PROCEEDINGS

OF THE FOURTH SYMPOSIUM

ON THE GEOLOGY OF THE BAHAMAS

Editor

John E. Mylroie

Production Editor

Donald T. Gerace

Sponsored by the Bahamian Field Station

June 17 - 22, 1988

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ISBN 0-935909-31-1

Printed by Don Heuer in the U.S.A.

NOTES ON THE TAPHONOMY OF COMMON SHALLOW-WATER BENTHIC FORAMINIFERA FROM SAN SALVADOR, BAHAMAS

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ABSTRACT

Four different processes were investigated with regard to their effects on the preservation potential of benthic foraminifera common in the reefs and lagoons around San Salvador. Twenty-two different species, comprising approximately eight percent of the total specimens studied, showed signs of selective predation as evidenced by large borings that were perpendicular to test surfaces and that had beveled edges. While there was selective predation of foraminifera, this predation was not species selective. The most abundant species were the most heavily preyed upon in any given area. It was also discovered that a foraminiferan, *Rosalina* sp., used the tests of larger, commonly dead, foraminifera as a substrate.

Microborings are found in virtually any exposed carbonate substrate in the tropical Bahamian waters. Though most studies of microborings have found no differences between substrates, this study demonstrates that there are differences among the host taxa with respect to the extent of infestation and the location of infestation within the test. The primary differences are at the suborder level; members of the Suborder Rotaliina are not as bored as are specimens of the Suborder Miliolina taken from the same sample. Although the causes of these differences are not clear, it is suspected that differences in test wall composition may be a factor.

Abrasion and dissolution leave recognizable signatures on the test surface. Abrasion can break off large areas of the test, but it works relatively slowly and more frequently polishes the surface without causing extensive damage. The effects of dissolution are harder to detect at low magnifications than are those of abrasion. However, even small amounts of dissolution can affect the integrity of the test by removing surface layers and by weakening the test structure. Dissolution, including that caused by microboring organisms, is the primary process affecting preservation in this reefal environment.

INTRODUCTION

The taphonomy of shallow-water benthic foraminifera has received relatively little attention in contrast to deeper water species (studies of dissolution) and in contrast to other shallow-water organisms. Taphonomic processes affecting shallow benthic foraminifera have been suggested by comparing living and dead assemblages (Murray, 1973; Douglas et al., 1980; and Smith, 1987), but relatively few studies have isolated taphonomic processes and examined them in detail. Notable exceptions are: Murray and Wright, 1970 (dissolution), Butcher and Steinker, 1979 (fungal and bacterial degradation in *Archaias angulatus*), Collen and Burgess, 1979 (the diagenetic processes of dissolution, overgrowth, and recrystallization in *Notorotalia*), and Cottey and Hallock, 1988 (abrasion, dissolution and breakage for *Archaias angulatus*).

Predation also plays a significant role in the preservation of foraminifera. Indiscriminate deposit feeders may ingest living and dead foraminifera as part of the sediment, or smaller predators may selectively prey on foraminifera, leaving behind bored and otherwize damaged tests. Tests of foraminifera have been recovered from the digestive tracts of gastropods (Walker, 1971; Buzas and Carle, 1979), polychaetes (Lipps and Ronan, 1974; Buzas and Carle, 1979), decapods (Buzas and Carle, 1979), and fish (Daniels and Lipps, 1978; Buzas and Carle, 1979). Bored tests of foraminifera have been described by Sliter (1971), Hickman and Lipps (1983), and Arnold et al. (1985). These borings were inferred to have been the result of gastropod and nematode predation.

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Our purpose is to review the senior author's research on the taphonomy of the common foraminifera found at San Salvador. An important theme of the several investigations described herein is the comparison of effects among a number of taxa to ascertain potential preservational biases. This research was done as part of the requirements for the Master of Science degree at Auburn University, and with substantial assistance from the personnel of the Bahamian Field Station on San Salvador. A complete history of previous research is beyond the scope of this summary, but can be found in the references cited and in Peebles, 1988; Peebles and Lewis, 1988; and Peebles and Lewis, in press.

METHODOLOGY

All samples used in this study were collected during the summer of 1986 from five areas around the island of San Salvador. The samples were collected directly by using SCUBA equipment and small hand-held coring tubes. Environments sampled include: (1) a shallow *Thallassia* (turtle grass) meadow near Cut Cay (water depth 1m), (2) a protected patch reef in French Bay dominated by *Montastrea annularis* and *Acropora palmata* (water depth 6.5m), (3) a shallow back-reef near Gaulin's Reef (water depth 3m), (4) an unprotected shallow-water patch reef dominated by *Montastrea annularis* (Snapshot Reef, water depth 4m), and (5) a similar reef dominated by *Acropora cervicornis* and *M. annularis* (Telephone Pole Reef, water depth 5m).

The samples were stained with rose bengal at the Bahamian Field Station in order to identify specimens living at the time of collection (Walton, 1952). As noted by other workers (Benda and Puri, 1962; Atkinson, 1971; Le Calvez and Cesana, 1972; Martin and Steinker, 1973) this technique often fails to stain living specimens and sometimes stains dead tests. Therefore, no attempts were made to count living specimens. A large proportion of one species, *Discorbis rosea*, appeared to be vividly stained in addition to its characteristic red coloration. The majority of these were apparently living as shown by the occurrence of protoplasm in many randomly sampled tests. No other species studied was as consistently stained nor had as many specimens with visible protoplasm. Specimens showing abrasion, breakage, and dissolution textures were assumed to be dead at the time of collection.

Representative specimens from each of the studies were coated with a gold-palladium alloy using the Auto Conductovac IV sputter coater, examined using an ISI40 scanning electron microscope, and photographed with Kodak TMAX 400 ASA film. Illustrations will be found in the references cited above.

PREDATION

Approximately three hundred foraminifera were counted in two samples from each locality, and the bored foraminifera were picked and mounted for further study. Specimen totals and the number of Milolina, Rotaliina, and Textulariina were noted from each sample site. Measurements were taken of the bore-hole sizes using a stage micrometer. The borings were classified into large and small predationary borings. Specimens were counted if they contained one or more borings. Total specimens bored were recorded, along with the number of Miliolina, Rotaliina, and Textulariina bored by predators, and the number of borings made by *Rosalina* sp.. The total number of species at each site, the number of the two most common species, and the number of species preyed upon at each site were also recorded. Two distinct size ranges of borings are found in this study. Small borings range in size from 10μm to 30μm and have a mean diameter of 20μm. Large borings range in size from 40μm to 100μm and have a mean diameter of 59μm. Borings in both size ranges are circular to oval in shape, commonly have beveled edges, and are perpendicular or nearly perpendicular to the test wall. The specimens with this type of boring comprise 8.3% of the 2974 specimens. Several of the borings in the small size range resembled those classified as nematode borings (Sliter, 1971), but we consider it unlikely that nematodes produced them. We tentatively identify both the large and the small borings as naticid gastropod borings.

Ninety percent of the bored tests had the small-size borings, suggesting that juvenile gastropods are the primary hole-producing predator on the benthic foraminifera of San Salvador. Our data indicates that predation is opportunistic rather than selective; the predators feed on the most abundant foraminiferal taxa, whatever that happens to be.

A small foraminiferan, *Rosalina* sp., was found in its boring in the test of 43 specimens. These borings differ from those described above by being strongly beveled on one side, failing to penetrate through the test wall, and containing a specimen of *Rosalina* sp. The tests bored by *Rosalina* appeared to have been dead at the time of collection, thus ruling out predation. Specimens of *Rosalina* sp. were also noted on other highly weathered skeletal types and on unidentifiable sediment grains. Of the 43 tests bearing *Rosalina*, 32 were *A. angulatus*, with the remaining 11 comprising assorted miliolines and textulariines. This also suggests a nonselective pattern.

MICROBORINGS

Only one sample was used in this investigation in order to compare the effects of microboring in different genera. The sample used in this study was taken at a depth of three meters from a patch reef dominated by *Montastrea annularis*, located in French Bay, off the southern tip of the island.

Six genera were selected for this study (*Discorbis*, *Amphistegina*, *Quinqueloculina*, *Peneroplis*, *Cyclorbiculina*, and *Archaias*) because of their high abundance in all samples. Representative specimens were embedded in Spurr's low viscosity embedding medium in the manner described by Golubic et al., 1970, and the calcite tests were dissolved in acid. Resin casts of the micoborings were then examined using SEM (Peebles and Lewis, 1988).

Microboring intensity was characterized by the use of four categories: not infested, sparsely infested, moderately infested, and heavily infested. The areas of the tests infested with microborers were designated by three categories: proloculus (if the majority of casts occurred either directly on the proloculus or in the group of chambers immediately adjacent to the proloculus), outer margin (if the majority of casts were noted on the outer wall or near the group of chambers directly adjacent to the outer wall and far away from the proloculus), and scattered (if the casts were found in all areas of the test except the proloculus).

The rotaliines *Discorbis* and *Amphistegina* are the only taxa that consistently showed specimens with no visible endoliths. In the bored specimens, the degree of infestation was slight, and was most often noted in the outer margin.

Among the Miliolina, *Quinqueloculina* and *Peneroplis* commonly contained some microboring casts, although the degree of infestation is often slight. *Peneroplis* is the only genus that consistently contained casts on or near the proloculus. In specimens which were heavily bored, the majority of casts were scattered throughout the test, with only a few cases of heavy infestation along the outer margin.

In *Archaias* and *Cyclorbiculina* the majority of specimens were moderately to heavily infested. Microboring casts were most often scattered indiscriminately throughout the test in *Cyclorbiculina*. In *Archaias* many of the casts were located along the outer margin. Though a few casts were noted in the proloculus area in both taxa, they never constituted the majority of casts found in any specimen.

SURFACE TEXTURES

Ten species were chosen for this study: the miliolines *Archaias angulatus*, *Borelis pulchra*, *Cyclorbiculina compressa*(?), *Peneroplis proteus*, *Pyrgo comata*, and *Quinqueloculina tricarinata*; the rotaliines *Amphistegina* sp., and *Discorbis rosea*; and the textulariines *Clavulina tricarinata*, and *Valvulina* sp. (classification of Loeblich and Tappan, 1964). For each species eighty specimens were selected which best exhibited the unaltered characteristics of each taxon, and one test per species was chosen as a control. Ten specimens from each taxon were used for the dissolution experiment and 60 per taxon were used in the abrasion experiment. The remaining 100 specimens were used in preliminary experiments.

The six hundred specimens used for the abrasion experiment were weighed to the nearest one hundredth of a gram and were then placed in a one dram bottle 12mm in diameter containing buffered seawater with a pH of 7.45. This bottle was then placed into a standard tumbling barrel. The tumbling barrel rotated at 40 revolutions per minute, while the smaller bottle inside rotated approximately 280 revolutions per minute. In order to approximate the relative distance the specimens moved, it is estimated they tumbled from 1-3mm with every revolution. Weights were recorded and specimens were taken periodically for 376 hours. One specimen of each taxon was extracted at selected intervals for examination with a scanning electron microscope. After the 376th hour the tumbling barrel was allowed to run continuously for 1624 hours bringing the total time to 2000 hours, or the equivalent of 34-100km of movement. Susceptibility to abrasion was estimated by the number of specimens remaining after 2000 hours of tumbling. If all specimens of a species were completely destroyed, the degree of damage at 376 hours was used for ranking. Types of damage taken into account were the amounts of outer wall remaining, the amount of breakage, and the percent weight lost by each taxon.

Dissolution was studied in two simple experiments designed to indicate changes in the various taxa over time. The first experiment began by placing ten specimens of each species into a petri dish containing formic acid with a pH of 3.90. One specimen of each taxon was then removed for examination at logarithmic intervals starting at twenty minutes and ending at 10,240 minutes (170.5 hours). In the second experiment, the effects of extreme dissolution were examined by rapidly etching tests in hydrochloric acid with a pH of approximately 1.5 for one minute. Susceptibility to dissolution was estimated from the degree of damage visible after 10,240 minutes in the formic acid solution. Types of damage noted were the approximate amounts of material removed in each species and the approximate time for complete dissolution in the hydrochloric acid.

Foraminifera extracted from two Pleistocene Cockburn Town Reef rock samples were examined for evidence of abrasion and dissolution textures. The 1-kilogram limestone samples were disaggregated by boiling them in a solution of approximately 2.0 gm/l sodium hexametaphosphate (calgon) and water for approximately five minutes. The samples were then crushed by hand and again boiled in the calgon and water solution for approximately five minutes. The resulting sediment was placed in an ultrasonic bath for eight hours, and was washed in tap water to remove the clay-sized particles. A total of 38 specimens were found in the two samples. These consisted of 36 specimens of *Archaias* sp., one quinqueloculine test, and one unidentified milioline.

Both of the rotaliine genera used in the laboratory experiments are radial-walled (after Loeblich and Tappan, 1964) with the surface appearing smooth at low SEM magnifications, while at higher magnifications the borders of the oriented crystallites can faintly be seen. The majority of the miliolines studied exhibit three layers. An outer, unordered layer of very fine particles is evident on most tests and has been described previously for other miliolines (e.g., Walker, 1971). Underneath this layer lies a thin veneer of oriented calcite laths that vary slightly in shape and size with different species. The lowermost layer is composed of unoriented crystallites in an organic matrix.

After 64 hours of tumbling (1-3km), 48% of the specimens exhibited a slight degree of damage. Most of this is evident in small breaks and polishing around the perimeter or aperture of all of the specimens. Several specimens of *Pyrgo*, *Clavulina*, and *Valvulina* are altered by the appearance of small holes or are missing large portions of a chamber. However, other than the missing holes or chambers, the degree of damage is very slight and would be difficult to recognize without undamaged control specimens for comparison.

Damage is much easier to document after 376 hours (6-18km), with 72% of the tests exhibiting damage visible at a magnification of 50X. Portions of the tests that are elevated above other test surfaces show the most damage. Evidence of this is illustrated by missing chamberlet walls in the soritids, flattened ornamentation in *Quinqueloculina*, broken apertures and faint scratches in the rotaliines, and a loss of detail in the sutures of the textulariines. The thin veneer of agglutinated(?) particles is removed from most of the miliolines, and, especially in *Borelis*, the thin veneer of oriented laths is beginning to be removed. All of the specimens exhibit some degree of polishing, but the rotaliines are the only suborder that are visibly scratched.

After 2000 hours (34-100km), all of the small specimens, including all of the *Borelis* and *Discorbis* specimens, were destroyed. The percentage of other species that were destroyed varies; 88% of the *Pyrgo*, 81% of the *Amphistegina*, 71% of both *Peneroplis* and *Clavulina*, 68% of the *Quinqueloculina*, 59% of the *Valvulina*, 34% of the *Archaias*, and 4% of the *Cyclorbiculina* specimens. All of the remaining specimens were damaged in the same ways as discussed for 376 hours, except to a greater degree. The veneer of oriented crystallites was not completely removed from all of the miliolines. The rotaliines exhibit more scratches and pits than do the miliolines and textulariines. A textulariine surface texture discernible at high magnifications includes ridges of cement surrounding areas from which the agglutinated particles have been removed.

Dissolution textures are coarser than abrasion textures. After 20 minutes in the formic acid, all of the fine agglutinated particles on the miliolines were removed, and, after 80 minutes, the thin veneer of oriented calcite laths was completely removed. Once this outer layer was removed, the surface texture of the miliolines consisted of only the unoriented calcite crystallites, which appeared the same regardless of the degree of dissolution, or the pH of the acid used, until the tests were completely dissolved. At lower magnifications (less than 500X) the crystallites could not be seen, and the tests were characterized by a very coarse, uneven appearance.

The rotaliines were less susceptible to dissolution than were the miliolines or the textulariines, as has been reported by other workers (Murray and Wright, 1970; Walker, 1971). Dissolution textures in the rotaliines were not readily apparent, using magnifications of less than 100X.

The two Pleistocene samples investigated were difficult to interpret due to the high degree of diagenetic cementation and crystal overgrowth common in carbonate environments (Collen and Burgess, 1979). All of the specimens were coated with small, acicular aragonite(?) crystals. Approximately half of the specimens had visible cement or particles cemented to a portion of the test. However, a majority (30 out of the 38 specimens) exhibited probable dissolution textures, a rough surface from which much of the outer wall had been removed. The remaining 8 specimens had probable abrasion textures as indicated by the removal of surface detail.

DISCUSSION

Taphonomy is an important subdiscipline of paleontology that has not yet fully been exploited in the study of foraminifera. Predation, as evidenced by borings, is a topic that illustrates the intimate relationship between taphonomy and paleoecology. It is an ecologic study in that it is a record of the interactions between groups of organisms during life. It is a taphonomic study by virtue of its preservation in skeletal parts after predation causes the death of the foraminiferan, and because the test's preservation potential could be adversely affected by the borings. The predators are inferred to be juvenile naticid gastropods feeding in an opportunistic pattern. Recognition of such predation patterns in the fossil record could possibly aid in delineating generalized paleoenvironments. For example, opportunistic patterns could indicate an abundant and diverse prey in an unrestricted environment, while species-selective predation could imply fewer and less diverse prey in a restricted environment. Predational borings have been implicated in some environments as the cause for preferential dissolution of heavily preyed species by opening more surface area to dissolution (Douglas, 1973). Although this has been suggested, and probably occurs, borings have also commonly been found preserved in fossils (e.g., Sliter, 1975).

In addition to predation, it was found that a small foraminiferan, *Rosalina* sp., commonly bores into the tests of larger, usually dead foraminifera. The larger foraminifera tests apparently were used as a substrate. Only miliolid and textulariid species were bored in every location where *Rosalina* sp. occurred, with no observed borings on rotaliid species. In the second investigation of this thesis it was found that miliolids were infested by microboring organisms to a greater degree than were rotaliids. Thus, there is also the possibility that the larger foraminiferan tests provided a food source for *Rosalina* sp..

Unlike previous studies of microborers, the second study indicates some consistent differences in infestation among the host organisms. These differences are evident at the suborder level, particularly between the Rotaliina and the Miliolina in the degree and in the test location of infestation. Less obviously, the type of microboring casts seem to represent different assemblages in the two suborders studied. Fundamental differences in test composition and microstructure could be the major factor in these microboring distributions. By simply exposing more surface area to dissolution they could negatively bias the preservation potential of the affected taxa. There is also the possibility that in certain situations they could positively bias the preservation potential by the formation of a micritic crust.

Abrasion and dissolution textures, treated in the third study, may be used as environmental indicators because each leaves a recognizable signature on the surface of the test. One slightly surprising conclusion of this study is that dissolution appears to be the predominant destructive force acting on the tests found at the island. This supports a recent geochemical investigation that indicated a greater degree of dissolution in shallow carbonate environments and on the continental shelves than in the deep sea (Walters and Burton, 1987). This is caused primarily by the high degree of infaunal activity and by the large amounts of unstable carbonates (aragonite and high-magnesium calcite) in shallow environments. Dissolution is a pervasive process that happens very quickly over geologic time. After only moderate amounts of dissolution, many surface features are destroyed, and further dissolution may be difficult to recognize. However, abrasion does not destroy surface features as rapidly or as completely, and may prove to be more useful in determining relative transport distance or sediment residence time.

Taphonomy has grown from being simply a description of the preservational processes and how they bias the fossil record into a subdiscipline in which the goal is the retrieval of all possible information. Each of the processes described in this summary plays a role in test destruction, but at the same time adds ecologic and environmental information that would not be apparent in a study of the foraminifera *per se*. Predation, because it focuses on the interactions between species, adds more ecologic information to an environmental investigation than would a simple cataloging of species distributions. Microboring studies hold great promise for environmental interpretations. With further research from San Salvador and a variety of other locations it may be possible to classify microborings into easily recognizable sub-environments. A combination of foraminifera and the microborings preserved in their tests may permit finer resolution of paleoenvironments.

With the identifications of abrasion and dissolution textures it is possible to make estimates of the amount of transportation and/or sediment residence time. After further study, abrasion and dissolution textures could also aid in delineating environments, especially if abrasion and dissolution indices are made from many areas.

ACKNOWLEDGEMENTS

We thank Donald T. Gerace, Executive Director of the Bahamian Field Station, for his assistance with the logistics of the field work involved in this study, and acknowledge the following for financial support of field operations: (MWP) The College Center of the Finger Lakes, The Alabama Academy of Science, and The Geological Society of America; (RDL) the Auburn University Grant-in-Aid Program. We also thank Roland R. Dute and Ann E. Rushing, Department of Botany-Microbiology, Auburn University, for their assistance with the SEM photography; Charles E. Savrda, Department of Geology, Auburn University, for his many valuable discussions concerning methodology and results; and Ira F. Holston, Department of Geology, Auburn University, for his valuable input concerning carbonate dissolution; and Robert A. Gastaldo, Department of Geology, Auburn University, for his critical reading of the manuscript.

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