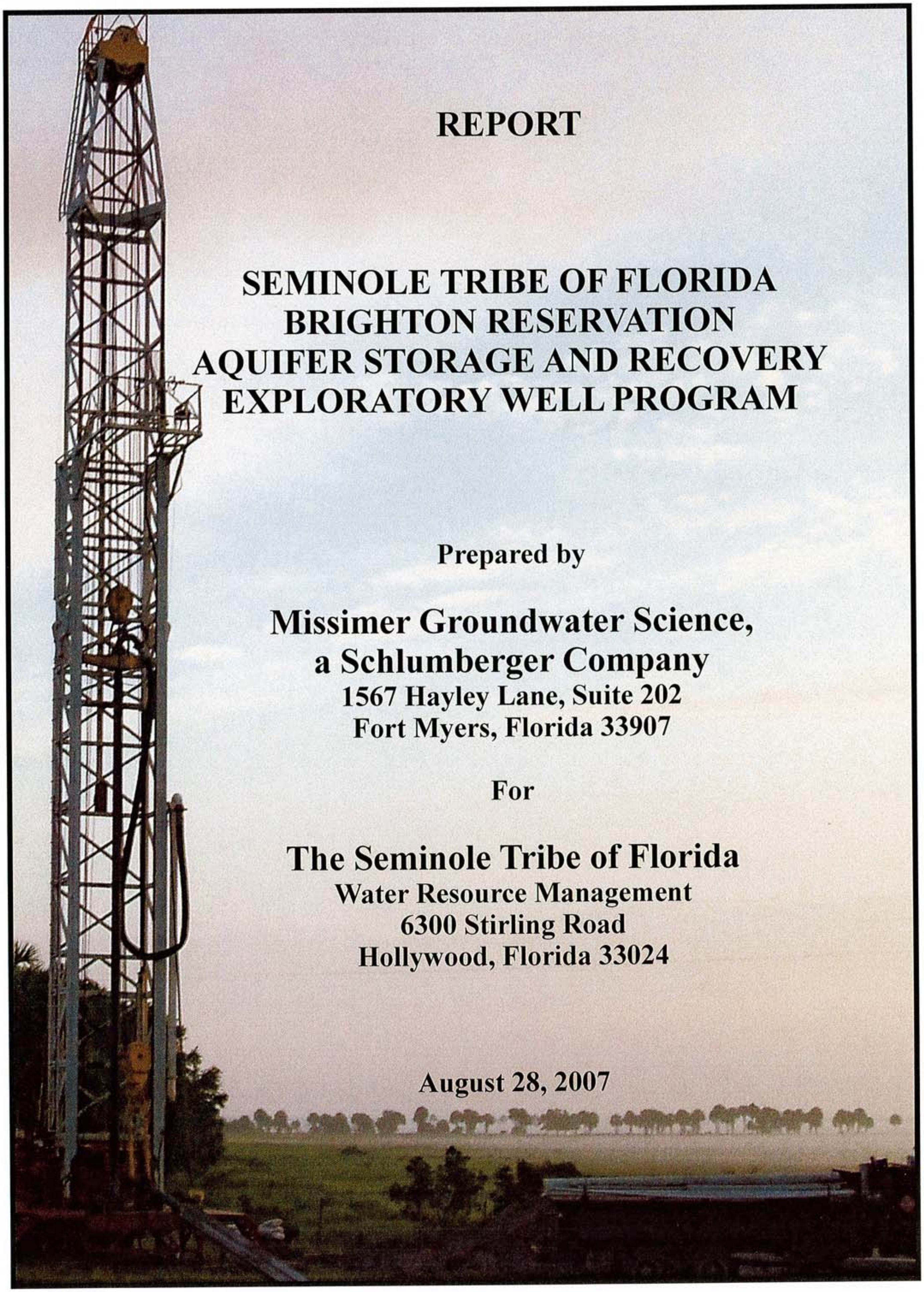


REPORT

SEMINOLE TRIBE OF FLORIDA BRIGHTON RESERVATION AQUIFER STORAGE AND RECOVERY EXPLORATORY WELL PROGRAM

Prepared by

Missimer Groundwater Science,
a Schlumberger Company
1567 Hayley Lane, Suite 202
Fort Myers, Florida 33907

For

The Seminole Tribe of Florida
Water Resource Management
6300 Stirling Road
Hollywood, Florida 33024

August 28, 2007

REPORT

SEMINOLE TRIBE OF FLORIDA BRIGHTON RESERVATION AQUIFER STORAGE AND RECOVERY EXPLORATORY WELL PROGRAM

Prepared by

Missimer Groundwater Science
A Schlumberger Company
1567 Hayley Lane, Suite 202
Fort Myers, Florida 33907

For

SEMINOLE TRIBE OF FLORIDA
Water Resource Management
6300 Stirling Road
Hollywood, Florida 33024

August 28, 2007

Project No. 0050-0093

Robert G. Maliva, Ph.D., P.G.
Professional Geologist #1549

Thomas M. Missimer, Ph.D., P.G.
Professional Geologist #144

Contents

FIGURES

TABLES

SECTION 1 EXECUTIVE SUMMARY AND RECOMMENDATIONS

An exploratory well was drilled north of the C-41 (Harney Pond) Canal and west of Harney Pond Road, in order to further assess the feasibility of aquifer storage and recovery (ASR) on the Seminole Tribe of Florida Brighton Reservation. The main goals of the exploratory well program were to identify a potential storage zone and obtain information on its hydrogeology, water quality, and potential well capacity.

The results of the exploratory well program greatly exceeded expectations. The Upper Floridan Aquifer at the test well site was found to be much more productive than was suggested by the regional hydrogeologic data. A potential ASR storage zone is present in the Avon Park Formation, between approximately 1,200 and 1,400 feet below land surface (ft bls) that is likely transmissive enough for ASR wells with capacities of 3 to 5 million gallons per day (Mgd). The 1,200 to 1,400 ft bls zone is only mildly brackish with a chloride concentration of approximately 750 to 900 milligrams per liter (mg/L). Water with a chloride concentration of 250 mg/L or less is typically considered to be fresh. Chloride concentrations below 1,000 mg/L are favorable for high ASR system recovery efficiencies because considerable mixing of native and injected water can occur before the recovered water exceeds applicable water quality thresholds for potable or irrigation water use. Chloride concentrations of 900 mg/L are near or close to the upper limit for irrigation water for some crops.

An additional important result of the exploratory well program is that a new aquifer was encountered between the Surficial Aquifer System and the Floridan Aquifer System. The aquifer is present between 250 and 340 ft bls and is composed predominantly of very coarse-grained quartz sand, which is sometimes referred to in Florida as a "ball bearing" sand. Based on its very coarse sand lithology, the aquifer is expected to be very productive. Wells completed in similar sands in Hendry County have yields of 0.5 to 1.0 Mgd or greater. The very coarse sand aquifer is expected to contain freshwater, but water quality could not be obtained in the exploratory well program because the upper part of the well was drilled using the mud-rotary method.

The results of the exploratory well program indicate that there is a high probability that ASR is feasible on the Brighton Reservation. The results also raise the possibility of some additional non-ASR water supply and management options on the Brighton Reservation. If the very coarse sand aquifer has good water quality and favorable aquifer hydraulics, it could potentially be used for:

- Potable water supply,
- Supplemental irrigation water supply,
- Emergency water source for fire fighting, and

- Seasonal water supply to charge the ASR system during initial testing and/or long-term operation.

The later option is important in that the very coarse sand aquifer may be a much less expensive source of freshwater to charge an ASR system than to construct and operate a canal intake and surface water treatment system. Using a raw groundwater source for an ASR system may reduce the potential for adverse fluid-rock interactions, such as arsenic leaching.

The mildly brackish salinity of the Upper Floridan Aquifer water at the Brighton Reservation may allow the aquifer to be used directly (without ASR) as a supplemental irrigation water source. The salinity of the Upper Floridan Aquifer water could be lowered to meet irrigation requirements by blending with surface water. Alternatively, the Upper Floridan Aquifer could also be blended with water from the very coarse sand aquifer.

1.1 Recommendations

It is recommended that the Brighton Reservation ASR project (and ASR projects in general) be implemented in a phased manner so that the full cost of constructing the system is not incurred until there is a high confidence that the system will operate satisfactorily and meet the expectation and needs of the Seminole Tribe. ASR feasibility, design options, and costs should be evaluated after each project phase and a Go/No Go decision made. In addition, it is also recommended that ASR implementation should allow for alternative uses of the wells and other infrastructure, to the extent practically possible, so that the Seminole Tribe will still obtain some value from its investment should a decision be ultimately made to not implement ASR.

The first two phases of the ASR investigation, (1) a desktop feasibility study and (2) an exploratory well program, have been completed. The next phase of the ASR program is the design and permitting of a pilot ASR system, which will consist of one ASR (injection and recovery) well, associated monitor wells, and water treatment facilities.

The results of the exploratory well program were very favorable for ASR in that a highly productive storage zone was identified that has a low salinity, which would be favorable for a high system recovery efficiency. A critical unresolved technical issue concerning ASR at the Brighton Reservation is source and treatment requirements of the water to be stored. As was discussed in the desktop study report (Schlumberger Water Services, 2006), the water injected into an ASR system must meet applicable groundwater standards, which would be the USEPA primary drinking water standards. The principal standards of concern for an ASR system at the Brighton Reservation storing surface water from the C-41 Canal are microbiological parameters and disinfection byproducts produced during the treatment of the surface water. The surface water treatment system would, at a minimum, require filtration and disinfection.

Cost estimates prepared as part of the CERP program indicate that the costs to construct and operate surface water treatment systems may equal or exceed those of the ASR system. Water supply/treatment costs are thus a critical element in the cost-benefit analysis of ASR systems, and they should be addressed before the decision is made as to whether or not to pursue full-scale implementation of ASR.

It was recommended in the desktop study (Schlumberger Water Services, 2006) that consideration be given to alternatives to conventional surface water treatment that may have substantially lower construction and operational costs. One option is bank filtration, in which water is withdrawn from the C-41 Canal through a series of wells located parallel to the canal bank. Microorganisms and other suspended solids would be filtered out as the water flows through the canal bed sediments and aquifer to the extraction wells. Bank filtration is attractive in that it can potentially eliminate the need to construct and operate a much more expensive canal intake structure and above ground filtration system. The water recovered from a bank filtration would also become more geochemically compatible with the ASR storage zone rock and water because some of the dissolved oxygen would be removed.

A main technical concern for a bank filtration is that the aquifer strata should have a high enough hydraulic conductivity so that an excessively large number of wells are not required to obtain the desired volume of water. The exploratory well was drilled through the Surficial Aquifer System using the mud-rotary method, which did not allow for the collection of high quality samples of the strata that was penetrated. The samples that were collected consisted mostly of very fine to fine sand-sized and silt-sized quartz, which would be expected to have a low to moderate hydraulic conductivity. However, in the event that natural bank filtration is not feasible, an artificial filtration system may be constructed along the canal banks, which would essentially consist of an excavation filled with coarse sand.

The very coarse sand unit encountered from 250 to 340 ft bls in the exploratory well is a potential source of freshwater from the Brighton Reservation with multiple potential uses including:

- Supplemental irrigation water source,
- Potable water supply,
- Emergency water source for fire fighting,
- Source water to charge an ASR system, and
- Blend water to reduce the salinity of Upper Floridan Aquifer water for use as an irrigation water supply.

Production wells completed in the very coarse sand unit could be used directly for water supply during dry periods and used to charge the ASR system during wet periods when minimal water is needed for irrigation. Depending upon the potential aquifer yields, water quality, and crop salinity tolerance, reservation irrigation water requirements during drought periods could potentially be met by a blend of groundwater from the Upper Floridan Aquifer water, the very coarse sand aquifer, and available surface water.

Evaluation of the water quality, extent, and hydraulics of the very coarse sand unit should be given the highest priority because of its multiple potential uses and thus value for the Seminole Tribe.

Based on the results of the exploratory well program, the following ASR implementation strategy is recommended:

Task 1) Very Coarse Sand Aquifer Evaluation. A test production well and observation well should be constructed in the very coarse sand aquifer at the ASR site and an aquifer performance test (APT) run in order to determine aquifer hydraulics. An observation well should also be constructed in the upper part of the Surficial Aquifer System, which would be used as part of the APT and to evaluate potential bank filtration well yields. At least two additional test wells should be drilled elsewhere in the ASR site vicinity in order to evaluate the extent of the very coarse sand aquifer. The test wells should be installed using the sonic drilling method, which has the advantages of (1) allowing for the collection of high quality samples of unconsolidated formations, (2) rapid well installation, and (3) minimal generation of cuttings and waste drilling fluids.

Task 2) Bank Filtration Preliminary Assessment. Water treatment is likely the greatest cost element of ASR using surface water for storage. Extracting water from the C-41 Canal using a bank filtration system consisting of an alignment of wells oriented parallel to the canal has the potential for a very large cost savings over a conventional canal intake and surface water treatment system. It is recommended that a preliminary assessment of bank filtration at the C-41 Canal site be performed. The assessment would consist of the installation of a small diameter (4-inch) test wells and two observation wells, and the performance of a pumping test to determine potential well yields and aquifer hydraulics. Task 2 can be performed simultaneously with Task 1, which would reduce costs by requiring only one mobilization of the drilling contractor. The results of the preliminary assessment would indicate whether further evaluation of the bank filtration option is warranted.

Task 3) Permitting of a Pilot ASR System. An application package should be submitted to the USEPA for the construction and operation of a pilot ASR system. The proposed pilot ASR system would consists of (1) a single ASR (injection and recovery well), (2) conversion of the ASR exploratory well into a dual-zone monitor well, and (3) construction of one additional storage zone monitor well. The conversion of the exploratory well into a dual-zone monitor well would result in a substantial cost savings in that it would eliminate the need to construct a dedicated shallow monitor well. The final design of the wells will be required as part of the application package. The possibility of obtaining an area permit that would include future additional ASR wells should be explored. However, the USEPA may not be receptive to an area permit until the successful testing of the pilot ASR system.

Task 4) <u>Final Design.</u> Upon completion of permitting, specifications and drawings will be prepared for the final design of the pilot ASR system (excluding wells, which would be designed in Task 3). The final design will include water treatment infrastructure, electrical supply, instrumentation and controls (SCADA), final wellheads, and piping.

Task 5) <u>Construction and Operational Testing of the Pilot ASR System.</u> The pilot ASR system and associated infrastructure will be constructed and operationally tested. Operational testing typically includes multiple cycle tests performed over a 2-year period.

Task 6) <u>System Expansion.</u> The ASR system capacity can be expanded to meet reservation water needs by the construction of additional ASR wells.

SECTION 2 INTRODUCTION

Schlumberger Water Services (SWS) previously conducted a desktop evaluation of the feasibility and conceptual design of an aquifer storage and recovery (ASR) system at the Seminole Tribe of Florida (Seminole Tribe), Brighton Reservation in Glades County, Florida. The results of the study were presented to the Seminole Tribe in a report dated September 13, 2006. The primary irrigation water supply on the Brighton Reservation is surface water from South Florida Water Management District (SFWMD) canals. Analyses of canal flows and irrigation water demands indicate that there may be periods in which an adequate supply of water may not be available to meet irrigation demands. ASR is being considered as a water management tool for ensuring that the Brighton Reservation has a reliable, long-term water supply to meet current and future irrigation water demands.

A key ASR feasibility issue, discussed in the desktop study report (Schlumberger Water Services, 2006), is locating a storage zone with suitable hydraulics and water quality for a high recovery efficiency. Recovery efficiency is the ratio of recovered water to injected water for an operational cycle. The ASR storage zone should also have a high enough transmissivity for economic well capacities, which for Floridan Aquifer wells would be a minimum of 1 to 2 million gallons per day (Mgd). The desktop study evaluated regional hydrogeologic data, but very few data were available for the Upper Floridan Aquifer in the immediate vicinity of the Brighton Reservation.

SWS was contracted by the Seminole Tribe to implement an ASR exploratory well program at the Brighton Reservation. The exploratory well was drilled at a location, identified in the desktop study, north of the C-41 (Harney Pond) Canal and approximately ½ mile northwest of Harney Pond Road. A location map is provided in **Figure 2-1** and an aerial photograph of the exploratory well area is provided in **Figure 2-2**.

The specific goals of the ASR exploratory well program at the Brighton Reservation were:

1) To obtain site-specific information on the hydrogeology of the Brighton Reservation,

2) To evaluate whether or not an aquifer zone is present in the upper part of the Floridan Aquifer System that is suitable for use as an ASR storage zone,

3) To obtain data on the water quality and well capacity (specific capacity) of potential ASR storage zones,

4) To further assess ASR feasibility at the Brighton Reservation using the obtained site-specific hydrogeologic data, and

5) Construction of the exploratory well so that it can serve as one of the required monitor wells for an ASR system.

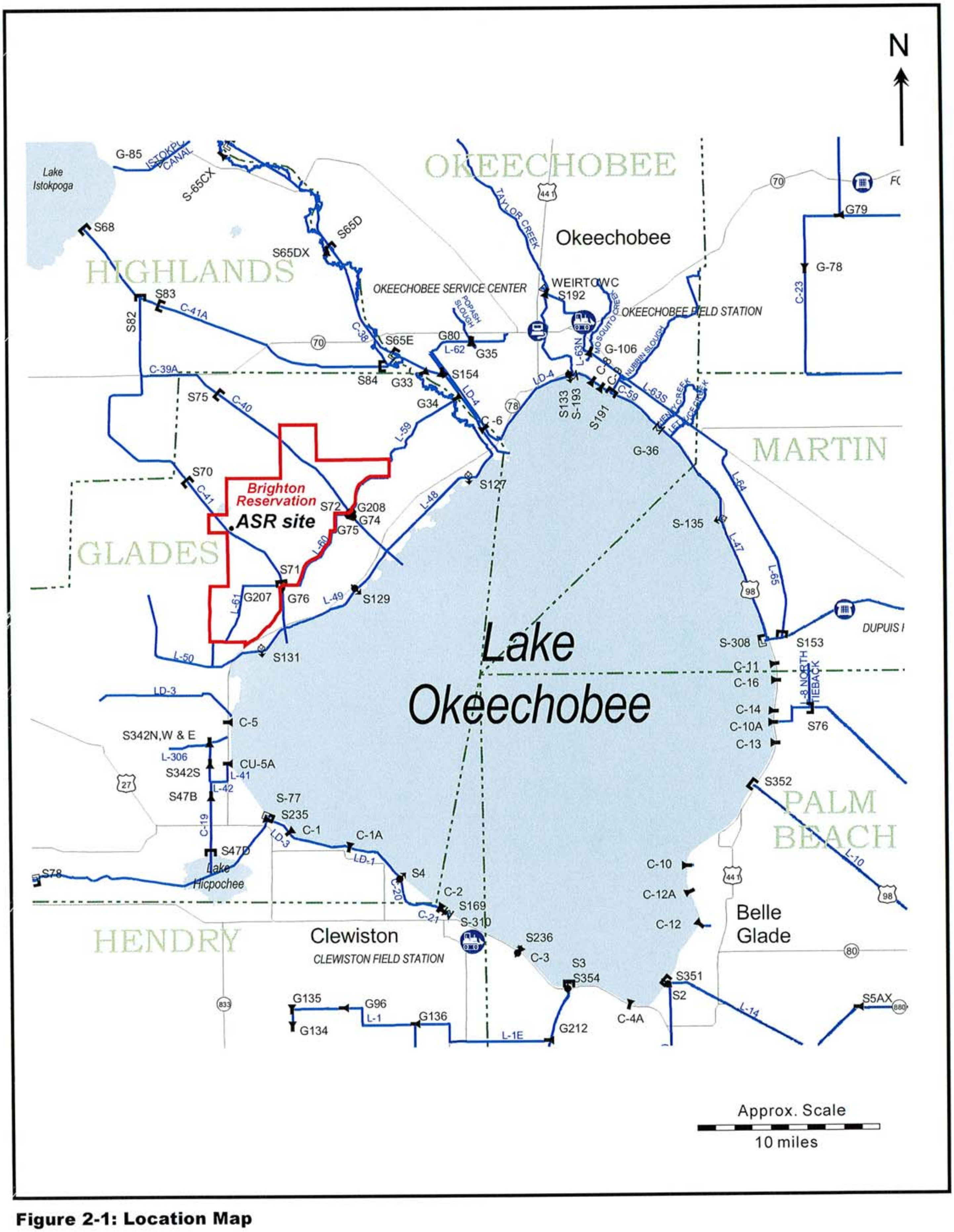


Figure 2-1: Location Map

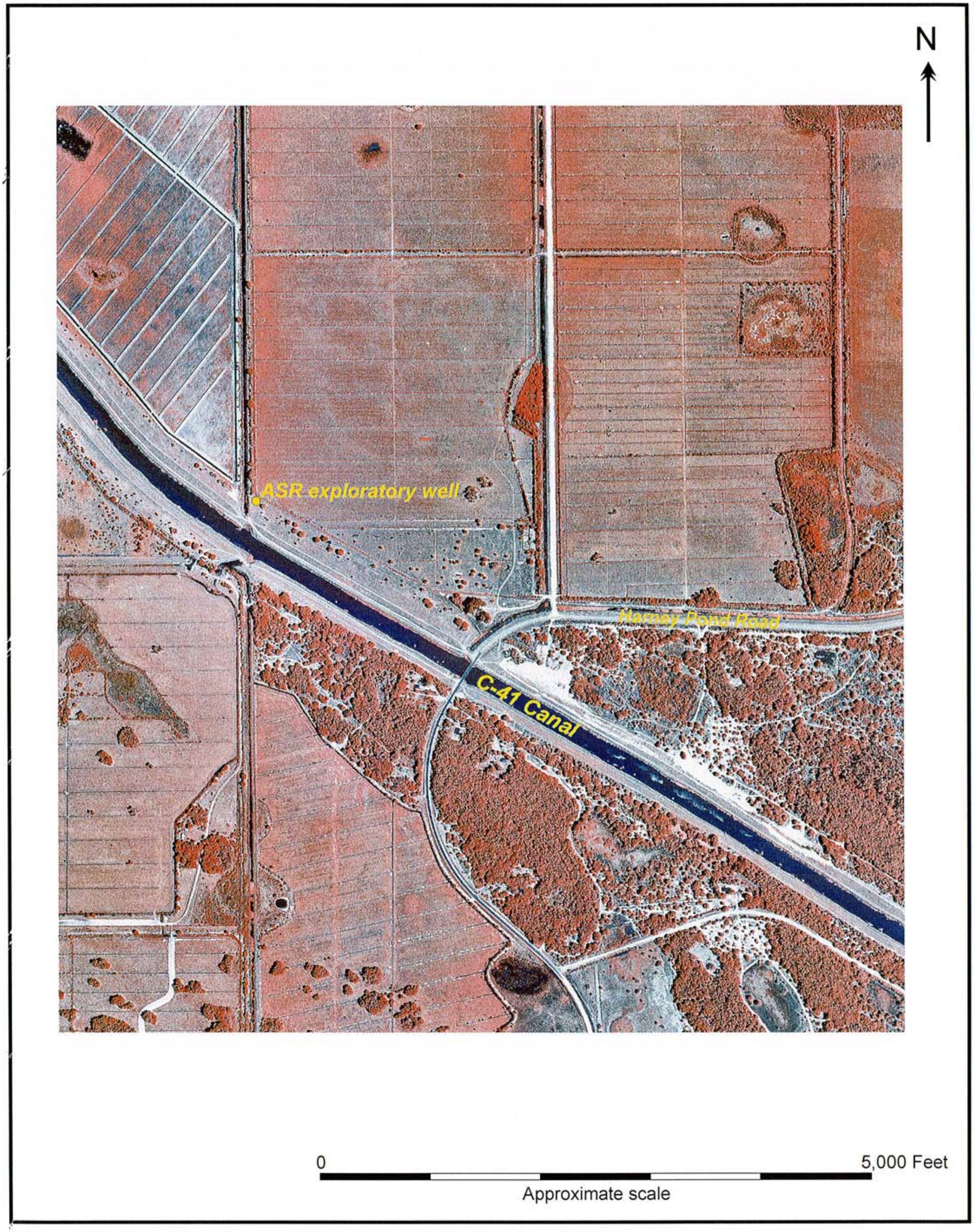


Figure 2-2: Aerial Photograph Showing ASR Exploratory Well Location

SECTION 3 WELL CONSTRUCTION AND TESTING

3.1 Well Construction

MGS contracted Hydrologic Associates USA, Inc. (HAI) to drill the exploratory well. HAI subcontracted David Cannon Well Drilling, Inc. (DCWD) to install the casing string to the top of the Floridan Aquifer System. An as-built diagram of the exploratory well is provided in **Figure 3-1** and a well construction and testing chronology is provided in **Table 3-1**.

Table 3-1: Well Construction Chronology

Date	Activity
5/30/07	Drilled nominal 24" diameter hole to 179 ft bls.
5/30/07	Installed and cemented 18" diameter casing to 162 feet. 150 sacks of neat cement.
5/31/07 to 6/1/07	Drilled nominal 17" diameter hole to 640 ft bls.
6/4/07 to 6/6/07	Installed and cemented 10" diameter casing to 634 ft bls. 550 sacks of neat cement in 3 stages.
6/6/07 to 6/13/07	Switched drilling rigs.
6/14/07 to 6/20/07	Drilled using the dual-tube rotary method to 936 ft bls. Nominal 9" diameter borehole to 900 ft bls and 6" to 936 ft bls.
6/21/07	Performed aquifer test no. 1.
6/22/07 to 6/25/07	Resumed dual-tube rotary drilling to 1,216 ft bls.
6/26/07 to 6/28/07	Performed aquifer test no. 2
6/29/07 to 7/3/07	Resumed dual-tube rotary drilling to 1,436 ft bls
7/4/07	Performed aquifer test no. 3
7/9/07 to 7/11/07	Resumed drilling using the reverse-air rotary method with a tricone bit to 1,616 ft bls (total depth).
7/17/07 to 7/18/07	Reamed hole with a 7 3/8" diameter bit.
7/19/07	Performed geophysical logging (MV Geophysical).
7/20/07	Tripped back into hole and cleared to total depth.
7/27/07	Performed geophysical logging (Schlumberger).
7/30/07	Performed aquifer test no. 4.
7/31/07	Attempted to backplug well, but could not get tremie pipe below about 1,400 ft bls due to obstruction.
8/15/07 to 8/17/07	Mobilized drill rig to clear hole.
8/22/07 to 8/22/07	Cleared hole to total depth and back-plugged to 1,410 ft bls.
8/27/07 to 8/28/07	Performed aquifer test no. 5
8/28/07	Disinfected well.

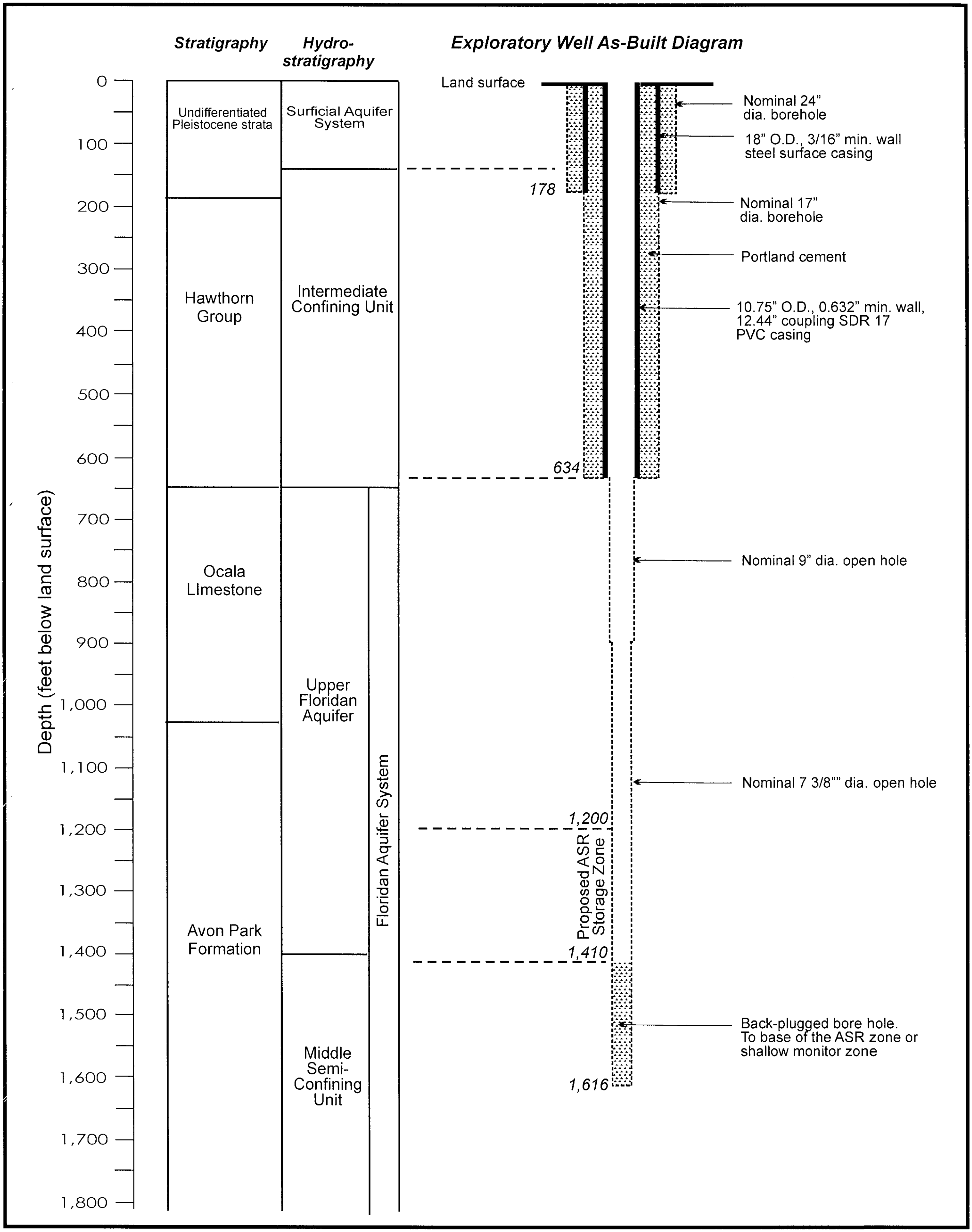


Figure 3-1: Exploratory Well Construction Diagram

A nominal 24-inch diameter borehole was drilled to 184 ft bls, through the entire Surficial Aquifer System, using the mud-rotary method by DCWD. An 18-inch diameter surface casing was then installed to 162 ft bls and cemented in place using neat Portland cement. The first cement stage for all casing string was pressure grouted from the bottom of the casing upwards. The surface casing serves two main purposes: (1) to prevent the unconsolidated sands of the Surficial Aquifer System from collapsing into the borehole during subsequent drilling and (2) to seal off and thus protect the freshwater of the Surficial Aquifer System.

A nominal 17-inch diameter borehole was then drilled using the mud-rotary method to approximately the top of the Floridan Aquifer System at 640 ft bls. Geophysical logs were run by MV Geophysical Surveys, Inc. (MV Geophysical). A 10-inch diameter Certa Lok^{TM} SDR-17 PVC casing was then installed to 936 ft bls and cemented in place in three stages using neat Portland cement (550 sacks). Larger than planned diameter surface casing (18-inch versus 14-inch) and final casing (10-inch versus 8-inch) were installed to give more room for subsequent drilling through the Floridan Aquifer System. The larger diameter casing now allows for the well to be converted into a dual-zone monitor well, which would eliminate the need to construct a dedicated shallow monitor well (and thus provide a substantial cost savings to the Seminole Tribe) if an ASR system is constructed at the site.

After the 10-inch diameter casing was set, DCWD demobilized and HAI set up their drilling rig at the site. HAI drilled a nominal 5 7/8-inch diameter borehole to 1,618 ft bls using the dual-tube rotary method. The dual-tube rotary method was chosen because it allows for the collection of high quality (minimal mixing) water samples with depth and the recovery of large, intact samples of aquifer rock. The upper part of the hole (to 900 ft bls) was reamed to 9-inches in diameter during dual-tube rotary drilling to facilitate drilling at greater depths.

The drilling plans called for drilling of the borehole to approximately 1,700 ft bls. The water quality data indicated that salinity starts to rapidly increase with depth below 1,550 ft bls. Continued drilling to 1,700 ft bls would have potentially created adverse impacts associated with the discharge of saline water to canals or the ground. Inasmuch as the potential ASR storage zone is located above 1,400 ft bls, there was little technical need to continue drilling below 1,618 ft bls. The decision was therefore made, with the concurrence of the Seminole Tribe and SFWMD staff, to terminate drilling at 1,618 ft bls. The borehole was subsequently reamed to 7 3/8-inches in diameter to provide adequate room for geophysical logging.

The borehole was then logged by MV Geophysical. An obstruction was encountered in the bore at approximately 1,510 ft bls, which was rock that had fallen into the well from above and bridged the borehole. The Upper Floridan Aquifer rock below approximately 1,200 ft bls is fractured in places and pieces of rock have fallen into the well, which was unpreventable. HAI tripped back into the hole and cleared the well to total depth. Schlumberger then ran a suite of advanced geophysical logs. The borehole had become blocked again at approximately 1,400 ft bls before the last 3 logs were run. All logs were run through the proposed ASR storage zone.

HAI unsuccessfully attempted to clear the well using 1 ½-inch diameter steel tremie pipe prior to backfilling the well with cement to the base of the identified ASR storage zone at 1,400 ft bls. An uncemented borehole is a potential conduit for the upwards migration of saline water into the ASR storage zone. The decision was then made to remobilize a drilling rig and clear the borehole. The borehole was cleared and back-plugged to 1,410 ft bls feet by DCWD. The depth to the top of the cement was confirmed by tagging with the drill string.

The well was completed with a water-tight flange assembly on top of the 18-inch diameter casing. The wellhead assembly can be modified or replaced to accommodate future uses of the well (e.g., dual-zone monitor well).

3.2 Well Testing and Data Collection

The well testing and data collection program was designed to efficiently obtain site-specific hydrogeologic information that is needed to assess ASR feasibility at the test site, to make an informed Go/No Go decision, and to proceed into USEPA permitting of a pilot ASR system. Additional hydrogeologic information would be obtained during subsequent project phases. In particular, more accurate data on aquifer hydraulics (storage zone transmissivity, storativity, and leakance) would be obtained from a multiple well aquifer performance test performed after the ASR wells are permitted and constructed.

3.2.1 Well Cuttings Analysis

Samples of the cuttings and core material recovered during drilling were described in the field and subsequently re-examined by Missimer Groundwater Science (MGS) staff in the office using a stereomicroscope. The recovered material was described using a color chart prepared by the Geological Society of America, which is based on the Munsell system, and examined for composition, texture, macroporosity (visible porosity), and apparent permeability. Limestone samples were categorized for composition and texture using the classification scheme of Dunham (1962). The geologic log for the exploratory well is provided in **Appendix A**.

3.2.2 Thin Section Analysis

Thin sections are approximately 30 micron (0.030 millimeter) thick slices of rock that are mounted on glass slides. When examined using a petrographic microscope, information can be obtained on the composition, texture, and porosity (amount, type, and geometry) of the rock. Thin section analysis (petrography) is particularly valuable for identification of mineral phases that are either very finely crystalline or present in trace quantities. Thin sections were prepared of 7 limestones from the exploratory well and examined by MGS staff. Photomicrographs and descriptions of the samples are provided in **Appendix B**.

3.2.3 Geophysical Logging

Borehole geophysical logging techniques allow for the in situ measurement of the petrophysical properties and composition of the penetrated rock, sediment, and formation fluids. Three suites of geophysical logs were run during the drilling of the ASR exploratory well on the Brighton Reservation, which are summarized in **Table 3-2**. Copies of the geophysical logs are provided separately. Interpretations of the geophysical logs are provided in **Appendix C**.

Table 3-2: Geophysical Log Summary

Stage	Depths (ft bls)	Date	Logs
Nominal 17" diameter borehole	130 - 630	6/1/2007	X-Y caliper, gamma ray, dual induction, spontaneous potential.
Nominal 7 3/8" diameter borehole	0 – 1,580	7/19/07	X-Y caliper, gamma ray, dual induction, spontaneous potential, flowmeter, fluid conductivity and temperature, video survey.
Nominal 7 3/8" diameter borehole	0 – 1,610	7/27/07	Magnetic resonance imaging; high resolution focused array induction with spontaneous potential; fully-oriented borehole electrical resistivity imaging with four arm caliper and borehole inclinometry; dipole sonic that digitally measures full compressional, shear, and Stoneley (flexural) waveforms; natural gamma ray spectroscopy; elemental neutron capture spectroscopy; compensated density with photoelectric effect; compensated neutron porosity; and environmental measurement sonde with 6 independent caliper arms.

Upon completion of the nominal 17-inch diameter borehole to the top of the Floridan Aquifer System, MV Geophysical ran caliper, natural gamma ray, and dual-induction logs, which were used to determine the actual borehole diameter and for lithologic analysis.

Upon completion of the borehole to total depth, MV Geophysical ran a suite of conventional geophysical logs. Although not within our scope of work, MGS also had MV Geophysical run a borehole video, which allows for visual analysis of the borehole rock and observation of potential flow features, such as fractures and solution cavities. Schlumberger then ran an advanced suite of geophysical logs, which allowed for in situ measurements of rock composition, water quality, porosity, permeability, and fine-scale imaging of the borehole strata.

3.2.4 Aquifer Testing

A total of five short-term pumping/flow tests were performed during drilling in order to identify potential well yields (specific capacity) and the water quality of potential flow zones. Specific capacity is the well flow rate divided by drawdown and is typically expressed in gallons per minute (gpm) per foot. Regional hydrogeologic data summarized in the desktop study report (Schlumberger Water Services, 2006) suggested that the Upper Floridan Aquifer has relatively low well yields in the Brighton Reservation vicinity. It was anticipated that the aquifer testing in the relatively small diameter ASR exploratory well would be performed by pumping at rates of 100 to 300 gpm. Instead, below 1,200 ft bls, the well had an artesian flow at the extraordinary and unexpected rate of roughly 3,000 gpm, as estimated from the height of the water jet above the casing. Aquifer testing was, therefore, performed by measuring the wellhead pressure at different natural flow rates. Water samples were collected at the end of each test and analyzed for salinity parameters.

The results of the aquifer test are summarized in **Table 3-3**, and described below:

Table 3-3: Aquifer Test Summary

No.	Date	Depths (ft bls)	Flow rate (gpm)	Drawdown (feet)	Specific capacity (gpm/ft)	Chloride* (mg/L)
1	6/21/07	640-936	38	15.5	2.4	1,700
2	6/28/07	640-1,216	965	23.0	42.0	655
3	7/4/07	1,216 - 1,436	117	16.4	7.1	740
4	7/30/07	640 – 1,616	1364	13.0	105	740
5	8/27/07	640 – 1,410	1349	13.8	98.7	900

* Chloride and TDS (total dissolved solids) for sample collected at end of test.

<u>Aquifer Test No. 1</u>

Aquifer test no. 1 was performed on June 21, 2007, upon drilling to 936 ft bls. The static water pressure was 8.3 psi at 1 foot above land surface, which is equivalent to approximately 20 feet above land surface. The well had a small artesian flow of approximately 38 gpm.

The transmissivity of the 640 to 936 ft bls interval is approximately 244 ft^2/day, as estimated from the pressure buildup data (**Figure 3-2)** using the Cooper-Jacob Method (aka "straightline" method, as described by Driscoll, 1986, page 219). A transmissivity of 244 ft^2/day corresponds to an average hydraulic conductivity of 0.82 ft/day for the 296 foot tested interval.

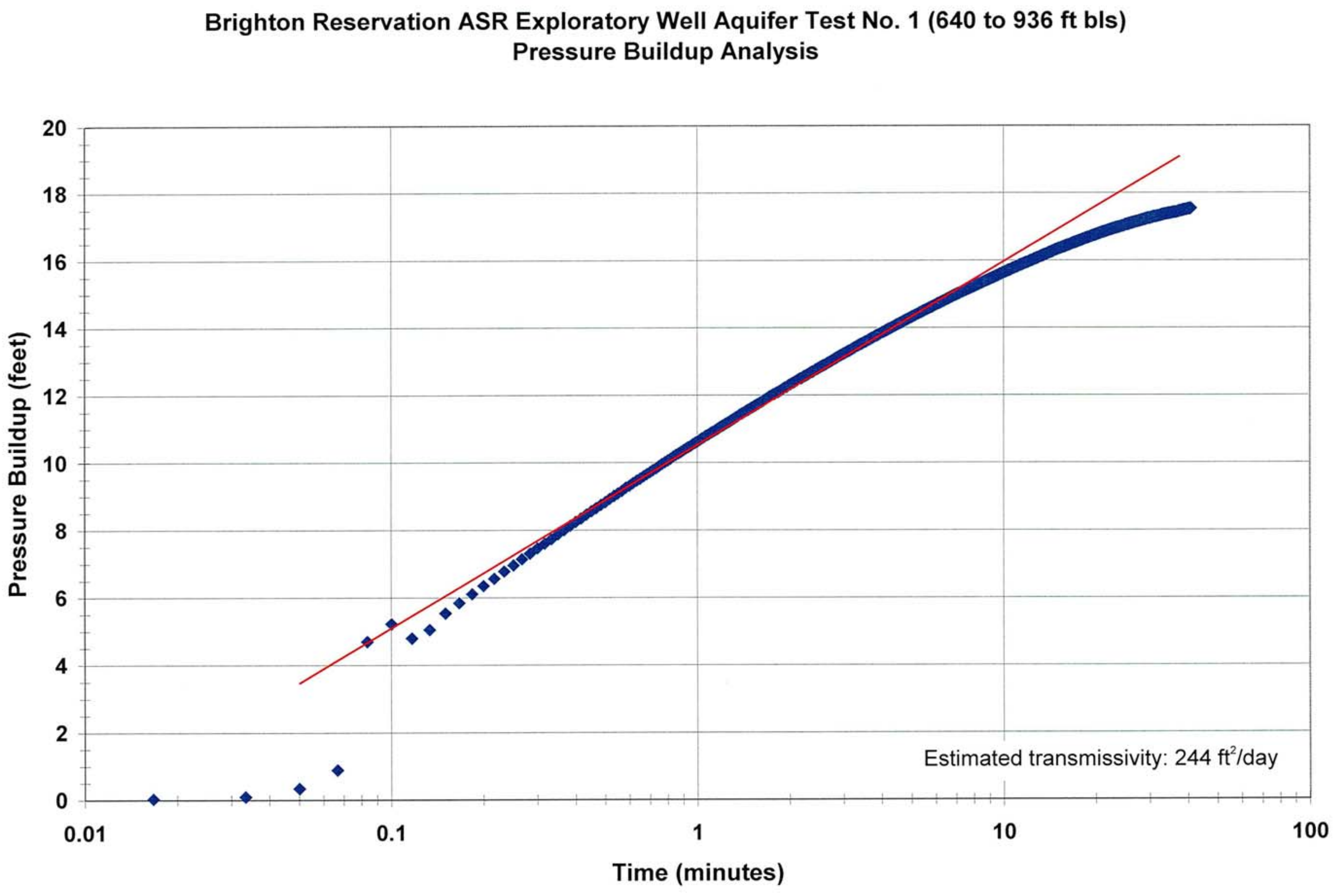


Figure 3-2: Brighton Reservation ASR Exploratory Well Aquifer Test No. 1 Analysis

Aquifer Test No. 2

Aquifer test no. 2 was performed on June 27 and 28, 2007, upon drilling to 1,216 ft bls. The bottom of the test interval had just penetrated the top of a major flow zone of fractured limestone, located between approximately 1,202 and 1,210 ft bls on the MV Geophysical flowmeter log. The flow zone was also evident during drilling by a pronounced increase in artesian flow. The artesian flow was approximately 1,000 gpm, and the static water level was approximately 23 feet above land surface. A constant rate flow test was first performed, which gave a drawdown of 23 feet at an average flow rate of 965 gpm. The large flow volume and limited disposal capacity restricted the test duration to only 1 hour and 23 minutes. Quantitative analysis of time-drawdown/recovery data was not performed because it was not possible to obtain an instantaneous start or stop of the large artesian flow.

Aquifer transmissivity can be estimated from specific capacity values by the formula:

T (gpd/ft) = SC (gpm/ft) * 2000 (Driscoll, 1986; page 1021).

The estimated transmissivity of the 640 to 1,216 ft bls interval is approximately 84,000 gpd/ft or 11,200 ft^2/day. The estimated transmissivity value likely significantly underestimates the actual transmissivity because of the large head loss in the small diameter borehole, particularly in the rough borehole between the top of the fracture zone and the bottom of the casing (≈ 640 to 1,200 ft bls).

The second test performed was a step-drawdown test at different flow rates. The test results are summarized in **Figure 3-3**. The water produced during pumping test 2 had a chloride concentration of 740 mg/L (SWS analysis). The Lee County Environmental Laboratory (LCEL) analysis gave a lower concentration of 655 mg/L. The water quality data reflects the composition of water produced from the 1,200 to 1,216 ft bls interval, from which most of the water originated.

Aquifer Test No. 3

Aquifer test no. 3 was performed on July 4, 2007, after drilling to 1,436 ft bls. The drill string was raised to 1,216 ft bls, and the tested interval was thus from 1,216 to 1,436 ft bls interval. The test was performed by allowing water to flow through the approximately 3-inch diameter drill string. The test had a total duration of over four hours and consisted of 5 flow steps. The results of aquifer test no. 3 are summarized in **Table 3-4**.

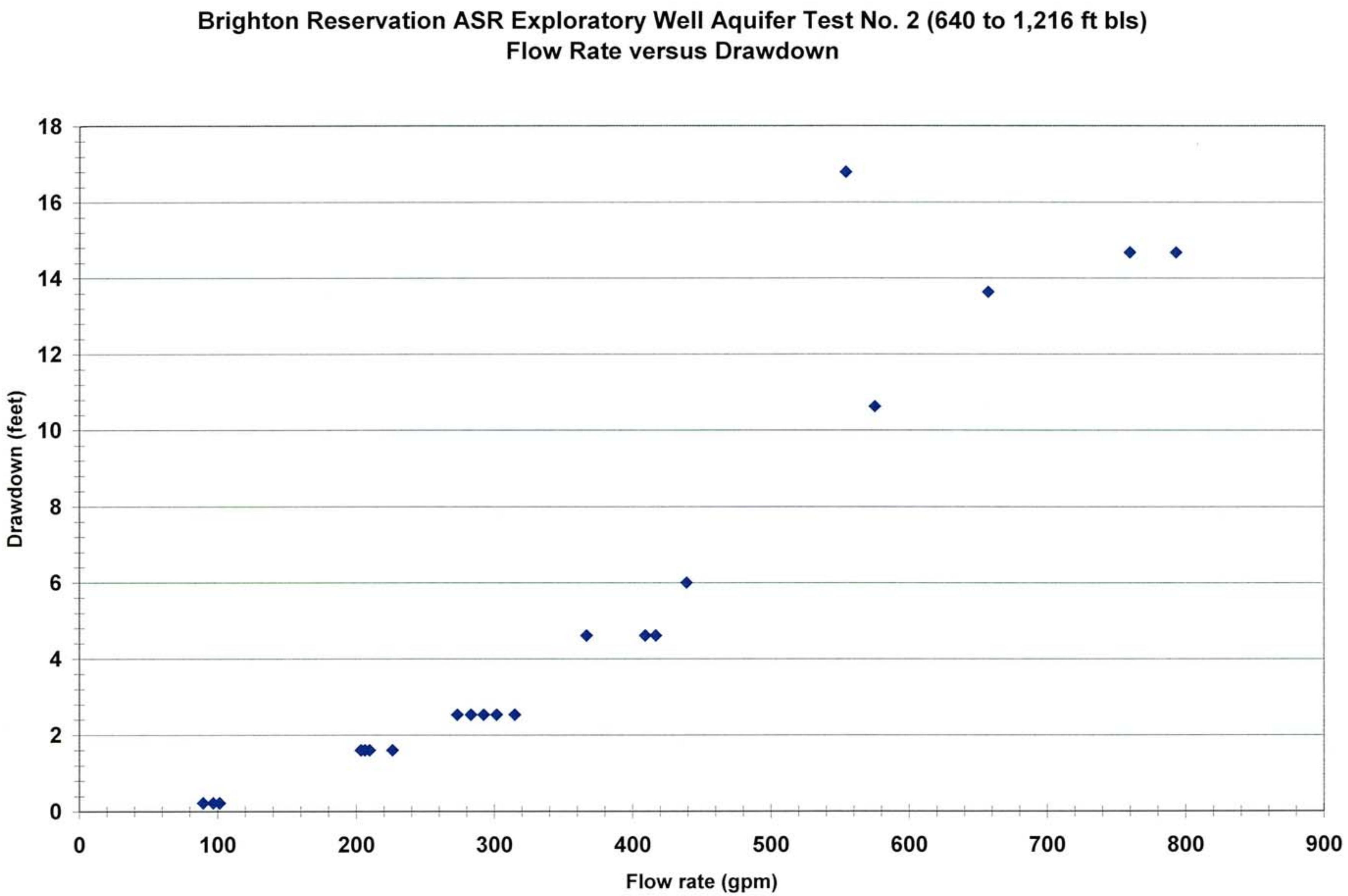

Brighton Reservation ASR Exploratory Well Aquifer Test No. 2 (640 to 1,216 ft bls)
Flow Rate versus Drawdown

Figure 3-3: Brighton Reservation ASR Exploratory Well Aquifer Test No. 2 Flow Rates Versus Drawdown

Table 3-4: Summary of Aquifer Test No. 3

Flow rate (gpm)	Drawdown (feet)	Specific Capacity (gpm/ft)
24.6	1.0	24.6
50.8	3.1	16.4
73.1	5.8	12.6
101.5	10.9	9.3
116.8	15.4	7.6

The 116.8 gpm flow rate was the full artesian flow (valve completely open) and static water level was approximately 19 feet above land surface. The friction loss in 1,200 feet of 3-inch pipes is substantial, approximately 5.2 and 6.6 feet, at flow rates of 101.5 and 116.8 gpm, respectively, as determined using the Hazen Williams method and a roughness coefficient of 100. The fraction-loss corrected specific capacities are 18.8 and 13.3 gpm/ft for flow rates of 101.5 and 116.8 respectively. The estimates transmissivities are 5,000 and 3,500 ft^2/day, for flow rates of 101.5 and 116.8 respectively. These transmissivity values are significantly underestimated based on the flow rate.

The water sample from aquifer test no. 3 had a chloride concentration of 740 mg/L. The results of aquifer test no. 3 indicate that there was substantial flow from the upper main flow zone.

Aquifer Test No. 4

Aquifer test no. 4 was performed after the completion of drilling to total depth (1,616 ft bls). An eight hour flow test was performed on the entire open hole interval. The well produced approximately 1,364 gpm with 13 feet of drawdown, which corresponds to a specific capacity of 105 gpm/ft. The estimated transmissivity is 28,000 ft^2/day. Salinity decreased over the duration of the aquifer test. The initial chloride concentration was 810 mg/L, and the final concentration was 740 mg/L.

Aquifer Test No. 5

Aquifer test no. 5 was a constant rate flow test performed after back-plugging the well to 1,410 ft bls. The test was run from approximately 9:30 P.M. on August 27, 2007 to 8:30 A.M. on August 28, 2007. The duration of flow test was approximately 11 hours. The average flow rate was 1,349 gpm (1.94 Mgd) and the drawdown 13.8 feet, which corresponds to a specific capacity of 98.7 gpm/ft. The pressure build-up after the well was shut in was very rapid, which prevented estimation of transmissivity from the time-build-up data The transmissivity estimated from the specific capacity value is 26,400 ft^2/day. Comparison of the results of aquifer test nos. 4 and 5 indicate that there is minimal flow from below 1,410 ft bls.

3.2.5 Water Quality Testing

Water samples were collected at a minimum of 20 foot intervals (every drilling rod addition) during dual-tube rotary drilling. The interval was decreased to 10 feet near the bottom of the well to allow for better resolution of the anticipated transition to more saline waters near the base of the Upper Floridan Aquifer. The samples were tested in the field for specific conductance using a YSI 30 salinity conductivity and temperature meter. The samples were re-tested for specific conductance and analyzed for chloride concentration by MGS staff in the office. Chloride concentration was measured using the argentometric method in which a 25 mL water sample was titrated using a 0.141 N silver nitrate solution and potassium chromate as an indicator. Standards and duplicate analyses were run, and the methodology was accurate within ± 20 mg/L. Errors on the chloride standard runs, if present, were on the high side (10 to 20 mg/L overestimation). The results of the chloride analyses are compiled in **Appendix D**.

Water samples collected at the end of each pump/flow test were analyzed by LCEL for the following parameters: chloride, calcium, specific conductance, sulfate, calcium, magnesium, sodium, total alkalinity, total dissolved solids, and total hardness. Samples were collected from the well at its final open hole interval (~ 640 to 1,410 ft bls) and analyzed for Florida drinking water standards, and major cations and anions, by TestAmerica (formerly STL Laboratories). The results of the LCEL and TestAmerica analyses are included in **Appendix D**.

SECTION 4 GEOLOGY AND HYDROGEOLOGY

The geology and hydrogeology of the Brighton Reservation were discussed in the desktop study report (Schlumberger Water Services, 2006). The geology and hydrogeology of the exploratory well site are discussed below. A geologic column for the ASR exploratory well is provided in **Figure 4-1**.

4.1 Geology of the ASR Exploratory Well Site

Four main stratigraphic (geologic) units were penetrated by the Brighton Reservation ASR exploratory well. They are, in descending order, (1) undifferentiated Pleistocene to Pliocene sands, (2) Hawthorn Group, (3) Ocala Limestone, and (4) Avon Park Formation. These four units are described below:

Undifferentiated Pleistocene to Pliocene Sands

The ASR exploratory well site at the Brighton Reservation is underlain by quartz sands from land surface down to a depth of approximately 178 ft bls. The sand is predominantly very fine to fine-grained and, in some intervals, contains a considerable amount of silt-sized quartz. Recovery of the sands was poor during drilling because the very fine material passed through the strainer used for sample collection. Shell was sparse from 0 to 55 ft bls. Thin-shelled bivalves fragments were common below 55 ft bls.

The sands from 0 to 64 ft bls appear to have a relatively low clay content. Clay is more abundant from 64 to 143 ft bls. Clay content further increases below 143 ft bls, and the recovered cuttings were more cohesive and contained trace phosphate sand. The interval from 143 to 178 ft bls still has a relatively low activity on the natural gamma ray geophysical log.

Hawthorn Group (Peace River Formation)

The Hawthorn Group, which is of Pliocene to Oligocene age, is a compositionally heterogeneous unit that is composed of marl and clay, with varying amounts of sand, silt, limestone, dolomite, and phosphate. The term "marl" is used in this report to described calcareous clays, which have a strong reaction to dilute hydrochloric acid. The high phosphate and clay content of the Hawthorn Group result in its having characteristic intervals of high activity on natural gamma ray logs. The top of the Hawthorn Group is identified in the Brighton Reservation ASR exploratory well at approximately 178 ft bls by a pronounced downhole increase in gamma ray activity and the first appearance of dark greenish gray, cohesive clayey silts.

The Hawthorn Group from 178 ft bls to approximate 255 ft bls consists predominantly of olive gray to dark greenish gray clayey silts and sands. Silt and sand-sized material (quartz and carbonate) constitutes over 50% of the volume of the samples.

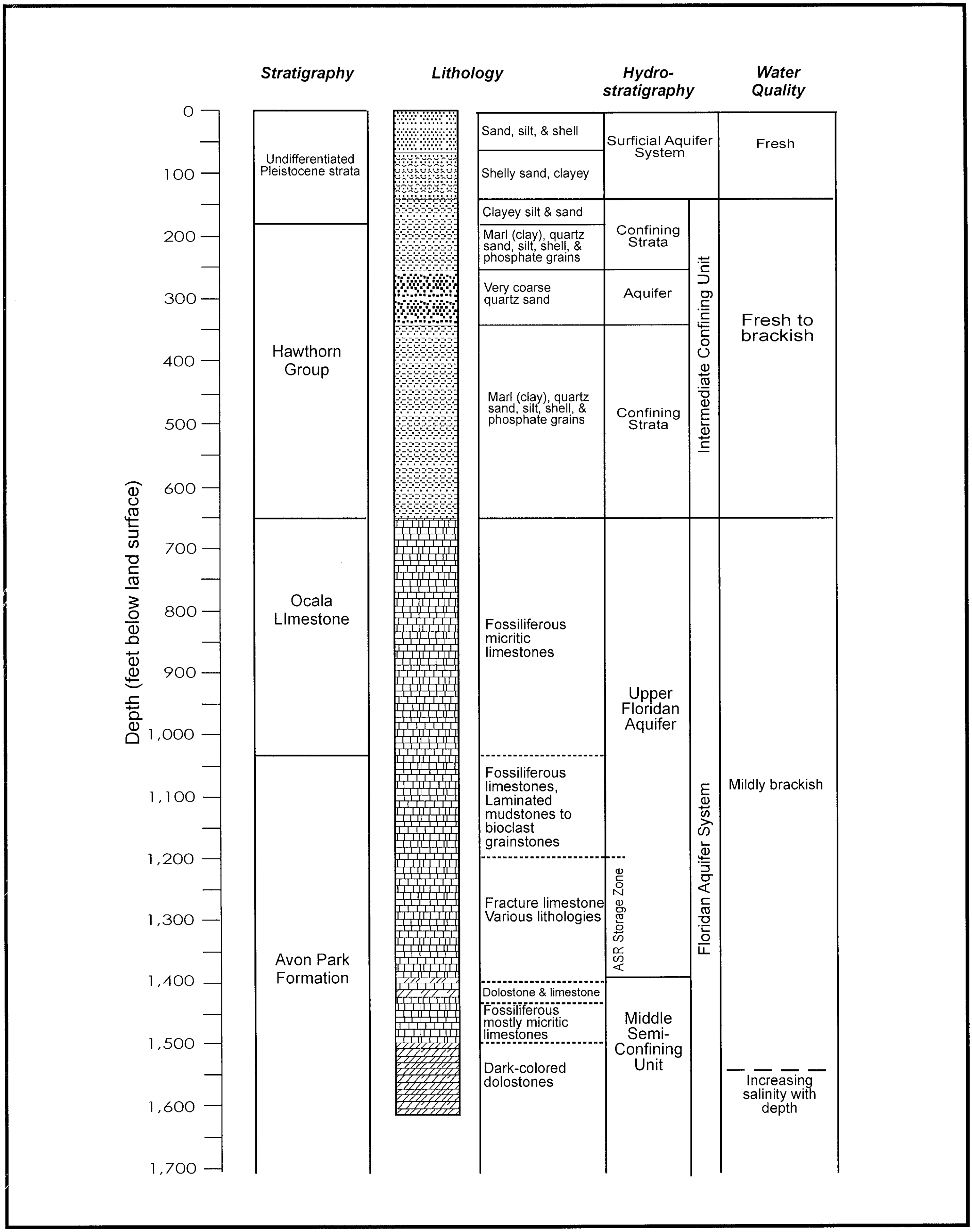


Figure 4-1: Geology and Hydrogeology of the Brighton Reservation ASR Exploratory Well.

Very coarse-grained quartz sand was encountered from approximately 255 ft bls to 345 ft bls. The quartz grains have diameters mostly in the 1 to 3 millimeter range. The very coarse sand unit is readily identifiable on the natural gamma ray log by its low gamma ray activity (**Figure 4-2**) and on the elemental capture spectrometer (ECS) log by a relatively high silicon and low aluminum and calcium concentration, which indicates a high ratio of quartz to clay and carbonate minerals.

Clayey silts and sands, and fossiliferous marls are present from 345 ft bls to approximately 650 ft bls. Some sandstone is also present from approximately 620 to 650 ft bls. The strata from 345 ft bls to 650 ft bls has a variable phosphate content (typically between 1% and 5%). The phosphate occurs mainly in the form of sand and silt-sized grains and, much less commonly, larger fossil fragments (fish teeth and bone fragments).

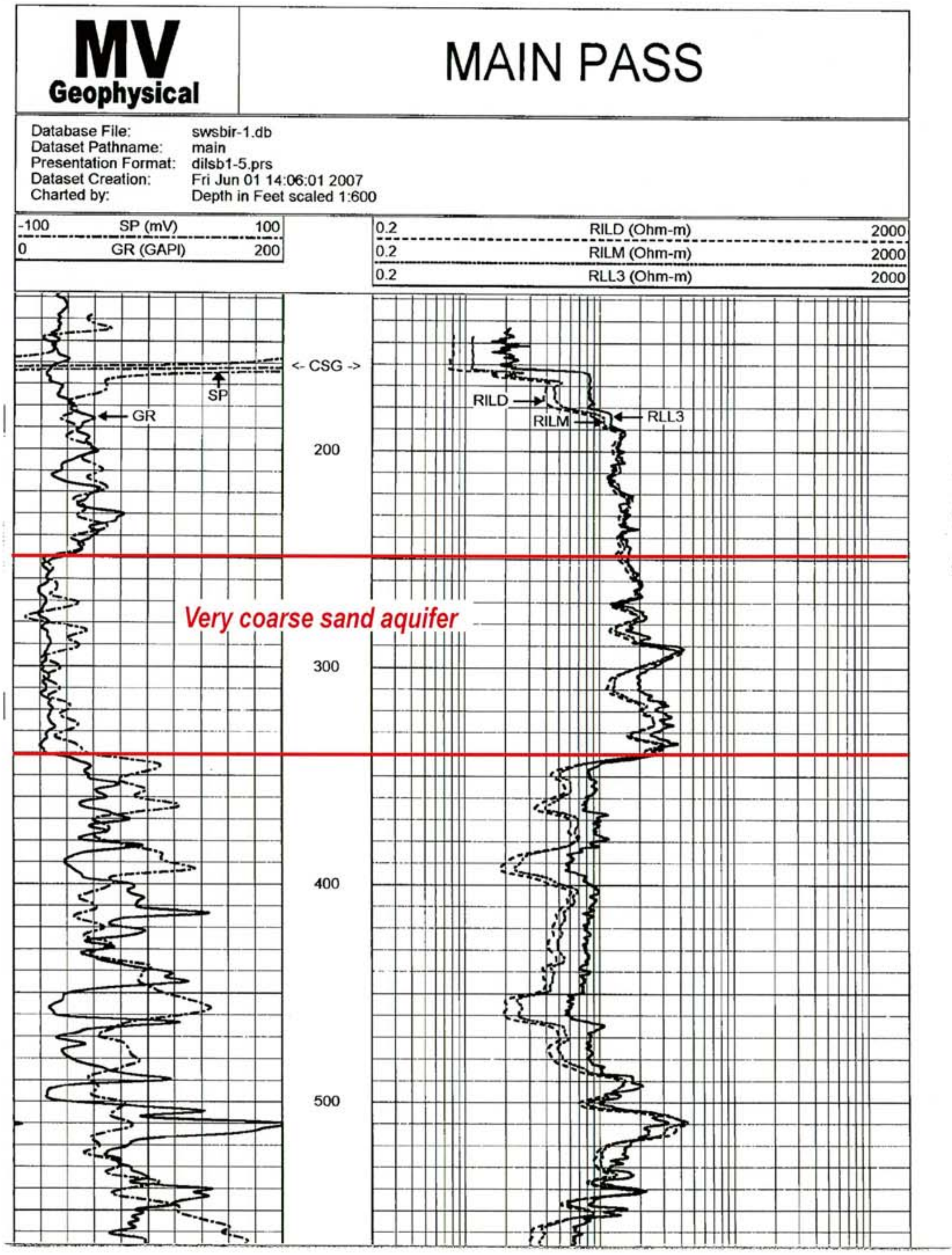
Ocala Limestone

The top of the Ocala Limestone (Upper Eocene) occurs at approximately 650 ft bls and is marked by a pronounced downhole lithologic change from gray and greenish gray clayey strata to light colored (yellowish gray) fossiliferous limestone. The limestones of the Ocala Limestone are relatively pure, and the top of the formation can be identified by a pronounced downhole decrease in natural gamma ray activity. The contact between the Hawthorn Group and Ocala Limestone is a major, regional unconformity. The Arcadia Formation of the Hawthorn Group and the Suwannee Limestone were not present in the Brighton Reservation ASR exploratory well.

With reference to the limestone classification scheme of Dunham (1962), the limestones of the Ocala Limestone are texturally composed mostly of mudstones to packstones. The limestones are very fine-grained and generally contain abundant lithified carbonate mud (micrite). Foraminifera are common, particularly large discoid forms such as *Lepidocyclina, sp.* The limestones are soft to moderately hard and have low macroporosities (visible porosity) and apparent hydraulic conductivities. The low density of dry samples indicate that the limestones have a relatively high total porosity (microporosity).

The Schlumberger porosity logs confirm that the Ocala Limestone has a high total porosity, mostly in the range of 40 to 45%. The nuclear magnetic resonance (NMR) log indicates three main permeability zones within the Ocala Limestone. The upper part of the formation (~ 652 to 744 ft bls) has permeabilities in the 1,000 to 3,000 millidarcies (md) range, which corresponds to hydraulic conductivities of 2.7 to 8.1 ft/day. The NMR log estimates permeability, whereas aquifer testing results quantify hydraulic conductivity. The NMR log permeabilities were converted to hydraulic conductivity values using the approximation of 1 md = 0.0027 ft day (1 darcy = 2.7 ft/day)

The middle part of the formation, from 652 to 990, has a low permeability in the range of 50 to 200 md (0.14 to 0.54 md). The magnetic resonance flow log indicates minimal flow from this interval. The lowermost part of the formation (990 to 1,036 ft bls) has distinctly higher permeabilities in the 1,000 to 3,000 millidarcies (md) (2.7 to 8.1 ft/day)



MV Geophysical

MAIN PASS

Database File: swsbir-1.db
Dataset Pathname: main
Presentation Format: dilsb1-5.prs
Dataset Creation: Fri Jun 01 14:06:01 2007
Charted by: Depth in Feet scaled 1:600

Figure 4-2: Geophysical Logs of the Very Coarse Sand Aquifer in the Brighton Reservation ASR Exploratory Well.

range. The NMR hydraulic conductivities are roughly in line with the average hydraulic conductivity value calculated from the aquifer test no. 1 data.

The formation micro-imager (FMI) log and bore hole video indicate that the Ocala Limestone strata are horizontally bedded and bioturbated, and that there is minimal fracturing. Below 1,205 ft bls, fine-scale laminations become more pronounced on the FMI log. The elemental capture spectrometer (ECS) log shows very well the major drop in clay content across the boundary between the Hawthorn Group and Ocala Limestone. The ECS log indicates that the Ocala Limestone is composed almost entirely of calcite, with minimal impurities.

Avon Park Formation

The top of the Avon Park Formation in the Brighton Reservation ASR exploratory well occurs at approximately 1,036 ft bls. The boundary between the Ocala Limestone and Avon Park Formation is often subtle, particularly in wells. The top of the formation is indicated by the first occurrence of common, distinctive cone-shaped (dictyoconid) foraminifera and centimeter-sized echinoids belonging to the species *Neolaganum dali,* which was found by Vernon (1951) to be very abundant in the upper 50 feet of the Avon Park. The contact between the Ocala Limestone and Avon Park Formation can also commonly be recognized by a downhole increase in natural gamma ray activity and difference in resistivity.

The Avon Park Formation in the Brighton Reservation ASR exploratory well is a heterogeneous unit that is composed predominantly of limestones from 1,036 ft bls to 1,386 ft bls. Interbedded limestone and dolostone is present between approximately 1,386 and 1,429 ft bls. The Avon Park Formation from approximately 1,496 ft bls to the bottom of the exploratory well consists predominantly of dolostone.

The limestones of the Avon Park Formation consist of interbedded laminated mudstones and peloidal fossil (bioclast) wackestones, packstones and grainstones. Porous bioclast grainstones containing abundant foraminifera (particularly dictyoconids), which is a typical productive Avon Park Formation lithofacies in South Florida, is particularly common between approximately 1,200 and 1,317 ft bls.

Thin section photomicrographs of representative samples of the Avon Park Formation are provided in Appendix B. All lithologies have high porosities. The grainstones (cemented carbonate sands) have large interconnected intergranular porosities, which would result in them having relatively high matrix permeabilities. Foraminifera and peloids (carbonate mud clasts of uncertain origin) are the most common grain types. Iron sulfide minerals, such a pyrite, are generally sparse. Pyrite was found rarely within some fossils and was also associated with organic-rich layers in laminated mudstones. Iron sulfide minerals are the likely source of the arsenic that has leached into the stored water in some ASR systems. However, not all iron sulfide minerals are enriched with arsenic and other metals.

The Avon Park Formation dolostones are dark-colored (dark yellowish brown, medium yellowish brown, to dusky yellowish brown) and range from dense to, less commonly, highly porous (microsucrosic). The pore types include intercrystalline and vuggy. Dolostones are readily recognizable on geophysical logs by their higher resistivity than adjacent limestones.

The Schlumberger porosity logs indicate that uppermost 170 feet of the Avon Park Formation consists of limestones with porosities mostly in the range of 28% to 42%. NMR permeabilities are variable, ranging from 600 to 6,000 md (1.62 to 16.2 ft/day). The ECS log indicates that the Avon Park Formation limestones above 1,200 are relatively pure, with minor quartz and clay minerals locally present.

The FMI log shows that the Avon Park Formation from 1,036 ft bls to about 1,135 ft bls consists of horizontally laminated limestones. Laminations and bedding is evident on several scales. Bedding of variable resistivity is present on a scale of 1 to 3 feet. Some individual beds contain fine-scale laminations on a scale of less the 0.1 feet or less.

Fracturing, not associated with borehole enlargement, is evident on the FMI log from 1,075 to 1,096 ft bls. Some hairline fracturing is present down to 1,110 ft bls. Larger scale fracturing is evident on the FMI log from 1,167 to 1,190 ft bls.

The strata between approximately 1,203 and 1,398 ft bls consists of zones of alternating fractured intervals with enlarged boreholes (20 to 36-inches) and less fractured strata (borehole diameters ≤ 14-inches). The porosities of the unfractured limestones are mostly in the range of 30% to 42%. NMR permeabilities range mostly from 500 to 3,000 md (1.4 to 8.1 ft/day). The intervals of borehole enlargement detected by the geophysical logs and observed in the borehole video are not cavities penetrated during drilling, but rather fractured zones in which the cavities formed after drill bit penetration. The cavities are typically bounded by planar fracture surfaces and formed as the result of local collapse/spalling of the borehole wall. Fractures are also enlarged during drilling. The actual apertures for the most part appear to be relatively narrow.

The ECS log shows that non-carbonate minerals are more abundant in the 1,205 and 1,398 ft bls than above, but still below 5% for the bulk of the interval. Several thin zones are present (1225, 1231, 1239, and 1289 ft bls) that contain 18% to 50% non-carbonate minerals, mostly quartz and subsidiary clays. The ECS pyrite indicator indicates pyrite is associated with the non-carbonate clay-rich layers.

A pronounced downhole decrease in borehole diameter (≤ 11 inches) occurs below 1,398 ft bls, which reflects an increase in rock hardness and decrease in fracturing. Fractured zones with associated cavity development during drilling are present between 1,398 and 1,425 ft bls and, to a lesser degree, between 1,450 and 1,490 ft bls.

4.2 Hydrogeology of ASR Exploratory Well Site

Three main hydrostratigraphic units were penetrated by the Brighton Reservation ASR exploratory well. The hydrostratigraphic units are, in descending order, (1) Surficial Aquifer System, (2) Intermediate Confining Unit, and (3) Floridan Aquifer System.

Surficial Aquifer System

The Surficial Aquifer System in Florida is defined as the "permeable hydrogeologic unit contiguous with land surface that is comprised principally of unconsolidated clastic deposits" (Southeastern Geological Society Ad Hoc Committee, 1986). The Surficial Aquifer System comprises all materials from the water table to the top of the Intermediate Confining Unit. The base of the Surficial Aquifer System is marked by a significant decrease in the average hydraulic conductivity relative to the Surficial Aquifer System.

The base of the Surficial Aquifer System in the Brighton Reservation ASR exploratory well occurs at approximately 143 ft bls, which corresponds to the top of the olive gray clayey silt and sands of the undifferentiated Pleistocene and Pliocene strata. No data were collected on the hydraulics and water quality of the Surficial Aquifer System. The Surficial Aquifer System is expected to contain freshwater and, based on its very fine-grained lithology, is expected to have a low to moderate hydraulic conductivity.

Intermediate Confining Unit

The Intermediate Confining Unit is defined as including "all rocks that lie between and collectively retard the exchange of water between the overlying Surficial Aquifer System and the underlying Floridan Aquifer System" (Southeastern Geological Society Ad Hoc Committee, 1986).

The Intermediate Confining Unit, particularly in southwestern Florida, may contain one or more aquifers that contain freshwater or brackish water and are used for potable or irrigation water supply. An unexpected discovery in the exploratory well program was the presence of a very coarse sand aquifer between approximately 250 and 340 ft bls. Based on comparisons with compositionally similar units in Hendry County, the very coarse sand aquifer is expected to be very productive, with potential well yields of 0.5 to 1.0 Mgd (or even greater). No information was obtained on the water quality of the very coarse sand aquifer. The aquifer is expected to contain freshwater based on regional hydrogeology.

The vertical and horizontal extents of the very coarse sand aquifer on the Brighton Reservation are also unknown. In general, coarse sand units in South Florida are channel deposits that are elongated in the north-south direction (roughly parallel to the axis of the Florida peninsula) and may have limited extent (several miles) in the east-west direction.

Floridan Aquifer System

The Floridan Aquifer System is one of the most productive aquifers in the United States and underlies all of Florida and parts of Georgia and South Carolina for a total area of about 100,000 square miles. The Floridan Aquifer System consists of an extensive sequence of thickly bedded Tertiary-aged limestones and, less abundantly, dolostones that are connected to varying degrees. The Floridan Aquifer System is heterogeneous with respect to hydraulic conductivity (transmissivity) with intervals of high transmissivity (hydraulic conductivity multiplied by thickness) separated by intervals of rock with very low hydraulic conductivity. The Floridan Aquifer System in South Florida is subdivided into three main units based on their relative permeabilities: the Upper Floridan Aquifer, the Middle Confining Unit, and the Lower Floridan Aquifer.

The limestones present between approximately 650 and 1,200 ft bls have a low to moderate hydraulic conductivity. The artesian flow of the well when open from 650 to 936 ft bls was approximately 120 gpm, and the transmissivity estimated from a constant rate flow test was approximately 280 ft^2/day.

The artesian flow of the well increased dramatically below approximately 1,200 ft bls. The estimated flow rate was on the order of 3,000 gpm, based on the height of the water jet above the casing. This methodology for estimating transmissivity is discussed by Driscoll (1986; Appendix 16.F, page 1024). The flowmeter log run by MV Geophysical indicates that a major flow zone is present in the well between 1,200 and 1,210 ft bls. The large response on the flowmeter log between 1,200 to 1,210 ft bls reflects both an increase in flow as well as a downhole increase in borehole diameter. The strata below the 1,200 to 1,210 ft bls flow zone was not stressed during the running of the flowmeter log because of the great flow of the zone. Deeper flow zones may not, therefore, be evident on the flowmeter log.

The proposed ASR storage zone extends from approximately 1,200 to 1,400 ft bls. The zone consists of porous limestone with open fractures, which were enlarged during drilling. The fracture zones are readily identifiable on the caliper, porosity, and NMR logs and borehole video. The Schlumberger NMR flow profile log indicates that approximately 80% of the flow enters the well between 1,200 and 1,384 ft bls. The flow is more evenly distributed throughout the interval that is suggested by the flowmeter log. Another 10% of the flow enters between 900 and 1,200 ft bls.

The strata from 1,400 to 1,618 ft bls consists predominantly of micritic limestones (mudstones to packstones) and dolostones, which appear to have relatively low hydraulic conductivities. Water quality data (Section 4-3) indicate minimal, if any, contribution to the well flow below 1,400 ft bls. The deeper strata (below 1,400 ft bls) contains progressively more saline water, but the water flow from the well when opened to total depth (1,618 ft bls) has essentially the same salinity as the water flow from 1,200 to 1,400 ft bls. The base of the Upper Floridan Aquifer and top of the Middle Confining Unit is thus interpreted to be located at approximately 1,400 ft bls, which is consistent with the regional hydrogeologic analysis of Miller (1986).

4.3 Water Quality Data

Within the Floridan Aquifer System of Florida, salinity usually increases with depth, reaching seawater values in the lower part of the aquifer system. The chloride concentration data (**Figure 4-3**) of samples collected during dual-tube rotary drilling of the Brighton Reservation ASR exploratory well have an inverted profile, with chloride concentrations in the Upper Floridan Aquifer actually decreasing with depth. Chloride concentrations from 976 to 996 ft bls ranged from 1,080 to 1,420 mg/L. The concentration dropped to the 400 to 740 mg/L range from 1,016 to 1,196 ft bls, and was mostly in the 740 to 780 mg/L range from 1,196 to 1,416 ft bls. Chloride concentration steadily increased with depth from 1,516 to 1,616 ft bls, reaching a maximum recorded value of 3,960 mg/L at 1,516 ft bls.

The regulatory base of the Underground Source of Drinking Water (USDW), defined by the 10,000 mg/L total dissolved solids isopleth, was not penetrated by the exploratory well. The base of the USDW is estimated to occur at approximately 1,650 ft bls at the Brighton Reservation ASR exploratory well site, by extrapolating the trend of increase in chloride concentration with depth and using the seawater chloride to TDS ratio (1 :1.8).

The water samples from the 640 to 1,410 ft bls meets USEPA and State of Florida primary and secondary drinking water standards with the except of the salinity correlated parameters (chloride, sodium, and total dissolved solids). The chloride concentration of the initial and final samples collected during aquifer test no. 5, performed on the completed (back-plugged) well was 900 mg/L, which largely reflects the composition of the water produced from the proposed ASR storage zone (1,200 to 1,400 ft bls) and with a lesser contribution from overlying strata. The actual chloride concentration of the proposed ASR storage zone likely falls between the aquifer test no. 5 concentration (900 mg/L) and the concentrations measured in the dual-tube rotary drilling water samples collected from 1,200 to 1,400 ft bls.

The salinity profile obtained from the Schlumberger ECS log shows that salinity increases below 1,330 ft bls. The increase in salinity was not detected in the water samples collected during dual-tube rotary drilling. The salinity of the produced water could therefore be reduced (1) casing off the strata above 1,000 ft bls, which contains more saline water, and (2) limiting the total depths of wells to less than 1,330 ft bls. Reducing the salinity of the produced water would be an important consideration if the Upper Floridan Aquifer is to be used as a blend water source.

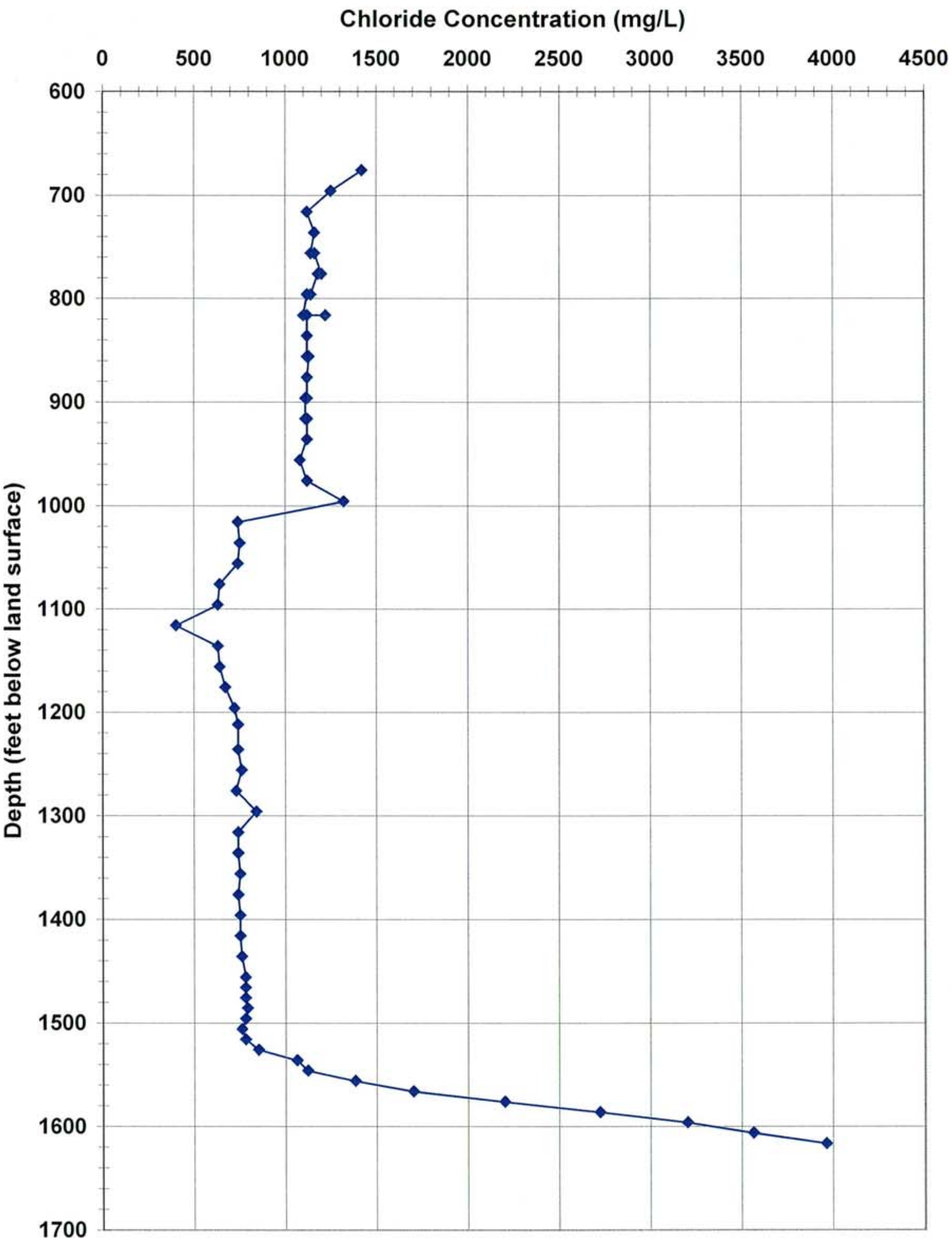


Figure 4-3: ASR Exploratory Well Chloride Concentration Data.

SECTION 5 ASR FEASIBILITY ASSESSMENT

ASR is considered to be feasible at a site if the local hydrogeologic conditions will allow for a system to be operated at an acceptable recovery efficiency and have economic well capacities. Recovery efficiency is defined herein as the ratio of the volume of usable water recovered to the total injected volume for an operational cycle. The term "usable" allows for some mixing of native and injected water and also implies that fluid-rock interaction has not resulted in a deterioration of water quality, such that the water is unfit for its intended use.

There is no universal value for what constitutes an "acceptable" recovery efficiency. Typically values of 70% of greater are considered good. However, an ASR system with a recovery efficiency of less than 70% may still be a valuable water management tool if it provides additional water during high demand or low supply periods at a lower cost than other supplemental water supply options.

The following hydrogeologic conditions are favorable for high recovery efficiencies:

- Storage zone transmissivity suitably high enough to allow for injection at target rate with acceptable wellhead pressures,
- Transmissivity not so great so as to allow for rapid lateral migration of injected water,
- Effective vertical confinement above and below storage zone,
- Low to moderate storage zone salinity,
- Low degree of storage zone heterogeneity with respect to hydraulic conductivity,
- Predominance of matrix flow versus fracture and solution conduit flow,
- Low regional hydraulic gradients, and
- Geochemical compatibility of injected water with storage zone water and rock.

Not all of the above factors need to be present at their optimal values for an ASR system to be successful in meeting the requirements and expectations of the owner or operator of the system. ASR systems that use storage zones with low salinities are more "forgiving" in that considerable mixing of the injected and stored water can occur before the recovered water exceeds an applicable water quality threshold. Low salinities are also favorable for high recovery efficiencies because it results in minimal buoyancy-induced migration of stored freshwater.

The low salinity (≈ 750 to 900 mg/L chloride concentration) of the proposed Brighton Reservation ASR storage zone is favorable for high (> 70%) recovery efficiencies. The system could accommodate moderate mixing of injected water and native groundwater.

For example, a mixture of 76% injected water with a chloride concentration of 40 mg/L (approximate average C-41 Canal water value) with 24% native water with a chloride concentration of 900 mg/L would result in a recovered water chloride concentration of 250 mg/L (the secondary drinking water standard). The native water mix would be 42% for a blend of 400 mg/L, which would be suitable for many irrigation uses, particularly on a short-term basis.

The 1,200 to 1,400 ft bls interval has an adequate transmissivity to support ASR wells with capacities in the 3 to 5 Mgd range. All other factors being equal, large capacity wells reduce overall ASR system costs (per Mgd of capacity) by decreasing the number of wells needed and thus the costs for well construction, pumps, wellheads, and associated above ground infrastructure.

The proposed ASR storage zone has a large component of fracture flow versus nitric flow, which is generally unfavorable for high recovery efficiencies. Matrix flow refers to flow through the internal pore system of the bulk rock or sediment, as opposed through flow conduits, such as fractures and solution cavities. Fracture flow adversely impacts recovery efficiency in several manners. First is that the restriction of flow to relatively thin fractures can result in a great horizontal extent of injected fluids. Secondly, the hydraulic conductivity of fractures may also be orders of magnitude greater than that of the aquifer matrix rock, which can result is rapid migration of injected fluid away from ASR wells under prevailing hydraulic gradients. Thirdly, native formation water within the matrix will diffusionally mix with (bleed into) injected freshwater in the fracture systems. Fracture-dominated flow systems will thus tend to experience a relatively high degree of mixing of injected water and native formation water. Nevertheless, the low salinity of the storage zone water should, to a large degree, offset of the adverse impacts of the additional mixing caused by fracturing.

The proposed ASR storage zone is confined above and below by micritic (carbonate mud-rich) limestones, which are expected to provide acceptable vertical confinement. The proposed 1,200 to 1,400 ft bls storage zone would also have a minimum of 100 feet thick buffer above and below before water with a chloride concentration of 1,100 mg/L or greater is encountered.

As was discussed in the desktop study report (Schlumberger Water Services, 2006), the Brighton Reservation is located in an area in which the Upper Floridan Aquifer has low horizontal hydraulic gradients. The 200-foot thickness of the storage zone is also greater than typically used, which may impact recovery efficiencies. The 200-foot thickness would allow for a maximization of system capacities. However, the option is retained of reducing the ASR storage zone thickness in the future by back-plugging the well with cement.

The results of the exploratory well program thus indicate that ASR is likely feasible on the Brighton Reservation. A storage zone is present that has a combination of water quality and apparent aquifer hydraulics that are favorable for high recovery efficiencies.

SECTION 6 REFERENCES

Driscoll, F.G., 1986, Groundwater and Wells, 2nd Edition, Johnson Filtration Systems, 1,089 p.

Dunham, R. J., 1962, Classification of carbonate rocks according to depositional texture. In: Ham, W. E. (ed.), Classification of carbonate rocks: American Association of Petroleum Geologists Memoir, p. 108-121.

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.

Schlumberger Water Services, 2006, Seminole Tribe of Florida Brighton Reservation Aquifer Storage and Recovery Conceptual Design Phase (September 13, 2006).

Southeastern Geological Society Ad Hoc Committee on Florida Hydrostratigraphic Unit Definition, 1986, Hydrogeology Units of Florida: Florida Geol. Survey Special Publication No. 28, 9 p.

Vernon, R.O., 1951, Geology of Citrus and Levy counties: Florida Geol. Survey Bull., v. 33, 256 p.

Appendix A

Geological Log

Geological Log
Brighton Reservation ASR Exploratory Well

Location: Seminole Tribe of Florida Brighton Reservation
North of C-41 Canal, approximately 0.45 miles NW of Harney Pond Road

SW ¼ SW ¼ Section 15, Township 39 South, Range 32 East

Depth (ft bls)	**Lithology**
0 – 5	SAND, very pale yellowish brown (10YR 7/2) to medium yellowish brown (10YR 5/2), quartz, fine-grained, unfossiliferous.
5 – 27	SAND, medium olive gray (5Y 5/1) to olive gray (5Y 4/1), quartz, very fine to fine-grained, unfossiliferous. *Nearly all of material passed through the sample strainer during mud-rotary drilling. Samples were periodically collected by straining mud flow through cloth sample bags.*
27 – 55	SAND and SILT, olive gray (5Y 4/1), quartz, predominantly coarse silt to very fine sand-sized (1/32 to 1/8 mm), sparse to common fossils, which consist of sand-sized fragments of thin-shelled mollusks. Shell becomes more common below about 37 feet. Some coarse quartz sand grains were recovered. *Nearly all of material passed through strainer during mud-rotary drilling. Samples were periodically collected by straining mud flow through sample bags.*
55 – 64	SAND and SHELL, light olive gray (5Y 6/1 to 5/1), quartz, very fine to fine-grained. Fossils consist mostly of millimeter-sized mollusk fragments and include sparse echinoid spines and ossicles. Sparse phosphate grains. Somewhat more clayey below 60 feet (slight change in drilling mud color). *Recovered material consists mostly of shell with minor attached sand. Most of sand passed through strainer.*
64 – 75	SHELLY SAND, CLAYEY, light olive gray (5Y 6/1), quartz, very fine to fine-grained, common millimeter-sized fossils (bivalve fragments), some minor coarser grained quartz (to very coarse sand-sized). *Most of material passed through strainer during mud-rotary drilling. Samples were periodically collected of both the material captured in a strainer and filtered out by allowing the mud to flow through a sample bag.*

Brighton Reservation ASR Exploratory Well

Depth (ft bls)	**Lithology**
75 – 85	SHELLY SAND, CLAYEY, same as above.
85 – 94	SHELLY SAND, CLAYEY, same as above.
94 – 105	SHELLY SAND, CLAYEY, same as above.
105 – 115	SHELLY SAND, CLAYEY, same as above. 1% to 3% phosphate sand. Trace poorly cemented sandstone cuttings.
115 – 124	SHELLY SAND and minor SANDSTONE, medium olive gray (5Y 5/1) to olive gray (5Y 4/1), quartz, silt to fine sand-sized, poorly sorted, abundant shell (mollusk) fragments. SANDSTONE is very poorly cemented. *Most of material passed through strainer.*
124 – 135	SHELLY SAND and minor SANDSTONE, same as above.
135 – 143	SHELLY SAND, CLAYEY, olive gray (5Y 4/1), quartz, silt to very fine sand-sized. Slightly more clayey than above; some clayey, slightly cohesive cuttings recovered.
143 – 148	CLAYEY SILT and SAND, medium olive gray (5 Y 5/1), quartz, silt to very fine sand-sized, common bivalve fragments. Cohesive, more cuttings recovered.
148 – 154	CLAYEY SILT and SAND, olive gray (5Y 4/1 to 5/1) to dark greenish gray (5 GY 4/1 to 5/1), quartz, silt to very fine sand-sized, trace phosphate sand.
154 – 164	CLAYEY SILT and SAND, same as above.
164 – 170	CLAYEY SILT and SAND, same as above.

Top of the Hawthorn Group occurs at approximately 178 ft bls based on a downhole increase in gamma ray activity.

180 – 185	CLAYEY SILT, olive gray (5Y 5/1) to dark greenish gray (5GY 4/1), some minor very fine-grained sand, trace phosphate, calcareous (mild reaction with dilute hydrochloric acid.
185 – 190	CLAYEY SILT, same as above.
190 – 195	CLAYEY SILT, same as above.

Brighton Reservation ASR Exploratory Well

Depth (ft bls)	**Lithology**
195 - 200	CLAYEY SILT, same as above.
200 - 205	CLAYEY SILT, same as above.
205 - 210	CLAYEY SILT, same as above.
210 - 215	CLAYEY SILT, same as above, except for increased shell fragments.
215 - 220	CLAYEY SILT, same as above.
220 - 225	CLAYEY SILT, same as above.
225 - 230	CLAYEY SILT, same as above.
230 - 235	CLAYEY SILT and SAND, olive gray (5Y 5/1) to dark greenish gray (5GY 4/1), much more quartz sand than above (still subsidiary to silt), poorly sorted, very fine to fine-grained, minor thin-shelled bivalve fragments.
235 - 240	CLAYEY SILT and SAND, same as above.
240 - 245	CLAYEY SILT and SAND, same as above.
245 - 250	CLAYEY SILT and SAND, same as above.
250 - 255	CLAYEY SILT and SAND, same as above.
255 - 260	SAND and subsidiary CLAYEY SILT and SAND (same as above). SAND, light olive gray (5Y 6/1), very coarse-grained, rounded, 1% to 2% phosphate sand. May be interbedded with clayey silt and sand, as sample contained pieces of this lithology.
260 - 265	SAND, light olive gray (5Y 6/1), very coarse grained, rounded, 1% to 2% phosphate sand. High apparent permeability.
265 - 270	SAND, light olive gray (5Y 6/1), very coarse grained, rounded, 1% to 2% phosphate sand. Subsidiary CLAYEY SILT and SAND, which could be either interbeds or material from above that fell into hole. High apparent permeability

Depth (ft bls)	**Lithology**
270 - 280	SAND, light olive gray (5Y 6/1 to 5/1), quartz, very coarse to granule-sized (1 to 3 millimeters), rounded, some sandstone grains (same size as quartz), common (2% to 4%) phosphate sand. High apparent porosity and permeability.
280 - 290	SAND, similar to above except finer grained (medium to coarse) and less well sorted.
290 - 300	SAND, same as above.
300 - 310	SAND, same as above.
310 - 320	SAND, similar to above, except coarser grained (very coarse sand to granule-sized; similar to 270 to 280 feet).
320 - 330	SAND, similar to above except somewhat finer grained (very coarse) and less well sorted. Abundant sandstone clasts.
330 - 340	SAND, same as above.
340 - 345	SAND, same as above.
345 - 350	SAND and CLAYEY SILT and SAND (interbedded), light olive gray (5Y 6/1 to 5/1), quartz, very coarse to granule-sized (1 to 3 millimeters), soft, sticky. Abundant fine-grained clay sand and silt grains, finely phosphate (3 to 5%).
350 – 360	SAND and CLAYEY SILT and SAND, same as above.
360 – 370	CLAYEY SILT and SAND, olive gray (5Y 4/1), silt to very fine sand-sized, 4% to 7% phosphate sand, fossiliferous (bivalves fragments), unlithified, low apparent permeability, soft, sticky.. Common (≈ 5%) very coarse quartz sand, rounded, similar to that in overlying sands. *Very coarse sand likely fell into hole from above.*
370 – 375	CLAYEY SILT and SAND, same as above.
375 – 380	CLAYEY SILT and SAND, light olive gray (5Y 6/1), common very fine and fine-grained sand; minor very coarse to granular quartz, soft, sticky. Common (2% to 5%) very fine phosphate, fossiliferous (bivalves).

Brighton Reservation ASR Exploratory Well

Depth (ft bls)	**Lithology**
380 - 390	SILTY and SANDY MARL, light olive gray (5Y 6/1), Common (2% to 4%) phosphate, fossiliferous (5%), bivalves, soft, sticky. Minor very coarse quartz sand.
390 – 400	SILTY and SANDY MARL, olive gray (5Y 4/1 to 5GY 4/1), fossiliferous (10%, bivalves and gastropods), soft, sticky, trace very quartz sand.
400 – 405	SILTY and SANDY MARL, same as above.
405 – 410	CLAYEY SILT and SAND, medium olive gray (5Y 5/1), more quartz and and silt than above, phosphatic (3% to 6%, mostly very fine to fine sand-sized), fossiliferous (bivalves).
410 – 420	CLAYEY SILT and SAND, similar to above except more phosphatic (6% to 10%).
420 – 430	CLAYEY SILT and SAND, similar to above except slightly less phosphatic (4% to 8%).
430 – 440	CLAYEY SILT and SAND, same as above.
440 – 450	CLAYEY SILT and SAND, same as above.
450 – 452	CLAYEY SILT and SAND, same as above.
452 – 455	SANDY and SILTY MARL, light olive gray (5Y 6/1), phosphatic (3% to 5%), fossiliferous (3% to 5%, bivalves), matrix appears to be dolomitic (dolosilt), strong hydrochloric acid reaction.
455 – 460	SANDY and SILTY MARL, same as above.
460 – 465	SANDY and SILTY MARL, same as above.
465 – 475	SILTY MARL, medium olive gray (5Y 6/1), phosphatic (1% to 2%), fossiliferous (2% to 5%, bivalves), matrix appears to be dolomitic (dolosilt), strong hydrochloric acid reaction.
475 – 480	SANDY/SILTY MARL, light olive gray (5Y 6/1) phosphatic (3% to 5%), fossiliferous, strong hydrochloric acid reaction.
520 – 530	FOSSILIFEROUS MARL, same as above.

Depth (ft bls)	**Lithology**
530 – 540	FOSSILIFEROUS MARL, same as above, except slightly more phosphate (2% to 3%).
540 – 550	SILTY and SANDY FOSSILIFEROUS MARL, light olive gray (5Y 6/1), 10% to 20% fossil fragments (mostly bivalves), 2% to 3% phosphate sand.
550 – 560	SILTY and SANDY FOSSILIFEROUS MARL, same as above.
560 – 570	FOSSILIFEROUS CLAYEY SAND, medium to olive gray (5Y 5/1 to 4/1), darker than above, abundant quartz (silt and very fine to very coarse sand-sized, poorly sorted), phosphate (2% to 3%), abundant fossils (bivalves).
560 – 570	FOSSILIFEROUS CLAYEY SAND, same as above.
570 – 580	FOSSILIFEROUS CLAYEY SAND, same as above.
580 – 590	FOSSILIFEROUS CLAYEY SAND, same as above.
590 – 600	FOSSILIFEROUS CLAYEY SAND, same as above.
600 – 610	FOSSILIFEROUS CLAYEY SAND, same as above.
610 – 620	FOSSILIFEROUS CLAYEY SAND, same as above.
620 – 630	FOSSILIFEROUS CLAYEY SAND and subsidiary SANDSTONE, light olive to medium gray (5Y 6/1 to 5/1), lighter than above, abundant quartz (silt and very fine to very coarse sand-sized, poorly sorted), phosphate (2% to 3%), abundant fossils (bivalves). Interval may contain more sandstone than in sample, with much of the finer material coming from above.
630 – 640	FOSSILIFEROUS CLAYEY SAND and SANDSTONE, same as above.

Note: Geophysical log indicates that the top of the Floridan aquifer occurs at approximately 650 ft bls.

655 - 660	LIMESTONE, yellowish gray (5Y 8/1), fossil bioclast grainstone, well cemented, hard. Fossils include foraminifera and bivalves. Low moldic and total porosity and apparent permeability. Trace pyrite (black material).

Depth (ft bls)	**Lithology**
660 – 664	LIMESTONE, yellowish gray (5Y 8/1), bioclast/peloid packstone (or grainstone). Grains are silt to very fine sand-sized. Very soft (friable), low macroporosity and apparent permeability.
664 – 668	LIMESTONE, same as above.
668 – 676	LIMESTONE, yellowish gray (5Y 8/1), fossil bioclast/peloid packstone to wackestone. Soft, low macroporosity, but apparent high porosity (low density), low apparent permeability. Fossils include bivalves.
676 – 680	LIMESTONE, same as 664 to 668 ft bls.
680 – 696	LIMESTONE, yellowish gray (5Y 8/1), fossil bioclast/peloid packstone/grainstone. Common fossils include molds of bivalves and corals. Moderate hardness, low macroporosity and apparent permeability.
696 – 700	LIMESTONE, same as above, except for some intervals with abundant fossils and a high apparent permeability. Trace pyrite (black material).
700 - 704	LIMESTONE, yellowish gray (5Y 8/1), fossil bioclast/peloid grainstone. Moderate hardness, low to medium macroporosity and apparent permeability. Fossils include bivalves and gastropods.
707 – 710	LIMESTONE, yellowish gray (5Y 8/1), fossil mudstone/wackestone. Soft to moderately hard, low macroporosity and apparent permeability. Abundant large flat discoidal foraminifera (*Lepidocyclina* sp. ?). *Typical Ocala Limestone foraminifera fauna.*
710 – 716	LIMESTONE, same as above.
716 – 724	LIMESTONE, yellowish gray (5Y 8/1), fossil mudstone, soft, low macroporosity and apparent permeability. Matrix may be peloidal.
724 – 736	LIMESTONE, same as above. Large discoidal foraminifera and bivalves.
736 - 746	LIMESTONE, same as above.
746 – 756	LIMESTONE, yellowish gray (5Y 8/1), fossil wackestone and mudstone, soft, low macroporosity and apparent permeability. Matrix may be peloidal. Abundant large discoidal foraminifera (including *Lepidocyclina*), and gastropods and bivalves.

Depth (ft bls)	Lithology
756 – 764	LIMESTONE, yellowish gray (5Y 8/1), fossil mudstone, soft, very low macroporosity and apparent permeability. Chalky appearing when dry. Low density, which suggests a high total (micro) porosity.
764 – 786	LIMESTONE, same as above.
786 – 796	LIMESTONE, same as above.
796 – 816	LIMESTONE, same as above.
816 – 836	LIMESTONE, same as above, except common gastropods molds in places.
836 – 857	LIMESTONE, same as above.
857 – 876	LIMESTONE, same as above.
876 – 896	LIMESTONE, same as above.
896 – 936	LIMESTONE, same as above.
936 – 964	LIMESTONE, same as above.
964 – 982	LIMESTONE, yellowish gray (5Y 8/1), fossil mudstone to wackestone, minor (1%) black material (pyrite), bioturbated, matrix apprears to be silty (peloidal). Soft, low macroporosity and apparent permeability.
982 – 996	LIMESTONE, yellowish gray (5Y 8/1), fossil bioclast grainstone, very hard, moderate macroporosity (moldic), low permeability. Fossils includes gastropods, bivalves, and small foraminifera.
996 – 1028	LIMESTONE, yellowish gray (5Y 8/1), variable lithologies, fossil/bioclast grainstone to fossil mudstone, moderate hardness, variable porosity and apparent permeability. Fossils includes gastropods, bivalves, and small foraminifera.
1028 - 1036	LIMESTONE, yellowish gray (5Y 8/1), fossil mudstone, moderate hardness, very low macroporosity and apparent permeability. Chalky appearance when dry.

Increase in gamma ray activity and presence of dictyconid foraminifera and Neolaganum dali? echinoids suggests that the top of the Avon Park Formation occurs at approximately 1036 feet.

Depth (ft bls)	Lithology
1036 – 1063	LIMESTONE, yellowish gray, bioclast grainstone or packstone, bioclasts are mostly fine to medium sand-sized. Mostly hard, moderate porosity and apparent permeability. Minor small echinoids (1049-1056; *Neolaganum dali*?) and trace dictyoconid foraminfera,
1963 – 1083	LIMESONE, same as above, except some mudstone layers.
1083 – 1086	LIMESTONE, light olive gray (5Y 7/1), mudstone, moderate hardness, very low macroporosity and apparent permeability. Low density
1086 – 1096	LIMESTONE, yellowish gray (5Y 8/1), variable lithologies, bioclast grainstone to less commonly fossil mudstone. Mudstones have very low macroporosity and apparent permeability. Grainstones have a moderate to high macroporosity and moderate apparent permeability.
1096 – 1106	LIMESTONE, yellowish gray (5Y 8/1), mudstone to bioclast grainstone, similar to above.
1106 – 1116	LIMESTONE, yellowish gray (5Y 8/1), fossil peloid packstone/grainstone. Moderate hardness, low macroporosity and apparent permeability. Low density (high total porosity). Matrix may be peloidal (silt to very fine sand-sized). Fossils include small echnoids and foraminifera.
1116 – 1123	LIMESTONE, yellowish gray (5Y 8/1) to white (N9), variable lithologies, fossil bioclast/peloid mudstone to packstone (micritic lithologies). Soft to moderate hardness, low macroporosity and apparent permeability. Chalky appearance when dry. Mudstones are laminated.
1123 – 1153	LIMESTONE, similar to above.
1153 - 1156	LIMESTONE, yellowish gray (5Y 8/1) clasts in a pale yellowish brown (10YR 6/2) matrix, fossil intraclast wackestone, moderate hardness, low macroporosity and apparent permeability. Fossils include foraminifera. Darker matrix may be very finely dolomitic.
1156 – 1160	LIMESTONE, yellowish gray (5Y 8/1), fossil mudstone/wackestone, moderate hardness, low macroporosity and apparent permeability.

Depth (ft bls)	**Lithology**
1160 – 1168	DOLOSTONE, very pale yellowish brown (10YR 7/1), fossil intraclast wackestone. Dolomite is microsucrosic, finely porous (intercrystalline and moldic), moderate porosity and apparent permeability.
1168 – 1172	LIMESTONE, yellowish gray (5Y 8/1), bioclast grainstone/packstone and laminated mudstone, moderate hardness, low macroporosity and apparent permeability.
1172 – 1176	LIMESTONE, yellowish gray (5Y 8/1), mixed lithologies, mudstone to more abundant bioclast packstone and grainstone, moderate hardness, low macroporosity and apparent permeability. Packstones and grainstone contain common dictyoconid foraminifera.
1176 - 1180	LIMESTONE, same as above.
1180 – 1182	LIMESTONE, same as above.
1182 – 1184	LIMESTONE, yellowish gray (5Y 8/1), mostly bioclast grainstone and packstone, generally moderate hardness, low to moderate macroporosity and apparent permeability. Common (1% to 2%) dictyoconid foraminifera.
1184 – 1192	LIMESTONE, yellowish gray (5Y 8/1), mixed lithologies, mudstone to more abundant bioclast packstone and grainstone, moderate hardness, low macroporosity and apparent permeability.
1192 – 1196	LIMESTONE, yellowish gray (5Y 8/1), variable lithologies, interbedded mudstones and porous bioclast grainstones. Some vuggy samples. Variable macroporosity (0 to 30%) and apparent permeability. Vuggy samples have a very high permeability and hardness.
1196 – 1200	LIMESTONE, very pale yellowish brown (10YR 7/2), mixed lithologies, mostly bioclast/peloid grainstone, subsidiary fossil/bioclast wackestone.
1200 - 1204	LIMESTONE, yellowish gray (5Y 8/1), partially dolomitized bioclast grainstone/packstone, moderate hardness, low to moderate macroporosity and apparent permeability. Abundant foraminifera, including dictyoconids.
1204 – 1208	DOLOMITIC LIMESTONE and CALCAREOUS DOLOSTONE, very pale yellowish brown (10YR 7/2) to medium yellowish brown (10YR 5/2). Dolomite ranges from scattered rhombs to dense mosaics, crystal

Depth (ft bls)	**Lithology**
	size 125 to 250 µm. Generally low to moderate macroporosity and apparent permeability.
1208 – 1212	LIMESTONE and CALCAREOUS DOLOSTONE. LIMESTONE, yellowish gray, fossil wackestone to packstone, generally low to moderate macroporosity and apparent permeability CALCAREOUS DOLOSTONE, same as above.
1212 – 1214	LIMESTONE and DOLOSTONE, same as above.
1214 – 1220	LIMESTONE, very pale yellowish brown (10YR 7/2), bioclast grainstone, moderate hardness, moderate to macroporosity and apparent permeability. Fossils include foraminifera (including dictyoconids) and bivalves.
1220 – 1224	LIMSETONE, yellowish gray (5Y 8/1), bioclast grainstone, same as above, locally vuggy. Subsidiary fossil peloid packstone, low to moderate macroporosity and apparent permeability.
1224 – 1230	LIMESTONE and subsidiary DOLOSTONE, yellowish gray (5Y 8/1), mixed lithologies, mudstone to bioclast grainstone, moderate hardness, variable porosity and apparent permeability. DOLOSTONE, microsucrosic.
1230 – 1236	LIMESTONE, yellowish gray (5Y 8/1), bioclast fossil mudstone and wackestone, moderate hardness, low macroporosity and apparent permeability, matrix may be peloidal.
1236 – 1249	LIMESTONE, yellowish gray (5Y 8/1), bioclast grainstone with vuggy porosity, high apparent permeability. Micritic lithologoies (mudstone to packstone) with low macroporosities and apparent permeabilities, moderate hardness.
1249 – 1256	LIMESTONE, yellowish gray (5Y 8/1), bioclast/peloid packstone/grainstone and mudstone. Moderate hardness, low (mostly) macroporosity. Mostly micritic lithologies.
1256 - 1266	LIMESTONE, same as above.
1266 – 1276	LIMESTONE, yellowish gray (5Y 8/1), bioclast grainstone, moderate hardness, high macroporosity and apparent permeability.
1276 - 1281	LIMESTONE, very light olive gray (5Y 7/1), bioclast grainstone, hard, well-cemented, low macroporosity and apparent permeability.

Depth (ft bls)	Lithology
1281 – 1288	LIMESTONE, yellowish gray (5Y 8/1), bioclast mudstone to packstone (micritic lithologies), low macroporosity and apparent permeability. Mudstones are laminated.
1288 – 1296	LIMESTONE, yellowish gray (5Y 8/1), mixed lithologies, bioclast/peloid grainstone to (less common) laminated mudstone. Grainstones have high intergranular porosities and moderate to high apparent permeabilities. Micritic lithologies are tight.
1296 – 1302	LIMESTONE, same as above.
1302 – 1307	LIMESTONE, yellowish gray (5Y 8/1), bioclast/peloid packstone/grainstone, fine-grained, moderate hardness, moderate macroporosity (intergranular) and apparent permeability.
1307 – 1316	LIMESTONE, yellowish gray (5Y 8/1), mixed lithologies, mudstone to bioclast grainstone, moderate hardness, low to moderate macroporosity and apparent permeability.
1316 – 1317	LIMESTONE, very pale orange (10YR 8/2) to very pale yellowish brown (10YR 7/2), laminated mudstone/wackestone and bioclast grainstone/packstone, moderate hardness, low macroporosity and apparent permeability. Low density, which suggests a high total (micro) porosity.
1317 – 1322	LIMESTONE, yellowish gray (5Y 8/1), fossil (bioclast) mudstone to packstone (micritic lithologies), chalky appearance when dry, moderate hardness, low macroporosity and apparent permeability.
1322 – 1326	LIMESTONE, yellowish gray (5Y 8/1), bioclast peloid packstone/grainstone, low to moderate macroporosity (intergranular) and apparent permeability
1326 -1333	LIMESTONE, yellowish gray (5Y 8/1), mixed lithologies (mostly micritic), fossil bioclast mudstone to packstone, hard, low macroporosity and apparent permeability.
1333 - 1336	LIMESTONE, yellowish gray (5Y 8/1) to less commonly medium yellowish brown (10YR 5/2), various lithologies (mostly micritic), mudstone to bioclast grainstone and intraclast packstone, moderate hardness, low macroporosity and apparent permeability.
1336 – 1349	LIMESTONE, various lithologies, same as above.

Depth (ft bls)	**Lithology**
1349 – 1353	LIMESTONE, very pale orange (10YR 8/2), fossil wackestone (foraminifera, bivalves), hard, low macroporosity and apparent permeability.
1353 – 1360	LIMESTONE, very pale yellowish brown (10YR 7/2 to 8/2), bioclast grainstone, abundant foraminifera (including dictyoconids), moderate hardness, high macroporosity and apparent permeability.
1360 – 1362	LIMESTONE, yellowish gray (5Y 8/1), mixed lithologies (mostly micritic), fossil wackestone to packstone, moderate hardness, low macroporosity and apparent permeability.
1362 – 1367	LIMESTONE, same as above.
1367 – 1376	LIMESTONE, same as above.
1376 – 1380	LIMESTONE, same as above.
1380 – 1383	LIMESTONE, very pale orange (10YR 8/2) to medium yellowish brown (10YR 5/2), laminated mudstone and fossil wackestone, hard, low macroporosity and apparent permeability.
1383 – 1392	CONGLOMERATIC and DOLOMITIC LIMESTONE, DOLOSTONE, medium to dark yellowish brown (10YR 5/2 to 4/2), soft, micosucrosic, highly porous, very finely crystalline. LIMESTONE, clasts, mixed, mostly micritic lithologies, similar to above.
1392 – 1396	DOLOSTONE, medium olive gray (5Y 4/1) to medium yellowish brown (10YR 5/2), very finely crystalline, appears to be a replacement of micritic limestone, dense, very hard, very low macroporosity and apparent permeability.
1396 – 1405	LIMESTONE, yellowish gray (5Y 8/1), fossil bioclast packstone/grainstone, moderate hardness, low to moderate macroporosity and apparent permeability.
1405 – 1414	DOLOSTONE, same as 1392 to 1396 ft.
1414 – 1416	LIMESTONE, same as 1396 to 1405 ft
1416 – 1426	LIMESTONE, same above except some bioclast grainstone with moderate to high porosity porosity and permeability.

Depth (ft bls)	**Lithology**
1426 – 1429	DOLOSTONE, light olive gray (5Y 6/1 to 5/1), very finely crystalline, dense, hard, high macroporosity (vuggy), low to moderate apparent permeability (vugs do not appear to be interconnected).
1429 – 1440	LIMESTONE, yellowish gray (5Y 8/1), bioclast grainstone/packstone, hard, moderate macroporosity (intergranular and vuggy) and apparent permeability.
1440 – 1456	LIMESTONE, same as above.
1456 – 1460	LIMESTONE, same as above.
1460 – 1464	LIMESTONE, same as above.
1464 – 1476	LIMESTONE, same as above.
1476 – 1480	LIMESTONE, same as above, except more micritc, lesser grainstones.
1480 – 1491	LIMESTONE, same as above.
1491 – 1496	LIMESTONE, same as above
1496 – 1516	DOLOSTONE, dark yellowish brown (10YR 4/2) to medium yellowish brown (10YR 5/4), finely crystalline (crystal size 100 to 200 µm), microsucrosic to dense, very hard, variable porosity; low to high (intercrystalline and vuggy). Apparent permeability is generally low (could be enhanced by fracturing not evident in recovered cuttings).
1516 – 1536	DOLOSTONE, same as above.
1536 – 1538	DOLOSTONE, same as above.
1538 – 1549	DOLOSTONE, same as above.
1549 – 1556	DOLOSTONE, same as above.
1556 – 1576	DOLOSTONE, same as above.
1576 – 1588	DOLOSTONE, same as above.
1588 – 1590	DOLOSTONE, same as above.

Brighton Reservation ASR Exploratory Well

Depth (ft bls)	**Lithology**
1590 – 1596	DOLOSTONE, same as above.
1596 – 1599	DOLOSTONE, same as above.
1599 – 1608	DOLOSTONE, same as above, except darker colored, dusky yellowish brown (10YR 2/2) to dark yellowish brown (10YR 4/2).
1608 – 1613	DOLOSTONE, same as above.
1613 – 1618	DOLOSTONE, same as above.