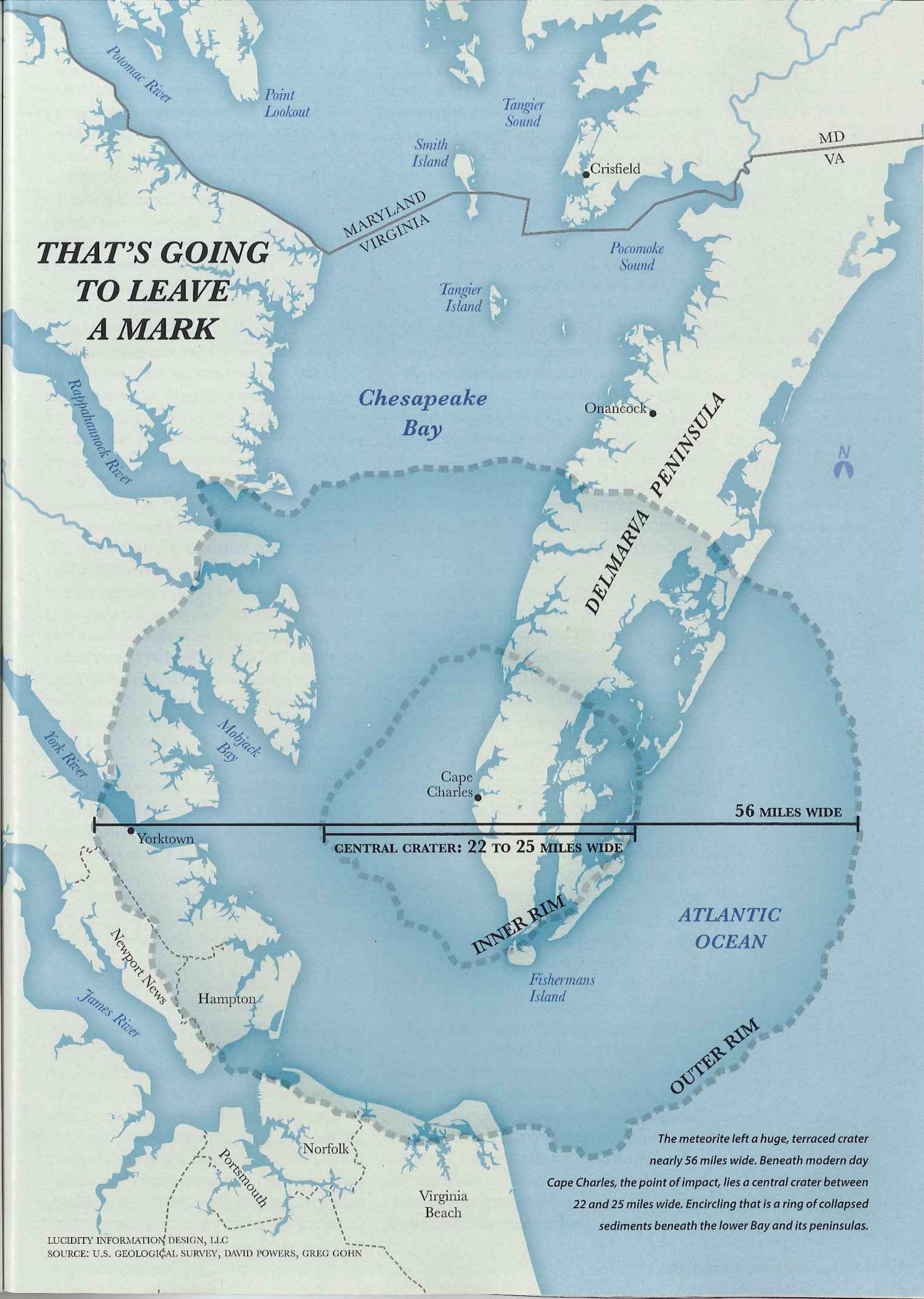
the *Hole* at the Bottom of the Bay

Twenty-five years ago it was a plausible but slightly whacky theory. Now there's little doubt about it: Millions of years ago, an unimaginably huge meteorite struck the earth, leaving a miles-deep, miles-wide scar under the surface. Ground zero? That would be modern-day Cape Charles, Va.

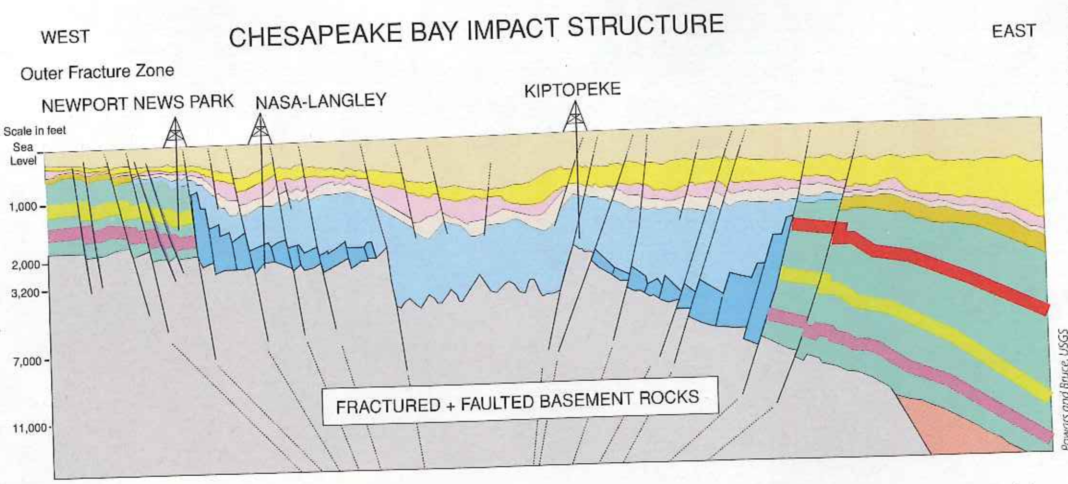
It's no secret to local boaters: Cape Charles is a special place. A harbor of refuge just inside the mouth of the Bay, this small town offers visitors neither too many nor too few attractions, but a just-right mix—two modern marinas, a lovely beach, a handful of neighborly pubs and inns, and the amenities of a nearby resort. And it lies distant enough to dissuade visitors from overrunning this remote outpost on the southern tip of the Delmarva Peninsula. ¶ There's one thing most visitors don't know about Cape Charles: for a very long time, this place hid the evidence of its very violent past. ¶ About 35 million years ago this tranquil spot became, in a flash, the epicenter of an apocalyptic event. An extraordinarily large meteorite or "bolide"—perhaps two miles in diameter and traveling at an anywhere from 40,000 to 134,000 miles per hour (a broad ballpark

by Marty LeGrand ■ illustrations by Robert Cronan

THAT'S GOING TO LEAVE A MARK



The meteorite left a huge, terraced crater nearly 56 miles wide. Beneath modern day Cape Charles, the point of impact, lies a central crater between 22 and 25 miles wide. Encircling that is a ring of collapsed sediments beneath the lower Bay and its peninsulas.



An early (1999) side-view illustration of the impact crater, showing the deep central crater, the collapsed rubble in the outer ring and the original sediment layers beyond. The derricks show the approximate east-west locations of drilling sites.

guess, yes, but a minor distinction if you're the target) entered the earth's atmosphere, blazed southward along the Atlantic Coast and smashed into the shallow ocean precisely where Cape Charles now sits. The resulting explosion was unimaginably huge—some say more powerful than the world's combined nuclear arsenal—and caused unfathomable destruction. The meteorite blasted a miles-deep hole in the continental shelf, emitting a mushroom cloud of vaporized water and molten rock that likely rose 30 miles high and scattered debris as far away as present-day Texas and the Caribbean. Powerful earthquakes shook the Eastern seaboard. A mile-high wave quickly engulfed the coast, nearly reaching the Blue Ridge Mountains and triggering tsunamis that rolled across the North Atlantic.

The event left behind one of the world's largest impact craters, a 56-mile-wide terraced chasm well over a mile deep. No bigger crater has been found in the United States. But the Chesapeake Bay crater's most remarkable distinction may be this: until the late 20th century, no one even suspected it was there. Embalmed under nearly 1,500 feet of marine sediments, the crater lay immaculately preserved beneath the lower Bay and Eastern Shore until it was located by chance 28 years ago. Geologists who've studied the crater say it still affects those who live in southeastern Virginia and it may have profoundly shaped the Bay itself in ways scientists are just beginning to understand.

Scientists can't quite agree on what to call what was probably an extraordinarily large fragment of an asteroid or comet. The term *bolide*—meaning a fiery piece of space rock of unknown origin—has emerged in recent years, but it's not widely accepted, nor does it mean much to a lay person. Scientists do seem to agree, however, that a space projectile such as this should be called a meteor when it's flaming through the atmosphere and a meteorite if it survives the trip and strikes the earth. So for the purposes of this article, we'll stick with "meteorite."

Geologists don't know precisely how big the Bay meteorite was, or its exact speed. And this was 35 million years ago, so they can't even pinpoint the whereabouts of the mid-Atlantic coastline at the time—though an educated guess puts it somewhere along the line stretching from Richmond to Washington to Baltimore. So if they're so fuzzy on that, how can they talk of a 30-mile-high splash and a tsunami four times taller than the Empire State Building? Simply put, it's what the rocks have told them. Since the crater was discovered, geologists have bored into it many times to take samples—of the deep parts, the shallow parts and the sheared outer edges. Based on data from these samples, numerical modelers using supercomputers have been able to simulate the Chesapeake's prehistoric apocalypse.

About 150 miles northwest of Cape Charles, at his office in the Reston, Va. headquarters of the U. S. Geological Survey (USGS), geologist Greg Gohn prepares to run one of these simulations. A

Embalmed under 1,500 feet of sediment, the crater lay perfectly preserved until 28 years ago.

soft-spoken man with a dry wit, Gohn has studied the crater since 2000. He served as co-chair of the USGS's Chesapeake Bay Impact Crater Project and was one of four scientists assigned to oversee an internationally funded effort to drill into the crater's deepest point in 2005. "Retired" from the agency since 2007, the scientist emeritus ("that's Latin for 'volunteer,' " he says) still spends many workdays in his Reston office, where soil and rock cores from the crater are stored only a hallway or two away. "I try to pick stuff out of the drawers that we never quite got to," he says. "We're still learning new things."

On Gohn's computer monitor, a big gray ball represents the Bay meteorite—or half of it, anyway; there is so much data that even this powerful program can render only one side of the event. The ball's target—the continental shelf's crystalline bedrock, covered by thousands of feet of wet sediments and a few hundred feet of seawater—is depicted in tightly spaced horizontal lines of gray, brown and blue in the simulation.

Gohn clicks the "play" arrow. The ball slams into the surface, sending the lines completely haywire. Gray lines are smashed together to form a deep bowl (the blast crater), sending up a tri-colored plume of molten rock, sediments and seawater (the 30-mile-splash) into the air along the crater's rim.

A large wave generated by the impact peaks and topples over, rolling ominously toward the edge of the computer screen (the tsunamis). Meanwhile, a liquidy gray lump (which Gohn will explain later) rises in the center of the crater and then subsides. Gray lines slosh around the surface of the hole for a while until brown and blue lines eventually flow back in and cover the crater. Beneath the surface, nothing looks the way it did before. The gray lines are fractured, stopping abruptly at the crater's sloping wall. The cavity is filled with a solid gray mass that's flecked with brown spots. Atop that lies a brown layer dotted with specks of gray.

Gohn replays the simulation, pausing it frequently to interpret the collision's three vague-sounding stages—"impact and compression," "excavation" and "relaxation"—all of which unfolded in about 20 biosphere-altering minutes.

"The impact forms a cavity that is close to eight kilometers [over four miles] deep. You can see that it gets pushed down," he says, pointing to the squashed gray lines representing suddenly "fluidized" rock. Scientists estimate about two-thirds of the material in the blast cavity was compressed and the rest, the "ejecta" (rock, sediments and vaporized seawater), was blasted out. Most debris fell back into the cavity, but some bits of airborne melt rock (called tektites) were strewn across North America.

Less than a minute after impact, the walls of the blast cavity began to slump inward, followed over the next 10 minutes or so by an avalanche of sediments and rocks, including skyscraper-sized boulders. Tumbling into the collapsing cavity, the rubble mixed with the melted rock, remnants of the collapsing vapor cloud and debris swept into the hole by the resurging ocean.

As the cavity filled, the fluid rock at the center of impact bounced back like a trampoline. Called the central uplift, the peak leveled off somewhat and solidified, leaving a mini-mountain buried directly below ground zero (a.k.a. Cape Charles).

"You'll notice there's a constant vibration, seismic waves—basically an earthquake," Gohn says. "So you've got melting and vaporization and ejecta. You've got tsunami trains. It's the perfect catastrophe, in essence."

The simulation shows what takes place in the central crater, the debris-filled 25-mile-wide hole in the rock bed. Because the Bay was a "wet" target, Gohn explains, its crater is wider

> ***"You've got melting and vaporization and ejecta," he says. "You've got tsunami trains. It's the perfect catastrophe."***

and more complex than land craters. The impact destabilized surrounding water-saturated sediments, sinking them. Encircling the central crater, like the rim of a soup bowl, is this shallower sediment collapse. Newport News, Hampton, Mobjack Bay and the Bay Bridge-Tunnel all sit above this 16-mile-wide trough. Beyond the trough, the impact fractured and faulted subsurface rocks in what's called the "outer fracture zone."

For the next 35 million years, the multi-tiered crater lay buried by a thickening blanket of sediments spread by the continually rising and falling sea. Its existence remained a mystery until a steamy August day in 1986.

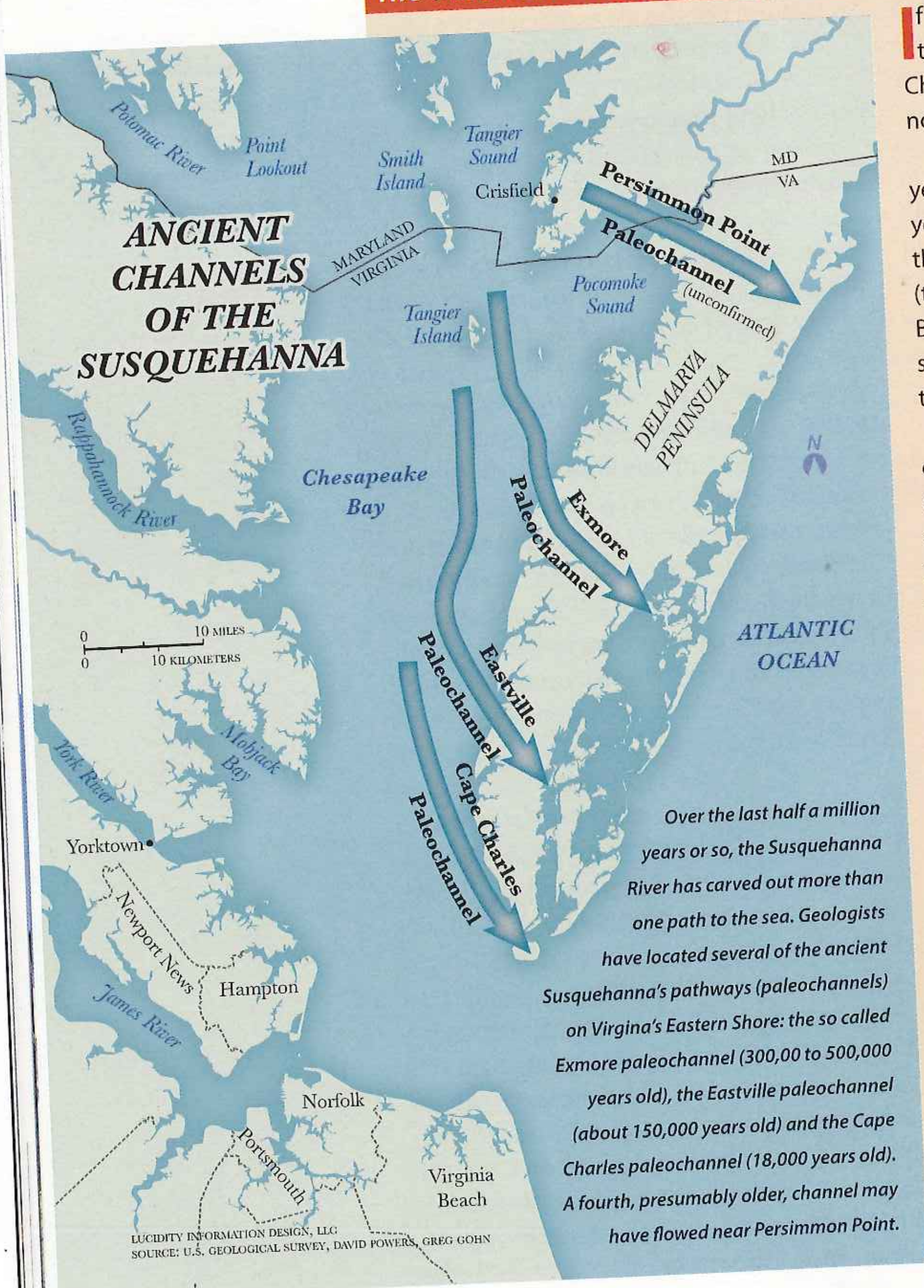
David Powars, a USGS research geologist, and T. Scott Bruce, a hydrologist with Virginia's Department of Environmental Quality, were reviewing samples from a core-drilling project their agencies were conducting near the village of Exmore, about 20 miles north of Cape Charles. What the scientists saw puzzled them. Rather than the orderly, chronological deposit of the sands, clays and embedded fossils they expected to find here, they found what looked like fodder from a food processor: a chaotic mix of vastly different sediments from vastly different time periods.

Bruce had observed a similar jumble in a previous sample his team unearthed. In that case he had written it off as some kind of mix-up, literally, during collection, but a second instance was not so easily dismissed. Sure enough, paleontologists who examined the Exmore samples found 35-million-year-old fossils intermixed with specimens hundreds of millions of years older. No one could explain why.

Powars suggested three possibilities: an earthquake, a catastrophic collapse of the continental shelf, or perhaps an extraterrestrial impact. Even Powars figured his third idea was slightly crazy. His colleagues thought it was completely so. "David was pretty much out there by himself for awhile," Gohn recalls.

"Out there" is where Powars occasionally lives, professionally. Once a biology major and aspiring surgeon, he switched to geology and began probing the subsurface layers and geologic history of the mid-Atlantic coastal plain. More inclined to speculation than his colleagues, the bearded Virginian was proven right at Exmore. Decades later, he's become the public face of crater research, frequently appearing on television and at educational lectures.

The Crater that *Created* the Bay? Maybe not so much. . . .



Over the last half a million years or so, the Susquehanna River has carved out more than one path to the sea. Geologists have located several of the ancient Susquehanna's pathways (paleochannels) on Virgina's Eastern Shore: the so called Exmore paleochannel (300,00 to 500,000 years old), the Eastville paleochannel (about 150,000 years old) and the Cape Charles paleochannel (18,000 years old). A fourth, presumably older, channel may have flowed near Persimmon Point.

If you've read anything about the impact crater before, it is probably this: that it "created" Chesapeake Bay. Strictly speaking, that's just not so.

The impact that produced the 35-million-year old crater did not directly create the far, far younger Bay. However it may well have shaped the modern Chesapeake by creating a low spot (the sediment-buried crater) into which the Bay's mother river, the Susquehanna, and its southern tributaries tended to drain. This is the theory of crater-Bay creationism.

Another hypothesis (call it the barrier-Bay evolutionary theory) says the Chesapeake evolved as fluctuations in global sea level slowly formed the Delmarva Peninsula, an impenetrable barrier that kept redirecting the Susquehanna southward until the sea drowned the river following the last ice age, birthing the world's largest estuary.

Neither theory denies the central tenant of the other: that the crater formed a topographic low or that sea level/glacial changes built the Delmarva. It's a question of which exerted the defining influence on the embryonic Bay.

Did the crater "create" the entire drowned Susquehanna River valley, aka the Chesapeake Bay? The experts differ—or defer judgment.

Crater co-discoverer C. Wiley Poag has long held that the crater influenced the Bay's formation. "The impact crater created a long-lasting topographic depression, which helped determine the eventual location of Chesapeake Bay," he wrote as early as 1998 in a USGS fact sheet.

"If you like the hypothesis that subsidence of the crater caused the Susquehanna to come

"The explosion that accompanies the formation of this crater makes all of our nuclear [arsenal] in its heyday look like a firecracker. It's much more violent than we can imagine," he says, with characteristic exuberance. "This thing shook the [continental] shelf!"

He believes the data suggest the blast opened a hole closer to 10 kilometers (over 6 miles) deep and that the floor of the filled-in central crater lies 3.5 kilometers (over 2 miles) down, far deeper than is now thought. He also contends that debris initially blown outward by the explosion not only tumbled back into the crater rim, but was also sucked in from afar by the powerful vacuum the blast created. "That's why nothing is sitting within even kilometers of where it was originally. It's all been moved around," he says. "The cores we have argue for that! The seismic [data] we have argues for that!"

Initially, though, Powars and Bruce had to interpret what the Exmore cores were telling them. The answer lay deep within the crystalline structure of the fine-grained sediments.

"When you have a hypervelocity impact you produce shock waves, acoustic waves—we call them sound waves—going through the rock faster than the speed of sound," Gohn says. "They produce a characteristic fracture pattern in quartz veins [the most commonly occurring

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way south before turning out [to sea] then it did affect it," says USGS geologist emeritus Greg Gohn.

Gohn, Poag and other crater researchers say there is evidence that suggests the crater has affected the course of the lower Bay's rivers, notably the James and York, which abruptly change course from southeast to northeast upon reaching the crater rim (i.e. turning to flow into the low spot).

Others aren't so sure, among them Carl (Woody) Hobbs III of the Virginia Institute of Marine Science, author of a 2004 scientific journal article, "Geological History of Chesapeake Bay." The article maintains the ancestral Chesapeake Bay formed and grew to the march of the emerging Delmarva Peninsula.

"There are several things in the physical geography of the Bay and Bay region that appear to be aligned with the crater," he says, "but while there may be correlations, causation is not always clear." He thinks the jury is still out, for example, on the significance of the James' and York's changes of direction, citing similar about-faces by several Maryland rivers.

Just how old is the Bay? About 18,000 years ago, near the end of the last glacial period, sea level was so low there was no Bay, only rivers that gouged narrow valleys en route to the sea. When the glaciers melted some 6,000 years later, sea level rose and drowned the river valleys, including the Susquehanna's. Using seismic profiling and core sampling, scientists have unearthed clues to the ancient

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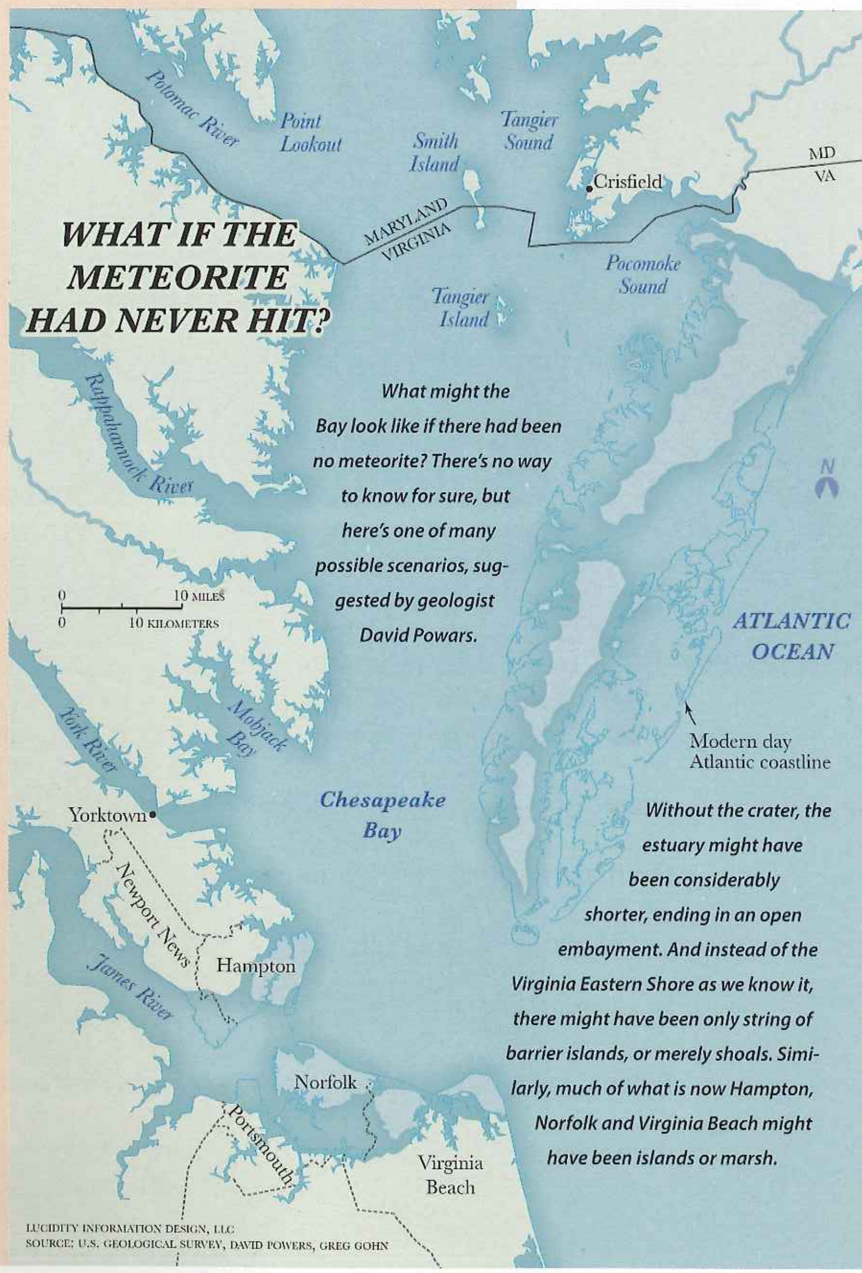
WHAT IF THE METEORITE HAD NEVER HIT?



What might the Bay look like if there had been no meteorite? There's no way to know for sure, but here's one of many possible scenarios, suggested by geologist David Powars.

Without the crater, the estuary might have been considerably shorter, ending in an open embayment. And instead of the Virginia Eastern Shore as we know it, there might have been only string of barrier islands, or merely shoals. Similarly, much of what is now Hampton, Norfolk and Virginia Beach might have been islands or marsh.

LUCIDITY INFORMATION DESIGN, LLC
SOURCE: U.S. GEOLOGICAL SURVEY, DAVID POWERS, GREG GOHN

The Hole at the Bottom of the Bay *continued from page 35*

mineral in the region]. In a natural setting, the only way to produce shocked quartz is an extraterrestrial impact."

But in 1986, crater geology was in its infancy; none of the Virginia geologists knew what those microscopic fractures meant. The nation's leading crater expert examined the Exmore samples and in a single grain of sand found proof of a meteorite impact. Still, the question remained: where?

Three years prior to the Exmore revelation, a New England geologist supervising a drilling project off the coast of New Jersey also made an important discovery. C. Wylie Poag of the USGS office in Woods Hole, Mass., found tektites in the drilling cores. He felt certain they came from a meteorite strike somewhere in the mid-Atlantic.

When word of the later Exmore discovery spread, Poag compared his samples with Powars's and Bruce's. They were the same age and origin. Poag's theory: the Exmore deposits washed there via a tsunami caused by an impact off the New Jersey coast.

With validation of an impact, the hunt was on to locate the crater. Other Reston researchers began to find clues as well. Lucy Edwards specializes in microfossils, specifically dinoflagellate cysts, a dormant stage the single-celled organism assumes when its marine habitat evaporates. Cysts found in sediment samples can help researchers date the specimen and evaluate its environment.

In 1982, four years before Powars's and Bruce's discovery at Exmore, Edwards was asked to analyze core collected in the 1970s. "Every once in awhile I'd find [a sample] that I thought must be contaminated. I was pretty upset about it," she recalls. Having no explanation for the cysts' wildly differing ages and "rotten preservation," she fired off an irritable note to colleagues: "I hate samples like this. The taxa listed do not belong together. So pick your favorite age and interpretation for this sample."

When she received the Exmore core

for examination, Edwards made a startling discovery. "I pulled out the slides and put my [micro]scope on them. Oh my goodness!" These battered samples were also completely whacky, representing 20 different ages of dinoflagellates. The cysts, mostly fragments, were "pretty beat up." Their spines were fused together and one grotesquely flattened specimen was "shot full of holes and crispy looking," she recalls. She dubbed it "Freddie Krueger."

Edwards immediately called Powars. "We're not talking about one piece of rubble," she told him. Evidence of a crater in southeastern Virginia was popping up everywhere. Meanwhile, Powars, Bruce and Poag continued drilling throughout the region to pinpoint the presumed crater and further the commonwealth's study of unusually salty groundwater throughout southeastern Virginia. But there was another set of data—thus far inaccessible—that could, literally, complete the picture.

Oil giant Texaco and its partner, Exxon, had conducted marine deep-seismic reflection surveys in the lower Bay, searching for oil in the basement rock. Imagine how valuable seismic imaging of the Bay's bottom contours could be to scientists looking for evidence of a crater. Imagine, too, how invaluable the information was to these very competitive oil companies and their bottom lines. Texaco and Exxon weren't inclined to share.

After repeated USGS requests were rebuffed, Powars tried a different tack. If we can't get the entire seismic profile, how about giving us everything above the bedrock, he asked (overlaying sediments being of little value in oil exploration). "Nobody's every asked us for that," Texaco's representative told Powars. In 1993 and '94 the companies released the data for the sediment layer.

The USGS had its version of "black gold." The seismic imagery offered visual proof of what Powars surmised: a steep-rimmed depression lined with a dense layer of debris. Their colleagues' skepticism dispelled, Powars and Poag oversaw more exploratory drilling. In all, USGS would drill in 17 different locations—on both shores of the lower Bay—to determine the limits of the crater. In 2003, the Chesapeake Bay Impact Crater Project applied for and later received a grant to pay for its most ambitious investigation yet: drilling deep into the very heart of the crater. In September 2005, a team of scientists from the International Continental Scientific Drilling Program joined USGS researchers at Eyreville Farm about four miles north of Cape Charles. For the next three months, they supervised as a deep-drilling rig worked 24/7 to extract core from the surface to the crater's deepest point.

After several weeks of drilling, the drill hit solid granite nearly 3,600 feet below the surface. It was the crater floor, thought some, believing that interpretations of the seismic data were incorrect. The crater was much smaller, they said. Arguments ensued about whether to stop. Powars urged Gohn to stay the course: "I said we're *going* to come out of it. It's not [basement rock]. We're going to come out into the sand." Gohn ordered the drilling to continue. It took weeks to bore through the 900-foot-thick block, a piece of impact-dislodged rock that had slid into the crater. Farther down, the drillers encountered melt rock and the collapsed vapor cloud. On December 4, the drill reached its final depth, 5,795 feet (1.1 miles). That was very likely not the bottom of the crater, Gohn says, but the project had used up its funding. "Drilling projects end for only one reason," he says, "and that's money."

Still, the project paid huge dividends—more than a mile of continuous core from the center of the crater, something that scientists around the world analyze for decades.

After that 20-year burst of funded digging, the active phase of crater sleuthing subsided. The international drilling team extracted its final core in May 2006 and departed. The USGS crater team disbanded; its members (except for retiree Gohn) now pursue other assignments. "All of us have moved on to other projects we needed to do, but the science was never really finished," says J. Wright Horton, a Reston-based research geologist. "We have a lot of unpublished, partially finished work."

Intriguing questions remain. Could the Chesapeake Bay crater and several of similar age point to a meteor shower from a comet in the late Eocene? Are the faulted rocks beneath the crater's outer rim the cause of past earthquakes in Virginia? Has the crater contributed to the region's abnormally high rise in relative sea level? Those questions, along with that of how the meteorite might have influenced the Bay's current shape [see sidebar], will be the subject of study and debate for decades to come.

It seems rather certain, however, that the impact crater is responsible for southeastern Virginia's mysterious and long-known dearth of drinkable groundwater. "Your expectation in a coastal area is that the water would be salty right at the top and then would get fresher [lower down]," Gohn says. Not so in southeastern Virginia; here the water gets saltier as you go down.

In 1864, Union soldiers stationed at Hampton, Va.'s Fort Monroe started digging a well to find drinkable water. More than five years later, all they had to show for it was a 900-foot-deep hole filled with undrinkable saltwater. In the early 20th century, two USGS geologists who were mapping the region's groundwater, by way of well samples, described an inland "wedge" or "bulge" of saline water. At the center of this semicircular bulge was the town of Cape Charles. One of the two, D. J. Cederstrom, noticed something else: the subsurface sediments that washed out of wells he drilled seemed oddly juxtaposed.

In published work in the 1940s Cederstrom theorized that the intermingled soils and minerals had some connection to the unusual intrusion of salty water. At the time, no one believed him. A half-century later his theory found a more receptive audience. "We stood on his shoulders to figure out the puzzle," Powars says. "He knew there was some structural basin there and he knew the groundwater was related to it somehow."

Among the long-term casualties of the collision, it seems, were the region's major aquifers. Like the truncated gray lines on Gohn's computer screen, the layered aquifers were abruptly sealed along the crater's outer rim. Inside the basin the groundwater is hypersaline, in places up to twice as salty as seawater. Scientists believe the salty groundwater may be ancient seawater trapped at the time of the impact.

"This may be some of the oldest water sitting still for the last 35 million years," Powars says, "or at least since the hydrothermal activity ended 100,000 to 200,000 years after the event." (According to a recent article in the journal *Nature*, deep water in the crater may be even older than that, 100 to 145 million years of age.) In any case it's sobering news for local governments that must conserve precious fresh water while trying to meet the growing needs of millions of Virginia residents and businesses.

Cape Charles is among the municipalities affected. Since the crater's discovery, however, the town has made peace with this invader from outer space and embraces its central role in the saga. A sign near the harbor describes the impact and a crater exhibit at the Cape Charles Museum on Randolph Avenue includes seven core samples.

Museum visitors can also watch a video featuring Powars. He's standing on the town beach, his arms raised towards the heavens as he explains the significance of his location: "Thirty five and a half million years ago you'd have been vaporized to nothing right here!" Welcome to ground zero. ⚓

The Crater that Created the Bay? *continued from page 35*

Susquehanna's pathways (paleochannels), which show the river valley's varying lengths.

"What you expect to find in shallow depths on southern Delmarva—at least in places—are ocean bottom sediments with [ancient] shells in them," Gohn says. "Then in some places you start drilling and all of a sudden you find this valley that's full, mostly, of sand and younger material. That's the old Susquehanna valley."

Geologists have located and dated at least three buried channels where the river once met the sea [see map page 34]: at Exmore (the oldest, 300,00 to 500,000 years old), Eastville (150,000) and Cape Charles (18,000) just north of the Bay's present mouth. Gohn's USGS colleague, David Powars, believes he has found another paleochannel, north of and presumably older than the Exmore channel. He calls it the Persimmon Point channel, for an obscure point of land near the mouth of the Pocomoke River in northernmost Accomac County.

Powars thinks the meteorite affected the Bay by lengthening the mainstem Susquehanna. "The crater indirectly relates to [formation of the Bay] because it's a drowned river system and the crater has been affecting the drainage," he says.

If the crater did at least influence the modern-day shape of the estuary, what might the Chesapeake look like today had the meteor struck elsewhere? There's no way of knowing, but Powars and Gohn hazard some guesses. It might have been a considerably shorter estuary, Powers says, emptying into an embayment to the south—which may or may not have had a string of barrier islands, or at least shoals, across its mouth [see illustration, page 35]. Or it may have all ended up dry land, he says.

"The history and location of the Susquehanna would have been different," Gohn says. It's even possible, he says, that the Susquehanna and Potomac channels would never have met; each might have taken its own path to the Atlantic Ocean.

—M.L.