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Deep drilling in the Chesapeake Bay impact structure—An overview

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ABSTRACT

The late Eocene Chesapeake Bay impact structure lies buried at moderate depths below Chesapeake Bay and surrounding landmasses in southeastern Virginia, USA. Numerous characteristics made this impact structure an inviting target for scientific drilling, including the location of the impact on the Eocene continental shelf, its three-layer target structure, its large size (~85 km diameter), its status as the source of the North American tektite strewn field, its temporal association with other late Eocene terrestrial impacts, its documented effects on the regional groundwater system, and its previously unstudied effects on the deep microbial biosphere.

The Chesapeake Bay Impact Structure Deep Drilling Project was designed to drill a deep, continuously cored test hole into the central part of the structure. A project workshop, funding proposals, and the acceptance of those proposals occurred during 2003–2005. Initial drilling funds were provided by the International Continental Scientific Drilling Program (ICDP) and the U.S. Geological Survey (USGS). Supplementary funds were provided by the National Aeronautics and Space Administration (NASA) Science Mission Directorate, ICDP, and USGS. Field operations were conducted at Eyreville Farm, Northampton County, Virginia, by Drilling, Observation, and Sampling of the Earth's Continental Crust (DOSECC) and the project staff during September–December 2005, resulting in two continuously cored, deep holes. The USGS and Rutgers University cored a shallow hole to 140 m in April–May 2006 to complete the recovered section from land surface to 1766 m depth.

The recovered section consists of 1322 m of crater materials and 444 m of overlying postimpact Eocene to Pleistocene sediments. The crater section consists of, from base to top: basement-derived blocks of crystalline rocks (215 m); a section of suevite, impact melt rock, lithic impact breccia, and cataclasites (154 m); a thin interval of quartz sand and lithic blocks (26 m); a granite megablock (275 m); and sediment

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blocks and boulders, polymict, sediment-clast–dominated sedimentary breccias, and a thin upper section of stratified sediments (652 m). The cored postimpact sediments provide insight into the effects of a large continental-margin impact on subsequent coastal-plain sedimentation.

This volume contains the first results of multidisciplinary studies of the Eyreville cores and related topics. The volume is divided into these sections: geologic column; borehole geophysical studies; regional geophysical studies; crystalline rocks, impactites, and impact models; sedimentary breccias; postimpact sediments; hydrologic and geothermal studies; and microbiologic studies.

INTRODUCTION

The Chesapeake Bay impact structure is among the largest and best preserved of the known impact features on Earth. Several characteristics of this late Eocene impact event (ca. 35.4 Ma; Horton and Izett, 2005; Pusz et al., 2009) also make it one of the most intriguing terrestrial impact structures. These characteristics include the rheologically variable, three-layer structure of the continental-shelf target (pre-Mesozoic silicate rocks, Cretaceous-Paleogene sediments, and ocean water) (Poag et al., 2004; Horton et al., 2005b; Collins and Wünnemann, 2005), the genetic association of the impact structure and the North American tektite strewn field (Poag et al., 1994; Koeberl et al., 1996; Deutsch and Koeberl, 2006), and the temporal association of the Chesapeake Bay impact structure with other late Eocene impact structures (Farley et al., 1998; Tagle and Claeys, 2004).

Geologic and hydrologic studies of water wells by D.J. Cederstrom (1945a, 1945b, 1945c) provided the first indication that a large subsurface structure of uncertain origin was located beneath the southern Chesapeake Bay area. Nearly 50 years later, the recovery and analysis of polymict breccias from core holes on the Delmarva Peninsula (Powars et al., 1992) (Fig. 1) led to the recognition that this structure was the result of the impact of a large extraterrestrial projectile (Poag et al., 1992, 1994; Koeberl et al., 1996). Since the mid-1990s, an increasing number of marine- and land-based seismic reflection studies, and core holes, have provided the data needed to describe the basic morphology, structure, and stratigraphy of the Chesapeake Bay impact structure (e.g., Poag, 1996, 1997; Poag et al., 1999, 2004; Powars and Bruce, 1999; Powars, 2000; Horton et al., 2005a, 2005b, 2008; Catchings et al., 2008).

The Chesapeake Bay impact structure lies buried beneath several hundred meters of postimpact sediments in the southern Chesapeake Bay area in southeastern Virginia, USA (Fig. 1). It consists of a central crater (collapsed transient cavity) that is ~35–40 km in diameter and is surrounded by a less deformed, outer annular zone that has a radial width of ~25 km. Poag et al. (2004), Horton et al. (2005b), Catchings et al. (2008), and most other previous studies refer to this outer zone as the annular trough (Fig. 1).

Scientific interest in the Chesapeake Bay impact structure has not been limited to impact processes and crater structure. It has been known for decades that some aquifers in southeastern Virginia contain saltwater at locations that are ~50 km inland of the expected limit of saltwater along the coast (Sanford, 1913; Cederstrom, 1945a). The discovery of the Chesapeake Bay impact structure in the early 1990s, and its spatial coincidence with this "inland saltwater wedge," led to investigations of the promising hypothesis that the Chesapeake Bay impact was the cause of the saltwater wedge (e.g., Sanford, 2003, 2005; Poag et al., 2004; McFarland and Bruce, 2005). Coastal plain aquifers are an important water resource in the rapidly developing southeastern part of Virginia (Hammond and Focazio, 1995), and the potential for migration of the saltwater into heavily used aquifers has remained a concern (McFarland and Bruce, 2005).

The effects of the Chesapeake Bay impact on regional subsidence and sedimentation also are of interest. The Chesapeake Bay impact structure formed on a passive continental margin where tectonism is largely controlled by thermal and thermal-flexural subsidence (Watts, 1981; Kominz et al., 1998). Yet, there has been

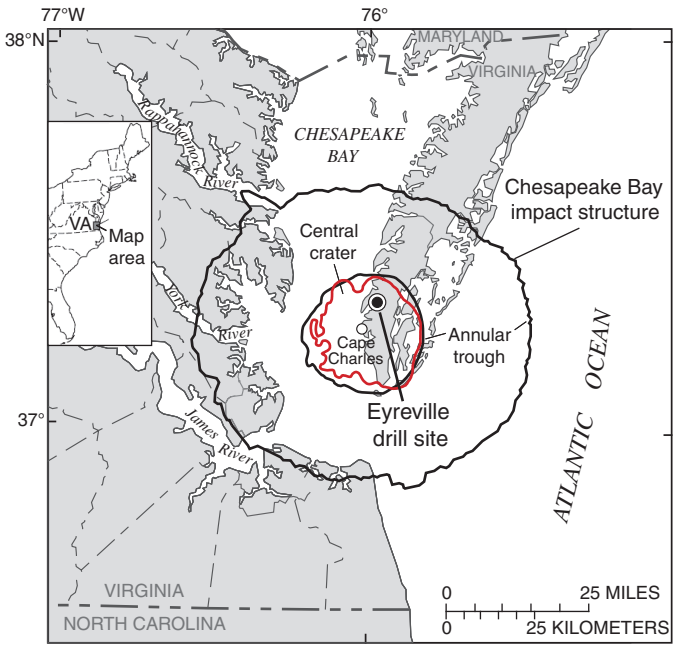

Figure 1. Location map for the Chesapeake Bay impact structure and the Eyreville drill site. Alternative locations for the margin of the central crater are from Powars et al. (this volume) (black outline) and Poag et al. (2004, their figures 4.1, 4.35, 4.36) (red outline).

a healthy debate on the controls of sedimentation on the U.S. Mid-Atlantic margin (New Jersey to North Carolina) between two camps, one that favors control by global sea-level (eustatic) changes (e.g., Olsson and Wise, 1987; Miller et al., 1996) and one that favors nonthermal tectonism (e.g., Brown et al., 1972; Owens and Gohn, 1985). Continuous coring in the New Jersey and Delaware coastal plains has documented that glacioeustatic change controlled the deposition of unconformity-bounded sequences (Miller et al., 1996), modulated by minor (tens of meters scale) nonthermal tectonism (Browning et al., 2006). Regional comparisons clearly show that there are differences in passive margin sedimentation between New Jersey and the Delmarva Peninsula (including the Chesapeake Bay impact structure) that must be attributed to nonthermal tectonism (e.g., Brown et al., 1972; Owens and Gohn, 1985), but quantification of these effects has been lacking. The Chesapeake Bay impact structure also significantly affected sedimentation by the nearly instantaneous generation of accommodation space, subsequent compaction of impactites, and possible thermal overprints (Hayden et al., 2008).

Continuing interest in the Chesapeake Bay impact event, and its effects on regional groundwater resources and continental-margin tectonics and sedimentation, led to the development of an international deep-drilling program for the Chesapeake Bay impact structure. Following two years of operational and scientific planning, deep-core drilling was completed successfully during 2005 and 2006 (Gohn et al., 2006), and preliminary results were presented at the Geological Society of America Annual Meeting and Exposition (28–31 October 2007, Denver, session T105; Gohn et al., 2008). In this paper, we discuss the development of the drilling program, drilling operations and results, and an overview of the scientific results presented in the various chapters in this volume.

THE ICDP-USGS DRILLING PROJECT

The creation of the Chesapeake Bay Impact Structure Deep Drilling Project began with a request by J.E. Quick (U.S. Geological Survey [USGS]), G.S. Gohn (USGS), and K.G. Miller (Rutgers University) to the International Continental Scientific Drilling Program (ICDP) for funding for a planning workshop. ICDP approved this request, and the workshop was held in September 2003 at Herndon, Virginia. Over sixty scientists and science managers representing ten countries attended the three-day event (Edwards et al., 2004).

Existing data sets and interpretations of the Chesapeake Bay impact structure were reviewed in preparation for determining the first-order scientific questions about the structure that could be addressed with deep core holes. In addition, a new major scientific goal was identified, the determination of the short- and long-term local effects of the Chesapeake Bay impact on subsurface microbial communities.

It also was recognized that the proposed deep drilling would provide the opportunity to compare the Chesapeake Bay impact structure with observations reported from other impact structures formed in shallow-marine environments, such as the Montagnais (Jansa et al., 1989), Mjølnir (Dypvik et al., 1996), and Lockne (Ormö and Lindström, 2000) impact structures. As the seventh-largest impact crater currently known on Earth, the Chesapeake Bay impact structure also can be compared with the large Chicxulub impact structure, another impact crater that formed on a continental shelf and is the third largest known on Earth.

The discussion of drilling targets quickly focused on the central crater where no scientific test holes of any significant depth had been drilled and relatively little seismic information was available below depths of ~1 km. This paucity of information contrasted with the eight core holes and hundreds of kilometers of seismic-reflection profiles located in the outer part of the Chesapeake Bay impact structure, the annular trough (Fig. 1).

Three major structural features of the central crater characterized by distinctive gravity anomalies were considered as drilling targets: (1) the central uplift, (2) the deepest part of the central crater (the "moat") that surrounds the central uplift, and (3) the rim of the central crater. Each target addressed a different set of scientific issues, with some overlap. After consideration of the relative merits of each target for addressing major scientific questions about the structure, the "moat" was the consensus choice for the drill site.

The workshop resulted in the submittal of a full proposal to ICDP in January 2004 by the editors of this volume for the funding of a 2.2-km-deep core hole. This proposal was accepted in early 2005, and additional funding from the USGS was received at about the same time. Supplementary emergency funding was received during the drilling operations from ICDP, USGS, and the National Aeronautics and Space Administration (NASA) Science Mission Directorate in November 2005. The initial funding from ICDP was contingent upon the completion of additional site characterization studies, primarily the completion of a pilot test hole and regional and local seismic surveys in the vicinity of the proposed drill site, as described in the following section.

SITE SURVEYS

Cape Charles Core Hole

The USGS drilled two test holes at the Sustainable Technology Park near Cape Charles (Fig. 1) during May and June 2004 (Sanford et al., 2004; Gohn et al., 2007). The goals of this pilot drilling effort were to determine the feasibility of coring the materials within the central crater, to collect core samples of crater materials from the structure's central uplift, and to collect groundwater data.

The first hole (STP1) was abandoned at a depth of 91.4 m because a surficial sand layer caved around the surface casing. The second hole (STP2) was drilled to a depth of 822.7 m (Fig. 2). Cores were collected between depths of 427.2 and 433.0 m and between 743.7 and 822.7 m. Cuttings samples were collected from the uncored intervals below 85.3 m depth. Interim sets of geophysical logs were acquired during the drilling operation, and one set was acquired after the drilling was completed.

Two wells were installed in the STP2 test hole. The deep well (designated 62G-24) was screened between 688.8 m and 694.9 m depth, and the shallow well (designated 62G-25) was screened between 414.5 m and 420.6 m depth. Groundwater salinities stabilized at 40 parts per thousand for the deep well and 20 parts per thousand for the shallow well.

The geologic section encountered in the STP2 hole consists of three main units (Fig. 2): (1) postimpact Eocene, Oligocene, Miocene, Pliocene, and Pleistocene sands and clays between land surface and a depth of 354.9 m; (2) sediment-clast breccias of the impact structure between depths of 354.9 and 655.3 m; and (3) suevite and shocked quartzofeldspathic gneiss of the impact structure between depths of 655.3 and 822.7 m. The suevite contains partly glassy, flow-laminated melt-rock clasts and lithic clasts that typically contain shocked quartz (Horton et al., 2008). Osmium isotope ratios and platinum-group-element (PGE) compositions indicated a minor meteoritic component in the suevite, although the chemical nature of the projectile could not be constrained with these data (Lee et al., 2006).

Regional Seismic Survey

The USGS acquired a series of seismic profiles across the Chesapeake Bay impact structure in October 2004 to delineate its dimensions and structural features. Unpublished high- and low-resolution seismic-reflection images and a tomographic P-wave velocity model generated from these data were used to characterize and to confirm the suitability of the proposed drill site. Initial analyses suggested that the crater floor was at a depth of ~2.2 km (Catchings et al., 2005), which was the proposed target depth for the Eyreville drilling program. Subsequent analyses suggested that the crater floor could be as deep as ~2.75 km and perhaps as deep as ~3.5 km (Catchings et al., 2008). Ultimately, the new drilling project recovered cores of basement-derived blocks of target crystalline rocks at 1551–1766 m depth (Horton et al., this volume, Chapter 2).

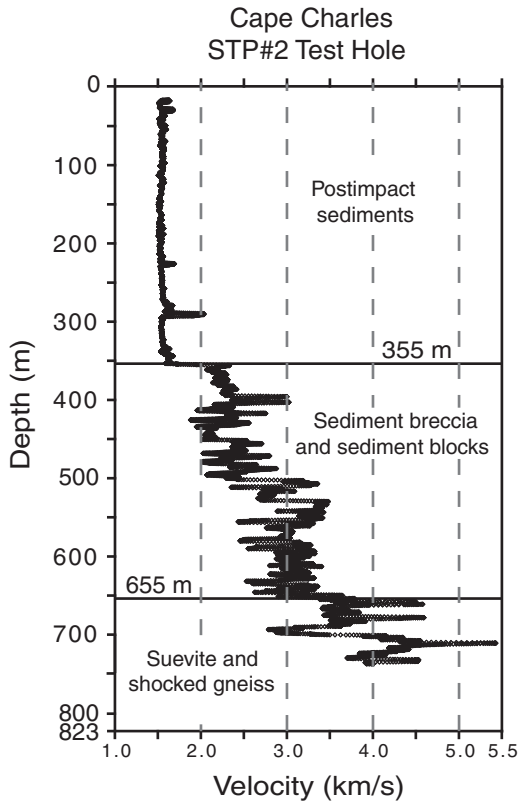

Figure 2. Geologic column and P-wave velocity log for the STP2 test hole near Cape Charles (Fig. 1).

DRILLING OPERATIONS

The drill site is located on private land, known locally as Eyreville Farm (Fig. 3), in Northampton County, Virginia, ~7 km north of the town of Cape Charles (Fig. 1). Three core holes were drilled at the Eyreville site (Table 1). The general drilling

Figure 3. Low-altitude aerial view of the Eyreville drill site, Northampton County, Virginia, USA. Photograph is courtesy of D.S. Powars (U.S. Geological Survey).

contractor was Drilling, Observation, and Sampling of the Earth's Continental Crust (DOSECC), Inc.

Site preparation and preliminary drilling began in July 2005. A local drilling company, Somerset Drilling, Inc., drilled (no coring) to a depth of ~128 m and installed large-diameter steel casing to a depth of 125 m. The principal contract driller, Major Drilling America, Inc., began coring at that depth on 15 September 2005 using a CP-50 wireline coring rig (Fig. 3). Coring with a PQ-diameter sampling system (117.5 mm rod diameter, 85 mm core diameter) continued to a depth of 591.0 m, when mud circulation was lost on 23 September 2005, and the CHD-134 ("PQ") drilling rods became trapped in the hole (Fig. 4). Coring resumed on 24 September 2005 using the PQ rods as casing and an HQ-diameter coring system (88.9 mm rod diameter, 63.5 mm core diameter with a rock shoe). HQ coring continued to a depth of 940.9 m, on 8 October 2005, when mud circulation again was lost. At that time, the HQ rods and drill bit were pulled up to the depth of 591.0 m. Attempts to ream the hole back to 940.9 m depth continued for over a week because of repeated loss of mud circulation due to expanding and sliding red-clay sections.

The bit returned to a depth of 940.9 m on 20 October 2005. However, during the reaming process, the bit had deviated from the original hole at a depth of 737.6 m. As a result, duplicate cores were collected between depths of 737.6 m and 940.9 m (Fig. 4). The original core hole to 940.9 m was designated as the Eyreville A core hole, and the new core hole below the deviation point at 737.6 m was designated as the Eyreville B core hole (Fig. 5; Table 1).

Coring with the HQ-diameter system continued to a depth of 1100.9 m in Eyreville B, where the HQ bit was deliberately stuck within a granite section on 26 October 2005 (Fig. 4), leaving the HQ rods in the hole as casing. Coring with an NQ-diameter sampling system (69.9 mm rod diameter, 47.6 mm core diameter) started on 27 October 2005 at 1100.9 m and continued without major problems to the final depth of 1766.3 m on 4 December 2005.

TABLE 1. CORED INTERVALS AND CORE SIZES FOR THE EYREVILLE CORE HOLES

Eyreville A	126.9 to 591.0 m, PQ core (85.0 mm diameter) 591.0 to 940.9 m, HQ core (63.5 mm diameter)
Eyreville B	737.6 to 1100.9 m, HQ core (63.5 mm diameter) 1100.9 to 1766.3 m, NQ core (47.6 mm diameter)
Eyreville C	0 to 140.2 m, HQ core (63.5 mm diameter)

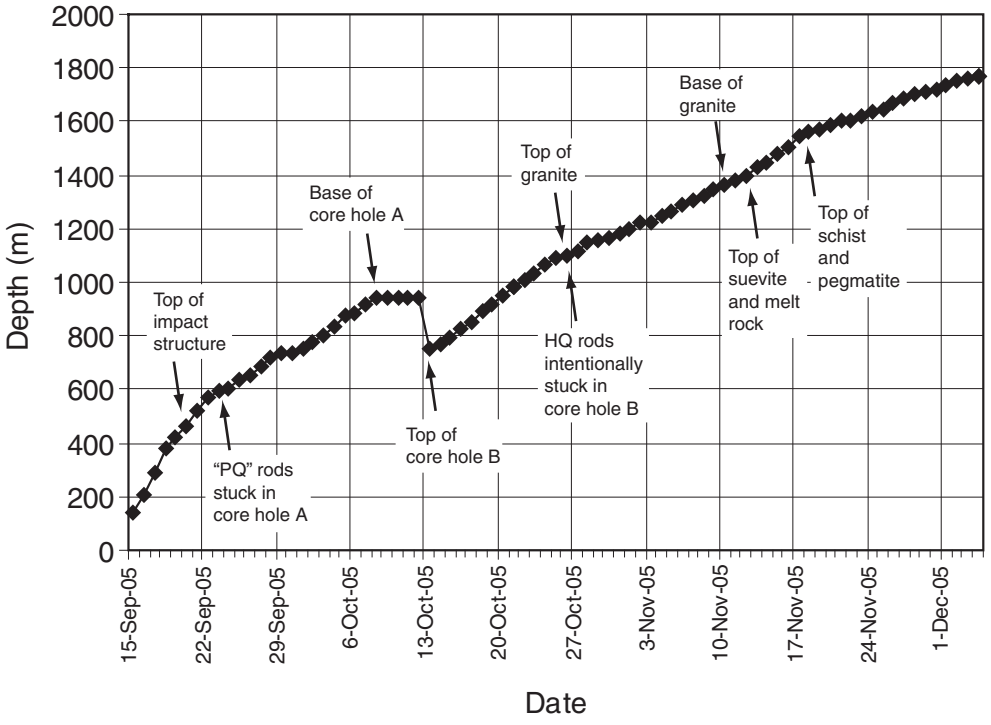

Figure 4. Chart showing the drilling history of the Eyreville A and B core holes.

The third core hole, Eyreville C, was drilled in April–May 2006 using a truck-mounted Mobile B-61 wireline coring rig (Fig. 6) by the USGS Eastern Earth Surface Processes Team. HQ-diameter cores were recovered to a total depth of 140.2 m between April 29 and May 4 (Table 1) using a Christensen 94 mm (HQ) system and an 11.4 cm Longyear bit that produced a nominal 63.5 mm core diameter. For unconsolidated sand, an extended ("snout") shoe was used to contact the sample 3.8–6.4 cm ahead of the bit. Actual core diameters were 61 mm with the rock shoe and 53 mm with the snout shoe. The upper part of the postimpact sediment section was sampled in Eyreville C to complement the deeper section of postimpact sediments sampled in Eyreville A.

Suites of geophysical logs (natural gamma, spontaneous potential, resistivity) were acquired from the upper 125 m of the Eyreville A core hole and from the 140 m section in the Eyreville C core hole. However, planned geophysical logging of the deeper part of combined core holes A and B was compromised by trapped drill rods, logging equipment malfunctions, and bridging of the open hole after the NQ rods were removed. Three logs were acquired after the coring was completed on 4 December 2005. The USGS logger acquired a natural gamma log and

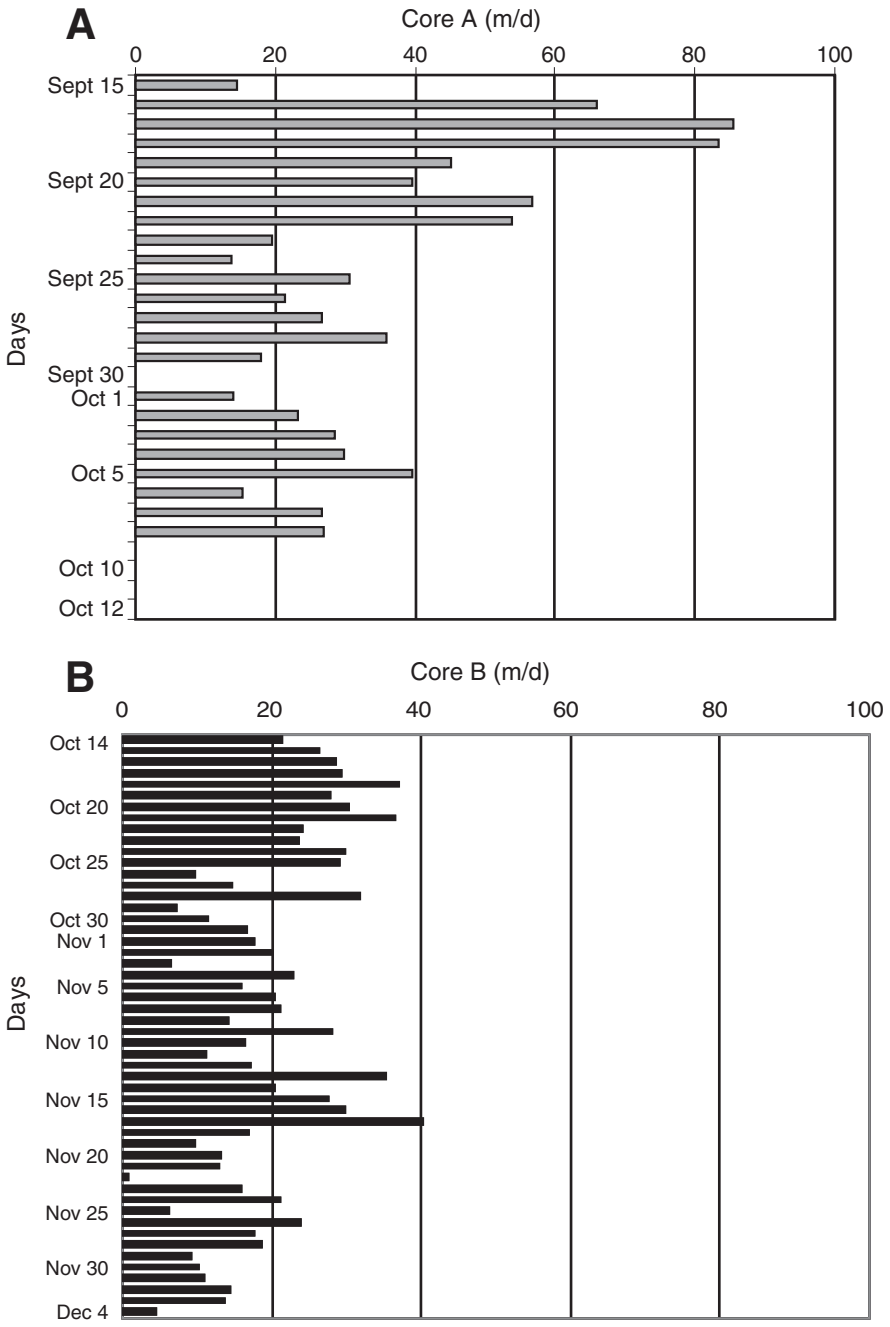

Figure 5. Daily drilling rates for the Eyreville deep core holes: (A) Eyreville A core hole, (B) Eyreville B core hole.

a temperature log inside the NQ rods for nearly the entire length of combined holes A and B. The Karlsruhe University logger acquired temperature logs to ~1400 m on 6 December 2005 and ~1130 m on 9 December 2005 (Heidinger et al., this volume). The Karlsruhe University logger acquired additional temperature logs to ~1100 m in the A-B core hole in early May 2006 (Heidinger et al., this volume).

DRILLING RESULTS

The ICDP-USGS drilling program was designed to continuously sample the entire section of postimpact sediments and crater fill, and a short section of autochthonous fractured rock in the crater floor, to a depth of ~2.2 km. However, problems with lost mud circulation, trapped drill rods, and occasionally slow penetration rates during the drilling of core holes A and B (Fig. 5) ultimately limited the total depth to 1.766 km (Gohn et al., 2006). The section of rocks and sediments recovered from the Eyreville core holes consisted of 1322.4 m of impact-generated breccias and fractured rocks beneath 443.9 m of postimpact Cenozoic sediments (Fig. 7) (Edwards, this volume, Chapters 3 and 4; Horton et al., this volume, Chapter 2).

The section of impact-modified materials consists of five major lithologic units. The deepest unit is 215 m thick and consists primarily of fractured mica schist, pegmatite, and coarse granite, with lesser amounts of gneiss, mylonitic rocks, and graphitic cataclasite (Horton et al., this volume, Chapter 2; Gibson et al., this volume; Townsend et al., this volume). Veins and small dikes of impact-generated polymict breccias, as well as pre-impact or impact-generated cataclastic zones crosscut the other rock types.

A 154-m-thick section of suevite, clast-rich impact melt breccias, lithic impact breccias, and cataclasite boulders overlies the schists, pegmatites, and related rocks (Bartosova et al., this volume, Chapter 15; Horton et al., this volume, Chapters 2 and 14; Wittmann et al., Chapters 16 and 17). Polymict impact breccias and blocks of cataclastic gneiss dominate the lower part of this section, whereas suevites and clast-rich melt breccias dominate the upper part.

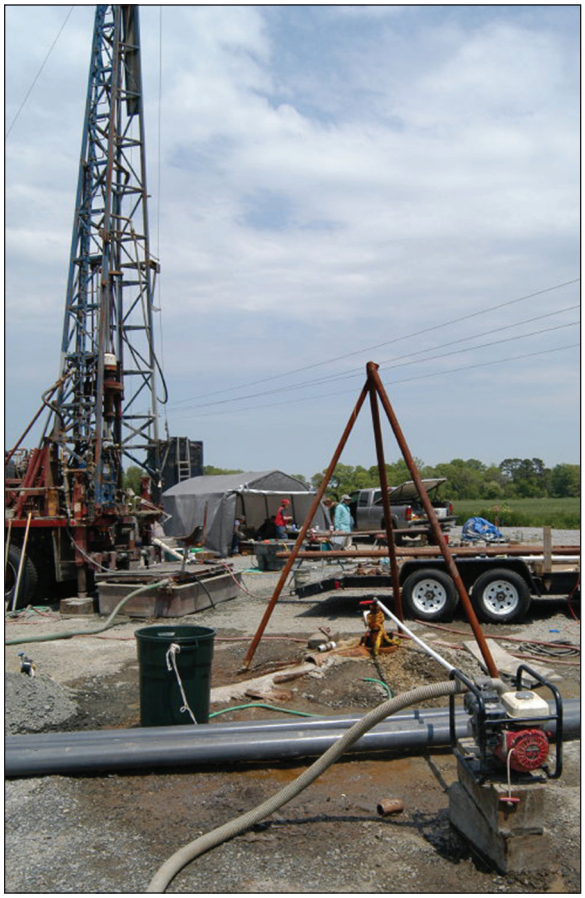

Figure 6. View of the Eyreville drill site during the drilling of core hole C in April–May 2006. The tripod is centered above core hole A–B. Photograph is courtesy of D.S. Powars (U.S. Geological Survey).

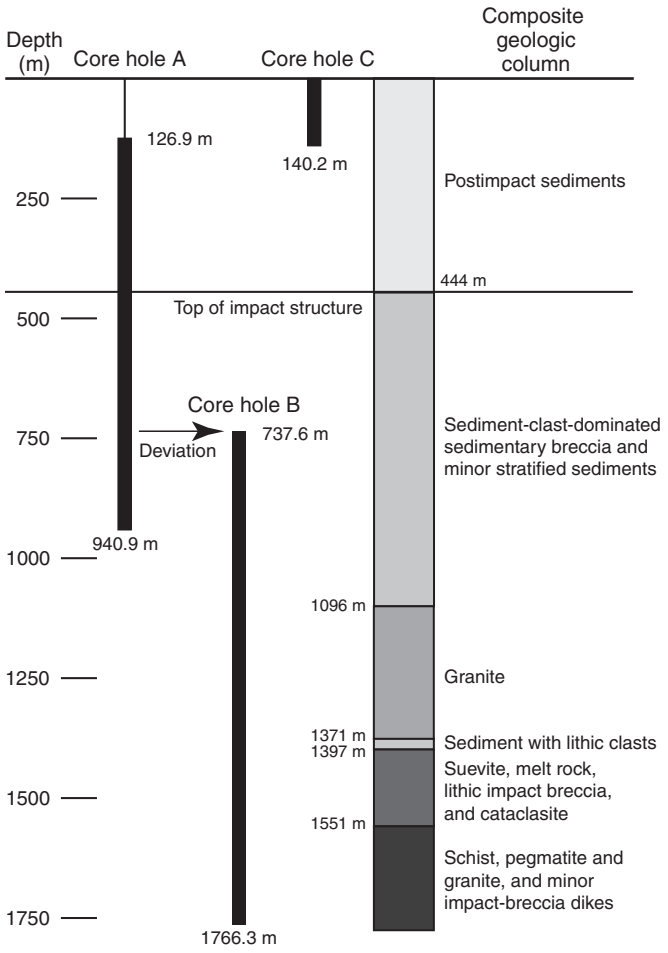

Figure 7. Core hole depths and composite geologic column for the Eyreville core holes.

A thin section of quartz sand (26.1 m) that contains large and small lithic clasts overlies the suevites and related rocks (Horton et al., this volume, Chapter 2). The sand section contains a 13.3-m-thick block of amphibolite near its center; reworked impact melt clasts, a cataclasite boulder, and a small suevite boulder are present near the base.

A 275-m-thick megablock of fractured granite lies above the quartz sand (Fig. 7). Several chapters in this volume refer to this megablock as a "slab" (>65.5 m, <1048.6 m), using the grain-size nomenclature of Blair and McPherson (1999). Four intermingled granite types are present: gneissic biotite granite, fine-grained biotite granite, medium- to coarse-grained biotite granite, and a 7 m basal zone of altered red biotite granite (Horton et al., this volume, Chapter 2).

The uppermost and thickest impactite unit consists of ~652 m of sediment blocks and polymict sedimentary breccia (Fig. 7) (Edwards et al., this volume, Chapter 3). These blocks and breccias consist almost entirely of Lower to basal Upper Cretaceous nonmarine sediments and Upper Cretaceous to upper Eocene marine sediments derived from the target sediment layer. Shocked crystalline clasts and melt particles are a relatively minor component, mostly occurring in the upper part of this interval (Reimold et al., this volume).

The postimpact sedimentary section consists of 444 m of upper Eocene to Pliocene (ca. 5.3 to ca. 1.8 Ma) continental-shelf sediments and Pleistocene (ca. 1.8 to ca. 0.01 Ma) nonmarine sediments (Edwards et al., this volume, Chapter 4). Thick upper Eocene and middle Miocene to Pliocene sections contrast with relatively thin lower Miocene and Oligocene sections.

RESEARCH SUMMARY AND DISCUSSION

Geologic Column

Lithologic Descriptions

Horton et al. (this volume, Chapter 2) and Edwards et al. (this volume, Chapters 3 and 4) provide detailed lithologic and stratigraphic summaries of the rock and sediment units encountered in the Eyreville cores. This information is presented as written descriptions, geologic logs, graphical summaries, and representative core photographs. In addition, Durand et al. (this volume) provide a complete photographic record of the Eyreville A, B, and C cores on the DVD found at the back of this volume. Photographs of each core box taken at the drill site and after sampling (where available) are included, along with original depths assigned to the cores at the drill site (feet as boxed, ft*) and adjusted depths (revised meters composite depth, rmcd).

The Exmore Formation

Polymict, sediment-clast–dominated sedimentary breccias with a muddy, glauconitic quartz sand matrix are widespread in the Chesapeake Bay impact structure and typically are referred to informally as the Exmore beds, Exmore breccia, Exmore tsunami breccia, or similar terms (e.g., Powars et al., 1992; Powars and Bruce, 1999; Poag, 1997; Poag et al., 1994, 2004; Horton et al., 2008). In this volume, Edwards et al. (this volume, Chapter 3) formally define the Exmore Formation and establish its type section as the interval from 443.9 to 866.7 m in Eyreville core A. The Exmore unit was first encountered in a core hole near Exmore, Virginia (Powars et al., 1992). However, the Exmore section in that core was only 57 m thick, and the lower contact of the unit was not reached. The Eyreville core, located ~27 km from Exmore, contains the thickest cored section of the Exmore unit (423 m) and contains the upper and lower contacts of the unit. Individual chapters in this volume use either the earlier informal nomenclature or the new formal definition for the Exmore unit. The chapters that use an informal name vary in their choice of a basal contact.

Edwards et al. (this volume, Chapter 3) also define four informal members of the Exmore Formation in Eyreville core A; from base to top, they are: the lower diamicton member, the block-dominated member, the upper diamicton member, and the stratified member. Sediment-clast breccias consisting almost entirely of Cretaceous nonmarine target sediments below the Exmore Formation and above the granite megablock (866.7–1095.7 m) are informally named the sediment boulder and sand section (Edwards, et al., this volume, Chapter 3).

Borehole Geophysical Studies

The lack of a complete suite of borehole geophysical logs for the Eyreville core holes increased the need for laboratory measurements of the petrophysical properties of the cores. Mayr et al. (this volume), Elbra et al. (this volume), and Pierce and Murray (this volume) collectively present measurements of porosity, density, resistivity, P-wave velocity and amplitude, shear-wave velocity, magnetic susceptibility, and thermal properties from sets of relatively closely spaced core samples. These measurements complement the natural gamma log and the temperature logs (Heidinger et al., this volume) collected in the deep core holes.

The measured physical properties vary considerably throughout the core, generally following expected trends controlled by lithologic variations and increasing depth. For example, porosity decreases from 40 to 60 vol% in the postimpact sediments and 27–44 vol% in the sedimentary breccias to 1–25 vol% in the section of suevite, melt breccia, and lithic impact breccia, 1–13 vol% in the basal schists and pegmatite, and <1 vol% in the granite megablock (Mayr et al., this volume). Differences in measured values of some parameters between sample sets likely resulted from differences in methodologies. For example, measurements by Pierce and Murray (this volume) using a GeoTek Multi-Sensor Core Logger were acquired using dry samples, in contrast to measurements by Mayr et al. (this volume), who used water-saturated samples where feasible.

Elbra et al. (this volume) analyzed Eyreville core samples, including postimpact, impact-produced, and basement-derived units, in order to investigate the magneto-mineralogy, to provide

physical parameters for understanding impact effects on petrophysical and rock-magnetic properties, and to provide rock-magnetic data for magnetic modeling. The results indicate a complex variation of magnetic properties in the various lithologies affected by shock-induced changes.

Regional Geophysical Studies

Gravity, magnetic, and seismic surveys acquired in the southern Chesapeake Bay area provide a regional context for the interpretation of the impact and postimpact events represented in the Eyreville cores. Plescia et al. (this volume) integrated newly acquired land and shipboard gravity data with existing databases to create a new gravity map of the Chesapeake Bay impact structure area. They consider the gravity data to be consistent with the interpretation of the Chesapeake Bay impact structure as an 85-km-diameter complex impact structure with an ~40-km-diameter central crater (Fig. 8). Observed anomalies include a positive anomaly over the central uplift and a negative anomaly over the annular structural depression (the moat) that

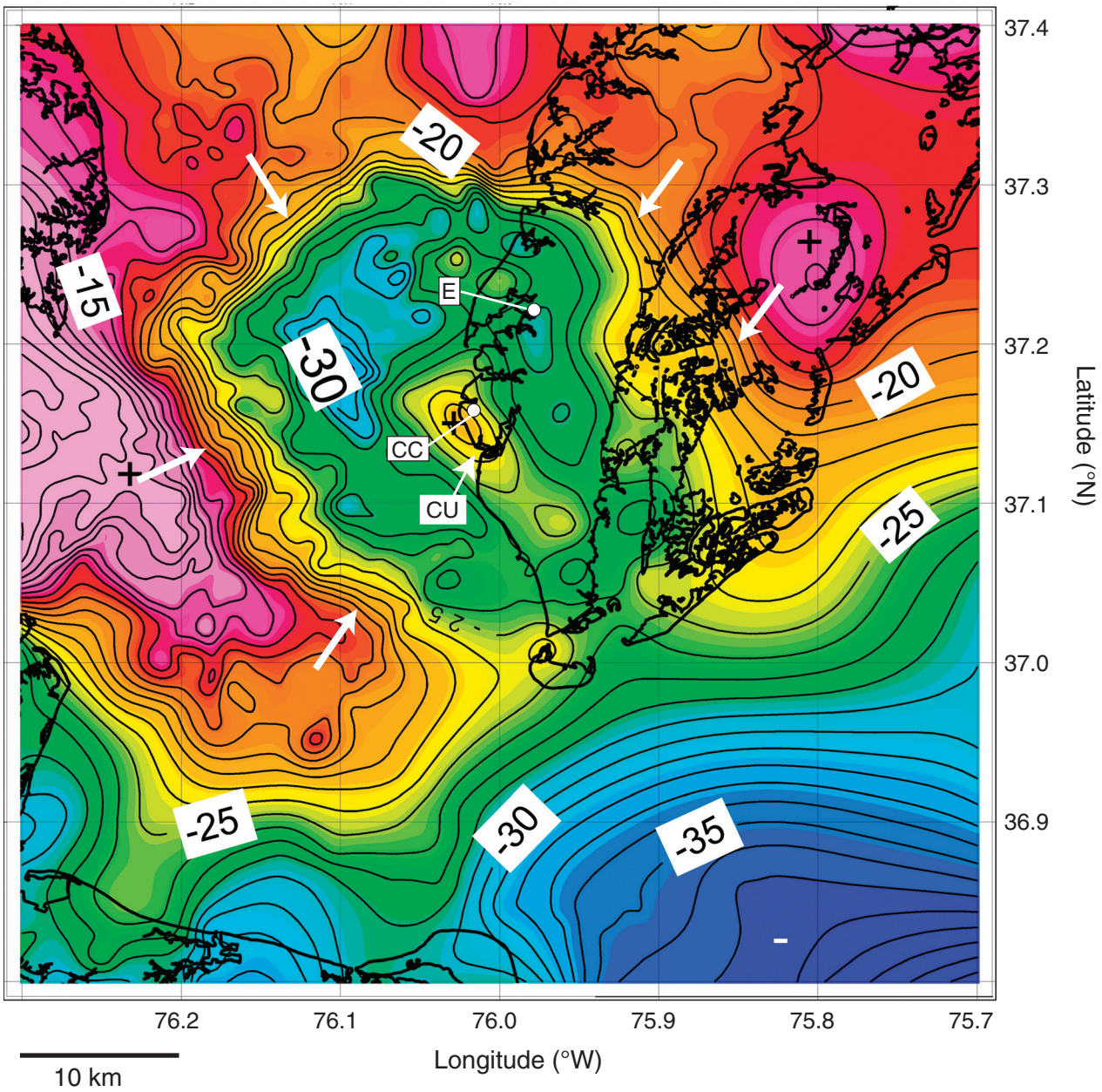

Figure 8. Shaded Bouguer gravity map of the Chesapeake Bay impact structure gravity anomaly. The white arrows mark the rim of the Chesapeake Bay impact structure central crater. The central uplift (CU), the Eyreville drill site (E), and the Cape Charles STP2 drill site (CC) are labeled. The contour interval is 1 mGal. Figure was modified from Plescia et al. (this volume, their figure 6).

surrounds the uplift. Gravity anomalies are not spatially associated with the annular trough or the outer rim of the Chesapeake Bay impact structure, which suggests only shallow impact deformation in those areas.

Shah et al. (this volume) used measurements of magnetic susceptibility and remanent magnetization for the Eyreville and Cape Charles cores, and newly and previously collected magnetic field data, to constrain structural features within the central part of the Chesapeake Bay impact structure. Forward modeling of the magnetic field shows that magnetic sources in the crater fill may represent basement-derived megablocks that are a few hundred meters thick or melt bodies that are a few dozen meters thick.

Powars et al. (this volume) present two ~1.4-km-long, high-resolution seismic-reflection surveys that cross the Eyreville drill site. Generally horizontal, high-amplitude parallel reflections above ~527 m depth represent the postimpact sediments and the uppermost part of the sedimentary breccias. Moderate-amplitude, discontinuous, dipping reflections below that depth correlate with the sediment and rock breccias recovered in the cores. Reflections with 10–20 m of relief in the uppermost part of the crater-fill and lowermost part of the postimpact section suggest early postimpact differential compaction of the crater-fill materials and related subsidence. Concave-upward reflections in the Miocene and younger sections suggest the presence of numerous paleochannels.

Basement-Derived Blocks

The lowermost sequence of basement-derived lithologies (1551.2–1766.3 m) and the 275-m-thick allochthonous megablock of granite and granite gneiss (1095.7–1371.1 m) represent a unique and extensive sample of crystalline basement from beneath the eastern Atlantic Coastal Plain. Initial chronology on various granite facies has shown that both Neoproterozoic and Permian granite emplacement events are recorded in this core (Horton et al., this volume, Chapter 14). Detailed mineralogic, textural, and structural analysis of this extensive sequence has provided a new body of regional tectonic and metamorphic information (Gibson et al., this volume; Townsend et al., this volume). The upper section of the basement-derived sequence consists mostly of schist and cataclastic schist, whereas the lower part is dominated by granite and granite pegmatite. The granite megablock is essentially undeformed, with the exception of moderate fracturing and a few thin cataclastic zones. Cataclasis and fracturing are present throughout the lowermost core section. This is particularly true in the schists immediately below the impactite sequence; the obvious interpretation is that this rock deformation is related to the impact event and that the affected rocks represent part of the crater floor (see following). The deeper granite pegmatite and granite are, however, moderately fractured and only weakly deformed. Isolated cataclastic zones are the only locations of significant deformation. It is not clear whether this represents impact-related deformation or a pre-impact tectonic overprint. Kenkmann et al. (this volume) indicate that multiple phases of both ductile and brittle deformation are represented, which forces the conclusion that both pre-impact and synimpact deformation are in evidence.

Shock-diagnostic deformation is rare in the basement-derived rocks and entirely absent in the granite megablock. It is possible that shock pressures below 8 GPa may be recorded in a few rock samples by planar fracturing of mineral grains (Glidewell et al., 2008). Shock-deformed material does occur in narrow veins and dikes of impact breccia (Reimold et al., 2007; Horton et al., this volume, Chapter 2), including suevite (melt-bearing breccia) and polymict lithic impact breccia (without a melt component). The presence of a range of shock levels from <10 GPa (as indicated by planar fracturing [PF] and single sets of planar deformation features [PDFs]) to >50 GPa (the regime where bulk melting is induced by shock), and the presence of exotic clasts, including sediment from the upper part of the target, signify that the breccia veins and dikes are injections of mixed materials derived from all parts of the transient cavity. In addition to the shocked vein and dike breccias, wall rock immediately adjacent to a few breccia injections contains rare quartz grains with one or two sets of PDFs (W.U. Reimold and J.W. Horton Jr., 2008, personal commun.), which are indicative of shock pressures between 8 and 20 GPa. The association of breccia dikes and shocked wall rocks indicates that shock enhancement occurred along the same preexisting discontinuities, such as fractures or cataclastic zones, that were the preferred zones of weakness for impact-breccia injection.

The scarcity of shock deformation in the basement-derived rocks requires that these blocks were derived from a zone of the impact crater where shock deformation was <10 GPa. Consequently, Horton et al. (this volume, Chapter 14) and Kenkmann et al. (this volume) conclude that these blocks were transported into the inner part of the transient cavity from original sites that were higher on its outer margin. Alternatively, blocks could have been derived from the edge of the central uplift, although rocks from that area would likely display more pervasive evidence for shock metamorphism. It is reasonable to assume that block movement would have occurred during late modification of the impact structure, namely, during the avalanche and resurge activity during and following the collapse of the transient cavity and the formation and collapse of the central uplift (Kenkmann et al., this volume). These authors present results of numerical modeling and calculations that demonstrate the possibility that very large blocks (hundreds of meters in size) can be transported over significant distances by impact-triggered ocean-resurge currents.

Suevites, Melt Rocks, and Lithic Breccias

Several suevite units, two intervals of impact melt rock, polymict lithic breccias, and blocks of cataclastic gneiss constitute 154 m of the Eyreville B drill core, from 1397.2 to 1551.2 m (Horton et al., this volume, Chapter 2; Wittmann et al., this volume, Chapters 16 and 17). A small suevite boulder was found between 1393.0 and 1393.4 m depth within gravelly sand above

the impactite section, and some melt particles (thought to be derived from reworked suevite) are present within that sand between 1396.4 and 1397.2 m (Horton et al., this volume, Chapter 2). Suevite also occurs in the form of several impact-breccia veins and dikes in the crystalline basement, as noted above (Reimold et al., 2007).

The impact breccia section (Bartosova et al., this volume, Chapter 15; Horton et al., this volume, Chapters 2 and 14) is subdivided on the basis of petrographic observations into, from top to bottom: (1) the upper suevite (SU, 1397.2–1402.0 m depth); (2) a clast-rich impact melt rock (M2, 1402.2–1407.5 m depth); (3–4) two suevite units (S3 and S2, 1407.5–1432.3 m, and 1433.8–1450.2 m depth, respectively), which are separated by a boulder of cataclastic quartz-feldspar schist; (5) a clast-rich impact melt rock (M1, 1450.2–1451.2 m depth); (6) a suevite unit (S1, 1451.2–1474.1 m depth); and (7) a complex intercalation (1474.1–1551.2 m) of several blocks of cataclastic gneiss (B5 to B1) with core-length intervals of 2.4–17.8 m and polymict impact breccias (P4 to P1) with core-length intervals of 3.7–16.2 m, as well as a 2.3-m-thick, graphite-rich brecciated gneiss from 1542.8 to 1545.1 m depth.

The suevites consist of lithic clasts of sedimentary, metamorphic, and igneous origin, displaying all stages of shock metamorphism, and melt particles embedded in a fine-grained lithic matrix (Bartosova et al., this volume, Chapter 15; Wittmann et al., this volume, Chapter 16). The abundance of matrix and melt particles decreases with depth (Bartosova et al., this volume, Chapter 15; Wittmann et al., this volume, Chapter 16). Sizes of lithic clasts are quite variable, generally increase with depth, and reach up to 50 cm at the base of this section (Wittmann et al., this volume, Chapter 16). The amount of sediment clasts decreases significantly with depth within this section. Two thin layers at 1402.0–1407.5 m and around 1450 m depth consist of clast-rich impact melt rocks (Fernandes et al., 2008; Wittmann et al., this volume, Chapters 16 and 17).

Many polymict impact breccia samples contain highly altered microscopic melt particles (Bartosova et al., this volume, Chapter 15), which classify these breccias as suevite (Stöffler and Grieve, 2007). However, the amount of melt in some individual samples of polymict impact breccia is very low, and, in some cases, it is not yet clear whether dark, aphanitic clasts actually represent melt fragments or are altered and thermally affected shale clasts. Samples without clearly recognizable melt particles have been classified as polymict lithic impact breccia, in accordance with the recommended impactite nomenclature of Stöffler and Grieve (2007). Bartosova et al. (this volume, Chapter 15) found that melt particles are most abundant near the top of the impact breccia section (above 1409 m) and around 1450 m, where the suevite grades into impact melt rock. Five different types of melt particles have been recognized by Bartosova et al. (this volume, Chapter 15): (1) clear colorless to brownish glass; (2) melt-altered to fine-grained phyllosilicate minerals; (3) recrystallized silica melt; (4) melt with microlites; and (5) dark-brown melt. Proportions of matrix and melt in the suevite are highly variable (2–67 vol% and ~1–67 vol%, respectively, and the remainder consists of lithic clasts).

The cataclastic, coarse-grained, quartz-plagioclase gneisses (B5 to B1) were strongly deformed and metamorphosed prior to the impact under amphibolite-facies and retrograde greenschist-facies conditions. They are believed to have been brecciated as a result of the impact (Gibson et al., this volume; Horton et al., 2008, this volume, Chapter 14; Townsend et al., this volume). The polymict impact breccias (P4 to P1) of the basal 77 m of the impact breccia section contain angular to subrounded, unshocked and shocked clasts, mainly of metamorphic origin, which range in size from centimeters to decimeters, but can locally be up to several meters.

In terms of shock features, Bartosova et al. (this volume, Chapter 15) noted that quartz grains in suevite commonly show planar fractures and/or planar deformation features (one or two, rarely more, sets); some PDFs are decorated. On average, ~16 relative % of quartz grains in suevite samples are shocked (i.e., show PFs and/or PDFs). Sedimentary clasts (e.g., graywacke or sandstone) and polycrystalline quartz clasts have relatively higher proportions of shocked quartz grains, whereas quartz grains in schist and gneiss clasts rarely show shock effects. Rare feldspar grains with PDFs and mica with kink banding were observed. Ballen quartz ("bubble-wall" texture) was noted in melt-rich samples. Evidence of hydrothermal alteration, namely, the presence of smectite and secondary carbonate veins, was found especially in the lower parts of the impact breccia section. Studies by Belkin and Horton (this volume) indicate the presence of fresh, unaltered glasses, which shows that hydrothermal alteration was not pervasive. In addition, these authors note that the variety of glass compositions points to a mixture of components that experienced widely different temperatures. Declercq et al. (this volume) investigated the experimental alteration of suevites and glasses to reproduce the postimpact hydrothermal conditions at Chesapeake Bay. Comparison between the phases formed in their experiments and those in the cores suggests that the natural alteration occurred under hydrothermal conditions similar to those reproduced in the experiment. However, their study found that a general model for prediction of alteration processes and products could not be developed because of the compositional complexity of the melt rocks.

The chemical composition of the polymict impactites, as described by Schmitt et al. (this volume) and Bartosova et al. (this volume, Chapter 18), does not vary much in the upper part of the section (above ~1450 m), whereas larger differences occur in the lower part. In general, the compositions of the impact breccias overlap the compositional range for the Exmore Formation. Polymict impactites show a decrease of the SiO_2 content and slight increases of the TiO_2, Al_2O_3, and Fe_2O_3 abundances with depth. This is in agreement with an increase of the relative schist/gneiss abundance with depth. Mixing calculations of proportions of components involved in formation of the polymict impactites show that the rocks derived from the metamorphic basement rocks (gneiss and schist) constitute the main components

of the polymict impactites (more than ~75%), together with a sedimentary component (~20%), and possible additional minor components (e.g., pegmatite/granite and amphibolite). The sedimentary component is represented mostly by material from the thick Cretaceous Potomac Formation. However, the proportion of the metamorphic basement-derived rocks is higher than expected from the petrographic observations (Bartosova et al., this volume, Chapter 15).

Skála et al. (this volume) used their analyses of melt particles from the suevites for comparison with late Eocene tektites from Texas (bediasites) and found some close correspondences. However, the siderophile element data, and the abundances of the platinum group elements, do not indicate the presence of an extraterrestrial component (McDonald et al., this volume). Therefore, the question regarding the projectile type that produced the Chesapeake Bay crater remains open. This is unfortunate given that the late Eocene was a time of enhanced impact activity and enhanced accretion of extraterrestrial material on Earth (see the review by Koeberl, 2009), which possibly had a common origin related to an asteroid or comet shower (e.g., Farley et al., 1998; Farley, 2009).

Vanko (this volume) reports the occurrence of numerous vein and cavity-filling minerals in the granite megablock and underlying impactites and crystalline rocks. Some secondary calcite contains liquid-only fluid inclusions with trapping temperatures less than or equal to ~50 °C. Salinities of the inclusion fluids are mostly around 4.3 ± 1 wt% NaCl equivalent, or ~43,000 ± 10,000 mg/L total dissolved solids (TDS). The presence of these low-temperature hydrothermal (or diagenetic) minerals suggests that widespread, high-temperature hydrothermal convection was not omnipresent in the central crater, as also indicated by the work of Belkin and Horton (this volume).

Sedimentary Breccias

Gohn et al. (this volume) interpret the sedimentary breccias of the Eyreville cores to represent avalanche and ocean-resurge deposits. The sediment boulder and sand section (~867–1095.7 m) and the block-dominated member of the Exmore Formation (618.2–~855 m) consist almost entirely of Cretaceous nonmarine target sediments as coherent clasts in an autoclastic matrix. These sedimentary breccias are interpreted as one or more large rock avalanches from one or more sectors of the transient-cavity wall.

The lower diamicton member (~855–~867 m) and upper diamicton member (450.95–618.2 m) of the Exmore Formation consist of abundant clasts of Cretaceous nonmarine sediments and very sparse clasts of Paleogene and Cretaceous marine sediments in a matrix of calcareous, muddy, glauconitic quartz sand. These unsorted and unstratified units are interpreted as ocean-resurge debris-flow deposits. The thin stratified member of the Exmore (450.95–443.9 m) consists of muddy turbidite sands and overlying laminated silts and clays that represent the cessation of ocean resurge and the transition to normal shelf sedimentation.

Ormö et al. (this volume) analyzed clast frequency and size in the ocean-resurge sediments from the upper diamicton member of the Exmore Formation in Eyreville core A, and from the diamicton member of the Exmore in the Langley core, which is located in the structure's annular trough (Gohn et al., 2005). At both locations, there is a clear change in clast frequency and size between a lower unit interpreted to be slumped material and an upper unit of resurge deposits. The data provide some evidence for an outward antiresurge from a collapsing water plume or a second inward resurge pulse, as well as a transition to oscillating resurge.

Self-Trail et al. (this volume) analyzed calcareous nannoflora and palynomorphs from the clasts and matrix in the sedimentary breccias. These fossil assemblages confirm the abundance of Cretaceous nonmarine sediments and the paucity of Upper Cretaceous and Paleogene marine sediments as clasts in these breccias. In contrast, glauconitic quartz–sand matrix found primarily in the lower diamicton and upper diamicton members of the Exmore Formation contains Early Cretaceous, Late Cretaceous, Paleocene, and Eocene microfossils representative of at least eleven distinct ages. Early Cretaceous pollen assemblages in the gravelly sand below the granite megablock are older than Barremian (Valanginian-Hauterivian[?] to possibly Berriasian) and, thus, are older than the Aptian-Albian assemblages found in the sediment-clast breccias above the granite megablock.

Sedimentary breccias in the two Exmore diamicton members consist primarily of clasts and matrix derived from the target sediment layer. However, Reimold et al. (this volume) report a small component of shock-deformed quartz and feldspar and more abundant, but still scarce, shard-shaped, altered melt particles throughout the matrix in this section. Shocked-rock pebbles and cobbles also are present. Concentrations of the melt component are notably greater in two intervals, between 514 and 527 m and between ~458 and 469 m. This distribution suggests that the deposition of ejecta fallout from the collapsing ejecta plume ended at the time of deposition of the ~458 m material (see also Kenkmann et al., this volume). The relative abundance of shocked granitic rocks, and mineral grains derived from them suggests that the shocked material largely originated from crystalline target rocks.

Larsen et al. (this volume) investigated the mineralogy of the sedimentary breccias using X-ray diffraction, petrographic, and scanning electron microscope (SEM) analysis. The results indicate that only diagenetic alteration at a maximum temperature of <90 °C is prevalent in the sedimentary breccias of the Eyreville cores. In contrast, sedimentary breccias from the Cape Charles core hole show more advanced authigenesis with Fe-rich chlorite, common quartz overgrowths, and mixed-layered illite-smectite. Below the sedimentary breccias in the Cape Charles STP2 core, a low-temperature hydrothermal assemblage made up of quartz, albite, chlorite, white mica, calcite, and other trace metamorphic mineral phases is present in suevite and crystalline-clast breccias.

The primary mineral formed from the alteration of impact melt glass in the upper part of the sedimentary breccias is nontronite

(Ferrell and Dypvik, this volume). The upper part of the upper diamicton member of the Exmore Formation (452–495 m) may contain 13 vol% of unaltered glass and 13–19 vol% of clays produced by alteration of melt. The clay fraction in the stratified member of the Exmore also is dominated by nontronite.

Postimpact Sedimentary and Tectonic History

Poag (this volume) documented the paleoenvironmental transition from late synimpact to postimpact sedimentation through a study of benthic foraminifera in the Eyreville core and eight previously drilled cores. The transitional succession, as expressed by depositional style and microfossils, consists of four phases: (1) small-scale turbidites devoid of indigenous microfossils that lie directly above sediment-clast breccia, (2) very thin, parallel, sand and silt laminae that accumulated on a relatively stagnant seafloor lacking benthic biota, (3) marine clay deposition accompanied by a burst of microfaunal activity (agglutinated foraminifera), and (4) disappearance of the agglutinated foraminifera and development of an equilibrium calcareous foraminiferal community. Core sites outside and near the outer crater rim show no evidence of long-term biotic disruption from the impact event.

The 444 m of postimpact sediments at Eyreville reflect processes of "normal" passive-margin sedimentation (compaction, loading, simple thermal subsidence, eustasy), complicated by the effects of filling a major crater. To disentangle these effects, the section was described lithologically (Edwards et al., this volume, Chapter 4), broken into sequences, and dated (Browning et al., this volume), and regional versus local signals were evaluated (Kulpecz et al., this volume).

The Eocene sediments consist primarily of clays assigned to the Chickahominy Formation (Edwards et al., this volume, Chapter 4) that were deposited in deep water, ~300 m according to Poag (this volume) and ~200 m according to Browning et al. (this volume). Smectite and illite in the basal 30 m suggest long-term reworking of impact debris (Schulte et al., this volume). Common agglutinated benthic foraminifera indicate relatively reducing conditions and/or stressed environments (Poag, this volume). The Eocene section is relatively homogeneous and resists sequence stratigraphic subdivision, but it is tentatively divided into two stratigraphic sequences (Browning et al., this volume; Schulte et al., this volume).

The Oligocene sediments are very thin and consist primarily of glauconitic sands and silts. They are divided into two sequences (Sr isotopic ages of ca. 27 and ca. 28 Ma) that correspond to the Drummonds Corner beds and Old Church Formation (Edwards et al., this volume, Chapter 4; Browning et al., this volume). The dramatic shift in facies from the Eocene to the Oligocene is associated with a long (>5 Ma) hiatus that may be attributed to a combination of eustatic fall, uplift, and sediment starvation (Browning et al., this volume; Edwards et al., this volume, Chapter 4; Hayden et al., 2008; Schulte et al., this volume).

The lower Miocene strata also are highly dissected and thin. Sedimentation rates increase dramatically (~60 m/Ma) in a fine-grained biosiliceous middle Miocene section that is divided into three sequences within the Calvert and Choptank Formations. A long hiatus (8–~13 Ma) was followed by deposition of shelly sandy upper Miocene to Pliocene strata that can be divided into six sequences within the St. Marys, Eastover, Yorktown, and Chowan River Formations. The Pleistocene consists of two paralic sequences assigned to the Nassawadox Formation (Browning et al., this volume; Edwards et al., this volume, Chapter 4).

Comparison of the ages of the Miocene-Pleistocene sequences with a global oxygen isotopic compilation shows that sequence boundaries correlate with $\delta^{18}O$ increases, suggesting a glacioeustatic control (Browning et al., this volume). Age control is based primarily on Sr-isotope stratigraphy supplemented by biostratigraphy (dinocysts, calcareous nannofossils, and planktonic foraminifers), with a resolution of ±0.5 Ma for the early Miocene and ±1.0 Ma for older and younger sequences (Browning et al., this volume).

Though eustasy influenced the formation of most sequence boundaries, other processes contributed to the filling of the crater. Regional comparisons (Fig. 9) show that processes of impactite compaction, thermal subsidence, crater subsidence and uplift, and regional subsidence and uplift all molded the Eyreville stratigraphic record (Hayden et al., 2008; Kulpecz et al., this volume). During the late Eocene, rapid compaction of impactites was partially responsible for a deep basin and differential subsidence of the central crater (Kulpecz et al., this volume). Regional uplift in the Oligocene to early Miocene may be partly attributed to thermal blanketing effects of the cold impactites (Hayden et al., 2008). Middle to early late Miocene uplift of the Norfolk arch south of the Chesapeake Bay impact structure (Fig. 9) resulted in a long hiatus (Kulpecz et al., this volume). Differential subsidence during the late Miocene to Pliocene resulted in preservation of shallow-marine strata that are missing in the region to the north (New Jersey and Delaware; Kulpecz et al., this volume). These uplift and subsidence events may be related to differential movement of basement structures in response to variations in intraplate stress (Kulpecz et al., this volume).

Hydrologic and Geothermal Studies

Sanford et al. (this volume) analyzed pore water from over 100 samples from the Eyreville cores for major cations and anions, stable isotopes of water and sulfate, dissolved and total carbon, and biologically available iron. Their results indicate that a broad downward transition from freshwater to saline water occurs in the postimpact sediments and that the crater-fill breccias and crystalline rocks below 444 m depth are filled almost entirely with brine. Major ion values indicate residual effects of thermal diagenesis and a pre-impact origin for the brine. High levels of dissolved organic carbon and the distribution of electron acceptors indicate an environment that may be favorable for microbial activity throughout the drilled section. Sluggish groundwater flow conditions in the Chesapeake Bay impact

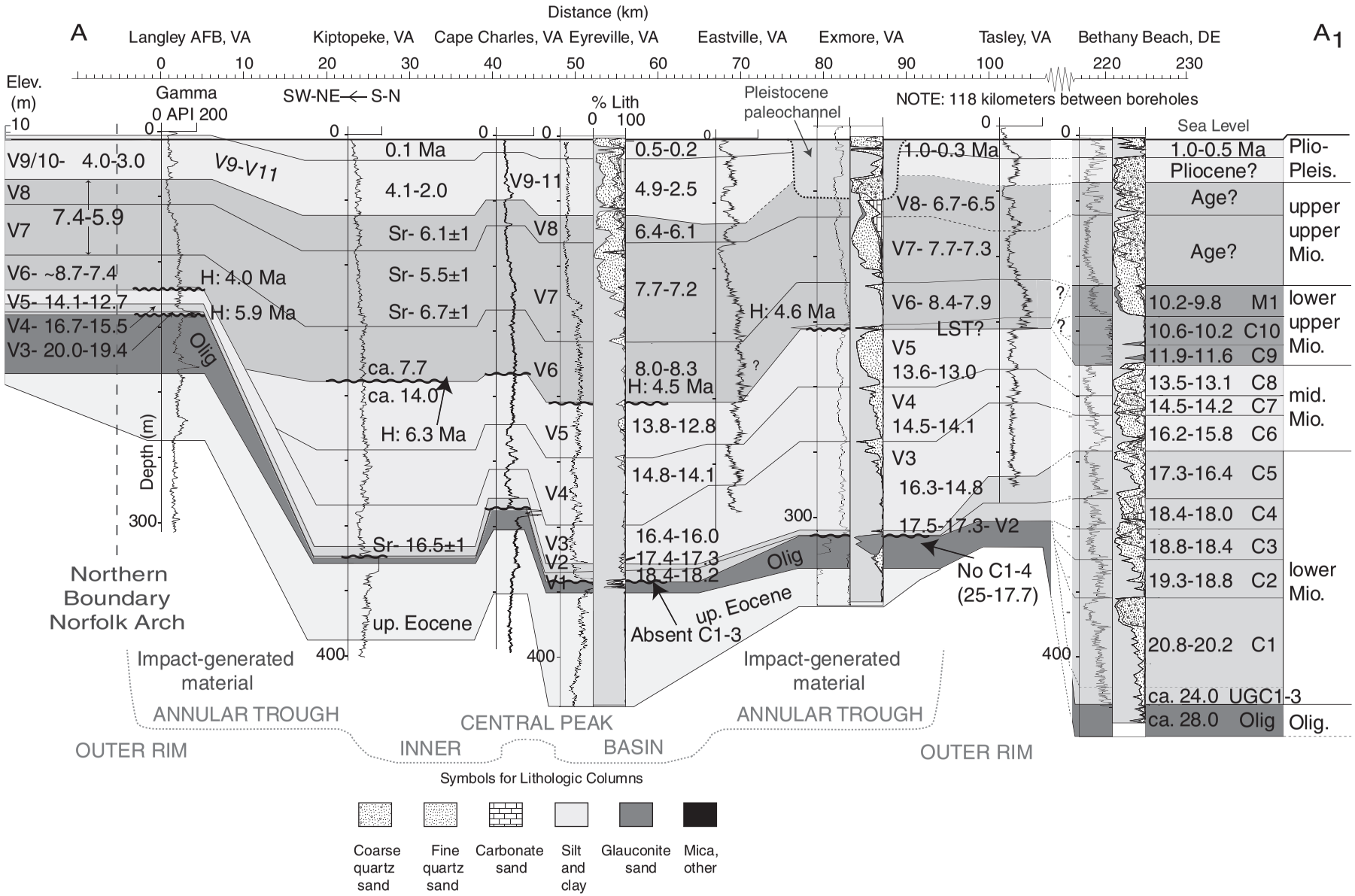

Figure 9. Core-hole and well-log cross section from Langley, Virginia, to Bethany Beach, Delaware (A–A1) modified from Gohn et al. (2008) and Kulpecz et al. (this volume). Bethany Beach, Langley, Kiptopeke, Cape Charles, and Exmore are core holes; Eastville and Tasley are gamma-ray logs. Sequence ages (Ma) are based on age-depth plots primarily using Sr isotopes. Thin black lines represent sequence boundaries. Thick, wavy black lines indicate coalesced sequence boundaries (unconformities) at which one or more sequences are absent. The numbers after the letter H represent the duration of the hiatus across these surfaces. Ages denoted by "Sr-" represent single Sr-age estimates. The underlying diagram of the Chesapeake Bay impact structure is not to scale; it is intended to show the position of postimpact sequences relative to crater morphology. Note the change in transect orientation at Kiptopeke from W-E to SW-NE. See Kulpecz et al. (this volume) for additional details. AFB—Air Force Base; Mio.—Miocene; Olig.—Oligocene.

structure may limit the potential for brine intrusion into aquifers near the structure.

Rostad and Sanford (this volume) analyzed the distribution of dissolved organic carbon in pore-water samples extracted from the Eyreville cores. Positive and negative ionization spectra for polar organic compounds from the pore waters were compared to spectra from drilling fluids, and no indications of drilling-fluid contamination were found.

Heidinger et al. (this volume) determined a vertical heat-flow-density (HFD) profile from the vertical temperature gradient and laboratory measurements of saturated samples from the Eyreville B core. The resulting local, terrestrial HFD value of 65 ± 6 mW/m^2 is significantly higher than the predicted values for this area (42–52 mW/m^2; Morgan and Gosnold, 1989).

Malinconico et al. (this volume) collected vitrinite reflectance data from the Eyreville deep cores that show patterns of postimpact maximum-temperature distribution that resulted from a combination of conductive and advective heat flow. Thermal modeling of the Eyreville suevite as a 390 °C, cooling sill-like hot-rock layer, supplemented by compaction-driven vertical fluid flow of cooling fluids and pre-impact basement brines upward through the sediment breccias, closely reproduces the measured reflectance data. This scenario would replace any marine water trapped in the structure with more saline brine similar to that currently found there and would produce temperatures sufficient to kill microbes in sediment breccias within 450 m above the suevite.

Microbiologic Studies

Cockell et al. (this volume) examined the present distribution of microbes in the Eyreville cores as a basis for inferring the effects of a large impact event on the deep subsurface biosphere. Microbiological enumerations indicate the presence of three broad microbiological zones. The upper zone (127–867 m) is characterized by a logarithmic decline in microbial abundance from the surface to a depth well within the sedimentary breccias. Microbial abundances were below the detection level in the middle zone (867–1397 m). The lower zone (below 1397 m) has a moderate microbial abundance and coincides with the sections of suevite and related impactites and the basement-derived crystalline-rock blocks. Hence, the present-day microbial abundance patterns correspond to the major impact-related lithologic transitions in the Eyreville cores.

Contamination of core samples by drilling fluids is a major impediment to the chemical analysis of pore waters and the study of microbes in core samples. Gronstal et al. (this volume) discuss the methods used successfully in the Eyreville drilling to allow collection of uncontaminated pore-water and microbe samples. These methods included the use of fluorescent microbeads and a chemical tracer (Halon 1211) in the drilling fluids, chemical characterization of dissolved organic carbon in samples and comparison of the sample signatures with signatures for the drilling fluids (Rostad and Sanford, this volume), and comparison of microbial contaminants in the drilling mud using clone libraries for comparison to species cultured from core samples. Twenty-two of 47 subcore samples were free of contamination by all the methods and were subsequently used for microbiological analysis.

Glamoclija et al. (this volume) discuss the occurrence of micrometer-size anatase rods embedded in chlorite coatings on pyrite in a vein from the granite megablock. They discuss the competing hypotheses that this occurrence of selective TiO_2 permineralization of microorganisms is a result of fossilization processes or metabolic collection of Ti by bacteria.

UNRESOLVED PROBLEMS

Chesapeake Bay Impact Structure

This volume is the first detailed research report for the Eyreville cores. To a large extent, these cores recovered allochthonous sediment and rock breccias and blocks that arrived at their present positions during or slightly prior to the late-stage collapse of the seafloor transient crater and the ocean-water column (Kenkmann et al., this volume). These cores provided a substantial basis for advancing our understanding of marine impact processes and the relative timing of those processes, including ejecta flow, vapor-plume interactions, transient-crater wall collapse, ocean-resurge erosion and sedimentation, hydrothermal alteration, postimpact sedimentation, and hydrologic and biologic consequences.

Although the papers in this volume represent major advances based on the new core and core-hole data, the Eyreville cores provide fertile ground for future research. For example, the results of an initial search for an extraterrestrial component in impact melt from the Eyreville cores did not provide unambiguous verification of an extraterrestrial signature (McDonald et al., this volume). The analysis of additional melt samples from the cores could produce important new results.

Also, deepening of the Eyreville core holes A and B could resolve remaining questions about the depth to the floor of the Chesapeake Bay impact structure. Blocks of crystalline target rocks at 1551–1766 m in Eyreville core B probably are similar to target rocks located in the crater floor. However, the cored blocks display few shock features, and they probably were displaced from relatively high positions on the transient-crater wall but were not ejected. Layered reflections on regional seismic images at depths of ~1750 to ~2750 m suggest that additional breccias and blocks may intervene between the cored section and parautochthonous rocks of the crater floor (Catchings et al., 2008). Numerical simulations of the impact-cratering process (Collins and Wünnemann, 2005; Kenkmann et al., this volume) also suggest that the crater floor may be located below the bottom of the Eyreville B core hole.

In addition, investigations of other primary characteristics of the Chesapeake Bay impact structure would benefit from the drilling of additional core holes at other locations within the structure. For example, the apparent deficiency of impact melt (Wittmann et al., this volume, Chapter 17) and the abundance of essentially unshocked crystalline target rocks in the Eyreville

cores could be addressed by a core hole drilled to ~1700 m depth on the central uplift at or near the Cape Charles STP2 core hole (total depth 823 m; Sanford et al., 2004). This core hole would produce an ~1000-m-long section of suevite and shocked crystalline rocks that likely would reveal a record of the decrease in shock intensity with depth and additional information about melt abundance.

Postimpact Atlantic Coastal Plain Sediments

The postimpact dating and paleoenvironmental data provided by the Eyreville studies constitute the most detailed record from cores in the Chesapeake Bay impact structure. Kulpecz et al. (this volume) and Kulpecz et al. (2008) provide detailed age and paleoenvironmental estimates for the Exmore core in the annular trough, but further studies of other existing cores in the annular trough (Langley, Kiptopeke, and Bayside) are warranted. Hayden et al. (2008) used relatively coarse age and paleoenvironmental information to provide preliminary backstripping of the Exmore, Langley, and Kiptopeke cores, and Kulpecz (2008) used detailed data from Browning et al. (this volume) and Kulpecz et al. (this volume) to refine the backstripping of the Exmore core and compare it to the backstripped record from Eyreville. Refined age and paleoenvironmental data from Langley, Kiptopeke, and Bayside are needed to refine the backstripped estimates of tectonic subsidence and uplift of this complex structure. In addition, a core hole between the Chesapeake Bay impact structure and regions outside the structure to the northeast is sorely needed. The closest core hole to the Chesapeake Bay impact structure is at Bethany Beach, Delaware, but it is ~118 km away from the nearest Chesapeake Bay impact structure core hole at Exmore, Virginia. A core hole near the Virginia-Maryland border is needed to test the long-distance well-log correlations shown in Figure 9. A core hole at this site would reveal the regional extent of the Oligocene to lower Miocene section that is thin and condensed in the Chesapeake Bay impact structure but expanded in Delaware and New Jersey.

ICDP Drilling Programs in Impact Structures

The Chesapeake Bay impact structure is the third impact structure drilled by the international scientific community using ICDP funds. The ICDP previously sponsored drilling of the Chicxulub crater in Mexico (Urrutia-Fucugauchi, et al., 2004) and the Bosumtwi crater in Ghana (Koeberl et al., 2007). In addition, drilling at the El'gygytgyn crater in Russia (Siberia) is under way (2008–2009; http://elgygytgyn.icdp-online.org) and additional deep drilling of the Chicxulub crater was completed in May 2009.

SUMMARY

The ICDP-USGS Chesapeake Bay Impact Structure Deep Drilling Project completed three core holes to a total depth of 1766 m in the central part of structure during 2005 and 2006. More than 2000 core samples were distributed to project scientists for geologic, geophysical, hydrologic, and microbiologic analysis. The initial data and interpretations resulting from this multidisciplinary study are described in the 42 chapters in this volume. These chapters constitute a significant contribution toward a better understanding of the Chesapeake Bay impact event and its consequences, and of impacts into the marine environment in general.

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