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AN ANALYSIS OF ZOOPLANKTON IN FLOOD TIDE WATER FROM TWO ANCHIALINE POND CONDUITS ON SAN SALVADOR ISLAND, BAHAMAS

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ABSTRACT

Anchialine ponds are land-locked saline bodies of water with connections to the ocean, often in the form of conduits. This study examined the subterranean conduits as possible sources of origin for planktonic organisms found in two anchialine ponds in the northeast corner of San Salvador Island, Bahamas. Plankton samples were collected from flood tide water flowing through the conduit openings in the ponds, as well as from control sites in the ponds and in the ocean. Temperature, salinity and dissolved oxygen were measured at each of the sample sites. Samples were analyzed quantitatively for types of organisms present and the relative abundance of organisms was then used in coefficient of community analysis to compare sites. Conduit water was characterized as having relatively high temperature, marine salinity, and low dissolved oxygen. Organisms were found in conduit water during flood tides but had only minimal resemblance to ocean plankton samples. Conduit water organisms more closely resembled those found in the ponds, however relative abundance and, in turn, community composition differed between conduits and pond controls. It does not appear that oceanic plankton enter the ponds through the conduit system on a tidal basis. Rather, planktonic and benthic organisms may be transported from the ponds and into the subterranean conduit system during ebb tides, to be returned to the ponds on a later flood tide. This tidal transport, when coupled with stresses within the subterranean environment, could result in the observed flood tide conduit community dominated by benthic organisms.

INTRODUCTION

San Salvador is a tropical island located on the eastern edge of the Bahamian platform. The island is almost entirely composed of carbonate sediments and sedimentary rock. Over time, the mixing of saltwater and freshwater with calcium carbonate has resulted in the dissolution of the rock and the formation of a subsurface karst system of caves and conduits (Edwards, 1996; Godfrey et al., 1994). There are numerous land-locked saline ponds on the island where seawater from subsurface caverns has filled low-lying areas between lithified sand dunes. Most of the ponds still have permanent connections to the ocean via subsurface conduits or areas of high permeability (Godfrey et al., 1994). Ponds that possess this type of connection with the ocean are termed "anchialine" (Edwards, 1996; Por, 1985).

Por (1985) classified anchialine ponds into three categories according to salinity with each category possessing a corresponding set of biota. Hypersaline ponds are characterized by salinities greater than 70 ‰ and minimal species diversity. Metahaline ponds have salinities ranging between 38 ‰ and 70 ‰ and are inhabited by typical marine organisms. Polyhaline-Euhaline ponds have salinities at or below 38 ‰ and are characterized in the Caribbean by the presence of red shrimp, *Barbouria cubensis*. Benthic copepods have also been found in this type of anchialine pond .

Each of San Salvador's anchialine ponds has a unique water chemistry and biota (Godfrey et al., 1994). During the tidal cycle, water flows in and out of the conduits, raising and lowering the water level in the ponds and altering the water chemistry (Davis and Johnson, 1989). It is possible that marine plankton are carried through the conduit system and subsequently enter the ponds with flood tide water. Presumably, once organisms are in the ponds some are able to survive the variable environment while others are not. Those that live to reproduce may establish new populations or may be incorporated into existing ones. This hypothesis allows for each pond to develop over time a unique and potentially dynamic biota, based in part on its conduit connection to the ocean. Observations in Bermuda that among anchialine ponds with similar temperature, salinity, and dissolved oxygen, ponds with greater marine exchange show greater diversity of organisms support this hypothesis (Thomas et al., 1992).

This study explores whether planktonic animals are entering the inland ponds through the conduits. We hypothesize that this mechanism of transport occurs in anchialine ponds and consequently oceanic plankton can be found in water samples taken directly from the conduits. The evaluation of this hypothesis would allow for a more complete understanding of the biological diversity in anchialine pond ecosystems and the varying subterranean conduit systems associated with the ponds.

MATERIALS AND METHODS

This study focused on two ponds, Pain Pond and Crescent Pond, in the northeastern region of San Salvador Island during January 11-14, 1999. Crescent Pond (size 500 m x 75 m, maximum depth 4 m, average salinity 36-38 ‰) experiences a tidal range 30-40% of ocean tidal range and a tidal lag of 2.5 hours. The bottom of the pond is covered by a flocculent layer containing organic material and microorganisms. Two major conduits, large holes surrounded by substantial invertebrate communities with shell hash substrate in the direction of the flow, have been located near the West end of the pond (Godfrey et al., 1994). Pain Pond (size 110 m x 60 m, maximum depth 1.5 m, average salinity 36 ‰) experiences a tidal range of approximately 80% of the ocean tide and tidal lag is 1.5 hours. Pain Pond has a single conduit located at the eastern edge, below an outcrop of eroded limestone (Godfrey et al., 1994).

Plankton samples were taken directly from the conduit openings during pond flood tides. In Crescent Pond, two conduits (A and B) were sampled by attaching a plankton net (19.2 cm diameter; 72 μm mesh) perpendicular to a line with weighted ends placed inside the conduit openings for 30 minutes. The duration of sampling was arbitrarily selected to provide enough time for a representative sample of flood tide water. Potential contamination of the conduit samples was reduced by transporting the plankton net to the conduit openings in a Ziploc bag. In Pain Pond, the conduit was sampled by suspending the net in front of the conduit in an area of visible water flow for 30 minutes.

Control samples were taken from Crescent Pond by swimming the plankton net at approximately 1 m depth along a 50 m transect running East-West between Conduits A and B four times for a total distance of 200 m. Control samples were taken from Pain Pond by towing the net alongside a raft at approximately .25 m depth for 5 minutes. Control samples were taken from two ocean sites within Grahams Harbor. An offshore sample was taken near Gaulin Cay by swimming the net alongside a boat at approximately 1 m depth for 5 minutes. A near-shore sample was taken near the Bahamian Field Station dock by swimming the net at approximately 1 m depth along a 100 m transect twice for a total distance of 200 m.

Where possible, the volume of water sampled for plankton tows was determined using one of two methods. A flow meter (MJP Geopacks model MFP51) was attached across the opening of the plankton net and the velocity of water flowing into the net was calculated. The second method involved towing the net along a known distance and using the following equation:

Volume of water sampled (m^3) =
[area of net opening (m^2)] x
[horizontal distance towed (m)]

(Eaton et al., 1995). Samples involved towing the net in each direction along the transect to compensate for the influence of moving water on the total volume of water sampled.

Physical parameters of conduit, pond, and ocean water were determined from water samples collected at the site and time of plankton collection. Temperature and salinity were measured using a YSI model 30 salinity-conductivity-temperature meter. Dissolved Oxygen (DO) was measured using a YSI model 51-b DO meter.

Samples were initially fixed in the Bahamas to preserve them for later analysis. The flock was allowed to settle for about 1 hour, and the aqueous layer containing organisms was then pipetted into either 100% EtOH or 50% EtOH (freshwater mix) and later transferred into 80% EtOH. It had been previously determined for all sample sites that after 1 hour of settling the flock was devoid of organisms. Upon returning to Dickinson College, all samples underwent a rehydration/fixation procedure in order to remove any crystalline precipitate and to permanently fix the samples. The rehydration/fixation procedure involved transferring the samples through the following sequence of solutions: 80% EtOH to 30% EtOH to deionized water to 10% buffered formalin. Intact sample contents, ignoring shell fragments, were identified and enumerated using compound and dissecting microscopes (analysis by J.H.C.; Coates and Barnes, 1998; Steinberg and Nelson, 1998; McEdward, 1995; Reutzler, 1992; Sterrer, 1986).

Plankton data from each sampling period were combined for each site. Relative abundance of organisms was calculated for each site. To determine similarities in community composition among sample sites, statistical analysis was performed with the coefficient of community index using relative abundance data from two selected sites after Cox (1995):

$C_{\%}$ =
Σ (lower of the two % values for shared species)

Coefficient of community returns a percent similarity between 0 and 100%, with percentages above 50% suggesting significant similarity in community composition between the two sites selected (Cox, 1995). A series of comparisons were made to evaluate similarities in community composition among sites sampled.

RESULTS

Figure 1 lists groups of organisms collected from the control, conduit, and ocean sites. The ocean control had the greatest diversity of organisms, most of which were not found at other sites (Fig. 1A). In the ponds, conduit and control samples contained similar groups of organisms, however the number of individuals varied (Fig. 1B). In Crescent Pond, the control site had a greater number of individuals than either conduits A or B, whereas the conduits had a greater diversity of organisms including ostracods, hydromedusae, and buds from the sponge *Cinachyrella* sp. In Pain Pond, the control site had both a greater number of individuals and a greater diversity of organisms, e.g. ostracods and hydromedusae, than the conduit site. The Pain Pond control site had a greater diversity of organisms than Crescent Pond control site but fewer individuals. The Pain Pond conduit site had both a lower diversity of organisms and a lower number of individuals than either of the Crescent Pond conduit sites.

Water flow from all conduit sites was sufficient to fully extend the net and to move particles suspended in the water column away from the conduit opening. It was not possible to quantify the total volume of water sampled at Crescent Pond conduit B or at the Pain Pond conduit due to equipment failure. Of the quantified samples, Crescent Pond conduit A .

A.

- Barnacle nauplii
- Barnacle cyprid
- Calanoid copepod (Acartia sp.)
- Copepod nauplii
- Decapod zoea
- Crustacean metanauplii
- Ostracod
- Bryozoan coronate larvae
- Foraminifera
- Gastropod veliger larvae
- Polychaete metatrochophore larvae
- Polychaete nectochaeta larvae
- Polychaete chaetosphaera larvae
- Mite
- trochophore larvae
- planula larvae
- eggs (unidentified)

B.

		Sites				
		Crescent Control	Crescent Conduit A	Crescent Conduit B	Pain Control	Pain Conduit
Taxa	Calanoid copepod	321	2	1	0	0
	Harpacticoid copepod	10	171	20	80	12
	Cyclopoid copepod	0	154	34	531	7
	copepod nauplius	5838	3	4	301	4
	trocophore larvae	1	0	1	2	1
	Arenicola sp. trocophore	0	0	0	3	1
	Ostracod	0	2	1	1	0
	Cinachyrella sp. bud	0	6	5	0	0
	Hydromedusae	0	1	1	1	0
Totals	Number of Groups	4	7	8	7	5
	Number of Individuals	6170	339	67	919	25
	Volume of Water Sampled [m^3]	11.6	27.0	no data	5.0	no data
	Number of Individuals/m^3	533	13	no data	182	no data

Figure 1. Taxa lists for sample sites. A) Taxa found in the Ocean samples. Data are pooled from one offshore tow (11 JAN99) and one near-shore (14JAN99) in Graham's Harbor. The total volume of water sampled was 9.3m^3. These samples could not be quantified due to a crystalline precipitate that formed during fixation with ethanol. B) Taxa found in the Crescent and Pain Pond samples. Numbers of individuals pooled from three sampling periods at each site are reported (except Crescent Pond control, n=2). Volume of water sampled at each site was calculated using a flowmeter or a known tow distance and represents the total volume sampled. The number of individual/m3 of water sampled is presented where possible.

had the most water sampled, while Pain Pond control had the least (Fig. 1B).

In general, conduit water had a higher temperature than either control or ocean water. There was greater variation between temperature measurements taken on two consecutive days for the Pain Pond and Crescent Pond control sites than for the Pain Pond and Crescent Pond conduit sites (Fig. 2). Salinity was higher for all conduit sites than for their respective controls. The ocean control had the highest salinity values. The Pain Pond control showed more variability between salinity measurements than the other sites (Fig. 2). Dissolved oxygen (DO) was higher in control sites than in their respective conduit sites. DO in both Pain Pond and Crescent Pond controls were variable, while all conduit sites showed relatively similar DO values. All conduit DO values were lower than the ocean control (Fig. 2).

Despite similarities in the types of organisms found at the pond sites, the relative abundance of these organisms varied. The Crescent Pond control site was dominated by copepod nauplii, whereas both Crescent Pond conduit sites were dominated by adult cyclopoid and harpacticoid copepods (Fig. 3). In Crescent Pond conduit A, harpacticoid copepods were more abundant than cyclopoid copepods, while in Crescent Pond conduit B, cyclopoid copepods were more abundant than harpacticoid copepods. In both Crescent Pond conduit sites, buds from the sponge *Cinachyrella* sp. were moderately abundant (1.8% in conduit A, 7.5% in conduit B). The Pain Pond control site was dominated by cyclopoid copepods and copepod nauplii while the Pain Pond conduit site, like Crescent Pond conduits A and B, was dominated by harpacticoid and cyclopoid copepods (Fig. 3).

Coefficient of community analysis showed the Crescent Pond control to be significantly different in community composition than both Crescent Pond conduits A and B. The relationship between the Pain Pond control and conduit suggested a significant similarity in community between these sites. The Pain Pond control was also significantly similar to both Crescent Pond conduits A and B. The conduits sampled in both Crescent and Pain Ponds had significantly similar community composition (Fig. 4).

DISCUSSION

It was hypothesized that organisms present in the ponds were entering through the conduits on flood tides. Plankton samples from the conduits showed that some organisms do enter the ponds during flood tides. Our data suggest, however, that the organisms entering the ponds are not from the ocean. There were 17 groups of organisms present in the ocean control samples, whereas the numbers for groups of organisms found at each of the conduit sites ranged between 5 and 8. There was only a minimal overlap of organism groups between the ocean and conduit samples.

The data suggest that there is a relationship between types of organisms present in each pond and those found entering through their conduits on flood tides. In both ponds, similarities existed between control and conduit sites in terms of organisms present. For both Crescent Pond and Pain Pond, all of the groups of organisms found at the control sites were also found at the conduit sites. In both ponds, however, the numbers of individuals varied widely between control and conduit sites. There were 5838 copepod nauplii present in the Crescent Pond control sample, whereas there were 3 and 4 individuals found in conduits A and B respectively. Part of this difference could be due to the presence of *Arenicola* sp. mucus present in the control sample, which may trap copepod nauplii *in situ*, thereby concentrating nauplii in the sample. However, the Pain Pond control sample, which contained minimal *Arenicola* sp. mucus, had 301 copepod nauplii, while only 4 nauplii were found in the conduit sample. These differences in numbers suggest that early stage copepods are not entering the ponds through the conduits. Rather, the bulk of copepod reproduction occurs within the pond.

Community analysis revealed a similarity in community composition among all conduit sites and the Pain Pond control site.

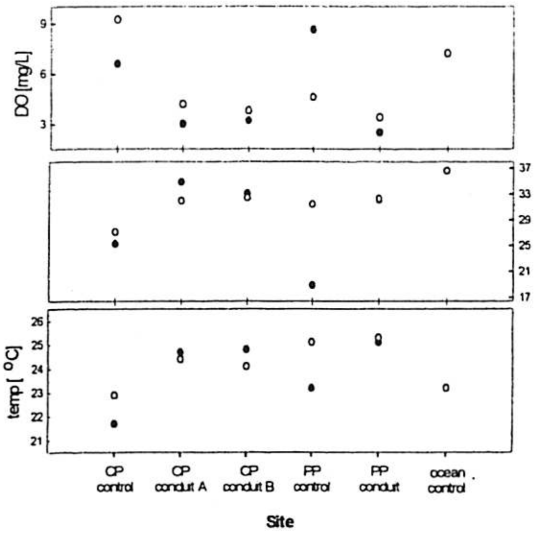
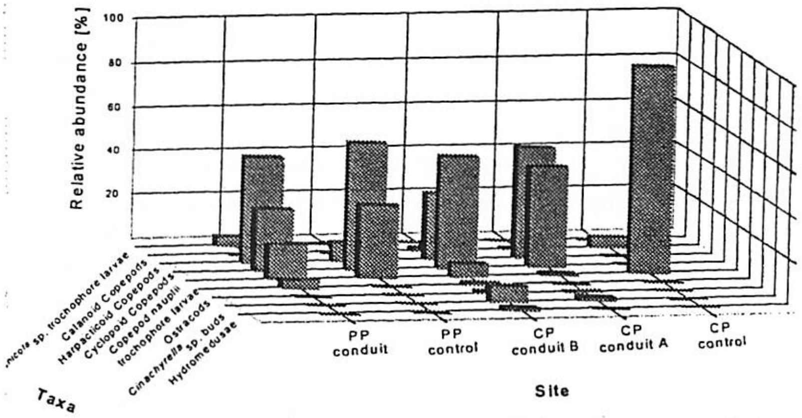


Figure 2. Temperature, salinity, and dissolved oxygen (DO) measured in conduit and control water samples. Solid circles represent 13JAN99 samples and open circles represent 14JAN99 samples. CP refers to Crescent Pond and PP refers to Pain Pond. There is considerable variability in both the Crescent and Pain Pond control measurements for all parameters, whereas the conduit measurements are more consistent.

Figure 3. Relative abundance of organisms found in samples from Crescent and Pain Ponds. Relative abundance was calculated using number of individuals in pooled samples. CP refers to Crescent Pond and PP refers to Pain Pond.



	Crescent Pond control	Crescent Pond conduit A	Crescent Pond conduit B	Pain Pond control
Crescent Pond conduit A	1.7%			
Crescent Pond conduit B	7.7%	79.5% *		
Pain Pond control	33.0%	55.2% *	65.8% *	
Pain Pond conduit	16.2%	76.9% *	65.4% *	53.2% *

Figure 4. Matrix of percent similarity between sites returned by coefficient of community analysis. A series of comparisons between two sites were made after Cox (1995). Coefficient of community analysis returns a percent similarity between 0% and 100%, with percentages above 50% suggesting significant similarity in community composition between the sites tested. Significantly similar pairs of sites are marked with an asterisk.

This suggests that common conditions may exist within the conduit systems for both ponds. Pain Pond has a large tidal range (80% of ocean tide) and relatively small size, resulting in a large exchange of water between pond and conduit during each tidal cycle. This may serve to maintain a homogeneous community of organisms between the conduit and pond. Crescent Pond appeared to have a unique community composition with respect to all conduit sites and the Pain Pond control. This may be due to the physical characteristics of Crescent Pond, i.e. large size and low tidal range, compared to those of Pain Pond.

A severe limitation to using coefficient of community analysis with taxonomic data above the species level, as was done in this study due to uncertainties in zooplankton species identification, is that dissimilar communities may appear to be related. This could occur for example, if two communities containing multiple species of harpacticoid copepods were analyzed at the level of Order, i.e. Order Harpacticoida. In this case, a similarity in community composition may be incorrectly assigned. Regarding our analysis, the groups that weighed most heavily were copepod nauplii, and two families of adult copepods (harpacticoid and cyclopoid). While it was not possible to positively identify these organisms to species, it appeared that only a limited number of species (1 harpacticoid, 2 cyclopoid) were present in the samples collected. Therefore, the large groups of organisms used in the analysis actually represent much lower taxonomic levels.

The consideration of reported habitat preferences for abundant organisms at the sites suggests an interesting trend. A considerable number of the organisms in the conduit samples were benthic (e.g. harpacticoid copepods; see Sterrer, 1986) while fewer benthic organisms were found in the control samples. If ebb tide water flow into the conduits is comparable to the observed flow out of the conduits during flood tides, it is possible that ebb tide pond water transports both planktonic and benthic pond fauna into the conduit system. Organisms that are pulled into the conduits must then cope with the biological and physical conditions within the conduit for the duration of the ebb tide. The lack of oceanic organisms in the conduit water samples suggests that minimal exchange of organisms occurs between the ocean and the ponds over a given tidal cycle. Therefore, organisms removed from the pond with an ebb tide may be returned to the pond with the following flood tide.

The data suggest that the subterranean environment is warm (24.1-25.4 °C), relatively marine in salinity (32.0-34.9 ‰) and is low in dissolved oxygen (2.5-4.2 mg/L). Organisms trapped in this environment must be tolerant of these specific conditions if they are to survive. Organisms such as harpacticoid copepods inhabit benthic sediments, which may have relatively saline interstitial water due to the tendency for density to increase with salinity. The temperature of interstitial water may be high and the dissolved oxygen low due to metabolic activity in the sediments (Edwards, 1996). It is likely that benthic organisms, which are accustomed to these environmental stresses, would be better suited to successfully cope with the conduit environment than planktonic organisms such as calanoid copepods and copepod nauplii. Therefore, the majority of the living organisms that are returned to the pond during flood tide from the conduit alive would be benthic, as was observed.

Certain features of the conduit systems feeding the ponds may be revealed from the data. For example, buds of the sponge *Cinachyrella* sp. were collected only from the Crescent Pond conduits. This requires that somewhere along the Crescent Pond conduit system there is space for these particular sponges to grow and reproduce. It also implies that water flow through this conduit system is powerful enough to move the buds from their parent sponges to the pond. Despite similarities in physical parameters between the Crescent Pond and Pain Pond conduits, the absence of sponge buds in the Pain Pond plankton samples suggests a slightly different conduit structure that prevents buds from reaching the ponds.

The temporal scale of this study may not have been great enough to capture an accurate representation of the flood tide plankton community structure in the conduits. Future studies that examine both water leaving the ponds through the conduits on ebb tides as well as water entering ponds on flood tides would help to evaluate the possibility that even though a variety of organisms enter conduits during ebb tides, benthic organisms tend to dominate flood tide conduit communities due to their ability to survive the subterranean environment. An intriguing hypothesis that could explain transport of organisms and diversity among ponds is that plankton are transferred from pond to pond and ocean to pond via water droplets on feathers or in mud on the feet of wading birds (Edwards, pers. comm. 1999). In light of this study, hypotheses that explore intermediates such as birds in organismal transport into anchialine ponds seem worthy of consideration.

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