Internat. Rev. Hydrobiol.	83	1998	1	65–75

RICHARD E. BROCK[1] AND JULIE H. BAILEY-BROCK[2]

[1]Sea Grant College Program, University of Hawaii, 1000 Pope Road, Honolulu, Hawaii U.S.A. 96822
[2]Department of Zoology, University of Hawaii, 2538 The Mall, Honolulu, Hawaii U.S.A. 96822

An Unique Anchialine Pool in the Hawaiian Islands

key words: anchialine, shrimp, colonization, watertable, Hawaiian

Abstract

The Sailor's Hat crater was artificially formed on the south coast of Kaho'olawe Island in 1965 with explosives. The explosion formed a crater about 50 m from the shoreline, which penetrates the watertable to a 5 m depth. The pool at the bottom of the crater meets the criteria of an anchialine pond because it shows tidal fluctuation, has measurable salinity, and lacks surface connections to the sea. The water chemistry of this pool is similar to the ocean except silica is elevated and salinity is slightly depressed suggesting a small groundwater influence. The fauna is dominated by waterboatmen, an endemic shrimp and tubeworm, polychaetes, amphipods, an ostracod, gastropod, solitary ectoproct, anemone, flatworm and sponge. The atyid shrimp, *Halocaridina rubra*, is a characteristic species of Hawaiian anchialine systems and probably colonized this 32-year old pool by active migration via the watertable. Colonization by the remaining fauna may have occurred by storm surf (for marine species) or with the wind. Most predators are unable to inhabit anchialine ponds because of difficult access due to physical barriers, or to unsuitable ecological conditions. The anchialine habitat and life history strategy of the atyid shrimp have probably been important influences on the adaptative success of *H. rubra* in the Hawaiian Islands, and may be important characteristics of hypogeal anchialine species elsewhere.

1. Introduction

Anchialine pools are land-locked brackish bodies of water that undergo tidal fluctuations, but lack surface connections to the sea. Anchialine pools are restricted to highly porous substrates such as recent lavas or limestone adjacent to the sea. These pools are inhabited by a distinctive assemblage of organisms, some of which are endemic (HOLTHUIS, 1973; MACIOLEK, 1983). Perhaps the most striking are a number of red-colored shrimp in the Family Atyidae.

The anchialine habitat is widely distributed globally, it is known from the Sinai Peninsula in the Red Sea, islands in the Indian and Atlantic Oceans, and from the tropical Pacific including the Hawaiian Islands. Localities with numerous anchialine pools are known from Fiji, the Ryukyus, and the Hawaiian Islands. Although the Hawaiian Islands probably have the greatest number of anchialine pools, many of them have been seriously disturbed by introduced exotic species (BROCK, 1985; BAILEY-BROCK and BROCK, 1993) such that today the anchialine habitat and usual complement of native species are rare in the Hawaiian Islands.

The water in anchialine pools displays a wide range in physical and chemical conditions due to the mixing of seaward flowing groundwater with intruding seawater (BROCK *et al.*, 1987) Because of these varying parameters of the habitat, many anchialine species are extremely physiologically tolerant and thrive in a variety of physical conditions. The Hawaiian anchialine habitats are characterized by a wide range in salinities over daily and seasonal changes, and all known pools show some depression in salinity due to groundwater percolation.

2. Hydrology and Geology of Kaho'olawe

Kaho'olawe is an island with very limited freshwater resources. An historical review of freshwater resources of the island indicates that freshwater pools are temporary following rain events. STEARNS (1940, page 122) notes:

"On December 7, 1857, P. NAHAOLELUA, Govenor of Maui, and IOANE RICHARDSON made a report to King Lot Kamehameha after inspecting the island (Kaho'olawe). The following is quoted from this report: 'There is no freshwater but the old residents stated that during the rainy times freshwater may be found in small pools, but these waters did not last, when the sunny times came they soon dried up.

There are not many places on this island where brackish water may be found. There is only one brackish water which is accessible seen by us, at Ahupu harbor, this brackish water being on the northwest of said island.

And the old residents informed us, that there is another brackish water on the southeast (southwest) side of said island, it is in a bad place under cliff at a place called Waikaalulu (Waikahalulu), Kanapou, the well where Kalaepuni was murdered. These are the only three places known where brackish water may be found on Kaho'olawe' ".

STEARNS (1940) recorded that there had been seven wells dug on the island; four developed in ancient times and were blocked or dry, and three modern wells. One of the modern wells (at Kaulana) was dry in 1939 (Fig. 1), the two remaining modern wells contained water with relatively high chloride levels (the Ahupu well = 3,250 ppm and the Hakioawa well = 12,600 ppm). Two seeps are known near Kanapo'u Bay; these have a combined flow estimated to be less than half a pint per minute and are probably from perched-water bodies (TAKASAKI, 1991). These records suggest that Kaho'olawe has very poor groundwater resources and if the historical records are accurate, naturally occurring anchialine pools probably never existed on the island. Since 1941 Kaho'olawe has been under military control, with limited public access. The military has imported drinking water for its use, and has not relied on natural water sources.

In 1965 the Navy carried out an experiment at Kaho'olawe to test the impact of high explosives in close proximity to ships. The experiment comprised a series of three explosions each utilizing 500 tons of TNT. These explosives were denotated in February, March and June 1965 on a small peninsula forming the western end of Honokanai'a Bay. The resulting crater formed by these explosions is approximately 50 m in diameter with a pool at the bottom (at sealevel) that is about 5 m in depth (Fig. 2). The pool was named "Sailor's Hat" after the project's name.

An initial biological inventory was made of Sailor's Hat pool by the the Nature Conservancy of Hawaii (1992). They reported that the salinity of the pool was probably in excess of 12‰ (but it was not measured) and species observed included the native red shrimp or opae'ula (*Halocaridina rubra*), amphipods, snails, red polychaete tubeworms as well as an exotic aquatic insect (family Corixidae). High turbidity was attributed to high phytoplankton densities. The Nature Conservancy of Hawaii report (1992) is the only biological study that has been done on this man-made pool which is the only known anchialine pool on Kaho'olawe Island. The present paper characterizes the water chemistry and benthic community composition of this recently formed habitat, the Sailor's Hat pool, and explores the ecological requirements of the anchialine species in this unique habitat.

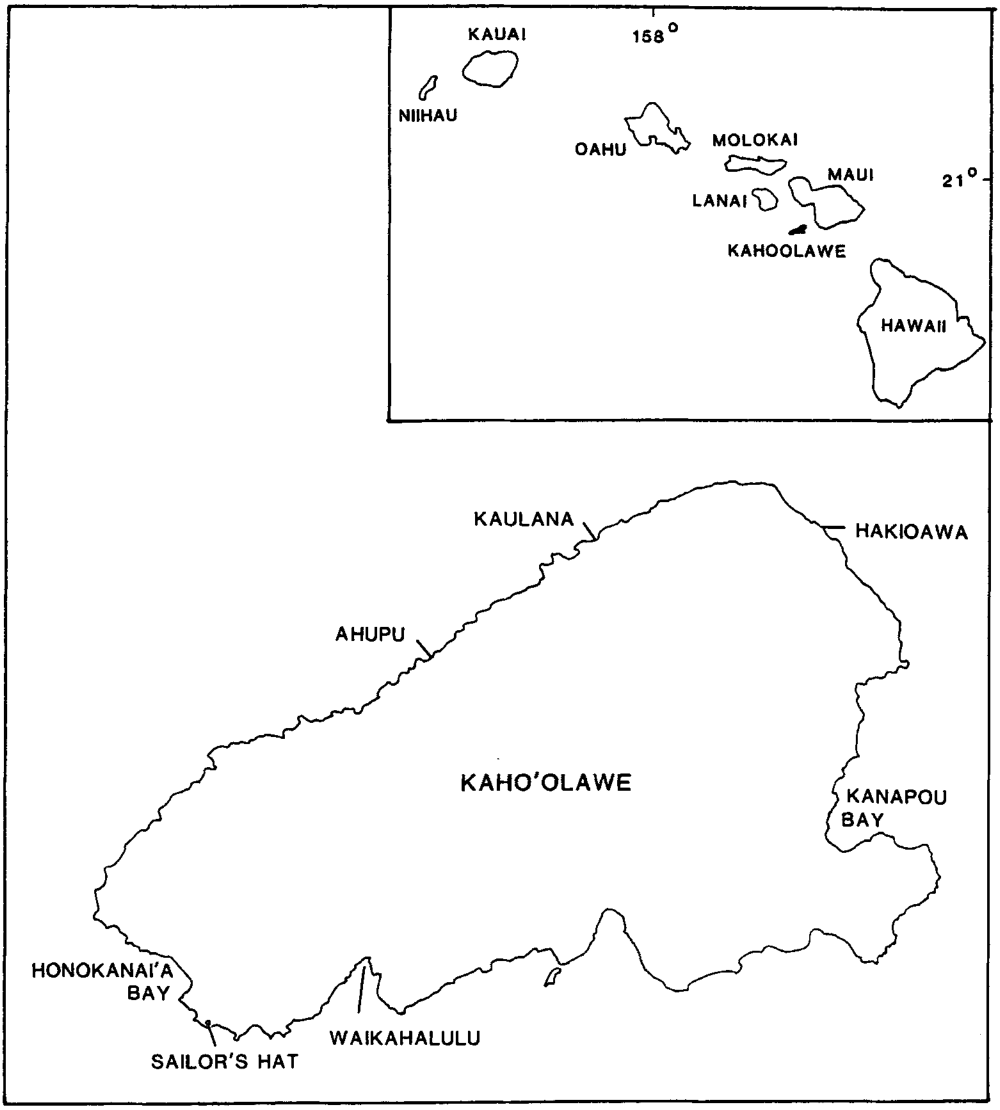

Figure 1. Map of Kaho'olawe Island showing Sailor's Hat pool, well sites and seeps at Kanapou Bay. Inset shows proximity of Kaho'olawe (shaded) to main Hawaiian Islands.

Figure 2. Aerial view of Sailor's Hat pool, near the west end of Honokanai'a Bay, Kaho'olawe, 14 May 1993. The steep sides and talus covered walls of the crater were formed when 1500 tons of explosives were detonated in 1965. For scale, the pool at the bottom of the crater is about 50 m in diameter. Photograph by PAUL JOKIEL.

3. Methods

Water chemistry parameters were measured in the field and laboratory. Parameters measured include ammonium, nitrite + nitrate nitrogen (hereafter referred to as nitrate), ortho-phosphorus, silica, chlorophyll-*a*, salinity, temperature and pH. Oxygen concentration was not measured in the field, but is suspected to be near saturation due to the high phytoplankton biomass which made the water turbid.

Samples for laboratory analysis were collected on 14 May 1993 on a rising tide (+15 to +25cm) in one litre triple-rinsed, acid cleaned, polyethylene bottles by swimming to the center of the pool (taking care to avoid splashing and mixing surface with deeper layers), and filling a bottle at a 10 cm depth (top sample) and one at 50 cm above the substratum at a depth of 4.5 m (bottom sample). Water samples for dissolved nutrient analyses were immediately processed through glass fiber filters (GF/F 2.5 cm) into 125 ml acid-washed and triple-rinsed polyethylene bottles which were placed on ice and subsequently frozen until analysis. Laboratory analyses were done at the University of Hawaii using standard procedures given in STRICKLAND and PARSONS (1972), SMITH *et al.* (1982), GRASSHOFF (1983) and Standard Methods (1985).

Chlorophyll-*a* samples were collected by filtering known volumes of seawater through 2.5 cm GF/F glass microfiber filters, and storing filters in light-tight containers which were frozen until laboratory analyses were carried out. Pigments were extracted and chlorophyll content determined fluorometrically (Standard Methods 1985). Water for salinity measurement was collected in clean 125 ml polyethylene bottles, filled completely and capped tightly, and measured on an AGE Model 2100 Minisal salinometer in the laboratory. Temperature and pH readings were made in the field with a portable pH/temperature meter (Hanna Model 9025C).

Biota were collected by SCUBA diving in the pool and capturing specimens with a 2 mm mesh net or removing small rocks with associated epifauna. Observations from the shoreline were done to estimate the relative abundance of shrimp (*Halocaridina rubra*) on the pond bottom and in the water column, and to collect representative pieces of substratum. Some organisms were transported live from Sailor's Hat pool for laboratory study.

4. Results

The crater slope into the man-made pool is steep and covered with loose talus; and there are angular basalt rocks and boulders up to about 3 m in greatest dimension along the water's edge (Fig. 2). These shoreline rocks show evidence of tidal fluctuation by the presence of a white silica precipitate at the upper reach of the tide and by a poorly developed algal mat below it. The tidal fluctuation was estimated to be between 50–75 cm. Subtidally, the pool walls are similarly steep, ending abruptly at a relatively flat mud substratum. The mud is red-brown and derived from windblown dust and *in situ* biological activity. The bottom of the pool is covered by a fine mud that is overgrown in places by an amorphous cyanobacterial and diatomaceous mat. Attempts to collect this unconsolidated veneer of fine sediment was unsuccessful, but a number of diatoms were collected on the rocks with the tubeworms. Most of the exposed hard substratum in the pool is around the perimeter and not in the center of the pond bottom.

Field work was carried out on 14 May, 1993. Results of analyses of the two water samples from the middle of Sailor's Hat pool are given in Table 1. The concentration of nitrate nitrogen (NO_2 + NO_3) and orthophosphorus (PO_4) are low and similar to that found in coastal waters (BIENFANG, 1980). Ammonium (NH_4) is slightly elevated which is probably related to the biological activity (metabolism) in the pool. Silica is elevated over what is usually found in Hawaiian nearshore marine waters (DOLLAR and ATKINSON, 1992); this slight elevation is probably due to the small amount of groundwater that enters the pool. Salinity samples show a slight depression over normal full strength seawater (i.e., 33.8‰ in the pool versus 34.8‰ in the ocean), and some stratification is evident. The high salinity of this pool suggests that there is little groundwater intruding into the pool.

The aquatic fauna collected that comprise the biological inventory are listed under major taxa in Table 2. There are several species that are easily seen, and dominant in the pool at the time of sampling; these species include red serpulid tubeworms (*Vermiliopsis torquata*), gastropods (*Bittium zebrum*), red caridean shrimps or opae'ula (*Halocaridina rubra*) and waterboatman (*Trichocorixa reticulata*).

The gastropod, *Bittium zebrum*, has an Indo-Pacific distribution and is one of the dominant microgastropods of shallow coral reefs and tidepools in Hawaii (Kay, 1979). The serpulid

Table 1. Summary of the water chemistry parameters from two samples collected in Sailor's Hat pool on Kaho'olawe on 14 May 1993. Nutrient concentrations in µM.

Sample Location	Nitrite + Nitrate N	Ammonia N	Ortho P	Silica
Top	0.10	2.21	0.29	257.24
Bottom	0.16	1.74	0.26	259.86

Sample Location	Chlorophyll *a* (µg/l)	Salinity ‰	Temp °C	pH
Top	10.325	33.8727	27.5	8.25
Bottom	9.674	33.8852	27.6	8.26

Table 2. Summary of the biological collection made on 14 May 1993 in Sailor's Hat pool, Kaho'olawe.

Taxon	Remarks
Phylum Porifera	Silvery-white sponge encrusting lower surfaces of rocks collected close to shoreline – common.
Phylum Platyhelminthes	
Order Acoela	Flatworm (not in Poulter, 1987); on underside of rock.
Phylum Cnidaria	
Subclass Zoantharia	Small anemone found on rock.
Phylum Entoprocta	
Family Loxosomatidae	
Loxosoma sp.	Solitary entoproct, some with 2 buds attached near fecal strands of serpulid tubeworms on undersides of rocks.
Phylum Annelida	
Family Serpulidae	
Vermiliopsis torquata	Abundant tubeworm found on underside of rocks along the shoreline. Tubes are white, worms are brillant red and quite conspicuous when projecting from their tubes.
Family Dorvilleidae	
Ophryotrocha n sp.	11-setiger specimens with brown/black mandibles and serrated margins. Simple and compound setae present but no forked setae. New species known from other Hawaiian and European locations (PAAVO *et al.* Submitted).
Family Syllidae	
Syllid Species 1	Prostomium with a pair of large lobed palps, antennae and dorsal cirri strongly moniliform. Parapodia short and rounded. Dorsal cirri of alternate setigers are long and short. Ventral cirri digitiform and not articulated. Body cylindrical, anterior region with six red eyes and a long gizzard. Setae are compound, serrated blades with bifid tips that vary in length from short to long within a fascicle and long acicular setae with curved tips occur singly on the parapodia. Color pale with some brown pigment on anterior regions. Living adjacent to tubeworms on rock.
Syllid Species 2	Single juvenile with 5 setigers. Head with 4 eyes, round anterior margin, a single median antenna and 2 ciliated grooves. Dorsal cirri digitiform, setae compound with one acicular seta with a dorsal curved tip. Living adjacent to tubeworms on rock.
Phylum Mollusca	
Family Cerithiidae	
Bittium zebrum	Abundant on dorsal surfaces of rocks; common in tidepools and shallow reef areas in Hawaii.
Phylum Arthropoda	
Subclass Ostracoda	
Family Hemicyatheridae	
Jugosocytheris sp.	Species is very similar to *J. venulosus* which has been described as a fossil.
Order Amphipoda	
Nuuanu amikai	Species has reduced eyes.
Eriopisa laakona	Blind species; probable cavernicolous life history.

Table 2. (continued)

Taxon	Remarks
Order Decapoda	
Family Atyidae	
Halocaridina rubra	Confined primarily to edges of pool near rocky substratum; density estimated at 1 shrimp/m^3 of water. Little pigmentation so shrimp are pale and mean body size from tip of rostrum to posterior margin of the telson is 8–9 mm.
Class Insecta	
Family Corixidae	
Trichocorixa reticulata	Waterboatman - abundant in the water column; common in fresh to saline ponds; exotic species.

tubeworm, *Vermiliopsis torquata*, is common in tidepools of rock benches and on shallow Hawaiian coral reefs where turbidity is low (BAILEY-BROCK, 1987). This serpulid is considered to be a Hawaiian endemic (STRAUGHAN, 1969), but it is not known from any other Hawaiian anchialine system. The opae'ula (*Halocaridina rubra*) is an endemic species that is only characteristic of Hawaiian anchialine pools (HOLTHUIS, 1973). The aquatic insect, a hemipteran or waterboatman (*Trichocorixa reticulata*) is a North American species that became established in the Hawaiian Islands (ZIMMERMAN, 1948). This waterboatman is found in many aquatic habitats from fresh water to coastal saline pools. There were two species of amphipods, the most common is *Nuuanu amikai* which is a robust species with reduced eyes and known from anchialine ponds on Maui (MACIOLEK, 1986), the second is *Eriopisa laakona*, which completely lacks eyes and is characterized by very elongate third uropods. The small ostracod belongs to the genus *Jugosocytheris*. This podocopid ostracod is very close to *J. venulosus*, a fossil species (HOLDEN, 1967).

Some invertebrates were not identified to species because only a few specimens were collected, the dorvilleid polychaete, *Ophryotrocha* n.sp. (two specimens), or only juvenile stages were found (Family Syllidae, species 2), or due to difficulty with the taxonomy of the group (e.g., white sponge and small anemone). This fauna is quite depauperate relative to Hawaiian marine tidepools where many more invertebrate species may be encountered (TOWNSLEY *et al.*, 1962; BROCK and BROCK, 1974).

5. Discussion

The Sailor's Hat pool complies with the definition of an anchialine pool (HOLTHUIS, 1973), i.e., is land-locked, lacking surface connection to the sea, has measurable salinity, and shows tidal fluctuation. Most Hawaiian anchialine pools have salinities between 2 to 12‰ (MACIOLEK and BROCK, 1974) and there are a few that exceed 25‰ in Hawaii (The Nature Conservancy 1992). Many of the rare or more unique anchialine species are found only in pools with salinities above 12 to 15‰ (BROCK, 1985). Thus despite its creation through human activities, Sailor's Hat pool represents a rare anchialine habitat in Hawaii.

The nutrient and salinity data show that the water in the pool is primarily oceanic. The low concentrations of nitrate nitrogen and orthophosphorus are similar to oceanic waters which are typically low in these nutrients (LAWS, 1980). Similarly, silica concentrations are low in oceanic waters but like nitrate and orthophosphorus are high in Hawaiian groundwater (BROCK *et al.*, 1987). The slight elevation of silica and small salinity depression, about 1‰, suggests that some small amount of groundwater does enter the Sailor's Hat pool.

Chlorophyll-*a* is a measure of phytoplankton biomass. The relatively high concentrations of chlorophyll-*a* (phytoplankton) encountered in the Sailor's Hat pool probably serves to strip nutrients (nitrate and orthophosphorus) from any groundwater entering the system. This results in the low nutrient levels measured in the pool. Only one visit to this unique pool on Kaho'olawe Island was possible because of restricted access due to unexploded ordnance on the island. Further water quality measurements will better define the range in these variables.

The high salinity in Sailor's Hat pool is not unexpected with the historical accounts of little freshwater present on the island. Chloride concentration was measured in May 1983 and was reported at 20,300 ppm (36.7‰, YUEN and Associates, 1990) which is slightly hypersaline. Hypersaline conditions probably occur during periods of low rainfall and little groundwater input. The brackish water well at Hakioawa (Fig. 1), the last extant well on the island, has been sampled on a number of occasions since 1939. Chloride concentrations in this well have ranged from 18,000 ppm (32.6‰) down to 1,200 ppm (2.2‰) following 381 mm of rainfall (TAKASAKI, 1991). In 1939 STEARNS (1940) sampled the Ahupu well (Fig. 1) and found a chloride concentration of 3,250 ppm (5.9‰). Since that time, the Ahupu well has gone dry or is otherwise filled in (YUEN and Asssociates, Inc. 1990).

Use of explosive charges in aquatic environments may result in a transitory elevation of nitrate (BROCK, unpub. data). The limited water quality data collected in this study suggests that any nitrate residue from the explosion creating the Sailor's Hat pool has long since disappeared. Explosive charges may locally alter the permeability of the surrounding rock through which sea and groundwater flows as well as alter the movement of colonizing organisms. Most Hawaiian volcanic rocks have high permeability but where groundwater occurs, flow rates are on the order of a few meters per day due to the small differences in elevation through which it travels (MACDONALD *et al.*, 1983). This high permeability enhances the movement of colonizing hypogeal or otherwise cryptic organisms.

The amphipods identified in this collection from Sailor's Hat are known from Hawaiian coral reefs (BARNARD, 1970). The reduced eyes in *Nuuanu amikai* and the absence of eyes in *Eriopisa laakona* suggest that these amphipods may usually reside in cavernicolous habitats; BARNARD (1970) describes both species as nestlers. The ostracod, *Jugosocytheris* sp. is unusual in that it closely resembles a species known only from the fossil record (*Jugosocytheris venulosus*). HOLDEN (1967) reports that fossils of *J. venulosus* have been collected from the littoral zone in Fiji, and to depths exceeding 600 m off the Hawaiian Islands.

All the macrobiota except the opae'ula (*Halocaridina rubra*) and the exotic hemipteran (*Trichocorixa reticulata*) are marine in origin. The diversity of species in Sailor's Hat pool is low compared to other anchialine systems in Hawaii, and depauperate compared to the marine environment. This low species richness may be related to, isolation of this pool from the ocean, young age of the pool, occasional hypersaline conditions, and few opportunities to sample the pond due to military control of the island. Probable mechanisms for colonization of the pool by marine species are by (1) wind, (2) waves overtopping the berm separating the pool from the ocean, and (3) active migration from the ocean through subterranean labyrinth of crevices to the pool. Wind dispersal may be important for species that produce small, lightweight spores such as some of the algae. Overtopping of the berm separating the pool from the ocean must occur. The distance between the pool and ocean is about 50 m and height of the berm is less than 12 m. During our survey, we did find some beach sand along the seaward end of the pool which is consistent with deposition by high surf. All the species other than *Halocaridina rubra*, may have colonized the pool by being carried in during periods of high surf. On the West Hawaii coast high surf has been hypothesized as an important mechanism for colonization of anchialine pools by marine fish (BROCK, 1977).

Halocaridina rubra is the only species presently encountered in Sailor's Hat pool that is restricted to anchialine habitats. This atyid shrimp is relatively long lived, with a low reproductive capacity, it is euryhaline and tolerates frequent salinity fluctuations, and is an omnivore. The shrimp is a grazer on microorganisms and filamentous algae, and is known to live in the coastal brackish water table on Hawaii, Maui and Oahu islands (BAILEY-BROCK and BROCK, 1993). Although it has been recorded from Molokai (MACIOLEK, 1982, 1983) it has not been seen at the cited location for a number of years. The presence of *H. rubra* in Sailor's Hat suggests that this species is also established in the coastal water table of Kaho'olawe Island. *Halocaridina rubra* will rapidly recruit to newly constructed brackish ponds on the Kona, Hawaii coast (BROCK, 1985). These ponds were made using construction equipment (backhoe) to replace ponds filled in by resort development. They have typical anchialine biota and are visibly indistinguishable from natural ponds. A perturbation with much greater impact is the introduction of exotic predatory fishes into a pond. Fishes entering a pond cause *H. rubra* to quickly vacate the pool for the water table below to escape predation, but shrimp may return within hours if the predators are removed (BROCK, unpub. data). Exotic fish species that complete their life cycles in the pool cause changes in the benthic and planktonic communities and greatly alter the characteristics of the habitat (BAILEY-BROCK and BROCK, 1993).

The population density of *Halocaridina rubra* in Sailor's Hat pool is low. In most Hawaiian anchialine systems, *H. rubra* is numerically abundant with densities exceeding a thousand individuals per square meter of substratum (BROCK, 1985). It has been hypothesized that the high densities in pools are the result of the relatively high productivity of the system that provides ample food resources (BROCK, 1985). In contrast, food resources in the subterranean water table beneath anchialine pools must be much lower and the abundance of shrimp in this hypogeal part of their habitat is probably similarly low (BAILEY-BROCK and BROCK, 1993). The estimated abundance of *H. rubra* in the Sailor's Hat pool on the day of our visit was about one individual per cubic meter of water. Reasons for the low density of *H. rubra* are unknown but may be related to the large numbers of waterboatmen (*Trichocorixa reticulata*) that are present. Waterboatmen are omnivorous, feeding on filamentous algae, diatoms and small animals in the mud and ooze at the bottoms of ponds (ZIMMERMAN, 1948). Waterboatmen may prey on juvenile *H. rubra*, or there may be other unidentified predators in Sailor's Hat that keep their numbers down. An alternative may be that the ecological conditions in the pool or surrounding water table may not favor *H. rubra*.

There are several anchialine shrimp species that are very rare, being known from just a few sites on Maui and Hawaii Island (HOLTHUIS, 1973; MACIOLEK, 1983). In some cases, species such as *Vetericaris chaceorum* and *Halocaridina palahemo* are known from a single site (KENSLEY and WILLIAMS, 1986). The one environmental attribute common among the known sites having rare species is that all have salinities above 12 to 15‰ (BROCK, 1985). Thus the Sailor's Hat pool with salinity above 30‰ may be an appropriate habitat for these rare species, and if not already present and given sufficient time, may be colonized by them. Sailor's Hat pool has only been in existence for 32 years while the ponds on the other islands are in lava flows that range in age from a hundred to many thousands of years old (MACDONALD *et al.*, 1983).

The life history and behavior of *Halocaridina rubra* suggests that it is a fugitive species that cannot tolerate the high level of predation that is present in most Hawaiian aquatic systems. Thus *H. rubra* colonizes and is successful in marginal habitats that most predators are either unable to colonize because of physical barriers or the ecological conditions are inappropriate. Sailor's Hat pool probably represents such a marginal habitat and may be the only site on Kaho'olawe where this shrimp species has sufficient food resources and protection from predators to sustain a viable population level. Given the ecological characteristics of this pool and barring further disturbance from humans or predators, it may be colonized and serve as a habitat for other rare Hawaiian anchialine species in the future.

6. Acknowledgements

The authors wish to thank the military personnel stationed on Kaho'olawe for their help on our 14 May, 1993 visit. We also wish to thank Drs. F. COX and P. JOKIEL (Hawaii Institute of Marine Biology) for their support and logistical help in the field, and Dr. W. COOKE for identifying the ostracod and amphipods. The Waikoloa Anchialine Pond Program funded water quality analyses.

7. References

BAILEY-BROCK, J. H., 1987: Section 3 Part II. Annelida. pp. 213–454. – *In*: DEVANEY, D. M. and L. G. ELDREDGE (eds.). Reef and shore fauna of Hawaii. – B.P. Bishop Museum Special Publ. 64 (2 and 3). Honolulu.

BAILEY-BROCK, J. H. and R. E. BROCK, 1993: Aspects of the feeding, reproduction and sensory biology of the Hawaiian anchialine shrimp, *Halocaridina rubra* HOLTHUIS (Atyidae). – Pac. Sci. **47**: 338–355.

BARNARD, J. L., 1970: Sublittoral Gammaridea (Amphipoda) of the Hawaiian Islands. – Smithsonian Contr. Zool. **34**: 1–286.

BIENFANG, P., 1980: Water quality characteristics of Honokohau Harbor: a subtropical embayment affected by groundwater intrusion. – Pacif. Sci **34**: 279–291.

BROCK, J. H. and R. E. BROCK, 1974: The marine fauna of the coast of northern Kona, Hawaii - An inventory of fishes and invertebrates recorded during summer 1972. – University of Hawaii Sea Grant Advisory Report UNIHI-SEAGRANT-AR-74-02, Honolulu. 30 p.

BROCK, R. E., 1977: Occurrence and variety of fishes in mixohaline ponds of the Kona, Hawaii coast. – Copeia 1977 (1): 134–139.

BROCK, R. E., 1985: An assessment of the conditions and future of the anchialine pond resources of the Hawaiian Islands. Pp. C-1-C-12 – *In*: U.S. Army Corps of Engineers, Honolulu District. Final environmental impact statement U.S. Department of the Army permit application Waikoloa Beach Resort, Waikoloa, South Kohala District, Island of Hawai'i.

BROCK, R. E., J. E. NORRIS, D. A. ZIEMANN and M. T. LEE, 1987: Characteristics of water quality in anchialine ponds of the Kona, Hawaii, coast. – Pac. Sci. **41**: 200–208.

GRASSHOFF, K., 1983: Methods of seawater analysis. – Verlag Chemie, Weinheim. 419 p.

DOLLAR, S. J. and M. J. ATKINSON, 1992: Effects of nutrient subsidies from groundwater to nearshore marine ecosystems off the island of Hawaii. – Estuar. Coastal and Shelf Sci. **35**: 409–424.

HOLDEN, J. C., 1967: Late Cenozoic ostracodes from drowned terraces in Hawaii. – Pac. Sci. **21**: 1–50.

HOLTHUIS, L. B., 1973: Caridean shrimps found in land-locked saltwater pools at four Indo-West Pacific localities (Sinai Peninsula, Funafuti Atoll, Maui and Hawaii Islands), with a description of one new genus and four new species. – Zool. Verhand. (Leiden) **128**: 1–48.

KAY, E. A., 1979: Hawaiian marine shells. Reef and shore fauna of Hawaii. Section 4: Mollusca. – B.P. Bishop Museum Special Publ. **64**(4). Honolulu. xviii + 653 p.

KENSLEY, B. and D. WILLIAMS, 1986: New shrimps (Family Procarididae and Atyidae) from a submerged lava tube on Hawaii. – J. Crust. Biol. **6**: 417–437.

LAWS, E. A., 1980: Effects of waste-water discharges on phytoplankton communities. pp.13–40. – *In*: University of Hawaii, Sea Grant Cooperative Report UNIHI-SEAGRANT-CR-80-1.

MACDONALD, G. A., A. T. ABBOTT and F. L. PETERSON, 1983: Volcanoes in the sea: the geology of Hawaii. – Second edition. University of Hawaii Press, Honolulu. x + 517 pp.

MACIOLEK, J. A., 1982: Lakes and lake-like waters of the Hawaiian Archipelago. – B.P. Bishop Museum, Occ.Pap. **25**(1): 1–14.

MACIOLEK, J. A., 1983: Distribution and biology of Indo-Pacific insular hypogeal shrimps. – Bull. Mar. Sci. **33**: 606–618.

MACIOLEK, J. A., 1986: Environmental features and biota of anchialine pools on Cape Kinau, Maui, Hawaii. – Stygologia **2**(1/2): 119–129.

PAAVO, B. L., B. AKESSON and J. H. BAILEY-BROCK, (Submitted): Morphology and life history of *Ophryotrocha* sp.n. (Polychaeta, Dorvilleidae). – Proc. Biol. Soc. Wash.

POULTER, J., 1987: Section 2, Platyhelminthes. pp. 13–58. – *In*: DEVANEY, D. M. and L. G. ELDREDGE (eds.). Reef and shore fauna of Hawaii. – B.P. Bishop Museum Special Publ. 64 (2 and 3). Honolulu.

SMITH, S. V., W. J. KIMMERER, E. A. LAWS, R. E. BROCK and T. W. Walsh, 1982: Kaneohe Bay sewage diversion experiment: perspectives on ecosystem responses to nutritional perturbation. – Pac. Sci. **35**: 279–397.

Standard Methods, 1985: Standard methods for the examination of water and wastewater. – Sixteenth Edition. American Health Assoc., Washington, D.C. Port City Press, Baltimore, Md. 1268 p.

STEARNS, H. T., 1940: Geology and groundwater resources of the islands of Lanai and Kahoolawe, Hawaii. – U.S. Geol. Survey Bull. 6. Dept. Interior, Washington, D.C. 173 p.

STRAUGHAN, D., 1969: Intertidal zone formation in *Pomatoleios kraussii* (Annelida: Polychaeta). – Biol. Bull. **136**: 469–482.

STRICKLAND, J. D. H. and T. R. PARSONS, 1972: A practical handbook of seawater analysis. Second Edition. – Bull. Fish. Res. Bd. Canada, 167. 310 p.

TAKASAKI, K. J., 1991: Water resources of the island of Kahoolawe, Hawaii: preliminary findings. – Division of Water and Land Development, Department of Land and Natural Resources, State of Hawaii. Honolulu. 17 p.

The Nature Conservancy of Hawaii, 1992: Biological database and reconnaissance survey of Kaho'olawe Island including rare plants, animals and natural communities. – Prepared for Kaho'olawe Island Conveyance Commission, Consultant Report 6.

TOWNSLEY, S. J., L. TROTT and E. TROTT, 1962: A preliminary report of the rehabilitation of the littoral marine community on a new lava flow at Kapoho, Hawaii. – Ecology **43**: 728–730.

YUEN, G. A. L. and Associates, Inc. 1990. State water resources protection plan. Volume II. Appendix. – Prepared for State Water Resources Management Commission, Department of Land and Natural Resources, State of Hawaii. Honolulu. 202 p + appendices.

ZIMMERMAN, E. C., 1948: Insects of Hawaii, Volume 3: Heteroptera. – Univ. Hawaii Press, Honolulu. 255 p.

Manuscript received June 20th, 1997; revised October, 1997; accepted November 9th, 1997