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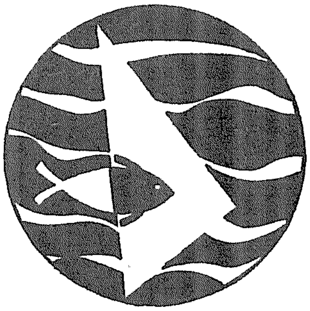
FAO Fisheries Synopsis No. 128 SAST – Panulirus cygnus – 2,29(01)001,15



SYNOPSIS OF BIOLOGICAL DATA ON THE WESTERN ROCK LOBSTER *Panulirus cygnus* (George, 1962)

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

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FAO Fisheries Synopsis No. 128
(Distribution restricted)

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SYNOPSIS OF BIOLOGICAL DATA ON THE WESTERN ROCK LOBSTER

Panulirus cygnus George, 1962

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FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome 1980

M-42

ISBN 92-5-101025-X

PREPARATION OF THIS SYNOPSIS

Due to a temporary interruption in the publication of CSIRO Species Synopsis, and in view of the desirability of making available this up-to-date account on the valuable Western rock lobster fishery without delay, it was decided, upon request of the CSIRO Division of Fisheries and Oceanography, to include the present document in the FAO Species Synopsis series.

ABSTRACT

This synopsis reviews all available data on identity, distribution, life history, population dynamics, exploitation, protection, management and artificial cultivation of the western rock lobster, *Panulirus cygnus* George, 1962.

Distribution

Authors
FAO Fisheries Department
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Regional Fisheries Councils and Commissions
Selector SM

For bibliographic purposes this document should be cited as follows:

Phillips, B.F., G.R. Morgan and C.M. Austin, 1980 Synopsis of biological data on the western rock lobster, *Panulirus cygnus* George, 1962. FAO Fish. Synop., (128):64 p.

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1 IDENTITY

1.1 Nomenclature

1.11 Valid name

Panulirus cygnus George, 1962

1.2 Taxonomy

1.21 Affinities

- Suprageneric

Kingdom Animalia
 Subkingdom Metazoa
  Phylum Arthropoda
   Class Crustacea
    Subclass Malacostraca
     Series Eumalacostraca
      Superorder Eucarida
       Order Decapoda
        Suborder Reptantia
         Section Macrura
          Family Palinuridae

- Generic

Panulirus White, 1847

Marine rock or spiny lobster with long flagella on the antennules, dorsally smooth supra-orbital horns, endopod of pleopod of second abdominal segment of female without stylamblys, antennal base with stridulating organ, carapace cylindrical (after Holthuis, 1946).

- Specific

- Identity of type specimens

Holotype. Adult male 104 mm carapace length, measured in the midline from the anterior transverse ridge between the supra-orbital horns to the posterior margin of the carapace. Total length 290 mm (to the end of telson). Western Australian Museum (W.A.M., 90-62).

- Type locality

The type locality is Radar Reef, Rottnest Island, Western Australia (32°00'S, 115°30'E), in reef pool at depth of one metre.

- Diagnosis

Adult specimens of *P. cygnus* (Figure 1) are readily separated from the two most closely related species, *Panulirus japonicus* (von Siebold, 1824) and *P. longipes longipes* (A. Milne-Edwards, 1868).

Although the colour (brick-red) and colour patterns are very similar, the following characteristics distinguish *P. cygnus* from *P. japonicus*:

(a) The antennular plate of *P. cygnus* has 4-8 spines arranged in two rows behind the principal pair of spines (Figure 2c), whereas *P. japonicus* has no spines or a few very small spinules in this position (Figure 2f).

(b) The transverse grooves of the second to fifth abdominal segments of *P. cygnus* are continuous with the corresponding pleural grooves whereas in *P. japonicus* the transverse grooves of segments 2, 3 and 4 at their lateral ends curve forward and end abruptly before reaching the pleural grooves.

(c) The male pleopod of the second abdominal segment of *P. cygnus* does not have an endopod (Figure 2a) whereas in *P. japonicus* there is a distinct endopod on that pleopod (Figure 2g).

Adult specimens of *P. cygnus* and *P. longipes longipes* are very similar morphologically but can be most readily distinguished by the colour pattern of the carapace (George, 1962; George and Holthuis, 1965). The carapace of *P. cygnus* is uniformly coloured and bears no obvious spots or markings. In *P. longipes longipes* however the carapace is brightly marked and spotted, the central region is darker than anterior, posterior and lateral regions and in addition the carapace is marked by distinct pale spots distributed over it and the dorsal surface of the supra-orbital horns; there is also a longitudinal pale mark on the side of the carapace leading back from the post-antennal spine toward the cervical groove. A bow-shaped pale mark demarks the posterior margin in the dark central region.

In addition to these colour markings, three morphological features, although variable, are useful in the separation of *P. cygnus* and *P. longipes longipes*.

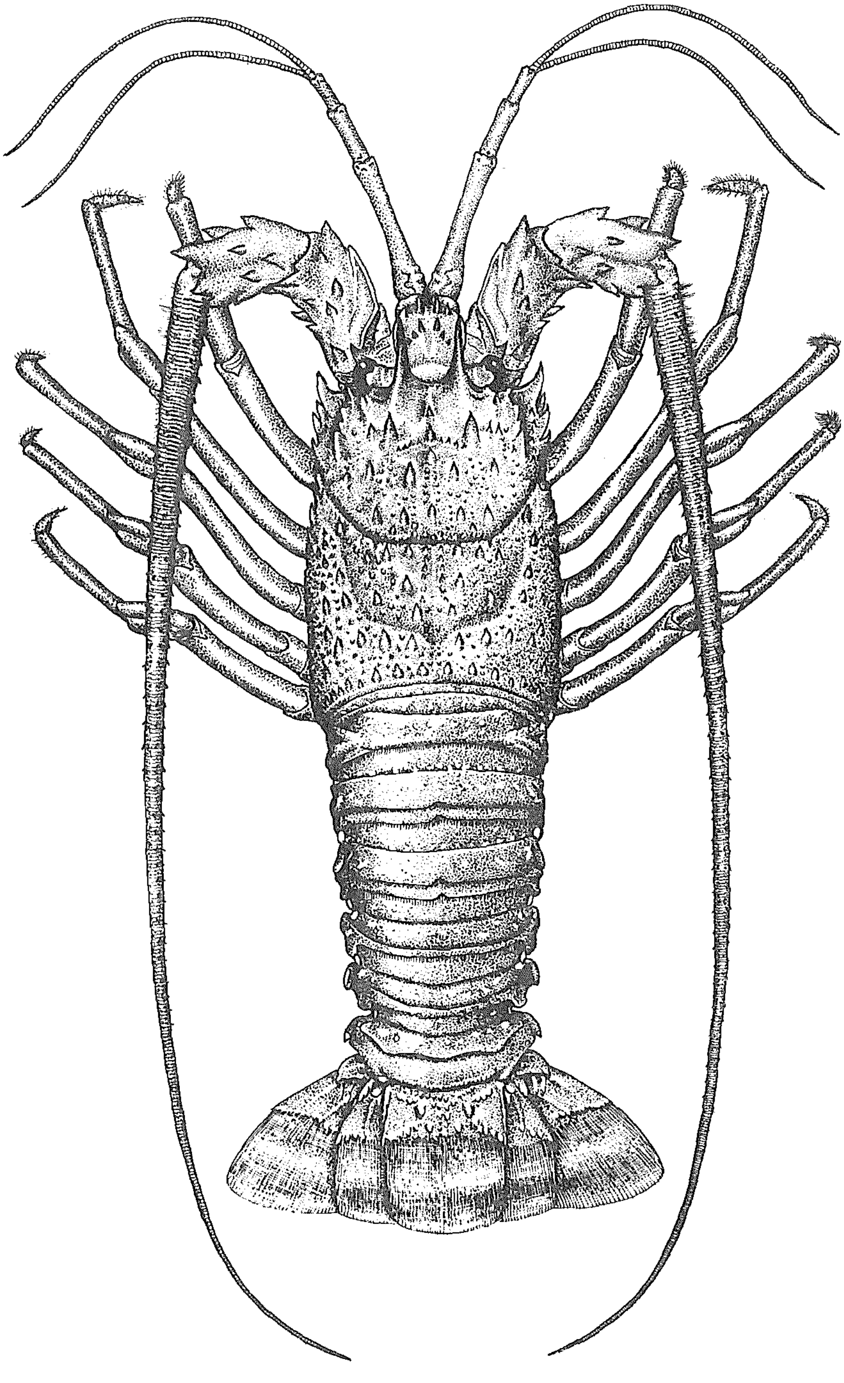

Figure 1 *Panulirus cygnus*

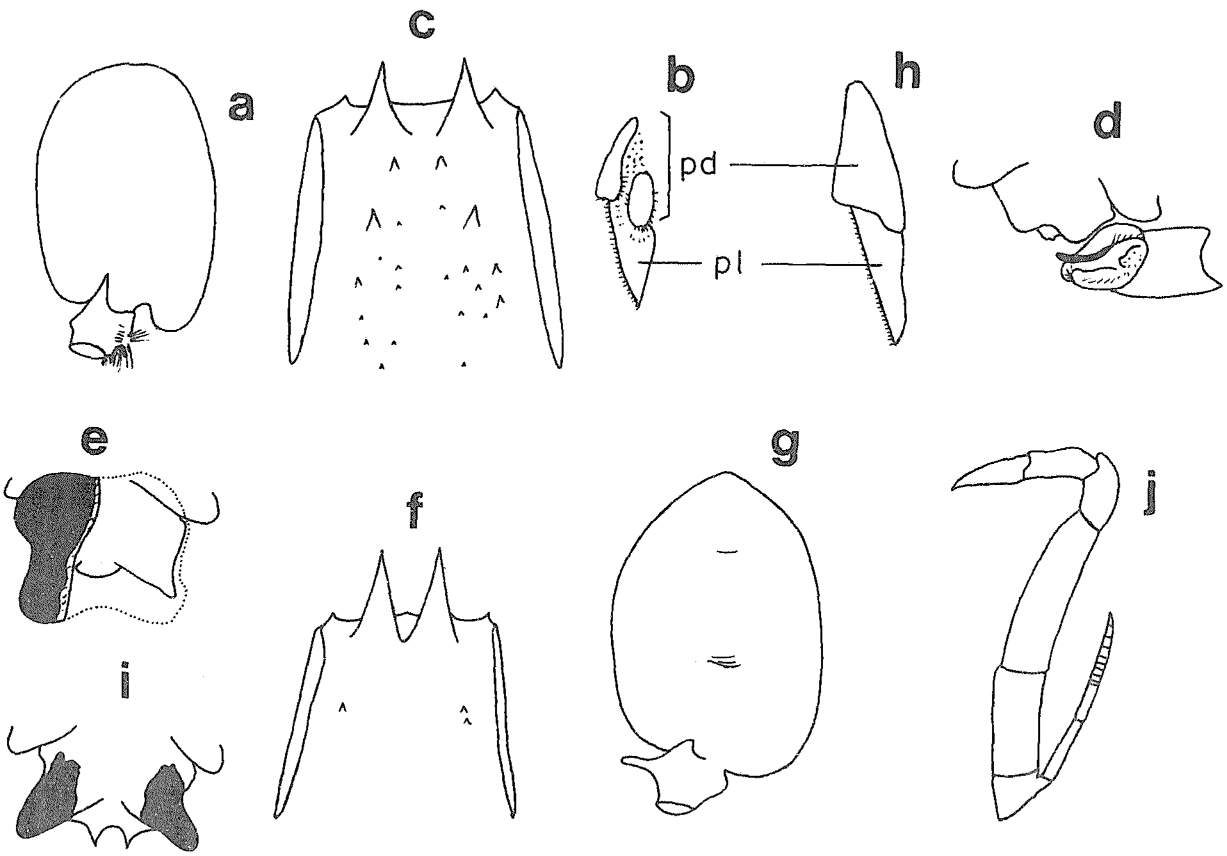

Figure 2 (a-d) *Panulirus cygnus;* Holotype male; (a) left pleopod of second segment of abdomen from behind. c. 1 1/2 x nat. size; (b) pleuron (pl) and "plate D" (pd) of first abdominal segment, from left. Note the vertical division of "plate D" by a hairy groove, c. nat. size; (c) antennular plate, from above, c. 1 1/2 nat. size; (d) posterior thoracic segment, from below, c. 3/4 x nat. size; (e) *Panulirus cygnus*, posterior thoracic segment of mated female, part of spermatophore removed, from below, c. nat. size; (f-g) *Panulirus japonicus* (von Siebold), male; (f) antennular plate, from above, c. 2 x nat. size; (g) left pleopod of second segment of abdomen, from behind, c. 2 1/2 x nat. size; (h-i) *Panulirus longipes longipes* (Milne-Edwards), mated female; (h) pleuron and "plate D" of first abdominal segment, from left. Note that "plate D" is not divided, c. 1 1/4 x nat. size; (i) posterior thoracic segment from below, c. 3/4 x nat. size; (j) *Panulirus cygnus*, left third maxilliped, setae omitted, c. nat. size (after George, 1962).

(a) In adults of both sexes of *P. longipes longipes*, there are two sharp spines on the posterior margin of the thoracic sternum (Figure 2i) where in *P. cygnus* adult females have no spines (Figure 2e) and in males the two teeth are only poorly developed (Figure 2d).

(b) A triangular area ("plate D") (Figure 2b) on the first abdominal segment is fully divided by a vertical hairy groove in most *P. cygnus* whereas in *P. longipes longipes* it is usually not divided (Figure 2h).

(c) *P. cygnus* usually has a band of setae across the posterior half of each abdominal tergum between the transverse groove and the posterior margin whereas in *P. longipes longipes* only the first segment shows a band of setae.

- Subjective synonomy

None

- Keys

George and Holthuis (1965) constructed two keys for the Indo-West Pacific species of the genus *Panulirus*; the first uses morphological criteria and the second is based exclusively on the colour pattern of the animals.

(a) Key to the Indo-West Pacific Species of *Panulirus* Based on Morphological Features

1. Each abdominal somite with a transverse groove 2

   Abdominal somites without transverse grooves 8

2. Anterior margin of abdominal transverse grooves crenulate . . . . . *P. homarus homarus* (L)

   Anterior margin of abdominal transverse grooves not crenulate. 3

3. Antennular plate with 4 equal principal spines, which are fused at the base . . . . *P. penicillatus* (Olivier)

4. Transverse grooves of abdominal somites III and IV do not join the corresponding pleural grooves. Pleopods of second abdominal somite of male with exdopod and exopod . . . . *P. japonicus* (von Siebold)

   Transverse grooves of abdominal somites III and IV join the corresponding pleural grooves. Pleopods of second abdominal somite of male without endopod 5

5. Transverse groove of abdominal somite II does not join the pleural groove . . . . *P. pascuensis* Reed

   Transverse groove of abdominal somite II joins pleural groove 6

6. Anterior margin of pleuron of abdominal somite II with a series of distinct teeth, abdomen transversely banded. . *P. marginatus* (Quoy & Gaimard)

   Anterior margin of pleuron of abdominal somite II without teeth, abdomen dorsally spotted 7

7. Posterior margin of thoracic sternum of adult female with two distinct teeth, posterior half of the abdominal somite II without pubescent area . . *P. longipes longipes* (A. Milne-Edwards)

   Posterior margin of thoracic sternum of adult female without teeth, abdominal somite II with a transverse band of pubescence behind the transverse groove . . . . *P. cygnus* George

8. Flagellum of exopod of second maxilliped well developed, multi-articulate . . . . . . *P. polyphagus* (Herbst)

   Flagellum of exopod of second maxilliped small or absent 9

9. Groove before the posterior margin of the carapace narrower than the marginal ridge behind it, of about the same width throughout. Abdomen smooth and naked, without narrow transverse pale bands . . . . *P. ornatus* (Fabricius)

   Groove before posterior margin of the carapace at least as wide as the marginal ridge, widened in middle. Abdomen with or without narrow transverse pale bands 10

10. Abdominal somites with distinct sunken pubescent areas. Fifth pleopod of male about twice as long as wide. Abdomen rather uniformly covered wtih minute pale speckles, without transverse pale bands . . . . *P. stimpsoni* Holthuis

    Sunken pubescent areas usually absent from abdomen or indistinct. Fifth pleopod of male about three times as long as wide. Abdomen with conspicuous narrow transverse pale bands . . . . . . *P. versicolor* (Latreille)

(b) Key to the Indo-West Pacific Species of *Panulirus* Based on Colour Markings

1. Abdomen with narrow transverse pale bands 2

   Abdomen without narrow transverse pale bands 5

2. Legs striped 3

   Legs not striped 4

3. Carapace with spots . . . . . .*P. pascuensis*

   Carapace with lines of colour . . . .*P. versicolor*

4. Merus of pereiopods plain, joints ringed . . . .*P. marginatus*

   Merus of pereiopods blotched or spotted . . . . . *P. polyphagus*

5. Dorsal surface of abdomen, apart from a white spot behind each of the articulations of the somites, unspotted or with a few very small and indistinct spots on anterior somites only; general impression of the abdomen as being of uniform colour 6

   Dorsal surface of all abdominal somites with distinct spots 7

6. Pereiopods with transverse coloured rings or with large irregular spots. . . . . . . *P. ornatus*

   Pereiopods with longitudinal colour stripes . . . . *P. japonicus*

7. Abdomen with a moderate number of moderate sized spots on the dorsal surface. 8

   Abdomen with very many fine spots on dorsal surface 9

8. Carapace brightly spotted and marked . . . . *P. longipes longipes*

   Carapace plain . . . . *P. cygnus*

9. Legs spotted or blotched . . .*P. homarus homarus*

   Legs striped 10

10. Outer surface of merus of pereiopods with 3 or more pale lines, outer surface of propodus with 2 lines. Abdominal pleura uniformly spotted, without white line. No conspicuous large pale spot behind the articulation of the abdominal somites. .*P. penicillatus*

    Outer surface of merus of pereiopods with one or two white lines, which may be strongly reduced; outer surface of propodus with one line which may be largely absent. Abdominal pleura with a white line extending upward from the tip. Behind each of the articulations of the abdominal somites a large and conspicuous white spot (only those on the second somite rather narrow) . . . . *P. stimpsoni*

1.22 Taxanomic status

P. cygnus belongs to the *P. japonicus* group which also includes the Indo-West Pacific species - *P. pascuensis*, *P. marginatus* and *P. longipes longipes* all of which are characterized by possessing:

(1) the exopod of the second and third maxilliped well developed and provided with a distinct flagellum;

(2) abdominal somites with deep uninterrupted, straight transverse grooves, and

(3) two principal spines on the antennular plate.

P. cygnus was previously misidentified in many publications as *P. penicillatus* or *P. longipes* (see George, 1962). In addition, since the publication of its description, *P. cygnus* has been considered to be, erroneously, either a subspecies of *P. longipes* (Chittleborough and Thomas, 1969) or identical with *P. longipes* (Chittleborough, 1975; Phillips and Rimmer, 1975; Chittleborough and Phillips, 1975). The present authors support the view that "the description by George (1962) represents a sound and valid taxonomic publication fulfilling all the essential criteria for establishing that *P. cygnus* is an endemic species restricted to subtropical Western Australia (22°-34°S latitude)". (Editor, Australian Journal of Marine and Freshwater Research, pers. comm.).

1.23 Subspecies

No subspecies of *P. cygnus* have been recognized.

1.24 Standard common names, vernacular names

The common name of *P. cygnus* was officially accepted by the Western Australian Government in the Fisheries Act Amendment Bill (1969) as the "western rock lobster".

Vernacular names have also included Western Australian Crayfish, Dongara Crayfish, Abrolhos Crayfish, Rottnest Crayfish, White Crayfish.

1.3 Morphology

1.31 External morphology

- General

No detailed studies of the external morphology with quantitative data have been made. The only morphological information available is contained in the holotype description which highlights the specific characteristics to allow positive identification (i.e., George, 1962).

Flagellum of exopod of third maxilliped multiarticulate (Figure 2j) reaching to middle of merus. Single uninterrupted transverse groove to tergum of each abdominal segment. Antennular plate with seven spines arranged in two posteriorly diverging rows (four in the right row, three in the left row) behind the principal pair (Figure 2c). Transverse grooves of second to fifth abdominal segments joined to and continuous with corresponding pleural groove, grooves covered by fringe of setae. Posterior half of each abdominal tergum with transverse band of short erect setae, decreasing in abundance on posterior segments. Pleopod of second abdominal segment without endopod (Figure 2a). Mid-posterior margin of thoracic sternum with pair of small teeth (Figure 2d). Triangular plate (referred to as Plate D) at anterolateral margin of first abdominal segment divided vertically by groove containing erect setae (Figure 2b).

Carapace dark red without obvious spots or markings, abdomen spotted dorsally and laterally; each walking leg with broad pale longitudinal stripe on dorsal surface and less obvious, narrower, ventral and lateral stripes.

- Geographical variation

North to south variation in the distribution and density of setae on parts of *P. cygnus* has been found by George (1962). All specimens over 70 mm carapace length from between Point Peron and Dirk Hartog Island possessed bands of setae on the posterior region of all abdominal segments although the setae on segments 5 and 6 were sometimes sparse. In contrast, the last two abdominal segments of specimens from Point Cloates and North West Cape were without bands of setae and in some cases lacked setae on segments 4, 3, or even 2. In these specimens, setae on other parts were either sparser or absent compared with specimens from the southern areas. It was also found that northern specimens did not always have a distinct hairy groove on Plate D like the specimens from the south.

- Seasonal variation

A seasonal variation in colour occurs in *P. cygnus*. The usual colour of fresh specimens is dark red, but in November and December pale pink lobsters, called whites, accumulate in the shallow waters (George, 1958a).

- Morphological changes which occur during growth

George (1962) examined specimens of *P. cygnus* of various sizes and found several morphological features which change during growth.

The total number of antennular plate spines in the two main rows behind the principal spines may be 4, 5, 6, 7 and 8 in specimens larger than 30 mm carapace length (c.l.). All specimens smaller than 30 mm c.l. have 6 spines (3 pairs) some of which may show as sharp prominences in the position of incipient spines. Smaller spines or tufts of erect setae may be found covering the remainder of the plate. Thoracic teeth were found to be absent in the puerulus stage, but they develop subsequently so that by the time the animals have grown to a carapace length of 20 mm all possess them. Animals smaller than 20 mm c.l. have a distinct groove in Plate D. Setae occur on all abdominal segments on specimens greater than 70 mm c.l. although the setae on segments 5 and 6 may be sparse. Specimens in the size range 30 to 70 mm c.l. have bands of setae on segments 1, 2 and 3 and may not have them on segments 4, 5 and 6 while specimens smaller than 30 mm c.l. only occasionally have sparse setae on segments 2 and 3 but none on segments 4, 5 and 6.

2 DISTRIBUTION

2.1 Total Area

- Land area[1/]

600 Oceania, 612 Western Australia (Sheard, 1949)

- Sea area[1/]

P.S.E. (Southern Ocean, E.) Southern limit: Hamelin Harbour latitude 34°30'S (George, 1962)

- Geological features

Coastal limestones and the remains of eroded dune sandstones form a complex tangle of onshore and offshore reefs between the Bunbury area and the Murchison River (see Figure 3). Large islands (e.g., Garden and Rottnest) of this same material exist offshore in the general Fremantle area, with smaller islands at intervals northward. Onshore coral reefs of an earlier age are found at Bunbury, Rottnest Island, the Moore River, and at Point Leander, Dongara. A small amount of living coral reef is found at Rottnest; elsewhere on the coast from Cape Naturaliste to Shark Bay there are isolated coral growths, but none is of reef-forming dimensions. Older limestones and sandstones occur between Red Point on Gantheaume Bay and the northern point of Dirk Hartog Islands, a distance of 216 km. These are vertical cliffs with deep reefs and rock ledges lying at various depths up to 8-11 km offshore. No granite reefs have been recorded existing between a little north of Cape Naturaliste to North-West Cape.

The area between Shark Bay and Carnarvon possesses many reefs, sandbanks and mud flats. Old limestone cliffs commence near Quobba Point running to about 16 km northward on Red Bluff then follow sandy beaches and recent limestone cliffs to Cape Farquhar and northward nearly to Maud's Landing, a distance of 56 km. Ledges and reefs extend offshore from 3-5 miles with some sand bottoms present in the northern sector. Offshore, from below Point Maud to near Vlaming Head, a barrier reef with coral growth on an old sandstone and limestone base lies offshore at a distance of 1.5-6.5 km, extending for about 96 km.

Offshore 64 km from Geraldton lies the Houtman's Abrolhos, a group of islands and reefs, which extend along an arc for about 80 km and cover from 6.5 to 800 km^2 (Sheard, 1949).

- Biogeographical and natural characteristics

The oceanic waters off the western coast of Australia have very low productivity (Chittleborough, in press), with the surface waters very deficient in dissolved nutrients (Kirkwood, 1967; Rochford, 1962, 1967, 1969) and also very low in zooplankton (Tranter, 1962). Tranter compares this area with the Sargasso Sea as extreme examples of oligotrophic waters where both primary production and standing crops of zooplankton are at their lowest.

Chittleborough (1975) found that, within shallow reef areas off Garden Island, Jurien Bay and Seven Mile Beach (see locality map, Figure 3), the salinity ranged from 34.4°/oo following winter rains to an occasional peak of 37.7°/oo with high evaporation during summer.

The water circulation of the southern-eastern Indian Ocean is complex and cannot be described as characterized or dominated by any single feature (see Andrews, 1977; Hamon, 1965, 1972; Kitani, 1977; Rochford, 1969, 1977; Wyrtki, 1962, 1973; Wyrtki et al., 1971). Currents for the most part are variable and weak. Mass transport of waters in the upper 300 m is generally toward the west coast of Australia throughout the year (Wyrtki et al., 1971; Wyrtki, 1973) but random variation in geostrophic currents of a non-seasonal nature frequently complicate or obscure the general picture (e.g., Hamon,

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[1/] Land/sea areas taken from Rosa (1965)

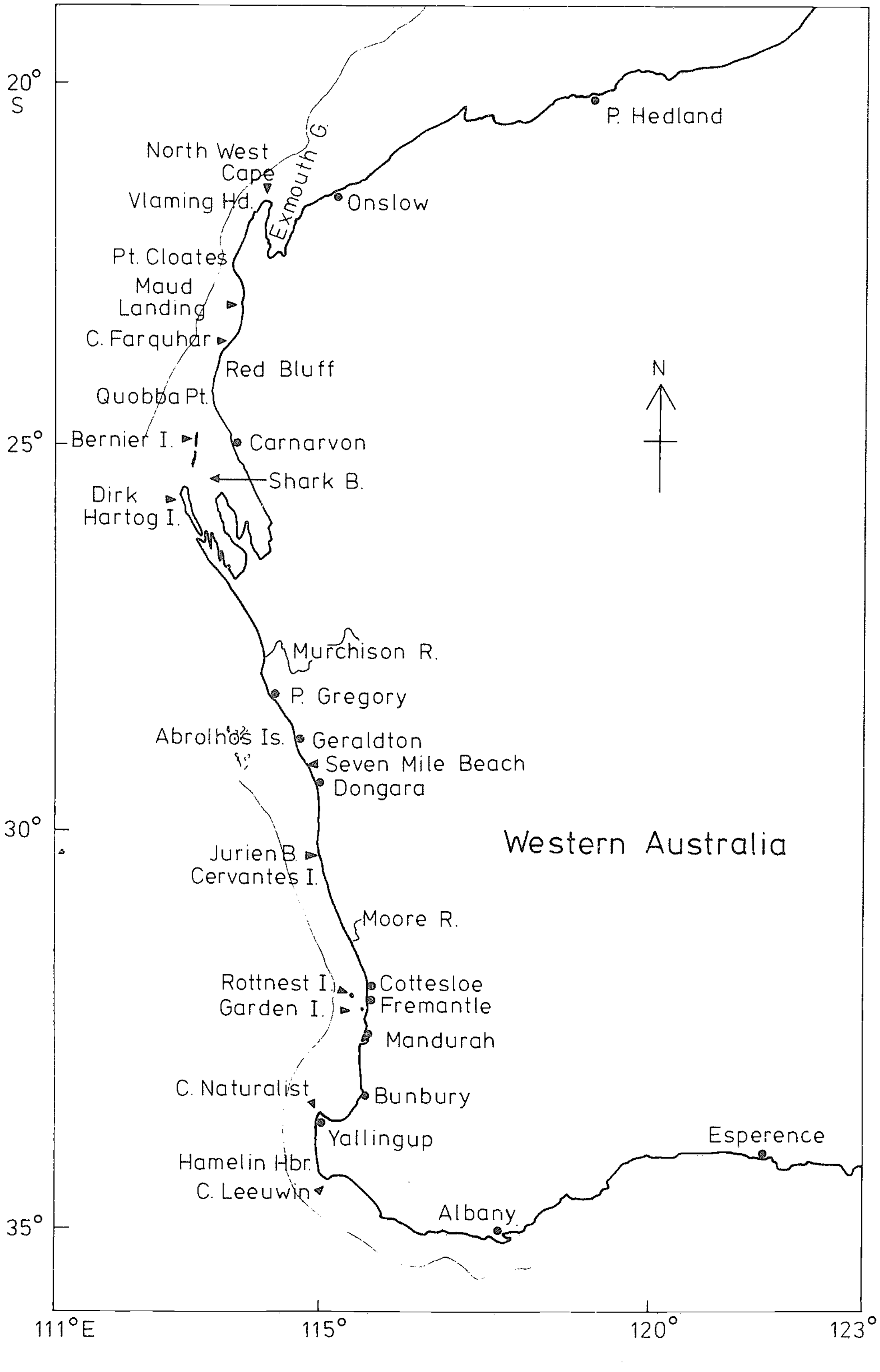


Figure 3 Locality map of Western Australia

1972). A large cyclonic eddy or gyre of variable strength, approximately 100 km in diameter, centred about 32°00'S, 110°00'E and with an onshore flow in the region of 29°00'S to 31°00'S, was described as a permanent feature of the circulation by Wyrtki (1962). Andrews (1977) described this feature as a result of a meandering current which is associated with a number of "mesoscale" eddies about 100 to 200 km in diameter and which produced a coastward flow in the same region. The current then turned southward to run parallel to the continental shelf. Eddies of a similar nature were described in the area by Cresswell (1977), Golding and Symonds (1978) and Kitani (1977). Application of the classical theory of wind-driven circulation off the west coast of Australia showed surface transport vectors were seasonally variable and did not necessarily coincide with the movement of underlying water (Cresswell, 1972).

2.2 Differential Distribution

2.21 Larvae and juveniles

- Areas of occurrence and seasonal variations

The distribution and abundance of the larvae of *P. cygnus* (see Section 3.22 for developmental stages) has been studied by Chittleborough and Thomas (1969), Phillips et al. (1978), Rimmer and Phillips (1979), Phillips et al. (1979) and Rimmer (in press).

It has been found that the phyllosoma larvae are transported over large distances in the south eastern Indian Ocean during their 9-11 month larval life. This begins during the late spring and summer (November-February) when hatching occurs and the majority of phyllosoma larvae are rapidly transported offshore while developing through Stages I to II. Few larvae remain on or near the continental shelf. By the time the larvae develop to the mid stages the majority have not only been transported well offshore but are also distributed over an extensive area of the south eastern Indian Ocean.

The westward limit of larval distribution has not been determined but significant numbers of larvae have been found as far offshore as 99°00'E (1 500 km offshore) at 29°30'S (Phillips et al., 1979). The area of greatest abundance was approximately west of the centre of the adult distribution.

Studies of the late phyllosoma and puerulus larvae of *P. cygnus* (Phillips et al., 1978) showed that at the end of their planktonic existence the late phyllosoma larvae are transported back by the water circulation of the south eastern Indian Ocean toward the coast of Western Australia. This results in a concentration of late stage phyllosoma larvae in the waters off the continental shelf in the region of 29°-30°S between August and December. Mixing of oceanic waters with the waters of the continental shelf of Western Australia occurs only on the outer third of the shelf. Because of this lack of mixing of the shelf and oceanic waters, the majority of late stage phyllosoma larvae are not carried onto the continental shelf but are carried southward down the West Australian coast outside the shelf by the water currents.

The last phyllosoma larvae moults to the puerulus stage in the waters beyond or just on the continental shelf and the puerulus completes the planktonic cycle by swimming approximately 40 km across the shelf and settling in the shallow inshore reef areas. The puerulus stage is not at the surface in the waters on the shelf but just prior to settlement rises to the surface in the inshore area (Phillips et al., 1978).

The peak of settlement occurs during the spring and early summer (September-January) (Phillips and Hall, 1978). (See also Section 2.34 for vertical distribution of larvae.)

The puerulus stage metamorphoses into a juvenile rock lobster and then spends the next 4-5 years on the shallow "nursery" reefs (Chittleborough, 1975). The younger juveniles concentrate on the shallow limestone reefs to depths of 10 m, with some larger juveniles being found at depths up to 20 m (Chittleborough and Phillips, 1975). Each juvenile was found by Chittleborough (1974b) to have a relatively small home range, remaining on the one segment of shallow reef for several successive years.

2.22 Adults

Most of the adult population lives in a broad strip of the continental shelf at depths of 30-90 m. Where offshore islands rise steeply from depths of 30 m or more, and also where the coastal zone (0-30 m) is very narrow, breeding adults may be found on shallow reefs together with the juveniles. Fishermen sometimes locate patches of western rock lobsters in deep water (to 160 m), but only a low proportion of the total stock lives deeper than 90 m (Chittleborough, in press). *P. cygnus* lives in the crevices and caves of reefs and ledges and amongst coral growths (where these exist) in which shelter and an adequate food supply can be found (Sheard, 1962). Discontinuous distribution is related to the availability of these suitable reefs.

George (1958a) showed by tagging studies that there is an annual migration in November and December of juvenile (pre-adult) *P. cygnus* into the adult population in deeper water. These *P. cygnus* are usually pale in colour and are commonly referred to as "whites". These animals assume the usual darker colour during subsequent moults.

2.3 Determinants of Distribution Changes

2.31 Currents

George and Main (1967) consider that evolution in genus *Panulirus* was governed primarily by the response of the pelagic larval stages to water circulation patterns. It is believed that the ancestral species is best represented by *P. longipes longipes* and it was envisaged that by the end of the first plicene glaciation, *P. cygnus* along with *P. japonicus*, *P. marginatus*, *P. pascuensis* were peripheral, isolated representatives of "*P. longipes*" each species perhaps responding to separate "endemic" current systems.

Chittleborough (in press) considers a major source of larval losses may be the variability of water circulation off the coast of Western Australia, causing fluctuations in the numbers returned close enough to the continental shelf for successful settlement, thus possibly limiting population distribution toward the periphery of the range of *P. cygnus*.

Rimmer and Phillips (1979) have shown that diel migrations and vertical distribution have a vital role in the relationships between circulation in the southeastern Indian Ocean and in the transport and dispersal of the phyllosoma larvae of *P. cygnus* (see Sections 2.34 and 2.1). Early stages became displaced offshore by wind-driven ocean surface transport by being at the surface at night when offshore vectors dominated and below the depth of wind-induced transport during the day when offshore vectors were small or negative. Mid and late larval stages, because of their deeper daytime distribution and absence from the surface on moonlit nights, became subject to the circulation of the water underlying the immediate surface layer. A coastward mass transport has been demonstrated for waters of the southeast Indian Ocean in the upper 30 m. It is hypothesized that this accounts for the return of the phyllosoma to areas near the continental shelf edge from whence the larval cycle can be completed by the puerulus stage.

- Weather conditions

The vertical migration of the larval Stages I and II is disrupted by rough weather conditions, apparently because the swimming ability of these early stages is not adequate to allow them to move upward in turbulent conditions. They therefore become distributed more or less uniformly through the mixed layer at night. They appear capable of moving downward to attain their normal daytime distribution despite the turbulence. Weather conditions do not appear to affect the vertical movement of the mid and late stages.

2.32 Temperature

P. cygnus has a wide temperature tolerance. Chittleborough (1975) recorded the temperature ranges from winter to summer at two research areas. In the southern part of the coastal range of *P. cygnus*, at Garden Island, the sea water temperature ranged from 15.9°C to 24.7°C while at Seven Mile Beach, close to the centre of its coastal range the temperature ranged from 15.8°C to 27.6°C. Sheard (1949) suggested that temperature could be a limiting factor since *P. cygnus* is found in slightly cooler waters than most other species of *Panulirus*.

George and Main (1967) considered that, during the evolution of the genus *Panulirus*, temperature played an important role in determining distribution but thought that this was secondary in importance to water circulation.

No association was found between water temperature and the geographic distribution of phyllosoma larvae (Chittleborough and Thomas, 1969; Ritz, 1972a), or the spatial distribution of the larvae (Rimmer and Phillips, 1979).

2.33 Food

Both growth and survival of the last larval stage of *P. cygnus* may be restricted by shortages of planktonic food, due to the low productivity of the waters off the coast of Western Australia (Chittleborough, 1979).

It is likely that food availability affects the distribution of juvenile and adult *P. cygnus*. Chittleborough (1975) found that shortages of food through overcrowding on nursery reefs was one of the major causes of density-dependent mortality.

2.34 Light

Generally the early stage phyllosoma larvae of *P. cygnus* are found within the upper 70 m of the water column and mid to late stages within the upper 150-200 m. All stages are positively phototrophic to low intensity light and negatively phototrophic to high intensity light. Consequently they migrate toward the surface as daylight fades during the afternoon and descend as it increases through the morning.

There is a change in the phyllosomas' response to low light levels as they develop. The threshold for negative phototrophism is at a higher light intensity for early stages than for late stages. The early stages appear at the surface at night irrespective of the intensity of moonlight while the late stages only appear at the surface when lunar illuminance is less than about 5 percent of full moonlight. Peak densities of late stages are found at increasingly greater depths at night with increasing lunar illuminance. The depths where phyllosoma occur during daylight concur with this concept of the larvae following a zone of optimal light intensity, with the optimum for early stages being higher than for late stages. The range of optimal illuminance is in the order of 50-250 $\mu Em^{-2}sec^{-1}$ for early stages, 20-200 $\mu Em^{-2}sec^{-1}$ for mid stages and 5-50 $\mu Em^{-2}sec^{-1}$ for late stages. The greatest numbers of early phyllosoma reach a maximum depth of about 30-60 m at about midday. Mid and late stage midday peaks occur in the 50-120 m range (Rimmer and Phillips, 1979).

2.35 Salinity

It is unlikely that salinity is an important factor in determining the distribution of *P. cygnus*. The salinity ranges over its distribution (see Section 2.1) are well within the tolerance limits of *P. cygnus*, found by Dall (1974a) to be from 25°/oo to 45°/oo.

The vertical distribution of larvae was found to be unaffected by changes in surface salinity, which ranged from 35.13 to 35.99°/oo (Rimmer and Phillips, 1979).

2.36 Behaviour

Chittleborough (1975) found that juvenile *P. cygnus* can be limited in their distribution on an uncrowded reef due to their gregarious behaviour and limited home ranges.

As described under 2.22 is a migration of pre-adult juveniles to deeper water where the majority of the adults are located and breeding occurs.

2.4 Hybridization

Near-adult specimens of *P. cygnus* with pale spots on the legs, characteristic of specimens of *P. longipes longipes* from the type locality of Zanzibar, have been taken occasionally from reefs on the coast of Western Australia. Chittleborough and Thomas (1969) showed that the phyllosoma larvae of *P. cygnus* are not completely separated from the phyllosoma larvae of tropical populations of *P. longipes longipes* in the Indian Ocean so there is apparently some gene flow from the north.

3 BIONOMICS AND LIFE HISTORY

3.1 Reproduction

3.11 Sexuality

- Hermaphroditism, heterosexuality, intersexuality

P. cygnus is dioecious and heterosexual

- Sexual dimorphism

Sheard (1949) demonstrated sexual dimorphism of the walking legs with mature males over 108 mm c.l. having longer legs than equivalent size females.

3.12 Maturity

- Size at which sexual maturity is reached and its variations with sex, subpopulations and rate of growth.

Estimates of the size at first maturity for *P. cygnus* have involved females since the males do not possess satisfactory indicators of sexual maturity. Several criteria have been used for females, namely, the presence of well developed setae on the endopodites (George, 1958b), the size of the smallest mature animal (Sheard, 1954; Chittleborough, 1976b), the size of the largest mature animal (Sheard, 1954) and the size at which 50 percent of the females are breeding (George, 1958a; Chittleborough, 1976b; Morgan and Barker, 1974, 1975, 1976 and 1977).

Chittleborough (1976b) found that the presence of setae on the endopodites is an unreliable indicator of sexual maturity and used in preference the carapace length at which 50 percent were breeding and the carapace length of the smallest breeding female. By reference to Table I it can be seen that based on these criteria the size of females at first breeding is much smaller at the Abrolhos Islands than elsewhere, which is in accord with similar findings by George (1958a, 1958b).

Data from Morgan and Barker (1974, 1975, 1976 and 1977) show that the size at first maturity varies significantly throughout the range of *P. cygnus* with size ranging from around 80 mm c.l. in northern areas to 95 mm in southern areas.

Chittleborough (1976b) estimated from studies on the growth of juvenile *P. cygnus* that the mean age at first breeding would be at 7-8 years of age and he considered that the smallest sizes of mature animals at the Abrolhos Islands did not indicate an earlier age of maturity but rather that the growth rate must be severely retarded in this area.

From aquarium studies Chittleborough (1974a) determined the age at maturity to be from 4.9-5.6 years for females and concluded that males mature at the same time or earlier. The sizes at first maturity (87-106 mm) were considerably greater than those found in wild population and were apparently due to the optimal environmental conditions in captivity.

TABLE I

Size of females of *Panulirus cygnus* at first breeding each summer (December to February) at various localities (after Chittleborough, 1976b)

Locality	Smallest breeding c.l. (mm)	c.l. at first breeding (mm)	
		Mean	s.d.
Fremantle (30°03'S)			
1954 (George, 1958a)	74	77.2	3.5
1971-72	83	93.0	4.5
1972-73	83	96.2	5.4
1973-74	78	98.0	4.7
1974-75	85	96.2	5.7
Lancelin (31°01'S)			
1972-73	82	95.7	5.3
1973-74	83	95.0	6.7
1974-75	86	96.4	6.0
Jurien Bay (30°17'S)			
1971-72	67	86.0[a]	5.6
1972-73	70	80.7[a],[b]	7.6
1973-74	71	91.0[a]	7.8
1974-75	72	86.5[a]	4.2
Dongara (29°15'S)			
1971-72	77	87.4	3.9
1972-73	78	81.7[b]	3.2
1973-74	-	-	-
1974-75	77	91.0	4.9
Abrolhos Islands (28°43'S)			
Oct. 1964	59	64.9	4.6
Dec. 1974	56	70.1	5.3

c.l. = carapace length; [a] Excluding those taken at +55 m depth; [b] January data only

3.13 Mating

Mating is by limited polygamy (Sheard, unpublished).

3.14 Fertilization

Fertilization is external.

Sperm packets are deposited on the sternum and a cementing material is extruded around the spermatophores which darkens and hardens rapidly to form the 'tar-spot'. During spawning the sub-chelate dactyls of the fifth walking legs are used to break through the protective coat of the cement material, opening the spermatophores so that eggs can be fertilized when they are swept back to adhere to the elongated setae on the endopodites of the pleopods (Chittleborough, 1976b).

3.15 Gonads

- Relation of egg numbers to body length

Fecundity of *P. cygnus* was estimated by Morgan (1972). These estimates were based on egg counts of samples from "berried" females obtained from three locations (see Table II). A linear relationship is evident for the number of spawned eggs produced against carapace length. No geographical variation in fecundity was found, and it appears that fecundity is size-specific rather than age-specific. An estimated fecundity was obtained by pooling the data from the several localities. In Figure 4 the number of newly spawned (orange) and late stage (brown) is plotted against carapace length.

The egg loss during incubation in *P. cygnus* is not significant and this is consistent with its relatively short incubation period (Morgan, 1972).

TABLE II

The total number of eggs (N) for each specimen of *Panulirus cygnus* (Morgan, 1972)

Abrolhos area		Fremantle area		Jurien Bay area	
Carapace length (mm)	$10^{-3}N$	Carapace length (mm)	$10^{-3}N$	Carapace length (mm)	$10^{-3}N$
(a) Newly Spawned Eggs (Orange)					
64.0	116	72.6	242	80.7	282
64.1	117	72.4	290	91.0	362
64.9	127	82.0	303	93.8	487
65.2	129	94.3	406		
70.0	204	97.9	499		
70.9	210	104.7	627		
73.1	256	116.7	682		
73.3	257				
76.0	284				
76.2	286				
79.3	251				
79.3	291				
83.0	259				
83.2	299				
86.0	338				
86.1	339				
93.7	395				
93.7	394				
(b) Late Stage Eggs (Brown)					
65.3	61	94.7	371		
70.0	96	94.9	388		
73.6	126	97.8	442		
74.6	133	99.1	381		
86.0	216	104.2	484		
94.6	343	114.4	505		
99.2	383	117.8	529		

- Number of broods

See number of eggs per brood (Section 3.15) and number of spawnings per year (Section 3.16).

- Correlation between the number of eggs and the nature of the environment

No data are available.

3.16 Spawning

- Number of spawnings per year

Chittleborough (1976b) found that 77 percent of females breeding in aquaria at ambient temperatures had two successive spawnings in a breeding season. Chittleborough (in press) found that in natural populations densities less than 12 percent of breeding females spawn twice in a season, but when food is abundant a higher proportion of females spawn twice in a season.

- Spawning seasons

Along the coastal part of its distribution *P. cygnus* spawns during the spring and early summer (September-December) with the possibility of some variations (Chittleborough, 1976b). At the Abrolhos Islands however breeding commences at least one month earlier (George, 1958a).

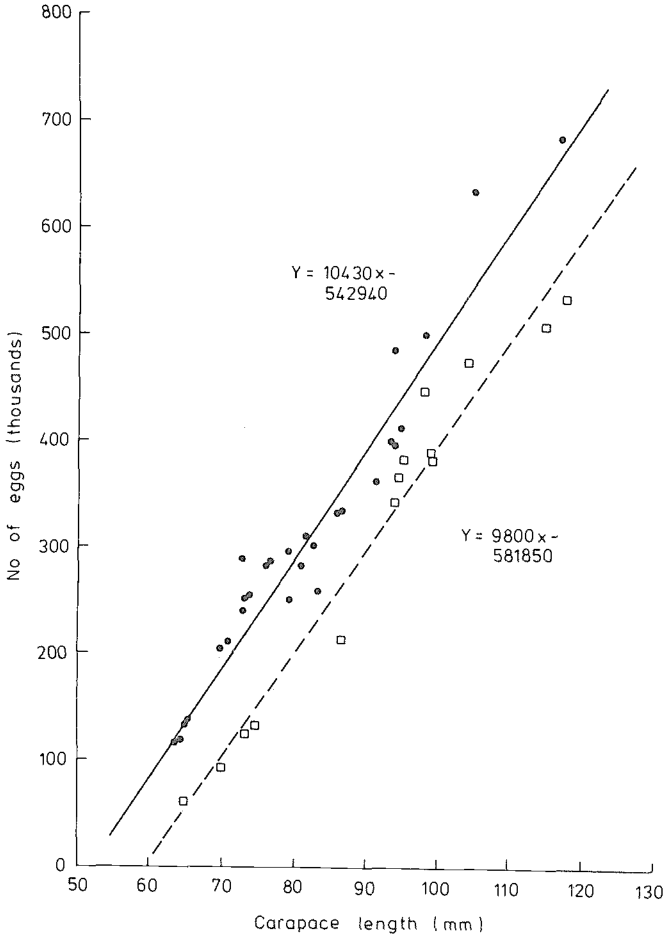


Figure 4 Relation between total number of eggs of *Panulirus cygnus* carried and carapace length for newly spawned (● ____ ●) and late stage (□ _ _ _ □) eggs

- Factors influencing spawning time

Early rises in water temperatures have been implicated in causing earlier hatching of larvae by stimulating earlier maturation of gonads (Chittleborough and Thomas, 1969).

- Location and type of spawning grounds

P. cygnus does not have specific spawning grounds as breeding females can be found throughout the range of the adult population and small numbers of adults are found on the shallow reefs together with the juveniles (Chittleborough, 1979). However, the greatest numbers of breeding females have been found to occur between the 37-55 m (20-30 fath) depth range (Morgan and Barker, 1974, 1975, 1976 and 1977).

- Reproductive isolation

See Section 2.4.

- Induction of spawning

Chittleborough (1976b) induced *P. cygnus* to spawn repetitively in captivity. Adult females, when kept at a constant temperature of 25°C with abundant food, bred continuously, averaging six spawnings a year.

In the field it has been postulated that the rising water temperature in spring and early summer induced spawnings by stimulating the maturation of the gonads (Chittleborough and Thomas, 1969).

3.17 Spawn

- Description of external morphology

Apart from the observation made by George (1958b) that freshly extruded eggs are bright orange in colour there are no data available on the nature of the spawn.

3.2 Pre-Adult Phase

3.21 Embryonic

- General features of development of embryo

The eggs of *P. cygnus* show a marked change in coloration during embryonic development, from a bright orange to brown (George, 1958b). Eye spots become discernible 22 days after spawning in eggs of a captive "berried" female (Chittleborough, 1967).

- Rates and periods of development and survival and factors affecting these, including parental care

The incubation period of eggs was found to vary from 19 to 68 days by Chittleborough (1976b) and was inversely related to water temperature, being longest at 19°C and shortening toward an asymptote at 25°C.

Chittleborough (1967) observed that captive "berried" females shield their eggs when moving and at rest, repeated movements of the fifth pair of legs are noticeable, the dactyls being employed in the manipulation of the eggs. The pleon is raised and partially extended at intervals, while the uropods are employed in waving and beating motions. Chittleborough considered these actions as an attempt to increase the circulation of the water around the eggs, or to free them from parasites or other foreign bodies.

A small amount of egg loss was found to occur during incubation (Morgan, 1972) but it was not significant.

- Effect of environment, spawn size and subpopulations on rates of development and survival

Morgan (1972) found that the percentage of infertile eggs was independent of carapace length. This means that fertility is also independent of spawn size since there is a linear relationship between carapace length and number of eggs produced. Table III gives the percentage of infertile eggs in 0.5 g samples of late stage eggs.

- Mode of hatching

Chittleborough (1974a) reported that in the laboratory eggs all hatch more or less simultaneously (within the space of a few hours) and the larvae concentrate at the surface of the water.

3.22 Larval phase

- General features of development

George and Cawthorn (unpublished) made the first attempt to delimit the phyllosoma larval stages of *P. cygnus*. The resultant 11-stage key was unsatisfactory and Chittleborough and Thomas (1969) constructed a simplified 9-stage key. However, this also was found to be unsatisfactory because there were individual variations in the sequence in which certain morphological features appeared and differences in the rate of development of some appendages. As a result, Braine *et al.* (1979) made more definite descriptions of the development of the phyllosoma stages and produced a new 9-stage key.

Key to Phyllosoma Stages of *Panulirus cygnus*

1.	Eyestalk simple, unsegmented. . .	Stage I
	Eystalk segmented	2
2.	Exopod of 3rd pereiopod not setose.	Stage II
	Exopod of 3rd pereiopod setose . .	3
3.	4th pereiopod shorter than abdomen and not segmented. . . .	Stage III
	4th pereiopod segmented and as long as or longer than abdomen	4
4.	Antennule comprises 2 segments, exopod of 4th pereiopod not setose.	Stage IV
	Exopod of 4th pereiopod setose . .	5
5.	Antennule comprises 3 segments. . .	Stage V
	Antennule comprises 4 segments . .	6
6.	Uropods not bifid	Stage VI
	Uropods bifid	7
7.	Distal pair of pleopods not bifid, abdomen not segmented or segmentation very weakly defined.	Stage VII
	Distal pair of pleopods bifid, abdomen segmented	8
8.	Gills not present at base of pereiopods or adjacent thorax pleopods without appendix interna, uropods without lateral spine.	Stage VIII
	Gills present on dorsal surface at base of pereiopods and adjacent thorax. Pleopods with appendix interna, uropods with lateral spine	Stage IX

Braine *et al.*, (1979) examined the distributions of the length frequencies of the phyllosoma larvae. Stages I, II, III, V and IX were found to be unimodal, and it was concluded that these stages were represented by single instars. On the same basis, Stages IV and VIII were considered having 2 instars, from a bimodal distribution, and it was tentatively suggested that Stage VI had 5 instars, from a polymodal distribution, making a total of 14 instars.

TABLE III

Percentage of infertile eggs in 0.5 g samples of late stage eggs (Morgan, 1972)

Abrolhos		Fremantle	
Carapace length (mm)	Infertile (%)	Carapace length (mm)	Infertile (%)
65.3	4.2	94.7	3.8
70.0	7.0	94.9	6.8
73.6	3.6	97.8	6.1
74.6	5.1	99.1	3.3
86.0	3.9	104.2	3.4
94.6	4.1	114.4	4.1
99.2	3.2	117.8	4.6

The last phyllosoma larva (Figure 5) metamorphoses into a transitional stage called the puerulus (Figure 6) which, for a time, forms part of the plankton or possibly the nekton. It subsequently settles in the shallow inshore reef areas and moults into a post-larval or early juvenile stage in which the adult morphology has been assumed (Phillips, 1972).

The puerulus stage has been described by George (1962) as follows: Carapace dorso-ventrally compressed with two lateral carinae, each terminating anteriorly at a spine. Posterior half of carapace without spines, anterior region with one pair of depressed conjoined supraorbital spines, one pair of spines behind these, one pair behind the eyes and one pair at antero-lateral angles of carapace. Antennae gradually tapered to tip, slightly longer than total length of body (antennae 1.02 to 1.14 times total length). Tergum of antennular plate small, without spines. Posterior margin of thoracic sternum smoothly concave without teeth.

Abdominal terga transverse without grooves; pleura of segments 2-6 terminate in single posteriorly recurved spines. Each pleopod biramous, setose along margin and with appendix interna on endopod.

Exopod of third maxilliped uniarticulate, extends at least to base of merus. Exopod of second maxilliped reaches distal end of carpus. Pereiopods more or less uniform in length, without trace of exopods.

Live specimens are transparent except for some pigment on the eyes and the tips of the antennae, preserved specimens opaque or light brown. Sexes at the puerulus stage are externally indistinguishable.

- Rates and period of development and survival, and factors affecting these

Chittleborough and Thomas (1969) estimated that the average planktonic period of *P. cygnus* is between 9 and 11 months. Data collected by Phillips et al. (1979) support this estimate.

The duration of each phyllosoma larval stage is not known, but the time for *P. cygnus* phyllosoma to develop through Stages I to V appears to be approximately three months. The average time to develop through Stages VI to IX appears to be six to seven months. The greater length of time for the later stages may be accounted for in part by the number of instars. The average intermoult period for Stages I to V is probably of the order of 2-3 weeks, and for Stages VI to IX is approximately three weeks or perhaps slightly longer (Phillips et al., 1979).

Chittleborough (1979) considered that during the oceanic planktonic life of the larvae mortality was very high, and could be greater than 99.9 percent. Chittleborough (1979) considered that predation may account for a high proportion of this mortality. Some of the plankton or part plankton feeders that predate *P. cygnus* larvae are the pilchard (*Sardinops neopilchardus*), Spanish mackerels (*Scomberomorus* spp.) and various tuna species (Chittleborough, 1974a).

- Effects of environment, subpopulations, density on rates of development and survival

Variability of water circulation off the Western Australian coast causing fluctuations

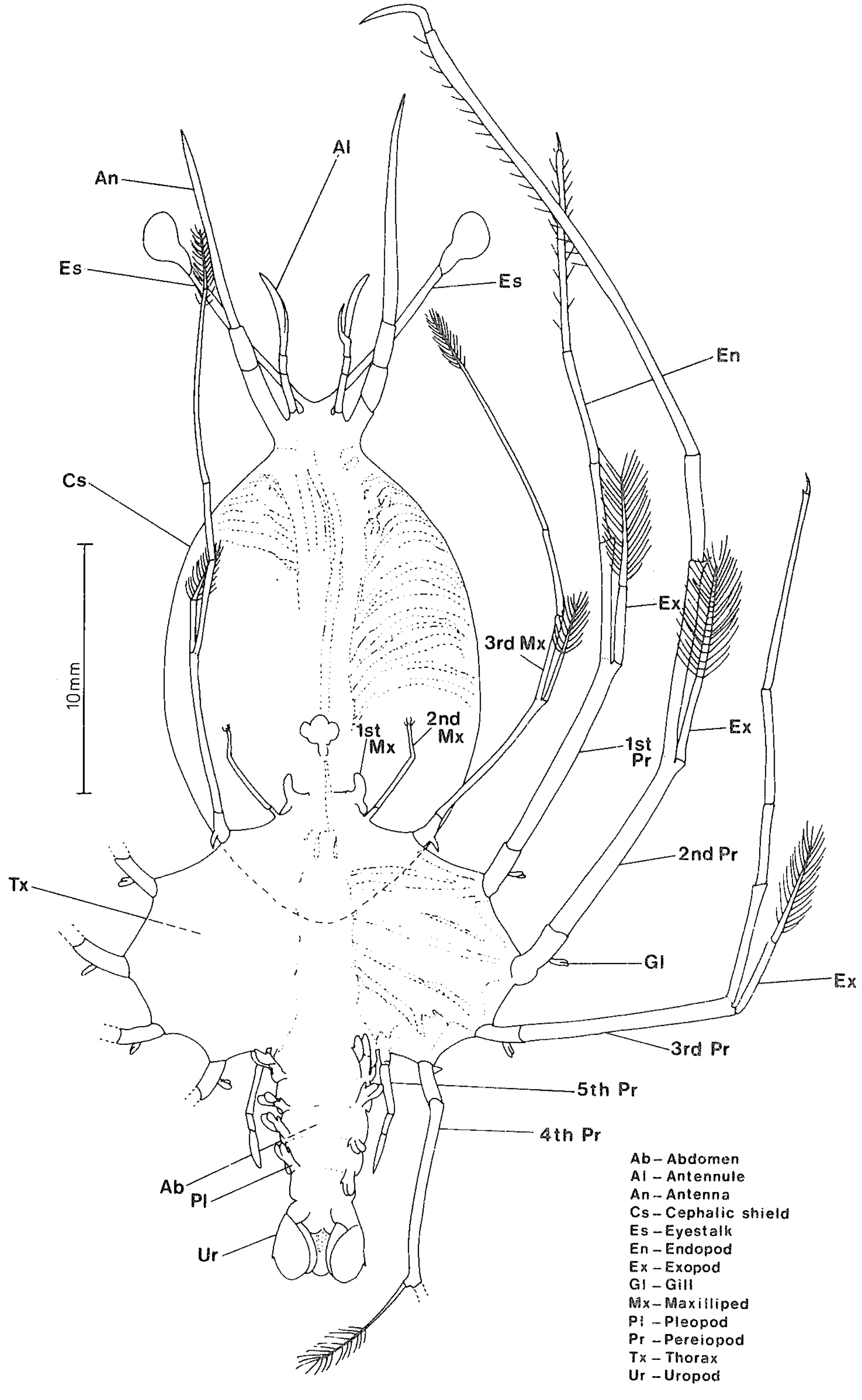


Figure 5 Stage IX phyllosoma larvae of *Panulirus cygnus* showing abbreviations used in the key to these stages

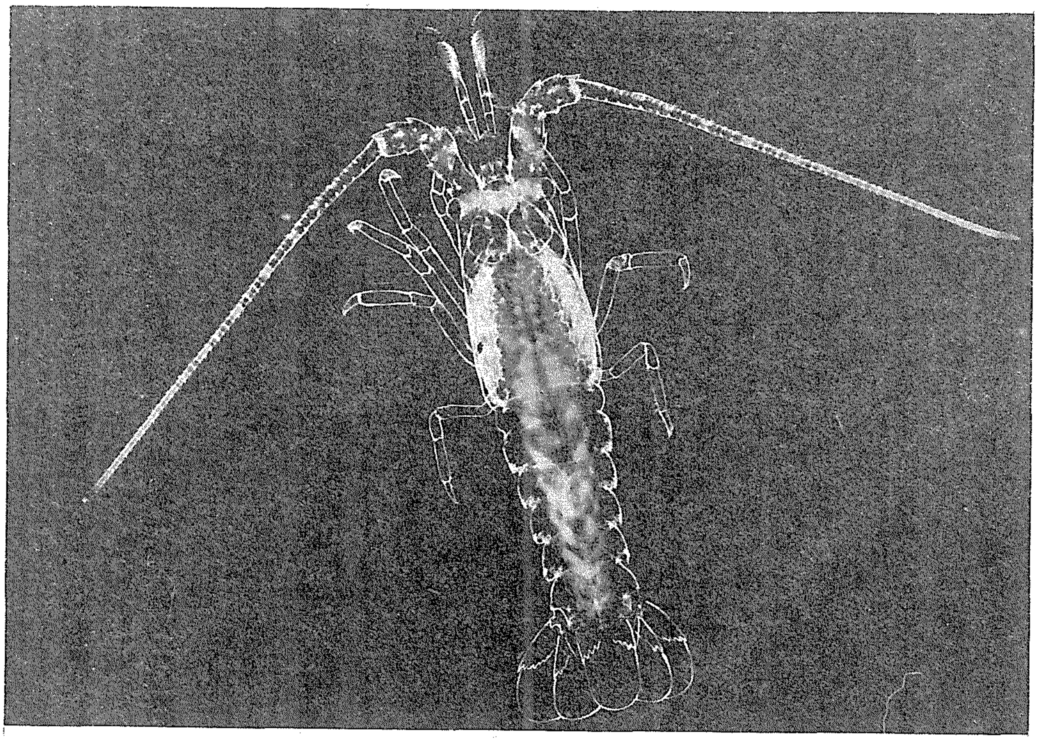


Figure 6 Puerulus stage of *Panulirus cygnus*

in the number of larvae returned close enough to the continental shelf for successful settlement may be an important cause of larval loss. The low productivity of the oceanic waters off the western coast of Australia has also been implicated in causing density dependent mortality of larvae and shortages of planktonic food, which also restrict growth (Chittleborough, 1979).

Ritz (1972) reported that the densities of early stage phyllosoma larvae of *P. cygnus* appeared to be independent of plankton biomass but found a correlation between plankton biomass and the densities of late stage phyllosoma larvae.

No relationship was found between the density of the puerulus stage of *P. cygnus* and nekton biomass (Phillips et al., 1978).

Phillips (1972) found that the puerulus stage of *P. cygnus* could be captured using collectors composed of artificial seaweed. Settlement followed a lunar periodicity, with the peak occurring during the spring and early summer (Chittleborough and Phillips, 1975).

Further work (Phillips, 1975b) showed that almost all settlement of puerulus of *P. cygnus* on the collectors occurs at night near the time of the new moon with most occurring during the period of no moon and ceasing when the moonlight intensity rises above a threshold value of about 10 percent of full moonlight. It has been suggested that moonlight intensity normally prevents puerulus entering into the area and hence restricts settlement on the collectors at nights other than near the time of new moon. However, since settlement does not commence until after the start of the dark phase, variations in light intensity alone do not fully explain the pattern of puerulus settlement. The manner in which the lunar phase acts on the puerulus to prevent settlement in unknown, as is the reason why moonlight can prevent settlement, but illumination of the collectors increase their catching effectiveness (Phillips, 1977).

Phillips (1975b) examined data on the water currents flowing into a settlement area and the catches of the puerulus stage of *P. cygnus* on collectors. No relationships were found between the volume of water flowing into the area and the catches of the collectors, either as a cyclic flow related to moon phase, or from night to night at the time of settlement. The puerulus entered the area and settled on the collectors during the night. On the nights on which settlement occurred, the puerulus may make use of the incoming water currents to aid them in swimming into the area (Phillips, 1977).

The catches on the collectors were shown to be useful measures of seasonal patterns and relative strengths of puerulus settlement. The settlement pattern on the collectors showed a similar pattern to that expected from the results of larval sampling programmes and the circulation pattern of the eastern Indian Ocean. The data on the relationship between the catches on the collectors and natural settlement were less satisfactory, and it was not possible to detect a definite relationship between the levels of catches of puerulus on the collectors and the resulting juvenile densities at the site examined. This may have been because the relationship was masked by the effects of natural mortality (which is probably density-dependent) and by the effect on this mortality of environmental factors (Phillips and Hall, 1978).

- Sensory systems

Some sensory aspects of vision and sound are known, there being no information on other senses such as touch, chemicals, etc. Early phyllosoma larvae of *P. cygnus* have been shown to be positively phototactic to very dim light (Ritz, 1972a). Ritz (1972b) also observed that late stage phyllosoma larvae tend to concentrate at the surface on darker nights and that in general few were taken in plankton net catches at the surface in bright moonlight. Underwater lights were used to observe free swimming puerulus larvae of *P. cygnus* and it was reported that the puerulus were either attracted or bemused by the light, but certainly not repelled (Phillips, 1975a). Phillips (1975a) found that nocturnal illumination of collectors resulted in increased catches of the puerulus larvae of *P. cygnus*.

On the basis of anatomical evidence the eye of the puerulus stage of *P. cygnus* may be capable of extremely efficient perception of polarized light (Meyer-Rochow, 1975a, b).

It has been shown that the rasping sound produced by juvenile and adult rock lobsters cannot be produced by the puerulus stage of *P. cygnus* as the physical mechanism is only partly developed in the puerulus stage (Meyer-Rochow and Penrose, 1974).

- Behaviour

Phyllosoma larvae of *P. cygnus* are not well adapted for swimming but can perform some movements (Phillips, 1977). Minimal rates of net vertical movement have been estimated for the larvae by Rimmer and Phillips (in press). Early stages exhibited mean net rates of ascent and descent of 13.7 and 13.0 m h $^{-1}$, respectively, while the rates for mid stages were 16.0 and 16.6 m h $^{-1}$ and for late stages 19.4 and 20.1 m h $^{-1}$.

The swimming behaviour of the puerulus stage of *P. cygnus* was studied by Phillips and Olsen (1975). All puerulus larvae observed were found to be swimming alone and no contacts or reactions between individuals were noticed. Swimming speeds of approximately 33 cm s^{-1} (max) and approximately 15 cm s^{-1} (mean) were recorded. The puerulus stage was found to be capable of avoidance reactions by a rapid flexing of the abdomen.

The puerulus stage has a strong grasping reaction presumably related to its transitional role between the planktonic and benthic existence (Phillips, 1972). Chittleborough (1967) reported that puerulus were found adhering to seaweed, and fishermen often found them clinging to ropes and pots. The grasping behaviour has been used by Phillips (1972) to develop a collector composed of artificial seaweed to catch the puerulus stage of *P. cygnus*.

- Type of feeding

According to Chittleborough (1967) the *P. cygnus* larvae are predominantly carnivorous at each phase of their life cycle. Newly hatched larvae in aquaria will accept brine shrimp larvae. Late stage phyllosoma take larger planktonic crustacea such as euphausiids (Chittleborough and Thomas, 1969).

3.3 Juvenile and Adult Phase[1/]

3.31 Longevity

- Average age

No data are available. For details of mean size from catch records refer to Section 4.13.

- Maximum age

P. cygnus may reach an age of 15 years or more (Phillips, 1975c).

3.32 Hardiness

- Limits of tolerance to changes in or of environments, and feeding

Chittleborough (1975) investigated environmental factors affecting growth and survival of juvenile *P. cygnus* in the laboratory and related these findings to the field.

[1/] The juvenile and adult phases have been combined together in the one section, because the majority of information gathered from research on juveniles is equally applicable to the adult phase. However, in those areas where there is doubt about the applicability to both age groups, the age group to which the data refer has been designated in the text

A mild deficiency of oxygen (60-70 percent saturation) caused a smaller size increment at a moult, further depression to 47-55 percent saturation caused death at ecdysis. Details of the effects of other environmental factors are given in Sections 2.2 and 3.53, and the effects of changes in feeding are given in Section 3.4.

- Limits of tolerance to handling and life in the aquaria or other confined environments

Bowen (1963) considered that the mortality of animals below the legal minimum length (76 mm c.l.) when caught and returned to the sea was higher than those not caught, due to damage by handling. This problem has been greatly alleviated by the introduction of escape gaps in rock lobster pots (Bowen, 1971).

- Variations in hardiness with age, size and physiological state

The period during the hardening of the carapace just after moulting is critical to *P. cygnus*. The soft carapace makes the animals particularly susceptible to predation and to cannibalism (Phillips, 1975c). Since juveniles moult at a higher rate than legal size animals (Chittleborough, 1970), the natural mortality rate reduces with age (see Section 4.41).

3.33 Competitors

Over the greater part of its range *P. cygnus* has no allied species as a competitor. Competition occurs only with *Janus lalandei* in the extreme southern part of the range of *P. cygnus* and with the rock lobsters *P. penicillatus*, *P. ornatus*, *P. versicolor*, *P. homarus* and *P. polyphagus* in the northern part. Competition is direct with *J. lalandei* but it may not be so with the five northern species which may fill quite different ecological niches (Sheard, 1949).

Evidence put forward by Chittleborough (1975) indicates that octopus can compete for shelter on reefs. Rock lobsters will actively avoid the sites occupied by octopus.

Several species of fish and crabs compete with rock lobsters for food. On some of the more exposed reefs the frequency with which the crab *Plagusia chabrus* is taken in rock lobster traps indicates that this species may compete strongly for food (Chittleborough, 1975).

3.34 Predators

- Types of predators

Among direct predators on *P. cygnus* are the octopus, *O. tetricus* (Joll, 1977) and various fish, including the Abrolhos groper (*Choerdon cyanodus*), the bald-chin groper (*Choerdon payneil*), Westralian dhufish (*Glaucosoma hebraicum*), snapper (*Chrysophys unicolor*), and the whiskery shark (*Furgaleus ventralis*) (Sheard, 1949; Chittleborough, 1975).

3.35 Parasites, diseases, injuries and abnormalities

- Parasites and diseases

Large numbers of *P. cygnus* were caught in November 1978, at the commencement of the fishing season, from apparently normal reefs, with extensive and deep shell lesions (Dall, in press).

- Injuries and abnormalities

The autotomy of limbs is the most prevalent injury incurred by *P. cygnus* and it has been regarded as having its main survival value in escaping from predators (Chittleborough, 1975). However, Chittleborough (1975), from laboratory observations on moulting animals, noted that those animals which experienced difficulty in freeing limbs from exuviae readily autotomized the offending limbs in order to escape from the old shell. Chittleborough (1975) considered this of great survival value for *P. cygnus* because any delay in freeing themselves from the exuviae during ecdysis means that the rapid intake of water at the time may result in the animal being trapped in the partly shed exuviae and dying.

- Ability of regeneration

From experiments conducted in the laboratory Chittleborough (1975) found that missing legs were replaced at the following moult.

- Effect on physiology and survival of individuals

The effects of limb loss will probably incorporate a reduced ability to compete for food and to escape from predators (Chittleborough, 1975).

An investigation into the effects of limb loss on growth in *P. cygnus* was conducted by

Chittleborough (1975). Using animals which were supplied with excess food he found that the regular removal of two legs led to precocious moulting. However, there was in fact a slight increase in the overall growth rate due to the higher frequency of moulting with no suppression of the growth increment per moult. In contrast the regular removal of four legs resulted in an overall decrease in growth rate because the higher frequency of moulting was accompanied by a lower growth increment per moult.

3.4 Nutrition and Growth

3.41 Feeding

- Time of day

According to George (1958b) *P. cygnus* is relatively inactive during the day and feeds mostly at night. Chittleborough (1975) thought that the feeding behaviour of *P. cygnus* was similar to that of *Panulirus japonicus* (V. Siebold) which is a nocturnal forager having a bimodal feeding activity with peaks corresponding to dusk and pre-dawn. In contrast Phillips (1975a) states that *P. cygnus* feeds mostly after sunset although some animals can be found feeding at any time during the night. This view is supported by Morgan (1978) who found that peak locomotor activity occurs just after dusk (see Section 3.53).

- Place, general area

According to Sheard (1962) *P. cygnus* feeds in close proximity to its shelter, with the direction and extent of its foraging controlled by characteristics of the reef topography and occurrence of suitable food. This view was supported by Chittleborough (1974b) who found that juveniles did not feed at random over a relatively uncrowded reef. The juveniles possessed definite home ranges which did not exceed 15 m in radius. Chittleborough (1974b) emphasized the importance of food supply in determining the foraging areas, which were considerably larger on more crowded reefs.

- Variation of feeding habits

Chittleborough (1970, 1975) examined food intake in *P. cygnus* which was found to be lowest immediately prior to moulting and highest shortly after moulting. Juvenile *P. cygnus* aged 2+ ceased feeding 2-6 days before moulting. Feeding recommenced within 2 days of moulting, food intake rising rapidly to a peak on the 4th or 5th day. Thereafter, the daily food intake followed a downward trend, though fluctuating very considerably until it finally ceased prior to the next moult.

Feeding rate varies with temperature. A group of juveniles kept at 26°C had a significantly faster feeding rate than a group kept at 23°C (Chittleborough, 1975).

When food is in short supply, as often occurs on crowded reefs, *P. cygnus* will forage over a wider area (Chittleborough, 1974b) and may even feed during daylight (Phillips, 1975c).

- Absention from feeding

P. cygnus abstains from feeding just prior to moulting and just after moulting. However, the lengths of time involved are not known precisely. George (1958b) thought that feeding did not occur for a period of 12 days after moulting whereas Phillips (1975c) considered this time period to be from 3-4 days for juveniles.

Chittleborough (1975) from laboratory studies found that juveniles (2+ years) did not feed for a period of 2-6 days prior to feeding but recommenced feeding within 2 days after moulting.

Unlike other species of lobsters, female *P. cygnus* carrying eggs will actively forage (Chittleborough, 1974a).

3.42 Food

- Types eaten and their relative importance in the diet

The western rock lobster is basically a scavenger, feeding on the sedentary or semisedentary reef flora and fauna.

From an examination of gut contents, George (1958b) found fragments of plant, animal and substrate, which included *Ulva*, coralline alga, echinoderm spines, small gastropods, crustaceans, annelids, sabellids and sipunculids.

Chittleborough (1975) obtained through experiments in aquaria an indication of the food preferences of this species. In general *P. cygnus* prefers molluscs and fish rather than mammalian flesh, and fresh food is preferred rather than stale. Western rock lobsters held in aquaria fed readily on abalone (*Haliotis roei*), mussels (*Mytilus edulis planatus*), and *Octopus* sp. flesh, various teleosts, crabs and less readily on sea urchins (*Heliocidaris* sp). To test for preference toward either fish or abalone, 12 aquaria each holding four juvenile rock lobsters were supplied daily with weighed quantities of fish and abalone in equal numbers of pieces. Uneaten pieces were removed the next day, drained and weighed. Over three nights the 48 rock lobsters consumed a total of 401 g of abalone muscle and 87 g of fish (i.e., a ratio of 46:1).

- Volume of food eaten during a given feeding period

The quantity of food eaten was determined by Chittleborough (1975) by holding juvenile western rock lobsters in separate aquaria, supplying a weighted piece of abalone foot muscle each day, and weighing the uneaten residue remaining the next morning.

The mean daily intake of food throughout each intermoult period was compared and the feeding rate for 2-year old juveniles held at 26°C (2.67 ± 0.20 g/d) was significantly higher than at 23°C (2.06 ± 0.20 g/d).

There was no regular pattern of feeding activity, but the results did indicate a period of intense feeding after moulting which thereafter followed a downward trend though fluctuating considerably.

3.43 Growth rate

- Moulting; manner and moulting cycle

Thomas (1966) has described in detail the moulting behaviour of *P. cygnus*. It involves, as in other decapod crustaceans, an escape from the old exoskeleton between the cepholothorax and the first abdominal segment first withdrawing the anterior region, and then flipping off the 'tail' shell. The actual moult (i.e., the withdrawal from the old shell) occupied 8-10 minutes.

- Absolute growth patterns and rates

Growth in *P. cygnus*, as in other decapod crustaceans, takes place discontinuously in a series of steps when ecdysis occurs. Therefore growth consists of two components: (1) moult increment, (2) moult frequency.

Chittleborough (1976a) compared the growth of six juvenile *P. cygnus*, raised for six years in aquaria, with the growth of juveniles in the wild population using single moult increments as well as annual growth. The growth rate of the latter juveniles was determined by shifts in modal growth and returns of tail punched and tagged individuals. Tagging was carried out using the "western rock lobster tag" developed by Chittleborough (1974c) which is particularly effective in mark and recapture studies of growth.

The increments per moult for the aquaria reared juveniles was found to be greatest during the third and fourth year of life. Under the conditions of minimal environmental stress in which these juveniles were raised, no significant difference in moult increments between the sexes was observed (see Table IV). The growth rate of these aquarium-held juveniles was found to be well represented by the von Bertalanffy (1938) growth equation:

$$t = 113.47 \{1 - \exp(-0.495 (t - 1.045))\}$$

Growth rates in different natural populations varied considerably. At three of the four localities examined, the growth of juveniles on shallow nursery reefs was retarded compared to growth under aquarium conditions.

The single moult increments in carapace length for three localities is given in Table V.

At Garden Island the mean increment per moult for males and females aged 3+ years was significantly less than in the aquarium. Moult increments of males increased from the age of 3+ to 5+ years while those of females did not vary significantly between these age groups. At Seven Mile Beach single moult increments were less than at Garden Island; however, there were no significant differences between age groups or sexes.

The annual growth in carapace length (mm) of marked juvenile *P. cygnus* 3+ and 4+ years at three localities is given in Table VI while a comparison of the growth rate at two of these localities with that under aquarium conditions is shown in Figure 7.

The growth of early juvenile *P. cygnus* in aquaria has been studied by Phillips et al. (1977) from the last larval stage to approximately three years of age. The growth rate was adequately described by the von Bertalanffy (1938) equation. The growth curves for two sets of juveniles held under different temperature regimes is given in Figure 8a and b.

Information on the growth of *P. cygnus* has also been obtained by Morgan (1977). The von Bertalanffy (1938) growth equation was found to adequately describe the growth rate at Fremantle and Geraldton. Details of the moult increment and moult frequency recorded for both sexes over a range of sizes at Rat Island is given in Table VII. The average intermoult period was 96 days.

- Condition factors

Dall (1974b) attempted to find an index of nutritional state in the western rock lobster

TABLE IV

Single moult increments in carapace length (mm) of six juvenile western rock lobsters reared under near-optimal conditions in aquaria for six years (after Chittleborough, 1976a)

Age (years)	No.	Males mean	s.e.	No.	Females mean	s.e.	No.	Total Range	Total Mean	s.e.
2+	15	5.0	0.2$^{\text{n.s.}}$	14	5.6	0.2	29	3.6-7.6	5.3	0.2
3+	11	5.1	0.5$^{\text{n.s.}}$	12	4.3	0.4	23	1.1-7.3	4.7[a]	0.3
4+	11	3.5	0.5$^{\text{n.s.}}$	10	4.0	0.3	21	1.8-5.6	3.8[c]	0.2
5+	5	2.5	0.4$^{\text{n.s.}}$	8	2.0	0.3	13	1.1-3.8	2.2[c]	0.3
6+	5	1.4	0.3$^{\text{n.s.}}$	9	0.8	0.1	14	0.0-2.2	1.0	0.2

TABLE V

Single-moult increments in carapace length (mm) of juvenile western rock lobsters in reef populations for 1970-74 (after Chittleborough, 1976a)

Age (years)	No.	Males mean	s.e.	No.	Females mean	s.e.
			Garden Island			
3+	80	4.3[a]	0.1[a]	87	4.0$^{\text{n.s.}}$	0.1
4+	80	4.7$^{\text{n.s.}}$	0.1[b]	128	4.1$^{\text{n.s.}}$	0.1
5+	10	5.4	0.3[c]	20	3.8	0.1
			Jurien Bay			
4+	16	4.6	0.4$^{\text{n.s.}}$	13	4.0$^{\text{n.s.}}$	0.5
5+				8	5.0	0.5
			Seven Mile Beach			
3+	76	3.0$^{\text{n.s.}}$	0.1$^{\text{n.s.}}$	97	3.0$^{\text{n.s.}}$	0.1
4+	38	3.1$^{\text{n.s.}}$	0.2$^{\text{n.s.}}$	83	2.9	0.1
5+	10	3.0	0.4			

a/ $0.01<P<0.05$; b/ $0.001<P<0.01$; c/ $P<0.001$; n.s. Not significant

TABLE VI

Annual growth in carapace length (mm) of marked juvenile western rock lobsters resident on nursery reefs at various localities (after Chittleborough, 1976a)

Locality		Age 3+ years			Age 4+ years		
		Males		Females	Males		Females
Seven Mile Beach	No.	44		58	26		41
	Range	1.1-21.7		2.0-18.9	1.2-16.9		0.8-12.6
	Mean	8.4	n.s.	8.2	7.7	n.s.	7.0
	s.e.	0.5 c/		0.4 c/	0.7 a/		0.5 c/
Garden Island	No.	138		195	84		111
	Range	3.0-22.0		4.0-21.0	0.6-20.0		3.0-15.5
	Mean	11.3	n.s.	11.0	9.7	n.s.	9.0
	s.e.	0.3		0.2	0.4 a/		0.3 n.s.
Jurien Bay	No.	2		1	10		9
	Range	16.6-18.1		8.6	9.0-18.0		4.6-14.0
	Mean				12.4	a/	8.7
	s.e.				1.0		1.0

a/ 0.01<P<0.05; c/ P<0.001; n.s. Not significant

TABLE VII

Moult increment and moult frequency in *Panulirus cygnus* (after Morgan, 1977)

	Males (mm)	
Size	60-76	77-90
Moult increment	5.3	3.8
Moult frequency per year	3	2
	Females (mm)	
Size	60-70	70-90
Moult increment	4.7	2.3
Moult frequency per year	3	2

by examining blood and tissue constituents and water content. No satisfactory single index of nutritional state suitable for field use with wild population of the *P. cygnus* was found. Greater success was obtained by using the gastric fluid constituents (Dall, 1975b). The concentration of gastric fluid protein was found to be a reliable index of nutritional state, but cannot be used uncritically. The wide range of values for wild populations, the effect of handling, and possible seasonal influences, all need to be taken into account, as well as the moult stage. It was concluded that a combination of gastric fluid protein concentrations and blood volume estimations may provide the best simple means of estimating nutritional state.

- Relationship of growth to feeding, spawning, to other activities and environmental factors

Chittleborough (1975) found that juvenile *P. cygnus* held in aquaria required daily feeding to maintain a maximal growth rate. The first effect of a mild shortage of food (fed three times a week) was a decreased frequency of moulting. With greater food deprivation (fed only once a week) not only was moulting delayed further but also the growth increment at moulting was smaller.

The effects of temperature, photoperiod, oxygen and crowding have also been examined by Chittleborough (1975). Growth rate increased with temperature to a maximum of 26°C above which both growth rate and survival declined.

Photoperiod length did not affect the growth rate except that growth rate was depressed significantly in continuous darkness.

A mild deficiency of oxygen (60-70 percent saturation) at the time of ecdysis resulted in a slower rate of growth while oxygen levels of 47-55 percent saturation depressed the growth increment at moult and increased the risk of death.

Growth increment per moult was not affected by crowding while food supply was in excess. However, frequency of moulting was affected markedly by crowding as those animals held in isolation showed greatly increased intermoult periods and hence reduced growth rates.

- Food; growth relations

Chittleborough (1975) used the ratio of total food eaten during an intermoult period

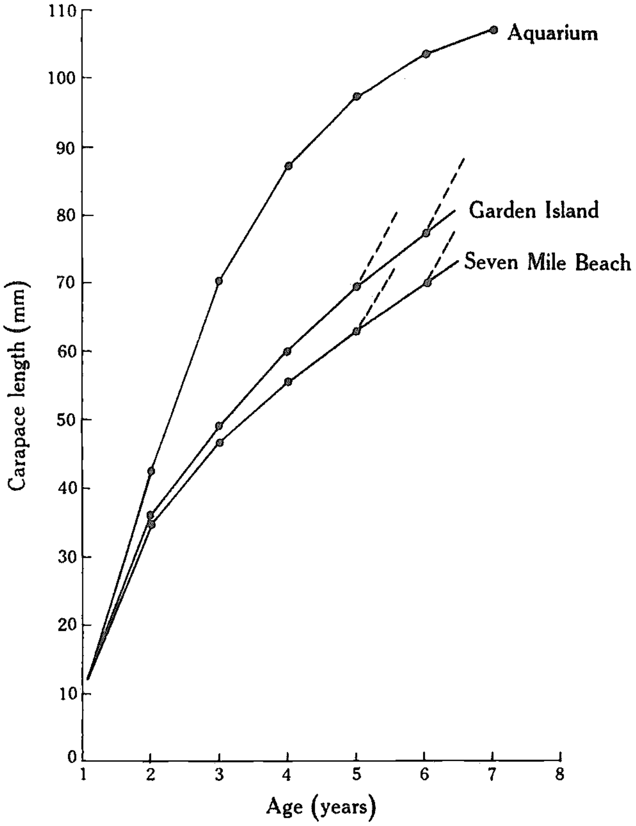


Figure 7 Growth of juvenile *Panulirus cygnus* on nursery reefs compared with those reared in an aquarium under near-optimal conditions (after Chittleborough, 1976a)

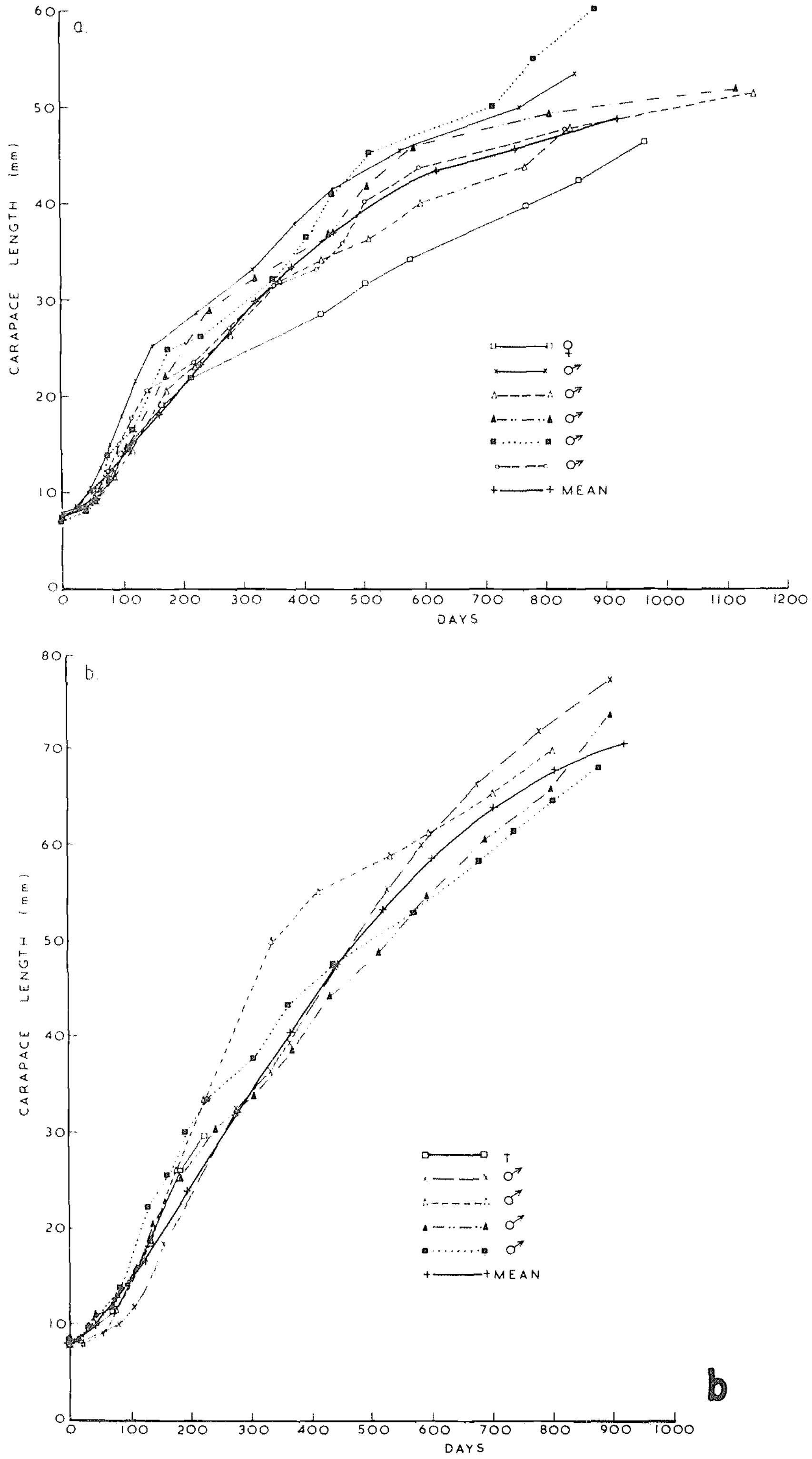


Figure 8 *Panulirus cygnus*. Growth of isolated individuals held at (a) temperatures of incoming sea-water, annual range 14.9° to 25.9°C; and (b) at a temperature of 23°C ± 0.5°C. The mean growth curves were calculated from the individual coefficients weighted by the reciprocal of the asymptotic variance. Open squares: individual died before sex determined (after Phillips et al., 1977)

to the total water uptake at the moult prior to that period to give a measure of the efficiency of food conversion. These measurements were made on a group of juvenile *P. cygnus* aged 2+ years held in isolation at constant temperatures of 26°C and 28°C and fed daily on abalone (*Haliotis roei*).

The relationship between mean daily food intake and estimated growth in tissue weight per day is given in Figure 9. There was no significant difference found in the conversion ratio of food to body tissue at the two temperatures tested, except for the indirect effect of the lower temperature delaying moulting and so increasing the total amount of food utilized for maintenance requirements.

The relationship between mean daily food intake (f) and estimated growth in flesh weight gained per day (w) was:

$$f = 1.035 + 2.096\ w$$

3.44 Metabolism

- Metabolic rates

No data are available

- Endocrine systems and hormones

The induction of viable ecdysis in *P. cygnus* by 20-hydroxyecdysone (crustecdysone, ecdysterone, β-ecdysone) was examined by Dall and Barclay (1977). It was found that 20-hydroxyecdysone injections totalling 20 $\mu g\ g^{-1}$ wet weight of animal successfully induced apolysis (separation of epidermis from the old cuticle). Provided the treatment was given after 35 percent of the moult cycle had elapsed, proecysis (premoult) was shortened by as much as 42 percent, 20-hydroxyecdysone did not reduce the size increment by more than 25 percent except when multiple injections were given late in the cycle. 20-hydroxyecdysone appears to initiate proecydsis by a short-term peak of secretion without the tissues being primed by other hormones. The response to the hormones may be critically temperature dependent.

Water uptake at ecdysis and its possible control by factors from the central nervous system has been investigated by Dall and Smith (1978b). Water ingestion was 16.071 ± 2.365 ml $kg^{-1}h^{-1}$ during swelling just before ecdysis (stage D4(s)) and 23.099 ± 1.238 ml $kg^{-1}h^{-1}$ during stage A. The total water ingested was 13.7 percent of the proecdysis weight. However the total water uptake by wet weight calculated from a carapace length-weight formula gave values ranging from 18.4-21.4 percent. It was suggested that water ingestion absorbed primarily by the digestive gland was the main source of swelling of the cephalothorax in stage D4(s) and after ecdysis both ingested water and external absorption enables the flaccid abdomen and appendages to swell rapidly.

Investigation into the effects of water soluble and acetone-soluble extracts from the C.N.S. were inconclusive but it was considered that further investigations into this area were warranted.

Investigations have also been made by Dall and Smith (1978a) of the changes in apparent permeability to water during the moulting cycle.

- Osmotic relations

Dall (1974a) investigated osmotic regulation in the western rock lobster and found that it is poikilosmotic over its tolerated salinity range, 25-45 °/oo. It was considered likely then that osmotic adjustment to any salinity change is made by direct exchange of major electrolytes across the gills. Subsequent investigations by Dall (1975b) revealed that ninhydrin-positive substances (NPS) play an important role in osmoregulation. In a hyposaline medium, NPS concentrations in muscle were sharply reduced within 24 hours, but with increased salinity, concentrations rose over seven days suggesting that NPS are produced by intracellular processes.

It is apparent that adaptation to lowered salinity involves a loss from the body of osmotically active nitrogenous components from the tissues, mostly in the form of non-essential, and therefore expendable, amino acids. This mechanism, though wasteful, permits the tissues of osmoconformer such as *P. cygnus* to adapt osmotically to a limited change in salinity, thereby reducing the loss of essential electrolytes.

Ionic regulation was also investigated by Dall (1974a). Ions are regulated independently, and a range of regulation types from poikilosmotic to homeo-osmotic is shown. Blood sodium is accumulated while chloride concentration is reduced. Sodium and chloride vary directly with the external salinity, although maintaining their differences in the same proportion as normal salinity (36°/oo). Potassium concentration is equivalent to the level in the external water at normal salinity but is increased with lowered salinity and decreased with raised salinity. The mechanisms for the regulation of sodium, potassium and chloride are not clearly understood. It is probable that the gills, perhaps in conjunction with the gut, carry out this regulation, with the likelihood that the regulation of ions between blood and tissues plays a part. Calcium is

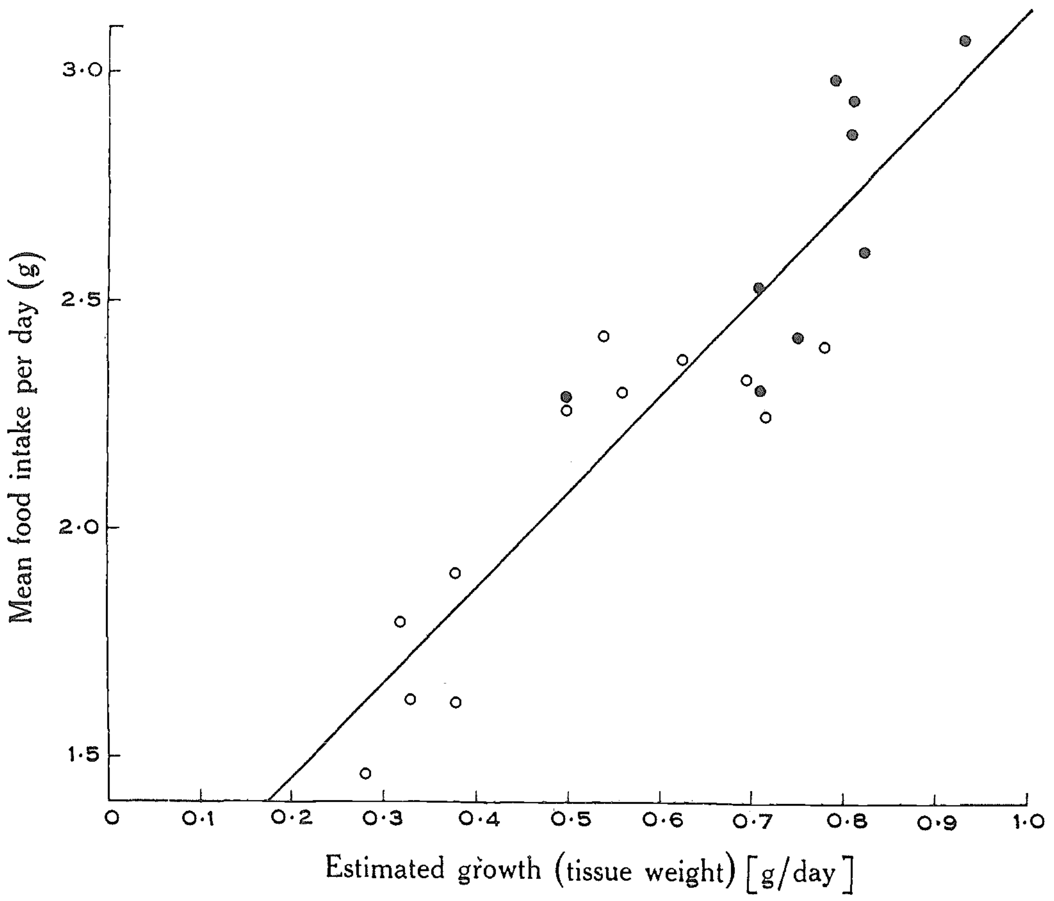


Figure 9 Relation between mean daily food intake and estimated growth in tissue weight per day for *Panulirus cygnus* aged 2+ years. Held at 26°C (●) and 23°C (o) (after Chittleborough, 1975)

accumulated, ranging from over 150 percent of sea water concentration at salinity 20°/oo to about 117 percent at salinity 45°/oo. This process may be continuous so that excess calcium has to be excreted, partly at least into the gut. Lastly, magnesium is reduced to about one third that of the external concentration over the salinity range 20-40°/oo, but regulation begins to break down at 45°/oo. From the results of other workers (cited in Dall, 1974a) it is probably that the antennal glands are responsible for this considerable reduction, although this excretion appears to be quite slow and inefficient.

- Composition of body fluids and tissues

Beck and Sheard (1949) examined the copper and nickel content of the blood and found a wide range of values for the copper content of the blood (43-208 μg Cu ml^{-1}), with the majority of values between 140-170. Traces of nickel were found in the blood but the amounts were variable and very small.

Investigations by Dall (1974b, 1975a and 1975b) provide detailed data on the concentration of ions in the blood tissues and in the gastric fluid (Table VIII), blood carbohydrate concentrations for each moult stage (Table IX) and a comparison of constituents in fed and starved rock lobsters (Table X). Also, Dall (1975c) found eight amino acids common to both blood and muscle, i.e., leucine, valine, proline, tyrosine, alanine, taurine, glutamic acid and glycine, with arginine also occurring in muscle. Proline, leucine and valine were present in the greatest concentrations in both blood and muscle. Five unidentified ninhydrine-positive spots were also found in blood extracts.

TABLE VIII

Blood ions compared with gastric fluid in normal animals. Concentrations in mg/l;
Ionic concentrations (mM/kg wet wt) in tissues and organs: concentrations in mM/l;
(after Dall, 1974a and b)

Fluid space, tissue or organ	No. of animals sampled	Na	Cl	K	Mg	Ca	Total ions
Blood	15	551.0 (5.21)	533.7 (2.81)	12.2 (0.36)	13.5 (0.30)	12.6 (0.27)	1 127.0 (6.53)
Gastric fluid	15	528.9 (5.15)	519.8 (11.00)	11.6 (0.31)	33.6 (2.60)	16.3 (0.50)	1 113.5 (17.12)
Antennal glands	8	217.8 (11.38)	231.9 (10.74)	64.1 (5.57)	13.7 (0.85)	8.8 (1.98)	536.4 (19.51)
Digestive glands	8	156.3 (14.24)	179.4 (15.51)	52.4 (7.36)	11.9 (1.14)	7.3 (0.56)	407.4 (30.22)
Gills	4	421.9 (12.04)	446.7 (16.06)	21.6 (1.69)	33.0 (2.33)	12.4 (1.20)	935.8 (26.77)
Abdominal muscle	6	58.03 (4.47)	69.2 (2.15)	106.0 (4.13)	19.7 (0.44)	3.7 (0.49)	257.1 (9.23)
Leg muscle	7	103.9 (6.87)	121.0 (6.87)	84.9 (4.94)	14.7 (0.82)	-	213.5 (11.03)

Note: Standard errors in parentheses

3.5 Behaviour

3.51 Migration and local movements

A limited migration occurs annually (George, 1958a; Sheard, 1962). During November of each year large numbers of immature rock lobsters on coastal reefs moult. These newly moulted animals are light in colour due to a reduction in colouring pigment. Once the new exoskeleton is hardened sufficiently these individuals, known colloquially as "whites", leave the shallow onshore reef areas and move seaward to deeper reefs during the latter part of November and December.

An additional limited movement of *P. cygnus* has been observed by Sheard (1962), which consists of a tendency for both males and females to accumulate for mating purposes during July and August on the shallow parts of a reef system. However, in general, juvenile and adult *P. cygnus* are relatively sedentary. Movements are mostly local, confined to foraging close to shelter. The extent and direction of these movements are determined by the reef topography and incidence of food organisms.

Chittleborough (1974b) examined the home range of a group of juveniles inhabiting a relatively uncrowded reef at Garden Island and observed that it did not exceed a radius of 15 m. In contrast, however, he found that the displacement of individuals to different reef sites caused random dispersion, with only a few individuals remaining on their new sites or returning to their old locations.

3.52 Schooling

P. cygnus does not school in the conventional sense but it is regarded as gregarious, especially amongst the younger juvenile stages. Individuals have little capacity for aggressive defensive behaviour, so aggregations may allow better detection of enemies and more efficient utilization of the spiny antennae for defence (Hindley, 1977). The juvenile *P. cygnus* illustrated in Figure 10 has assumed a typically defensive pose with antennae spread out and erect.

Berrill (1976), from laboratory observations, found that young juveniles of *P. cygnus* gregarious in sharing a variety of

TABLE IX

Carbohydrate concentrations (μg/ml whole blood) in blood cells, plasma oligosaccharides and glycoproteins (after Dall, 1975b)

	Moult-stage						
	C_4	D_c	B_2	F	B_2 (corrected for volume	(corrected B_2 values)	d.f.
Blood cells							
Glucose	29.6 *(5, 1.69)	26.0 (9, 3.46)	12.8 (5, 1.83)	6.61	19.0 (5, 2.74)	2.20	2,16
Glucosamine	40.8 (10, 6.45)	36.5 (4, 0.65)	26.0 (5, 3.27)	1.48	38.2 (5, 4.89)	0.11	2,16
Total carbohydrate (as anthrone carbohydrate)	104.0 (5, 6.38)	109.8 (5, 13.58)	70.0 (5, 15.37)	3.00	103.4 (5, 22.64)	0.05	2,12
Plasma oligosaccharides							
Glucose	186.3 *(21, 13.70)	146.8 (17, 16.07)	87.3 (16, 6.50)	13.27	128.8 (16, 9.62)	4.52	2,51
Total (as anthrone carbohydrate)	22.5 (15, 10.78)	231.4 (15, 22.94)	168.4 (17, 12.12)	5.43	284.4	0.70	2,44
Plasma glycoproteins							
Glucose	56.2 (5, 1.62)	53.6 (5, 2.96)	40.2 (5, 4.12)	7.80	59.4 (5, 6.00)	0.53	2,12
Glucosamine	687.2 (10, 47.01)	728.7 (12, 34.33)	500.8 (7, 28,55)	8.65	738.7 (7, 42.15)	0.52	2,26
Other sugars (as anthrone carbohydrates)	809.8 (5, 125.00)	742.4 (12, 96.94)	510.9 (7, 51.82)	2.07	753.6 (7, 76.48)	0.09	2,21
Whole blood total carbohydrate							
(Sum of mean values)	1 879.1	1 875.9	1 290.3		1 903.5		

* number of animals and ± s.e., respectively; F, the variance ratio; d.f., degrees of freedom of F

TABLE X

Comparison of constituents in fed and starved rock lobsters
(after Dall, 1974b)

	Blood			Legs			Whole abdomen	Abdominal muscle		Digestive gland		
	Volume †%	Protein mg/ml	Amino acids µM/ml	Water ‡%	Protein mg/*g	Amino acids µM/*g	Water ‡%	Water *%	Protein mg/*g	Wet weight †%	Dry weight †%	Water †%
Fed *ad lib.*	26.8 (1.03)	115.5 (5.80)	5.9 (0.46)	61.0 (0.33)	160.2 (8.30)	272.2 (12.40)	67.9 (0.29)	74.3 (0.14)	185.0 (58.00)	5.5 (0.38)	2.3 (0.22)	3.2 (0.35)
Number of animals	10	10	10	10	5	10	5	5	5	5	5	5
P	0.001	0.001	0.001	0.001	0.9	0.9	0.1	0.1	0.1	0.1	0.001	0.4
Starved 4 weeks	18.2 (1.10)	67.6 (2.90)	2.8 (0.12)	2.8 (0.24)	158.6 (13.60)	289.2 (4.57)	70.8 (0.56)	76.6 (0.43)	157.2 (39.00)	4.1 (0.12)	1.1 (0.11)	3.0 (0.29)
Number of animals	11	11	11	11	5	11	5	5	5	5	5	5

P significance of differences

* per gramme wet weight of muscle

†% total wet weight of animal

‡% of the relevant part (whole wet weight)

± s.e. in parentheses

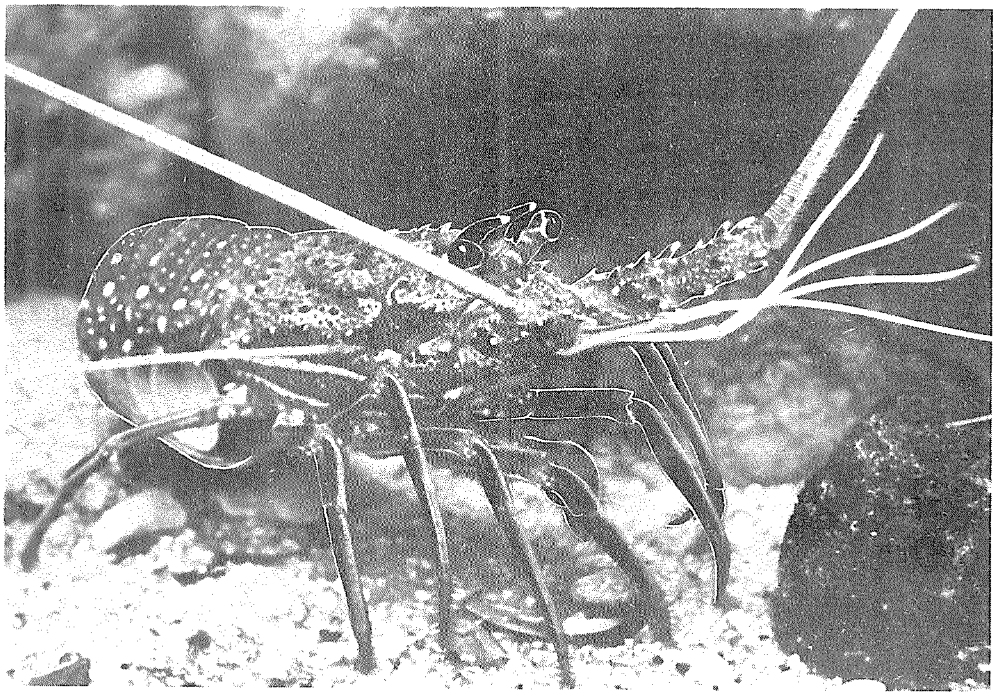


Figure 10 *Panulirus cygnus*, this juvenile has assumed a typically defensive pose with antennae spread out and erect

types of protective cover. However, aggressive contacts occurred especially during competition for limited space or food, with the older juveniles possessing longer antennae invariably dominating the younger stages.

It should be noted that gregarious behaviour generally relates to the time of day during which the animals are passive. During the time of more active locomotion, juvenile *P. cygnus* become solitary (Hindley, 1977).

3.53 Responses to stimuli

- Mechanical

P. cygnus can both produce and perceive sound (Hindley, 1977). Meyer-Rochow and Penrose (1974, 1976) investigated the sound production puerulus stage (Section 3.22) juvenile and adult *P. cygnus*. Sound is produced by a rasping or stridulating mechanism. A concave process (plectrum) located on the inner side of the basicerite of the antennae scrapes over a longitudinal swelling of the rostrum, the stridulation file, and so produces the sound.

The biological significance of the sound produced is uncertain. It is produced most often in stressful and high stimulus situations, such as during attack by predators and during intra-specific encounters (Berrill, 1976, Meyer-Rochow and Penrose, 1974, 1976). Meyer-Rochow and Penrose (1976) consider that the function of the sound is to deter predators such as octopus, fish and seals, and point out that the sound is well within the sensory capabilities of these potential predators. It is postulated that attackers will learn to associate the sound with injuries inflicted by the strongly spined antennae, and that this will discourage future attacks. Berrill (1976) disagrees with Meyer-Rochow and Penrose (1974, 1976). He considered that rasping typifies intra-specific competition for shelter. He was unable to detect rasping sounds from animals being pursued and eaten by predators.

Oldfield (personal communication cited Hindley, 1977), by recording changes in behaviour when the animals were subjected to a noise, demonstrated that *P. cygnus* is capable of perceiving sound.

- Chemical

There are only limited data available in regard to responses to chemical stimuli.

Hancock (1974) demonstrated that the catch of *P. cygnus* was drastically reduced by dead or dismembered *P. cygnus* placed in the lobster pots and he implied that chemoreception was involved in the avoidance of these pots by the rock lobsters.

Salinity, or some associated component, affects the activity of *P. cygnus* since the catchability coefficient has been found to be significantly correlated with changes in salinity (Morgan, 1974b).

- Thermal

Chittleborough (1970) found that catchability of juvenile *P. cygnus* at Garden Island seemed to follow water temperature. Morgan (1974b) substantiates this by showing that the catchability coefficient of a population of *P. cygnus* was positively correlated with water temperature.

Laboratory studies by Morgan (1978) showed that the mean locomotor activity of animals in an intermoult stage increased with increasing temperature between 17°C and 25°C but then declined. By comparison animals in a premoult condition showed no significant trend with temperature, activity rates remaining at a low level. Morgan (1978) also observed that the individual variation in the response of intermoult animals increased with temperature and he suggested that it may be a contributing factor to high daily variation in commercial catch rates during months of high water temperature.

- Optical

Meyer-Rochow (1975a, 1975b) investigated the structure of the eye of puerulus and adult *P. cygnus*. He concluded that, although the structure of the eye appeared to make it capable of detecting polarized light, the arrangement of the rhabdomes may be a device to make the eye polarization independent. Meyer-Rochow (1975b) speculated that it may be an advantage for a marine animal to be insensitive to polarization patterns because these are more prominent in the sea than in the air.

According to Hindley (1977) it has generally been accepted that palinurids are predominantly crepuscular and nocturnal. Most locomotion, feeding, moulting, mating, etc., occurs at night, whereas during the day the animals remain quiescent and normally concealed. Morgan (1978) investigated the locomotor activity rhythms of *P. cygnus* in captivity and confirmed that they were essentially nocturnal, however, they were of a non-crepuscular nature with peak activity occurring immediately after the onset of darkness.

An examination of average weekly catch rates for a fishing season revealed a distinct lunar cycle in both shallow and deep water, with the lowest catch rates occurring at full moon (Morgan, 1974b).

Hindley (1977) and Hindley and Penn (1975) investigated the effects on activity of high intensity light of short duration (i.e., photographic flash). No changes in behaviour were observed even following regular exposure to such light.

4 POPULATION

4.1 Structure

4.11 Sex ratio

- Sex ratio of the population

Morgan (1977) collected data which give the sex ratio for the rock lobster population at Rat Island (Table XI). He found that the sex ratio of rock lobsters below legal size (76 mm c.l.) which were taken in pots was not significantly different from that taken by diving, while for animals of 76 mm c.l. or greater some selectivity was evident in that the proportion of females taken by pots was in general significantly lower than the proportion taken by diving. This means that the sex ratio of the commercial catch will tend to underestimate the female proportion of the population.

- Sex ratio of the catch of *P. cygnus*

The sex ratio of the catch taken during experimental fishing trials at the Pelsart group, Houtman Abrolhos is given in Table XII (George, 1957). The sex ratio of the rock lobsters caught by commercial pots for the 1974-75 season by month and depth category are given in Table XIII (Morgan and Barker, 1977).

- Variations of ratios with size, age and season

See sections above for variation with season and depth.

- Sex ratio on spawning grounds

Although breeding females are found throughout the range of the adult population,

TABLE XI

Sex ratios (females:males) of diving-caught and pot-caught rock lobsters in each of two size groups (i.e., legal size and below legal size) for the research area at Rat Island (from Morgan, 1977)

Month	Legal size (76 mm and over)		Below legal size (<76 mm)	
	Pot-caught	Diving-caught*	Pot-caught	Diving-caught
November 1969	25:75	35:65	56:44	52:48
March 1970	24:76	50:50	58:42	55:45
December 1970	21:79	35:65	50:50	55:45
December 1971	32:68	41:59	60:40	51:39
June 1972	38:62	46:54	61:39	63:37
October 1972	45:55	49:51	74:26	73:27
Total	31:69	43:57	60:40	60:40

* Figures based on a sample size of 198 (legal size animals taken by diving in in October 1972)

TABLE XII

Sex ratio of the catch during experimental fishing trials at the Pelsart group, Houtman Abrolhos (George, 1957)

	1948	1953
Male	57%	54%
Female	43%	46%

TABLE XIII

Sex ratio by month and depth category
Figures given are percentages of females in the total

Area	Depth Range (fath)	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.
Dongara	0-10	50	60	52	52	56	60	51		51	53
	10-20		63	58	53	58	58	52		49	
	20-30			68				54		76	63
	30+			68		68	56	54			
Jurien	0-10	48	62	54	50	49	59	58	56	50	59
	10-20	47	60		61	59	64	66	41	54	
	20-30			67	60		69			84	
	30+			65							
Lancelin	0-10	52	48	55	48	58	62	58	58	58	55
	10-20		57		61	55					70
	20-30			59	78		59				
	30+										
Fremantle	0-10	56	48	46	47	52	60		54		
	10-20	43		53						54	52
	20-30		57	68	75		38	62			
	30+		50								

After Morgan and Barker, 1977

TABLE XIV

Carapace length (mm) of juvenile *Panulirus cygnus* at Garden Island
(from Chittleborough, 1976a)

	2 years	3 years	4 years
Males	29-40	41-53	54-68
Females	28-39	40-51	52-66

the majority of spawning females are taken in the 20-30 fathom depth range (Morgan and Barker, 1974). Therefore, reference should be made to the above sections with special reference to the 20-30 fathom depth range in Table XIV.

4.12 Age composition

- Age composition of the population as a whole

The final larval stage, the puerulus, settles in the shallow coastal areas after larval phase of 9-11 months. The younger juveniles concentrate on shallow limestone reefs (to depths of 10 m, with some larger juveniles to 20 m) and remain there for three to six years. At about five to six years of age the juveniles migrate onto the continental shelf into depths of 30-150 m. They may live for more than 15 years (Phillips, 1975c).

Chittleborough (1970, 1976a) worked on the determination of age groupings in the western rock lobster. It was found that, due to the fact that the growth rate of *P. cygnus* is highly variable and easily depressed, the determination of age groupings in a population is difficult except for the younger juveniles. By regular trapping of animals in special test areas it was possible to obtain a sample of sufficient size to enable the progression of modal size groups to be followed in the younger age groups. Table XIV shows the ranges in carapace lengths which were selected as approximate age groupings.

These values were determined from the test area at Garden Island and were found to apply reasonably well to polymodal distribution of sizes recorded at Seven Mile Beach and Jurien Bay, but not at Cliff Head.

- Age distribution of catch

No data are available

- Variations with depth, distance off the coast, density, time of day, season

Apart from the information contained in the above section, no data are available.

- Age at first capture

According to Chittleborough (1970) juveniles will begin to enter baited traps shortly before they are two years old.

- Age at maturity

See Section 3.12

- Maximum age

Phillips (1975c) indicated that old animals may be more than 15 years of age.

- Density of age groups

No data are available

4.13 Size composition

- Length of the population as a whole

Length frequency data for *P. cygnus* obtained from the commercial catch at the Houtman Abrolhos are tabulated by Sheard (1962) for the period 1947-56.

The mean carapace lengths of males and females in various depth categories at Fremantle, Lancelin, Dongara and Jurien Bay for the seasons 1971-72 to 1974-75 are tabulated by Morgan and Barker (1974, 1975, 1976 and 1977).

Morgan (1977) obtained length frequency data from commercial packing records by using (1) the average carapace length of rock lobsters in each grade category, and (2) the total number of rock lobsters caught in each category. Table XV contains the average catch, in numbers of rock lobsters in each of four grade categories for the years 1967-68 to 1972-73.

- Length composition of the catch for each age group over the whole range of distribution of the species

Due to the fact it has not been possible to determine age groupings for adult rock lobsters (see Section 4.12), the length composition of the catch for each age group cannot be determined.

- Variations with depth, distance off the coast, density, time of day, season

Morgan and Barker (1974, 1975, 1976 and 1977) give the mean size of males and females in the various depth categories at Fremantle, Lancelin, Dongara and Jurien through the fishing season from 1971-73. Table XVI gives these data for the 1974-75 fishing season. The major trends appear to be an increase in mean size with depth, with no significant variations between localities over time.

Density has been found to play an important role in determing the size composition of populations. Chittleborough (1979) found that where the density of the breeding stock is highest, the mean size at first breeding is lowest and the adults are generally stunted. The converse was found to be true at localities where density is low.

- Size at first capture

Chittleborough (1970) found that small juvenile rock lobsters of 36 mm c.l.

TABLE XV

Average catch, in numbers of *Panulirus cygnus* in each of four grade categories for the years 1967-68 to 1972-73 (after Morgan, 1977)

Grade	Size Range (mm)	Average Catch (x 10^6)
A	76.0-79.7	3.21
B	79.7-88.8	6.40
C	88.8-102.4	2.93
D-E	>102.4	1.09
Total		13.63

enter baited traps readily. Management regulations restrict the commercial catch to animals with a minimum carapace length of 76 mm (Bowen, 1971). A two-inch escape gap as a legal requirement for all lobster pots was found by Bowen (1963) to allow a minimum size at first capture of 66 mm c.l. whereas a two and one eighth-inch (54 mm) escape gap (the present legal requirement) results in a minimum size of first capture of about 72 mm c.l.

- Size at maturity

See Section 3.12

- Maximum size

According to Phillips (1975c) adults of *P. cygnus* can weigh up to 4.5 kg. Sheard (1949) reported a rock lobster taken at the Abrolhos weighing 4.00 kg, with a total length of 45.21 cm and a carapace length of 178 mm.

- Density of size groups

No data are available

- Length and weight relationship

Sheard (1962) gives the relation to live weight to carapace length and the relation of tail weight to carapace length. Bowen (cited in Morgan, 1977) collected data on carapace length and total weight at a processing factory for legal sized male and female lobsters, which gave the following relationship:

$$\log W = 2.744 \log L - 2.5480$$

4.2 Abundance and Density

4.21 Average abundance

- Estimation of population size

Bowen and Chittleborough (1966) estimated the average abundance by taking the catch per unit of effort to be a measure of stock density. It was calculated that the original fishable stock of *P. cygnus* was approximately 63.6 x 10^6 kg.

4.22 Changes in abundance

- Changes caused by hydrographic conditions, food competition, predation, fluctuations and fishing

It was estimated that by 1963, some 20 years after the beginning of intensive commercial fishing, the size of the fishable stock had decreased by approximately three quarters to 16.1 x 10^6 kg (Bowen and Chittleborough, 1966).

4.23 Average density

- Annual mean density

Estimates of the density of juvenile *P. cygnus* on shallow coastal reeds were made by Chittleborough (1970) and Chittleborough and Phillips (1975) using single census mark-recapture method. The densities (number per hectare) for the three test localities are given in Table XVII.

TABLE XVI

Mean carapace lengths (mm) of male and female *Panulirus cygnus* in various depth categories throughout the fishing season (after Morgan, 1977)

Season	Area	Month	(0-5 m)		(5-10 m)		(10-15 m)		(10 m)	
			Male	Female	Male	Female	Male	Female	Male	Female
74/75	Fremantle	Nov.	78	75	87	83				
		Dec.	77	75			91	86	93	86
		Jan.	79	76	93	87	94	90		
		Feb.	75	72			104	98		
		Mar.	78	75						
		Apr.	77	77			91	86		
		May					98	92		
		June	76	73						
		July			88	85				
		Aug.	77	74						
74/75	Lancelin	Nov.	73	70						
		Dec.	76	75	85	80				
		Jan.	71	70	108	99				
		Feb.	74	72	104	97	114	105		
		Mar.	76	73	99	87				
		Apr.	75	73			102	94		
		May	74	72						
		June	74	72						
		July	73	72						
		Aug.	75	73	103	102				
74/75	Jurien	Nov.	74	73	76	75				
		Dec.	78	75	77	74				
		Jan.	75	73			90	84	93	87
		Feb.	75	73	79	75	89	83		
		Mar.	75	73	79	76				
		Apr.	77	74	79	79	96	88		
		May	76	74	77	75				
		June	76	73	77	79				
		July	75	72	79	76	93	90	98	91
		Aug.	76	74						
74/75	Dongara	Nov.	69	68						
		Dec.	80	76	79	76				
		Jan.	74	72	74	72	95	89	96	93
		Feb.	75	74	76	74				
		Mar.	76	74	79	76			98	90
		Apr.	73	73	76	74			101	89
		May	76	74	81	78	94	86	103	92
		June								
		July	71	69	79	75	90	91		
		Aug.	76	74			94	87		

TABLE XVII

Density (number per hectare) of juvenile *Panulirus cygnus* in January each year
as measured by trap-mark-recapture technique on test reefs
(after Chittleborough and Phillips, 1975)

Locality	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974
Garden Island										
Density	5 144	2 834	5 386	1 753	1 343	1 958	1 811	1 402	1 877	1 896
s.e.	119	152	223	94	61	111	107	62	134	179
Jurien Bay										
Density	-*	-	-	-	-	-	4 824	1 290	1 635	4 068
s.e.							458	109	168	410
Seven Mile Beach										
Density	-	-	-	-	-	11 830	10 130	9 374	11 863	19 587
s.e.						798	646	721	650	882

* Not measured

TABLE XVIII

Panulirus cygnus at Rat Island, Abrolhos Islands
Corrected estimates of population density, $\hat{D}_i$ (number per hectare), and its standard error (s.e.)
(after Morgan, 1977)

Month	$\hat{D}_i$	s.e.	Month	$\hat{D}_i$	s.e.
Dec. 1969	1 694	294	Aug. 1971	661	23
Feb. 1970	1 559	76	Sept.	658	25
Mar.	1 155	37	Oct.	606	30
Apr.	925	30	Nov.	679	40
June	831	48	Dec.	2 065	432
July	778	44	Jan. 1972	1 638	287
Aug.	503	20	Feb.	1 539	64
Sept.	502	50	Mar.	1 138	41
Nov.	861	56	Apr.	936	40
Dec.	1 290	229	May	764	37
Jan. 1971	1 969	291	June	614	17
Feb.	1 459	45	July	546	28
Mar.	1 295	47	Aug.	465	23
Apr.	900	29	Oct.	329	15
May	919	34	Nov.	371	48
June	742	28	Dec.	1 195	216
July	754	26	Jan. 1973	1 221	211

- Density of adult females

No data are available

4.24 Changes in density

- Landings per unit of fishing effort

See Section 5.41

- Seasonal variation in available stock

Morgan (1977) estimated monthly densities of *P. cygnus* at a 10.27 ha test reef at Rat Island, Abrolhos Islands and these are shown in Table XVIII. It is evident that there is one major period of recruitment to the population during the year (in November and December) which corresponds with the beginning of the fishery for the "white" rock lobster (George, 1958a) in coastal areas. After this one period of recruitment, the population appears to be relatively stable for the remainder of the year and is gradually reduced by the effects of mortality and emigration until the lowest densities are reached during November.

4.3 Natality and Recruitment

4.31 Reproduction rates

- Annual egg production

For details of fecundity see Section 3.15

- Survival rates

See Section 3.22 for details of survival from hatching to puerulus larval stage

- Forecasting of potential yields

See Section 4.33

4.32 Factors affecting reproduction

- Density-dependent factors: cannabalism, food supply, predation

Chittleborough (1976b) has shown that there are two ways in which density dependent regulation of fecundity may operate on adult western rock lobsters. When given abundant food, 77 percent of females breeding in aquaria at ambient temperature had two successive spawnings in a breeding season, whereas in a relatively crowded part of the natural population less than 12 percent of the breeding females spawned twice in a season. The number of eggs produced per spawning has been shown (Morgan,1972) to be related linearly to size (carapace length) which in turn is density determined through growth rate. In that part of the population where the present density of the breeding stock is highest, the mean size at first breeding is smallest, adults are generally stunted, and fecundity correspondingly low. At other localities where the density is much lower, both size at first breeding and the average size of adult females are greater so that more larvae are produced per individual breeding cycle. There is some indication that before commercial exploitation had reduced the density of the breeding stock, the size at first spawning may have been less and hence, individual fecundity lower than now observed.

Therefore, as the density of the breeding stock is lowered, the state of nutrition of each female is improved, resulting in a higher growth rate and increased fecundity (Chittleborough, 1979).

- Physical factors

Temperature is the most important physical factor affecting reproduction, the annual cycle of water temperature confining breeding cycles to the spring and summer (Chittleborough, 1976b). Chittleborough and Thomas (1969) suggested that the reason for hatching commencing earlier in some years was possibly due to an earlier rise of water temperature during spring which stimulated earlier maturation of gonads. Chittleborough (1976b) stated that off Fremantle an early spawning does make a second spawning in a season possible, although there is no direct evidence to support this.

4.33 Recruitment

- Level of recruitment to the fishable stock

There is only one major period of recruitment by migration to the fishable stock each year and it is the basis of the important "whites" fishery (George, 1958a) during which time catches are made up almost entirely of pale-coloured, newly-moulted, immature rock lobsters with the darker "red" rock lobsters contributing only a very minor proportion of the catch (Morgan, 1977). An independent index of new recruits within the fishery is the catch per unit effort achieved by the fishermen operating during the "white" season (Chittleborough and Phillips, 1975). "Whites" catch and effort data are given in Table XIX.

Bowen and Chittleborough (1966) have indicated that annual rates of exploitation of the

TABLE XIX

Catch and effort data for the "whites" catch of *Panulirus cygnus* (after Morgan and Barker, 1974, 1975, 1976, 1977)

Season	"Whites" catch (kg)	"White" effort (pot lifts)	Catch per effort
1972-73	2 676 136	2 535 600	1.055
1973-74	1 693 043	2 514 074	0.673
1974-75	2 496 953	2 423 562	1.030
1975-76	2 550 820	2 561 362	0.996

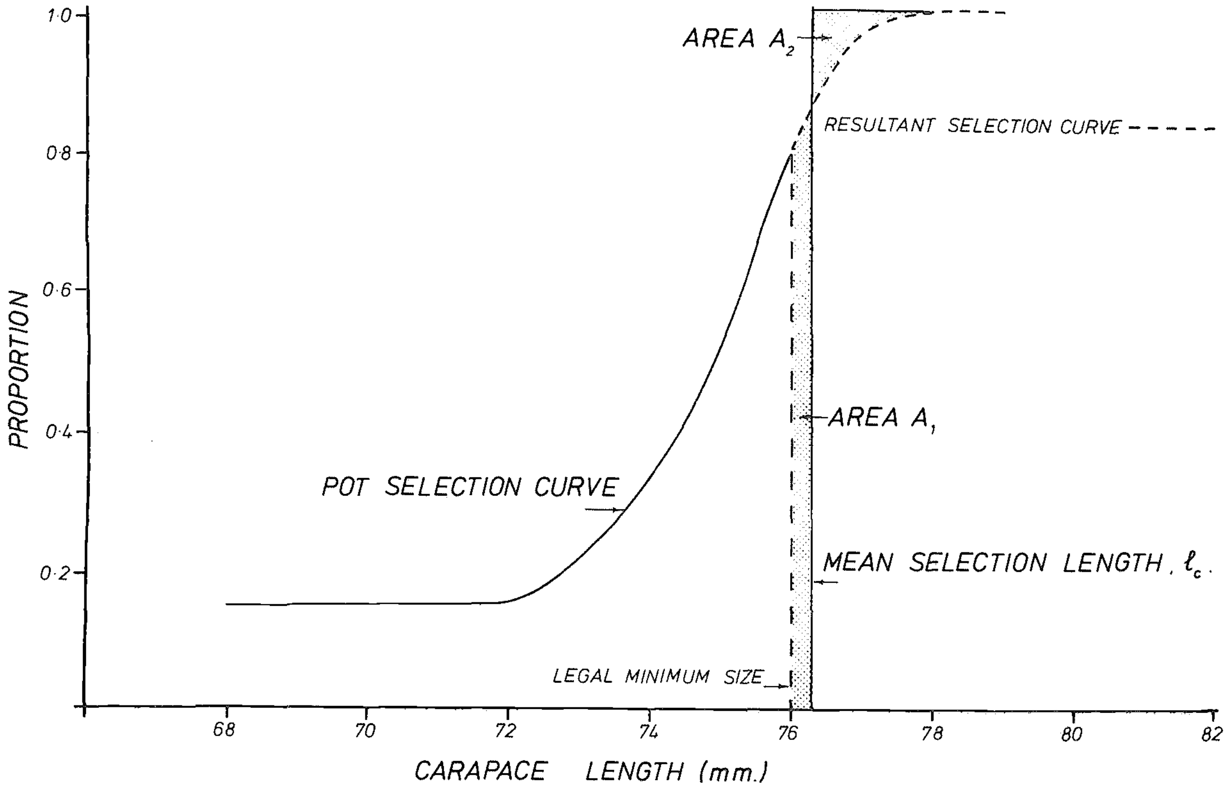


Figure 11 Derivation of the mean selection length, 1 c' (when $A_1 = A_2$) from the pot selection curve and the legal minimum length (after Morgan, 1977)

western rock lobsters are high (up to 70 percent and hence the fishery is largely dependent on these annual recruits to provide the basis for the fishery during the following season. As the size range of the recruits overlaps the legal minimum size of 76 mm c.l. (Chittleborough, 1970), the length frequency of young rock lobsters recruited to the fishable stock will be a resultant of (1) the length frequency distribution of the recruits, (2) the selection of animals by the pot, and (3) the action of the legal minimum size.

Morgan (1977) examined these factors and derived the pattern of entry of recruits to the fishable stock for a combination of the selection curve for animals by the pot and the legal minimum size. This combined curve is shown in Figure 11 and demonstrates how, at a length larger than 76 mm c.l. and up to 78 mm, selection by the pot is important whereas since animals below that length are returned to the water it may, providing it can be assumed that they all survive, be ignored. From Figure 11, a value of 76.3 mm c.l. can be derived for the mean selection length which is similar to the legal minimum size of 76 mm. Thus, all recruited animals above 76.3 mm c.l. may be assumed to be subjected to the full effects of fishing mortality whereas those below 76.3 mm may be assumed to suffer no fishing mortality.

Apart from the size, the density of recruits leaving the shallow inshore reefs is also important in determining the eventual level of recruitment to the fishery in any particular year. At present such data are only available in sufficient detail for the 1974 "whites" season and hence no comparisons of density of recruits between years can be made, although at Garden Island, Chittleborough (1970) showed that densities there varied by a factor of about two between the years 1965 and 1969.

- Factors determining recruitment (growth, movements)

Chittleborough (1970) has shown that the number of recruits entering the commercial fishery is dependent on two factors, viz.: (1) the density of emigrants from the shallow reef areas, and (2) the previous growth rate of these emigrants which determines the proportion attaining the legal minimum size of 76 mm c.l.

The various components of the environment likely to affect recruitment in the Garden Island test area population have been examined by Chittleborough (1975) who concluded that the predominant factor limiting survival and growth of juveniles is the limited availability of food on the coastal reefs. The level of recruitment from a particular year-class depends on (i) its initial density, i.e., at the time of larval settlement; (ii) the strength of other year-classes pre-existing on the "nursery" reefs; (iii) the density of food species; and (iv) the density of predator species.

Chittleborough and Phillips (1975, 1979) found that in most years the level of puerulus settlement along the coast is well above the carrying capacity of the nursery reefs. They concluded that, provided the initial settlement of puerulus larvae on the shallow water reefs is adequate, density-dependent mortality during the juvenile phase of the life cycle results in the range of variation in recruitment to the fishery being significantly less than the range of variation in recruitment of puerulus larvae. However, in some years (e.g., 1968-69 and 1973-74), the year-class strength may be inadequate (i.e., below the holding capacity of the shallow water reefs) so that poor recruitment to the fishery will result. So, although density dependent mortality during the juvenile phase will ensure reasonably constant recruitment to the fishery over a wide range of initial year-class strengths, conditions may occur which result in lowered recruitment to the fishery (Morgan, 1977).

- Seasonal pattern of recruitment

Emigration of the large (5-7 years of age) individuals from the shallow coastal reefs toward deeper water occurs in November and December (George, 1958a; Chittleborough, 1970).

- Variation in annual recruitment

Information on the variation in recruitment may be obtained from the catches of "whites" by commercial fishermen operating during November and December (see earlier this section) (Morgan, 1977).

- Relation of recruitment to stock size and reproductive rate

According to Morgan (1977) one of the factors which is obviously implicated in the strength of a particular year-class is the relationship between the abundance of the parent stock and the subsequent recruitment. Chittleborough (1979) found that the intensive fishing since 1957 had reduced the breeding stock but has not impaired recruitment to the fishable stock. It was also observed by Chittleborough that the potential existed for natural regulation of larval numbers in the western rock lobsters, because as the density of breeding stock is lowered, the state of nutrition of each female is improved, resulting in a higher growth rate and increased fecundity. The size of the breeding stock continues to decline (Morgan, 1977). However, it is not known at what level there will be an impairment to recruitment to the fishery.

4.4 Mortality and Morbidity

4.41 Mortality rates

- Instantaneous total mortality coefficient

Morgan (1977) examined various methods of calculating the instantaneous total mortality coefficient (Z). It was concluded that the best values of Z for *P. cygnus* were those derived from the average carapace length of rock lobsters in the grade categories B to E and shown in Table XX.

- Natural mortality coefficient

A method for estimating M, the natural mortality coefficient is described by Morgan (1977). The natural mortality can be calculated from the instantaneous total mortality coefficient (see above) over a range of effort values which are averaged over a period that is equal to the time taken to grow from the size at recruitment to fishable stock to the average size in the catch.

From a linear regression a value of 0.226 ± 0.105 was obtained for an estimate of the natural mortality coefficient. This value of M is less than the average value of 0.71 found by Chittleborough (1970) for small juvenile *P. cygnus* but this is expected since animals of the size range he examined, moult at a higher rate than legal size animals and Chittleborough (1970) has indicated that most mortality occurs at moulting. Bowen and Chittleborough (1966) arrived at values of M for a five-month period of 0.222, 0.731 and 0.781 for three groups of the Abrolhos Islands, but as these values were estimated from changes in uncorrected catch per unit effort during a season they are subject to influence by both recruitment and changes in availability (Morgan, 1977).

- Fishing mortality coefficient (F)

Since $Z = F + M$, F can be estimated from a knowledge of Z and M. Taking M as 0.226 ± 0.105 the values of F for the years 1954-55 to 1960-61 and 1967-68 to 1972-73 can be calculated from the values of Z in Table XXI. These range from 0.250 in 1958-59 to 1.036 in 1972-73.

- Density dependence of natural mortality

According to Chittleborough (1979) both growth and natural mortality of juveniles are density dependent with food and shelter comprising the major limiting factors.

Little direct information is available on the variation of natural mortality rate within the area of operation of the fishery, although this can vary with the density of rock lobsters. The catch rates of *P. cygnus* at Fremantle, Jurien Bay and Dongara are similar and hence, if catchability is also similar at these locations, the densities may be considered to be comparable. Hence, if mortality is density dependent no variation in natural mortality (due to variation in average density of rock lobsters) may be expected at these localities (Morgan, 1977).

Morgan (1977) found an indication that the mortality rate is density dependent over the population sizes encountered at the Abrolhos Island test area. It was suggested that a size-dependent natural mortality relationship may exist based on the fact that frequency of moulting and therefore susceptibility to cannabilism decreases with size.

4.42 Factors causing or affecting mortality

- Predators

No quantitative studies have been made on the natural predators of *P. cygnus*.

Joll (1977) investigated the predation of pot-caught *P. cygnus* and concluded that octopus are by far the most serious predator (Table XXII). Several species of octopus are found within the range of the fishery but only one, *Octopus tetricus*, is a predator of pot-caught rock lobsters. The giant cuttlefish, *Sepia apana*, occasionally enters pots and predates *P. cygnus*. Several species of fish, including baldchin groper (*Choerdon pagnoi*), snapper (*Chrysophrys unicolor*), parrot fishes (family Labridae), leather jackets (family Aluteridae) and wobbegong or carpet sharks (*Orectolobus ornatus*), have been reported as predators of pot-caught rock lobsters.

Examination of the mounds of old food items at the entrances to octopus lairs suggests that octopuses are not major predators of rock lobsters in their natural habitat.

TABLE XX

Values of the instantaneous total mortality coefficient (Z) derived from the average carapace length of *Panulirus cygnus* ($\bar{l}$) in grade categories B to E using the Beverton and Holt 1956 relationship $Z = K \frac{(L_\infty - \bar{l})}{\bar{l} - l_c}$ with K = 0.565, $L_\infty = 110$ mm and $l_c = 79.7$ mm

Season	Average carapace length (mm) based on grades A-E	Average carapace length (mm) based on grades B-E	Z based on grades B-E
1954/55	87.59	94.90	0.561
1955/56	87.54	95.59	0.512
1956/57	86.64	95.56	0.514
1957/58	85.16	94.48	0.593
1958/59	85.64	96.14	0.476
1959/60	85.36	95.17	0.542
1960/61	86.13	94.10	0.624
1967/68	86.99	90.05	1.089
1968/69	85.55	90.55	1.013
1969/70	86.01	89.23	1.231
1970/71	86.74	89.75	1.138
1971/72	87.17	89.53	1.177
1972/73	88.36	89.07	1.262

After Morgan, 1977

TABLE XXI

Values of the instantaneous fishing mortality rate, F, for *Panulirus cygnus* for the seasons 1954-55 to 1960-61 and 1967-68 to 1972-73 derived from values of Z shown in Table XX and taking M = 0.226

Season	F
1954-55	0.335
1955-56	0.286
1956-57	0.288
1957-58	0.367
1958-59	0.250
1959-60	0.316
1960-61	0.398
1967-68	0.863
1968-69	0.787
1969-70	1.005
1970-71	0.912
1971-72	0.951
1972-73	1.036

TABLE XXII

Estimated number of *Panulirus cygnus* predated by octopus, cuttlefish and fish in the 1974-75 and 1975-76 seasons (from Joll, 1977)

Season	Octopus predated	Cuttlefish predated	Fish predated
1974-75	334 000	39 000	4 000
1975-76	321 000	5 000	14 000

- Food of larvae and post-larvae and its availability

See Sections 3.41 and 3.42

Shortages of planktonic food may restrict both growth and survival, the oceanic waters off the western coast of Australia having very low productivity (Chittleborough, 1979).

- Physical factors

The major physical factor affecting mortality acts upon the larvae. The variability of water circulation off the Western Australian coast could cause fluctuations in the numbers of larvae returned close enough to the continental shelf for successful settlement (Chittleborough, 1979).

- Indirect effects of fishing

Following the introduction of escape gaps for rock lobster pots in 1964 the indirect effects of fishing on mortality of undersized rock lobsters have been greatly reduced. It was considered that the handling and the return of undersized rock lobsters to the seabed greatly increased their mortality rate (Bowen, 1963).

4.5 Dynamics of the Population

- Construction and application of mathematical models for long- and short-term prediction of characteristics of catches of a unit fishery considering required population parameters

The concept of the unit stock of *P. cygnus* has been examined by Morgan (1977) who considered that although there were geographical trends in some population characteristics (notably growth rate) the fishery may, at least for a first analysis, be considered to be operating on a single stock. Models used in the assessment of the fishery for *P. cygnus* have therefore referred to this unit stock.

Bowen and Chittleborough (1966) used changes in catch per unit of fishing effort within a fishing season to make the first preliminary assessment of the fishery for *P. cygnus*. Their model used within-season changes to calculate the instantaneous total mortality coefficient, Z, for each year and then, by calculating the line of best fit for plots of Z against recorded effort, f, for a number of years, estimates were obtained by the instantaneous natural mortality coefficient, M and q, the catchability coefficient.

Bowen and Chittleborough (1966) listed values of Z, F, P_o, (the stock at the beginning of the season) P_1 (the stock at the close of the season) R (recruitment) and E (the exploitation rate) for each year for the inner areas of the Abrolhos Islands and from these concluded that the fishery was being exploited at a high, but constant rate. Also the model enabled the level of recruitment to be examined and it was concluded that in all areas investigated, recruitment to the fishable stock had fallen during the course of the development of the fishery. Furthermore, they noted that "the catch per unit of effort may be approaching a relatively stable condition" for most areas and hence they derived an "equilibrium catch" for the whole fishery based on these stable levels of catch per unit of effort. However, these "stable levels" would only continue to be stable if the effort remained constant at the 1963 level whereas in fact the effort has risen appreciably since that time.

One of the crucial assumptions that this model relies upon is that the catchability coefficient q, remains constant during the first five months of the Abrolhos Islands season so that the decline in catch per unit of effort during this time may be wholly attributable to changes in population density. However, Morgan (1974b) found that catchability does change from month to month in the period March to July each year and hence, the estimation of Z using the Bowen and Chittleborough (1966) model will be biased.

Morgan (1977) in a critical examination of the utility of the Bowen and Chittleborough (1966) model concluded that, since the method appears to be influenced by variable catchability and variable recruitment, year-to-year comparisons of the various population parameters are hazardous. Also, since recruitment of growth of undersized rock lobsters may change in magnitude from year to year, the model cannot be profitably altered by calculating the total mortality coefficients from a knowledge of the densities of rock lobsters in successive months. However, perhaps the greatest disadvantage of the method is a lack of flexibility and application. For example, the model is not predictive in any way so that the effect of, say, an increase or decrease in effort cannot be evaluated; i.e., the precise position on the yield curve is not known. Also, no assessment can be made of likely effects of changes such as variations in the legal minimum size. However, provided that the assumptions concerning catchability and recruitment are fulfilled or taken into account, the model is useful in examining trends in recruitment and in this respect it has already led to significant changes in the management of the fishery.

The application of the dynamic pool models of Beverton and Holt (1957) and Ricker (1958) to the fishery for *P. cygnus* have been examined by Morgan (1977). He concluded that because of the lack of precision in the growth and mortality parameters the models did not provide a good description of the commercial fishery. However, a yield per recruit approach was not considered inappropriate since the rate of recruitment to the commercial fishery is relatively steady from year to year. This is apparently achieved despite the strong compensatory relationship between spawning stock and subsequent larval settlement, by density-dependent growth and mortality processes which have been shown by Chittleborough (1970) to operate during the juvenile stages.

Because of the problems associated with estimating mortality rates from animals (such as *P. cygnus*) which cannot be aged, an assessment using cohort analysis related to length composition data (Jones, 1974) was made by Morgan (1977). Again, the model was shown not to be a good description of the commercial fishery because of the lack of precision in the mortality and growth parameters.

Morgan (1977) concluded that, at the present level of knowledge, surplus yield models provided the most adequate description of the fishery for *P. cygnus*. Catch and fishing effort information is available for the entire history of the commercial fishery and the available models provided a good fit to the observed data (Figure 12). Based on the application of surplus yield models, it was calculated that the maximum yearly catch is in the order of 8.1 - 8.6 x 10^6 kg at an optimum fishing effort of 5.6 - 5.9 10^6 units. This compares with the catch in 1974-75 of 8.9 x 10^6 kg at a level of effort of 8.0 x 10^6 units (Morgan, 1979a).

4.6 The Population in the Community and the Ecosystem

- Physical features of the biotope of the community

Juvenile *P. cygnus* initially inhabit beds of seaweeds and seagrasses, and then move to shallow coastal reef areas where they remain for approximately four to five years (Anon., 1974). Adults are generally confined to deeper waters where they inhabit limestone reefs and ledges along the coast and the limestone and coral growths of the Houtman Abrolhos. In the deeper waters *P. cygnus* is also found on slightly eroded ledges and flat rock areas that are sometimes covered with consolidated sand and considerable marine growth (Sheard, 1962).

- Species composition of the community

Data on the species composition of the community are limited. Chittleborough (1975) examined some of the species which constitute an important part of the environment of *P. cygnus*, as a food source or as a threat to survival (see Sections 3.3 and 3.4).

The sublittoral zone off Rottnest Island in the southern portion of the range of *P. cygnus* has been examined superficially by Hodgkin et al. (1959). Extensive areas of seagrasses exist in the sandy bays surrounding Rottnest. The principal species are *Posidonia australis* and *Cymodocea antarctica* which are heavily epiphytized by smaller algae. The sublittoral rocks in the better illuminated areas are generally covered by large algae over a lithothamnion encrustation, though flat surfaces sometimes carry a thick cover of coralline algae such as *Jania*. The brown algae, *Ecklonia radiata*, *Scytothalia dorycarpa*, *Scaberia agardhii* and *Sargassum* spp. are abundant; also the red alga, *Metamostophora flabellata*, on well illuminated rocky substrata toward the sublittoral fringe and there is an abundance of Siphoneae, Dictyotales and Ceramiales.

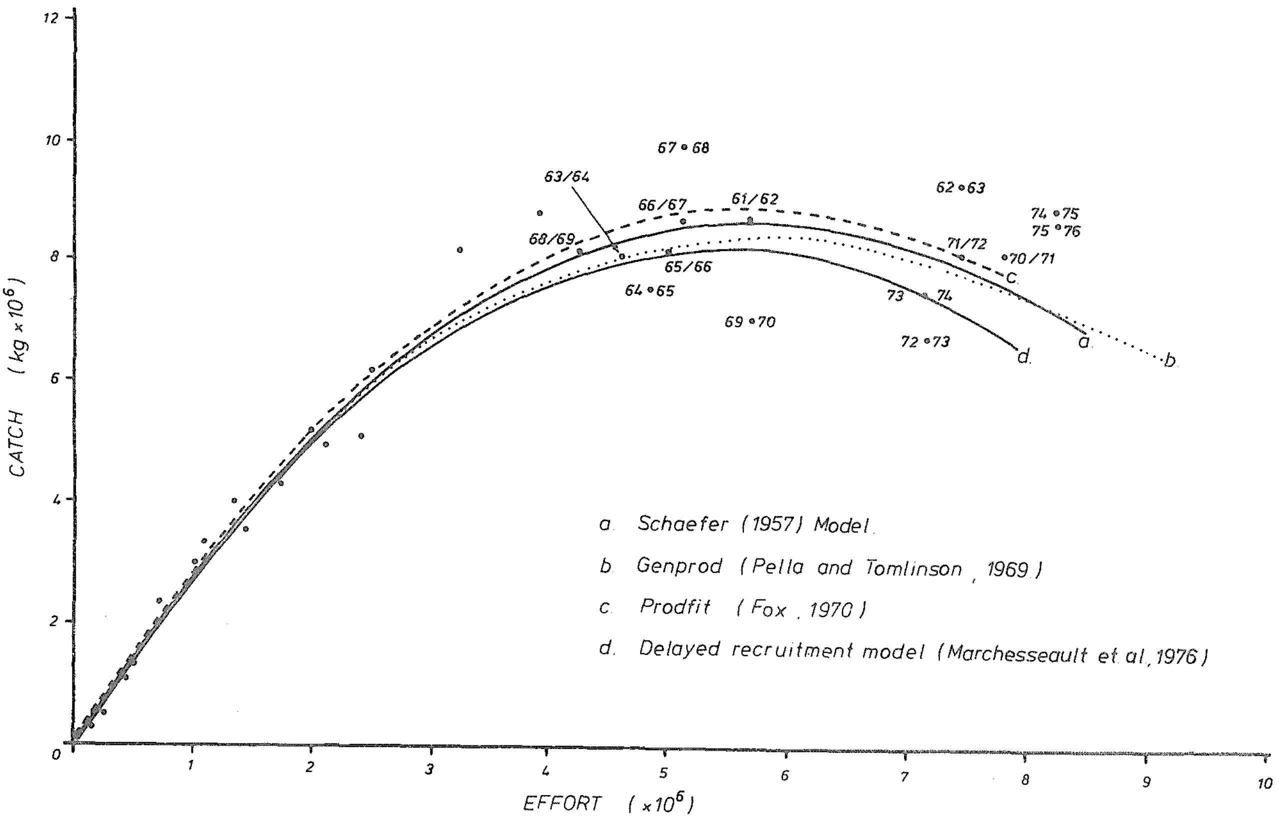


Figure 12 Surplus yield models fitted to observed catch and effective effort data for the fishery for *Panulirus cygnus* (after Morgan, 1977)

The undercut intertidal platforms are again covered by encrusting coraline algae, while leafy algae are sparse and confined to a few Rhodophyceae. Deeper into the ledges beneath the overhanging rock exist many sponges, hydroids, zoanthids, alcyonarians, corals, the gorgonian *Mopsella* spp., bryozoans and simple and compound ascidians. Actively moving animals are not abundant; they include nudibranchs, gastropods, ophiuroids and a great variety of worms under the lithothamnion, sponges and ascidians.

- Interrelations of the population of the species in the community and ecosystem

Chittleborough (1979) considers the low productivity on coastal reefs the major limiting factor responsible for regulating the population and maintaining relatively steady recruitments. *P. cygnus* therefore conforms well to the generalization by Chekunova (1972) that members of the Palinuridae are mainly confined to well balanced communities in hydrologically stable waters without upwelling and associated fluctuations in productivity. These communities are characterized by complex trophic systems associated with moderate or low productivity. According to George (1958b) *P. cygnus* occupies the role of scavenger in the community.

5 EXPLOITATION

5.1 Fishing Equipment

5.11 Gear

Bowen (1971) and Hughes (1971) reviewed the methods and the gear used in the commercial fishery for *P. cygnus*.

P. cygnus is caught commercially in pots and traps. The technique is to entice the lobsters into the pots through a narrow tapered entrance through which it is difficult to escape. Baits are used to attract the lobsters to the pot, the most commonly used being fish heads, e.g., Australian salmon (*Arripis trutta*), whole small fish, e.g., Australian herring (*Arripis georgianus*), mullet (*Mugil cephalus*), bony herring (*Fluvialosa vlaminghi*), sheep heads, cattle hocks or cattle hide and, in 1974, fishermen used an artificial bait for the first time (Morgan and Barker, 1977).

There are three main types of pots in general use, batten, stick or cane beehive or iron beehive. The beehive pot is the most extensively used and is considered most suitable for deep water (over 28 m). The stick concentration of this pot is generally preferred, particularly in the Fremantle area. In contrast the batten pot is recognized as ideal for shallow (1.8-28 m) protected waters, and is used almost exclusively in the Abrolhos Islands.

Batten pots are constructed either entirely from wood or have a welded steel bottom and wooden sides and top. The neck may be made from wooden battens, similar to those used for the sides, or plastic necks may be used. One end of the pot can be removed to allow baiting and removal of the catch (See Figure 13a).

Dimensions in cm:

Length	81-86
Width, base	71-81
Height	38
Width	30-53
Neck	18x18
Depth	15-20

Beehive pots have the general dimensions:

Diameter of the base	91-107
Height of pot	64-74
Diameter, neck	18-30
Width of cane apron	8-13

Stick beehive pots have a frame made from 19-24 pieces of heavy galvanized wire (approximately 4.8 mm diameter) and the neck or entrance and apron are close woven with 9.5 mm diameter cane. When the apron and surround to the neck are complete, t-tree sticks are woven between the frame wires at the desired spacing. As weaving progresses the wires are bent to shape the pots. Pots composed completely of cane are woven by the same method (see Figure 13b).

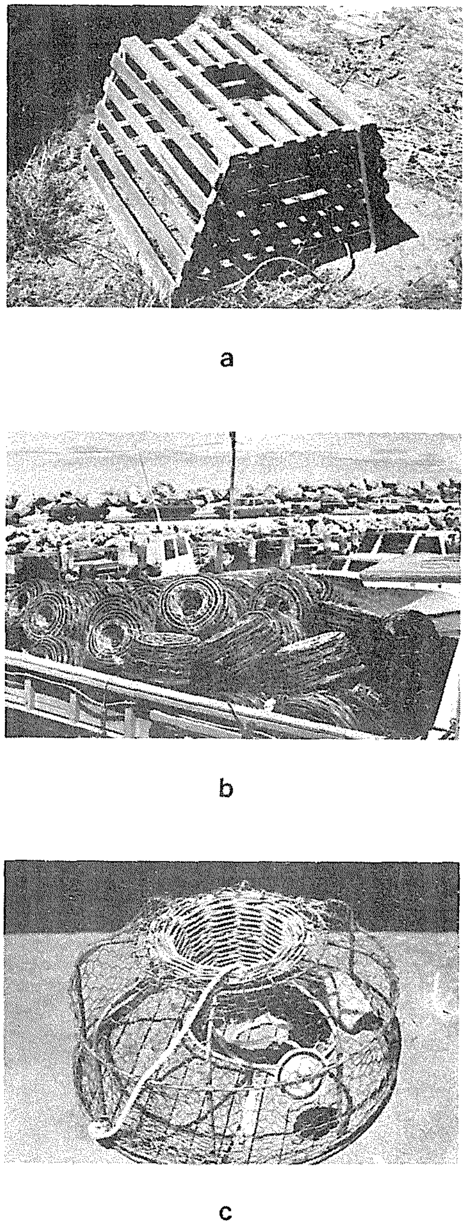


Figure 13 The three types of rock lobster pots used in the western rock lobster fishery; (a) a wooden batten pot; (b) a load of cane beehive pots; (c) a steel and wire beehive pot with bait basket

Iron beehive pots have frames usually fabricated from 9.5-12.7 mm diameter mild steel rods with horizontal stiffening rings welded to the 8-12 vertical frames. The bottom is made either of reinforcing wire mesh of suitable size or of mild steel straps spaced and welded to the circular base frame. The vertical frames are in turn welded to this base frame. A covering of heavy galvanized wire netting is next wrapped around the circumference of the pot and laced to the base with tie wire. Woven cane, or moulded plastic necks and aprons are used (see Figure 13c).

All pots are required by law to have incorporated in them a 54 mm escape gap which allows the majority of below legal size rock lobsters to escape before the pots are pulled (Bowen, 1971; Morgan and Barker, 1974).

Hydraulically operated winches and automatic pot tippers are universal throughout the fishery (Morgan, 1977). Table XXIII gives details of equipment carried by boats included in an economic survey current to 1974.

- Changes in type of gear during the development of the fishery

According to Brownfield (1963) the method of capture by baited pots set on the bottom has remained substantially unaltered although refinements of the pots have occurred. The major changes have been in the lifting of pots, from hand pulled to mechanically lifted and the use of synthetic rope.

- Use of echo-sounding

The progressive increase in the use of echo-sounding equipment to aid in the location of the reefs which are the rock lobster's habitat has occurred since the late 1950s and early 1960s (Bowen, 1971).

Hughes (1971) states that in the Abrolhos Islands practically all boats over 7.7 m (25 ft) are equipped with echo-sounders, where it is essential amongst the shallow reefs.

5.12 Boats

- Changes in type of boats during the development of the fishery

The number of boats in the fishery increased rapidly from 103 in 1948 to 695 in 1962. There was an initial sharp increase in the number of boats prior to the introduction of licence limitation in 1963 and in 1964 there were about 830 vessels in the fishery. This had since slowly declined to 809 in 1975 (Morgan and Barker, 1977). In the 1940s most boats were sail powered but some had auxiliary engines (see Figure 14a).

During the 1950s and early 1960s significant technological progress was made; new boats were built specifically for the rock lobster industry, and these included provision of pot winches, large deck space for carrying gear, and a hull design which permitted rapid movements of pots each day (Figure 14b).

Most of these new boats were small, fast, high-powered, shallow-drafted "scooter" boats, but in the late 1940s and early 1950s small ships of 15.4-21.5 m (50-70 ft) in length known as freezer ships were fitted out as mobile refrigerated processing plants (Bowen, 1971). Refer to Table XXIV for the size distribution of the fishing fleet.

5.2 Fishing Areas

5.21 General geographic distribution

- Land area

600 Oceania, 612 Western Australia

- Sea area

PSE (Southern Ocean, E) Southern limit Mandurah (32°35'S). ISW (Indian Ocean) Northern limit Kalbarri (28°S) (George, 1962).

5.22 Geographical ranges

- Distance from coast

The fishery extends to about 32-40 km from the coast, as well as including the reef systems of the Houtman Abrolhos (Anon., 1974).

- Areas of greatest abundance

The chief areas of commercial production lie between latitudes 29°S and 32°S. These areas extend from Port Gregory, 70 km north of Geraldton, to Rottnest and Garden Islands off Fremantle, and include coastal waters from 30-40 km offshore, together with the inner and outer reef systems of Houtman Abrolhos. This highly productive region occupies some 480 km of coastline and covers a rock lobster bearing area of approximately 3.3 x 10^6 ha within the 83 m depth contour (Sheard, 1962).

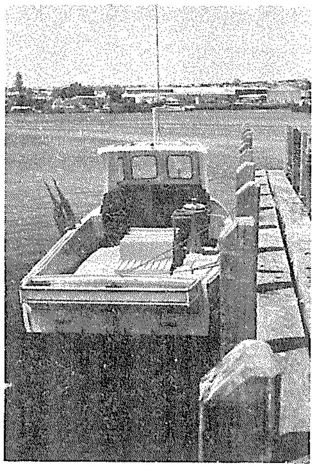
TABLE XXIII

Equipment carried by boats included in an economic survey by boat length
(Anon., 1974)

Equipment	Boat length Under 7.6 m (%)	7.6 m and under 7.9 m (%)	7.9 m and under 10.7 m (%)	10.7 m and under 13.7 m (%)	13.7 m and over (%)	All boats (%)
			Houtman Abrolhos Boats			
Echo-sounder	80	67	100	75	100	82
Radio receiver	-	33	-	-	-	7
Radio transceiver	100	67	100	100	100	93
Pot hauler	100	100	100	100	100	100
Pot tipper	100	100	100	100	100	100
Petrol engine	80	-	-	-	-	30
Diesel distillate engine	20	100	100	100	100	70
Automatic pilot	-	-	-	-	50	2
Steel hull	-	-	-	25	-	3
Planked timber hull	-	-	17	50	100	14
Plywood hull	100	100	83	25	-	83
Aluminium hull	-	-	-	-	-	-
Fibreglass hull	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-
			Freezer Boats			
Echo-sounder	-	-	-	-	-	91
Radio receiver	-	-	-	-	-	-
Radio transceiver	-	-	-	-	100	100
Pot hauler	-	-	-	-	100	100
Pot tipper	-	-	-	-	100	100
Petrol engine	-	-	-	-	-	-
Diesel distillate engine	-	-	-	-	100	100
Automatic pilot	-	-	-	-	64	64
Steel hull	-	-	-	-	9	9
Planked timber hull	-	-	-	-	91	91
Plywood hull	-	-	-	-	-	-
Aluminium hull	-	-	-	-	-	-
Fibreglass hull	-	-	-	-	-	-
Refrigeration	-	-	-	-	100	100

TABLE XXIII continued

Equipment	Boat length Under 7.6 m (%)	7.6 m and under 7.9 m (%)	7.9 m and under 10.7 m (%)	10.7 m and under 13.7 m (%)	13.7 m and over (%)	All boats (%)
Fremantle Boats						
Echo-sounder	33	100	96	100	100	88
Radio receiver	-	-	-	-	-	-
Radio transceiver	17	100	96	100	100	85
Pot hauler	67	100	100	85	86	90
Pot tipper	50	100	100	100	100	92
Petrol engine	33	-	-	-	-	5
Diesel distillate engine	67	100	100	100	100	95
Automatic pilot	-	-	15	8	-	8
Steel hull	-	-	-	8	-	2
Planked timber hull	50	38	46	77	100	56
Plywood hull	33	62	50	15	-	38
Aluminium hull	-	-	4	-	-	2
Fibreglass hull	17	-	-	-	-	3
Refrigeration	-	-	-	-	-	-
Geraldton Coastal Boats						
Echo-sounder	75	100	100	100	100	94
Radio receiver	25	17	-	-	-	10
Radio transceiver	75	63	100	100	100	90
Pot hauler	100	100	100	100	100	100
Pot tipper	100	100	100	100	100	100
Petrol engine	25	-	-	-	-	6
Diesel distillate engine	75	100	100	100	100	94
Automatic pilot	-	-	22	50	25	15
Steel hull	-	-	-	17	75	8
Planked timber hull	-	17	44	33	25	24
Plywood hull	100	83	56	50	-	68
Aluminium hull	-	-	-	-	-	-
Fibreglass hull	-	-	-	-	-	-
Refrigeration	-	-	-	-	25	2



a

b

Figure 14 Typical vessels used in the rock lobster fishery; (a) an older style of carvel planked fishing boat; (b) modern bondwood vessel showing a large deck space, pot winch (right) and automatic pot tipper (left)

- Differential abundance associated with hydrological features

P. cygnus is most prolific in situations such as reef-ledge and reef-flat systems, and not in sand, mud and fine shell grounds (Sheard, 1962).

- Changes in range during development of the fishery

In its infancy the range of the rock lobster fishery was controlled by three factors; (1) suitability of the boat to cope with the prevailing weather conditions, (2) the ability of the skipper to locate reef areas, (3) the fact that the pot had to be lifted by hand. This meant that initially the rock lobster was fished mainly on the shallow reef areas, particularly around the islands off Fremantle, and the shallow water areas within the Houtman Abrolhos.

With the subsequent development and improvement in boats and gear (see Sections 5.11 and 5.12) exploitation of deeper waters as well as the more intensive fishing of shallower grounds was possible (Bowen, 1971; Morgan, 1977).

5.23 Depth ranges

The fishery extends to a depth of about 110 m (from about 32-40 km off the coast) but the most highly productive region occurs within the 83 m line (Sheard, 1962; Anon., 1974). Morgan (1977) states that *P. cygnus* is taken in depths from shallow reef areas of 1 m to approximately 180 m, but fishing in deeper water is often limited by difficult sea and weather conditions.

5.3 Fishing Season

5.31 General pattern of season(s)

- Pattern of season within whole area

The fishing season for *P. cygnus* may be subdivided into three distinct phases. Firstly, the "whites" fishery, described by George (1958a), which begins by proclamation on 15 November and arbitrarily finishes at the end of December. During this part of the season fishermen set their pots in shallow waters close to the shore and take large quantities of newly moulted, immature rock lobsters. Tagging studies (George, 1958a; George, unpublished data) have shown that these "white" lobsters undertake a seaward migration during November and December so that as the "whites" season progresses, fishermen set their pots in increasingly deeper water as they follow this migration.

TABLE XXIV

Size distribution of the fishing fleet
(from Anon., 1974)

Boat length	Under 7.6 m No.	Under 7.6 m %	7.6 m and under 7.9 m No.	7.6 m and under 7.9 m %	7.9 m and under 10.67 m No.	7.9 m and under 10.67 m %	10.67 m and under 13.7 m No.	10.67 m and under 13.7 m %	13.7 m and over No.	13.7 m and over %	All boats No.	All boats %
Fremantle boats	62	16	57	15	158	41	77	20	33	8	387	100
Geraldton coastal boats	50	25	51	25	60	30	24	12	16	8	201	100
Houtman Abrolhos boats	71	37	39	21	47	25	26	14	6	3	189	100
Freezer boats	-	-	-	-	-	-	-	-	44	100	44	100
Total	183	22	147	18	265	32	127	16	99	12	821	100

The second phase commences at the beginning of January and continues until the season closes on 30 June and is known as the "coastal red" fishery. The fishermen work closer to the coast during this part of the season although fishing in deeper water is continued by some fishermen, particularly those with larger vessels.

Lastly, the third phase of the season is the Abrolhos Islands fishery which is open from 15 March to 30 June (Morgan and Barker, 1974; Morgan, 1977).

5.32 Dates of beginning, peak and end of season

Management regulations determine the beginning and end of the fishing season. In the coastal areas the season is from 15 November to 30 June and in the Abrolhos Islands the season is limited to a 3 1/2-month period between 15 March and 30 June (until 1979 the seasons ended on 14 August).

The peak of the season occurs during the "whites" season with the largest catches usually occurring during December with a usually smaller peak at the commencement of the Abrolhos Islands fishery (Morgan and Barker, 1974, 1975, 1976, 1977).

5.33 Variation in date or duration of season

Prior to 1978 the coastal and Abrolhos seasons finished on 14 August each year.

The amount of effort declines considerably in the winter months of the fishery (June, July and August) due to bad weather. The average number of days/worker per boat-month in August declines to approximately a quarter of that recorded for December (Morgan and Barker, 1974, 1975).

Prior to 1963 there have been some further variations of the period of open season, which have been reviewed by Sheard (1962).

5.4 Fishing Operations and Results

5.41 Effort and intensity

- Type of unit of effort

Several types of units of effort have been cited by various workers. Sheard (1962) used a fisherman working for a given period and a pot working for a month as units of effort, whereas Bowen and Chittleborough (1966) considered the pot fishing for one unit as the ideal unit of effort.

Morgan and Barker (1974, 1975, 1976, 1977) in their annual reviews of the western rock lobster fishing seasons present the effort data as pot lifts both monthly and seasonally. Morgan (1979b) showed that pot lift data, suitably adjusted for month-to-month variation in vulnerability, provided the best measure of effort in that it remained in constant proportion to the instantaneous fishing mortality rate, F.

- Catches per unit of fishing effort

Bowen and Chittleborough (1966) gives catches per unit of fishing effort from 1948 to 1964 in weight per pot night.

Catch and effort data for the seasons 1971-72 to 1974-75 are given by Morgan and Barker (1974, 1975, 1976, 1977) using number of pot lift for effort, for each month (Table XXV). Catch per effort data from 1944-45 to 1975-76 are shown in Figure 15 with the effort having been corrected by weighting each month's effort in pot lifts according to the relative catchability in that month (Morgan, 1979b).

- Fishing effort per unit area

No data are available

- Total fishing intensity

Information on the fishing effort applied annually in the form of pot lifts from the 1944-45 season to 1975-76 season can be seen in Figure 15.

- Causes of variation in fishing effort and intensity

Management regulations introduced in 1963 were designed to stabilize the amount of effort applied in the fishery. However by reference to Figure 15 it can be seen that there has been an increase in the amount of effective effort, which according to Morgan and Barker (1974) is due to increased efficiency of the fishing fleet.

Seasonal variation in fishing effort and intensity is indicated by changes in the average number of days worked per boat per month. Weather conditions and fluctuations in the price of rock lobsters are the primary determinants of fishing intensity (see Table XXVI). Morgan and Barker (1974) suggested that the decrease in the number of boat-days worked per month in the 1972-73 season was due to the poor weather during the winter while the better weather conditions in the 1975-76 season permitted a larger number of days (Morgan and Barker, 1977).

5.42 Selectivity

- Selective properties of gear

Management regulations require all pots to have an unobstructed rectangular escape gap measuring not less than 54 mm in width and 305 mm in length fitted to the side or top of the pot. This allows the majority of undersized rock lobsters to escape from the pot before hauling, thus reducing mortality (Bowen, 1963). The pot selectivity curve has been estimated by Morgan (1977) and shown in Figure 11. Selectivity for size and sex has been detected in aquarium experiments (Morgan, 1979b).

5.43 Catches

- Total annual yields

The total catch of *P. cygnus* from the 1944-45 season to the 1975-76 season is shown in Figure 15. The total catch, nominal and effective fishing effort, mean number of boats working per month, mean number of days worked per boat per month and mean number of pots worked per port from 1964-65 to 1975-76 are shown in Table XXVII.

- Total annual yields from different fishing grounds

Morgan and Barker (1974, 1975, 1976, 1977) give the annual yields, in various statistical blocks (see Figure 16) for the seasons 1971-72 to 1975-76 (see Table XXVIII).

- Maximum equilibrium yield

Bowen and Chittleborough (1966) calculated the sustainable level of catch for the *P. cygnus* fishery to be 7 272 727 ± 909 090 kg/year (16 000 000 ± 2 000 000 lb). Morgan and Barker (1977) investigated the population dynamics of *P. cygnus* and related these findings to the management of the fishery. He concluded that in recent years (see Figure 15) the maximum sustainable yield is being taken from the fishery.

6 PROTECTION AND MANAGEMENT

6.1 <u>Regulatory (Legislative) Measures</u>

6.11 Limitation or reduction to total catch

- Limitation on the efficiency of fishing units

Management of the rock lobster fishery is achieved through a series of regulations which are aimed at limiting effort in an attempt to maintain an average annual catch. These regulations have been reviewed by Bowen (1971) and summarized by Morgan (1977). The principal regulations which achieved this were introduced in 1963 and limit the number of licensed boats,

TABLE XXV

Catch per unit effort (pot lift) per month for *Panulirus cygnus* (after Morgan and Barker, 1974, 1975, 1976, 1977)

Season	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Total
1971-72	0.39	1.24	0.88	0.58	0.95	0.87	0.63	0.52	0.56	0.59	0.72
1972-73	0.75	1.19	0.64	0.50	0.76	0.78	0.58	0.48	0.22	0.23	0.61
1973-74	0.47	0.76	0.63	0.55	0.97	0.77	0.60	0.52	0.52	0.53	0.69
1974-75	0.59	1.19	0.71	0.63	0.97	0.89	0.64	0.57	0.53	0.63	0.81

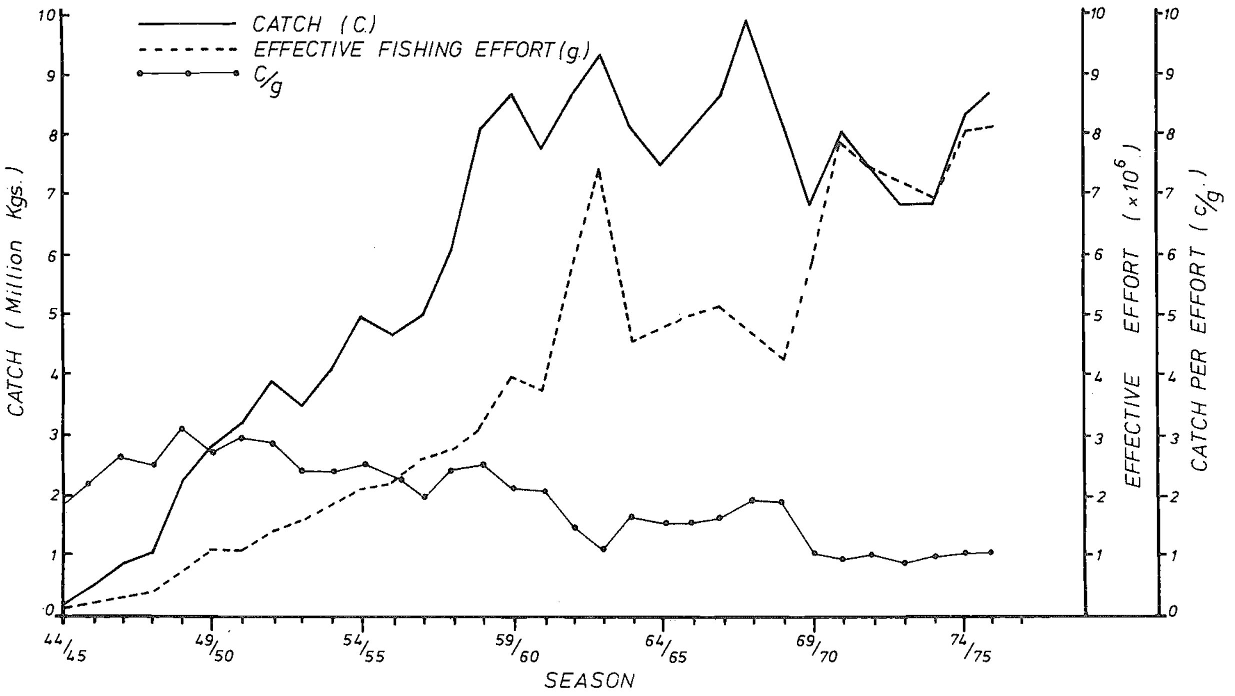


Figure 15 Catch, effective fishing effort and catch per unit of effort data for *Panulirus cygnus* (after Morgan and Barker, 1977)

TABLE XXVI

Average number of days worked per boat per month
(after Morgan and Barker, 1974, 1975, 1976, 1977)

Season	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Average
1971/72	9.9	25.0	17.8	16.6	20.8	20.7	16.9	15.6	14.7	8.2	17.2
1972/73	11.5	24.7	15.6	16.1	19.4	19.7	15.6	13.3	13.6	6.6	16.2
1973/74	10.8	24.5	16.6	16.7	21.7	20.1	15.9	14.7	15.0	6.6	17.0
1974/75	11.7	24.2	16.7	18.9	20.6	21.2	18.4	15.6	14.4	8.9	17.6

TABLE XXVII

Total catch (C), nominal fishing effort (g), effective fishing effort (f), mean number of boats working per month (B), mean number of days worked per boat per month (D), mean number of pots worked per boat (P) for the western rock lobster fishery (1964-65 to 1975-76)

Season	C(kg x 10^6)	g (pot lifts x 10^6)	f(x 10^6)	B	D	P
1964-65	7.486	6.817	4.798	551	15.2	75.4
1965-66	8.120	7.414	5.036	581	15.2	78.8
1966-67	8.635	7.595	5.147	575	15.4	80.0
1967-68	9.853	7.930	5.173	603	15.1	81.0
1968-69	8.078	8.478	4.292	613	15.6	83.8
1969-70	6.918	8.477	5.771	613	16.0	82.9
1970-71	8.013	9.063	7.888	650	16.8	84.5
1971-72	8.171	10.002	7.536	670	16.6	86.3
1972-73	6.809	9.091	7.253	648	16.2	85.2
1973-74	6.780	9.864	7.127	667	17.0	87.3
1974-75	8.877	10.255	8.035	663	17.6	88.4
1975-76	8.873	10.258	8.100	659	17.0	89.3
Average change per year	-0.016 (NS)	+0.318 (***)	+0.348 (***)	+10.5 (***)	+0.22 (***)	+1.2 (***)
Average percentage change 1964-65 to 1975-76	-	+56.5%	+94.2%	+22.7%	+17.6%	+17.6%

After Morgan and Barker, 1974, 1975, 1976, 1977

Note: Average change per year and percentage changes are calculated from fitted linear regressions

NS = Not Significant at 0.05 level

*** = Significant at 0.001 level

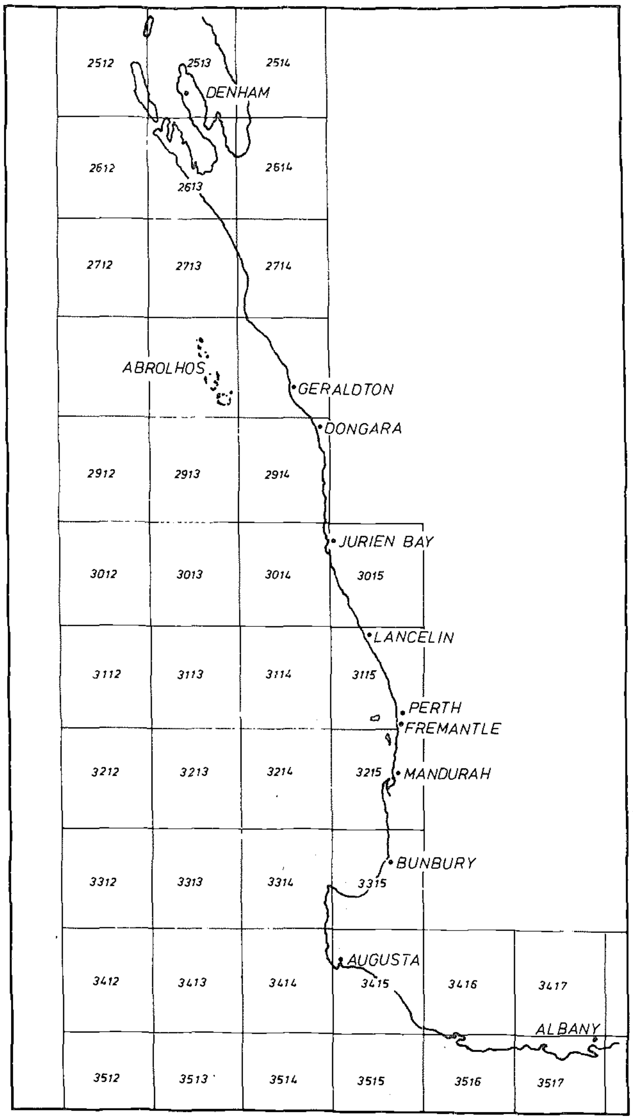


Figure 16 *Panulirus cygnus* fishery areas, statistical blocks (after Morgan and Barker, 1976)

the number of licensed pots (to 9.84/m (3/ft) of boat length with a maximum of 200 m) and place restrictions on the size of replacement boats.

- Limitations on the number of fishing units, fishermen

Amateur fishermen are limited to two pots and the use of spear guns or hand guns is prohibited (see also above). There are no restrictions on the number of professional fishermen.

- Limitation on total catch (quota): daily, seasonal, annual

Catches by amateur fishermen are limited to a bag limit of eight rock lobsters per day. There is no quota on commercial catches.

(a) Boats and men may fish either between 30°S and 33°S or between 28°S and 30°S in one year, but not in both areas.

(b) Boats which fish between 28°S and 33°S in any year may fish north of 28°S and south of 33°S during the same year.

(c) Boats fishing in the defined Abrolhos Islands area may not fish outside that area from 15 March to 14 August.

(d) Boats which did not fish in the defined Abrolhos Islands area during the three years prior to 1 January 1966, are not permitted to fish in that area.

- Closed seasons

Closed seasons are from 1 July to 14 March for the declared Abrolhos Islands area and 1 July to 14 November for all other Western Australian waters.

- Restrictions based on sex or condition

The taking of female rock lobsters carrying eggs is prohibited.

- Restrictions based on size

Minimum length of 76 mm carapace length and a minimum tail weight of 140 g.

- Limitations on size and efficiency of gear or craft

Rock lobster pots with more than one entrance are prohibited and every pot is

TABLE XXVIII

Catch of *Panulirus cygnus* in kg weight in various statistical blocks
(after Morgan and Barker, 1974, 1975, 1976, 1977)

Block	1971-72	1972-73	1973-74	1974-75	1975-76
2612	7 880	-	-	-	-
2613	2 155	1 392	12 146	53 445	5 983
2712	-	871	-	-	1 283
2713	159 856	151 251	165 081	210 629	179 376
2714	90 895	88 002	112 126	130 769	94 134
2812	48 683	5 756	16 536	10 193	14 662
2813	1 432 409	1 195 781	1 243 791	1 311 699	1 346 994
2814	703 129	641 479	610 330	699 447	698 699
2912	11 791	-	6 370	1 022	-
2913	64 959	54 385	89 153	44 985	59 398
2914	1 794 200	1 302 781	1 299 158	1 590 886	1 756 148
3012	2 041	11 794	17 313	1 667	-
3013	27 922	32 681	25 711	13 024	-
3014	1 344 845	984 869	1 032 721	1 287 901	1 435 613
3015	304 840	276 602	240 842	327 137	276 652
3112	16 897	17 963	14 825	20 629	-
3113	25 537	9 199	14 387	14 618	-
3114	207 523	170 503	176 238	254 395	312 294
3115	1 545 666	1 363 633	1 344 912	1 841 501	1 890 504
3212	295	-	-	-	-
3213	1 187	-	-	-	-
3214	1 300	4 130	3 077	-	12 124
3215	342 648	260 242	331 404	421 510	594 033
3314	4 100	2 463	3 994	773	10 148
3315	23 345	27 835	17 469	23 314	32 735
3414	6 649	2 489	2 088	470	-
Total	81 707 520	66 061 030	67 796 720	82 600 140	8 719 780

required to have an unobstructed rectangular escape gap measuring not less than 54 mm in width and 305 mm in length fitted to the side or top of the pot.

Freezer boats are not permitted to operate within territorial waters between Mandurah and Geraldton from 1 January to 14 August and no additional freezer boats will be licensed as processing establishments.

- Restrictions on use of fish

Rock lobsters may only be processed or cut up or dismembered by registered processing and export establishments. Processing in the Abrolhos Islands area is prohibited.

7 ARTIFICIAL CULTIVATION

7.1 Procurement of Stocks

Chittleborough (1968, 1974d) attempted to culture *P. cygnus*. It was found that it was impossible to maintain larvae hatched from eggs but individuals could be successfully reared from the puerulus stage to adulthood.

The puerulus stage can be procured from artificial seaweed collectors designed by Phillips (1972). The settlement of the puerulus on the artificial seaweed simulates the natural settlement of this species and apparently exploits a strong grasping reaction developed by this stage when it is ready to begin a benthic existence.

7.2 Spawning

Adult western rock lobsters breed actively in captivity (Chittleborough, 1968).

7.3 Development Times

No data are available on the duration of the larval stages in the laboratory due to the difficulties in maintaining larvae under laboratory conditions (Chittleborough, 1968).

7.4 Survival

The long and complex life cycle of *P. cygnus* precludes successful cultivation from the egg under laboratory conditions. Food preferences change with larval stage and the temperature has to be maintained between narrow limits, any minor deviations from these strict requirements resulting in death (Chittleborough, 1968).

Chittleborough (1974a) has found it possible to successfully rear *P. cygnus* from the puerulus stage to adult and has determined optimal environmental conditions for maximal growth and survival, with less than 5 percent mortality.

7.5 Foods, Feeding

See Section 3.22

7.6 Parasites, Diseases and Their Control

No data are available

7.7 Commercial Application

At present there is no commercial application for cultivating *P. cygnus* from eggs due to the difficulty in maintaining the larvae. However it could be economically viable to raise the western rock lobster from the puerulus stage. Under optimal environmental conditions the growth rate can be improved greatly, reducing the time taken by those lobsters aged two years to reach market size to a factor 0.4 times that required by the wild stock.

The present regulations state that it is illegal to catch and hold undersized rock lobsters (Chittleborough, 1974a).

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ISBN 92-5-101025-0