Maliva, R.

Dolomitization-induced aquifer heterogeneity: Evidence from the upper Floridan aquifer, southwest Florida

Robert G. Maliva*
Gordon P. Kennedy
W. Kirk Martin
Thomas M. Missimer
Elizabeth S. Owosina
Camp Dresser & McKee, Inc., 8140 College Parkway, Suite 202, Fort Myers, Florida 33919, USA
J.A.D. Dickson
Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK

ABSTRACT

Large variations in artesian flow and specific capacity encountered during the installation and testing of a well field completed in the upper Floridan aquifer in Collier County, Florida, are related to differences in dolomite abundance among wells. The wells produce primarily from some thin intervals of fractured crystalline and microsucrosic dolomite that have limited areal extent, as evidenced by a strong boundary effect detected during an aquifer performance test. Microfacies and stable isotopic composition ($\delta^{18}O = 1.39‰–1.57‰$, $\delta^{13}C = 0.15‰–1.70‰$, Peedee belemnite [PDB]) indicate that the dolomite formed by the replacement of marine limestone in marine or brackish pore waters. Dolomite fracturing is likely related to folding that occurred no earlier than the late Miocene. The upper Floridan aquifer behaves as a large-scale dual-porosity system, in that the dolomite intervals with high hydraulic conductivities increase the specific capacities of some wells. The dolomite intervals have little effect on the total volume of water that can be produced from the aquifer, which is controlled by the surrounding lower hydraulic conductivity limestone. The results of this interdisciplinary investigation reveal the high degree of heterogeneity and unpredictability that may occur in carbonate aquifers as the result of diagenesis. Because of uncertainty over fluid-flow paths, heterogeneities in aquifer hydraulics related to diagenesis may greatly impact projects requiring recovery of a specific volume of water, such as pump-and-treat remediation and aquifer storage-and-recovery systems.

Keywords: carbonate, diagenesis, dolomite, Florida, hydrology, Miocene.

INTRODUCTION

A basic objective of hydrogeological investigations is the prediction of aquifer behavior under different pumping, injection, and natural flow scenarios. Virtually all analytical and numerical groundwater modeling procedures include, either implicitly or explicitly, assumptions on aquifer heterogeneity, the validity of which affects the accuracy of predictive simulations. Carbonate aquifers in general tend to have high degrees of heterogeneity because of their relatively high variability in depositional porosity and permeability and their susceptibility to diagenetic alteration, which can change profoundly the hydraulic properties of carbonate rock. The most extreme example of diagenesis controlling aquifer hydraulics is karstification, where limestone dissolution creates large-scale flow conduits. On a finer scale, carbonate depositional texture has been shown to influence the preservation of matrix porosity and permeability in limestones during burial (e.g., Budd, 2001).

Studies of the relationship between diagenesis and the porosity and permeability of carbonate rocks have been based typically on core plug and probe permeameter data (e.g., Halley and Schmoker, 1983; Scholle and Halley, 1985; Amthor et al., 1994; Budd, 2001). The limitation of the core plug and probe permeameter data is that they provide information on only the properties of the tested volumes of rock, and large-scale aquifer or reservoir hydraulic behavior can only be inferred. Actual aquifer testing is necessary to reveal the nature of the aquifer heterogeneity. Fertile ground exists for interdisciplinary studies in which petrographic, diagenetic, and aquifer testing data are integrated to improve conceptual and quantitative models of carbonate aquifer systems, particularly those involving the extent, origin, and controls of aquifer heterogeneity.

Large variations in well yields and specific capacities that appear to be related to dolomitization were recorded between wells during the construction and testing of a well field in the upper Floridan aquifer at the North County Regional Water Treatment Plant (North County Plant), Collier County, Florida (Fig. 1). A relationship between dolomitization and high transmissivities in the Floridan aquifer system has been documented previously. For example, fractured dolomites in the lower Floridan aquifer, particularly the so-called "Boulder Zone" of the Oldsmar Formation (early Eocene) may have extremely high transmissivities (Kohout, 1965, 1967; Vernon, 1970; Puri and Winston, 1974; Miller, 1986; Meyers, 1989; Haberfeld, 1991; Safko and Hickey, 1992; Duerr, 1995; Winston, 1995, 1996; Maliva and Walker, 1998) with reported values as high as 2.29 × 10^6 m^2/d (Singh et al., 1983). Dolomitization was a regional event in the lower Floridan aquifer, whereas the dolomitization in the upper Floridan aquifer was a much more localized phenomenon.

---

*E-mail: malivarg@cdm.com.

GSA Bulletin; April 2002; v. 114; no. 4; p. 419–427; 9 figures; 1 table.

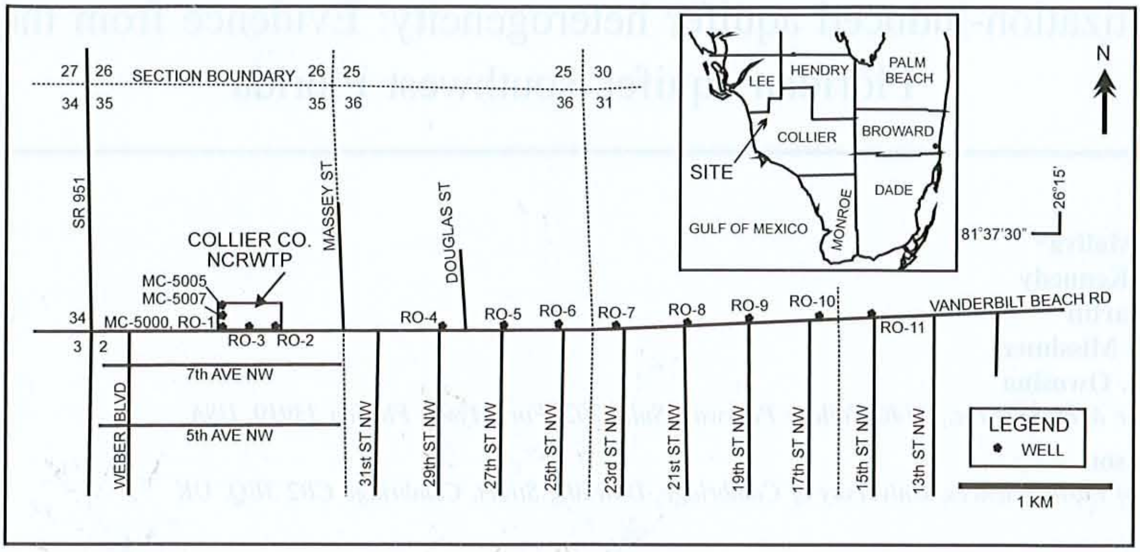

Figure 1. Well location map.

An interdisciplinary investigation was performed to determine the relationship between the hydrology of the North County Plant well field and the structural geology, sedimentology, and diagenesis of the aquifer. The principal objective of this study was to determine what insights the upper Floridan aquifer can provide on the hydraulic behavior of diagenesis-controlled aquifers in general.

GEOLOGIC SETTING AND REGIONAL HYDROGEOLOGY

The North County Plant is located in the Golden Gate area of Collier County, ~13 km northeast of Naples and 14 km east of the Gulf of Mexico. A test production well (designated MC-5005) and two observation wells (MC-5000 and MC-5007) were installed near the western end of the North County Plant property (Fig. 1) as part of a regional hydrogeologic investigation to locate a brackish water supply for a reverse-osmosis desalination facility. A well field was subsequently installed near the North County Plant site that consists of 11 wells (RO-1 through RO-11) that have an east-west alignment.

Collier County is underlain by ~5700 m of sedimentary rock (Lloyd, 1985) deposited in a gradually subsiding basin that has been variously referred to as the South Florida basin or embayment and the Okeechobee basin. Three aquifer systems are recognized in southwest Florida: the surficial aquifer system, the intermediate aquifer system, and the Floridan aquifer system (Fig. 2) (Miller, 1997).

The Floridan aquifer system, which is present at the North County Plant from ~220 to 975 m below land surface, consists predominantly of limestones and dolomites that were deposited in a mostly subtidal marine environment. On a regional scale, the Floridan aquifer system has been divided into the upper Floridan aquifer, middle confining unit, and lower Floridan aquifer (Miller, 1986, 1997). The upper Floridan aquifer, in turn, may locally contain several carbonate aquifer zones that are separated from one another by limestone and marl intervals with relatively low hydraulic conductivities. The North County Plant production wells are completed in the uppermost aquifer zone of the upper Floridan aquifer, which is referred to as the lower Hawthorn aquifer. The production zone includes the lower part of the Arcadia Formation (Hawthorn Group) and the uppermost Suwannee Limestone. The North County Plant production wells flow at land surface and had initial chloride concentrations of 1900–3000 mg/L.

The Suwannee Limestone and Hawthorn Group mark a fundamental change in the depositional pattern of the Florida platform from relatively pure marine carbonate deposition during the Eocene to mixed carbonate and siliciclastic deposition, as terrigenous sediment was transported southward down the length of the platform (e.g., Walker et al., 1983; Missimer, 1997; Scott, 1997; Missimer and Ginsburg, 1998). The top of the upper Floridan aquifer is marked in southwest Florida by an upward lithologic change from very pale orange, micritic limestones or pale yellowish-brown dolomite to light olive gray and darker marls.

The North County Plant well field is underlain by a buried syncline with a maximum relief (trough to flank) at the top of the upper Floridan of 32 m (Fig. 2). The folding persists up section to at least the base of the sandstone aquifer in the intermediate aquifer system (middle Peace River Formation), which indicates that the folding occurred no earlier than late Miocene. Folding of Hawthorn Group strata of a similar magnitude as that in the North County Plant vicinity is well exhibited in high-resolution seismic reflection profiles taken ~40 km to the north-northwest in Lee County (Missimer and Gardner, 1976). The maximum fold relief in the upper Hawthorn Group in Lee County is ~40 m. The folds are buried by Pliocene, Pleistocene, and Holocene-aged sediment and rock. The land surface at the North County Plant is now essentially flat lying.

METHODS

Test and production wells were drilled using the mud-rotary method to the casing seat depth at the top of the upper Floridan aquifer. The wells were completed with open holes that were drilled using the reverse-air-rotary method. The lengths of the open-hole intervals of the production wells were varied depending on well yields, with the poorer producing wells having the longest open-hole intervals to maximize production. All of the production wells were constructed of 30-cm-diameter (12-in.-diameter) fiberglass casing that was increased to 41 cm (16 in.) at ~30 m below land surface to accommodate a pump. A suite of geophysical logs, including caliper, resistivity (short and long normal, or dual induction), gamma ray, and temperature were run on all wells. Borehole video surveys were also performed on the production wells. Dynamic and static flowmeter (propeller-type)

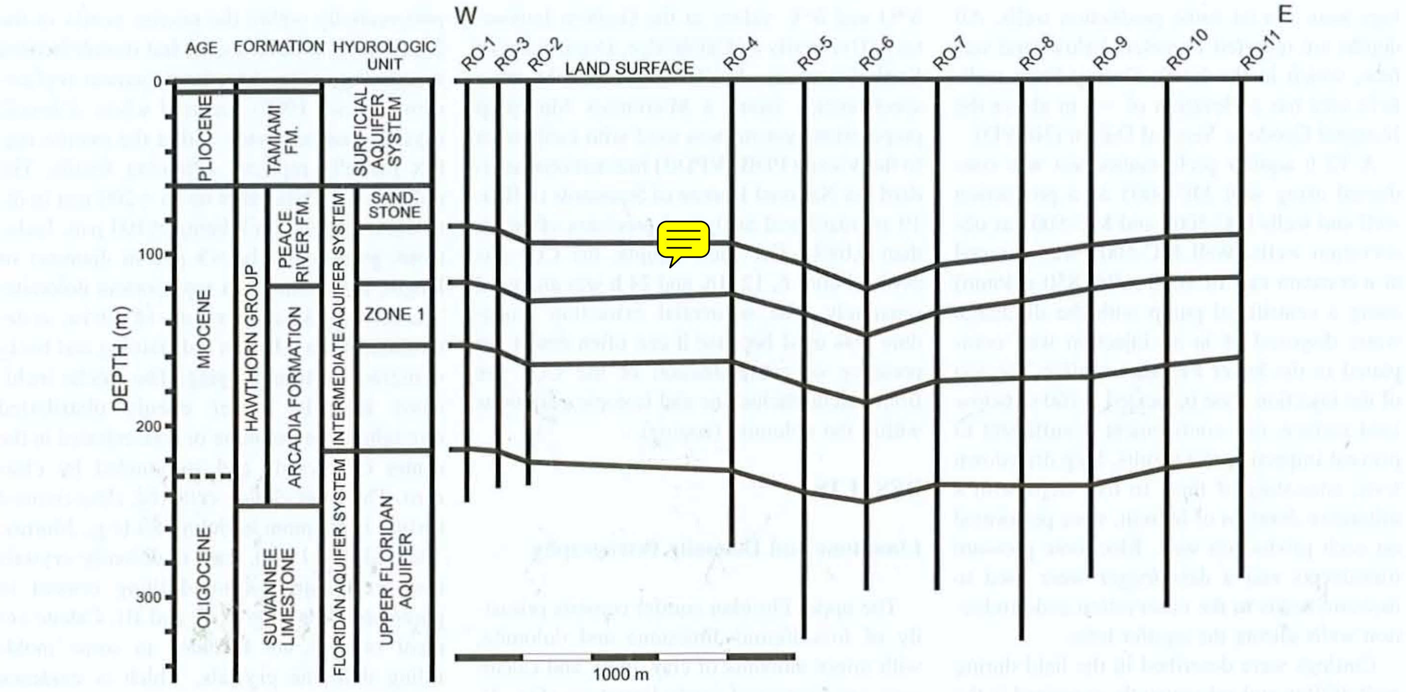

Figure 2. Stratigraphy, hydrogeology, and structural cross section of the North County Regional Water Treatment Plant vicinity. The well field occurs within a buried syncline.

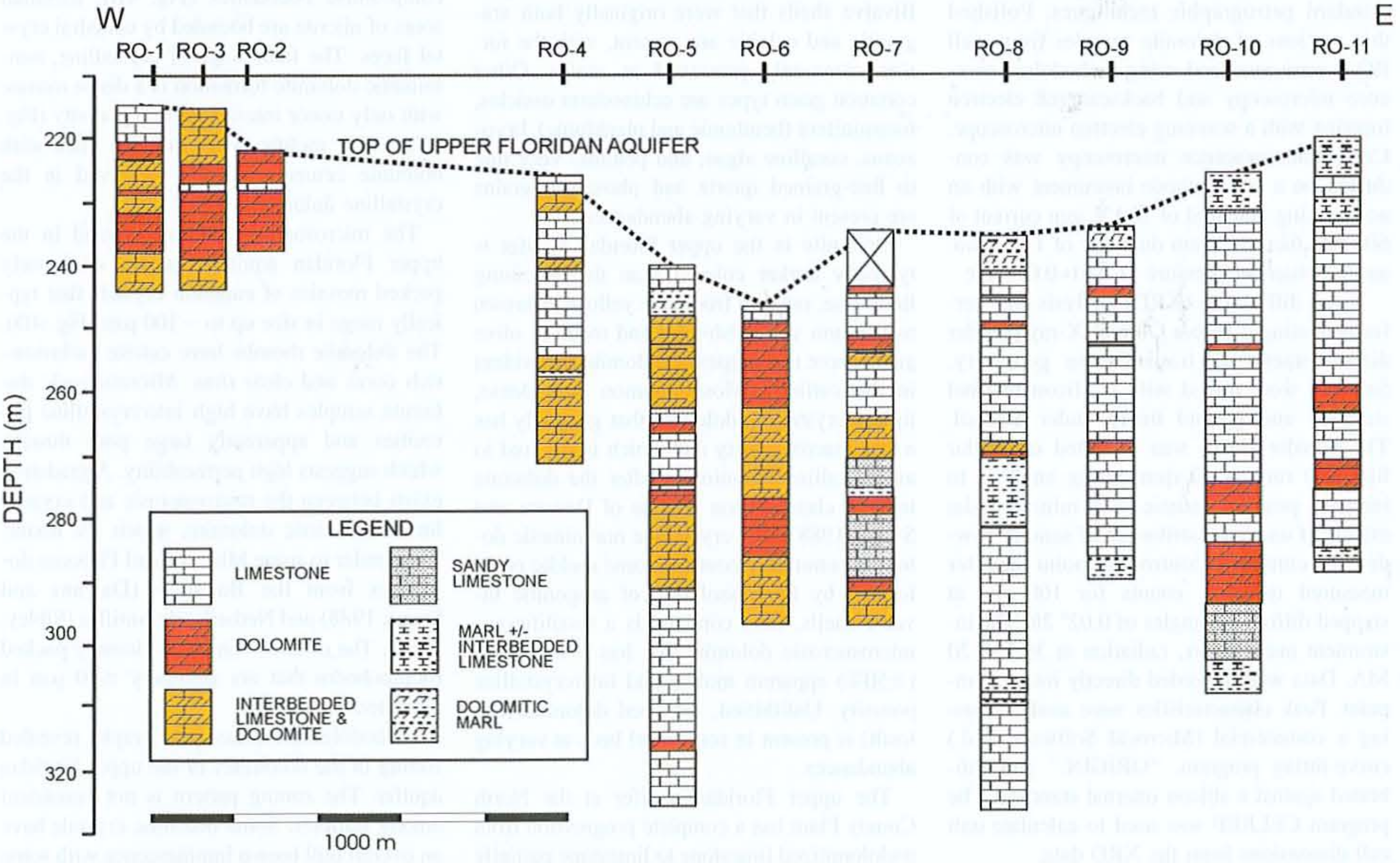

Figure 3. Lithologic cross section of the upper Floridan aquifer at the North County Regional Water Treatment Plant. Considerable variation in dolomite abundance occurs between wells. Wells RO-1, RO-2, RO-3, RO-5, and RO-6 contain relatively abundant dolomite, whereas dolomite is relatively uncommon in wells RO-8 and RO-9.

logs were run on some production wells. All depths are reported in meters below land surface, which in the North County Plant wellfield area has a elevation of ~4 m above the National Geodetic Vertical Datum (NGVD).

A 72 h aquifer performance test was conducted using well MC-5005 as a production well and wells MC-5000 and MC-5007 as observation wells. Well MC-5005 was pumped at a constant rate of 4600 m^3/d (850 gal/min) using a centrifugal pump with the discharge water disposed of in an injection well completed in the lower Floridan aquifer. The top of the injection zone is located ~760 m below land surface, and confinement is sufficient to prevent impacting test results. Step drawdown tests, consisting of three to five steps with a minimum duration of 60 min, were performed on each production well. Electronic pressure transducers and a data logger were used to measure heads in the observation and production wells during the aquifer tests.

Cuttings were described in the field during well drilling and subsequently examined in the laboratory using a stereomicroscope. Thin sections of cuttings from wells RO-2, RO-6, and RO-10 were examined for microfacies and diagenetic minerals and textures using standard petrographic techniques. Polished thin sections of dolomite samples from well RO-2 were analyzed using cathodoluminescence microscopy and backscattered electron imaging with a scanning electron microscope. Cathodoluminescence microscopy was conducted on a cold-cathode instrument with an accelerating potential of 26 kV, gun current of 600 nA, focused beam diameter of 1–10 mm, and air chamber pressure of 0.01–0.05 Torr.

X-ray diffraction (XRD) analysis was performed using a Huber Guinier X-ray powder diffractometer in transmission geometry. Samples were mixed with a silicon internal standard and ground finely under alcohol. The powder slurry was mounted on Mylar film that rotated 20 rpm during analysis to improve powder statistics and minimize the effects of uneven distribution of sample powder. A computer-controlled point counter measured radiation counts for 100 sec at stepped diffraction angles of 0.02° 2θ. The instrument used $CuK\alpha_1$ radiation at 30 kV, 20 MA. Data were recorded directly into a computer. Peak characteristics were analyzed using a commercial (Microcal Software, Ltd.) curve-fitting program, "ORIGIN," and calibrated against a silicon internal standard. The program CELREF was used to calculate unit cell dimensions from the XRD data.

Bulk-rock dolomite powders, treated with ethylenediamenetetraacetic acid (EDTA) to remove calcite inclusions, were analyzed for $\delta^{18}O$ and $\delta^{13}C$ values at the Godwin Laboratory (University of Cambridge, Department of Earth Sciences). A VG Isogas PRISM mass spectrometer, using a Micromass Multiprep preparation system, was used with calibration to the Vienna PDB (VPDB) international standard via National Bureau of Standards (NBS)-19 standard and analytical precision of better than 0.08‰. For each sample, the CO_2 gas evolved after 6, 12, 18, and 24 h was analyzed separately. The sequential extraction procedure was used because it can often detect the presence of contamination of the CO_2 gas from calcite inclusions and isotopic variations within the dolomite (zoning).

RESULTS

Limestone and Dolomite Petrography

The upper Floridan aquifer consists primarily of fossiliferous limestone and dolomite, with minor amounts of clay, marl, and calcareous sandstone and sandy limestone (Fig. 3). The limestones consist mostly of white, yellowish-gray, or very pale orange fossiliferous wackestones, in which mollusks (bivalves and gastropods) are the most common grain types. Bivalve shells that were originally both aragonitic and calcitic are present, with the former commonly preserved as molds. Other common grain types are echinoderm ossicles, foraminifera (benthonic and planktonic), bryozoans, coralline algae, and peloids. Very fine to fine-grained quartz and phosphate grains are present in varying abundances.

Dolomite in the upper Floridan aquifer is typically darker colored than the adjoining limestone, ranging from pale yellowish-brown to medium yellowish-gray and medium olive gray. Three main types of dolomite are evident in the cuttings. Most common is a dense, tightly crystalline dolomite that generally has a low macroporosity and which is referred to as crystalline nonmimetic after the dolomite textural classification scheme of Dawans and Swart (1988). The crystalline nonmimetic dolomite commonly contains some moldic pores formed by the dissolution of aragonitic bivalve shells. Less common is a fossiliferous, microsucrosic dolomite that has a very high (≥50%) apparent moldic and intercrystalline porosity. Unlithified, silt-sized dolomite (dolosilt) is present in some marl beds at varying abundances.

The upper Floridan aquifer at the North County Plant has a complete progression from undolomitized limestone to limestone partially replaced by scattered dolomite crystals to complete replacement with no calcite or aragonite remaining. Dolomite crystals formed preferentially within the micrite matrix of the limestone and have a euhedral rhombohedron morphology (Fig. 4A). Impingement replacement (Lucia, 1962) occurred where dolomite crystals that nucleated within the micrite matrix partially replaced adjoining fossils. The dolomite crystals range up to ~200 μm in diameter, with the bulk being ≤100 μm. Inclusions, predominantly ≤5 μm in diameter or length, are common in replacement dolomite. The inclusions consist mostly of calcite, as determined from Alizarin red staining and backscattered electron imaging. The calcite inclusions may be either evenly distributed throughout the dolomite or concentrated in the center of crystals and surrounded by clear rims. The latter cloudy-centered, clear-rimmed texture is common in dolomites (e.g., Murray, 1964; Sibley, 1980). Parts of dolomite crystals that precipitated as mold-filling cement in pores are clear (Fig. 4, A and B). Calcite cement crystals are included in some mold-filling dolomite crystals, which is evidence that dolomitization postdated both aragonite dissolution and some calcite cementation.

As dolomite abundance increases, euhedral crystal boundaries give way in abundance to compromise boundaries (Fig. 4B). Residual areas of micrite are bounded by euhedral crystal faces. The final stage of crystalline, nonmimetic dolomite formation is a dense mosaic with only minor intercrystalline porosity (Fig. 4C). Some moldic pores that are lined with dolomite cement may be preserved in the crystalline dolomite.

The microsucrosic dolomite found in the upper Floridan aquifer consists of loosely packed mosaics of euhedral crystals that typically range in size up to ~100 μm (Fig. 4D). The dolomite rhombs have calcite inclusion–rich cores and clear rims. Microsucrosic dolomite samples have high intercrystalline porosities and apparently large pore throats, which suggests high permeability. A gradation exists between the microsucrosic and crystalline nonmimetic dolomite, which are texturally similar to some Miocene and Pliocene dolomites from the Bahamas (Dawans and Swart, 1988) and Netherlands Antilles (Sibley, 1982). The dolosilt consists of loosely packed rhombohedra that are generally ≤50 μm in diameter.

Cathodoluminescence petrography revealed zoning in the dolomites of the upper Floridan aquifer. The zoning pattern is not consistent among samples. Some dolomite crystals have an overall dull brown luminescence with some faint lighter- and darker-colored bands. Other samples have bright orange cores and dull rims (Fig. 5).

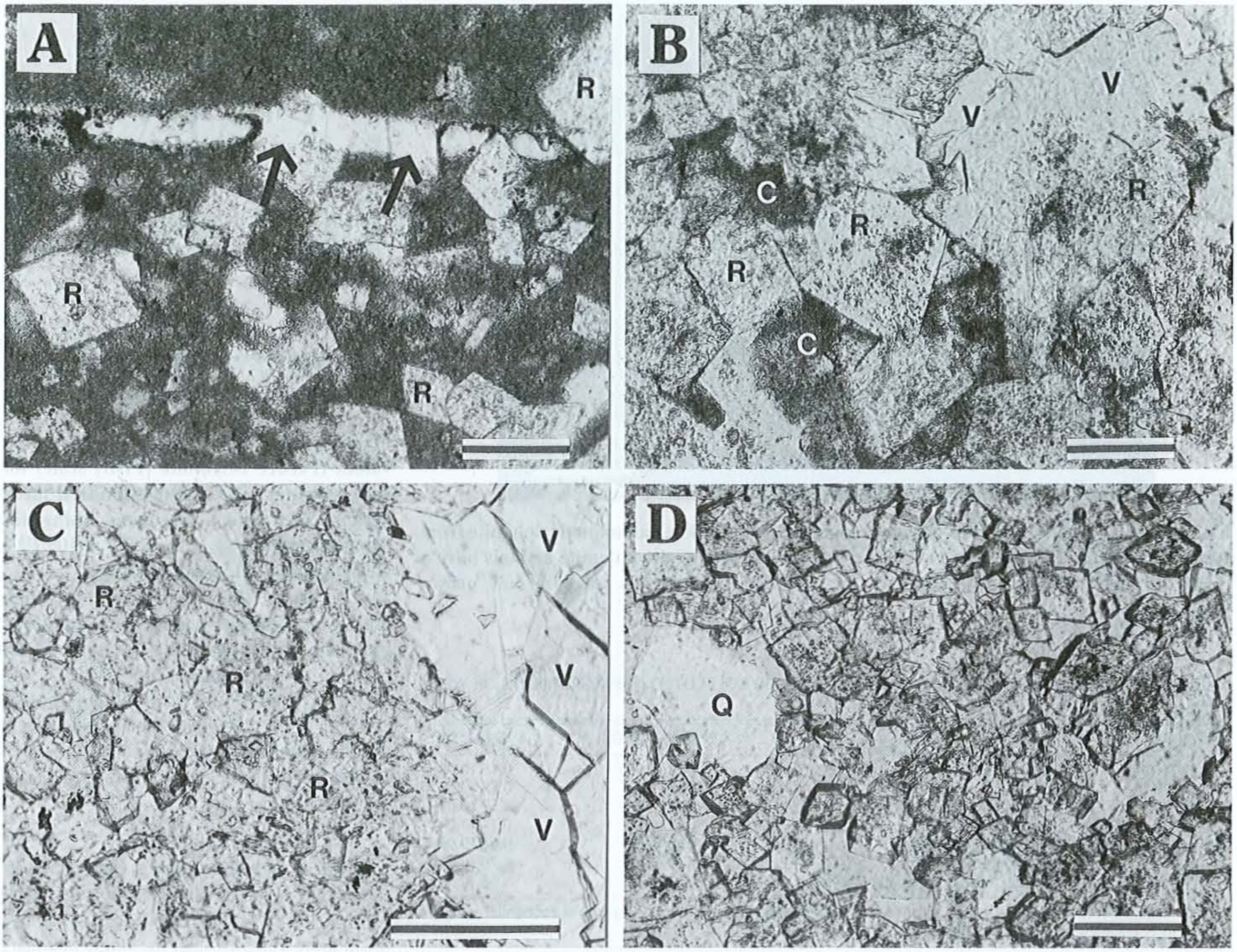

Figure 4. Thin section photomicrographs of dolomites from the upper Floridan aquifer. Bar scales = 100 µm. (A) Partially dolomitized limestone in which replacement dolomite crystals (R) contain abundant calcite inclusions. The parts of dolomite crystals that filled a bivalve mold (arrows) are clear. Well RO-10, 274.3–277.4 m. (B) Nearly completely dolomitized limestone. Residual unreplaced calcite (C) between replacement dolomite crystals (R) is bounded by euhedral dolomite crystal faces. Void-filling dolomite (V) is clear, whereas replacement calcite contains abundant calcite inclusions. Well RO-6, 274.3–277.4 m. (C) Crystalline, nonmimetic dolomite containing both replacement (R) and mold-filling (V) dolomite. Virtually no macroporosity is evident. Well RO-6, 210.3–213.4 m. (D) Microsucrosic dolomite consisting of loosely packed rhombohedral crystals. A quartz sand grain (Q) is present. Well RO-6, 268.2–271.3 m.

Dolomite Geochemistry

X-ray diffraction analyses indicate that the dolomites of the upper Floridan aquifer have well-ordered structures. The upper Floridan aquifer dolomite unit cell dimensions (a = 4.8203–4.8235 Å, c = 16.1205–16.1313 Å) are close to those of an ideal dolomite standard (a = 4.8083 Å, c = 16.0116 Å).

The stable isotope data show relatively little variation both between dolomite samples and between sequentially extracted CO_2 gas samples from the same dolomite sample (Table 1). The small variation between the sequential analyses suggests that there was minimal contamination from calcite inclusion and variation between cement zones. The δ^{18}O values of the well RO-2 dolomite samples ranged from 1.39‰ to 1.57‰ (PDB). Dolomite δ^{18}O values are a function of the temperature and δ^{18}O values of pore waters during precipitation. The current aquifer temperature of $\sim$31 °C is likely the highest temperature the strata experienced. The present-day average temperature in January in south Florida is on the order of 20 °C (Henry et al., 1994). As a conservative approximation, the minimum possible temperature during dolomitization is estimated to have been 20 °C, although temperatures during the Miocene were likely higher than at present (Missimer, 1997). Pore water δ^{18}O values during dolomitization were therefore likely in the range of +0.5‰ to −2.0‰ (standard mean ocean water [SMOW]) (Fig. 6). The oxygen isotope data thus suggest dolomite formation in either marine or brackish water. The δ^{13}C values of +0.15‰ to +1.70‰ (PDB) are also close to seawater ratios. Dolomite δ^{13}C values increase with depth in well RO-2. The reason for the increase is uncertain.

Aquifer Performance Test

Hydrostatic head in the upper Floridan aquifer at the North County Plant is tidally

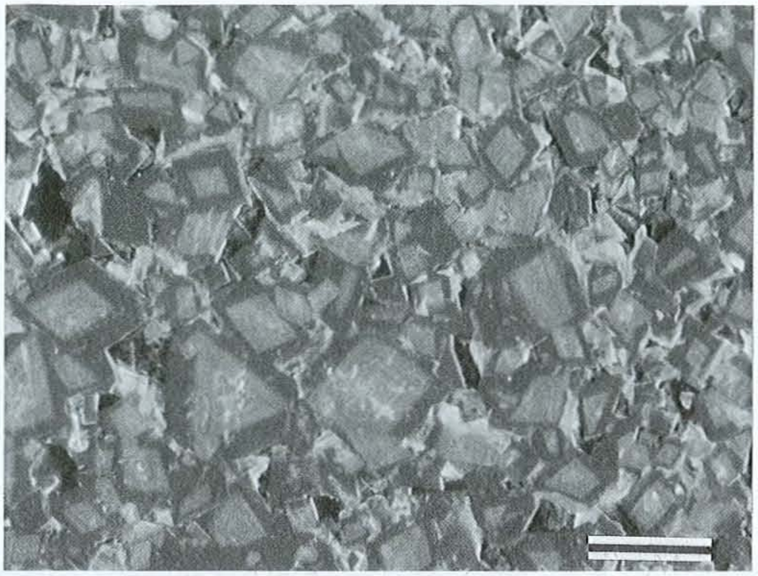

Figure 5. Cathodoluminescence photomicrograph of crystalline-nonmimetic dolomite from well RO-2, 231.6–234.7 m. The calcite inclusion-rich cores of the dolomite crystals have a bright orange luminescence, whereas the relatively clear rims have a dull brown luminescence.

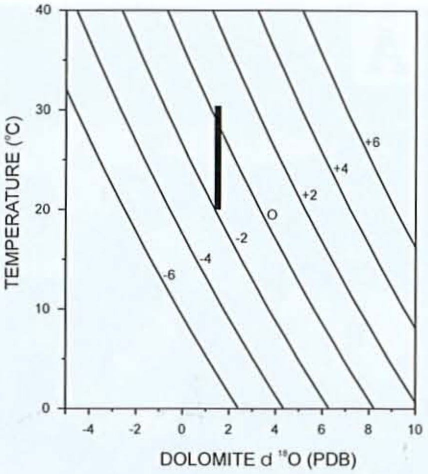

Figure 6. Temperature vs. dolomite $\delta^{18}O$ values (Peedee belemnite [PDB] scale) for various water $\delta^{18}O$ values (standard mean ocean water scale) calculated using the equations $10^3\ln_{\text{calcite-water}} = 2.78 \times 10^6\ T^{-2} - 2.89$ (O'Neil et al., 1969) and $\delta_{\text{dolomite}} - \delta_{\text{water}} = 3.8$ (Land, 1985). The black rectangle marks an envelope bounded by the upper Floridan aquifer dolomite $\delta^{18}O$ values, the current aquifer temperature (31 °C), and an inferred minimum possible temperature (20 °C). The oxygen isotopic composition of the dolomite thus indicates pore water $\delta^{18}O$ values in the +0.5 to−2.0 range during dolomitization.

TABLE 1. STABLE ISOTOPIC COMPOSITION OF DOLOMITES COLLECTED DURING DRILLING OF WELL RO-2

Depth (m)	Type	$\delta^{18}O$ (‰, PDB)	$\delta^{13}C$ (‰, PDB)
213.4–216.4	Dolosilt	1.57 (0.06)	0.15 (0.02)
216.4–219.5	Dolosilt	1.52 (0.10)	0.62 (0.05)
219.5–222.5	Nonmimetic crystalline	1.42 (1.42)	0.57 (0.01)
222.5–225.6	Nonmimetic crystalline	1.45 (0.04)	0.79 (0.04)
225.6–228.6	Nonmimetic crystalline	1.39 (0.05)	0.98 (0.03)
231.6–234.7	Nonmimetic crystalline	1.49 (0.05)	1.70 (0.02)
234.7–237.7	Microsucrosic-nonmimetic crystalline	1.49 (0.08)	1.56 (0.01)

Note: Stable isotope ratios are the mean of sequential analyses. The standard deviations of sequential analyses are given in parentheses. PDB—Peedee belemnite.

influenced, with an amplitude on the order of 0.1 m (Fig. 7). The 72 h aquifer performance test was started at the beginning of a tidal peak, as determined from background water-level monitoring, in order to minimize tidal effects in the early data. Because of the large amplitude of the tidal influence relative to the rate of drawdown, attempts to correct for tidal impacts based on calculated lag times met with only limited success and had little effect on data analysis.

Time-drawdown data for aquifers that meet the conditions of the Theis (1935) nonequilibrium equation, such as infinite areal extent and isotropic and homogenous hydraulic conductivity, fall on a straight line in semilogarithmic plots. Aquifer transmissivity can be estimated from the slope of the line using the methods developed by Cooper (1963) and Cooper and Jacob (1946) as follows:

$$T = 0.183\ Q/\Delta s,$$

where T = transmissivity (m^2/d), Q = pumping rate (m^3/d), and Δs = change in drawdown over one log cycle (Driscoll, 1986). Changes in the slope of time-drawdown plots are indicative of departures from the assumptions of the Theis nonequilibrium equation. A sharp increase in the slope of the semilogarithmic plots of the time-drawdown data after ~3 h strongly suggests production from a bounded aquifer at the North County Plant (Fig. 7). Inasmuch as the upper Floridan aquifer is laterally continuous, the detected boundary in all likelihood corresponds to a discontinuity in aquifer hydraulic conductivity or possibly a change in storativity. The Stallman (1963) solution to flow in a bounded aquifer, which utilizes image well theory, allows for the determination of the distance to an aquifer boundary. The theoretical aquifer boundary detected in aquifer performance test data was calculated to be ~340–560 m from the observation well (MC-5005) based on the Stallman constant of proportionalities (K) of 15–25. The geometry and hydraulic properties of the aquifer discontinuity, however, are likely much more complex than the single boundary system of the Stallman (1963) solution. More rigorous hydraulic analysis of multiple boundary aquifer systems (e.g., Ferris et al., 1962) would not have greater predictive value because of the uncertainty over the geometry of the high-hydraulic conductivity zones and the general aquifer heterogeneity.

In order to approximate future aquifer responses to pumping, apparent transmissivities can be calculated from the early (40 000–45 000 m^2/d) and late (4700–7100 m^2/d) test data using the Cooper and Jacob method. The apparent transmissivity values allow for the extrapolation of the aquifer performance test results. The time-drawdown data collected after 3 h likely reflect aquifer response under long-term pumping conditions. It must be emphasized that the apparent transmissivity values and projected aquifer responses are rough estimates because the aquifer does not meet the assumptions of the Theis nonequilibrium equation. Nevertheless, hydraulic parameters calculated from the aquifer performance test data using the Theis equation (and modifica-

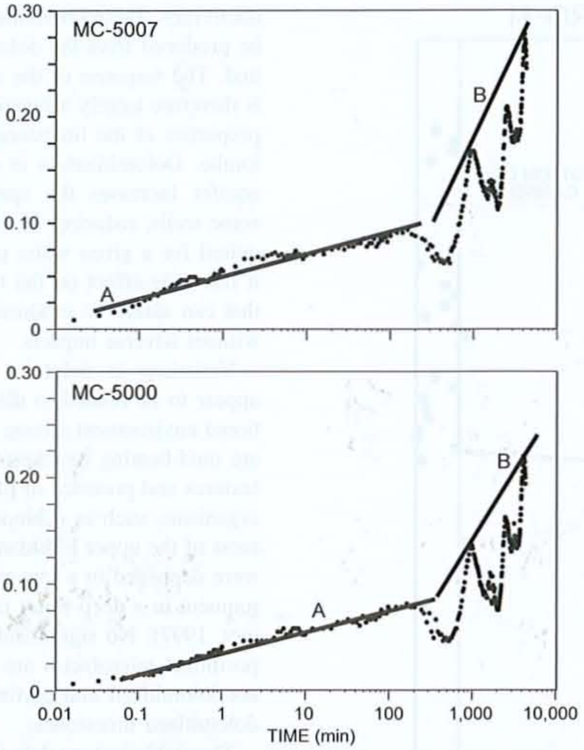

Figure 7. Semilogarithmic plots of time-drawdown data from 72 h aquifer-performance test. Well MC-5005 was pumped at 4600 m^3/d and drawdown was recorded in observation wells MC-5000 and MC-5007, which are located 168 m and 45 m, respectively, from the production well. The test was started at the beginning of a tidal peak and tidal fluctuations are evident in the late data. A hydraulic barrier was reached at ~3 h into the test as evidenced by the steepening of the time-drawdown slope.

tions thereof) can be used as initial values in the development of calibrated numerical models.

Step-Drawdown Tests

The step-drawdown test revealed large differences in specific capacity (*SC*—well yield/drawdown) among the North County Plant production wells (Fig. 8). For example, well RO-3 produced 15 800 m^3/d with 5.9 m of drawdown ($SC = 2660$ m^3/d/m), whereas well RO-8 produced only 545 m^3/d with 5.5 m of drawdown ($SC = 99$ m^3/d/m). There is no apparent relationship between well location and specific capacity. The least productive wells, RO-8 and RO-7, for example, are located near the highly productive well RO-6. No relationship is evident either between structural position and specific capacity.

Flowmeter Logs

The combination of dynamic flowmeter and caliper logs can provide information on the location of production zones in open-hole wells. The dynamic flowmeter log provides data on flow velocity, and the caliper log can be used to approximate borehole cross-sectional area. The percentage of the total flow passing different well depths can be estimated by multiplying the difference between the dynamic and static flowmeter logs by the borehole cross-sectional area and normalizing the data for 100% flow in the well casing. The flowmeter and caliper log data for production wells RO-10 and RO-11 (Fig. 9) and test well MC-5000 all show that the bulk (>60%) of the flow entered the pumped well from a 1.5 m or less section of the aquifer. The thin primary production intervals identified in the flowmeter logs consist of fractured dolomite. The subvertical fractures and associated borehole collapse zones are evident in borehole video surveys. The fractured intervals can be detected also in some caliper logs by a sharp increase in borehole diameters resulting from borehole collapse during drilling. Preferential borehole enlargement of fractured dolomite beds is common in the lower Floridan aquifer of south Florida (Maliva and Walker, 1998, and references therein).

DISCUSSION

The considerable variation in the specific capacity of production wells at the North County Plant correlates with dolomite abundance (Fig. 6). The three most productive (highest specific capacity) wells (RO-2, RO-3, and RO-6) all contain abundant dolomite. Dolomite is relatively uncommon in the three lowest specific capacity wells (RO-7, RO-8, and RO-9). Contrary to the general pattern, dolomite is not particularly abundant in the relatively high specific capacity well RO-11 (Fig. 3). However, fractured dolomite is present between 260 and 264 m in RO-11, which

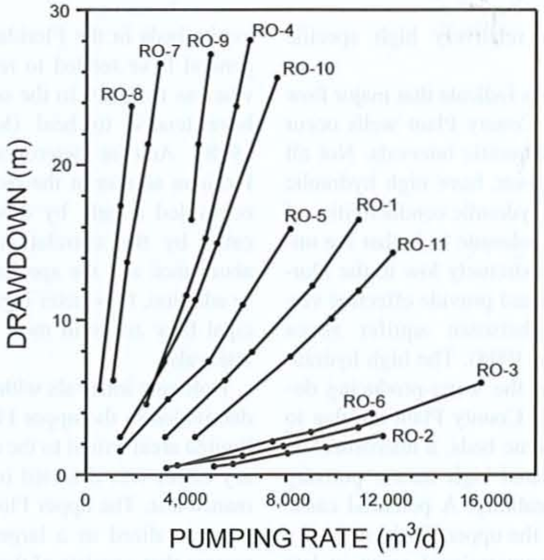

Figure 8. Drawdown vs. pumping rate plots from step-drawdown tests, which illustrate the very large differences in well performance (specific capacity) between wells.

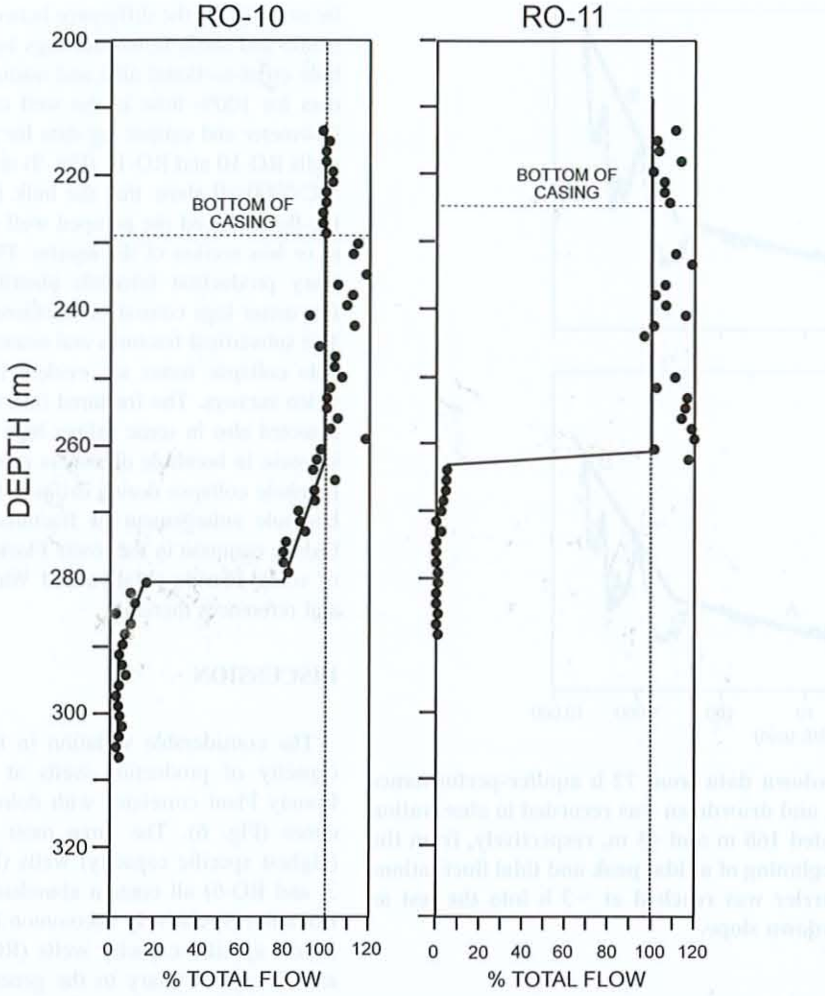

Figure 9. Plots of percentage of total flow vs. depth obtained from flowmeter and caliper log for wells RO-10 and RO-11. Both plots show that >60% of the flow entered the well from thin (1–2 m thick) dolomitic intervals.

gives the well its relatively high specific capacity.

The flowmeter logs indicate that major flow zones in the North County Plant wells occur invariably within dolomitic intervals. Not all dolomite beds, however, have high hydraulic conductivities. The hydraulic conductivities of densely crystalline dolomite beds that are unfractured are often extremely low in the Floridan aquifer system and provide effective vertical confinement between aquifer zones (Maliva and Walker, 1998). The high hydraulic conductivities of the water-producing dolomites at the North County Plant are due to fracturing and, in some beds, a microsucrosic texture with associated high matrix porosity and apparent permeability. A potential cause of the fracturing of the upper Floridan aquifer dolomites is the compressional event in late Miocene that resulted in the folding of the middle Miocene and older strata (Fig. 2). Dolomite beds in the Floridan aquifer system in general have tended to retain open fractures, whereas fractures in the softer limestone beds have tended to heal (Maliva and Walker, 1998). Aquifer heterogeneity in the upper Floridan aquifer at the North County Plant is controlled largely by dolomitization as indicated by the correlation between dolomite abundance and the specific capacity of wells. In addition, flowmeter logs show that the principal flow zones in most wells are dolomitic intervals.

Dolomite intervals with high hydraulic conductivities in the upper Floridan aquifer have limited areal extent to the degree that a boundary effect was detected in the aquifer performance test. The upper Floridan aquifer can be conceptualized as a large-scale dual-porosity system that consists of three-dimensional bodies of highly conductive dolomite enclosed within limestones having lower hydraulic conductivities. The total volume of water that can be produced from the dolomite bodies is limited. The response of the aquifer to pumping is therefore largely a function of the hydraulic properties of the limestone adjoining the dolomite. Dolomitization in the upper Floridan aquifer increases the specific capacities of some wells, reducing the number of wells required for a given water production rate, but it has little effect on the total yield of water that can safely be produced from the aquifer without adverse impacts.

Variations in dolomite abundance do not appear to be related to differences in depositional environment among wells. The carbonate mud-bearing (wackestone and packstone) textures and presence of fossils of stenohaline organisms, such as echinoderms, suggest that most of the upper Floridan aquifer limestones were deposited in a low-energy, marine environment in a deep-water ramp setting (Missimer, 1997). No significant differences in depositional microfacies are evident among the nondolomitized and partially and completely dolomitized limestones.

The stable isotope data (calculated pore water $\delta^{18}O$ values of +0.5‰ to −2.0‰, SMOW) indicate that dolomitization occurred in waters that were either isotopically close to seawater or mixed seawater and fresh water. Dolomite abundance in the upper Floridan aquifer was presumably controlled in some manner by paleohydrology, but the nature of the relationship is not ascertainable because of the inherently limited amount of data available from the studied wells. If dolomitization did occur in or near a coastal mixing zone, then it is reasonable to speculate that dolomite bodies might be orientated parallel to the shoreline at the time of dolomitization. Paleogeographic and lithofacies maps for the Miocene suggest a north-south– or northwest-southeast–oriented shoreline (Randazzo, 1997; Scott, 1997). Dolomite bodies in the upper Floridan aquifer may therefore have a general north-south or northwest-southeast orientation. That dolomitic intervals are not continuous across the North County Plant well field is evidence that they do not have an east-west orientation.

CONCLUSIONS

The results of this interdisciplinary investigation illustrate the large variability and unpredictability that may occur in aquifers strongly affected by diagenesis. During the installation of the North County Plant production wells it was not possible to predict well performance in advance of the drill bit. A combination of geologic, geophysical, and aquifer-test data can reveal the nature and magnitude of diagenesis-induced heterogeneities in aquifer hydraulics and provide insights into general aquifer behavior. In the absence of a grid of closely spaced wells or other fine-scale subsurface data, however, some aspects of aquifers will remain indeterminate. Fluid-flow paths and dispersivity, in particular, cannot be accurately evaluated without knowledge of the fabric and three-dimensional geometry of bodies of high-hydraulic conductivity rock within the aquifer. Calibrated numerical models may still be used for meaningful prediction of large-scale aquifer responses to pumping and other stresses. The accuracy of simulations of diagenesis-controlled aquifers may be limited on the local scale in the absence of fine-scale hydrogeologic data. Heterogeneities in aquifer hydraulics caused by dolomitization and other diagenetic processes, such as dissolution, cementation, and neomorphism, may greatly impact projects requiring recovery of a specific volume of water, such as pump-and-treat remediation and aquifer storage-and-recovery systems. The uncertainty associated with the hydrology of diagenesis-controlled aquifers, once they are identified as such, does not preclude modeling of the behavior of such aquifers, but rather suggests that there may be significantly higher errors associated with the results of predictive simulations.

ACKNOWLEDGMENTS

This manuscript benefited from the thoughtful reviews of Janet Herman, Jonathan Martin, and H. Leonard Vacher. We thank Collier County, Florida, for permission to publish the North County Regional Water Treatment Plant hydrogeological data collected under contract with Camp Dresser & McKee, Inc.

REFERENCES CITED

Amthor, J.E., Mountjoy, E.W., and Machel, H.G., 1994, Regional-scale porosity and permeability variations in Upper Devonian Leduc buildups: Implications for reservoir development and prediction in carbonates: American Association of Petroleum Geologists Bulletin, v. 78, p. 1541–1559.

Budd, D.A., 2001, Permeability loss with depth in the Cenozoic carbonate platform of west-central Florida: American Association of Petroleum Geologists Bulletin, v. 85, p. 1253–1272.

Cooper, H.H., Jr., 1963, Type curves for non-steady radial flow in an infinite leaky artesian aquifer, *in* Bentall, R., ed., Short-cuts and special problems in aquifer tests: U.S. Geological Survey Water-Supply Paper 1545-C, p. C48–C55.

Cooper, H.H., Jr., and Jacob, C.E., 1946, A generalized graphical method for evaluating formation constants and summarizing well field history: Eos (Transactions, American Geophysical Union), v. 27, p. 526–534.

Dawans, J.M., and Swart, P.K., 1988, Textural and geochemical alterations in late Cenozoic Bahamian dolomites: Sedimentology, v. 35, p. 385–403.

Driscoll, F.G., 1986, Groundwater and wells (second edition): St. Paul, Minnesota, Johnson Filtration Systems, 1089 p.

Duerr, A.D., 1995, Types of secondary porosity of carbonate rocks in injection and test wells in southern peninsular Florida: U.S. Geological Survey Water-Resources Investigation Report 94–4013, 78 p.

Ferris, J.G., Knowles, D.B., Brown, R.H., and Stallman, R.W., 1962, Theory of aquifer tests: U.S. Geological Survey Water-Supply Paper 1536-E, p. 69–174.

Haberfeld, J.L., 1991, Hydrogeology of effluent disposal zones, Floridan aquifer, South Florida: Ground Water, v. 29, p. 186–190.

Halley, R.R., and Schmoker, J.W., 1993, High-porosity carbonate rocks of south Florida: Progressive loss or porosity with depth: American Association of Petroleum Geologists Bulletin, v. 67, p. 191–200.

Henry, J.A., Portier, K.M., and Coyne, J., 1994, The climate and weather of Florida: Sarasota, Florida, Pineapple Press, 264 p.

Kohout, F.A., 1965, A hypothesis concerning cyclic flow of salt water related to geothermal heating in the Floridan aquifer: Transactions of the New York Academy of Sciences, Series II, v. 28, p. 249–271.

Kohout, F.A., 1967, Ground-water flow and the geothermal regime of the Floridan Plateau: Transactions of the Gulf Coast Association of Geological Societies, v. 17, p. 339–354.

Land, L.S., 1985, The origin of massive dolomite: Journal of Geological Education, v. 33, p. 112–125.

Lloyd, J.M., 1985, Annotated bibliography of Florida basement geology and related regional and tectonic studies including an appendix of Florida deep well data: Florida Geological Survey Information Circular 98, 72 p.

Lucia, F.J., 1962, Diagenesis of a crinoidal sediment: Journal of Sedimentary Petrology, v. 42, p. 848–865.

Maliva, R.G., and Walker, C.W., 1998, Hydrogeology of deep-well disposal of liquid wastes in southwest Florida, USA: Hydrogeology Journal, v. 6, p. 538–548.

Meyers, F.W., 1989, Hydrogeology, ground-water movement, and subsurface storage in the Floridan aquifer system in southern Florida: U.S. Geological Survey Professional Paper 1403-G, 59 p.

Miller, J.A., 1986, Hydrogeologic framework of the Floridan aquifer system in Florida and in parts of Georgia, Alabama, and South Carolina: U.S. Geological Survey Professional Paper 1403-B, 91 p.

Miller, J.A., 1997, Hydrogeology of Florida, *in* Randazzo, A.F., and Jones, D.S., eds., The geology of Florida: Gainesville, University Press of Florida, p. 69–88.

Missimer, T.M., 1997, Late Oligocene to Pliocene evolution of the central portion of the south Florida platform: Mixing of siliciclastic and carbonate sediments [Ph.D. thesis]: Miami, Florida, University of Miami, 414 p.

Missimer, T.M., and Gardner, R.A., 1976, High-resolution seismic reflection profiling for mapping shallow aquifers in Lee County, Florida: U.S. Geological Survey Water-Resources Investigation Report 76–45, 30 p.

Missimer, T.M., and Ginsburg, R.N., 1998, Homogenized carbonates and siliciclastics in the Tertiary of southwest Florida: Transactions of the Gulf Coast Association of Geological Societies, v. 48, p. 263–274.

Murray, R.C., 1964, Preservation of primary structures and fabrics in dolomite, *in* Imbrie, J., and Newell, N., eds., Approaches to paleoecology: New York, John Wiley, p. 388–403.

O'Neil, J.R., Clayton, R.N., and Mayeda, T.D., 1969, Oxygen isotope fractionation in divalent metal carbonates: Journal of Chemical Physics, v. 51, p. 5547–5548.

Puri, H.S., and Winston, G.O., 1974, Geologic framework of the high transmissivity zones in south Florida: Florida Bureau of Geology Special Publication 20, 97 p.

Randazzo, A.F., 1997, The sedimentary platform of Florida: Miocene to Cenozoic, *in* Randazzo, A.F., and Jones, D.S., eds., The geology of Florida: Gainesville, University Press of Florida, p. 39–56.

Safko, P.S., and Hickey, J.J., 1992, A preliminary approach to the use of borehole data, including television surveys, for characterizing secondary porosity of carbonate rocks in the Floridan aquifer system: U.S. Geological Survey Water-Resources Investigation Report 91-4168, 70 p.

Scholle, P.A., and Halley, R.B., 1985, Burial diagenesis: Out of sight, out of mind, *in* Schneidermann, N., and Harris, P.M., eds., Carbonate cements: Society of Economic Paleontologists and Mineralogists Special Publication 36, p. 309–334.

Scott, T.M., 1997, Miocene to Holocene history of Florida, *in* Randazzo, A.F., and Jones, D.S., eds., The geology of Florida: Gainesville, University Press of Florida, p. 57–67.

Sibley, D.F., 1982, The origin of common dolomite fabrics: Clues from the Pliocene: Journal of Sedimentary Petrology, v. 52, p. 1087–1100.

Singh, W.P., Eichler, G.E., Sproul, C.R., and Garcia-Bengochea, J.I., 1983, Pump testing Boulder Zone aquifer, south Florida: Journal of Hydraulic Engineering, v. 9, p. 1152–1160.

Stallman, R.W., 1963, Type curves for the solution of single boundary problems, *in* Bentall, R., ed., Short-cuts and special problems in aquifer tests: U.S. Geological Survey Water-Supply Paper 1545-C, p. C45–C47.

Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground water storage: Transactions of the American Geophysical Union, v. 2, p. 519–524.

Vernon, R.O., 1970, The beneficial use of zones of high transmissivity in the Florida subsurface: Florida Bureau of Geology Information Circular 70, 36 p.

Walker, K.R., Shanmugan, G., and Ruppel, S.C., 1983, A model for carbonate to terrigenous clastic sequences: Geological Society of America Bulletin, v. 94, p. 700–712.

Winston, G.O., 1995, The Boulder Zone dolomites of Florida, Volume 1. Paleogene and Upper Cretaceous zones of the southeastern peninsula and the Keys: Coral Gables, Florida, Miami Geological Survey, 70 p.

Winston, G.O., 1996, The Boulder Zone dolomites of Florida, Volume 2. Paleogene zones of southwestern Florida: Coral Gables, Florida, Miami Geological Survey, 64 p.

Manuscript Received by the Society March 12, 2001
Revised Manuscript Received November 27, 2001
Manuscript Accepted November 27, 2001

Printed in the USA