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High-Porosity Cenozoic Carbonate Rocks of South Florida: Progressive Loss of Porosity with Depth[1]

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ABSTRACT

Porosity measurements by borehole gravity meter in subsurface Cenozoic carbonates of south Florida reveal an extremely porous mass of limestone and dolomite which is transitional in total pore volume between typical porosity values for modern carbonate sediments and ancient carbonate rocks. A persistent decrease of porosity with depth, similar to that of chalks of the Gulf Coast, occurs in these rocks. We make no attempt to differentiate depositional or diagenetic facies which produce scatter in the porosity-depth relationship; the dominant data trends thus are functions of carbonate rocks in general rather than of particular carbonate facies. Carbonate strata with less than 20% porosity are absent from the rocks studied here.

Aquifers and aquicludes cannot be distinguished on the basis of porosity. Although aquifers are characterized by great permeability and well-developed vuggy and even cavernous porosity in some intervals, they are not exceptionally porous when compared to other Tertiary carbonate rocks in south Florida. Permeability in these strata is governed more by the spacial distribution of pore space and matrix than by the total volume of porosity present.

Dolomite is as porous as, or slightly less porous than, limestones in these rocks. This observation places limits on any model proposed for dolomitization and suggests that dolomitization does not take place by a simple ion-for-ion replacement of magnesium for calcium. Dolomitization may be selective for less porous limestone, or it may involve the incorporation of significant amounts of carbonate as well as magnesium into the rock.

The great volume of pore space in these rocks serves to highlight the inefficiency of early diagenesis in reducing carbonate porosity and to emphasize the importance of later porosity reduction which occurs during the burial or late near-surface history of limestones and dolomites.

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INTRODUCTION

This paper presents and discusses porosity data obtained from borehole gravity measurements in Cenozoic carbonate rocks of peninsular Florida. Tested depths range from about 6 to 2,700 ft (2 to 830 m), and the study includes Pleistocene to Paleocene rocks that partly span the transition between modern high-porosity carbonate sediments and ancient low-porosity carbonate rocks. This paper is a companion to one that surveys carbonate-rock porosity throughout the south Florida peninsula to depths of 18,000 ft (5,500 m) (Schmoker and Halley, 1982). The present paper emphasizes the significance of very highly porous (approaching 40% porosity on average) carbonate rocks in the upper part of the south Florida carbonate platform.

The diagenetic processes associated with the porosity decrease from modern to ancient carbonates have been the subject of considerable research. Until recently, a lack of evidence in ancient limestones and dolomites for significant physical compaction has led to a focus on cementation as the primary mechanism for porosity loss. The generalities of material transport and carbonate cementation have been discussed by Weller (1959), Dunham (1969), Bathurst (1975, 1976), and Friedman (1975), but difficulties in quantitative evaluation of the roles of mechanical compaction and of pressure solution have been continuing problems (Pratt, 1982; Wanless, 1982). Both processes may be more important than previously thought (Shinn et al, 1977; Wanless, 1979; Buxton and Sibley, 1981).

With increasing detail, carbonate petrographers have documented the processes and products of the transition from carbonate sediments to carbonate rocks and have described the petrographic, mineralogic, and geochemical transformations which occur early in the history of carbonate diagenesis. Ancient carbonate rocks likewise have been extensively studied, and the typically complex series of diagenetic events leading to a given end product has been documented for many formations. However, petrographic studies often do not quantitatively examine porosity, and despite progress toward a general understanding of carbonate diagenesis, attendant volumetric changes in porosity are rather poorly documented.

Borehole-gravity measurements of porosity are derived from in-situ sample sizes on the order of hundreds of cubic meters.

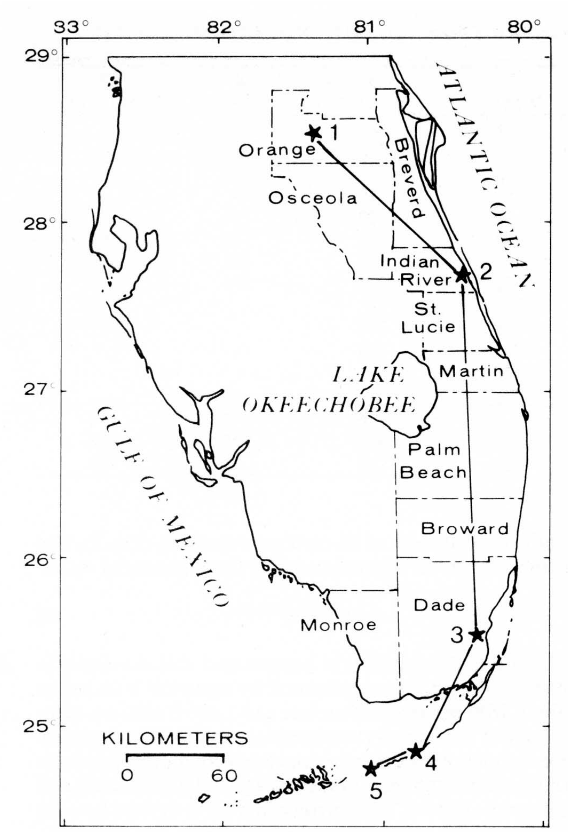

Figure 1. Index map showing location of wells in south Florida logged for this study.

Our data suggest that on this scale of measurement, diagenetic processes have reduced the porosity of typical south Florida limestone and dolomite units from roughly 45% near the surface to 25 or 30% at a depth of 2,600 ft (800 m). Carbonate rocks in south Florida retain porosity during mineralogic transformation at shallow depths. The character of the pore space is greatly modified during mineralogical stabilization, resulting mainly in cementation and development of secondary porosity as documented by many workers including Schlanger (1963), Friedman (1964), Land et al (1967), Robinson (1967), Matthews (1968), Gavish and Friedman (1969), Steinen (1974), Harrison (1975), and many others. Considerable porosity is carried into the subsurface after early diagenesis, and depth-burial-dependent cementation and compaction probably account for most of the porosity loss in the limestones and dolomites studied here.

SCALE PROBLEM IN MEASUREMENT OF CARBONATE POROSITY

Pore size in carbonate rocks ranges from micrometers to tens of meters. Linear pore dimensions can thus vary by 6 or 7 orders of magnitude and pore volumes by 18 to 21 orders of magnitude. In addition, the distribution of pores can be heterogeneous at almost any scale. Clearly, adequate estimation of carbonate porosity presents a significant sampling problem.

Table 1 lists many of the methods used to evaluate porosity

Scanning electron microscopy*	$10^{-12}/10^{-4}$
Thin-section analysis	10^{-2}
"Perm" plug analysis (porosimeter)	10
Gamma ray attenuation porosity evaluation (GRAPE)	10
Whole core analysis	10^{2}
Neutron log analysis	10^{5}
Borehole gravimetry	10^{9}

*Typically this method is used only qualitatively.

Table 1. Techniques for Porosity Measurement and associated Typical Sample Volumes (cm^3)

in carbonate rocks and gives estimates of the sample volume investigated by each. Implicit in the use of a given method are the assumptions that pores are evenly distributed and are small relative to the volume being investigated. In reality, these assumptions often are not satisfied, and a strategy of analyzing a large number of small samples is frequently adopted in the hope that their average porosity will approach that of the whole rock.

The scale problem can be particularly acute when laboratory methods of porosity measurement are applied to highly porous (more than 35% porosity) carbonate rocks. Core recovery in such rocks may be poor, causing a sampling bias toward less porous zones. Pores are likely to be large and irregularly distributed in highly porous carbonate rocks. Laboratory samples are too small to adequately represent pore-space distribution. In addition to these factors, thin-section porosity estimates are subject to systematic measurement errors (Halley, 1978). We believe that measurement inaccuracies associated with the scale problem and thin-section analyses have resulted in an apparent porosity decrease in carbonate sediments during early, freshwater diagenesis as reported by Robinson (1967), Land et al (1967), Pittman (1974), and Friedman (1964). Our porosity measurements, discussed below, suggest little or no porosity loss during freshwater diagenesis. Such porosity preservation during diagenesis has significant implications for understanding the mass transfer of calcite in the subsurface. For example, it eliminates the difficulties of insufficient geological time encountered by Enos and Sawatsky (1981) who modeled cementation of Pleistocene limestones. It avoids problems associated with mass-balance calculations and the source of "excess" cement encountered by Steinen (1974) and Harrison (1975). Finally, early porosity preservation underscores the importance of later diagenetic events in reducing porosity.

In this study of high-porosity carbonate rocks, borehole gravimetry was selected as the best technique to determine the average porosity of samples having vertical dimensions ranging from 10 to 100 ft (3 to 30 m^3) and effective volumes greater than 3,500 ft^3 (100 m^3). This large measurement scale is uncommon in carbonate studies and, compared to other methods of porosity measurement, more closely approaches the size of hydrocarbon reservoirs and aquifers. Our objective was to smooth and average the effect of porosity variations on the scale of centimeters and even meters in order to examine in-situ bulk-rock porosity as a function of depth.

METHODS

The borehole gravity meter has an effective radius of investiga-

[3]Use of brand names in this paper is for descriptive purposes only and does not imply endorsement by the U.S. geological Survey.

Well Number from Figure 1	1	2	3	4	5
Florida Bureau of Geology Number	W13287	W14167	W13768	W13752	W12799
Unconsolidated quartz sand and clay	0	0	--	--	--
Miami Oolite (Pleistocene)	--	--	0	--	--
Key Largo Limestone (Pleistocene)	--	--	--	0	0
Fort Thompson Formation (Pleistocene)	--	--	10	--	--
Tamiami Formation (Pliocene)	--	30	30	34	53
Hawthorn Formation (Miocene)	33	137	76	84	107
Tampa Limestone (Miocene)	--	--	116	190	174
Suwannee Limestone (Oligocene)	--	152	277	274	
Ocala Limestone (Eocene)	--	236	--		
Avon Park Limestone (Eocene)	53	298	343		
Lake City Limestone (Eocene)	168	451	526		
Oldsmar Limestone (Eocene)	426	610			
Cedar Keys Formation (Paleocene)	700				
Top logged interval	2	2	6	2	2
Base logged interval	733	716	842	296	178
Number of porosity intervals	31	30	65	33	28

*Dashes indicate units are absent.

Table 2. Approximate Formation Tops and Logged Intervals (in Meters Below Surface) for Wells Located in Figure 1*

tion that is measured in meters and is comparable to large carbonate pore spaces (caverns). It is a density logging tool that is not significantly influenced by casing, borehole rugosity, or formation damage caused by drilling. Rocks away from the borehole can be sensed because gravity is not attenuated by intervening material.

The U.S. Geological Survey-LaCoste and Romberg[3] borehole gravity meter (described by McCulloh et al, 1967a, b) was used in early 1979 to conduct borehole gravity surveys in five cased wells penetrating the Cenozoic sediments and rocks of peninsular Florida (Fig. 1). Full details of the borehole gravity surveys are given by Schmoker et al (1979).

A comprehensive listing of references to fundamentals of borehole-gravity logging and interpretation can be found in Robbins (1980). In the absence of complicating structural factors, the relation between formation density and measurements of gravity in a borehole is given by (McCulloh, 1966; Robbins, 1981):

$$\varsigma = 39.131(F - \Delta g/\Delta z), \qquad (1)$$

where ς is the average formation density (g/cm^3) between two vertically separated points in the borehole, F is the free-air vertical gradient of gravity (mgal/ft), Δg is the measured difference in gravity between the vertically separated points (mgal), and Δz is the vertical separation (ft). In evaluating equation 1, a value for the free-air gradient of 0.09409 mgal/ft, appropriate for the latitudes of south Florida, was used.

Porosity, ϕ, was computed from the borehole-gravity density, ς, using the equation:

$$\phi = 100(\varsigma_G - \varsigma)/(\varsigma_G - \varsigma_F), \qquad (2)$$

where ς_G is the grain density and ς_F is the pore-fluid density (g/cm^3). Pores were assumed to be 100% water saturated, with water density ranging between 1.00 and 1.02 g/cm^3 depending upon salinity. Grain density was estimated from lithologic logs prepared from well cuttings, with the assumption that such logs are representative of rocks within the radius of investigation of the borehole gravity meter.

GEOLOGIC SETTING

The strata investigated in this study are primarily shallow-water carbonate rocks that accumulated on the stable Florida platform in a wide range of depositional environments. Secondary lithologies include sulfates, uncommon in Eocene rocks but widespread in Paleocene strata, and lower Pliocene and Miocene terrigenous clastic deposits. A summary of the formations and depth intervals logged is presented in Table 2. Many of the formation boundaries, particularly within the Eocene rocks, are quite subjective. Puri and Winston (1974, p. 26) described the problem: “Lack of any consistent lithologic horizon in the almost universally porous limestone, as well as the erratic nature of dolostone occurrence, precluded using lithologic parameters for subdividing the section.”

Reefs and carbonate-sand bodies are represented in the Pleistocene Key Largo Limestone and Miami Oolite, respectively (Stanley, 1966; Hoffmeister et al, 1967; Halley et al, 1977; Perkins, 1977). Platform-interior facies, well represented in Oligocene and Eocene formations (Table 2), include open-marine grainstones, wackestones and mudstones, lagoonal wackestones and mudstones, and nearshore and tidal-flat limestones and dolomites that were deposited in a cyclic succession interpreted as reflecting transgressions and regressions across central Florida (Randazzo, 1972; Randazzo and Saroop, 1976; Zachos, 1978).

Complex diagenetic facies, spanning a range of typical early-diagenetic alteration styles, also occur in these carbonate rocks. Diagenetic alteration in many of the formations has been described by Fischer (1953), Stanley (1966), Robinson (1967), Hanshaw et al (1971), Randazzo (1972), Randazzo et al (1977), Perkins (1977), Halley and Rose (1977), and Randazzo and Hickey (1978). Alteration has occurred along surfaces of subaerial exposure, in fresh-water vadose zones and fresh-water phreatic zones, and in zones of mixing between fresh and sea water. Dolomite in the aquifers of south Florida may be the result of mixing-zone dolomitization (Hanshaw et al, 1971), and this and other origins

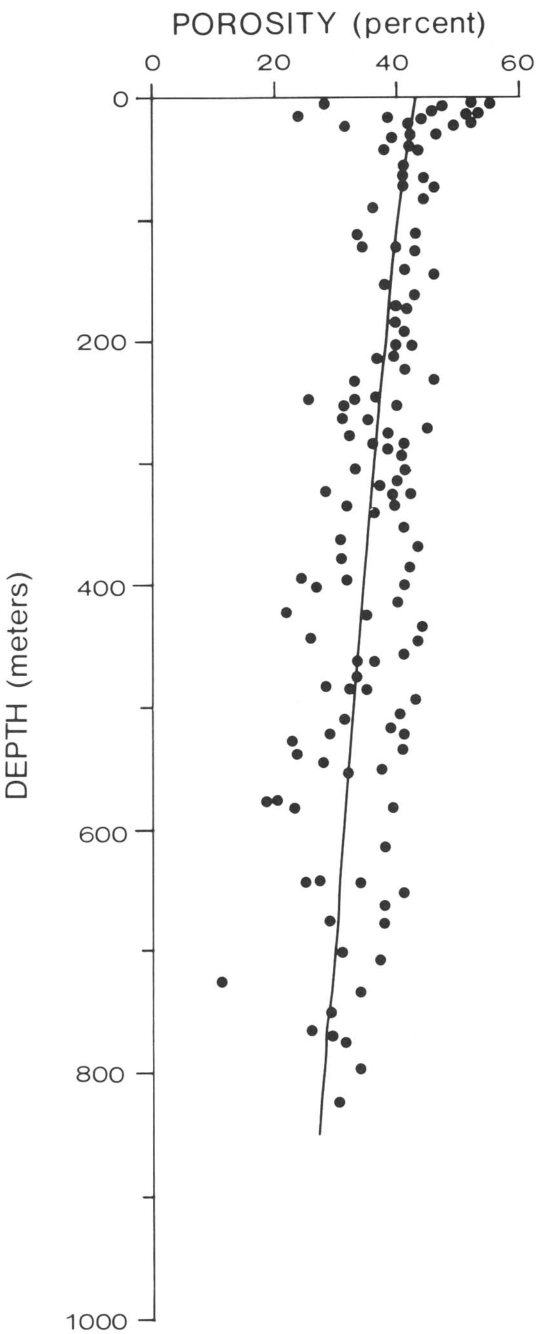

Figure 2. Composite plot of porosity versus depth for five wells illustrated in Figure 3. Sulfate and terrigenous clastic intervals have been omitted. Line indicates exponential fit to data points.

for Eocene dolomites are discussed by Puri and Winston (1974). About 40% of the rocks examined in this study are very permeable and occur in the high-permeability zones of Puri and Winston (1974). About half of these rocks, or 20% of the total, are vuggy and cavernous, but porosity measurement by borehole gravimetry was considered a reliable measurement technique.

The climate of south Florida today is humid (about 39 to 59 in. [100 to 150 cm] rainfall per year) but was much more arid in the past as evidenced by evaporites in Paleocene formations of the peninsula. The effect of climate changes on carbonate porosity, if any, is unclear and must await further investigation. A significant study of petrographic, mineralogic, and trace-element changes during progressive diagenesis of carbonate rocks from an arid environment by Gavish and Friedman (1969) did not include quantitative porosity measurements.

RESULTS

Porosity data for the five logged wells are shown collectively in Figure 2 and for individual wells in Figure 3. Zones with clear evidence of porosity plugging by sulfate minerals have been eliminated from Figure 2, as have intervals containing more than 50% shale or quartz sand. No attempt, other than separating dolomites and limestones in Figure 4, has been made to differentiate facies that may be petrographically or lithologically distinct, although the depositional and diagenetic variations described in the previous section probably account for much of the porosity scatter at a given depth (Fig. 2). The general data trends thus are functions of carbonate rocks in general, rather than of particular carbonate facies.

In the following paragraphs, Figures 2, 3, and 4 are discussed with respect to six main points:

1. Average porosity of the carbonate sequence is high.
2. Near-surface porosity approaches that of modern carbonate sediments.
3. Porosity decreases with depth in a gradual, irregular, but persistent manner.
4. Carbonate intervals with less than 20% porosity are rare.
5. Aquifers and aquicludes cannot be distinguished on the basis of porosity.
6. Dolomite porosity is less than or equal to limestone porosity.

The average porosity of the carbonate intervals shown in Figure 2 is 37%, reflecting an extremely porous mass of limestone and dolomite. For comparison, six south Florida oil reservoirs in the Cretaceous Sunniland Limestone average 18% porosity at a depth of about 11,500 ft (3,500 m). Nine oil reservoirs between 4,600 and 5,900 ft (1,400 and 1,800 m) in the carbonate Jurassic Smackover Formation of Arkansas have an average porosity of 22%. The rocks logged in this study seem unusually porous compared to "average" limestones and dolomites, but are probably not atypical compared to other Cenozoic carbonate accumulations buried to similar depths and deposited in similar tectonic settings. Highly porous sequences such as that of south Florida should occur in other thick Cenozoic carbonate deposits, such as those of the Bahama Islands, Yucatan Peninsula, and some Pacific atolls.

The average porosity of 15 carbonate intervals near the surface (with tops above 82 ft [25 m]) is 44%, a value approaching that of modern carbonate sands. Enos and Sawatsky (1981) found the average porosity of modern grainstone and packstone equivalents to be 44 and 55%, respectively. The porosity of modern ooid sands and Holocene oolites also falls in this range (Halley and Harris, 1979). The high porosities measured in this study support previous studies by Halley and Beach (1979) which indicate that early mineralogical stabilization of shallow water carbonates does not greatly affect average porosity, although the character of the pore space is greatly altered.

Porosity in each well shows an irregular but persistent decrease

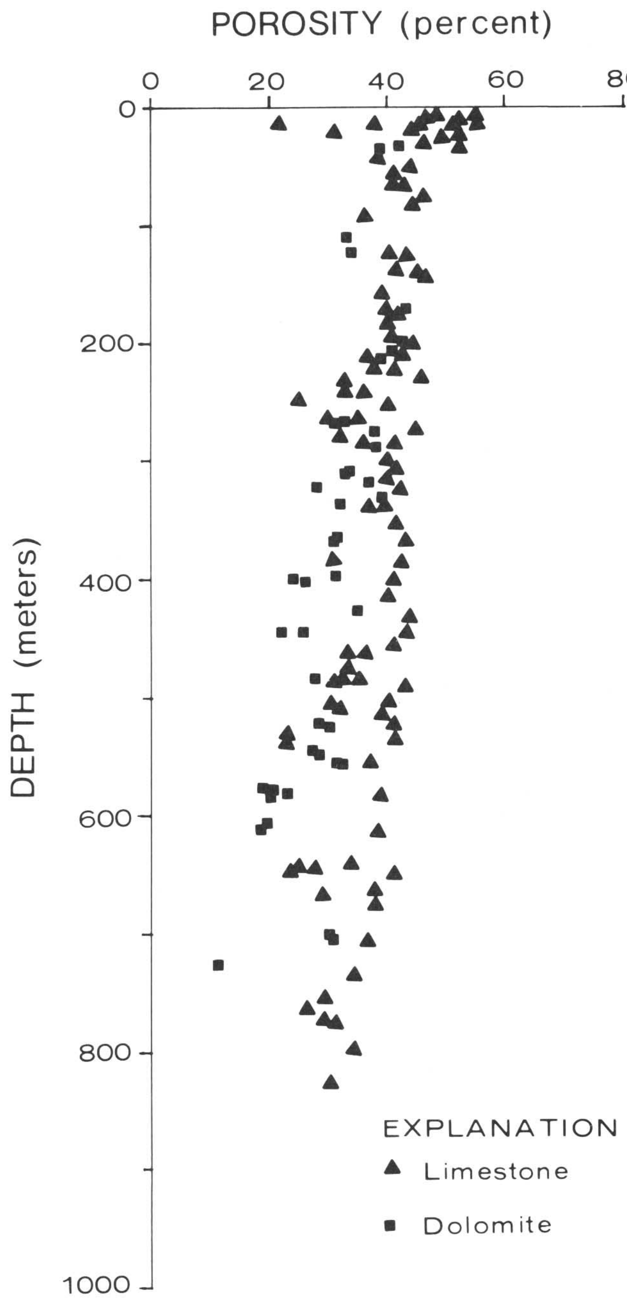

Figure 4. Composite porosity plot as in Figure 2, both with dolomite and limestone differentiated.

with increasing depth (Fig. 3), as does the composite porosity plot of all carbonates intervals (Fig. 2). The composite plot is approximated by the exponential curve:

$$\phi = 43.2e^{-0.000575z}, \qquad (3)$$

where ϕ is the porosity in percent and Z is the depth in meters. Porosity as represented by equation 3 decreases about 16% between the surface and 2,600 ft (800 m). Scatter about the primary exponential trend is due to experimental measurement errors and the secondary dependence of porosity upon factors such as age and depositional and diagenetic history. The porosity-loss curve derived here for shallow-water carbonate rocks is similar to that for chalks from the United States Gulf Coast described by Scholle (1977). The rate of porosity loss with depth for these rocks is less than that for Celtic Sea and Berkshire chalks both greater than that of Scotian Shelf and North Sea chalks. The mineralogic and textural homogeneity of chalks aids in establishing pressure solution and cementation (solution transfer of Bathurst, 1975) as the primary process causing porosity loss with depth in pelagic carbonates (Schlanger and Douglas, 1974; Scholle, 1977).

Carbonate intervals with less than 20% porosity are rare in the Cenozoic rocks examined here (Fig. 2). On the sample scale of borehole gravimetry, complete or near-complete porosity destruction does not occur. At a much smaller scale, samples with little or no porosity can be found (Fig. 5a), but such samples are not representative of the whole rock.

The wells near Vero Beach and Miami (Fig. 1, numbers 2 and 3) were drilled into the Floridan aquifer as waste-disposal wells. In well 2, the top of the Floridan aquifer is at about 330 ft (100 m) and confining beds occur from 1,398 to 1,952 ft (426 to 595 m) and from 2,119 ft (646 m) through the deepest measurement interval. In well 3, the top of the aquifer is at about 755 ft (230 m), and confining beds occur from 1,903 (580 m) through the deepest measurement interval. The porosity of these confining beds is not significantly different from that of the more transmissive parts of the Floridan aquifer (Fig. 3). Likewise, five measurements in the Biscayne aquifer (uppermost 115 ft [35 m] of well 3) yield an average porosity of 38%. The 259 ft (80 m) of confining beds in the Floridan aquifer between 1,916 and 2,175 ft (584 and 663 m) in this well also average 38% porosity. Aquifers and aquicludes cannot be differentiated on the basis of porosity, illustrating that permeability and total porosity do not correlate strongly in the rocks considered here.

The data of Figure 2 are replotted in Figure 4 to show limestone (50 to 100% limestone) and dolomite (50 to 100% dolomite) intervals. About one-third of the intervals is dolomite. (The dolomite interval at 2,380 ft [725 m] with a porosity of 11% is probably partly cemented with anhydrite.) For the rock units and depth range considered here, dolomites are not more porous than limestones. Below about 1,150 ft (350 m), dolomites appear to be less porous than limestones. Because of the limited number of wells and the possible effects on porosity of lateral formation variations, different ages, and different depositional and diagenetic histories, we would be very cautious about generalizing these observations. Nevertheless, within the data set described in this report, the porosity of limestones is greater than or equal to that of dolomites.

DISCUSSION

The porosity of carbonate rocks investigated in this study ranges from about 45% near the surface to 25 or 30% at a depth of 2,600 ft (800 m). The trend of decreasing porosity with depth is present in the data of individual wells (Fig. 3) and in the composite plot of all carbonate intervals (Fig. 2). Carbonate rocks of south Florida retain significant porosity as they are buried in the subsurface during basin subsidence. The grouping of data representing rocks of different ages and significantly different depositional and diagenetic histories does not mask the basic trend of porosity decrease with depth. With the exception of the thin cavernous intervals mentioned above, no particularly unusual physical influences appear to be acting upon the shallow carbonate rocks of peninsular Florida. We speculate that the porosity data presented here may be representative of the "typical" transition from near-surface to deeply buried limestones and dolomites.

Loss of Porosity with Depth

The borehole gravity measurements do not indicate directly the causative processes affecting porosity in the subsurface. Thin sections show evidence of mechanical compaction and associated porosity loss (Fig. 5b). However, laboratory compaction of carbonate sediments over a pressure range equivalent to depths of 0 to 2,950 ft (900 m) (Terzaghi, 1940; Fruth et al, 1966; Hathaway and Robertson, 1961; Robertson, 1967; Morelock and Bryant, 1971; E. A. Shinn, personal commun., 1980) reduces porosity to a minimum of only 35% (Fig. 6). In nature, early cementation strengthens the sediment fabric and inhibits grain readjustment, fracturing, and deformation relative to laboratory results. Thus mechanical compaction is probably not the primary cause of the porosity-depth relations shown in Figures 2 and 3.

A steady deposition of cement as a function of time or depth is another possible reason for the decrease of porosity observed in our data. Thin-section examples of cement deposition are common (Figs. 5c, d), but to directly evaluate the nature and significance of cementation on a reservoir scale is difficult.

Porosity loss due to the precipitation of externally derived cement carried by the circulation of pore water should be a permeability-dependent process. However, our data show little porosity difference between permeable (aquifer) and impermeable (aquiclude) lithologies. Carbonate aquicludes are not the more cemented, less porous equivalents of carbonate aquifers.

The porosity decrease associated with the accumulation of externally derived cement might be a time-dependent rather than a depth-dependent process, and we can look for evidence of time dependence in our data. No consistent porosity changes are associated with the unconformities penetrated in wells 1, 2, and 3 (Fig. 3, Table 2). The average porosity of the Eocene Avon Park, Lake City, and upper Oldsmar Limestones is plotted as a function of average depth for wells 1, 2, and 3 in Figure 7. Connecting lines paralleling the exponential curve imply depth-dependent porosity; connecting lines trending more to the vertical imply age-dependent porosity. Both examples are present, and the evidence presented by Figure 7 is mixed. Taken as a whole, our indirect evidence bearing on the question of externally derived cement is also mixed, due in large part to lateral formation variations, few available wells, and a limited age and depth range. The importance of this mechanism in the shallow carbonate rocks of south Florida cannot be evaluated here.

Another cement-producing process that is a likely contributor to the porosity trend of Figures 2 and 3 is that of pressure solution. Petrographic evidence of pressure solution occurs as shallow as 390 ft (120 m) in the rocks studied here (Figs. 5e, f). In the high-porosity ranges typical of our data, dissolution at grain contacts is by itself sufficient to reduce porosity significantly; the redeposition of cement derived from pressure dissolution is a relatively unimportant porosity-reducing mechanism. For example, for packed spherical grains it can be shown that more than two-thirds of the porosity loss is due to grains moving closer together. In contrast, less than one-third of the porosity loss is due to the addition of cement derived from pressure solution, until total porosity drops to around 20% (Manus and Coogan, 1974; Mitra and Beard, 1980).

Pressure solution is generally regarded as a significant depth-dependent process in deeply buried carbonate rocks, but published evidence for pressure solution at shallow depths is meager. Schlanger (1964) described microstylolites formed under less than 330 ft (100 m) of overburden. Dunnington (1967) observed pressure-solution features when overburden reached 1,970 to 2,950 ft (600 to 900 m), and Buxton and Sibley (1981) documented extensive pressure-solution features in a Devonian limestone buried to a maximum depth of 4,900 ft (1,500 m).

Theoretical calculations by Neugebauer (1973, 1974) indicate that pressure solution should be a significant process at depths less than 3,300 ft (1,000 m) if pore fluids have low magnesium concentrations. The Cenozoic rocks of south Florida may have been exposed to waters with relatively low magnesium content at various times in their burial history, allowing the process of pressure solution to operate at relatively shallow depths. Pressure-solution contacts between grains in the Avon Park Limestone at 390 ft (120 m) depth (Fig. 5e) may owe their existence to fresh water now present within this formation beneath much of peninsular Florida.

Bearing on Dolomitization

The porosity of dolomites relative to associated limestones has received much attention, especially with respect to hydrocarbon reservoirs at depths greater than those considered here. The general belief, particularly when Paleozoic rocks are considered, is that dolomites are more porous than limestones (Pray and Murray, 1965), although permeability may sometimes be equated with porosity in these comparisons. The observation that dolomite is not more porous than limestone at shallow depths in southern Florida is perhaps best understood by recalling that dolomite is the replacement product of highly porous limestones or metastable carbonate sediments. During dolomitization, porosity is inherited from preexisting carbonate rock and sediment.

Wely (1960) pointed out that a 13% volume decrease is associated with the replacement of calcite by dolomite if the replacement is accomplished by an ion-for-ion replacement of calcium for magnesium. This reaction is described by the equation:

$$Mg^{++} + 2CaCO_3 \rightarrow MgCa(CO_3)_2 + Ca^{++}. \qquad (4)$$

Because of the high initial porosity of these limestones, this mechanism of dolomitization would result in a porosity increase of only 8 to 9%. Such a porosity increase is not observed and may be overshadowed by compaction and cementation processes. Alternatively, dolomitization may proceed by incorporating new carbonate in addition to magnesium. This reaction is represented by the equation:

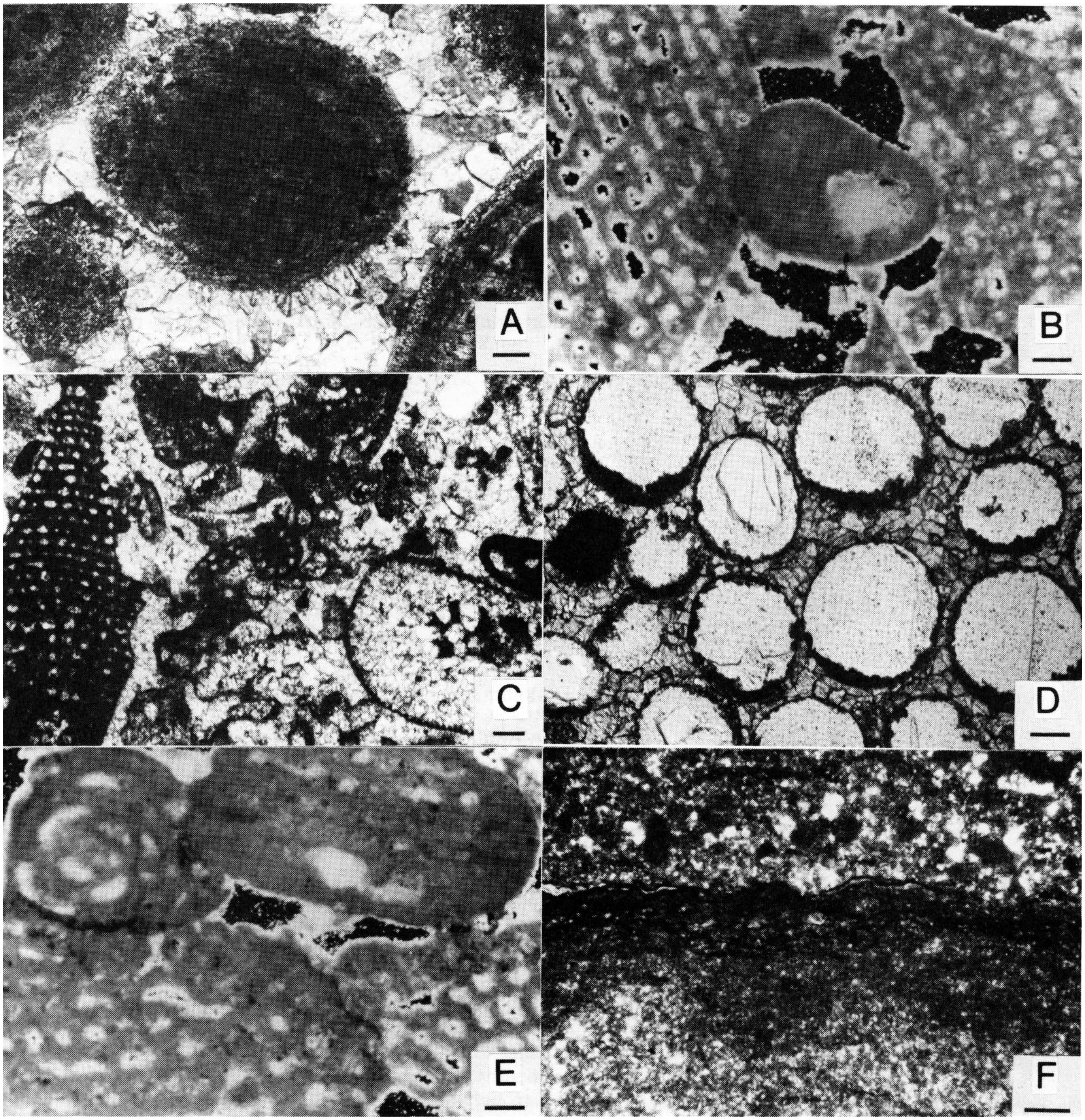

Figure 5. Photomicrographs illustrating petrographic features associated with porosity modification of Cenozoic rocks of south Florida. The character and distribution of many of these features preclude quantitative evaluation. Nevertheless, their occurrences in these rocks demonstrate several mechanisms discussed in text. Bar scales below figure letters are 100 µm. 5a. Completely cemented part of Miami Oolite, common in thin section but not representative of unit as a whole. 5b. Grain interpenetration, a compaction feature that may or may not involve dissolution of calcite at grain boundaries. Because carbonate grains typically contain intragranular porosity, grain interpenetration may be accommodated by grain deformation rather than dissolution along grain boundaries. 5c. Well-cemented grainstone in Avon Park Limestone. Such early cement may or may not result in net porosity loss depending on volume of secondary porosity developed during early diagenesis. 5d. Cement in Miami Oolite, derived from aragonite dissolved from ooid grains so that total porosity remains almost unchanged. 5e. Stylolitic contacts between grains, from Avon Park Limestone, 390 ft (120 m) below surface, evidence of shallow pressure solution. These contacts are characterized by a dark residue, perhaps organic matter, along stylolitic seams. 5f. Similar seams occur in mudstones but are difficult to evaluate in absence of recognizable grains.

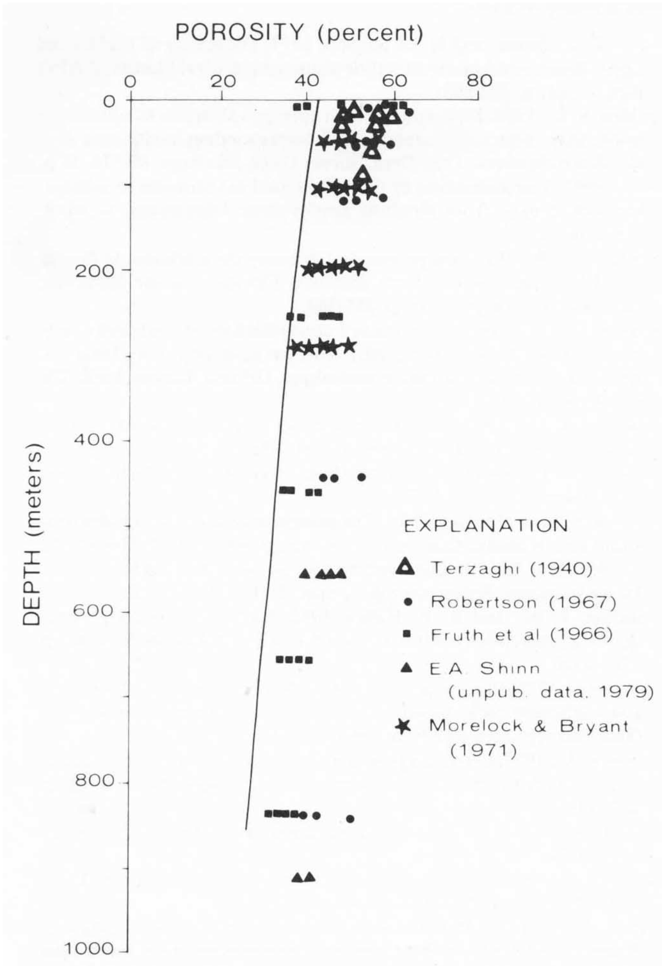

Figure 6. Comparison of south Florida porosity (line is exponentially fit from Fig. 2) with laboratory compaction data.

$$Mg^{++} + CO_3^{--} + CaCO_3 \rightarrow MgCa(CO_3)_2, \qquad (5)$$

and results in a volume increase during dolomitization. If both reactions 4 and 5 contribute to dolomitization, reaction 5 would have to occur twice as often as reaction 4 for there to be no volume change associated with dolomitization. A third possibility is that some dolomite has been added as cement, a process represented by the reaction:

$$Mg^{++} + Ca^{++} + 2CO_3^{--} \rightarrow MgCa(CO_3)_2. \qquad (6)$$

Complete porosity loss is possible through the addition of dolomite cement to the rock. Porosity data reported here suggest reaction 4 is not the predominant dolomite forming mechanism in the Cenozoic of south Florida and that both magnesium and carbonate have been added to the rocks during dolomitization. Such a loss of porosity during dolomitization has been observed elsewhere and is termed "overdolomitization" by E. J. Lucia (personal commun., 1981).

Significance to Early Cementation

The plethora of early-cementation studies during the past 20 years has led to a particularly heavy emphasis on early diagenesis in carbonate rocks. Some authors suggest that most cementation may occur at relatively shallow depths (Friedman, 1975; Longman, 1980). Such work has strongly influenced the study of ancient sequences and resulted in interpretations which may be skewed toward early diagenetic processes at the expense of later burial alterations. This influence is particularly true with reference to porosity loss. Early diagenetic processes undoubtedly exert a strong influence on permeability characteristics and later diagenetic modifications of carbonate rocks. However, from the volume of pore space preserved in south Florida carbonates, we see that early diagenesis (with the exception of marine cementation) is ineffective at reducing porosity. Significant porosity reduction does not begin until carbonate strata are buried several hundred meters below the surface. It is the later porosity reduction during burial that must be documented to construct a workable understanding of porosity evolution of carbonate rocks.

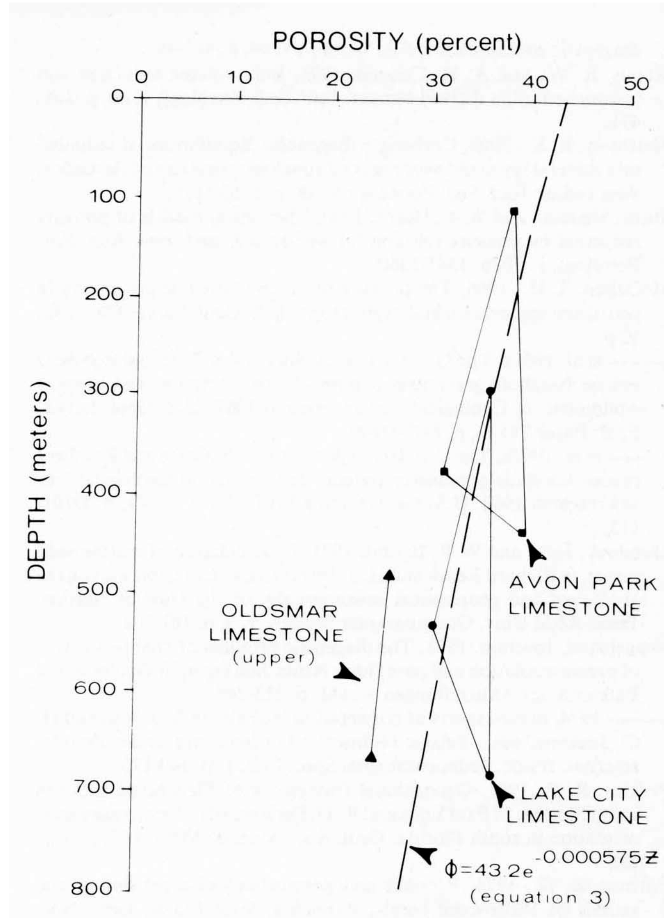

Figure 7. Age dependence versus depth dependence of porosity from Cenozoic carbonates of south Florida. See text for detailed explanation.

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