15 Summary and Conclusions

We have presented a comprehensive geological and geophysical synthesis of the Chesapeake Bay crater, the largest known bolide impact structure in the United States. The structure, morphology, stratigraphy, and age of the crater and the nature and depositional history of the crater-fill rocks are documented by >2,000 km of seismic reflection profiles and >2,000 m of continuously cored and logged borehole sections (Chapter 1).

The Chesapeake Bay bolide struck the ~300-m-deep continental shelf of eastern North America ~35.78 Ma at a site now covered by the lower part of Chesapeake Bay, the low-lying peninsulas of southeastern Virginia, and the shallow marine waters of the inner Atlantic Continental Shelf. The impactor struck a three-layered target (Chapter 2). The upper layer comprised a column of seawater ~300 m deep; the middle layer encompassed 600–1000 m of poorly consolidated, water-saturated, sedimentary rocks (Early Cretaceous to late Eocene strata); the basal layer was a crystalline basement composed of metasedimentary and metaigneous rocks (Proterozoic to Paleozoic in age).

The bolide impact created a crater 85 km wide and 1.3–2.0 km deep (Chapter 4). Today the crater features a steep sedimentary outer-rim escarpment (300–1200 m high), a relatively flat, crystalline-floored annular trough (15–28 km wide), a crystalline peak ring (35–45 km wide; 40–300 m high), a deep, crystalline-floored inner basin (10–18 km wide; 1.3–2 km deep), and an irregular crystalline central peak (12 km wide; 200–600 m high), all attributes typical of other large complex craters found on Earth and its planetary neighbors. The Chesapeake Bay crater is filled with an orderly succession of inferred and documented synimpact deposits (Chapters 6, 11, 12). Filling the lower part of the inner basin is an inferred layer of fallback breccia, dekameters thick, presumably dominated by meter-to-dekameter-sized clasts of crystalline basement rocks. Such fallback breccia is known from the deep inner basins of other complex craters, but the inner basin at Chesapeake Bay has not yet been cored. One of the Chesapeake Bay coreholes, however, the Bayside corehole, contains ~20 m of matrix-supported breccia above the basement surface, whose abundant crystalline and sandstone lithoclasts appear to represent fragments of rocks from deep within the inner basin, and thus may constitute a modest section of fallback breccia.

The basal synimpact deposit in the annular trough at Chesapeake Bay is an ~300-m-thick layer of hectometer-to-kilometer-sized, displaced, sedimentary megablocks (slumpback lithofacies; Chapter 6). These megablocks are derived from the shock-generated collapse and basal fluidization of poorly consolidated, mainly Lower Cretaceous sediments that sloughed off the crater's outer rim.

Seismic reflection profiles indicate also that kilometer-sized megablocks of crystalline basement have slumped from the walls of the inner basin.

The next highest crater-fill deposit, 100–200 m thick, is surgeback breccia, a sediment-dominated, subaqueous deposit, which covers the entire crater, burying both the fallback and megablock deposits, as well as the peak ring and central peak. Surgeback breccia was formed by hydraulic erosion and gravity-driven collapse of the sedimentary crater rim and the tops of the displaced megablocks. An enormous hydraulic head developed as the 300-m-thick oceanic water column plunged back into the crater cavity.

Above the surgeback deposits is a sediment-dominated, matrix-supported, upward-fining, washback breccia, dekameters thick. The matrix is characteristically a greenish gray to nearly black, glauconite/quartz sand, containing stratigraphically mixed microfossils. This washback breccia not only covers the entire crater, but also extends as a breccia apron a few kilometers outside the crater rim. The washback breccia is a tsunamiite, created by runup and washback processes as impact-generated tsunami wave trains eroded and redistributed shock-weakened sediments from the inner continental shelf and coastal plain.

Both the surgeback and washback breccias contain granitoid clasts derived from the crystalline basement, which have been variably shock metamorphosed from <5 to > 45 (~60) GPa (Chapter 6). The geochemistry of these two breccia deposits indicates derivation from a sedimentary, upper crustal, post-Archean source, similar to the source inferred for the North American tektite strewn field (Chapter 6).

The antepenultimate synimpact crater-fill deposit is a clayey silt unit, a few meters thick, which displays evidence of multidirectional sediment flow during deposition. This is a flowin unit, attributable to hypercanes that moved across the continental shelf and triggered successions of small debris flows from the crater rim.

The final synimpact crater-fill deposit is a thin (1–5 cm thick), clayey silt, which contains evidence of impact-derived microspherules (Chapter 6). The 1-mm cavities that originally contained the microspherules are preserved in distinctive pyrite lattices, from which glass-derivative clay may have been inadvertently washed away during routine sample preparation. We infer that this microspherule layer is a fallout product of the condensing impact vapor plume.

Outside the primary crater, seismic profiles reveal 23 small structures that appear to be secondary craters (3–6-km diameters), because they display characteristic downfaulted sedimentary rims, raised lips, and chaotic crater-fill reflections (Chapter 5). Though no recent coreholes have penetrated any of the secondary craters, there is evidence from older boreholes that at least one of the possible secondaries contains crater-fill deposits lithologically equivalent to the Exmore breccia.

Perhaps the most dramatic aspect of the impact process is the enormous speed with which it took place. Computer simulations of the impact indicate that the 85 x 1.3 km excavation (4,300 km^3) was created and refilled within a geological blink-of-the-eye (a few minutes to hours; Chapter 12).

The age of the Chesapeake Bay impact structure has been determined indirectly by biochronological and magnetochronological studies of sediments (the Chickahominy Formation) directly overlying the crater-fill (Chapter 7). Microfossil biochronology indicates that the Chesapeake Bay impact took place during a 0.8-myr interval in which the top of planktonic foraminiferal biochron P15 (upper boundary at 35.2 Ma) overlaps the base of calcareous nannofossil biochron NP19-20 (lower boundary at 36.0 Ma; Chapter 8). A similar crater age (35.2 ±0.3 to 35.5 ±0.3 Ma) has been derived from radiometric analyses ($^{40}Ar/^{39}Ar$) of distal ejecta from the North American tektite strewn field (DSDP Site 612 and Bath Cliff, Barbados), currently thought to be a product of the Chesapeake Bay impact. Extrapolation of a magnetochronologically-derived sediment-accumulation rate from the lower part of the Chickahominy Formation at the Kiptopeke site refines the impact age to 35.78 Ma. This age for the Chesapeake Bay impact is statistically indistinguishable from the 35.7 ±0.4 Ma radiometric age of the Popigai crater in Northern Siberia and the 35.7 ±0.4 age of the distal ejecta that crops out near Massignano, Italy. The stratigraphic separation of microkrystite ejecta (derived from Popigai) from microtektite ejecta (derived from Chesapeake Bay) in deep-sea cores (Atlantic Ocean and Caribbean Sea), however, indicates that the Chesapeake Bay impact is younger than that of Popigai by 10–20 kyr.

The Chesapeake Bay crater and its sedimentary fill are buried now by 300–500 m of postimpact (late Eocene to Holocene) siliciclastic, mainly marine, sediments (Chapters 2, 7, 13). The initial postimpact deposit is a 20-cm-thick, laminated silt layer, which contains no indigenous biota, and represents the first ~0–3 kyr of lifeless marine deposition following the bolide impact (Chapter 7). Thereafter, normal marine deposition resumed and formed the Chickahominy Formation, a sandy-to-silty, massive-to-laminated, glauconitic, micaceous, highly microfossiliferous marine clay, of relatively deep-water origin (~300 m paleodepth). The Chickahominy represents the final 2.1 myr of Eocene sediment accumulation over the crater. Three distinct episodes of sedimentation (distinguished by different rates of accumulation) can be documented within the Chickahominy clay (Chapter 13). These three depositional intervals correspond roughly to three cycles of low-to-high species richness among the benthic foraminiferal community. Culmination of the first cycle represents full recovery of the benthic foraminiferal community ~36 kyr following the bolide impact. Superimposed on these three cycles of species richness are five biotic subzones defined by characteristic associations of benthic foraminiferal species. As a whole, the Chickahominy benthic foraminifera record a succession of paleoenvironments characterized by oxygen deficiency and an abundant supply of organic detritus at the seafloor and in shallow interstitial waters. Phytodetrital feeders were prominent members of this benthic community, especially in the upper part of the formation.

Though no immediate global loss of marine or terrestrial species comparable to that of the K-T mass extinctions arose from the Chesapeake Bay impact, there is evidence that long-term climatic changes may have resulted from it. The climatic perturbations, in turn, may have triggered a major extinction event in the early Oligocene, ~2 myr after the Chesapeake Bay impact (Chapter 13). Stable isotope records ($\delta^{18}O$ and $\delta^{13}C$) derived from the tests of the benthic foraminifer *Cibicidoides pippeni* indicate that postimpact climate at the impact site was punctuated by at least three warm pulses. The final pulse was accompanied by a notable negative excursion in $\delta^{13}C$ values. The $\delta^{18}O$ results are best understood in the context of a late Eocene comet shower, which produced unusually high concentrations of extraterrestrial ^3He at the late Eocene outcrop near Massignano, Italy, which contains 35.7-myr-old impact ejecta. We infer that a succession of impacts during the comet shower (including those at Chesapeake Bay and Popigai) produced the climatic warming indicated by the $\delta^{18}O$ record.

Though buried for the last ~36 myr, the Chesapeake Bay crater and its related deposits still have important consequences for the citizens of southeastern Virginia (Chapter 14). The Exmore breccia subsided differentially as it compacted under a load of postimpact sediments, and this subsidence, in turn, produced a vast network of near-surface faults. The pervasive fault systems have destabilized the bayfloor, seafloor, and low-lying wetlands above and near the crater, contributing to rapid rates of relative sea-level rise that characterize the Chesapeake Bay region.

The most important modern consequence of the ancient impact may be the presence of high-salinity groundwater (derived from flash-evaporation of huge volumes of seawater during the bolide impact) at shallow depths within the Exmore breccia. This brine limits the quality and availability of potable shallow groundwater for more than two million citizens in the rapidly growing urban corridor surrounding lower Chesapeake Bay (Chapter 14).

Comparison of the Chesapeake Bay crater and its associated deposits with other complex craters of comparable submarine origin reveals some significant similarities (Chapters 10,11,12). On the other hand, each known crater has distinct characteristics that set it apart from all the rest. Our analyses lead us to emphasize the following principal points: (1) The succession of marine modification processes associated with surgeback, washback, and flowin depositional regimes appear to be unique to submarine impacts on shallow continental margins. These processes are responsible for the unusually thick body of sediment-clast breccia that fills the Chesapeake Bay crater and several other submarine craters. Surgeback processes may also operate in deeper, open-ocean settings, but washback and flowin processes require a nearby, easily erodable, land surface or shallow continental shelf. (2) The density differential between crystalline basement rocks and overlying sedimentary rocks is important in constraining both the excavation and modification processes of submarine crater development. This differential appears to account for the great structural and morphological disparity in between the Chesapeake Bay and Mjølnir craters, for example. (3) This density differential depends in large part on the degree of water saturation and lithification of the sedimentary target rocks. In the case of Chesapeake Bay, the sedimentary target rocks are primarily loosely consolidated quartz sands and silts, most of which today are (and presumably were in the late Eocene) important freshwater or saline aquifers. Their weak consolidation must have facilitated acoustic fluidization of the basal target sediments by the impact shock wave, thereby promoting widespread sliding and slumping of megablocks along a basement décollement, without producing pervasive brittle deformation features, such as faults, which ordinarily are expected in décollement zones. This displacement of megablocks significantly widened the crater. (4) Though there is scattered evidence of an upturned lip on the outer rim of the Chesapeake Bay crater, the lip is insubstantial compared to the lips of well-preserved subaerial craters on Earth and other planetary bodies. This appears to be, in part, due to intense modification of the outer rim by surgeback and washback processes. The lack of a well-defined outer-rim lip appears to be common to all known submarine impact craters.

The principal structural, morphological, depositional, and paleoenvironmental aspects of the Chesapeake Bay impact crater are now thoroughly documented by borehole, seismic-reflection, and gravimetric data. Acquisition and analysis of new cores and geophysical surveys continue at Chesapeake Bay, however, and, undoubtedly, will help to refine and revise some of the interpretations we have presented. Several critical questions remain to be answered, especially regarding the central features of the structure: (1) What is the nature (composition, shock history) of the crystalline basement that comprises the peak ring, central peak, and floor of the inner basin? (2) Does fallout breccia dominated by large crystalline clasts occupy the floor of the inner basin? (3) Are large melt bodies or melt sheets associated with this structure? (4) What is the radiometric age of the crater? (5) Is there a breach in the southeastern margin of the peak ring, as suggested by the pattern of gravity anomalies? (6) What is the configuration of the basement surface in the eastern sector of the crater? and (7) Are displaced sedimentary megablocks, which are common to the western sector, also present in the eastern sector?

Questions 1–4 can best be answered by obtaining cores from the central features of the crater. The cores can be obtained from a series of deep coreholes (700–2,000 m deep) drilled on the Delmarva Peninsula near the town of Cape Charles, Virginia. Questions 5–7 require additional deep seismic reflection surveys across the southern part of the Delmarva Peninsula and the inner continental shelf east of Delmarva. The search for these answers will provide stimulating challenges for a new generation of planetary geologists. The answers themselves will contribute significantly to understanding the essential role of bolide impacts in the history of our solar system and their implications for its living species.