Geological History of Gray's Reef

National Marine Sanctuary

A

Final Report

to

U. S. Department of Commerce, National Oceanic and Atmospheric Administration, Marine and Estuarine Management Division under Cooperative Agreement NA-87-AA-H-CZ033.

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INTRODUCTION

The presence of reefs, or live bottoms, on the continental shelf of the southeastern United States has been known to commercial and sports fishermen for several decades (Strusaker, 1969; Barans and Burrell, 1976; Harris, 1978). However, little information has been available concerning their geological nature and distribution.

Increasing usage of the continental shelf waters by all interests led to the realization that at least one representative segment of the unique features should be afforded protection. Therefore, in 1981, an area of live bottom located 33 km east of Sapelo Island, Georgia was designated a National Marine Sanctuary. This area, known as Gray's Reef, is characterized by outcrops of calcarenite, dissected into a series of northeast-southwest trending ridges and troughs supporting abundant epifauna.

The first systematic investigation of the live bottom consisted of faunal collections initiated in 1960 by the late Milton B. Gray (Gray, 1961), biological curator for the University of Georgia Marine Institute on Sapelo Island, and for whom the feature was named. Except for a brief statement of the existence and possible origin of the reef by Henry and Hoyt (1968), it and other live bottoms on the interior shelf of the Georgia Bight were not studied geologically until the work of Hunt (1974). This was followed by the work of Harris (1978) who reported on the resident fish populations, and by other faunal studies by the South Carolina Marine Resources Research Institute and the Georgia Department of Natural Resources, who in 1981 conducted research under the sponsorship of the U. S. Bureau of Land Management, Department of Interior.

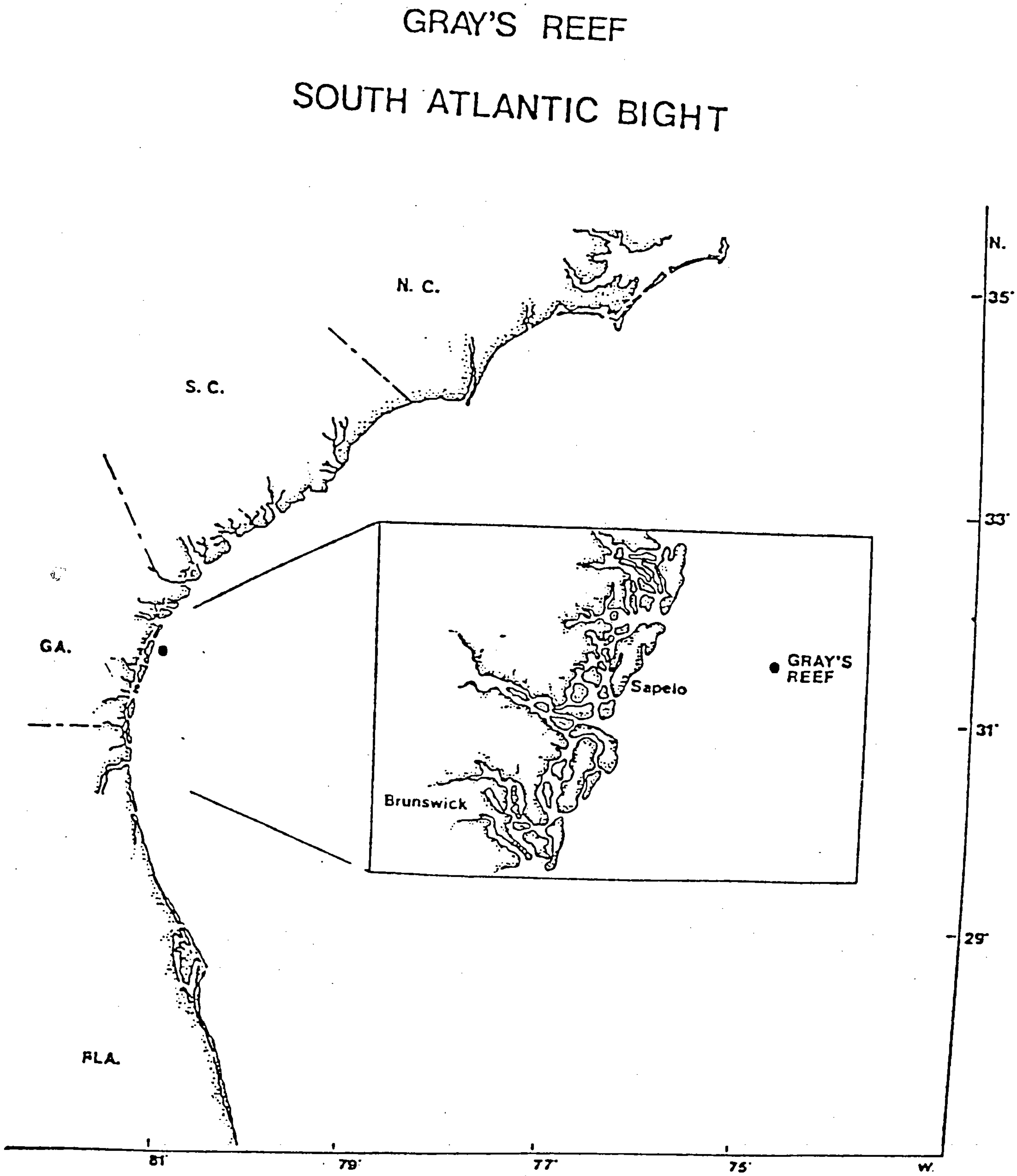

Figure 1. Location of Gray's Reef National Marine Sanctuary.

Following the designation of Gray's Reef as a National Marine Sanctuary in January, 1981, the funded research has been primarily directed towards aspects with managerial objectives, including a hydrographic survey (Henry and Van Sant, 1982) which utilized SCUBA, side-scan sonar, and underwater CCTV to characterize the morphology and density of the hard bottom zones of the National Marine Sanctuary and adjacent areas. A high resolution seismic sub-bottom profiler system was also employed to obtain data on the structural and stratigraphic aspects of the substrate.

Prior to this report, the last study of a geological nature was a comprehensive hydrographic and geophysical survey done in 1983 onboard the NOAA ship *Whiting*. This task, described by Henry (1985), and sponsored by the Sanctuary Programs Division, Office of Ocean and Coastal Resources Management, resulted in the development of a high resolution, two-dimensional side-scan SONAR mosaic of the seafloor within the Sanctuary, supplemented by transparent overlays depicting seabed sedimentary texture and substrate morphology. A three-dimensional bathymetric model of the Sanctuary was also prepared, a wooden replica of which is on public display at the University of Georgia Marine Extension Center on Skidaway Island, where the Interpretative Center for the Gray's Reef National Marine Sanctuary (GRNMS) is located.

With the exception of the thesis work by Hunt (1974), the geological studies conducted on Gray's Reef prior to that described in this report were primarily geophysical in nature, augmented by rock sampling and analyses. In the case of this investigation, the reverse was the case, wherein rock sampling was the central focus, with some geophysical data collected while on site.

DESCRIPTION OF WORK

Field Phase

The principal objective of the research begun in 1987 was to establish, from the geological and paleontological standpoints, the origin and developmental history of Gray's Reef. It was anticipated that examinations of lithological texture, mineralogy, and faunal composition would yield useful interpretative data in order to delineate the formational history of the reef, starting with the environment in which the original sediments were deposited.

In July, 1987, rock and sand samples were collected within the boundaries of the GRNMS under the authorization of the Cooperative Agreement NA-87-AA-H-CZ033, from NOAA. The R/V *Seadawg*, operated by the University of Georgia Marine Extension Service, was utilized for the field portion of the study.

Four sample groups were collected, the locations of which are given in Table 1 and shown in Figure 2. Water depths ranged from 50 to 65 feet, and the samples were obtained from the rock ledges that constitute the positive bathymetric expression of the reef proper, as well as from the sand veneer which cloaks the intervening spaces between the outcrops. Additionally, several samples were collected of the rocky substrate which commonly occurs beneath the veneer of unconsolidated sand.

Although it was originally planned to utilize an underwater rock corer to be borrowed from the U. S. Geological Survey, its availability did not coincide with the ship-time, and samples were obtained using prybars and sledge hammers.

Table 1

Location Data for Gray's Reef Samples Collected July 22-24, 1987 from R/V *Seadawg*.

Sample Group	Coordinates Latitude-Longitude	Remarks
1	31°23'42"N, 80°53'24"W	Water Depth 60-65' Medium to coarse sand cover 2" to 10" thick with sparse outcrops
2	31°22'39"N, 80°53'00"W	Water depth 55-60' Bottom conditions same as #1
3	31°23'12"N, 80°53'41"W	Water depth 60-65' Coarse sand cover 2" to 6" thick; sparse outcrops
4	31°22'18"N, 80°52'36"W	Water depth 50-55' Medium sand cover, 4" thick - some outcrops

The samples were collected by a team of divers from Georgia State University and the University of Mississippi's Mineral Resources Institute, during July, 1987. Also, eleven additional samples were furnished by the Georgia Department of Natural Resources, Coastal Resources Division, located in Brunswick, Georgia. These latter samples were collected during ground-truth investigations coincident to a side-scan SONAR survey of Gray's Reef, as reported by Henry (1985). The locations are given in Table 2 and shown in Figure 2.

Laboratory Phase

All of the samples were logged and returned to the University of Georgia Marine Extension Service sedimentation laboratory on Skidaway Island for descriptive analysis. The unconsolidated sand samples were dried, split into statistical portions, ro-tapped for standard grain-size analysis, impregnated with epoxy to construct grain mounts, and examined under a binocular microscope for faunal, mineralogic, and textural characteristics.

The indurated rock samples from the outcrops and the substrate were sawn into manageable slabs, labeled and submitted to a commercial laboratory for the preparation of thin-section slides. A total of 108 oriented thin sections were made and subsequently examined under plain and polarized light using a petrographic microscopic. The petrographic examination revealed the lithologic and textural characteristics of the rocky substrate, including texture, classification of rock type and mineralogy. Also, information was obtained concerning the geologic and depositional environments of the hard-ground constituents, such as diagenetic changes and dolomitization.

Table 2

Gray's Reef Samples Obtained from Coastal Resources Division, Georgia Department of Natural Resources, Brunswick, Georgia, and Thin-sectioned for this Study.

Sample No.	Location
1	31°24.17'N; 80°51.51'W
2	Heading of 060° - 30 m from #1
3	Heading of 060° - 50 m from #1
4	Heading of 240° - 50 m from #1
5	31°22.52'N; 80°53.09'W
6	Heading of 180° - 50 m from #5
9	31°24'N; 80°50.47'W
10	Heading of 180° - 50 m from #9
11	31°24.23'N; 80°54.14'W

Sample #1 was from a plateau area, 30 m away from a ledge. Sample #2 was associated with rock rubble at the base of this ledge. Sample #3 was from directly below the ledge. Sample #4 was from the sand flats; #5 from the plateau, above a ledge break; #6 from a live bottom plateau area; and #9, 10, and 11 were from uniform sand areas.

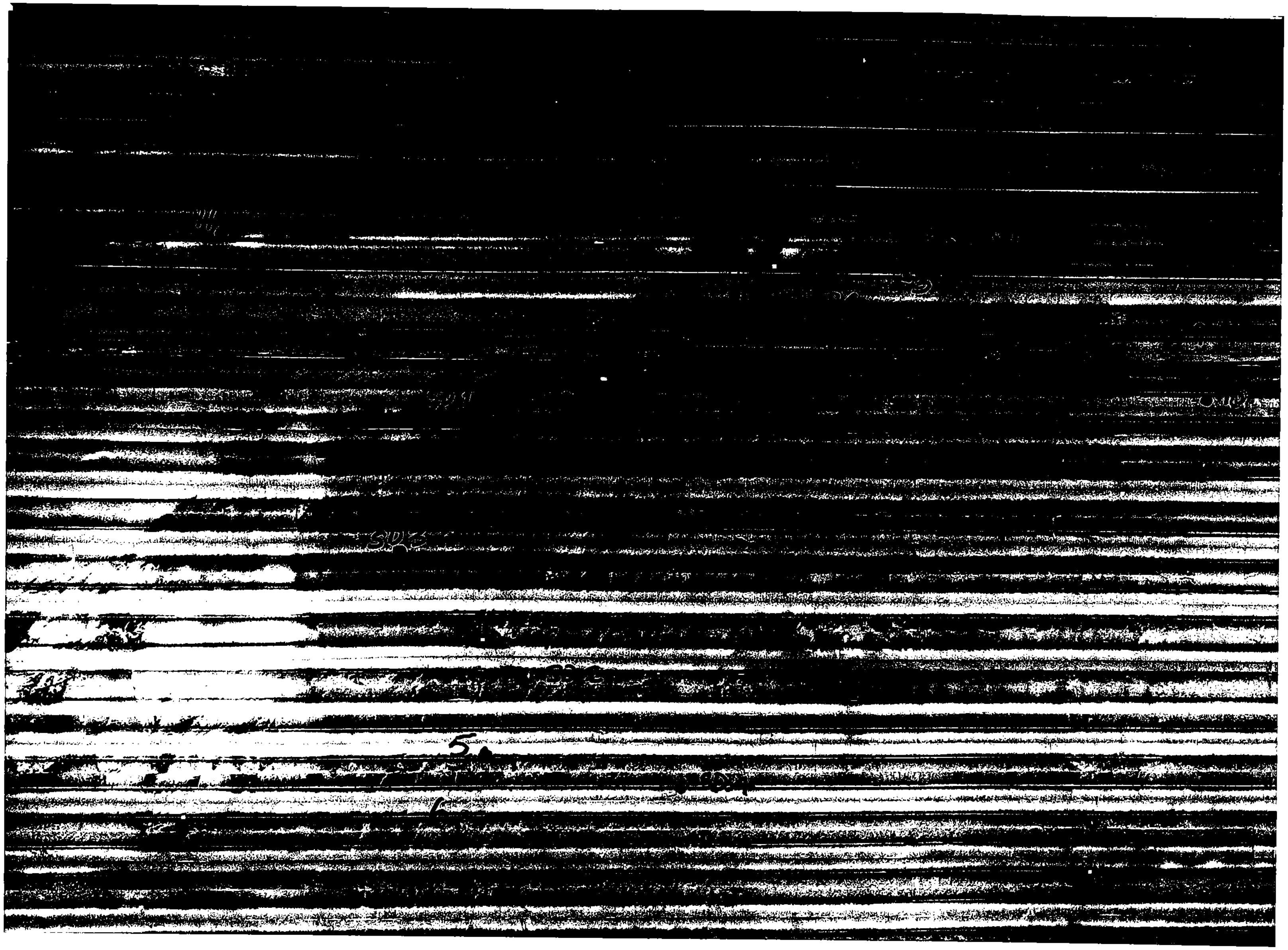

Figure 2. Sample locations on sonogram mosaic.

Photomicrographs were made of selected thin sections to characterize rock classification and highlight other significant features.

The results of the petrographic analysis are presented in the Appendix. A more detailed treatment of the carbonate petrology and petrography of the samples will be given in the descriptive text of a professional paper to be submitted to a refereed journal as a consequence of this study, pending approval of this report.

DESCRIPTION OF SAMPLES

Sand Samples

The predominant constituent of the sand veneer which comprises approximately 50 percent of the seafloor area within the Gray's Reef National Marine Sanctuary is quartz. Quartz grains, which are angular to sub-angular, range from 40 to 70 percent of the total sand volume. Second in abundance is feldspar, with microcline in equal or slightly greater amounts than plagioclase feldspar. Third in terms of abundance in the unconsolidated sand fraction is skeletal debris, much of which was identified as molluscan in origin. Other skeletal fragments are echinoid spines, bryzoa, coralline algae, and benthic foraminifera. The remainder of the sand fraction consists of lithic fragments, fecal pellets, glauconite grains, phosphate grains, and minor occurrences of heavy minerals such as ilmenite, rutile, zircon, and amphiboles-hornblendes. Trace amounts of mica, mostly muscovite, also were noted.

The non-biogenic constituents of the sand fraction represent material which was transported to the Sanctuary site by fluvial systems extant since the last transgressive rise in sealevel, i.e., the Holocent-Recent interval of geologic time. It is doubtful if any of the riverine systems currently present along the Georgia coast are supplying such material to the Sanctuary area.

The skeletal debris and other constituents of biogenic origin represent recent material which is constantly being added to the sediment veneer by the natural demise of organisms and subsequent fragmentation processes common to all areas of the continental shelf. A detailed report on the petrologic analysis of the surficial sand cover in the Sanctuary has been provided by McCulloch (1987).

Rock Samples

The majority of the rock samples were collected from outcroppings of ridges and overhangs within the Sanctuary boundaries. A few indurated rocks were also collected from the lithified substrate which underlies the sand veneer in intra-ridge zones. However, due to the difficulty of such sampling, only the uppermost foot or so was represented in the samples.

Visual Examination

Upon visual examination, without optical aids (other than a hand lens), the majority of the hard specimens appear, texturally, to be sandstones, i.e., siliciclastics and calcarenites. These range from light and dark gray to buff-colored and are poorly cemented; in fact, the majority are quite friable and porous.

Based on binocular and petrographic examination, calcarenites are predominant, with the carbonate fraction consisting of biosparites, biomicrites, boundstone, and grainstone. The classification schemes utilized in describing the thin sections follow those of Folk (1959) and Dunham (1962), the principal segments of which are defined below:

Biosparite - a limestone composed largely of biogenic tests of bottom-dwelling and previously floating organisms, with a crystalline matrix (usually sparry calcite).

Biomicrite - a group of biogenic limestones containing a significant admixture of fine-grained (mud) carbonate material filling the spaces between the biogenic fragments.

Boundstone - carbonate rocks exhibiting signs of having been bound together during or immediately after deposition, such as by coralline algae, encrusting foraminifera, etc.

Grainstone - a carbonate rock lacking a cement or matrix, which is held together by grain-support.

The terms given above can be used to petrographically describe the majority of the rock types collected in the GRNMS in conjunction with this investigation. A few specimens were classified with different terms, but except for those containing significant amounts of crystalline dolomite, they are unimportant in helping to decipher the geologic origin of the Gray's Reef rocks. The dolomite was described utilizing terminology of Sibley and Gregg (1987).

Carbonate Mineralogy

Unlike terrigenous sediments, which can be transported great distances prior to final deposition, carbonate rocks are comprised of material formed at or very near to the site of accumulation. In older limestones, two carbonate minerals are common: calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). In recent carbonate rocks, especially in shallow marine environments, the mineral aragonite, also $CaCO_3$, is abundant. The difference between calcite and aragonite is not one of chemical composition, but rather involves a difference in crystallographic structure, with calcite being in the hexagonal (rhombohedral) system and aragonite in the orthorhombic system. Aragonite, however, is metastable under conditions which are not totally marine and therefore is usually dissolved when the host rock is exposed to meteoric waters. Furthermore, it can also be converted in situ by a process of recrystallization into calcite. Dolomite is usually a secondary mineral, having formed after the original lithification process, although in rare cases, it can be of primary origin.

These mineralogic relationships are paramount to the interpretation of the depositional history of the rocks which constitute the strata of Gray's Reef.

Petrography

Biosparites - The majority of the biosparites consist of fine-grained bioclasts (biogenic fragments) and pelletal grains cemented by sparry calcite. Admixed with the bioclasts are quartz and feldspar grains as well as other non-biogenic constituents. In some of the sections there were indications of diagenesis having occurred since deposition. Such indications consisted of a grumose texture, wherein patches of sparry calcite appear to have invaded shell debris, other clasts, and the original matrix. Such a rock has a clotted appearance in thin section. The development of this type of texture may be related to crystallization or recrystallization of portions of the matrix. It is readily identifiable, as the recrystallized areas remain dark (partially opaque), dense, and are usually surrounded by coarsely crystalline sparite. Such a texture and the diagenesis associated with it are indicative of a change in the physio-chemical environment of a rock since its original cycle of deposition, compaction, and cementation leading to lithification. In the case of the Gray's Reef rocks, such changes could have been initiated as a result of fluctuations in sealevel since deposition, which obviously resulted in periodic exposure to subaerial weathering processes. With this in mind, the thin sections were carefully examined for evidence of inversion, which is a process wherein unstable minerals change to a more stable form with the same or similar composition. The most common of such inversions in carbonate rocks is the change from the mineral argonite to calcite (discussed above). The results of dolomitization was also observed in some thin sections. The importance of these features will be discussed in detail under the section on Petrology.

<u>Biomicrites</u> - The preponderance of biomicrite in the thin sections has important implications for understanding the origin of the rock strata of Gray's Reef. Micrite is microcrystalline calcite in the form of grains less than 5μm in diameter. It forms in the area of deposition, either as a direct precipitate from seawater or from the disintegration of the hard parts of organisms. Sometimes the term "carbonate mud" is also used for this fine material, but mud can contain particles of clay and silt-size (up to 62 μm).

The presence of micrite in the intergranular voids as well as in the form of infilling of spatial cavities in bioclasts indicates a relatively quiet depositional environment, lacking strong wave and current activity which would have removed the mud from the pore spaces.

Boundstones - As stated in the brief definition given previously, a boundstone is a limestone which is essentially bound together by organisms, such as occur in many reefs. The boundstones examined in the Gray's Reef thin sections consist of skeletal debris (usually molluscan), held together by algae and in some cases by serpulid worm tubes.

Grainstones - There were a few examples of grainstones in the thin sections. These are rocks in which the grains support one another with little or no cement. Such a limestone is extremely porous and is also highly friable, with a tendency to crumble upon even gentle rubbing. Rocks of this type, collected from Gray's Reef, were extremely difficult to both cut on the rock saw and to subsequently thin section due to their friability.

Dolomite - Dolomite, $CaMg(CO_3)_2$, forms a significant portion of carbonate rocks. It is usually secondary, having replaced the original carbonate minerals. Unlike the calcite, it often occurs as euhedral rhomb-shaped crystals, and it is in this form that it appears in the Gray's Reef thin sections. Sometimes these crystals contain inclusions, probably of calcite, and are therefore cloudy. The term "probably" is used here due to the fact that the optical properties of calcite and dolomite are very similar and therefore difficult to distinguish. Some of the dolomite rhombs occur in the matrix or cement, and in these cases, represent replacement of the original matrix, but in other cases, the allochems (grains) have resisted replacement, and are still of the original mineralogic composition. In no case was complete replacement by dolomite encountered.

It should be kept in mind that the term dolomite is used for both the mineral and the rock and hence can lead to some confusion. Dolomitic rocks are classified according to their dolomite content as follows:

0- 10% dolomite - limestone
10- 50% dolomite - dolomitic limestone
50- 90% dolomite - calcitic dolomite
90-100% dolomite - dolomite

The processes which lead to dolomitization and the implications these offer to deciphering the geologic history of the reef will be given in the section on Petrology.

The general nature of the petrographic suite of lithologic types of the Gray's Reef rocks correlated quite well with those described by Lemon (1979), the majority of which were collected from outcrops on the minor continental shelf north of the Gray's Reef National Marine Sanctuary.

Paleontology

The majority of the skeletal debris (bioclasts) are fragmented, and hence cannot be identified to the genus, let alone species level. These include the most abundant forms: the molluscs, which cannot be differentiated beyond bivalves and gastropods. Echinoderms, and especially the echinoid spines are very distinctive in thin sections, but add nothing to the understanding of the geologic history, as they are present in limestones dating from the Paleozoic to the present. The same is true for the corals and the algae. Foraminifera, which were fairly abundant (especially in the biomicrites) could be identified only to the family level. These were the Miliolidae and Peneropliidae. However, here again, these were of little use for ascertaining the geologic history as they are benthic forms with a long history of occurrence as regards geologic time.

The use of paleontology to date the rocks of Gray's Reef is limited to the identification of a thin-shelled Pliocene pelecypod, *Amusium mortoni*, which is found in the uppermost rocks of the reef. These shells are indicative of a low-energy environment and also help in dating the strata through stratigraphic extrapolation to other sites in areas adjacent to Gray's Reef.

Shallow Stratigraphy

As described by Hunt (1974), high resolution seismic profiles were run from Sapelo Whistle Buoy R "25" to Gray's Reef and from Doboy Sound Sea Buoy (Nun "D") to the reef. A flat-lying, somewhat discontinuous seismic reflector, located approximately 3 m below the bottom at the Whistle Buoy was traced to the live bottom area where it intersected the bottom. This reflector was also traced intermittently from the reef to the Doboy Sound Sea Buoy, where it was located slightly more than 6 m sub-bottom or about -16 m MSL. Projected to the southern tip of Sapelo Island, approximately 6 m to the west, the reflector was approximately coincident with a thin but dense fossiliferous marl with abundant fragments of the pelecypod *Amusium mortoni* found at -18 m MSL in a boring at that locality by Woolsey (1977) and described as being Middle Pliocene in age. A similar fauna and age was reported by Wait (1962) for a marl found at approximately -15 m MSL in a water well drilled in Sapelo Island, approximately 2 km to the west of Woolsey's boring. A detailed high resolution seismic survey of the Georgia estuaries and inshore areas (Henry, *et al.*, 1979) shows the presence of a regionally continuous reflector at approximately this depth that correlates with Pliocene material described by Woolsey (1977) from numerous borings in Georgia estuaries and nearshore areas and from fossiliferous samples described by Frey *et al.* (1975) from a number of estuarine localities along the Georgia coast.

Petrology

Reef Substrate - Few fresh surfaces of substrate were exposed. Even smaller rocks scattered about the area were heavily encrusted by bryozoa, mollusc shells, serpulid worm tubes, and calcareous algae. All surfaces were extensively bored by the mollusc *Lithophaga* spp.

On a freshly exposed surface, the rocks varied in color from light and olive gray to very dark gray (see photomicrographs in Appendix B). Quartz grains and fossil fragments were abundantly distributed in a fine-grained limestone matrix. The hand specimens collected exhibited low to very high porosity and were slightly to well indurated.

The substrate of Gray's Reef is a moderately to strongly dolomitized, sandy biomicrite. All the rocks collected from the substrate were very similar in composition. Allochemical constituents varied from 9 to 10 percent and were predominantly mollusc and echinoid fragments with minor amounts of foraminifera, bryozoa, coral, pelletoidal grains, and interclasts. Terrigenous constituents accounted for 22 to 45 percent with fine- to medium-grained quartz being the predominant mineral. Quartz grains were sub-rounded to sub-angular and poorly sorted. Some quartz grains appeared strained and others were fractured.

Orthochemical constituents ranged from 55 to 63 percent. The micrite was calcitic and appeared to have been the original cement. Dolomite constituted from 20 to 46 percent of the rocks and appeared to have replaced the micrite. Pelletoidal phosphatic concretions from 0.1 to 0.4 mm in diameter represented between 1 and 4 percent of the rocks. These grains were oval, light yellowish-green to brown under plain polarized light and were extinct under crossed nicols.

Pore space appeared to be the result of partial solution. Voids commonly occurred on one side of mollusc fragments and appeared randomly oriented with respect to both concave and convex sides of the shells. In some cases, the mollusc fragments themselves had been leached entirely away, creating moldic porosity.

Recrystallization and dolomitization were extensive in all rocks of the substrate. Monocrystal syntaxial overgrowths of dolomite were abundant. In some cases, complete recrystallization of foraminiferal tests, mollusc fragments, and other biogenic material had occurred, leaving only a color difference in an otherwise evenly-textured groundmass. Dolomitization was noted to be partially digesting fossil fragments or pelletal grains. Dolomite also occurred as subhedral to euhedral rhombs scattered throughout the micrite and commonly lined grains "floating" in the micrite. Sparry calcite was rare, but where present seemed to have at the expense of the micrite. The calcite was very fine-grained and, in some cases, was noted to fill cracks in the quartz and feldspar grains.

DISCUSSION

Geological History of Gray's Reef

Initially, the reef substrate appears to have been formed under intermittently wave-agitated conditions. A moderate amount of energy was necessary to fragment or transport most of the fossils and to introduce intraclasts. Conversely, periods of relatively low energy permitted the deposition of lime mud as described by Plumley *et al.* (1964).

The site of the present reef was probably located between a carbonate and clastic sedimentary regime as indicated by the moderate amount of quartz sand present in the rocks. The occurrence of fragmented mollusc, bryozoa, and coral suggests an initial shallow marine environment followed by a supratidal environment as suggested by the nature of the cement. *Amusium mortoni* shells in the rocks from the upper section of the reef substrate indicate a low-energy environment during the latter stage of formation. Most of the diagenetic dolomitization of the reef substrate appears to have taken place shortly after deposition as indicated by five modes of dolomite occurrence:

(1) subhedral to euhedral rhombs are randomly distributed in the micrite and resulting from aggrading porphyroid and coalescive neomorphs (Randazzo *et al.*, 1977); the resulting texture is similar to that described by Folk and Land (1975) for "limpid" dolomite;

(2) "dolomite rim cement" (as described by Schmidt, 1975) around void spaces and surrounding allochemical grains throughout the rocks;

(3) total replacement, destructive in many cases, of intraclasts by anhedral dolomite rhombs, some of which cross the grain boundaries;

(4) dolomitic echinoid plates and spines with dolomitic monocrystal syntaxial overgrowths; and

(5) selective dolomitization of a bryozoan colony.

Schmidt (1965) introduced the terms "early and late diagenesis" to imply diagenesis influenced by the depositional and post-depositional environments, respectively. One feature all dolomite has in common is that the mineral has to form in a dynamic environment; that is, actively circulating fluids must be present to supply magnesium ions (Hanshaw *et al.*, 1971). Several theories for sources of magnesium ions have been advanced by Adams and Rhodes (1960), Goodell and Garmon (1969), and Land *et al.* (1975).

Goodell and Garmon (1969) described the process of "solution-cannibalization" as solution of the upper high-magnesium carbonate rocks in a sequence as a source of the magnesium ions and the dolomitization of the rocks below the area of solution by the downward percolation of magnesium-rich water. Substantial amounts of high-magnesium calcite have to be dissolved to dolomitize even a relatively small unit of rocks below the zone of solution. In the case of Gray's Reef rocks, this process is a doubtful explanation for the origin of the magnesium ions required for dolomitization because the entire sequence is relatively thin. A thick sequence above the reef substrate to supply the necessary ions could have initially been present and subsequently eroded away; however, this phenomenon is highly unlikely. The time factor alone would be prohibitive. For a thick unit of carbonate rocks to completely deteriorate and erode away would involve much more time than has been available.

Adams and Rhodes' (1960) theory for dolomitization discusses a process of "seepage-refluxion" with the seepage of ocean water through or over a natural barrier into a semi-closed or closed hyper-saline lagoon. The sea salts are concentrated in the lagoon and the dense brines formed percolate through the underlying strata and back into the sea, thereby dolomitizing the underlying rocks or sediment.

A modified version of Adams and Rhodes' theory, together with the conceptual model described by Randazzo *et al.* (1977), is the most likely explanation for the dolomitization of the Gray's Reef substrate. The environment of deposition became a shallow, quiet body of water as indicated by the *Amusium mortoni* shells found in the upper-most rocks in the Gray's Reef sequence. Evaporation of the seawater in a shallow, possibly restricted, body of water initiated formation of dense, rich brines which percolated downward through the porous sediments or rocks and dolomitized the underlying beds.

Dolomitization prior to the first subaerial exposure of the areas is indicated by the higher percentage of dolomite in the uppermost layer of rocks. Otherwise, dolomitization would be fairly even throughout the relatively thin sequence of rocks. Ground water percolation would dissolve much of the micrite out of the uppermost layer leaving behind the quartz sand and dolomite. Additionally, the upper layer of Gray's Reef exhibits a leached appearance while the underlying layer is much more consolidated and has a slightly higher micrite content. Exposure to ground waters is indicated by the mollusc fragments that were recrystallized to mosaic calcite, probably by dissolution-reprecipitation (Friedman, 1964). Exposure to ground water would also remove any evaporite minerals, particularly anhydrite, leaving molds of the crystals. As described by Murray (1960), calcite-dissolution must accompany dolomitization if the fluids bearing the magnesium ions are carrying insufficient carbonate ions. This process could also have caused some of the porosity evident in the Gray's Reef substrate.

Land *et al.* (1975) discussed the importance of meteoric-seawater mixing in causing dolomitization. Subterranean fresh water will mix with salt water in response to hydraulic conditions and in the zone at intermixing, salinity and Mg-Ca ratios may come within the necessary limits for dolomitization to occur. This process could have been responsible for the formation of some of the subhedral to euhedral crystals of dolomite by aggrading neomorphic processes. Although the exact time of subaerial exposure of the Gray's Reef area is not definite, the fact that the rocks were subaerially exposed is suggested by the prevalent jointing in the substrate caused by dessication and settling.

The outcrop patterns seen in certain parts of the Gray's Reef area (i.e., the ledges and undercuts, overhangs, etc.) indicate a period of exposure to the surf action. The rock was consolidated prior to exposure to the surf because it could not have survived the action of the surf had it been unconsolidated. No fine rubble was found anywhere on or beneath the bottom under the ledges.

The reef rock has undergone little change other than being encrusted by the abundant growth of sessile benthos and perhaps some settling and collapsing of the ledge areas since inundation by the advancing sea. Although observations indicate that sediment is transported across the reef during severe weather, no thick accumulation of sediment has occurred in the immediate past.

Geological Age of the Gray's Reef Substrate

JR Woolsey (SK10)

Rock samples dredged by the authors from Turtle River near Brunswick, Georgia, and from Sapelo Sound closely resembled the Gray's Reef rocks in external appearance. Thin-section examination revealed the rocks to be sandy, micritic, skeletal limestone very similar to the uppermost layer of Gray's Reef. Fossil faunal assemblages of the three localities were very similar, including the presence of *Amusium mortoni*

Several core samples were collected by the authors on Sapelo Island, Georgia, and Amelia Island, Florida, and a hard crust underlain by marly, gravelly sand was found at depths of 13.7 to 21.3 meters and 10.7 to 18.3 meters, respectively. One sample on Sapelo Island at a depth of 13.7 meters contained large fragments of *Amusium mortoni*.

As previously discussed, seismic profiles run from Gray's Reef to the vicinity of Doboy Sound immediately south of Sapelo Island revealed a somewhat discontinuous reflector at a depth of 15.0 meters near the sound and that cropped out at Gray's Reef. A lithologically similar layer identified by Woolsey (1977) as the Duplin Marl of Middle Pliocene age was encountered in core holes on Sapelo Island and in Sapelo Sound at approximately the same depth as the reflector discussed above near Doboy Sound. There is, therefore, strong evidence that the Gray's Reef substrate is of Pliocene age and directly correlates with the Duplin Marl formation of coastal Georgia.

CONCLUSIONS

The outcrop pattern, bathymetry, and sessile benthic accumulations of a live-bottom reef have been mapped in an area 33 kilometers east of Sapelo Island, Georgia.

Gray's Reef, located 33 kilometers east of Sapelo Island, Georgia, was found to be an outcrop of a moderately to strongly dolomitized, sandy biomicrite and, on the basis of similar stratigraphic position, fauna, and lithology, correlates with the Pliocene Duplin Marl.

Fossil fragments of certain molluscs, bryozoa, echinoids, and coral and their state of fragmentation, indicate that the rock was deposited in a shallow marine environment. Although the exact time of dolomitization is difficult to determine, evidence indicates that the dolomite was diagenetic in origin and occurred as a result of evaporation of seawater in a broad, shallow, possibly restricted, body of water. The brines then percolated downward through the sandy biomicrite causing extensive dolomitization.

Following partial lithification, the Gray's Reef substrate was subaerially exposed several times during the Pleistocene Epoch as a result of eustatic fluctuations of sea level. (Curray 1965 Emery 1967) Fresh ground water percolation leached some of the micrite from the uppermost layer of rocks in the area resulting in a higher dolomite and quartz sand content than in the lower layers. During the latest transgression, Gray's Reef was exposed to wave action. The consolidated rock was undercut and some of the larger blocks were left scattered about the base of the ledges.

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APPENDIX A

Petrographic Descriptions of Thin Sections and Sand Samples from Gray's Reef

Sand Sample PP 1

plagioclase feldspar
quartz - sub-angular to sub-rounded - some sutured with bubble trains
orthoclase
mollusc fragments
kyanite
benthic foraminifera (milliolids)

Sand Sample PP 2

80% quartz grains
orthoclase and plagioclase feldspars
mollusc fragments
echinoid spines and plates
benthic foraminifera
biotite and muscovite
kyanite

Sand Sample PP 3

80%+ quartz grains; sub-angular to sub-rounded, sutured
mollusc fragments
feldspars
algal fragments (bryzoa?)
muscovite

Sand Sample PP 4

75% quartz
feldspars
mollusc fragments
lithic fragments
fecal pellets

Sand Sample PP 5

large quartz grains - (coarse-grained sand)
opaque heavy minerals
phosphatic minerals
phosphatic grains
mollusc fragments
amphiboles

Sand Sample PP 6

medium-sized quartz grains
feldspars
mollusc fragments
benthic foraminifera
fecal pellets

Sand Sample PP 7

80%+ quartz - poorly sorted sand
feldspars
mollusc fragments

Sand Sample PP 8

very high quartz content (85-90%) - low temperature, metamorphic
feldspars
mollusc fragments
foraminifera

Sand Sample PP 9

quartz
feldspars
amphibole
mollusc fragments

DNR SAMPLES

Thin Section PP 10

Classification: Biosparite

Quartz and feldspar grains with molluscan fragments cemented by sparry calcite with minor amounts of syntaxial dolomitic overgrowths; sparite appears to have formed, at least in part, via grain-growth recrystallization from micrite.

Thin Section PP 11

Classification: Biosparite

Quartz, feldspar grains with molluscan fragments cemented by sparry calcite and small rhombohedral dolomite crystals forming along grain contacts, dolomite is euhedral.

Thin Section PP 12

Classification: Biomicrite

Allochems consist of algae, quartz grains, plagioclase, glauconite; iron-staining predominant; micritic matrix in interstitial pore spaces of molluscan debris, foraminifera, etc. Very little evidence of grain growth.

Thin Section PP 13

Classification: Biomicrite and Boundstone

Quartz, feldspar, muscovite, glauconite, molluscal fragments, coral-algae forms part of cement-matrix; remainder is micrite. High iron-staining.

Thin Section PP 14

Classification: Arenaceous limestone (micrite-sparite cement)

Mostly quartz grains with minor bioclasts in the form of molluscan fragments, and small skeletal debris; some micrite cement and infilling of pore spaces in biogenic clasts recrystallizing to sparry calcite.

Thin Section PP 15

Classification: Arenaceous limestone (biomicrite)

Thin section petrography same as in PP 14, except some diagenetic dolomite is also present, which appears to have formed at the expense of the biomicrite.

Thin Section PP 16

Classification: Boundstone

This thin section consists of coral and coralline algal fragments which are bound together by filaments without the presence of recognizable cement. Neither the coral nor the algae can be identified, but the latter are probably codiacean forms, such as Halimeda, which were prevalent during the Late Tertiary and still are present today.

Thin Section PP 17

Classification: Boundstone

This thin section is identical in content to PP 16 (above), consisting of algae and coral fragments, and totally lacking in matrix, cement, or pore space filling.

Thin Section PP 18

Classification: Boundstone

This thin section is very similar to PP 16 and PP 17, in that it consists primarily of algae and coral fragments. It differs from the other two, however, as it contains micrite in pore spaces and as partial cement.

Thin Section PP 19

Classification: Arenaceous limestone (biomicrite)

This section consists of quartz and feldspar grains along with bioclasts cemented in part by micritic material and in part by binding algae. There is a slight indication of incipient diagenesis in the form of micrite changing to sparite.

Thin Section PP 20

Classification: Biosparite

Bioclasts (molluscs, foraminifera, algae, echinoida, bryzoa, etc.), minor quartz and feldspar, cemented together by sparry calcite with some micrite in pores.

Thin Section PP 21

Classification: Arenaceous limestone (biomicrite)

Thin section petrography very similar to PP 20, except there is more micrite than sparite; what sparry material is present appears to be a diagenetic product of micrite.

Thin Section PP 22

Classification: Biomicrite

Skeletal allochems and minor quartz particles cemented by micrite, with micritic infillings in pore spaces as well. Very minor recrystallization of micrite to sparry calcite is present.

Sand Sample PP 23

60-65% angular to sub-angular quartz grains
feldspar
molluscs
echinoid plates and spines
muscovite

DIVE STATION 1 (Sample Group 1)

Thin Section PP 24

Classification: Arenaceous limestone (biomicrite)

Fifteen to 25% angular to sub-angular quartz; some feldspar grains, 10% bioclasts consisting of foraminifera, echinoid spines, plates; minor dolomitization

Thin Section PP 25

Classification: Arenaceous limestone (biomicrite)

Essentially the same as PP 24, with the same bioclasts, but with much more dolomite. All the quartz present in angular grains.

Thin Section PP 26

Classification: Biomicrite

Very few allochems; bioclasts rare; all together constitute less than 10% of sample. No dolomite.

Thin Section PP 27

Classification: Dolomitic sandstone (biosparite)

Thiry to 40% very angular to angular quartz grains. Very few bioclasts; sample probably originally cemented entirely by micrite, but large-scale digestion of micrite cement by dolomitization. Approximately 75% dolomite (matrix).

Thin Section PP 28

Classification: Dolomitic sandstone

Very similar to PP 27; quartz grains highly angular - few bioclasts. High in dolomite, but good evidence of recrystallization is lacking.

Thin Section PP 29

Classification: Biosparite

High content of benthic foraminifera - fringing crystals around bioclasts - may be aragonite.

Thin Section PP 30

Classification: Biomicrite

Bioclasts consist of molluscs, echinoids, fecal pellets; glauconite present; high iron staining.

Thin Section PP 31

Classification: Biosparite

High content fusilinid foraminifera; the tests of which are calcitic, this was the only specimen with these forms.

Thin Section PP 32

Classification: Biomicrite

Bioclasts consist of mollusc fragments, foraminifera, echinoids, corals - cemented by micrite; only very minor diagenesis to calcite/dolomite.

Thin Section PP 33

Classification: Calcareous Sandstone

Very high quartz and feldspar content; minor percentages of mica (muscovite), and plagioclase; matrix is biomicrite; very little diagenesis in evidence.

Thin Section PP 34

Classification: Calcareous Sandstone

This thin section is very similar to PP 33; less plagioclase and more mica present - matrix is biomicrite.

Thin Section PP 35

Classification: Calcareous Sandstone

High quartz content; abundant feldspar, muscovite, mollusc fragments; biomicrite cement; little or no indication of diagenetic alteration.

Thin Section PP 36

Classification: Calcareous Sandstone

Very similar to PP 35; higher content of bioclastic debris; cement is micrite.

Thin Section PP 37

Classification: Calcareous Sandstone

High quartz content; plagioclase and orthoclase feldspar, bioclastic debris; cement is micritic with very little alteration.

Thin Section PP 38

Classification: Calcareous Sandstone

Poorly sorted, high angular quartz grains (may be indicative of dunal origin); bioclasts; biomicrite cement.

Thin Section PP 39

Classification: Calcareous Sandstone

Much higher mollusc content than in previous thin sections, mostly pelecypods; quartz and feldspar still abundant; cement is micrite, but widespread recrystallization to calcite spar is present.

Thin Section PP 40

Classification: Calcareous Sandstone

Very high quartz content (80%); cementing material is biomicrite - no indication of recrystallization.

DIVE STATION 2 (Sample Group 2)

Thin Section PP 41

Classification: Biomicrite (Boundstone)

Coral fragments bound together by algae; very high FeO staining; no cement or pore in-filling.

Thin Section PP 42

Classification: Biomicrite

Quartz and feldspar 25-30%; bioclastic debris; micritic cement, but alteration to calcite present.

Thin Section PP 43

Classification: Calcareous Sandstone

Quartz grains very angular; some coral fragments, echinoid plates and spines; benthic foraminifera (miliolidae), both micrite and sparite cement.

Thin Section PP 44

Classification: Biomicrite

Abundant bioclastic debris, large echinoid spines; FeO staining; micrite cement.

Thin Section PP 45

Classification: Calcareous Sandstone

Some boundstone present, high degree of FeO staining; micrite cement.

Thin Section PP 46

Classification: Biomicrite

Angular quartz grains; high content of mollusc fragments, echinoid parts; micrite cement.

Thin Section PP 47

Classification: Calcareous Sandstone

High content of angular quartz grains, some boundstone present - cement mostly micrite, but some alteration to sparry calcite present.

Thin Section PP 48

Classification: Calcareous Sandstone

Quartz grains are poorly sorted and highly angular; biomicrite cement.

Thin Section PP 49

Classification: Biosparite

Quartz grains exhibit zonations; cement appears to have been originally micrite (some cloudy material left) which is almost completely altered to sparry calcite.

Thin Section PP 50

Classification: Boundstone

Biomicrite present in pore spaces of coral and algal bioclasts; high FeO staining.

Thin Section PP 51

Classification: Calcareous Sandstone

Very dense, low porosity - high mollusc content, some foraminifera; quartz grains poorly sorted, angular to sub-rounded; mixture of micrite and sparite cement.

Thin Section PP 52

Classification: Biomicrite

Highly angular quartz grains; mollusc fragments abundant; micrite cement.

Thin Section PP 53

Classification: Calcareous Sandstone

Very high quartz content, angular to sub-rounded; biomicrite cement; some sparite present.

DIVE STATION 3 (Sample Group 3)

Thin Section PP 54

Classification: Biomicrite

High bioclastic content; very small fragments, angular quartz grains; micrite cement.

Thin Section PP 55

Classification: Calcareous Sandstone

Angular quartz grains; matrix a 50/50 mixture of micrite and sparite; some dolomite present.

Thin Section PP 56

Classification: Calcareous Sandstone

Very similar to PP 55; quartz is angular and well sorted; some boundstone; micrite and sparite cement.

Thin Section PP 57

Classification: Biomicrite (Boundstone in part)

Quartz poorly sorted; bioclastic debris very fine-grained; algal boundstone; some micrite recrystallized to dolomite.

Thin Section PP 58

Classification: Biomicrite with boundstone

Very similar in composition to PP 57; some plagioclase and mica present.

Thin Section PP 59

Classification: Calcareous Sandstone

Quartz grains poorly sorted; micrite cement; some boundstone (algal).

Thin Section PP 60

Classification: Biomicrite

Quartz poorly sorted; bioclasts very fine-grained; micrite cement; dense, very low porosity.

Thin Section PP 61

Classification: Biomicrite

Quartz grains angular and poorly sorted; bioclasts very fine-grained; some plagioclase; micrite cement.

Thin Section PP 62

Classification: Calcareous Sandstone

Quartz grains poorly sorted; bioclasts very fine-grained; micrite cement.

Thin Section PP 63

Classification Sandstone

Same composition as PP 62, except some algal boundstone present; micrite cement.

Thin Section PP 64

Classification: Calcareous Sandstone

Same as previous slide, without boundstone; quartz angular; micrite cement.

Thin Section PP 65

Classification: Calcareous Sandstone

Very dense rock, low porosity; high mollusc content, some foraminifera; quartz grains poorly sorted, angular to sub-rounded; mixture of micrite and sparite cement.

Thin Section PP 66

Classification: Calcareous Sandstone

Very loosely cemented; most of original micrite altered to sparry calcite.

Thin Section PP 67

Classification: Calcareous Sandstone

Very dense, similar to PP 65; low porosity; quartz is angular to sub-rounded; mostly micrite cement, but some sparite at grain contacts.

Thin Section PP 68

Classification: Calcareous Sandstone

Quartz angular and moderately well-sorted; micrite cement.

Thin Section PP 69

Classification: Calcareous Sandstone

Some algal boundstone present; micrite cement; bioclasts very fine-grained; angular to sub-rounded quartz grains.

Thin Section PP 70

Classification: Calcareous Sandstone

Angular quartz grains; micrite cement; bioclasts very fine-grained.

Thin Section PP 71

Classification: Calcareous Sandstone

Quartz grains angular to sub-rounded; very dense micrite cement, low porosity; fine-grained bioclasts; echinoid plates and spines; muscovite.

Thin Section PP 72

Classification: Calcareous Sandstone

Quartz very poorly sorted; some algal boundstone; micrite cement.

Thin Section PP 73

Classification: Calcareous Sandstone

Quartz grains highly angular; very fine-grained bioclasts; micrite and sparite cement.

DIVE STATION 4 (Sample Group 4)

Thin Section PP 74

Classification: Calcareous Sandstone

Very loosely cemented; some algal boundstone present; very fine-grained bioclasts; quartz angular to sub-rounded, poorly sorted.

Thin Section PP 75

Classification: Grainstone (biosparite)

Very loosely cemented, what cement is present appears to be sparry calcite; abundant mollusc fragments.

Thin Section PP 76

Classification: Calcareous Sandstone

Quartz grains are highly angular; micrite cement.

Thin Section PP 77

Classification: Calcareous Sandstone

Similar in composition and texture to PP 76.

Thin Section PP 78

Classification: Calcareous Sandstone

Very loosely cemented - grain supported (over 60% allochems); some micrite.

Thin Section PP 79

Classification: Calcareous Sandstone

Very similar to PP 78, except that cement, where present, is mostly sparite.

Thin Section PP 80

Classification: Arenaceous limestone

Loosely cemented, grain supported; mixture of micrite and sparite cement (latter from recrystallization).

Thin Section PP 81

Classification: Arenaceous limestone

Very similar in composition and texture to PP 80.

Thin Section PP 82

Classification: Arenaceous limestone

Thin laminae present - micro-stratification; micrite cement; partially algal boundstone.

Thin Section PP 83

Classification: Calcareous Sandstone

Quartz grains are poorly sorted; fine-grained bioclastic debris; mollusc fragments; cement is both micrite and sparite; one end of slide heavily stained by FeO (case-hardening?)

Thin Section PP 84

Classification: Arenaceous limestone

Very poorly sorted quartz grains; micrite cement.

Thin Section PP 85

Classification: Arenaceous limestone (biomicrite)

Mud-supported grains, i.e., very few allochems in contact with one another; micrite cement.

Thin Section PP 86

Classification: Wackestone (mud-supported carbonate rock)

Higher degree of mud-support that PP 85 - otherwise the same.

Thin Section PP 87

Classification: Calcareous Sandstone

Quartz grains poorly sorted; mica, plagioclase; mud-supported; micrite cement.

Thin Section PP 88

Classification: Calcareous Sandstone

Loosely cemented; high content of angular quartz; micrite matrix.

Thin Section PP 89

Classification: Biosparite

Loosely cemented, grain supported; sparry cement (some dolomite).

Thin Section PP 90

Classification: Calcareous Sandstone (biosparite)

Large degree of grain support - what little cement present is sparry calcite.

Thin Section PP 91

Classification: Biosparite

Similar in texture and composition to PP 90

Thin Section PP 92

Classification: Arenaceous limestone

Very loosely cemented, grain supported; quartz grains angular to sub-rounded; cement a mixture of micrite and sparite.

Thin Section PP 93

Classification: Arenaceous limestone

Identical in texture and composition to PP 92

Sand Sample PP 94

quartz
feldspar
mollusc fragments (mostly pelecypods)
algae and coral
foraminifera (benthic)
echinoid plates and spines

Thin Section PP 95

Classification: Calcareous Sandstone

Quartz grains well sorted; mostly grain supported, very little cement.

Thin Section PP 96

Classification: Calcareous Sandstone

Grain supported; quartz grains well sorted; mixture of micrite-sparite matrix.

Thin Section PP 97

Classification: Biosparite

Loosely cemented admixture of mollusc fragments; fecal pellets; echinoid plates; quartz grains angular to sub-rounded; sparite adjacent to grain boundaries.

Thin Section PP 98

Classification: Arenaceous limestone

Poorly cemented - mostly grain supported; bioclasts medium grained; sparite sparse with no micrite.

Thin Section PP 99

Classification: Arenaceous limestone

Poorly cemented - mostly grain supported; some sparite; sparse dolomite.

Thin Section PP 100

Classification: Calcareous Sandstone

Highly angular quartz grains, mostly grain supported; both micrite and sparite cement.

Thin Section PP 101

Classification: Calcareous Sandstone

Very high quartz content; fecal pellets, foraminifera; mollusc fragments; sparite cement - dolomitic in part.

Thin Section PP 102

Classification: Calcareous Sandstone

Angular quartz grains, mostly grain supported; mixture of micrite and sparite cement.

Thin Section PP 103

Classification: Biosparite

High content mollusc fragments, echinoid parts, foraminifera, algal material; sparry calcite cement.

Thin Section PP 104

Classification: Biosparite

Similar in both texture and composition to PP 103

Thin Section PP 105

Classification: Calcareous Sandstone

Quartz grains angular to sub-rounded; medium grained bioclasts, mostly mollusc fragments; sparite cement, where present adjacent to grain boundaries.

Thin Section PP 106

Classification: Calcareous Sandstone

Similar to PP 105, except higher degree of grain support.

Thin Section PP 107

Classification: Calcareous Sandstone

Identical to PP 106.

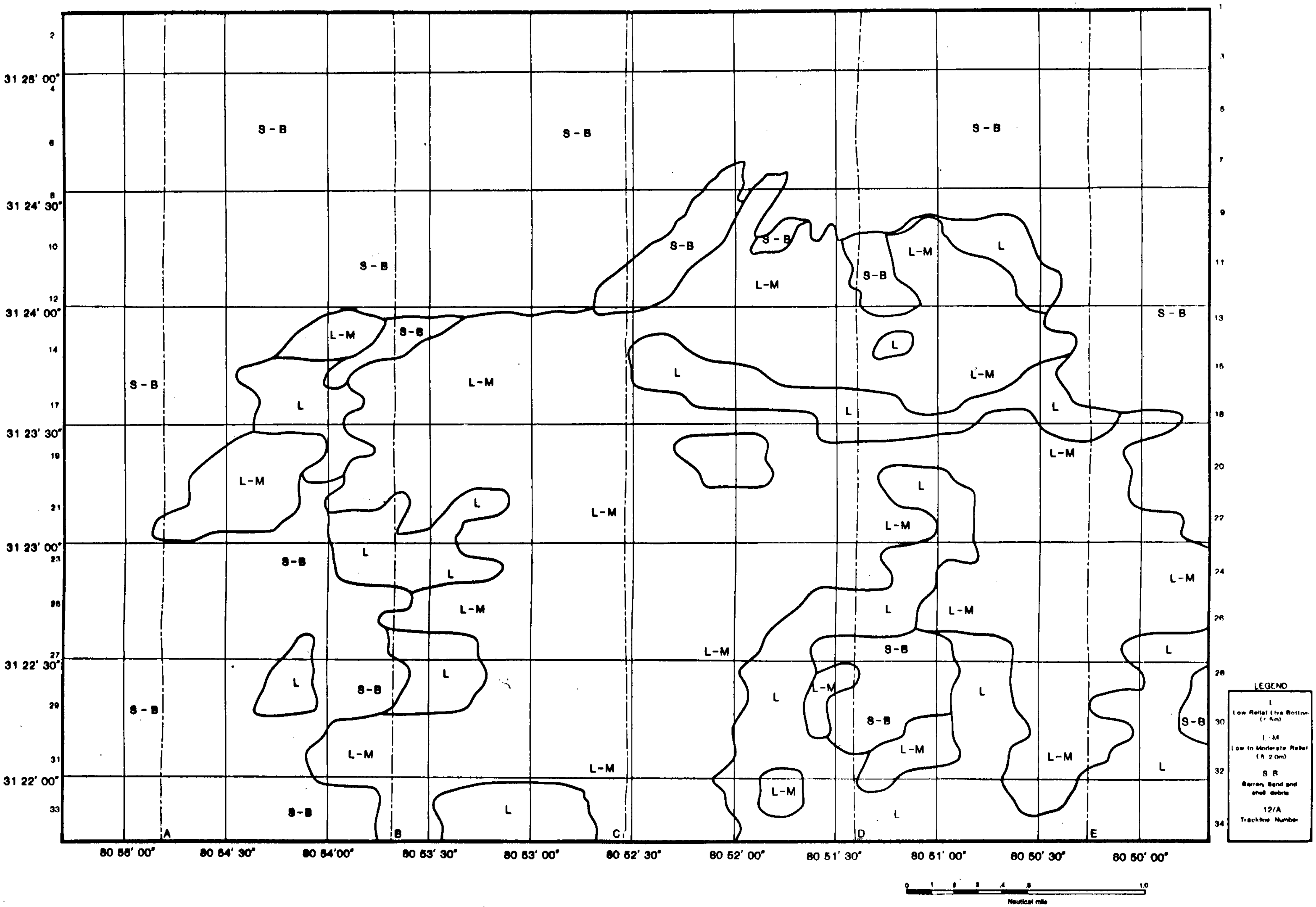
Thin Section PP 108

Classification: Calcareous Sandstone

Same as PP 106, 107, except both micrite and sparite present in matrix.

APPENDIX B

Photomicrographs of Selected Thin Sections from Rocks Collected on Gray's Reef National Marine Sanctuary


LEGEND
L
Low Relief Live Bottom
L-M
Low to Moderate Relief
S-B
Barren, Sand and shell debris
12/A
Trackline Number
31 25' 00"
31 24' 30"
31 24' 00"
31 23' 30"
31 23' 00"
31 22' 30"
31 22' 00"
80 55' 00"
80 54' 30"
80 54' 00"
80 53' 30"
80 53' 00"
80 52' 30"
80 52' 00"
80 51' 30"
80 51' 00"
80 50' 30"
80 50' 00"
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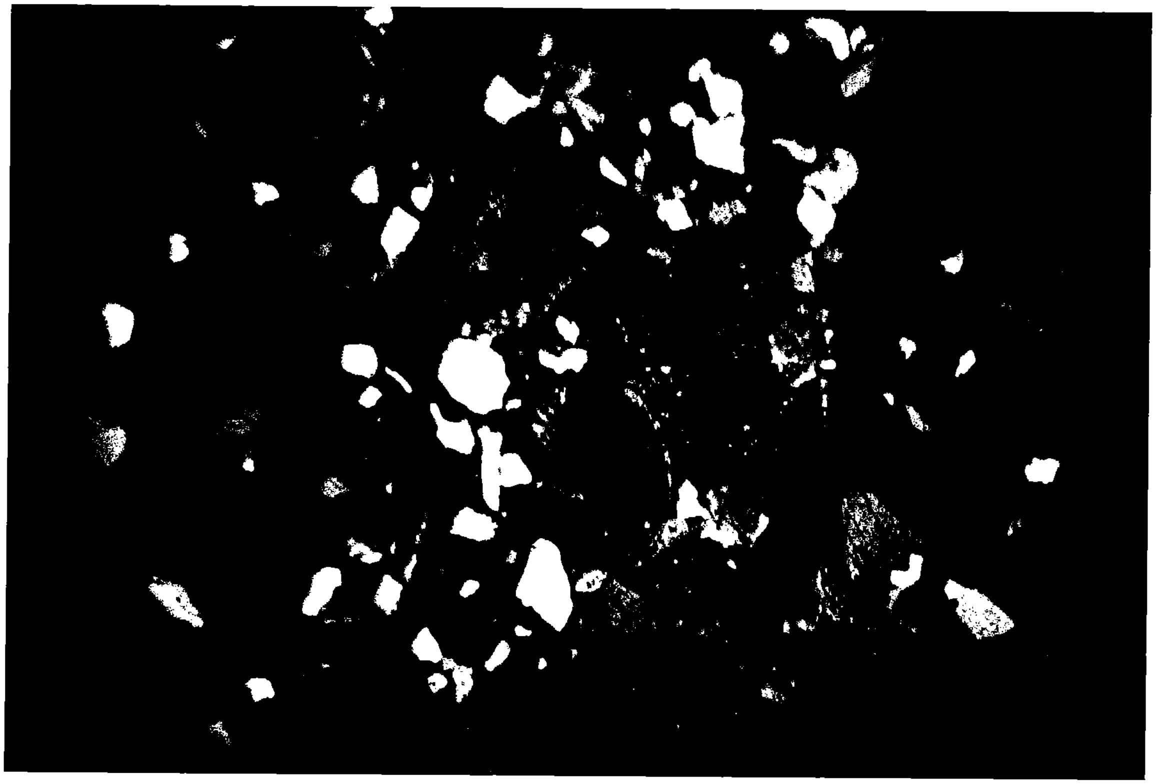
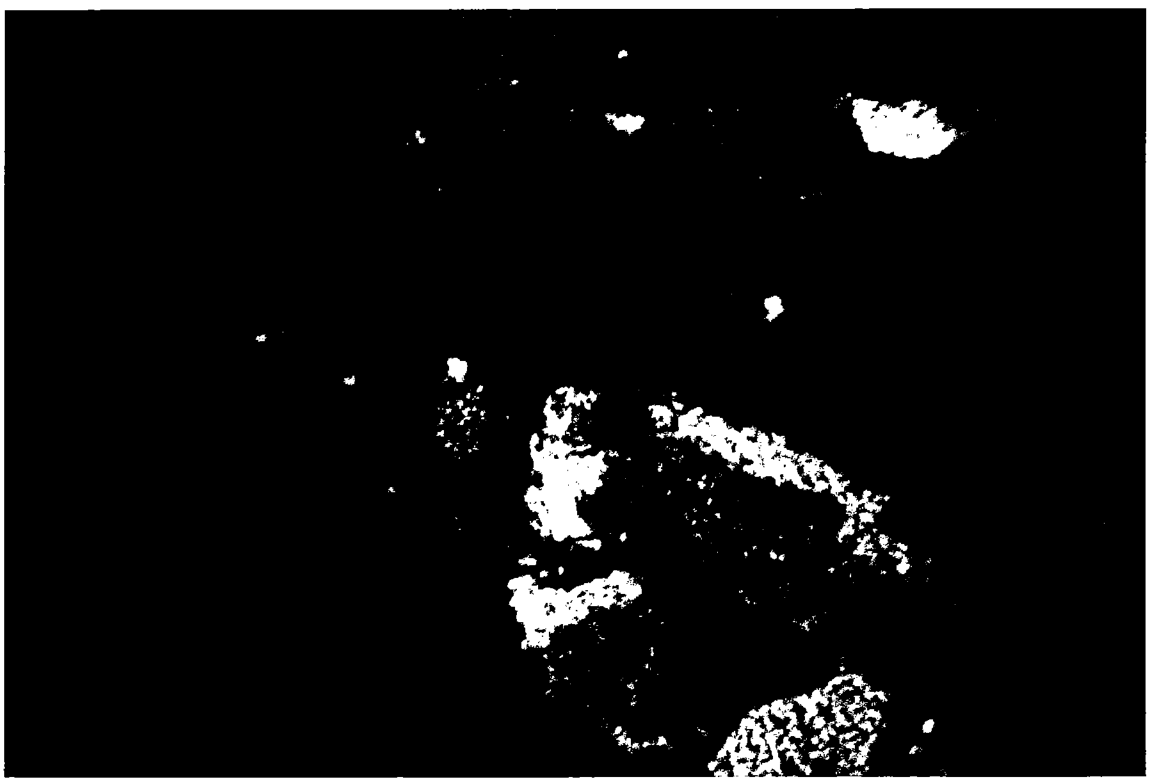
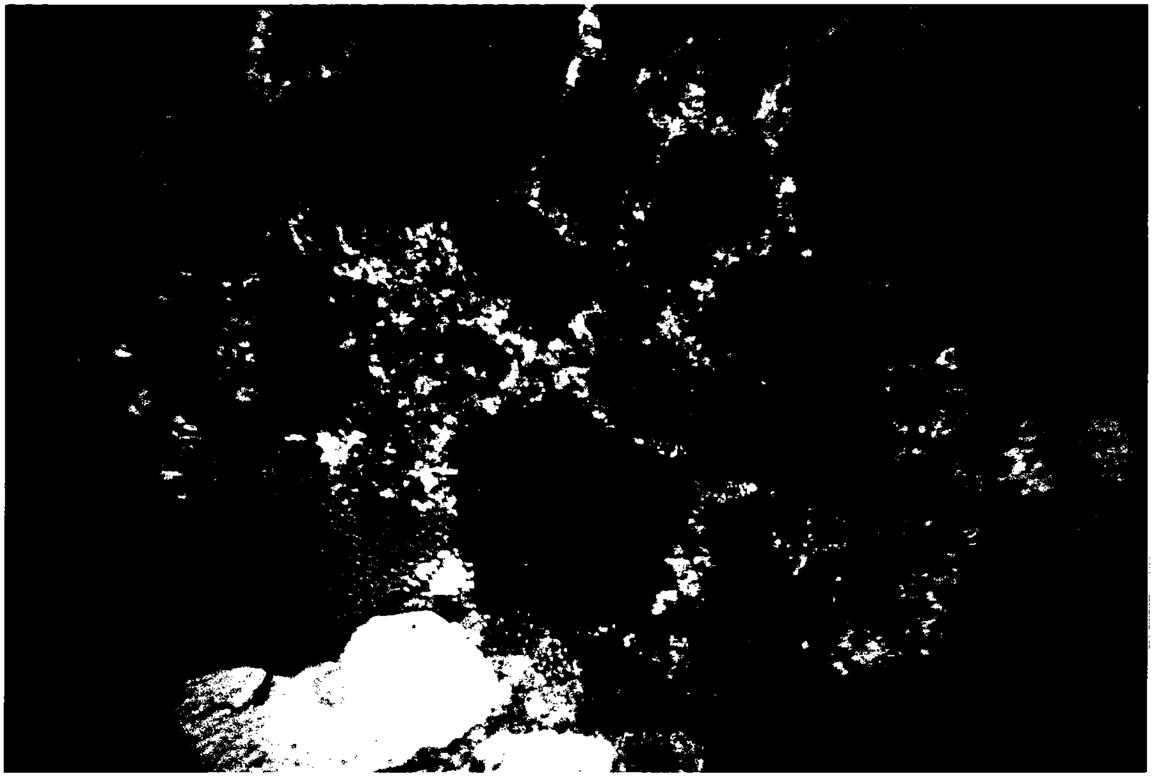
L
Nautical mile
0
1.0



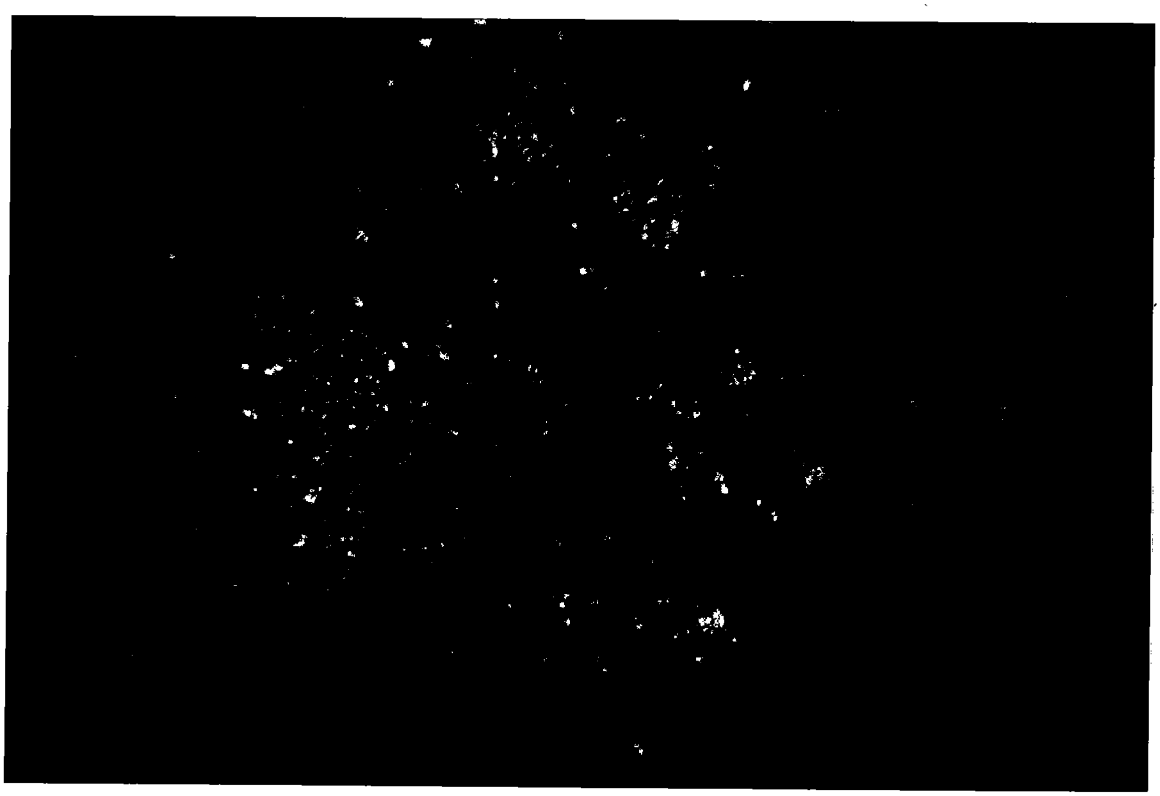
1) Biomicrite
Molluscan debris, quartz grains, cemented by micrite
Crossed Nicols x 150



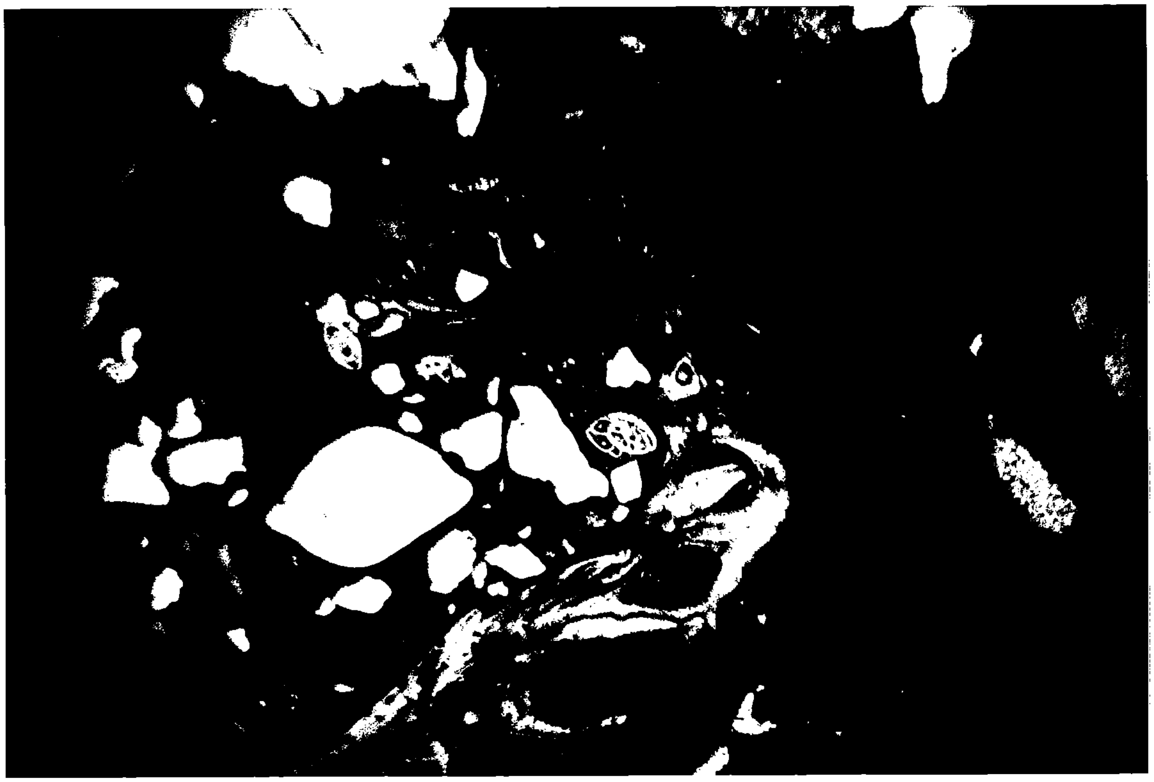
2) Biomicrite
Molluscan debris, foraminifera, quartz, cemented by micrite
Crossed Nicols x 250



3) Biosparite
Quartz grains, molluscan fragments, echinoid plate, plagioclase; cemented by sparry calcite. Crossed Nicols x 250



4) Sparite
Sparry calcite cement. Crossed Nicols x 250

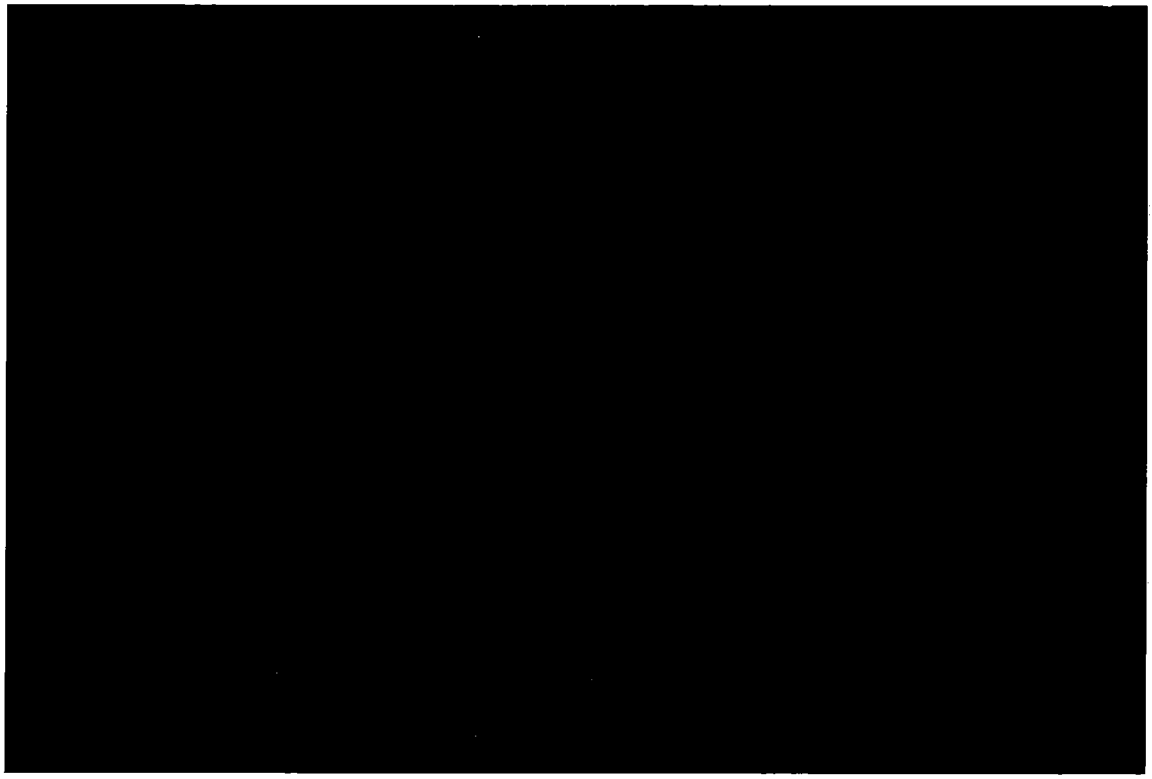


5) Boundstone

quartz grains, molluscan fragments, pellets, cemented by algae with dense micrite infilling. Crossed Nicols x 150

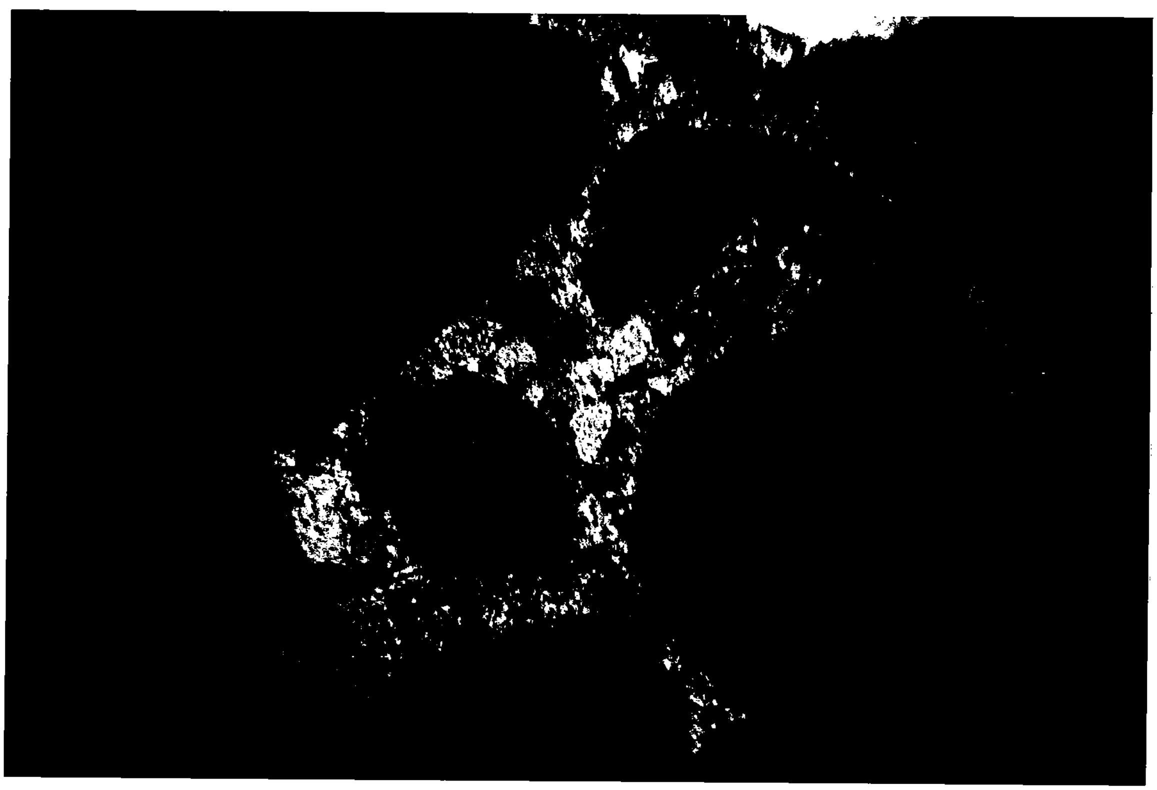
6) Boundstone

Coralline algae, infilled with micrite
Crossed Nicols x 150



7) Calcareous sandstone

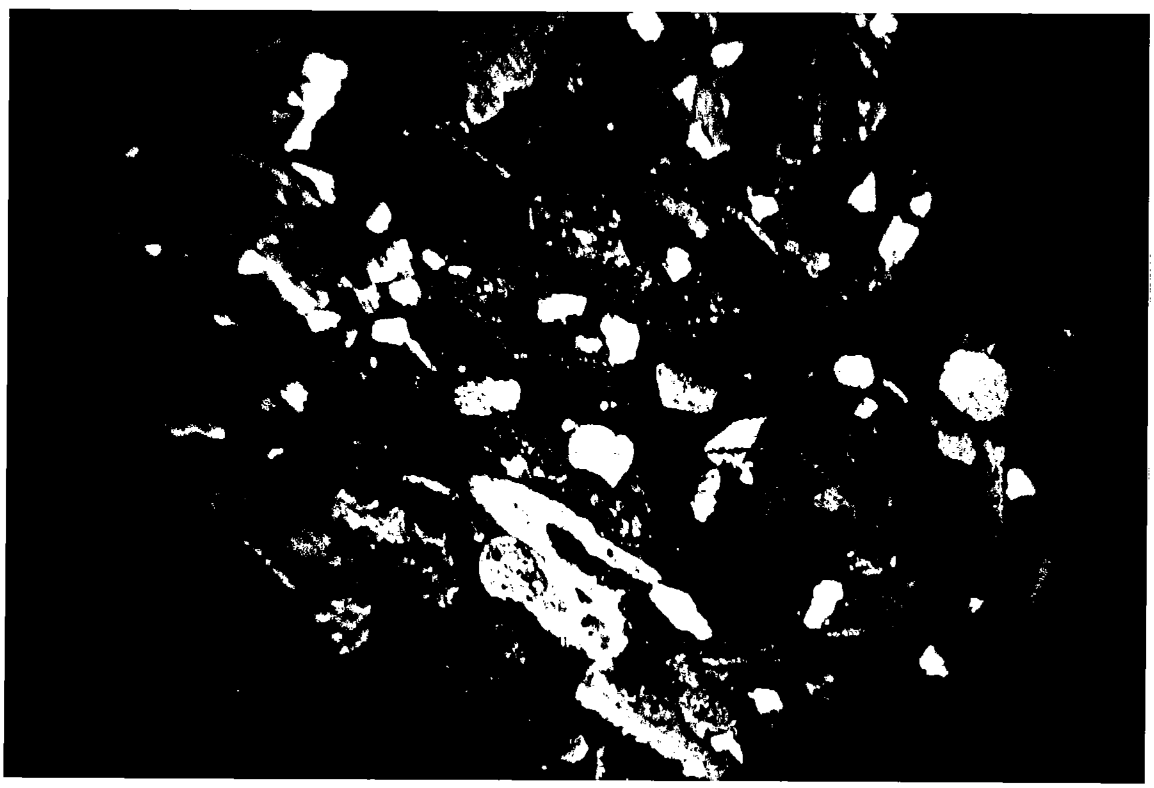
Quartz and feldspar grains, cemented by sparry calcite. Calcite appears to have formed by diagenesis from micrite (some of which is still present in intergranular areas. Plain light x 150



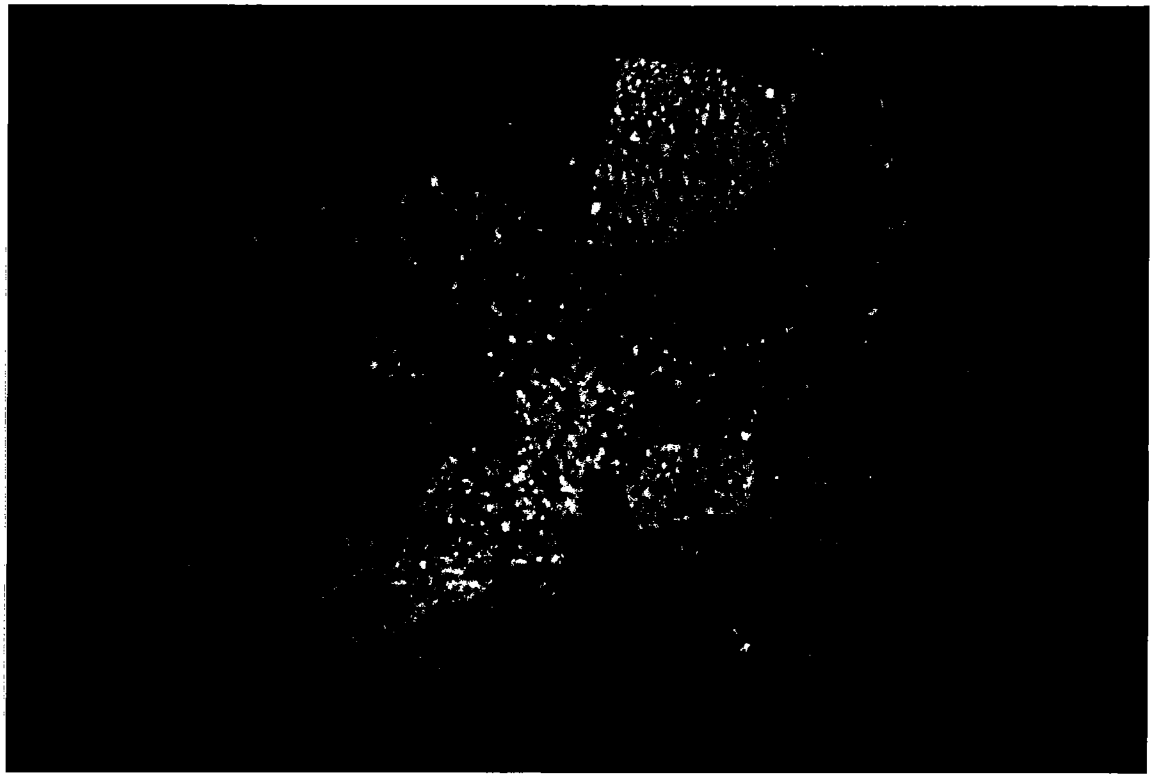
8) Calcareous sandstone

Quartz grains cemented by sparry calcite. Crossed Nicols x 250

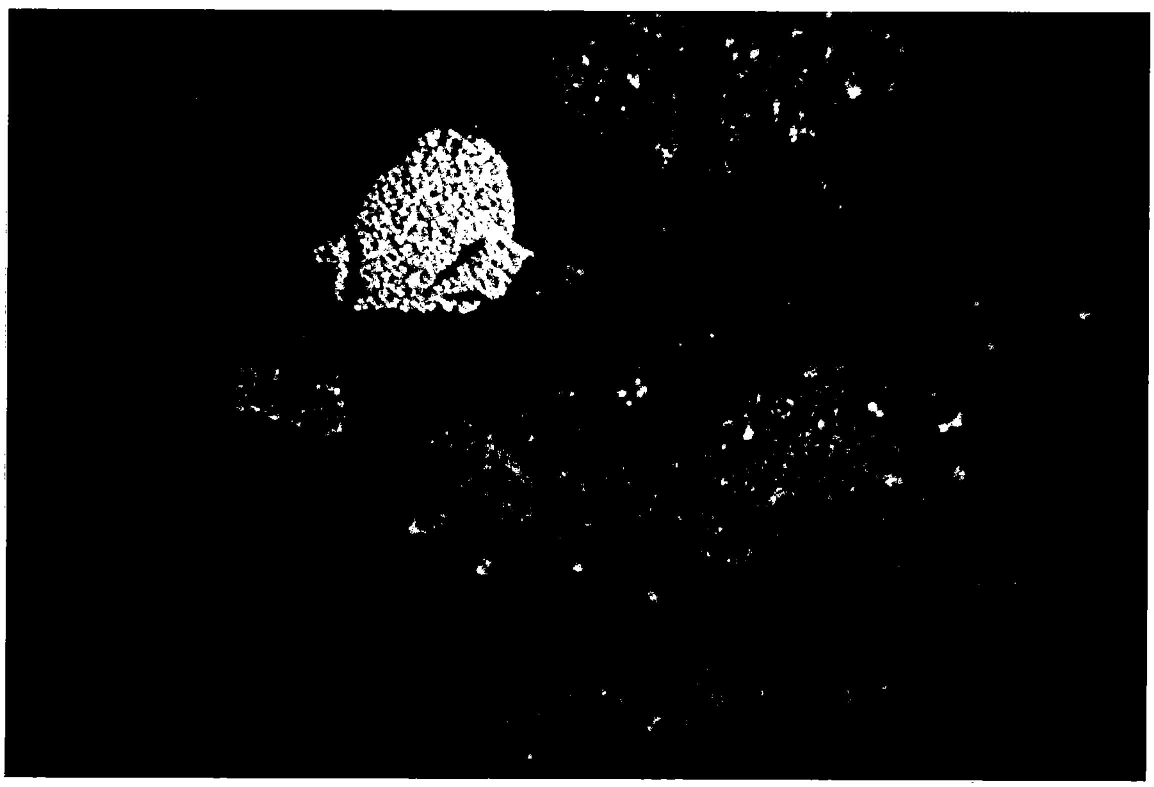
9) Calcareous sandstone
Crossed Nicols x 250



10) Arenaceous biomicrite
Quartz and feldspar grains, admixed with molluscan debris; high degree of grain support. Crossed Nicols x 150



11) Dolomitic limestone
Small rhoms of dolomite formed at expense of micrite cement. Two quartz grains and one shell fragment shown. Crossed Nicols x 250

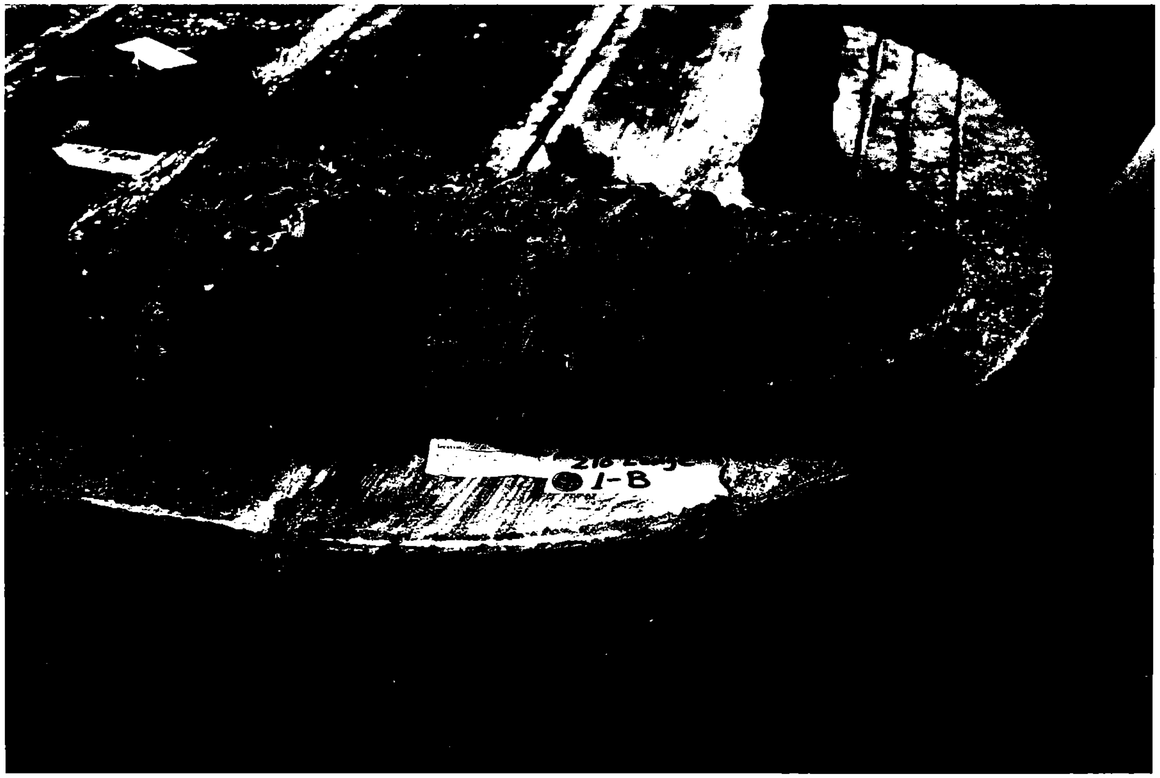


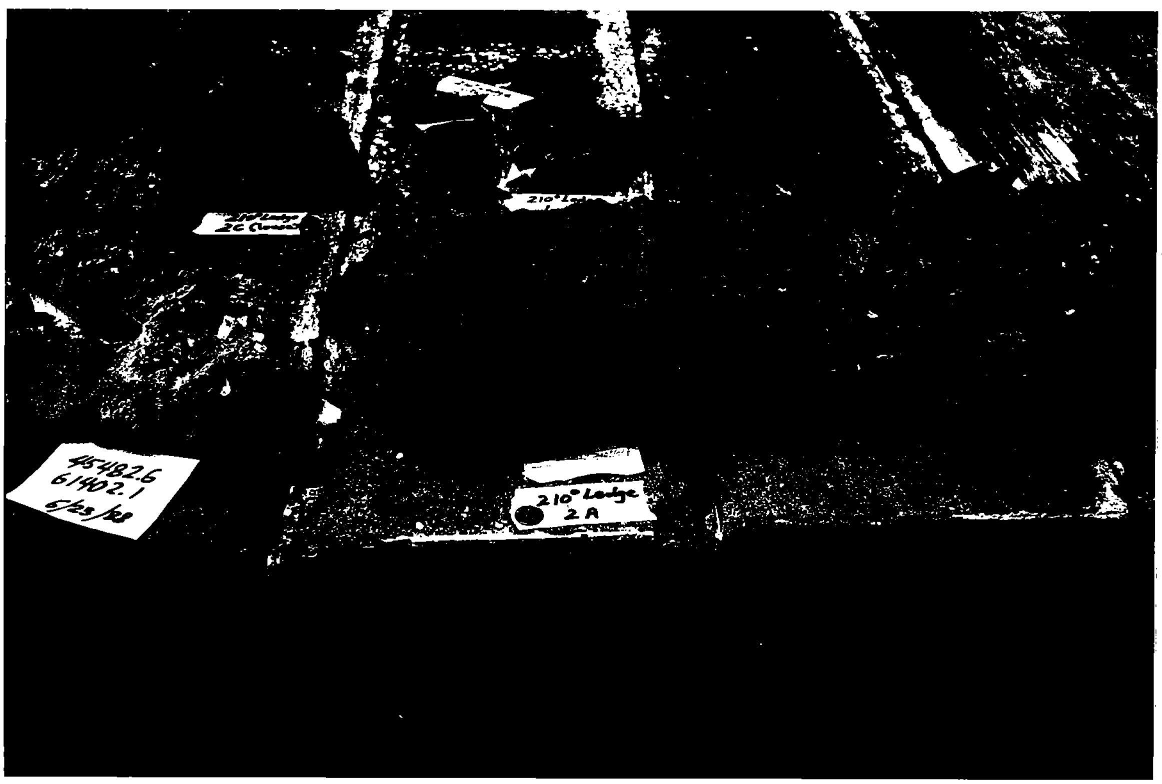
12) Dolomitic limestone
Small rhoms of dolomite in left portion of photo; right portion contains micrite cement. Crossed Nicols x 250

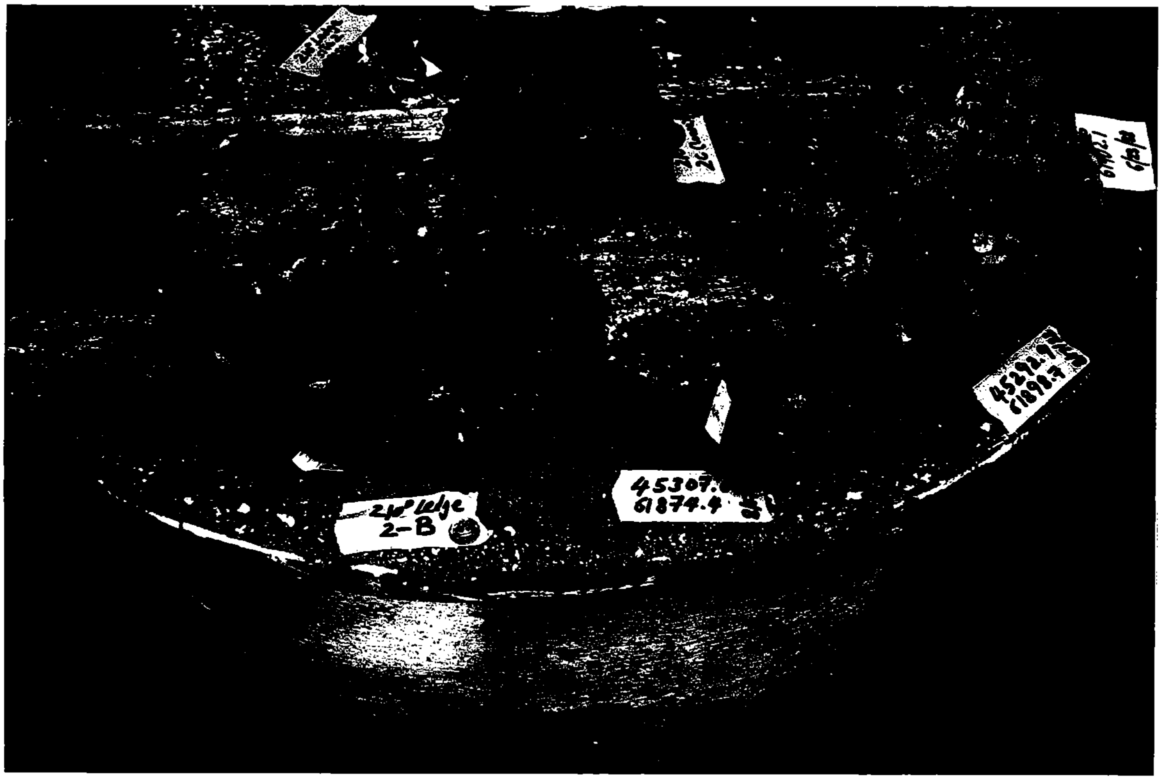
APPENDIX C

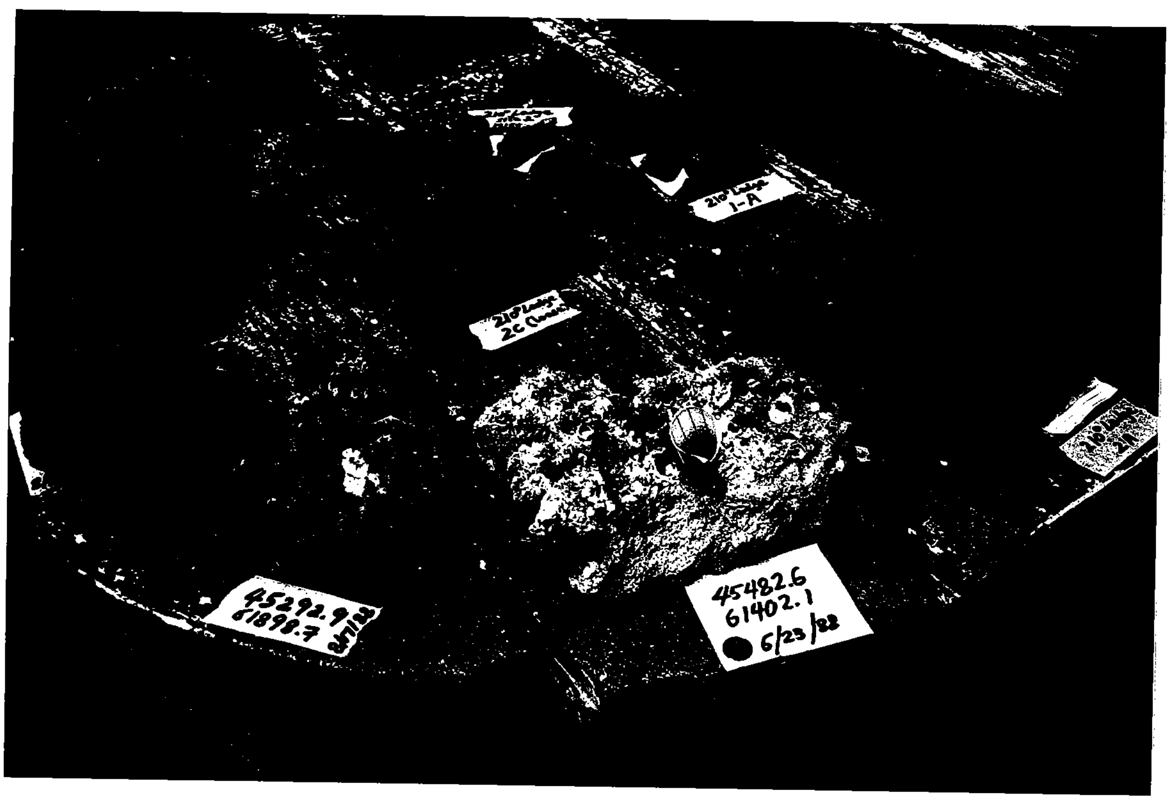
Rock Specimens from Gray's Reef

Prior to Thin Sectioning


1-B


454826
614021
6/23/08
210° Ledge
2 A


2-B
61874.4


1-A
45292.9
61898.7
45482.6
61402.1
6/23/82