Distribution, Origin, and Resource-Management Implications of Ground-Water Salinity along the Western Margin of the Chesapeake Bay Impact Structure in Eastern Virginia

By E. Randolph McFarland and T. Scott Bruce

Chapter K of
**Studies of the Chesapeake Bay Impact Structure—
The USGS-NASA Langley Corehole, Hampton, Virginia, and
Related Coreholes and Geophysical Surveys**

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Contents

Figures

Table

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By E. Randolph McFarland[1] and T. Scott Bruce[2]

Abstract

Stratified unconsolidated sediments that compose a regionally extensive system of aquifers and confining units beneath the Virginia Coastal Plain contain saltwater approximately 50 kilometers (30 miles) landward of its normally expected position along the coast. Part of the Chesapeake Bay impact structure (formed by the collision of a large asteroid or comet) underlies the Virginia Coastal Plain. The impact severely disrupted preexisting sediments, and its effects are still influencing the regional ground-water flow. Geologic and hydrologic evidence indicates that the impact structure contains seawater emplaced during a regional inundation approximately 2 million years ago, along with much older seawater and evaporative brine emplaced potentially as far back as the impact event 35 million years ago.

With emergence of the coastal plain and resumption of ground-water recharge during the past 2 million years, freshwater flushing displaced residual seawater across the region but was impeded across the impact structure by the clayey Chickahominy Formation. Flushing took place laterally along the crater outer margin through underlying crater-fill sediments, followed by upward leakage and surface discharge to areas outside of the crater. Saltwater within the impact structure maintained its present position even as flushing outside of the impact structure extended in places nearly to the edge of the continental shelf during the Pleistocene glacial maximum of 18,000 years ago. Sea level has since risen to its present position, and the residual seawater has merged with the modern ocean along an inverted and unstable transition zone along the western margin of the impact structure that separates fresh ground water to the west from saltwater to the east.

During the past century, hydraulic gradients have been greatly increased and flow has been redirected landward across regional cones of depression centered on industrial pumping centers located outside of the impact structure. Saltwater intrusion across regional distances from the impact structure has not taken place, however, because most of the ground water now present was emplaced prior to the onset of heavy pumping. Because saltwater within the impact structure maintained its present position for millennia during freshwater flushing prior to pumping, a potentially very long timeframe could be required for regional saltwater intrusion to occur even under present gradients.

In contrast, localized saltwater movement along the western margin of the impact structure is possible across relatively short distances because of municipal withdrawals being made from within the saltwater transition zone. Major increases in withdrawal and desalinization of brackish ground water from the transition zone are being projected to address rapidly growing demands for public supplies during the coming several decades. Water-supply planning is challenged, however, by future increases in ground-water salinity that are difficult to estimate because of complex hydrogeologic controls and withdrawal-induced effects within the transition zone. A detailed local-scale characterization of hydrologic conditions along the western margin will be critical to assessment of the potential for saltwater movement.

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Introduction

Part of the Chesapeake Bay impact structure underlies the coastal plain of eastern Virginia (fig. K1). The structure was produced approximately 35 million years ago by the collision of a large asteroid or comet (Powars and Bruce, 1999). The area that became eastern Virginia was covered by the Atlantic Ocean at the time of impact. The discovery of the buried structure in the 1990s has led to a new understanding of regional ground-water flow.

Coastal plain aquifers are a heavily used water resource in Virginia (Hammond and Focazio, 1995). Large and increasing withdrawals have resulted in significant and continuing water-level declines (Hammond and others, 1994a,b,c) and have altered ground-water flow directions to create the potential for saltwater intrusion. In order to characterize and understand the hydrologic function of the aquifer system, a regional-scale hydrogeologic framework (Meng and Harsh, 1988) and ground-water flow model (Harsh and Laczniak, 1990) of the Virginia Coastal Plain were developed by U.S. Geological Survey (USGS) scientists during the early 1980s under the Regional Aquifer-System Analysis (RASA) Program. The framework and model were adopted by the Virginia Department of Environmental Quality (VDEQ) as a means to organize ground-water information and to evaluate the potential effects of proposed and existing withdrawals on ground-water levels and flows (McFarland, 1998).

In the RASA model, the Virginia Coastal Plain was depicted as a seaward-dipping and seaward-thickening, stratified sequence of unconsolidated sediments that made up a regionally extensive, vertically layered system of aquifers and confining units (fig. K2). The old model was based on the following ideas: (1) The unconfined aquifer at the land surface was recharged by infiltration of rainwater, some of which leaked downward through underlying confining units to recharge deeper confined aquifers. (2) Water flowed laterally through the aquifers toward the coast. (3) Upon encountering more dense saltwater, flow was diverted back to the surface as upward leakage and was discharged to Chesapeake Bay and the Atlantic Ocean.

Ground-water management efforts need to keep pace with changing demands on the resource and with current knowledge of the aquifer system. The amounts and locations of ground-water withdrawals have changed from those that were incorporated in the RASA model. In addition, recent efforts to further characterize the aquifer system have identified significant features that are not adequately represented in the original framework and model. Among these, the Chesapeake Bay impact structure requires changes to previous conceptualizations of the aquifer system as having a relatively simple layered configuration. The preexisting composition and structure of sediments within the impact area are now known to have been severely disrupted by the force of the collision, resulting in a complex stratigraphic and structural configuration. Strata affected by the impact were partly to entirely truncated across a crater and replaced by a chaotic mix of crater-fill sediments. The configuration of the outer regions of the impact structure is theorized to be controlled by a complex array of faults.

USGS and VDEQ scientists are investigating the Chesapeake Bay impact event and its effects on the geologic history of the region. Concomitantly, USGS and VDEQ researchers are analyzing geologic, hydrologic, and geophysical data to revise the hydrogeologic framework of the Virginia Coastal Plain, including the impact structure. In addition, a comprehensive assessment is being made of the quantities and distribution of ground-water withdrawals. All of these components are planned to contribute to an in-depth analysis and revision of the ground-water flow model.

In addition to the above studies, research is being done to obtain a better understanding of the processes affecting the distribution of saltwater within the aquifers. Parts of some aquifers across eastern Virginia have been known for many decades to contain saltwater approximately 50 kilometers (30 miles) landward of its expected position along the coast (Sanford, 1913; see fig. K1 of this chapter). The zone of saltwater is termed the "inland saltwater wedge"; it predates large ground-water withdrawals and was formed under unstressed conditions. Although localized increases in chloride concentration of several percentage points have been observed at various times during the history of ground-water development (Smith, 1999), regional saltwater intrusion has not taken place despite stress-induced water-level declines and altered flow directions. The western margin of the saltwater wedge is now recognized to coincide with the western margin of the Chesapeake Bay impact structure (Powars and Bruce, 1999). Thus, the impact structure has been inferred to play some role in the origin of the saltwater wedge and in controlling its response to pumping stresses.

Although some explanations for the presence of the saltwater wedge have been suggested both prior to (Cederstrom, 1943) and following (Powars and Bruce, 1999) the discovery of the impact structure, no definitive findings have been previously documented. Knowledge of processes controlling the salinity distribution is needed to support sound management of the ground-water resource. In addition to historically lowered water levels and altered flow directions that create the potential for saltwater intrusion, recent trends of increasing ground-water withdrawals within areas of elevated salinity (with subsequent desalinization treatment) pose the likelihood of additional effects on the salinity distribution. Hence, a clear understanding of the origin and emplacement of the saltwater is needed to predict its future response to numerous and diverse stresses on the flow system.

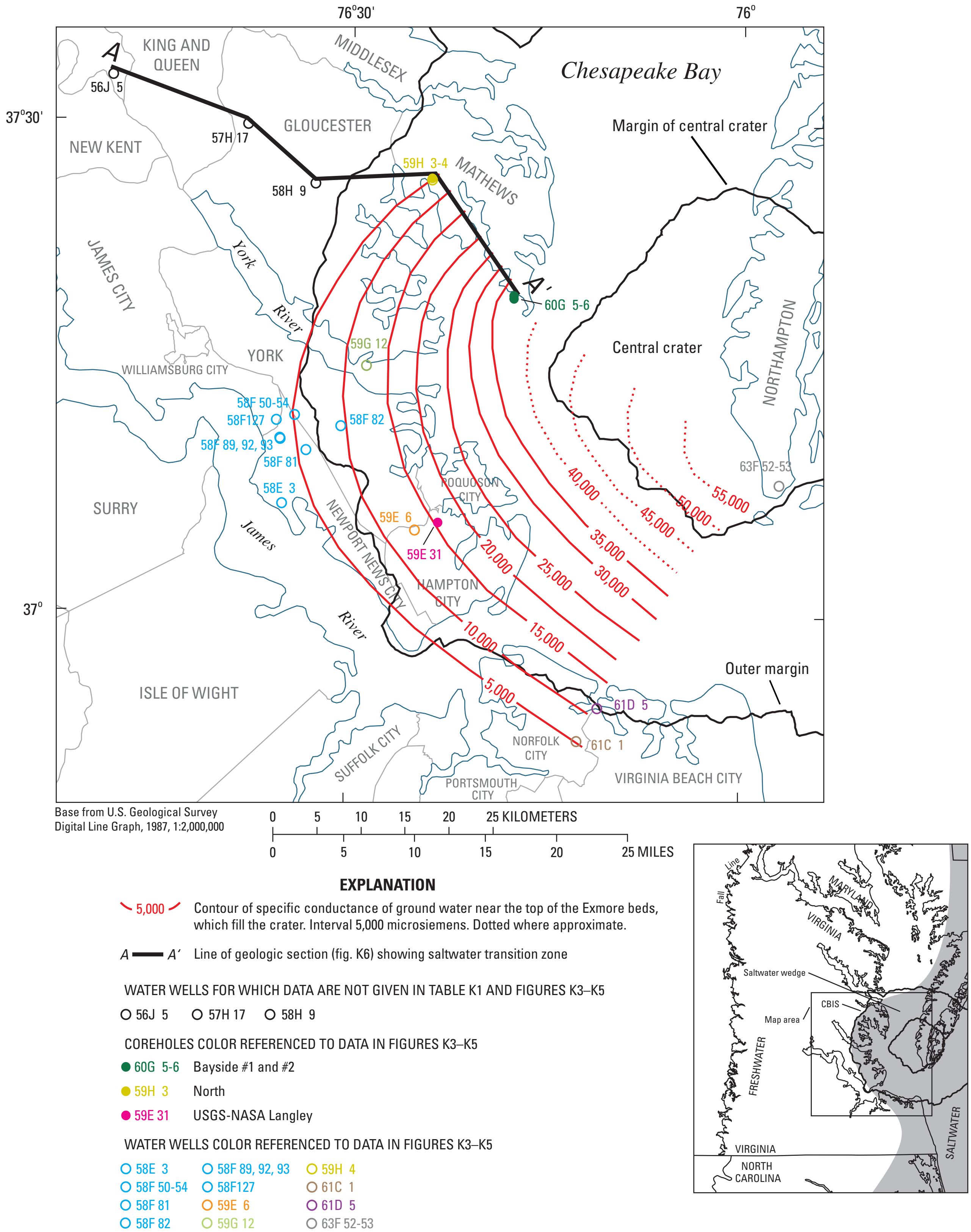

Figure K1. Map showing locations of sediment-core sites (coreholes) and well sites and ground-water specific conductance near the top of the Exmore beds along the western margin of the Chesapeake Bay impact structure (CBIS) in the Virginia Coastal Plain. Site locations are color referenced to sample data shown in figures K3–K5; chemical data for samples from these sites are in table K1 (at end of this chapter). Three open black circles indicate wells for which data are plotted in section *A–A'* in figure K6; no data for these wells are given in table K1 or figures K3–K5. Crater margins from Powars and Bruce (1999) and Powars (2000). Index map shows the distribution of fresh (unshaded) and salty (shaded) ground water and the location of the saltwater wedge.

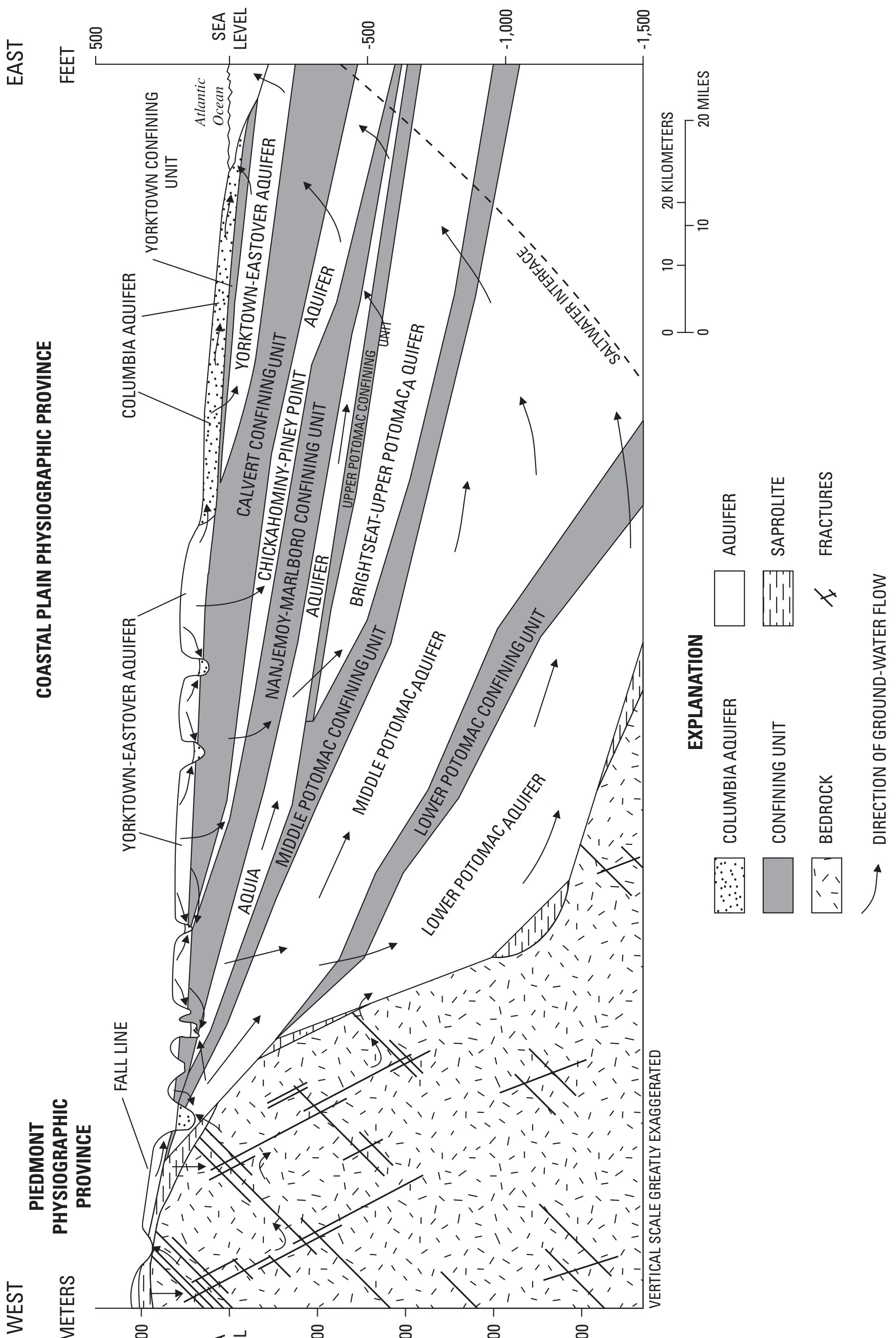

Figure K2. Conceptual hydrogeologic section representing the Virginia Coastal Plain Province as vertically layered aquifers and confining units. Modified from Harsh and Laczniak (1990). This section illustrates concepts held before the discovery of the Chesapeake Bay impact structure.

Purpose and Scope

As part of studies of the geology of the Chesapeake Bay impact structure, continuous sediment cores were obtained at three locations along the western margin of the impact structure during 2000–2001 (fig. K1, table K1 at end of this chapter): USGS-NASA Langley corehole (site 59E 31), North corehole (site 59H 3), and Bayside coreholes 1 and 2 (sites 60G 5 and 60G 6). In order to interpret various aspects of the impact event and its effects on the geologic history of the region, detailed analyses are being performed of the USGS-NASA Langley core; they focus on stratigraphy and structure (Gohn and others, this volume, chap. C; Poag and Norris, this volume, chap. F; Powars and others, this volume, chap. G), petrology (Horton and others, this volume, chap. B; Horton and Izett, this volume, chap. E), and paleontology (Frederiksen and others, this volume, chap. D; Edwards and others, this volume, chap. H). In addition, to delineate the extent and configuration of the impact structure, the Langley core data are being used with borehole and surface geophysical data (Catchings and others, this volume, chap. I; Pierce, this volume, chap. J).

USGS and VDEQ scientists are collecting ground-water quality data and additional information for the area having elevated salinity in ground water along the western margin of the Chesapeake Bay impact structure in the coastal plain of eastern Virginia. As part of this effort, ground water was extracted from samples of the Langley, North, and Bayside cores and was analyzed. Additional existing ground-water quality data collected from 19 nearby water-well sites also have been examined (table K1).

This chapter, K, presents data from chemical analyses of ground water extracted from sediment cores and collected from water wells, describes the distribution of the data areally and with depth, and delineates the configuration of the saltwater transition zone. The origin of the saltwater is assessed by relating possible sources of the salinity to chemical evidence. Lastly, ideas on the origin of the salinity are used to identify possible effects of present and future ground-water withdrawal on the salinity distribution.

Methods

Sediment-Core Water

Continuous sediment cores were obtained at three locations along the western margin of the Chesapeake Bay impact structure during 2000–2001 (fig. K1): USGS-NASA Langley, North, and Bayside coreholes. Hydraulic-rotary drilling with wire-line coring was performed to obtain cores having a nominal diameter of 6.4 centimeters (cm; 2.5 inches (in.)); the cores provide nearly complete sediment profiles from land surface into underlying basement bedrock to depths of nearly 730 meters (m; 2,400 feet (ft)). Thicknesses of overlying sediment of more than 700 m (2,300 ft) were penetrated and include preimpact formations, crater-fill sediments, and overlying postimpact formations.

Comprehensive sampling of 163 subsections (about 15 cm (6 in.) long) of sediment core was performed during drilling operations at all three sites to provide high-resolution detail of vertical changes in ground-water salinity and related chemistry. Sample collection and processing followed procedures developed by Manheim and others (1994). Care was taken with field procedures to preclude conditions that could potentially alter the chemistry of ground water retained in the core sediment, including invasion of drilling mud into the sediment or evaporation of ground water from the sediment.

Following retrieval of core in lengths as great as 3 m (10 ft) from the borehole, sample subsections were collected only from core that was promptly extruded from the core barrel, and any delayed core was left unsampled. In addition, only clearly intact intervals of core were selected, and any deformed or suspect intervals were avoided. Upon extrusion, each sample subsection was quickly measured and sliced from the core prior to rinsing the remaining core to remove drilling mud. The subsection was placed on a clean, dry plastic cutting board, where drilling mud and the outer approximately 1 cm (0.5 in.) of core sediment were sliced away with a clean, dry knife. The resulting innermost diameter of the subsection was then isolated in an air-tight glass jar for storage and transfer from the field to the laboratory for further processing.

Upon transfer from the field, each sample was initially processed by disaggregating the sediment in its glass jar to homogenize it with the retained ground water. Ground water was then extracted from the sediment by using high-pressure squeezing techniques (Manheim and others, 1994). A portion of sediment was placed inside a hand-sized steel cylinder-and-piston device, from which the water was forced under a 12-ton hydraulic press into a small syringe. Typically, several milliliters of water were obtained by each extraction.

All water samples were analyzed for specific conductance immediately upon extraction. Subsequently, selected samples underwent additional analysis. Concentrations of chloride in 36 samples, bromide in 26 samples, and iodide in 27 samples from all three core sites were determined by colorimetry by the USGS National Water-Quality Laboratory (NWQL). Hydrogen (deuterium) and oxygen stable-isotope ratios, calculated relative to Vienna Standard Mean Ocean Water (Fritz and Fontes, 1980), in 15 samples from all three core sites were determined by mass spectrometry by the USGS Isotope Research Laboratory. Isotope ratios of chlorine-36 to total chloride ($^{36}Cl/Cl$) in 12 samples from the USGS-NASA Langley core site were determined by accelerator mass spectrometry by the Purdue Rare Isotope Measurement Laboratory (PRIME Lab).

Well Water

Existing ground-water quality data collected from water wells near the western margin of the Chesapeake Bay impact structure were retrieved from the USGS water-quality database (http://waterdata.usgs.gov/va/nwis/qw). Table K1 shows data for 44 samples collected at 19 water-well sites during 1967–2002. Multiple samples were collected from some wells by zone testing within the borehole during drilling. Specific conductance was determined for all 44 samples, chloride concentrations were determined for 42 samples, bromide concentrations were determined for 28 samples from 13 wells, and iodide concentrations were determined for 9 samples from 2 wells. Hydrogen (deuterium) and oxygen stable-isotope ratios were determined for samples from two wells, one of which was also analyzed to determine the $^{36}Cl/Cl$ ratio, as described above for the samples of sediment-core water.

Ground-Water Salinity

The dissolved constituents in ground water in the area of the Chesapeake Bay impact structure are dominated by sodium cations and chloride anions (Focazio and others, 1993). Other constituents are present at generally much smaller concentrations. Chloride is the constituent of greatest concern for management of the ground-water resource in the Virginia Coastal Plain. Water having a chloride concentration below the U.S. Environmental Protection Agency's (1990) secondary maximum contaminant level of 250 milligrams per liter (mg/L) is commonly referred to as "fresh." Water having chloride concentrations between those of freshwater and seawater (19,000 mg/L according to Hem, 1985) is referred to as "brackish"; such brackish water is widespread in the major water-supply aquifers of the eastern part of the Virginia Coastal Plain. Water having a chloride concentration above that of seawater is called "brine."

Distribution

Chemical data (table K1) were compiled on ground water extracted during 2000–2001 from sediment cores obtained along the western margin of the Chesapeake Bay impact structure and on ground water collected during 1967–2002 from existing water wells in adjacent areas. Corehole and well-site locations collectively span the western and southwestern parts of the impact structure (fig. K1). All three core sites (site numbers 59E 31, 59H 3, and 60G 5–6) are within the estimated structural boundary described as the crater's outer margin (Powars and Bruce, 1999; Powars, 2000). The wells are generally located near the crater's outer margin, and most are outside it. Two wells (63F 52–53) are within the estimated central crater and are closer to the center of the impact structure than any of the other sites. Although well-sample collection times span 35 years, regionally significant changes in ground-water quality have not been observed (Smith, 1999), and the well data generally represent current conditions.

Sediment-Core-Water and Well-Water Chemistry

Chloride concentrations were determined for selected samples of water extracted from sediment cores and for all but two of the samples collected from wells (table K1). Specific conductance was measured in all samples from both cores and wells. Chloride concentration is strongly correlated with specific conductance (correlation coefficient greater than 0.95) in samples for which both determinations were made, ranging from relatively small values through the specific conductance and chloride concentration of seawater of 45,000 microsiemens (μS), and 19,000 mg/L (Hem, 1985), respectively, and higher. Because the dominant constituents of the water are sodium cations and chloride anions, and because specific conductance is related to total dissolved solids, specific conductance can provide a reliable surrogate for chloride concentration in samples for which chloride concentration was not determined. Thus, trends among the much larger number of specific conductance values indicate similar trends among chloride concentrations and can provide greater detail on the spatial distribution of salinity than the chloride concentrations alone.

In eastern Virginia, the specific conductance of ground water generally increases from the western margin of the Chesapeake Bay impact structure toward its center (fig. K1). Specific conductance also generally increases with depth (fig. K3), in a few instances exceeding that of seawater by as much as 35 percent and thus indicating that the ground water is brine. Variations from the generally downward increasing trend are also apparent, however, across some intervals at all three of the core sites and among the group of wells centered on northern Newport News (shown in blue in figures K1 and K3). As noted above, chloride concentrations likely are similarly distributed.

Specific conductance exhibits a greater degree of small-scale variation at the USGS-NASA Langley core site (site number 59E 31) than at the other sample locations (fig. K3), possibly as a result of closely spaced short-interval samples. Because the USGS-NASA Langley core was the first for this study to be sampled for water extraction, the sample interval required to adequately characterize the salinity distribution was unknown. Accordingly, samples of the USGS-NASA Langley core were collected from almost every retrieved length of core, approximately every 3 m (10 ft). On the basis of these initial results, more widely spaced samples from approximately every 15–30 m (50–100 ft) were later collected from the North (59H 3) and Bayside (60G 5–6) cores.

Identical sample-collection procedures were followed for all three cores (see "Methods") to prevent intrusion of drilling fluid into the sediment and contamination of the retained

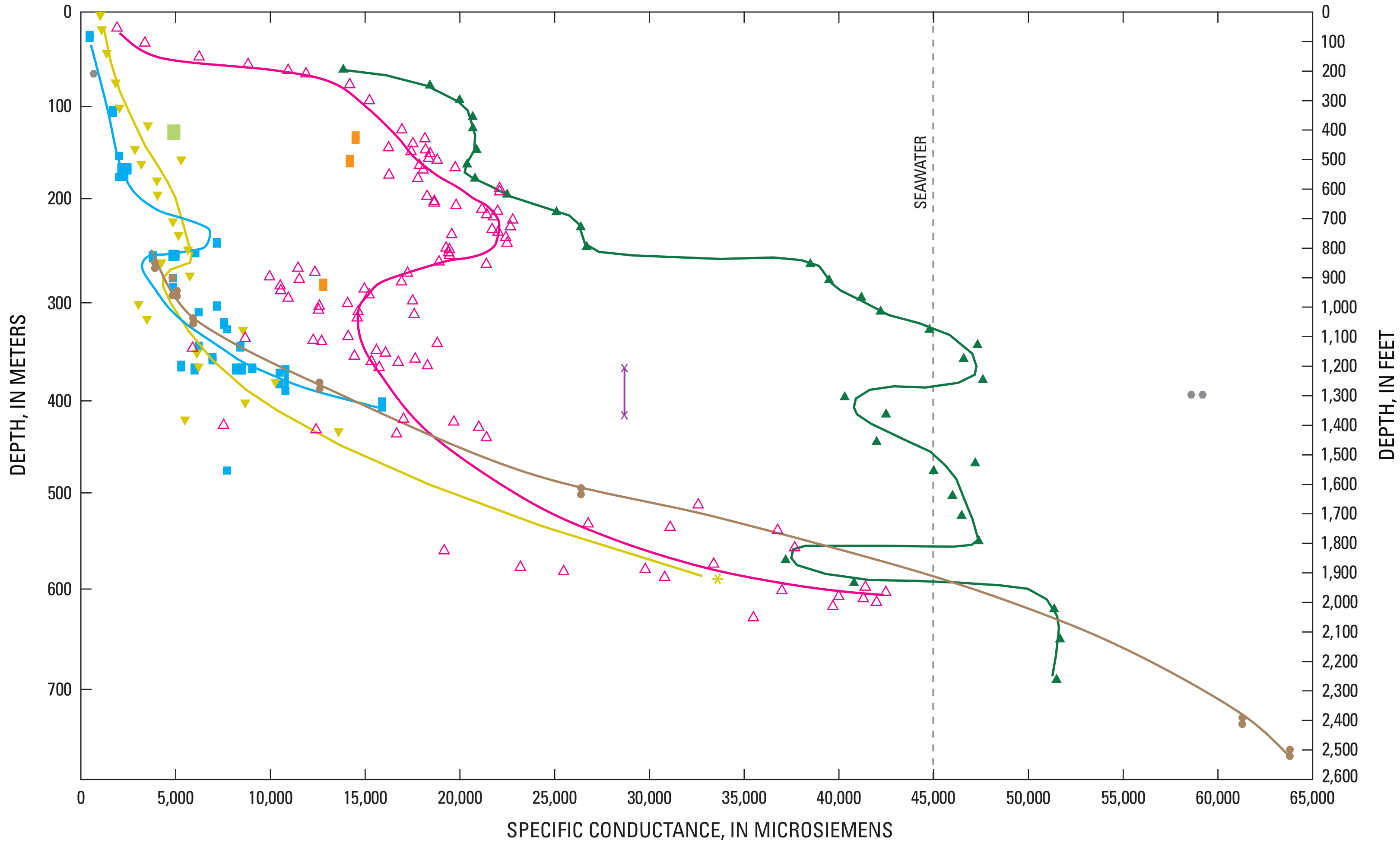

Figure K3. Graph showing the relation of specific conductance of sediment-core water and well water to depth below land surface along the western margin of the Chesapeake Bay impact structure in the Virginia Coastal Plain. Sample intervals are color referenced to sample locations shown in figure K1. Corresponding curves indicate general trends with depth. Samples shown in blue represent closely spaced wells centered on northern Newport News. Other colors represent single locations.

ground water. The validity of the procedures is confirmed by the lack of bias between the specific conductance of samples from the USGS-NASA Langley core of fine-grained, low-permeability sediments (which are very unlikely to be contaminated) and the specific conductance of coarser grained, higher permeability sediments.

Subsets of the Langley data based on farther spaced samples generally exhibit decreased variability of specific conductance and have distributions that are similar to those at North and Bayside. The well samples also were vertically spaced relatively far apart and were collected across screen intervals generally of several meters (table K1), which are long compared to the core-sample intervals. Thus, small-scale variations in specific conductance possibly exist at the other sample locations but are not exhibited by samples that are farther spaced and—in the case of the wells—have longer collection intervals.

Concentrations of bromide and iodide also were determined for selected samples of water extracted from sediment cores and for some samples collected from wells (table K1). Bromide concentrations generally are smaller than chloride concentrations by approximately three orders of magnitude, and iodide concentrations are smaller than chloride concentrations by four to five orders of magnitude. The relation of the ratio of bromide concentration to chloride concentration (Br/Cl) to depth below land surface was examined (fig. K4). The bromide concentration of seawater is 65 mg/L according to Hem (1985), and the Br/Cl ratio of seawater is 0.003; most of the samples exhibit Br/Cl ratios that exceed that of seawater by an average of approximately 24 percent, although four ratios are below that of seawater. The iodide concentration of seawater is 0.06 mg/L according to Hem (1985), and the iodide-to-chloride concentration ratio (I/Cl) of seawater is 3.2×10^{-6}; the I/Cl ratios for the samples generally range from one to two orders of magnitude above that of seawater (table K1).

Stable-isotope ratios, in per mil relative to Vienna Standard Mean Ocean Water (Fritz and Fontes, 1980), of the hydrogen isotope deuterium (expressed as δD) and oxygen (expressed as $\delta^{18}O$) were determined for 15 samples of water extracted from sediment cores and for 2 samples from wells (table K1). All values of both ratios are negative, indicating depletion of the heavy isotopes of the elements relative to the lighter isotopes. Hence, all the samples are isotopically lighter than modern seawater, which has a value of zero for both ratios. The δD values are strongly correlated with the $\delta^{18}O$ values, although two distinct relations are apparent in the graph of the data shown in figure K5: most samples indicate freshwater-seawater mixing, whereas several samples indicate evaporation. In addition, samples with the most negative values have a relatively small specific conductance, whereas less negative samples (including three samples of brine) have a large specific conductance.

Isotope ratios of chlorine-36 to total chloride ($^{36}Cl/Cl$) are shown as <1 in table K1 for 12 samples from the USGS-NASA Langley core (site 59E 31) because the ratios were below the analytical detection limit of 10^{-15}. The $^{36}Cl/Cl$ ratio of one sample from a well (site 63F 52) had a low value of 12.1×10^{-15}. The $^{36}Cl/Cl$ ratio of modern seawater is below 10^{-15} (Phillips and others, 1986). The well sample also differed from the core-water samples in being generally deeper, approximately 395.3 m (1,297 ft) to 401.4 m (1,317 ft) compared to 45.9 m (150.5 ft) to 599.2 m (1,965.8 ft), and in exhibiting a greater specific conductance of 58,600 µS compared to 6,260 to 42,500 µS.

Configuration of the Saltwater Transition Zone

Initial understanding of the physical principles governing the nature of the transition from freshwater to saltwater in coastal aquifers has been widely attributed to Ghyben (1888) and Herzberg (1901). In a homogeneous unconfined aquifer under hydrostatic conditions, freshwater is separated from the more dense seawater by a landward-sloping interface. Subsequent workers have expounded significantly on the original concept. Hubbert (1940) elaborated that with steady-state outflow to the sea, the interface is displaced seaward. Henry (1960) described the transition as a dispersive mixing zone rather than a sharp boundary, which Pinder and Cooper (1970) further characterized with transient movement in a confined aquifer.

Meisler (1989) provided a comprehensive analysis of the distribution of ground-water salinity and the processes controlling it in the Atlantic Coastal Plain from New Jersey through North Carolina. A relatively broad transition zone between freshwater and saltwater was described. Large-scale salinity variations (both areally and with depth) were attributed to variations in flow rates among different parts of the aquifer system and to variable sea-level fluctuations across the region. For the Virginia Coastal Plain, Larson (1981) described similar relations between fresh and brackish ground water in the upper few hundred meters of sediment.

The eastward- and downward-increasing specific conductance of ground water along the western margin of the Chesapeake Bay impact structure reflects a broad and generally landward-dipping transition zone between fresh ground water to the west and saltwater to the east (fig. K6). An inversion of part of the transition zone is exhibited across an interval where the vertical trend is reversed. The presence of relatively deep freshwater along the inverted interval possibly is reflected by anomalously large earth resistivities detected along the crater outer margin by using audio-magnetotelluric methods (Pierce, this volume, chap. J). The salinity inversion was described by Meisler (1989, p. D9) as a deep “freshwater wedge” that extends north of the lower Chesapeake Bay (that is, north of the impact structure) and east beneath the Atlantic coast; it becomes more broad and thick beneath the upper Chesapeake Bay, the Delmarva Peninsula, and the continental shelf off New Jersey, where it attains depths as great as 150 to 460 m (500 to 1,500 ft) below sea level. The salinity inversion also has been locally observed south of the impact structure, but apparently it does

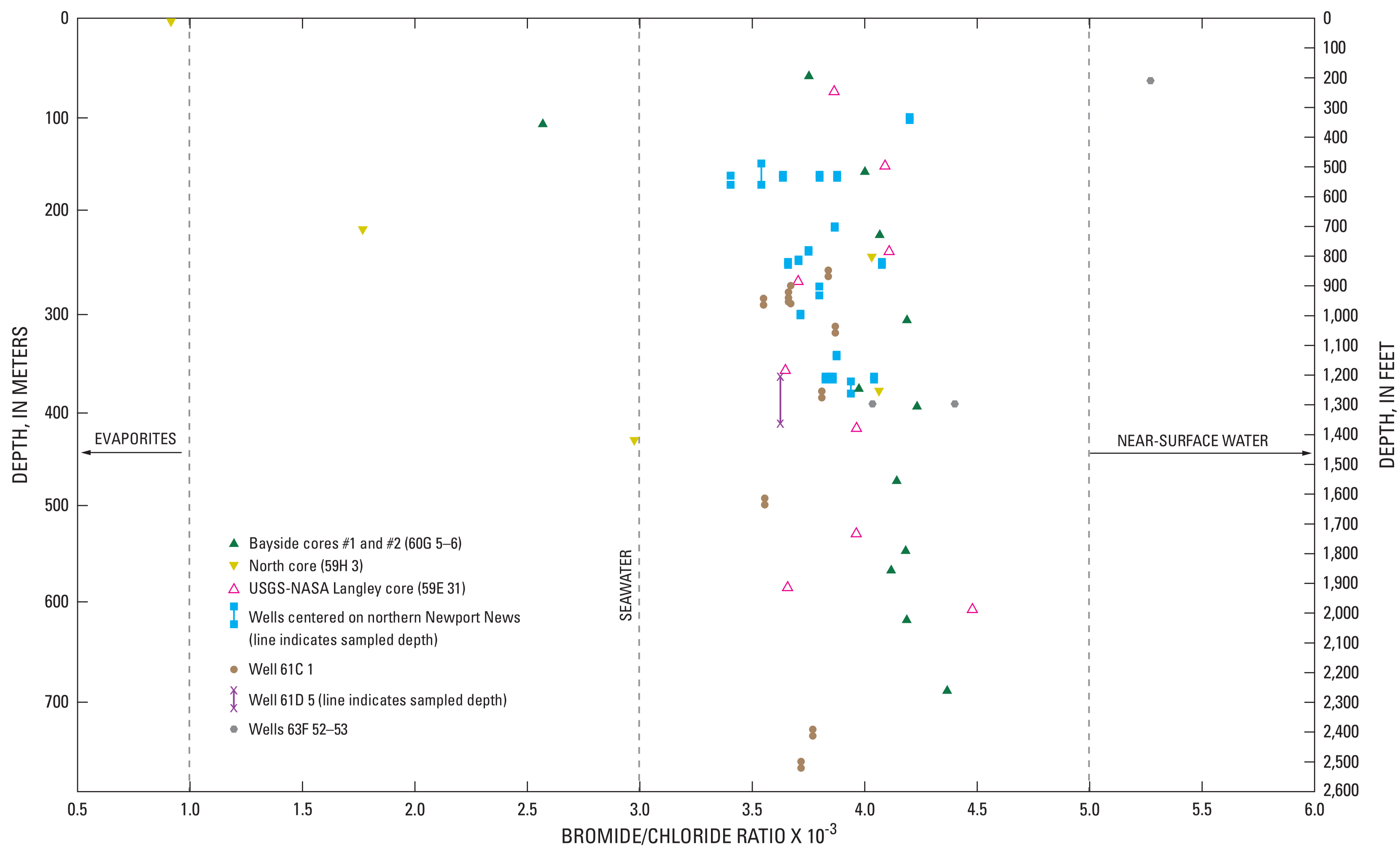

Figure K4. Graph showing relation of the ratios of bromide concentration to chloride concentration (Br/Cl) of sediment-core water and well water to depth below land surface along the western margin of the Chesapeake Bay impact structure in the Virginia Coastal Plain. Sample intervals are color referenced to sample locations shown in figure K1. Data from table K1.

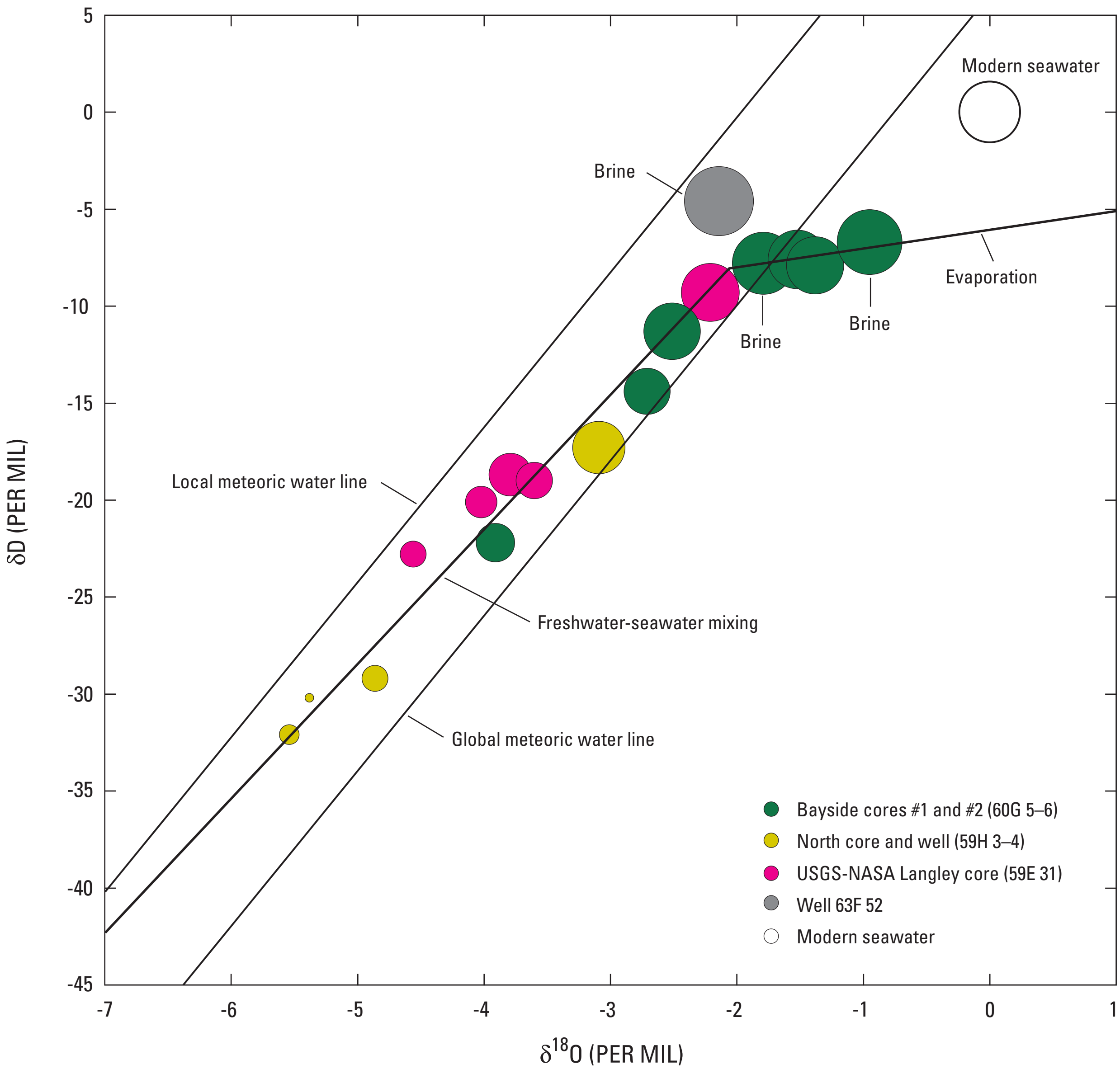

Figure K5. Graph showing the relation between hydrogen (δD) and oxygen ($\delta^{18}O$) isotope ratios and specific conductance of sediment-core water and well water along the western margin of the Chesapeake Bay impact structure in the Virginia Coastal Plain. Sample symbols are color referenced to sample locations shown in figure K1. One well (63F 52) is within the central crater. Symbol diameter is proportional to sample specific conductance; that of modern seawater is 45,000 microsiemens (Hem, 1985). Brines have a specific conductance higher than that of seawater. Global meteoric water line from Coplen (1993). Local meteoric water line from Dunkle and others (1993).

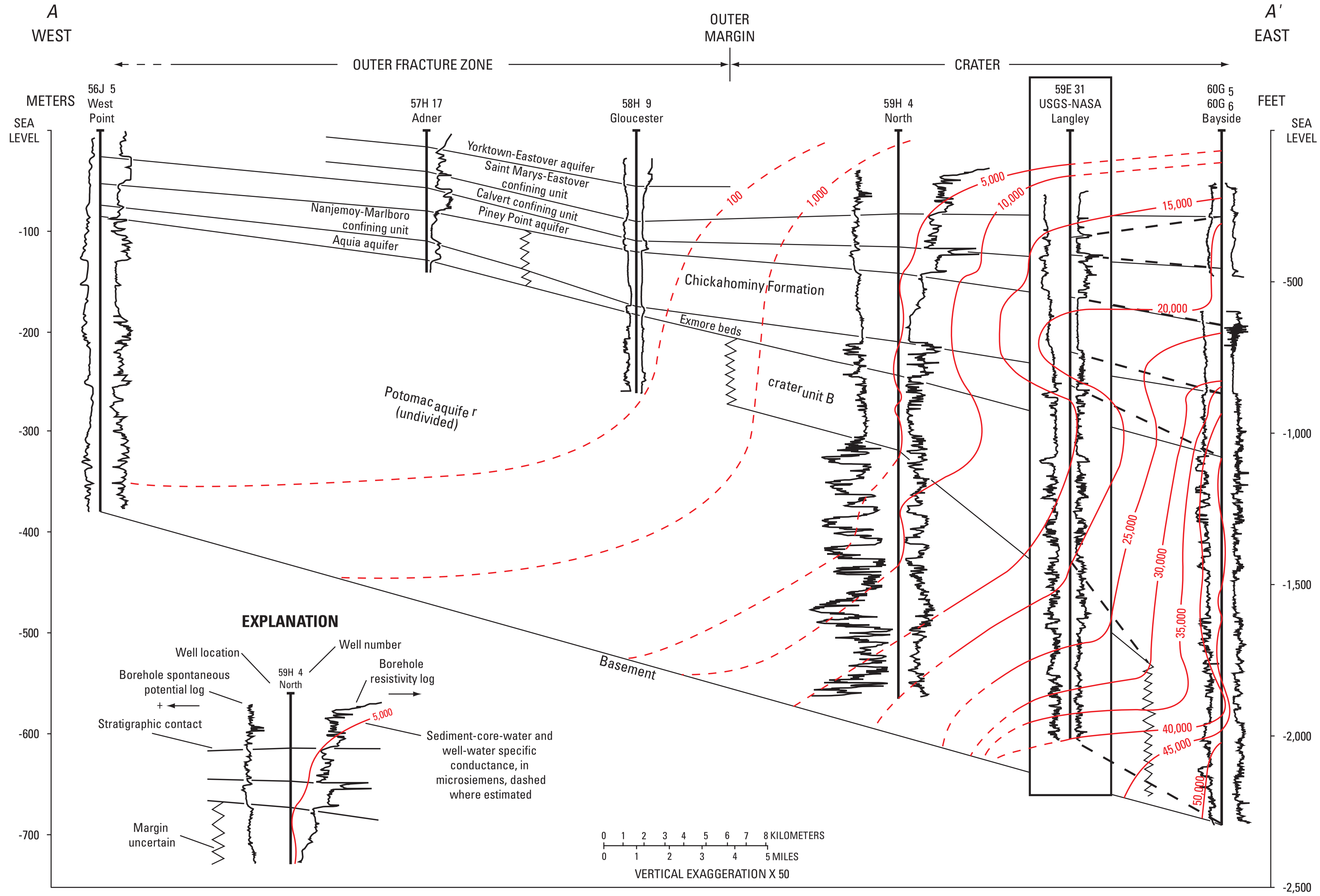

Figure K6. Simplified preliminary composite section across the western margin of the Chesapeake Bay impact structure showing the configuration of the saltwater transition zone as indicated by specific conductance contours. The line of section *A–A′* is shown in figure K1. The USGS-NASA Langley corehole (site 59E 31) is projected onto the section line. The westward distribution of specific conductance is estimated from Focazio and others (1993).

not extend into the North Carolina Coastal Plain (Winner and Coble, 1996).

Areally, the coincidence of elevated ground-water specific conductance with the western margin of the Chesapeake Bay impact structure (fig. K1) is consistent with the aforementioned descriptions of the saltwater transition zone in eastern Virginia as being an inland saltwater wedge. In three dimensions, the transition zone exhibits a convoluted configuration. Additionally within the broad regional trend, dispersive mixing is indicated by small-scale variations in specific conductance (fig. K3), as observed where closely spaced samples were collected from the USGS-NASA Langley core (site 59E 31). Similar variations possibly exist toward the center of the impact structure, where the saltiest water may be present in isolated pockets. Because of the scarcity of data, however, small-scale variations in salinity are unknown across this area.

Origin

Diverse processes can potentially affect the chemical composition of ground water in coastal aquifers. Among these, Jones and others (1999) listed mixing, ion exchange, diagenesis, and oxidation-reduction reactions. Back (1966) provided a comprehensive analysis of the geochemistry of ground water in the northern Atlantic Coastal Plain to characterize controls on ground-water composition. On the regional scale, the chemical composition of ground water evolves eastward with time along flow paths; it initially undergoes carbonate dissolution, followed by exchange of calcium for sodium on clays, and finally mixing with seawater near the coast. In this study, only partial chemical data are available for all of the ground-water samples, and a complete geochemical analysis is beyond the scope of this chapter. As demonstrated below, however, the available data are useful in inferring the relative likelihood of various mechanisms that have been suggested to explain the elevated salinity of ground water in eastern Virginia.

Sources of Salinity

At least three hypotheses can be considered to explain the origin and emplacement of the inland saltwater wedge in eastern Virginia: differential flushing, diffusion of solutes from basement evaporite deposits, and membrane filtration by clays. The hypotheses are summarized below.

Differential flushing.—Cederstrom (1943) described the area of the then-unknown impact structure as a “structural depression” where stratigraphic dips steepen, and around which ground water was proposed to flow in a “differential flushing” manner that has left residual seawater retained in the now-recognized crater-fill sediments. Regional inundation of the coastal plain by the Atlantic Ocean was thought to have initially saturated the sediments with seawater. A coincidence of faults with the saltwater wedge has been noted; Rogers and Spencer (1971) suggested that the faults promoted migration of seawater into the deepest sediments. Upon re-emergence of the coastal plain and resumption of recharge with meteoric water, seawater would have been gradually flushed from the sediments by freshwater.

The observed salinity distribution alone, however, provides only circumstantial evidence for differential flushing. Chemical data that could indicate the source of the salinity and hydrologic information to demonstrate the behavior of the flow system also are needed to support more definitive conclusions. The resource-management implication of differential flushing is that, given adequate knowledge of the flow system, withdrawal amounts and locations could be configured to enhance movement of fresh ground water and to minimize the spread of saltwater.

Diffusion of solutes from basement evaporite deposits.—As an alternative to the differential flushing hypothesis, Manheim and Horn (1968) and Meisler (1989) cited upward diffusion of solutes from the dissolution of basement evaporite deposits as having produced at least some of the saltwater in the Atlantic Coastal Plain sediments, particularly where brines have been observed. Differential flushing alone can account only for brackish ground water. In the context of present knowledge, the Chesapeake Bay impact structure is seen as a possible conduit for evaporite solutes to produce the saltwater wedge. Because the source of salinity is within basement bedrock, however, it remains unclear whether diffusion or advection in the area of the impact structure would have dominated solute transport under the unstressed flow conditions in which the saltwater wedge was formed.

As with the differential flushing hypothesis, information to indicate the source of the salinity and to demonstrate the behavior of the flow system is needed. The resource-management implication of evaporite solutes as the dominant source of salinity depends on whether diffusion or advection is the dominant transport mechanism. Because diffusion is probably much slower than advection, the amounts and locations of withdrawals would potentially have little effect on the distribution of salinity if diffusion were to remain dominant under present-day stressed flow conditions.

Membrane filtration by clays.—A third potential mechanism to explain the saltwater wedge is salinity production from membrane filtration by clays. Russel (1933) first suggested that under pressure a reversed osmotic movement of water can be induced between particles of clay from areas of high salinity toward areas of lower salinity. Because the clay particles are electrically charged, they repel and impede the movement of dissolved ions, causing the remaining solution to become more concentrated with time. Bredehoeft and others (1963) hypothesized that the requisite large hydraulic gradients could arise in sedimentary basins having sufficiently uplifted margins, and Hanshaw and Coplen (1973) demonstrated with laboratory studies that the process is theoretically possible. Specifically for the Virginia Coastal Plain, Larson (1981) cited membrane filtration along with the previously described mechanisms among various possible explanations for the presence of elevated ground-water salinity. Powars and Bruce (1999) theorized that loading, compaction, and dewatering of crater-fill sediments within the Chesapeake Bay impact structure could have produced the saltwater wedge, presumably by membrane filtration.

Although the above-cited studies treated membrane filtration with reasoned speculation, an overview by Hanor (1983) indicated that its role in the production of saltwater had not been clearly demonstrated. Further, the feasibility of membrane filtration appears to be problematic in light of some observations. Manheim and Horn (1968) pointed out that regionally along the Atlantic coast, present-day hydraulic gradients are far below those required to achieve a significant degree of filtration. Within the Chesapeake Bay impact structure during the geologic past, hydraulic gradients likely were not appreciably greater than those existing at present even during basin compaction, because the basin margins would not have been sufficiently uplifted. Recently, Neuzil (2000) demonstrated that very low porosities of approximately 0.05 are required for appreciable membrane efficiency. By contrast, preliminary estimates of porosities of sediment core from the Chesapeake Bay impact structure range from 0.21 to 0.54 (E.R. McFarland, unpub. data, 2004).

Chemical Evidence

The composition of natural waters can be interpreted with respect to controlling chemical processes to infer the origin and history of the water and source(s) of its solutes. On a theoretical basis, either differential flushing or dissolution of evaporites appears to be a possible alternative mechanism for formation of the saltwater wedge associated with the Chesapeake Bay impact structure. In contrast, current information casts significant doubt on membrane filtration as a plausible mechanism to explain the saltwater wedge. Accordingly, formation of the saltwater wedge from either differential flushing or dissolution of evaporites was further assessed by using ground-water concentration ratios of bromide to chloride, stable hydrogen and oxygen isotopes, and chlorine-36 to total chloride.

Ratios of the concentrations of bromide and chloride ions (Br/Cl) in ground water have received increasingly widespread application to differentiate various sources of salinity (Davis and others, 1998). For example, Andreasen and Fleck (1997) used Br/Cl ratios to identify intrusion of brackish water from Chesapeake Bay into the Aquia aquifer in the Maryland Coastal Plain. This and other studies generally have compared Br/Cl ratios of ground water with those that are characteristic of various sources of salinity. Modern seawater has a Br/Cl ratio of approximately 0.003. Bromide can be enriched relative to seawater in organic matter and also in precipitation as a result of the kinetics of evaporation from the ocean surface (B.F. Jones, U.S. Geological Survey, oral commun., 2002). As a result of contributions from these sources, water near land surface (surface water and shallow ground water) is enriched in bromide and has Br/Cl ratios of 0.005 or greater. Organic matter within deeper coastal plain sediments can be an additional potential source of bromide to ground water.

Bromide also is partitioned during precipitation of evaporite minerals such that the minerals are depleted in bromide and have Br/Cl ratios below 0.001 as a result of different solubilities among the various halide minerals; the remaining solution is proportionately enriched in bromide and has Br/Cl ratios as great as 0.02. Conversely, solutions resulting from the dissolution of evaporite minerals are depleted in bromide and have correspondingly low Br/Cl ratios below 0.001.

Most of the ground-water samples from along the western margin of the Chesapeake Bay impact structure have Br/Cl ratios above that of seawater by an average of approximately 24 percent (fig. K4). The ratios exhibit no clear trend with areal location or depth, although a few samples deviate from the rest. Similarly, no trend of Br/Cl ratios with chloride concentration is apparent because chloride concentration generally increases with depth.

Most of the Br/Cl ratios in figure K4 are consistent with the chloride having originated from seawater that was enriched with bromide by roughly 24 percent but are too high to be consistent with dissolution of evaporite minerals. Among the four samples having Br/Cl ratios below that of seawater, only one sample has a ratio value below 0.001 (fig. K4); such a low ratio usually indicates that the chloride originated from dissolution of evaporites. This sample was collected from the North core (site 59H 3) at a shallow depth of approximately 4.3 m (14 ft) (table K1) beneath a graveled commuter parking lot, where most of the chloride probably originated from pavement de-icing salts.

Some of the chloride in the three remaining samples having Br/Cl ratios below that of seawater also possibly originated partly from dissolution of small amounts of evaporite minerals deposited with the sediments at these particular depths; the chloride is probably not from basement evaporite deposits because of the isolated occurrence of the samples and the lack of known evaporites in the nearby basement. Evaporite minerals are not expected to remain in the sediments because observed salinities are well below their saturation points. Although halite has been observed in a core from Kiptopeke, Virginia (Powars and Bruce, 1999), it likely was precipitated in the sediment after drilling as the core dried and high-salinity water evaporated.

The Br/Cl ratios indicate that the observed range of ground-water salinity likely resulted from various mixtures of seawater with freshwater having much less chloride. Although the parent seawater possibly had a Br/Cl ratio greater than that of the modern ocean, enrichment of bromide relative to modern seawater in most of the samples also could have resulted from (1) decay of organic material from near-surface sources and (or) at depth in the sediments and (or) (2) precipitation of evaporite minerals as a result of evaporation of the parent seawater. Additional evidence as discussed below indicates that both mechanisms are probable.

Various forms of organic matter are widespread within the Virginia Coastal Plain sediments and have likely contributed to enrichment of bromide in ground water relative to seawater. Organic matter, particularly nearshore marine vegetation, is even more enriched in iodide than in bromide relative to seawater; the iodide concentration of seawater is 0.06 mg/L (Hem, 1985). Iodide-to-chloride concentration ratios of the sediment-core-water and well-water samples range approximately from one to two orders of magnitude greater than that of seawater (table K1); the I/Cl ratios reflect a much greater enrichment of iodide than of bromide. Thus, bromide and iodide have undergone different degrees of enrichment in ground water that are consistent with their relative amounts in organic matter, which is probably their dominant source.

Enrichment of bromide from organic matter possibly is indicated by the greatest Br/Cl ratio value of 0.0053 (fig. K4) from well 63F 53 on the Virginia Eastern Shore (fig. K1). This sample is from a relatively shallow depth in the Yorktown-Eastover aquifer and has a correspondingly small specific conductance of 684 μS (table K1). By contrast, the much deeper well 63F 52 in the Exmore beds at the same location exhibits a much higher specific conductance of 59,200 μS but a lower Br/Cl ratio of 0.00403; the Br/Cl ratio is similar to the ratios of most of the other samples from various locations and spanning a range of depths and specific conductances. Thus, the highest Br/Cl value in well 63F 53 is isolated and possibly reflects local conditions. The Yorktown-Eastover aquifer in some parts of Virginia contains large amounts of organic matter as bedded peat. The peat beds locally are as thick as several meters but are generally discontinuous laterally; their proximity to well 63F 53 is unknown. Although iodide concentrations and other information are not available to demonstrate that bromide was enriched in well 63F 53 from organic matter, the peat is at least one possible source.

In addition to decay of organic matter, a probable source of bromide enrichment in ground water along the western margin of the Chesapeake Bay impact structure is the precipitation of evaporite minerals as a result of evaporation of the seawater. Surface evaporation of modern seawater results first in precipitation of calcium carbonate (calcite and (or) aragonite) followed by calcium sulfate (gypsum) (Drever, 1988). Concentrations of both chloride and bromide in the resulting brine increase above that of the parent seawater, and calcium and sulfate are relatively depleted, but the Br/Cl ratio remains unchanged. Not until 90 percent of the water is removed does halite (NaCl) begin to precipitate; the consequent removal of chloride causes the Br/Cl ratio of the remaining water to increase.

Some of the ground-water samples show evidence for evaporation of seawater. Deep samples from the Bayside core (site 60G 5–6) and from wells 61C 1 and 63F 52 (fig. K1) have specific conductance values that exceed that of seawater by as much as 35 percent (fig. K3) and thereby constitute brine. Because mixtures of freshwater and seawater cannot produce brine, its presence elsewhere in the Atlantic Coastal Plain has been cited (Manheim and Horn, 1968; Meisler, 1989) to indicate dissolution of evaporites as the source of salinity. Br/Cl ratios from the brine samples here, however, lie in the same range as ratios of the less concentrated samples (fig. K4) and indicate bromide enrichment rather than the bromide depletion that would have resulted from evaporite dissolution. An alternative to evaporite dissolution is evaporation of seawater to have produced the brine and to have precipitated halite and thereby enriched bromide in the brine. The salinity required to reach halite precipitation, however, is roughly 30 times that of the most concentrated brine observed. Although such a "super brine" has not yet been found within the impact structure, mixing with less concentrated water (originating as freshwater and (or) seawater) following the initial formation of the brine would likely have diluted it back down to observed salinities.

The mechanism of evaporation of seawater whereby the resulting brine would enter the ground-water system has not yet been clearly demonstrated. In some present-day arid regions, ground water is closely associated with seawater evaporating from restricted coastal supratidal sabkha environments (Drever, 1988). Whether such conditions have ever existed in the area of the Chesapeake Bay impact structure, however, is unknown. Alternatively, evaporation associated with the impact event 35 million years ago has been demonstrated to be theoretically possible, as a result of hydrothermal activity associated with the dissipation of residual heat retained in the sediments following the impact (Sanford, 2003). Although very rapid vaporization of seawater from the intense heat of the blast seems likely, heat-conduction calculations indicate that maximum temperatures greater than 400°C in the crater-fill sediments would have not been reached until 10,000 years after the impact and that associated brine generation would have likely continued for another million years.

In addition to Br/Cl ratios, stable-isotope ratios of hydrogen and oxygen have been applied toward understanding diverse origins and histories of ground water (Coplen, 1993), and they provide additional insight on the formation of the saltwater wedge associated with the Chesapeake Bay impact structure. Relations between δD and δ^{18}O values of sediment-core water and well water from along the western margin of the impact structure (fig. K5) indicate that mixing of freshwater and seawater and possibly evaporation of seawater have taken place. Most of the samples follow a relatively steep trend line that is between the local and global meteoric water lines, which reflect the fractionation of the isotopes between atmospheric moisture and precipitation. Because fresh ground water originates as isotopically light precipitation, the trend for most samples represents various mixtures of freshwater (having the most negative δD and δ^{18}O values) with isotopically heavier seawater (less negative values). Mixing is also reflected by specific conductance increasing in the direction of less negative values.

In addition, a few of the deepest samples from the Bayside core (site 60G 5–6) having specific conductance values near and above that of seawater appear to deviate from the others and possibly follow a second, less steep trend that is characteristic of water having undergone evaporation. Additional samples are needed from elsewhere within the impact structure, particularly near the center of the crater where the greatest salinities are expected, to determine whether stable-isotope ratios show any further indication of evaporation.

In addition to Br/Cl and stable-isotope ratios, the ratios of chlorine-36 to total chloride (^{36}Cl/Cl) have been applied to differentiate various sources of ground-water salinity and to estimate ground-water age where the chloride is of primarily meteoric origin (Phillips and others, 1986). For example, Purdy and others (1996) used ground-water ^{36}Cl/Cl ratios from the Aquia aquifer in the Maryland Coastal Plain to determine ground-water ages as great as 100,000 years. Importantly, concentrations of total chloride in the Aquia aquifer in Maryland are only a few milligrams per liter, and most of the chloride is of meteoric origin. Although significant amounts of cosmogenic ^{36}Cl are produced in the atmosphere, seawater represents a very large reservoir of much older chloride in which most of the ^{36}Cl has decayed and cannot be used to estimate age.

Thirteen samples of ground water from the Chesapeake Bay impact structure were analyzed for ^{36}Cl/Cl ratios. Twelve of the samples are from the USGS-NASA Langley core (site 59E 3, fig. K1); for all twelve Langley samples, the ^{36}Cl/Cl ratios are below the analytical detection limit of 10^{-15}, and they are consistent with earlier results in indicating that most of the chloride originated from seawater.

Only the remaining sample from well 63F 52 in the Exmore beds on the Virginia Eastern Shore (in the central crater, fig. K1) has a ^{36}Cl/Cl ratio above the detection limit; its value is 12.1×10^{-15} (table K1). The high concentration of total chloride (23,000 mg/L) in well 63F 52 indicates that the chloride is probably of seawater rather than meteoric origin and is not the source of the ^{36}Cl. More likely, ground water in well 63F 52 is old enough for secondary ^{36}Cl to have accumulated in the subsurface as a result of decay of solid-phase uranium in the sediments.

Formation of the Inland Saltwater Wedge

Values of Br/Cl ratios, δD, δ^{18}O, and ^{36}Cl/Cl ratios for ground-water samples indicate that seawater was the source of salinity along the western margin of the Chesapeake Bay impact structure and that evaporation of seawater produced the observed brine. The seawater and brine have mixed with freshwater to produce the observed range of ground-water salinities. Thus, the results of this study support Cederstrom's (1943) original hypothesis that the saltwater wedge resulted from differential flushing of residual seawater.

Seawater has been emplaced throughout the Atlantic Coastal Plain sediments during regional inundations by the Atlantic Ocean. Large parts of the Virginia Coastal Plain were repeatedly inundated during the Tertiary Period between 2 million and 65 million years ago, as recorded by sediments of that age. The most recent marine deposits are of Pliocene age and formed approximately 2 million to 4 million years ago. Regionally extensive younger sediments are largely of fluvial origin. Although several additional inundations took place as recently as 115,000 years ago during interglacial periods of the Pleistocene Epoch, sea levels then were higher by at most 6 m (20 ft) because the climate was not significantly warmer than today's climate (Bradley, 1999); only areas near the Chesapeake Bay impact structure were inundated.

In addition to geological evidence, hydrologic information suggests a relatively old age for seawater still present in the crater-fill sediments. The youngest ground water in the Virginia Coastal Plain is in the fresh-to-brackish zone outside of the crater and has ages as great as 40,000 years determined from carbon-14 analyses (D.L. Nelms, U.S. Geological Survey, oral commun., 2001). Within the crater, ground-water δD and δ^{18}O values are uniformly negative (fig. K5), indicating that the hydrogen and oxygen isotopic composition of the original seawater is lighter than that of modern seawater. By contrast, seawater of the most recent geologic past during the Pleistocene Epoch was generally heavier than modern seawater because of the cooler climate. Thus, the original seawater likely predates the Pleistocene and has been buried since at least the last regional inundation of 2 million to 4 million years ago, when the climate was warmer than present. Further evidence indicates that potentially much older seawater from previous inundations could be present. The ^{36}Cl/Cl ratio of 12.1×10^{-15} in well 63F 52 (table K1) is based on ^{36}Cl that probably was produced by decay of solid-phase uranium in the sediments, which could take several million years or more depending on their uranium content. In addition, calculated estimates of solute advection and diffusion rates indicate that at least some seawater, along with hydrothermally produced brine, likely remains in the crater fill from the time of the impact (Sanford, 2003).

Areal ground-water recharge resumed following emergence of the Atlantic Coastal Plain from the last regional inundation during the Pliocene Epoch. The consequent flow of fresh ground water since then has to varying degrees flushed residual seawater from the coastal plain sediments, thereby affecting the position and configuration of the saltwater transition zone. At the extreme during the last Pleistocene glacial maximum of 18,000 years ago, sea levels were as far as 120 m (390 ft) lower than present (Bradley, 1999), and the Atlantic shore was located several tens of kilometers eastward of its present position. Freshwater flushing extended nearly to the edge of the continental shelf and was vigorously driven by fresh ground-water heads that were high relative to the low sea level. Warming since then has resulted in sea level rising to its present location.

The manner in which differential flushing of the residual seawater has taken place across the Chesapeake Bay impact structure can be inferred from the relation of the saltwater transition zone to the configuration of various geologic units along the western margin of the impact structure (fig. K6). Specifically, the vertical salinity inversion along the crater outer margin coincides with the interval occupied by the Chickahominy Formation and underlying crater-fill sediments (crater unit B and Exmore beds as described by Gohn and others, this volume, chap. C). Preexisting sediments were highly disrupted by the impact and were chaotically mixed and deposited under very high energy conditions immediately following the impact in a large crater that was formed by the blast. Among these, crater unit B consists of clast-supported boulder-sized and larger blocks of preexisting formations that were violently rolled, swept, or hurled into the crater. The overlying and thinner Exmore beds consist of matrix-supported cobbles and smaller fragments floating in densely packed and poorly sorted sand that was washed in by tsunamis to further fill the crater. Lastly, the Chickahominy Formation consists of very fine grained clay that was deposited under low-energy conditions in a deep marine basin left by the impact; it is preserved only in the immediate vicinity of the crater. Undisrupted preimpact sediments outside of the crater are truncated against these units along the crater outer margin, and postimpact sediments overlie all earlier units. A complex array of faults is theorized to influence the configuration of the margin between preimpact and crater-fill sediments and to also propagate upward through postimpact sediments and laterally into preimpact sediments across an outer fracture zone (Johnson and others, 1998).

The configuration of the saltwater transition zone (fig. K6) indicates that differential flushing has taken place in a complex three-dimensional fashion across the western margin of the Chesapeake Bay impact structure. The salinity inversion along the crater outer margin indicates that flushing of saltwater has been impeded across the clayey Chickahominy Formation, beneath which greater flushing has taken place through the more sandy crater fill. The lithologic compositions of these units suggest that permeabilities and ground-water flow rates could be directly related to their contrasting degrees of flushing. Coincidentally, sediments that comprise the Chickahominy Formation as currently recognized appear to have been represented in the RASA ground-water flow model as part of the Nanjemoy-Marlboro confining unit (Harsh and Laczniak, 1990; see fig. K2 of this chapter). As a necessary feature to successfully calibrate the model, the distribution of vertical-leakance values assigned to the Nanjemoy-Marlboro confining unit decreases abruptly approximately across the now-known crater outer margin. Hence, the hydraulic effect of the impact structure had apparently been manifest in this analysis even though the investigators were unaware of its presence. Preliminary analyses since undertaken in developing a revised model of the Virginia Coastal Plain demonstrate explicitly the likelihood that differential flushing across the impact structure formed the saltwater wedge (Heywood, 2003).

The differential flushing exhibited along the crater outer margin does not appear to persist across the entire impact structure. Farther into the impact structure, the specific conductance of ground water increases abruptly to that of seawater (45,000 μS) and greater at depth (fig. K6). In addition, no large salinity inversion is apparent, and the saltwater transition zone assumes a nearly vertical orientation across most of the sediments. Apparently little or no flushing of saltwater has taken place through sediments across the inner part of the impact structure. Possibly lesser permeabilities in the crater fill toward the center of the impact structure and (or) the greater density of the saltwater create a barrier to flow. Estimates of solute advection and diffusion rates (Sanford, 2003) indicate that saltwater in the deepest part of the impact structure at its center likely has undergone essentially no flushing since being emplaced at the time of the impact.

For differential flushing to provide a complete explanation, the means by which ground water is discharged from the flow system must be identified. Across the eastward downgradient part of the Virginia Coastal Plain, upward leakage and discharge to Chesapeake Bay, its major tributaries, and the Atlantic Ocean are the primary means by which water exits the flow system (fig. K2) (Harsh and Laczniak, 1990). The configuration of the saltwater transition zone across the crater outer margin, however, indicates that little or no upward leakage and associated flushing have taken place from the crater fill through the overlying Chickahominy Formation (fig. K6). Neither does ground water that flushed differentially along the outer margin appear to continue across the impact structure toward the ocean. The only other apparent exit is by lateral flow around the outer margin, followed by upward leakage and surface discharge to areas outside of the crater where the Chickahominy Formation is not present (fig. K7).

The complex array of faults theorized to span the margin of the Chesapeake Bay impact structure likely exerts some control on differential flushing, although in what manner is largely unknown. Given the unconsolidated nature of the sediments, most faults would likely not exist as open fractures along which enhanced flow could take place. Permeability within the sediments could potentially be either increased or decreased along faulted intervals, depending on how the sediments had been altered at the intergranular scale. At a minimum, some faults probably juxtapose adjacent aquifers and confining units that would otherwise have continuous extents. Effects of faulting on fluid migration in evolving sedimentary basins can potentially be highly variable both spatially and temporally (Stover and others, 2001), depending on specific relations among faults, the strata they penetrate, and the distribution of fluid pressure. These relations within the impact structure have likely changed since the time of the impact, as the structure has evolved with ongoing sediment deposition, subsidence, and fault propagation. In addition to effects on lateral flow around the crater outer margin, faults across the outer fracture zone could potentially facilitate ground-water discharge by enhancing upward leakage in areas outside of the crater.

Lateral flow and flushing possibly have taken place preferentially toward the north side of the impact structure rather than toward the south, as indicated by the area of elevated spe-

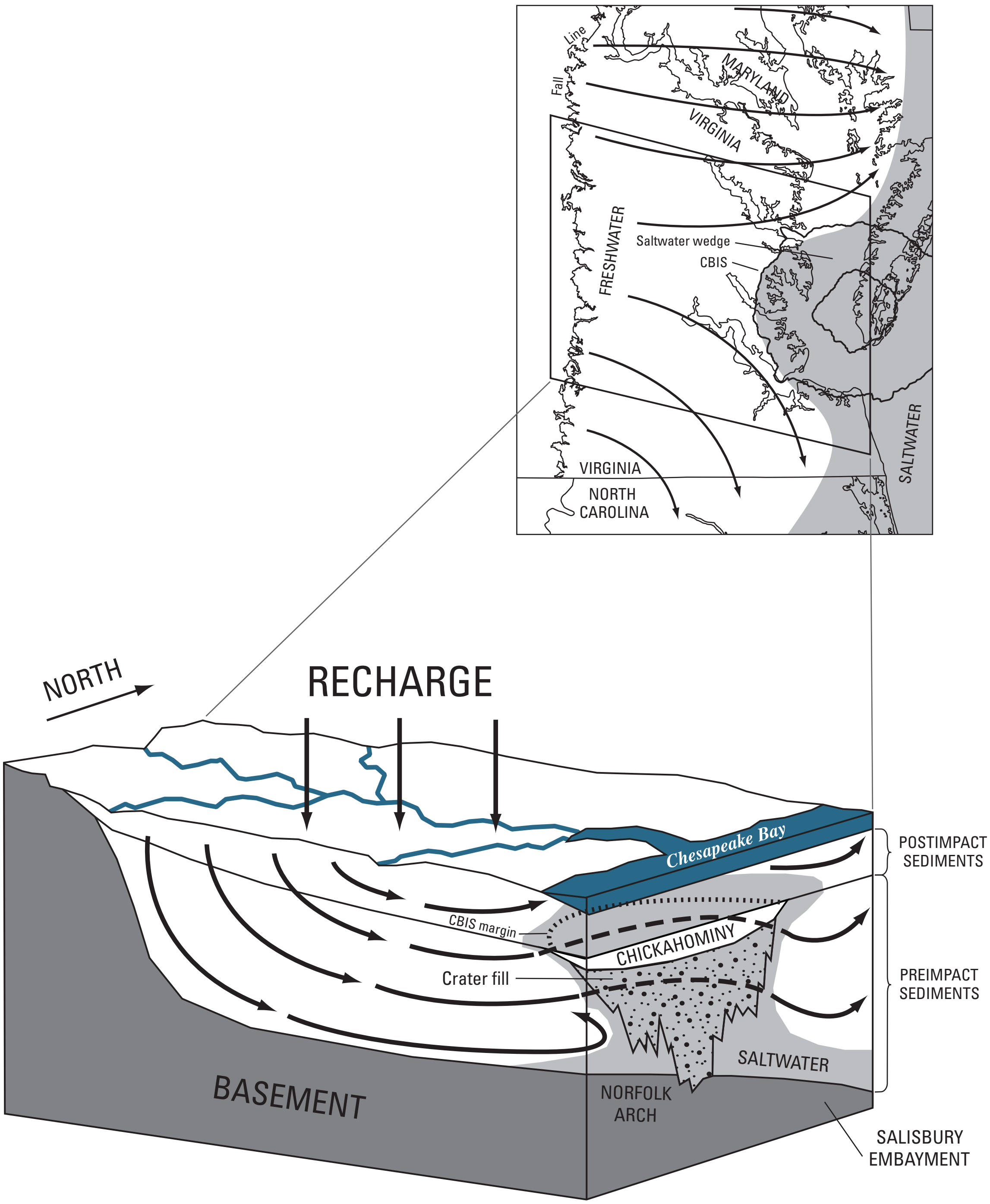

Figure K7. Schematic block diagram representing hypothetical differential ground-water flow directions (arrows) across the Chesapeake Bay impact structure (CBIS) prior to large ground-water withdrawals. The map shows the location of the saltwater wedge and of the region represented in the block diagram. The dashed lines in the block diagram indicate flow diverted around and behind the impact structure (dotted line).

cific conductance, which is shifted southward several kilometers relative to the position of the crater (fig. K1). Several controls on ground-water flow possibly have acted in combination to cause preferential northward flow. First, recharge during the Pleistocene Epoch possibly was enhanced across the northern part of the Atlantic Coastal Plain as a result of a large amount of infiltration associated with glacial outwash and a strong seaward gradient from the elevated and nearby Fall Line. Second, depth of basement and sediment thickness markedly increase northward from the impact structure into the Salisbury embayment (fig. K7), possibly providing the most transmissive path for lateral flow around the impact structure. The salinity inversion along the crater outer margin broadens, thickens, and deepens northeastward beneath Chesapeake Bay, the Delmarva Peninsula, and the continental shelf off New Jersey and is a relict feature of vigorous Pleistocene flushing (Meisler, 1989).

In contrast to flow north of the impact structure, southward lateral flow along the crater outer margin could be relatively constrained. Climate was warm enough even during the Pleistocene Epoch that glacial outwash was not present to provide an enhanced source of infiltration. The Fall Line is also farther inland and at a lower elevation, thereby reducing the seaward gradient. In addition, the basement is increasingly shallow across the Norfolk arch and into North Carolina (fig. K7), and so sediment thicknesses and transmissivities are less. Hydraulic continuity of the sediments also could be interrupted to the south across a zone roughly aligned with the James River (Powars, 2000), along which numerous stratigraphic discontinuities have been discerned. The salinity inversion along the crater outer margin does not appear to continue as far south as North Carolina (Winner and Coble, 1996), possibly as a result of constraints on lateral flow and flushing.

Flushing by fresh ground water of residual seawater from coastal plain sediments has continued to the present, from its onset during the emergence of the coastal plain at the end of the Pliocene Epoch, through its peak with the lowest sea level during the last Pleistocene glacial maximum of 18,000 years ago. The climate has warmed since then, sea level has risen to its present position, and seawater has re-inundated the continental shelf as well as the Pleistocene-age valley of the Susquehanna River, thereby forming Chesapeake Bay. Consequently, the saltwater transition zone has migrated landward during the past 18,000 years, and flushing at present is less vigorous than at its maximum.

With the rise in sea level to its present position, seawater has begun to reenter sediments underlying the re-inundated continental shelf and Chesapeake Bay, but at a rate slower than sea-level rise because the seawater advance has been relatively rapid compared to ground-water flow rates. As a result, the Atlantic Ocean and Chesapeake Bay have ridden over a volume of freshwater now stalled beneath saltier shallow ground water, thereby producing the salinity inversion that extends from the continental shelf off New Jersey southwestward beneath the Delmarva Peninsula and Chesapeake Bay and along the western margin of the Chesapeake Bay impact structure. Hence, the configuration of the saltwater transition zone represents an unstable transient condition in which the overriding seawater is not in equilibrium hydrodynamically with underlying fresh ground water. Solute-transport modeling of inundation of thick, relatively low-permeability sediments demonstrates how rapid inundation can produce a poorly mixed saltwater transition zone overlying a freshwater zone (Kooi and others, 2000). Sea level would have to maintain its present position for some period for the saltwater transition zone to attain a stable equilibrium configuration. Alternatively, should the climate continue to warm and sea level to rise, seawater will inundate additional areas and ride over and stall a greater volume of fresh ground water, thereby further propagating the salinity inversion.

Resource-Management Implications

Ground-water withdrawals in the Virginia Coastal Plain have increased during the past century to roughly 150 million gallons per day. A major part of this withdrawal has historically occurred at industrial pumping centers located outside of the Chesapeake Bay impact structure. Regional cones of depression centered on the industrial withdrawals exhibit water-level declines as great as 60 m (200 ft) and presently dominate the head distribution across the entire Virginia Coastal Plain (Hammond and others, 1994a,b,c). As a result, hydraulic gradients have been greatly increased and flow has been largely redirected landward from the saltwater wedge associated with the impact structure. The industrial withdrawals have been maintained at relatively stable rates for several decades. In addition, withdrawals for public supplies have been increasing in rapidly growing metropolitan areas positioned along the western margin of the impact structure and underlain by the saltwater transition zone. Desalinization of brackish ground water is being actively developed in these areas as a means to address growing water demands expected during the coming several decades.

Regional Saltwater Intrusion

The present withdrawal-induced head distribution has imposed a potential for saltwater intrusion across most of the Virginia Coastal Plain during much of the past century. The saltwater wedge, however, was recognized even earlier and prior to the onset of large ground-water withdrawals (Sanford, 1913). Thus, the saltwater wedge cannot be attributed to withdrawal-induced intrusion and must have formed under earlier, largely unstressed conditions. Conversely, intrusion in the form of landward expansion of the saltwater wedge across regional distances has not occurred (Smith, 1999) despite several decades of heavy pumping.

Diverse geologic and hydrologic evidence indicates that the saltwater wedge originated from seawater that was emplaced throughout the Virginia Coastal Plain sediments during regional inundation as recently as approximately 2 million years ago, along with much older seawater and evaporative brine within the Chesapeake Bay impact structure that was emplaced potentially as far back as the impact event 35 million years ago. With emergence of the coastal plain and resumption of ground-water recharge during the past 2 million years, residual seawater has been displaced by varying degrees by freshwater flushing, which at its most vigorous extended nearly to the edge of the continental shelf during the Pleistocene glacial maximum of 18,000 years ago. Because the saltwater wedge is still present today, it must have persisted during this maximum emergence even while some adjacent areas were being so vigorously flushed as to emplace freshwater far beyond the impact structure across most of the continental shelf. Preliminary simulation analyses demonstrate that saltwater within the impact structure maintained its present position during the Pleistocene emergence even as freshwater was being emplaced on all sides (Heywood, 2003). Since then, sea level has risen to its present position and the residual seawater has merged with the modern ocean.

Insufficient time has elapsed from the onset of heavy pumping to achieve the degree of regional flow under present gradients needed for significant landward expansion of the saltwater wedge. Despite greatly increased gradients and altered flow directions, the actual movement of ground water under stressed conditions has been relatively little throughout the Virginia Coastal Plain. Ground-water ages range from tens of thousands of years across much of the area outside of the Chesapeake Bay impact structure to several millions of years or more within the impact structure, and most of the ground water now present was emplaced prior to large withdrawals. Because of the preponderance of storative fine-grained sediments, much of the water withdrawn during the past century has apparently been derived from the release of old water from storage and not from flow across regional distances to pumping wells. As a result, ground-water salinity remains fundamentally as it was distributed under unstressed conditions.

The amount of time needed to induce sufficient flow in response to present gradients to cause landward expansion of the saltwater wedge across regional distances is unknown. Some details of the future behavior of the flow system under stressed conditions, however, could impose important controls. Conceivably, a threshold in terms of the duration and (or) magnitude of withdrawal could be reached beyond which removal from storage no longer provides most of the withdrawn water, and regional flow under present gradients becomes dominant. In addition, the hydraulic sluggishness of the Chesapeake Bay impact structure that enabled the saltwater wedge to persist during Pleistocene emergence could be expected to likewise lead to a lack of response to strong landward gradients. Predictive numerical simulation of regional flow and solute transport is one means to assess if and how the saltwater wedge could expand significantly landward in response to present and (or) projected pumping stresses, but it is beyond the scope of this chapter. Because the saltwater wedge has apparently maintained its present extent for millennia, our subjective judgment is that landward expansion across regional distances even under withdrawal-induced gradients could require a very long timeframe by human standards.

Saltwater Movement along the Western Margin

Although the saltwater wedge has not expanded regionally in response to large industrial withdrawals located outside of the Chesapeake Bay impact structure, relatively small changes in ground-water salinity have occurred along the western margin of the impact structure in association with co-located municipal withdrawals (Smith, 1999), some of which are of brackish ground water. The saltwater transition zone is positioned along the western margin of the impact structure and exhibits a convoluted configuration resulting from a large salinity inversion formed by complex differential flushing across and around crater-fill sediments (figs. K6 and K7). Additionally at the meter scale, the salinity distribution across the western margin exhibits a large degree of spatial variability (fig. K3). Although some large-scale controls on prepumping differential flushing along the western margin are apparent, such as the distribution of contrasting sediment lithologies, many small-scale hydrogeologic details, such as possible effects of faults, remain unknown.

In addition to hydrogeologic controls on the salinity distribution that have existed since unstressed conditions, localized effects now imposed by withdrawals located along the western margin are likewise unknown but possibly are even more complex. Many of these primarily municipal withdrawals have historically been episodic, ranging in duration from several months to several years to supplement surface-water supplies during prolonged drought, and have been interrupted by extended periods of no withdrawal (Focazio and Speiran, 1993). Manifold hydraulic interactions are likely among closely spaced wells operated by different municipalities and having diverse pumping histories. Within the coming decade, municipal withdrawal and desalinization of brackish ground water along the western margin are expected to increase significantly in response to population growth; municipal withdrawals may become as large as the industrial withdrawals located far inland from the western margin.

Unlike regional landward expansion of the saltwater wedge, localized saltwater movement along the western margin is possible within a relatively short timeframe. Withdrawals are increasing from wells placed directly within the saltwater transition zone where the salinity distribution is locally highly variable. At this scale, solute transport paths and traveltimes are relatively short. Were ground water within several tens of meters of a particular well to have a different salinity than that in which the well is first constructed, the salinity of the withdrawn water could potentially change within a period of several years after the onset of pumping. Under these conditions, saltwater movement could take place not only laterally through an aquifer but also vertically between aquifers (Smith, 1999).

The potential for localized withdrawal-induced redistribution of salinity within the saltwater transition zone poses a challenge to planning for increasing ground-water withdrawal by municipalities located along the western margin. Desalinization of brackish ground water is being increasingly relied on as a means to provide for the rapidly growing water demand. Future localized changes in the ground-water salinity distribution, however, could be difficult to assess. Similar to assessing regional landward expansion of the saltwater wedge, predictive numerical simulation of localized flow and solute transport along the western margin is one means to assess if and how salinity changes could occur in response to present and projected pumping from within the saltwater transition zone. Historically, these withdrawals have been difficult to project for the complex array of various municipal well systems that operate with a high degree of temporal and spatial variability and in response to unpredictable climate-driven demands (Focazio and Speiran, 1993). Significant uncertainty associated with a simplified simulation of solute transport across part of the western margin (Smith, 1999) resulted from limited information on withdrawal histories, as well as local-scale details of the configuration and hydraulic properties of aquifers and confining units, and on the spatial distribution and temporal changes in ground-water salinity.

Because hydrogeologic controls and withdrawal-induced effects within the saltwater transition zone are complex, a detailed local-scale characterization of hydrologic conditions will be critical to support any meaningful future assessment of the potential for saltwater movement along the western margin. Adequate spatial delineation of aquifer and confining-unit configurations and hydraulic properties, and of the distribution and changes in salinity, will require very densely arrayed data on sediment stratigraphy and structure (including the effects of faults) and ground-water levels, large-magnitude aquifer pumping tests, and long-term ground-water quality monitoring. Similarly, detailed histories of ground-water withdrawal will be needed. If ground water becomes a major component of the total water supply along the western margin, then future withdrawals could be more consistent and less episodic than past usage and, thus, easier to model.

Summary and Conclusions

The Chesapeake Bay impact structure in eastern Virginia is encompassed by a regionally extensive and heavily used aquifer system. Large and increasing withdrawals have resulted in significant and continuing water-level declines and have altered ground-water flow directions to create the potential for saltwater intrusion. The discovery of the impact structure requires changes to previous conceptualizations of the aquifer system as having a relatively simple layered configuration. To provide a basis for ground-water management decisions, the USGS and VDEQ are revising the hydrogeologic framework and an associated ground-water flow model of the entire Virginia Coastal Plain.

The impact structure has been inferred to play a role in controlling the salinity distribution in eastern Virginia. For this study, chemical analyses were performed on samples of ground water extracted from three sediment cores and collected from wells along the western margin of the impact structure. Increasing specific conductance values and increasing concentrations of chloride with depth reflect a broad but generally landward-dipping transition zone across the western margin that separates fresh ground water to the west from saltwater to the east. Areal coincidence of the transition zone with the western margin of the impact structure is consistent with earlier descriptions of the transition zone in eastern Virginia as comprising an inland saltwater wedge. Dispersive mixing is exhibited by small-scale variations in specific conductance where closely spaced samples were collected.

Ratios of bromide to chloride, iodide to chloride, and chlorine-36 to total chloride and stable hydrogen and oxygen isotope ratios indicate mixing of freshwater and seawater and support differential flushing of residual seawater among various competing hypotheses to explain the presence of the inland saltwater wedge. In addition, evaporation of seawater probably produced some ground water having specific conductance values that exceed that of seawater by as much as 35 percent; the mechanisms may have been (1) evaporation in restricted coastal environments under arid conditions, (2) rapid vaporization caused by the impact event, and (or) (3) evaporation caused by residual heat and associated hydrothermal activity following the impact.

The saltwater wedge originated from seawater emplaced throughout the Virginia Coastal Plain sediments during a regional inundation as recently as approximately 2 million years ago and from much older seawater and evaporative brine within the impact structure that were emplaced potentially as far back as the impact event 35 million years ago. With emergence of the coastal plain and resumption of ground-water recharge during the past 2 million years, residual seawater has been displaced to varying degrees by freshwater flushing.

Freshwater flushing across the crater outer margin was impeded by the clayey Chickahominy Formation, beneath which greater flushing took place through crater-fill sediments, and little or no flushing took place farther into the impact structure. As a result, water exited the flow system by lateral flow and flushing around the outer margin, followed by upward leakage and surface discharge to areas outside of the crater and possibly enhanced by faults. Within the impact structure, the saltwater wedge maintained its present position even during the Pleistocene glacial maximum of 18,000 years ago, while the most vigorous flushing outside of the impact structure extended nearly to the edge of the continental shelf. Since then, sea level has risen to its present position and the residual seawater has merged with the modern ocean along an inverted and hydrodynamically unstable transition zone.

A potential for saltwater intrusion across most of the Virginia Coastal Plain has been imposed during much of the past century by regional cones of depression centered on industrial pumping centers located outside of the Chesapeake Bay impact structure. The saltwater wedge predates the onset of heavy pumping, however, and has not since expanded across regional distances because most of the ground water now present was emplaced prior to large withdrawals. Predictive numerical simulation could be undertaken to assess whether a potentially very long timeframe could be required for regional expansion of the saltwater wedge.

Localized saltwater movement along the western margin of the impact structure could take place as a result of increasing withdrawals being made directly from the saltwater transition zone. Assessment of the potential for saltwater movement along the western margin represents significant technical challenges because of complex hydrogeologic controls and withdrawal-induced effects within the transition zone. Predictive simulation would require a detailed local-scale characterization of aquifer and confining-unit configurations and hydraulic properties, the distribution and changes in salinity, and withdrawal histories.

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References Cited

Andreasen, D.C., and Fleck, W.B., 1997, Use of bromide:chloride ratios to differentiate potential sources of chloride in a shallow, unconfined aquifer affected by brackish-water intrusion: Hydrogeology Journal, v. 5, no. 2, p. 17–26.

Back, William, 1966, Hydrochemical facies and ground-water flow patterns in northern part of the Atlantic Coastal Plain: U.S. Geological Survey Professional Paper 498–A, p. A1–A42.

Bradley, R.S., 1999, Paleoclimatology; Reconstructing climates of the Quaternary: New York, Academic Press, 613 p.

Bredehoeft, J.D., Blyth, C.R., White, W.A., and Maxey, G.B., 1963, Possible mechanism for concentration of brines in subsurface formations: American Association of Petroleum Geologists Bulletin, v. 47, no. 2, p. 257–269.

Cederstrom, D.J., 1943, Chloride in ground water in the coastal plain of Virginia: Virginia Geological Survey Bulletin 58, 36 p.

Coplen, T.B., 1993, Uses of environmental isotopes, *in* Alley, W.M., ed., Regional ground-water quality: New York, Van Nostrand Reinhold, p. 227–254.

Davis, S.N., Whittemore, D.O., and Fabryka-Martin, June, 1998, Uses of chloride/bromide ratios in studies of potable water: Ground Water, v. 36, no. 2, p. 338–350.

Drever, J.I., 1988, The geochemistry of natural waters (2d ed.): Englewood Cliffs, N.J., Prentice-Hall, 437 p.

Dunkle, S.A., Plummer, L.N., Busenberg, E., Phillips, P.J., Denver, J.M., Hamilton, P.A., Michel, R.L., and Coplen, T.B., 1993, Chlorofluorocarbons (CCl_3F and CCl_2F_2) as dating tools and hydrologic tracers in shallow groundwater of the Delmarva Peninsula, Atlantic Coastal Plain, United States: Water Resources Research, v. 29, no. 12, p. 3837–3860.

Focazio, M.J., and Speiran, G.K., 1993, Estimating net drawdown resulting from episodic withdrawals at six well fields in the Coastal Plain physiographic province of Virginia: U.S. Geological Survey Water-Resources Investigations Report 93–4159, 21 p., 7 oversize pls.

Focazio, M.J., Speiran, G.K., and Rowan, M.E., 1993, Quality of ground water in the Coastal Plain physiographic province of Virginia: U.S. Geological Survey Water-Resources Investigations Report 92–4175, 20 p.

Fritz, P., and Fontes, J.C., 1980, Introduction, *in* The terrestrial environment, A, v. 1 *of* Fritz, P., and Fontes, J.C., eds., Handbook of environmental isotope geochemistry: Amsterdam, Elsevier, p. 1–19.

Ghyben, W.B., 1888, Nota in verband met de voorgenomen putboring nabij Amsterdam [Notes on the probable results of the proposed well drilling near Amsterdam]: Koninklijk Instituut van Ingenieurs Tijdschrift 1888–89, p. 8–22.

Hammond, E.C., and Focazio, M.J., 1995, Water use in Virginia; Surface-water and ground-water withdrawals during 1992: U.S. Geological Survey Fact Sheet 94–057, 2 p.

Hammond, E.C., McFarland, E.R., and Focazio, M.J., 1994a, Potentiometric surface of the Brightseat-upper Potomac aquifer in Virginia, 1993: U.S. Geological Survey Open-File Report 94–370, 1 p.

Hammond, E.C., McFarland, E.R., and Focazio, M.J., 1994b, Potentiometric surface of the lower Potomac aquifer in Virginia, 1993: U.S. Geological Survey Open-File Report 94–373, 1 p.

Hammond, E.C., McFarland, E.R., and Focazio, M.J., 1994c, Potentiometric surface of the middle Potomac aquifer in Virginia, 1993: U.S. Geological Survey Open-File Report 94–372, 1 p.

Hanor, J.S., 1983, Fifty years of development of thought on the origin and evolution of subsurface sedimentary brines, *in* Boardman, S.J., ed., Revolution in the earth sciences; Advances in the past half-century: Dubuque, Iowa, Kendall/Hunt, p. 99–111.

Hanshaw, B.B., and Coplen, T.B., 1973, Ultrafiltration by a compacted clay membrane; II. Sodium ion exclusion at various ionic strengths: Geochimica et Cosmochimica Acta, v. 37, no. 10, p. 2311–2327.

Harsh, J.F., and Laczniak, R.J., 1990, Conceptualization and analysis of ground-water flow system in the coastal plain of Virginia and adjacent parts of Maryland and North Carolina: U.S. Geological Survey Professional Paper 1404–F, p. F1–F100. (Also available online at http://water.usgs.gov/pubs/pp/pp1404-f/)

Hem, J.D., 1985, Study and interpretation of the chemical characteristics of natural water (3d ed.): U.S. Geological Survey Water-Supply Paper 2254, 263 p. (Also available online at http://water.usgs.gov/pubs/wsp/wsp2254/)

Henry, H.R., 1960, Salt water intrusion into coastal aquifers: International Association of Scientific Hydrology Publication 52, p. 478–487.

Herzberg, Alexander, 1901, Die Wasserversorgung einiger Nordseebader [The water supply of parts of the North Sea Coast]: Journal für Gasbeleuchtung und verwandte Beleuchtungsarten sowie für Wasserversorgung, v. 44, p. 815–819; v. 45, p. 842–844.

Heywood, C.E., 2003, Influence of the Chesapeake Bay impact structure on ground-water flow and salinity in the Atlantic Coastal Plain aquifer system of Virginia, *in* Proceedings of MODFLOW and More 2003; Understanding through Modeling: Golden, Colo., International Ground Water Modeling Center, p. 871–875.

Hubbert, M.K., 1940, The theory of ground-water motion: Journal of Geology, v. 48, no. 8, pt. 1, p. 785–944.

Johnson, G.H., Kruse, S.E., Vaughn, A.W., Lucey, J.K., Hobbs, C.H., III, and Powars, D.S., 1998, Postimpact deformation associated with the late Eocene Chesapeake Bay impact structure in southeastern Virginia: Geology, v. 26, no. 6, p. 507–510.

Jones, B.F., Vengosh, A., Rosenthal, E., and Yechieli, Y., 1999, Geochemical investigations, *in* Bear, Jacob, Cheng, A.H.-D., Sorek, Shaul, Ouazar, Driss, and Herrera, Ismael, eds., Seawater intrusion in coastal aquifers; Concepts, methods, and practices: Dordrecht, The Netherlands, Kluwer Academic Publishers, p. 43–63.

Kooi, H., Groen, J., and Leijnse, A., 2000, Modes of seawater intrusion during transgressions: Water Resources Research, v. 36, no. 12, p. 3581–3589.

Larson, J.D., 1981, Distribution of saltwater in the coastal plain aquifers of Virginia: U.S. Geological Survey Open-File Report 81–1013, 25 p., 2 oversize pls.

Manheim, F.T., Brooks, E.G., and Winters, W.J., 1994, Description of a hydraulic sediment squeezer: U.S. Geological Survey Open-File Report 94–584, 39 p.

Manheim, F.T., and Horn, M.K., 1968, Composition of deeper subsurface waters along the Atlantic continental margin: Southeastern Geology, v. 9, no. 4, p. 215–236.

McFarland, E.R., 1998, Design, revisions, and considerations for continued use of a ground-water-flow model of the coastal plain aquifer system in Virginia: U.S. Geological Survey Water-Resources Investigations Report 98–4085, 49 p. (Also available online at http://va.water.usgs.gov/online_pubs/WRIR/98-4085/g-wfmcpasys_va.html)

Meisler, Harold, 1989, The occurrence and geochemistry of salty ground water in the northern Atlantic Coastal Plain: U.S. Geological Survey Professional Paper 1404–D, p. D1–D51, 6 oversize pls.

Meng, A.A., III, and Harsh, J.F., 1988, Hydrogeologic framework of the Virginia Coastal Plain: U.S. Geological Survey Professional Paper 1404–C, p. C1–C82, 4 oversize pls. (Also available online at http://pubs.water.usgs.gov/pp1404-C/)

Neuzil, C.E., 2000, Osmotic generation of "anomalous" subsurface fluid pressures in geological environments: Nature, v. 403, no. 6766, p. 182–184.

Phillips, F.M., Bentley, H.W., and Elmore, David, 1986, Chlorine-36 dating of old ground water in sedimentary basins, *in* Hitchon, Brian, Bachu, Stefan, and Sauveplane, C.M., eds., Hydrogeology of sedimentary basins; Application to exploration and exploitation [Proceedings of the Third Canadian/American Conference on Hydrogeology, Banff, Alberta, Canada, June 22–26, 1986]: Dublin, Ohio, National Water Well Association, p. 143–150.

Pinder, G.F., and Cooper, H.H., Jr., 1970, A numerical technique for calculating the transient position of the saltwater front: Water Resources Research, v. 6, no. 3, p. 875–882.

Powars, D.S., 2000, The effects of the Chesapeake Bay impact crater on the geologic framework and the correlation of hydrogeologic units of southeastern Virginia, south of the James River: U.S. Geological Survey Professional Paper 1622, 53 p., 1 oversize pl. (Also available online at http://pubs.usgs.gov/prof/p1622/)

Powars, D.S., and Bruce, T.S., 1999, The effects of the Chesapeake Bay impact crater on the geological framework and correlation of hydrogeologic units of the lower York-James Peninsula, Virginia: U.S. Geological Survey Professional Paper 1612, 82 p., 9 oversize pls. (Also available online at http://pubs.usgs.gov/prof/p1612/)

Purdy, C.B., Helz, G.R., Mignerey, A.C., Kubnuk, P.W., Elmore, David, Sharma, Pankaj, and Hemmick, Thomas, 1996, Aquia aquifer dissolved Cl^- and $^{36}Cl/Cl$; Implications for flow velocities: Water Resources Research, v. 32, no. 5, p. 1163–1171.

Rogers, W.S., and Spencer, R.S., 1971, Ground-water quality and structural control in southeastern Virginia: Geological Society of America Bulletin, v. 82, no. 8, p. 2313–2318.

Russel, W.L., 1933, Subsurface concentration of chloride brines: American Association of Petroleum Geologists Bulletin, v. 17, p. 1213–1228.

Sanford, Samuel, 1913, The underground-water resources of the Coastal Plain province of Virginia: Virginia Geological Survey Bulletin 5, 361 p.

Sanford, Ward, 2003, Heat flow and brine generation following the Chesapeake Bay bolide impact: Journal of Geochemical Exploration, v. 78–79, p. 243–247.

Smith, B.S., 1999, The potential for saltwater intrusion in the Potomac aquifers of the York-James Peninsula, Virginia: U.S. Geological Survey Water-Resources Investigations Report 98–4187, 24 p.

Stover, S.C., Ge, Shemin, Weimer, Paul, and McBride, B.C., 2001, The effects of salt evolution, structural development, and fault propagation on late Mesozoic-Cenozoic oil migration; A two-dimensional fluid-flow study along a megaregional profile in the northern Gulf of Mexico basin: American Association of Petroleum Geologists Bulletin, v. 85, no. 11, p. 1945–1966.

U.S. Environmental Protection Agency, 1990, Secondary maximum contaminant levels (section 143.3 of part 143, National secondary drinking water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100 to 149, revised as of July 1, 1990, p. 674.

Winner, M.D., Jr., and Coble, R.W., 1996, Hydrogeologic framework of the North Carolina Coastal Plain: U.S. Geological Survey Professional Paper 1404–I, p. I1–I106, 24 oversize pls.

Table K1. Chemical Data for Sediment-Core Water and Well Water along the Western Margin of the Chesapeake Bay Impact Structure in Eastern Virginia

Table K1 contains data on ground water extracted during 2000–2001 from sediment cores obtained along the western margin of the Chesapeake Bay impact structure and on ground water collected during 1967–2002 from existing water wells in adjacent areas (fig. K1). All three core sites (site numbers 59E 31 (USGS-NASA Langley), 59H 3 (North), and 60G 5–6 (Bayside)) are within the crater's outer margin. Seventeen wells are near the crater's outer margin, and most of them are outside it. Two wells (63F 52–53) are within the central crater and are closer to the center of the impact structure than any of the other sites. Although well-sample collection times span 35 years, the well data generally represent current conditions.

Sampling and analytical techniques are described in the section on "Methods." Selected samples of sediment-core water were analyzed as follows:

- Concentrations of chloride, bromide, and iodide were determined by colorimetry by Glenda Brown and Ted Struzeski of the USGS National Water-Quality Laboratory (NWQL)
- Stable-isotope ratios, in per mil relative to Vienna Standard Mean Ocean Water (Fritz and Fontes, 1980), of the hydrogen isotope deuterium (expressed as δD) and oxygen (expressed as $\delta^{18}O$) were determined by mass spectrometry by Tyler Coplen of the USGS Isotope Research Laboratory
- Isotope ratios of chlorine-36 to total chloride ($^{36}Cl/Cl$) were determined by accelerator mass spectrometry by David Elmore of the Purdue Rare Isotope Measurement Laboratory (PRIME Lab)

Existing ground-water quality data collected from water wells during 1967–2002 were retrieved from the USGS water-quality database (http://waterdata.usgs.gov/va/nwis/qw).

Table K1. Chemical data for sediment-core water and well water along the western margin of the Chesapeake Bay impact structure in eastern Virginia.

[µS, microsiemens; mg/L, milligrams per liter; conc., concentration; Br/Cl, bromide to chloride; I/Cl, iodide to chloride; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; ‰, per mil; $^{36}Cl/Cl$, chlorine-36 to total chloride; $^{36}Cl/Cl$ ratios shown as <1 indicate ratios below the analytical detection limit of 10^{-15}; blank entries indicate no data]

Sample or well number	Depth to sample top (meters)	Depth to sample top (feet)	Depth to sample bottom (meters)	Depth to sample bottom (feet)	Geologic formation	Specific conductance (µS)	Chloride conc. (mg/L)	Bromide conc. (mg/L)	Br/Cl ratio ($x10^{-3}$)	Iodide conc. (mg/L)	I/Cl ratio ($x10^{-5}$)	δD (‰)	$\delta^{18}O$ (‰)	$^{36}Cl/Cl$ ratio ($x10^{-15}$)	Remarks
USGS-NASA Langley core pore water (well number 59E 31, drilled in 2000)															
1	15.6	51.3	15.8	51.8	Yorktown	1,918									Shelly fine sand
5	31.8	104.3	31.9	104.8	Eastover	3,390	216								Medium sand; poor cohesion
10	45.8	150.2	45.9	150.7	Eastover	6,260								<1	Medium sand; poor cohesion
12	53.1	174.2	53.2	174.7	Eastover	8,820						–22.8	–4.56		Medium sand; poor cohesion
14	59.7	195.9	59.9	196.4	Eastover	10,950								<1	Silty very fine sand
15	63.2	207.5	63.4	208.0	Eastover	11,890									Fine to medium sand
17	74.5	244.4	74.6	244.9	Saint Marys	14,200	3,960	15.3	3.87	0.377	9.52				Silty very fine sand
22	90.7	297.6	90.9	298.1	Saint Marys	15,230									Clay and shell
29	111.1	364.6	111.3	365.1	Saint Marys	16,450								<1	Clay
33	120.9	396.5	121.0	397.0	Saint Marys	16,950									Silty fine sand
36	130.1	426.8	130.2	427.3	Calvert	18,150									Silty fine sand
38	135.8	445.5	135.9	446.0	Calvert	17,530									Clayey fine sand
39	139.6	457.9	139.7	458.4	Calvert	16,240									Silty fine sand and shell
40	142.2	466.5	142.3	467.0	Calvert	18,180									Silty fine to medium sand, shell
41	143.7	471.3	143.8	471.8	Old Church	17,450									Glauconitic/phosphatic sand
42	145.8	478.4	146.0	478.9	Old Church	18,420									Glauconitic/phosphatic sand
43	150.7	494.5	150.9	495.0	Old Church	18,370	5,360	21.9	4.09	0.725	13.5				Glauconitic/phosphatic sand
44	152.5	500.3	152.6	500.8	Old Church	18,810									Glauconitic/phosphatic sand
45	157.6	517.2	157.8	517.7	Old Church	17,850									Glauconitic/phosphatic sand
46	160.4	526.2	160.5	526.7	Old Church	19,770									Glauconitic/phosphatic sand
47	162.8	534.0	162.9	534.5	Old Church	18,070									Glauconitic/phosphatic sand
48	167.6	549.9	167.8	550.4	Old Church	16,270									Glauconitic/phosphatic sand
49	171.3	562.0	171.5	562.5	Old Church	17,800									Glauconitic/phosphatic sand
51	181.7	596.0	181.8	596.5	Drummonds Corner beds	22,100									Glauconitic/phosphatic sand
52	184.9	606.6	185.0	607.1	Chickahominy	22,100									Dense clay
53	189.7	622.3	189.8	622.8	Chickahominy	18,270								<1	Dense clay
54	194.7	638.9	194.9	639.4	Chickahominy	18,640									Dense clay
55	196.8	645.8	197.0	646.3	Chickahominy	18,640									Dense clay
56	199.1	653.1	199.2	653.6	Chickahominy	19,800									Dense clay
57	203.3	667.1	203.5	667.6	Chickahominy	21,200									Dense clay
58	205.0	672.6	205.2	673.1	Chickahominy	22,000									Dense clay
59	209.4	687.1	209.6	687.6	Chickahominy	21,400									Dense clay

Table K1. Chemical data for sediment-core water and well water along the western margin of the Chesapeake Bay impact structure in eastern Virginia.—Continued

[µS, microsiemens; mg/L, milligrams per liter; conc., concentration; Br/Cl, bromide to chloride; I/Cl, iodide to chloride; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; ‰, per mil; $^{36}Cl/Cl$, chlorine-36 to total chloride; $^{36}Cl/Cl$ ratios shown as <1 indicate ratios below the analytical detection limit of 10^{-15}; blank entries indicate no data]

Sample or well number	Depth to sample top		Depth to sample bottom		Geologic formation	Specific conductance (µS)	Chloride conc. (mg/L)	Bromide conc. (mg/L)	Br/Cl ratio ($x10^{-3}$)	Iodide conc. (mg/L)	I/Cl ratio ($x10^{-5}$)	δD (‰)	$\delta^{18}O$ (‰)	$^{36}Cl/Cl$ ratio ($x10^{-15}$)	Remarks
	(meters)	(feet)	(meters)	(feet)											
USGS-NASA Langley core pore water (well number 59E 31, drilled in 2000)—Continued															
60	211.1	692.5	211.4	693.5	Chickahominy	21,800									Dense clay
61	214.4	703.5	214.7	704.5	Chickahominy	22,800									Dense clay
62	221.3	725.9	221.4	726.4	Chickahominy	22,700									Dense clay
63	224.3	735.9	224.5	736.4	Chickahominy	21,700									Dense clay
64	227.0	744.6	227.1	745.1	Chickahominy	22,000								<1	Dense clay
65	229.5	752.8	229.6	753.3	Chickahominy	19,570									Dense clay
66	232.6	763.0	232.8	763.7	Chickahominy	22,400						–18.7	–3.79		Dense clay
67	238.2	781.6	238.4	782.3	Exmore beds	22,500	6,480	26.6	4.11	0.634	9.77				Matrix
68	243.0	797.4	243.2	797.9	Exmore beds	19,250									Matrix
69	244.8	803.1	244.9	803.6	Exmore beds	19,480									Matrix
71	248.6	815.6	248.8	816.3	Exmore beds	19,410									Matrix
72	250.7	822.6	250.9	823.3	Exmore beds	19,440									Matrix
73	253.4	831.4	253.6	832.1	Exmore beds	18,870									Matrix
74	257.7	845.4	257.9	846.1	Exmore beds	18,900									Matrix
75	260.0	853.1	260.3	853.9	Exmore beds	21,400								<1	Matrix
76	263.7	865.1	263.9	865.9	Exmore beds	11,470									Clay clast
78	267.9	879.1	268.2	879.8	Exmore beds	12,380									Clay clast
79	269.1	882.8	269.2	883.3	Exmore beds	17,260	6,340	23.5	3.71	0.661	10.4				Sand clast
80	272.7	894.7	272.9	895.5	Crater unit B	9,970									Clay clast
81	275.0	902.2	275.2	903.0	Crater unit B	11,530									Clay clast
82	278.0	912.0	278.2	912.8	Crater unit B	16,930									Medium to coarse sand clast
83	281.9	925.0	282.2	925.7	Crater unit B	10,530									Clay clast
84	285.3	936.0	285.4	936.5	Crater unit B	14,960									Clayey sand clast
85	286.9	941.2	287.1	942.0	Crater unit B	10,550									Clay clast
86	291.0	954.7	291.2	955.4	Crater unit B	15,220									Clayey sand clast
87	294.5	966.3	294.8	967.1	Crater unit B	10,960									Clay clast
88	297.9	977.2	298.0	977.7	Crater unit B	17,500									Clayey sand clast
89	300.0	984.2	300.1	984.7	Crater unit B	14,090									Silty fine sand clast
90	302.9	993.8	303.1	994.5	Crater unit B	12,590						–20.1	–4.02		Clay clast
91	307.1	1,007.4	307.3	1,008.2	Crater unit B	12,550	4,740								Clay clast
92	308.8	1,013.1	308.9	1,013.6	Crater unit B	14,630									Clay clast
93	311.9	1,023.2	312.0	1,023.7	Crater unit B	17,610									Sand clast
94	315.1	1,033.7	315.2	1,034.2	Crater unit B	14,580								<1	Clay clast
95	334.0	1,095.7	334.1	1,096.2	Crater unit B	14,100									Clay clast
96	336.1	1,102.7	336.3	1,103.2	Crater unit B	8,680									Clayey sand clast
97	338.2	1,109.7	338.4	1,110.2	Crater unit B	12,260									Clay clast

Table K1. Chemical data for sediment-core water and well water along the western margin of the Chesapeake Bay impact structure in eastern Virginia.—Continued

[µS, microsiemens; mg/L, milligrams per liter; conc., concentration; Br/Cl, bromide to chloride; I/Cl, iodide to chloride; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; ‰, per mil; $^{36}Cl/Cl$, chlorine-36 to total chloride; $^{36}Cl/Cl$ ratios shown as <1 indicate ratios below the analytical detection limit of 10^{-15}; blank entries indicate no data]

Sample or well number	Depth to sample top		Depth to sample bottom		Geologic formation	Specific conductance (µS)	Chloride conc. (mg/L)	Bromide conc. (mg/L)	Br/Cl ratio ($x10^{-3}$)	Iodide conc. (mg/L)	I/Cl ratio ($x10^{-5}$)	δD (‰)	$\delta^{18}O$ (‰)	$^{36}Cl/Cl$ ratio ($x10^{-15}$)	Remarks
	(meters)	(feet)	(meters)	(feet)											
USGS-NASA Langley core pore water (well number 59E 31, drilled in 2000)—Continued															
98	339.5	1,113.7	339.6	1,114.2	Crater unit B	12,700									Clay clast
99	341.5	1,120.5	341.7	1,121.0	Crater unit B	18,820									Sand clast
100	347.0	1,138.3	347.1	1,138.8	Crater unit B	5,930									Sand clast
101	348.3	1,142.7	348.4	1,143.2	Crater unit B	15,610									Clayey sand clast
102	351.2	1,152.2	351.3	1,152.7	Crater unit B	16,100									Sand clast
103	354.2	1,162.2	354.4	1,162.7	Crater unit B	14,440									Sand clast
104	357.7	1,173.7	357.9	1,174.2	Crater unit B	17,660									Clayey sand clast
105	359.8	1,180.3	359.9	1,180.8	Crater unit B	15,340	6,180	22.5	3.65	0.0233	0.377				Sand clast
106	360.8	1,183.7	360.9	1,184.2	Crater unit B	16,760									Clayey fine sand clast
107	364.4	1,195.6	364.6	1,196.1	Crater unit B	18,330									Clayey sand clast
108	365.9	1,200.5	366.1	1,201.0	Crater unit B	15,750								<1	Sand clast
109	419.3	1,375.7	419.5	1,376.2	Crater unit B	17,060	5,620	22.3	3.96	0.169	3.00				Sand and clay
110	422.5	1,386.1	422.6	1,386.6	Crater unit B	19,700									Silty fine sand clast
111	426.1	1,398.1	426.3	1,398.6	Crater unit B	7,550									Medium to coarse sand clast
112	428.0	1,404.1	428.1	1,404.6	Crater unit B	21,000									Medium sand clast
113	430.7	1,413.0	430.8	1,413.5	Crater unit B	12,420									Clay clast
114	434.6	1,426.0	434.8	1,426.5	Crater unit B	16,670						–19.0	–3.60		Clayey fine sand clast
115	438.7	1,439.2	438.8	1,439.7	Crater unit B	21,400								<1	Silty fine sand clast
116	507.9	1,666.5	508.0	1,666.7	Crater unit A	32,600								<1	Sand
117	527.7	1,731.4	527.8	1,731.6	Crater unit A	26,800	9,850	39.0	3.96	0.703	7.13				Clay
118	531.1	1,742.6	531.2	1,742.8	Crater unit A	31,100									Sand
119	534.0	1,752.0	534.1	1,752.2	Crater unit A	36,800									Sand
120	552.2	1,811.6	552.3	1,812.0	Crater unit A	37,700									Medium sand
121	555.3	1,822.0	555.5	1,822.5	Crater unit A	19,180									Medium to coarse sand
122	569.0	1,866.8	569.2	1,867.3	Crater unit A	33,400								<1	Medium to coarse sand
123	572.3	1,877.5	572.4	1,878.0	Crater unit A	23,200									Medium to coarse sand
124	574.5	1,885.0	574.7	1,885.5	Crater unit A	29,800									Medium to coarse sand
125	576.7	1,892.0	576.8	1,892.5	Crater unit A	25,500									Medium sand
126	582.8	1,912.0	582.9	1,912.5	Crater unit A	30,800	12,200	44.5	3.66	1.18	9.67				Clay
127	593.1	1,945.9	593.3	1,946.4	Crater unit A	41,400						–9.30	–2.21		Silty fine to medium sand
128	596.6	1,957.5	596.8	1,958.0	Crater unit A	37,000									Medium sand
129	599.1	1,965.5	599.2	1,966.0	Crater unit A	42,500								<1	Medium to coarse sand
130	602.9	1,978.0	603.0	1,978.5	Crater unit A	40,000									Medium to coarse sand
131	605.1	1,985.4	605.3	1,985.9	Crater unit A	41,300	18,000	80.7	4.48	1.80	9.98				Medium to coarse sand
132	608.7	1,997.0	608.8	1,997.5	Crater unit A	42,000									Medium to coarse sand
133	613.1	2,011.5	613.3	2,012.0	Crater unit A	39,700									Clayey fine to medium sand
134	624.8	2,050.0	624.9	2,050.3	Crater unit A	35,500									Clayey medium sand

Table K1. Chemical data for sediment-core water and well water along the western margin of the Chesapeake Bay impact structure in eastern Virginia.—Continued

[µS, microsiemens; mg/L, milligrams per liter; conc., concentration; Br/Cl, bromide to chloride; I/Cl, iodide to chloride; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; ‰, per mil; $^{36}Cl/Cl$, chlorine-36 to total chloride; $^{36}Cl/Cl$ ratios shown as <1 indicate ratios below the analytical detection limit of 10^{-15}; blank entries indicate no data]

Sample or well number	Depth to sample top		Depth to sample bottom		Geologic formation	Specific conductance (µS)	Chloride conc. (mg/L)	Bromide conc. (mg/L)	Br/Cl ratio ($x10^{-3}$)	Iodide conc. (mg/L)	I/Cl ratio ($x10^{-5}$)	δD (‰)	$\delta^{18}O$ (‰)	$^{36}Cl/Cl$ ratio ($x10^{-15}$)	Remarks
	(meters)	(feet)	(meters)	(feet)											
North core pore water (well number 59H 3, drilled in 2001)															
136	4.2	13.7	4.3	14.2	Eastover	1,031	99.6	0.091	0.92	0.163	16.4				Silty very fine sand
137	19.2	62.9	19.3	63.4	Eastover	1,101						–30.2	–5.38		Medium sand; poor cohesion
138	43.2	141.7	43.3	142.2	Eastover	1,369									Fine to medium shelly sand
139	74.0	242.7	74.1	243.2	Saint Marys	1,842	229								Clay
140	99.8	327.5	100.0	328.0	Calvert	2,050									Clayey fine sand
141	118.2	387.9	118.4	388.4	Calvert	3,560	304								Clayey fine sand
142	142.6	468.0	142.8	468.5	Old Church	2,860									Glauconitic/phosphatic sand
143	153.2	502.5	153.3	503.0	Old Church	5,300	434								Glauconitic/phosphatic sand
144	157.9	517.9	158.0	518.4	Chickahominy	3,190	394								Dense clay
145	175.0	574.0	175.1	574.5	Chickahominy	4,020									Dense clay
146	189.6	622.0	189.7	622.5	Chickahominy	4,050									Dense clay
147	217.5	713.5	217.6	714.0	Chickahominy	4,870	945	1.67	1.77	0.133	14.1				Dense clay
148	231.4	759.1	231.5	759.6	Exmore beds	5,140						–32.1	–5.54		Matrix
149	246.1	807.5	246.3	808.0	Exmore beds	5,660	1,230	4.96	4.03	0.279	22.7				Matrix
150	259.6	851.7	259.8	852.2	Crater unit B	4,240	1,100								Clay clast
151	273.3	896.7	273.5	897.2	Crater unit B	5,740									Sand clast
152	302.7	993.0	302.8	993.5	Crater unit B	3,040	761								Clay clast
154	318.5	1,044.8	318.6	1,045.3	Crater unit B	3,490									Clay clast
155	329.2	1,080.1	329.4	1,080.6	Crater unit A	8,560									Sand clast
156	353.0	1,158.0	353.1	1,158.5	Crater unit A	6,120									Sand
157	367.1	1,204.5	367.3	1,205.0	Crater unit A	6,210									Silty very fine sand
158	383.1	1,256.8	383.2	1,257.3	Crater unit A	10,250	3,130	12.7	4.06	0.396	12.7				Sand
159	404.4	1,326.7	404.5	1,327.2	Crater unit A	8,680						–29.2	–4.86		Sand
160	421.5	1,383.0	421.7	1,383.5	Crater unit A	5,500	1,400			0.231	16.5				Sand
161	433.6	1,422.5	433.7	1,423.0	Crater unit A	13,620	4,650	13.8	2.98	0.560	12.1				Sand
Bayside #1 core pore water (well number 60G 5, drilled in 2001)															
162	58.5	192.0	58.7	192.5	Eastover	13,870	3,600	13.5	3.75	0.230	6.40				Silty fine sand
163	75.0	246.0	75.1	246.5	Saint Marys	18,420						–22.2	–3.91		Clayey sand
164	90.2	296.0	90.4	296.5	Saint Marys	20,000									Silty clay

Table K1. Chemical data for sediment-core water and well water along the western margin of the Chesapeake Bay impact structure in eastern Virginia.—Continued

[µS, microsiemens; mg/L, milligrams per liter; conc., concentration; Br/Cl, bromide to chloride; I/Cl, iodide to chloride; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; ‰, per mil; $^{36}Cl/Cl$, chlorine-36 to total chloride; $^{36}Cl/Cl$ ratios shown as <1 indicate ratios below the analytical detection limit of 10^{-15}; blank entries indicate no data]

Sample or well number	Depth to sample top (meters)	Depth to sample top (feet)	Depth to sample bottom (meters)	Depth to sample bottom (feet)	Geologic formation	Specific conductance (µS)	Chloride conc. (mg/L)	Bromide conc. (mg/L)	Br/Cl ratio ($x10^{-3}$)	Iodide conc. (mg/L)	I/Cl ratio ($x10^{-5}$)	δD (‰)	$\delta^{18}O$ (‰)	$^{36}Cl/Cl$ ratio ($x10^{-15}$)	Remarks
Bayside #1 core pore water (well number 60G 5, drilled in 2001)—Continued															
165	107.6	353.0	107.7	353.5	Calvert	20,700	7,200	18.5	2.57	1.00	13.9				Clayey silt
166	119.2	391.0	119.3	391.5	Calvert	20,700									Silty fine sand
167	141.4	464.0	141.6	464.5	Calvert	20,900									Silty fine sand
169	156.6	513.7	156.7	514.2	Calvert	20,400	7,110	28.5	4.00	1.02	14.4				Silty fine sand
170	171.2	561.7	171.4	562.2	Old Church	20,800									Glauconitic sand
171	187.8	616.0	187.9	616.5	Old Church	22,500									Glauconitic sand
172	205.6	674.5	205.7	675.0	Old Church	25,100									Glauconitic sand
173	221.4	726.5	221.6	727.0	Chickahominy	26,400	11,200	45.5	4.07	1.66	14.8				Dense clay
174	241.9	793.5	242.0	794.0	Chickahominy	26,700						–14.4	–2.71		Dense clay
175	259.8	852.4	260.0	852.9	Chickahominy	38,500	13,700								Dense clay
176	276.1	905.7	276.2	906.2	Chickahominy	39,500						–11.3	–2.51		Dense clay
177	294.1	965.0	294.3	965.5	Exmore beds	41,200									Matrix
179	308.6	1,012.6	308.8	1,013.1	Exmore beds	42,200	16,500	69.2	4.19	2.51	15.2				Matrix
180	327.4	1,074.3	327.6	1,074.8	Exmore beds	44,800									Matrix
181	343.1	1,125.5	343.2	1,126.0	Exmore beds	47,300						–7.80	–1.79		Matrix
Bayside #2 core pore water (well number 60G 6, drilled in 2001)															
182	357.3	1,172.4	357.5	1,172.9	Exmore beds	46,600									Matrix
183	379.1	1,243.8	379.3	1,244.3	Exmore beds	47,600	18,600	74.0	3.97	1.05	5.67				Silty sand clast
184	397.2	1,303.0	397.3	1,303.5	Exmore beds	40,300	14,700	62.2	4.23	2.09	14.2				Sand clast
185	414.8	1,361.0	415.0	1,361.5	Exmore beds	42,500									Clay clast
186	443.2	1,454.0	443.3	1,454.5	Exmore beds	42,000						–7.60	–1.52		Clay clast
187	465.0	1,525.5	465.1	1,526.0	Exmore beds	47,200									Silty sand clast
188	473.4	1,553.0	473.5	1,553.5	Exmore beds	45,000	18,900	78.4	4.14	1.49	7.87				Clay clast
189	498.6	1,635.7	498.7	1,636.2	Exmore beds	46,000									Clay clast
190	519.4	1,704.0	519.5	1,704.5	Exmore beds	46,500									Sand clast
191	545.3	1,789.2	545.5	1,789.7	Exmore beds	47,400	18,800	78.6	4.18	2.61	13.9				Sand clast
192	565.3	1,854.5	565.4	1,855.0	Exmore beds	37,200	14,200	58.4	4.12	1.19	8.37				Clay clast
193	588.9	1,932.1	589.1	1,932.6	Exmore beds	40,800						–7.90	–1.38		Silty sand clast
194	615.9	2,020.7	616.1	2,021.2	Exmore beds	51,400	21,800	91.4	4.19	2.92	13.4				Sand clast
195	647.1	2,123.0	647.2	2,123.5	Exmore beds	51,700						–6.70	–0.95		Sand clast
197	688.7	2,259.4	688.8	2,259.9	Exmore beds	51,500	21,500	93.8	4.37	1.30	6.06				Indurated sand

Table K1. Chemical data for sediment-core water and well water along the western margin of the Chesapeake Bay impact structure in eastern Virginia.—Continued

[µS, microsiemens; mg/L, milligrams per liter; conc., concentration; Br/Cl, bromide to chloride; I/Cl, iodide to chloride; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; ‰, per mil; $^{36}Cl/Cl$, chlorine-36 to total chloride; $^{36}Cl/Cl$ ratios shown as <1 indicate ratios below the analytical detection limit of 10^{-15}; blank entries indicate no data]

Sample or well number	Depth to sample top		Depth to sample bottom		Geologic formation	Specific conductance (µS)	Chloride conc. (mg/L)	Bromide conc. (mg/L)	Br/Cl ratio ($x10^{-3}$)	Iodide conc. (mg/L)	I/Cl ratio ($x10^{-5}$)	δD (‰)	$\delta^{18}O$ (‰)	$^{36}Cl/Cl$ ratio ($x10^{-15}$)	Remarks
	(meters)	(feet)	(meters)	(feet)											
Water wells															
58E 3	160.0	525	166.1	545		2,140	420								Mulberry Island, 1978
58F 50	364.2	1,195	367.3	1,205		5,300	2,100								Lee Hall, 1984
58F 50	367.3	1,205	370.3	1,215		6,000	2,000								Lee Hall, 1986
58F 50	367.3	1,205	370.3	1,215		8,190	2,400	9.7	4.0						Lee Hall, 1996
58F 50	367.3	1,205	370.3	1,215		8,520	2,410	9.31	3.86						Lee Hall, 1997
58F 51	249.9	820	253.0	830		5,000	1,300								Lee Hall, 1984
58F 51	249.9	820	253.0	830		4,860	1,300	5.3	4.1						Lee Hall, 1986
58F 51	251.5	825	254.5	835		3,800	1,400								Lee Hall, 1996
58F 52	160.6	527	163.7	537		2,400	540								Lee Hall, 1984
58F 52	160.6	527	163.7	537		2,200	500								Lee Hall, 1986
58F 52	160.6	527	163.7	537		2,430	490	1.9	3.9						Lee Hall, 1996
58F 52	160.6	527	163.7	537		2,460	502	1.91	3.80						Lee Hall, 1997
58F 53	101.5	333	104.5	343		1,700	160								Lee Hall, 1984
58F 53	101.5	333	104.5	343		1,686	150	0.63	4.2						Lee Hall, 1996
58F 54	23.8	78	26.8	88		460	17								Lee Hall, 1984
58F 81	213.4	700	214.9	705		5,740	1,500	5.8	3.9						Filtration plant, 1995
58F 81	247.5	812	249.0	817		6,040	1,700	6.3	3.7						Filtration plant, 1995
58F 81	303.0	994	304.5	999		7,180	2,100	7.8	3.7						Filtration plant, 1995
58F 81	345.0	1,132	346.6	1,137		8,430	2,400	9.3	3.9						Filtration plant, 1995
58F 81	372.5	1,222	384.7	1,262		10,490	3,300	13	3.9						Filtration plant, 1995
58F 82	237.7	780	239.3	785		7,190	2,000	7.5	3.7						Remote site, 1995
58F 82	367.3	1,205	368.8	1,210		9,050	2,600	10	3.8						Remote site, 1995
58F 89	310.1	1,017.4	344.7	1,131		6,230									Skiffes Creek, 1998
58F 92	161.5	530	170.7	560		2,300	470	1.6	3.4						Skiffes Creek, 1996
58F 93	274.9	902	284.1	932		4,870	1,300	4.93	3.80						Skiffes Creek, 2000
58F127	149.0	489	170.7	560		2,030	387	1.37	3.54						Skiffes Creek, 2000

Table K1. Chemical data for sediment-core water and well water along the western margin of the Chesapeake Bay impact structure in eastern Virginia.—Continued

[µS, microsiemens; mg/L, milligrams per liter; conc., concentration; Br/Cl, bromide to chloride; I/Cl, iodide to chloride; δD, delta deuterium; $\delta^{18}O$, delta oxygen-18; ‰, per mil; $^{36}Cl/Cl$, chlorine-36 to total chloride; $^{36}Cl/Cl$ ratios shown as <1 indicate ratios below the analytical detection limit of 10^{-15}; blank entries indicate no data]

Sample or well number	Depth to sample top		Depth to sample bottom		Geologic formation	Specific conductance (µS)	Chloride conc. (mg/L)	Bromide conc. (mg/L)	Br/Cl ratio ($x10^{-3}$)	Iodide conc. (mg/L)	I/Cl ratio ($x10^{-5}$)	δD (‰)	$\delta^{18}O$ (‰)	$^{36}Cl/Cl$ ratio ($x10^{-15}$)	Remarks
	(meters)	(feet)	(meters)	(feet)											
Water wells—Continued															
59E 6	127.4	418	132.0	433		14,500	4,800								Big Bethel, 1984; shell & sand
59E 6	151.8	498	156.4	513		14,200	4,700								Big Bethel, 1984; black sand
59E 6	279.5	917	284.1	932		12,800	4,400								Big Bethel, 1984; coarse sand
59G 12	120.4	395	128.0	420		5,050	1,110								Gloucester Point, 1969
59G 12	120.4	395	128.0	420		4,780	1,100								Gloucester Point, 1972
59H 4	584.3	1,917	584.3	1,917		33,600						–17.3	–3.09		North, 2002
61C 1	258.5	848	264.6	868		3,900	964	3.7	3.8	0.4	41				Moores Bridge, 1967
61C 1	274.3	900	292.6	960		4,840	1,280	4.7	3.7	0.1	7.8				Moores Bridge, 1967
61C 1	287.4	943	293.5	963		5,080	1,380	4.9	3.6	0.4	29				Moores Bridge, 1968
61C 1	316.1	1,037	322.2	1,057		5,940	1,680	6.5	3.9	0.4	24				Moores Bridge, 1968
61C 1	382.5	1,255	389.2	1,277		12,600	4,200	16	3.8	0.8	19				Moores Bridge, 1968
61C 1	491.9	1,614	498.0	1,634		26,400	9,560	34	3.6	2.1	22				Moores Bridge, 1968
61C 1	728.8	2,391	735.2	2,412		61,300	26,000	98	3.8	3.7	14				Moores Bridge, 1968
61C 1	761.7	2,499	768.1	2,520		63,800	26,900	100	3.72	3.7	14				Moores Bridge, 1968
61D 5	367.9	1,207	416.7	1,367		28,700	10,200	36.8	3.63						Ferry Road, 2000
63F 52	395.3	1,297	401.4	1,317	Exmore beds	59,200	23,000	92.8	4.03						Kiptopeke, 1997; top of breccia
63F 52	395.3	1,297	401.4	1,317	Exmore beds	58,600	22,500	99	4.4	9.27	41.2	–4.6	–2.14	12.1	Kiptopeke, 2002; top of breccia
63F 53	64.0	210	67.1	220	Yorktown-Eastover aquifer	684	62.6	0.33	5.3						Kiptopeke, 1997; postimpact