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Site report for USGS test holes drilled at Cape Charles, Northampton County, Virginia, in 2004

By Gregory S. Gohn, Ward E. Sanford, David S. Powars, J. Wright Horton, Jr., Lucy E. Edwards, Roger H. Morin, and Jean M. Self-Trail

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Volume		
gallon (gal)	3.785	liter (L)
Flow rate		
gallon per minute (gal/min)	0.06309	liter per second (L/s)
Pressure		
pound per square inch (lb/in^2)	6.895	kilopascal (kPa)

SI to Inch/Pound

Multiply	By	To obtain
Length		
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)

Horizontal coordinate information is referenced to the North American Datum of 1988 (NAD 88).

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Abstract

The U.S. Geological Survey drilled two test holes near Cape Charles, Virginia, during May and June 2004, as part of an investigation of the buried, late Eocene Chesapeake Bay impact structure. The first hole is designated as the USGS-Sustainable Technology Park test hole #1 (USGS-STP1). This test hole was abandoned at a depth of 300 ft; cuttings samples were collected, but no cores or geophysical logs were acquired. The second hole is designated as the USGS-Sustainable Technology Park test hole #2 (USGS-STP2). This test hole was drilled to a depth of 2,699 ft. Cores were collected between depths of 1,401.7 ft and 1,420.7 ft and between 2,440.0 ft and 2,699.0 ft. Cuttings samples were collected from the uncored intervals below 280-ft depth. Interim sets of geophysical logs were acquired during the drilling operation, and one final set was acquired at the end of drilling. Two wells were installed in the USGS-STP2 test hole. The deep well (designated 62G-24) was screened between 2,260 ft and 2,280 ft, and the shallow well (designated 62G-25) was screened between 1,360 ft and 1,380 ft. Ground-water salinities stabilized at 40 parts per thousand for the deep well and 20 parts per thousand for the shallow well. The geologic section encountered in the test holes consists of three main units: (1) Eocene, Oligocene, Miocene, Pliocene, and Pleistocene sands and clays are present between land surface and a depth of 1,163 ft; (2) sediment-clast breccias of the impact structure are present between depths of 1,163 ft and 2,150 ft; and (3) crystalline-clast breccias and cataclastic gneiss of the impact structure are present between depths of 2,150 ft and 2,699 ft.

Introduction

The U.S. Geological Survey (USGS) drilled two scientific test holes at Cape Charles, Northampton County, Virginia, during May and June 2004. These test holes are part of a multi-agency study of the buried Chesapeake Bay impact structure, which underlies Northampton County and surrounding areas. Sanford and others (2004) published a brief summary of the drilling operations and results at Cape Charles. This report presents a more detailed operational summary, and a preliminary geologic summary, for the two test holes.

The Cape Charles test holes are designated as the USGS Sustainable Technology Park test hole #1 (USGS-STP1) and the USGS Sustainable Technology Park test hole #2 (USGS-STP2). USGS-STP1 had to be abandoned at a depth of 300 ft because of a nearsurface sediment washout. No cores or geophysical logs were collected from this hole; cuttings were collected from the entire 300-ft section. USGS-STP2 reached a total depth of 2,699 ft. Cores were collected from two intervals in this hole, and four geophysical logging runs were completed; cuttings were collected from the uncored intervals below a depth of 280 ft. The two test holes are located about 65 ft apart,

and their geologic sections are considered collectively in this report. This section consists of postimpact sediments that overlie sediment-clast breccias, crystalline-clast breccias, and cataclastic gneiss within the impact structure.

Background

The Chesapeake Bay impact structure formed about 35 million years ago during the late Eocene when a comet fragment or asteroid struck the U.S. Atlantic continental shelf in the area now occupied by the southern part of Chesapeake Bay and adjacent landmasses in the Virginia Coastal Plain. The resulting structure is an approximately circular, 53-mile-diameter crater centered near the town of Cape Charles, Va. (Fig. 1). The geologic materials within the structure now lie buried beneath hundreds of feet of younger Cenozoic marine sediments. Additional information about the Chesapeake Bay impact structure is available in numerous published studies, including Koeberl and others (1996), Poag (1997), Powars and Bruce (1999), Powars (2000), Edwards and others, (2004a), Poag and others (2004), and Horton and others (2005a, b).
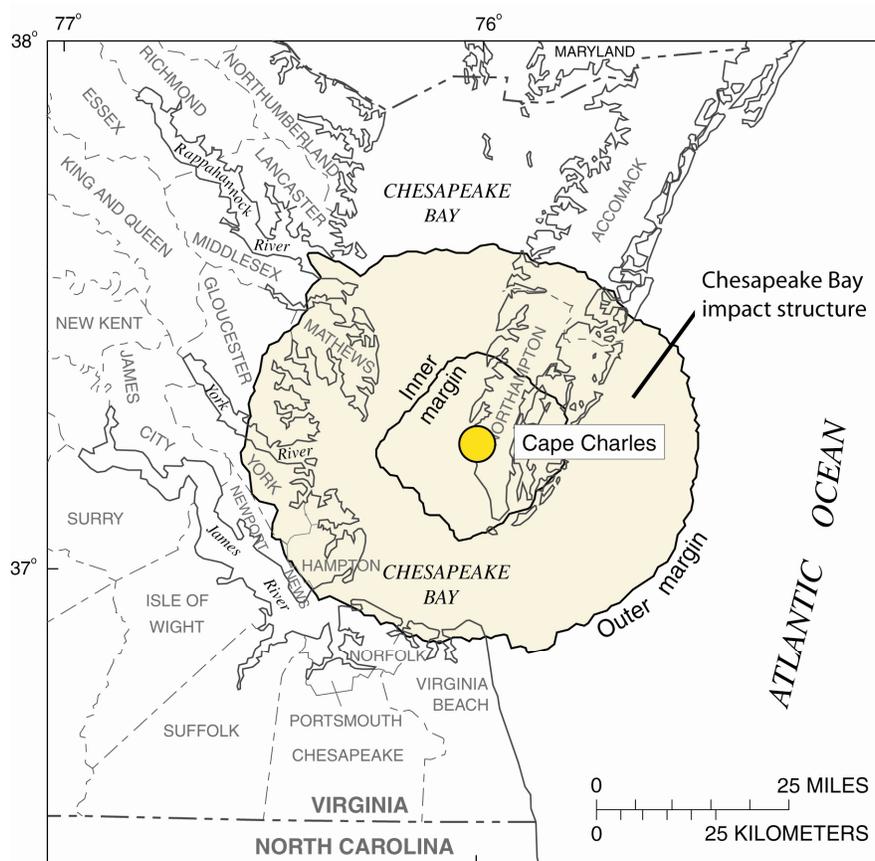
Figure 1. Regional map showing the location of the Chesapeake Bay impact structure and the USGS-STP drill site at Cape Charles (yellow circle).

The Chesapeake Bay impact structure spatially coincides with a long known, but poorly explained inland zone of salty ground water. This spatial association strongly suggests a genetic association (Powars and Bruce, 1999; McFarland and Bruce, 2005). The presence of the inland salt-water zone has practical significance because rapid population and commercial growth in areas

above and near to the salt-water zone requires an ever-increasing supply of fresh water (Emry and Miller, 2004). Detailed knowledge of the distribution of the salt-water zone and its formative processes are needed to determine whether increased ground-water pumping in adjacent areas will lead to migration of the salt water.

Drill Site

The USGS-STP test holes are located near the property line between the Cape Charles Sustainable Technology Park (STP) and the Bayshore Concrete Products plant, about 0.3 miles south of Cape Charles harbor (Fig. 2). The holes are located immediately west of the paved parking lot at the Sustainable Technology Park on a narrow grassy strip between the pavement and a wooded area to the west (Fig. 3). This location is near the southeastern corner of the Cape Charles 7.5-min topographic quadrangle (USGS, 1968).
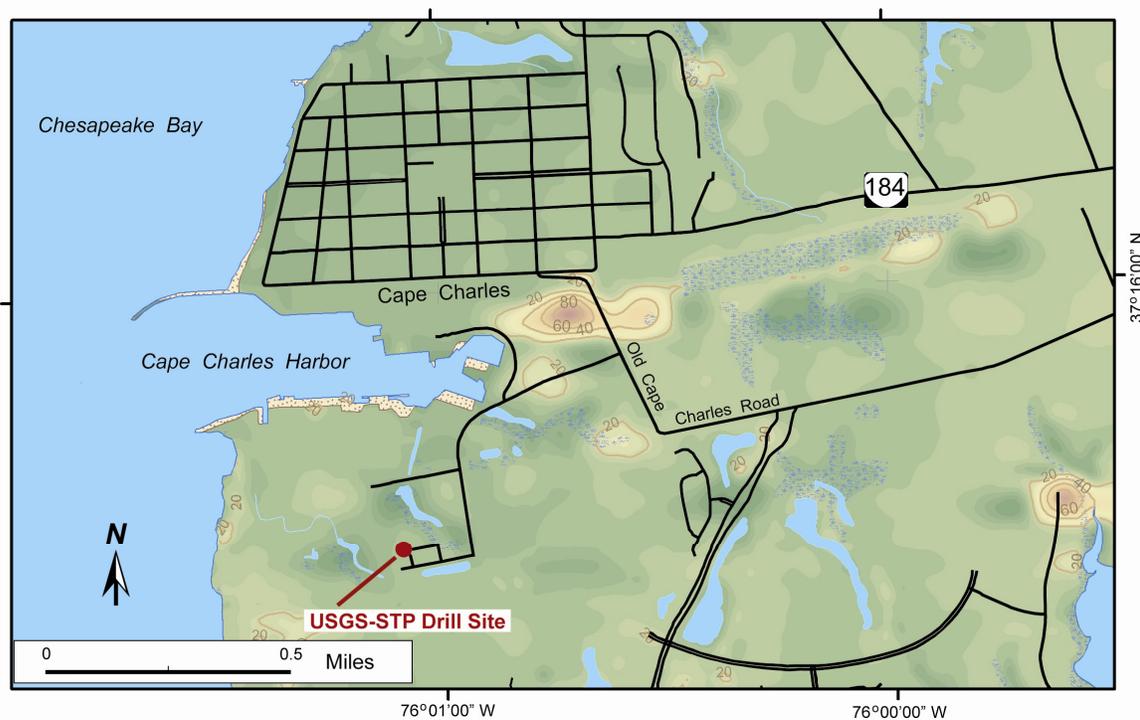
Figure 2. Topographic map showing the location of the USGS-STP drill site near Cape Charles, Va.

The latitude and longitude of the USGS-STP2 test hole are 37°15'33.17" N and 76°01'04.83" W. Coordinates were obtained using a Magellan ProMark X GPS receiver and were differentially post processed. The datum is NAD 88, and the accuracy is submeter (sub-yard). The surface elevation at the drill site is 7 ft (±1 ft), as estimated from the 1:24,000-scale topographic map of the Cape Charles 7.5-min quadrangle.

Figure 3. Photograph of the USGS-STP drill site during drilling operations in May 2004.

Drilling Operations

Drilling Equipment

The USGS-STP test holes were drilled by crews from the USGS Central Region Research Drilling Project between May 8 and May 26, 2004. Well installation and development continued into early June 2004. The test holes were drilled, and the wells installed, using a Gardner-Denver 17W hydraulic rotary rig.

Most of the drilling was conducted using 4.5-inch-diameter drilling rods and variety of wing (drag), roller, and claw bits. Coring was conducted using 3.7-inch-diameter coring rods and a ten-foot-long, Christensen H-size core barrel. The nominal core diameter is 2.5 inches. Mud viscosities were measured periodically using a Marsh funnel viscometer. Mud temperatures were not recorded.

Drilling and Logging History

The drill rig arrived at Cape Charles on Friday, May 7, 2004, and drilling commenced on the morning of May 8th. Drilling was halted at a depth of 18 ft, and 12-inch-diameter steel surface casing was installed to that depth by the end of work on May 8th. There was no overnight drilling on May 8-9. Drilling continued on the morning of May 9th, and a depth of 300 ft was reached by the end of work on that day. There was no overnight drilling on May 9-10. The crew returned to the drill site at 6:00 am on May 10th to discover that the surface casing had dropped slightly below land surface overnight and that a washout cavern had developed in the sandy surficial sediments. As a result, the drill rig was moved about 65 ft to the south.

The 300-ft-deep hole is USGS Sustainable Technology Park test hole #1. No geophysical logs or cores were acquired in this hole; however, cuttings were collected at 20-ft intervals from the entire 300-ft section.

The drilling of the second test hole, USGS Sustainable Technology Park test hole #2, started at 4:45 pm on May 10th and reached a depth of 60 ft by 5:30 pm. At that time, 56 ft of 12-inch-diameter, schedule 40, PVC casing was placed in the hole. About 220 gal of cement were placed around the casing between land surface and a depth of about 37 ft.   Work at the drill site ended at 9:00 pm on May 10th; there was no overnight drilling on May 10-11. On the morning of May 11th, the crew repaired the pump on the shaker trailer and installed the side-discharge tube and cuttings trough to facilitate sample collection. Round-the-clock drilling started at 1:55 pm using a 10 and 5/8-inch-diameter roller bit. Drilling continued to a depth of 394 ft at 11:12 pm on May 11th without significant mechanical problems or weather delays. The collection of cuttings samples began at a depth of 280 ft; no cuttings were collected above this depth in USGS-STP2.

The drill crew began to pull the rods from the hole at 11:14 pm on May 11th in preparation for geophysical logging and casing installation. The first logging probe (caliper) was lowered into the hole at 12:30 am on May 12th, and the borehole size was measured from about 390-ft depth to the land surface. The caliper log indicated that the borehole necked down to a diameter of about 2 inches at depths of 126 ft to 130 ft. The multifunction and sonic-velocity probes could not pass this constriction, and data were collected with those tools only above 125-ft depth. At 4:45 am, the drillers started reaming the borehole to allow additional geophysical logging to the total depth of the hole. Reaming was completed at 9:00 am, and the crew began to pull the rods from the hole at that time. Geophysical logging resumed at 9:55 am, and the full length of the open borehole was logged with the caliper, multifunction, sonic-velocity, neutron-porosity, and gamma-gamma density tools.

The drill crew began placing 8-inch (inside diameter) steel casing into the borehole at 4:45 pm. The casing reached a depth of 394 ft at 8:25 pm, and cementing of the casing began at the time. By 10:30 pm on May 12th, 442 gal of cement had been placed in and around the steel casing. Drilling was suspended until 3:15 pm on May 13th to allow the cement to harden. At that time, the crew began replacing the drill rods fitted with a 7 and 7/8-inch-diameter wing bit into the hole to drill out the cement plug.

Normal drilling with the wing bit resumed at 5:30 pm on May 13th at the previously reached depth of 394 ft. Drilling proceeded only to a depth of 400 ft and was then halted at 6:00 pm to await the arrival of a shipment of drilling mud additives. Drilling resumed at 7:59 pm, and a depth of 500 ft was reached at about midnight on May 13th. Drilling continued on May 14th and reached a depth of 940 ft at 9:35 pm. At that time, the crew began pulling the rods from the borehole in preparation for repairing the mast-line cable. The cable was replaced, and drilling resumed at 12:14 pm on May 15th using a 7 and 7/8-inch-diameter, three-cone roller bit. Drilling continued until 8:00 pm on that day when a depth of 1,100 ft was reached. At 8:15 pm, the crew began pulling the rods from the borehole in order to change bits. The roller bit was replaced with a 7 and 7/8-inch-diameter wing bit, and the rods were back to the bottom of the hole by 2:55 am on May 16th. The borehole was reamed where needed and extensively flushed during the replacement of the rods into the hole.

A depth of 1,340 ft was reached at 7:28 pm on May 16th at which time the crew began pulling the rods to change back to the 7 and 7/8-inch-diameter roller bit in the hope of increasing the drilling rate. The roller bit was placed back to the previous depth of 1,340 ft at 2:10 am on May 17th. At that time, the crew emptied the mud system and mixed new drilling mud. Drilling resumed at 3:40 am, and a depth of 1,400 ft was reached at 10:30 am. At that time, the drillers began pulling the rods from the hole in preparation for geophysical logging and wireline coring.

Geophysical logging operations to 1,400 ft consisted of collecting caliper, density, multifunction and sonic-velocity logs and were completed at 9:10 pm on May 17th. Assembly of the coring equipment began shortly thereafter, and the crew began placing the 3.7-inch-diameter coring rods with an H-size sampling system into the test hole at 10:27 pm. Placing the sampling system into the hole proved difficult as the coring bit was blocked repeatedly by sediment during its descent, and the rod string had to be raised to a shallower depth to re-establish mud flow on each occasion. The problem was corrected by removing the inner sample barrel from the outer barrel, thereby allowing better mud flow through the drill bit. Subsequently the inner barrel was placed downhole inside the rods, and it latched into place within the outer barrel without further difficulties. Two 10-ft coring runs were then completed between 3:05 pm and 4:42 pm on May 18th at depths of about 1,400 ft to 1,420 ft (Table 1).

After the coring runs, the coring rods were removed from the hole, and the drilling rods were returned to the borehole with a 6 and 3/4-inch-diameter claw (carbide-tooth) bit attached. The rods reached the bottom of the hole at 1,420 ft at 11:50 pm on May 18th, and drilling resumed at 1:17 am on May 19th. Drilling continued without equipment problems and only minor thunderstorm delays until a depth of 2,440 ft was reach at 6:44 pm on May 22nd. During this four-day period, the drill bit reached depths of 1,780 ft at about midnight on May 19th, 2,120 ft at about midnight on May 20th, and 2,240 ft at about midnight on May 21st. The decision to switch to continuous coring operations was made on May 22nd.

Wireline coring began at 9:44 pm on May 23rd. The crew completed twelve coring runs to a depth of 2,549 ft before midnight on May 24th. Eleven coring runs were completed on May 25th to a depth of 2,659 ft. Four coring runs were completed by 11:37 am on May 26th, thereby bringing the hole to its final depth of 2,699 ft. Drilling operations ended at about noon on May 26th. Drilling was followed immediately by the final stage of geophysical logging in the open-hole section, from the total depth of 2,699 ft to the bottom of casing at 394 ft. Caliper, multifunction, acoustic televiewer, sonic-velocity, neutron-porosity, and gamma-gamma density logs were acquired at that time.

Drilling Rate

The time needed to drill a given depth interval was recorded for most drilling runs in USGS-STP2. The recorded times are for 20-ft drilling runs above a depth of 2,440 ft and 10-ft coring runs below 2,440 ft. The 20-ft intervals correspond to the collection intervals for cuttings samples. Drill penetration rates varied between 0.4 and 1.8 ft/min in the postimpact sediments above a depth of 1,163 ft (Fig. 4). Typically slower penetration rates occurred in the sediment-clast breccias of the impact structure between depths of 1,163 ft and 2,150 ft, generally in the range of 0.2 to 1.0 ft/min with faster rates in the sandier sections. Penetration rates in the crystalline-clast breccias below 2,150-ft depth were similar to those in the sediment-clast breccias. Coring runs below a depth of 2,440 ft had the slowest penetration rates, typically less than 0.3 ft/min.

Drill Penetration Rate

Feet/minute
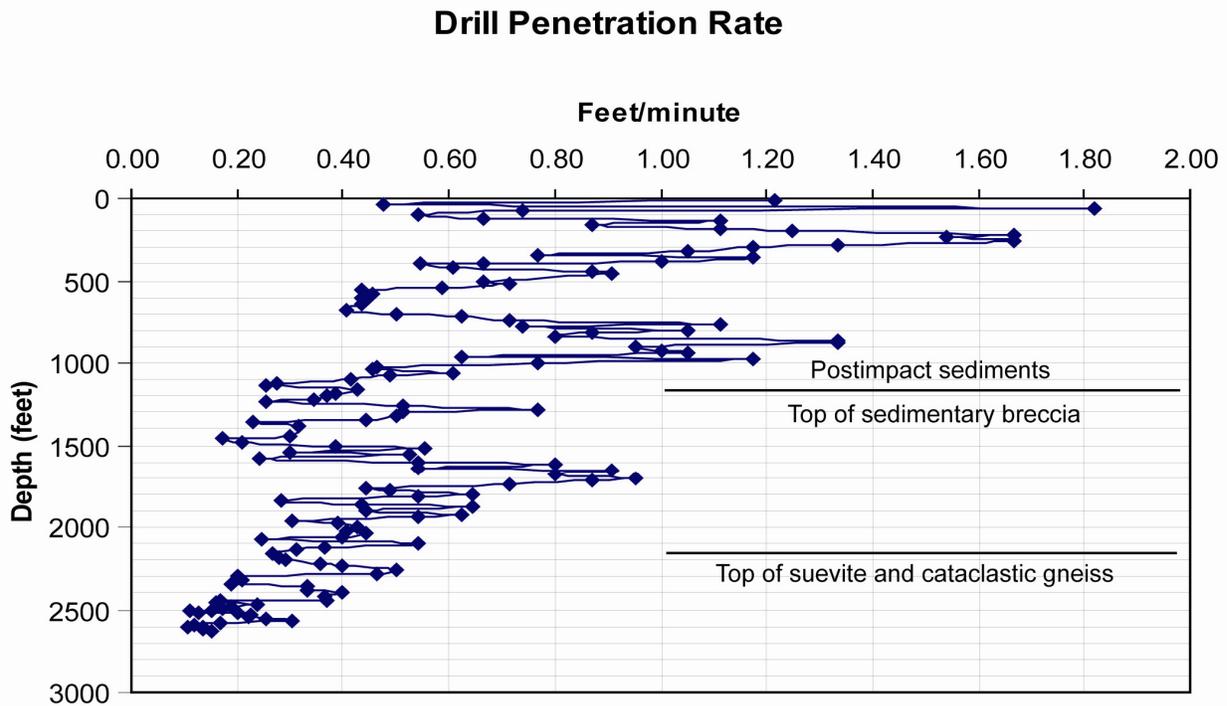
Figure 4. Drill penetration rate for the USGS-STP2 test hole.

Coring Runs

Twenty-nine coring runs were completed in the USGS-STP2 hole (Table 1). Two coring runs were conducted within sediment-clast breccias of the impact structure between depths of 1,401.7 and 1,420.7 ft. Twenty-seven coring runs were conducted in a section of crystalline-clast breccia and cataclastic gneiss between depths of 2,440 and 2,699 ft. A total of 278 ft of section was drilled with the core-sampling system.

Core recovery was moderately low (48.8 percent), owing in part to the alternation of hard and soft rocks within the breccia-gneiss section. Four coring runs recovered more than 70 percent of the drilled section, and five runs recovered less than 30 percent.

Cuttings samples were collected from the uncored intervals in USGS-STP2 below a depth of 280 ft. Individual cuttings samples generally represent 20 ft of section, equivalent to the 20-ft lengths of the drilling rods. The depth reference point for all core and cuttings samples was the land surface.

Table 1. Data for coring runs in the USGS-STP2 test hole.

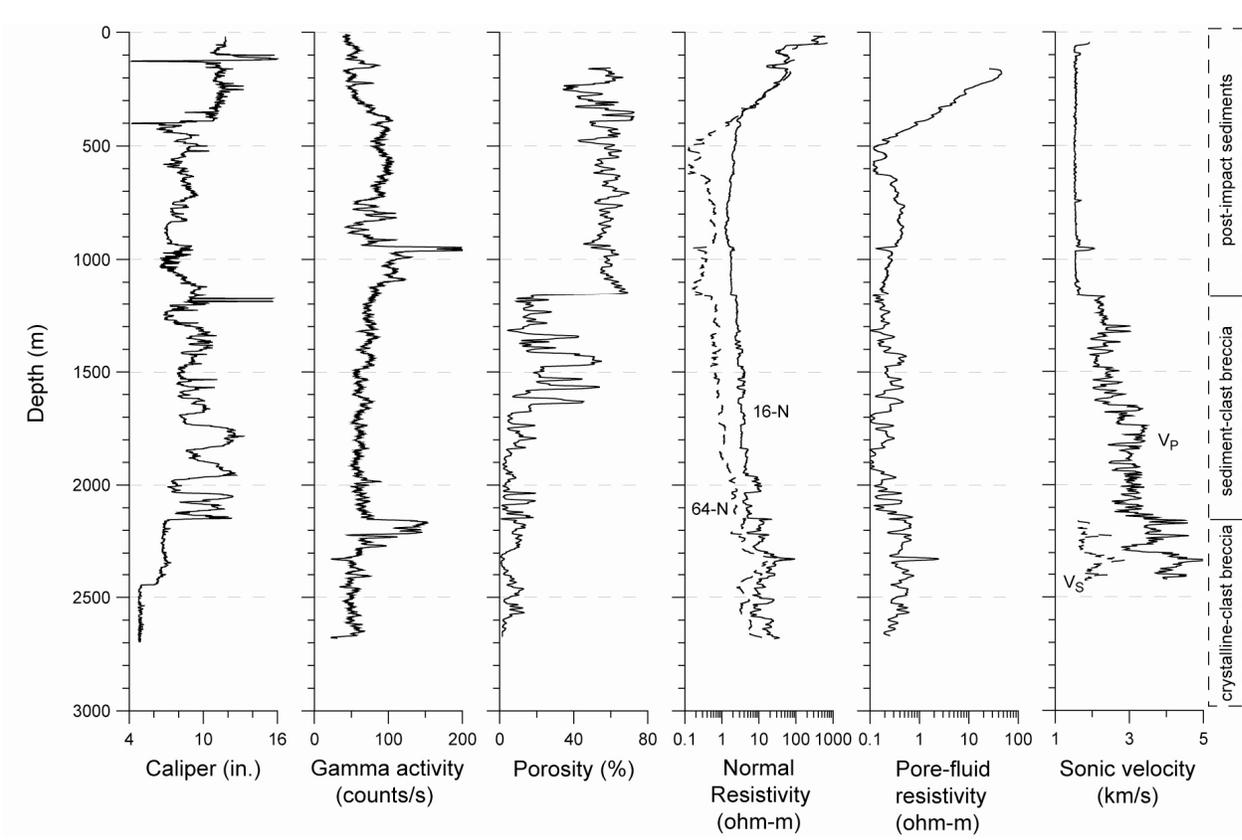[The indicated depths are listed as reported by the lead driller.]

Core	Top (ft)	Bottom (ft)	Top (m)	Bottom (m)	Recovery (ft)	Recovery (m)	Recovery (%)	Comments
1	1401.7	1410.7	427.24	429.98	8.6	2.62	95.6%	Loss at bottom; short run
2	1410.7	1420.7	429.98	433.03	4.9	1.49	49.0%	Loss at bottom
3	2440.0	2450.0	743.71	746.76	4.6	1.40	46.0%	Loss at bottom
4	2450.0	2460.0	746.76	749.81	5.1	1.55	51.0%	Loss at bottom
5	2460.0	2470.0	749.81	752.86	6.3	1.92	63.0%	Loss at bottom
6	2470.0	2480.0	752.86	755.90	3.2	0.98	32.0%	Loss at bottom
7	2480.0	2490.0	755.90	758.95	5.2	1.58	52.0%	Loss at bottom
8	2490.0	2500.0	758.95	762.00	4.2	1.28	42.0%	Loss at bottom
9	2500.0	2510.0	762.00	765.05	3.5	1.07	35.0%	Loss at bottom
10	2510.0	2515.0	765.05	766.57	3.1	0.94	62.0%	Loss at bottom; short run
11	2515.0	2522.0	766.57	768.71	3.0	0.91	42.9%	Loss at bottom; short run
12	2522.0	2529.0	768.71	770.84	1.0	0.30	14.3%	Loss at bottom; short run
13	2529.0	2539.0	770.84	773.89	3.4	1.04	34.0%	Loss at bottom
14	2539.0	2549.0	773.89	776.94	3.5	1.07	35.0%	Loss at bottom
15	2549.0	2559.0	776.94	779.98	0.2	0.06	2.0%	Loss at bottom
16	2559.0	2569.0	779.98	783.03	9.0	2.74	90.0%	Loss at bottom
17	2569.0	2579.0	783.03	786.08	6.6	2.01	66.0%	Loss at bottom
18	2579.0	2589.0	786.08	789.13	5.1	1.55	51.0%	Loss at bottom
19	2589.0	2599.0	789.13	792.18	1.9	0.58	19.0%	Loss at bottom
20	2599.0	2609.0	792.18	795.22	6.3	1.92	63.0%	Loss at bottom
21	2609.0	2619.0	795.22	798.27	2.7	0.82	27.0%	Loss at bottom
22	2619.0	2629.0	798.27	801.32	4.3	1.31	43.0%	Loss at bottom
23	2629.0	2637.0	801.32	803.76	2.3	0.70	28.8%	Loss at bottom; short run
24	2637.0	2649.0	803.76	807.42	3.9	1.19	32.5%	Loss at bottom; long run
25	2649.0	2659.0	807.42	810.46	5.3	1.62	53.0%	Loss at bottom
26	2659.0	2669.0	810.46	813.51	6.7	2.04	67.0%	Loss at bottom
27	2669.0	2679.0	813.51	816.56	9.0	2.74	90.0%	Loss at bottom
28	2679.0	2689.0	816.56	819.61	9.0	2.74	90.0%	Loss at bottom
29	2689.0	2699.0	819.61	822.66	3.8	1.16	38.0%	Loss at bottom
				Totals:	135.7	41.36	48.8%	

Geophysical Logging

Geophysical logging of the USGS-STP2 test hole was conducted in four stages at depths of 394 ft, 1,400 ft and 2,699 ft (Table 2). Geophysical tools consisted of the caliper, multifunction, full-waveform sonic velocity, neutron porosity, and gamma-gamma density probes. More information regarding the principles of operation of these logging tools can be found in Hearst and others (2000). A composite of the geophysical logs collected and analyzed from test hole USGS-STP2 is shown in Figure 5. The individual logs obtained from the four separate logging runs have been spliced together and have undergone a simple smoothing process to reduce high-frequency variations and improve visual recognition of trends at the scale of the plots. All log depths are referenced to land surface.

Table 2. Record of geophysical logging activities in the USGS-STP2 test hole.

Logging Runs	Run 1A	Run 1B	Run 2	Run 3
Date	May 12, 2004	May 12, 2004	May 17, 2004	May 26-27, 2004
Start Time	12:30 AM	9:55 AM	10:30 AM	4:30 PM
Nominal top logged interval (ft)	0	0	400	1,400
Nominal base logged interval (ft)	125/390	394	1,400	2,699
Base drilled interval (ft)	394	394	1,400	2,699
Probes (depth interval, ft)	Caliper (to 390)	Caliper (to 394)	Caliper (395-1,400)	Caliper (400-2,699)
	- - -	Density (26-377)	Density (140-1,400)	Density (1,360-2,430)
	Multifunction (to 125)	Multifunction (to 394)	Multifunction (397-1,400)	Multifunction (1,337-2,687)
	- - -	Porosity (26-394)	- - -	Porosity (80-2,655)
	Sonic (to 120)	Sonic (180-390)	Sonic (404-1,400)	Sonic (1,390-2,440)

Figure 5. Composite of geophysical logs obtained in test hole USGS-STP2. See list of Conversion Factors (above) to convert SI units to Inch/Pound units.

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An attempt was made during the final logging stage to record an acoustic televiewer log across a depth interval where the hole was reasonably intact and its diameter fairly uniform (2,380 ft to 2,430 ft). This tool provides magnetically oriented images of the borehole wall from which fractures, bedding, and other features may be identified and oriented. Regrettably, this run was unsuccessful due to the presence of thick mud in the hole that inhibited the transmission of acoustic pulses to the wall and back again to the tool transmitter-receiver. In addition, data acquired from the gamma-gamma density tool generally were unreliable and of poor quality, primarily because of large variations in borehole diameter that could not be adequately compensated by the tool. Consequently, acoustic televiewer data and density values are not included in the plots of Figure 5.

The three-arm caliper tool provides an approximate measure of borehole diameter. The three arms do not operate independently, and the resulting response is considered to be an average estimate of hole diameter. The caliper log in Figure 5 displays substantial enlargements in borehole diameter within the postimpact sediments and the sediment-clast breccia that extend well beyond bit gauge. This is indicative of a very unstable borehole and mechanically weak geologic materials. Conditions improve markedly below 2,150 ft in the more competent breccia-gneiss section, and the replacement of the drilling bit with the coring bit near 2,440 ft is recognized as a step reduction in diameter at 2,444 ft.

The multifunction tool is equipped to measure natural gamma activity, electrical resistivity, borehole fluid conductivity, and borehole fluid temperature. Borehole fluid conductivity and temperature data were not useful under these field conditions because of the significant disturbances to the fluid column imposed by numerous episodes of mud circulation required during drilling. Therefore, logs of borehole fluid properties are not included in this report. The gamma-activity log is a measure of natural gamma radiation being emitted by the surrounding rocks and sediments. Clays tend to accumulate radioisotopes through adsorption and ion-exchange processes, and zones of high gamma activity are typically interpreted as being clay rich. Feldspathic sandstones, phosphatic limestones, and glauconitic sands also are associated with high gamma responses. Two zones that display increased gamma counts in Figure 5 are present in the lower part of the postimpact sediments (940 ft to 1,150 ft) and the upper part of the breccia-gneiss section (2,150 ft to 2,220 ft).

Electrical resistivity measurements consisted of short-normal (16-inch) and long normal (64-inch) resistivities, also referred to as near and far resistivities, respectively. Saturated formation resistivity is primarily a function of porosity, pore-fluid resistivity, and mineralogy. It typically correlates positively with grain size and negatively with porosity. A lower resistivity corresponds to higher porosity or to smaller grain size because the surface area associated with fine particles promotes the transmission of electric current (Biella and others, 1983; Kwader, 1985). In addition, resistivity profiles are often effective in identifying freshwater-seawater interfaces.

Plots of the 16-inch (solid line) and the 64-inch (dashed line) resistivity logs are displayed in Figure 5 at a logarithmic scale. The separation between the two plots is attributed to the presence of a drilling mud that is more resistive than seawater but less resistive than fresh water. The far measurement (64-inch) has a greater volume of investigation beyond the borehole and is proportionally less influenced by drilling mud than is the near measurement (16-inch). The logs depict a gradual downward transition from freshwater to seawater in the upper 400 ft, with the far resistivity being slightly greater than the near one. Below this zone, the far measurement is consistently less than the near resistivity due to the salinity of the saturating pore fluid, although the difference is very small (logarithmic scale). Slight incremental increases in resistivity are seen at both major lithologic contacts (1,163 ft and 2,150 ft).

The neutron probe used in this study was a single-detector epithermal tool that yields an estimate of saturated formation porosity. This tool has been calibrated in specially designed test

pits, and the response of the neutron detector, in counts per second, can be accurately converted to quantitative values of total porosity provided the formation is saturated. This estimate of total porosity includes both free water and bound water on clay surfaces. The porosity profile presented in Figure 5 shows a marked shift at the sediment-breccia contact (1,163 ft) that clearly distinguishes between the high-porosity postimpact marine sediments (porosity ~ 60 percent) and the underlying sediment-clast breccia (porosity ~ 20 percent). The porosity estimates for the postimpact sediments, in the range of roughly 50 to 65 percent, are in good agreement with laboratory measurements conducted on various core samples from other drillholes (W. E. Sanford, USGS); porosities of the sediment-clast breccia are also in general agreement with core-derived data from other drill holes (E.R. McFarland, USGS, written communication).

The porosity and the resistivity logs were combined to arrive at estimates of pore-fluid resistivity using Archie's law (Archie, 1942), after making some general assumptions about cementation and grain size and shape. The far resistivity was used in this calculation because it was considered to be less affected by drilling-mud invasion into the formation than was the near resistivity. The resulting plot of resistivity of the saturating pore fluid is shown in Figure 5 at a logarithmic scale, and it tends to mimic the 64-inch resistivity log. The pore fluid appears to be fresh water near the surface (~ 40 ohm-meters), but gradually changes to brackish water (~ 4 ohm-meters) and finally to seawater (~ 0.4 ohm-meter) below 500 ft.

The full-waveform sonic tool is equipped with a variable frequency transmitter and three receivers. Logs were obtained at a frequency of 10 kHz and were later processed by means of a semblance technique (Paillet and Cheng, 1991) to arrive at estimates of sonic velocities. Plots of compressional-wave velocity V_P (solid line) and shear-wave velocity V_S (dashed line) are presented in Figure 5. A log of the compressional-wave velocity was constructed from the full waveforms down to 2,440 ft. This profile clearly delineates the contact between the postimpact sediments and the underlying sediment-clast breccia at 1,163 ft and indicates that the value of V_P in the sediments approaches that of water alone (~ 1.55 km/s). Below this contact, the compressional-wave velocities gradually increase downward in the sediment-clast breccia. Below 2,150 ft, V_P increases to almost 5 km/s as the rocks become more indurated and mechanically competent. Because of poor sampling conditions (borehole enlargements, mud invasion), it was difficult to transmit enough energy into the surrounding rocks to generate a detectable shear wave in all but the hardest rocks. Consequently, the plot of V_S is limited to only the lowermost breccia-gneiss section, where V_S is roughly half the velocity of V_P. These values fall within a well-constrained lithology band presented by Paillet and Cheng (1991).

Well Installation

Well installation in USGS-STP2 began on May 27th following the geophysical logging and lasted about three days. Two wells were completed in this single borehole (Fig. 6). Both wells were constructed of 2.5-inch-diameter, schedule-80, flush-jointed PVC with 20-ft stainless-steel, wire-wrap screens and 5-ft stainless-steel sumps. The deep well and shallow well were assigned USGS unique numbers 62G-24 and 62G-25, respectively. The screen of the deep well was installed between 2,260 ft and 2,280 ft with the sump extending to 2,285 ft. The screen of the shallow well was installed between 1,360 ft and 1,380 ft with the sump extending to 1,385 ft. The screen locations were chosen based on the formation lithologies and geophysical logs.

The annular spacing around the wells was filled with a combination of pea gravel, bentonite pellets, and bentonite grout. The section of the hole beneath the bottom screen, from 2,320 ft to 2,699 ft, was plugged with abandonment bentonite grout. The section around the deep screen, from 2,070 ft to 2,320 ft, was filled with pea gravel. A section above the pea gravel from 2,010 ft to 2,070 ft was then filled using bentonite pellets with minor amounts of pea gravel. The section from there up to the shallow screen, from 1,415 ft to 2,010 ft, was filled with a high-solids abandonment bentonite grout. A short section below the shallow screen, from 1,400 ft to 1,415 ft, was filled using bentonite pellets with minor amounts of pea gravel. The area around the shallow screen, from 1,300 ft to 1,400 ft, was filled with pea gravel. Another short section above the gravel, from 1,275 ft to 1,300 ft, was filled using bentonite pellets with minor amounts of pea gravel. The remaining hole down to 1,275 ft was filled with a high-solids abandonment bentonite grout, except for the top 10 ft, which was finished with cement.

The wells were developed using air immediately following their installation. Air was injected at high flow rates at about 500 ft below land surface, which brought a combination of air, mud, and formation fluid to the land surface. The air development was continued for a time period of ten hours before the drilling crew returned to Denver for a break. The crew returned about a week later to pack their equipment and drive back to Denver. The drilling mud was made with fresh water, which was used as one indicator of the extent to which the wells were developing. The deep well produced water at a decent rate such that, after ten hours, salt water was the dominant fluid coming out of the hole. The shallow well, however, had a lower yield, such that after ten hours the fresh-water-based drilling fluid had not been completely purged from the well.

Slug tests were performed on the wells on October 29, 2004, before the purging continued. At this point in time, the water level in the deep well was 5.83 ft bmp (below the measuring point, i.e., the top of the well casing), and the shallow well was shut in with a pressure of 5 psi. The artesian head on the shallow well was attributed to the fresh drilling fluid (less dense than the formation water) that remained in the well casing. The deep well was drawn down to 28 ft bmp after pumping for 15 minutes at a rate of about 1 gpm. The pump was then turned off and the water level recovered to 7.8 ft bmp after 45 minutes. The shallow well was drawn down to 31 ft bmp after pumping for 15 minutes at a rate of about 1 gpm. The pump was then turned off and the water level recovered to 11.6 ft bmp after 7 hours.

The purging process was continued beginning in May 2005 using a remote system consisting of pumps, data loggers, pressure transducers, conductivity meters, on/off switches for the pumps, and a solar panel. The wells were purged remotely for over a month until the conductance of the discharging fluids stabilized. The wells were then sampled on June 28, 2005. Final salinities of the waters stabilized at 40 parts per thousand for the deep well and 20 parts per thousand for the shallow well. The water level in the shallow well eventually stabilized below the top of the well casing at some time during the summer of 2005.
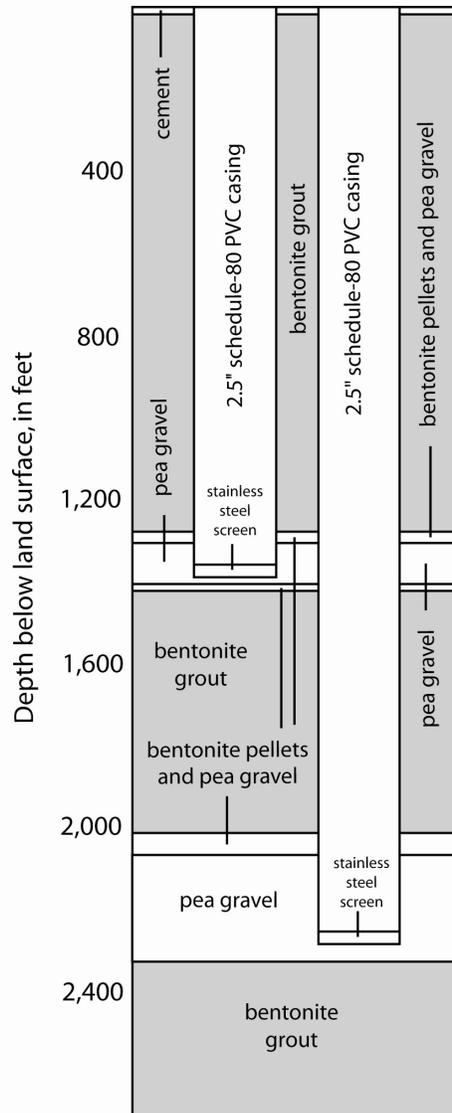
Figure 6. Diagram showing water wells 62G-24 (deep well) and 62G-25 (shallow well) in the USGS-STP2 test hole.

Preliminary Site Geology

The geologic section in the USGS-STP test holes consists of three major units (Sanford and others, 2004; Horton and others, 2004, 2005b): (1) a lower impact-structure section of crystalline-clast breccia and cataclastic gneiss, (2) an upper impact-structure section of sediment-clast breccia, and (3) postimpact sediments (Figs. 5, 7).

The lower and upper impact-structure sections are present from the base of the test hole at 2,699-ft depth to 1,163-ft depth, for a total penetrated thickness of 1,536 ft. These sections are separated by a contact at 2,150-ft depth. Thus, the section of crystalline-clast breccia and cataclastic gneiss is at least 549 ft thick, and the section of sediment-clast breccia is 987 ft thick. The postimpact section extends from 1,163 ft depth to the land surface.

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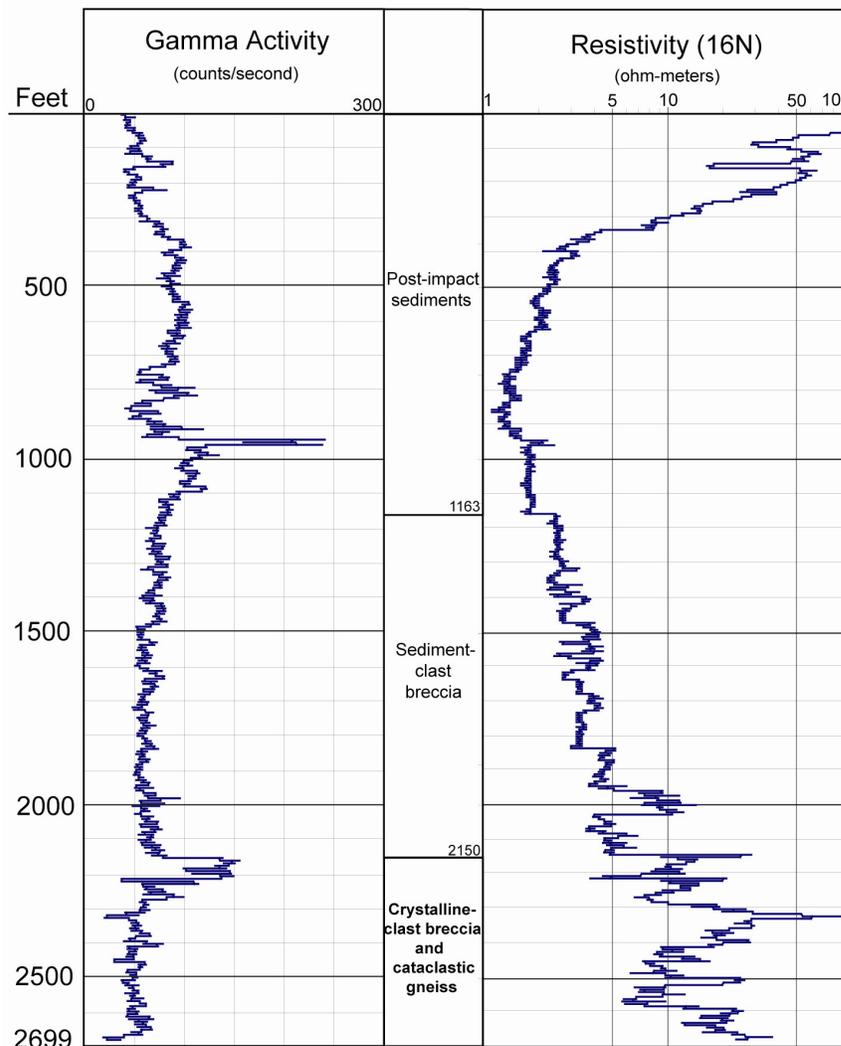
Figure 7. Generalized geologic column, and gamma-activity and short-normal-resistivity logs, from the USGS-STP2 test hole.

Crystalline-clast Breccia and Cataclastic Gneiss

The deepest part of the USGS-STP2 section consists primarily of crystalline-clast breccia and cataclastic gneiss. The upper contact of this rock unit is defined at 2,150 ft depth by the appearance of abundant crystalline-rock chips in the drill cuttings. This contact also is coincident with down-hole increases in resistivity, compressional velocity, and natural gamma activity on the borehole geophysical logs (Figs. 5, 7). Drill cuttings below 2,150 ft contain chips of granitic rock, gneiss, slaty rock, and minor fine-grained mica schist, in addition to clay and sand from higher levels in the test hole.

Drill cores were obtained from 2,440 ft to the base of the test hole at 2,699 ft depth. This cored section consists of polymict crystalline-clast breccia, cataclastic quartzofeldspathic gneiss, slate and slaty metasiltstone, and smaller amounts of cataclastic chlorite-rich mafic rock (Horton and others, 2005c). Some of the crystalline-clast breccia is suevite (Horton and others, 2004,

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2005c), meaning that it contains clasts of impact-melt rock (see Lee and others, 2006), although clasts of quartzofeldspathic gneiss and chloritic mafic rock are more abundant. The suevitic breccia is crumbly to moderately cohesive.

Minerals in the crystalline-clast breccia and cataclastic gneiss include plagioclase (mainly albite), quartz, chlorite, minor calcite, and traces of pyrite (Horton and others, 2005c). The rocks also contain shocked quartz and other shocked minerals (Horton and others, 2004, 2005c; Jackson and others, 2006). Secondary chlorite and albite are attributed to hydrothermal alteration (Horton and others, 2004, 2005b; Sanford, 2005).

Sediment-Clast Breccia

The central part of the test-hole section is interpreted to consist of sediment-clast breccias that are typical of the sediment-clast breccias found throughout the Chesapeake Bay impact structure (Powars and Bruce, 1999; Poag and others, 2004; Horton and others, 2005b). The top of this breccia in the USGS-STP2 test hole is marked by the first (highest) down-hole appearance of abundant loose granules and medium to very coarse sand that consist primarily of quartz, glauconite, and feldspar, along with drilling chips that consist of a wide variety of sediments and crystalline rocks. This first appearance is in the upper part of the cuttings sample from 1,160 to 1,170 ft. The naturally heterogeneous composition of the sediment-clast breccia, combined with the mixing and caving of cuttings produced by rotary drilling, prevents the identification of all but the broadest lithologic trends within this section in USGS-STP2.

Loose grains in the breccia cuttings consist of quartz, glauconite, and feldspar with minor amounts of shell fragments, white mica, and pyrite and trace amounts of microfossils, wood, phosphate, and fish teeth. Coherent chips of sediment in the cuttings primarily consist of silty clays and clayey silts in a wide variety of colors. Chips of oxidized clayey silts and sands from the Cretaceous Potomac Formation are particularly common, whereas soft chips of muddy glauconitic sand from the breccia matrix are rare. Caved chips from the postimpact sedimentary section encountered higher in the test hole also are common, including cemented quartz-glauconite sand, muddy quartz sand, and shelly limestone.

Chips of crystalline rocks in the breccia cuttings primarily consist of granitic rocks and chert. Less common rock types include light-red or light-gray felsite, chloritic gneiss, diabase, slate, and finely crystalline or aphanitic mafic rocks.

Two runs recovered 13.5 ft of core from the interval between depths of 1,401.7 ft to 1,420.7 ft. The cored material is heterogeneous and contains: (1) glauconite-bearing quartz sand that contains mixed-age and impact-damaged microfossils and darkened plant debris, (2) massive coarse to very coarse sand with granules and pebbles (possible fluidized Cretaceous sand), (3) medium to coarse sands that show high angle lamination (possible clasts of Cretaceous sediment), (4) sand with clay clasts up to 2 inches (possible fluidized Cretaceous sand or clast), (5) a one-foot-thick concentration of pebbles up to 1.2 inches, where the pebbles are rounded to angular and include quartz, rock fragments, and clasts of red silty clays. Contacts between these lithologies are sharp.

The geophysical logs show general increases in resistivity and compressional velocity, and a general decrease in porosity, with increasing depth within the sediment-breccia section (Fig. 5, 7). Lithification of the clay cuttings from the sediment-clast breccia also progressively increases with depth. These trends may indicate postimpact compaction, early postimpact hydrothermal alteration, or both. A more abrupt downward increase in compressional velocity and a more abrupt downward decrease in porosity near 1,650 ft depth may indicate increases in the number and size of sediment clasts that have retained their preimpact densities. Below about 1,650 ft, the log patterns

suggest intervals of relatively uniform lithology that may represent sediments blocks that are tens of feet, to perhaps 100 ft, in thickness.

Regionally within the impact structure, the lower part of the sediment-clast breccia consists of blocks and megablocks (tens to hundreds of feet in diameter) of pre-impact sediments within a matrix of exotic and (or) locally derived sediments (Powars and Bruce, 1999; Poag and others, 2004; Gohn and others, 2005). In the outer part of the structure, the sediment blocks are primarily autochthonous to parautochthonous, having been disrupted in place by the impact. In the central part of the structure, the sediment blocks are allochthonous, having slumped into the central part of the impact structure during late-stage gravitational collapse.

The informally defined Exmore beds (Powars et al., 1992) constitute the upper part of the sediment-clast breccia throughout the structure. As seen in other cored test holes, the Exmore beds consist of abundant pebbles, cobbles, and small boulders of preimpact Cretaceous and lower Tertiary sediments and sparse pebbles and cobbles of preimpact crystalline rocks dispersed in an unstratified and unsorted matrix of calcareous, muddy, quartz-glauconite sand and granules (Powars and Bruce, 1999; Poag and others, 2004; Gohn and others, 2005). These materials are interpreted to represent ocean-resurge deposition within the impact structure.

The transition from synimpact to postimpact sedimentation is marked by a thin interval of laminated, clayey sands and silts in coreholes drilled within the impact structure (Poag and others, 2004; Powars and others, 2005). A few laminated silt and clay chips found in the cuttings may indicate the presence of a similar transition zone in the USGS-STP2.

Postimpact Sediments

Upper Eocene Section – Chickahominy Formation (1,163 ft to 993 ft)

Upper Eocene sediments in the USGS-STP2 test hole were sampled only as cuttings from depths of about 1,163 ft to 993 ft. The lower contact with the sediment-clast breccia was picked on the basis of the first (highest) down-hole appearance of abundant glauconite and lithic fragments in the run from 1,180-ft to 1,160-ft depth. There also are sharp down-hole increases in resistivity and compressional velocity, and a sharp down-hole decrease in porosity, between depths of 1,165 ft and 1,162 ft (Figs. 5, 7).

The upper contact of the upper Eocene sediments with the overlying Oligocene sediments was difficult to pick during drilling because the Eocene lithology returned few cuttings and tended to form "clay boots" (clay adhering to the drill bit and rods), particularly when a roller bit were used instead of a wing bit. The upper contact was placed at 993-ft depth by comparison of the USGS-STP2 gamma-activity log with the equivalent log from the USGS-Watkins School corehole, located in Newport News, Va. (Edwards and others 2004b), and the onsite observation of a sandier interval in the middle of the 1,000-ft to 980-ft interval.

The upper Eocene sediments in the USGS-STP2 hole are approximately 179 ft thick and are assigned to the Chickahominy Formation. This unit is known only in the subsurface and only in the vicinity of the Chesapeake Bay impact structure (Powars and Bruce, 1999; Poag and others, 2004). Chickahominy cuttings from the USGS-STP2 test hole consist of very stiff, very clayey silt that contains sparse to abundant foraminifera, local shell fragments, and a trace to 2 percent of glauconite in the silt to very fine sand fraction. The sediment color is olive gray (5Y3/2) to grayish olive (10Y4/2). Minor variations in the drilling speed likely reflect minor variations in grain size (Fig. 4).

Oligocene Section - Delmarva Beds, Drummonds Corner Beds, Old Church Formation (993 to 955 ft)

Three Oligocene units are recognized in the subsurface of the Virginia Coastal Plain (Edwards and others, 2005; Powars and others, 2005). These are, in ascending order, the informal Delmarva beds, the informal Drummonds Corner beds, and the Old Church Formation. The lower two units are known only from the subsurface; the Old Church crops out in a thin band in the eastern Virginia mainland and also is present in the subsurface. These Oligocene units are recognized from 993-ft to 955-ft depth in the USGS-STP2 test hole on the basis of cuttings lithologies and comparison of the gamma-activity log with the equivalent log from the Watkins School corehole (Edwards and others, 2004b). The contact between the base of the Oligocene section (base of Delmarva beds) and the underlying Chickahominy Formation is placed at the base of a small gamma spike at 993-ft depth. (Fig. 7) The upper contact of the Oligocene section at 955 ft is placed at the base of the higher of two closely spaced, prominent gamma spikes (Fig. 7). Where dated by microfossils from corehole sections, sediments of the higher prominent gamma spike are early Miocene in age. Patterns of gamma spikes similar to the one seen in the USGS-STP2 log are typical of Oligocene sections in other drill holes in southeastern Virginia (Powars and Bruce, 1999). In the USGS-STP2 cuttings, a 0.24-inch phosphate pebble was recovered near the end of the run from 960 ft to 940 ft.

Approximate depths for the Oligocene units in the USGS-STP2 hole are: Delmarva beds, 993 ft to 980 ft; Drummonds Corner beds, 980 ft to 962 ft; and Old Church Formation, 962 ft to 955 ft. Cuttings from the Delmarva beds and Drummonds Corner beds consist of clayey silt that contains less conspicuous foraminifera and more prominent glauconite and (or) phosphate than the silts from the underlying Chickahominy. Cuttings from the Old Church Formation consist of brownish-black to olive-black glauconite-phosphate sand in a clayey silt matrix. Some of the recovered cuttings show burrows of sand into lighter colored clayey silt.

Lower and Middle Miocene Section – Calvert and Choptank Formations (955 ft to 606 ft)

Lower and middle Miocene sediments are present at depths of about 955 ft to about 606 ft in the USGS-STP2 test hole. This 349-ft-thick interval consists primarily of clayey silt. The lower contact at 955 ft is placed at the base of a characteristically large gamma-activity spike (Fig. 7) that is produced by phosphatic sediments and correlates well with the gamma-activity log from the nearby Kiptopeke corehole in Northampton County, Va. (Powars and Bruce, 1999). At Kiptopeke, this gamma spike represents the basal beds of the lower Miocene deposits that Powars and Bruce (1999) named the Newport News beds of the Calvert Formation. In the USGS-STP2 test hole, cuttings from the run at depths of 960 ft to 940 ft show the first down-hole appearance of shelly very fine to fine quartz sand with scattered fine to granular phosphate grains (fine pebbles). The upper contact is placed at 606-ft depth where an abrupt change in the drilling rate was recorded (Fig. 4).

These shallow-marine deposits are distinctly olive gray (5Y3/2) to olive gray (5Y4/1) to grayish olive (10Y4/2). The clayey silt has abundant microfossils (mostly foraminifera and diatoms) and sparse, scattered shell fragments. Glauconite (<1% to 5%) is present locally, mica (1% to 3%) is present, and very fine to fine quartz sand and very thin slightly sandier intervals are observable in cuttings.

Most of the lower and middle Miocene section in the USGS-STP2 test hole is considered to be the lower and middle Miocene Calvert Formation (Newport News beds and Fairhaven, Plum Point, and Calvert Beach Members); however, approximately the upper 20 ft may represent the

middle Miocene Choptank Formation. A thin Choptank Formation was identified in the updip Watkins School core (Edwards and others, 2004b) and correlation of the Watkins School gamma-activity log to the equivalent USGS-STP2 log suggests that the presence of the Choptank in the USGS-STP2 hole should be considered. Although Powars and Bruce (1999) did not identify a Choptank section in the Kiptopeke corehole, the dinocyst data of de Verteuil and Norris (1996; their highest sample assigned to the Calvert Formation) support the presence of the Choptank at Kiptopeke.

Upper Miocene Section – St. Marys and Eastover Formations (606 ft to 168 ft)

Upper Miocene sediments in the USGS-STP2 test hole were sampled only as cuttings between depths of about 606 ft and 168 ft. The lower contact is marked by a dramatic down-hole color change from dark greenish gray (5GY5/1 to 5GY4/1) to olive gray (5Y3/2) and an abrupt down-hole change to much denser, more brittle clayey silt that drilled significantly more slowly than the upper Miocene sediments (Fig. 4). There may be a thin cemented bed at the top of the underlying middle Miocene sediments. The lower contact also is marked by the down-hole appearance of fine sand with phosphate chips in the lower few feet of the upper Miocene section. The upper contact was picked on the basis of similarities between the USGS-STP2 gamma-activity log and the gamma-activity log for the Langley corehole (Powars and others, 2005). This contact is placed at the base of a high-gamma spike in the lower part of the overlying Pliocene section in the USGS-STP2 test hole (Fig. 7).

The lower 266 ft of the upper Miocene section is assigned to the St. Marys Formation (606 ft to 340 ft depth). This formation consists, in part, of a basal fine sand that is only a few feet thick. The basal sand is overlain by 50 ft of very clayey silt, that is overlain, in turn, by silty clay that grades upward at about 440-ft depth into a clayey silt. The upper 172 ft of the upper Miocene section is assigned to the Eastover Formation (340 ft to 168 ft depth). The Eastover sediments are well sorted, variably shelly, silty, very fine to fine sand.

Pliocene Section – Yorktown and Chowan River Formations (168 ft to 32 ft)

Sediments from depths of about 168 ft to 32 ft in the USGS-STP2 test hole are assigned to the Pliocene on the basis of cuttings descriptions and correlation of the geophysical logs with the nearby Kiptopeke corehole (Powars and Bruce, 1999). The lower contact with the underlying upper Miocene sediments was placed at 168-ft depth on the basis of comparisons with the Kiptopeke gamma-activity and resistivity logs. Cuttings logged at 180 ft to 160 ft included shelly (turritellids and *Chesapecten*), fine to medium quartz sand with bone fragments and phosphate and glauconite (up to 15%), as well as silty fine sand with phosphate and glauconite (up to 10%). The upper contact with the overlying Pleistocene Nassawadox Formation at a depth of 32 ft is obvious, with yellow pebbly sand of the Nassawadox overlying dark-greenish-gray (5GY4/1), finer grained, shelly sands of the Pliocene section.

The Pliocene section is 136 ft thick. The lower 22 ft consists of grayish-green (10G4/2), variably shelly, fine to medium sand. The sediments above this basal sand are dark-greenish-gray (5GY4/1), clayey, silty, very fine to medium quartz sand with variable amounts of glauconite and phosphate (1% to 50 %). Fragmental and perhaps whole mollusks shells appear to be concentrated locally into thin beds (about 1-ft-thick), which also contain glauconite and phosphate as coarse sand, granules, and pebbles up to 0.6 inches, and which may contain bone chips and sharks teeth. Clay and silt cuttings from the Pliocene interval are typically medium dark gray (N4) and have less shell material, but more common foraminifera and sponge spicules, than the sands.

Following Mixon (1985) and Powars and Bruce (1999), most of the Pliocene section in the USGS-STP2 test hole is assigned to the Yorktown Formation. However, correlation with the Kiptopeke corehole (Powars and Bruce, 1999) suggests that the upper 28 ft of the USGS-STP2 Pliocene section may represent the Chowan River Formation, which typically fills paleovalleys or overlies ravinements cut into the top of the Yorktown.

Pleistocene Section – Nassawadox Formation (32 ft to 5 ft)

Cuttings recovered from the interval between depths of 32 ft and 5 ft in the USGS-STP test holes consist of poorly sorted, yellow to tan, fine to coarse sand with organic fragments (up to 5%) and scattered shell fragments, which grades downward to a very coarse pebbly sand at the unit's base. The sand and pebbles are subrounded to rounded. These lithologies are consistent with Mixon's (1985) description of the marginal-marine, late Pleistocene Butlers Bluff Member of the Nassawadox Formation. The Butlers Bluff Member is mapped across the Franktown Plain (flat upland surface and adjacent bay-side terrace), which includes the Cape Charles area. The Butlers Bluff Member is interpreted as a southward-building complex of spit-platform sands and very shallow shoals.

Modern Artificial Fill (5 ft to 0 ft)

Poorly sorted, pebbly, fine to coarse sand is present from a depth of about 5 ft to the land surface. This material is interpreted as artificial fill that was emplaced during construction of the parking lot located adjacent to the drill site.

Acknowledgments

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Appendix A: Drill-Site Staff

Drillers

USGS, Denver, Colo. Arthur C. Clark (Supervisor), Jeffery D. Eman (Field Foreman), Stephen J. Grant (Lead Driller), Robert R. Hunley (Lead Driller), Ronald A. Funkhouser, Michael J. Schulz, James O. Stull, and Michael E. Williams.

Site Geologists and Biologists

USGS, Reston, Va. Wilma B. Aleman Gonzalez, Lucy E. Edwards, Gregory S. Gohn, J. Wright Horton, Jr., Julie Kirshtein, James B. Murray, Joseph H. Murray, David S. Powars, Ward E. Sanford, Ellen L. Seefelt, Jean M. Self-Trail, and Mary A. Voytek.

University of Memphis, Memphis, Tenn. Daniel Larsen

Geophysical Loggers

USGS, Denver, Colo. Roger H. Morin and Barbara S. Corland