SPECIAL PUBLICATION 7 FAUNAL AND DIAGENETIC CONTROLS OF POROSITY AND PERMEABILITY IN TERTIARY AQUIFER CARBONATES, NORTH CAROLINA

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By
Paul A. Thayer and Daniel A. Textoris

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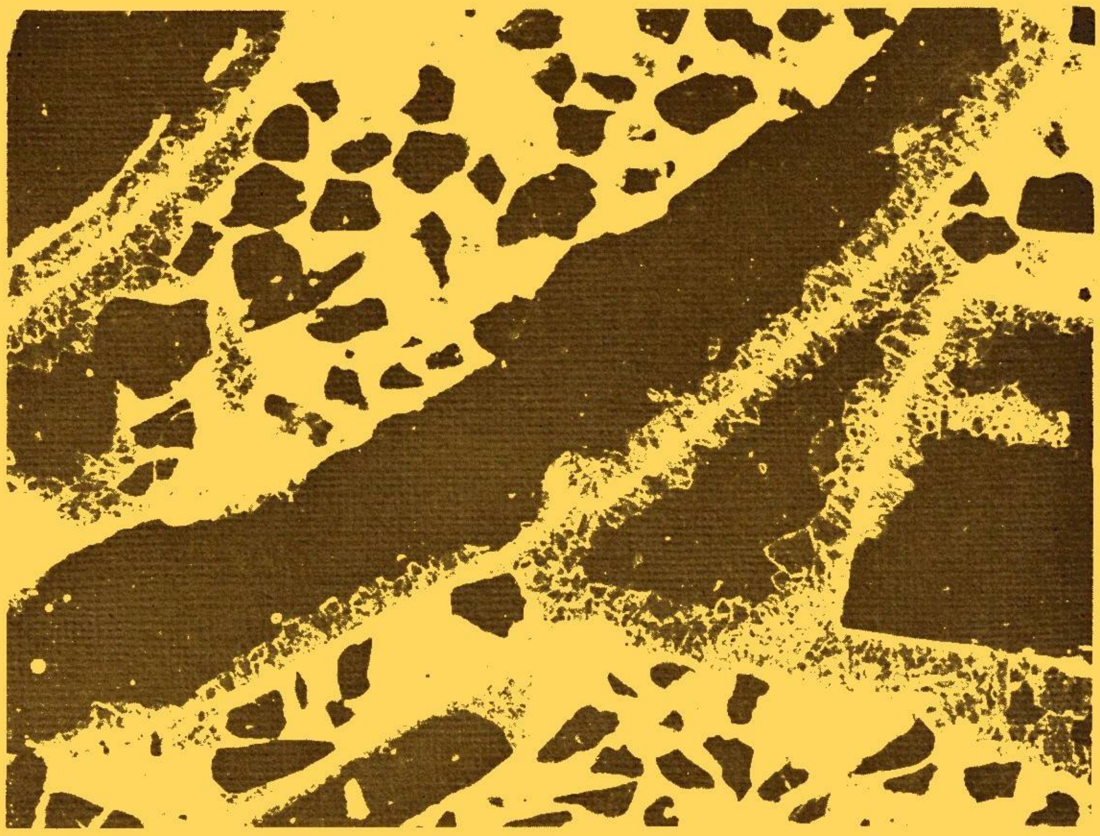

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DEPARTMENT OF NATURAL AND ECONOMIC RESOURCES
DIVISION OF EARTH RESOURCES
GEOLOGY AND MINERAL RESOURCES SECTION

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COVER PHOTO: MICROPHOTOGRAPH OF CASTLE HAYNE LIMESTONE
SHOWING CARBONATE CRYSTALS FORMING IN SHELL MOLDS

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FAUNAL AND DIAGENETIC CONTROLS OF POROSITY AND PERMEABILITY IN TERTIARY AQUIFER CARBONATES, NORTH CAROLINA

By Paul A. Thayer[1] and Daniel A. Textoris[2]

ABSTRACT

The Superior Stone Company quarry northwest of New Bern exposes sandy, molluscan-mold biomicrudite and biosparrudite assigned to the Eocene Castle Hayne Limestone 30.19 ft (9.2 m) and an overlying unnamed Oligocene unit 6.6 ft (2 m).

Porosities in these units range from 9 to 42 percent (X = 25 percent, s = 8 percent). Ninety percent of the porosity is localized in meso- and megamolds formed by solution of aragonitic mollusk shells. Many of the molds have been solution-enlarged or partially reduced, whereas some have been completely filled with low-magnesium sparry calcite. Less abundant pore types include: meso- and megavugs, meso- and megachannels created by merging of solution-enlarged molds and vugs; mesointerparticle between clastic grains and allochems; meso-intraparticle in bryozoans and foraminifers; microintercrystalline in micrite, peloids, and cement; and shelter. Porosity was chiefly controlled by: selective leaching of aragonite shells in the vadose zone, which produced molds, solution-enlarged molds, vugs, and channels; amount of filling of molds, vugs, channels, and interparticle pores by low-magnesium calcite precipitated from carbonate of allochthonous and autochthonous origins; amount of insoluble residue; amount of micrite and degree to which it aggraded by neomorphism to microspar and pseudospar.

Permeabilities show extreme variability, ranging from 0.1 to 15,400 md (X = 1,329 md, s = 3,231 md). High values are associated with large well-connected molluscan molds due to intimate packing of original skeletal debris, and small amounts of low-magnesium calcite filling the molds.

INTRODUCTION

GENERAL

During the last 25 years a number of geologists (Adams, 1953;

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Edie, 1958; Powers, 1962; Thomas, 1962; Choquette and Traut, 1963; Klovan, 1964; Harbaugh, 1967; Textoris, 1967 and 1969; Rauch and White, 1970; Thayer, 1972; and Textoris and others, 1972) have stressed the importance of facies-selective porosity in the development of carbonate reservoirs and aquifers. According to this concept, variations in carbonate facies reflect differences in ancient depositional environments and fossil communities, which, in turn, dominantly control development of primary and secondary pore systems in carbonate rocks. Thus, systematic petrology, paleoecology, and the study of diagenesis, and nature of pore systems in carbonate rocks can be rewarding to more successful economic exploration for oil and gas reservoirs, ground-water aquifers, and mineral deposits.

This paper presents an in-depth study of the nature and origin of pore systems in Tertiary aquifer carbonates near New Bern, North Carolina. Our objectives are 1) to demonstrate the relationship between pore-system evolution and faunal and lithologic parameters, originally controlled by ancient depositional environments and fossil communities; 2) to determine the effect of subsequent diagenesis on porosity and permeability, and 3) to ascertain what sedimentary properties directly control porosity and permeability.

LOCATION AND REGIONAL STRATIGRAPHY

The locality chosen for this study is the Superior Stone Company quarry, located 4.5 mi. (7.2 kilometers) northwest of New Bern, North Carolina (fig. 1). Here, 30.19 ft (9.2 meters) of Middle and Upper Eocene Castle Hayne Limestone (Brown, 1963, p. 32) is disconformably overlain by 6.6 ft (2 m) of an unnamed Oligocene carbonate unit (Brown, 1963, p. 33). Because of lithologic similarity, both are included in the Castle Hayne aquifer system (Textoris, 1967), which is the most important one in eastern North Carolina.

Castle Hayne and Oligocene strata crop out in an elongate belt along the eastern edge of the North Carolina Coastal Plain (fig. 1) and thicken downdip in the subsurface toward the sea. Outcrop thickness of the Castle Hayne is variable, ranging to a maximum of approximately 49.2 ft (15 m)(Richards, 1967), and thickening downdip to 649.44 ft (198 m) in the Cape Hatteras well (Maher, 1971, pl. 12). At present little is known about areal extent or thickness variations of the Oligocene stratum. The carbonates under discussion

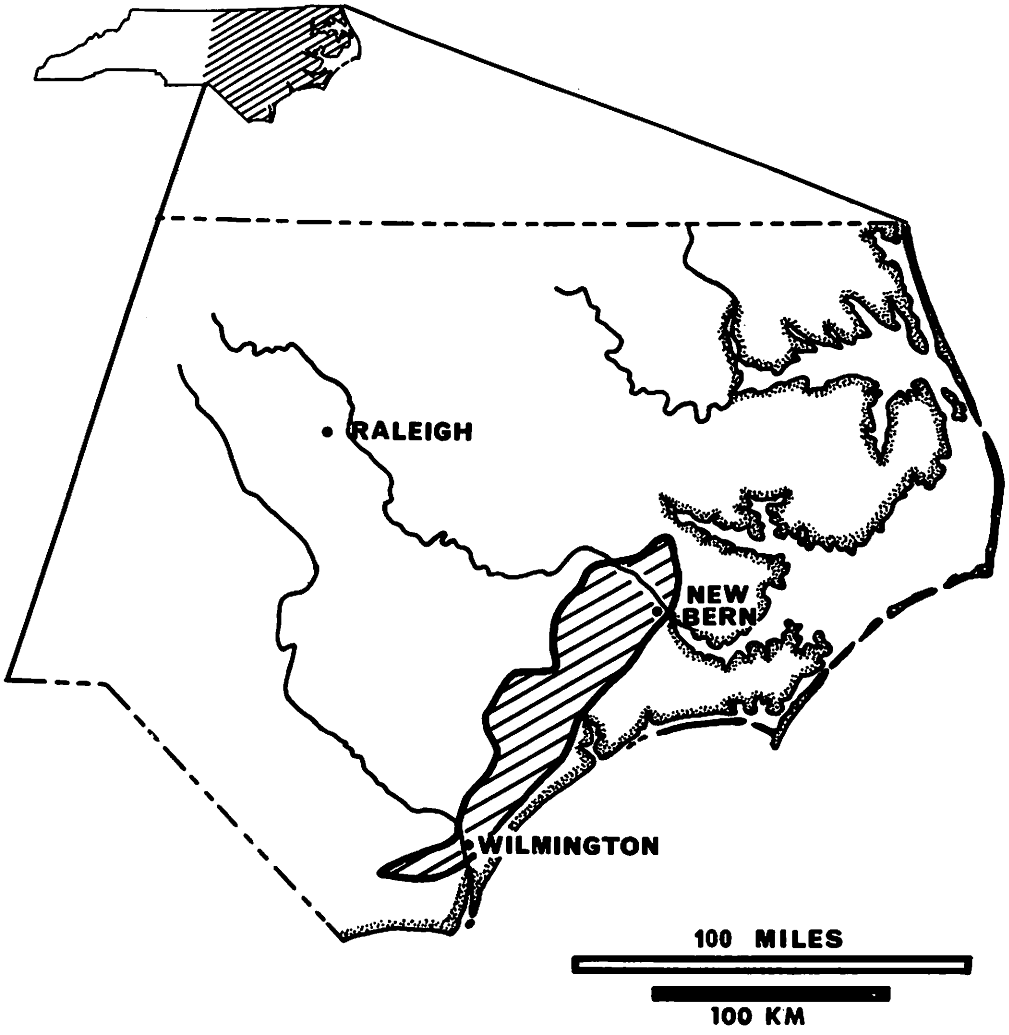

Figure 1.--Location of New Bern and outcrop belt of Eocene Castle Hayne Limestone and related strata of the aquifer system in eastern North Carolina.

have never been buried very deeply, and have not, therefore, undergone the mesogenetic phase of diagenesis defined by Choquette and Pray (1970). The early and late stages merged; that is, the eogenetic and telogenetic. Additional information on regional relations of the Castle Hayne Limestone and associated carbonates of the aquifer system are in Thayer and Textoris (1972), Brown and others (1972), Baum and others (1977), and Harris and others (1977).

PREVIOUS WORK

Reports on hydrology of the Castle Hayne aquifer system have been presented by Bain (1970), Blankenship (1965), Brown (1958, 1959), DeWiest, Sayre, and Jacob (1967), LeGrand (1960), Lloyd (1968), Lloyd and Floyd (1968), Pusey (1960), and Sumsion (1970). Regional reports dealing with Tertiary aquifer carbonates along the southeastern United States Coastal Plain include Stringfield and LeGrand (1966), LeGrand and Stringfield (1966), and Stringfield (1966).

Papers concerned with detailed petrographic and diagenetic aspects of the Castle Hayne aquifer system include Textoris (1967), Cunliffe (1968), Cunliffe and Textoris (1969), Thayer (1972), Thayer and Textoris (1972), Upchurch (1973), Upchurch and Textoris (1973), and Harris (1975). Textoris, Randazzo, and Thayer (1972) related petrologic and diagenetic information to origin of porosity in Cretaceous and Tertiary carbonates of the southeastern Atlantic Coastal Plain. The Castle Hayne aquifer is included in their discussion. Their paper, and the one by Thayer and Textoris (1972) present detail on the New Bern section under discussion here. Thayer and Textoris (1972) present evidence that the Castle Hayne is primarily a low energy, shallow marine bank deposit, and the Oligocene unit is an inner or middle shelf deposit that accumulated below wave base.

METHODS

Fifty-eight closely spaced samples were collected from a composite vertical section (fig. 2) measured in the Superior Stone Company quarry near New Bern, North Carolina. Porosity and permeability values were measured for 30 of the samples (core plugs parallel to bedding) by standard commercial techniques. In addition, rock

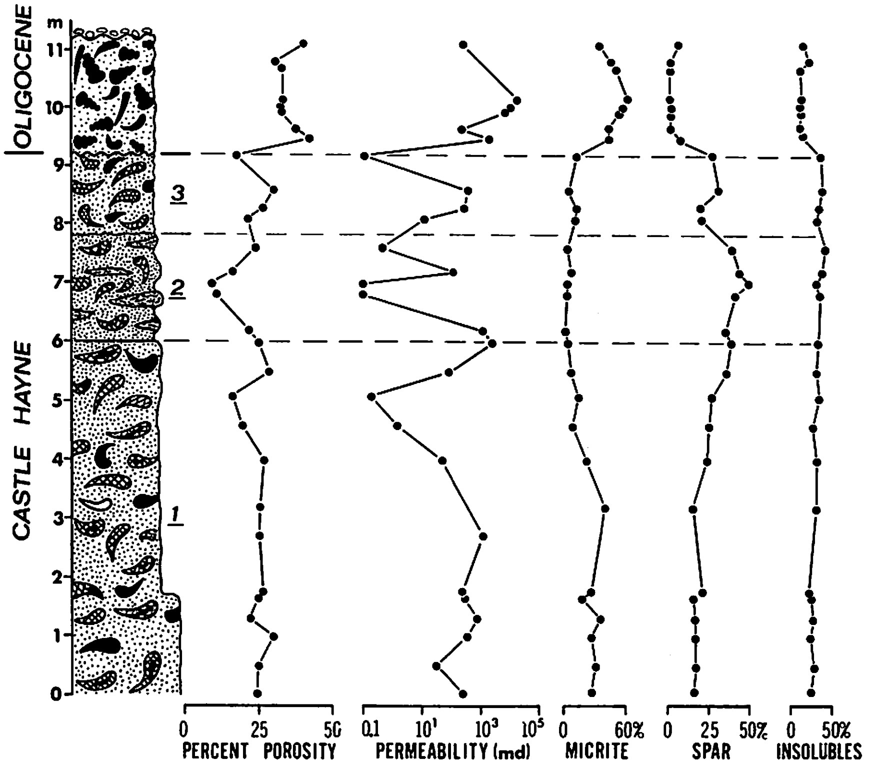

Figure 2.--Composite section at Superior Stone Company quarry, New Bern, North Carolina. In the Castle Hayne part, unit 1 = sandy, pelecypod-mold biomicrudite, with pseudospar matrix; unit 2 = sandy, pelecypod-mold biosparite and biosparrudite; unit 3 = sandy, pelecypod-mold biomicrudite, with pseudospar matrix. The Oligocene unit is a sandy, molluscan-mold biomicrudite. On the section, matrix is shown with a stippled pattern, spar filling of molds is a crosshatched pattern, voids are black, and original fossil shells are white. Porosity and permeability data were obtained by standard commercial methods, micrite and spar (both neomorphic and void-filling) data were obtained by point counting thin sections and are shown as volume percent, and insoluble residue data are shown as weight percent.

slabs, thin sections, and insoluble residues were prepared. Forty-four etched rock slabs were studied for texture, fabric, sedimentary structures, and fossil types. Volume-percent composition, including micrite and calcite spar, was determined by point counting 36 oversize thin-sections. Carbonate staining procedures and X-ray diffraction were used for carbonate mineral identifications. Insoluble residues were obtained from 49 samples and the results are presented here as weight percentages. Percentages of various porosity types were determined by point counting rock slabs and thin-sections. Porosity terminology of Choquette and Pray (1970) and the limestone classification of Folk (1959) are used.

ACKNOWLEDGMENTS

Field and laboratory work was supported by Texas A and I University Faculty Research Grant 449-G-70 to Thayer, and University of North Carolina Research Council grants to Textoris. M. L. Upchurch assisted in the field. G. B. Love and D. A. Morrill aided with much of the laboratory work. Fossils were identified by C. G. Lalicker, Jeremy Reiskind, and Victor Zullo.

RESULTS

PETROLOGY

Figure 2 shows the vertical section at the quarry. The lower 30.19 ft (9.2 m) consists of three units of the Eocene Castle Hayne Limestone, and the upper unit is 6.6 ft (2 m) of an unnamed Oligocene stratum. The carbonate in the section is entirely low-Mg (low-magnesium) calcite. Petrographic details are given in Thayer and Textoris (1972), and only a summary is presented here.

The lowest unit of the Castle Hayne Limestone (fig. 2, unit 1) is a sandy, pelecypod-mold biomicrudite, with pseudospar matrix (fig. 3). It consists of 30 percent molds of pelecypods in various stages of filling by low-Mg calcite cement. The pelecypods, other allochems (gastropod, foraminifer, bryozoan, echinoderm, ostracode, bone, intraclast, peloid, and glauconite), and quartz are set in microspar and pseudospar that originated by aggrading neomorphism of an original peloid and micrite matrix. The pelecypods are mainly *Macrocallista*; however, *Panope, Phacoides,* and *Glycimeris* also are common. Rare types are *Crassatellites, Pecten, Venericardia,* and *Ostrea.* Micrite averages 22 percent and calcite spar is 16 to 35 percent. The latter includes both microspar and pseudospar, and true void-filling spar. Insoluble residue averages 28 percent.

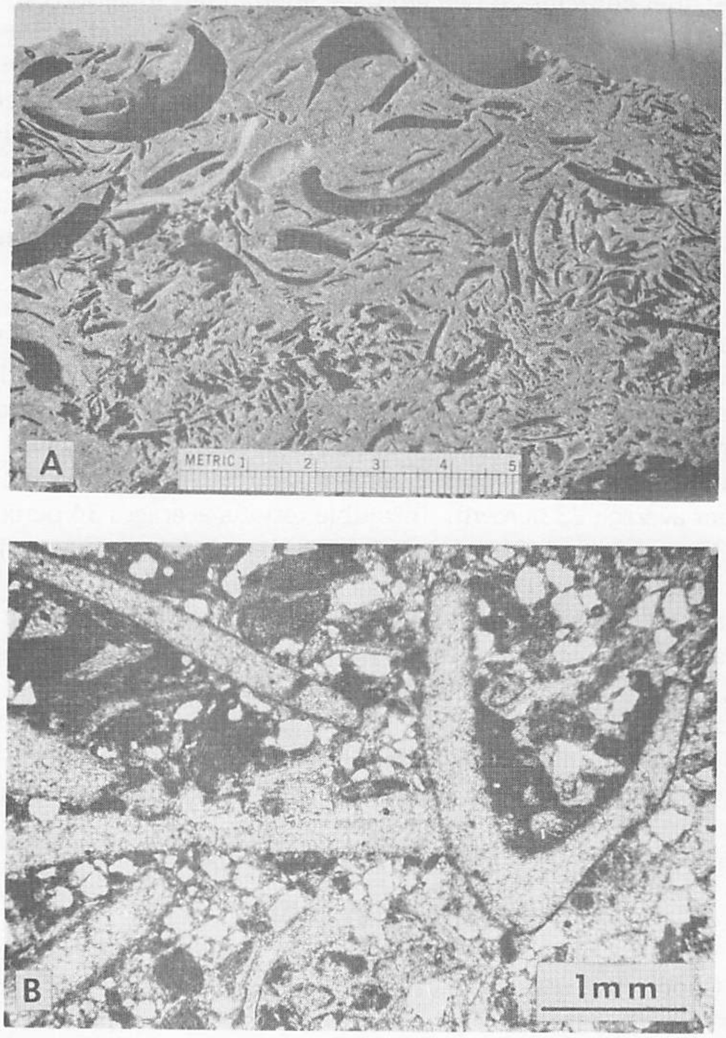

Figure 3.--Sandy, pelecypod-mold biomicrudite with pseudospar matrix, unit 1 of Castle Hayne Limestone.

A. Polished slab showing texture and moldic porosity.

B. Thin section showing several pelecypod valves (originally aragonite) that were dissolved and subsequently filled with low-Mg sparry calcite. Valves are outlined by micrite envelopes. Pelecypod allochems, along with echinoderms, peloids, and quartz grains are set in low-Mg calcite pseudospar. Plain light.

Unit 2 is a sandy, pelecypod-mold biosparite and biosparrudite (fig. 4) that contains 26 percent pelecypod molds in various stages of filling by low-Mg calcite cement. These and other allochems and quartz are cemented by void-filling low-Mg calcite. In the northwestern part of the quarry, this unit grades into quartz sand and calcite-cemented quartz sandstone. Data for the sand facies are not given in figure 2. Pelecypod types are similar to those in the unit below, as are other allochems. The amount of micrite is low. Sparry calcite, as interparticle pore filling and mold filling, averages 41 percent. Insoluble residue averages 36 percent.

The third unit is a sandy, pelecypod-mold biomicrudite, with pseudospar matrix (fig. 5). This unit is lithologically similar to the lowest unit. Fossil content is nearly identical with that of the lowest unit except for a higher percentage of pelecypod molds (average 34 percent). *Venericardia, Glycimeris,* and *Pecten* are slightly more abundant. Micrite averages 9 percent, and neomorphic and void-filling spar average 23 percent. Insoluble residue averages 34 percent.

The unnamed Oligocene stratum is a sandy, molluscan-mold biomicrudite (fig. 6) consisting of 21 percent pelecypod valves (as molds) and unaltered oyster shells. Turritellid and naticid gastropod molds form 11 percent of the rock. Other allochems include scaphopods, forminifers, echinoderms, ostracodes, nautiloids, and bone, and some peloids, intraclasts, and glauconite. Along with quartz, these are set in micrite (average 49 percent). Insoluble residue averages 12 percent. Sparry calcite averages 8 percent, and occurs as partial or complete fillings of some molluscan molds. Remnants of original aragonite shell fill some turritellid molds.

DESCRIPTION OF PORE TYPES

Choquette and Pray (1970) classified a number of porosity types in carbonate rocks on the basis of whether the pores are fabric selective, not fabric selective, or fabric selective or not. We have selected from their classification the basic pore types that are common in the rocks we are studying (fig. 7). Further, we have adopted modifying terms as shown in figure 8 to indicate the size of a pore. Examples of moldic porosity are shown in figures 3 to 6 and 9A. This is the most common pore type, constituting 90 percent of total porosity. Other porosity types, as defined in figure 7, are illustrated with photomicrographs in figures 9B to 12. Only fracture porosity is not illustrated.

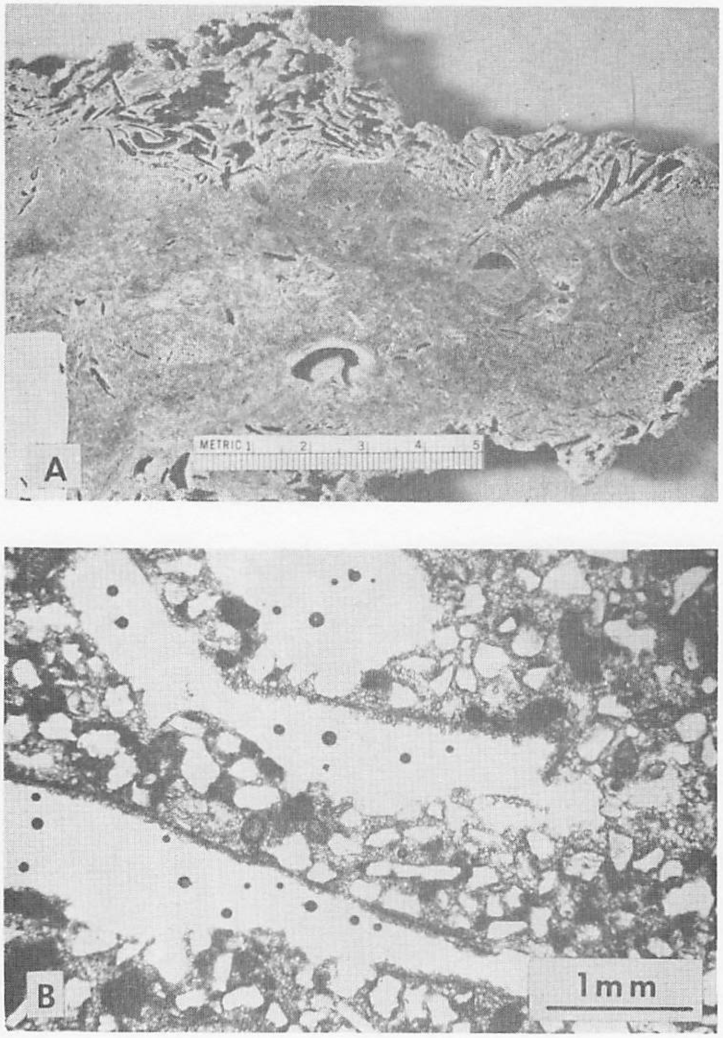

Figure 4.--Sandy, pelecypod-mold biosparite and biosparrudite, unit 2 of Castle Hayne Limestone.

A. Polished slab showing texture and moldic porosity.

B. Thin section showing three molds of pelecypod valves that were originally aragonite. Drusy low-Mg calcite crystals line most of the molds. These molds, along with peloids, intraclasts, and quartz grains are set in void-filling low-Mg calcite spar. Plain light.

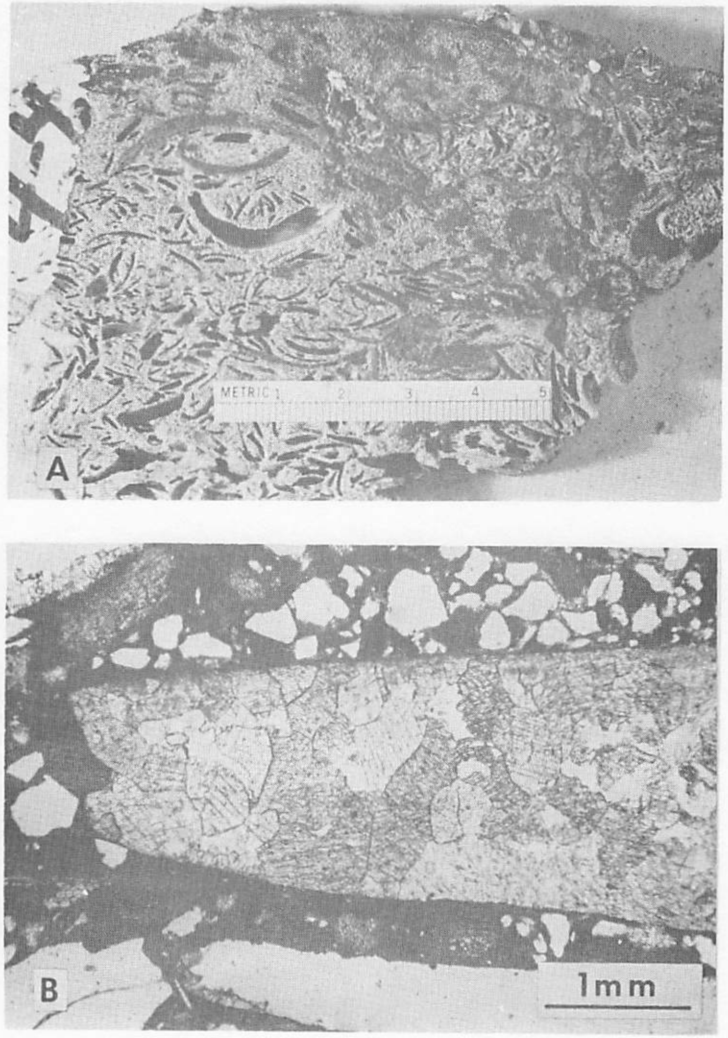

Figure 5.--Sandy, pelecypod-mold biomicrudite with pseudospar matrix, unit 3 of Castle Hayne Limestone.

A. Polished slab showing texture and moldic porosity.

B. Thin section showing a large low-Mg calcite spar-filled pelecypod mold in center, and two pelecypod molds at bottom. These, along with quartz grains are set in low-Mg micrite and microspar. Plain light.

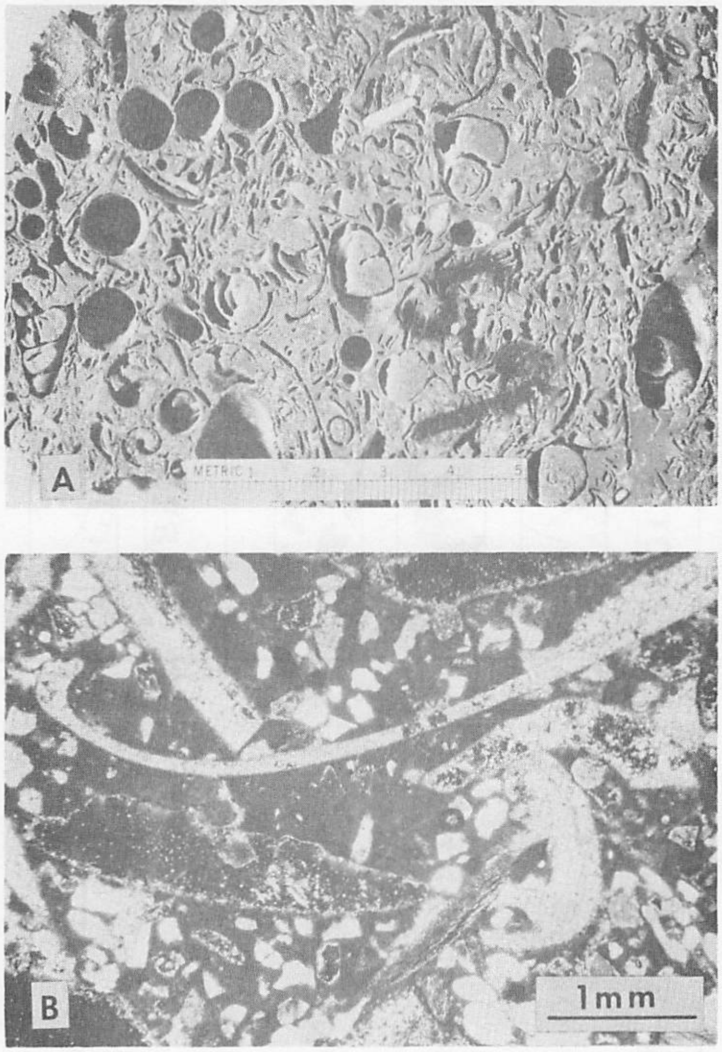

Figure 6.--Sandy, mollsucan-mold biomicrudite, unnamed Oligocene unit.

A. Polished slab showing texture and moldic porosity.

B. Thin section showing originally aragonitic molluscan allochems as molds, reduced molds, and molds completely filled with low-Mg calcite spar. These, with quartz grains are set in low-Mg micrite. Crossed nicols.

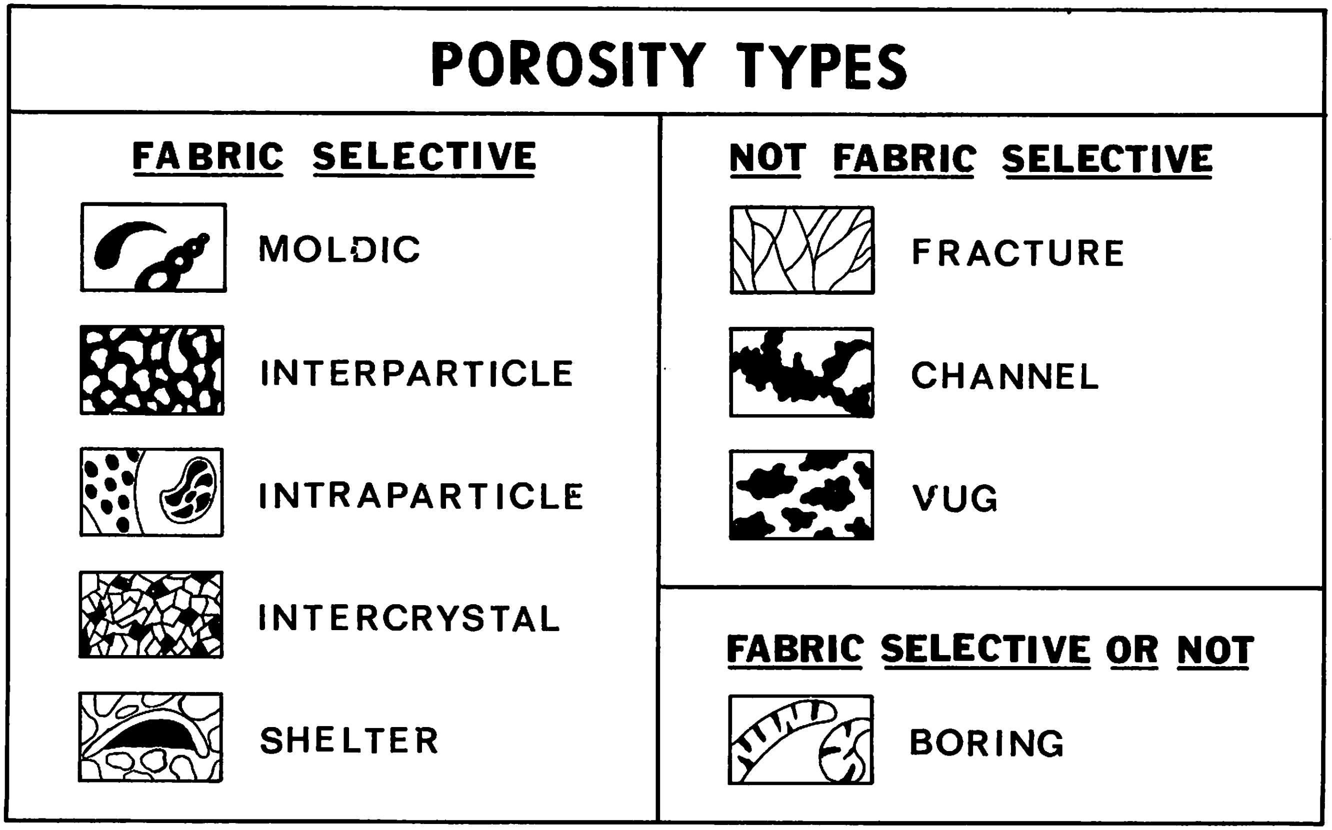

Figure 7.--Classification of basic pore types found in the New Bern quarry. (Modified from Choquette and Pray, 1970.)

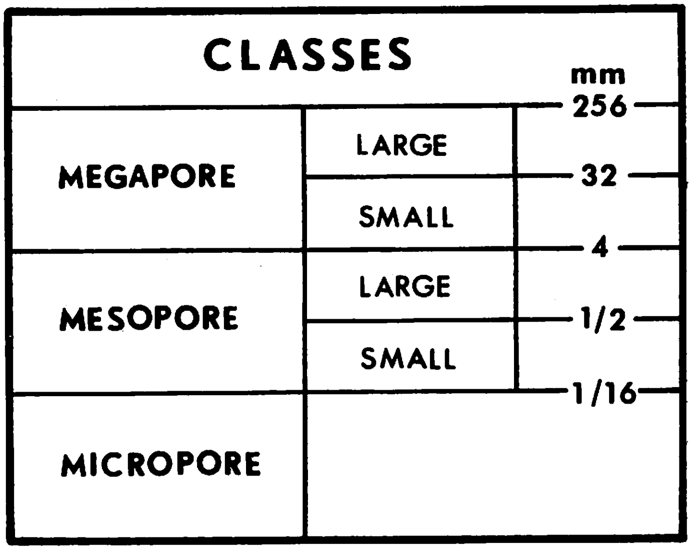

Figure 8.--Pore-size modifiers (from Choquette and Pray, 1970).

POROSITY AND PERMEABILITY IN THE CASTLE HAYNE LIMESTONE

UNIT 1

Porosity averages 25 percent (range 16 to 30 percent; fig. 2). Most pores are meso- and megamolds formed by solution of original aragonitic pelecypod valves, many of which show evidence of enlargement by solution. Permeability is 0.2 to 1,198 md (millidarcies) (average 289 md). High porosity and permeability values antecedent are related to abundance and close packing of pelecypod molds, an aspect of original sedimentation. Vug and channel (created by merging of solution-enlarged molds and vugs); interparticle; and intraparticle (in bryozoans and foraminifers) pore types are less abundant. Sponge borings, shelter zones, and intercrystal porosity are rare.

UNIT 2

Porosity averages 17 percent and ranges from 9 to 25 percent. Most pores are meso- and megamolds formed by solution of aragonitic

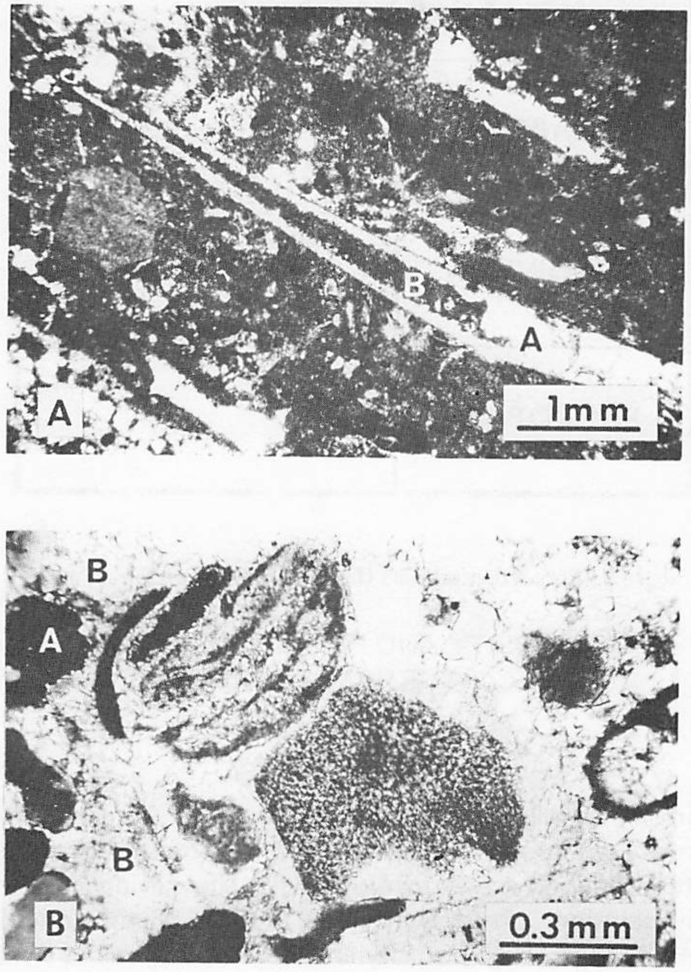

Figure 9.--A. An originally aragonitic pelecypod valve was dissolved producing a mold, which was subsequently partially reduced by low-Mg calcite spar (A) and then completely filled by the addition of internal sediment (micrite, B). Filling with internal sediment is rare. Unit 3 of Castle Hayne Limestone. Plain light.

B. Interparticle porosity (A), most of which has been reduced by low-Mg calcite spar cement (B). This pore type is rare. Unit 2 of Castle Hayne Limestone. Crossed Nicols.

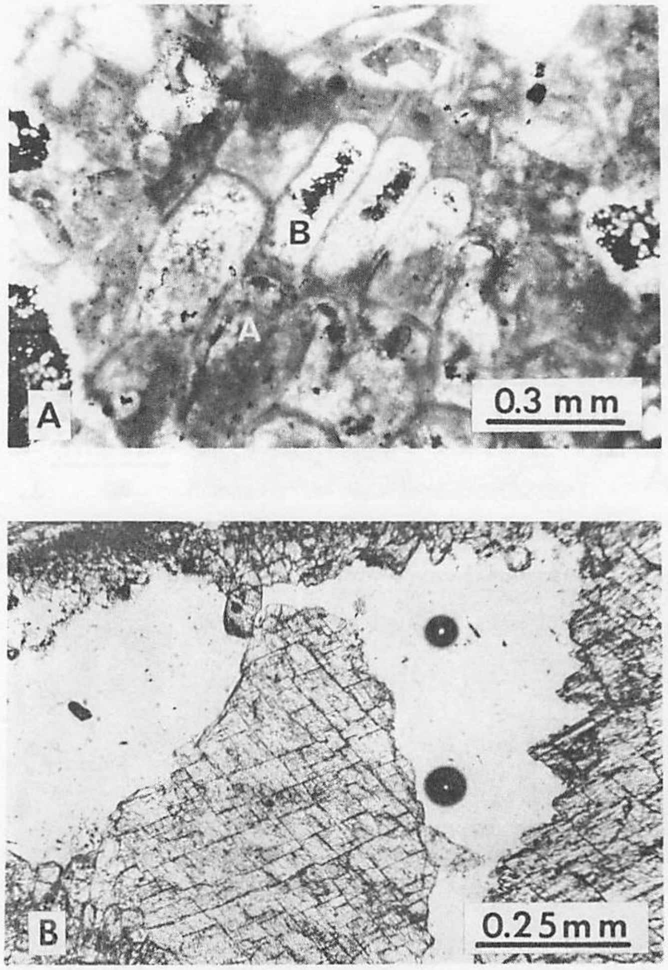

Figure 10.-- A. Partially reduced intraparticle porosity in a bryozoan allochem. Fillings of both micrite (A) and low-Mg calcite spar (B) are found. This pore type is rare. Unit 1 of Castle Hayne Limestone. Crossed nicols.

B. Intercrystal pores, rare, are located between equant and equal size calcite spar crystals. These could also be interpreted as partially reduced interparticle pores. Unit 2 of Castle Hayne Limestone. Plain light.

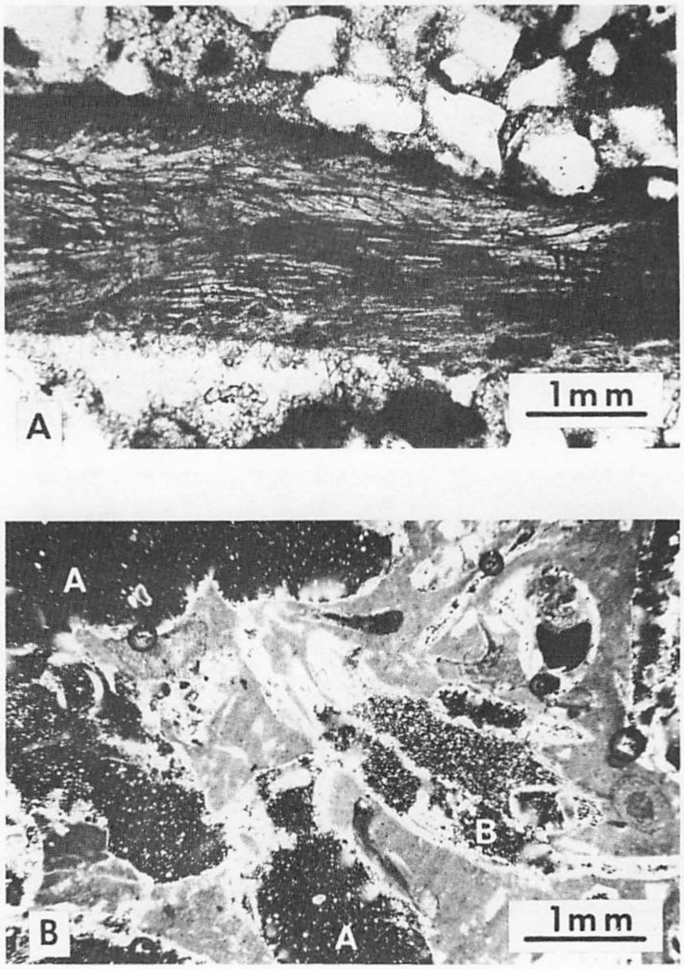

Figure 11.-- A. Partially reduced shelter porosity, a rare type, located beneath an original low-Mg calcite pelecypod valve. Drusy low-Mg calcite spar partially fills the pore. Unit 1 of Castle Hayne Limestone. Plain light.

B. Channel porosity (A), a common type, associated with molds of pelecypods (B) from which channels evolved by solution enlargement. Unnamed Oligocene unit. Crossed nicols.

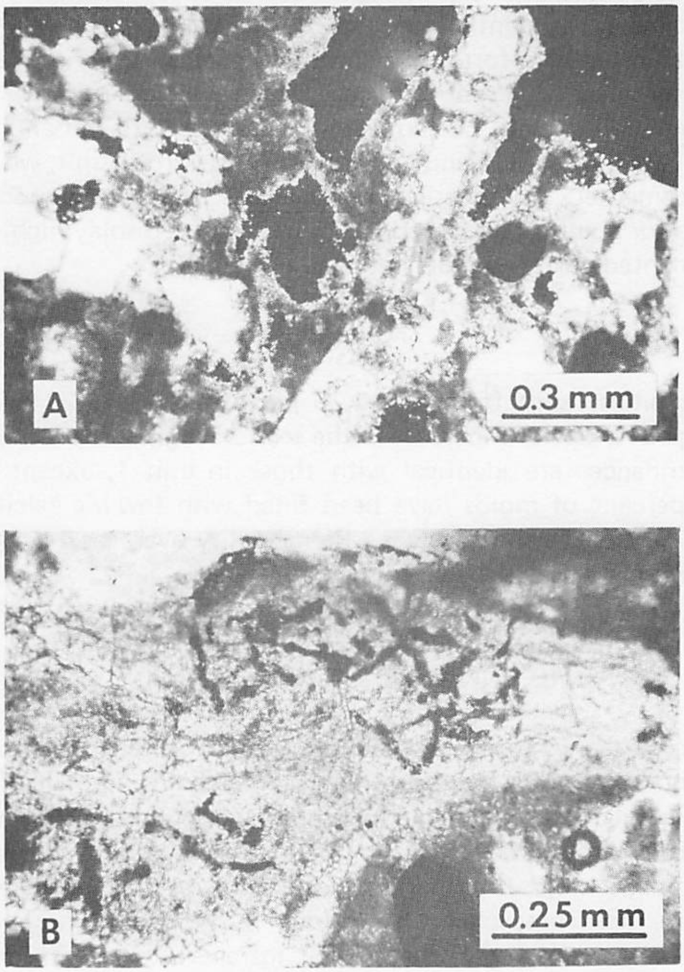

Figure 12.--A. Vug porosity, a common type, that probably evolved by solution enlargement of pelecypod molds. Unit 1 of Castle Hayne Limestone. Crossed nicols.

B. Completely reduced pores produced by boring into a molluscan allochem. Borings are common, but few have retained porosity. Most are filled with dark microcrystalline low-Mg calcite. Unit 3 of Castle Hayne Limestone. Plain light.

pelecypod shells; subordinate pores are micro- and mesopores as interparticle (initially very common due to spaces between framework grains subsequently reduced by low-Mg calcite cement) and intraparticle types in foraminifers and bryozoans. Many of the voids have been filled with sparry calcite cement; hence, porosity values are lower than in unit 1. Permeability averages 325 md and ranges from 0.1 to 1,725 md. Sandy and friable parts of the unit, which are poorly cemented due to original lack of aragonitic pelecypod shells available for solution and production of cement, display high values. Well-cemented parts have low permeabilities.

UNIT 3

Porosities range from 17 to 29 percent (average 23 percent), with a general upward increase in the section (fig. 2). Porosity types and abundances are identical with those in unit 1, except that a greater percent of molds have been filled with low-Mg calcite spar cement; hence, the lower values. Permeability averages 145 md and ranges from less than 0.1 to 327 md.

POROSITY AND PERMEABILITY IN THE UNNAMED OLIGOCENE UNIT

Porosity is 30 to 42 percent (average 34 percent), and exists in meso- and megamolds and solution-enlarged molds and vugs formed by solution of original aragonitic gastropod, pelecypod, and scaphopod skeletons. Porosity is high owing to the small amount of filling of the abundant molds by sparry calcite cement. Subordinate pore types are mesovugs; channels, formed by anastomosing solution-enlarged molds and vugs; interparticle; intraparticle within foraminifers and bryozoans; fracture; and inferred intercrystal micropores. Permeability averages 5,206 md, and ranges from 199 to 15,400 md. High values result from close packing of original skeletal material, that allowed formation of many interconnecting moldic pores upon solution.

POROSITY AND PERMEABILITY RELATIONSHIPS

The Oligocene stratum has the highest measured values of porosity and permeability (fig. 13) because pores are large and well-

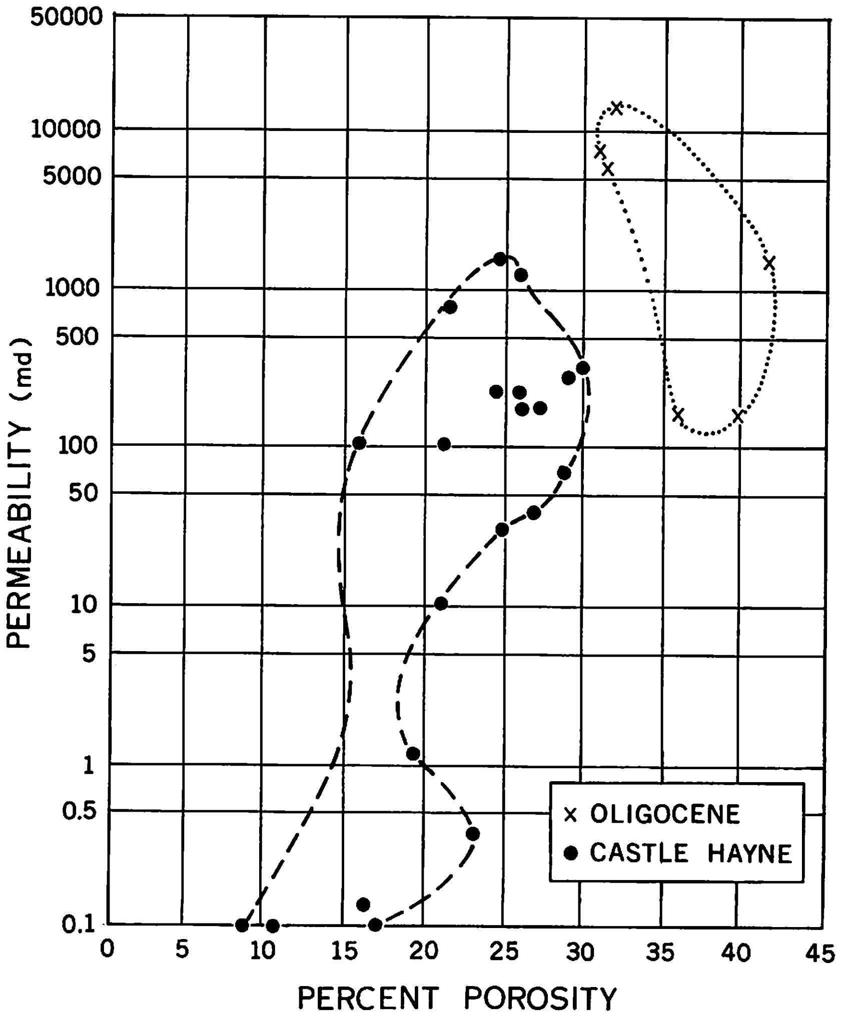

Figure 13.--Porosity-permeability characteristics of Castle Hayne and Oligocene carbonate rocks. Generally, the Oligocene stratum has more, larger (fewer reduced pores), and better connected pores; hence the higher porosity and permeability values.

connected due to close packing (numerous), and there is a small amount of calcite spar reducing the molds. Castle Hayne strata show varying porosity-permeability values depending chiefly on the amount of sparry calcite filling the molds. Generally, permeability values increase with increasing porosity in the Castle Hayne rocks. In contrast, the Oligocene stratum displays a decrease in permeability with an increase in porosity. The reason for this may be that the additional porosity above 35 percent may be localized in micropores (intercrystal?) that are too small or isolated to transmit liquids; hence higher porosity values do not influence permeability.

Porosity and permeability values of the Castle Hayne and Oligocene units were plotted as cumulative curves (fig. 14). Porosity

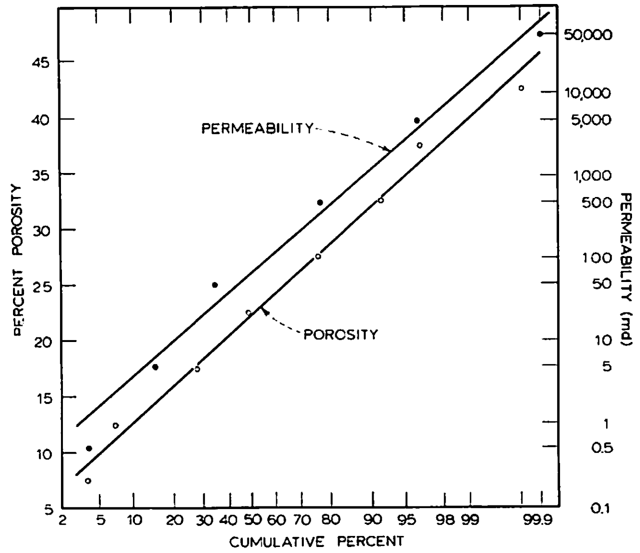

Figure 14.-- Cumulative curves of porosity and permeability of Castle Hayne aquifer samples. Porosity is plotted on a normal probability scale and permeability on a log-normal probability scale. All porosity measurements were grouped and plotted as midpoints of 5 percent intervals. All permeability measurements were grouped and plotted as midpoints of powers of 10 md intervals.

shows a normal distribution, whereas permeability shows a log-normal distribution. Similar relations have been reported for other geologic units by Law (1944), Bennion and Griffiths (1966), and Davis (1969). Mean porosity for the aquifer system is 25 percent and mean permeability is 1,329 md. Both porosity and permeability have moderately large standard deviations, 8 percent and 3,231 md respectively, which is to be expected in carbonate rocks (Bulnes, 1946, Seaber and Hollyday, 1967). This is due to several important variables such as packing of allochems and micrite, shell architecture, original skeletal mineralogy, and diagenesis (Textoris and others, 1972).

To determine the influence of various lithologic parameters (fig. 2) on porosity and permeability values, four scatterplots were prepared (figs. 15 to 18) and correlation coefficients computed. Other correlation coefficients were also computed, but showed no significance at the 95 percent confidence level; therefore, they are excluded from this discussion.

Figure 15 is a plot of calcite spar versus porosity. There is a negative correlation indicating that as the amount of spar increases,

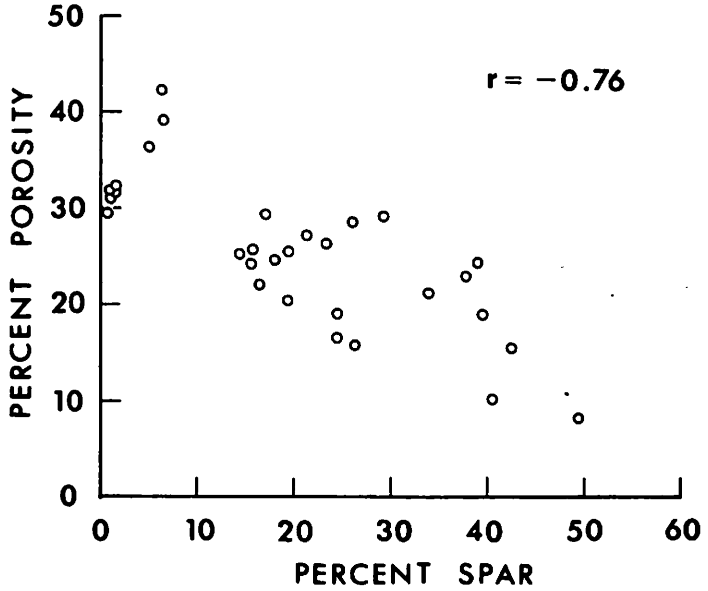

Figure 15.--Scatterplot of all Castle Hayne aquifer samples (percent spar vs porosity), with negative correlation coefficient.

porosity decreases. Since most of the spar occurs as void fillings (both interparticle and mold), this in effect means additional spar reduces total void space; hence porosity. Rauch and White (1970) suggested such a correlation could be due to fewer intercrystal boundaries and a subsequent decreased total surface area available for solution; hence a lower solution rate and fewer intercrystal pores. Thus, rock types with neomorphic spar, that is, micrite aggraded to microspar and pseudospar, fit this correlation. However, this has a minor influence on Castle Hayne aquifer porosity.

Total insoluble residue versus percent porosity displays a negative correlation coefficient (fig. 16), that is, porosity decreases as percent insoluble residue increases. There are probably several reasons for this relationship. Part of the insolubles are associated with clay minerals that may surround carbonate grains and protect them from solution, thus lowering the solution rate and development of porosity. More important, however, is that quartz, feldspar, and

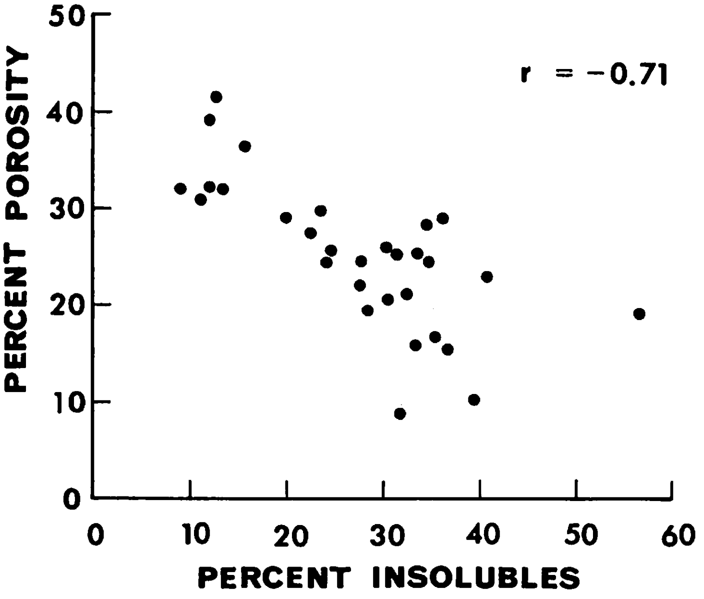

Figure 16.--Scatterplot of all Castle Hayne aquifer samples, (insolubles vs porosity) with negative correlation coefficient.

other insolubles that are present in higher concentrations lower the total carbonate available for solution, thus, fewer molds can form. Both ideas have also been put forth by Rauch and White (1970).

Micrite versus porosity (fig. 17) shows a positive correlation, indicating an increase in porosity as total micrite increases. There may be several reasons for this relationship. One possibility is that large amounts of micrite prevented molds from being filled with spar, thus maintaining porosity. Rauch and White (1970) found a similar relationship and suggested that since the surface free energy of micrite crystals is large, solubility rates would also be large leading to high porosities in rocks where micrite content is high (micropores in intercrystal areas). In the Castle Hayne aquifer system, rocks with high micrite values generally have little pseudospar. Formation of pseudospar from micrite effectively reduces porosity. Hence, rocks with low pseudospar invariably have high micrite values and high porosities. Also, micritic rocks contain more vugs, channels, and in some cases, fractures, thus helping to increase porosity. And, generally,

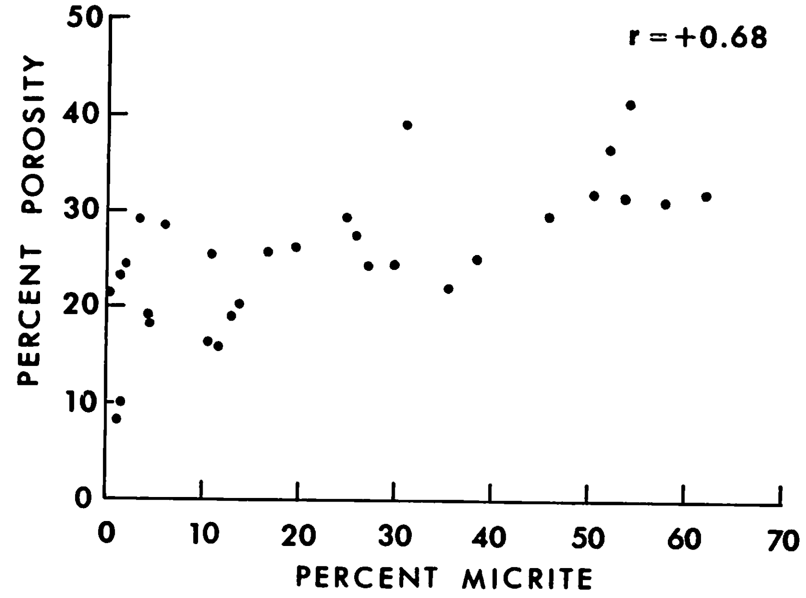

Figure 17.--Scatterplot of all Castle Hayne aquifer samples (micrite vs porosity) with positive correlation coefficient.

micritic rocks contain less insoluble residues allowing more carbonate to be available for solution.

Micrite plotted against permeability (fig. 18) shows a positive

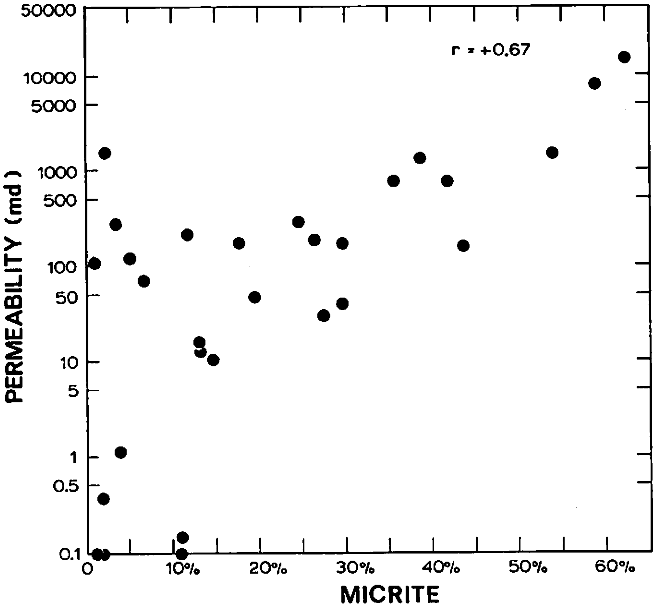

Figure 18.--Scatterplot of all Castle Hayne aquifer samples (micrite vs permeability), with positive correlation coefficient. Permeability is plotted on semi-log scale.

correlation, nearly identical with micrite versus porosity (fig. 17), indicating that permeability increases as micrite content increases. Large amounts of micrite may prevent the filling of biomolds by sparry calcite allowing pores to remain open and interconnected. Also, there are more vugs, channels, and fractures in micritic rocks allowing better interconnections.

DIAGENESIS

Because 90 percent of the porosity in the Castle Hayne Limestone and the unnamed Oligocene unit is fabric-selective moldic, particularly in pelecypod and gastropod skeletons, it is obvious that this is not the original depositional porosity. Indeed, interparticle zones that were originally pores are now filled with void-filling low-Mg sparry calcite. Thus, the rocks have an inverse porosity when compared to the original sediment. Generally the rocks were deposited in very shallow to moderately shallow normal marine water (Thayer and Textoris, 1972). The sediments have been exposed and resubmerged and reexposed a great number of times due to eustatic sea level changes during the Tertiary and Quaternary. The rocks have never been buried very deeply in this outcrop belt, although the oldest beds are on the order of 50 million years old (middle and late Eocene). Thus, diagenetic changes have affected the sediments and rocks while they were in the eogenetic and telogenetic zones, both of which are major surface realms (Choquette and Pray, 1970). Eogenesis includes all early diagenetic changes and processes affecting the sediment after initial exposure to surface conditions, and telogenesis embraces basically late diagenetic changes such as weathering, that normally follow deep burial. There is no evidence for deep burial, so we are dealing with continuous surface diagenetic processes and repeated marine encroachments for the development of the rock we now find.

Actually, most of the following information dealing with original skeletal mineralogy and various diagenetic changes affecting it, both in the production of spar or porosity, was beautifully set forth by Sorby (1879), and only recently "rediscovered."

A number of processes affected the development of porosity. Packing of allochems and availability of micrite controlled interparticle porosity. Architecture of skeletons controlled intraparticle porosity. Both reflect original environmental conditions. For the most part, however, these are now minor pore types because of subsequent filling by sparry calcite during eogenesis. Often, the amount of void-filling spar has been controlled by the amount of aragonitic skeletons originally present, because they provided the cement upon solution (forming molds) and reprecipitation (filling interparticle pores). Thus, interparticle porosity does not commonly exist in mollusk-bearing beds, due to original skeletal mineralogy (fig. 19).

Vugs and channels tend to be solution-enlarged molds. Some channels may have origins as fractures. These too may be in various stages of filling.

	ARAGONITE	ARAGONITE & CALCITE	CALCITE	Mg·CALCITE	Mg·CALCITE & ARAGONITE
MOLLUSKS					
PELECYPODS					
MACROCALLISTA	D				
PANOPE	D				
GLYCIMERIS	D				
PHACOIDES	D				
PECTEN		C	C		
VENERICARDIA	D				
CRASSATELLITES	D				
GASTROPODS					
NATICIDS	D				
TURRITELLIDS	D				
SCAPHOPODS	D				
BRYOZOANS	C			R	C
ECHINODERMS				D	
FORAMINIFERS	C		C	C	

Figure 19.--Most common fossil allochems and original skeletal mineralogy. D = dominant, C = common, and R = rare.

All of the carbonate is low-Mg calcite which is the most stable form under meteoric water conditions. It has been shown by a number of investigators (Bathurst, 1971) that the most common modern shallow-marine carbonate sediments consist of high-Mg calcite and aragonite, with only small amounts of low-Mg calcite. This is the order of increasing stability outside the marine environment. Because these shallow marine carbonates are mainly skeletal in origin, it is important to realize original mineralogy of skeletons of plants and animals in the environment (fig. 19).

In ancient limestones both aragonite and high-Mg calcite are rare. Rocks as young as Pleistocene, which originally contained large amounts of these minerals, now consist mainly of low-Mg calcite. Changes are attributed to exposure of the marine carbonates to meteoric water.

Upon exposure, high-Mg calcite is converted to low-Mg calcite by leaching of the Mg++ or solution-deposition on a micro-scale

(Friedman, 1964). This process does not form moldic porosity, and original skeletal textures remain intact. Intracrystal spaces are closed up, as in porous echinoderm plates.

Taft (1967) performed laboratory experiments in which aragonite conversion to low-Mg calcite took place in days when placed in pure water. This stabilization occurs early in the history of naturally occurring carbonates (Land, 1967; Gavish and Friedman, 1969).

Aragonite apparently changes to low-Mg calcite in one of two ways. The first, common in conversion of aragonite ooze to micrite, involves solid-state inversion (Folk, 1965). Some skeletal fragments may be converted in this manner also. This would allow preservation of some of the original shell texture, but this is rare in our studies. The second method of conversion is most common among the mollusks and involves solution and formation of moldic porosity (Friedman, 1964; Textoris, 1967; Bathurst, 1971). These molds may later be filled with low-Mg calcite spar, which is coarse and clear, but no traces will remain of the original shell texture. This solution process also provides part of the low-Mg calcite cement needed to lithify a carbonate sediment to a limestone (Textoris, 1967). Harris and Matthews (1968) concluded that precipitation of calcium carbonate as low-Mg calcite is occurring concurrently with solution of aragonite above the water table in Barbados. They estimated that the solution-precipitation process is operating at an efficiency of greater than 90 percent. We interpret the carbonate sediments of our study to have been greatly affected by this eogenetic process.

The foregoing diagenetic behavior of various carbonate mineral types, and effects on pore development, have been substantiated by our petrographic textural studies. In figure 20, we summarize the evolution of an aragonitic pelecypod shell in the fresh water environment, from simple solution to form a mold to various stages of further solution and possible fillings by low-Mg calcite spar.

Figure 21 is a review of the evolution of porosity and carbonate mineral changes. Although prepared from evidence for Bermuda by Land (1966), others have used similar diagrams to show general evolution, such as Gavish and Friedman (1969) for carbonates of the Mediterranean coast of Israel.

Stage 1 represents initial sedimentation, original porosity, and the two main types of carbonate, aragonite and high-Mg calcite as various allochems; primarily pelecypods, gastropods, and fewer

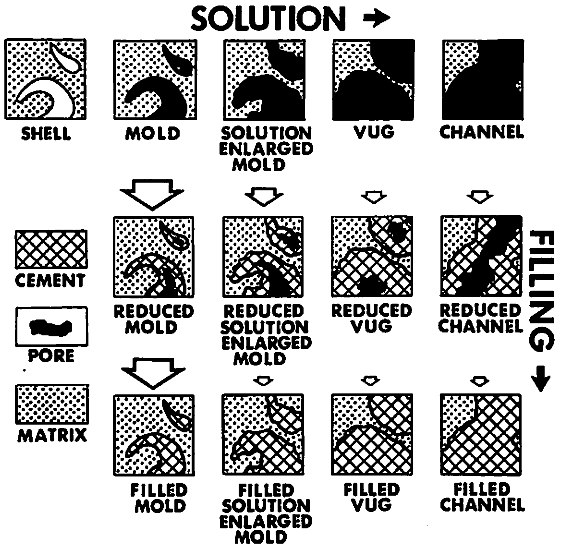

Figure 20.--Common stages in evolution of a basic pore type, a mold, the most common in the Superior Stone Company quarry. Size of arrows indicates most common avenues of evolution, involving solution and filling.

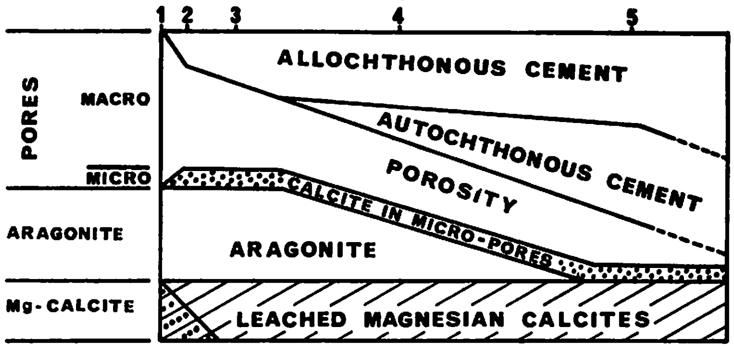

Figure 21.--Idealized diagram of subaerial diagenetic changes through five stages (from Land, 1966). Stage 1=initial sediment; Stage 2=first cement, probably subaerial; Stage 3=loss of Mg++ from high-Mg calcite; Stage 4=solution of aragonite shells and precipitation nearby as low-Mg calcite cement; Stage 5=culmination with all carbonate as low-Mg calcite.

bryozoans, echinoderms, and foraminifers. Very early subsea diagenesis occurred evidenced by large borings and microborings. The latter led to the formation of micrite envelopes.

Stage 2 represents the first cement. It could have precipitated in the subsea environment, in which case it would have been aragonite or high-Mg calcite as fine drusy spar around allochems (Bathurst, 1971), or low-Mg calcite in the vadose zone. In either case, it is allochthonous in origin and reduces interparticle porosity.

Stage 3 represents loss of Mg++ from high-Mg calcite allochems, such as echinoderms. This stage is very closely related to stage 2.

During stage 4 solution-precipitation dominates. Aragonite dissolves providing most of the cement for nearby precipitation (autochthonous), and porosity slightly decreases as there is an inversion of location of porosity (molds instead of interparticle pores). It may take as little as 80,000 to 100,000 years for evolution through this stage to be completed (Gavish and Friedman, 1969).

Stage 5 represents a culmination as all carbonates become low-Mg calcite, and the remainder of the rock is porous. After this, continued introduction of allochthonous cement will reduce the moldic porosity. This stage may go on for some time depending on supply of carbonate, usually from overlying or updip beds. Since the Castle Hayne aquifer rocks were never buried more than a few tens of meters, and not necessarily by younger carbonate, the rocks in the New Bern quarry are still in stage 5, especially those in the Oligocene stratum. We surmise that the rocks have been in stage 5 for nearly all of their 30- to 50-million-year history.

One important diagenetic change not shown on figure 21 is that of micrite and pelmicrite aggrading by neomorphism to form microspar and pseudospar. This change affected only the Castle Hayne Limestone, probably between stages 4 and 5. The Oligocene unit was not affected for reasons unknown.

CONCLUSIONS

Ninety percent of the porosity in the Castle Hayne Limestone and unnamed Oligocene unit is the fabric-selective moldic type, caused by preferential eogenetic solution of original aragonitic skeletal allochems, chiefly pelecypods and gastropods, in the vadose zone. Solution-enlarged molds, vugs, and channels are also important in the micrite-rich rocks of unit 1 of the Castle Hayne Limestone and the Oligocene stratum. Porosity types of lesser importance are reduced solution enlarged molds; reduced vugs; interparticle; intraparticle in foraminifers and bryozoans; borings; shelters; and microfractures (restricted to the Oligocene stratum). Porosity values are 9 to 42 percent (X = 25 percent, s = 8 percent).

The most favorable porosity is in the Oligocene unit (X = 34 percent), followed by unit 1 (X = 25 percent), unit 3 (X = 23 percent), and unit 2 (X = 17 percent) of the Castle Hayne Limestone. Porosity has been controlled chiefly by the amount of original aragonitic skeletal material available for solution, and the amount of filling of pores by sparry calcite cement.

Permeability ranges from less than 0.1 md to 15,400 md (X = 1,329, s = 3,231 md), and attains highest values in the Oligocene unit (X = 5,206 md). This is followed by unit 2 (X = 325 md), unit 1 (X = 289 md), and unit 3 (X = 145 md) of the Castle Hayne Limestone. Permeability has been controlled chiefly by primary packing of aragonitic pelecypods and gastropods, and the amount of filling of pores and interconnecting channels by sparry calcite cement.

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