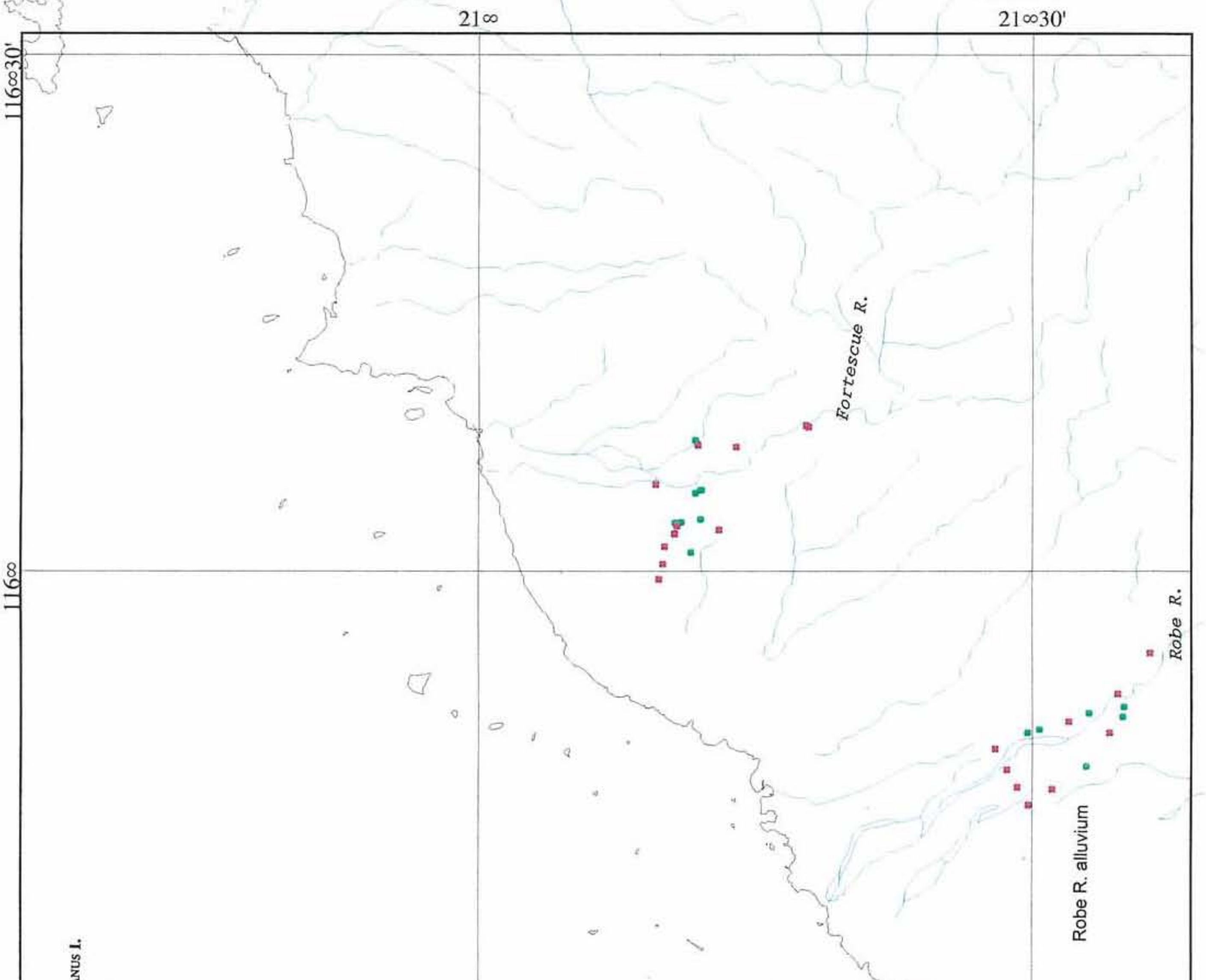

22∞
22∞30'
23∞
23∞30'
120∞
119∞30'
119∞
118∞30'
118∞
117∞30'
Upper Fortescue R.
Fortescue Marsh
Weeli Wolli
Nullagine
Newman
Wittenoom
Tom Price
Paraburdoo
Orebody 23 (BHP)
Yandi YJ (HI)
Yandi YS (HI)
Area C (BHP)
Mulga Downs
West Angelis (RR)
Turee Ck. (RR)
Marandoo (HI)
South Fortescue BF (HI)
Mt. Lionel BF (HI)
Hardey R. BF (HI)
Western Fortescue Plain

Figure 8



21∞
21∞30'
116∞30'
116∞
115∞30'
Fortescue R.
Robe R.
Robe R. alluvium
Varanus I.
Barrow I.

Figure 9

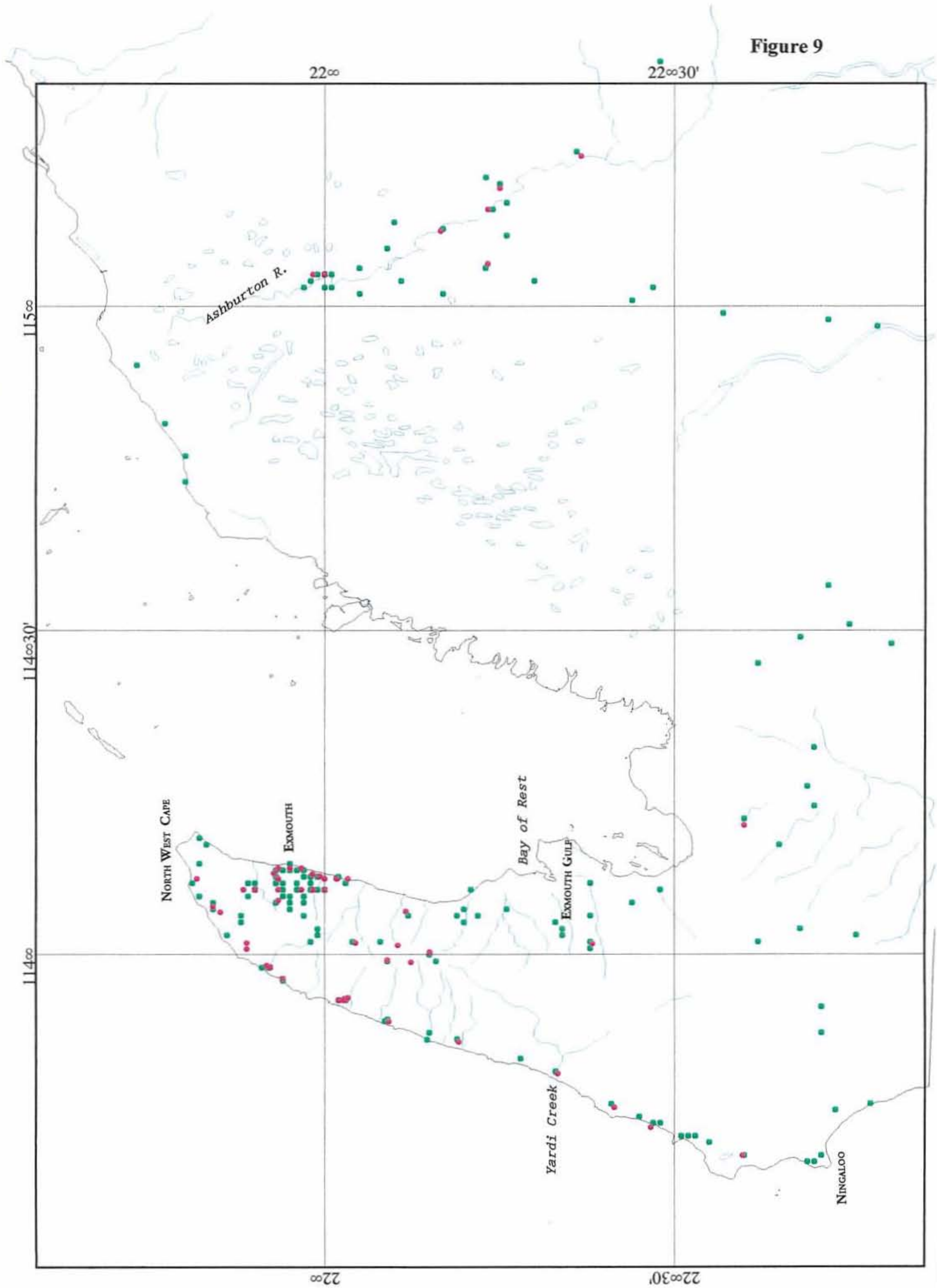
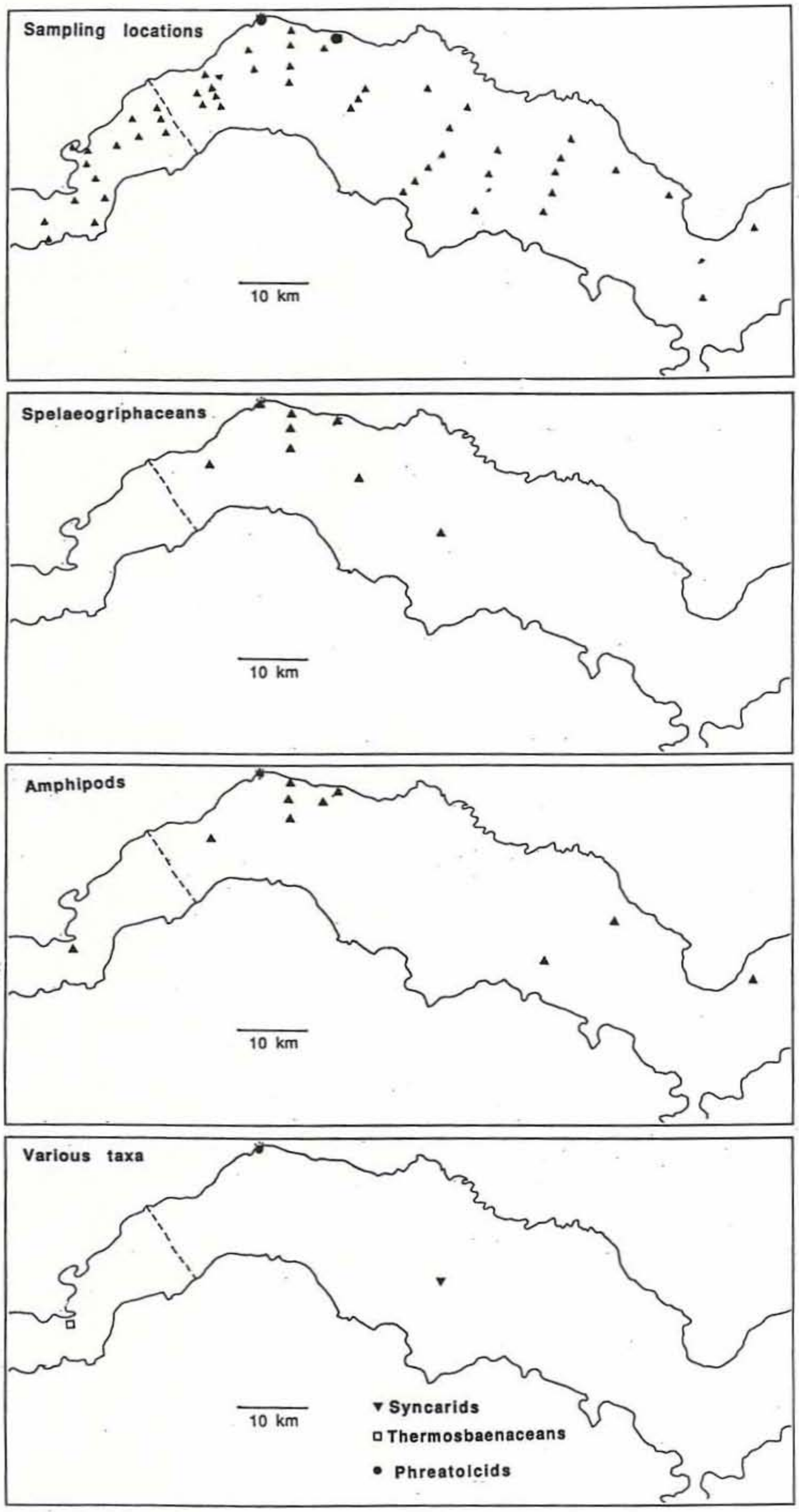
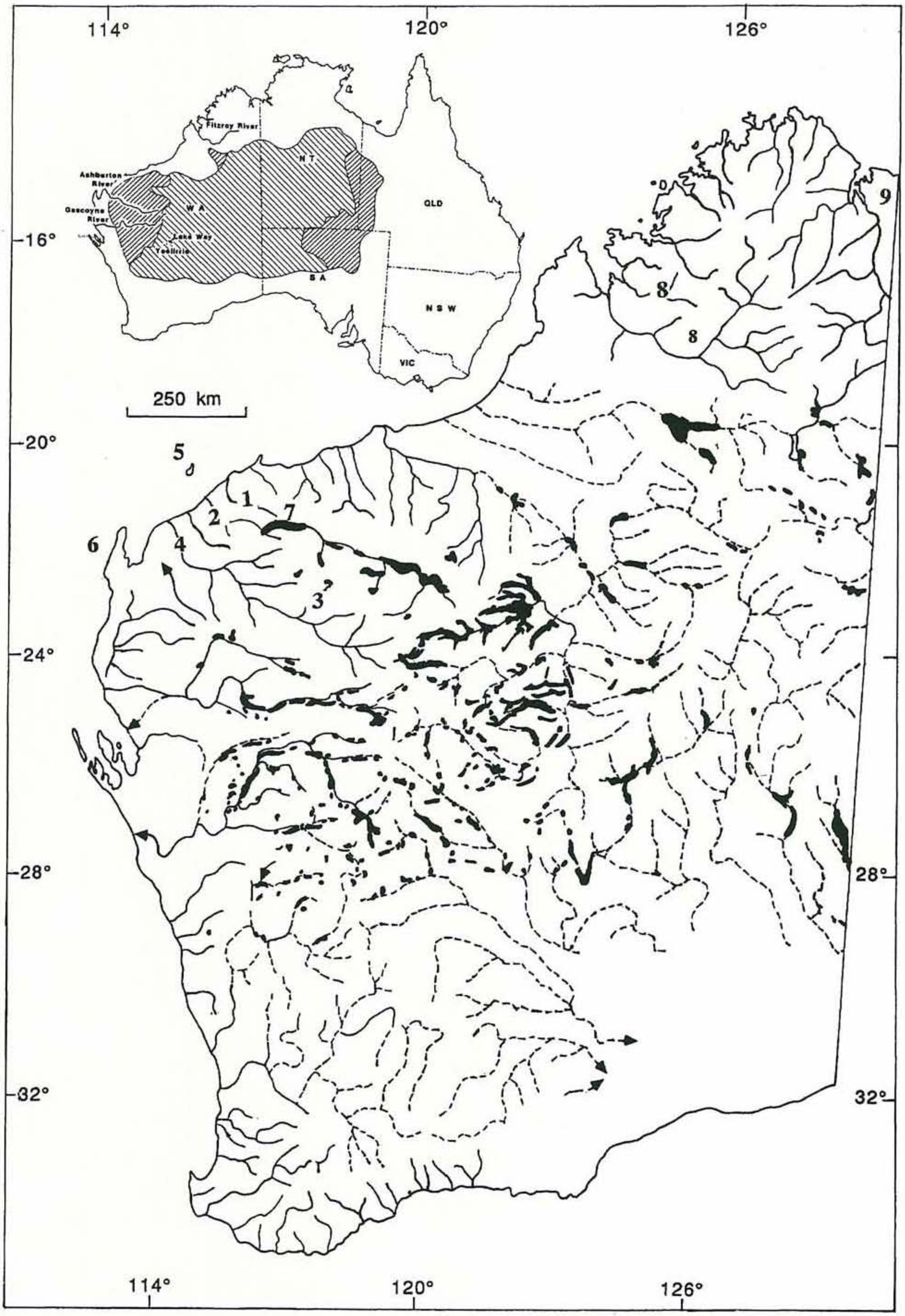

22∞
22∞30'
115∞
114∞30'
114∞
Ashburton R.
North West Cape
Exmouth
Bay of Rest
Exmouth Gulf
Yardi Creek
Ningaloo
22∞
22∞30'

Figure 10



Sampling locations
10 km
Spelaeogriphaceans
10 km
Amphipods
10 km
Various taxa
10 km
▼ Syncarids
□ Thermosbaenaceans
• Phreatoicids

Figure 11



114°
120°
126°
-16°
-20°
-24°
-28°
-32°
28°
32°
Fitzroy River
Ashburton River
Gascoyne River
Lake Way
Yeelirrie
W A
N T
S A
QLD
N S W
VIC
250 km
1
2
3
4
5
6
7
8
8
9


PORT HEDLAND
NEWMAN
TOM PRICE
PARABURDOO
PANNAWONICA
KARRATHA
WICKHAM
ROEBOURNE
CARNARVON
SHARK BAY

Figure 12

Figure 13

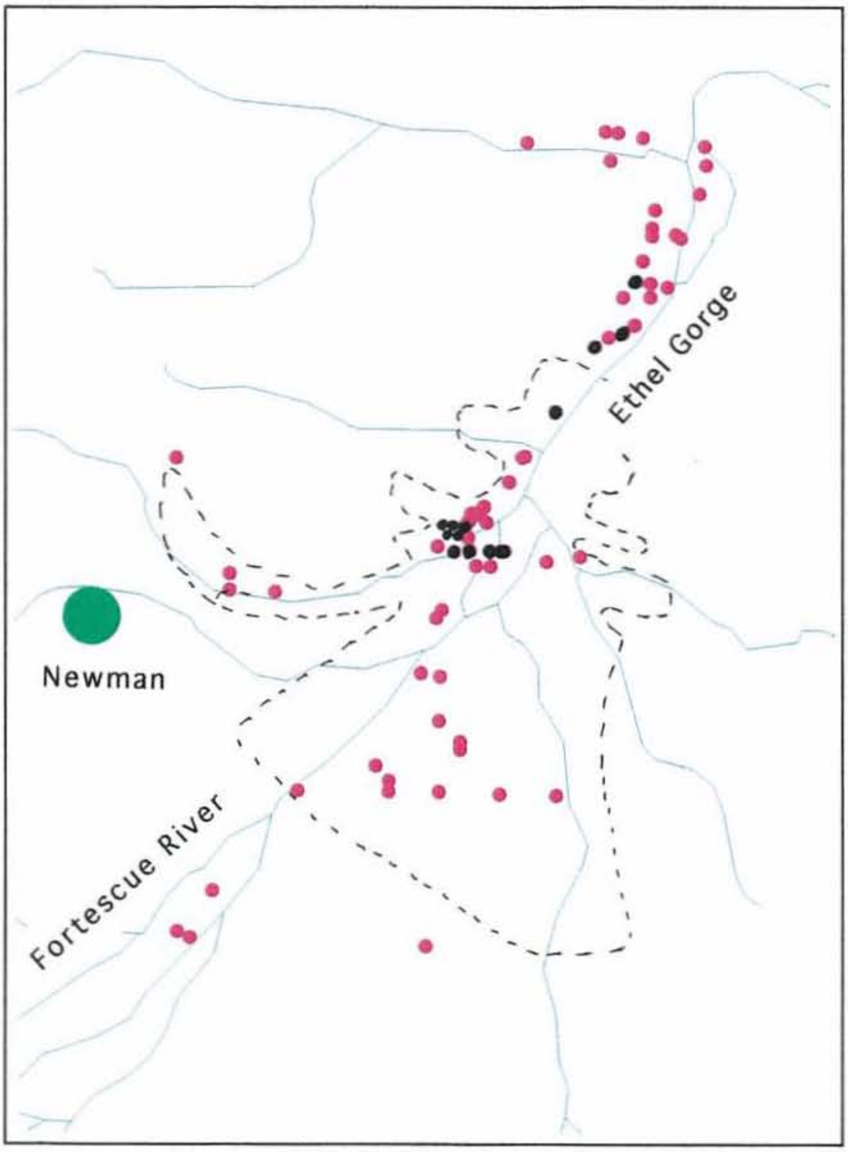
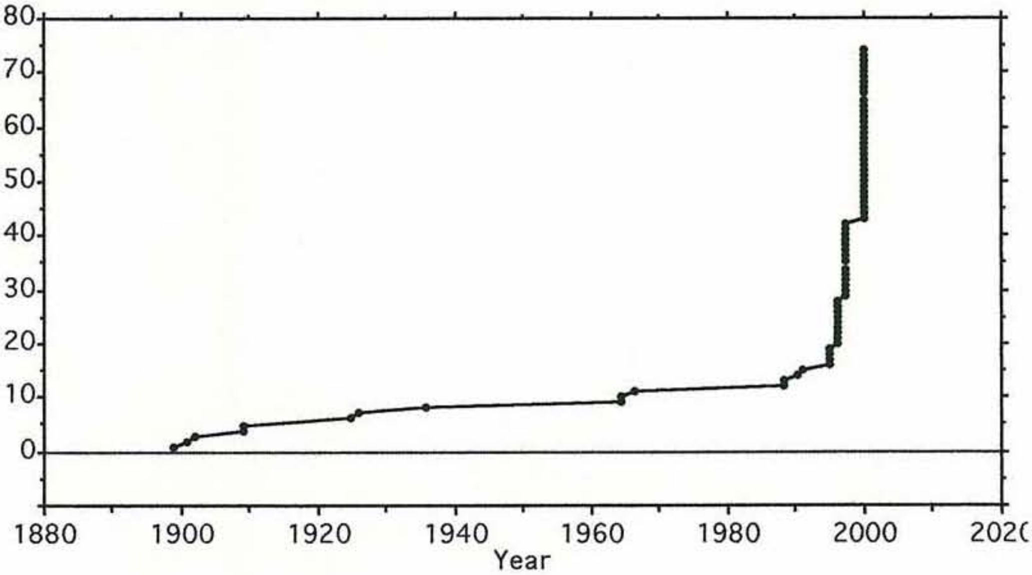
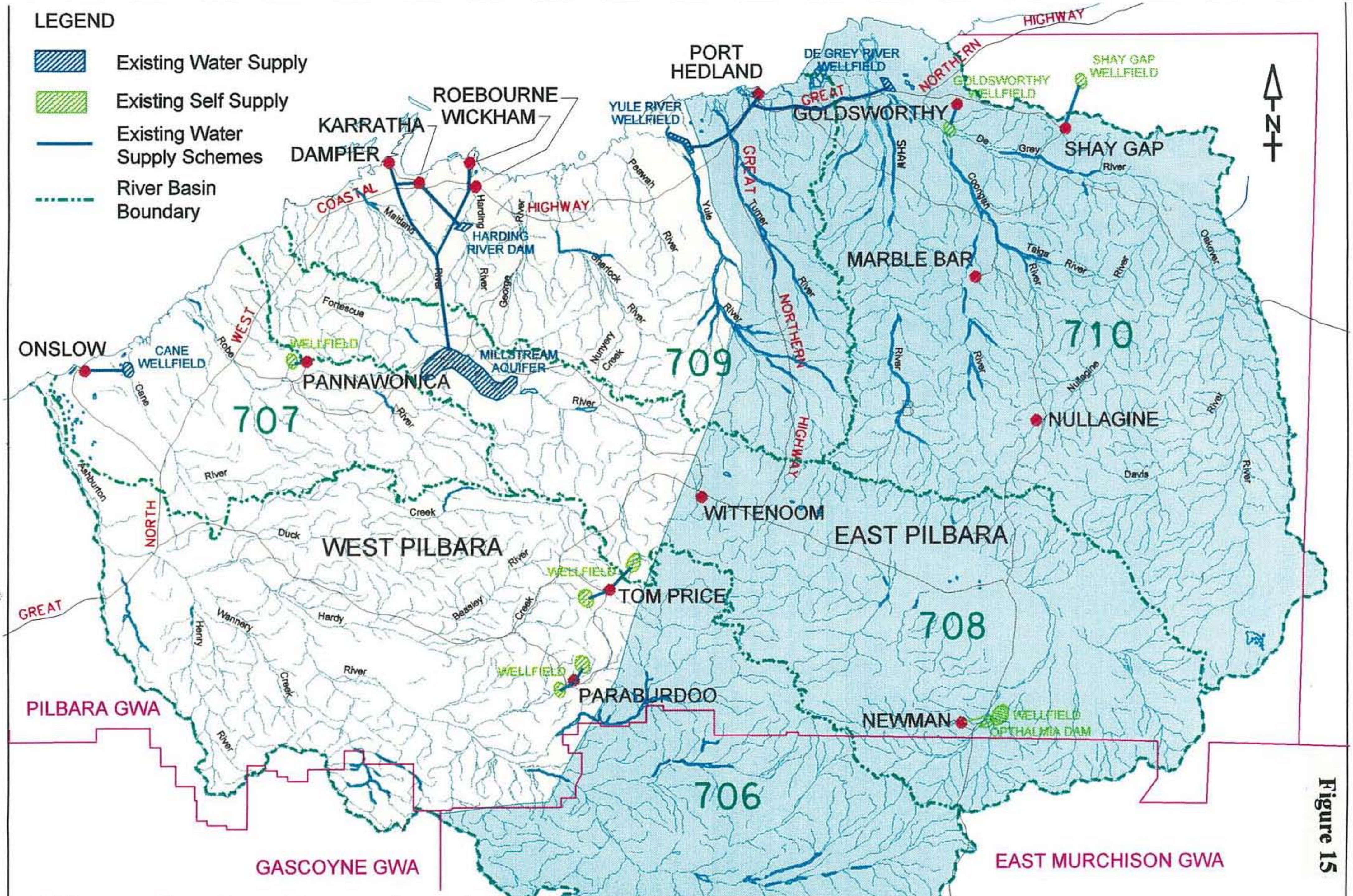


Figure 14


80
70
60
50
40
30
20
10
0
1880
1900
1920
1940
1960
1980
2000
2020
Year



Pilbara Region Ground and Surface Water Schemes

Figure 15