third the age of Earth. Nevertheless, the mass fraction of diamond observed in carburanium is several orders of magnitude smaller than that of carbonado. This presents a serious difficulty if a radiation process is to account for carbonado formation. Mass transport problems must be addressed; because <20% of the volume of carbonado is not diamond, some transport mechanism would have to concentrate diamond grains into large aggregates while removing the displaced uranium oxides and decay products. Because carburanium contains 500-nm polycrystalline aggregates, a sintering mechanism would then be required to coalesce these radiation-formed aggregates into the micrometer-sized single crystal grains typical of carbonado. These factors indicate that a radiation mechanism alone cannot satisfactorily explain the formation of carbonado.

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8. Fragments with a starting mass of 3.3 g were treated with HNO_3 plus HCl at 20° and 40°C, $K_2Cr_2O_7$ at 80°C, $HClO_4$ at 140° and 220°C, and HCl at 60°C, producing ~1 mg of white residue.
9. The polycrystalline aggregates were >95 atomic % C with trace amounts of Si, O, Fe, Al, Mg, and Ti. The yttrium phosphate crystals exhibited trace amounts of Dy, Er, Gd, and Yb. Carburanium is usually associated with rare-earth minerals such as zirtolite, xenotime, monazite, and uraninite.
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Impact Origin of the Chesapeake Bay Structure and the Source of the North American Tektites

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Seismic profiles, drill core samples, and gravity data suggest that a complex impact crater ~35.5 million years old and 90 kilometers in diameter is buried beneath the lower Chesapeake Bay. The breccia that fills the structure contains evidence of shock metamorphism, including impact melt breccias and multiple sets of planar deformation features (shock lamellae) in quartz and feldspar. The age of the crater and the composition of some breccia clasts are consistent with the Chesapeake Bay impact structure being the source of the North American tektites.

The recently discovered Chesapeake Bay structure is a complex peak-ring crater buried 300 to 500 m beneath the lower Chesapeake Bay, its surrounding peninsulas, and the adjacent inner continental shelf (*1*). The crater is centered at 37°16.5′N and 76°0.7′W, near the town of Cape Charles on Virginia's segment of the Delmarva Peninsula (Fig. 1). The existence of this unusual circular structure was determined on the basis of 10 multichannel seismic-reflection profiles transecting the bay and 3 single-channel profiles on the inner continental shelf, as well as 56 bore holes drilled inside and outside the crater rim (*1*). The seismic profiles define the outer rim of the structure, which is 90 km in diameter and is marked by concentric normal faults that dip down toward the crater (Fig. 2). A flat-floored annular trough 300 to 1200 m deep separates the outer rim from an irregular, low-relief peak ring (maximum height, ~175 m) (*1*). The peak ring, in turn, encircles a 30-km-wide inner basin with an estimated depth of ≤1.2 km.

Correlation of bore-hole stratigraphy with seismic reflection profiles showed that the preimpact coastal plain rocks consisted of a seaward-thickening wedge of mainly Lower Cretaceous to upper Eocene, poorly lithified, and mainly siliciclastic sedimentary rocks (Fig. 2). The sedimentary sequence rests on a crystalline basement complex comprising granitic and metasedimentary rocks of Proterozoic to Paleozoic age (*2*). Flexural downwarping due to thermotectonism and sediment loading (*3*) has tilted the surface of the crystalline basement eastward toward the axis of the Baltimore Canyon trough (*4*). The seismic profiles indicate that the floor of the eastern sector of the annular trough also steepens eastward, and as a result the trough is deeper in the east (Fig. 2). The faulted rim of the structure has undergone similar differential eastward subsidence.

Bore-hole samples showed that the structure is partly filled with a unit termed the Exmore breccia, which is mainly composed of autochthonous sedimentary clasts in a sandy matrix but also contains millimeter- to centimeter-sized basement clasts

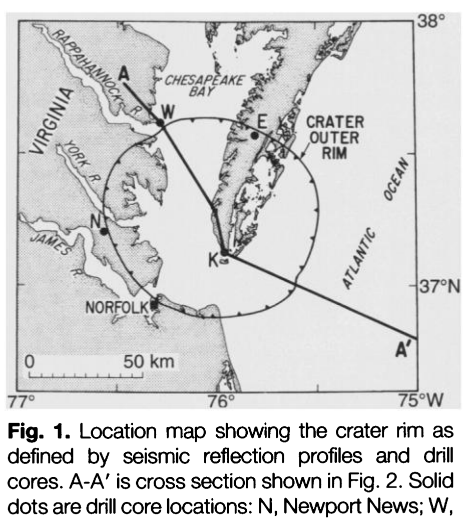

Fig. 1. Location map showing the crater rim as defined by seismic reflection profiles and drill cores. A-A′ is cross section shown in Fig. 2. Solid dots are drill core locations: N, Newport News; W, Windmill Point; E, Exmore; K, Kiptopeke.

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(*5*, *6*). The age of the structure has been estimated at 35.5 million years ago, on the basis of micropaleontological studies of the breccia (*7*) and correlation with nearby impact deposits (*8*). Although geophysical data are compatible with an impact origin of the Chesapeake Bay structure, and a connection to the coeval North American tektite strewn field has been suggested (*1*, *5*, *6*), petrographic and geochemical data are needed to demonstrate such an origin.

To support the geophysical and stratigraphic arguments for an impact origin of the Chesapeake Bay structure, we have combined simple Bouguer gravity measurements from southeastern Virginia with free-air gravity measurements from the inner continental shelf to produce a gravity anomaly map (*9*) (Fig. 3). The gravity anomaly pattern in southeastern Virginia consists of a broad band of negative anomalies between two north-south–trending, ridgelike, positive anomalies. Locally, the pattern consists of numerous elongate-to-subcircular negative anomalies, most of which are caused by intrusive igneous bodies composed of Petersburg, Portsmouth, or Dort granite (*10*). Others, like the Norfolk Rift Basin anomaly, represent the fill of small Triassic rift basins (*11*). However, a prominent circular negative anomaly, which is not associated with any pluton or rift basin, has an outline nearly identical to that of the inner basin of the Chesapeake Bay structure (as defined by seismic profiles) and coincides with the thickest part of the breccia deposit. The contours enclosing this gravity low range from –20 to –28 mgal. Five small, relative gravity highs (–25 mgal) are present within the low (Fig. 3) and may indicate a rugged relief within the inner basin. The gravity low stems chiefly from a zone of low density material in the crystalline basement rocks, produced by intense fracturing due to impact.

The gravity signature of most impact craters is conspicuous but can be complicated in some cases by variations in the target rock type and erosional condition. The anomalies associated with impact structures are typically negative, caused by lithologic and physical changes in the target rocks as a result of the impact process (*12*). Many complex impact structures also show, centered within the general gravity low, a central high that is associated with structural uplift of denser rocks from greater depth (*12*). This expression, however, depends on the density of the rocks that are present. Many medium-sized to large impact structures, most prominently the Ries crater in Germany (*13*), have no central gravity highs, only pronounced gravity lows, a pattern that is similar to that shown in Fig. 3. Thus, the gravity signature of the Chesapeake Bay structure is similar to that of other complex impact craters.

Confirmation of an impact origin, however, requires conclusive evidence that the rocks and minerals have under-

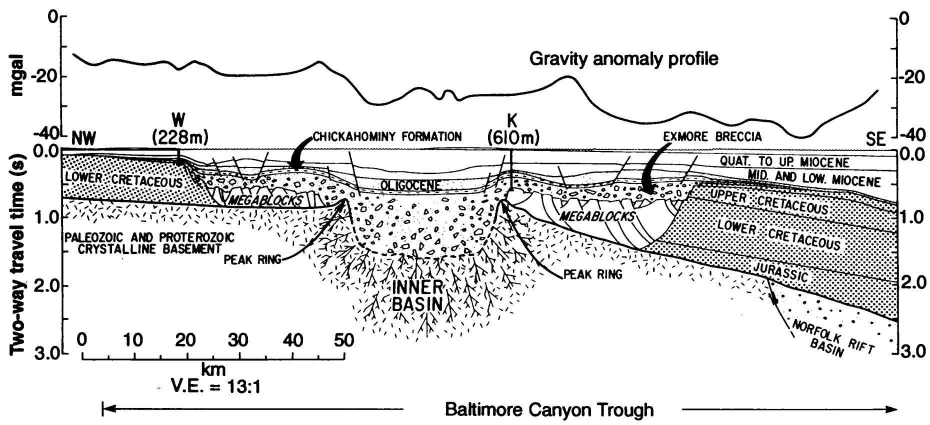

Fig. 2. Geological cross section of the Chesapeake Bay impact structure, constructed from drill core and seismic data. The crater interrupts a linear inflection in the regional structural gradient of the basement surface. At the inflection, the gradient steepens eastward into the axis of the Baltimore Canyon trough, the largest and deepest post-rift sedimentary basin along the U.S. Atlantic margin. The gravity profile along the cross section shows the same regional gradient, as well as a variation associated with the crater.

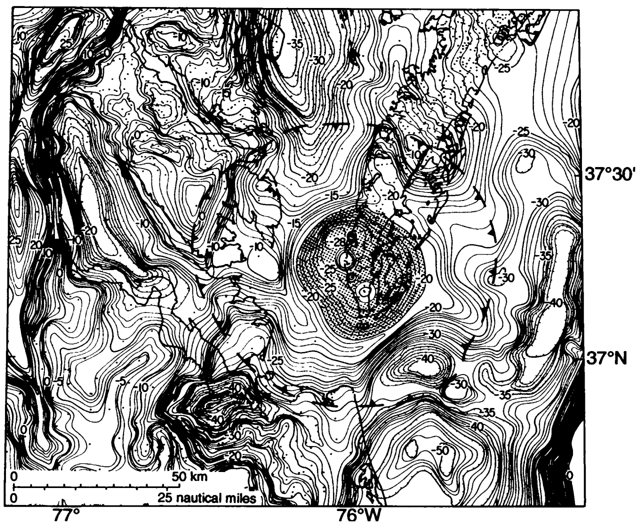

Fig. 3. Composite gravity anomaly map of southeastern Virginia showing a circular negative gravity anomaly (shaded) that coincides with the outline of the inner basin of the Chesapeake Bay structure as deduced from seismic profiles. Simple Bouguer values are used onshore and in the bay, and free-air values are used on the continental shelf. Contours are in milligals.

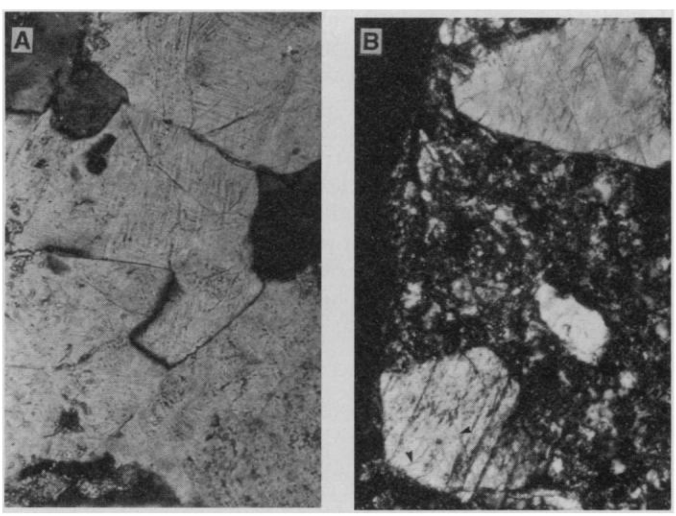

Fig. 4. Photomicrographs of rocks from the Exmore core, Chesapeake Bay structure, showing evidence for shock metamorphism. Sample numbers include the depth in feet. (**A**) Aggregate of quartz grains, each of which contains multiple sets of PDFs, in a centimeter-sized granite particle from sample 1329.2. Crossed polars, 565 μm wide. (**B**) Fragment of altered impact melt breccia (sample 1290.6) with shocked quartz (top right) with several sets of PDFs and shocked plagioclase (lower left; PDFs are marked with arrowheads), in matrix showing spherulitic devitrification texture. Crossed polars, 565 μm wide.

gone shock metamorphism, which is defined by higher pressures (up to 100 GPa), temperatures (up to several 1000°C), and strain rates associated with impact cratering (*14*). The type of shock metamorphic effects present depends on the peak shock pressure experienced. The most characteristic effects are microscopic features, such as planar microstructures, optical mosaicism, isotropization, and transformations of minerals to high-pressure phases. Planar deformation features (PDFs) are sets of thin (typically <1 to 3 μm) glass-filled (*15*) parallel planes, spaced about 2 to 10 μm apart, which occur in important rock-forming minerals such as quartz, feldspar, and olivine (*14*).

We have examined 65 samples from four drill cores [Exmore, Windmill Point, Kiptopeke, and Newport News (Fig. 1)] that have penetrated into the Exmore breccia (*16*). No core is available from the center of the structure, nor did any drill core reach basement. The Exmore samples contain a variety of lithologies. The core consists predominantly of poorly consolidated sedimentary units. In thin section, siltstones or sandstones (sometimes with glauconite) alternate with metasedimentary and crystalline fragments derived from the basement. Most particulate samples consist of a mixture of sedimentary and crystalline rock types, as well as mineral fragments derived from granitoids (*17*). Intragranular deformation of felsic minerals (mainly quartz and feldspar) is often limited to nondiagnostic microdeformation features, such as poorly developed irregular fracturing, undulatory extinction, occasional kinkbanding of mica, and locally strained calcite.

Evidence for shock metamorphism was found in 14 Exmore core breccia samples from depths of 372.0 to 415.6 m (Fig. 4). Some samples exhibit characteristic microfracture patterns, which indicate shock pressures of 5 to 10 GPa (*18*), as well as shock mosaicism in quartz. We found abundant shocked quartz grains with PDFs in individual quartz grains and in crystals from granitic fragments (Fig. 4A). In general, PDFs in shocked quartz are known to occur in intersecting sets of planes corresponding to specific crystallographic orientations, with the (0001) or *c* (basal), $\{10\bar{1}3\}$ or ω, and $\{10\bar{1}2\}$ or π orientations being the most common (*14*, *19–21*). In the Chesapeake Bay core samples, we identified quartz grains with up to six different sets of PDFs.

Shock deformation was also observed in feldspars, which showed up to three sets of PDFs. Perthitic alkali feldspar contains PDFs that are oblique to the perthite exsolution lamellae. Several shocked orthoclase crystals also contain glass, which implies incipient melting. A number of breccia samples also contain individual granitoid-derived rock fragments, which are partially or almost totally melted. These fragments represent impact melt because they commonly incorporate shocked quartz and feldspar clasts (Fig. 4B). No clasts of demonstrably sedimentary origin were seen in any of the melt rocks (*22*). Mafic minerals are rare, probably because of preferential melting of hydrous phases or postdeformational alteration, but several intensely kinkbanded biotite grains were found, which are typically observed in moderately shocked granite.

To confirm that the observed PDFs are of shock origin, their crystallographic orientations and frequencies have to be measured (*19–21*). Orientation measurements (*23*) show that the PDFs have the shock-characteristic orientations [(0001), $\{10\bar{1}3\}$, $\{10\bar{1}2\}$, $\{11\bar{2}2\}$, $\{10\bar{1}1\}$, $\{11\bar{2}1\}$, and $\{51\bar{6}1\}$ (*c*, ω, π, ξ, *r*, *z*, *s*, and *x*, respectively)] characteristic of shock metamorphism (*22*); only a few unindexed planes were observed (Fig. 5). The relative frequencies of the crystallographic orientations observed in the Exmore breccia indicate shock pressures of 20 to about 30 GPa, and provide evidence that the Chesapeake Bay structure is of impact origin.

The late Eocene age of the Chesapeake Bay structure and its geographical location have led to the suggestion that it might represent the source of the North American tektites (*1*). Tektites are natural glasses found in four Cenozoic strewn fields on Earth (North American, Central European, Ivory Coast, and Australasian) whose origin has been associated with hypervelocity impacts on Earth (*24*). Though the source crater is known for the Ivory Coast and Central European strewn fields, no source crater has been conclusively identified for the North American strewn field. The identification of a 20-cm-thick debris unit with tektite fragments, impact glasses, and shocked minerals at Deep Sea Drilling Project (DSDP) Site 612 (*25*) led to the suggestion that the North American tektite source crater must be in close proximity to DSDP Site 612 (*25*, *26*), which is situated approximately 330 km northeast of the center of the Chesapeake structure.

We performed major and trace element analyses to determine whether the Chesapeake Bay impact structure is indeed the sought-after source crater (*27*). The core samples consisted of small breccia frag-

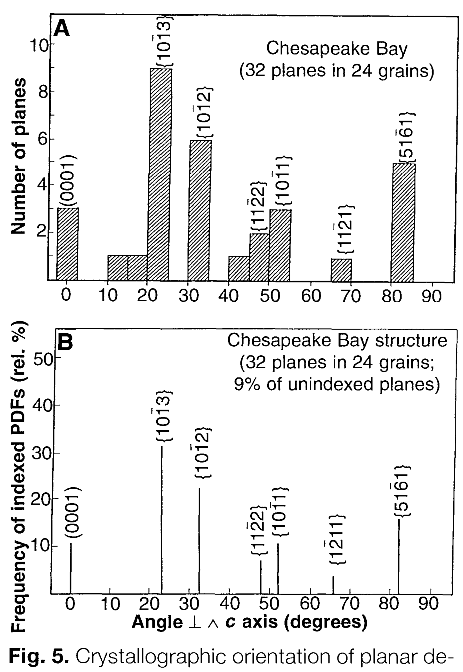

Fig. 5. Crystallographic orientation of planar deformation features (PDFs) in quartz from Exmore core samples, Chesapeake Bay structure. Samples were taken from depths ranging from 376.6 to 415.2 m in the core. (**A**) Standard histogram plot after Engelhardt and Bertsch (20), showing all measured data, and (**B**) Histogram showing frequency of indexed PDFs [after Grieve *et al.* (*21*)] versus angle between the *c* axis and the poles of PDFs after transformation of the optic axis into the center of a standard stereographic projection (*19–21, 23*).

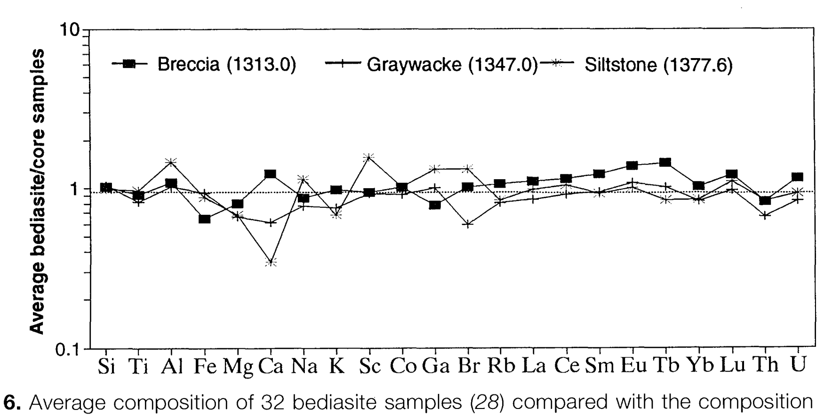

Fig. 6. Average composition of 32 bediasite samples (*28*) compared with the composition of three high-silica breccia fragments from the Exmore core. The abundances in the core samples were recalculated on a volatile-free basis; sample numbers correspond to depth in feet.

ments. The samples contained between 32 and 73 weight% SiO_2, with the low SiO_2 samples having high contents of carbonates. To compare the Chesapeake Bay crater core samples to North American tektites, the compositions were recalculated on a carbonate- and water-free basis. The compositions of some of the high SiO_2 rocks agree well with those of average North American tektites (*28*) for mostly nonvolatile elements (Fig. 6).

This result provides evidence that the North American tektites were formed during the Chesapeake Bay impact event. Furthermore, the Rb-Sr and Sm-Nd isotopic composition of North American tektites indicates that their source rocks are likely to be derived from the Appalachian orogen (*29*), which is represented in the lithologies that are present beneath the Chesapeake Bay. In addition, recent boron isotopic data on bediasites require the presence of marine carbonate or evaporite rocks among the source rocks of the North American tektites (*30*). This observation also agrees with a Chesapeake Bay source, as the crater formed in a submarine environment and the impact breccia contains limestone clasts (*1*). Thus, our geophysical, petrographical, and geochemical studies provide evidence for an impact origin of the Chesapeake Bay structure, as well as for the suggestion that the crater may be the source of the North American tektites.

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7. The biochronological age of the breccia was determined by analysis of planktonic foraminifera, calcareous nannofossils, and palynomorphs contained in the clasts and matrix (*1, 5, 6*). The youngest microfossils in the breccia are of late Eocene age, representing chronozone P15 of the planktonic foraminifera and chronozone NP19/20 of the calcareous nannofossils.
8. The Exmore breccia and the overlying upper Eocene section at the Chesapeake Bay crater correlate, respectively, with a debris deposit (containing shocked minerals, impact glass, and tektites) cored at DSDP Site 612 and with the upper Eocene chalk that overlies it [J. Thein, *Init. Rep. DSDP* **95**, 565 (1978); K. G. Miller, W. A. Berggren, J. Zhang, A. A. Palmer-Julson, *Palaios* **6**, 17 (1991)]. Graphic correlation between the upper Eocene section at the Chesapeake Bay structure and DSDP Site 612 indicates that normal sedimentation resumed almost simultaneously after impact at each location during early chronozone P15. The age of the Chesapeake Bay structure is, therefore, assumed to be identical to the radiometric age of the tektites from DSDP Site 612 at 35.5 ± 0.3 to 35.2 ± 0.3 million years ago [J. Obradovich *et al.*, *Geol. Soc. Am. Abstr. Programs* **21**, 134 (1989); J. Obradovich, in (*5*).
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16. Of the 65 breccia samples, 60 were from the breccia unit from depths ranging from 368.8 to 422.8 m in the Exmore core, one was from the Windmill Point core (depth, 171.8 m), one was from the Newport News core (depth, 131.7 m), and three were from the Kiptopeke core (depth, 405 to 406.2 m). Most samples are millimeter- to centimeter-sized breccia fragments that were extracted from their sedimentary matrices. The Newport News sample was a poorly sorted sediment consisting of bands of siltstone, shale, or graywacke, with quartz, glauconite, magnetite, calcite, feldspar, and muscovite. The Kiptopeke sample consisted of shale, aplite, and quartz particles, whereas the Windmill Point sample consisted of various sandstone fragments.
17. The modal compositions of individual samples vary from >90% by volume granitoid fragments to 100% by volume sedimentary grains, with few metasedimentary fragments. The sedimentary and metasedimentary component comprises pure sandstone, glauconitic sandstone, fine-grained quartzite, chert, pure glauconite, shale, siltstone, biotite schist, arkose, and calcite-rich carbonate. The granitoid fragments consist of fine- to coarse-grained granitic lithologies, mainly biotite-rich granite, and medium-to coarse-grained quartz particles and polycrystalline quartz aggregates, which could be derived from a quartz-vein or pegmatite component. Numerous mineral fragments, such as quartz, K-feldspar (often as microcline or perthite), and plagioclase, all derived from granitoids, are found in most mixed separates, which implies that these samples represent a polymict breccia.
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