Lucius G. Eldredge Memorial Volume. Edited by N.L. Evenhuis &
J.T. Carlton. *Bishop Museum Bulletin in Zoology* 9: 147-167 (2015).

The occurrence of the endangered tree snail *Partula gibba* in the Mariana Islands, with a focus on Pagan Island

Michael G. Hadfield
Kewalo Marine Laboratory, University of Hawaii at Manoa, 41 Ahui Street
Honolulu, Hawai'i 96813, USA; email: hadfield@hawaii.edu

Abstract. From 5 to 15 May 2010, a team of eight field biologists surveyed Pagan Island to locate terrestrial snails, with an emphasis on the rare tree snail *Partula gibba*, which is listed as "Endangered" by the Territory of Guam. Guided by results of prior snail surveys on the island, a vegetation map, and knowledge of the terrain and vegetation gained during early flights across Pagan Island, 13 discrete routes were surveyed for gastropods. They included all areas where vegetation appeared likely to support snail populations, with the exception of a small region at the extreme southeastern tip of the island that could not be accessed in the time available. Areas not intensely surveyed were covered by tall grasses or monodominant stands of coconut palms or *Casuarina equisetifolia*. *Partula gibba* was found only in forests of mixed native vegetation with a good understory and ground cover within the ancient caldera rim of the southern Pagan volcano. Although searches were not conducted to provide quantitative data, relatively large numbers of *P. gibba* were found (<200 in some locations). Forests where *P. gibba* had been collected in 1949, all lying around Mt. Pagan, are now without these animals, most likely due to the combined effects of ash fall from the 1981 eruption of Mt. Pagan and intense grazing by feral cattle that have removed understory of vegetation and left the forests very dry. Preliminary molecular genetic analyses indicate that the population(s) of *P. gibba* on Pagan Island are significantly divergent from those on Guam, Saipan and Sarigan Islands. Because these populations are very small, isolated and genetically unique, they are deserving of protection.

Background

Pagan Island (Fig. 1) lies near the center of the Northern Mariana Island chain in the Western Pacific Ocean, approximately 320 km north of Saipan. Nearest to Pagan Island are Alamagan Island to the south and Agrihan Island to the north. The northern Mariana islands are of similar geological age, about one million years old, compared to the southern Mariana Islands (Guam to Saipan), whose oldest rocks are greater than five million years old (Trusdell 2009). Because of their great ages, which provide a lengthy time for plants and animals to disperse between islands, and their relative proximities—the Mariana Islands lie less than 150 km apart—the biotas on the islands are closely related, with the most conspicuous forest plants and birds common to all (Vogt & Williams 2004). Knowledge of terrestrial invertebrate species in the Northern Mariana Islands is significantly less than it is for plants and vertebrates. For example, most terrestrial snails are only identified at the genus level, at best. The tree snails of the family Partulidae, which have been intensively studied in the southern islands from Guam to Saipan (Crampton 1925) and, to a lesser extent, at least surveyed on the Northern Mariana Islands, provide an exception.

The tree-snail family Partulidae has a broad distribution across the tropical Pacific islands, extending from the Mariana Islands through Micronesia, Melanesia and into French Polynesia, the last of which where multiple species were once abundant in Tahiti and Moorea. Due to a variety of factors, but mainly the impact of introduced predators, extinction in the partulid snails has been great (e.g., Murray *et al*. 1988). The two species of *Partula* endemic to Pohnpei have disappeared (Pelep & Hadfield 2011). On Guam, *Partula salifana* is apparently extinct, and *P. gibba*, once widespread, has been reduced to a few small and isolated areas (B. Smith, Univ. Guam, pers. comm., 2010; D. Sischo, State of Hawaii, Department of Forestry and Wildlife, pers. comm. 2014). *Partula gibba* has been listed as "Endangered" by the Territory of Guam and is a Candidate Species for listing by the U.S. Fish and Wildlife Service (USFWS). Extensive deforestation during World War II and subsequently for agriculture has most likely led to extinction of the species on Agiguan (Smith 2008a,

Published online: 8 December 2014
ISSN 0893-312X (print)
ISSN 2376-3213 (online)

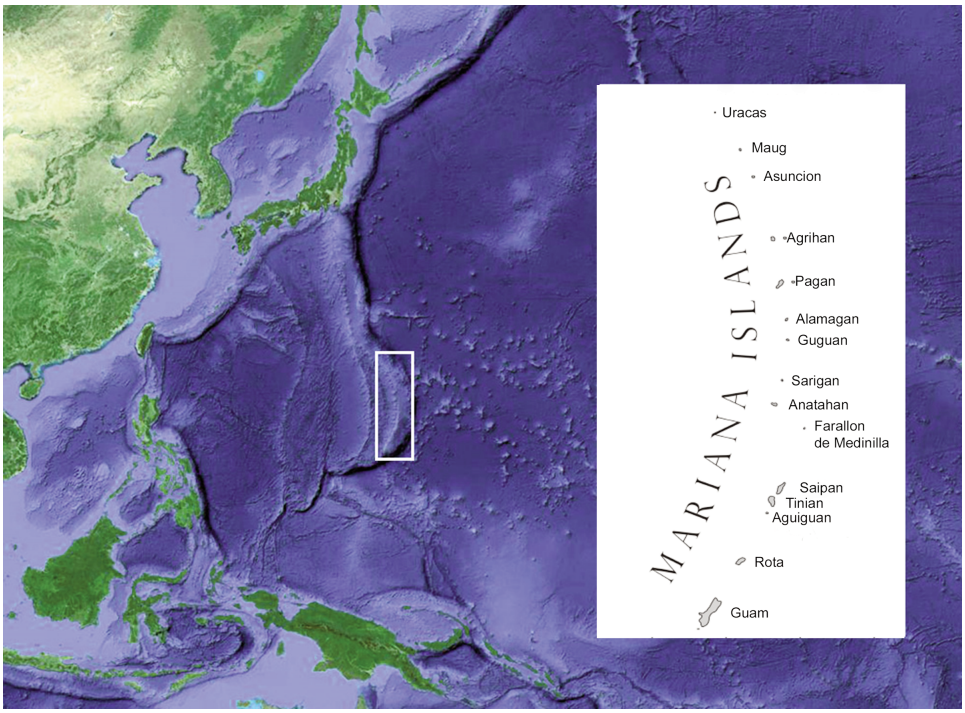

Figure 1. The Marianna Islands (outlined) lie in the western tropical Pacific Ocean. Inset: from south to north, the U.S. Territory of Guam, and the U.S. Commonwealth of the Northern Marian Islands, extending from Rota to Uracus. (Pacific map adapted from Google Earth; inset modified from Smith, B.D. 2008a).

2010). Recent surveys on Tinian have discovered a small remnant population in one hard-to-reach location (D. Sischo, pers. comm., 2014).

The partulid fauna of Guam included three species in the genus *Partula* and one species in the genus *Samoana* (Crampton 1925, Kondo 1970). Of these, only *Partula gibba* and *Samoana fragilis* have been recorded from Rota, the island closest to Guam. Moving northward, *Partula langfordi* was described from Agiguan Island, the next island north from Rota, where it co-existed with *P. gibba*. Only *P. gibba* was ever recorded on the more northerly islands, Tinian and Saipan. North from Saipan, *Partula gibba* has been collected on Anatahan, Sarigan, Alamagan and Pagan islands, making Pagan Island the most northerly point in the distribution of the species (Kondo 1970, Kurozumi 1994, Smith 2008b). Searches during the Chiba Museum expedition of 1992 on Uracus, Maug, Asuncion, and Agrihan, all located to the north of Pagan, failed to find any partulid species, nor were they found on Guguan (Kurozumi 1994). Thus, the total distributional range for *Partula gibba* extends from Guam in the south, to Pagan Island in the north, a distance of about 485 km, and includes (or once included) populations on nine islands. As will be noted below, we found again *P. gibba* on Saipan and Sarigan while en route to Pagan Island, as well as on Pagan Island, and have recently seen it on Guam (August 2010) and Rota (October 2010). Samples for genetic analyses were collected on all of these islands.

In addition to *P. gibba*, Yoshio Kondo found many smaller native and non-indigenous terrestrial gastropods when he spent ten days on Pagan Island in 1949 (Kondo 1949). Most of these were identified only to family or genus. The latter was also true of small gastropods collected by Kurozumi during the Chiba expedition of 1992 (Kurozumi 1994). Consultation of the accession catalog in the Malacology collection at Bishop Museum provided a list of terrestrial gastropods collected and identified by Kondo. Kondo cataloged 15 generic names, including the aliens *Subulina* and *Achatina*. For snail species he considered native to Pagan Island, Kondo listed 13 genera, but includ-

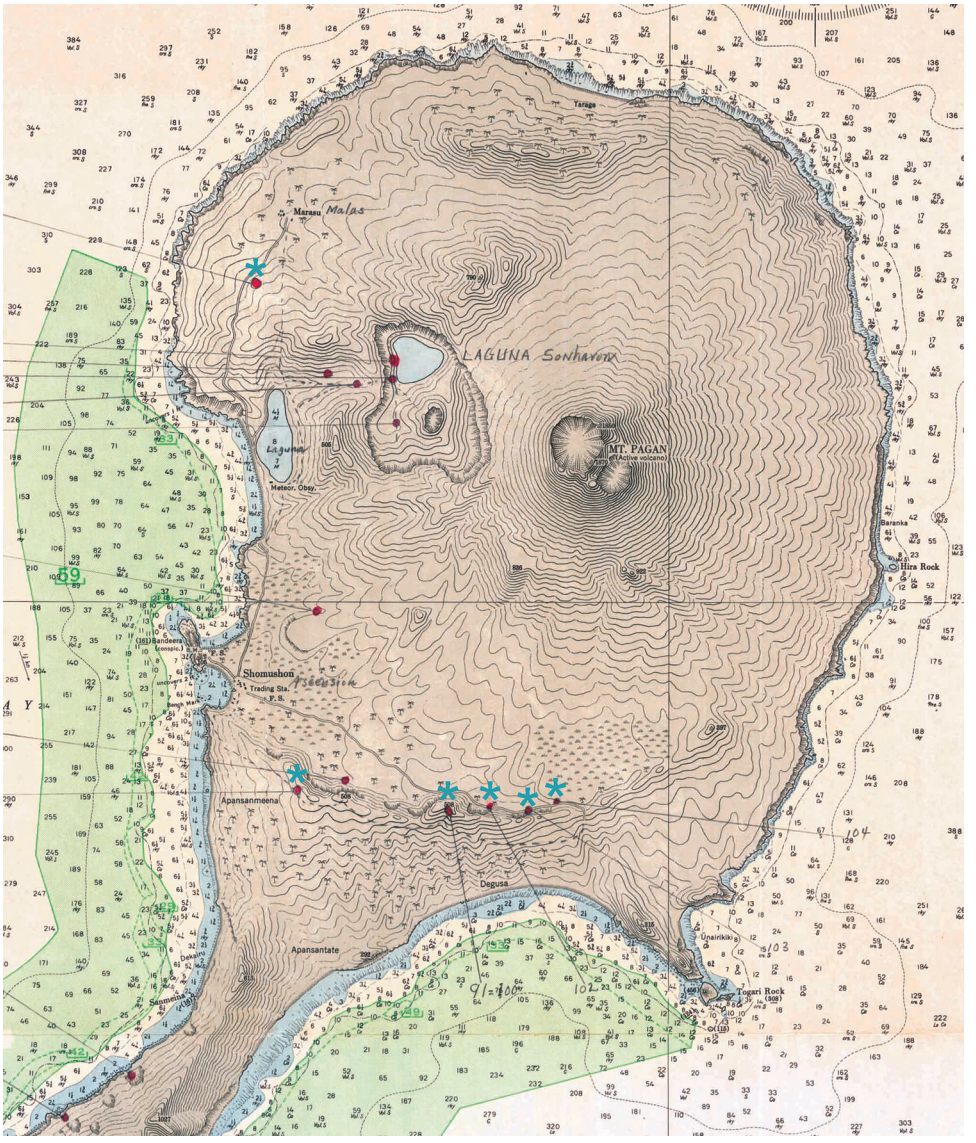

Figure 2. Map of the northern section of Pagan Island prepared by Y. Kondo showing sites of his field surveys and collections on Pagan Island during a ten-day stay on the island in 1949. Red dots indicate sites where Kondo collected terrestrial snails. Blue asterisks indicate sites where Kondo collected *Partula gibba* (B. P. Bishop Museum, Malacology Collection).

ed species names for only three: *Succinea quadrasi*, *Zonitoides arboreus* and *Paludinella conica*. It is impossible to know, at this time, whether any of the generic names listed by Kondo included more than one species, except for perhaps *Lamellidea*, for which Kondo entered an 'A' and a 'B' for some specimens.

Kurozumi (1994) also provided a list of snails he collected during the Chiba Museum's expedition to Pagan Island in 1992. It included 12 generic names and five species names, including *P. gibba*; the list included the well-known invasive species *Subulina octona*, *Achatina fulica*, *Gonaxis kibweziensis* and *Indoennea bicolor*. Kurozumi provided no species names for the eight genera of probably native species of snails that he collected. It is interesting to note that of 13 generic names

for native snails provided by Kondo and eight provided by Kurozumi, only four names appear on both lists. It would require a considerable investment in time in both the Bishop Museum in Honolulu, Hawaii and the Natural History Museum and Institute, Chiba, Japan, to determine how many of the species are actually the same. Given that Kurozumi (1994) collected at many of the same sites visited by Kondo, it is likely that many are the same species. Neither Kondo nor Kurozumi published subsequent information regarding their gastropod collections from Pagan Island, other than Kondo's brief discussion of *P. gibba* (Kondo 1970).

As noted, both Kondo (1949) and Kurozumi (1994) listed clearly alien snail species that they collected on Pagan Island. Among the latter were the Giant African Snail *Achatina fulica*, the predatory snail *Gonaxis kibweziensis*, and the very widely dispersed small snail *Subulina octona*. The first two were almost certainly deliberate human introductions, *A. fulica* for food (perhaps during the Japanese occupation), and *G. kibweziensis* as a biological control agent for *A. fulica*. *Subulina octona* is a small (<1 cm) leaf-litter species that has surely been carried with food plants and other materials during human migrations for a very long time. During Kondo's visit to Pagan Island, *A. fulica* was present in astoundingly high numbers. In his field notes (1949), Kondo wrote, "... ground lousy [with *A. fulica*] and an average sq. ft. had 26 specimens by actual count." And, "… the concentration was so heavy the snails are actually taking to trees of all kinds for food…" Kurozumi (1994) also included *A. fulica* in his collection list for Pagan Island. Although he collected 56 specimens across three locations, he did not comment on their relative abundance.

For the purposes of our surveys on Pagan Island from 5 to 15 May 2010, we focused on arboreal snails, those living on the leaves and trunks of shrubs and trees, with a special emphasis on *Partula gibba*, a 1–2 cm-long and typically conspicuous snail. At this time, *P. gibba* is not protected over its distribution in the Commonwealth of the Northern Mariana Islands.

This paper is derived from a report that was part of the *Marianas Expedition Wildlife Surveys 2010 (MEWS 2010)*, funded by a grant to the author at the University of Hawai'i from the U.S. Fish and Wildlife Service. The charge from the USFWS for the surveys to be conducted by the malacology group stated, "The particular focus of this project will be *Partula gibba*, which is a candidate for listing under the Federal Endangered Species Act. At each surveyed location, the occurrence of all native snail species will be recorded along with the composition and condition of the occupied habitat. Whenever possible, tree snail occurrences will be coordinated with vegetation plots and vegetation maps." The specific data on sites surveyed, the terrain and vegetation in those site areas and, especially, the distribution of *P. gibba* on Pagan Island are included here, because they provide useful baseline information about the island and its biological resources that are not available elsewhere.

Approach

Eight experienced field biologists joined the malacology survey team: M.G. Hadfield (project director), Stephen E. Miller, David R. Hopper, Kevin T. Hall, Jennifer E. Saufler, P. Bjorn Erickson, David R. Sischo, and Sheila Conant.

All surveys for Pagan Island snails were conducted by visual examination of trunks and foliage of available vegetation along each survey transect. Because it was clear at the outset that not all of Pagan Island could be surveyed, due to both topographical and time limitations, survey routes were selected in two ways: (1) areas where Y. Kondo located *Partula gibba* during his ten-day stay on the island in 1949 (Fig. 2), as well as Kurozumi's (1994) field notes; and (2) by consulting a vegetation map of Pagan Island (Fig. 3). The latter, provided by F. Amidon, USFWS, Honolulu, was based on a high elevation photo of Pagan Island. From the latter, areas were chosen that were shown as "native forest," "mixed coconut native forest," and "mixed ironwood native forest." From this information, 13 survey routes were selected (Fig. 4).

Access to survey routes relatively close to our base camp (located at the west end of the small runway, above the smaller black-sand beach) was by foot, with or without transport by one of the All-Terrain Vehicles (ATV) at the USFWS camp. This included survey routes 8, 9, 10 and 11 on Fig. 4. These surveys included all of the areas searched by Kondo in 1949 and most of those of Kurozumi in 1992. For one survey, we traveled by small boats (inflatable Zodiacs) along the southwestern shore to resurvey an area close to one where Kurozumi had found *P. gibba*; this is survey route 1 in Fig. 4.

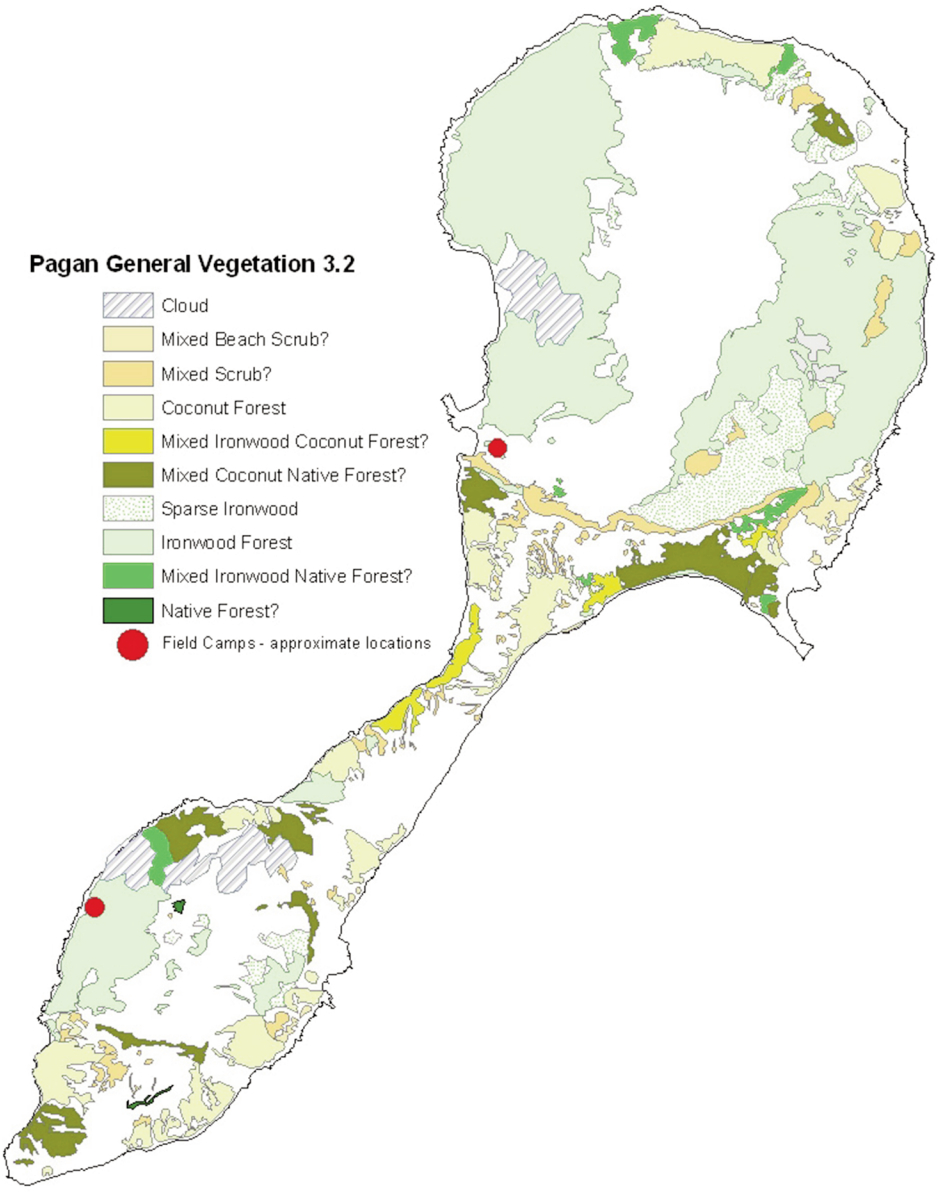

Figure 3. Map showing probable vegetation on Pagan Island (prepared by Fred Amidon, U.S. Fish and Wildlife Service, Honolulu).

We were very dependent on helicopter support provided by the USFWS to access both the upper elevations of the southern part of Pagan Island (survey routes 2–7) and areas along the northeastern shore and on opposite side of Mt. Pagan from our camp (survey routes 12 and 13). These surveys were carried out during three days.

All survey routes were examined by at least four members of the malacology team. For the surveys that required helicopter support, the group was divided into two teams of four each, and they

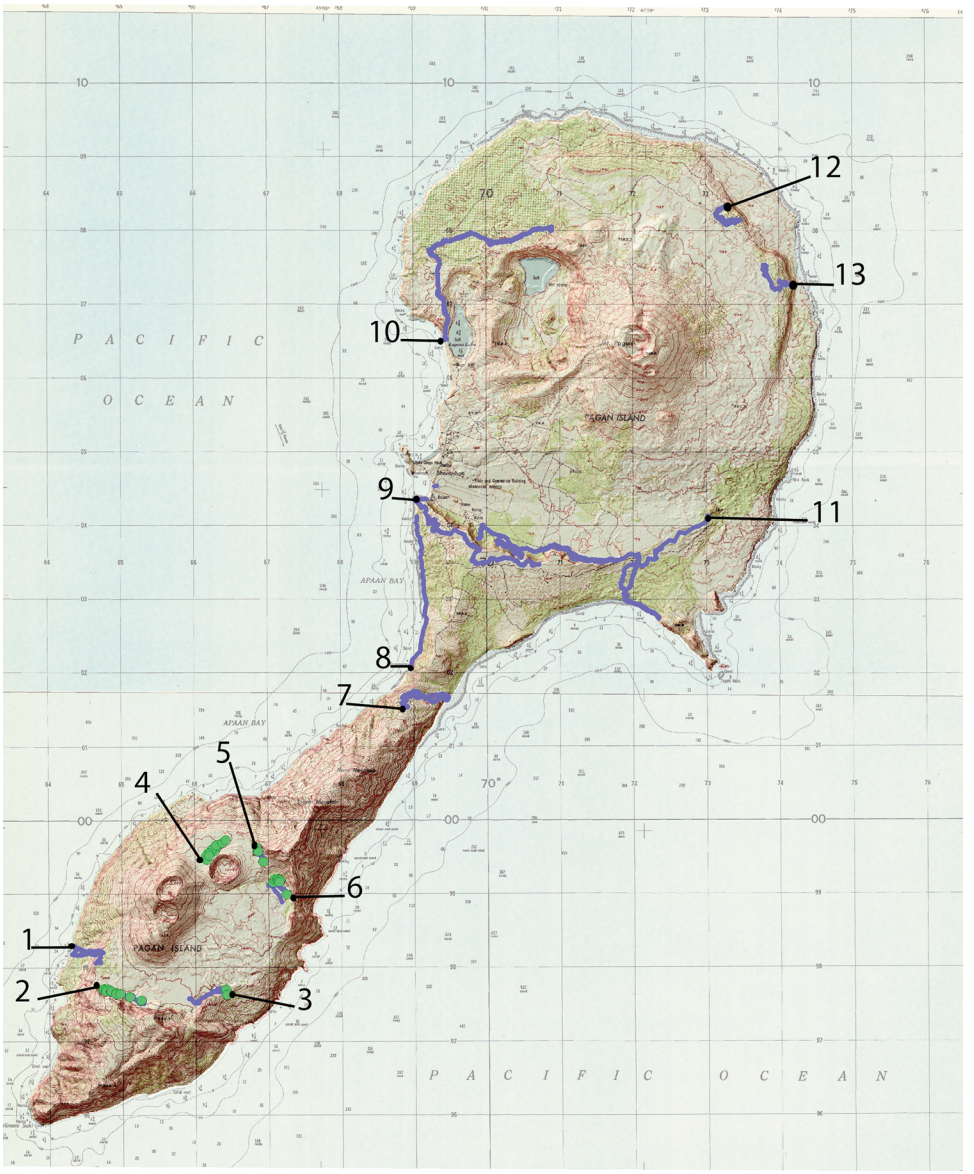

Figure 4. Contour map of Pagan Island illustrating 13 routes surveyed for terrestrial snails, especially the tree snail *Partula gibba* on Pagan Island in May 2010 (map modified from a contour map in the collection of the Malacology Division at B.P. Bishop Museum, Honolulu). Snails were found only where indicated by green circles on survey routs 2 to 6.

were landed in different areas selected from the air by the project director. Thus, routes 2 and 3 were surveyed on 7 May, routes 5 and 6 were surveyed in the morning on 8 May, routes 12 and 13 were surveyed in the afternoon on 8 May, and routes 4 and 7 were surveyed on 9 May. All members participated in the lengthy transect, no. 10, on 10 May. Because they could be reached on foot from camp, survey routes 8, 9 and 11 were conducted by four to eight team members and at times when other means of access were not available.

All types of vegetation were examined along each survey route, with special attention paid to plant species noted by Kondo to be major hosts or upon which our team found snails. Most time was

Figure 5. Habitat and vegetation along Survey Route 1. **A**. lower region; **B**. upper region, about 150 m above sea level

spent searching *Aglaia mariannensis*, a typically small, bushy tree found beneath a high canopy of other tree species. All arboreal snails found were recorded in our field notebooks. Also examined were parts of vegetation, such as the axils of *Pandanus* spp., that might harbor much smaller snails. In many areas, searches were made for shells on the ground, both in leaf litter and beneath easily turned stones. However, very few shells were found in this last way. All teams carried cameras, and snails were photographed to provide a record of their appearance and variation between locations. Nearly all of the survey tracks were linear due to the nature of the terrain and the way it confined good patches of native vegetation. The malacology team did not include botanical experts, and thus most of the tree identifications must be regarded as tentative.

Because of the intense level of endemic speciation found among tree snails on the Pacific islands, we considered it essential to determine the degree of relatedness, or differentiation, of partulid snails found. Using a non-sacrificial method long tested and employed for the federally endangered Hawaiian tree snails (Thacker & Hadfield 2000), we took minute tissue samples from at least 10 *Partula gibba* in each population found. If there was variation in shell pattern in the snails located on different survey routes, they were noted for each tissue sample taken. After returning from Pagan Island, DNA was extracted from the tissue samples and subjected to an initial sequence comparison among the Pagan Island specimens, and between snails sampled on Saipan and Sarigan Islands during stops before reaching Pagan Island. We subsequently gathered tissue samples from *P. gibba* on Guam in August 2010, and a population on Rota was sampled in October 2010. The only known populations from which we did not have tissue/DNA samples are those on Alamagan and Anatahan Islands. Only preliminary results of the genetic analyses are presented here.

The few shells collected on Pagan Island will be deposited at the Bishop Museum in Honolulu, Hawaii.

Findings

Survey results for each of the routes indicated in Figure 4 are presented below in geographical order, from the most southwestern sites to the most northeastern ones.

Survey Route 1: The eight team members were transported by Zodiac boat to go ashore on a rock platform on the southwest side of the island. The slope of the land at this site is great, and the lower ~100 m was forested with *Casuarina equisetifolia* mixed with broad-leafed trees (Fig. 5). Grazing by feral goats

Figure 6. Habitat and vegetation on Survey Route 2.

was intense in this area, resulting in an almost complete absence of understory plants. Higher up the slope, the terrain consists of areas covered by bunchgrass and open areas of loose cinders. The team ascended to a ledge at about 170 m elevation, where the terrain became more level. The forest here was a mix of *Ficus* sp., *Aglaia mariannensis* (which appeared very wilted), and *Casuarina*. Evidence of grazing by goats was abundant, and numerous goats were seen. This entire area appeared to be extremely dry, and it seemed that the the cinder soil would hold very little water, even in a rainy season. No arboreal or terrestrial snails were found.

We surveyed this route because Kurozumi (1994) reported that the Chiba expedition group had climbed from the shore up to "250–255 m" and found *P. gibba*. Unfortunately, Kurozumi provided no information on host trees or other area characteristics, and it was impossible to know from his small map exactly where the Chiba group had begun their climb. The fact that our team did not reach the height given by Kurozumi may explain our lack of success. However, see notes for Route no.2, below, which was successful at an elevation similar to Koizumi's.

Survey Route No. 2: This survey route was reached by helicopter and examined by four team members. The elevation across this survey route was 170–200 m. The survey passed along the base of an east-west escarpment that forms the south rim of an ancient caldera of the southern Pagan volcano. The broad floor of this caldera is covered by old a'a lava flows and deep grass. It appears that the a'a flow did not reach the edge of the older caldera wall and left a gulch, which is where coconut palms form a dense cover with a rich understory that included *Aglaia mariannensis, Hibiscus tiliaceus, Artocarpus* sp., *Barringtonia asiatica, Neisosperma oppositifolia, Guamia mariannae* and *Piper* sp. (Fig. 6). *Partula gibba* was abundant, inhabiting the leaves of *Aglaia mariannensis* along the entire route surveyed from west to east. Forty-nine (27 adults, 14 subadults, and 8 juveniles) snails were seen, and tissue samples were taken from 14 adult snails. Typical snails in this site are shown in Fig. 7.

Survey Route no. 3: This route, also accessed by helicopter, lies to the east of Survey Route 2, along the eastern end of the cleft between the base of the a'a flow on the caldera floor and the old caldera rim. The team members were dropped off on the a'a flow and made their way into the gulch at its sparsely forested western end.

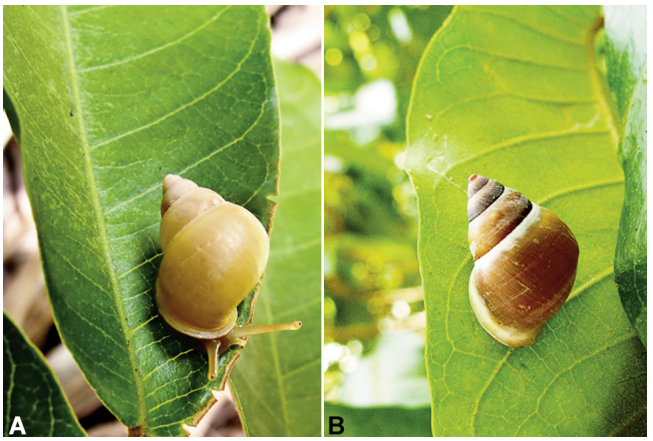

Figure 7. *Partula gibba* found on Survey Route 2.

Figure 8. Vegetation in lower portion of Survey Route 3.

Hiking eastward, they entered an area of dense vegetation dominated by very tall coconut palms, breadfruit trees, native trees, and understory. It is worth noting that despite the presence of feral goats and pigs (both seen in this area during the survey), the vegetation was mostly intact throughout this gulch (Fig. 8) and on the ridge above it to the south (Fig. 9). Dominant canopy trees include breadfruit, *Artocarpus* sp., coconut palms, *Ficus* sp. and a dense understory with abundant *Aglaia marianensis*, *Pandanus* sp. A single *P. gibba* was found on a leaf of a taro plant in the lower part of the survey route (Fig. 10A), and abundantly on *A. mariannensis* and a *Piper* sp. vine growing in the *A. mariannensis* (Fig. 10B).

Figure 9. Habitat for *Partula gibba* on upper portion of Survey Route 3; *Aglaia marianennsis.*

Survey Route No. 4: This route, reached by helicopter, lies at an elevation of about 308 m. The rich native forest was found in a gulch on the west side of a cinder cone located in the northern part of the caldera of the south Pagan volcano. The team traversed this gulch from

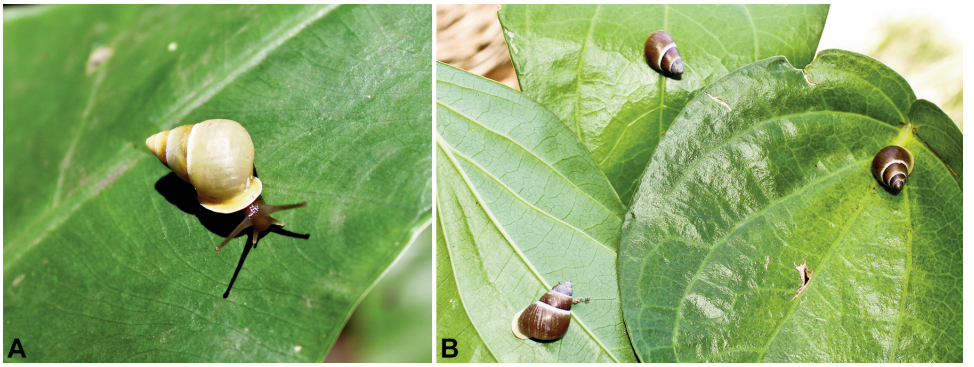

Figure 10. *Partula gibba* found on Survey Route 3. Note two color morphs; **A**. yellow snail found on a taro plant; **B**. purple morph found on *Piper* sp. growing in *Aglaia marianennsis*.

its southern to its northern end. This area lacked the higher coconut and breadfruit trees seen on Survey Routes 2 and 3. Instead, the canopy was lower and included *Melanolepis multiglandulosa, Aglaia mariannensis*, a tree tentatively identified as *Cananga odorata,* and many others with which we were not familiar (Fig. 11). There was also a rich groundcover in this area, including dense stands of ferns, *Pepperomia* sp. and other unfamiliar flora forms (Fig. 12).

Partula gibba was very abundant throughout this gulch, including many with a distinctly different shell pattern (Fig. 13). Snails were found on *A. mariannensis*, tree-climbing *Freycinetia* sp., ferns, and unidentified small trees. Fifty-seven snails were counted, but this was not exhaustive, because the goal was to determine the extent of the area inhabited by snails. There were undoubtedly many more. Tissue samples were taken from 10 adult snails, half of them from snails with the unusual, mottled shell pattern and the others from snails whose shells were of solid colors varying from gray to light yellow.

Survey Route No. 5: This area, reached by helicopter, lies east of the north end of the Survey Route

Figure 11. Vegetation on Survey Route 4.

Figure 12. Ground-cover vegetation on Survey Route 4.

4, against the base of a very high cliff that forms the northern edge of the ancient caldera of the south Pagan volcano (see Fig. 4). As described also for Survey Routes 2, 3 and 4, this patch of good forest lies in a depression at the foot of the escarpment, at an elevation of about 310 m. Vegetation here was very similar to that in Survey Route No. 4; *Freycinetia* sp. was especially abundant climbing the trees (Fig. 14), which included those named at Survey Route 4, plus *Ficus* sp., *Pandanus* sp., *Pisonia* sp., *Morinda citrifolia,* and betel nut palms.

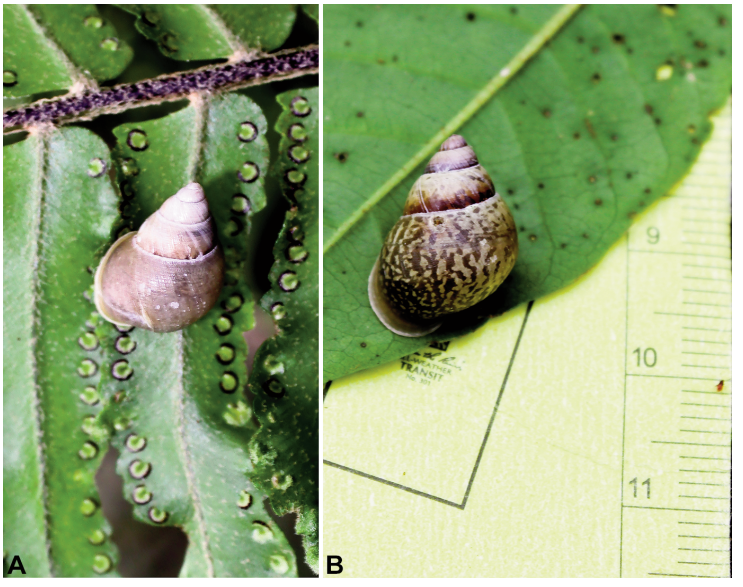

Figure 13. *Partula gibba* found on Survey Route 4. **A**. Solid colored morph. **B**. mottled shell, scale = cm.

Figure 14. Vegetation on Survey Route 5.

Partula gibba was found at this site, although not as abundantly as on Survey Route 4. Of 15 snails seen, only one had the unusual mottled shell. Tissue samples were collected from ten adult snails.

Survey Route No. 6: As can be seen in Fig. 4, this route, also reached by helicopter, lies further east from Survey Routes 4 and 5, but also in a depression at the base of the ancient caldera rim at about 260 m. The habitat was dominated by very tall coconut palms, an intermediate canopy that included *Ficus* sp., *Barringtonia asiatica,* and *Neisosperma oppositifolia,* and an understory of mainly *Aglaia mariannensis*. *Partula gibba* was abundant on the *Aglaia*, but specimens were also observed on *Ficus* sp., *B. asiatica*, *N. oppositifolia,* and *Piper* sp. growing in these trees. More than 209 snails were counted (105 adults, 73 subadults and 31 juveniles), most with shells of solid colors. However, the second morph with mottled shells was also observed in small numbers (Fig. 15). Tissue samples were taken from 15 adult snails.

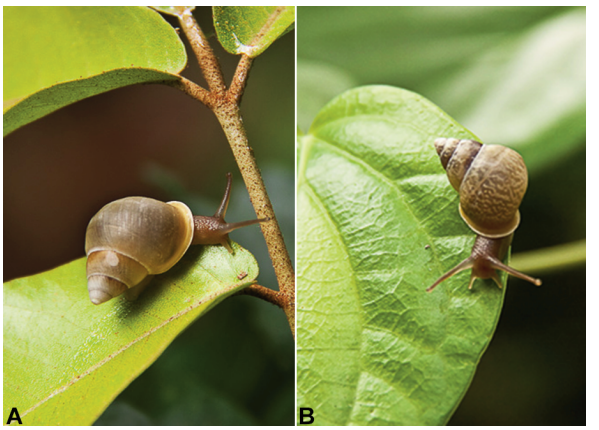

Figure 15. *Partula gibba* on Survey Route No. 6. Mottled morph is on the right.

Survey Route No. 7: This route was also accessed by helicopter. The team left the helicopter on the ridge that forms the narrow backbone of Pagan Island that connects the northern and southern volcanoes. The survey began at an elevation of about 165 m. Although the ridgeline was covered in grass (Fig. 16), the team was able to descend a short dis-

Figure 16. View northward from starting point of Survey Route 7, middle of Pagan Is.

tance into gullies on both east and west sides containing an *Aglaia* forest. Members of the team that descended in one eastward valley to sea level found it to be heavily impacted by feral cattle and goats, and no snails were found.

Survey Route No. 8: The steep island slope above the western middle coast of Pagan Island was reached by foot from the campsite (Fig. 17). Three team members hiked along this coast and climbed upward in wooded ravines where ever possible. The terrain was found to be very dry and heavily impacted by feral ungulates. No snails were seen.

Northern Surveys: Survey routes designated 9 through 13 in Figure 4 lie around Pagan Volcano, which underwent a major eruption in 1981. New lava flows covered terrain to the north and south of the main crater, and ash falls were very heavy to the north, northwest, west, and southwest of the crater (Trusdell *et al.* 2006). In addition, a large number (perhaps thousands) of cattle graze all accessible areas northward from about the narrow middle of the island.

Survey Routes 9 and 10: These routes were accessed by foot from the camp on several occasions. **Survey Route 9** lies along the western and upper edges of the steep escarpment formed by the southern wall of the ancient Pagan Volcano caldera, and **Survey Route 10** lies along the foot of the escarpment and extends eastward to pass along the eastern rim of the escarpment and along its eastern slope down to the shore. The forest at the foot of the escarpment consists of an intact canopy of *Erythrina variegata*, *Artocarpus* sp., *Barringtonia asiatica,* and *Neisosperma oppositifolia,* and an understory of *Pandanus* sp., *Aglaia mariannensis,* and other small trees. On the eastern slope of the caldera lies a huge coconut grove intermixed with some of the same canopy trees (Fig. 18). This entire area has been heavily impacted by ungulate grazing, especially cattle, and many hundreds of them were observed in this area (Fig. 19). The forest has been grazed up to the heights to which cows can feed (Fig. 20). Although Kondo found *Partula gibba* in several sites along these survey routes (see Fig. 2), we found none, not even old ground shells. We also failed to observe the invasive Giant African Snail, *Achatina fulica*, whose great abundance in this area was noted by Kondo (1949).

Survey Route 11: Access to this route was by ATV to the end of the road near the coastal lake and then by foot. The route traversed an area that had received intense ashfall during the 1981 eruption

Figure 17. Aerial view of Survey Route 8, looking north along western beach, south of campsite.

of Mt. Pagan. Although large trees remain in the gulches, the area is heavily grazed and without an understory. Kondo found *P. gibba* at a site near where this survey route turned from northward toward the east, but we found no remnant of this population, either living or dead.

Survey Routes 12 and 13 were selected from the vegetation map as probably having vegetation of "mixed coconut native forest." They were accessed by helicopter, with Team 1 at Survey Route 13 and Team 2 at Survey Route 12. Both were on the edge of a steep cliff that fell more than 150 m to sea level. The forest consists of extensive stands of coconut, probably once part of a copra plantation, large banyan trees (*Ficus* sp.), *Aglaia mariannensis, Pandanus* sp., and some other broad-leafed trees (Fig. 20). As noted, evidence of grazing was heavy, and the forest was extremely dry.

Figure 18. Habitat along the eastern end of Survey Route 10.

Figure 19. Cattle on Survey Route 10, west of Degusa Beach.

Other snail species: Although the focus on the Pagan Island surveys was on locating tree snails of the family Partulidae, we also noted other arboreal snails when they were observed. Of these, the only live snail encountered was a single specimen of *Succinea* sp. found on a leaf of *Aglaia mariannensis* on Survey Route 13. In this same area, a few very small shells, tentatively of a tornatellinine snail, were found deep in the axils of *Pandanus* sp. The snails that had inhabited these shells were dead, and the shells proved to be too fragile to collect. A small collection of shells found under loose stones in this area included species tentatively identified (from comparisons with Kondo's collec-

Figure 20. Vegetation on Survey Route 13, near the north shore of Pagan Island.

Figure 21. Forest on Survey Route 10, near the base of the escarpment.

tions in the Bishop Museum) as *Opeas* sp. and *Gastrocopta* sp., together with *S. octona* and other very small shells. Along Survey Route 11, at the base of the escarpment, a search on the ground turned up empty shells of what may be *Zonitoides* sp. and a small, narrow-shelled species tentatively assigned to *Opeas* sp., together with *Subulina octona, A. fulica,* and *Gonaxis kibweziensis*. A careful search of leaves, trunks and litter for tornatellinines was unsuccessful. The very dry conditions we encountered on Pagan Island may have caused resident populations of very small land-snail species to retreat into very cryptic places, and, in our efforts to locate the larger and seriously threatened *P. gibba,* we undoubtedly overlooked many smaller ground-dwelling species.

It is significant that we encountered only a single living *A. fulica* during our surveys of Pagan Island, on Survey Route 4. Although we found pieces of shells of this species along all of the northern survey routes (Nos. 9–13), they were never in any abundance. In the area along the base of the cliff where Kondo found greatest densities of *A. fulica* in 1949, our Survey Route 10, shells of *A. fulica* were very rare in May 2010. We also encountered old shells of *G. kibweziensis* in many locations, but they were rare. Shells of *S. octona* were found by turning over loose stones in many areas.

Discussion

The feral cattle on Pagan Island have heavily impacted the forests in all of the areas covered in our northern surveys (Fig. 4, survey routes 8–13), leaving only a high forest canopy dominated by *Cocos nucifera, Barringtonia asiatica, Artocarpus sp., Erythrina variegata* var. *orientalis, Artocarpus* sp., and some other large trees without an understory or ground cover (e.g., Survey Route 10, Fig. 21). These forests are extremely dry due to the absence of moisture-holding understory and ground cover, plus the added effects of a deep layer of ash, probably resulting from the 1981 eruption of Mt. Pagan, which very likely explains the total absence of *Partula gibba* in the areas where Kondo encountered them in 1949. It is likely that the cattle have been kept from over-running the southern part of the island by the absence of beaches, the very steep terrain that extends upward from the shore, and the absence of freshwater in the highlands. The large expanses of extremely rough and high-profiled a‘a lava in the large caldera of the southern Pagan volcano probably also serve as a barrier to the movement of cattle. We specifically cite the role of cattle in decimating the forest understory in the northern part of Pagan Island, because goats and pigs are widespread in both the north and the south, but

Figure 22. Cattle on Degusa Beach, east side of Pagan Island.

the forest understory is mostly intact in the upper elevations where the snails were found within the southern Pagan volcano caldera and where cattle do not occur.

We have not been able to determine exactly when the large numbers of cattle were brought to Pagan Island or, more importantly, when they were released to overrun much of the island. The only mention of cattle in Kondo's field notes from his 1949 survey on the island (Kondo 1949) refers to the skeleton of a cow found in a well. Had cattle been as abundant in 1949 as they are now, he would certainly have encountered them many times. Corte (1870) noted that the only mammals present were pigs, while Marche (1891), a few years later, saw both pigs and goats on the island. A 1957 account (U.S. Naval Administration 1957) reported six head of cattle and eight pigs, apparently in the village, plus "wild goats and chickens." The latter report notes (p. 35), "There is sufficient land areas for grazing of several hundred head of cattle at Laguna Sanhile where there is a fresh water lake available for drinking water." It seems likely that this recommendation was later followed and a ranch established. How many cattle may have been present when Mt. Pagan erupted in 1981, and all of the people removed, is not known. However, that is likely the time when the cattle became free to roam all of the accessible parts of the island. We saw hundreds of cattle, most abundantly along the eastern slope of the northern caldera and the central ridge between Mt. Pagan and the southern volcano. Corte (1870) reported that there was a spring on the eastern side of Pagan Island, at the foot of the mountain and close to the beach. This is likely to be the source of water for the many cattle we observed near the eastern beach labeled Degusa on some maps (Fig. 22).

The small areas with native forest and mixed introduced and native forest where we found *Partula gibba* in the old caldera of the southern volcano may provide the only remnant of a forest that was once much more prevalent on Pagan Island. These small areas are also the home of many native plants that we did not encounter in any of our northern transects. It is likely that elements of this biome extend along the summit

Figure 23. *Partula gibba* on Saipan.

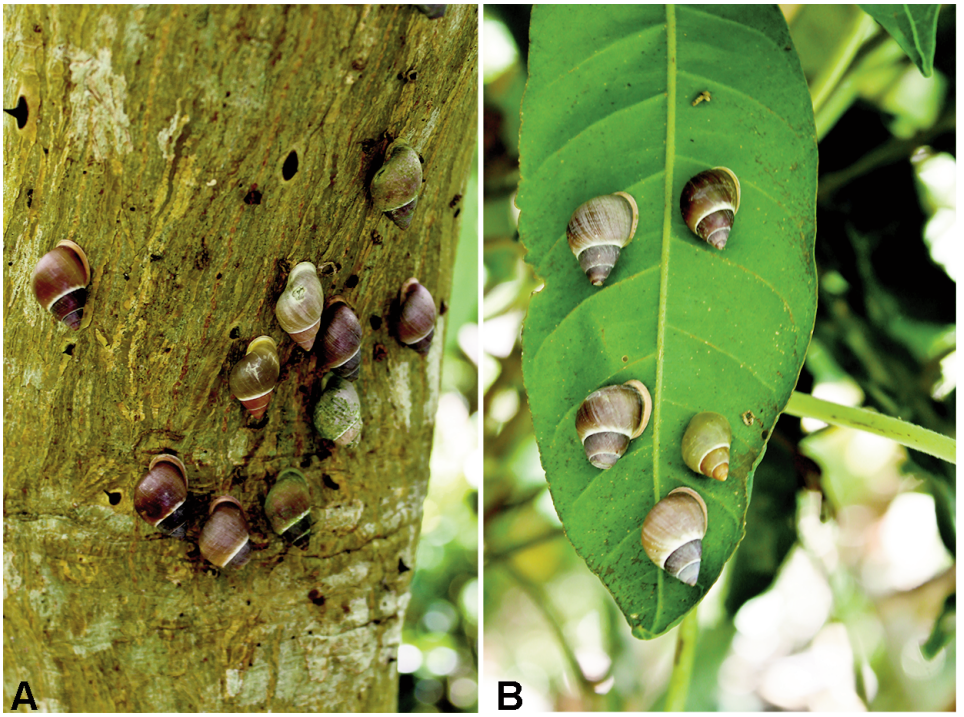

Figure 24. *Partula gibba* on Sarigan Island.

southeast of the southern Pagan caldera, an area we saw only from the edge during our Survey Route 3 and would be very difficult to access except via this route. These areas within and south of the southern caldera will be extremely important for the conservation of the native biota of Pagan Island.

Partula gibba on Saipan and Sarigan Islands

Saipan: While waiting for transport from Saipan to Pagan Island on 4 May 2010 and using information provided by Barry D. Smith of Guam, the snail team located a population of *Partula gibba*. At this site, only slightly above sea level in a very mixed forest near the American Memorial Park on the west side of Saipan, the team counted at least 42 *Partula gibba* on a variety of vegetation, including *Pandanus* sp., birds-nest ferns, and a tall branching fern. Tissue samples were collected from seven adult snails, and photos were taken (Fig. 23).

Sarigan Island: In route to Pagan Island by helicopter, three team members stopped on Sarigan Island where they camped overnight at an elevation of about 350 m. They found *Partula gibba* to be very abundant, and collected tissue samples from six adult snails in each of two areas. Other team members stopped briefly on Sarigan Island on their return flight to Saipan and photographed these dense assemblages of *P. gibba* (Fig. 24).

Between 1998 and 2000, all feral ungulates were removed from Sarigan, which was followed by a major recovery in the island's vegetation (Kessler 2002, Martin *et al*., 2008). Accompanying the vegetative regrowth was the recovery of *Partula gibba*. Prior to ungulate removal, the snails were considered uncommon; following ungulate removal, the tree snails became abundant within forested areas (Martin *et al*., 2008). Our brief stops on Sarigan in 2010 confirmed the great abundance of *Partula gibba* in the forested area, with snails easily numbering in the thousands.

One of the main host trees for the snails is *Erythrina variegata* var. *orientalis*, supporting many tens to hundreds of snails on the trunk and leaves of a single tree. Unfortunately, these trees are being attacked by the same *Erythrina* gall wasp, *Quadrastichus erythrinae* Kim, that has devastated the native Hawaiian *Erythrina sandwicensis*. (Samples were collected by Stephen Miller and returned to

Hawaii for identification by Bernarr Kumashiro at the Hawaii State Department of Agriculture.) In order to preserve *Erythrina* in the Mariana Islands and the important snail habitat that it provides we strongly recommend exploring the possibility of introducing the *Erythrina* gall wasp biocontrol agent, the parasitic wasp *Eurytoma erythrinae*, used so effectively, to date, in Hawaii (Stephen Miller, pers. comm. with Neil Reimer, October 2010).

Population Genetics of *Partula gibba* in the Mariana Islands

Using procedures developed for handling tissue samples from endangered Hawaiian tree snails (Holland & Hadfield 2002), we have extracted DNA from all tissues samples collected from *P. gibba* on Pagan Island, Sarigan Island and Saipan. This DNA is being used to examine the population genetics of the species across these islands with a goal of determining how related the populations are. A preliminary analysis of DNA sequence for a gene (CO1) that is abundantly used for this purpose, provides evidence that the populations are widely divergent. Genetic distances between populations of *P. gibba* on Saipan, Sarigan and Pagan are as great, or greater, than those typically observed between separate species in many animal taxa (F_{st} = 0.7–1.0). Additional gene sequences will be examined for the snails to determine if these values are anomalous. Also, in August 2010, I collected tissue samples from *Partula gibba*, plus two additional partulid species on Guam and, in October, David Sischo, traveled to Rota Island to sample tissues of *P. gibba* on that island. When DNA is extracted and analyzed from all of these snails, we will be able to establish the genetic differences between each island population of the snails from throughout its entire north-south range, and establish whether or not these snails must be considered variants, subspecies or even separate species. The data may also assist in determination of the routes of migration of snails between the Mariana Islands.

Acknowledgments

I am extremely grateful to the members of the malacology team who carried out the snail surveys on Pagan Island with me. Their efforts were critical to the success of the effort in every regard. Stephen Miller also contributed essential knowledge of the history of Sarigan Island and reviewed the initial draft of this report. David Sischo carried out the genetic analyses of tree-snail samples collected from Guam to Pagan Island; in addition, many of the photographs in this report were taken by him. The assistance of Ms. Regina Kawamoto, Malacology Collection, Bishop Museum, was invaluable in preparing for the Pagan Island surveys. She provided access to Y. Kondo's field notes and maps, downloaded files on Pagan snails from the accession records, and provided guidance in finding materials that I would otherwise have missed. The USFWS support group on Pagan Island greatly assisted our living and surveys, for which we are very grateful. I am especially indebted to Sandy Castro, Pagan Island's sole resident when we arrived, for his support and for sharing his deep knowledge of the history of the island. I also express my thanks to the late Lucius Eldredge, Bishop Museum, Honolulu, for providing access to his extensive library of materials on the Mariana Islands. While on the faculty of the University of Guam, he carried out in-depth bibliographic research on the biota of the Mariana Islands and copied from papers in the Micronesian Area Research Center the materials cited below as: Anonymous 1944; Corte 1870; Marche 1891; Olive y Garcia 1887; and U.S. Naval Administration 1957. I am grateful to Neal Evenhuis for helping me complete the citations for these classic papers.

References

Anonymous. 1944. Marianas. *Joint Intelligence Center, Pacific Ocean Areas. Information Bulletin* **7-44**: 66–78, plus maps. (Pacific Science Information Center, Bishop Museum, Honolulu)

Bauman, S. 1996. Diversity and decline of land snails on Rota, Mariana Islands. *American Malacological Bulletin* **12**(1/2):13–27.

Corte, Felipe de la and & Calderon, R. 1875. Memoria descriptiva é histórica de las islas Marianas y otras que las rodean, en relacion con nellas, y de su organizacion actual. Boletín del Ministerio de Ultramar, National Printing Office, Madrid. 257 pp. [English translation, H.L.

Paul, 1970, Micronesian Area Research Center, University of Guam, "A History of the Mariana Islands, November 1520 to May 1879, with a continuation by the Reverend Father José Palomo y Torres."]

Crampton, H.E. 1925. Studies on the variation, distribution, and evolution of the genus *Partula*; the species of the Mariana Islands, Guam and Saipan. Carnegie Inst. Washington Publ. No. 2228A, pp. 1–116, & plates 1–14.

Holland, B. & Hadfield, M.G. 2002. Islands within an island: phylogeography and conservation genetics of an endangered Hawaiian tree snail *Achatinella mustelina*. *Molecular Ecology* **11**: 365–375.

Kessler, C.C. 2002. Eradication of feral goats and pigs and consequences for other biota on Sarigan Island, Commonwealth of the Northern Mariana Island, pp. 132–140. *In*: Veitch, C.R. & Clout, M.N. (eds.), *Turning the tide: the eradication of invasive species*. IUCN-SSC Invasive Species Specialist group, IUCN, Gland, Switzerland and Cambridge, UK.

Kondo, Y. 1949. Field notes for land-snail surveys on Pagan Island, during the Pacific Science Board's *Achatina* survey of the Bonin and Mariana Islands, Palau and Truk. Unpublished, Malacology Collection, Bishop Museum, Honolulu.

Kondo, Y. 1970. Some aspects of Mariana Islands Partulidae. *Occasional Papers of the Bernice P. Bishop Museum* **24**(5): 73–90.

Kurozumi, T. 1994. Land molluscs from the Northern Mariana Islands, Micronesia. *Natural History Research (Natural History Museum and Institute, Chiba, Japan), Special Issue* **1**: 113–119.

Marche, M.A. 1891. Rapport générale sur une mission au Isles Mariannes. *Nouvelles Archives des Missions Scientifiques et Littéraires* (Nouvelle Série) **1**: 241–280. [English translation, S.E. Cheng, Micronesian Area Research Center, University of Guam, "The Mariana Islands."]

Martin, G. (ed). 2008. Wildlife and vegetation surveys of Sarigan Island, April 13–25, 2006. *Commonwealth of the Northern Mariana Islands, Division of Fish and Wildlife, 2008, Technical Report* **14**: separately paginated in 12 sections.

Murray, J., Murray, E., Johnson, M.S. & Clarke, B. 1988. The extinction of *Partula* on Moorea. *Pacific Science* **42**: 150–153.

Olive y Garcia, F. 1887. Islas Marianas. Lijeros apuntes acerca de las mismas, porvenir á que pueden y deben aspirer, Imprenta y Litografia de M. Perez, Manila, 105 pp. [Translation, Micronesian Area Research Center, University of Guam. "The Mariana Islands 1884–1887, Random Notes Concerning them."]

Pelep, P.O. & Hadfield, M.G. 2011. The status of the endemic snails of the genus *Partula* (Gastropoda: Partulidae) on Pohnpei, Federated States of Micronesia. *Micronesica* **41**(2): 253–262.

Raulerson, L. & Rinehart, A. 1991. *Trees and shrubs of the Northern Mariana Islands*. Coastal Resources Management, Office of the Governor, Commonwealth of the Northern Mariana Islands, Saipan. 120 pp.

Russell, S. 1998. Tiempon I Manmofo'na, Ancient Chamorro Culture and History of the Northern Mariana Islands. Commonwealth of the Northern Mariana Islands, Division of Historic Preservation. *Micronesian Archaeological Survey Report* **32**, 405 pp.

Smith, B.D. 2008a. Seven decades of disruption, decline, and extinction of land snails in Aguiguan, Mariana Islands. Report to the Department of Fish and Wildlife, Commonwealth of the Northern Mariana Islands. 19 pp.

Smith, B.D. 2008b. Preliminary assessment of endemic arboreal snails in three forest types in Sarigan, with notes on ground-dwelling species. Pp. 8–8-23. *In*: Martin, G. (ed), Wildife and vegetation surveys of Sarigan Island, April 13–25, 2006. *Commonwealth of the Northern Mariana Islands, Division of Fish and Wildlife, Technical Report* **14**.

Thacker, R.W. & Hadfield, M.G. 2000. Mitochondrial phylogeny of extant Hawaiian tree snails. *Molecular Phylogenetics & Evolution* **16**: 263–270.

Trusdell, F.A. 2009. Geology of the Mariana Islands, pp. 598–603. *In*: Gillespie, R.G. & Clague, D.A. (eds.), *Encyclopedia of islands*. University of California Press, Berkeley, California. 1074 pp.

Trusdell, F.A., Moore, R.B. & Sako, M.K. 2006. Preliminary geologic map of Mount Pagan volcano, *Pagan Island, Commonwealth of the Northern Mariana Islands. U.S. Geological Survey, Open-File Report* **2006-1386**, 19 pp. plus appendices.

U.S. Naval Administration. 1957. Survey report of the islands north of Saipan. U.S. Naval Administration Unit, Saipan District, Saipan, Mariana Islands, J.B. Johnson, Head, Survey Team. (Pacific Science Information Center, Bishop Museum, Honolulu).

Vogt, S.R. & Williams, L.L. 2004. *Common flora and fauna of the Mariana Islands*. WinGuide, Saipan, Northern Mariana Islands. 158 pp.