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Mineralogical Model of the Floridan Aquifer in the
Southwest Florida Water Management District

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ABSTRACT

The distribution of geological and hydrochemical parameters in cores and wells penetrating the Floridan aquifer along portions of the west coast of peninsular Florida is related to the occurrence of dolomite. Trace element analyses of the cores indicate correlations between strontium and sodium concentrations and the particular carbonate phase. Chloride, sulfate, and conductivity values indicate the position and extent of the freshwater-saltwater interface. Thick sequences of carbonate rocks in western peninsular Florida have been dolomitized in the freshwater-saltwater mixing zone of the coastal aquifer.

A multivariate computer analysis was made of the petrographic data from three of the cores studied. The resulting multidimensional scaling diagram revealed several trends of environment of deposition parameters. Energy levels and faunal diversities helped to reconstruct the paleoenvironments of these Tertiary carbonate rocks. These data were then coordinated with the stratigraphy of the study area.

Correlations between the occurrence of dolomite and specific stratigraphic formations suggest that dolomitization was rock-selective. Evidence of continuous formation of dolomite indicates that the process is actively occurring.

The nature and distribution of dolomite in the Floridan aquifer is significant in the development of carbonate rock porosity. The dissolution and replacement of minerals affect groundwater movement as the hydrologically dynamic system involves a continual interaction between water and rocks. Understanding these interactions will aid hydrologists to inventory more precisely present-day water supplies and to predict changes to be expected. More efficient water management can be achieved by integrating the mineralogical model with hydrologic data.

INTRODUCTION

The Southwest Florida Water Management District relies upon the Floridan aquifer for its principal supply of potable water. The geologic nature of this aquifer and its relationship to groundwater flow systems is of fundamental importance in proper water management techniques. A model was established in order to express the mineralogical distributions within the aquifer and to demonstrate mineral interactions with groundwater.

The mineralogical model of the Floridan aquifer in the Southwest Florida Water Management District relates specific geochemical, hydrologic, and geologic data to the occurrence of carbonate minerals in the aquifer. This model provides insight to the way carbonate aquifers develop. The aquifer represents a dynamic system in which waters of varying chemistry have or are reacting with subsurface rock sequences to produce porosity and permeability changes and the formation or destruction of certain minerals.

One major process which affects porosity and permeability in carbonate systems is dolomitization. Weyl (1960) showed through conservation of mass requirements that mole-for-mole replacement of calcium by magnesium will result in a 13 percent volume shrinkage, increasing porosity by joining smaller pores and thereby increasing permeability. Schmidt (1965) stated that in the normal sequence of neomorphism (Folk, 1965) of calcium carbonate grains, a mole-for-mole replacement of aragonite by calcite will increase the mineral volume (decrease the porosity) by 8.7 percent. Subsequent dolomitization of the calcite will result in a 13 percent volume decrease (increase the porosity). Dolomitization of an original aragonite matrix, however, will result in a volume decrease of only 5.4 percent.

Of course, in whichever sequence dolomitization occurs, such factors as original packing, compaction, and introduction of materials by percolating waters will affect the overall porosity and permeability. A better understanding of the processes that control dolomitization in a carbonate aquifer system can provide valuable knowledge to the way aquifers develop. Previous studies have related the occurrence of a mixing zone, where seawater and groundwater meet in a coastal aquifer, to dolomitization (Kohout, 1965, 1967; Rønnells, 1969; Hanshaw et al., 1971; Badiozamani, 1973; Land, 1973; Folk and Land, 1975; Hanshaw and Back, 1979).

The parameters considered in this study traditionally have been shown to be either of direct significance to the dolomitization process, or to be useful in defining a freshwater-saltwater interface. Trace element analyses of cores were conducted on strontium and sodium. Correlating their concentrations and distribution of the various mineralogies present led to a hypothesis of dolomitization by solutions of diluted seawater. Chloride, sulfate, and conductivity measurements from interstitial pore waters were used to define the present position and extent of the freshwater-saltwater interface.

Groundwater composition and flow characteristics are directly affected by these water-rock interactions. Zones of high transmissivity, as well as areas of water with high or low percentages of total dissolved solids, can be better explained by utilization of a mineralogical model. Likewise, this model can serve as a predictive tool for aquifer evolution.

This study involved a number of graduate students who made significant contributions to the total research effort. The investigation expanded upon two earlier endeavors (Randazzo, 1976, 1980) and represents a greater delineation and understanding of the Floridan aquifer. The reader is directed to the works of Saroop (1974), Stone (1975), Hickey (1976), Liu (1978), Zachos (1978), Fenk (1979), and Sharpe (1980) for specific details on the lithologic and paleontologic characteristics of the various lithofacies recognized. Hickey (1976), Sarver (1978), Zachos (1978), and Metrin (1979) discussed the diagenetic and geochemical aspects of the important carbonate rock-forming minerals, calcite and dolomite. Bloom (1982) summarized the data and conclusions from these earlier reports and integrated them with new data presented here.

GEOLOGIC HISTORY

At the beginning of the Tertiary Period a broad, stable carbonate bank existed over the Florida Platform (Chen, 1965). This bank was bounded by submarine escarpments on both the Atlantic and Gulf of Mexico sides, and was separated from the continental shelf to the north by the Suwannee Channel (Applin and Applin, 1944; Jordan, 1954; Chen, 1965) (Fig. 1). A warm shallow sea environment resulted in the deposition of the Cedar Keys Formation in the Paleocene, followed in superposed order by deposition of the Oldsmar, Lake City, Avon Park, and Ocala carbonate sequences during the Eocene. There

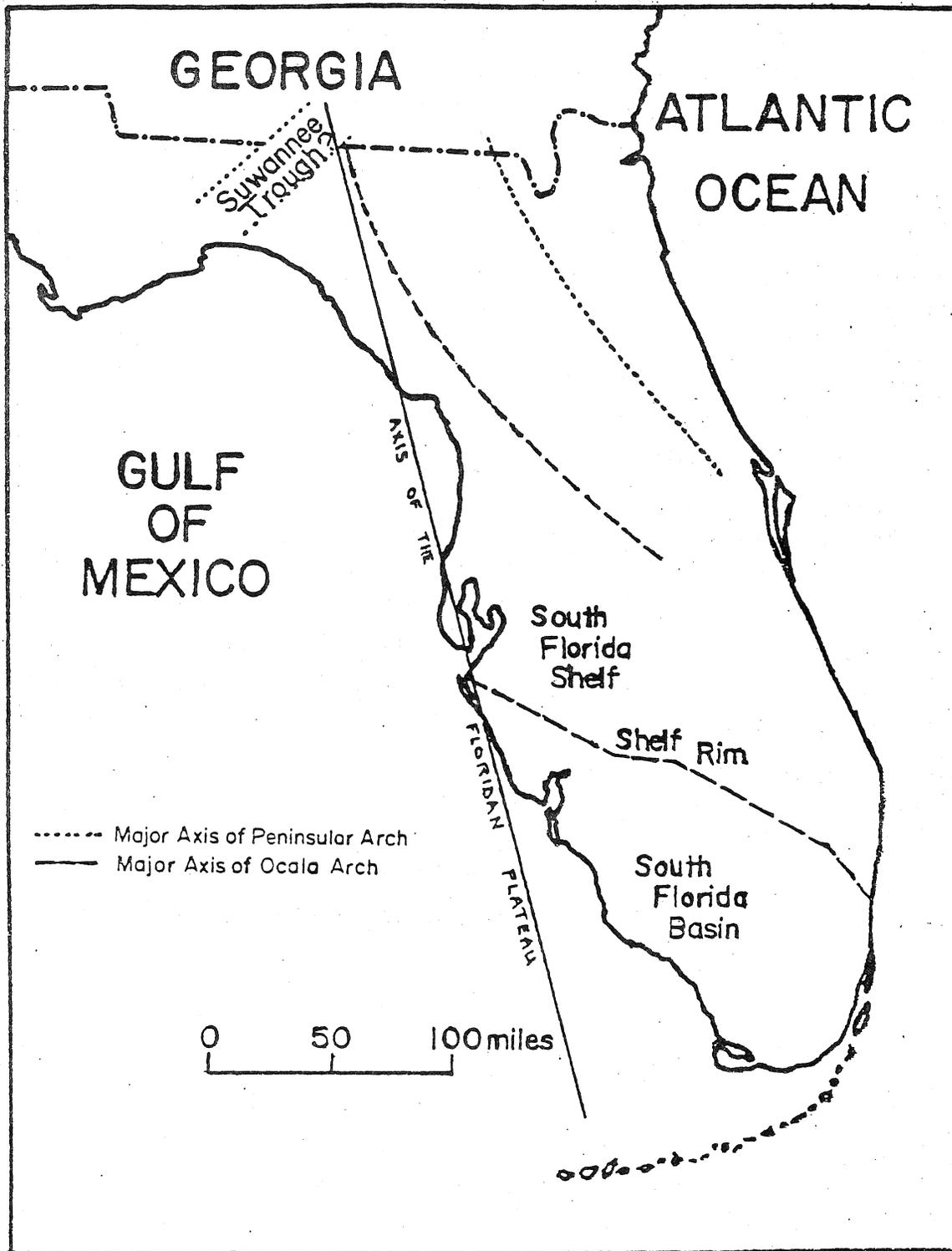


Figure 1. Major structural features of peninsular Florida.

were short episodes during the Eocene when great parts of the northern and central portions of the platform were emergent and subjected to nondeposition and subaerial erosion (Chen, 1965). These emergences are evidenced by numerous unconformities (Randazzo et al., 1977).

The carbonate facies deposited during the early Tertiary dip and thicken towards the south and the coasts, away from a subsurface structural high known as the Peninsular Arch (Vernon, 1951; Chen, 1965). The updip sections of the Floridan aquifer crop out at the contact with the Cretaceous Coastal Plain sediments in southern Georgia and Alabama. Vast quantities of water flow off of the southern Appalachians and infiltrate the porous carbonates here, creating an area of principal recharge to the aquifer.

Deposition of the Oligocene Suwannee Limestone was followed by a marine regression and an extensive period of post-Oligocene erosion (Vernon, 1951). The post-Oligocene seas exposed a structural high in western peninsular Florida. Originally described as a breached dome, this "Ocala Uplift" (Cooke, 1945; Vernon, 1951) has more recently been termed a "blister dome" (Winston, 1976). Winston believed that it formed when an increase in the rate of deposition of the Lake City Formation produced a curvature, reflected on the surface of deposition. Subsequently deposited carbonate sequences also reflected this curvature, and Oligocene or post-Oligocene tilting of the Florida Platform served to accentuate the dome.

The Ocala "blister dome" was exposed in the early and middle Miocene during which time shallow brackish water and marine facies of the Tampa Formation (early Miocene) and the Hawthorn Formation (middle Miocene) were deposited around it. Cooke (1945) found the Tampa-Hawthorn contact to be unconformable, and believed that the Hawthorn was deposited in an "expanded" Tampa sea. The upper part of the Hawthorn Formation, which consists of a heterogeneous mixture of lime mud, clays, marls, and phosphoric sands, forms a confining unit over the Floridan aquifer, and thus marks its upper boundary. At the close of the Miocene, the Hawthorn covered all of peninsular Florida except the area over the Ocala "blister dome." Artesian circulation probably began in the Floridan aquifer at that time, with recharge being confined predominantly to the areas of outcrop of the limestone (Stringfield and LeGrand, 1966; Vernon, 1951).

Today, local recharge occurs directly into the aquifer in areas of high elevation along the crest of the Ocala "blister dome" where the Hawthorn was not deposited. Where the Hawthorn is present, recharge can occur where it is breached, either by erosion or sinkholes. Discharge occurs mainly out into the Gulf of Mexico (Stringfield and LeGrand, 1966), and to a lesser extent through coastal springs (Wetterhall, 1965; Fetter, 1980).

Stringfield and LeGrand (1966) agreed with Cooke (1945) that the distribution of cavities within the Floridan aquifer, with their general decrease in size and numbers with distance from recharge and discharge areas, suggests that the present pattern of circulation developed in the Pleistocene during low sea level stands. Ranges in sea level during the Pleistocene are estimated to have been 270 feet above the present level (Cooke, 1945), and 500 feet below the present level (Donn et al., 1962). Thus, when sea level was at its lowest stand, it is conceivable that the groundwater level in western peninsular Florida was a few hundred feet lower than it is at the present time (Stringfield and LeGrand, 1966). During these stages, the Hawthorn was extensively eroded allowing more widespread recharge into the aquifer, accelerating dissolution of the limestone beneath.

The present-day nature of the carbonate aquifer is dependent upon the interrelations of its geologic history and the hydrologic conditions to which it has been subjected. Four geologic periods of aquifer development were cited by Stringfield and LeGrand (1966, p. 7-8). The "depositional period" establishes the volumetric extent of the carbonate unit and its primary permeability. During the "immediate post-depositional period" the carbonate deposit is elevated above sea level where it is exposed to meteoric weathering and possibly subaerial erosion. In addition to diagenetic changes which affect porosity, dissolution by infiltrating groundwater can greatly increase the permeability of the rock during this stage. The "subsequent pre-recent period" is marked by increased dissolution and permeability (assuming the deposit is still exposed to groundwater infiltration), compaction, consolidation, and recrystallization of the original limey deposits, and possibly the occurrence of some folding or faulting which might restrict groundwater circulation in some areas and promote it in others. Deposition of a sequence of sediments of low permeability will hinder groundwater dissolution of the underlying carbonates. The last period is marked by the "existing geologic setting and structure." Karst topography develops where the limestone crops out and is in the present groundwater circulation system.

The overall geologic structure is important in relation to topography and recharge-discharge areas. In western peninsular Florida recharge predominantly occurs north of Tampa Bay where porous carbonate units crop out, while south of Tampa Bay a layer of relatively impermeable clays inhibits recharge to the aquifer except where sinkholes breach this aquiclude.

DIAGENETIC SOLUTIONS

Carbonate diagenesis appears to occur more rapidly in the phreatic meteoric water environment than in the vadose meteoric or marine phreatic environments. Ginsburg (1957) noted that the Miami Oolite is better cemented where it presently exists below the modern water table than where it occurs in the vadose or marine phreatic environments. Friedman (1964), in observing that freshwater more commonly promotes mineralogical and textural changes which lead to lithification than marine waters, ran a series of experiments and concluded that low pH and low salinity of meteoric waters favor the diagenetic changes that occur.

In studying a fossil water table in Bermuda, Land (1970) judged that the phreatic meteoric water zone was where diagenesis of skeletal carbonates to coarse-grained sparry limestone was most rapid. These rocks were more highly altered and more stable mineralogically than rocks which spent more time in the vadose or marine zones. Also, he found larger crystals of cement in this zone where water could remain in pore spaces for long periods of time, as opposed to the vadose zone where flushing groundwater resulted in very little cement.

Land and Epstein (1970) discussed the mineralogical and isotopic changes that occur during meteoric water diagenesis. They stated that, generally, magnesium calcites incongruently dissolve rapidly to calcite, followed by dissolution of aragonite and reprecipitation as sparry calcite cement. As diagenesis proceeds, the unstable minerals dissolve, changing the cation and anion chemistry of the solution. Thus, the newly formed carbonates have lower concentrations of Sr^{+2} , Na^{+} , and Mg^{+2} , representing the interaction between meteoric water and the original marine sediments.

Steinen and Matthews (1973), reporting on a cored borehole on Barbados, observed that the upper part of their core had been in the vadose zone since its initial emergence from the marine environment. Although the carbonate sediments in this zone were composed of the unstable phases aragonite and high-magnesium calcite, they had not been affected to any great degree by dissolution. That part of the core that had occupied the freshwater phreatic

lens at least once during sea level fluctuations appeared to be mineralogically stable (composed of low-magnesium calcite), extensively cemented, and showed evidence of earlier dissolution. The lowest part of the core that was subjected to vadose meteoric diagenesis during glacial epochs and marine phreatic diagenesis during interglacial epochs, showed only minor cementation and dissolution, and retained most of its depositional mineralogy.

The diagenetic changes that occurred within the lithofacies described in this study that involve neomorphism of one carbonate mineral phase to another probably occurred upon introduction to a phreatic meteoric water environment.

The dolomite found within the cores in the study area has been categorized according to origin as penecontemporaneous dolomite formed in a supratidal environment; and secondary dolomite formed as a replacement of calcite by diagenetic solutions. Table 1 summarizes the characteristics of dolomite types as related to origin.

Table 1. Characteristics of dolomite types as related to origin.

Characteristics of Penecontemporaneous
Dolomite (Primary)

1. The dolomite is fine-grained (1-5 microns).
2. The dolomite occurs in association with supratidal sediments and structures, such as algal stromatolites, birdseye vugs, root casts, dessication features, and evaporite minerals
3. The dolomite is nonstoichiometric.
4. The dolomite forms by replacing lime muds, usually accompanied by a preservation of original sedimentary textures.
5. The dolomitized areas are thin and/or localized.
6. One would expect to find alternating layers of gypsum-dolomite-limestone in alternating supratidal-subtidal environments.
7. Trace element concentrations (Sr^{+2} and Na^{+}) are high, reflecting the hypersaline nature of the dolomitizing brines.

Characteristics of Dolomite Which Has Formed
in a Freshwater-Saltwater Mixing Zone
(Replacement)

1. The dolomite consists of larger crystals generally between 40-200 microns (Zenger, 1972). The more dilute the saline solution is, the larger the crystals and the more euhedral the crystal fabric.
2. The dolomite can occur in sediments associated with any depositional environment.

3. The dolomite is more-stoichiometric if the solution is quite dilute and the rate of crystallization is slow; and less-stoichiometric if it is only moderately dilute and accompanied by a faster rate of crystallization.
 4. Depositional texture is preserved more frequently in more-stoichiometric dolomite, and suggests slow recrystallization in less saline solutions.
 5. The dolomitized areas may vary in thickness, depending on the extent of migration of the mixing zone.
 6. More-stoichiometric dolomites are associated with lower Sr^{+2} and Na^{+} concentrations than less-stoichiometric dolomites, indicating formation in less saline solutions. Both of these dolomite types, however, contain lower trace element concentrations than penecontemporaneous dolomites because of freshwater dilution in the mixing zone.
 7. Coalescence neomorphism of original penecontemporaneous supratidal dolomites leads to rhombic crystals. Previously undolomitized limestones are recrystallized by a porphyroid neomorphic process that results in euhedral, rhombic dolomite crystals.
 8. More-stoichiometric dolomite shows a good clustering of points when Sr^{+2} and Na^{+} concentrations are plotted against mole-percent MgCO_3 . This indicates a longer residence time for the diagenetic solutions, and a greater approach to equilibrium between crystal and solution than occurs in less-stoichiometric dolomite (which characteristically produces a scattering of points when Sr^{+2} and Na^{+} are plotted against mole-percent MgCO_3).
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STUDY AREA

The area under investigation is the Southwest Florida Water Management District which occurs along the Gulf Coast of western peninsular Florida (Fig. 2). All of the cores and wells studied lie within this district except the Bell and Manatee Springs cores, which are within the Suwannee River Water Management District. A complete north-south traverse covers approximately 200 miles, and includes 29 wells, some as close together as 2 miles and others as distant as 47 miles.

METHODS OF ANALYSIS

The data compiled in this study came from various sources. X-ray analyses of cores 4-2, 6-3, 11-2, 17-1, 17-3, 19-3, and 21-2 were used to identify the presence of calcite and dolomite. Atomic absorption spectrophotometry was utilized to determine sodium and strontium concentrations in the rocks. Other stratigraphic, mineralogical and trace element data were obtained from the studies by Randazzo et al. (1977), Randazzo and Hickey (1978), Sarver (1978), Liu (1978), Zachos (1978), Fenk (1979), Metrin (1979),

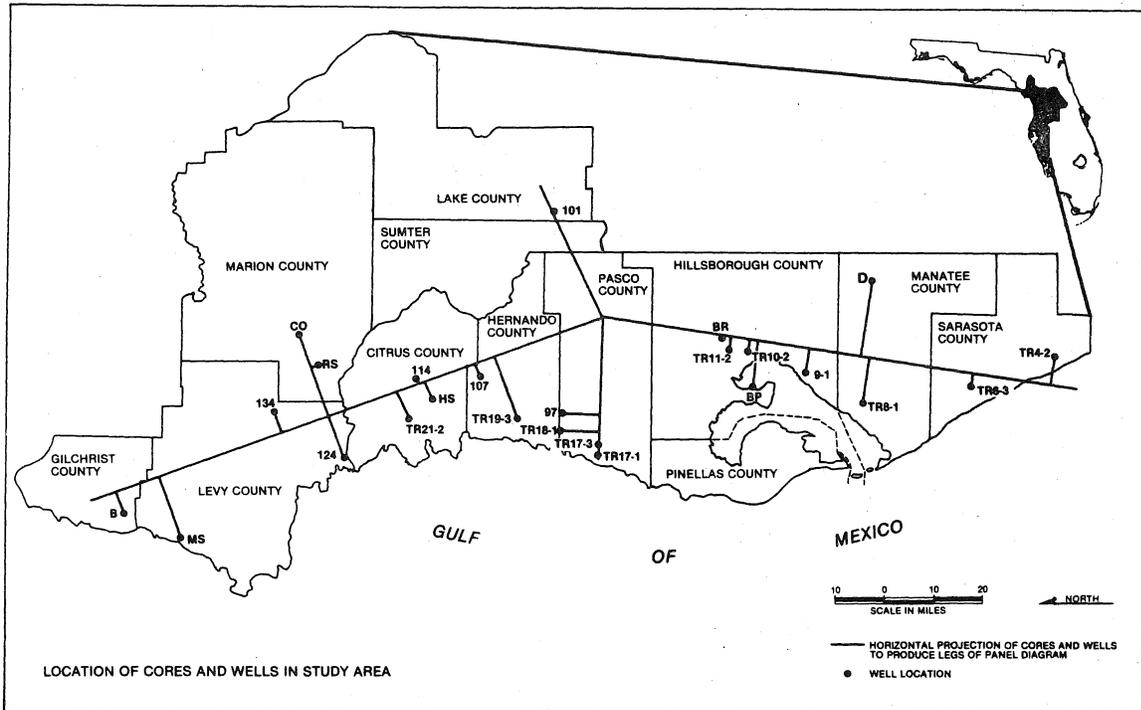


Figure 2.

Sharpe (1980), and Bloom (1982). Sulfate, chloride, and conductivity measurements were obtained from the Southwest Florida Water Management District. The Dicarb Radioisotope Company analyzed several dolomite samples for ^{14}C .

Panel diagrams are used to illustrate the variations of individual parameters across the study area. The panel diagrams were produced in conjunction with a United States Geological Survey potentiometric map (Fig. 3). The points where panels intersect were made to coincide with local recharge areas of 50 feet above mean sea level in Levy County, and 80 feet above mean sea level in Pasco County. In this way, the distribution of each parameter can be compared to the general flow of groundwater (Fig. 4).

DISTRIBUTION OF PARAMETERS

Environments of Deposition

Multidimensional Scaling Model

One of the most difficult problems in the utilization of a large quantity of data is the development of a combination of statistical methods for facilitating the environmental interpretation of carbonate rocks. In dealing with thin sections and modal analyses examination is made of tables of data which depict abundances and paucities of variable parameters. Interpretation of large amounts of data by "eye" is difficult. The final results are always partly intuitive. The capacity of computers to make comparisons provides a modern capability to establish objectively significant relationships among variables. Computers can compare variables within samples and recognize similarities, making interpretations more accurate.

Cluster analysis is a simple form of correlation analysis, a method of searching for relationships in a large symmetrical data matrix (Hayes, 1980). The advantage of cluster analysis is simplicity (Valentine and Peddicord, 1967, p. 502) because of the uncomplicated nature of the input and the resultant visibly distinct clusters. However, the numerical methods should not obviate the need to analyze the data objectively; they only aid in reducing the dimensionality of the data and when fully utilized can provide various insights not seen without computations.

A combination of statistical methods (multivariate analysis) were applied to the thin section data of the lithofacies to permit an environmental interpretation of the Tertiary carbonate rocks. Cluster analysis was applied in order to group-together variables such as allochems, lime mud,

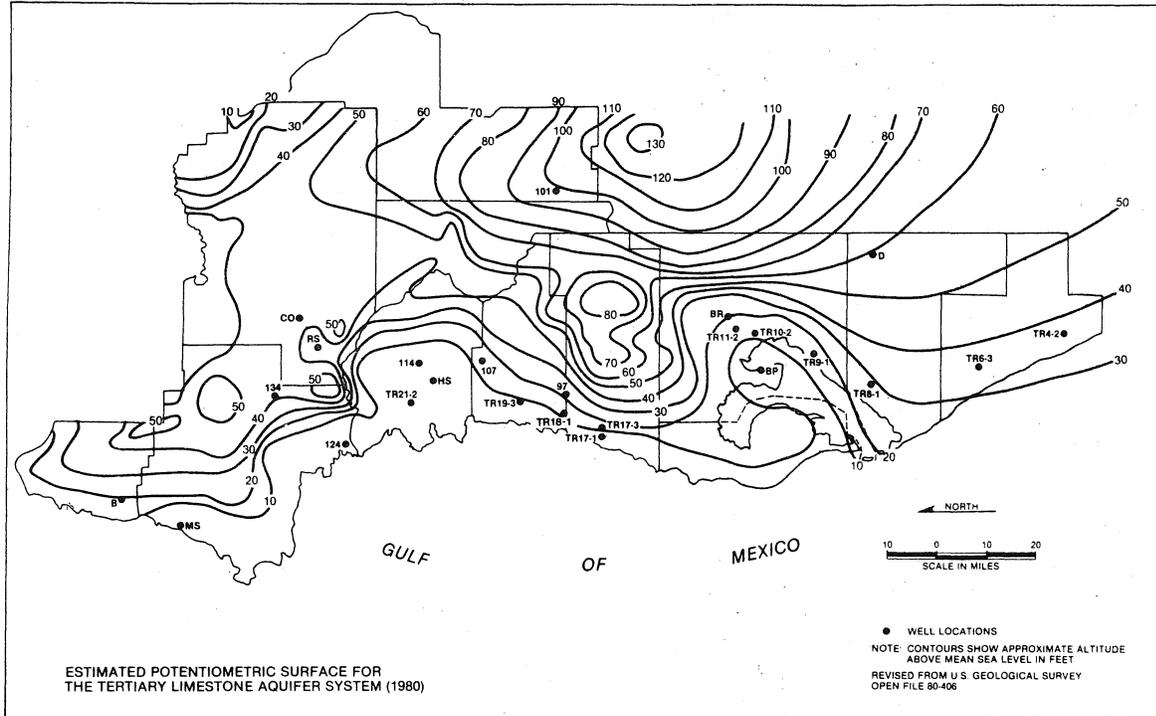


Figure 3.

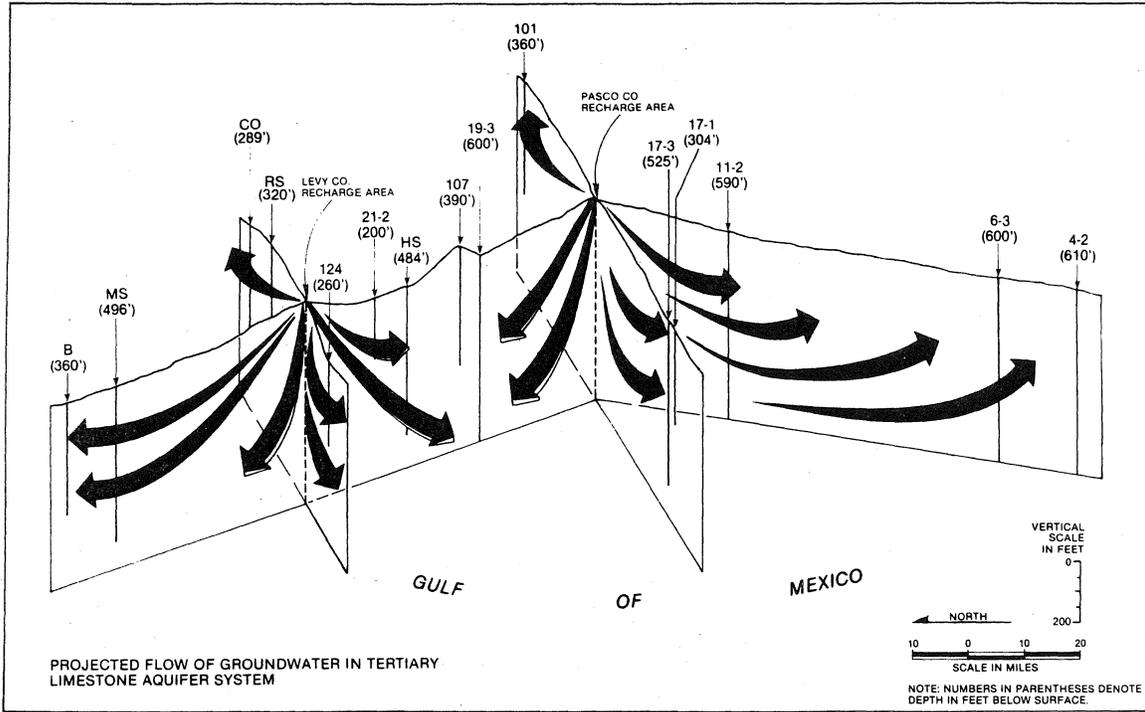


Figure 4.

calcite, dolomite, etc., (Table 2) that are most similar genetically. The variables considered are the product of environmental processes; therefore, variables most similar probably formed in the same depositional environment under similar processes. Multidimensional scaling (MDS), based on petrographic similarity, was used to order the samples on a two dimensional graph. Non-metric MDS is a technique illustrated by Kruskal (1964a) applied to geological problems (Whittington and Hughes, 1972; Smosna and Warshauer, 1979).

Multivariate analysis in carbonate petrology was employed by Imbrie and Purdy (1962) using factor analysis on data from Bahamian sediments. In factor analysis, however, the original data is ultimately lost in vectors, whereas cluster analysis does not abandon the original data and is immediately interpretable. In factor analysis mathematical techniques are used to promote correlation coefficients or secondary and tertiary data banks for and patterns. Therefore, the input data is processed and the final visible data is intelligible and correlatable but complicated because the worker is not viewing the original data. However, in cluster analysis similarities between the variables are processed and presented as groups of most similar variables showing the original data. Parks (1966) combined an R-mode cluster analysis and Q-mode cluster analysis to describe Bahamian sediments. Ekdale et al. (1976) used multivariate analysis for paleoecological interpretation of Cretaceous rudists. Comparisons sample by sample is a Q-mode clustering and variable by variable (within the sample) is an R-mode clustering (Sokal and Sneath, 1963). This computer application combines a variety of methods that are nonparametric (not based on normal distribution). Any method that reduces the dimensionality of the data causes distortion. Clustering imposes a hierarchical structure to the data. Almost inevitably the method introduces distortion in representing the multidimensional relations between the localities on a two dimensional dendrogram. This distribution of distortion is well known; the relations at the tips of the dendrogram are well-represented and distortion is greater in the later formed clusters (Rowell et al., 1973). The distortion of stress has to be taken into account when analyzing the clustering output. Because of the existence of this distortion Rowell et al. (1973, p. 3430) suggest that some form of ordination should be used as an alternative or complementary means of displaying structure in the data. Ordination is a comparative process. All samples or variables are compared to each other in a symmetrical matrix. Dissimilarity is measured and this produces a graphic geometric display. Cluster analysis often obscures the

Table 2. List of variables used in the multivariate analysis of three cores of mid-Tertiary carbonate rocks.

Allochems		Matrix	Detrital
Foraminifera	Peloid	Calcite	Quartz
Echinoderm	Intraclast	Micrite	
Mollusca	Pellet	Dolomite	

overall relationship, whereas ordination shows gradational relationships. The amount of distortion may be estimated by calculating a correlation between the interlocality distances in the reduced dimensional space and the corresponding distances in the original similarity matrix. The distortion that is typically present is distributed differently than that in a dendrogram. The distortion is greater in smaller distances and not larger distances between the data points. Ekdale et al. (1976) used an ordination algorithm versus the nonmetric algorithm used by Kruskal (1964a, 1964b). Kruskal's algorithm includes a built-in accommodation of stress (distortion).

Basically the method seeks to find a geometric configuration of n points (variables) in a reduced space of k dimensions (containing the variables) such that interpoint distances correspond to the similarities between points. The solution is the best fitting configuration that minimizes stress. Nonmetric MDS distributes distortion better than clustering.

The carbonate rocks of this study were lithologically distinct and were deposited under different environmental influences and processes. Ordering the thin section samples on a MDS plot reflects gradients of these processes. Multivariate analysis was performed on the thin section data from the lithofacies described in three of the cores studied (Sharpe, 1980) to illustrate the gradational trends of carbonate rock variables across a marine carbonate shelf.

An R-mode cluster analysis and a Q-mode cluster analysis were run on 176 thin-section samples for 52,800 observations. Seven clusters from the Q-mode were produced and scanned. Each cluster revealed characteristic variables that distinguish that individual cluster. They were: 1) dolomite, 2) dolomite/mud, 3) mud, 4) skeletal/mud, 5) intraclast, 6) quartzose mud and 7) skeletal/sparite. Because of the large number of samples (176) the three dimensional

MDS plot was extremely cluttered and gave no clear isometric projection. However, the two dimensional MDS plot shows well the gradations and is illustrated here (Fig. 5). The cluster boundaries displayed on the plot were delineated based on the Q-mode data. Some thin section points fell between the cluster boundaries. They were transitional samples with characteristics of the two nearest clusters. This illustrates the gradational nature of the MDS plot.

Cluster 1

Dolomite microfacies. - A mosaic of dolomite which completely obliterates all allochems, while preserving some megascopic sedimentary textures (e.g. faint laminations). These sediments are part of a Lithofacies of dolomitic mudstones and wackestones from the Avon Park Formation.

Cluster 2

Dolomite/mud microfacies. - The samples are dolomitized mudstones and wackestones with textures and allochems preserved. Within this cluster also falls a dolomitic sandstone.

Cluster 3

Mud microfacies. - These samples represent laminated mudstones and wackestones with sparse fauna. They include peat layers and algal laminated sediments.

Cluster 4

Skeletal/mud microfacies. - The samples are characterized by high faunal diversities and a high mud matrix content. This cluster contains the samples with large foraminifera (e.g. Nummulites sp.) from the Ocala Limestone.

Cluster 5

Intraclast microfacies. - Abundant mudstones and wackestone occur here. These samples have large intraclast contents, mud and sparse fauna.

Cluster 6

Quartzose mud microfacies. - The samples are predominantly wackestones and mudstones with sparse fauna but have very abundant detrital quartz (20 - 80 percent).

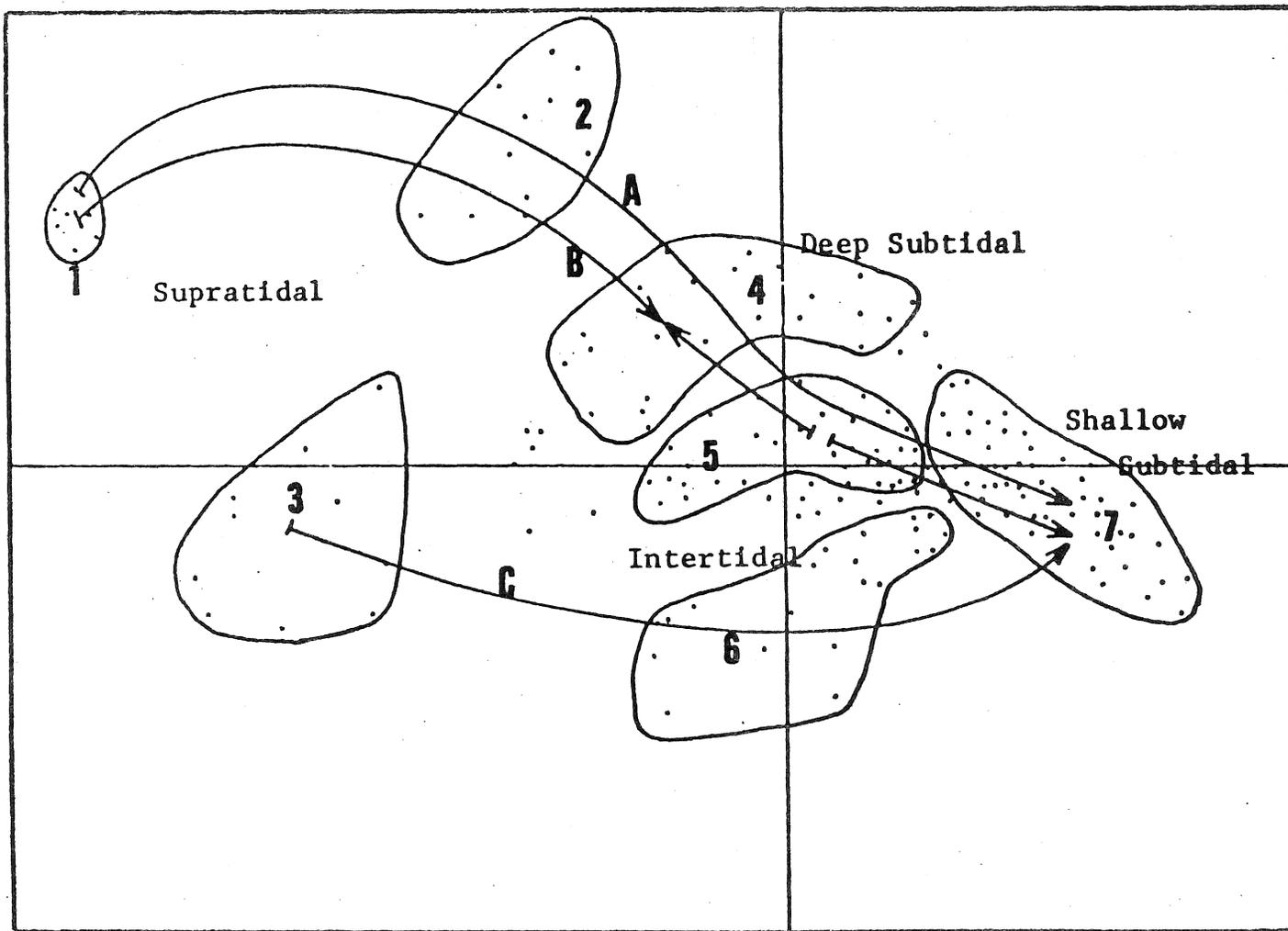


Figure 5. Two-dimensional MDS configuration displaying the relationships among 176 thin-sectioned samples based on ten variables (Table 2).

Cluster 7

Skeletal/sparite microfacies. - The samples are all skeletal grainstones with abundant void-filling spar and high faunal diversities.

Interpretation

Clusters 1, 2 and 3 correspond to those lithofacies interpreted as being deposited in the supratidal zone. The samples were independently described as supratidal deposits. Thus the multivariate analysis and clusters verified the similarity interpreted by conventional petrographic methods. The inclusion of a dolomite sandstone into these clusters is interesting. This unit was initially interpreted as a clastic bar deposit and yet the clustering indicates a supratidal (possibly beach) environment. The sandstone is very coarse and has associated organic material (dark color); therefore, this could very well represent a beach or supratidal channel deposit. Conversely, the presence of dolomite may have caused the cluster analysis to misclassify the two thin section samples containing this particular lithology (2 samples out of 176).

Cluster 4 is interpreted as representing deep subtidal deposits, with low wave energy allowing the mud to accumulate and a high faunal diversity, characteristic of the deep subtidal.

Both clusters 5 and 6 are interpreted as representing shallow water intertidal depositional regimes because of the abundant quartz and mud (restricted quiet water lagoon).

Samples found in cluster 7 represent shallow subtidal material seen predominantly in several lithofacies. These samples have a high faunal diversity, high faunal content and abundant sparry calcite.

Characteristics of the offshore depositional environments are gradational perpendicular to shore. Therefore, a plot of the various variables characteristic to one or more subenvironments should show this gradation. The multi-dimensional scaling configuration (Fig. 5) demonstrates the gradational nature of the 176 samples, allowing for an environmental interpretation. The clusters (containing the samples) seem closer to one another, showing geometrically the gradation.

In the interpretation of the MDS clusters, analysis must be made of chemical, physical and biological aspects of the clusters. The dolomite and mud-dominated clusters (1, 2 and 3) are interpreted as containing samples representing the supratidal zone. The intertidal zone is represented by samples in clusters 5 and 6, and samples of clusters 7 and 4 represent shallow subtidal and deep subtidal zones, respectively.

The cluster showing the highest energy (wave action) is cluster 7. Therefore, after placing the shoreline to the left of the diagram (supratidal), curve A can be constructed showing energy normal to the shore (Fig. 5), culminating in cluster 7, the shallow subtidal zone. The shallow subtidal zone shows the least mud and the most spar, and so represents the highest wave energy zone (cluster 7). The transect of hydrodynamic energy starts in the supratidal and gradually increases through the deep subtidal, through the intertidal and reaches the highest level in the shallow subtidal zone. This is illustrated by mud abundance varying from 81 percent in the supratidal samples, to 39 percent in the deep subtidal samples, to 27 percent in the intertidal samples, and 0-8 percent in the shallow subtidal. Conversely the amount of sparite increases from 0-3 percent in clusters 1, 2 and 3 to 35 percent in cluster 7 (shallow subtidal). The pattern of fabric support also parallels this trend passing from mudstones in clusters 1, 2 and 3 to grainstones in cluster 7. These properties parallel the direction of increasing energy and substrate mobility.

Faunal diversity is highest in the deep subtidal (4) and shallow subtidal (7). Therefore, paralleling the hydrodynamic trend (curve A) is a faunal diversity trend (curve B) showing increasing faunal diversity from clusters 1 and 2 to clusters 4 and 7 (Fig. 5).

The two intertidal clusters (5 and 6), together with the mud/quartz cluster (3), indicate that the MDS analysis also realized the regional change (advent of detrital quartz) in sediment characteristics. Consequently clusters 3 and 6 are interpreted as indicating more clastic intertidal and supratidal zones as shown by another hydrodynamic (energy) curve (C) (Fig. 5).

Diagenetic trends can also be shown on the MDS plot (Smosna and Warshauer, 1979). The susceptibility of supratidal sediments to dolomitization is illustrated by the dolomite being concentrated in the supratidal deposits and this is supported by previous work (Randazzo and Hickey, 1978). The trend does not show phases of dolomitization because there are different dolomitic textures within cluster 2.

The presence of two distinct clusters of dolomite is thought to illustrate different salinity conditions fluctuating from below normal to above normal (Smosna and Warshauer, 1979). The two dolomite clusters may indicate phreatic waters of different concentrations of Na, Mg, and Ca indicating the possibility that different groundwater systems may have acted on the samples

of these clusters. Another hypothesis is that the clusters may well indicate a difference in the time of contact with groundwater fluids.

Therefore, from this data presentation can be derived a hydrodynamic and paleoecological interpretation of the Tertiary carbonates of west-central Florida (Fig. 6). Figure 6A shows the carbonate platform with lowest water energy at the supratidal and highest energy in the shallow subtidal. Low faunal diversity is characteristic of the supratidal zone increasing in diversity offshore, and the most pronounced dolomitization has occurred in supratidal sediments. Figure 6B shows a slightly steeper gradient in a clastic influenced tidal regime, shown by samples in clusters 2, 3 and 6.

Stratigraphy

Figure 7 shows the stratigraphic distribution of the geologic units to a depth of 600 feet. From Hernando County to the south, the formations can be seen dipping to the south where they progressively become overlain by younger units. This feature reflects the deeper lying structures of the South Florida Shelf and the South Florida Basin (Fig. 1). The regional effects of the Ocala "blister dome" can be seen in the northern half of the diagram where the Ocala Limestone crops out.

Mineralogy

The distribution of limestone and dolomite are depicted in Figure 8. Analyses were conducted by x-ray diffraction, and only those samples in which the carbonate fraction was found to be 100 percent dolomite are illustrated here. One of the most distinguishing observations is that the Avon Park Formation has been significantly dolomitized in this area, while the Ocala and Suwannee Limestones lying above have not been. The limestone-dolomite boundary follows the Ocala-Avon Park boundary, and dips to the south. South of the Pasco County recharge area most of the Miocene age deposits contain dolomite. The dolomite zone here thickens southward and seaward, as do those stratigraphic units.

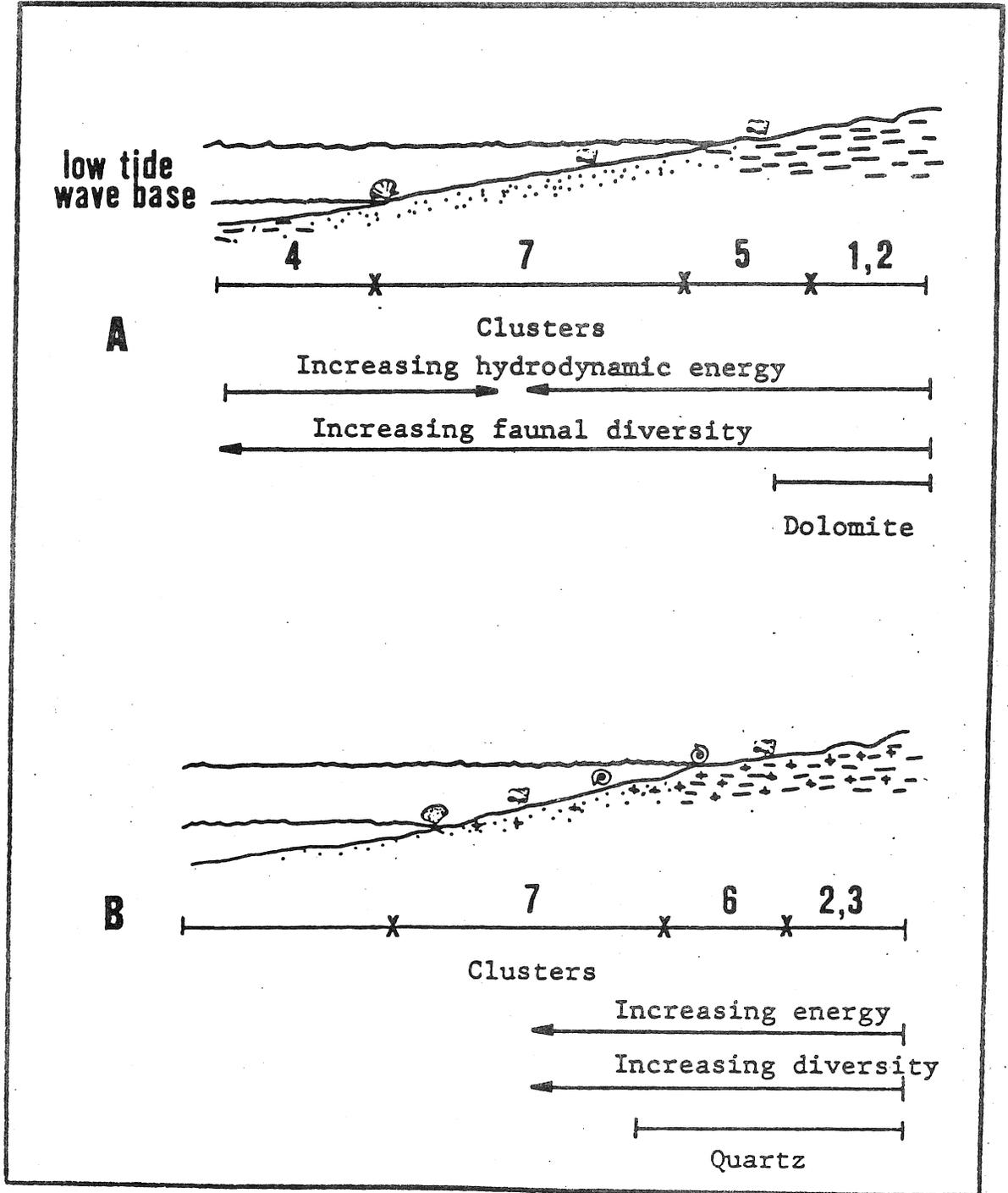


Figure 6. Schematic interpretation of Tertiary carbonate rocks illustrating the paleoenvironments. Plotted are the positions of the seven Q-mode clusters and environmental gradients. Part A shows the carbonate platform and the environmental interpretation. Part B is the clastic-influenced interpretation.

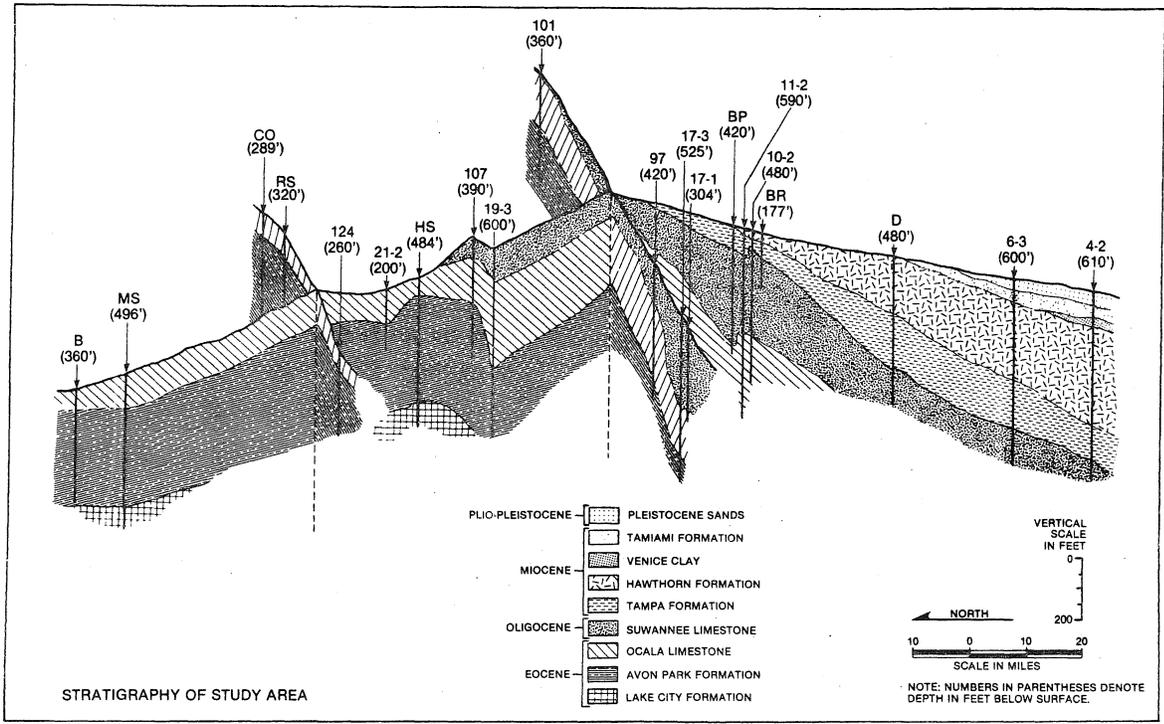


Figure 7.

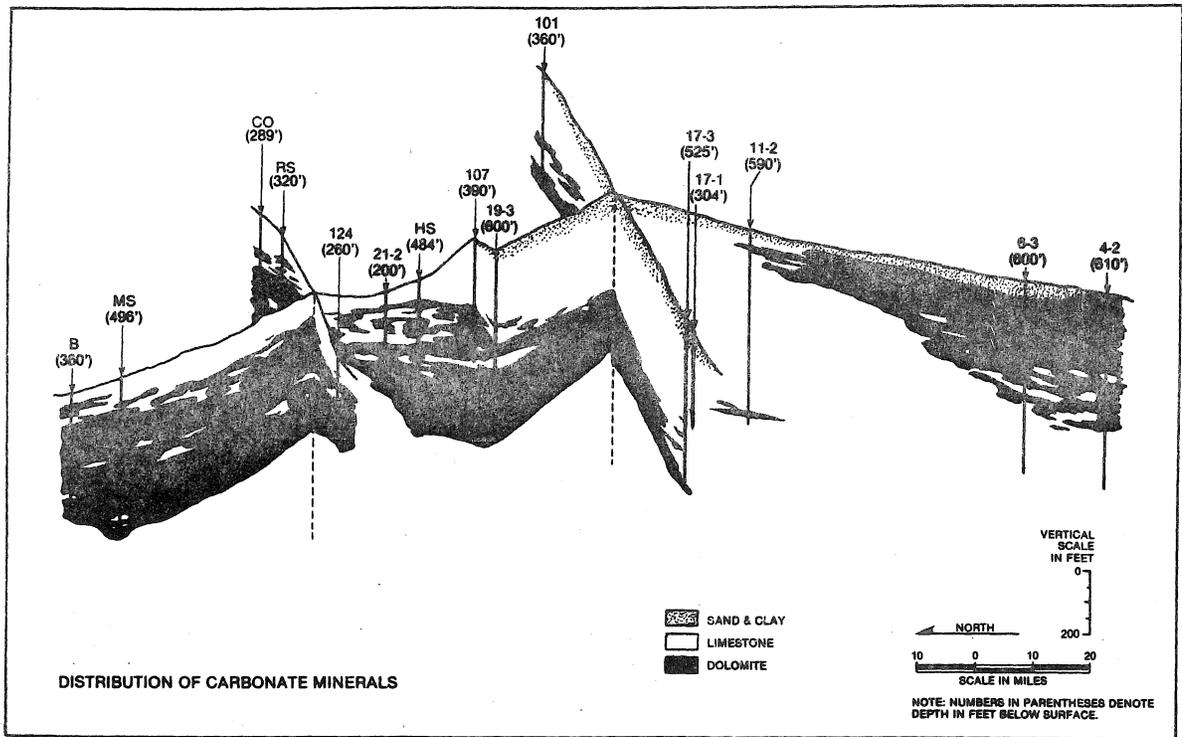


Figure 8.

Trace Elements and Geochemistry of Rocks

Strontium

The distribution of strontium is shown in Figure 9. Sr^{+2} concentrations greater than the 50-percent reduction associated with the formation of dolomite from calcite (Behrens and Land, 1972) have been explained by dolomitization occurring in waters more saline than those in which calcite formed (Randazzo and Hickey, 1978). The Sr^{+2} content in the northern cores (B, MS, CO, RS, 124, 21-2, HS, and 107) does not drop to lower values at the limestone-dolomite boundary, but rather changes farther down into the dolomite zone. Core 19-3 shows an increase in Sr^{+2} concentration in its deeper regions to over 800 ppm. Higher than average Sr^{+2} concentrations also occur at certain horizons in cores 21-2 and 17-1. These areas of high Sr^{+2} concentration indicate where dolomite formed from solutions more saline than did the surrounding rock. Across the entire transect of the northern cores, it appears that the dolomites of the uppermost part of the Avon Park formed in solutions more saline than the lower part.

The southern cores (19-3, 101, 17-1, 17-3, 11-2, 6-3, and 4-2) all contain higher Sr^{+2} concentrations, on a whole, than do the northern cores. The calcite samples in core 101 average twice the concentration of Sr^{+2} as do the calcites in the northern cores. The dolomite samples in core 101 contain approximately half the concentration of Sr^{+2} as do the calcite samples, implying that both carbonate phases probably formed in similar solutions.

Dolomite samples analyzed for cores 4-2, 6-3, and 11-2 occur in Miocene deposits which are considerably younger than the Eocene carbonates of the Ocala Limestone and Avon Park Formation. The Sr^{+2} concentrations of dolomites in the Miocene rocks are higher than anywhere else in the study area, ranging from less than 200 ppm to greater than 800 ppm. Figure 9 indicates that there is a steady increase in Sr^{+2} concentration in dolomite of these cores with depth. It should be noted that small amounts of Sr^{+2} may have been contributed by associated clay minerals which were sometimes present in the southern cores.

Sodium

According to Veizer et al. (1977) and Land (1980), sodium interpretations should be used cautiously because present methods of analysis cannot distinguish lattice-bound sodium from sodium trapped or absorbed in the crystal struc-

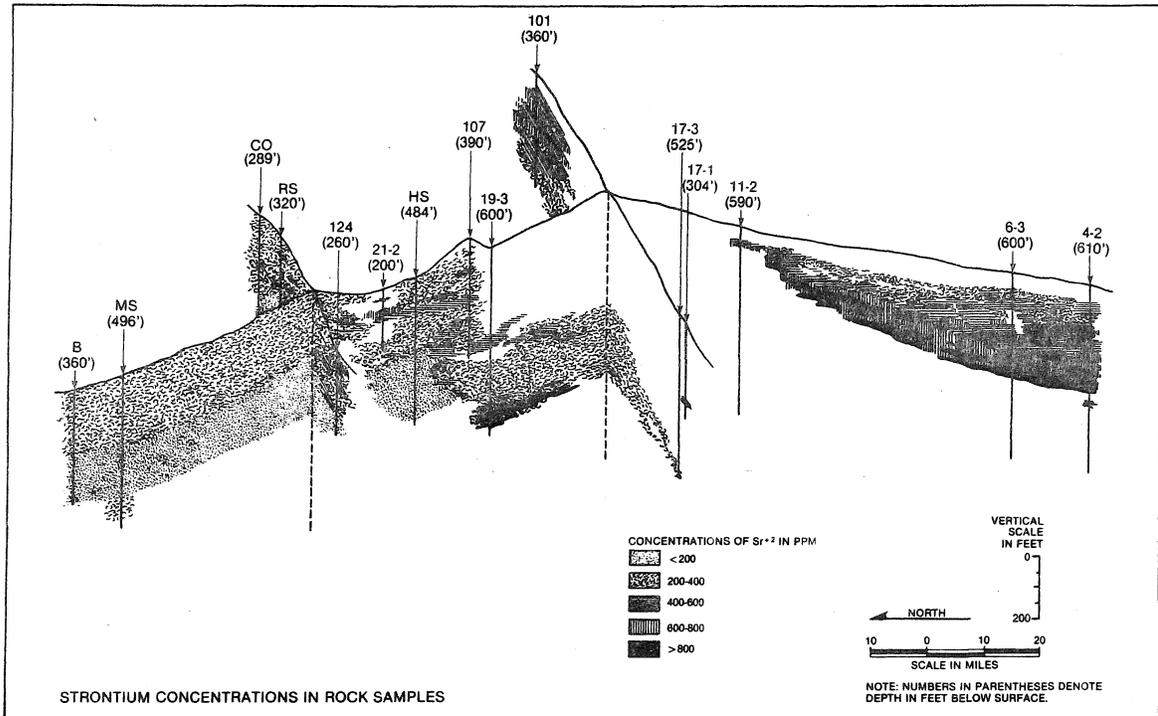


Figure 9.

ture as inclusions of NaCl. Because Na^+ is a small ion, it can substitute with equal facility into Ca or Mg lattice positions (Land and Hoops, 1973). Thus calcite and dolomite that have formed from similar solutions should contain similar quantities of sodium.

Figure 10 depicts sodium distribution in the rocks studied; and those wells that show incomplete data contain analyses on dolomite samples only. Again some Na^+ may have been contributed by associated clay minerals which sometimes were present in the southern cores.

All of the calcite samples within the diagram contain sodium in concentrations less than 500 ppm, which indicates diagenesis in relatively fresh waters. The dolomite samples show a range of sodium values from less than 500 ppm to over 2,000 ppm. The increase in sodium values exactly at the limestone-dolomite boundary in the northern cores and the decrease in sodium concentrations in the lower regions of the Avon Park Formation in those cores agrees well with the conclusion drawn from the strontium data - that the uppermost dolomites in the Avon Park formed in solutions more saline than the lower parts.

The cores adjacent to and south of the Pasco County recharge area (cores 4-2, 6-3, 11-2, 17-1, and 17-3) contain significantly higher levels of sodium than the other cores. This is in agreement with the Sr^{+2} distribution in Figure 9. However, the Sr^{+2} concentrations showed an increase with depth in the Miocene deposits, whereas the sodium concentrations appear to show no predictable alternation in pattern. Zones of high Na^+ values (> 2,000 ppm) occur among zones of low Na^+ values (< 500 ppm). Also, the base of core 19-3, which contains abnormally high strontium values, showed relatively low sodium concentrations in comparison.

It should be noted again that the dolomites in the cores south of Pasco County recharge occur in rocks younger than those to the north, and are associated with clay minerals. The sodium content of ancient dolomites have been found by many authors to be depleted relative to recent dolomites (Weber, 1964; Behrens and Land, 1972; Fritz and Katz, 1972; Land and Hoops, 1973). Land and Hoops (1973) believed that this was the result of re-equilibration with a meteoric reservoir. If this is true, then dolomite, originally equilibrated in saline solutions, could lose weakly held sodium from its lattice and bring about new equilibrium conditions when flushed by fresh-water. Because all of the cores within this study have been exposed in some degree to meteoric water, the sodium concentrations analyzed are probably all less than what they were originally.

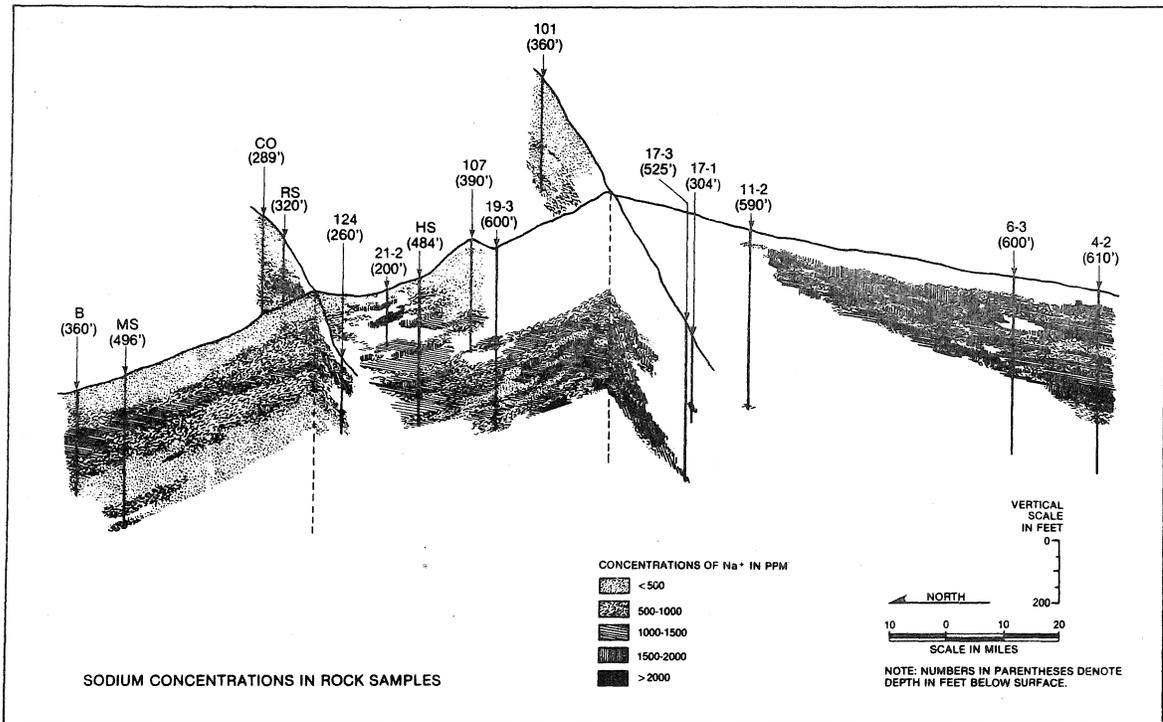


Figure 10.

Cores 21-2 and HS show higher sodium concentrations in comparison to neighboring cores. Both of these cores occur where the potentiometric surface (Fig. 3) is lower than in any of the other cores in the study area. The Ghyben-Herzberg principle (Reichenbaugh, 1972) states that saltwater intrusion occurs to a greater degree, and affects rocks closer to the surface, in areas of low potentiometric head. The strontium data from the dolomites in core HS correlate with the northern cores, illustrating a less saline dolomitizing solution for the lower part of the Avon Park. However, the sodium data for this core does not agree with its northern counterparts. The zone (< 500 ppm) illustrating this relationship in the lower parts of the northern cores is replaced by zones indicating dolomitizing solutions of much higher salinities in the HS core.

The distribution of sodium in Figure 8 indicates that while it substantiates the conclusions drawn from strontium analyses in some instances, in other cases it can lead to ambiguous interpretations. Because trapped and absorbed sodium in the carbonates can contribute to the total sodium detected in analysis, used alone it is not a reliable indicator of the salinity of diagenetic solutions. However, where there is agreement between sodium distributions and other trace element distributions, more confident conclusions may be reached regarding the salinity of diagenetic solutions.

Mole-percent $MgCO_3$

Dolomites are chemically characterized by their mole-percent $MgCO_3$ content. Randazzo and Hickey (1978) categorized the less-stoichiometric dolomite in their study as being composed of 44-48 mole-percent $MgCO_3$, and the more-stoichiometric dolomite 49-51 mole-percent $MgCO_3$. Figure 11 shows the distribution of mole-percent $MgCO_3$ of some of the dolomite in this study. The numerical divisions used in the index do not exactly correspond to the boundaries used by Randazzo and Hickey (1978), but offer a greater distinction of the degree of dolomite stoichiometry. More-stoichiometric dolomites generally indicate slow formation in waters less saline, with fewer competing ions to disrupt the resulting structure (Folk and Land, 1975; Randazzo and Hickey, 1978). It should be noted that other factors such as changing Mg/Ca ratios of pore waters, rechargeable sources of Mg^{+2} , crystal sizes, and permeability can affect the relationship between dolomite stoichiometry and the salinity of the dolomitizing solution (Lumsden and Chimahusky, 1980).

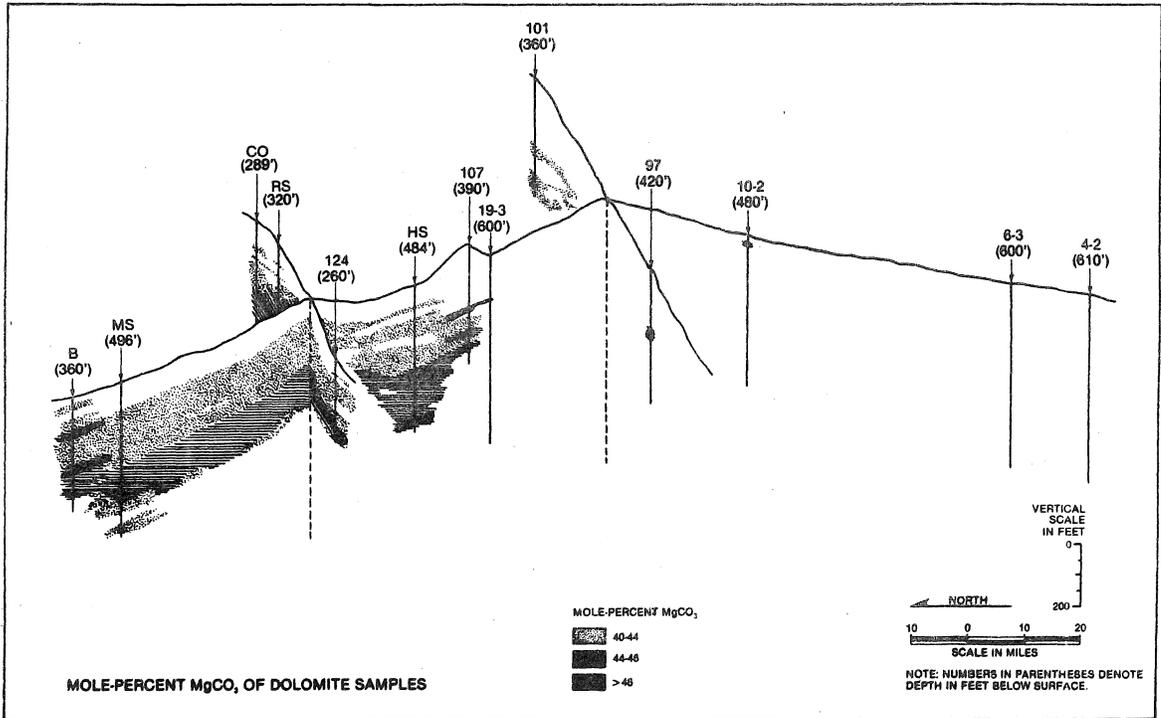


Figure 11.

Comparison of the distribution of mole-percent $MgCO_3$ with the distribution of Sr^{+2} for the cores in the northern portion of the study area (Figs. 9 and 11) shows a marked decrease in Sr^{+2} occurring at approximately the same depth as a marked increase in mole-percent $MgCO_3$. This inverse distribution of more-stoichiometric dolomite and low concentrations of Sr^{+2} suggests the formation of dolomite in solutions less saline than those acting upon the uppermost section of the carbonate sequence. The distribution of Na^+ in these same cores (Fig. 10), despite the limitations cited earlier, further substantiates the conclusion drawn about the salinity characteristics of the dolomitizing solutions.

^{14}C

Ten dolomite samples from cores 4-2, 6-3, 19-3, 21-2 and MS were analyzed for ^{14}C . The ^{14}C content of the samples was appreciable and would translate into "ages" of 26,470 - 38,760 years B.P. Although these "ages" cannot be interpreted rigorously as geologic ages, they clearly demonstrate that carbon has been exchanged between dolomite and the atmospheric reservoir in the geologically recent past. Though not conclusive, these data suggest that the formation, or at least partial recrystallization of dolomite occurred within the last 30,000 years.

Distribution of Hydrogeochemical Parameters

Data were obtained on chloride and sulfate concentrations, and specific conductance from selected wells. At intervals during drilling of the cores, water samples were collected from flowing water at the base of the wells. Readings were taken from these samples. Tight casing prevented waters from higher areas mixing with waters from the base of the well.

These data can be helpful in defining the position of a freshwater-saltwater interface that presently exists. If the present pattern of circulation within the Floridan aquifer developed during low stands of Pleistocene seas (Stringfield and LeGrand, 1966), then the present position of the interface may be related to the distribution pattern of dolomite in the region.

Chloride

The most reliable indicator of saltwater intrusion is the chloride content of the water (Wetterhall, 1964). The chloride ion concentration in pure seawater is approximately 19,000 mg/l (Gross, 1972; Duxbury, 1971).

Fresh Florida groundwater, on the other hand, contains chloride ion concentrations less than 50 mg/l (Wetterhall, 1964). Reichenbaugh (1972) used a chloride concentration of greater than 250 mg/l to indicate that a well had contacted the freshwater-saltwater interface. Thus Figure 12 provides a good indication of the salinity of encroaching solutions.

The values from wells 17-1, 17-3, and 21-2 denote the presence of highly saline solutions within the aquifer at shallow depths. A dramatic increase in chlorinity occurs from freshwater concentrations just below the surface, to concentrations near that of seawater at only 200 feet of depth. The chlorinity in wells 19-3 and 18-1 are under similar potentiometric heads as those wells which occur at close distances, yet they constitute freshwater all the way to their base. Wetterhall (1964) found that intruded saltwater may not be vertically continuous in the aquifer. He identified wells within the same area of Hernando County as 19-3, where zonation of the aquifer allowed freshwater to occur between layers of relatively salty water.

Wells 11-2, 6-3, and 4-2 all give data which indicate that saltwater has intruded into the southern region, but not to the degree that it has in some of the other wells. One reason for the low chloride concentrations in these wells is that the wells occur in the confining layers of low permeability overlying the aquifer. Water is not able to flow as freely into these formations either from the sea or from recharge as it can in the carbonate aquifer units which lie below. Another explanation, concerning the height of the potentiometric surface, can explain the distribution of chloride concentrations in all of the wells (except 19-3, 124, 97, and 18-1 - for which the previous interpretation will hold). The potentiometric levels in wells 17-1, 17-3, 21-2, and 124 are less than 10 feet (above mean sea level), while in wells 11-2, 6-3, and 4-2 the heights range from approximately 25-35 feet (Fig. 3). Assuming uniform permeability, the Ghyben-Herzberg principle denotes that the freshwater-saltwater interface should lie at less than 400 feet in those northern wells, while it should occur between 600-1,400 feet in the southern wells. Allowing for the low permeability of the Hawthorn Formation, saltwater encroachment would still not be expected to be as great at the depths penetrated by the southern wells, as at the depths penetrated by those wells north of the Pasco County recharge area.

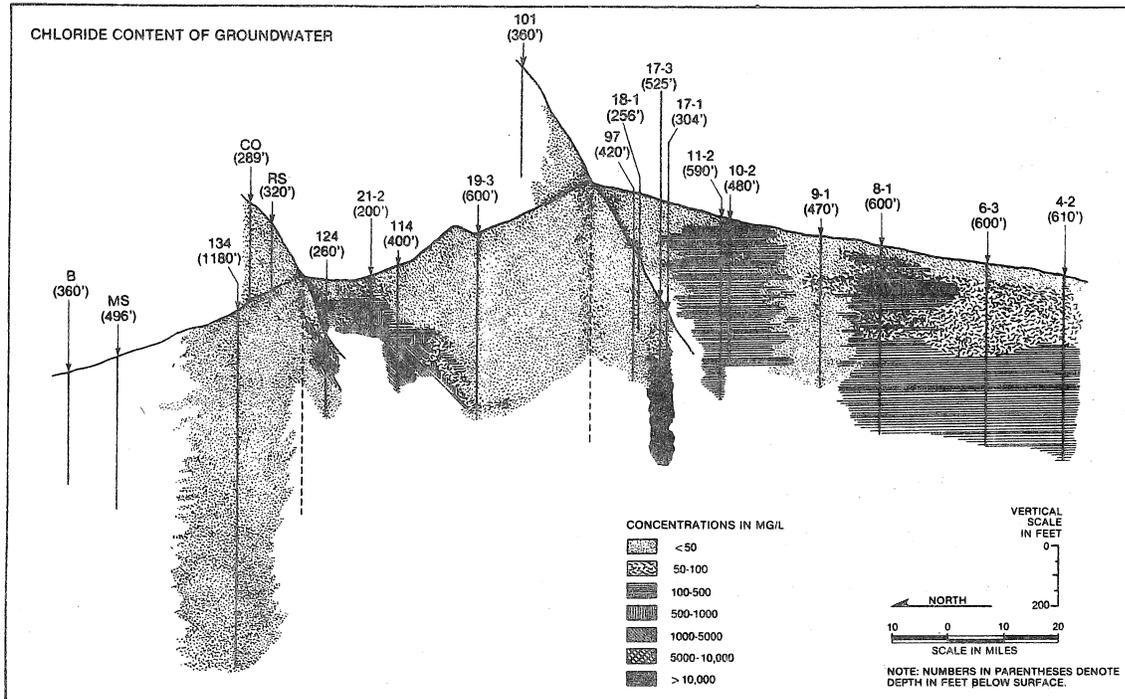


Figure 12.

Conductivity

In his geohydrologic reconnaissance of Pasco and southern Hernando Counties, Wetterhall (1964) found chloride content and specific conductance (conductivity) of the waters to be generally related. Figure 13 shows conductivity distribution in the waters from the same wells as Figure 12. These values correlate extremely well with the chloride values. Conductivity measurements for the waters (in microohms per centimeter) are approximately an order of magnitude greater than their corresponding chloride concentrations (in mg/l). Conductivity measurements reinforce the conclusions concerning salinity of the water inferred from the chloride data. Although the conductivity of seawater is temperature sensitive (Duxbury, 1971), the temperatures in the waters of these wells all range within a few degrees of 25°C (Plummer and Back, 1980).

Sulfate

Sulfate ion concentrations in pure seawater have been recorded at 2,511 mg/l (Gross, 1972) and 2,649 mg/l (Duxbury, 1971). Wells 6-3 and 4-2 contain low sulfate values (Fig. 14) in the Hawthorn Formation (less than 500 mg/l), as expected. Below the Hawthorn, in the Tampa and Suwannee where aquifer waters flow, an increase in sulfate concentrations occur, reflecting an advancing freshwater-saltwater interface. Wells 17-1, 17-3, 97, and 124 give high sulfate concentrations. Overall, the sulfate values are in agreement with the model of saltwater intrusion originally deduced from the chloride data.

DISCUSSION

In attempting to formulate a mineralogical model of the Floridan aquifer several factors must be considered: (1) the age of the carbonate units and their original lithologies and environments; (2) the mineralogical and physical evolution of the aquifer; (3) the nature and variations of the hydrologic regimes to which the aquifer rocks were subjected; and (4) the distribution of the various geochemical and hydrologic parameters.

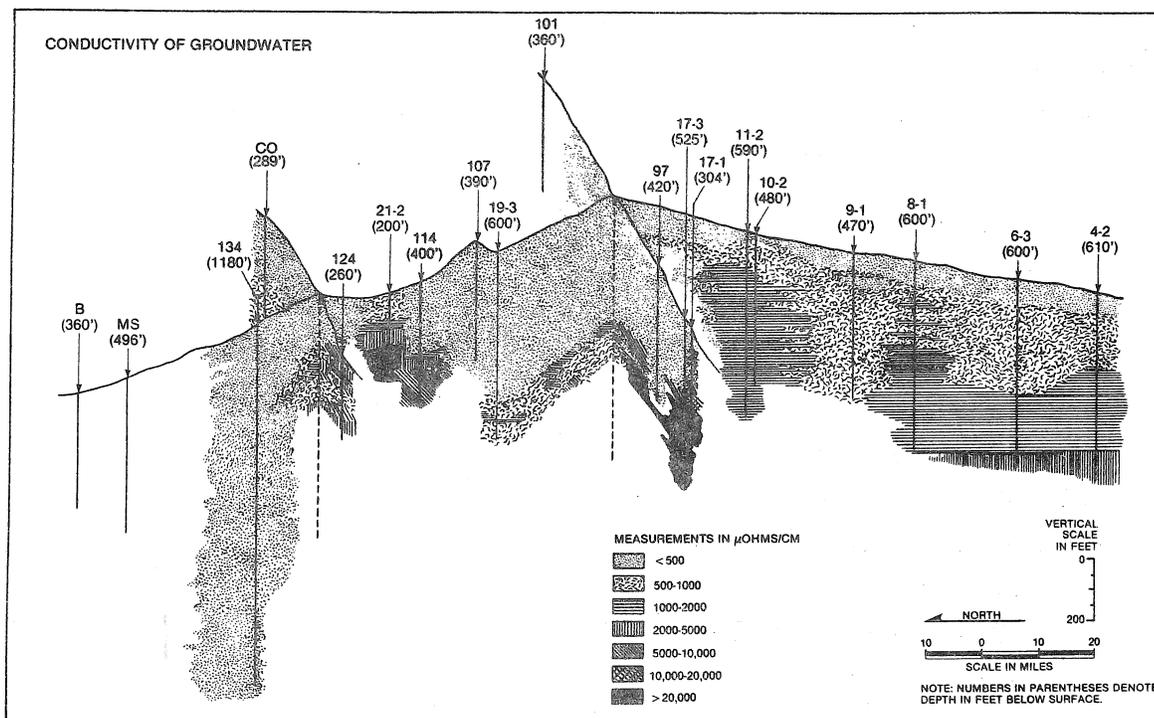


Figure 13.

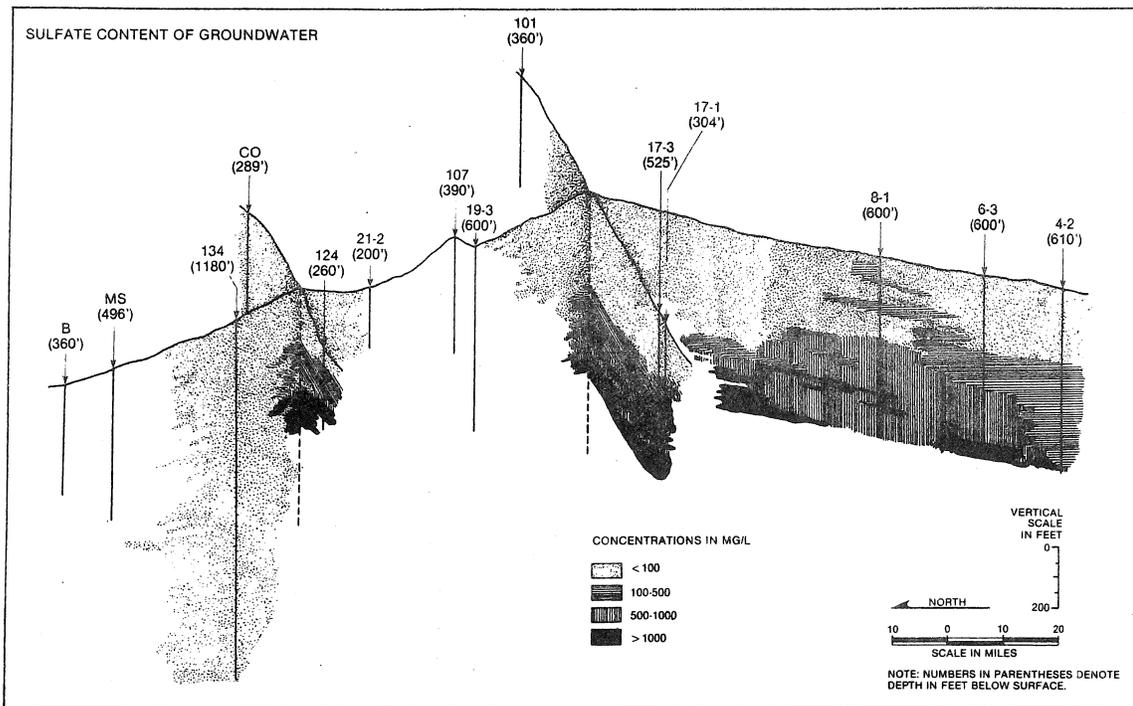


Figure 14.

In order to explain the water-rock interactions that led to the present mineralogical distribution within the study area, the evolution of the aquifer must first be considered. Following deposition and early diagenesis of the various carbonate units, a lowering of sea level exposed the sediments to meteoric groundwater solutions. When carbonate sediments first emerge from the marine environment and undergo flushing by freshwater, the dissolved solids content of the phreatic waters decrease, with the major ions in solution changing from Na^+ , Cl^- , Mg^{+2} , and SO_4^{-2} to Ca^{+2} and HCO_3^- . Meteoric waters are enriched in atmosphere-derived CO_2 and are undersaturated with respect to CaCO_3 . Therefore, the groundwaters will tend to dissolve CaCO_3 . In this manner, fractures and pore spaces in the rocks were enlarged as CaCO_3 was dissolved, initiating the flow-network of the aquifer.

Sea level fluctuated many times since the deposition of these carbonate rocks. Each time the sea level was lowered, meteoric groundwaters enriched in CO_2 gas enlarged and extended existing flow-networks by a process that led to further physical development of the aquifer. Calcite dissolution is a relatively fast process in CO_2 -enriched groundwaters. The flow-network within the aquifer probably developed by enlarging and extending pre-existing channels, rather than by developing new ones.

In western peninsular Florida, Hanshaw et al. (1971) found that by the time groundwater reaches the zone of mixing with seawater, it is saturated with respect to calcium carbonate. Seawater in the coastal mixing zone may also be saturated with respect to calcium carbonate. However, the seawater would be saturated under a different partial pressure of CO_2 gas than the groundwater. The mixing of the two waters, both saturated with respect to calcium carbonate, but having different partial pressures of CO_2 , will result in a range of mixed waters undersaturated with respect to calcium carbonate. It is this control on calcite saturation that allows calcite to be dissolved in the freshwater-saltwater interface. Back et al. (1979) described this process occurring today in the brackish zone of Xel Ha lagoon in Mexico.

Another condition fostering dolomite formation in the freshwater-saltwater interface is a sufficiently high $\text{Mg}^{+2}/\text{Ca}^{+2}$ ratio. Hanshaw et al. (1971) have shown that the three-phase equilibrium (calcite-dolomite-solution) occurs at a $\text{Mg}^{+2}/\text{Ca}^{+2}$ ratio of approximately 1 in the Floridan aquifer. Dolomitization can occur provided sufficient time and Mg^{+2} ions are available. The $\text{Mg}^{+2}/\text{Ca}^{+2}$ ratio is greater than 1 in the mixing zone of the Floridan aquifer in peninsular Florida (Hanshaw and Back, 1979). Thus the chemical and kinetic requirements are met for dolomitization to occur within the freshwater-saltwater mixing zone of the study area.

One of the most significant observations made in interpreting the data presented in the panel diagrams was that the Avon Park Formation is almost completely dolomitized in the study area, while the Ocala and Suwannee are mostly limestones. There must have been some factor (or factors) related to the lithologic character of the Avon Park that resulted in its preferential dolomitization.

Murray and Lucia (1967) described water-controlled dolomitization and rock-controlled dolomitization. In the case of water-controlled selectivity, the distribution of dolomite is directly related to the availability and access of the dolomitizing solution. They stated that dolomite may form in carbonate rocks that underlie supratidal sediments, as a result of the production of hypersaline brines on the supratidal mudflat. However, dolomite may be absent in carbonates of similar lithology that do not underlie supratidal sediments.

Rock-controlled dolomitization is directly related to the physical and chemical characteristics of the rock at the time of dolomitization. In their study, Murray and Lucia (1967) found a preference for dolomite to replace lime muds. A chemical factor they believed might be of importance involved the relative solubilities of the particles. They stated that because recent lime muds contain a higher percentage of aragonite than most other carbonate deposits, the difference in solubility between calcite and aragonite may be sufficient to cause some selectivity. They concluded that another likely physical factor involved the small particle size. The greater surface area of the micrites would enable more dissolution to occur and provide a greater opportunity for replacement by dolomite.

Similar rock-selective dolomitization of mudstones has been described by Choquette and Steinen (1980), of micrites by Land (1973), of wackestones by Inden and Koehn (1979), and of siliceous clays by Schmidt (1965). Land (1973) demonstrated the near contemporaneity of aragonite dissolution and dolomitization of the micrites of the Hope Gate Formation of Jamaica. Sibley (1980) concluded that high-magnesium calcite and aragonite are susceptible to dolomitization, while low-magnesium calcite is not in his study of rock-controlled dolomitization on Bonaire. Sibley stated that if the metastable aragonite and high-magnesium calcite can remain preserved until exposure to the freshwater-saltwater mixing zone, then they will be selectively dolomitized.

The dolomitized Avon Park in the study area consists predominately of mudstones and wackestones which were initially deposited as aragonite lime muds in supratidal and intertidal lagoons, while the Suwannee and Ocala consist to a greater extent of highly fossiliferous packstones and grainstones. If the dolomite selectivity were water-controlled, it would probably have been restricted to the extent of the mixing zone. However, Pleistocene terraces in peninsular Florida prove that sea level once stood 270 feet higher than its present level (Cooke, 1945). As sea level fell, the mixing zone would have passed through Ocala and Suwannee rocks. Because those units are not dolomitized in the study area, dolomite selectivity was more likely related to the fine-grained, high surface area nature of the lime muds in the Avon Park. The formation remained unlithified until it was exposed to a meteoric water regime (Randazzo et al., 1977). This supports the theory that the Avon Park micrites remained as the metastable, more soluble aragonite phase until their exposure to freshwater solutions. Direct dolomitization of aragonite precursors would then have been an additional rock-selective factor, as described by Murray and Lucia (1967) and Sibley (1980).

The parameters presented in the panel diagrams support a mechanism of dolomitization by a freshwater-saltwater mixing zone for the Avon Park lithofacies in the study area. The parameters also show that the composition and salinity of the waters in the mixing zone varied and resulted in the formation of dolomite with a range of mole-percent $MgCO_3$.

The mole-percent $MgCO_3$ diagram (Fig. 11) indicates that dolomite of a more-stoichiometric form developed in the lower reaches of the Avon Park within the study area. This would have been related to a freshwater-saltwater mixing zone of lower salinity than that which formed the less-stoichiometric dolomites lying above. Sarver (1978) suggested that the less-stoichiometric dolomites of the Avon Park formed in a saline, coastal mixing zone that moved laterally in response to sea level fluctuations. The more-stoichiometric dolomites, he believed, formed in a less-saline, inland mixing zone which moved vertically, mainly in response to atmospheric conditions and ground-water recharge. It is proposed here that sea level changes could also cause considerable vertical movement of the coastal mixing zone. During sea level regressions the coastline would have moved farther out to sea, exposing new areas to freshwater recharge. This added recharge, plus the movement of inland groundwaters flowing beneath the surface to a discharge point farther westward, could be sufficient to cause the seaward migration of the mixing

zone. Thus, the distribution of less-stoichiometric dolomite overlying more-stoichiometric dolomite could be a result of a mixing zone controlled by fluctuations in sea level.

Strontium and sodium data (Figs. 9 and 10) present additional evidence for the model described. The strontium content of the more-stoichiometric dolomites in the Avon Park averages less than 200 ppm, while the concentrations in the less-stoichiometric dolomites range between 200-400 ppm, indicating a more saline dolomitizing solution. It was also found that the Sr^{+2} concentration in the Avon Park dolomite, overall, is more than 50 percent higher than that of the calcite. As stated earlier, Sarver (1978) believed that this was the result of dolomitization having taken place in a more saline environment than calcite neomorphism. Another explanation, however, may be related to the mineralogy of the precursor sediments. Veizer and Demovic (1974) obtained higher Sr^{+2} concentrations in sediments that were originally aragonite muds than in other sediment types. The various carbonate mineral phases occur in two different crystal classes: (1) rhombohedral (calcite and dolomite), and (2) orthorhombic (aragonite). The orthorhombic structure is larger than the rhombohedral structure, and therefore large cations, such as Sr^{+2} , fit more readily into the orthorhombic aragonite structure than in the rhombohedral calcite structure (Hanshaw et al., 1971). If the majority of the Avon Park carbonates remained as aragonite until dolomitization, as proposed, then a larger concentration of Sr^{+2} would have been available for incorporation into the dolomite lattice than dolomitization of calcite would have allowed.

Sodium concentrations are less than 500 ppm for the calcite samples of the Ocala analyzed. Thus, the sodium data, in agreement with the other data, denote that the calcites of the Ocala Limestone within this study area were stabilized to low-magnesium calcite by a relatively freshwater solution. The more-stoichiometric dolomites also reveal low Na^{+} concentrations (< 500 ppm), while the less-stoichiometric dolomites analyze between 500-1,000 ppm with a layer of higher concentrations (1,000-1,500 ppm) occurring within it. The sodium data, therefore, agrees with the strontium and mole-percent MgCO_3 data concerning the paleoenvironmental interpretation of the dolomitizing solutions.

Rock-selective dolomitization is also indicated for the Miocene deposits of the study area. The Hawthorn Formation in western peninsular Florida

contains beds of clay, sand, and carbonates interfingering with one another (Weaver and Beck, 1977). In peninsular Florida the uppermost part of the Tampa Formation contains green-clays interbedded with carbonates, while the lower part contains only limestone (Weaver and Beck, 1977). X-ray analyses done in this study (cores 4-2, 6-3, and 11-2) indicate that dolomite occurs only in the Hawthorn and upper Tampa. Therefore, dolomite selectivity here is probably related to the occurrence of clay minerals in the formations. Dolomite selectivity has been related to clay minerals by Schmidt (1965) in Germany; and Kahle (1965) believed that clay minerals may contribute Mg^{+2} ions needed for dolomitization.

If dolomitization of the Hawthorn and upper Tampa occurred in the freshwater-saltwater interface, then the older units lying below should have been dolomitized. Again, some type of lithologic control must have been exerted by the Miocene sediments.

Other factors related to dolomite selectivity may be the fine grain size of the carbonates, and the low permeability of the sediments. Most of the dolomites found in the Miocene sediments are clay-sized and, together with the siliceous clay minerals, account for the low permeability of various parts within these units. Zones of lower permeability in the Hawthorn and upper Tampa result in longer residence time for the groundwater solutions. This factor would favor the formation of dolomite, because the length of time that the dolomitizing solution remains in contact with the precursor sediment is an important control over whether dolomitization will occur. These factors probably enhanced the secondary formation and growth of dolomite.

The trace element data (Figs. 9 and 10) for the Miocene dolomites are markedly different than for the Eocene dolomites. Strontium and sodium concentrations in the Hawthorn and upper Tampa dolomites are both higher and vary more with depth than in the Avon Park dolomites. This is likely a result of the age of the rocks and the flow pattern within the aquifer.

Given enough time, trace elements can be exorcized from the dolomite by subsequent recrystallizations (Kinsman, 1969). Successive recrystallizations would lead to lower values of Sr^{+2} in the rock. The fact that the Na^{+} content of Holocene dolomites is much higher than the Na^{+} content in ancient dolomites supports the belief that Na^{+} is also selectivity removed during subsequent recrystallizations (Land, 1980). The low concentrations of Sr^{+2} and Na^{+} in the Avon Park dolomites support the petrographic evidence reported by Randazzo and Hickey (1978) that extensive recrystallization occurred.

The higher trace element concentrations in the Miocene deposits may reflect the relative youthfulness of those carbonates, with a lesser degree of recrystallization having occurred.

The distribution of the hydrogeochemical parameters (Figs. 12, 13, and 14) reveal that the freshwater-saltwater interface does not encroach in a uniform manner upon the coastal aquifer. Wells 21-2, 17-1, 17-3, and 124 indicate that saltwater is close to the surface in their particular areas, but the remaining area is currently being flushed by relatively fresher water solutions. The discrepancies in the height that the saltwater has attained in those wells that penetrate the Ocala and Avon Park are a result of the physical structure and flow network of the aquifer. Dissolution conduits enable seawater to penetrate the aquifer in some places, while elsewhere the channels contain freshwater under pressure.

The greater abundance of impermeable Miocene sediments results in a higher potentiometric surface than in the other units (Fig. 3). As a result, the Ghyben-Herzberg principle predicts that the freshwater-saltwater interface should be at a lower depth under the Miocene formations. The hydrologic parameters signify this, because nowhere in the cores of the southern part of the study area does the saltwater lens rise to the level that it does in places in the northern part.

Slow percolation through the Hawthorn Formation is reflected in the gradual increases in salinity with depth. On the other hand, the development of the aquifer, itself, produced a network of large dissolution channels in which the groundwater lens and the saltwater lens can enter into each other's realm producing an irregular boundary along the coast. Therefore, the majority of the dolomitization of the Avon Park in the study area took place during times when sea level was higher than it is today, and seawater was able to infiltrate the aquifer through channels that are currently in the phreatic meteoric zone. Also, as a result, the Avon Park Formation was subjected to greater interaction with the coastal and inland mixing environments than the Hawthorn and upper Tampa.

THE MODEL-A SUMMARY OF DATA AND INTERPRETATIONS

Deposition of carbonate sediments occurred in the supratidal, intertidal, and subtidal environments of a carbonate bank along the west coast of peninsular Florida during the Tertiary Period. The position and extent

of these environments changed with fluctuations in sea level, and uplift and downwarping of the Florida Platform. Subtidal sediments were likely to have been originally low-magnesium calcite predominantly, while intertidal and supratidal sediments were mostly aragonite. Lime muds were more common in the supratidal and deep subtidal zones. The higher energy environment in which mud was winnowed developed high primary interparticle porosity.

A multivariate computer analysis, utilizing multidimensional scaling, revealed several trends that correspond well with interpretations based on petrographic and megascopic examinations of three cores representing the Avon Park and Ocala carbonate sequences. MDS was used to determine environmental characteristics normal to the shoreline for these sediments. The analysis revealed the changes in the carbonate bank depositional environments. This was depicted by two hydrodynamic curves produced by MDS which showed variations from muddy, dolomitic, quartzose, supratidal sediment clusters to a shallow subtidal, high energy sediment cluster.

During the Miocene carbonate muds and siliceous clays were deposited in brackish water lagoons, along with sands and phosphates. This resulted in the formation of a layer of low permeability which today defines the upper boundary of the Floridan aquifer. The Avon Park Formation probably remained unlithified until exposure to a meteoric water regime. Fine-grained dolomite crystals formed in the supratidal lithofacies from aragonite mud precursors.

During periods of subaerial exposure of the marine sediments, flushing by meteoric waters occurred. The unstable high-magnesium calcite sediments inverted to low-magnesium calcite, accompanied by the inversion of aragonite sediments. Lime mud inverted by porphyroid neomorphism to microspar, and in doing so, aided in lithification. Shell fragments and other sediments probably underwent dissolution-precipitation and recrystallization, which destroyed original textures and resulted in the formation of pseudospar. As the unstable minerals were dissolved, their cation and anion chemistry were contributed to the solution. The newly formed carbonates had lower concentrations of Sr^{+2} , Na^{+} , and Mg^{+2} .

The dissolution-precipitation process was also responsible for the formation of sparry calcite cement. In the vadose meteoric zone, finely crystalline cement was precipitated from meniscus solutions in interparticle pore spaces and at grain contacts. Large rhombohedral sparry crystals slowly precipitated in pores in the phreatic meteoric zone.

While groundwater was responsible for precipitating cements, it was also a major factor in the production of secondary porosities. Preferential dissolution of fossil tests resulted in moldic pores and vugs. Mudstones and wackestones developed less secondary porosity than packstones and grainstones because of their fewer allochems and lower permeability.

During periods when sea level was lowered, groundwater dissolution of the limestone enlarged existing pore spaces as the groundwater opened paths towards discharge out into the Gulf of Mexico. Succeeding marine transgressions resulted in inland migration of the freshwater-saltwater interface.

Selective dolomitization took place at the freshwater-saltwater interface in the Avon Park, Hawthorn, and upper Tampa Formation. The dolomite selectivity was related to (1) the fine grain size of the sediments with their high surface area/volume ratio; (2) the occurrence of earlier formed dolomite; (3) the precursor carbonate being aragonite; and (4) the occurrence of clay minerals.

Dolomitization proceeded in the freshwater saltwater mixing zone because (1) mixing freshwater and saltwater can result in a zone where the waters become undersaturated with respect to calcite, yet remain supersaturated with respect to dolomite; (2) the salinity of the mixing zone is lower than it is in seawater, therefore there is less foreign ion competition inhibiting dolomite formation; and (3) the Mg^{+2}/Ca^{+2} ratio remains well above the level of unity required for dolomitization.

Where the dolomitized precursor sediments were calcite, the dolomite crystals grew by coalescence neomorphism. Where penecontemporaneous dolomite crystals were already present in supratidal lithofacies, the fine crystals underwent porphyroid neomorphism, resulting in larger, more equant-shaped crystals. In both cases dolomitization proceeded by a process of dissolution-reprecipitation, accompanied by some loss of Sr^{+2} and Na^{+} - the amount depending upon the mineralogy of the precursor sediment, the role of clay minerals as a contributor of trace elements, the salinity of the dolomitizing solution, and the duration of time in which sediments were subjected to dolomitizing solutions.

The aggrading neomorphic growth of dolomite crystals resulted in the redistribution of many small pores into fewer, but larger, pores. Therefore, although the porosity may not have appreciably changed, permeability could have greatly increased. In the less saline reaches of the mixing zone, more-stoichiometric dolomite formed slowly without the interference of many foreign ions. This resulted in large, well-developed, rhombohedral crystals

with low Sr^{+2} and Na^{+} concentrations. Less-stoichiometric dolomite, with associated higher Sr^{+2} and Na^{+} values formed more rapidly in the more saline areas of the mixing zone.

Diagenesis of carbonate rocks is a continuous process. Both groundwater and saltwater solutions in contact with the rocks are constantly exchanging ions with the rock in an attempt to produce the most stable mineralogical conditions possible. The porphyritic neomorphic growth of dolomite crystals to larger dolomite rhombs is added evidence of this continuing process occurring in dolomites. The freshwater-saltwater interface is probably the most dynamic of the environments in which changes occur. ^{14}C data suggest formation or recrystallization of dolomite occurred in the last 30,000 years. Each time that sea level changes moved the mixing zone back into dolomitized units, recrystallization of the rocks could have occurred, with an accompanying trace element depletion. Therefore, it is reasonable to assume that dolomites which originally formed in the aquifer during earlier sea level fluctuations are still striving towards more-stoichiometric conditions in the present freshwater-saltwater mixing zone. Carbonate systems tend towards equilibrium with age and time (Lumsden and Chimahusky, 1980), and the expected trend for dolomite is towards a more nearly stoichiometric compound.

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