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The Chesapeake Bay bolide impact: a convulsive event in Atlantic Coastal Plain evolution

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Abstract

Until recently, Cenozoic evolution of the Atlantic Coastal Plain has been viewed as a subcyclical continuum of deposition and erosion. Marine transgressions alternated with regressions on a slowly subsiding passive continental margin, their orderly succession modified mainly by isostatic adjustments, occasional Appalachian tectonism, and paleoclimatic change. This passive scenario was dramatically transformed in the late Eocene, however, by a bolide impact on the inner continental shelf. The resultant crater is now buried 400–500 m beneath lower Chesapeake Bay, its surrounding peninsulas, and the continental shelf east of Delmarva Peninsula. This convulsive event, and the giant tsunami it engendered, fundamentally changed the regional geological framework and depositional regime of the Virginia Coastal Plain, and produced the following principal consequences. (1) The impact excavated a roughly circular crater, twice the size of Rhode Island (~6400 km^2) and nearly as deep as the Grand Canyon (~1.3 km deep). (2) The excavation truncated all existing ground-water aquifers in the target area by gouging ~4300 km^3 of rock from the upper lithosphere, including Proterozoic and Paleozoic crystalline basement rocks and Middle Jurassic to upper Eocene sedimentary rocks. (3) Synimpact depositional processes, including ejecta fallback, massive crater-wall failure, water-column collapse, and tsunami backwash, filled the crater with a porous breccia lens, 600–1200 m thick, at a phenomenal rate of ~1200 m/hr. The breccia lens replaced the truncated ground-water aquifers with a single 4300 km^3 reservoir, characterized by ground water ~1.5 times saltier than normal sea water (chlorinities as high as 25,700 mg/l). (4) A structural and topographic low, created by differential subsidence of the compacting breccia, persisted over the crater at least through the Pleistocene. In the depression are preserved postimpact marine lithofacies and biofacies (upper Eocene, lower Oligocene, lower Miocene) not known elsewhere in the Virginia Coastal Plain. (5) Long-term differential compaction and subsidence of the breccia lens spawned extensive fault systems in the postimpact strata. Many of these faults appear to reach the bay floor, and may be potential hazards for motion-sensitive structures in population centers around Chesapeake Bay. Near-surface fracturing and faulting generated by the impact shock may extend as far as 90 km from the crater rim. (6) Having never completely filled with postimpact sediments, the sea-floor depression over the crater appears to have predetermined the location of Chesapeake Bay. (7) As large impact craters are principal sources for some of the world's precious metals, it is reasonable to expect that metal-enriched sills, dikes, and melt sheets are present in the inner basin of the crater.

In addition to these specific consequences, the crater and the convulsive event that produced it, have widespread implications for traditional interpretations of certain structural and depositional features of the Atlantic Coastal Plain, particularly in southeastern Virginia.

Keywords: Crater; Bolide impact; Chesapeake Bay; Stratigraphy

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1. Introduction

Recent discussions of the geological evolution of the northern half of the Atlantic Coastal Plain (Owens and Gohn, 1985; Ward and Strickland, 1985; Olsson et al., 1988; Poag and Sevon, 1989; Poag and Ward, 1993) describe a ~200-m.y. record of subcyclical sedimentation and erosion on the slowly subsiding western margin of the North Atlantic basin. Sediment supply fluctuated mainly in response to changes in eustasy, paleoclimate, and migrating pulses of Appalachian tectonism. Depocenters evolved according to differential rates of thermotectonic subsidence modified by sediment loading and flexural rebound, to shifts in the position of dominant terrigenous source terrains, and to changing paleohydrographic regimes. But in the late Eocene, 35.2±0.3 to 35.5 ± 0.3 Ma (Obradovich et al., 1989; Poag and Aubry, 1995), this relatively tranquil continuum was dramatically interrupted by a *convulsive geological event* (an extraordinarily energetic event of regional influence; Clifton, 1988). The adjective *convulsive* is geologically more appropriate than *catastrophic*, because it "... is neutral in the sense of disaster, [and] carries no doctrinal implications ... " (Clifton, 1988, p. 1). The particular convulsion to which I refer was a bolide impact on the late Eocene inner continental shelf (Figs. 1 and 2). (I use *bolide* in the generic sense of Greeley (1994), to embrace all crater-generating Earth impactors, including meteoroids, asteroids, and comets.) The resultant impact crater is now buried 300–500 m beneath the lower part of Chesapeake Bay, its surrounding peninsulas, and the adjacent inner continental shelf (Poag et al., 1994b).

The Chesapeake Bay impact crater lies in the southern part of the Salisbury embayment, a gentle downwarp in the basement surface along the western margin of the Baltimore Canyon trough (Fig. 1). The crater is centered approximately beneath the town of Cape Charles, Virginia, on the western shore of the lower Delmarva Peninsula (lat. 37°16.5′N, long. 76°0.7′W; Poag et al., 1994b; Figs. 1 and 2). The faulted outer rim of the crater circumscribes a roughly circular excavation, ~90 km in diameter, and ~1.3 km deep (maximum rim-to-floor relief). The structural framework of the target rocks (rocks impacted by the bolide) has been established by numerous regional seismic, gravity, and magnetic surveys (Fig. 2; Ewing et al., 1937; Woollard et al., 1957; LeVan and Pharr, 1963; Taylor et al., 1968; Sabet, 1973; Johnson, 1977; Hawarth et al., 1980; Lyons et al., 1982; Dysart et al., 1983).

The regional stratigraphic framework is built upon detailed outcrop and bore-hole studies (Figs. 3–7; Cederstrom, 1945a,b,c, 1957; Richards, 1945, 1967; Cushman and Cederstrom, 1949; Maher, 1965, 1971; Brown et al., 1972; Teifke, 1973; Gibson, 1983; Owens and Gohn, 1985; Ward and Strickland, 1985; Gohn, 1988a,b; Mixon, 1989; Thomas et al., 1989). Recent syntheses of outcrop and bore-hole stratigraphy have been published by Ward and Krafft (1984), Poag (1985b), and Poag and Ward (1993). Powars et al. (1992), Poag and Aubry (1995), and Poag and Commeau (1995) provide stratigraphic details of the impact-related strata. I include, herein, detailed stratigraphic columns of outcrop and subsurface sections (Figs. 4–8), which contrast the rock record inside and outside the crater.

Crystalline basement rocks, which floor the southeastern Salisbury embayment, comprise Piedmont granitic and metasedimentary rocks (Proterozoic and Paleozoic) emplaced during the Appalachian orogeny. The basement surface dips gently eastward at 9 m/km between Richmond and the eastern coastline of the Delmarva Peninsula. From there, the dip increases at a rate of ~58 m/km into the axis of the Baltimore Canyon trough. Above the basement are chiefly siliciclastic sedimentary units. From a feather edge near the Fall Line, the sedimentary section thickens downdip (eastward) to about 1.6 km beneath the southern part of the Delmarva Peninsula. From there, the section expands fivefold to > 8 km thickness in the southern part of the Baltimore Canyon trough. The older sedimentary section onshore consists of mainly nonmarine Lower Cretaceous siliciclastic beds assigned to the Potomac Formation. Above that are mainly marine siliciclastic formations of Late Cretaceous, Paleocene, and Eocene age. One limestone unit, a facies of the Piney Point Formation (Jones, 1990), accumulated during the middle Eocene. Offshore, the oldest sedimentary unit affected by the impact consists of Middle and Upper Jurassic siliciclastic rocks.

Poag and Aubry (1995) and Poag and Commeau (1995) documented the biochronology of impact-related strata using planktonic foraminifera and

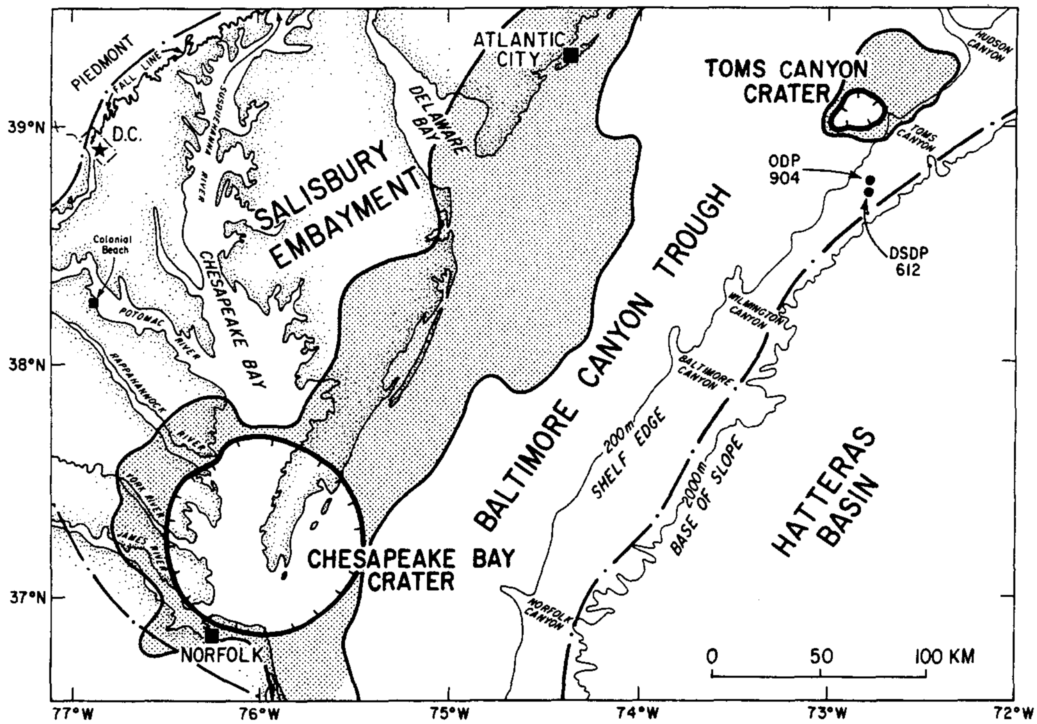


Fig. 1. Regional location map showing physiographical and geological features of study area. The Salisbury embayment, expressed by ovate, shallow, downwarp in basement surface, is onshore extension of much deeper Baltimore Canyon trough, whose boundaries are approximated by heavy dashed and dotted line. Shaded bands represent estimated distribution patterns of ejecta and tsunami deposits from Toms Canyon and Chesapeake Bay craters. *ODP* = Ocean Drilling Program; *DSDP* = Deep Sea Drilling Project.

calcareous nannofossils obtained from the impact breccia and overlying beds. Figs. 4–9 illustrate the detailed stratigraphic columns upon which those authors based their conclusions. The bolide convulsion occurred in biochrons P15 (foraminifera) and NP19/20 (nannofossils) of the late Eocene. This is biochronologically coincident with the Toms Canyon bolide, which struck the outer continental shelf 335 km to the northeast, off New Jersey (Poag, 1991; Poag et al., 1992, 1993; Fig. 1). The Toms Canyon ejecta cored at DSDP Site 612, is 35.2 ± 0.3 to 35.5 ± 0.3 m.y. old ($^{40}Ar/^{39}Ar$ plateau date by Obradovich et al., 1989; Poag and Aubry, 1995). Graphic correlation indicates that normal marine sedimentation resumed simultaneously at the Chesapeake and Toms Canyon sites (Fig. 10). Thus, I infer that the Chesapeake Bay crater is also ~35 m.y. old.

The chaotic deposit that surrounds and fills the upper part of the Chesapeake Bay crater is informally known as the Exmore breccia (previously called the *Exmore beds* by Powars et al., 1992 and the *Exmore boulder bed* by Poag et al., 1992), after the Virginia town where the first continuous breccia core (Fig. 6) was recovered. Some non-cored bore-hole sections, stratigraphically equivalent to the Exmore breccia, were extensively studied fifty years ago by Cederstrom (1945a,b, 1957). For lack of cores, however, he did not comprehend the nature or origin of those rocks. Cederstrom described a persistent subsurface interval of highly diverse, brightly colored, variegated rock types containing a mixture of Cretaceous, Paleocene, and Eocene foraminifera, which he identified in drill cuttings from more than 50 wells across southeastern Virginia. Cederstrom (1957) called the anomalous strata the Mattaponi Formation. The total lack of cores, however, resulted in an imprecise definition of the thickness, age, and boundaries of the Mattaponi. Furthermore, that formation name may not strictly apply to the Exmore breccia, because it is not certain that the type well for the Mattaponi For-

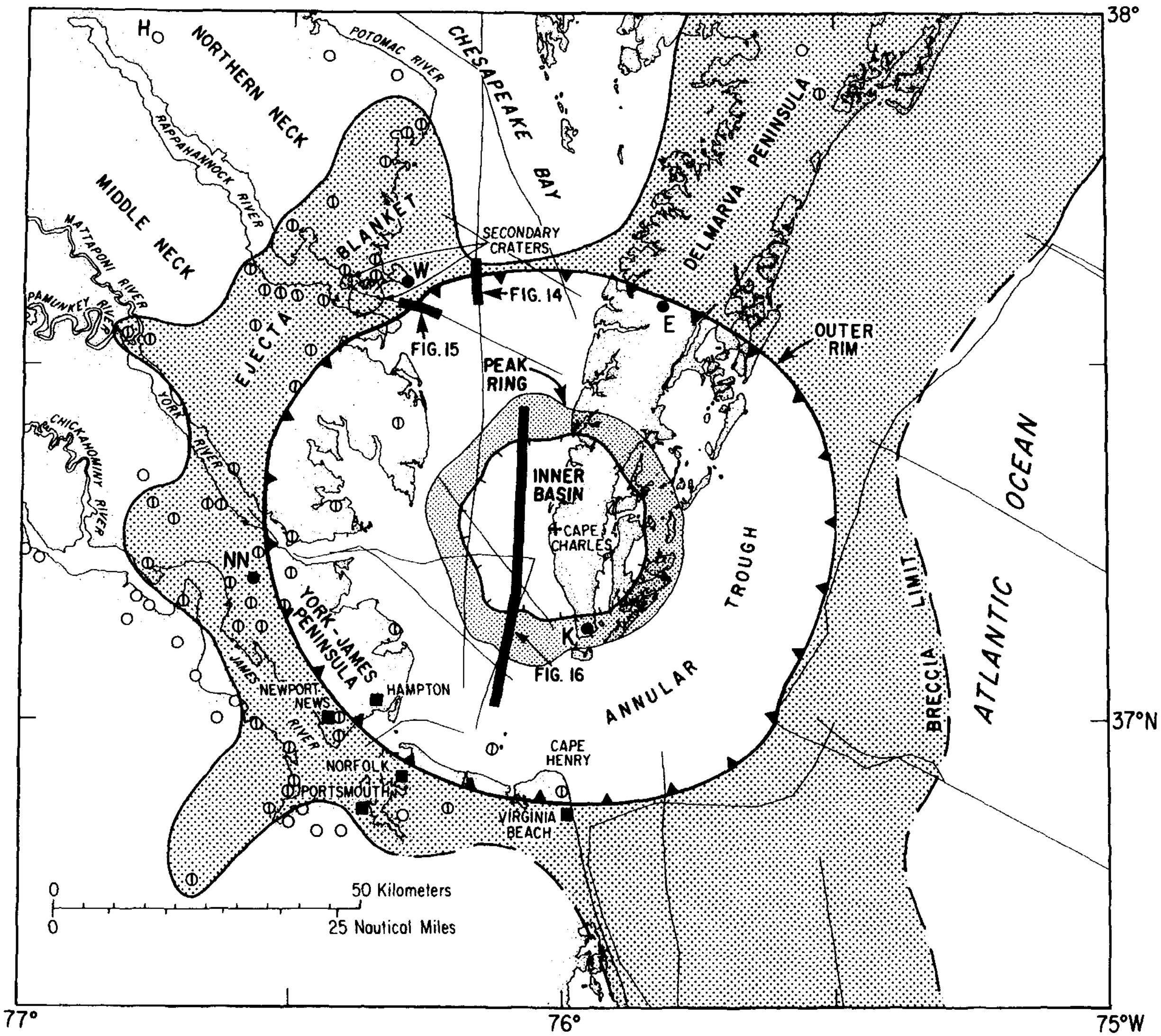


Fig. 2. Map of southeastern Virginia, showing tracklines for seismic profiles, bore-hole locations, physiographic features, and structural and depositional features associated with Chesapeake Bay crater. Outcrops of Paleocene, Eocene, and Oligocene deposits along Pamunkey River are located west of map margin (see Fig. 29). Note that the outer rim of crater is documented by seismic profiles at nine locations; peak ring is documented at seven locations. N = Newport News core hole; W = Windmill Point core hole; E = Exmore core hole; K = Kiptopeke core hole; H = Haynesville core hole.

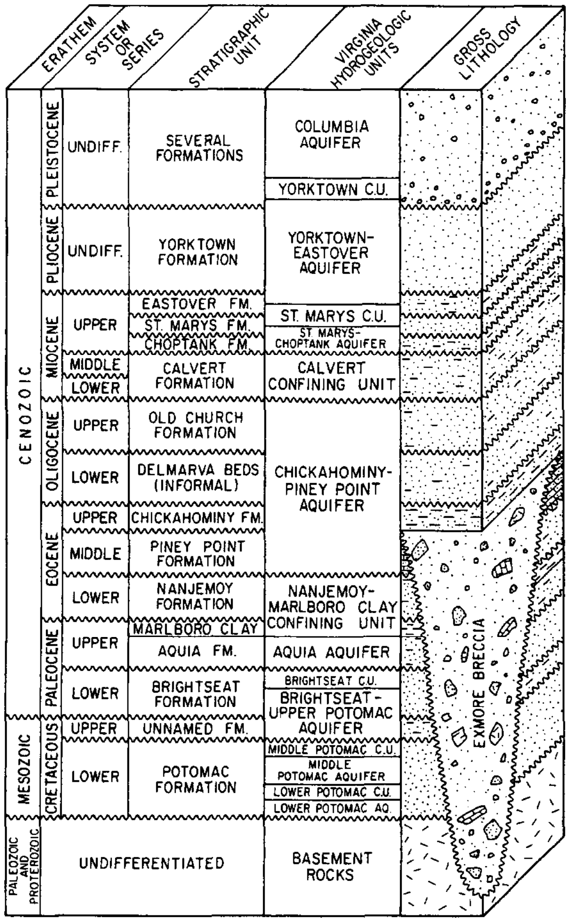


Fig. 3. General stratigraphic chart of Virginia Coastal Plain formations and geohydrologic units. Compiled from Ward and Strickland (1985), Meng and Harsh (1988), and Thomas et al. (1989). The Exmore breccia (informal unit) is partly equivalent to the subsurface Mattaponi Formation in much of southeastern Virginia. The Mattaponi is not shown here, because its precise stratigraphic boundaries are not clearly defined at the type well.

mation (at Colonial Beach on the south shore of the Potomac River; Fig. 1) actually contains the breccia (D.S. Powars, oral commun., 1993). Cederstrom apparently found it difficult to consistently identify his new unit, because the caving of bore-hole walls sometimes caused breccia-like stratigraphic mixing in wells where *bona fide* breccia was absent. Cederstrom further confused the issue by identifying Paleocene and Eocene beds *above* the Mattaponi Formation in some localities. This stratigraphic ambiguity caused some authors either to misuse the term Mattaponi Formation (Teifke, 1973), to ignore it (Meng and Harsh, 1988), or to call for its abandonment (Ward, 1984). Powars et al. (1990, 1991, 1992), who first reported the breccia in situ from cores, did not recognize the unit as a breccia, nor did they correlate it with the Mattaponi Formation. They believed that the chaotic, polymictic lithology represented unusual debris-flow or channel-fill deposits.

The first indication that the breccia might be associated with a bolide impact came from studies of foraminiferal assemblages from the Virginia core holes (Figs. 6 and 7; Poag, 1991; Poag et al., 1992). Those initial studies, and the subsequent more comprehensive analysis by Poag and Aubry (1995); Figs. 8–10), demonstrated that the Exmore breccia and the tektite-bearing debriite at Deep Sea Drilling Project Site 612 (Thein, 1987; Glass, 1989; Miller et al., 1991) 35 km south of Toms Canyon crater (Fig. 1), are biochronologically coeval. This stimulated a search for shock-altered minerals in the breccia, to provide diagnostic evidence of a bolide impact (Stöffler, 1971; Chao, 1968; Bohor et al., 1988; Grieve, 1991; Grieve and Pesonen, 1992; Stöffler and Langenhorst, 1994). Lawrence J. Poppe (USGS, Woods Hole) and Glen A. Izett (USGS, Denver, emeritus) found trace amounts of shocked quartz in the Exmore breccia from all four core sites (Poag et al., 1992). More recently, Koeberl et al. (1996) have identified abundant impact-derived planar deformation features in quartz and feldspar grains in clasts of crystalline basement within the breccia, along with centimeter-size specimens of melt rock. At the time of Poag et al.'s (1992) paper, however, the only late Eocene impact crater reported near southeastern Virginia was the Toms Canyon crater. This led Poag et al. (1992) to hypothesize that the Exmore breccia was a tsunamiite derived from the Toms Canyon impact. But when Texaco subsequently released seismic reflection profiles collected from Chesapeake Bay (Fig. 2), it became evident that the cores had sampled the breccia lens of the largest impact crater in the United States (Powars et al., 1993; Poag et al., 1994b; Koeberl, 1996). By analogy with numerous terrestrial and planetary impact craters (Jansa et al., 1989; Melosh, 1989; Grieve, 1991; Grieve and Pesonen, 1992), most of the Exmore breccia must have been generated from the target rocks disrupted by this giant impact and its resultant tsunami.

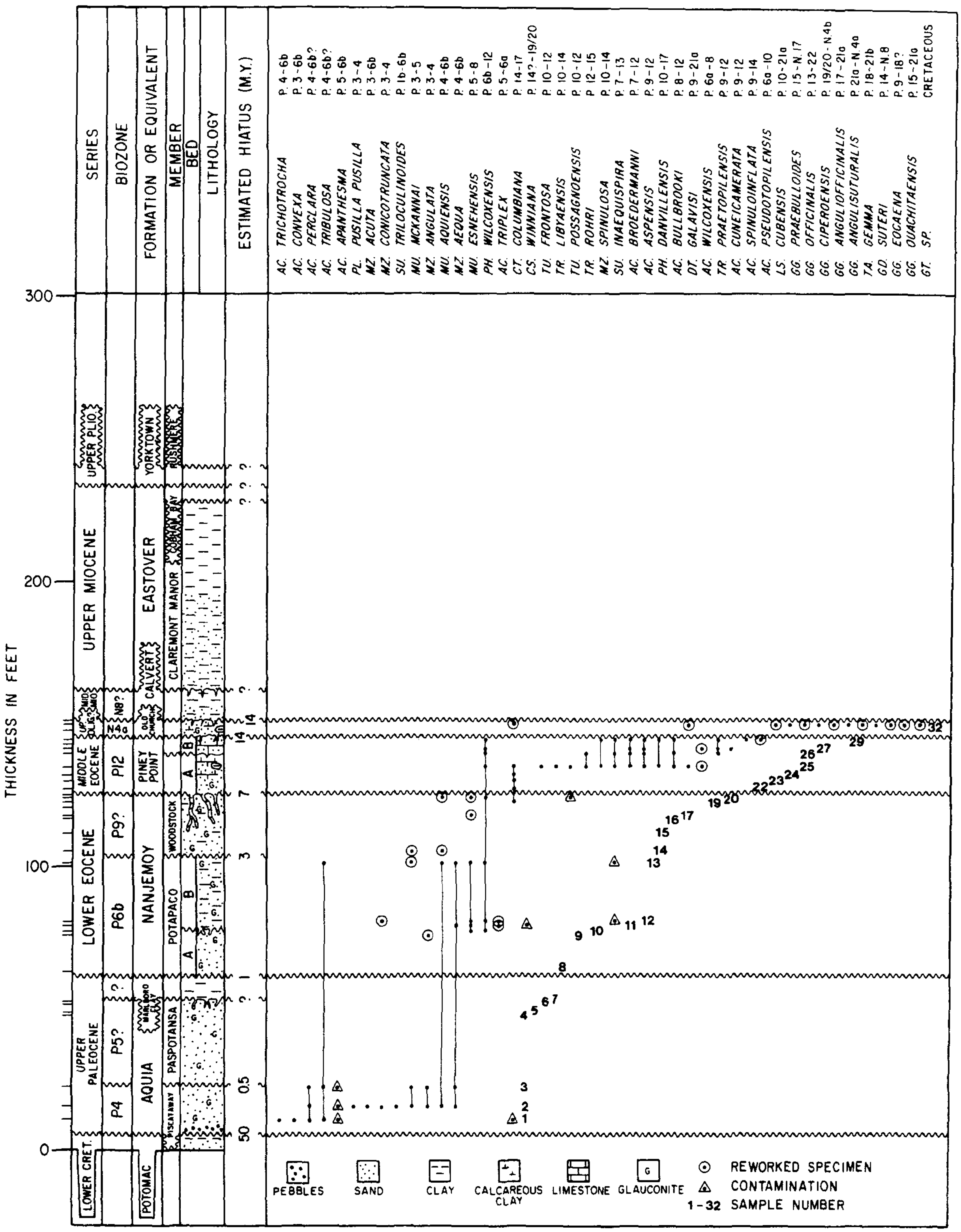


Fig. 4. Chart showing lithostratigraphy and ranges of planktonic foraminifera in composite stratigraphic section outside Chesapeake Bay crater, as exposed along Pamunkey River (see Fig. 29; Ward, 1984; Poag and Commeau, 1995). See Fig. 3 for full formation names.

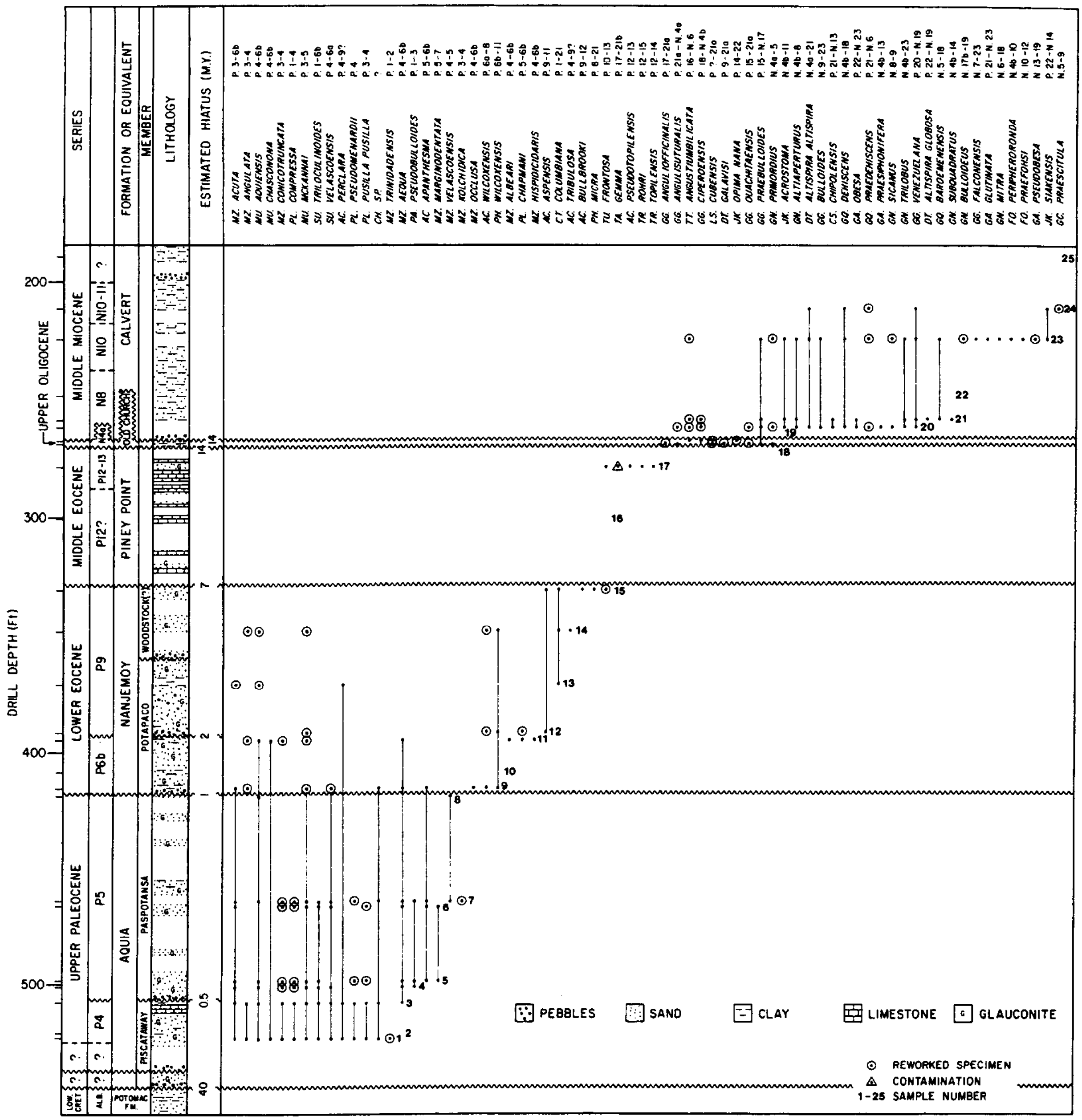


Fig. 5. Chart showing lithostratigraphy and ranges of planktonic foraminifera in normal subsurface stratigraphic section outside Chesapeake Bay crater, as documented in Haynesville core hole (see Fig. 2; Mixon, 1989; Poag and Commeau, 1995). See Fig. 3 for full formation names.

Structural data supporting an impact origin for the Chesapeake Bay crater consist mainly of seismic reflection profiles that traverse the bay and the inner continental shelf (Fig. 2). Though no profile directly crosses a drill site, the Windmill Point and Kiptopeke sites are only ~5 km away from a seismic line. I converted seismic travel time to depth using velocity analyses and synthetic seismograms pub-

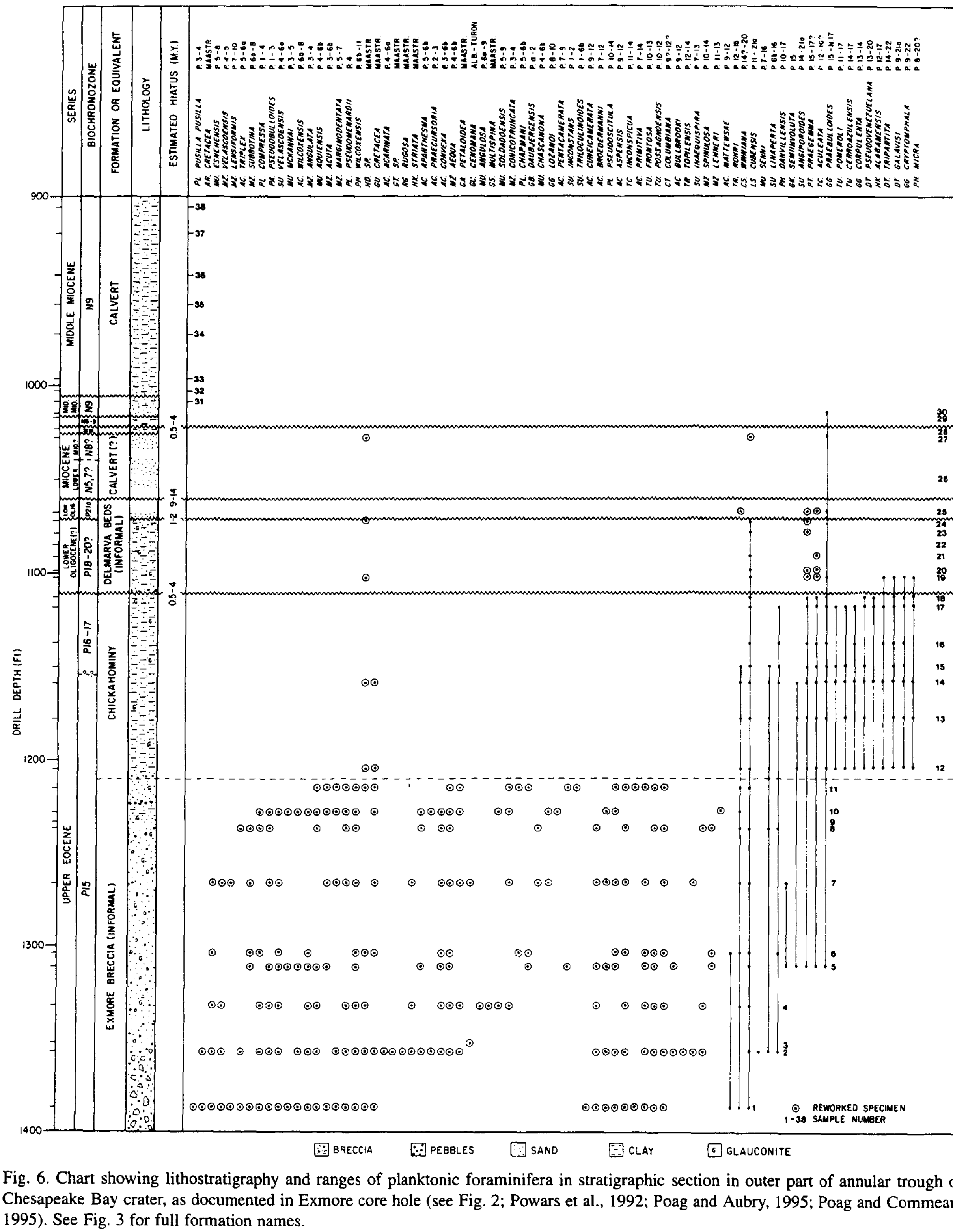


Fig. 6. Chart showing lithostratigraphy and ranges of planktonic foraminifera in stratigraphic section in outer part of annular trough of Chesapeake Bay crater, as documented in Exmore core hole (see Fig. 2; Powars et al., 1992; Poag and Aubry, 1995; Poag and Commeau, 1995). See Fig. 3 for full formation names.

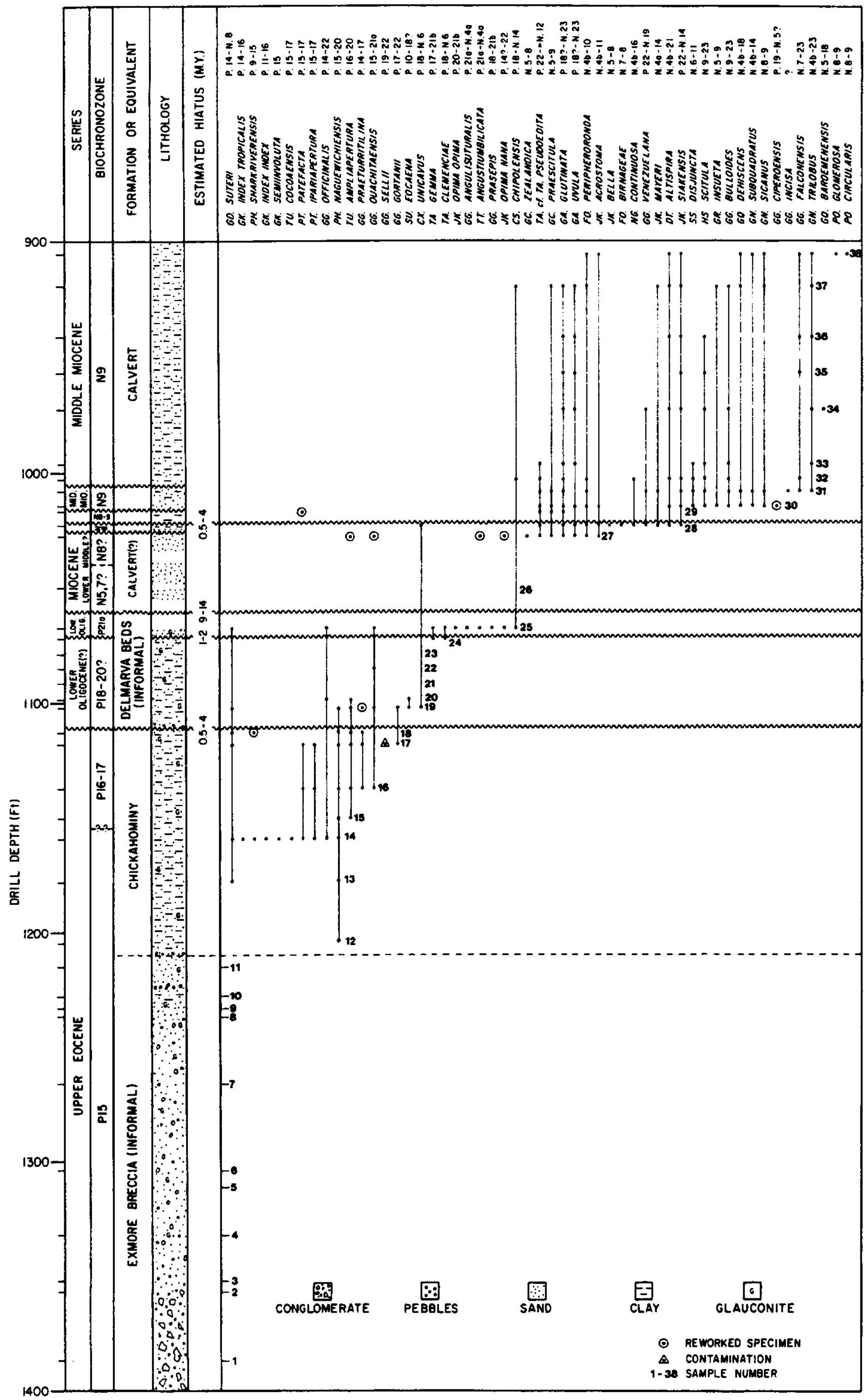


Fig. 6 (continued).

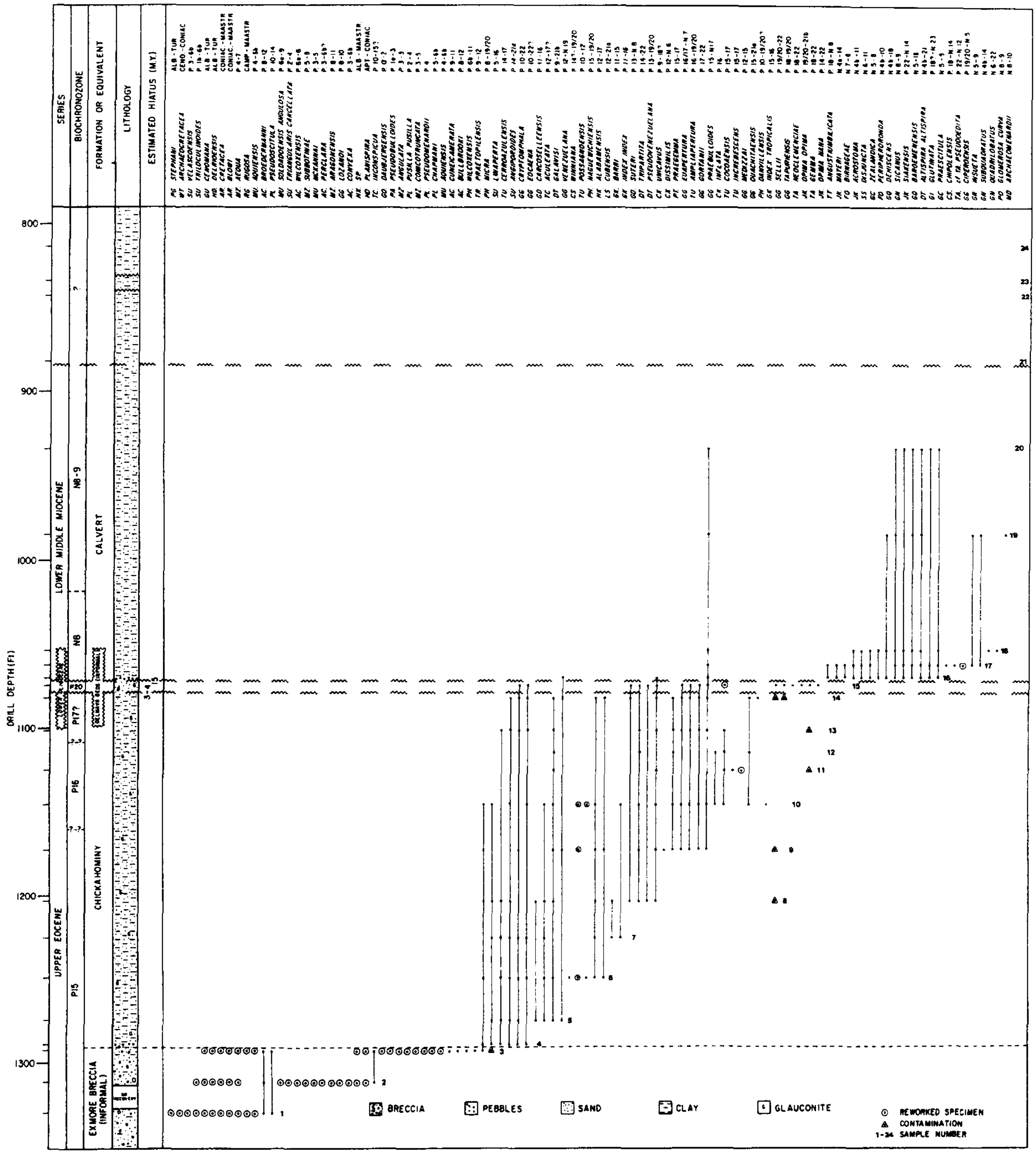


Fig. 7. Chart showing lithostratigraphy and ranges of planktonic foraminifera in stratigraphic section in inner part of annular trough of Chesapeake Bay crater, as documented in Kiptopeke core hole (see Fig. 2; Poag and Aubry, 1995; Poag and Commeau, 1995).

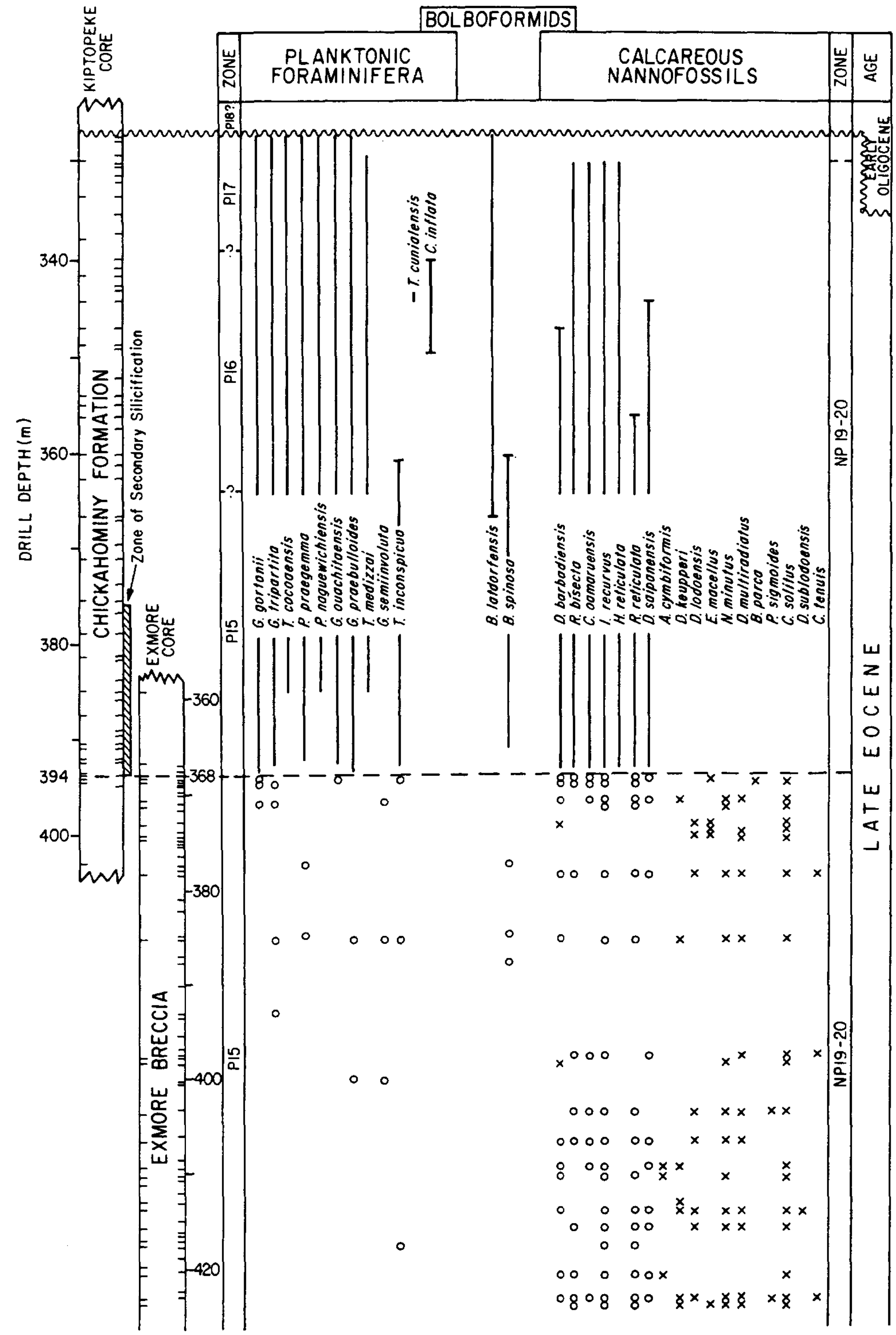


Fig. 8. Summary of planktonic foraminiferal, calcareous nannofossil, and bolboformid distribution in Exmore breccia (informal unit) and Chickahominy Formation, as documented by Poag and Aubry (1995). *o* = late Eocene specimens; *x* = allogenic specimens.

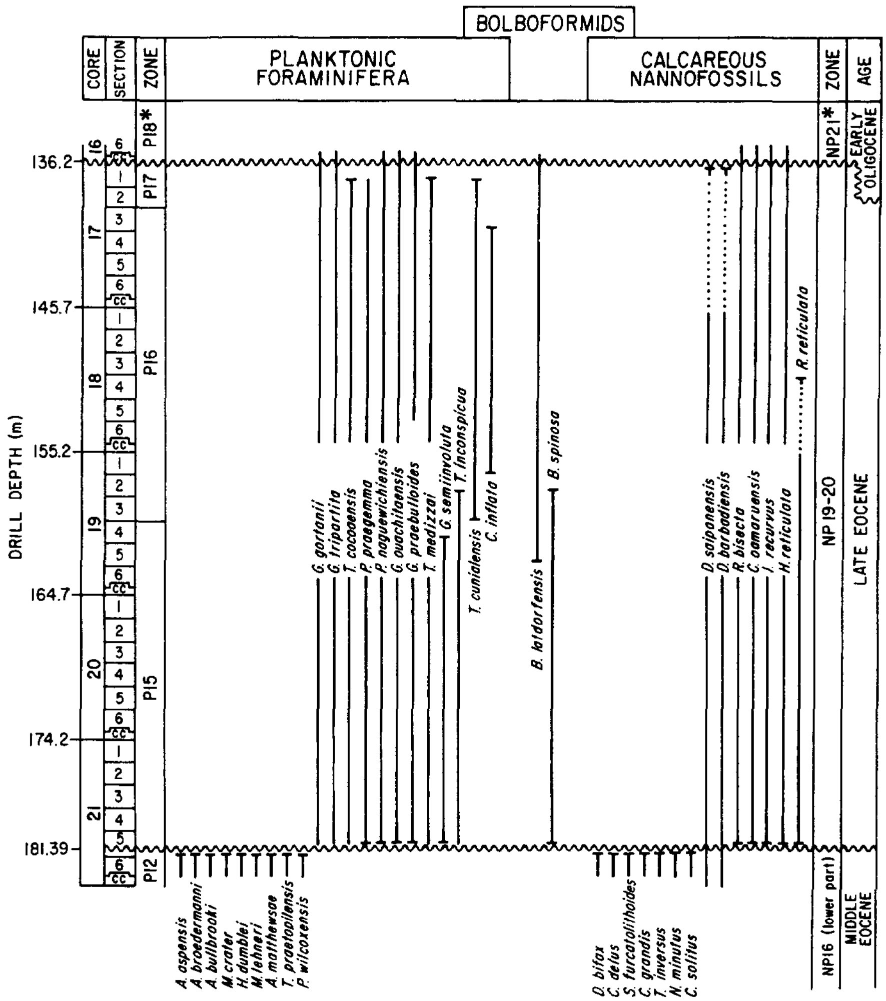


Fig. 9. Summary of planktonic foraminiferal, calcareous nannofossil, and bolboformid distribution in stratigraphic equivalents of Exmore breccia (informal unit) and Chickahominy Formation cored at DSDP Site 612 (see Fig. 1), as documented by Poag and Aubry (1995). Dotted line signifies few-to-rare specimens.

lished by Dysart et al. (onshore; 1982) and Klitgord et al. (offshore; 1994). The profiles document the position and structure of the outer rim of the crater at nine different locations, and they reveal the features of the peak ring at seven locations. I calibrated the seismic profiles with two continuous core holes drilled inside the crater and several drilled outside the crater (Figs. 2, 5–7), and with the subsurface stratigraphic analysis of Dysart et al. (1983). These structural and stratigraphic data are supplemented by reevaluation of Cederstrom's (1945a,b) published well records (Poag et al., 1994b), and by a 'bulls-eye' negative Bouguer gravity anomaly (−28 mGal low) over the inner basin (Fig. 11). Koeberl et al.'s (1996) documentation of shock metamorphism and melting in clasts from the Exmore breccia provides solid confirmation of the crater's impact origin.

The purposes of this paper are: (1) to describe the principal geological consequences of this convulsive impact event; (2) to examine their effects on subsequent evolution of the Atlantic Coastal Plain; and (3) to assess implications of the impact with respect to traditional explanations for certain structural and depositional features of the study area.

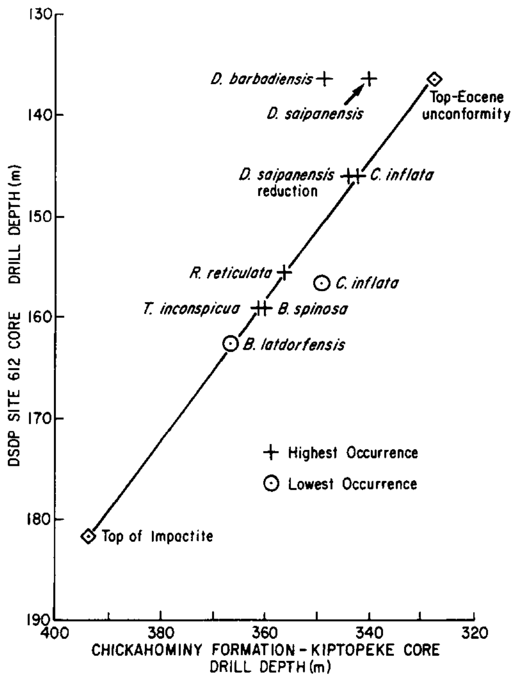


Fig. 10. Graphic correlation showing straight line-of-correlation between late Eocene strata from Kiptopeke core hole (Fig. 2) and from DSDP Site 612 (Fig. 1) (from Poag and Aubry, 1995). This correlation indicates that normal postimpact deposition resumed simultaneously within planktonic foraminiferal biochron P15 (and calcareous nannofossil biochron NP19-20) at both core sites. Species plotted include planktonic foraminifera, calcareous nannofossils, and bolboformids.

2. Geological consequences of the impact

2.1. Excavation of target rocks

The initial geological consequence of the Chesapeake Bay impact was deep excavation (ejection) of target rocks to form a crater twice the size of Rhode Island and almost as deep as the Grand Canyon (Figs. 12 and 13). The nearly circular crater is approximately 90 km in diameter and covers an area of ~6400 km^2, as determined from seismic profiles that cross the outer rim at nine different places (Fig. 2). Maximum crater depth (rim-to-floor relief) cannot be accurately determined, because seismic data collected from the deepest part of the inner basin show no distinct boundary reflector (Texaco, Inc., pers. commun., 1995). However, the scaling relationship developed by Grieve and Robertson (1979):

$$d_t = 0.52\ D^{0.2}$$

can be used to approximate the true depth (maximum rim-to-floor relief) of an impact crater carved into crystalline rocks, when D is the final diameter of the crater, and d_t is the true depth. For Chesapeake Bay crater, $D = 90$ km and $d_t = 1.28$ km.

The outer rim escarpment, whose crest is generally ~600–1200 m higher than the floor of the annular trough, truncates mainly Lower Cretaceous to middle Eocene sedimentary beds (Figs. 14 and 15). The broad, relatively flat floor of the annular trough is composed mainly of crystalline basement. On a gross scale, the annular trough is filled with two depositional units. Lying directly on the basement surface is a unit composed of displaced megablocks. The megablocks represent fractured sedimentary target rocks, which slumped into the annual trough during an intermediate stage of crater deformation. Above the megablocks is the Exmore breccia, which was deposited during a late stage of crater deformation.

The annular through of Chesapeake Bay crater is separated from the inner basin by a raised, subcircular ridge composed of crystalline basement rocks (Figs. 2 and 16). The peak ring is irregular in width, varying from 3 to 6 km. The maximum structural relief of the ring (relative to the floor of the annular trough) is ~175 m on the south side of the inner basin (Fig. 16), but on other seismic profiles the relief averages ~100 m. The peak ring and the walls of the inner basin comprise mainly Piedmont-type granitic and metasedimentary rocks (Proterozoic and Paleozoic), excavated and uplifted during an early stage of crater deformation.

The inner basin, like the annular trough, also appears to contain two principal depositional units. The upper unit is contiguous with, and seismically indistinguishable from, the Exmore breccia. I, therefore, infer that this unit is dominated by sedimentary clasts, which have undergone only slight or moderate shock metamorphism. The basal unit in the inner basin, by analogy with other terrestrial craters, probably contains breccia dominated by highly shocked crystalline basement clasts. Presumably, melt sheets and associated mineralized zones also are present in this unit.

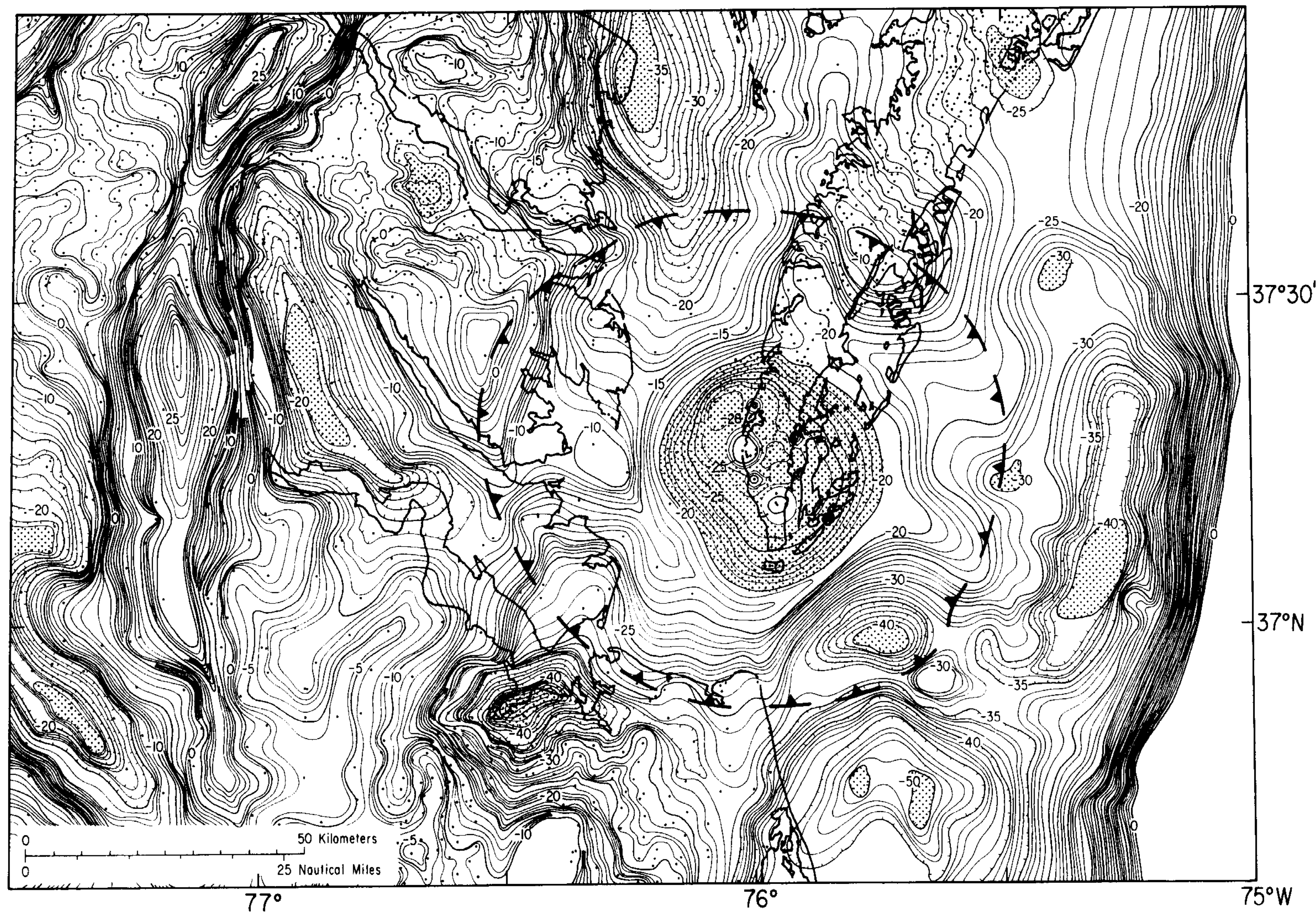


Fig. 11. Hand-contoured composite gravity anomaly map of Chesapeake Bay crater and vicinity. Onshore contours based on simple Bouguer values compiled by J.K. Costain. Offshore contours based on free-air values modified from Lyons et al. (1982). Contour interval 1 mGal. Note superposition of central negative gravity low (−20 to −28 mGal; shaded area) upon inner basin of crater. Small relative highs within gravity low may indicate irregular floor of inner basin. Dysart et al. (1983) and several other authors have published maps of this area showing a horseshoe-shaped negative anomaly (open to the southeast) over the inner basin of the crater. I have closed the contours based on seismic interpretation of basement structure.

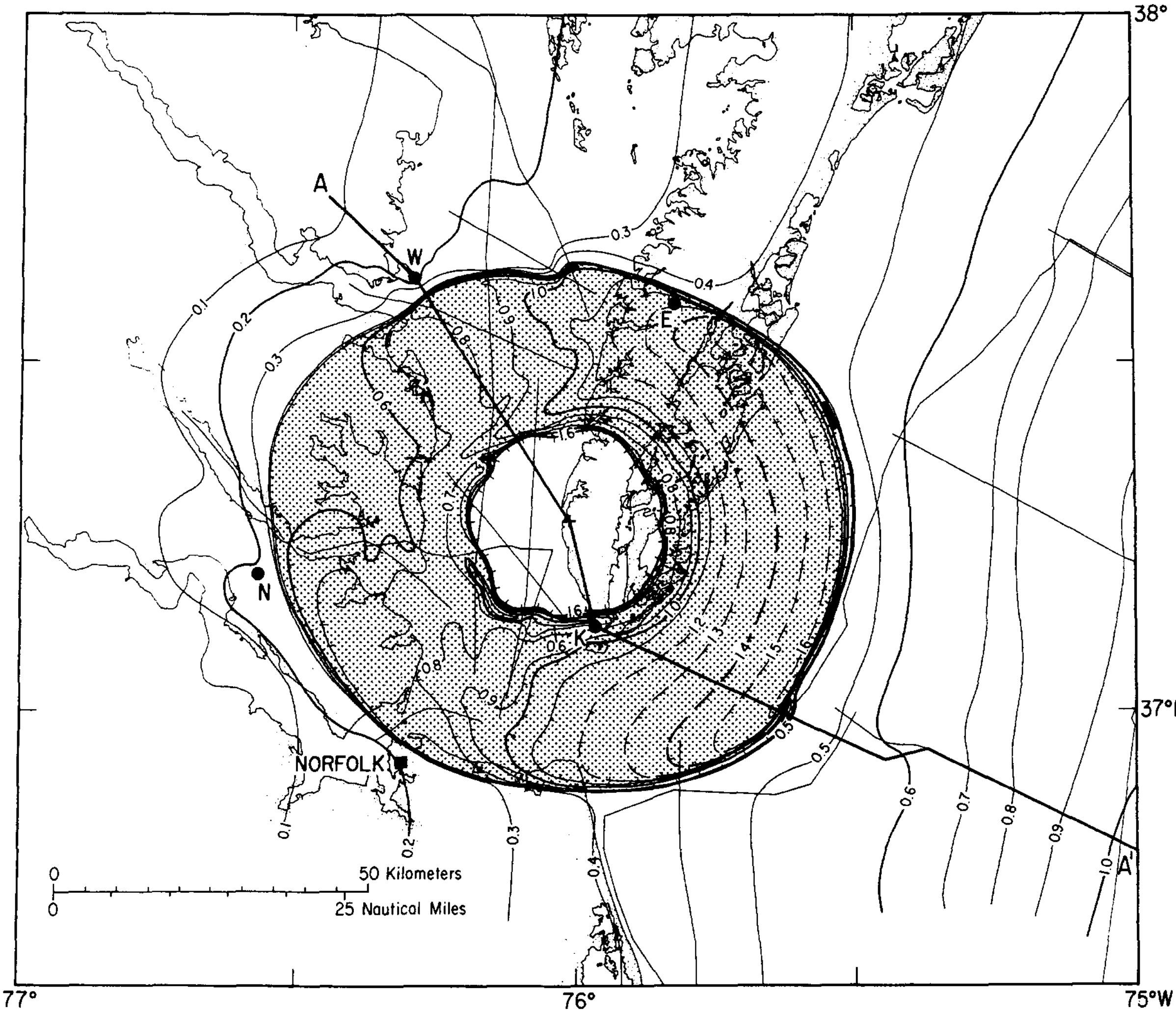


Fig. 12. Structure map of Chesapeake Bay crater. Contour interval 0.1 second two-way travel time (= approximately 100 m). Cross section *A–A′* illustrated in Fig. 13. Eastern sector of annular trough is deeper than western sector because of long-term differential subsidence of the crystalline basement and overlying sedimentary wedge prior to impact.

According to theoretical, experimental, and field evidence (Oberbeck, 1975; Kieffer and Simonds, 1980; Hörz et al., 1983 Melosh, 1989; Grieve, 1991; Poag et al., 1994b), much of the coarsest debris ejected from the crater fell back into the excavation. Intermediate-size debris formed an irregularly distributed, continuous ejecta blanket surrounding the crater rim to a maximum radial distance of ~55 km. Finest ejecta particles spread over a 9×10^6 km^2 area of the western North Atlantic, Gulf of Mexico, and Caribbean Sea, known as the North American tektite strewn field (Glass, 1989; Koeberl, 1989; Poag et al., 1994b).

The Chesapeake Bay bolide struck in the early to middle part of the late Eocene (according to the time scale of Cande and Kent, 1992), during the early phase of a significant sea-level rise (Poag and Ward, 1993; Poag and Commeau, 1995). A relatively thin layer (actual thickness unknown) of upper Eocene marine sediments must have covered the target site prior to impact, as evidenced by numerous upper Eocene planktonic foraminifera identified in

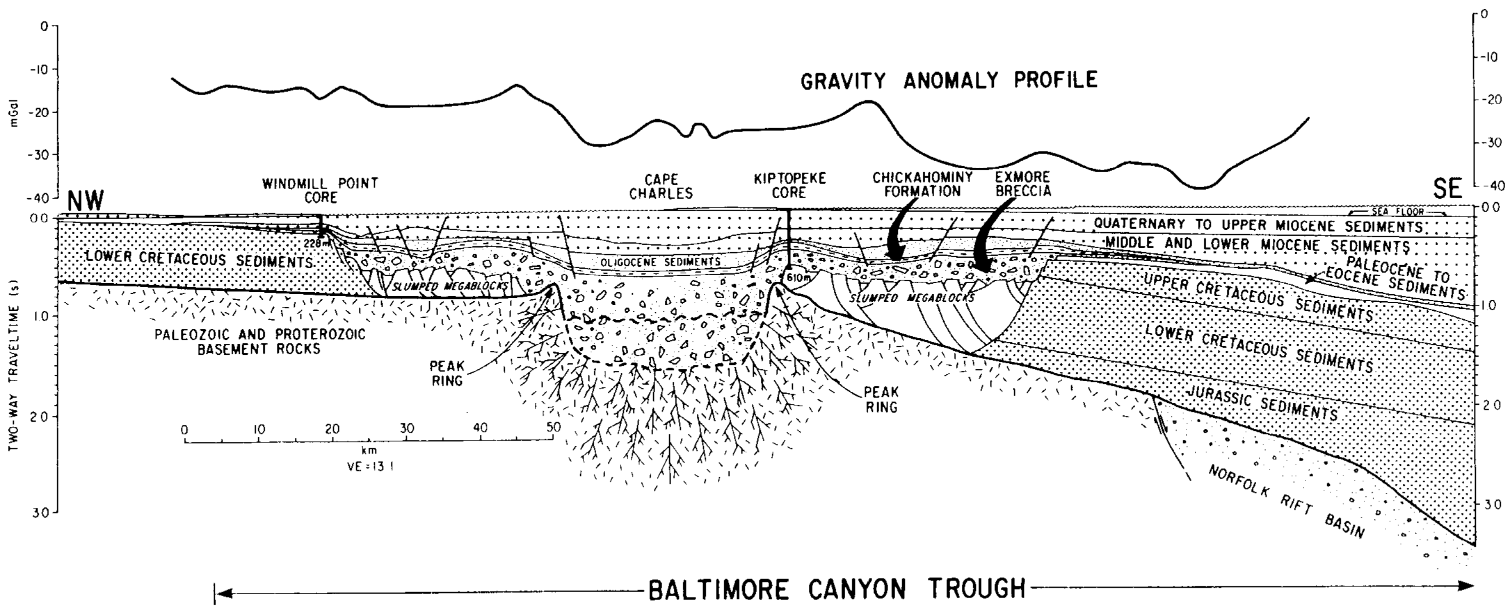


Fig. 13. Scaled cross section of Chesapeake Bay crater (see Fig. 12 for location of section). Section tied to Windmill Point and Kiptopeke core holes, and to seismic reflection profiles within Chesapeake Bay and on Atlantic Continental Shelf. Basement dips to east and sedimentary section thickens to east as result of differential subsidence into Baltimore Canyon trough.

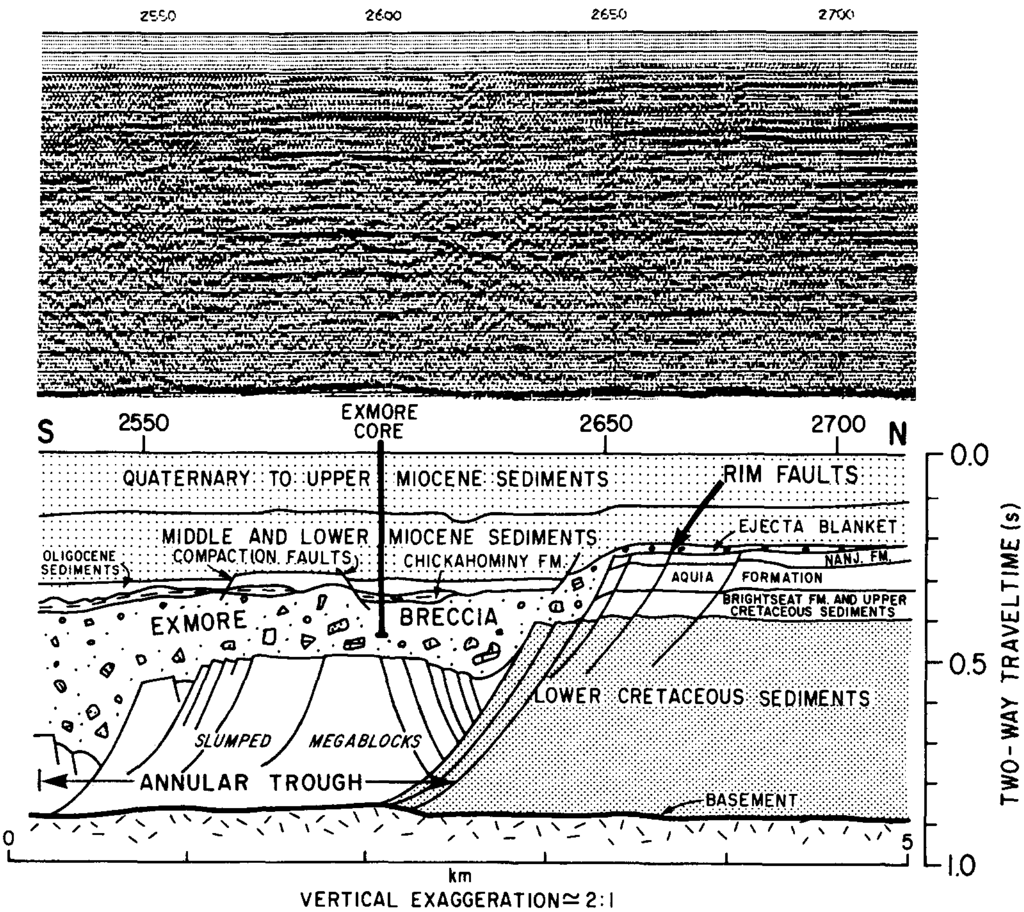


Fig. 14. Segment of unmigrated seismic reflection profile crossing outer rim of Chesapeake Bay crater east of mouth of Rappahannock River (see Fig. 1). *Above*, uninterpreted profile; *below*, geological interpretation. Exmore core hole projected to profile. Note structural sag and thickening of postimpact deposits inside crater rim.

the Exmore breccia (including specimens of *Globigerinatheka semiinvoluta*, the diagnostic species for biozone P15; Poag and Aubry, 1995). This initial upper Eocene deposit appears, however, to have been entirely removed from southeastern Virginia by the bolide impact. The youngest stratigraphic unit documented beneath the Exmore breccia (beneath the continuous ejecta blanket outside the crater rim) is the middle Eocene Piney Point Formation. Though the Piney Point is mainly sand at updip localities (including the type locality; Jones, 1990), the unit is represented by a shallow-water carbonate facies in the target area. Within the Exmore breccia, the Piney Point is represented by boulders, cobbles, and pebbles of indurated bioclastic limestone (illustrated in color by Poag et al., 1994b, fig. 5, Windmill Point core, 170.08–171.55 m).

2.2. New ground-water reservoir and seal

The Chesapeake Bay bolide truncated all ground-water aquifers and confining units existing in target rocks at the time of impact, including the lower and middle Potomac aquifers, the Brightseat–upper Potomac aquifer, the Aquia aquifer, and the lower part of the Chickahominy–Piney Point aquifer (Meng and Harsh, 1988; Focazio et al., 1993; Fig. 3). In their place, was deposited a three-part sediment lens, composed of: (1) slumped megablocks in the bottom of the annular trough; (2) a crystalline clast brec-

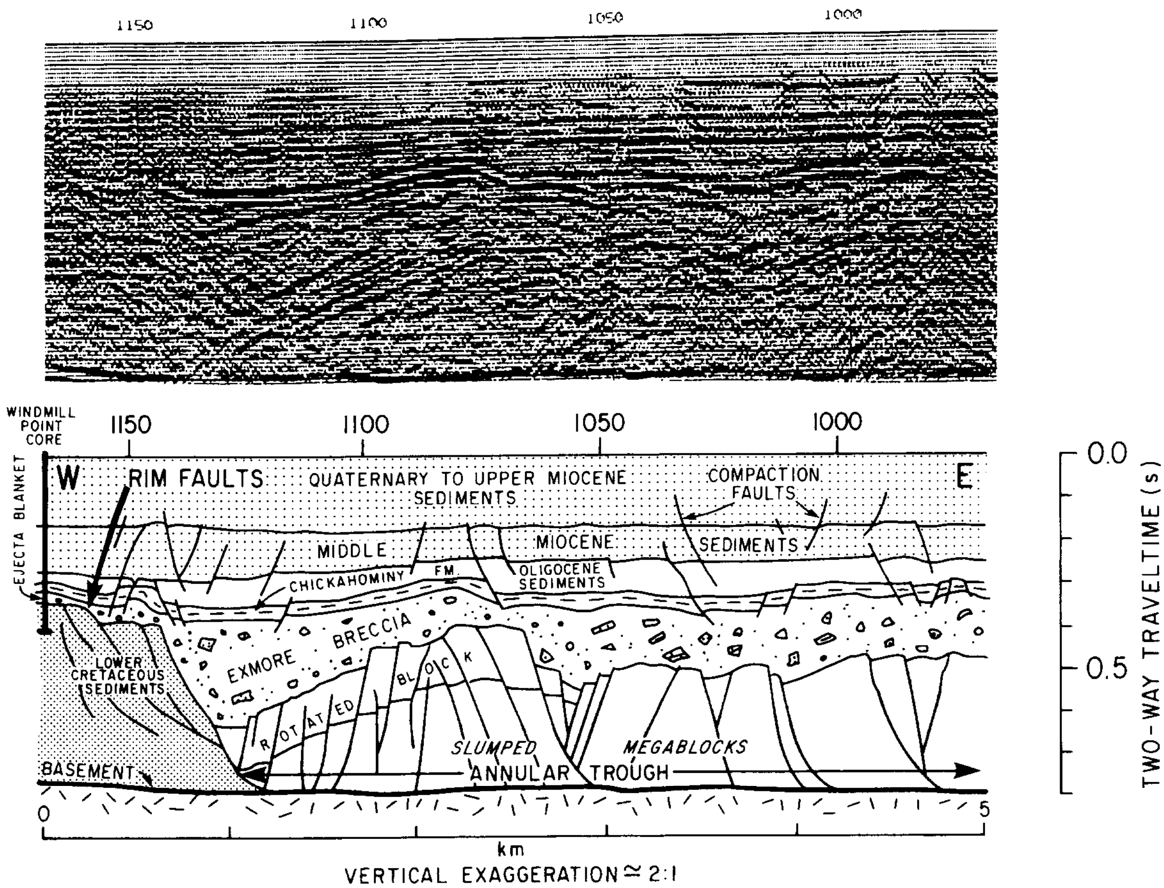
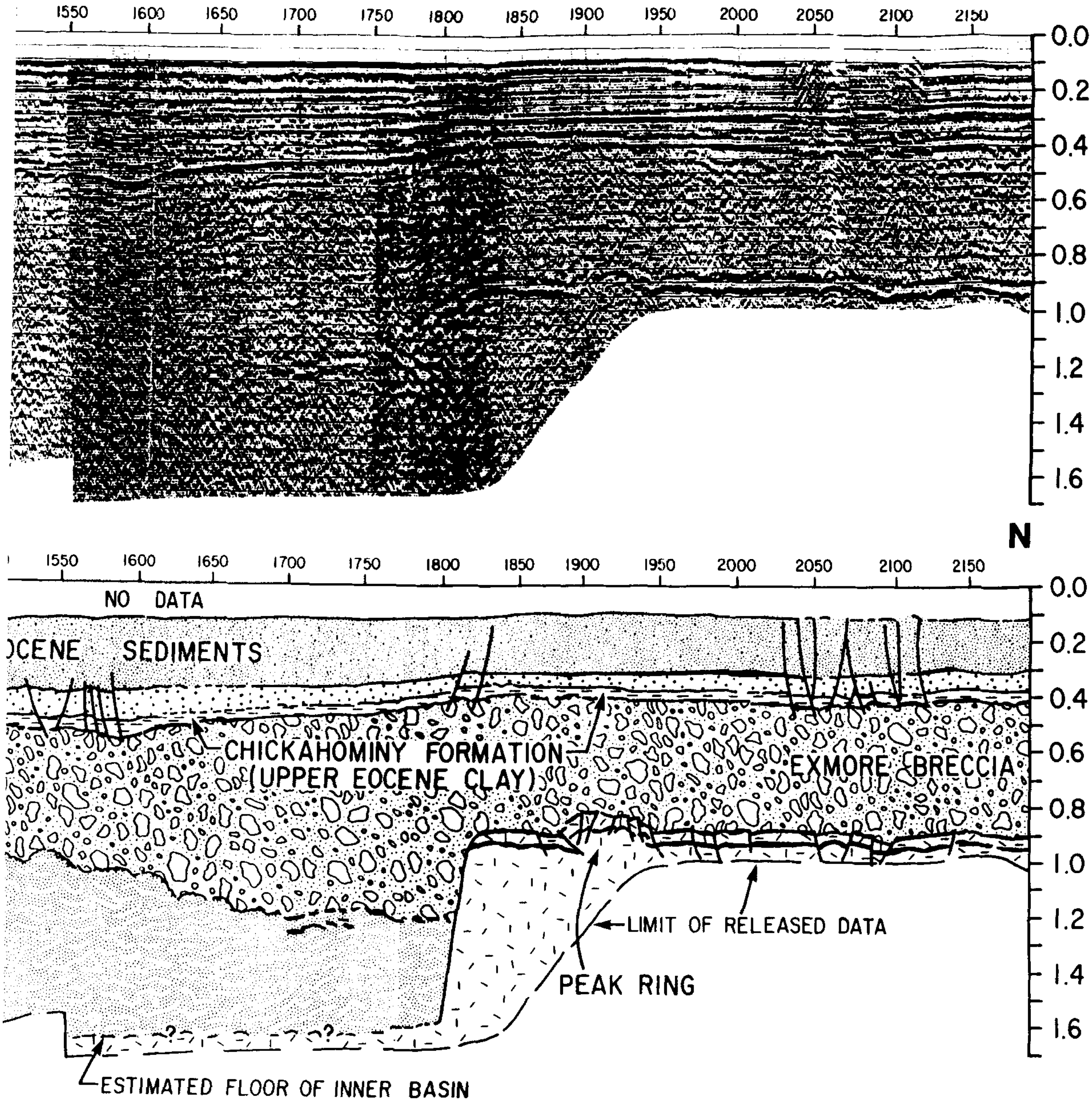
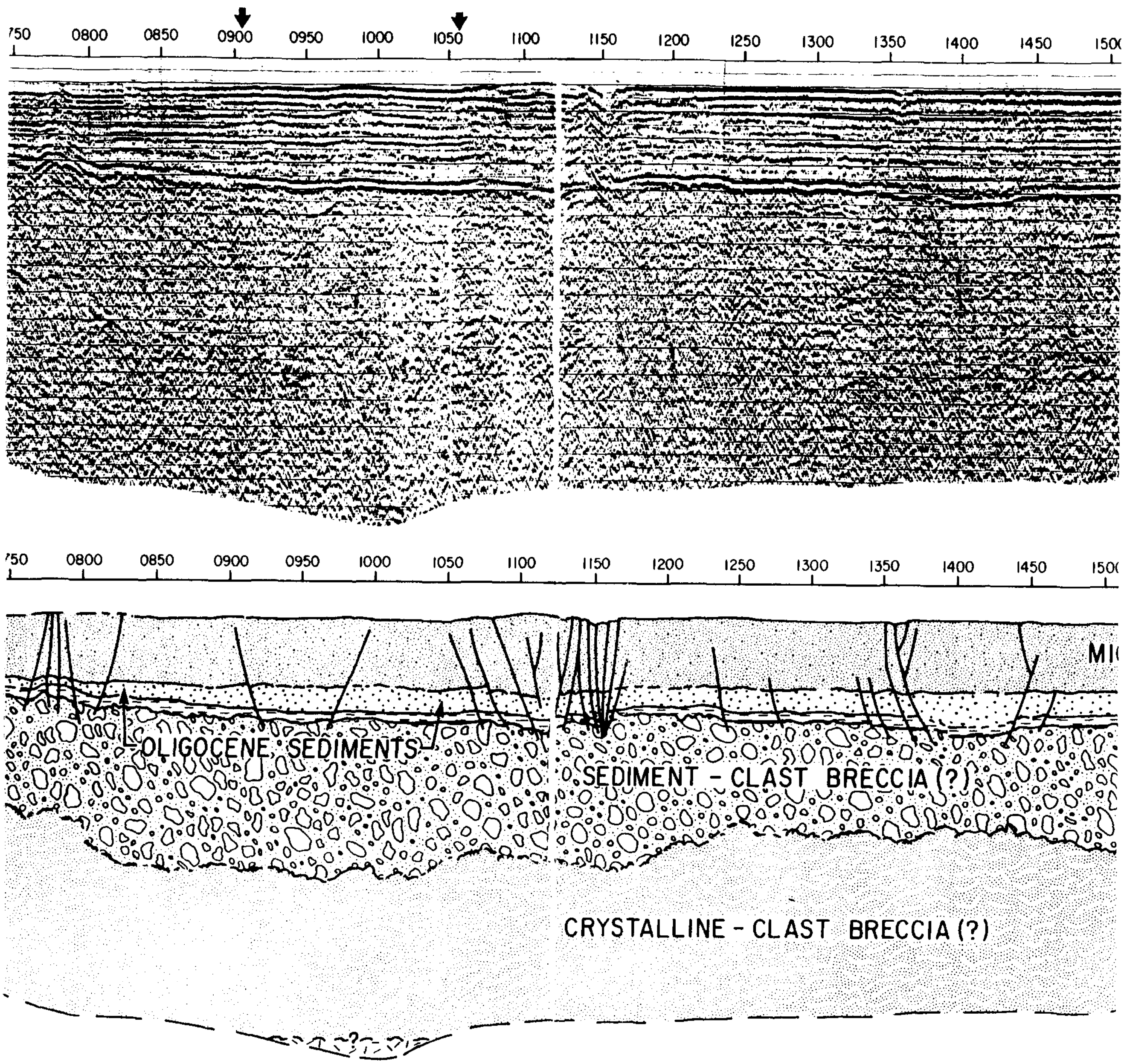


Fig. 15. Segment of unmigrated seismic reflection profile crossing outer rim of Chesapeake Bay crater within the lower reach of Rappahannock River (see Fig. 1). *Above*, uninterpreted profile; *below* geological interpretation. Windmill Point core hole projected 5 km to profile. Note structural sag and thickening of postimpact deposits inside crater rim. Note also 2-km-long rotated slump block of sedimentary target rocks.

cia in the bottom of the inner basin; and (3) the Exmore breccia and contiguous sediment–clast breccia spread over the entire crater. This huge, porous, lensoid body formed a ~4300 km^3 ground-water reservoir with a maximum thickness of at least 1200 m (Poag et al., 1994b; Powars et al., 1994; Fig. 12). Though most of the Exmore breccia is confined to the crater, it also extends as a continuous ejecta blanket as far as 55 km outside the outer rim. The Exmore breccia is a complex deposit, formed by several unusual, interactive, and nearly instantaneous sedimentary processes. Drawing on previous field studies, experiments, and models (e.g., Oberbeck, 1975; Roddy et al., 1977, 1987; Melosh, 1989), I infer the following general steps in breccia formation (Fig. 17). Shortly after impact, a large volume of the coarser, moderately shock-altered ejecta fell back into the crater to be incorporated with clasts of unshocked autochthonous strata ripped up by a viscous lateral ground surge. To this mixture was added debris derived from massive failure of the water-saturated sedimentary walls of the crater rim. Almost simultaneously, the aqueous walls of the upper part of the crater (the oceanic water column) collapsed back onto the sea floor. Elevated hydraulic pressure resulting from this collapse actuated additional failure of the sedimentary rim escarpment, which further widened the annular trough. These processes appear to have removed all evidence of a raised lip at the crater outer rim. The oceanic collapse also appears

pp. 63–66


1550
1600
1650
1700
1750
1800
1850
1900
1950
2000
2050
2100
2150
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
N
NO DATA
OCENE SEDIMENTS
CHICKAHOMINY FORMATION
(UPPER EOCENE CLAY)
EXMORE BRECCIA
LIMIT OF RELEASED DATA
PEAK RING
ESTIMATED FLOOR OF INNER BASIN



e, uninterpreted seismic profile;
:h. Note a few apparent reverse
ccia) and most postimpact units
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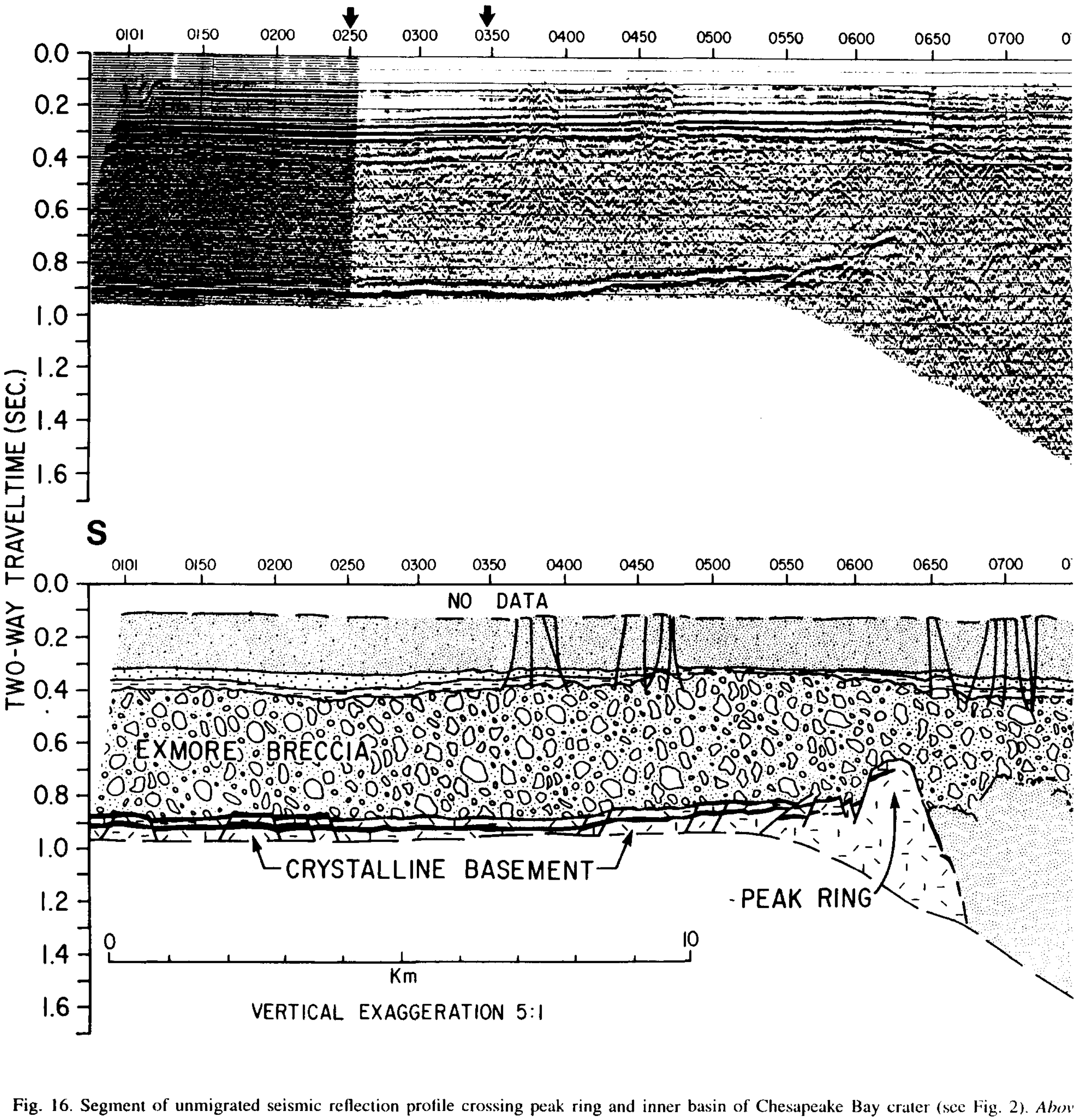


Fig. 16. Segment of unmigrated seismic reflection profile crossing peak ring and inner basin of Chesapeake Bay crater (see Fig. 2). *Abov* *below*, geological interpretation. This segment illustrates maximum known relief (~175 m) of peak ring relative to floor of annular troug faults in crystalline basement (as well as numerous normal faults) and thickening of Exmore breccia (or the contiguous sediment–clast bre in inner basin. Compaction faults in postimpact section extend to top of coherent seismic data (top of Miocene section). Arrows indicate profiles. Boundary between two breccia units in inner basin is more pronounced on profile intersecting at shot point 0900 (profile not show see Fig. 2).

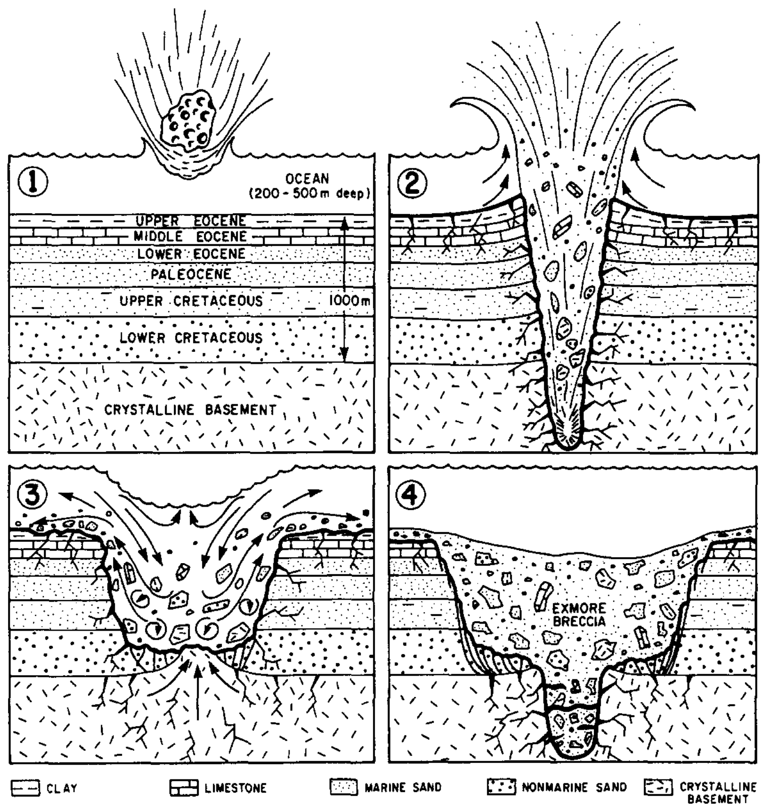


Fig. 17. Cartoon showing idealized stages of crater formation and breccia deposition. *1*, Bolide approaches target rocks (~1000 m of sedimentary rocks above crystalline basement on inner continental shelf) during early stages of late Eocene sea-level rise, in which water depths had reached 200–500 m. *2*, Bolide strikes ocean and target rocks at hypervelocity of 20–25 km/s, penetrating ~8 km into Earth's crust. Water column, bolide, and portion of target rocks vaporize; shock melts and metamorphoses other portions of target rocks; fractures walls of crater and near-surface rocks surrounding crater; raises rim at ocean floor; generates giant tsunami on ocean surface; ejects large volume of ocean water and target rocks. *3*, Downward-displaced basement rocks rebound; sedimentary megablocks slump onto floor of annular trough; oceanic water column collapses onto sea floor and enlarges crater by hydraulic erosion; lateral 'ground' surge along sea floor causes additional erosion, wall-collapse, and widening of annular trough. *4*, Shock-weakened basement subsides differentially to form inner basin surrounded by peak ring; additional megablocks collapse into annular trough; portion of coarser ejecta falls back and forms water-saturated breccia of mainly crystalline basement clasts in bottom of inner basin; finally, intermediate-size ejecta is washed back to form soupy sediment–clast breccia (Exmore breccia and equivalents), which fills upper part of inner basin and annular trough; remaining finer ejecta surrounds crater as continuous ejecta blanket. Though depicted here as discrete events, all these processes were interactive and short-lived. Most bolide-generated activity terminated after a few minutes, hours, or days.

to have washed portions of the surrounding ejecta blanket back into the crater (Jansa, 1993; Poag et al., 1994a,b). The final ingredients of the breccia came from backwash of the super tsunami generated by this impact (and by the Toms Canyon impact tsunami as well, assuming that it was a simultaneous event). Thus the lower (presumably thickest) part of the Exmore breccia was generated directly by the bolide impact and subsequent water-column collapse, whereas the upper (thinnest?) part probably was formed mainly by the tsunamis. We have not yet determined how to identify these two separate parts of the Exmore breccia. In fact, the cores taken to date may represent only the tsunamiite. All of this deposition would have taken place in only a few hours to a few days. Thus incredible sediment accumulation rates of ~1200 m/hr or higher were established during this short-lived convulsive event.

Among the clasts incorporated into the Exmore breccia are some lithofacies not known elsewhere

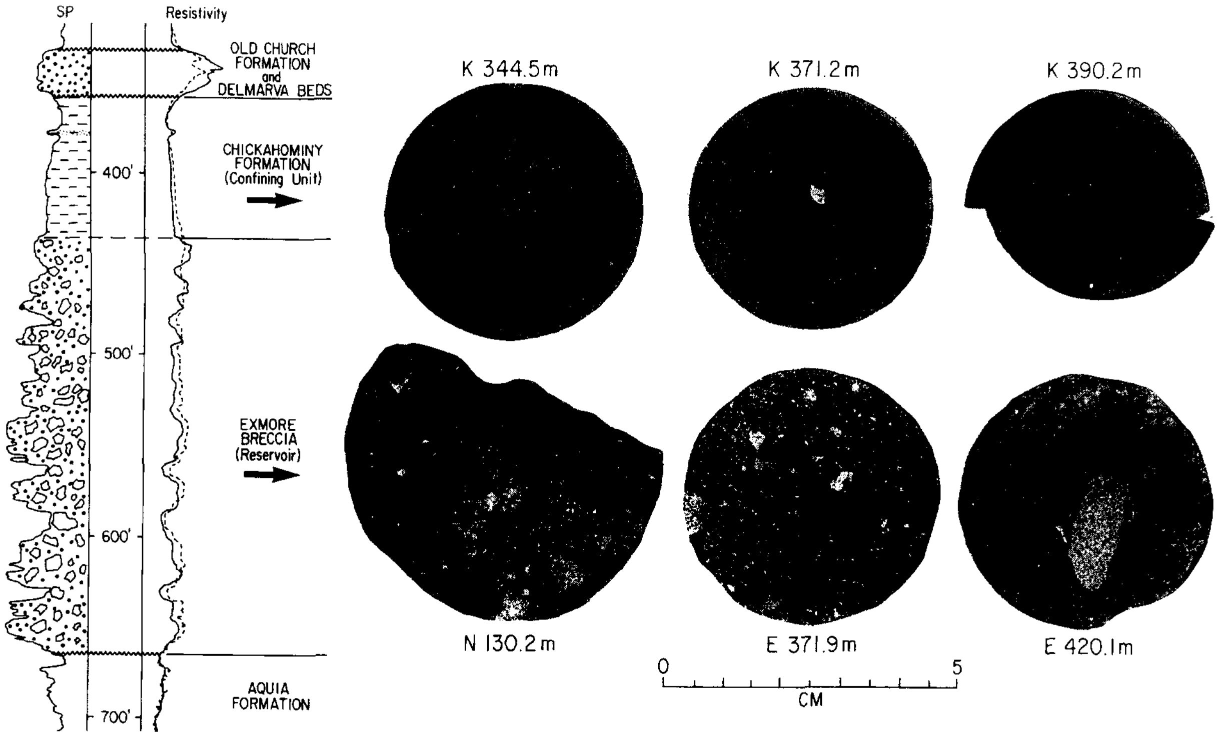


Fig. 18. Typical electrical log Eocene lithologies from Chesapeake Bay core holes. Windmill Point E-log shows contrasting SP and resistivity signatures of Exmore breccia (informal unit) and overlying Chickahominy Formation. Permeable Exmore breccia forms hypersaline ground-water reservoir, whereas massive clay of Chickahominy Formation forms confining unit. Photographs of core chips (horizontal slices) show contrast between massive clay of Chickahominy Formation and small clasts and supporting matrix of Exmore breccia (informal unit). Depths are drill depths below land surface (approximately sea level). K = Kiptopeke core; N = Newport News core; E = Exmore core.

from the Virginia Coastal Plain. Ironically, cores of the breccia represent the only means of studying those units. The best example of such a rock type is a highly fractured, massive, greenish-gray clay, seen in all four core holes. The clay contains a rich assemblage of upper Paleocene planktonic foraminifera representing Biozone P6a, and is correlative with the Aquia Formation, a glauconitic clayey sand. Poag et al. (1994b) illustrated this massive clay unit (in color) from the Windmill Point core; it appears in the middle of the second core segment of their fig. 5 (169.47–170.08 m).

When the bolide-generated convulsion abated, quiet, deep-water deposition resumed at the impact site and continued throughout the remaining ~1.2 m.y. of late Eocene time (time scale of Cande and Kent, 1992). Renewed deposition buried the Exmore breccia with a massive silty clay (sandy in some parts), which Cushman and Cederstrom (1949) named the Chickahominy Formation (Figs. 3 and 18). The Chickahominy forms a relatively uniform veneer (60–100 m thick) over the crater, and caps the porous Exmore breccia reservoir with a low-permeability seal or confining unit. Though many authors have extrapolated the standard succession of southeast Virginia aquifers and confining units into the crater region (Meng and Harsh, 1988; Meisler, 1989; Trapp, 1992; Focazio et al., 1993; Leahy and Martin, 1993), our new data invalidate these extrapolations. Virtually all previous conclusions regarding the geohydrological structure, flow characteristics, and geochemistry of this enormous ground-water reservoir, must be reevaluated.

2.3. Hypersaline ground water

Geohydrologists began to document hypersaline ground waters from southeastern Virginia in the early 1900s (Sanford, 1911, 1913). Particularly notable are unusually high chloride values measured in 'Cretaceous' aquifers around lower Chesapeake Bay. Brines with chloride values higher than that of normal sea water exist in many wells drilled on the York–James and Delmarva Peninsulas (Cederstrom, 1943, 1945a,b, 1957; Cushing et al., 1973; Larson, 1981; Meisler, 1981, 1989; Trapp, 1992; Focazio et al., 1993). Highest chloride values measured to date come from the upper part of the Exmore breccia in the Kiptopeke core hole, on Delmarva Peninsula. There the USGS and the Virginia State Water Control Board measured chlorinity of 25,700 mg/l (~1.5 times sea water; Powars et al., 1994). Evidence is building that the anomalous hypersaline ground water is not actually derived from in situ Cretaceous strata. Instead, it appears to be confined within the upper Eocene breccia lens, which replaced Cretaceous and Paleogene aquifers originally present in southeastern Virginia (Poag et al., 1994b; Powars et al., 1994). Chlorinity maps of the Bightseat–Upper Potomac, and middle Potomac aquifers (= Exmore breccia; Fig. 3), in particular, show that the shape and position of landward-embayed isochlors around lower Chesapeake Bay mimic the outline and position of the Chesapeake Bay crater (Focazio et al., 1993; Fig. 19). The chloride gradient also steepens markedly at the crater rim.

The ultimate cause of this hypersalinity is not known at present. Cederstrom (1946) and earlier authors thought the high values might be due mainly to incomplete flushing of ancient sea water. Larson (1981) and Meisler (1989) offered two additional possible explanations: (1) concentration of dissolved solids through reverse chemical osmosis and membrane filtration, enhanced by rapid sedimentation—the extremely rapid rate at which the breccia accumulated would be amenable to creating high formation pressures necessary to drive reverse osmosis; (2) migration of briny waters leached from evaporite beds. Meisler preferred the latter explanation, knowing that extensive evaporitic strata accumulated in the Baltimore Canyon trough in the Middle Jurassic, during the transition from North Atlantic rifting to sea-floor spreading (Swift et al., 1990; Poag, 1991). I speculate that a rift basin may have existed in the target rocks beneath the impact site, and that evaporites excavated from that basin are now components of the breccia lens. Additional bore-hole evidence is necessary to test these hypotheses.

Regardless of the origin of the hypersalinity, it is important to understand fully the geochemistry, distribution, and flow characteristics of the brine and its reservoir. This will allow prudent planning for future ground-water use in the lower Chesapeake region, and assist efforts to prevent the brine from contaminating fresh water supplies.

2.4. Postimpact lithofacies

The presence of the Chesapeake Bay crater directly influenced the structure, distribution, thickness, and lithic composition of postimpact deposits. Perhaps the most obvious evidence of such influence is the distribution of the Chickahominy Formation. Brown et al. (1972) mapped the upper Eocene Jacksonian strata (equivalent to the Chickahominy Formation) of southeastern Virginia, as an entirely subsurface unit covering a subcircular area beneath lower Chesapeake Bay and its adjacent peninsulas. This distribution pattern approximates the shape and position of the buried crater. I infer that the Chickahominy is the erosional remnant of an originally more widespread unit. The structural low over the crater appears to have preserved the Chickahominy during Oligocene and Miocene(?) sea-level falls, when the unit was eroded from higher elevations of the exposed sea floor (Poag and Ward, 1993; Poag and Commeau, 1995).

The distribution of two other postimpact units also appears to be constrained by the position of the crater rim. Lower Oligocene and lowest Miocene units cored at Exmore and Kiptopeke can be traced on seismic profiles over the crater, but they pinch out near the crater rim, and are not known elsewhere in southeastern Virginia.

Above the lower Miocene unit, coarser siliciclastic units of middle Miocene to Quaternary age are widespread throughout southeastern Virginia. Outside the crater, these units thicken gradually as they dip gently to the southeast. But where they cross the crater rim, the units abruptly thicken (moderately to slightly) and sag into the annular trough (Figs. 13–15, 20, 21). The same units sag and thicken even more where they overlie the inner basin (Fig. 16).

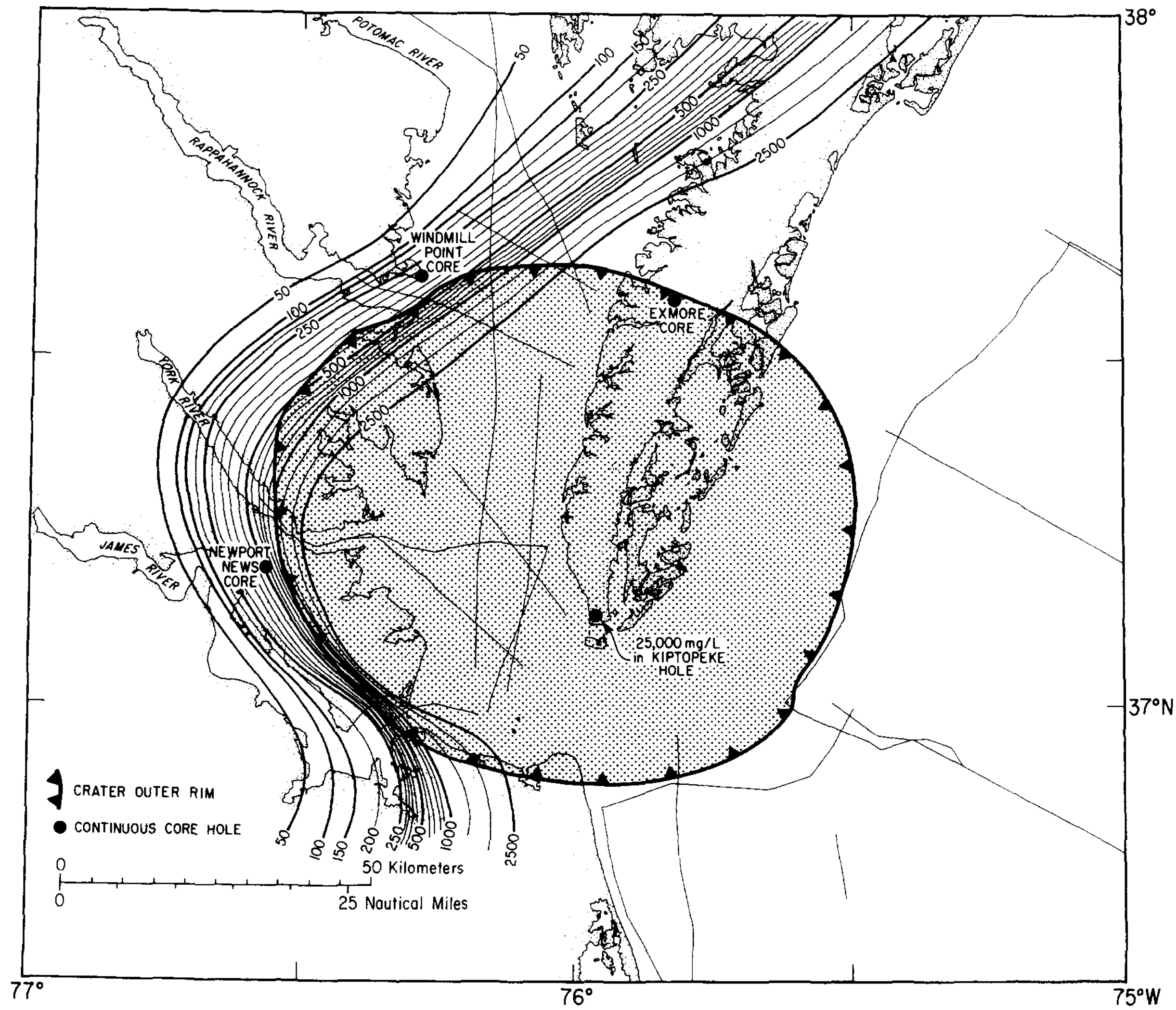


Fig. 19. Contour map of ground-water isochlors (mg/l) for Brightseat–Upper Potomac aquifer (contour interval variable; adapted from Focazio et al., 1993). Note close correspondence between outer rim of crater and orientation and gradient inflection of isochlors. See Fig. 3 for stratigraphic position of this aquifer.

2.5. Potential fault hazards

Within the crater perimeter, all postimpact depositional units are cut by numerous normal faults, which I infer to be the result of differential compaction and subsidence of the underlying breccia lens. I have counted more than 100 faults or fault clusters on the seismic profiles crossing the crater. Some of the faults appear to extend to (or near) the bay bottom, where they pose potential geohazards should they become reactivated (Figs. 13–16). The reactivation hazard could be particularly acute in the dense population centers, such as Norfolk, Hampton, Newport News, and Virginia Beach, which are built along the crater periphery. Motion-sensitive facilities, like the recently completed Continuous Electron Beam Accelerator Facility (CEBAF) in Newport News, numerous military installations around the bay, and various bay and river-mouth bridges would be especially susceptible to renewed fault activity. These fault sys-

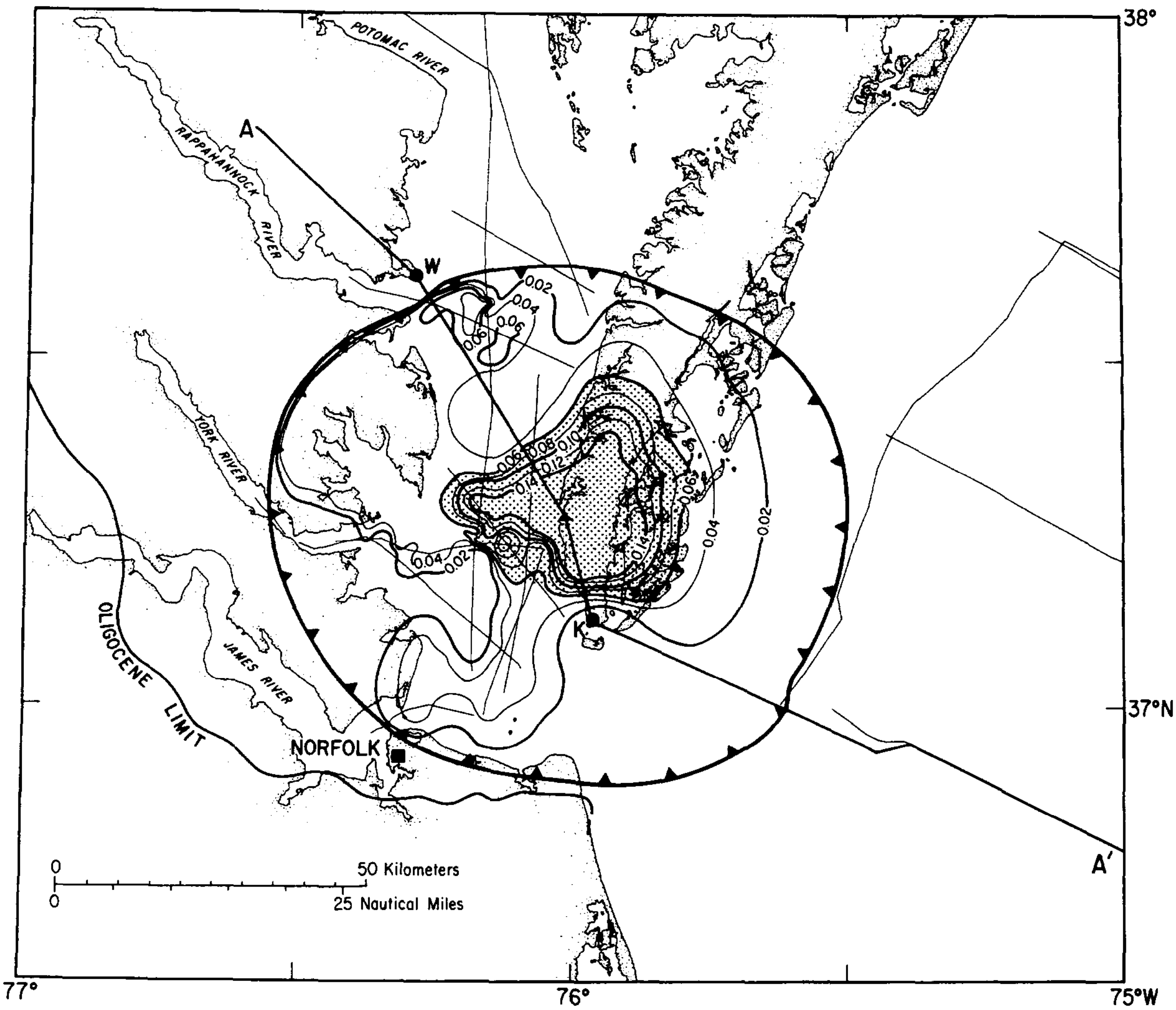


Fig. 20. Isochron map of undifferentiated Oligocene strata (Old Church Formation and informally designated Delmarva beds; see Fig. 3). Contour interval 0.02 s two-way travel time (= approximately 16 m). Note thickening of unit over crater; maximum thickness > 120 m.

tems need to be mapped in detail to allow judicious development and management of Chesapeake Bay's natural resources and municipal facilities.

2.6. Location of Chesapeake Bay

Structure and sediment-thickness (isochron) maps derived from the seismic profiles show that successive postimpact deposits continued to thicken and sag within the perimeter of the Chesapeake Bay crater for the last ~35 m.y. (Figs. 13–16, 20, 21). The evidence suggests that the thick breccia lens inside the crater continued to compact and subside more rapidly than deposits outside the crater, at least through the Pleistocene, and may continue even today. This evidence caused Poag et al. (1994b) to speculate that the presence of the Chesapeake Bay crater predetermined the present location of Chesapeake Bay. Surficial geomorphic and geological features beneath and on each side of the bay appear to support this contention.

For example, Mixon (1985) and Colman and

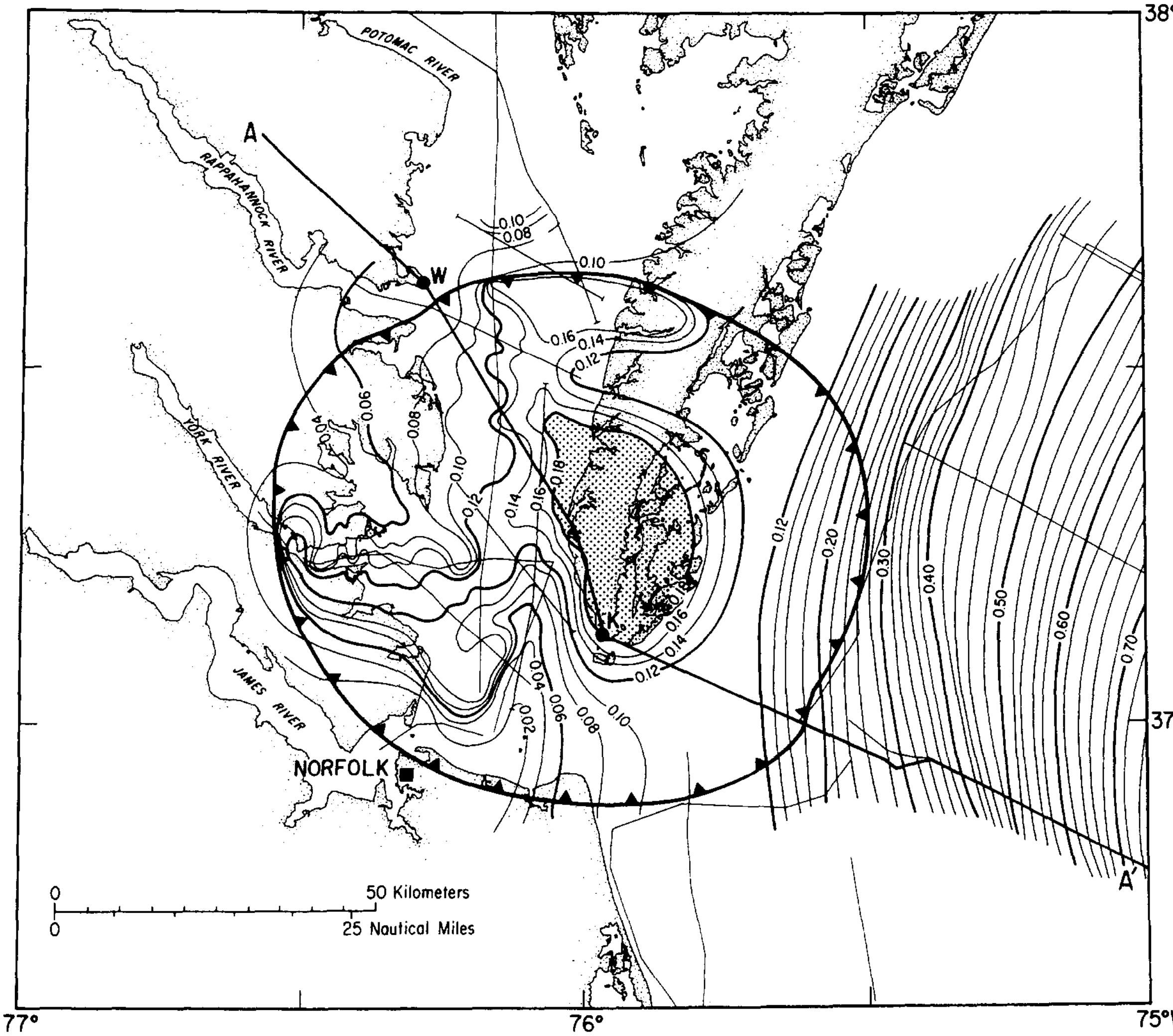


Fig. 21. Isochron map of middle Miocene strata (part of Calvert Formation; see Fig. 3). Contour interval 0.02 s two-way travel time (= approximately 16 m). Note thickening of unit over crater (maximum thickness > 150 m) and regional thickening eastward into Baltimore Canyon trough (maximum thickness > 600 m). Cross section *A–A′* illustrated in Fig. 13.

Mixon (1988) mapped the courses of the main Quaternary channels of the Susquehanna River and its principal tributaries beneath Chesapeake Bay and the Delmarva Peninsula. I recognize the same channels on the USGS seismic profiles discussed herein (Fig. 22). It is notable that each of the three successive main channels [Exmore (oldest), Eastville, Cape Charles (youngest)] takes a distinct turn to the southeast after it crosses the periphery of the buried crater. The channels exit the crater across its eastern margin, which is ~100–200 m structurally lower than the western margin. I take this as evidence that differential subsidence over the crater altered the courses of these drainage channels.

The orientation of the lower course of the modern James and York Rivers (Figs. 22 and 23) also may reflect differential subsidence across the crater rim. Instead of continuing its southeastward course toward Norfolk and crossing Cape Henry to reach the Atlantic Ocean, the James turns acutely to the northeast (toward the center of the crater), approximately above the buried crater rim. Likewise, the York River

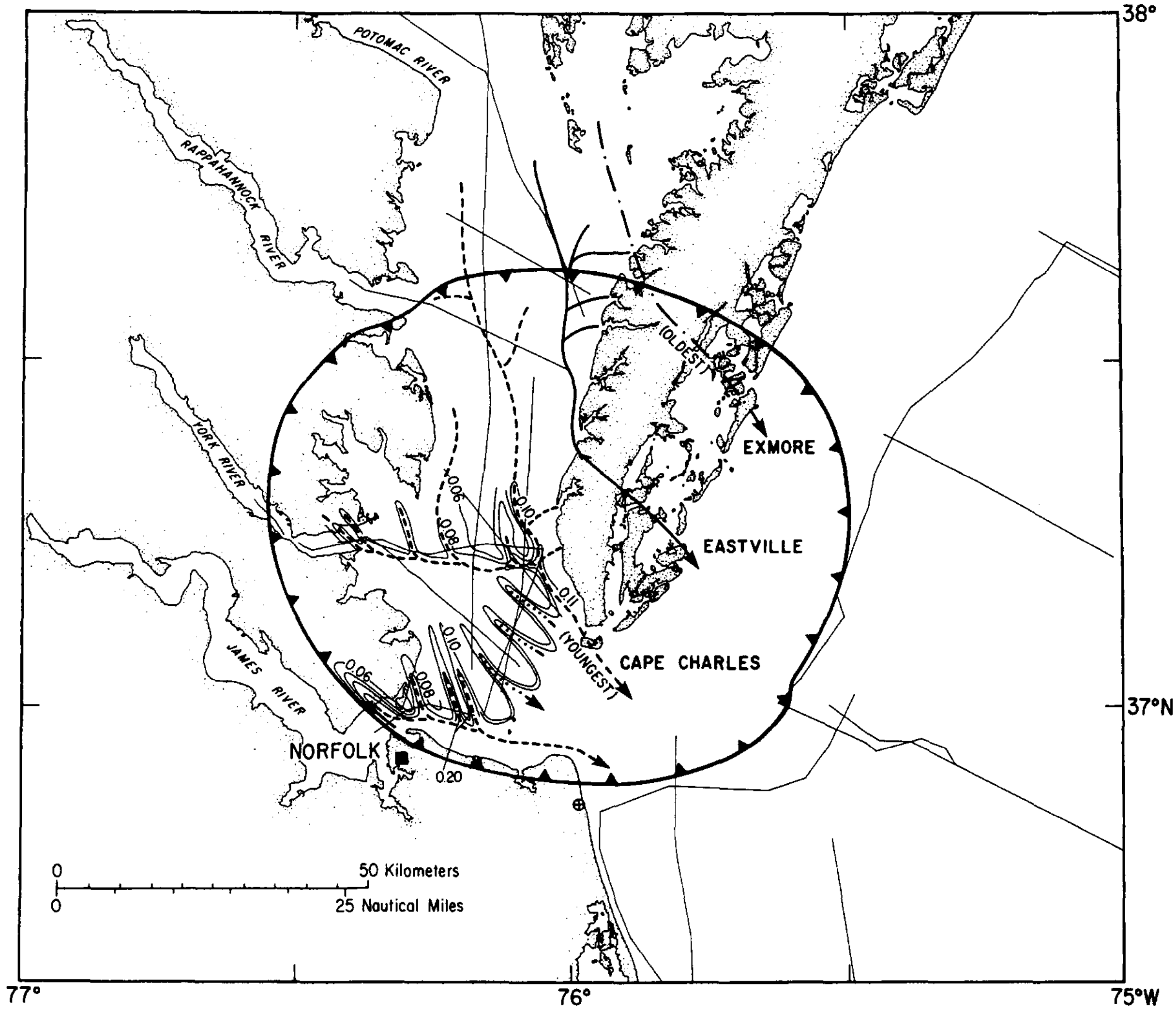


Fig. 22. Map showing locations of three successive buried Pleistocene channels of the ancient Susquehanna River (modified from Colman and Mixon, 1988). Note that each channel alters course from nearly due south to southeast after crossing crater rim.

turns abruptly east toward the crater center just after crossing the crater rim.

The geological map produced by Mixon et al. (1989), shows that the outcrop pattern of Quaternary deposits in southeastern Virginia also reflects the position of the buried crater rim (Fig. 23). The contact separating middle Pleistocene and older units from upper Pleistocene and younger units on the York–James Peninsula, on Middle Neck, and on the lower Delmarva Peninsula, approximates the position, shape, and orientation of the buried crater rim. The older units are present outside the crater, the younger units are inside. The diagonal truncation of middle Pleistocene units above the crater rim on the Delmarva peninsula is especially notable.

The modern topography of the Chesapeake Bay region also appears to reflect the buried crater's influence (Peebles, 1984; Mixon, 1985; Mixon et al., 1989). For example, the middle Pleistocene–upper Pleistocene contact approximates the position of the Suffolk scarp, a feature of 11–22 m relief, which parallels the curved western rim of the crater (Fig. 23). Eastward across the bay, the Accomac barrier-spit complex on the Delmarva Peninsula is abruptly trun-

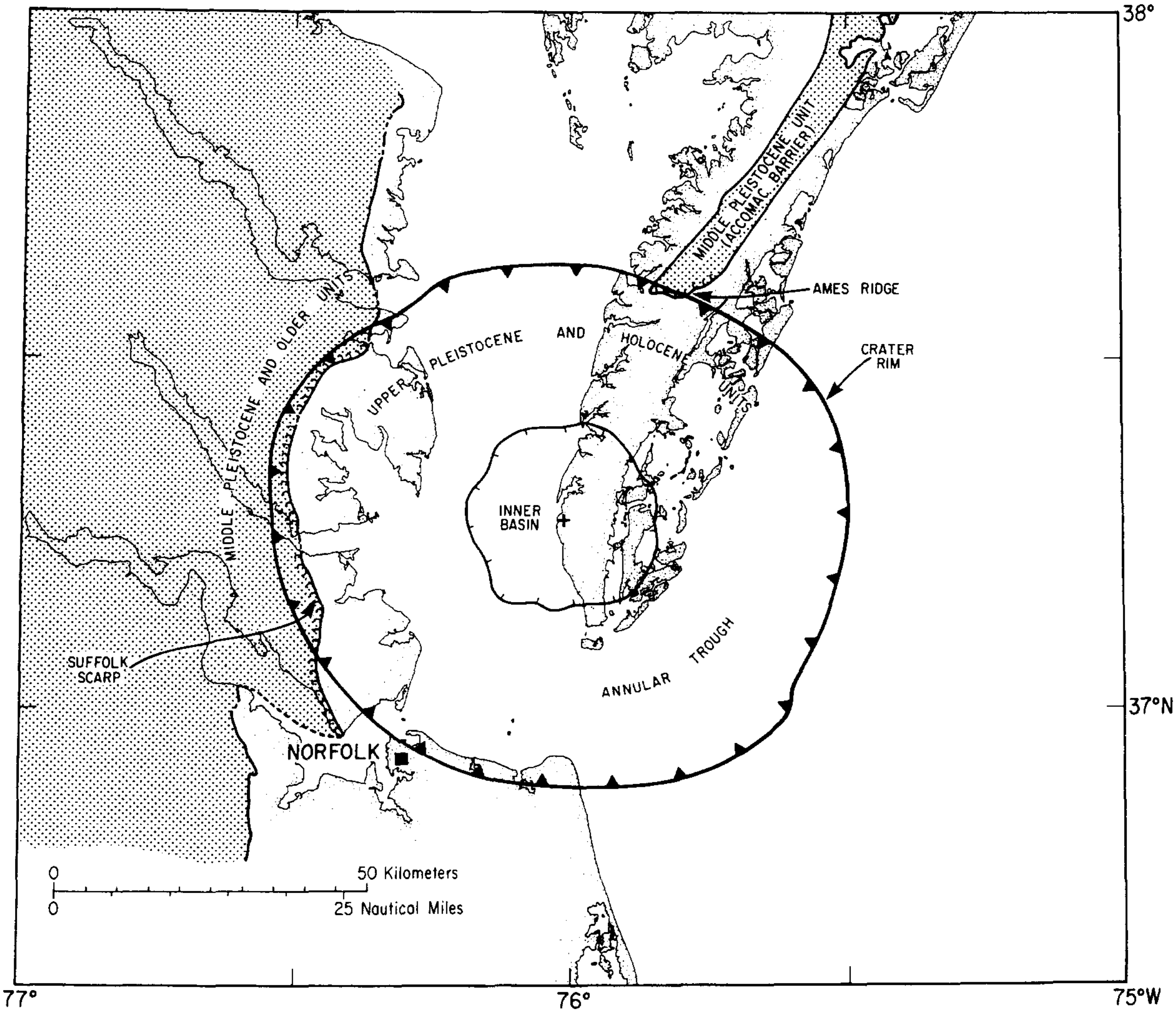


Fig. 23. Map of surficial geology and physiographic features influenced by buried Chesapeake Bay crater. Middle Pleistocene and older units are truncated near crater rim. Boundary between middle Pleistocene and upper Pleistocene units approximates 15-m contour in most places on western shore of bay (data from Mixon, 1989; Mixon et al., 1989). Note location and orientation of Ames Ridge and Suffolk scarp relative to crater rim. Note also that James and York Rivers turn abruptly toward center of crater as they cross buried crater rim.

cated to form Ames Ridge almost precisely above the buried crater rim (Fig. 23).

These observations lead me to conclude that greater differential subsidence over the buried crater maintained a structural and topographic low there since the late Eocene. The presence of this depression may account for the convergence of Quaternary river systems in this part of southeastern Virginia. The rivers incised their valleys there during the latest Quaternary lowstand, where rising Holocene sea level would subsequently flood them to form the Chesapeake Bay estuary. These are preliminary inferences, however, and must be corroborated by detailed field mapping and high-resolution seismic-reflection surveying.

2.7. Altered paleoenvironments

The gross aspects of physical paleoenvironmental alteration wrought by the Chesapeake Bay bolide

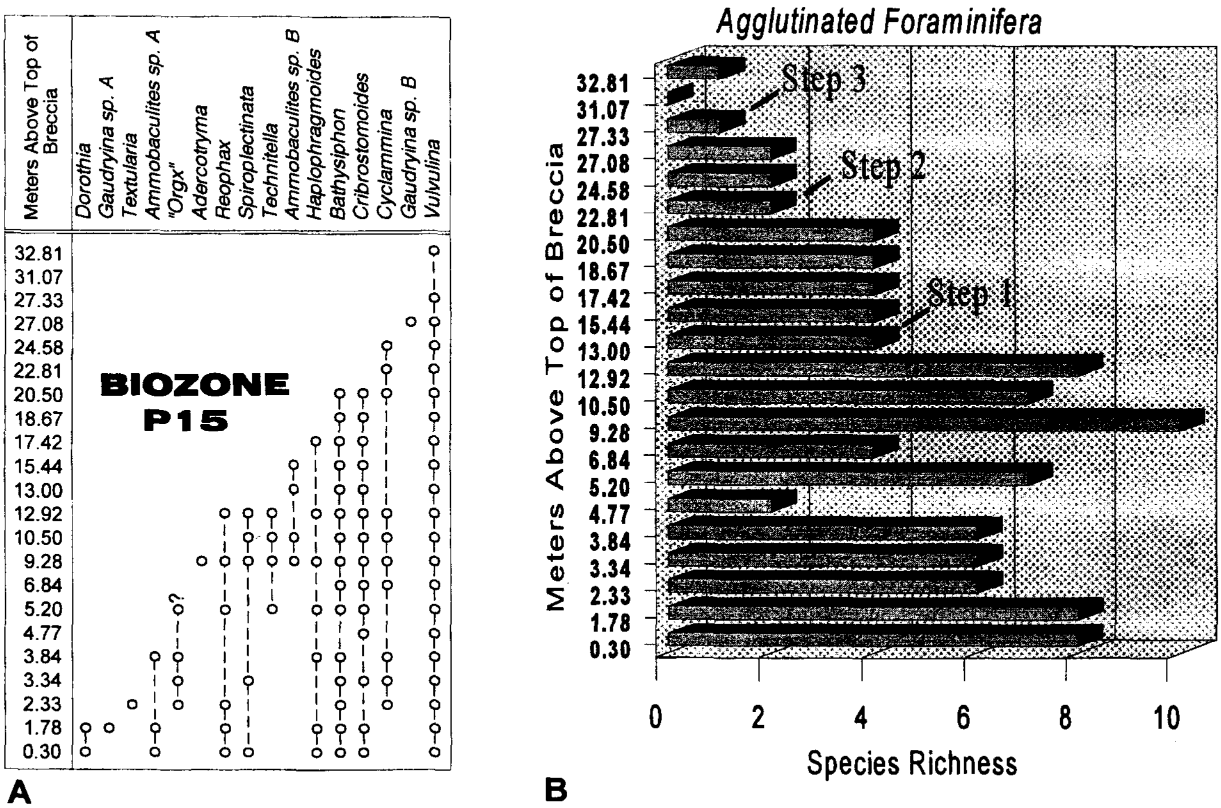
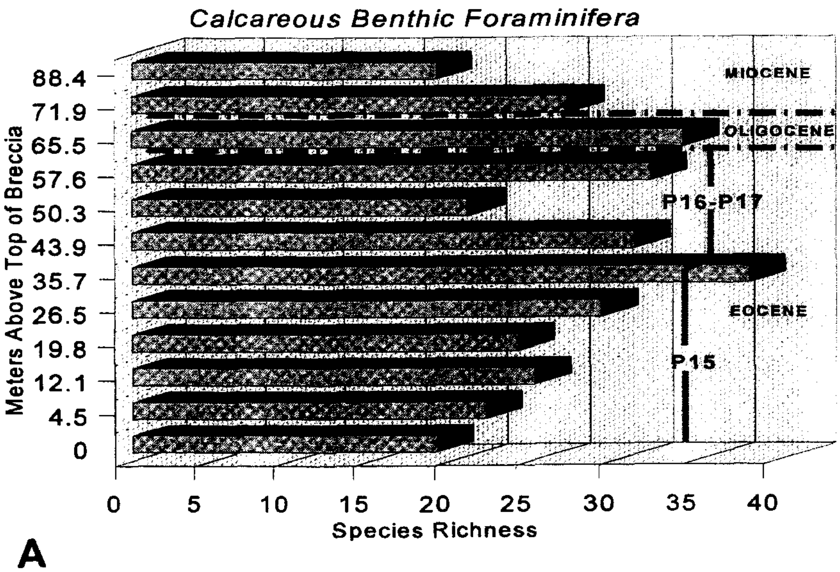


Fig. 24. (A) Stratigraphic distribution of agglutinated foraminiferal species in Chickahominy Formation in the Kiptopeke core. (B) Graph of species richness among agglutinated foraminifera in Chickahominy Formation in Kiptopeke core. Note step-wise disappearance of agglutinants.

impact are obvious, as discussed above. According to some authors, a crater this size could be expected to cause a mass extinction of 45 percent of the marine life on Earth (Raup, 1991a,b). Extensive studies of late Eocene biotic events during the past ten years have shown conclusively, however, that no such mass extinction took place during biochron P15 (MacLeod, 1990; Miller et al., 1991; Prothero and Berggren, 1992; Jansa, 1993).

Evidence of biotic and geochemical modifications by the Chesapeake Bay bolide is more subtle than the physical evidence, requiring, in part, extensive laboratory analysis. A significant initial problem is that the only knowledge of immediate preimpact conditions comes from specimens of upper Eocene planktonic foraminifera dispersed within the matrix of the Exmore breccia. We have not yet identified intact clasts of upper Eocene sediment, and the tremendous erosive forces of the impact and tsunamis appear to have stripped any preimpact late Eocene strata from the region. The abundance of late Eocene planktonic foraminifera and calcareous nannofossils within the breccia matrix (Poag and Aubry, 1995) argues for relatively deep-water marine conditions, but little additional preimpact environmental information has been gleaned from samples at hand.

A preliminary analysis of foraminiferal assemblages in the overlying Chickahominy Formation, however, yields possible evidence of an immediate local biotic and hydrographic response to the bolide impact (Poag, 1985b; Figs. 24 and 25). The lower ~33 m of the Chickahominy in the Kiptopeke core hole (approximately up to the P15–P16 biozone boundary; Figs. 7 and 25A) contains a distinctive group of agglutinated benthic foraminifera dominated by species of *Bathysiphon*, *Cribrostomoides*, and *Vulvulina* (Fig. 24A). The number of agglutinant specimens is low (less than 1% of the total



B

Meters Above Top of Breccia	*Gyroidinoides*	*Bolivina*	*Caucasina*	*Uvigerina*	*Epistominella*	*Globocassidulina*
63.7						o
62.5				o		
60.9					o	
57.6		o				
50.3				o		
43.9				o		
37.5		o				
26.5				o		
19.8		o			o	
12.1		o				
4.5	o	o	o	o		
0.0	o					

Fig. 25. (A) Graph of species richness among calcareous benthic foraminifera in basal ~33 m of Chickahominy Formation in Kiptopeke core. (B) Census of four predominant (representing 10 percent or more of the benthic specimens in one or more samples) calcareous benthic foraminiferal genera represented in basal ~33 m of Chickahominy Formation in Kiptopeke core. Other predominant taxa represented (but not shown) include *Bulimina*, *Globobulimina*, *Uvigerina*, and stilostomellids.

benthic assemblage), but representatives of the three dominant agglutinant species persist in almost every sample up to 20.5 m above the top of the breccia. The agglutinant species richness (number of different species represented) varies in an orderly way. Two successive peaks of species richness characterize the lower part of the Chickahominy section (one at the base; one at 9.28 m above the base). Following the second peak, species richness declines upsection in a three-step pattern; the agglutinant assemblage disappears at ~33 m above the base of the Chickahominy Formation (Fig. 24A, B). If one assumes a constant sedimentation rate at Kiptopeke for the ~1.8 m.y. of late Eocene time represented by the 66-m-thick Chickahominy Formation (Poag and Aubry, 1995), then the agglutinant succession spanned ~0.9 m.y. following the impact. The lowest peak in species richness lasted about 54 ka, and step one of the final decline of agglutinant species began ~0.4 m.y. after the impact.

The accompanying calcareous benthic assemblage is dominated mainly by elongate and lenticular specimens representing infaunal species (*Bolivina*, *Caucasina*, *Uvigerina*, *Bulimina*, *Globobulimina*, *Epistominella*), most of which possess notably thin-walled tests (Fig. 25B). The percentage of benthic vs. planktonic specimens is relatively low, generally less than 50%.

These faunal characteristics indicate that the lower part of the Chickahominy accumulated in oxygen-poor and (or) organic-carbon-rich, marine bottom waters of moderately great depth (200–500 m) (Poag, 1981, 1985a; Gibson, 1989; Nolet and Corliss, 1990; Hemleben et al., 1990; Corliss, 1991; Corliss and Fois, 1991; Rathburn and Corliss, 1994; Murray and Alve, 1994).

An additional characteristic of assemblages in the lower part of the Chickahominy is the abundance of radiolarian specimens, a sign of high primary productivity in surface waters (Casey, 1977; Riedel and Sanfilippo, 1977; Kling, 1978; Palmer, 1987), which often contributes to oxygen-poor bottom waters. In contrast, this group of siliceous microfossils is poorly represented in the Exmore breccia and in all preimpact formations in southeastern Virginia.

The species richness values for calcareous benthic foraminifera at Kiptopeke also reflect distinct progressive changes in the late Eocene paleoenvironment following the impact (Fig. 25A). Calcareous benthic species richness is lowest (19) immediately above the top of the breccia, whereas agglutinant species richness was high at this level. This presumably reflects relatively scarce niche availability and relatively high stress on the calcareous benthic foraminiferal populations. From this low point, calcareous benthic species richness climbs steadily to a peak value of 38 at 35.7 m above the top of the breccia (approximately the top of biozone P15), indicating decreasing population stress. Species richness values subsequently decrease to 21 at 50.3 m above the breccia, and then peak again (value of 34) in the Oligocene at 65.5 m above the breccia.

The accuracy of the microfossil census data in the lowest few Chickahominy samples, however, must be considered with caution. Diagenetic alteration is marked among many of the samples. The radiolarian assemblages, in particular, are poorly preserved due to silica dissolution and reprecipitation. Many foraminiferal tests also are coated with secondary silica.

Nevertheless, the microfossil associations in the lower part of the Chickahominy are similar to those recently documented from strata immediately overlying the bolide-generated Cretaceous–Tertiary boundary at Caravaca, Spain (Coccioni and Galeotti, 1994). In contrast to the Cretaceous–Tertiary convulsive event, however, we have no evidence that the Chesapeake Bay bolide impact stressed the late Eocene paleoenvironment on a global scale. Several papers, on the other hand, have raised the possibility of regional-scale (western North Atlantic) biotic effects within biochron P15. Maurasse and Glass (1976) and Sanfilippo et al. (1985), for example, reported that a few species of radiolarians disappeared from western North Atlantic localities at this time. Miller et al. (1991) later showed, however, that the tektite-associated radiolarian disappearances in Barbados were not coeval with those at DSDP Site 612.

As another example of possible biotic effects, Keller (1986), Keller et al. (1987), and MacLeod et al. (1990) interpreted anomalous planktonic foraminiferal assemblages at DSDP Site 612 as evidence of bolide-generated stress. In contrast, Thein (1987), Poag and Low (1987), and Poag and Aubry (1995) attributed the foraminiferal anomaly at Site 612 to faunal mixing in a debris flow. McHugh et al. (1996) reported additional evidence of sediment gravity flow in a stratigraphically correlative ejecta-bearing interval cored 5 km north of Site 612 at ODP Site 904. Thus, though there is evidence of local environmental effects, no clear correlation exists between the Chesapeake Bay bolide impact and any significant regional or global disruption of the biosphere. Nevertheless, some authors have suggested that this convulsion may have contributed to an accumulation of environmental stresses, which in composite, brought about abrupt biotic extinctions and turnovers 1.2 m.y. later at the Eocene–Oligocene boundary (Keller, 1986; Rampino and Haggerty, 1994).

3. Geological implications of the impact

3.1. Economic potential

Economically important deposits are associated with at least 35 of the more than 140 impact craters presently documented on Earth (Grieve and Masaitis, 1994). These deposits range from iron, uranium, gold, copper, nickel, and platinum ores, to oil and gas reserves and building materials (limestone). The type and abundance of the economic deposit depend in part on the size, composition, and velocity of the bolide, but primarily on the composition of the target rocks. The economic deposits may be conveniently placed in one of three categories: (1) deposits already present in the target rocks, which are redistributed by the impact (e.g., ores brought to the surface); (2) deposits generated directly by the impact (e.g., mineral-enriched melt sheets, dikes, and breccias); and (3) deposits produced by postimpact processes (e.g., oil and gas reservoirs formed in fractured target rocks). The economic value of known impact-derived deposits is not trivial. Grieve and Masaitis (1994) estimated that the total gross direct worth of materials extracted from such deposits is $5–6 billion per year for North America alone.

The most notable example of bolide-generated economic deposits is the Sudbury Igneous Complex (Ontario, Canada), a world-class source of copper, nickel, and platinum ores (Dietz, 1964; French, 1968; Dence, 1972; Peredery, 1972; Dressler et al., 1987; Grieve, 1994; Stöffler et al., 1994). Recent studies by Grieve et al. (1991) indicate that the Sudbury Igneous Complex originated as an unusually thick impact melt sheet. Craters as large as the Chesapeake Bay structure characteristically contain interior melt sheets, if the target rocks are crystalline (Kieffer and Simonds, 1980). Several empirical and computational methods have been suggested to relate expected impact–melt volume to crater dimensions. Grieve et al. (1977) estimated that a crater the size of the Chesapeake Bay structure (90-km-diameter) would yield a melt-sheet volume of ~10,000 km^3. The computational relationship developed by Lange and Ahrens (1979):

$$V = 3.8 \times 10^{-4} D^{3.4}$$

yields a Chesapeake Bay melt-sheet volume of ~1700 km^3 (V = volume of melt sheet; d = final crater diameter). It is reasonable, therefore, to assume that a significant volume of economic minerals would result from emplacement of such a melt sheet in the inner basin of the Chesapeake Bay crater. Corroboration of this assumption awaits drilling into the inner basin and identification of a melt sheet.

3.2. Arches and basins

The presence of the Chesapeake Bay crater, and other consequences of the impact that produced it, have far-reaching implications for some traditional interpretations of geological phenomena in southeastern Virginia. The concept of the 'Norfolk arch' is a good example. Cederstrom (1945b,c) concluded that a structural boundary separated the north and south sides of the James River near Hampton Roads (lower reach of the James River) in southern Virginia. He based his conclusion on cuttings samples from > 150 water wells and petroleum test wells, with which he documented the subsurface stratigraphic framework and structure of southeastern Virginia. In these early papers he showed that 'Eocene' beds (Pamunkey Group) abruptly thickened by more than 200 m and dropped structurally 100 m across the lower part of the James River (Battery Park to Old Point Comfort). This caused him to postulate that a marine basin developed north of the James during (or just prior to) the Eocene. He reasoned that a reactivated basement fault, which he called the Hampton Roads fault, probably marked the southern boundary of the Eocene basin. He mapped the margin of the basin as a conspicuous steepening of the structural gradient along the western side of Chesapeake Bay from Portsmouth to Yorktown (Fig. 26).

Cederstrom's concept of abrupt southward thinning of 'Eocene' strata in the vicinity of Norfolk was perpetuated in the literature (LeGrand, 1961; Richards, 1945, 1967), though Cederstrom (1957) himself repudiated the idea when he reinterpreted the age of his subsurface 'Eocene' unit. But as seismic profiling and deep drilling revealed the variable depth to basement along the coastline (Richards, 1950; Spangler, 1950; Spangler and Peterson, 1950), Cederstrom's concept was transformed. Realizing that the basement was considerably higher near Ft. Monroe (across the James River from Norfolk) than to the north and south, Richards and Straley (1953) introduced the term *Ft. Monroe high*. Some authors even went so far as to call it the Ft. Monroe uplift, implying active tectonism (Owens et al., 1968; Owens and Sohl, 1969; Owens, 1970; Olsson, 1978). The term Norfolk arch was introduced 14 years later by Gibson (1967), as a synonym of the same feature. Gibson did not document the structural aspects of the feature, but referred, instead, to the published work of Spangler and Peterson (1950). Later, Owens and Gohn (1985) envisioned the Norfolk arch/Ft. Monroe high as the northern corner of a much broader, relatively elevated, structural feature they called the Cape Fear–Norfolk high.

Researchers studying the offshore portion of the U.S. Atlantic margin have a different interpretation of the Norfolk arch. According to Klitgord and Behrendt (1979), Poag (1985b), Popenoe (1985), Klitgord et al. (1988), and Poag and Ward (1993), the arch is part of the northeastern margin of the Carolina platform, a structural high, which separates the Baltimore Canyon trough (and its landward extension, the Salisbury embayment; Fig. 1) from the Blake Plateau basin; the platform also forms the landward margin of the Carolina trough. The elevated structural position of the Carolina platform (and its constituent parts) is not the result of tectonic uplift, but of differential margin subsidence.

A recent manifestation of the Norfolk high as a minor basement flexure was published by Powars et al. (1992). Their basement map (fig. 18-1) shows the Norfolk arch as a small east–west-oriented nose on the homoclinal basement surface, whose structural contours run essentially north–south through southeastern Virginia and southern Maryland. In cross section, Powars et al. (1992) located the Norfolk

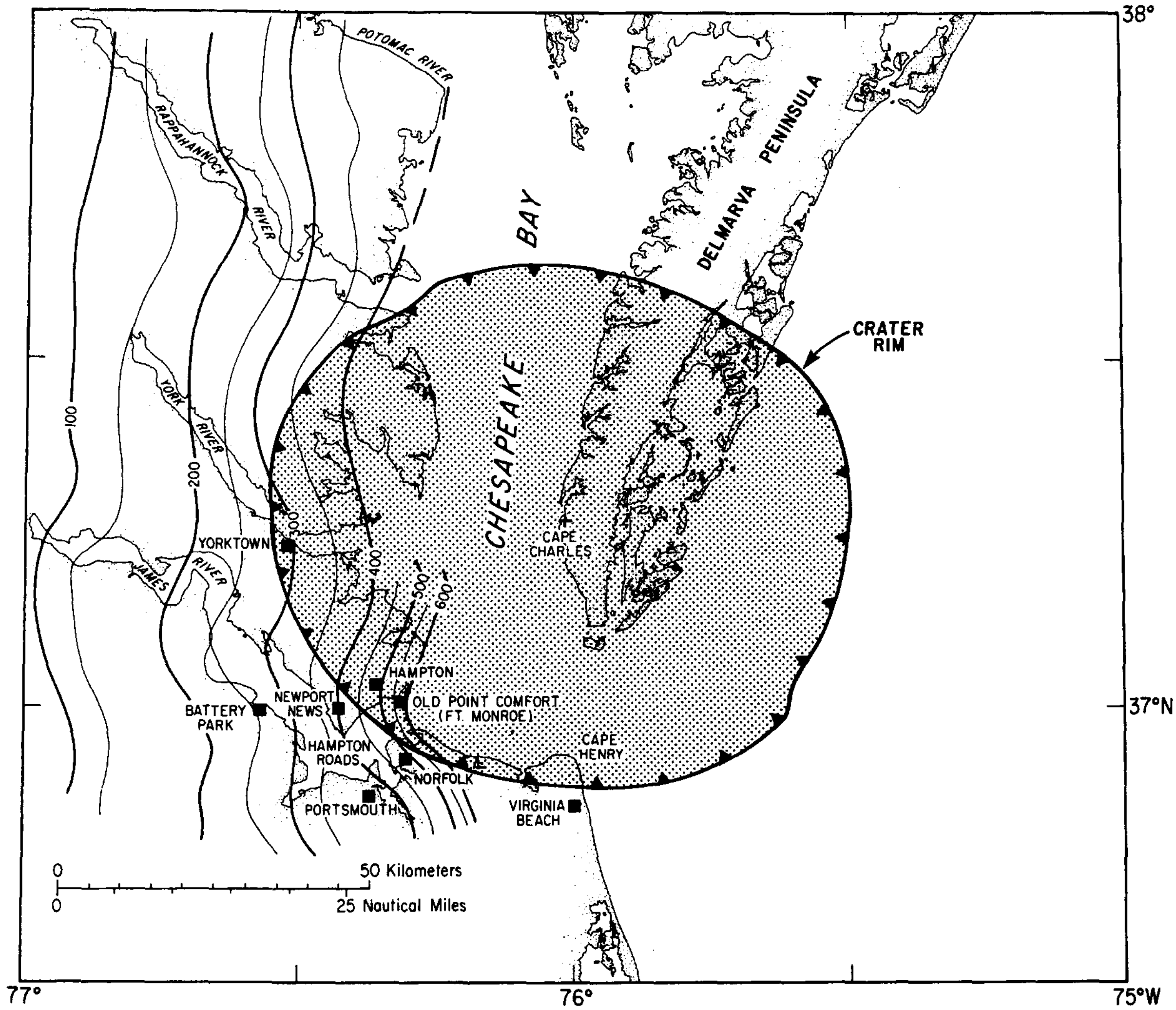


Fig. 26. Structure map showing steepened gradient marking southern boundary of 'Eocene' basin, as interpreted by Cederstrom (1957). Contour interval 50 ft. Note that location and orientation of gradient inflection resembles geometry of crater rim.

arch using structurally high, updip core holes (particularly, Dismal Swamp and MW4-1), which penetrated relatively thick Upper Cretaceous strata, but relatively thin Tertiary strata southwest of Norfolk. Powars et al. (1992) suggested that Cederstrom's (1945c) postulated Hampton Roads fault might form the northern boundary of the Norfolk arch, but they showed no such fault on the cross section. I have reinterpreted Powars et al.'s (1992) section to demonstrate the dramatic changes that take place across the crater rim (Fig. 27). I also have constructed a new three-dimensional perspective of the basement structure (Fig. 28), using the seismic reflection profiles to upgrade fig. 18.1 of Powars et al. (1992).

Altogether, there has been little consistency among researchers regarding the size, location, orientation, and origin of the 'Norfolk arch'. Knowledge of the Chesapeake Bay bolide impact requires us to reexamine the meaning of the term. There can be little doubt that the southern margin of Cederstrom's 'Eocene' basin and his Hampton Roads fault zone (and the northern boundary of the 'Norfolk arch', in the sense of Powars et al., 1992) represent the faulted outer rim of the Chesapeake Bay crater. It

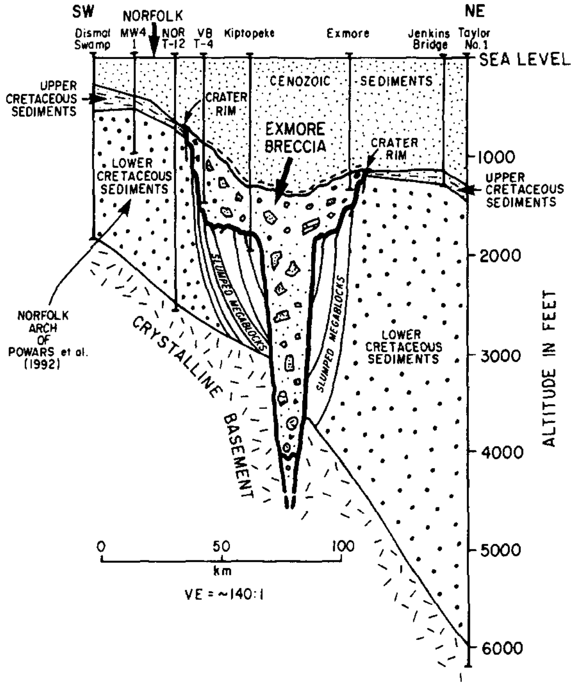


Fig. 27. Reinterpretation of fig. 18.3 of Powars et al. (1992) to show relationship between their concept of Norfolk arch and my interpretation of structural rim of Chesapeake Bay impact crater.

follows, that Cederstrom's postulated 'Eocene' marine basin is the annular trough of the crater, and the thickened 'Eocene' section he envisioned there is the Exmore breccia.

Later on, Cederstrom (1957) included the unit we now know as the Exmore breccia, as part of his Mattaponi Formation. Not realizing that stratigraphic mixing characterizes the breccia, Cederstrom inferred that Cretaceous, Paleocene and Eocene strata he identified within the Mattaponi (using foraminifera from cuttings samples), had been drilled in normal stratigraphic succession. We now know that the Mattaponi is not a normal succession of layered beds, and that (in most places) it is really an Eocene deposit after all, just as Cederstrom (1945b,c) originally thought. As shown herein, however, basinward thickening of the breccia is not limited to the north side of the James River. Thickening and sagging into the annular trough take place around the entire 283-km circumference of the crater. Furthermore, the seismic profiles show definitively that neither the sedimentary thickening nor the rim faulting is coupled to basement warping or faulting. Clearly, the concept of a Norfolk or Ft. Monroe *arch* or *uplift* is inappropriate to describe such relationships; the term should be either carefully redefined or discarded.

3.3. Coastal plain reverse faulting

Several significant reverse faults, fault systems, and anticlinal folds disrupt Cretaceous and Cenozoic sediments near the inner edge of the Virginia Coastal Plain (Mixon and Newell, 1977, 1978; Prowell, 1983, 1988; Mixon and Powars, 1984; Dischinger, 1987; Mixon et al., 1989; Mixon et al., 1992). Maximum displacement (above the basement) is seen in the Lower Cretaceous section (15–50 m), intermediate displacements occur in Paleocene and Eocene strata (10–15 m), and minor displacements have been noted in younger beds (1–3 m). The origin of the reverse faults has been ascribed to reactivation of extensional faults preexistent in the crystalline basement. Structural analogy with other terrestrial impact craters leads me to suggest that crustal shock derived from the Chesapeake Bay bolide may have reactivated some of these faults again in the late Eocene.

According to Gurov and Gurova (1982), Pilkington and Grieve (1992), and Masaitis (1994), near-surface fracturing and faulting can take place to a distance of approximately one-crater-diameter beyond the rim of a large impact crater. In the case of the Chesapeake Bay crater, this fracture zone would encompass a 270-km-diameter circle centered at Cape Charles. Its perimeter would reach the Maryland–Delaware border to the north, Richmond, Virginia, to the west, Elizabeth City, North Carolina, to the south, and beyond the edge of the continental shelf to the east (Fig. 29). Several possible candidates for distal bolide-generated or reactivated faults have been documented within, or just outside the western perimeter of this near-surface fracture zone. The strongest candidate is the Hopewell fault, located inside the fracture zone, approximately 75 km west of the crater rim (Dischinger, 1987; Mixon et al., 1989). The slightly arcuate fault trace has been mapped over a distance of 47 km, subparallel to the crater rim. The Port Royal fault and the Stafford and Brandywine fault systems (antecedent to the impact)

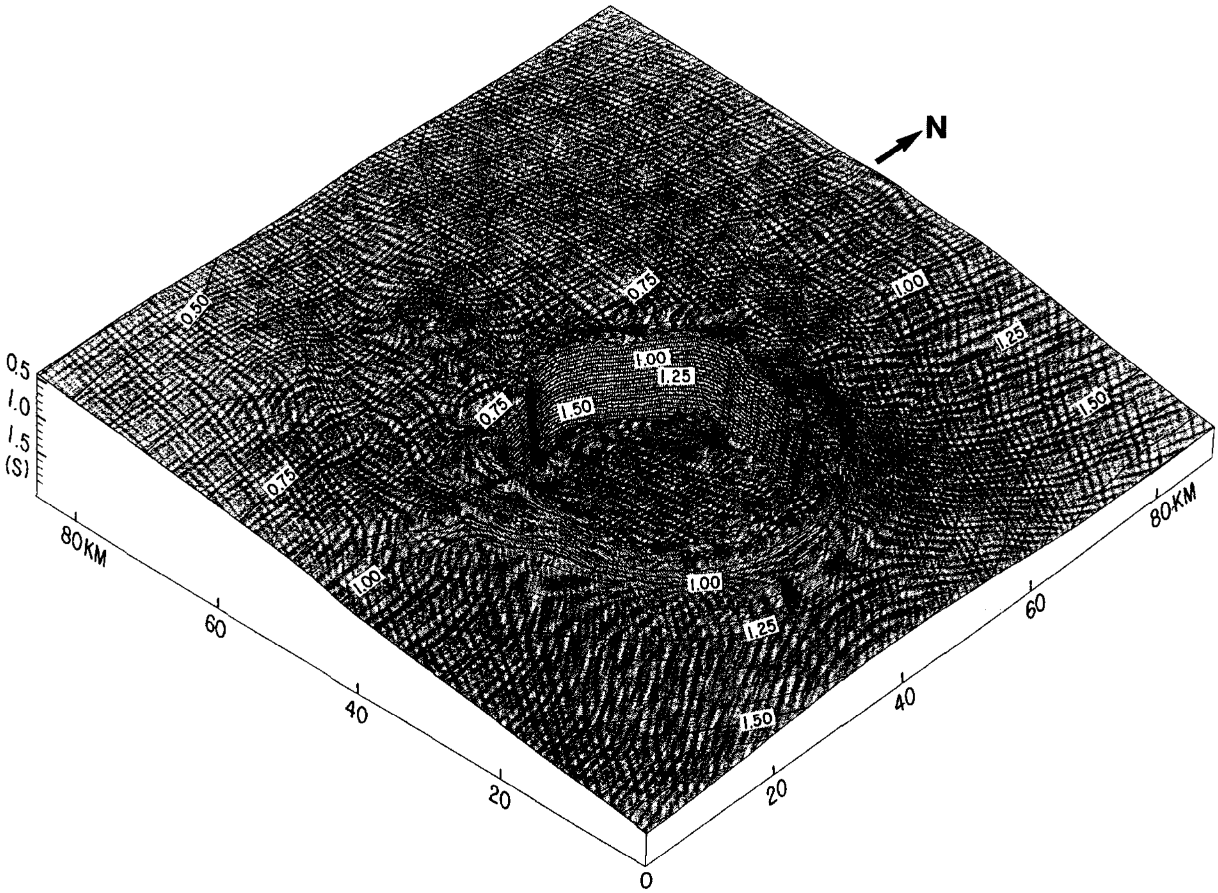


Fig. 28. Three-dimensional structural perspective of upper surface of crystalline basement, as identified on seismic reflection profiles and in bore holes. Contour interval 0.1 s, two-way travel time (≈ approximately 100 m). Inner basin of crater is enclosed by peak ring, a roughly circular ridge whose highest elevation is in southwest sector. Relative gravity highs in center of crater (see Fig. 11) may be evidence of an irregular floor in the inner basin. Structural gradient steepens east of crater, due to greater differential subsidence of Baltimore Canyon trough.

are several kilometers outside the fracture zone periphery, but they may be close enough to have been reactivated by the impact.

Newell and Rader (1982) identified a concentration of linear topographic features and tectonic joint systems, which they ascribed to probable subsurface faults. This concentration of lineaments also falls within the northwest quadrant of the bolide's near-surface fracture zone (Fig. 29). The traces of several faults, presumably related to this system of lineations, can be observed on seismic profiles where they cross the Potomac River south of Cobb Island, Maryland (Figs. 29 and 30). The westernmost fault clearly is a reverse fault where it cuts the basement surface (Fig. 30). The next three adjacent faults that displace the basement surface (Fig. 30) appear also to have been originally reverse faults, but have been reactivated as normal faults. The normal faults provide slip surfaces along which two elongate fold-blocks of preimpact sedimentary strata have been rotated. The tops of the rotated blocks appear to be covered by a thin layer of impact breccia (~85 m thick).

Distal faults generated or reactivated by the Chesapeake Bay bolide impact are more likely to be detected in locations near the Fall Line than along the coast or offshore. This is so, because the easily identified contact between crystalline basement

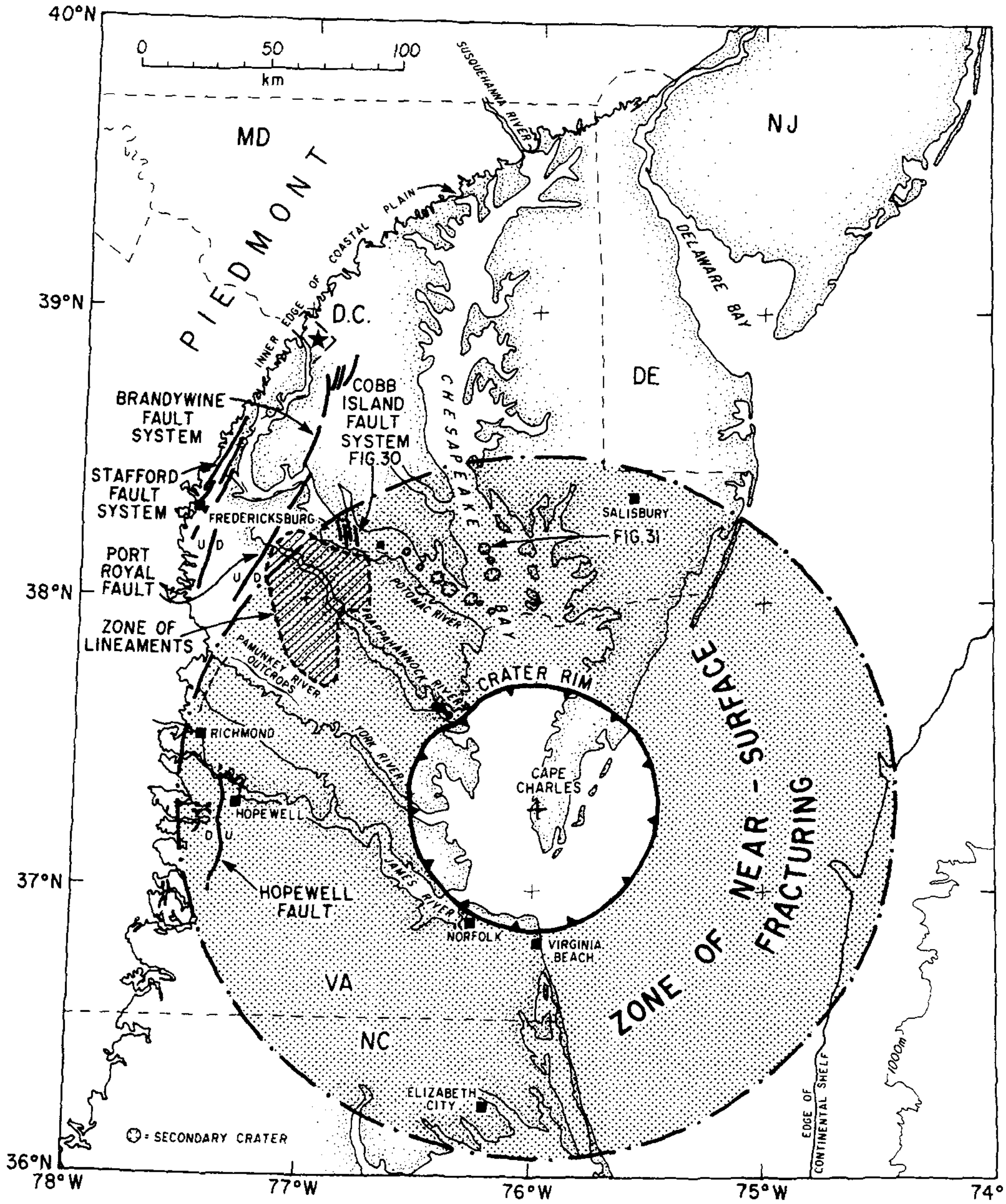


Fig. 29. Map showing location of Chesapeake Bay crater, its postulated near-surface fracture zone, and distribution of prominent reverse faults that displace Paleogene and Cretaceous coastal plain sediments (Mixon et al., 1989, 1992). Hopewell fault and zone of surficial lineaments (Newell and Rader, 1982) lie within near-surface fracture zone. Three other faults or fault systems are located a few kilometers outside zone. Some of these features may have been generated or reactivated by Chesapeake Bay bolide impact. Fourteen small secondary craters are present within zone of near-surface fracturing (identified from seismic profiles; three beneath Chesapeake Bay northeast of mouth of Potomac River; three in lower reach of Rappahannock River; eight beneath bed of Potomac River). Prominent faults that cross Potomac River south of Cobb Island, Maryland (faults antecedent to impact, but reactivated by impact), appear to be related to zone of lineaments (Fig. 30).

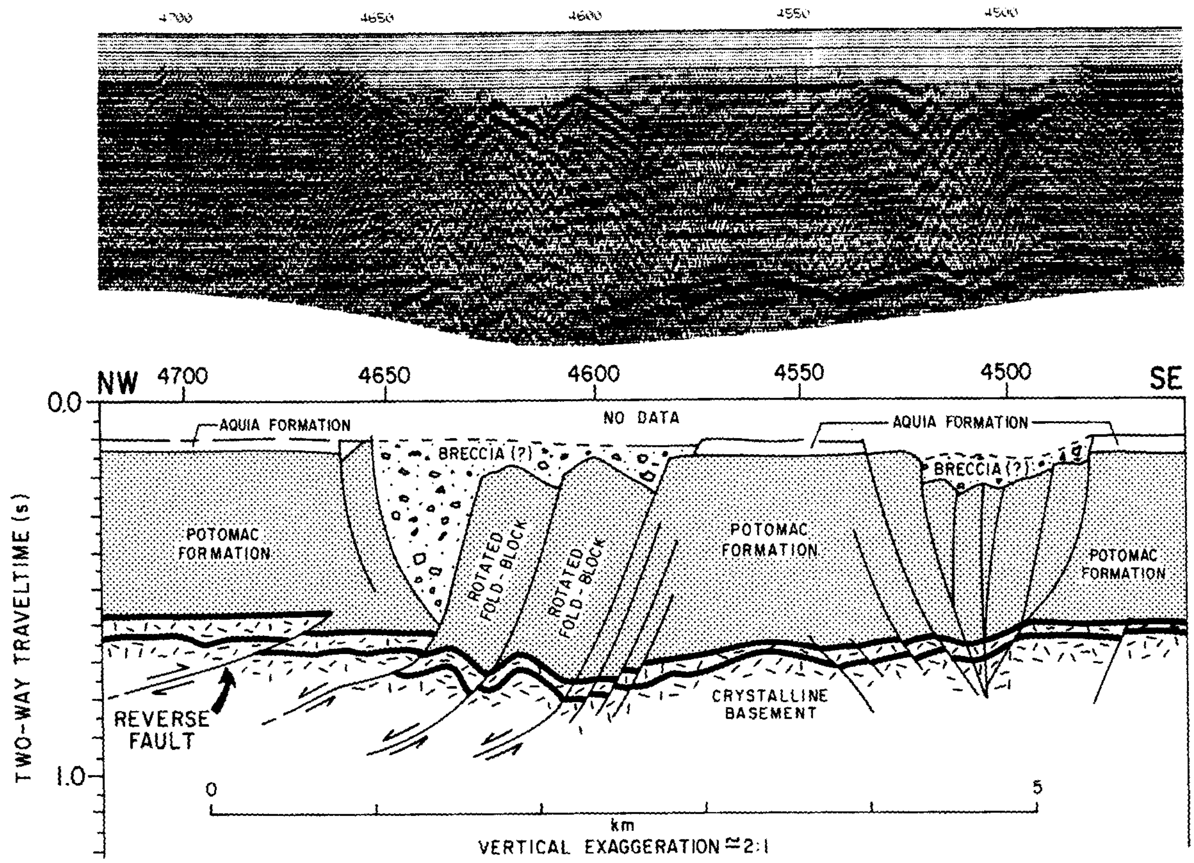


Fig. 30. Segment of unmigrated seismic reflection profile in Potomac River (see Fig. 29) showing traces of prominent Cobb Island fault system. *Above*, uninterpreted seismic profile; *below*, geological interpretation. Four antecedent reverse faults are discernable at left. Three of these reverse faults have been reactivated as normal faults, which offset rotated fold-blocks of preimpact sedimentary rocks.

and the preimpact sedimentary cover is exposed or only shallowly buried in the updip areas (Prowell, 1988). Faults that cut this crystalline–sedimentary contact are much easier to detect in the field than those displacing sedimentary rocks of similar lithology. Basement rocks also are more likely to have been fractured (by the bolide) in updip areas than at downdip locations, because updip sites were at (or closer to) the surface when the bolide struck. Analogy with other impact structures predicts that numerous additional impact-activated faults, as well as impact-generated faults, will be discovered within the western half of the near-surface fracture zone of the Chesapeake Bay bolide.

Anomalous reverse dips also have been noted among sedimentary beds within the Chesapeake Bay crater's near-surface fracture zone (Ward, 1984; Ward and Strickland, 1985; Mixon et al., 1992). Ward and Strickland (1985) attributed these reversals to possible subsurface faulting. As the reversals affect mainly Eocene to Pliocene deposits, one might reasonably postulate that some of the faults could have been initiated or reactivated by the bolide. As yet, however, few of the postulated faults have actually been documented.

3.4. Anomalous depositional patterns

In addition to dip reversal, researchers have reported anomalously rapid thickness changes and truncated distribution patterns among strata encompassed by the bolide's near-surface fracture zone. It has been customary to attribute these anomalies mainly to the presence of structural and topographic

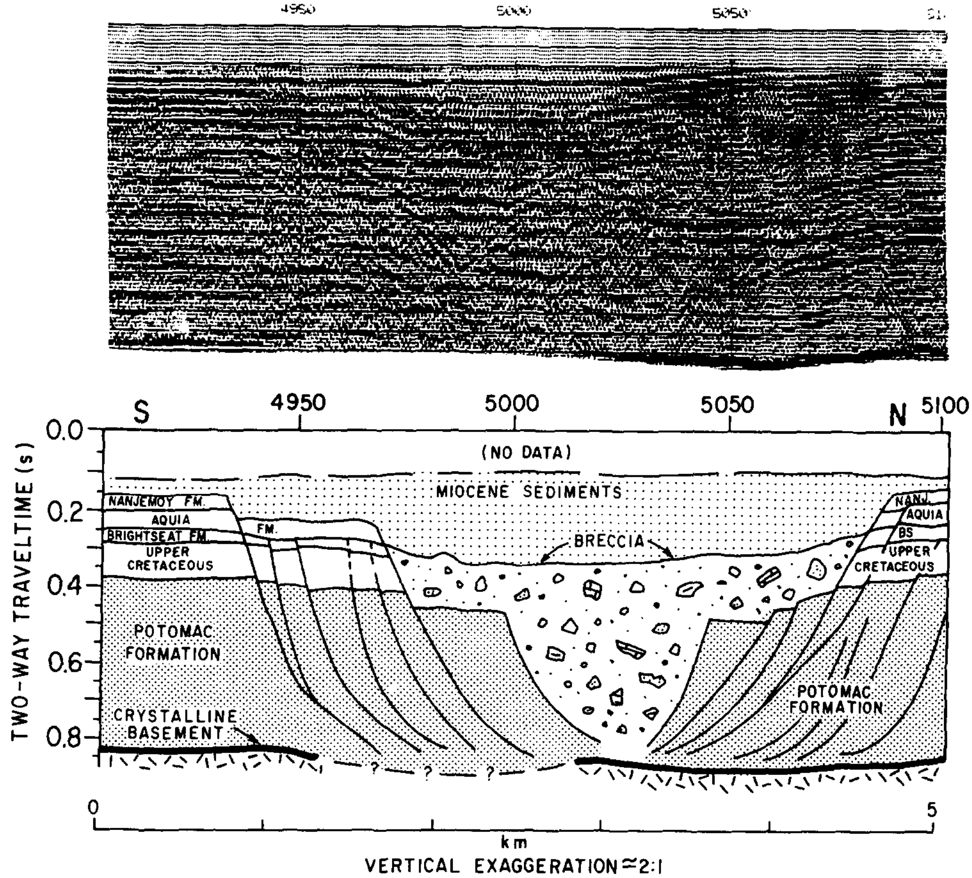


Fig. 31. Segment of unmigrated seismic reflection profile in Chesapeake Bay northeast of mouth of Potomac River (see Fig. 29) showing small secondary impact crater (apparent diameter 2.75 km) excavated by large block ejected ballistically from Chesapeake Bay primary crater. *Above*, uninterpreted seismic profile; *below*, geological interpretation. Note prominent disruption of normal strata (represented by horizontal, parallel reflections) and presence of numerous down-to-basin normal faults.

barriers to sedimentation (e.g., Ward, 1984; Ward and Strickland, 1985) or to mild tectonism (e.g., Gibson, 1970). Our newly gained knowledge of the Chesapeake Bay crater provides some possible alternative explanations for these anomalies. One possibility is that the bolide impact created a relatively high-relief topography on the late Eocene surface. Part of this relief may have been derived from deep linear channels and scour troughs, which would be expected to form during the runup and backwash of the bolide-generated tsunami(s) (Dawson, 1994). Additional topographic relief may have been created by secondary craters, which are formed by the impact of large blocks ejected from the primary crater, and characteristically are dispersed around the periphery of large impact craters (Oberbeck, 1975; Melosh, 1989; Greeley, 1994). To date, I have identified (on seismic reflection profiles) 14 small secondary craters (1–5 km diameters) within 50 km of the Chesapeake Bay crater rim; three north of the crater rim beneath Chesapeake Bay, three in the lower reach of the Rappahannock River, and eight beneath the bed of the Potomac River (Figs. 29 and 31). I suspect that these features are numerous, and are scattered widely across the Virginia Coastal Plain. Breccia compaction and subsidence, in addition to secondary faulting, could produce considerable topographic relief around these features.

Undoubtedly, other structural and depositional features and processes in the Virginia Coastal Plain deserve careful scrutiny and reappraisal in light of the variety of documented and postulated effects of the Chesapeake Bay bolide impact.

4. Summary and conclusions

The passive margin of southeastern Virginia was wracked by a short-lived geological convulsion at ~35 Ma during the late Eocene. A bolide struck the inner continental shelf, created a large complex impact crater, and generated a gigantic tsunami. This convulsive event fundamentally altered the geological, geohydrological, and geographical evolution of the Virginia segment of the Atlantic Coastal Plain, and appears to have predetermined the location of Chesapeake Bay. Data derived from seismic reflection profiles and core holes document the general framework in which this convulsion took place and provide evidence of its consequences.

(1) It removed ~4300 km^3 of target rocks while excavating a crater 90 km in diameter and ~1.2 km deep.

(2) It truncated all ground-water aquifers existing in southeastern Virginia in the early late Eocene.

(3) It replaced ejected rocks with an enormous (4300 km^3), porous, breccia lens containing briny waters, whose measured chlorinity values are greater than 25,000 mg/l.

(4) It constrained the distribution of several post-impact sedimentary deposits to the structural low caused by the crater.

(5) It indirectly produced postimpact compaction faults that pose potential geohazards to population centers and motion-sensitive facilities built over and near the buried crater.

(6) It created a structural and topographic low, which persisted for 35 m.y., and which may have predetermined the location of Chesapeake Bay.

(7) It may have produced mineral-enriched melt sheets in the crater's inner basin.

Armed with knowledge of the Chesapeake Bay impact and its consequences, I have offered some plausible alternatives to traditional interpretations of Atlantic Coastal Plain evolution. In particular, the bolide may have been responsible for some of the arches, basins, reverse faults, and sedimentary dip reversals previously ascribed to other causes. Much additional surveying, drilling, and mapping are required, however, to fully document the impact's consequences and the implications thereof.

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