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Camaenid land snails on Barrow Island: distributions, molecular phylogenetics and taxonomic revision

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ABSTRACT – Three species of camaenid land snails occur on Barrow Island: *Quistrachia barrowensis* and two previously unassigned species of *Rhagada*. Based on morphological re-evaluation and analysis of sequences of the mitochondrial gene COI, we have revised the taxonomy of these species, providing a clearer understanding of their geographic distributions and origins. The supposed Barrow Island endemic *Q. barrowensis* is synonymous with *Q. montebelloensis* from the Montebello and Lowendal Islands. The small species of *Rhagada*, confined to the northern tip of Barrow Island, is conspecific with *R. plicata*, whose distribution also includes the Montebellos and the Lowendals. The large species of *Rhagada* is described here as *R. barrowensis* sp. nov., known only from Barrow Island and adjacent Pascoe Island. The three camaenids represent deeply divergent lineages with different geographic origins, indicating that the local diversity on Barrow Island has come about through a complex history. With maximum geographic spans of only 22 to 70 km, the short-range endemism of these species highlights the conservation significance of Barrow Island.

KEYWORDS: COI mtDNA, endemic species, phylogeny, *Quistrachia*, *Rhagada*

INTRODUCTION

The Camaenidae are the dominant land snails across northern and eastern Australia, including the Pilbara region. They are represented on Barrow Island by three species from two genera (Solem 1997; Slack-Smith 2002; Johnson et al. 2006) (Figure 1). The most species-rich camaenid genus in the Pilbara region is *Rhagada* Albers, 1860 (Solem 1997), which is represented on Barrow by two distinct, unidentified species, which differ markedly in size, banding and sculpture of the shell (Johnson et al. 2006). Except for a brief mention of small, worn, dead shells, Solem's (1997) taxonomic review did not include *Rhagada* from Barrow Island. Although Withers et al. (1997) referred to the larger species as *R. tescorum*, this was tentative, and the species' morphological similarities to other species have rendered its taxonomic status unclear (Slack-Smith 2002). The second most species-rich camaenid

genus in the Pilbara is *Quistrachia* Iredale, 1939, within which Solem (1997) described *Quistrachia barrowensis* as an endemic species on Barrow Island and its associated islets. In this paper, we document the distributions of all three camaenids on the island, and revise their taxonomy, based on analyses of DNA sequences and morphology.

The *Quistrachia* on Barrow Island and associated islets was described as *Q. barrowensis* by Solem (1997). Its relatively thick shells are similar to those of *Q. lefroyi* from the Cape Range and Ningaloo Station and *Q. warroorana* from Warroora and Gnaraloo stations (Solem 1997). These species are free-sealers during aestivation, and phylogenetic analysis indicates that they are a separate clade from that of the rock-sealers *Q. legendrei* from the Dampier Archipelago and Burrup Peninsula and *Q. turneri* from the inland Pilbara, which have thinner shells and flared apertures (O'Neill 2008). That phylogenetic analysis did not include the fourth



FIGURE 1 Examples of the three camaenid species on Barrow Island. From left to right: *Quistrachia montebelloensis* (= *Q. barrowensis*), the large *Rhagada* (holotype of *Rhagada barrowensis* sp. nov.), and the small *Rhagada*. Note the epiphragm in *Q. montebelloensis*. Scale bar = 1 cm.

free-sealer, *Q. montebelloensis*, from the Montebello Islands, which is morphologically very similar to *Q. barrowensis* (Solem, 1997), and which has been included in the present study.

In the genus *Rhagada*, analysis of mtDNA sequences in all described species in the Pilbara region has revealed four, deep lineages, two of which are represented on Barrow Island (Johnson et al. 2012). The small species on Barrow Island is genetically very close to *R. plicata* from the Montebello Islands, as part of the lineage that also includes all but one of the species endemic to the Dampier Archipelago, but which is absent from the mainland. The large species of *Rhagada* from Barrow Island is part of the major mainland lineage, and is most closely related to populations

of the widespread *R. convicta* from the adjacent mainland, as well as *R. pilbarana* from Mount Herbert. In the present study of *Rhagada*, we examine additional samples from Barrow Island, the Montebello Islands and the nearby Varanus Island, to clarify the relationships of both species on Barrow Island.

MATERIALS AND METHODS

DISTRIBUTIONS

The distributions of camaenid snails were determined from the WAM collections and additional surveys (Slack-Smith 2002; Johnson et al. 2006). The samples recorded in Johnson et al. (2006)

were from searches for live snails, whereas many of the other records are of shells only. Because of close similarities of two of the species on Barrow Island with species in the Montebello Islands and the Lowendal Islands, samples from those groups were included for comparison.

GENETIC ANALYSES

Broad-scale phylogenetic analyses within both *Quistrachia* and *Rhagada*, including representatives of the Barrow Island species, have already been carried out using sequences of the mitochondrial genes 16S rRNA (16S) and cytochrome c oxidase subunit 1 (COI) (O'Neill 2008 for *Quistrachia*; Johnson et al. 2012 for *Rhagada*). Here, we added specimens specifically required to understand the relationships of the taxa on Barrow Island, and analysed these with the relevant subset of species in each genus. Because previous analyses confirmed consistency of relationships among species based on either 16S or COI and based on different phylogenetic analyses (neighbour joining, Bayesian or maximum likelihood), we simply report here maximum likelihood analyses of sequences of COI, which were conducted in Mega 5 (Tamura et

al. 2011). Trees are presented in linearized form, to indicate clearly the levels of divergence. Methods of DNA extraction, PCR, sequencing and analysis were as detailed in Johnson et al. (2012). COI is the usual gene used in DNA barcoding, and its use here to quantify genetic divergence allows consistent comparisons with other studies.

For *Quistrachia*, we include samples of *Q. montebelloensis* in the analysis of COI sequences of the four free-sealers, as well as samples of *Q. barrowensis* from Boodie Island and Pascoe Island, and similar specimens from Varanus Island in the nearby Lowendal Islands. The rock-sealer *Q. legendrei* was used as an outgroup.

To examine more fully the relationship of the small species to *R. plicata*, we increased the sample size on Barrow from two to five, and in the Montebellos from two to eight, including specimens from Hermite Island and Crocus Island. We also added specimens from Varanus Island. For the large species on Barrow Island, we added two specimens from Boodie Island to the two from Barrow examined previously. To place these in context, we included the published sequences of *R. convicta* from Exmouth, Giralia and Onslow, *R.*

TABLE 1 Locations and haplotype codes of specimens from Barrow Island, Varanus Island and the Montebello Islands sequenced for COI.

	°S	°E	<i>Quistrachia</i>	Small <i>Rhagada</i>	Large <i>Rhagada</i>
Boodie Island	20.9659	115.3335	QU512-513		
Boodie Island	20.9657	115.3341			R837-838
Pascoe Island	20.9608	115.3396	QA18		
Barrow Island	20.7012	115.4247	QA20, QA43		
Barrow Island	20.6967	115.4247	QA47		
Barrow Island	20.7012	115.4255		R533-536	
Barrow Island	20.8132	115.4259	QA21-22		
Barrow Island	20.8182	115.4383			R819-820
Barrow Island	20.6714	115.4420		R835-836	
Barrow Island	20.7311	115.4701	QA05-06, QA45		
Varanus Island	20.6476	115.5709	S83637		
Varanus Island	20.6527	115.5796	S83644		
Varanus Island	20.6556	115.5766		S83636	
Varanus Island	20.6566	115.5782		S83647	
Crocus Island	20.4194	115.5259	QU516-517	G14-16	
Hermite Island	20.4859	115.5273		R539, R540	
Hermite Island	20.4421	115.5320	QU518-520	G17-19	

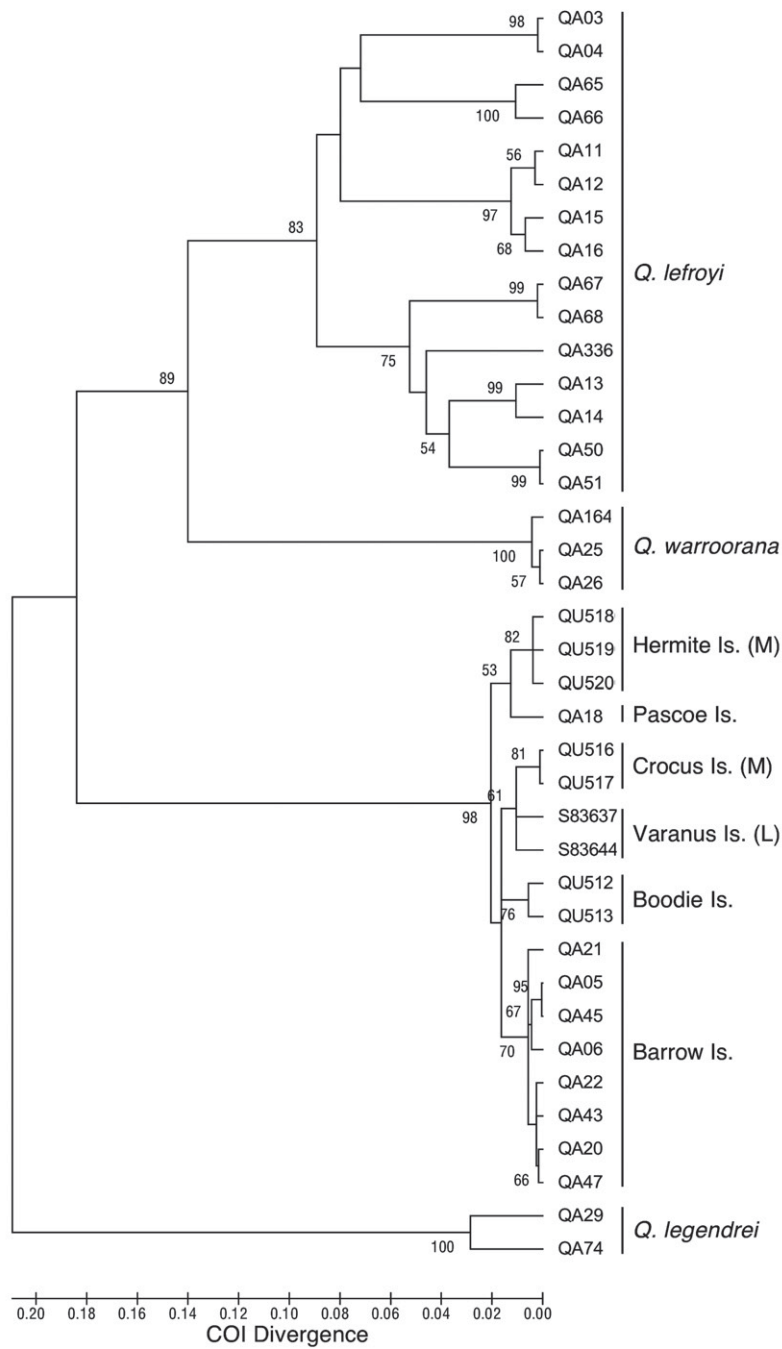


FIGURE 2 Maximum likelihood consensus tree of COI haplotypes in *Quistrachia* from Barrow Island and adjacent areas. (M) indicates *Q. montebelloensis* from the Montebello Islands; (L) indicates Lowendal Islands. Bootstrap values greater than 50% are shown. Haplotype codes are as in Table 1.

pilbarana, *R. capensis* from the Cape Range, and *R. perprima* from the Dampier Archipelago (Johnson et al. 2012). These are all the species whose shells are similar to those of the large species on Barrow Island (Solem 1997; Slack-Smith 2002). The locations

of the specimens of both *Rhagada* and *Quistrachia* from Barrow Island, the Montebellos and Varanus Island that were examined for COI are shown in Table 1. The GenBank accession codes for these new sequences are KC617888 to KC617919.

RESULTS

GENETIC RELATIONSHIPS

Haplotypes of COI in *Quistrachia* from Barrow Island and the associated Boodie and Pascoe Islands formed a tight clade with *Q. montebelloensis* from Hermite and Crocus Islands in the Montebellos and Varanus Island in the Lowendals, as a sister group of the mainland clade of *Q. lefroyi* and *Q. warroorana* (Figure 2). The haplotypes from Barrow and the Montebellos were interspersed within their clade. Genetic distances (*p*-distance)

within this clade were low, with a maximum of 0.038. The range between *Q. barrowensis* and *Q. montebelloensis* was 0.014 to 0.038, compared with 0 to 0.037 within species. The maximum distances were only half those seen in the diverse *Q. lefroyi* from the mainland, and also less than seen within *Q. legendrei*.

Haplotypes of COI from the small species of *Rhagada* on Barrow Island formed a clade with *R. plicata* from the Montebellos and Varanus Island (Figure 3). Although the three groups were separate clades on the tree, the genetic distances between them were low, averaging 0.022, comparable to the

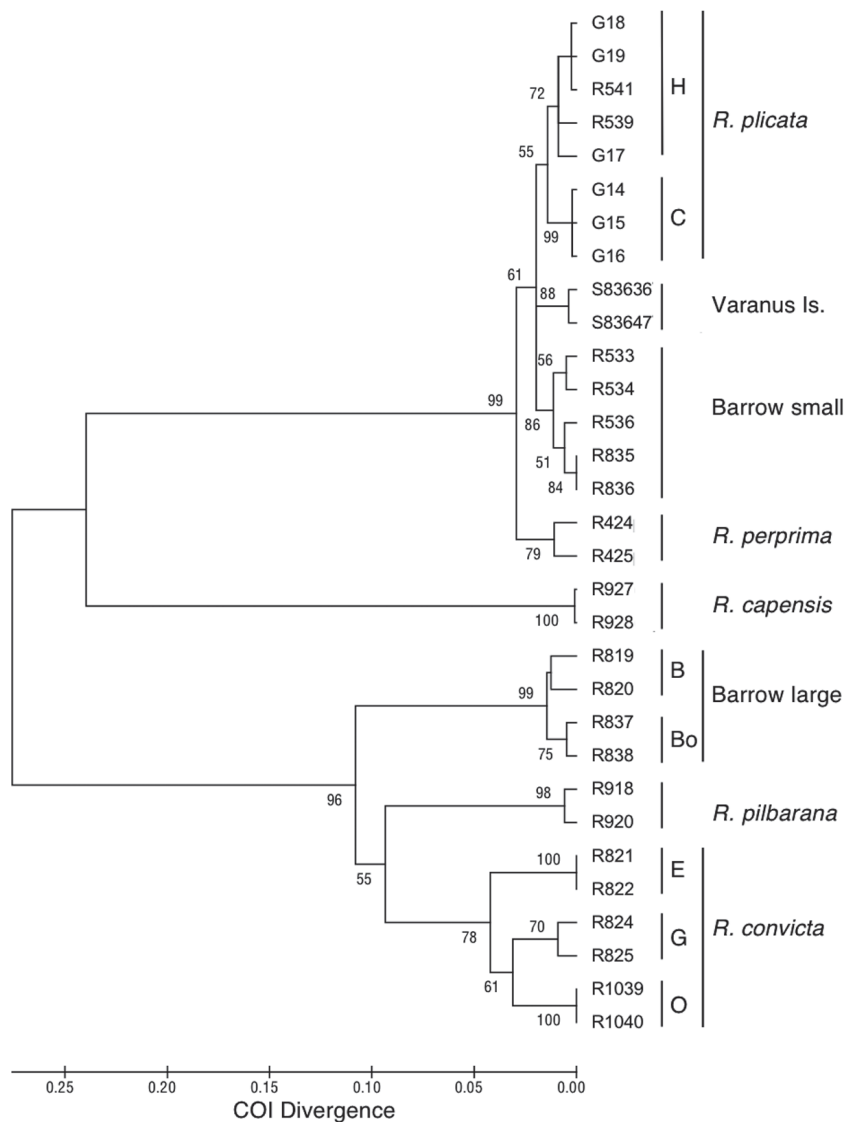


FIGURE 3 Maximum likelihood consensus tree of COI haplotypes in *Rhagada* from Barrow Island and contextual species. For *R. plicata* from the Montebello Islands, H = Hermite Island, and C = Crocus Island. For the large species on Barrow Island, B = Barrow Island and Bo = Boodie Island. For the mainland species *R. convicta*, E = Exmouth, G = Giralia, and O = Onslow. Haplotype codes are as in Table 1.

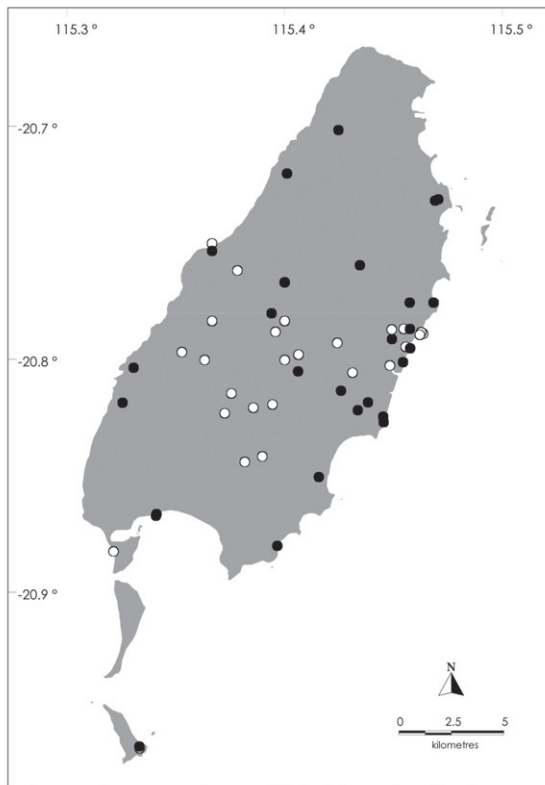


FIGURE 4 Records of the large camaenid (*Rhagada barrowensis* sp. nov.), on Barrow Island and adjacent Boodie Island. Filled circles indicate live-caught specimens, open circles shells only.

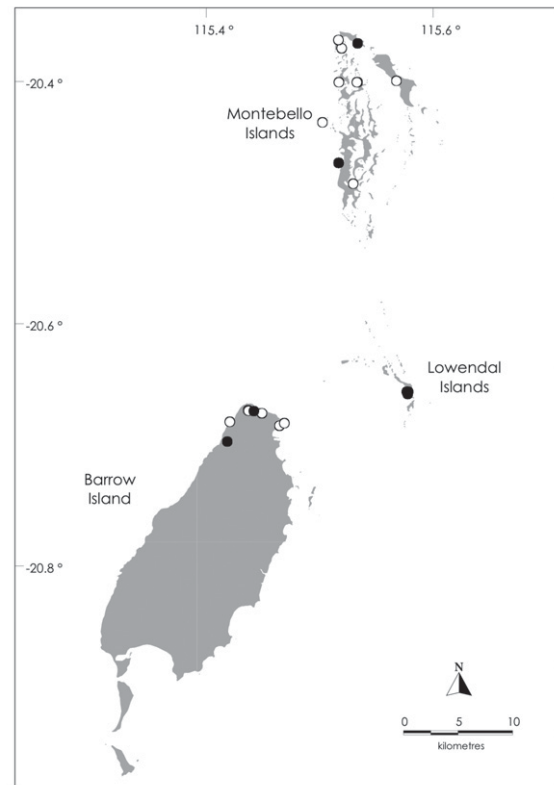


FIGURE 5 Records of the small *Rhagada* on Barrow Island, and *R. plicata* on the Lowendal and Montebello Islands. Filled circles indicate live-caught specimens, open circles shells only.

average distance of 0.026 between *R. plicata* from Crocus Island and those from Hermite Island. Genetic distances within the large species on Barrow were similar, averaging 0.025 between Boodie Island and the site on Barrow. The clade of this large species was well separated from its closest relatives, *R. pilbarana* and *R. convicta*, with an average genetic distance of 0.159 (Figure 3).

DISTRIBUTIONS

The large species of *Rhagada* is abundant and widespread on Barrow Island, occurring across most of the island, except for the northern tip, where it is replaced by the small species (Figure 4). The small species has been found only near the northern tip, and has not been found in sympatry with the large species (Figure 5). The intermediate-sized species, *Q. barrowensis*, also occurs widely on the island (Figure 6). Although the collections are not as extensive as those for the large *Rhagada*, casual observations indicate that *Q. barrowensis* may be more widespread and perhaps more abundant than *Rhagada*.

DISCUSSION

The genetic comparisons here help considerably to clarify the taxonomic relationships of the camaenid snails on Barrow Island. Care must be taken in the taxonomic interpretation of the sequences of COI, because the levels of sequence divergence associated with speciation vary considerably among taxa. In land snails, examples of highly divergent lineages that are reproductively compatible include the European species *Cepaea nemoralis* (Johnson et al., 1984; Thomaz et al., 1996; Davison and Clarke, 2000) and the slug *Arion subfuscus* (Pinceel et al., 2005), but in other taxa, there is reproductive isolation despite low levels of molecular divergence, such as in *Partula* in French Polynesia (Johnson et al., 1993; Goodacre, 2002). Based on a review of relevant studies in land snails, the best 'threshold' for delimiting species was 4% divergence for COI, but this performed poorly (Davison et al., 2009). A study combining mtDNA and reproductive anatomy with thorough sampling of *Amplirhagada* snails in the Bonaparte Archipelago, WA, found a clear threshold of 6%

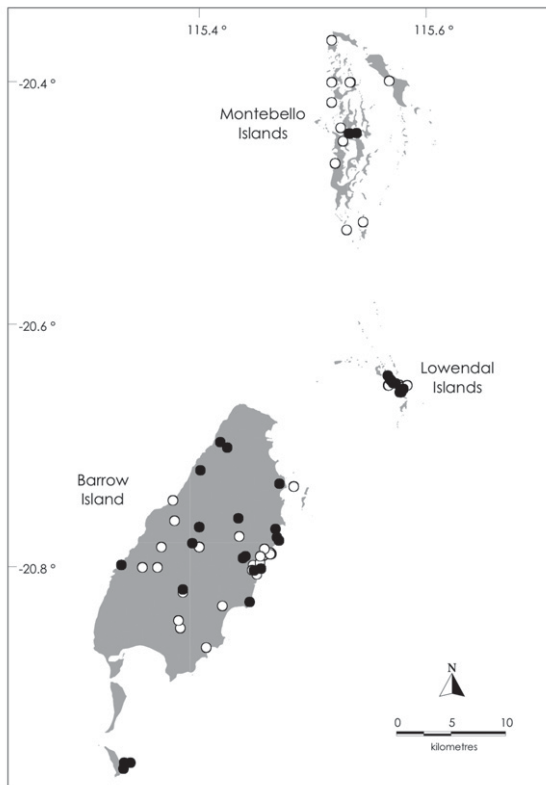


FIGURE 6 Records of *Quistrachia montebelloensis* (= *Q. barrowensis*) on Barrow Island, the adjacent Boodie and Pascoe Islands, and on the Lowendal and Montebello Islands. Filled circles indicate live-caught specimens, open circles shells only.

divergence between species (Köhler and Johnson 2012) but no gap was observed in the frequency distribution of intra- and interspecific pair-wise genetic distances.

Despite such variations, the results on Barrow Island are clear. The large species of *Rhagada* forms a distinct phylogenetic clade, within which divergences are $\leq 2.5\%$. Although we have examined COI from only two sites, the previous study of allozyme variation indicated very little genetic divergence among populations across the entire island (Johnson et al. 2006), so the genetic unity of the group is clear. The mtDNA clade of the large species on Barrow is highly divergent from its nearest relatives, and the comparisons included all previously described species of *Rhagada* from the Pilbara region (Johnson et al. 2012). The new species from Barrow Island is formally described below.

In contrast to this endemic species, the genetic comparisons indicate that the small species of *Rhagada* and *Quistrachia barrowensis* are conspecific with species from the Montebello and Lowendal Islands. In *Rhagada*, the very low levels of genetic divergence support the indications from shells; the

size, shape and sculpture of the small species on Barrow Island fit the description of *R. plicata* from the Montebellos (Solem 1997). In *Quistrachia*, Solem (1997) distinguished *Q. barrowensis* from the earlier described *Q. montebelloensis* on the basis of minor differences in shell size and form. However, these differences are well within the range of variation seen within other species. For example, detailed study of *Rhagada* in the Dampier Archipelago showed that much larger differences in shell form need not indicate reproductively isolated species (Stankowski 2011). The high genetic similarities and the phylogenetic interspersing of COI haplotypes indicate that *Q. barrowensis* is the same species as *Q. montebelloensis*.

These genetic and revised taxonomic perspectives give a clearer basis for interpreting the history of the camaenid snails on Barrow Island. The large, endemic *Rhagada* is part of the major clade that dominates the mainland Pilbara (Johnson et al. 2012). In contrast, the small *Rhagada* is part of the morphologically diverse clade of the Dampier Archipelago, forming the western edge of that clade's geographic distribution. These two clades are geographically complementary, meeting only in the southern portion of the Burrup Peninsula (Johnson et al. 2012), on East and West Lewis Islands in the Dampier Archipelago (Stankowski, unpublished), and on Barrow Island. Thus, Barrow Island is biogeographically interesting, in showing an unusual coming together of very distinct lineages of *Rhagada*. The mutual exclusion of the two lineages on Barrow Island, however, also highlights a general feature of camaenid snails in Western Australia: congeneric species very seldom occur together (Solem 1997).

Such exclusion does not apply between genera, and *Quistrachia* and *Rhagada* overlap broadly on Barrow Island. The occurrence of *Q. montebelloensis* (including *Q. barrowensis*) on Barrow Island and in the Montebellos and Lowendals has different geographic origins from the similar distribution seen in *R. plicata*. Whereas the relatives of *R. plicata* lie to the east, in the Dampier Archipelago, the closest relatives of *Q. montebelloensis* are to the southwest: *Q. lefroyi* and *Q. warroorana*, from the Cape Range to near Shark Bay. Thus, taken together, the camaenid snails on Barrow Island, the Montebello Islands and the Lowendal Islands indicate different geographic origins of the island fauna. In their restriction to the islands, however, all three species are clear examples of short-range endemism, and hence special vulnerability (Harvey et al. 2011). The range of the Barrow Island endemic, *R. barrowensis* sp. nov., spans only 22 km, with an area of about 250 km². Even for *R. plicata* and *Q. montebelloensis*, whose distributions include the Montebellos and the Lowendals, the maximum distances between known populations are only 40 km and 70 km, respectively,

most of which is over water. The presence of these short-range endemics highlights the conservation significance of Barrow Island.

SYSTEMATICS

Family Camaenidae Pilsbry, 1895

Genus *Quistrachia* Iredale, 1939

Quistrachia Iredale, 1939: 51–52.

TYPE SPECIES

Trachia monogramma Ancey, 1898, by original designation.

REMARKS

Based on Solem's (1997) revision and the present study, *Quistrachia* is a Western Australian endemic genus, including eight species, which occur between the Oscar Range and Dampier Land in the Kimberley, through the Pilbara, to Warroora Station, north of Shark Bay. The species have non-overlapping geographic distributions.

Quistrachia montebelloensis (Preston, 1914)

Figures 1, 2, 6

Rhagada montebelloensis Preston, 1914: 13, Figure in text; Richardson, 1985: 265.

Globorhagada montebelloensis (Preston): Iredale, 1938: 114; Iredale, 1939: 73, Plate 5, Figure 20.

Quistrachia montebelloensis (Preston): Solem, 1997: 1827–1829, Plate 228a–b, Figure 440d–f.

Quistrachia barrowensis Solem, 1997: 1821–1827, Plates 227f, 232a–e, Figures 440a–c, 441a–c. New synonymy.

TYPE LOCALITY

Montebello Islands.

MATERIAL EXAMINED

Australia: Western Australia: Barrow Island: 20.7447°S, 115.3769°E (WAM S34699); 20.7616°S, 115.3783°E (WAM S34697); 20.7666°S, 115.4000°E (WAM S5800, WAM S5801, WAM S8971, WAM S34696, WAM S14264); 20.7684°S, 115.4673°E (WAM S10944); 20.7744°S, 115.4352°E (WAM S61309); 20.7753°S, 115.4684°E (WAM S10943); 20.7779°S, 115.4702°E (WAM S14280); 20.7833°S, 115.4000°E (WAM S60827, WAM S61305, WAM S61297, WAM S61300, WAM S61311, WAM S61306, WAM S61854, WAM S61858, WAM S61855, WAM S61850, WAM

S61856, WAM S61857, WAM S61852, WAM S61853, WAM S61859); 20.7833°S, 115.3667°E (WAM S14256); 20.7847°S, 115.4575°E (WAM S65266); 20.7878°S, 115.4624°E (WAM S61301); 20.7879°S, 115.4625°E (WAM S61307); 20.7882°S, 115.4628°E (WAM S61299); 20.7887°S, 115.4636°E (WAM S61302°S, (WAM S61304); 20.7892°S, 115.4625°E (WAM S61851); 20.7902°S, 115.4565°E (WAM S61298); 20.7908°S, 115.4539°E (WAM S84024); 20.7908°S, 115.4408°E (WAM S60828); 20.7923°S, 115.4385°E (WAM S61296, WAM S84049); 20.7961°S, 115.4536°E (WAM S65268); 20.7980°S, 115.3314°E (WAM S14258, WAM S14259); 20.7983°S, 115.4474°E (WAM S65261); 20.8000°S, 115.3633°E (WAM S34695); 20.8000°S, 115.3500°E (WAM S84017, WAM S84023); 20.8009°S, 115.4544°E (WAM S61282); 20.8009°S, 115.4544°E (WAM S84020); 20.8022°S, 115.4467°E (WAM S84018); 20.8024°S, 115.4483°E (WAM S84050); 20.8057°S, 115.4507°E (WAM S60826); 20.8182°S, 115.3857°E (WAM S61176); 20.8205°S, 115.3856°E (WAM S84021); 20.8286°S, 115.4444°E (WAM S14261); 20.8319°S, 115.4204°E (WAM S61173); 20.8438°S, 115.3817°E (WAM S34700); 20.8500°S, 115.3833°E (WAM S61860); 20.8661°S, 115.4061°E (WAM S84019).

Double Island: 20.7333°S, 115.4833°E (WAM S60825, WAM S61165, WAM S84014).

Pascoe Island: 20.9610°S, 115.3396°E (WAM S61082); 20.9666°S, 115.3333 (WAM S84027).

Lowendal Islands, Bridled Island: 20.6500°S, 115.5669°E (WAM S12280). Varanus Island: 20.6556°S, 115.5766°E (WAM S83645, WAM S83625); 20.6556°S, 115.5782°E (WAM S83621, WAM S83634, WAM S83641); 20.6527°S, 115.5796°E (WAM S83644, WAM S83646, WAM S83638); 20.6512°S, 115.5802°E (WAM S83630); 20.6500°S, 115.5667°E (WAM S5684, WAM S5771, WAM S12278, WAM S61887, WAM S14366, WAM S12281); 20.6500°S, 115.5833°E (WAM S84015, WAM S84016); 20.6493°S, 115.5765°E (WAM S83624); 20.6482°S, 115.5732°E (WAM S83650, WAM S83640); 20.6476°S, 115.5709°E (WAM S83637, WAM S83643, WAM S83635, WAM S83639); 20.6459°S, 115.5692°E (WAM S83631); 20.6446°S, 115.5682°E (WAM S83649, WAM S83651, WAM S83628); 20.6416°S, 115.5662°E (WAM S83623).

Montebello Islands, Unlisted Island: 20.4333°S, 115.6167°E (WAM S5766); 20.4418°S, 115.5387°E (WAM S61083). Islet 1: 20.4486°S, 115.5267°E (WAM S5759). Islet 3: 20.4375°S, 115.5247°E (WAM S5764). Alpha Island: 20.4000°S, 115.5333°E (WAM S5758, WAM S5767); 20.4000°S, 115.5328°E (WAM S12005); 20.4000°S, 115.5167°E (WAM S61886); 20.4166°S, 115.5167°E (WAM S84025). Crocus Island: 20.4166°S, 115.5167°E (WAM S12006). Bluebell Island: 20.4000°S, 115.5169°E (WAM S12004). Hermite Island: 20.4666°S, 115.5167°E (WAM S5760, WAM S5761, WAM S5762, WAM S5768, WAM S12244); 20.4420°S, 115.5320°E (WAM S61081); 20.4421°S, 115.5328°E (WAM S61084). Trimouille Island: 20.4000°S, 115.5667°E (WAM S5757, WAM S5769).



FIGURE 7 Live adult of *Rhagada barrowensis* sp. nov.

Near Ah Chong Island: 20.5152°S, 115.5444°E (WAM S5765); 20.5216°S, 115.5300°E (WAM S5770). North West Island: 20.4333°S, 115.6167°E (WAM S5763); 20.3666°S, 115.5167°E (WAM S12271).

DISTRIBUTION

Quistrachia montebelloensis is known from the Montebello Islands, Lowendal Islands and Barrow Island. It is also recorded from a few satellite islets off Barrow Island.

REMARKS

Solem (1997), who described *Q. barrowensis*, distinguished it from *Q. montebelloensis* based on subtle variation in shell size and thickness of the apertural lip. No comparative anatomical material of *Q. montebelloensis* was available at that time. Both nominal species are considered to be identical for the lack of molecular and morphological differentiation between the two island forms.

Genus *Rhagada* Albers, 1860

Rhagada Albers, 1860: 108–109.

TYPE SPECIES

Helix reinga 'Gray' Pfeiffer, 1846, by original designation.

REMARKS

With 38 described species, *Rhagada* is second most diverse camaenid genus in Western Australia, behind the Kimberley genus *Amplirhagada* (Solem 1997, Köhler 2011). Species are allopatric, distributed from the Mitchell Plateau in the Kimberley to Shark Bay. Additional species occur in Indonesia (Maassen 2009).

Rhagada barrowensis sp. nov.

Figures 1, 3, 4, 7, 8

urn:lsid:zoobank.org:act:48D0D0F1-5488-47FC-9B99-9F03B75DD389

TYPE LOCALITY

Australia: Western Australia: Pilbara, Barrow Island, Terminal Tanks Road South, 20.8182°S, 115.4383°E, 18 March 2004, J. Fitzpatrick, L15 (*Triodia angusta* dominated plain).

MATERIAL STUDIED

Holotype

WAM S84062 (preserved specimen).

Paratypes

Australia: Western Australia: Barrow Island:

WAM S84063 (7 preserved, 1 dissected specimens) from 20.8182°S, 115.4383°E; WAM S84064 (8 preserved specimens) from 20.8184°S, 115.3256°E; WAM S84065 (8 preserved specimens) from 20.7316°S, 115.4691°E; WAM S84066 (8 preserved specimens) from 20.8502°S, 115.4157°E; WAM S84067 (8 preserved specimens) from 20.6714°S, 115.4420°E; WAM S84068 (8 preserved specimens) from 20.7800°S, 115.3940°E.

Other material examined (Non-types)

Australia: Western Australia: Barrow Island: 20.7666°S, 115.4000°E (WAM S5681, WAM S6171, WAM S8799, WAM S8803, WAM S8813, WAM S8853, WAM S8854, WAM S14253, WAM S14262); 20.7500°S, 115.3667°E (WAM S9070); 20.7666°S, 115.4000°E (WAM S10942); 20.7753°S, 115.4575°E (WAM S10947); 20.7833°S, 115.3667°E (WAM S14255); 20.8000°S, 115.3633°E (WAM S14257); 20.7753°S, 115.4684°E (WAM S14277); 20.7616°S, 115.3783°E (WAM S34698); 20.8438°S, 115.3817°E (WAM S34701); 20.7833°S, 115.4000°E (WAM S59285, WAM S61849); 20.8229°S, 115.3725°E (WAM S61167); 20.8144°S, 115.3756°E (WAM S61168); 20.8414°S, 115.3898°E (WAM S61169); 20.8055°S, 115.4312°E (WAM S61170); 20.8191°S, 115.3944°E (WAM S61171); 20.7927°S, 115.4242°E (WAM S61174); 20.7966°S, 115.3528°E (WAM S61175); 20.8024°S, 115.4483°E (WAM S64901); 20.7887°S, 115.4636°E (WAM S64902); 20.7879°S, 115.3958°E (WAM S64903); 20.7881°S, 115.4627°E (WAM S64906); 20.7882°S, 115.4628°E (WAM S64907); 20.7977°S, 115.4064°E (WAM S64909, WAM S64917); 20.8009°S, 115.4544°E (WAM S64910, WAM S84046); 20.7866°S, 115.4547°E (WAM S64914); 20.7869°S, 115.4492°E (WAM S64915); 20.7944°S, 115.4557°E (WAM S64918); 20.8205°S, 115.3856°E (WAM S64921, WAM S84022); 20.7892°S, 115.4621°E (WAM S65264); 20.7833°S, 115.3667°E (WAM S84026); 20.7500°S, 115.3667°E (WAM S84031); 20.8833°S, 115.3167°E (WAM S84032); 20.8000°S, 115.4000°E (WAM S84033); 20.8268°S,

115.4455°E (WAM S84045); 20.7950°S, 115.4577°E (WAM S84047); 20.8798°S, 115.3966°E (WAM S84048).

Boodie Island: 20.9666°S, 115.3333°E (WAM S84028).

DIAGNOSIS

Rhagada barrowensis possesses a large (mean diameter 20.9 mm), white shell with a brown to orange supra-peripheral band and generally no accessory banding. It differs in size (larger) and shell sculpture (smoother) from the nearby *R. plicata*. *R. perprima* from the Dampier Archipelago has more prominent supra-peripheral and subsutural banding. It is difficult to separate *R. barrowensis* from some members of the genus (*R. convicta* and *R. pilbarana*) based exclusively on shell features. Anatomically its very long, tapering penial verge and a spermatheca that is strongly kinked near the apex are distinctive.

DESCRIPTION

Shell (Figures 1 and 7, Table 2) solid, large for the genus, adult diameter 17.75–22.80 mm (mean 20.96, sd 0.92 mm), height 14.80–18.25 mm (mean 16.33, sd 1.12 mm), with 5.00–6.05 (mean 5.72, sd 0.17) rather tightly coiled, rounded convex whorls. Spire strongly elevated; body whorl large with evenly rounded periphery; protoconch short, translucent grey to light blue (when fresh), predominantly smooth with traces of very fine radial sculpture; teleoconch with regular radial growth ridgelets; umbilicus always closed (adults); body whorl descending noticeably behind lip, which is broadly expanded to form a sharp thickened rim; shell background colour white with narrow brown to orange supra-peripheral band present, ranging from very distinct to just visible; usually narrow (occasionally wide) subsutural band present on

TABLE 2 Shell variation in *Rhagada barrowensis* sp. nov. The grand mean excludes data for the holotype specimen. n, number of adult shells measured. Measurements in mm.

WAM number	n	shell height (sd)	shell diameter (sd)	H/D ratio (sd)	No. whorls (range)
S84062 (holotype)	1	17.10	22.66	0.75	5.80
S84063	8	17.03 (0.82)	21.23 (1.10)	0.80 (0.03)	5.71 (5.65-5.80)
S84064	8	15.36 (0.47)	20.10 (1.13)	0.77 (0.04)	5.74 (5.65-5.80)
S84065	8	16.28 (1.03)	21.25 (1.16)	0.77 (0.05)	5.53 (5.00-5.80)
S84066	8	16.40 (0.59)	20.48 (0.82)	0.80 (0.03)	5.81 (5.65-6.00)
S84067	8	16.49 (0.90)	21.56 (0.68)	0.77 (0.04)	5.81 (5.60-6.05)
Grand mean		16.31 (0.60)	20.92 (0.60)	0.78 (0.02)	5.72 (5.00-6.05)

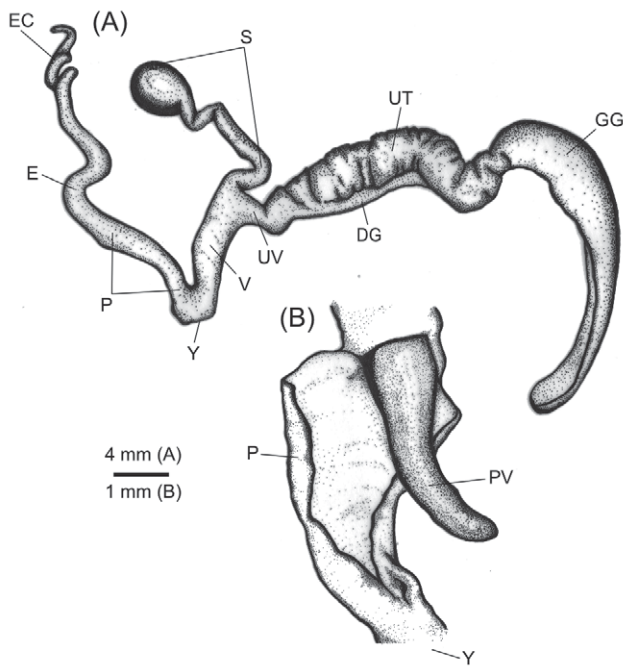


FIGURE 8 Reproductive system (A) and penial anatomy (B) of *Rhagada barrowensis* sp. nov. Abbreviations: GG, albumen gland; UT, uterus; DG, prostate; UV, oviduct; S, spermatheca; V, vagina; Y, atrium; P, penis, E, epiphallus; EC, Epiphallal caecum; PV, penial verge. All notation follow Solem (1997).

all whorls, usually faded but occasionally distinct, continuous with protoconch; very occasionally traces of narrow accessory bands (1–4) on shell base. Based on 41 measured adults (types).

Reproductive system (Figure 8) with large albumen gland (GG), similar in length to uterus (UT); short, free oviduct (UV); long spermatheca (S) with strong kinks near the apex; vagina (V) and penis (P) of a similar, medium length; vagina wider than penis; long epiphallus (E); epiphallal caecum (EC) long and tightly coiled; penial verge (PV) with smooth surface, very long and tapering, nearly three-quarters length of penis; interior penial wall smooth.

COMPARATIVE REMARKS

The shells of *R. barrowensis* closely resemble *R. convicta*. The two species cannot be reliably distinguished by their shell colour, banding and dimensions. *Rhagada perprisma* is also similar in colour, shell dimensions, and occasionally banding pattern, but tends to have a more prominent supra-peripheral band and subsutural banding. *R. pilbarana* can be distinguished by presence of

a prominent, red supra-peripheral band. *Rhagada barrowensis* and *R. plicata*, the other species of *Rhagada* known from Barrow Island, can be readily distinguished based on their shell diameter (17.75–22.80 mm and 9.00–12.05 mm, respectively) and pattern of sculpturing of the spire and body whorl (smooth and strongly ribbed, respectively). *Rhagada barrowensis* is often found in sympatry with *Q. montebelloensis*, but can be distinguished based by its larger shell (mean diameters of 20.92 mm and 15.13 mm, respectively), absence of an umbilical chink (adults) and less sculpture on the shell protoconch (almost smooth versus distinct radial riblets, respectively).

Anatomically *R. barrowensis* differs from *R. convicta* in several ways. *R. barrowensis* has a very long tapering penial verge, nearly three-quarters the length of the penis, while *R. convicta* has small triangular verge with a corrugated surface. Also *R. convicta* has a spermatheca that is only slightly kinked near the middle, while that of *R. barrowensis* is strongly kinked near the apex. *R. barrowensis* and *R. pilbarana* have similar reproductive systems, though the spermatheca of *R. pilbarana* is sharply kinked near the middle rather than at the terminal end, and, while elongated, the penial verge of *R. pilbarana* is club-shaped instead of tapering. *R. plicata* has a much shorter penial verge with a corrugated, rather than smooth, surface.

DISTRIBUTION

This species is recorded from Barrow Island and its southern satellite Boodie Island (Figure 4).

REMARKS

Solem (1997) did not list any species of *Rhagada* from Barrow Island, although he had previously identified some specimens from Barrow Island in the collections of the WA Museum as *Rhagada tescorum* Benson, 1853 (type locality Shark Bay), a species that he did not mention in the section dealing with the genus *Rhagada* (Solem 1997) or in later publications on the Western Australian snail fauna. In their physiological study, Withers et al. (1997) tentatively used the name *R. tescorum* for this species, but this was incorrect. Examination of Solem's rather large number (~70 lots) of mainland *R. tescorum* in the WA Museum collection suggests it is a complex of other named *Rhagada* species. Smith (1992) listed *R. tescorum* as *incertae sedis* because of a dispute on where the holotype was held, but it could also have been because of the uncertainty of where to place the species.

Some long-dead, mostly juvenile shells from Hermite Island (WAM S5761, WAM S6243, WAM S12244, WAM S12272) and Varanus Island (WAM S12282) in the WA Museum collection resemble *R. barrowensis* but were unsuitable for comparison.

ETYMOLOGY

For Barrow Island, adjective.

***Rhagada plicata* Preston, 1914**

Rhagada plicata Preston, 1914: 13–14, Figure in text; Hedley, 1916: 70; Solem, 1997: 1737–1741, Plates 207a, 221a–d, Figures 418a–b, 419a–c.

Bellrhagada plicata (Preston): Iredale, 1938: 114; Iredale, 1939: 71, Plate 5, Figure 16; Richardson, 1985: 65.

Rhagada sp. (small) Johnson et. al., 2006: Figure 1.

TYPE LOCALITY

Montebello Islands.

MATERIAL EXAMINED

Australia: Western Australia: Barrow Island: 20.6665°S, 115.4389°E (WAM S6168); 20.6836°S, 115.4645°E (WAM S64919); 20.6816°S, 115.4689°E (WAM S64920); 20.6783°S, 115.4167°E (WAM S28091); 20.6733°S, 115.4491°E (WAM S64904); 20.6712°S, 115.4373°E (WAM S64900, WAM S64913); 20.6709°S, 115.4370°E (WAM S64911); 20.6808°S, 115.4683°E (WAM S10948).

Lowendal Islands, Varanus Island: 20.6574°S, 115.5774°E (WAM S83629, WAM S83648); 20.6556°S, 115.5766°E (WAM S83626, WAM S83636); 20.6556°S, 115.5782°E (WAM S83622, WAM S83647).

Montebello Islands: Alpha Island: 20.4000°S, 115.5333°E (WAM S6014); 20.4000°S, 115.5328°E (WAM S12009). Bluebell Island: 20.4000°S, 115.5169°E (WAMS 12007). Brooke Island: 20.4333°S, 115.5000°E (WAM S6244). Hermite Island: 20.4838°S, 115.5294°E (WAM S84013); 20.4666°S, 115.5167°E (WAM S28108, WAM S6009, WAM S6017, WAM S84012, WAM S84034). North West Island: 20.3680°S, 115.5332°E (WAM S61086); 20.3666°S, 115.5167°E (WAM S6015). Primrose Island: 20.3719°S, 115.5194°E (WAM S61085). Trimouille Island: 20.4000°S, 115.5667°E (WAM S6016).

DISTRIBUTION

Rhagada plicata is known from the Montebello Islands, Lowendal Islands (Varanus Island) and the northern portion of Barrow Island.

REMARKS

In his section on *R. plicata*, Solem (1997) mentioned a few specimens found on Barrow Island that were unsuitable for description or taxonomic placement. Presumably those specimens were long-dead, worn *R. plicata* shells.

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