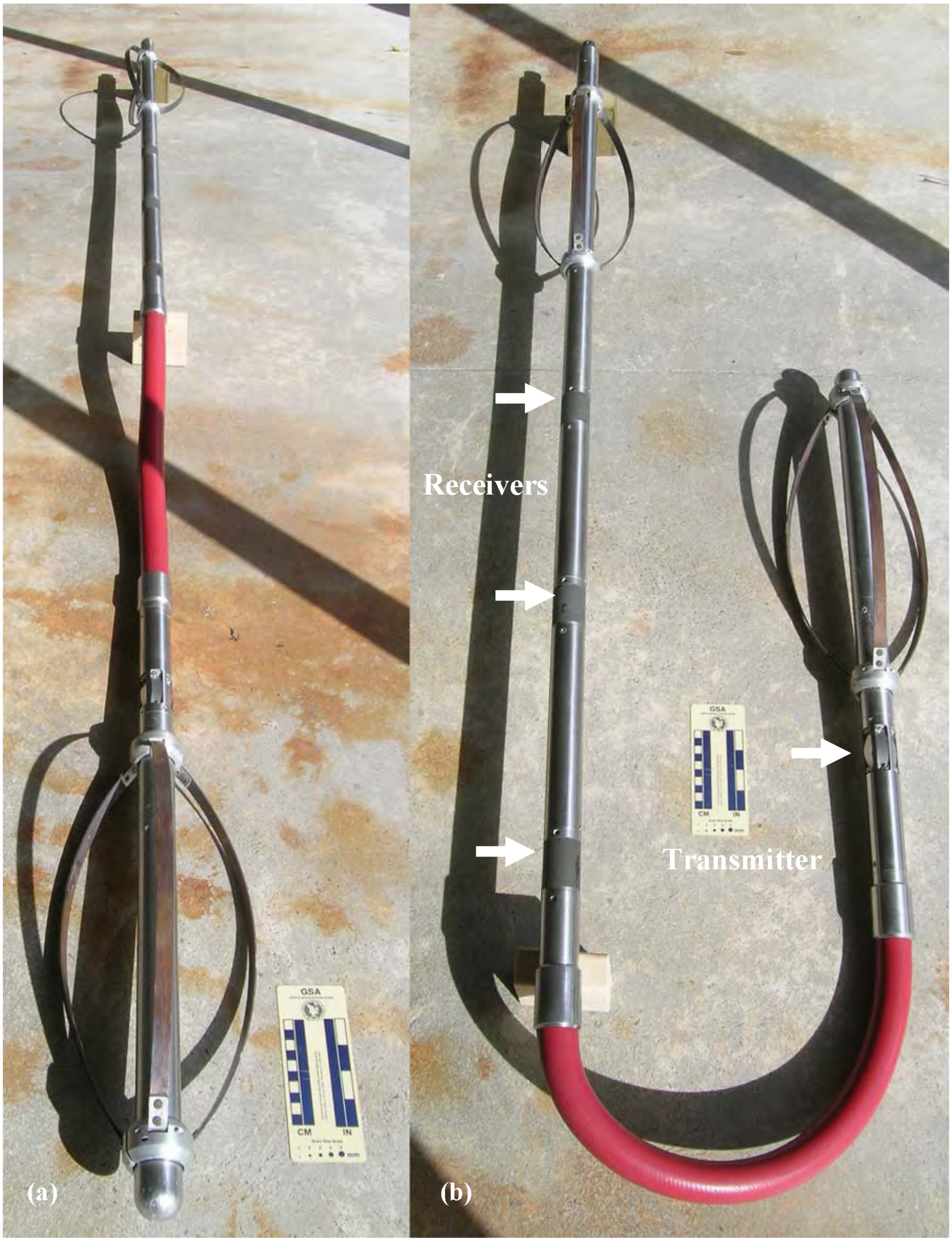

Figure 8. Views of full waveform sonic tool showing (a) full tool length and (b) detail of the transmitter and three receivers.

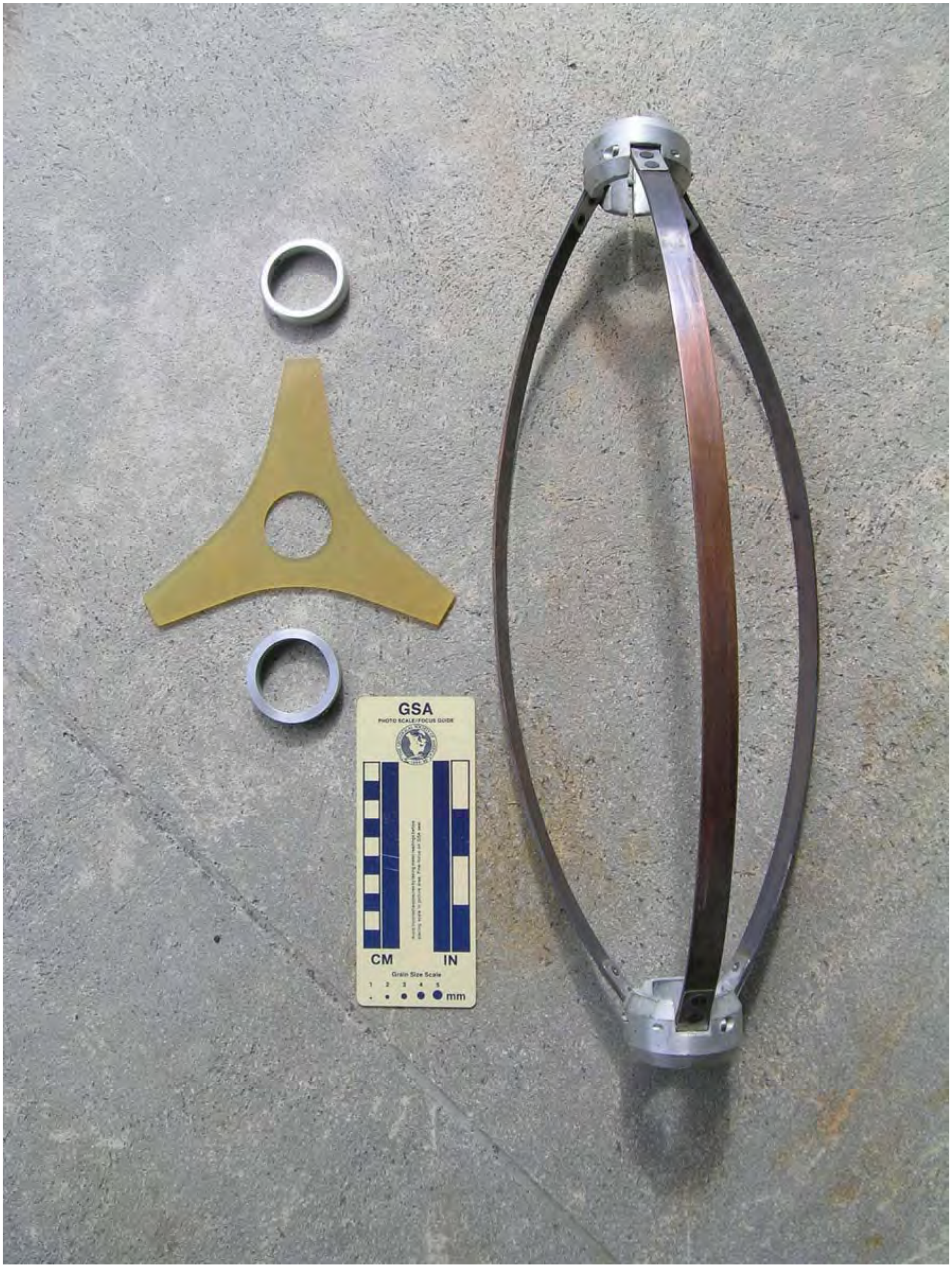

Figure 9. Available centralizer types, plastic rod-spring with locking collars (left) and copper bow-spring (right).

Figure 10. Student holding OBI-49 fitted with plastic rod-spring centralizers. Inset shows detail of optical head.

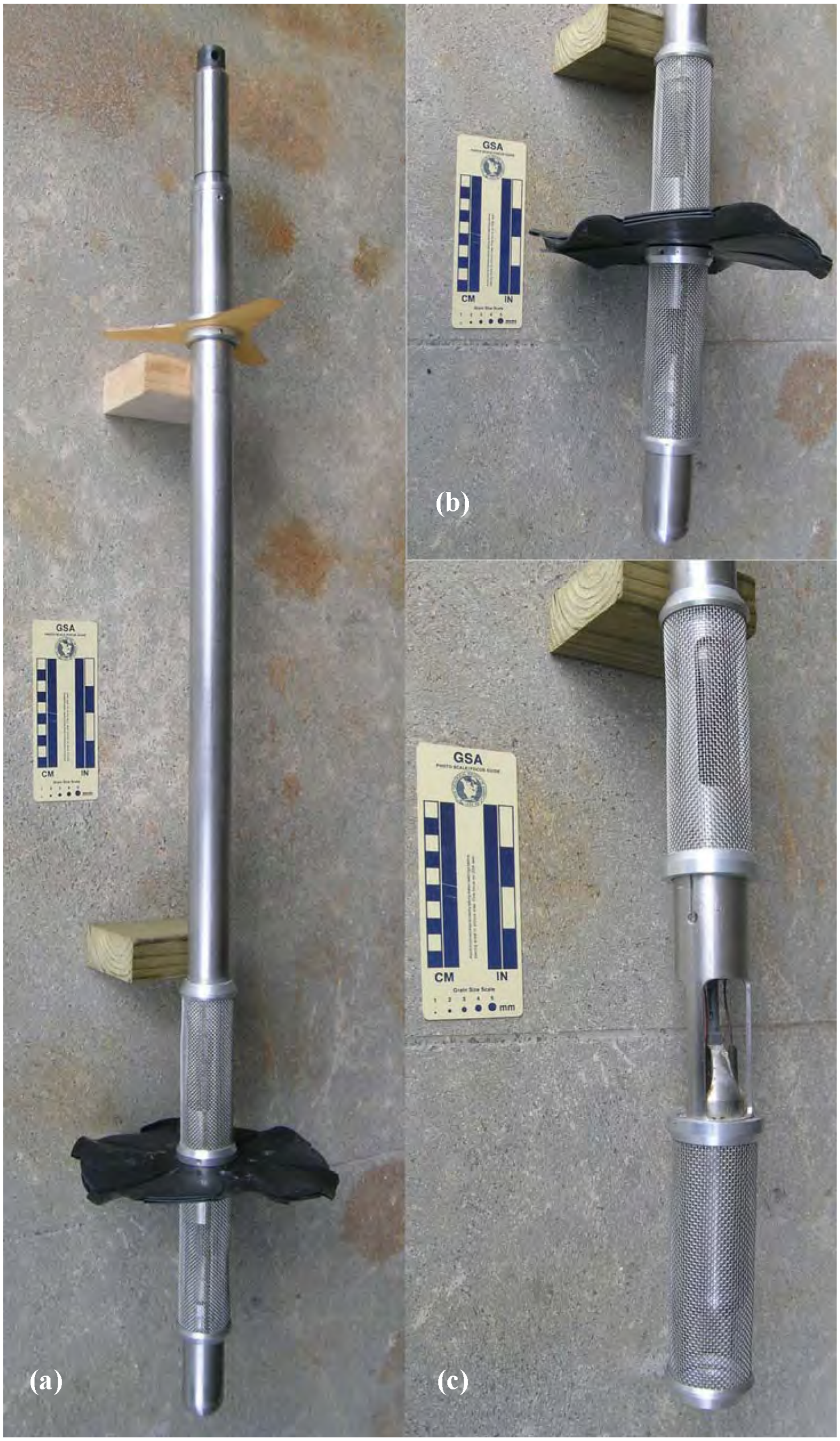

Figure 11. Heat pulse flowmeter showing (a) proper tool set-up, (b) detail of flow diverter and screens, and (c) detail of lower thermistor.

Figure 12. Lower section of the spinner flowmeter showing the two available cage and propeller sizes.

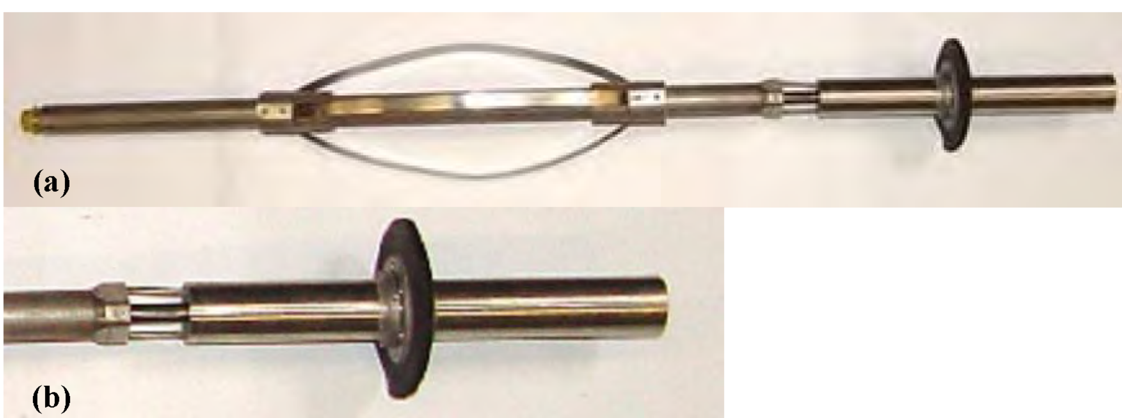

Figure 13. (a) EM flowmeter (USGS-FISC flowmeter does not have a centralizer) and (B) detail of flow divertor.

Appendix A

Available Tools

All tools and associated equipment are made or distributed by Mount Sopris Instrument Company, Inc., Golden, Colorado with the exception of the EM flowmeter, which is made by Century Geophysical Corp., Tulsa, Oklahoma. All are portable and can operate down to at least 3,280 feet.

Natural Gamma	HLP-2375/S	SN-2202
With spontaneous potential (SP) and single-point resistance (SPR) capability.		
Three-arm Caliper	2CAA-1000	SN-2702
w/ Fluid Temp. & Resist.	2SFB-1000	SN-2703
Electromagnetic Induction	2PIA-1000	SN-3114
Full Waveform Sonic	2SAA-1000/F	SN-3023
Transmitter		SN-3042F
Receiver One		SN-3047F
Receiver Two		SN-2863F
Receiver Three		SN-3088F
Digital Optical Borehole Imager	OBI-40, MK III	SN-3110
with vertical borehole deviation instrumentation.		
Heat-Pulse Flow Meter	HPF-2293	SN-2706
Diverter sizes: 5, 7, and 9 inches.		
Spinner Flow Meter	FLP-2492	SN-2372
Cage sizes: 2 and 4 inches.		
Electromagnetic (EM) Flow Meter	Century-9721	SN-1188
w/ Fluid Temp. & Resist.		

Available Winches

Large Winch	4MXC1000	SN-2011
1000 m (3,280 ft) of 3.17 mm (0.125 in) single conductor cable		
MGXII Console	5MCA/5TMA	SN-1186
Portable Logger	5MGB-1000	SN-1083
170 m (558 ft) of 3.17 mm (0.125 in) single conductor cable		

Software/Hardware

MSLog	Version 7.43 build 729	
MSHeat	Version 1.0 build 626	
MSLConfig	Version 2.3.9.25	
WellCAD	Version 4.0 build 729	SN-510133356
(Note: Dongle required)		
Image and Full Waveform Sonic modules activated.		
Log Cruncher	Version 1.0 build 307.27 Beta	SN-57C7118D7B06372C
Sonic Processing and Formation Evaluation modules activated.		
Dell Laptop	LATITUDE D-610	Windows XP

Appendix B

Available Geophysical Logs

Digital Borehole Image Log

Requires the borehole fluid to be clear with no suspended material. Can be aligned to magnetic north and exported in a BITMAP format.

Full Waveform Sonic Logs

Post processing produces compressional, shear, and Stoneley-wave velocity logs; Stoneley amplitude log can yield a sonic porosity log using the Raymer-Hunt or Wylie equations. Can also create a cement bond log and with additional processing, and logs of various engineering properties.

Flowmeter Logs

Measures vertical fluid flow within a borehole. Three types available based on flow velocity, (1) heat-pulse flowmeter (units are in gallons per minute, GPM, does not provide a continuous log) for flow less than 1.5 down to 0.03 GPM, (2) spinner flowmeter (units are CPS) for flow greater than 6.5 feet per minute (FPM), and (3) an EM flowmeter (units are GPM and FPM) which works in a wide range of flow velocities (0.01 to 10.6 GPM), but requires additional calibration and maintenance issues.

Borehole Deviation Log

Derived from OBI-40 three-axis orientation data.

Computed Vuggy Porosity Log

A computer generated log that requires a digital optical borehole image log and outside processing from a consultant.

Acoustic Borehole Image Log

Requires rental of the ABI-40 downhole tool. Additional logs available are Acoustic Caliper Logs, borehole volume computation and cross sections, and a virtual acoustic core.

Fluid Logs, temperature and resistivity

Additional logs are conductivity, specific conductance, and salinity (Riley and Skirrow, 1975).

Caliper Log

Mechanical, three-arm.

Natural Gamma

In units of counts per second (CPS).

Electromagnetic Induction, formation conductivity

A formation resistivity log is also produced using the inverse relationship.

Spontaneous Potential and Single Point Resistance

Borehole Logging Requirements

Tool	Minimum Hole Diameter	Cased/Uncased	Fluid	Other
Gamma	2-in	Both	No requirements	Casing corrections can be applied.
SP/SPR	2-in	Uncased	Fluid filled	None
Caliper	2-in with small arms and 2.25-in with large arms	Uncased	No requirements	Two arm lengths for maximum diameters of 17-inch or 30-inch.
Fluid/Resistivity	2-in	Both	No mud filled holes	Conductivities 0-1000 µS/cm.
EM Induction	2-in	Both (PVC only)	No requirements	Three ranges: 0-100 mS/m 0-1000 mS/m 0-10,000 mS/m.
Full Waveform Sonic	2.5-in 10-in max. 7-in optimal	Both (uncased best for rock properties)	Fluid filled boreholes only	Centralizer noise effects quality.
Digital Optical Imager (OBI 40 MK III)	2.5-in 12-in max. 7.5 in optimal	Both (uncased for rock view)	Clear water only	Particulate settling time and air-lift for clear and stable hole.
Acoustic Borehole Imager ABI 40	2-in 24-in max. 7-in optimal	Both (uncased best)	Fluid filled (water/mud)	Must have space behind casing to image.
Heat-Pulse Flowmeter	3.5-in (2-in, no diverter)	Both (if slotted casing)	Fluid filled, little or no mud	0.03-1.0 GPM, can be read up to 1.5 GPM.
Spinner Flowmeter	2-in Catches on obstructions in hole.	Both (if slotted casing)	Fluid filled, little or no mud	6-200 ft/min Output in CPS. Extensive calibration required to convert to GPM.
EM Flowmeter (Fluid resistivity and temperature)	3.75-in Diverters may have to be created or modified.	Both (if slotted casing)	Fluid filled, little or no mud	0.01-10.5 GPM Calibration and repair issues.

Florida Integrated Science Center

Borehole Geophysical Logging Program: Incorporating New and Existing Techniques in Hydrologic Studies

Overview

The borehole geophysical logging program at the U.S. Geological Survey (USGS)-Florida Integrated Science Center (FISC) provides subsurface information needed to resolve geologic, hydrologic, and environmental issues in Florida. The program includes the acquisition, processing, display, interpretation, and archiving of borehole geophysical logs. The borehole geophysical logging program is a critical component of many FISC investigations, including hydrogeologic framework studies, aquifer flow-zone characterization, and freshwater-saltwater interface delineation.

New Borehole Geophysical Logging Capabilities in Florida

In addition to acquiring standard borehole-log information such as caliper, gamma, spontaneous potential, and electromagnetic induction data (table 1), FISC utilizes new technologies and procedures to generate advanced logs. Of particular importance are digital borehole imaging and electromagnetic flowmeter logging, both of which are now used to augment existing techniques.

Digital borehole optical televiewers equipped with a high-resolution cameras can create detailed, 360-degree images of borehole walls and simultaneously collect borehole deviation data. The digital borehole images can be used to (1) accurately determine the depths for a well completion interval, (2) position a recovered core to its proper depth, (3) acquire a high-resolution borehole image that serves as a surrogate for intervals having no core recovery (Ward and others, 2003), and (4) characterize aquifer pore systems. Fracture and bedding plane orientations can also be determined, because borehole images can be oriented to magnetic north. In combination with a new digital log acquisition system, a digital borehole image can be acquired at relatively high logging speeds (about 3-15 feet per minute, depending on desired pixel density). Various log presentation software can be used to display these images, as well as standard logs on multilog-paper displays up to 36 inches wide. A digital copy of the display can be viewed on a computer using nonproprietary software readers.

To address difficulties in accurately quantifying relative transmissivity in aquifer flow zones, FISC is now using an electomagnetic flowmeter to accurately measure flow at intermediate velocities. Previously, heat pulse flowmeters and spinner flowmeters were solely used to measure flow across all velocities. Heat pulse flowmeters, however, can only measure low-velocity flow and do not generate continuous logs. Spinner flowmeters adequately measure high velocity flow and generate continuous logs, but quantifying the amount of flow from spinner revolutions is time consuming and difficult. The electromagnetic flowmeter accurately measures medium flow velocities, generates a continuous log of flow velocity and direction, and can make stationary measurements like the heat pulse flowmeter. The logs generated by the electromagnetic flowmeter can help show the relative transmissivity of flow zones within a well. A fluid meter built into the tool also displays changes in temperature and fluid resistivity, which also aids in the identification of flow zones.

Although most borehole geophysical log acquisition is performed from a vehicle, equipment portability also allows easy transport to remote well sites, such as those in offshore marine or wetland environments. Wells up to 3,200 feet deep and greater than 2 inches in diameter can be accommodated, providing access to all major aquifers in Florida, including much of the Floridan aquifer system.

FISC Hydrologic Investigations Employing Borehole Geophysical Logging Techniques

Geophysical logs run in exploratory or investigative boreholes can provide valuable hydrogeologic information, especially in areas with poor lithologic and (or) hydrologic control. Geophysical logs also can provide much needed information to help in determining the correct placement of well completion depths or intervals. The acquisition of borehole geophysical logs can become the determining factor in solving complex subsurface issues. The following studies highlight new and existing techniques used by FISC to resolve geologic, hydrologic, and environmental issues.

Hydrogeologic Framework Studies

Partially recovered core samples typically can only be placed within a 5- to 10-foot range of core barrel depth. Placement of core material or recognition of void space within these poor recovery intervals is often difficult using examination of the core and standard borehole geophysical methods. With the aid of a digital optical borehole image log, a trained user can accurately reconstruct core sample depths (Ward and others, 2003) and use image log data to aid in pore-type characterization (including large cavities) for both intervals with and without recovered core. Cunningham and others (2004a, b; 2006a, b) used digital images to identify lithology, pore type, and zones of concentrated ground-water flow to show the connection between stratigraphy and the development of porosity and permeability within the Biscayne aquifer. Further study led to the development of a multilayer, conceptual hydrogeologic framework for the Biscayne aquifer along the Everglades-Urban corridor (Lake Belt area) in northwestern Miami-Dade County (Cunningham and others, 2006a).

Digital optical borehole imagery was used in combination with core data to construct stratigraphic sections that show the areal extent of macroporous flow zones within the Miami-Dade Northwest Well Field (Renken and others, 2005; 2008). Tracer tests conducted during 2003-04 at the well field demonstrated the continuity of touching-vug flow zones and the potential for rapid, long-distance chemical and colloidal transport within the Biscayne aquifer (Shapiro and others, 2008; Harvey and others, 2008). Digital optical borehole imagery was used to determine the dimensions of macropores, and was also used with core data to develop hydrostratigraphic cross sections to help show the connectivity of macroporosity between wells. Previous studies may have underestimated the porosity, as well as the areal extent of macroporosity.

Aquifer Flow-Zone Characterization

Borehole fluid temperature and conductivity logs collected during one of the Miami-Dade Northwest Well Field tracer tests have been used to illustrate well-to-well tracer movement within preferential flow zones (Cunningham and others, 2006b; Renken and others, 2008). Observation well borehole fluid temperature logs were used to show that a single flow zone constitutes the dominant horizon for well-to-well hydraulic interconnection and for the migration of most of the tracer mass (fig. 1). The observed monotonic increase in temperature with depth shortly after injection (1252 hours) suggests that conservative tracers traveling within the shallow flow zone approximately 41 feet below land surface arrived at the observation well prior to tracers traveling within touching-vug pore zones at greater depths (Renken and others, 2008).

Table 1. Available geophysical logs for use in FISC research.

[cps, counts per second; EM, electromagnetic; FISC, Florida Integrated Science Center; ft/min, foot per minute; gal/min, gallon per minute; PVC, polyvinyl chloride]

Geophysical logging tool and log type	Tool use	Interpretive value of log
Borehole deviation	Measures deviation of borehole from vertical.	Used as input for calculation of true vertical depth.
Borehole fluid	Generates logs of water-quality properties that include the following: borehole fluid temperature, resistivity, conductivity, specific conductance, salinity, pressure, redox, dissolved oxygen concentration, and pH.	Identification of ground-water flow zones penetrated by the borehole and sources of incoming water.
Caliper	Measures borehole diameter, using mechanical, three-arm, or high-resolution acoustic caliper.	Determination of cavity size and geometry.
Digital, optical and acoustic borehole image	Televiewer creates digital, optical and acoustic images of borehole wall or casing.	Used to reference core to original depth, detect cavities, faults, and fractures, as well as characterize pore systems. Optical and acoustic log types can be aligned to magnetic north and exported in BITMAP format.
Electromagnetic induction	Measures formation conductivity in both cased and uncased wells. Produces a formation resistivity log using the inverse relations with conductivity.	Determination of depth to freshwater-saltwater interface in boreholes. Help identify zones of ground-water flow.
Flowmeter	Measures vertical fluid flow within a borehole. Measures flow under both ambient and pumping conditions. Tool choice is based on fluid flow velocity: (1) heat pulse flowmeter (units in gal/min) for flows less than 1.5-0.03 gal/min, (2) spinner flowmeter (units in cps) for flows greater than 6.5 ft/min, and (3) EM flowmeter (units in gal/min or ft/min) measures a wide range of flow velocities (0.01-10.6 gal/min).	Identification of ground-water flow zones penetrated by the borehole and determination of relative transmissivity of flow zones.
Full waveform sonic	Measures acoustic wave travel time through borehole fluid and the surrounding rocks. Post processing creates compressional, shear, and Stoneley-wave logs.	Compressional velocity logs are used to create a sonic porosity log with either the Raymer-Hunt or Wylie equations. Stoneley-wave amplitude log is used to estimate permeability. Additional processing yields cement bond logs, as well as logs showing various engineering properties, and synthetic seismic wiggle traces.
Natural-gamma	Measures gamma radiation of natural radioisotopes in surrounding formation (output is in cps).	Correlation of lithologic units between wells.
Spontaneous potential and single-point resistance	Measures the natural potential that originates from electrochemical differences between borehole and formation fluids at lithologic boundaries. Requires an open borehole.	Used to infer lithologic changes. Single-point resistance log can be used to detect sections of slotted casing in completed wells.

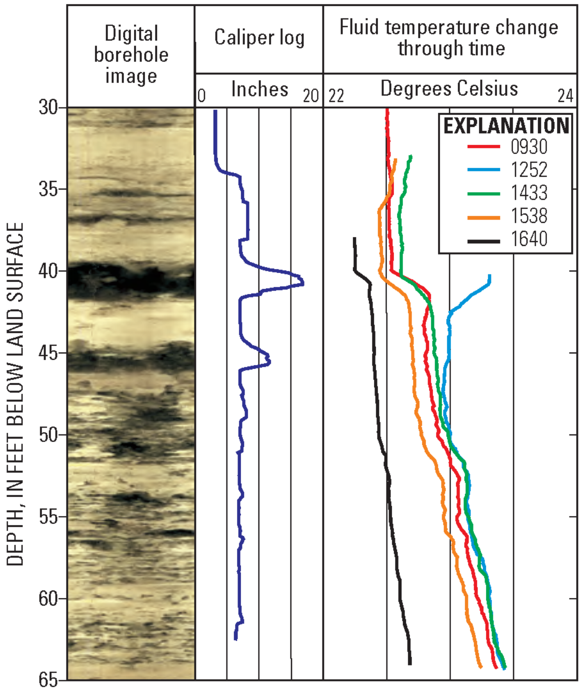

Figure 1. Temporal change in borehole temperature caused by the migration of a tracer within a touching-vug flow zone at a depth of 41 feet below land surface in an observation well (modified from Renken and others, 2008). Tracer injection occurred at 0930 hours. Fluid temperature log at 1252 hours was not completed because the top of the logging tool was lodged against the casing bottom.

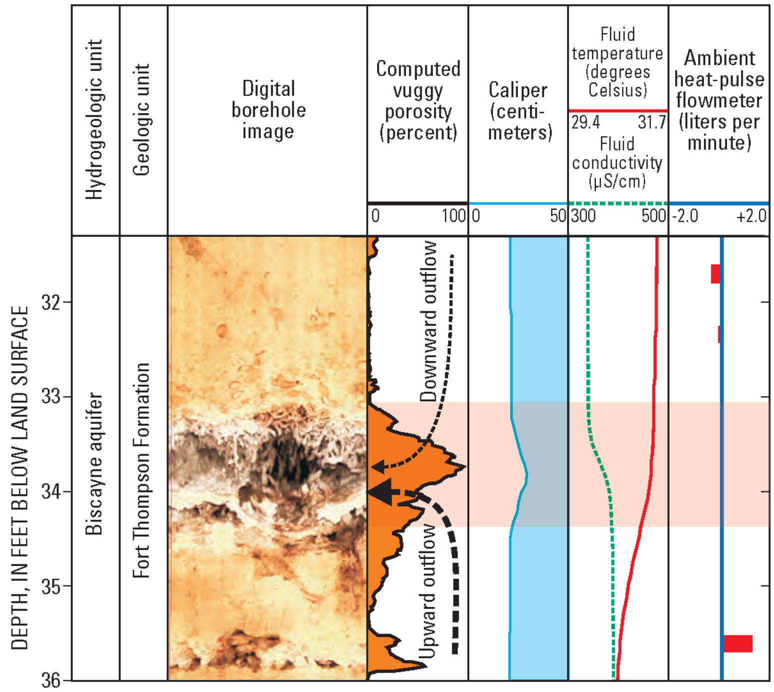

Figure 2. Comparison of borehole image, computed vuggy porosity, geophysical, and flowmeter logs for the G-3788 test corehole showing evidence of water outflow from the borehole into a preferential flow zone. Abbreviation µS/cm is microsiemens per centimeter.

High-resolution heat pulse, electromagnetic, and spinner flowmeters are routinely used by FISC scientists to measure vertical fluid flow within a borehole over a wide range of flow rates and under both ambient and pumping conditions. Borehole flowmeter measurements have been used to identify permeable flow zones in the Biscayne aquifer (Cunningham and others, 2004a; 2006a), and assess vertical hydraulic gradients. Flowmeter measurements combined with data from digital borehole images and fluid-temperature and conductivity logs can be used to accurately evaluate and characterize flow zones within the context of a high-resolution conceptual hydrogeologic framework (fig. 2). As an example, Cunningham and others (2004b) used ambient flowmeter and borehole fluid-temperature and conductivity logs to hypothesize sources of ground-water recharge. Data from flowmeter and borehole-fluid logs collected in seven wells along an 8-mile reach of the L-31 Canal in Miami-Dade County were used to identify sections that were consistent with aquifer recharge by surface water from Everglades National Park. Horizontal flowmeters were also placed within preferential flow zones of the Biscayne aquifer identified by digital borehole images during this study (Cunningham and others, 2004b) as part of a continuous ground-water monitoring program operated by the South Florida Water Management District. The real-time flow data (which are still being analyzed) from these horizontal flowmeters show variable ground-water flow directions and rates. These data, along with data from Cunningham and others (2004b), were later used to further hypothesize that nearby ground-water pumpage in excess of the permitted allotment was also influencing recharge.

Freshwater-Saltwater Interface Delineation

Electromagnetic induction logs have been used to obtain detailed vertical profiles of the conductivity of the aquifer around each well, and used in combination with surface-geophysical methods and chloride concentration data, to map the position of the saltwater interface in southeastern Florida (Hittle, 1999). Detection and monitoring of the saltwater front through induction logging in cased wells over time is an ongoing effort by the USGS and State, county, and municipal cooperators. The induction logging tool measures the bulk electrical conductivity of rock and pore fluids to delineate lithology, porosity, and fluid salinity within open and polyvinyl chloride (PVC)-cased boreholes. Within these casings, this logging tool can measure changes in the dissolved-solids concentration of pore fluid over time. Data collected from USGS monitoring wells as part of the ongoing induction logging program indicate that interface movement is irregular within the vertical section of the well, and possibly related to differential lateral movement of brackish to saline water within zones of higher permeability (fig. 3).

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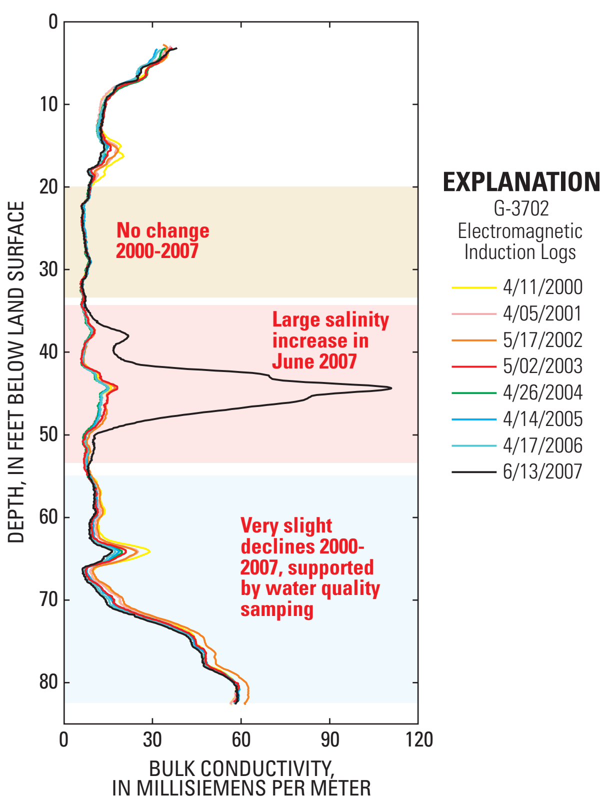

Figure 3. Comparison of electromagnetic-induction logs collected in well G-3702 from April 2000 through May 2007 along Black Creek Canal in Miami-Dade County (Scott Prinos, U.S. Geological Survey, written commun., 2008). An increase in conductivity is evident between 40 and 50 feet.

—*Michael A. Wacker and Kevin J. Cunningham*

For more information, please contact:

Michael A. Wacker
e-mail: mwacker@usgs.gov

Kevin J. Cunningham
e-mail: kcunning@usgs.gov

U.S. Geological Survey
Florida Integrated Science Center
(FISC—Ft. Lauderdale)
3110 SW 9th Ave.,
Ft. Lauderdale, FL 33315

U.S. Department of the Interior
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Water Resources Data
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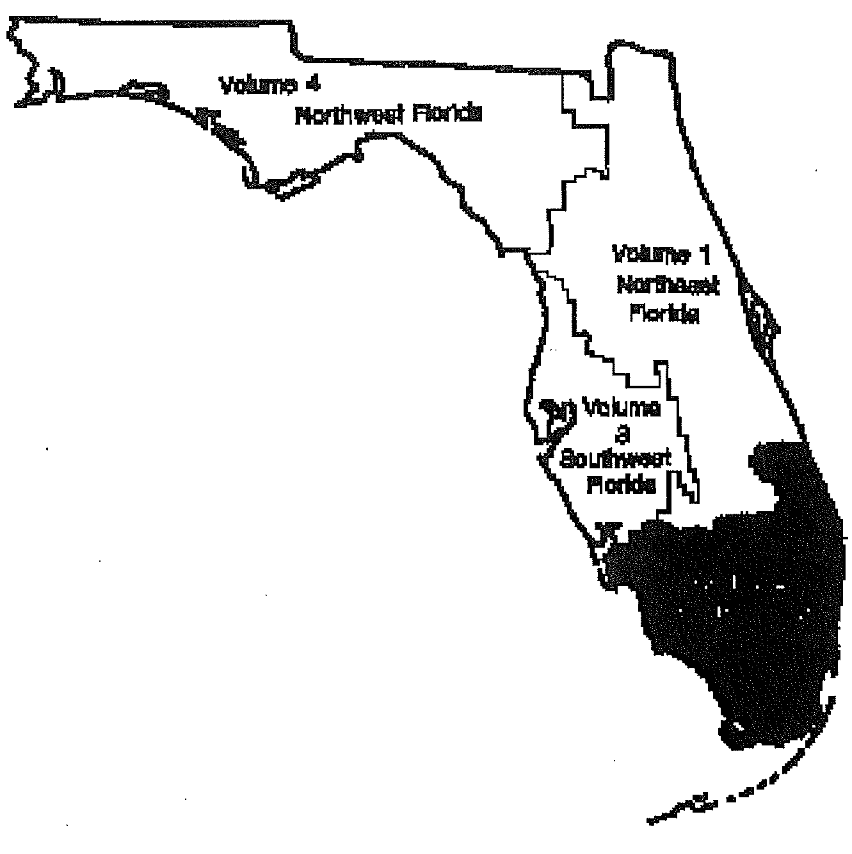
Volume 2B. South Florida Ground Water

By S. Prinos, K. Overton, M. Byrne

Water-Data Report FL-01-2B



Prepared in cooperation with the
State of Florida and with other agencies

RECORDS OF BULK ELECTRICAL CONDUCTIVITY

Bulk conductivity is the combined electrical conductivity of all material (including pore water) within an approximately 8 to 40 inch doughnut shaped area surrounding an induction probe (McNeill and others, 1990). Bulk conductivity is affected by different physical and chemical properties of the material including the dissolved solids content of the pore water and lithology and porosity of the rock. PVC casings do not interfere with these measurements but for those wells where a steel or galvanized iron casing extends part way down the well, the probe can not sense the materials outside of the casing. Usually, as the probe moves down the well and out of the influence of a metallic casing, a spike is created in the data. As the probe passes through different layers of rock, the different physical properties will cause conductivity values to vary. Generally, a clean sand or sandstone will produce lower conductivity values than clay or mudstone. While the properties of the rocks or well construction will remain constant from year to year, those of the porewater may change due to saline intrusion. Conductivity values from freshwater-saturated rocks are typically less than 25 mS/m, whereas conductivity values from saltwater-saturated rocks are typically greater than 67 mS/m (Hittle, 1999). Therefore, induction logging can be used to assess increases or decreases in the conductivity of pore waters caused by movement of the saltwater interface.

Data Collection and Computation

Measurements are generally made during the period of lowest aquifer water levels in April of each year. However, some wells may have additional logs. During periods of decreased water-levels, saltwater intrusion into a freshwater aquifer is likely at a maximum. In wells where saltwater is detectable, the graphic representation of data from successive years will show any vertical movement of the saltwater-freshwater interface. Measuring this vertical movement of the interface is the primary use of the bulk conductivity logs published in this report. Upward movement of the interface between freshwater and saltwater in a monitoring well indicates that saltwater intrusion is increasing in that area. Downward movement of the interface indicates recession of the saltwater front near the monitoring well.

In the conductivity plots of some of the wells logged for this report, the interface position can be seen as the point where low values of conductivity increase suddenly to values generally above 67 mS/m (usually near the bottom of the well). However, the interface position is not as apparent in other wells and in some, there is no interface.

In wells selected for induction logging, a water sample may be collected and analyzed as a check on the level of salinity. Because the bulk conductivity is a function of fluid conductivity, lithology, and porosity, the relationship between these logs and the chloride samples may not be as obvious as the relationship between fluid conductivity and chloride concentrations generally are. If the rock is not very porous then the change in bulk conductivity caused by changes in the salinity of the pore water may be smaller than might be expected. None the less, the long-term changes in the bulk conductivity logs are sufficient to assess upward or downward movement of the interface. To aid in interpretation of the bulk conductivity logs whenever chloride samples are collected on the same day as that log, the chloride concentration is shown on the plot of bulk conductivity.

The instrument used to collect data for this report is calibrated prior to each field session. The calibration procedure results in a calibration factor that converts raw instrument readings into calibrated values of conductivity. When data were graphed for the 2000 annual water resources data report, offsets and amplitude differentials occurred in the calibrated values of bulk conductivity for each well between successive years. Investigation revealed that the discrepancies were a function of differing calibration factors between years. Most calibration factors differed because of temperature and humidity differences during calibration procedures. Calibration procedures, adapted during the 2000 water year, are designed to minimize the influence of variable temperature and humidity. Before calibrating, the induction probe was run into a well and allowed to equilibrate in the water column. The probe was then removed from the well and the instrument immediately calibrated.

Factors other than variable temperature and humidity also have caused offsets and amplitude differentials. Because of an error while calibrating the instrument for the 1998 water year, a high-end calibration parameter was used that differed from other years. The differing parameter caused a data offset at higher ends of the scale. A second factor that may have caused data offset and amplitude differentials occurred with data collected for the 2000 water year. Prior to logging for the 2000 water year, the instrument was updated with respect to firmware and software. After logging, it was found that the data had been truncated at the decimal point (see Accuracy of Bulk Conductivity).

Accuracy of Bulk Conductivity

There are two components that affect the quality of the induction logs published in this report: (1) vertical or depth accuracy and (2) accuracy and precision of measured bulk conductivity. As indicated in the preceding section, the vertical accuracy which affects the interface position is the most critical factor in this monitoring effort. Therefore, as long as the interface is clearly indicated in the logs of bulk conductivity, the accuracy with which its depth can be determined is the primary component of interest. A quality control program sets the velocity of the probe at 12 feet per minute while logging. Before logging begins, a spot on the probe, 3.32 feet above the sensing head, is aligned with the measuring point of the well. Wherever possible, the data that was recorded as the probe was moved up the well was used to produce the plots for this report. Depth values between successive water years were adjusted, if needed, to coincide at explicitly identifiable conductivity peaks recorded from an upper part of the well. Depth values are interpolated to the nearest tenth of a foot. The precision of depth determinations using this reporting method should be considered to be about ±0.1 foot.

The accuracy and precision of measured bulk conductivity are a function of both the inherent accuracy of the induction probe and its calibration. The inherent precision of the probe is considered by the manufacturer to be ±5 percent of the full scale. The induction probe was calibrated to a full scale of 1,000 mS/m. This translates into a precision of ± 50 mS/m at full scale. Analysis indicated that the offsets caused by the effects of temperature and humidity on calibration were well within this range.

Accuracy of data collected during the 2000 water year may have been affected by the firmware or software update in December, 1999. The data collected using this new software and firmware was considerably offset when compared to previous induction logs. In addition, the final values were truncated at the decimal point, whereas those collected prior to the update were recorded to the thousandths decimal place. These final values are the result of a multiplication of the raw data from the instrument and a calibration factor. It is unknown whether or not the raw values were truncated at the decimal point. If so, the resulting error could be on the order of 5 mS/m too low. Because the offsets data from the 2000 water year is often 5 mS/m lower than the data from other years, truncation of the raw data is probably the explanation.

Data Presentation

Records of conductivity are published individually on the page immediately following the well manuscript. Data for conductivity are identified by well number. Each record consists of a single graph representing conductivity, a lithologic log, and a brief explanation.