Physical Geology of the Impact-Modified and Impact-Generated Sediments in the USGS-NASA Langley Core, Hampton, Virginia

By Gregory S. Gohn, David S. Powars, T. Scott Bruce, and Jean M. Self-Trail

Chapter C of

**Studies of the Chesapeake Bay Impact Structure—
The USGS-NASA Langley Corehole, Hampton, Virginia, and
Related Coreholes and Geophysical Surveys**

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By Gregory S. Gohn,[1] David S. Powars,[1] T. Scott Bruce,[2] and Jean M. Self-Trail[1]

Abstract

The USGS-NASA Langley corehole penetrated a complete section of impact-modified and impact-generated sediments in the outer annular trough of the late Eocene Chesapeake Bay impact structure. The U.S. Geological Survey (USGS) and cooperators drilled the Langley corehole to a total depth of 635.1 meters (m; 2,083.8 feet (ft)) at the National Aeronautics and Space Administration (NASA) Langley Research Center in Hampton, Va.

The continuously sampled Langley core contains 390.6 m (1,281.6 ft) of impact-related sediments between the top of basement granite at 626.3 m (2,054.7 ft) depth and the base of upper Eocene postimpact sediments at 235.65 m (773.12 ft) depth. Preimpact Cretaceous and lower Tertiary sedimentary sections disrupted by the impact consisted of noncalcareous, nonglauconitic Lower Cretaceous and basal Upper Cretaceous fluvial and deltaic sediments overlain by glauconitic and calcareous Upper Cretaceous and lower Tertiary marine sediments.

Three informally defined, impact-related sedimentary units are recognized in the Langley core: crater unit A, crater unit B, and the Exmore beds. Crater unit A overlies basement granite at a depth of 626.3 m (2,054.7 ft) and consists of 183.8 m (603.0 ft) of minimally to moderately disrupted Cretaceous fluvial and deltaic sediments of the Potomac Formation. Crater unit A does not contain shocked ejecta or infiltrated exotic sediments.

Crater unit A is divided into two informal subunits: the lower beds and the upper beds. The contact between the subunits is placed at a depth of 558.1 m (1,831.0 ft). Primary (Cretaceous) sedimentary structures and cycles, including horizontal bedding and laminations, are virtually pristine in the lower beds, indicating little or no impact disruption. Similar primary structures and cycles are present in the upper beds, but massive (structureless) sands and fractured finer grained beds also are present.

Crater unit B overlies crater unit A at a depth of 442.5 m (1,451.7 ft) in the Langley core. The unit contact is placed at the base of the lowest zone of injected exotic matrix within crater unit B. Crater unit B is 173.0 m (567.7 ft) thick and consists of coherent blocks (4 millimeters to <1 m (0.16 inch to <3.3 ft) in diameter), megablocks (1 m to <25 m (<82 ft)), and megablock zones (multiple megablocks with block-on-block contacts) of Potomac Formation sediments separated by intervals of mixed native and exotic sediments called matrix zones.

The matrix zones consist of blocks of deformed Potomac Formation sediments suspended in a matrix of typically noncalcareous, muddy, pebbly, quartz-glauconite sand. The glauconite in these zones is an exotic component that represents injection of disaggregated Upper Cretaceous and Tertiary marine sediments downward into the nonglauconitic sediments of the Potomac Formation.

Crater unit B is divided into two informal subunits: the lower beds that contain glauconitic matrix only in a thin interval at their base and the upper beds that contain abundant glauconitic matrix zones. The contact between the subunits is placed at a depth of 427.7 m (1,403.3 ft).

Crater units A and B represent an autochthonous to parautochthonous sedimentary section within the impact structure's annular trough. These units present no evidence for large-scale removal of preimpact sediments by excavation flow or for shock deformation near the Langley corehole.

The basement granite, crater unit A, and the lower beds of crater unit B constitute an autochthonous section in which impact deformation was limited to local fluidization of sand beds and fracturing and faulting. Exotic sediments in this composite interval are limited to a 0.3-m-thick (1-ft-thick) interval of glauconitic matrix at the contact between crater units A and B. The upper beds of crater unit B constitute a parautochthonous section that contains widespread evidence of fracturing, slumping, and rotation of blocks and megablocks of the Potomac Formation, fluidization of sands, and injection of exotic sediments.

Inferred impact-generated deformation features in crater units A and B and their inferred causative mechanisms include the following: fractures and faults due to early tensional fracturing and (or) late-stage gravitational collapse, massive

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sand layers produced by increased pore-water pressure in sand beds or acoustic fluidization of sand beds, and dikes of disaggregated, near-surface, preimpact Cretaceous and Tertiary glauconitic sediments that were injected into an underpressured interval of the Potomac Formation.

The Exmore beds are 33.8 m (110.9 ft) thick; they overlie crater unit B and extend from 269.4 to 235.65 m (884.0 to 773.12 ft) depth in the Langley core. The Exmore beds consist of abundant clasts of unshocked, preimpact Cretaceous and Tertiary sediments and sparse shocked crystalline ejecta suspended in an unsorted and unstratified matrix of calcareous, muddy, quartz-glauconite sand and granules (polymict diamicton). A thin interval of clayey silts and fine sands (transition sediments) is present at the top of the Exmore beds above the diamicton at depths of 235.92 to 235.65 m (774.03 to 773.12 ft).

The diamicton is interpreted as debris-flow deposits produced by strong resurge currents that resulted from the late-stage gravitational collapse of the transient crater, including the water-column crater. The presence of two debris-flow units in the Exmore beds in the Langley core is inferred from the pattern of coarse-tail grading of large clasts and variations in the distribution of reworked Cretaceous fossils.

The fine-grained transition sediments represent fallout of impact-suspended sediments from the water column and the return to normal continental-shelf sedimentation. Poag (2002, *Geology,* v. 30, p. 995–998) and Poag and Norris (this volume, chap. F) interpret the presence within the transition sediments of a microspherule (microtektite) layer and an overlying biologic dead zone that lacks an indigenous fauna.

Introduction

Chesapeake Bay Impact Structure

The Chesapeake Bay impact structure is the dominant subsurface feature of the southeastern Virginia Coastal Plain and Inner Continental Shelf. It was formed about 35 million years ago by the impact of a comet fragment or asteroid on the late Eocene continental shelf of eastern North America and subsequently was buried beneath hundreds of meters of upper Eocene through Quaternary marine and paralic sediments.

The Chesapeake Bay impact structure is a complex crater that consists of an inner, highly deformed central crater (also called the inner basin) surrounded concentrically by a relatively less deformed annular trough (fig. C1) (Poag and others, 1994; Poag, 1997; Poag, Hutchinson, and others, 1999; Poag, Plescia, and Molzer, 1999; Powars and Bruce, 1999; Powars, 2000). The central crater is about 35 kilometers (km; 21.8 miles (mi)) in diameter. The annular trough extends outward from the central crater to the faulted outer margin, a radial distance of about 25 km (15.5 mi). Therefore, the outer margin (also called the outer rim) has a diameter of about 85 km (53 mi), which is the value typically cited as the size of the Chesapeake Bay impact structure.

This chapter discusses the lithologic, stratigraphic, structural, and depositional characteristics of impact-modified and impact-generated sediments of the Chesapeake Bay impact structure encountered in the USGS-NASA Langley core. The Langley corehole is located within the structure's annular trough near its southwestern margin at Hampton, Va. (fig. C1).

USGS-NASA Langley Corehole

Several coreholes were drilled into or near the annular trough of the Chesapeake Bay impact structure during the late 1980s and the 1990s (Powars and others, 1992; Powars and Bruce, 1999; Powars, 2000). The discovery of severely disrupted coastal plain deposits in these cores prompted the early investigations (Poag and others, 1991; Powars and others, 1991, 1992) that ultimately led to our present understanding of the Chesapeake Bay impact structure. However, none of these coreholes penetrated the lower part of the sedimentary section within the annular trough or the basement rocks below the sedimentary section.

In 2000, the U.S. Geological Survey (USGS) drilled a 635.1-meter (m)-deep (2,083.8-foot (ft)-deep), continuously cored test hole through the entire postimpact and impact-deformed sedimentary section and into the underlying basement rock at the National Aeronautics and Space Administration (NASA) Langley Research Center, Hampton, Va. (figs. C1, C2). This research was conducted in cooperation with the Hampton Roads Planning District Commission, the Virginia Department of Environmental Quality, the NASA Langley Research Center, and the Geology Department of the College of William and Mary (see “Acknowledgments”). Gohn and others (2001), Poag and the Chesapeake Coring Team (2001), Powars, Bruce, and others (2001), and Powers, Gohn, and others (2001) provided operational details and preliminary geologic analyses for the Langley corehole. The Langley corehole is located in the Newport News North 7.5-minute quadrangle (USGS, 1986) at lat 37°05'44.28" N., long 76°23'08.96" W. (North American Datum of 1927), at a ground-surface altitude of 2.4 m (7.9 ft) above the North American Vertical Datum of 1988.

Sediments modified or generated by the Chesapeake Bay impact are present in the Langley core between the top of basement rock at 626.3 m (2,054.7 ft) depth and the base of postimpact sediments at 235.65 m (773.12 ft) depth. This 390.6-m-thick (1,281.6-ft-thick) section is divided informally, from base to top, into crater unit A, crater unit B, and the Exmore beds. Inferences about the nature of the impact processes within the annular trough may be drawn from the patterns of sediment deformation, sediment removal, and resedimentation seen in the Langley core. This lithologic study is facilitated by the analysis of a high-resolution seismic-reflection survey conducted by the USGS at the NASA Langley Research Center (Catchings and others, this volume, chap. I).

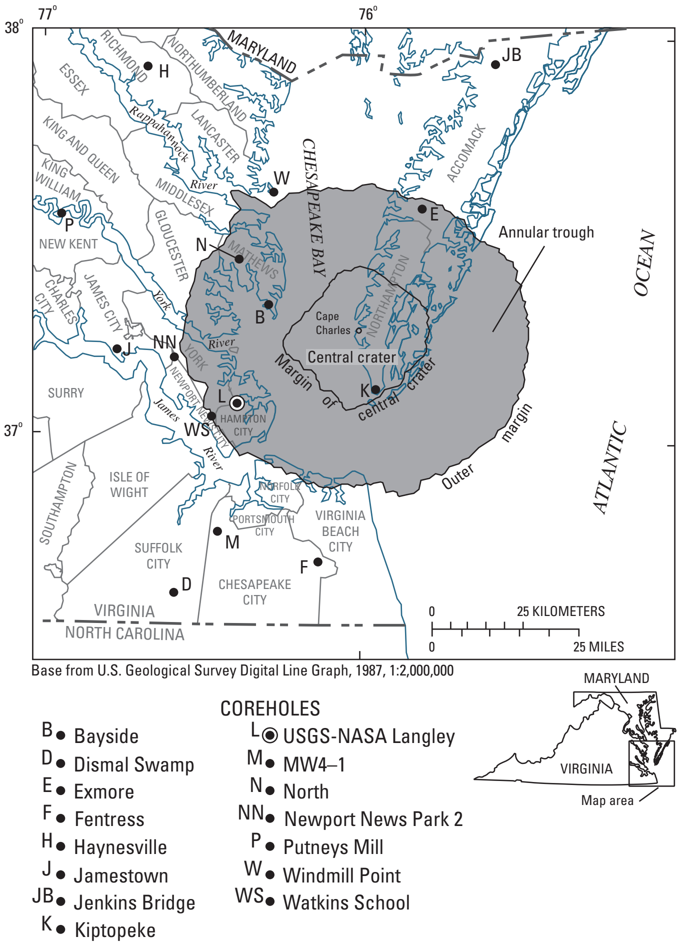


Figure C1. Regional map showing the location of the Chesapeake Bay impact structure, the USGS-NASA Langley corehole at Hampton, Va., and some other coreholes in southeastern Virginia. Locations of the central crater and outer margin are from Powars and Bruce (1999). Illustration modified from Powars, Johnson, and others (2002) and Edwards and Powars (2003).

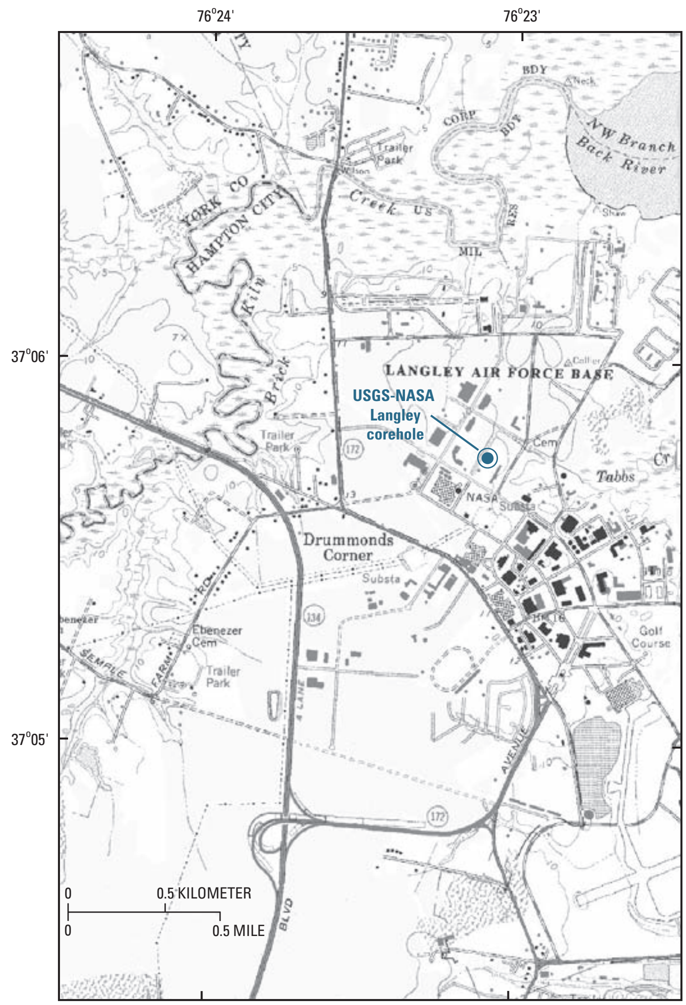


Figure C2. Detailed map showing the location of the USGS-NASA Langley corehole, Hampton, Va.

In this chapter, crater unit A, crater unit B, and the Exmore beds are discussed following a summary of the preimpact coastal plain stratigraphy of the southern Chesapeake Bay area. Horton and others (this volume, chap. B) provide an analysis of the basement rock at the bottom of the Langley core and a discussion and references for the regional geology of the pre-Cretaceous rocks below the coastal plain deposits of the impact area.

Regional Preimpact Stratigraphy

Cretaceous and lower Tertiary sediments of the Virginia Coastal Plain constituted a significant portion of the materials affected by the late Eocene Chesapeake Bay impact. Therefore, the postimpact distribution and character of these disrupted sediments within and near the impact structure constitute a major part of the complex record of impact-related deformation and sedimentation. The preimpact coastal plain units of the southern Chesapeake Bay area, as presently seen outside the impact structure, are reviewed here to provide the background needed for discussion of the impact-modified and impact-generated sediments in the Langley core.

The preimpact section of the study area consists of Lower Cretaceous, Upper Cretaceous, and lower Tertiary sedimentary units that differ significantly in their preimpact distributions and lithologic characteristics. Separate stratigraphic columns are shown in figure C3 for the areas west, south, and north (Delmarva Peninsula) of the impact structure.The Delmarva section includes data from deep drill holes in the adjacent part of the Maryland Coastal Plain north of the Chesapeake Bay impact structure. Ward (1985), Ward and Strickland (1985), Powars and Bruce (1999), and Powars (2000) provided maps that show the distributions of preimpact and postimpact stratigraphic units in the Virginia Coastal Plain. A discussion of the preimpact stratigraphy in southeastern Virginia also is provided by Poag, Koeberl, and Reimold (2004).

Lower Cretaceous and Basal Upper Cretaceous Stratigraphy

A thick, widespread section of Lower Cretaceous and basal Upper Cretaceous fluvial and deltaic sediments is assigned to the Potomac Formation in Virginia (for example, Powars and Bruce, 1999) and the equivalent Potomac Group in Maryland (for example, Hansen, 1982). The Potomac Formation constitutes most of the impact-modified section in the Langley core.

Regionally, the Potomac Formation consists of repetitive sections of noncalcareous silty and sandy clays, clayey silts, and muddy to moderately well sorted, typically feldspathic sands, gravelly sands, and gravels (Anderson, 1948; Reinhardt, Christopher, and Owens, 1980; Owens and Gohn, 1985; Powars and Bruce, 1999). The Potomac deposits include light- to dark-gray, locally lignitic and pyritic sediments as well as color-mottled, oxidized sediments. Sedimentary structures, cyclic sedimentation patterns, and the near absence of marine fossils indicate deposition in channels, bars, flood plains, and related subenvironments within fluvial to delta-plain environments (Hansen, 1969; Reinhardt, Christopher, and Owens, 1980).

In the absence of calcareous faunas and floras, palynomorphs (primarily pollen and spores) have been the principal source of data for biostratigraphic analysis of the Potomac Formation (Brenner, 1963; Doyle and Robbins, 1977; Reinhardt, Christopher, and Owens, 1980; Doyle, 1982). These microfloras indicate Barremian(?) through early Cenomanian ages for the Potomac Formation (Group) throughout the Virginia and Maryland Coastal Plains (fig. C3). Older Lower Cretaceous sediments and Jurassic(?) sediments are present in the Maryland and Virginia sections of the Delmarva Peninsula north of the Chesapeake Bay impact structure (Brown and others, 1972; Hansen, 1982), but their presence within the impact structure is not documented, and they probably are absent from that area.

The Potomac Formation thickens from a featheredge at the western margin of the coastal plain to hundreds of meters near the modern Atlantic coast (Anderson, 1948; Hansen, 1969, 1982; Brown and others, 1972). The Potomac Formation is at least 305 m (1,000 ft) thick immediately west of the impact structure on the York-James Peninsula (Powars and Bruce, 1999) and at least 546 m (1,790 ft) thick near the southern margin of the impact structure in the Norfolk area (Brown and others, 1972). The total thickness of Lower Cretaceous and Jurassic(?) sediments north of the impact structure in Virginia is about 1,400 m (about 4,600 ft), and sections that are 1,220 m to at least 1,525 m (4,000 to 5,000 ft) thick are present farther north in Maryland (Anderson, 1948; Hansen, 1982).

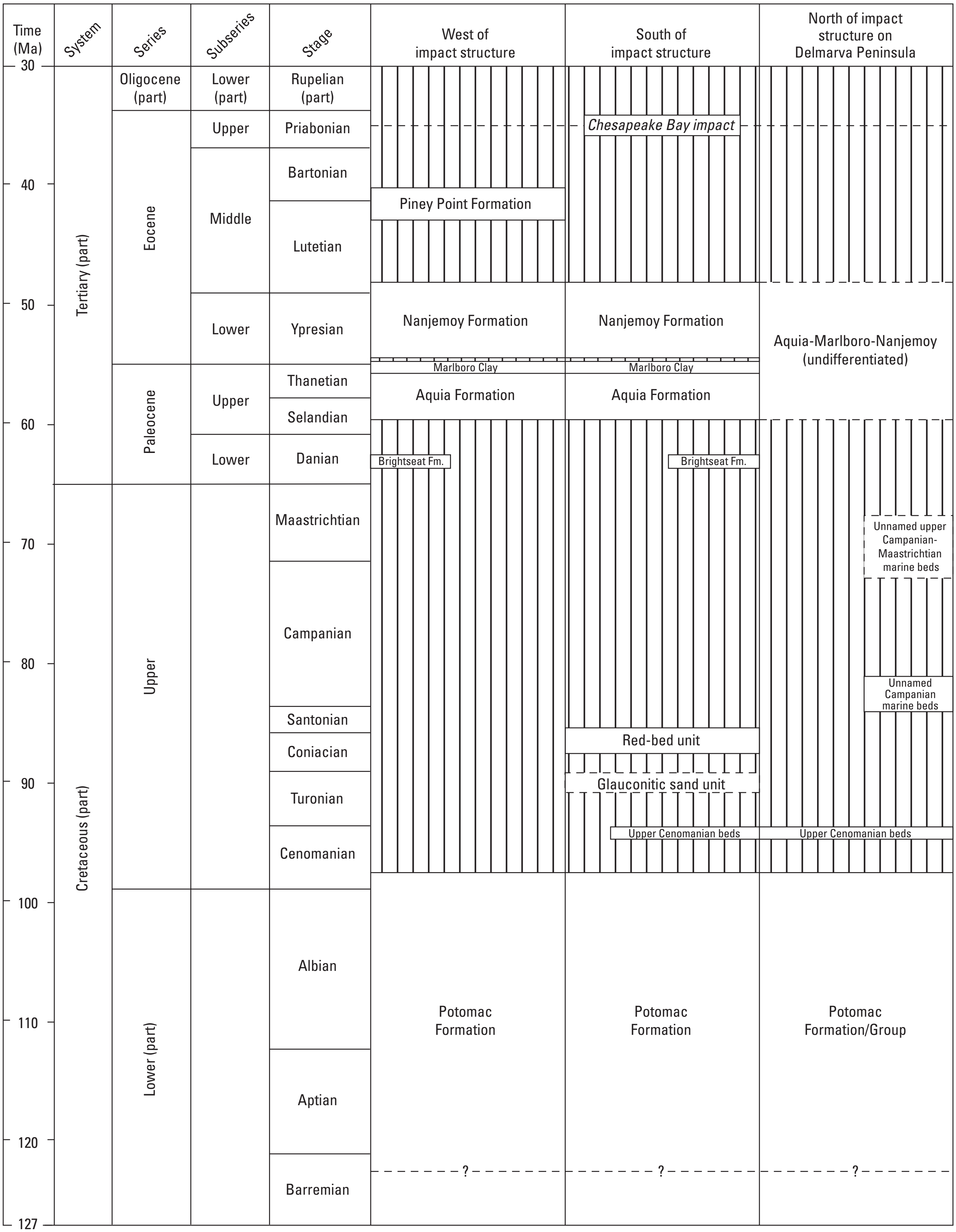
Upper Cretaceous Stratigraphy

The Upper Cretaceous stratigraphic units of the southern Chesapeake Bay area consist of relatively thin sections of primarily marine sediments that are restricted in their stratigraphic and geographic extents. Common lithologies include gray and greenish-gray, fossiliferous, glauconitic quartz sands and calcareous, fossiliferous muds that contrast with the locally oxidized, nonmarine sediments of the Potomac Formation. Upper Cretaceous sediments are not present west of Chesapeake Bay and the impact structure in Virginia (Owens and Gohn, 1985; Powars and Bruce, 1999).

Unnamed upper Cenomanian beds constitute the oldest and most widespread Upper Cretaceous unit, occurring both north and south of the impact structure. South of the structure, this unit consists of numerous fining-upward repetitions of shelly, glauconitic sand and fossiliferous, burrowed muds that are overlain by micaceous, lignitic, muddy sands (Powars and others, 1992; Powars and Bruce, 1999; Powars, 2000). Collectively, these lithologies suggest deposition on the inner shelf above wave base and possibly in delta-front environments. Similar upper Cenomanian sediments are present north of the impact structure on the Delmarva Peninsula (Anderson, 1948; Hansen and Wilson, 1990; Powars and others, 1992; Powars and Bruce, 1999).

A late Cenomanian age for these beds is indicated by their palynomorphs (Doyle and Robbins, 1977; G.J. Brenner, *in* Hansen and Wilson, 1990), mollusks (Stephenson, 1948a,b; N.F. Sohl, USGS, oral commun., 1988), and ostracodes (G.S. Gohn, USGS, unpub. data). The upper Cenomanian beds thicken to the southeast in the area south of the impact structure; known thicknesses in that area range from 10.0 m (33 ft) to 64.6 m (212 ft) (Powars, 2000). North of the structure in Virginia, the upper Cenomanian beds are about 12.2 to 33.5 m (40 to 110 ft) thick (Doyle and Robbins, 1977; Hansen and Wilson, 1990; Powars and others, 1992).

Figure C3 (facing page). Regional stratigraphic columns for the Cretaceous and lower Tertiary sedimentary units in the vicinity of the Chesapeake Bay impact structure. The geologic time column is adapted from Berggren and others (1995) and Gradstein and others (1995). References for the stratigraphic units are listed in the text. Vertical bars indicate the absence of sediments.


Time (Ma)
System
Series
Subseries
Stage
West of impact structure
South of impact structure
North of impact structure on Delmarva Peninsula
30
40
50
60
70
80
90
100
110
120
127
Tertiary (part)
Cretaceous (part)
Oligocene (part)
Eocene
Paleocene
Upper
Lower (part)
Lower (part)
Upper
Middle
Lower
Upper
Lower
Rupelian (part)
Priabonian
Bartonian
Lutetian
Ypresian
Thanetian
Selandian
Danian
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Aptian
Barremian
Chesapeake Bay impact
Piney Point Formation
Nanjemoy Formation
Nanjemoy Formation
Aquia-Marlboro-Nanjemoy (undifferentiated)
Marlboro Clay
Marlboro Clay
Aquia Formation
Aquia Formation
Brightseat Fm.
Brightseat Fm.
Unnamed upper Campanian-Maastrichtian marine beds
Unnamed Campanian marine beds
Red-bed unit
Glauconitic sand unit
Upper Cenomanian beds
Upper Cenomanian beds
Potomac Formation
Potomac Formation
Potomac Formation/Group
?
?
?

Two informally recognized Upper Cretaceous units are present above the upper Cenomanian beds in the area south of the impact structure in Virginia; these are the glauconitic sand unit and the red-bed unit of Powars and others (1992), Powars and Bruce (1999), and Powars (2000). The glauconitic sand unit is known from two coreholes in southeastern Virginia where about 16.8 to 18.0 m (55 to 59 ft) of these marine deposits overlie the upper Cenomanian beds. No fossils have been examined from the glauconitic sand unit, but its stratigraphic position (fig. C3) suggests a Turonian age (Christopher and others, 1999).

The red-bed unit overlies the glauconitic sand unit and consists of oxidized, color-mottled muds, sands, and gravelly sands. These deposits are noncalcareous and contain mudcracks, rootlets, and paleosols that indicate continental environments of deposition similar to those inferred for the Potomac Formation.

Observed thicknesses of the red-bed unit range from 16.3 to 27.8 m (53.4 to 91.3 ft). Palynomorphs from this unit indicate a Coniacian to Santonian age (N.O. Frederiksen, USGS, written commun., 1999). The palynologic age, stratigraphic position, and lithologies of the red-bed unit suggest that it is a northward continuation of the widespread Cape Fear Formation of the Carolinas (Christopher and others, 1999).

Two additional Upper Cretaceous marine units are recognized north of the impact structure on the Delmarva Peninsula in Virginia and Maryland (fig. C3). The older of these unnamed units reaches a maximum thickness of about 15 m (about 50 ft) and contains microfossils that indicate a late Santonian(?) to early Campanian age (Anderson, 1948; Swain, 1948; R.K. Olssen, *in* Hansen and Wilson, 1990; Powars and others, 1992; G.S. Gohn, USGS, unpub. data). The presence of unnamed upper Campanian to Maastrichtian beds may be inferred from mollusks described from sediment cores of the Hammond test hole in Maryland (Stephenson, 1948b) and from reworked Maastrichtian microfossils found in impact-generated sediments of the impact structure (Powars and others, 1992). These Santonian(?) to Maastrichtian sections consist primarily of fossiliferous, fine-grained sediments (Anderson, 1948; Powars and others, 1992).

Lower Tertiary Stratigraphy

The preimpact Tertiary section of the Virginia Coastal Plain (fig. C3) consists of marine sediments of the Paleocene and Eocene Pamunkey Group (Ward, 1985); from oldest to youngest, the Pamunkey Group contains the Brightseat Formation, Aquia Formation, Marlboro Clay, Nanjemoy Formation, and Piney Point Formation. Except for the Brightseat, the formations of the Pamunkey Group are widespread in the Virginia Coastal Plain. In detailed studies, the Aquia, Nanjemoy, and Piney Point Formations typically are divided into members and (or) beds. Common lithologies include shelly limestones, muds, and muddy quartz, quartz-glauconite, and glauconite sands. Calcareous macrofossils and microfossils are moderately abundant throughout the Pamunkey Group in sections that have not been leached of their calcium carbonate. Lithologies, ages, distributions, and thicknesses of the lower Tertiary formations described in the following summary paragraphs are derived from Gibson and others (1980), Reinhardt, Newell, and Mixon (1980), Ward (1985), Ward and Strickland (1985), Mixon (1989), Hansen and Wilson (1990), Powars and others (1992), Poag and Ward (1993), Poag and Commeau (1995), Powars and Bruce (1999), and Powars (2000).

The oldest preimpact Tertiary unit is the lower Paleocene Brightseat Formation, which consists of fossiliferous, micaceous muddy fine sands. The Brightseat is generally considered to be present only in updip areas of the Virginia Coastal Plain north of the Rappahannock River. However, Powars and others (1992; also see Powars, 2000, p. 33) referred a thin section of lower Paleocene muddy, glauconitic sand in the Virginia Coastal Plain south of Chesapeake Bay and the impact structure to the Brightseat Formation on the basis of lithologic and paleontologic data (fig. C3).

The widespread upper Paleocene Aquia Formation consists of variably macrofossiliferous and microfossiliferous, muddy, glauconite and quartz-glauconite sands that extend beneath most of the Virginia Coastal Plain. The Aquia maintains a thickness in the range of 6.1 to 18.3 m (20 to 60 ft) in areas adjacent to the impact structure.

The uppermost Paleocene and lowermost Eocene Marlboro Clay is a thin but widespread unit in areas west and south of Chesapeake Bay. The Marlboro consists of distinctive, sparingly fossiliferous, gray and pale-red, kaolinitic silty clay that contrasts with the greenish glauconitic sediments of the overlying and underlying units. Thicknesses of the Marlboro are in the range of 2.4 to 5.5 m (8 to 18 ft) in areas adjacent to the western and southern margins of the impact structure.

The widespread lower Eocene Nanjemoy Formation consists of typically fossiliferous, burrowed muds and muddy fine to coarse glauconite-quartz sands. The thickness of the Nanjemoy ranges from about 12.2 to 18.3 m (40 to 60 ft) in areas near the western and southern margins of the impact structure.

The middle Eocene Piney Point Formation is composed of muddy, glauconitic, highly fossiliferous, locally calcite-cemented, quartz-glauconite sand and quartzose and glauconitic, moldic, pelecypod limestone. The Piney Point does not occur in the area south of the impact structure but is widespread in the area west of the impact structure and Chesapeake Bay. Thicknesses of 1.8 to 6.1 m (6 to 20 ft) are recorded for the Piney Point in the area adjacent to the western margin of the impact structure.

The geology of the Pamunkey Group in the Virginia part of the Delmarva Peninsula north of the impact structure is not well documented. However, data from the adjacent part of the Maryland Coastal Plain suggest that Paleocene through middle Eocene sections of marine deposits in that area are about 40 to 100 m (about 120 to 300 ft) thick (Anderson, 1948; Brown and others, 1972; Hansen, 1978; Hansen and Wilson, 1990; Poag and Commeau, 1995).

Implications for Impact Crater Analysis

The Cretaceous and lower Tertiary sedimentary section disrupted by the late Eocene Chesapeake Bay impact consisted of two lithologically distinct parts: a lower section of Lower Cretaceous and basal Upper Cretaceous nonmarine sediments and an upper section of Upper Cretaceous and lower Tertiary marine sediments. The lower section consisted of nonglauconitic, noncalcareous, locally oxidized, interbedded sands and clays, whereas the upper section consisted of glauconitic to very glauconitic, typically calcareous, sparingly oxidized, fine-grained deposits. The lithologic contrast between these two sections is a useful tool for analyzing the character and extent of impact-produced sediment disruption and mixing in the annular trough.

USGS-NASA Langley Core

Stratigraphy of the Annular Trough

Previous studies divided the sedimentary section within the annular trough of the Chesapeake Bay impact structure into two units: the megablock unit and the overlying Exmore beds (Poag, 1996, 1997; Poag, Hutchinson, and others, 1999; Powars and Bruce, 1999; Powars, 2000). Poag (1997, p. 57) considered the megablocks to be slumped blocks of fractured sedimentary rocks that were affected by the impact. His interpretations of the megablocks on seismic-reflection profiles show normal-fault-bounded, locally rotated blocks having typical dimensions of tens to hundreds of meters (Poag, 1996, 1997; Poag, Hutchinson, and others, 1999). Powers and Bruce (1999, p. 30–31) stated, on the basis of limited core data, that the megablocks consisted primarily of Lower Cretaceous fluvial and deltaic deposits (Potomac Formation).

Powers and Bruce (1999, p. 29) described the Exmore as a lithologically variable unit, which consists of shelly, glauconitic, muddy, pebbly sand that serves as a matrix between abundant clasts of preimpact sediments, sparse clasts of crystalline rock and melt rock, and sparse shocked quartz grains (also see Koeberl and others, 1996). Informal stratigraphic names previously applied to the Exmore unit include the “Exmore beds” (Powars and others, 1992), the “Exmore boulder bed” (Poag and others, 1992), the “Exmore breccia” (Poag, 1996, 1997), and the “Exmore tsunami-breccia” (Powars and Bruce, 1999; Powars, 2000). Powars, Bruce, and others (2001) referred to these deposits in the Langley core as “unit C.”

In this chapter, the sedimentary section of the annular trough recovered in the Langley core is divided informally into crater unit A, crater unit B, and the Exmore beds. These units are defined on the basis of physical criteria observed in the core (fig. C4), including the lithology, size, and deformation of sediment blocks and clasts, the presence or absence of preimpact Tertiary sediments as detrital clasts, exotic blocks, or exotic matrix, and the presence or absence of fluidized sands, resedimented deposits, and shocked and (or) cataclastic crystalline-rock ejecta.

We consider the megablock sections of previous authors to be generally equivalent to crater unit A of this chapter on the basis of similarities in sediment types and postimpact stratigraphic position. Sections of crater unit B probably were assigned to the Exmore beds in previous reports because of the gross lithologic similarity of crater unit B to the Exmore beds (sediment blocks or clasts in matrix). However, the Exmore beds are more narrowly defined in this chapter, where block-in-matrix sections with a strong dominance of Potomac Formation blocks and a paucity of crystalline-rock and Tertiary sediment blocks are excluded from the Exmore and included in crater unit B.

Poag and Norris (this volume, chap. F) continue the use of a two-part subdivision (megablocks and Exmore breccia) for the sedimentary section in the Langley core (fig. C5). They indicate that their definition of the term “Exmore breccia” includes crater unit B and the Exmore beds of this chapter.

The Exmore breccia of Poag and Norris (this volume, chap. F) does not include a thin interval of fine-grained sediments that we include as the uppermost part of the Exmore beds in this chapter (fig. C5). Instead, they assign this fine-grained interval to a lower “fallout layer” and an upper “dead zone” that are located above their Exmore breccia and below the postimpact Chickahominy Formation (also see Poag, 2002). Poag and Norris (this volume, chap. F) place the fallout layer and dead zone between depths of 235.87 and 235.65 m (773.85 and 773.12 ft) in the Langley core. After reconsideration of the original core photographs and field notes for the Langley core, we consider these fine-grained sediments to extend from a depth of 235.92 m to 235.65 m (774.03 ft to 773.12 ft) (fig. C5) and refer to them as the “transition sediments” of the Exmore beds.

Terminology for Coarse-Grained Materials

Two sets of grain-size terminology are used in this chapter to describe the very large particles present in the crater materials of the Langley core. The standard Wentworth grade scale and class terms (Wentworth, 1922) are used for the Exmore beds because this unit is interpreted to consist of allogenic clastic sediments. Hence, particles having diameters longer than 4 millimeters (mm; 0.16 inch (in.)) in the Exmore beds are described as pebbles, cobbles, and boulders; the term “clast” is used to refer collectively to these size classes. The Wentworth (1922) scale also is used for primary detrital particles within the preimpact sediments.

In contrast, crater units A and B are interpreted to consist of autochthonous to parautochthonous sedimentary sections in which the formation of large constituent pieces was primarily the result of impact-induced fracturing and faulting. For these materials, the word “block” is used for particles that are 4 mm (0.16 in.) to less than 1 m (3.3 ft) in diameter. Particles that are 1 m to less than 25 m (82 ft) in diameter are called “megablocks.” Particles larger than 25 m were not recognized in the

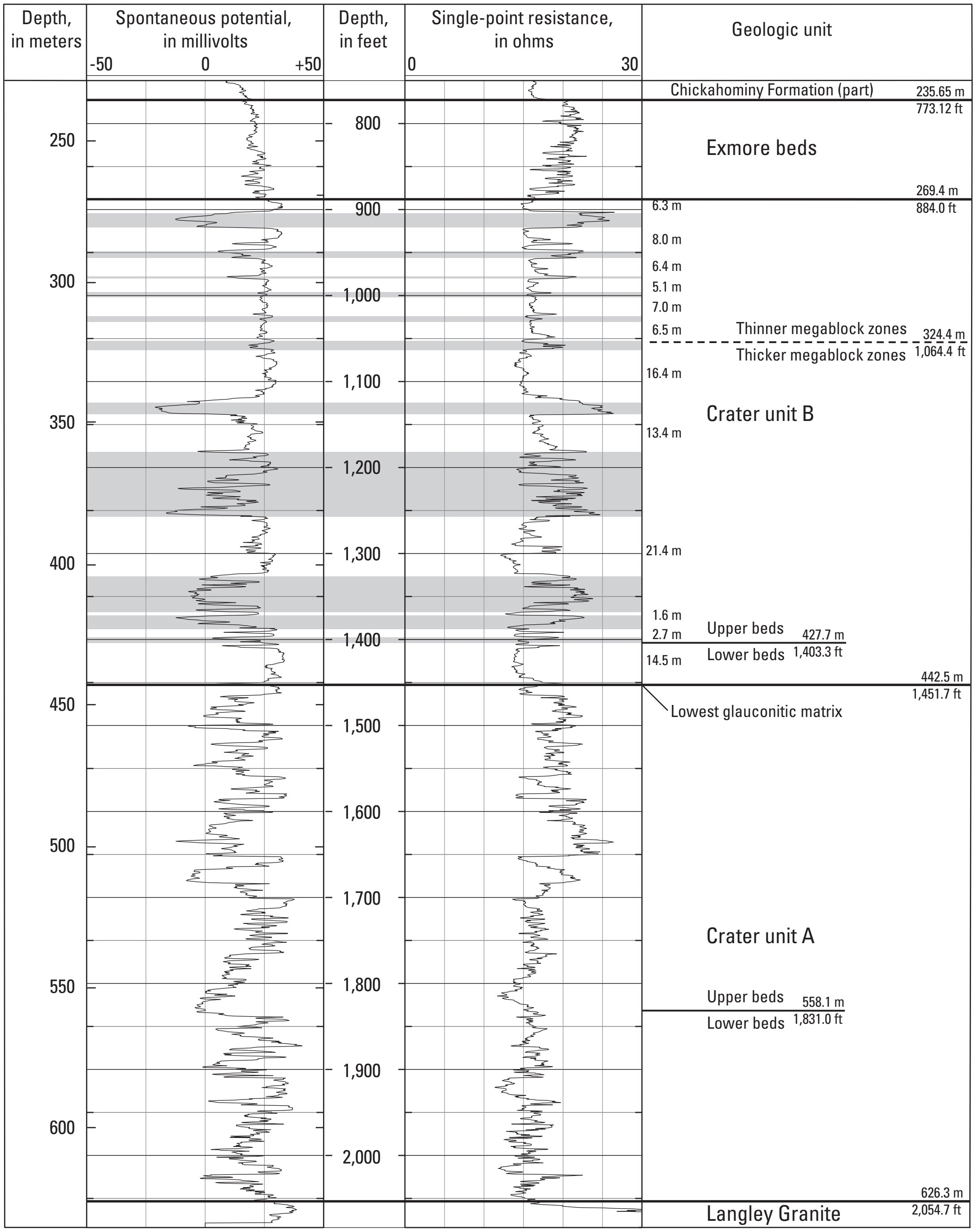


Figure C4. Summary geologic column and geophysical logs for the impact-modified sediments (crater units A and B) and impact-generated sediments (Exmore beds) in the USGS-NASA Langley core. Thicknesses of sediment megablocks in crater unit B are indicated; see also figure C7. Shaded intervals are zones of injected glauconitic matrix in crater unit B.

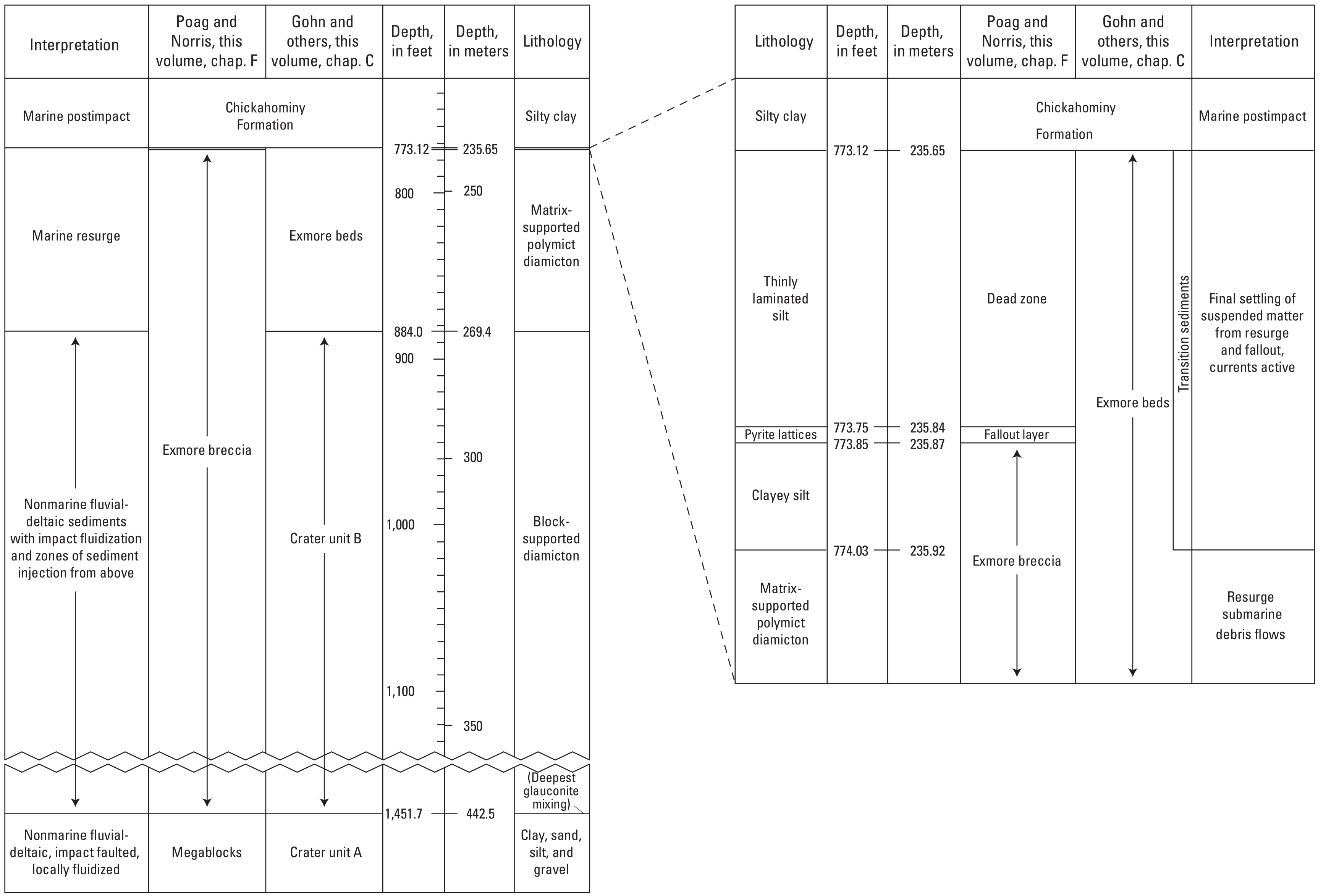


Figure C5. Correlation diagram for part of the USGS-NASA Langley core comparing informal usage of the terms "Exmore beds" and "Exmore breccia" in relation to lithology and interpretation of ocean-water resurge deposits. The stratigraphic terms defined in this chapter (Gohn and others, chap. C) are used throughout this volume except in chapter F (Poag and Norris), which follows the stratigraphy of Poag, Koeberl, and Reimold (2004). From Horton and others (this volume, chap. A, fig. A6).

Langley core, although fault-bounded blocks of greater size probably are present (Catchings and others, this volume, chap. I).

The term "megablock" in this chapter refers to constituent particles that are smaller than the fault-bounded, slumped megablocks defined by Poag (1996, 1997), Powars and Bruce (1999), and others. The term "fault blocks" might be more appropriate for the large "megablocks" (tens to hundreds of meters in diameter) described by these authors.

Crater Unit A

General Lithology and Thickness

Crater unit A comprises poorly to moderately compacted sediments of the Cretaceous Potomac Formation between depths of 626.3 m (2,054.7 ft) and 442.5 m (1,451.7 ft) in the Langley core (fig. C4); thus, it is 183.8 m (603.0 ft) thick. The basal contact of crater unit A with the underlying weathered granite is sharp and nonconformable. Approximately the basal meter (3 ft) of crater unit A contains abundant subangular to angular granite pebbles and cobbles.

Crater unit A consists of noncalcareous, nonglauconitic, silty and sandy clays, clayey silts, muddy fine sands, gravelly coarse sands, sandy quartz-feldspar-chert gravels, and sandy clay-intraclast gravels**.** The sands and gravelly sands are more abundant than the finer grained sediments throughout the unit. Sediment colors vary from light and dark gray to less common red and brown oxidation colors. Repetitive fining-upward sedimentary cycles with erosional bases, basal sandy gravels, and distinctive sequences of sedimentary structures and lithologies are typical of crater unit A. Shocked or cataclastic ejecta (Horton and Izett, this volume, chap. E), exotic clasts of Tertiary sediment, and exotic disaggregated Tertiary sediments were not observed in crater unit A.

The contact between crater unit A and the overlying crater unit B at a depth of 442.5 m (1,451.7 ft) is placed at the base of the lowest (deepest) occurrence of muddy, gravelly, quartz-glauconite sand (referred to as "matrix") between blocks and megablocks of Potomac Formation sediments (see following section on "Crater Unit B"). The lowest occurrence of glauconitic matrix is a useful field criterion for defining these units, and it has genetic significance with regard to the limit of impact-induced mixing of glauconitic and nonglauconitic sediments.

Crater unit A is divided into two informal subunits: the lower beds and the upper beds. Physical characteristics used to divide these subunits are the presence of highly fractured clays and thick, massive (structureless), gravelly sands in the upper beds and the paucity of these features in the lower beds. The contact between the subunits is placed at the base of the stratigraphically lowest, massive gravelly sand at 558.1 m (1,831.0 ft) depth.

Lower Beds of Crater Unit A

Undisrupted primary (Cretaceous) sedimentary features characterize the lower beds of crater unit A. Horizontal and low-angle bedding and laminations are present throughout this unit, indicating that little or no rotation of the cored section has occurred. Silty and sandy clay beds in this interval display moderate- to high-angle fractures and small faults but do not show evidence of slumping and rotation, which is common in clays of the upper beds.

Upper Beds of Crater Unit A

Primary (Cretaceous) sediment types, sedimentary structures, and sedimentary cycles in the upper beds (fig. C6*A*) are similar to those in the lower beds. However, thick intervals of massive gravelly sand also are present in the upper beds, particularly from 558.1 m to about 542.5 m (1,831.0 ft to about 1,780.0 ft) depth and from 503.4 to 486.2 m (1,651.5 to 1,595.0 ft) depth. These sands contain disseminated quartz, chert, and clay pebbles but lack stratification (fig. C6*B*). The pebbles do not occur in distinct size-graded beds or at predictable positions within sedimentary cycles, as seen in the lower beds of crater unit A. Fractured and faulted, oxidized clays from 486.2 to 482.0 m (1,595.0 to 1,581.5 ft) depth contain bedding and laminations inclined at moderate angles and overlie the higher interval of massive sand.

Crater Unit B

General Lithology and Thickness

Crater unit B is present in the Langley core from 442.5 m (1,451.7 ft) to 269.4 m (884.0 ft) depth and has a thickness of 173.0 m (567.7 ft). This unit consists, in large part, of Cretaceous sediments of the Potomac Formation that are generally similar in their primary depositional characteristics to the Potomac Formation sediments in crater unit A. However, Potomac Formation sediments in crater unit B are substantially more disrupted than those in crater unit A.

We refer to intervals in crater unit B that consist of locally derived sediment blocks suspended in a finer grained matrix of mixed exotic and locally derived sediments as "matrix zones." The matrix zones intervene between larger coherent megablocks and between intervals of multiple blocks and megablocks that we refer to as "megablock zones" (fig. C7).

Crater unit B is divided into two informal subunits: the lower beds and the upper beds. The contact between the subunits is placed at a depth of 427.7 m (1,403.3 ft); it separates Potomac Formation sediments with minimal exotic matrix in the lower beds from an overlying thicker section of Potomac Formation sediments disrupted by numerous matrix zones in the upper beds. The only matrix zone in the lower beds is present at the base of the unit from 442.5 m (1,451.7 ft) to 442.2 m (1,450.8 ft) depth.

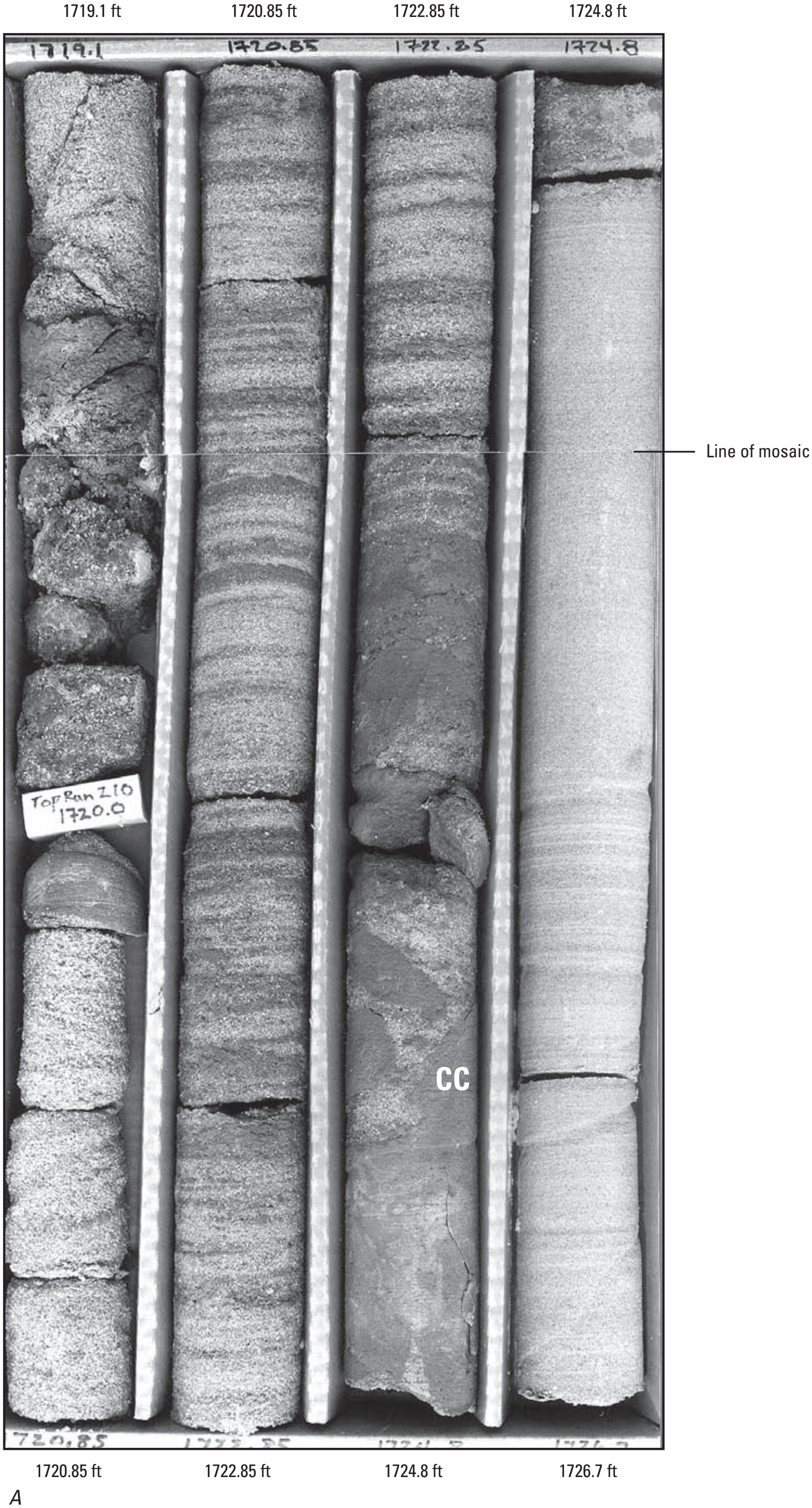


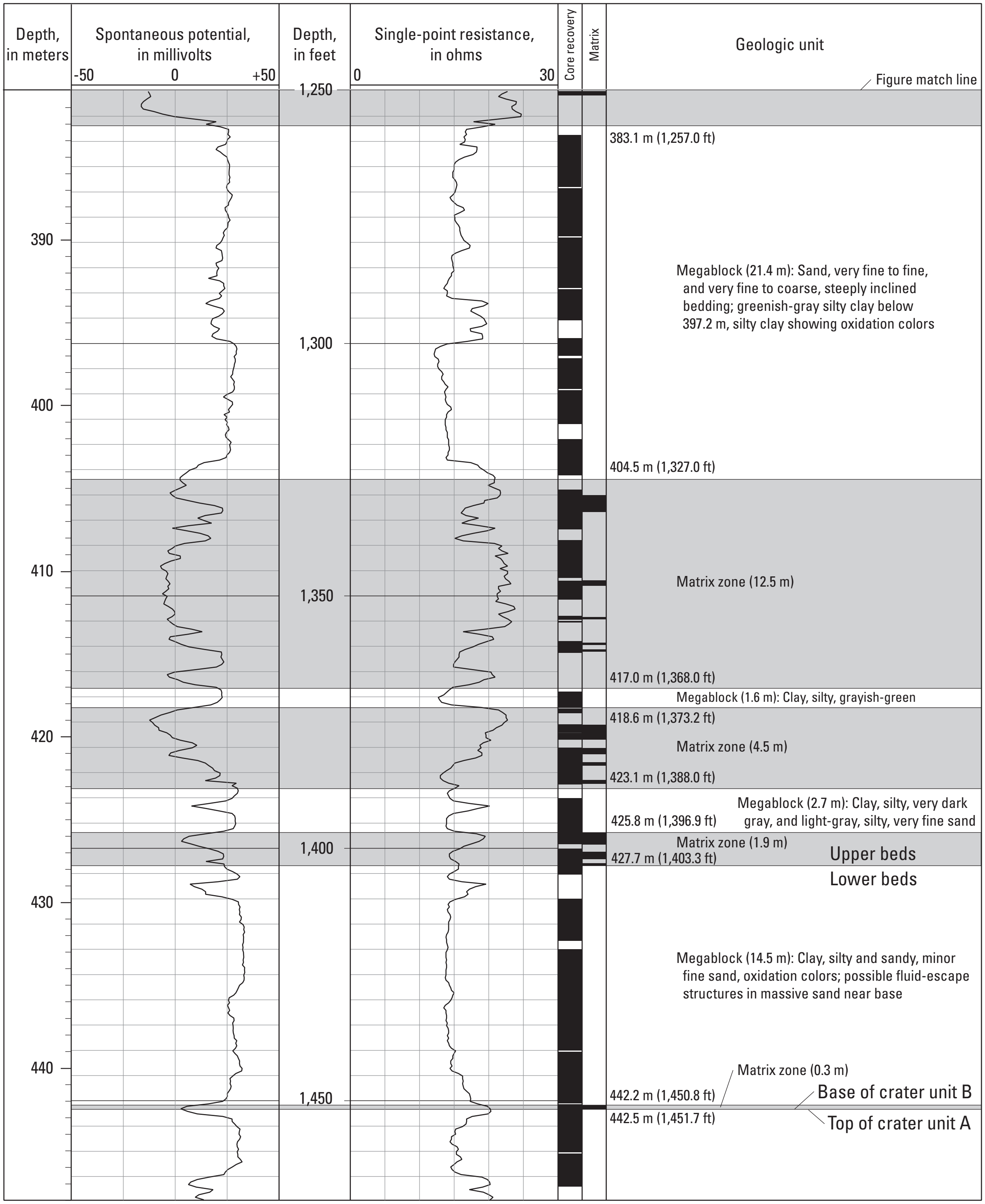
Figure C6. Photographs of the upper beds of crater unit A in the USGS-NASA Langley core. Depths handwritten on the core boxes in feet are repeated in type for clarity. Section tops are at the upper left corners of the boxes. *A,* Composite photograph of core box 173 showing horizontally laminated and cross-laminated sands, horizontally interbedded and interlaminated sands and clays, and clay-clast gravels. The clay clasts (CC) in the third tray from the left are uniform in composition and locally derived. Metric depth values for the top and bottom of box 173 are 524.0 m and 526.3 m. *B,* Photograph of core box 165 showing massive (fluidized) sand with disseminated quartz and clay pebbles. Metric depth values for the top and bottom of box 165 are 493.9 m and 496.8 m.

1620.5 ft 1622.5 ft 1624.5 ft 1626.5 ft

1622.5 ft 1624.5 ft 1626.5 ft 1630.0 ft

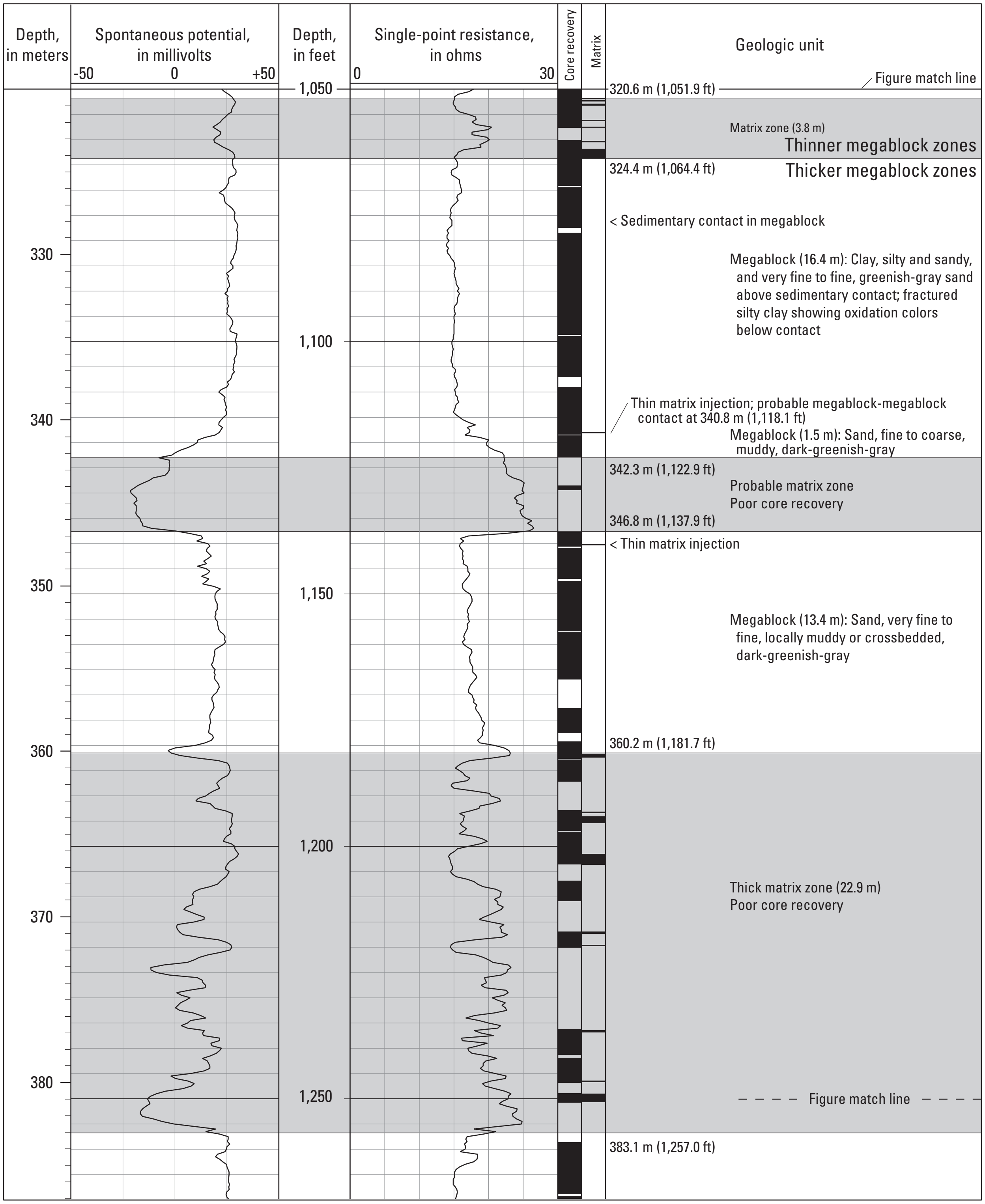
B

Figure C6. Continued.



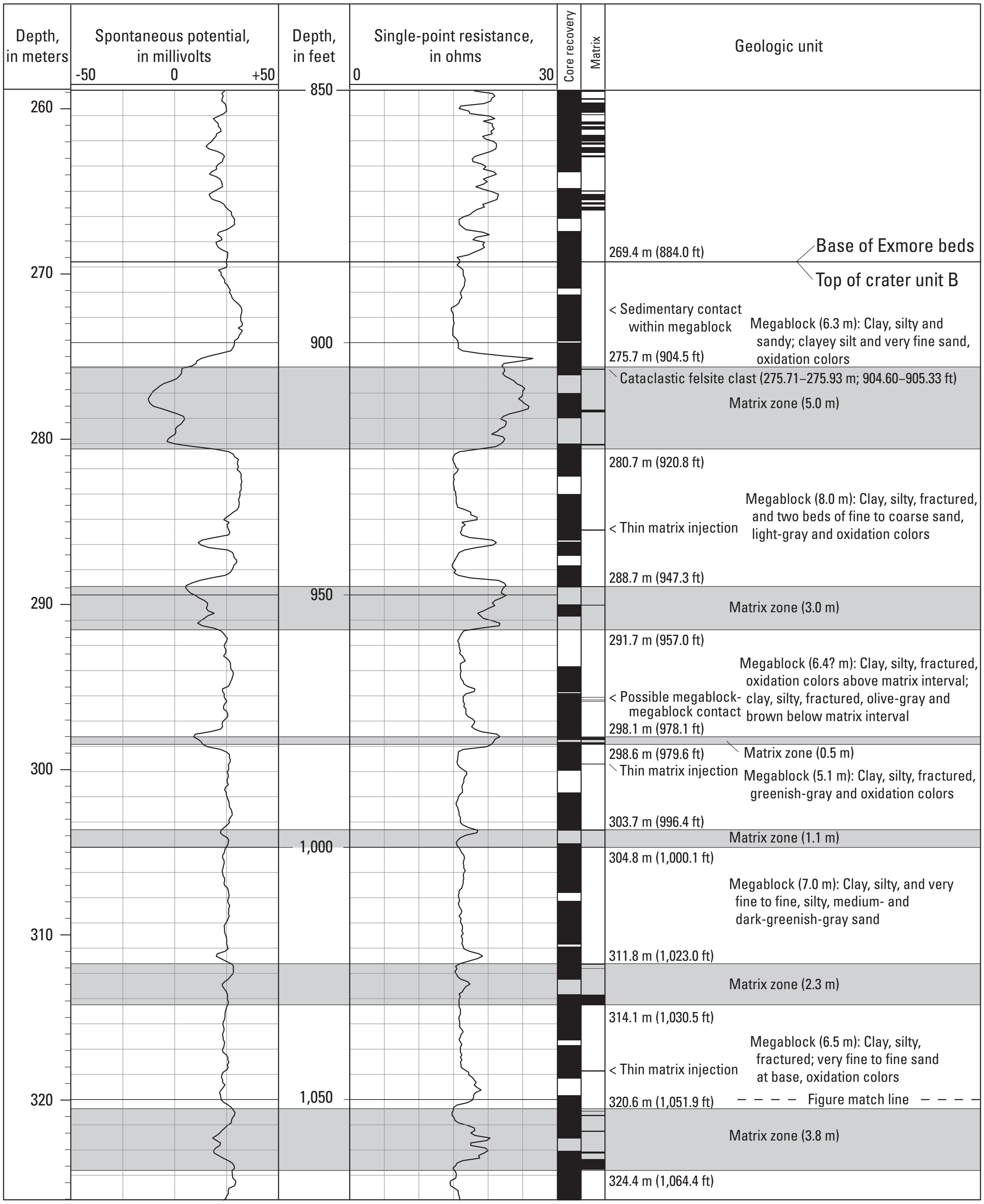
A. Lower part of crater unit B

Figure C7. Geologic column and geophysical logs for crater unit B in the USGS-NASA Langley core. Depths to contacts between blocks, megablocks, and matrix zones are listed, and thicknesses and lithologies of blocks and megablocks are indicated. Core recovery (black), individual matrix occurrences (black), and matrix zones (gray) also are indicated. The data are presented in three pages, and match lines are shown on each page. *A,* Lower part of crater unit B from 442.5 m (1,451.7 ft) to 383.1 m (1,257.0 ft) depth. *B,* Middle part of crater unit B from 383.1 m (1,257.0 ft) to 320.6 m (1,051.9 ft) depth. *C,* Upper part of crater unit B from 324.4 m (1,064.4 ft) to 269.4 m (884.0 ft) depth.



B. Middle part of crater unit B

Figure C7. Continued.



C. Upper part of crater unit B

Figure C7. Continued.

Megablocks and Megablock Zones

Definition and lithologies.—Megablocks in crater unit B consist entirely of coherent, slightly to moderately deformed pieces of the Potomac Formation. Some megablocks consist of a single lithology, whereas others contain a range of clays, silts, sands, and gravelly sands. Primary bedding, laminations, crossbedding, and erosional contacts between beds are present within many megablocks. Individual megablocks may consist primarily of multicolored oxidized sediments, light- to dark-gray sediments, or both.

A variety of structural and sedimentary features hinders the recognition of certain megablock contacts. In some sections of the Langley core, convincing examples of primary sedimentary contacts (and other stratification) within coherent megablocks are present, including cases where contrasting lithologies are separated by primary sedimentary contacts. However, planar contacts between two separate megablocks, especially contacts between two megablocks that consist of the same sediment type, can be difficult to distinguish from the sedimentary contacts within megablocks. In other examples, centimeter-scale layers of glauconitic matrix separate megablocks having similar or contrasting lithologies. In these examples, it can be difficult to distinguish a matrix-filled fracture within an otherwise coherent megablock from a block-on-block contact with a trace of matrix between two megablocks. For these reasons, we have defined megablock zones in crater unit B as composite sections of two or more Potomac Formation blocks and megablocks separated by probable block-on-block contacts. Recognized megablock contacts within megablock zones are listed in figure C7.

Nearly structureless, nonglauconitic, very fine to very coarse grained sand with a few thin intervals of disrupted relict laminations is present above the basal glauconitic matrix zone in the lower part of the lower beds from 442.2 m (1,450.8 ft) to about 439.6 m (1,442.2 ft) depth. Oxidized fine-grained sediments are present in the lower beds from about 439.6 m (1,442.2 ft) to the subunit contact at 427.7 m (1,403.3 ft).

Megablocks and megablock zones from 427.7 m (1,403.3 ft) to 340.8 m (1,118.1 ft) depth in the upper beds of crater unit B primarily consist of gray and greenish-gray, carbonaceous clays, silts, and sands (fig. C8*A*). Beds of very fine to fine and very fine to coarse sands in this interval are noncalcareous, variably muddy, and locally lignitic or gravelly. Cross laminations and crossbedding, clay laminations, burrows, and clay intraclasts are common in these sands. Thicker clay beds in this interval typically are dark gray, lignitic, silty, and sandy. Oxidized silty and sandy clays and muddy fine sands are present from 404.5 m (1,327.0 ft) to 397.2 m (1,303 ft) depth.

Megablocks and megablock zones in the upper beds of crater unit B above 340.8 m (1,118.1 ft) depth consist primarily of oxidized red, brown, and light-gray sediments (fig. C8*B*). The most common sediment type is color-mottled, noncalcareous, silty and locally sandy clay. These clays are dense and contain abundant faults with slickensides; primary bedding generally is difficult to discern. Root casts and crumbly and blocky fabrics suggest primary subaerial environments of deposition. A second sediment type in this interval is color-mottled, noncalcareous, micaceous, clayey silt and very fine sand. The sands are locally cross laminated or massive. Dominantly gray, noncalcareous, well-sorted, very fine to fine sands also are present. These sands typically are massive but locally contain clay-silt laminae and primary clay-silt intraclasts.

Thickness and distribution.—Megablocks and megablock zones in crater unit B range in thickness from about 1.5 to 21.4 m (4.9 to 70.2 ft) (fig. C7). These measured thicknesses represent the maximum apparent vertical dimension of each megablock or megablock zone.

The thicker megablocks and megablock zones (about 16.0 to 22.0 m; 52.5 to 72.2 ft) occur in the lower half of crater unit B below 324.4 m (1,064.4 ft) depth, whereas those above 324.4 m (1,064.4 ft) depth range from about 5.0 to 8.0 m (16.4 to 26.2 ft) in thickness. The change from thicker to thinner megablocks and megablock zones does not correspond to the subunit boundary between the lower and upper beds of crater unit B (fig. C4).

Structures.—Several megablocks in crater unit B display oversteepened bedding (figs. C7 and C8). Dips from 45° to about 75° are locally present, indicating significant rotation of these blocks. Fractures and faults of uncertain displacement also are typical within or bounding individual megablocks.

Matrix Zones

Definition and lithologies.—The matrix zones consist of sediment blocks from the Cretaceous Potomac Formation suspended in a matrix of disaggregated Cretaceous and Tertiary sediments (fig. C9). Megablocks, which are particles larger than 1.0 m (3.3 ft) are rare in the matrix zones. Block boundaries range from irregular and embayed to essentially smooth, and orientations range from horizontal to inclined at moderate and steep angles. Block contacts with the matrix may be sharp, slightly gradational, or broadly diffuse across a centimeter (1 cm; 0.4 in.) or more. In general, the sandier, more friable blocks show the most diffuse contacts.

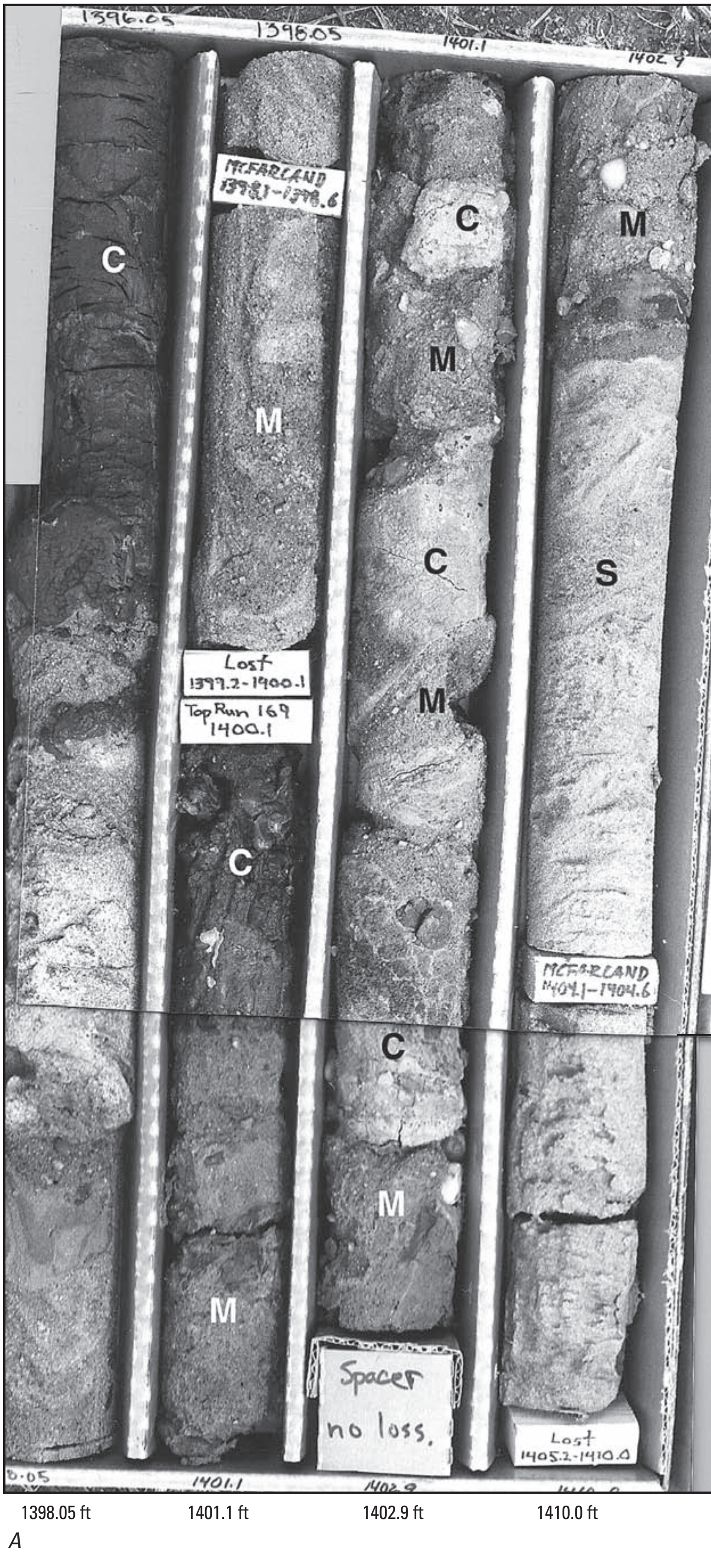
Blocks in the matrix zones are strongly deformed. Their internal bedding typically is distorted or fractured and inclined at all angles from horizontal to vertical and perhaps overturned. Vertically extended and distorted bedding in partially disaggregated blocks suggests vertical fluid movement within the matrix zones.

Blocks in the matrix zones of crater unit B are locally derived pieces of the Potomac Formation. These native blocks contain a wide range of Potomac Formation sediment types that closely resemble the Potomac sediments in crater unit A and in the megablocks and megablock zones of crater unit B. Common sediment types found in the matrix-zone blocks include light- to dark-gray, noncalcareous, typically micaceous and lignitic clays and sands and noncalcareous, gray-, red-, and brown-mottled silty clays, clayey silts, muddy sands, and sandy gravels. Well-rounded quartz, quartz-feldspar, chert, and quartzite pebbles are common as disseminated particles in the matrix zones

Figure C8. Photographs of megablocks in crater unit B in the USGS-NASA Langley core. Depths handwritten on the core boxes in feet are repeated in type for clarity. Section tops are at the upper left corners of the boxes. *A*, Composite photograph of core box 124 showing steeply dipping and locally fractured, interlaminated and burrowed sands and clayey silts within a megablock in crater unit B. Metric depth values for the top and bottom of box 124 are 353.3 m and 357.5 m. *B*, Composite photograph of core box 111 showing red and brown silty clay within a megablock in crater unit B. The megablock is overlain by matrix-zone material in the left-hand tray (see dashed line). Metric depth values for the top and bottom of box 111 are 313.7 m and 316.2 m.

Figure C8. Continued.

1396.05 ft 1398.05 ft 1401.1 ft 1402.9 ft



Line of mosaic

1398.05 ft 1401.1 ft 1402.9 ft 1410.0 ft

A

Figure C9. Photographs of matrix zones in crater unit B in the USGS-NASA Langley core. Depths handwritten on the core boxes in feet are repeated in type for clarity. Section tops are at the upper left corners of the boxes. *A*, Composite photograph of core box 144 showing blocks of sand (S) and clay (C) in glauconitic matrix (M). Metric depth values for the top and bottom of box 144 are 425.5 m and 429.8 m. *B*, Composite photograph of core box 128 showing blocks of sand (S) and clay (C) in glauconitic matrix (M). Note inclined, distorted bedding (DB). Metric depth values for the top and bottom of box 128 are 368.4 m and 377.4 m.

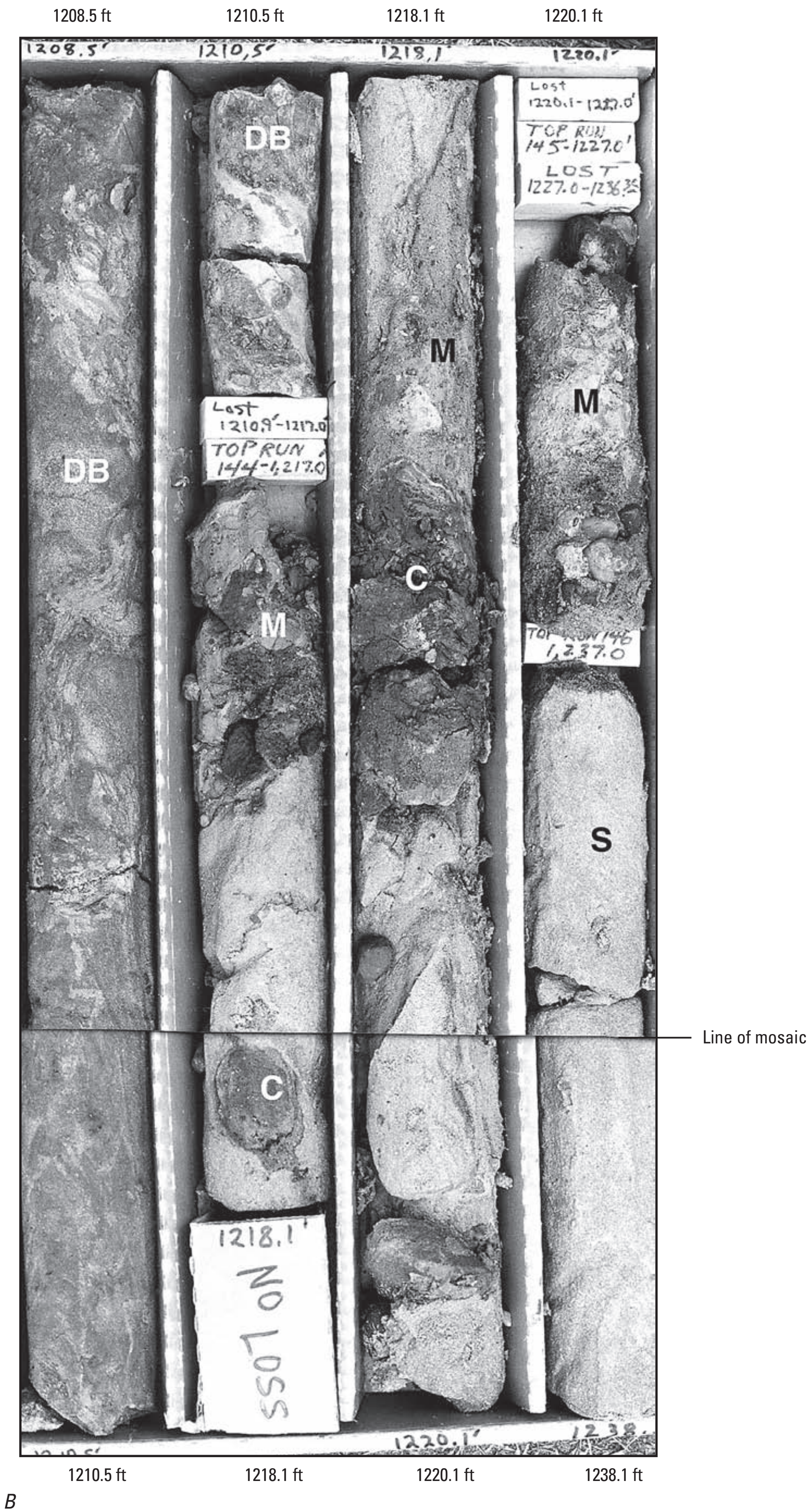


Figure C9. Continued.

and likely were derived locally from fluvial channel gravels in the Potomac Formation.

Almost all of the igneous- and metamorphic-rock fragments in the matrix zones also are subrounded to rounded pebbles that lack cataclastic fabrics and appear to be preimpact detrital sediments from the Potomac Formation (Horton and Izett, this volume, chap. E). A single 22-cm-long (8.7-in.-long) clast of cataclastic felsite from a depth of about 275.8 m (905.0 ft; see fig. C7*C*) contains shocked quartz and indicates the presence of rare impact ejecta in the matrix zone closest to the top of crater unit B (Horton and Izett, this volume, chap. E). This felsite clast is immediately below a 6.3-m-thick (20.7-ft-thick) megablock of oxidized Potomac Formation sediments that forms the uppermost part of crater unit B.

No exotic sediment blocks of certain Late Cretaceous or Tertiary age have been recognized in the matrix zones of crater unit B, although some greenish-gray muds and muddy fine sands potentially represent the preimpact unnamed Upper Cretaceous marine units, the Aquia Formation (upper Paleocene), and (or) the Nanjemoy Formation (lower Eocene).

The matrix between the blocks within the matrix zones consists of unsorted and unstratified, noncalcareous, muddy, quartz-glauconite sand and granules. Glauconite grains are common to abundant and are readily detected in all matrix zones. Glauconite typically is absent or extremely sparse in the preimpact Potomac Formation (Anderson, 1948; Reinhardt, Christopher, and Owens, 1980), but it is common to abundant in the Upper Cretaceous and lower Tertiary preimpact marine units in the region (see the section above on "Regional Preimpact Stratigraphy"). Hence, it appears that a substantial amount of disaggregated Upper Cretaceous and (or) Tertiary marine sediment has moved downward into the matrix zones of crater unit B. In addition to this exotic component, the matrix contains a native component of disaggregated, medium to very coarse feldspathic quartz sand and resistate pebbles derived from the sands and gravels of the Potomac Formation.

The matrix of crater unit B is similar in macroscopic appearance to the matrix between clasts in the Exmore beds above crater unit B (see the following section on the "Exmore Beds"). However, the Exmore matrix is uniformly calcareous and macrofossiliferous and microfossiliferous, whereas the matrix in crater unit B is very sparingly calcareous and fossiliferous. No macrofossil fragments or microfossils were observed during petrographic inspection of the sand fraction of 17 matrix samples from crater unit B. Fossils were found in two matrix samples processed for calcareous nannofossils or dinoflagellates, as described below

Fossils.—Ten of eleven matrix samples from crater unit B processed for calcareous nannofossils were barren (Frederiksen and others, this volume, chap. D, fig. D7). The sample from a depth of 298.5 m (979.3 ft) contains a mixed early Tertiary assemblage of uncertain origin. This sample is from a thin matrix section at the top of a coring run. As such, it was particularly susceptible to drilling-mud contamination during core recovery and handling.

Two samples from the matrix of crater unit B were processed for dinoflagellates; one was barren (Frederiksen and others, this volume, chap. D). The other matrix sample, which was from 278.4 m (913.3 ft) depth, contained a mixed early Tertiary assemblage of dinoflagellates.

Thickness and distribution.—The matrix zones range from a few centimeters (a few inches) to slightly over 20 m (65.6 ft) in thickness. Zones in the upper half of crater unit B are consistently less than 5 m (16.4 ft) thick, whereas zones thicker than 10 m (32.8 ft) are restricted to the lower half, although thinner zones also occur in the lower half of the unit. This pattern resembles the distribution of thicker and thinner megablocks and megablock zones in crater unit B. The change from thicker to thinner matrix zones does not correspond to the subunit boundary between the lower and upper beds of crater unit B.

Moderate to poor core recovery was typical of the matrix zones of crater unit B in the Langley core, particularly the thicker zones. This pattern likely results from the poorly consolidated nature of the material in these zones.

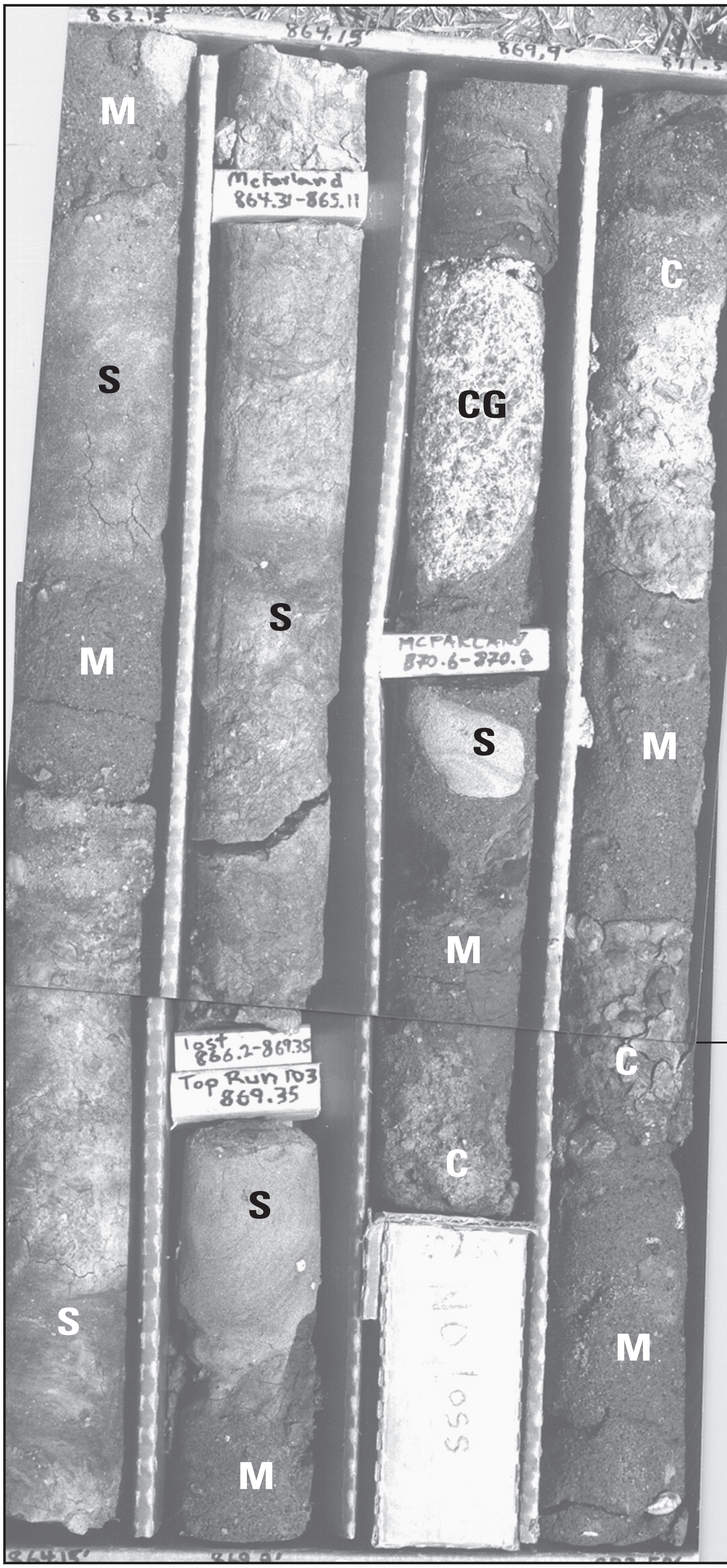
Exmore Beds

Lithology, Thickness, and Nomenclature

The Exmore beds are present between depths of 269.4 m (884.0 ft) and 235.65 m (773.12 ft) in the Langley core and have a thickness of 33.8 m (110.9 ft). The Exmore section below 235.92 m (774.03 ft) depth consists of unsorted sedimentary deposits that contain abundant pebbles, cobbles, and small boulders of preimpact sediments and rocks suspended in a finer grained matrix (fig. C10*A*–*D*). This interval is uniformly matrix supported except in the basal 3.0 m (9.8 ft). We refer to these unsorted deposits descriptively as the "polymict diamicton" of the Exmore beds; the term is derived from one defined by Flint and others (1960). The calcareous, laminated, clayey, quartz silt and very fine sand at the top of the Exmore beds from 235.92 m (774.03 ft) to 235.65 m (773.12 ft) depth (fig. C5) are referred to as the "transition sediments" of the Exmore beds, as noted above in the section on "Postimpact Stratigraphy of the Annular Trough." The transition sediments were not studied in detail for this chapter, and discussions of these sediments in following sections are derived primarily from Poag (2002) and Poag and Norris (this volume, chap. F).

The lower contact of the Exmore beds at 269.4 m (884.0 ft) depth separates a 6.3-m-thick (20.7-ft-thick) megablock of oxidized clayey silts and muddy very fine sands at the top of crater unit B (fig. C7*C*) from an overlying 0.5-m-thick (1.6-ft-thick) boulder of greenish-gray, muddy, very fine to coarse sand at the base of the Exmore section. The noncalcareous Potomac Formation blocks and megablocks and the sparingly calcareous matrix below this contact (crater unit B) contrast with the polymict clasts and calcareous matrix above the contact (Exmore beds). Rare exceptions to these lithologic distinctions in crater unit B are noted in the section above on "Crater Unit B."

862.15 ft 864.15 ft 869.9 ft 871.53 ft



Line of mosaic

864.15 ft 869.9 ft 871.53 ft 873.53 ft

A

Figure C10. Photographs of the diamicton of the Exmore beds in the USGS-NASA Langley core. Depths handwritten on the core boxes in feet are repeated in type for clarity. Section tops are at the upper left corners of the boxes. *A,* Composite photograph of core box 97 showing clasts in glauconitic matrix (M). Clast types include sand (S), clay (C), and cataclastic granite (CG). Metric depth values for the top and bottom of box 97 are 262.8 m and 266.3 m. *B,* Composite photograph of core box 94 showing clasts in glauconitic matrix (M). Clast types include clay (C), calcareous quartz-glauconite sand (QGS), and cataclastic felsite (CF). Metric depth values for the top and bottom of box 94 are 255.7 m and 258.2 m. *C,* Composite photograph of core box 90 showing clasts in glauconitic matrix. Clast types include sand (S) and limestone (L). Metric depth values for the top and bottom of box 90 are 245.3 m and 248.0 m. *D,* Composite photograph of core box 87 showing clasts in glauconitic matrix. Clast types include clay (C) and clayey sand (S). Metric depth values for the top and bottom of box 87 are 236.3 m and 240.2 m.

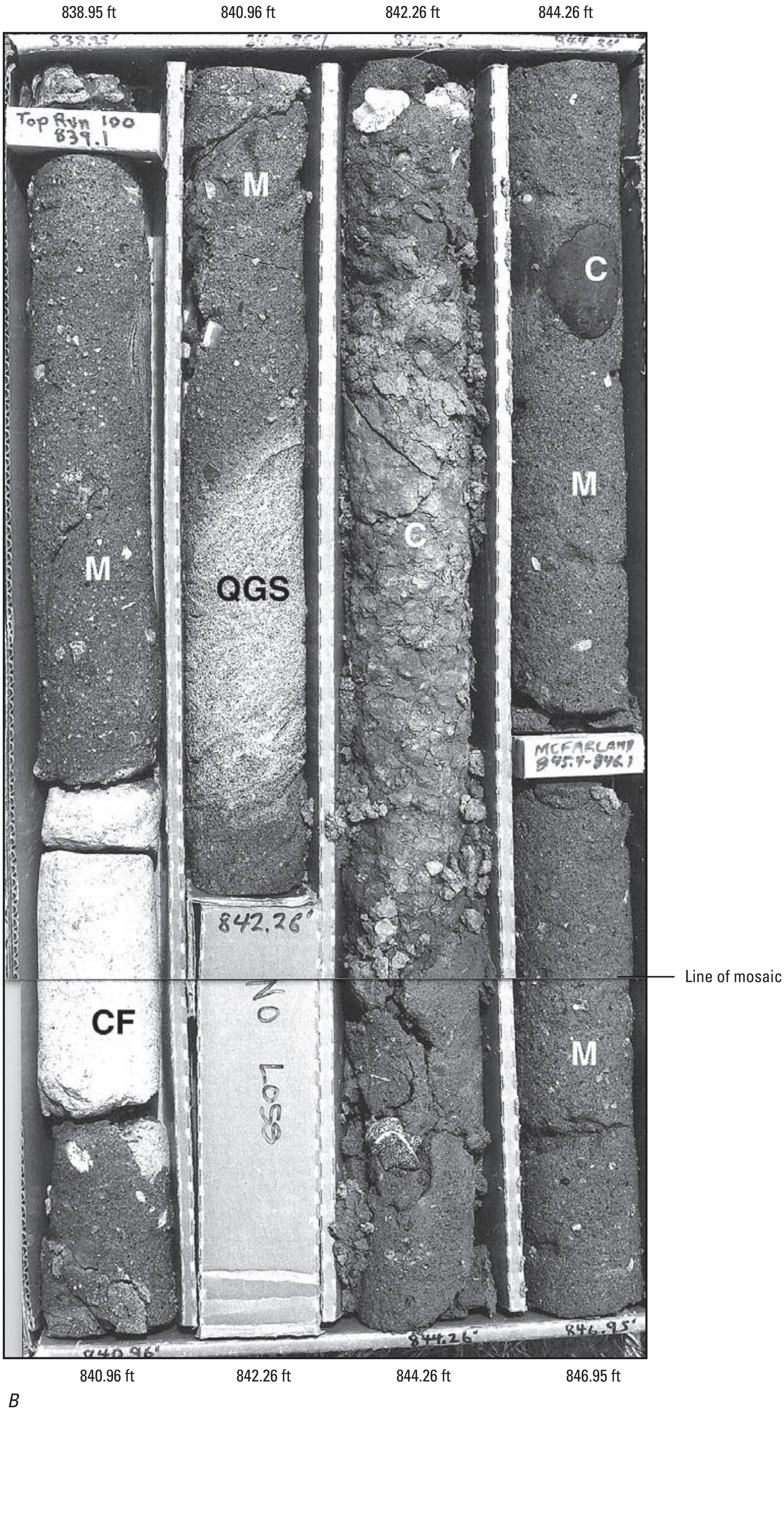
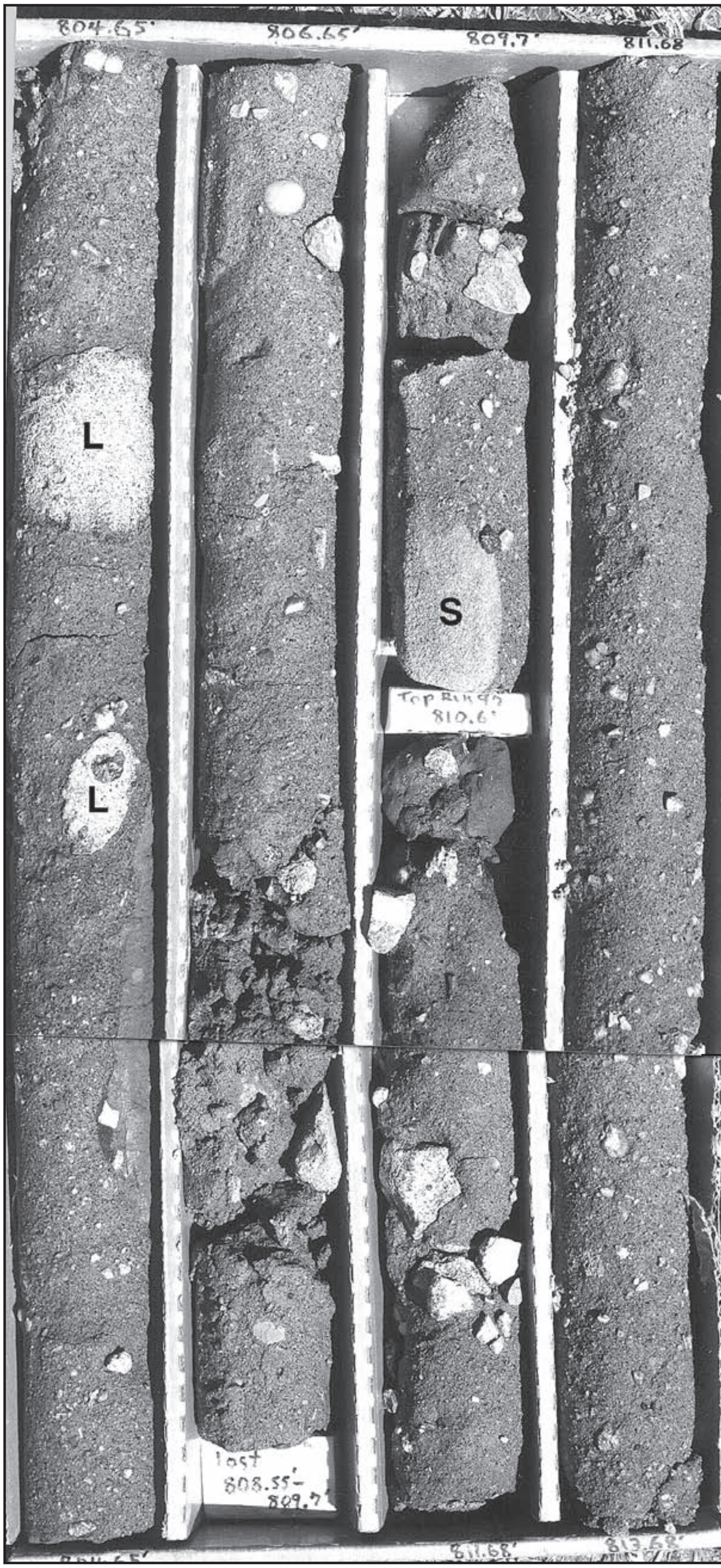


Figure C10. Continued.

804.65 ft 806.65 ft 809.7 ft 811.68 ft



806.65 ft 809.7 ft 811.68 ft 813.68 ft

C

Figure C10. Continued.

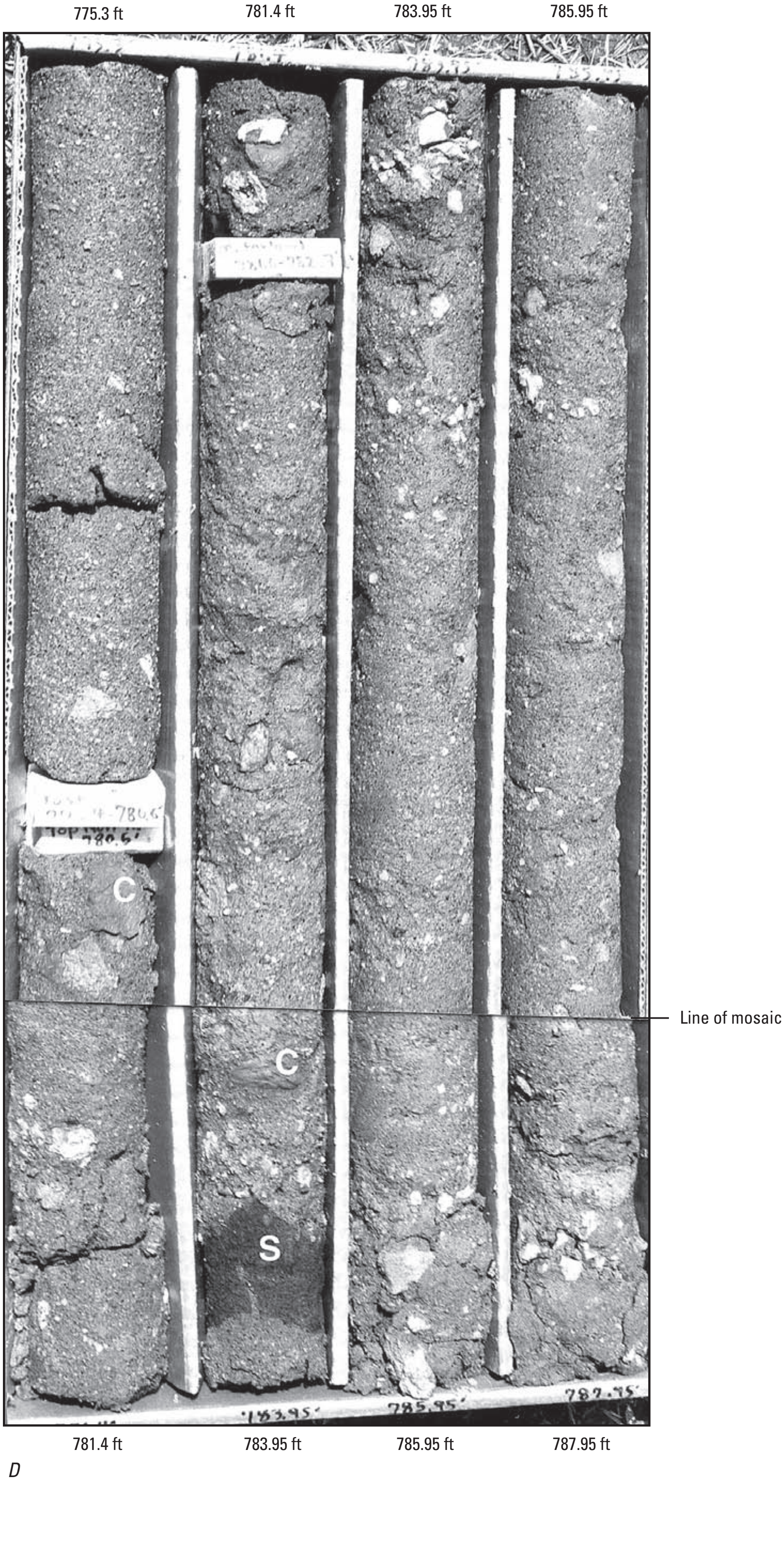


Figure C10. Continued.

Lithology, Texture, and Age of the Diamicton Matrix

The matrix of the diamicton in the Exmore beds consists of unsorted and unstratified, calcareous, muddy, quartz-glauconite sand and granules smaller than 4 mm (0.16 in.). Matrix colors in fresh, wet cores vary from dark gray to dark olive gray and olive gray.

Grain-size analyses (wet sieving at 1.0-phi intervals) of 11 matrix samples from the Exmore beds indicate little variation in grain-size distribution with depth and typically poor sorting (fig. C11). Medium sand is the most abundant size fraction throughout the section (about 25 to 30 weight percent), and the total sand fraction contains about 70 to 75 weight percent of the sediment. The mud (silt and clay) fraction ranges from 18 to 25 weight percent, and the granule fraction is in the range of 2 to 9 weight percent.

Petrographic inspection of the 11 matrix samples indicates that quartz constitutes about 50 to 80 percent of the sand fraction in individual samples. The quartz is predominantly angular to subangular with some subrounded grains; sphericity of the quartz grains typically is low. Glauconite is the most abundant sand-sized mineral after quartz. The glauconite grains typically are well rounded and dark green; they contain pervasive cracks filled with clay, quartz silt, and locally pyrite. There is a distinct down-section decrease in glauconite from about 20 to 35 percent of the sand fraction in the upper part to about 5 percent in the lower part. Additional sand- and granule-sized grains include common mollusk fragments and feldspar as well as sparse white mica and microfossils, primarily benthic foraminifera and ostracodes. Pyrite is locally sparse to common as sand-sized grains, as encrustations on glauconite and carbonate grains, and as fills within benthic foraminifera tests. Shocked quartz is present but sparse in the sand fraction of the matrix (Horton and Izett, this volume, chap. E). Viewed separately from the clast fraction, the matrix may be classified petrologically as a gravelly, glauconitic arkosic wacke (Pettijohn, 1975).

The diamicton matrix in the Langley core contains palynomorphs and calcareous microfossils and nannofossils that represent a wide range of Cretaceous and early Tertiary ages (Frederiksen and others, this volume, chap. D). Similar mixed faunas and floras are present regionally in other studied sections of the Exmore beds (Poag and Aubry, 1995; Poag, 1997). Late Eocene fossils constitute the youngest assemblages in the matrix and indicate a biochronologic age that is indistinguishable from that of the overlying, postimpact Chickahominy Formation (Poag, 1997; Frederiksen and others, this volume, chap. D; Poag and Norris, this volume, chap. F; Edwards and others, this volume, chap. H).

Lithologies, Textures, and Ages of the Diamicton Clasts

The size and distribution of clasts within the diamicton of the Exmore beds were evaluated by two methods, in addition to a general inspection of the core. Line counting of clasts was conducted by tracing a straight pencil line vertically down the core exterior as presented in the core boxes. The sizes, lithologies, and depths of all particles larger than 4 mm (0.16 in.) that touched the line were recorded (fig. C12). The recorded depth for each clast represents the position of its midpoint measured along the vertical axis of the core.

To further determine the distribution of the largest clast fraction, the size, lithology, and depth of the largest clast in each 0.61-m (2.0-ft) length of core were recorded (fig. C12). For this count, the position of the clast was recorded at the midpoint of each measuring interval. This method is less accurate than the line-counting method for determining depths of clasts because clast midpoints rarely were at the interval midpoints and because some large clasts extended across measuring intervals. The depth for a clast that crossed a measuring boundary was plotted at the midpoint of the interval containing the majority of the clast. Therefore, some discrepancies exist in the plotted depths of individual large clasts that appear on the line-count graph and on the maximum-clast-size graph. It also should be noted that the clast size recorded for all clasts larger than the core diameter (nominally 6.1 cm, 2.4 in.) is the apparent maximum size along the vertical core axis.

As seen on the line-count graph (fig. C12), clasts having diameters in the range of 4 mm to 10 cm (0.16 to 3.9 in.; pebbles and small cobbles) are present throughout nearly the full vertical extent of the Exmore beds. Their apparent absence from some intervals near the bottom of the Exmore section likely results from the fact that the full volume of the core in those intervals is occupied by individual large clasts. Some core intervals also were unrecovered. The distribution of the matrix (particles less than 4 mm (0.16 in.) in diameter) throughout the Exmore beds is described in the section above (fig. C11).

Unlike the distribution of the finer grained materials, the distribution of the larger clasts has biases. On the line-count graph (fig. C12), clasts having diameters in the range of 10 cm to 1 m (3.9 in. to 3.3 ft; large cobbles and small boulders) are restricted, with one exception, to approximately the lower half of the Exmore section below a depth of about 250 m (820 ft). The only boulder larger than 1 m (3.3 ft) is present slightly above the base of the Exmore section. In contrast, clasts larger than about 2 cm (0.8 in.) are absent from the upper 2 m (6.6 ft) of the Exmore section.

These biases also are apparent on the maximum-clast-size graph (fig. C12). With one exception, the recorded maximum clast sizes range from 1 to 10 cm (0.4 to 3.9 in.; pebbles and small cobbles) above about 250 m (820 ft) depth. Below that depth, maximum clast sizes are primarily in the range from 10 cm to 1 m (3.9 in. to 3.3 ft; large cobbles and small boulders); the single boulder larger than 1 m (3.3 ft) is again recorded near the base of the unit.

The correspondence in the distribution of the larger clasts on the two graphs is expected because the small diameter of the core samples (relative to the sizes of the larger clasts) dictates that the large clasts encountered in the line count are the same clasts recorded in the maximum-clast-size count. This effect is less important above the depth of about 250 m (820 ft) but is particularly prevalent in the lower part of the diamicton, where large clasts occupy the full volume of the core.

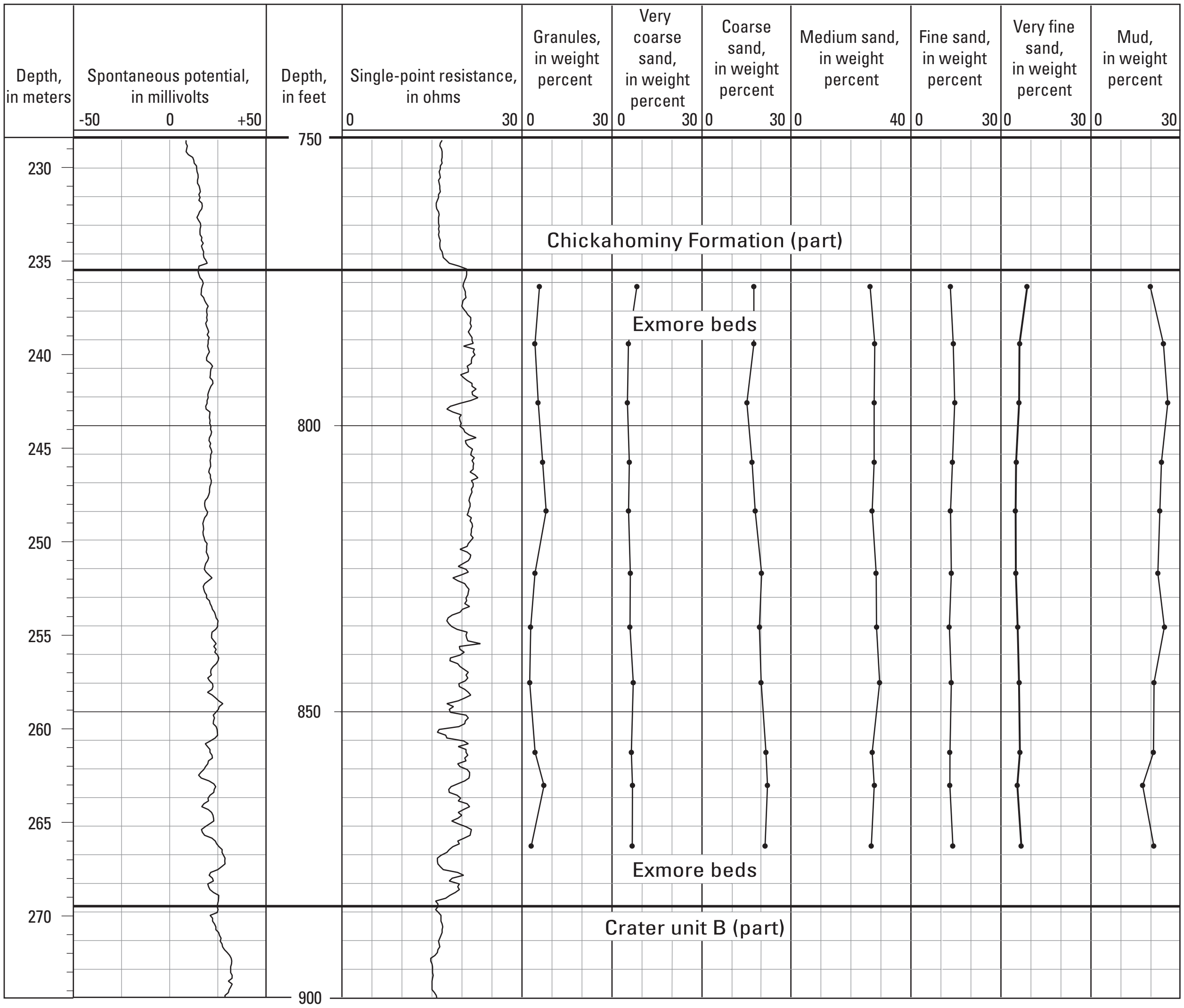


Figure C11. Graph of the grain-size distribution of 11 matrix samples from the Exmore beds in the USGS-NASA Langley core.

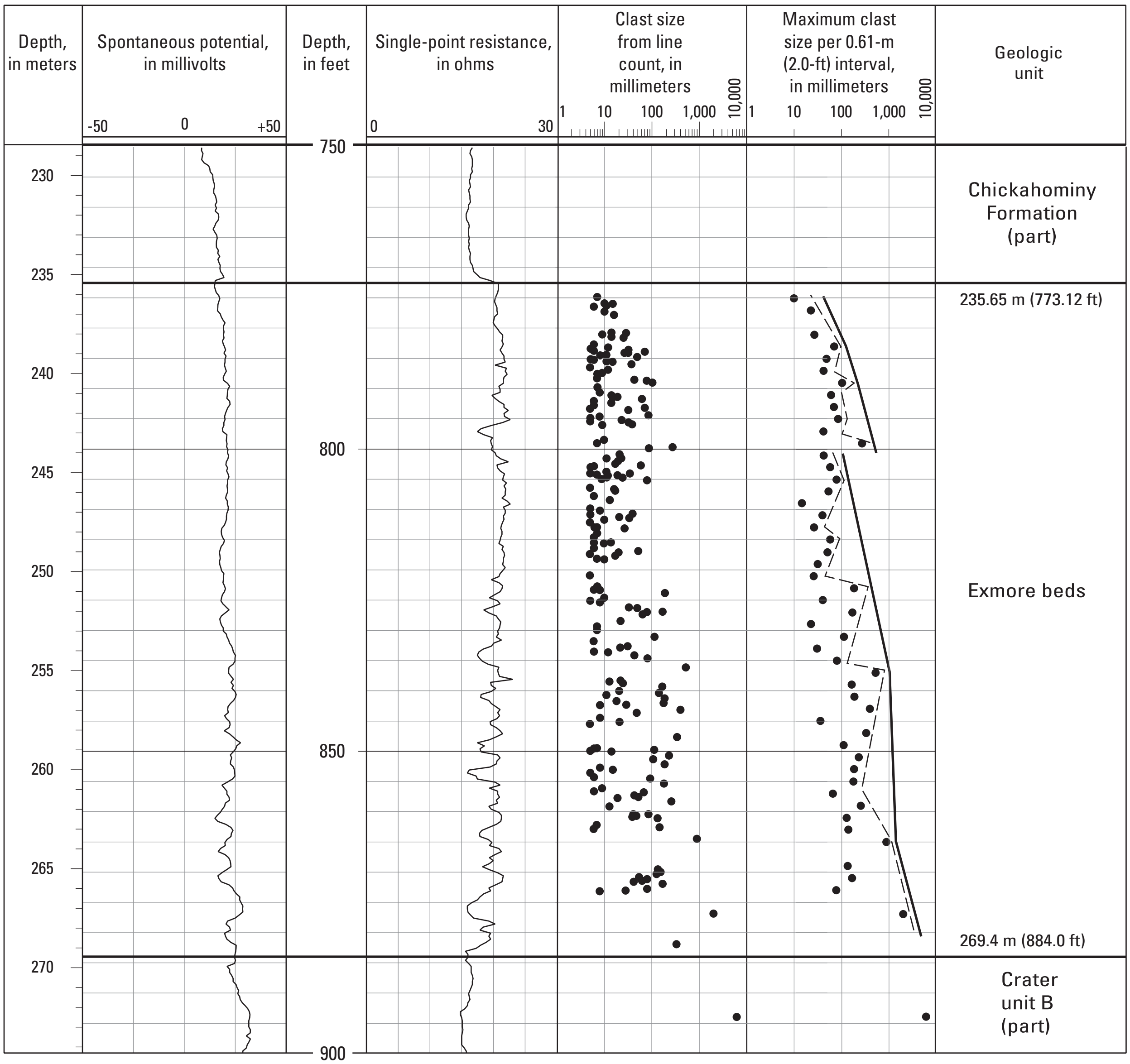


Figure C12. Graph of the grain-size distribution of clasts (>4 mm (>0.16 in.)) in the Exmore beds in the USGS-NASA Langley core. Methodology is explained in the text. The dashed line in the maximum-clast-size column highlights the local trends in maximum-clast-size distribution. The heavy line in the same column highlights the major trends in maximum-clast-size distribution.

There is considerable variation in the shape, rounding, orientation, and boundary characteristics of the clasts in the Exmore beds. Shapes of the smaller clasts vary from subspherical to elongate and irregular. The shapes of the larger clasts cannot be evaluated from the core samples. Clasts range from angular to well rounded, although most clasts are subangular to subrounded. Clast orientation appears to be random, to the degree that that parameter can be evaluated in the Langley core. Most clast boundaries are sharp except for some clasts of well-sorted sand that have diffuse boundaries across distances of less than 1 cm (0.4 in.).

There is a wide range of clast types in the Exmore beds that represents most or all of the formations affected by the Chesapeake Bay impact (fig. C3). Common sedimentary clast types include limestone, muddy sand, interbedded sand and clay, and sandy and silty clay. Individual clasts may be calcareous or noncalcareous and glauconitic or nonglauconitic; clast colors vary from gray, greenish-gray, and brownish gray to red, brown, and yellow oxidation colors.

Lithoclasts and mineral grains encountered during line counting and maximum-clast-size counting of the Exmore beds, and during general examinations of the core, have been separated on the basis of lithology into 17 categories (table C1). Fifteen categories consist of weakly to strongly compacted or cemented, siliciclastic or carbonate sediments, whereas the remaining two categories consist of igneous rocks. The lithologic categories have been numbered for ease of reference. The numbers reflect a crude preimpact stratigraphic ordering of the categories from category 1 (older) through category 17 (younger).

General geologic ages were assigned to the sediment clast categories through lithologic comparison with the undisturbed sedimentary sections outside the Chesapeake Bay impact structure in the Virginia Coastal Plain (fig. C3) (Ward, 1985; Mixon, 1989; Powars and others, 1992; Powars and Bruce, 1999; Powars, 2000). In addition, direct assessments of clast ages are available from paleontologic studies of selected Exmore clasts in the Langley core (Frederiksen and others, this volume, chap. D).

Categories 1 and 2 consist of granitic rocks and felsic volcanic rocks of pre-Mesozoic age. Horton and Izett (this volume, chap. E) discuss these clasts in detail.

Clast categories 3, 4, and 5 consist of oxidized sands, muds, and interbedded sands and muds of the Lower Cretaceous and basal Upper Cretaceous Potomac Formation. These noncalcareous, oxidized materials are readily distinguished from the gray and gray-green Upper Cretaceous and lower Tertiary marine deposits that constitute several other categories. However, some small volume of the material in categories 3 through 5 could have been derived from the Upper Cretaceous red-bed unit (possible northward extension of the Cape Fear Formation) found in the subsurface south of the impact crater (fig. C3).

Categories 6, 7, and 8 consist of angular to subrounded, single-mineral grains and chert lithoclasts that are generally in the size range from 4 to 10 mm (0.16 to 0.4 in.). The mineralogy and relatively large size of these pebbles suggest derivation from the Potomac Formation, which contains most of the gravelly preimpact deposits in the study area. Similarly, category 9 consists of well-rounded quartz, chert, and quartzite pebbles that likely represent multicycle sediments derived from fluvial channel deposits of the Potomac Formation. Very sparse, well-rounded phosphate pebbles of category 10 could also represent channel deposits of the Potomac Formation, or they could have been derived from lag deposits in the Upper Cretaceous and lower Tertiary marine section.

Clast categories 11 through 14 contain a variety of typically gray or gray-green, in part calcareous and glauconitic, marine sands and muds derived from the Upper Cretaceous and lower Tertiary formations of the impact area. Some portion of the noncalcareous gray sediments in categories 11 and 13 could represent non-oxidized sections of the Potomac Formation; in particular, gray noncalcareous sediments containing significant amounts of lignite likely represent Potomac lithologies. Category 15 consists of fragmented macrofossils, primarily mollusks, derived from the Upper Cretaceous and lower Tertiary marine deposits. Limestone clasts in categories 16 and 17 were derived from lower Tertiary formations, particularly the middle Eocene Piney Point Formation.

Table C1. Ages and lithologic categories of clasts recorded from the diamicton of the Exmore beds in the USGS-NASA Langley core during line counting and maximum-clast-size counting.

[Clasts have diameters greater than 4 millimeters (0.16 inch)]

Clast category	Age	Lithology
17	Tertiary	Limestone, shelly, cemented
16	Tertiary	Limestone, glauconitic, shelly
15	Tertiary, Cretaceous	Fossils (mollusk fragments)
14	Tertiary, Cretaceous	Mud, calcareous, gray
13	Tertiary, Cretaceous	Mud, noncalcareous, gray
12	Tertiary, Cretaceous	Sand, calcareous, gray
11	Tertiary, Cretaceous	Sand, noncalcareous, gray
10	Tertiary, Cretaceous	Rounded phosphate pebbles
9	Cretaceous	Rounded quartz and chert pebbles
8	Cretaceous	Angular quartz pebbles
7	Cretaceous	Angular chert pebbles
6	Cretaceous	Angular feldspar pebbles
5	Cretaceous	Muds, oxidized
4	Cretaceous	Sands, oxidixed
3	Cretaceous	Sands and muds, oxidized
2	Pre-Mesozoic	Igneous rocks, volcanic
1	Pre-Mesozoic	Igneous rocks, plutonic

Clast Distribution by Lithologic Category

Figures C13 and C14 show the distribution of selected clast categories in the Exmore beds of the Langley core as determined in the line count of clasts. Figure C13 shows the distribution of oxidized sand and mud clasts (categories 3, 4, and 5; table C1) that primarily represent the Potomac Formation. As such, these clasts represent material from the lower part of the preimpact sedimentary section within the impact area. Note that this category of clasts is present throughout the vertical extent of the diamicton, although vertical variations in clast size and abundance are present. Specifically, clasts in these categories are moderately abundant, and some moderately large specimens are present above a depth of about 244 m (800.5 ft). Clasts in the same categories are relatively smaller and less abundant between about 256 and 244 m (839.9 and 800.5 ft). This population of clasts achieves its greatest abundance and largest sizes between about 256 m (839.9 ft) depth and the base of the Exmore beds.

Figure C14 shows the distribution of limestone clasts (categories 16 and 17; table C1) in the diamicton of the Exmore beds. Most of these clasts represent the middle Eocene Piney Point Formation, whereas some likely represent the Paleocene Aquia Formation, the Eocene Nanjemoy Formation, and possibly the Upper Cretaceous marine units. Collectively, they represent material from the upper part of the preimpact sedimentary section within the impact area. Note that the limestone clasts also are distributed throughout most of the diamicton section, although they are distinctly less abundant below about 256 m (839.9 ft) depth, where large clasts from the Potomac Formation dominate the cored section.

Sedimentary Structures

Physical and biogenic sedimentary structures are sparse within the diamicton section of the Exmore beds. No bedding, crossbedding, burrows, or dewatering structures were observed in the matrix. Disrupted and undisrupted primary stratification and burrows are present in the interiors of some clasts but are truncated at the clast boundaries.

The size grading of the largest clasts noted above, particularly the relegation of the largest clasts to the lower part of the section, is the only pronounced sedimentary structure. This biased distribution of only the larger clasts in an otherwise unsorted deposit is referred to as coarse-tail grading (Middleton, 1967; Middleton and Hampton, 1973).

Transition Sediments

In this chapter, we consider that the transition sediments of the Exmore beds consist of three thin stratigraphic layers (fig. C5). The lowest layer consists of clayey silt between depths of 235.92 m (774.03 ft) and 235.87 m (773.85 ft). This layer is included in the Exmore breccia of Poag (2002, fig. 3) and Poag and Norris (this volume, chap. F, fig. F7).

Above this basal layer, Poag (2002) and Poag and Norris (this volume, chap. F) recognize a layer of clayey silt that contains pyritic microstructures (pyrite lattices) between depths of 235.87 m (773.85 ft) and 235.84 m (773.75 ft). Poag (2002, p. 996) described the pyrite lattices as exhibiting "smooth-walled, closely spaced, hemispherical depressions (concavities), separated from one another by curved, knife-edge partitions." Poag (2002) and Poag and Norris (this volume, chap. F) infer that the pyrite lattices originally enclosed 0.5- to 1.0-mm (0.02- to 0.04-in.) microspherules that were diagenetically removed or lost during sample processing. Poag and Norris (this volume, chap. F) refer to this layer as the "fallout layer."

Above the pyrite lattices, the upper layer consists of clayey silt laminae that are interlayered at a millimeter scale with laminae of better sorted silt and very fine sand; this section also contains sparse oval (compressed?) burrows filled with pyritic quartz sand. Poag and Norris (this volume, chap. F) refer to this upper layer as the "dead zone."

Discussion

Crater Units A and B

Principal Characteristics of Impact-Modified Sediments in the Annular Trough

Crater units A and B of the Langley core represent an impact-deformed, autochthonous to parautochthonous sedimentary section within the annular trough of the Chesapeake Bay impact structure. Observed features of inferred impact origin in this section include fractured, slumped, and rotated sediment blocks and megablocks, fluidized sand beds, and injected or infiltrated exotic sediments. The distributions of these impact features vary with depth and sediment type; the general intensity of impact deformation increases upward.

There is no evidence for large-scale removal of preimpact materials by excavation flow near the Langley corehole. The main preimpact stratigraphic units in the annular trough are the Neoproterozoic granite and the nonconformably overlying fluvial and deltaic sediments of the Cretaceous Potomac Formation. These units are deformed but preserved in recognizable stratigraphic order in the Langley core and vicinity (Horton and others, this volume, chap. B; Catchings and others, this volume, chap. I; and this chapter). Primary (Cretaceous) sedimentary structures, cycles, and lithologies typical of the Potomac Formation outside the crater (Powars and Bruce, 1999; Powars, 2000) are found throughout crater unit A and within the megablocks of crater unit B in the core. This correlation indicates that the preimpact Cretaceous sediments have not been removed and subsequently replaced by impact-generated sediments.

There also is no evidence for shock deformation within crater units A and B. The only shocked mineral grains are in a single felsite clast near the top of crater unit B that is readily interpreted as crystalline-rock ejecta injected or infiltrated into

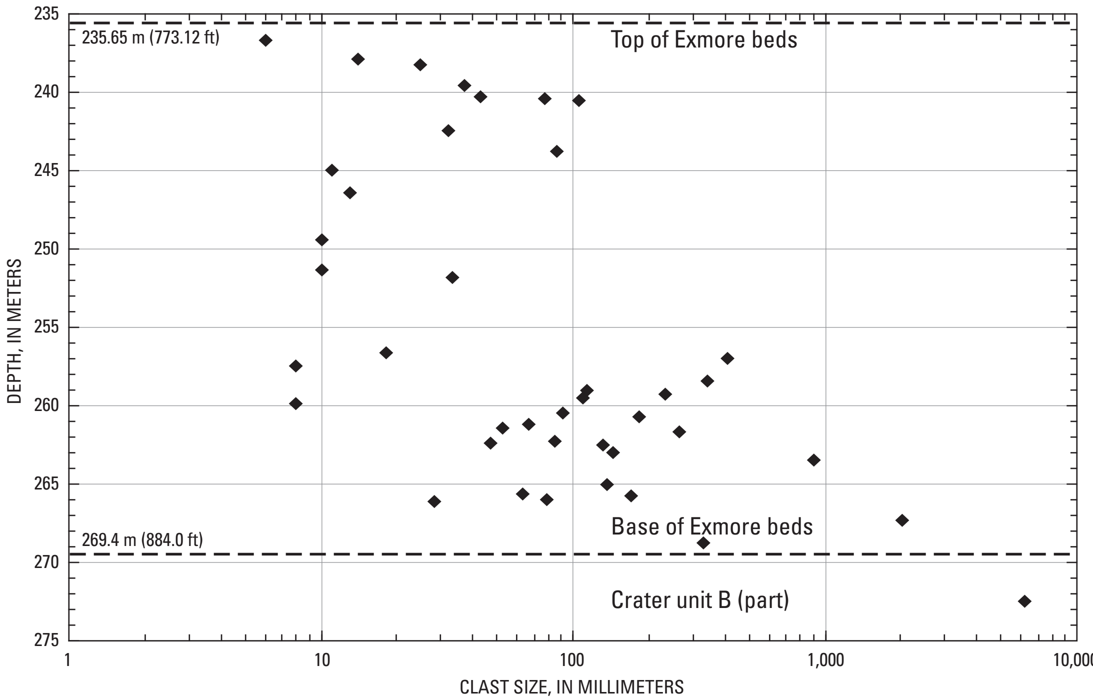


Figure C13. Graph of the distribution and size of oxidized sand and mud clasts (>4 mm (>0.16 in.)) of categories 3, 4, and 5 (table C1) in the Exmore beds in the USGS-NASA Langley core. Clasts were identified in the line count as explained in the text.

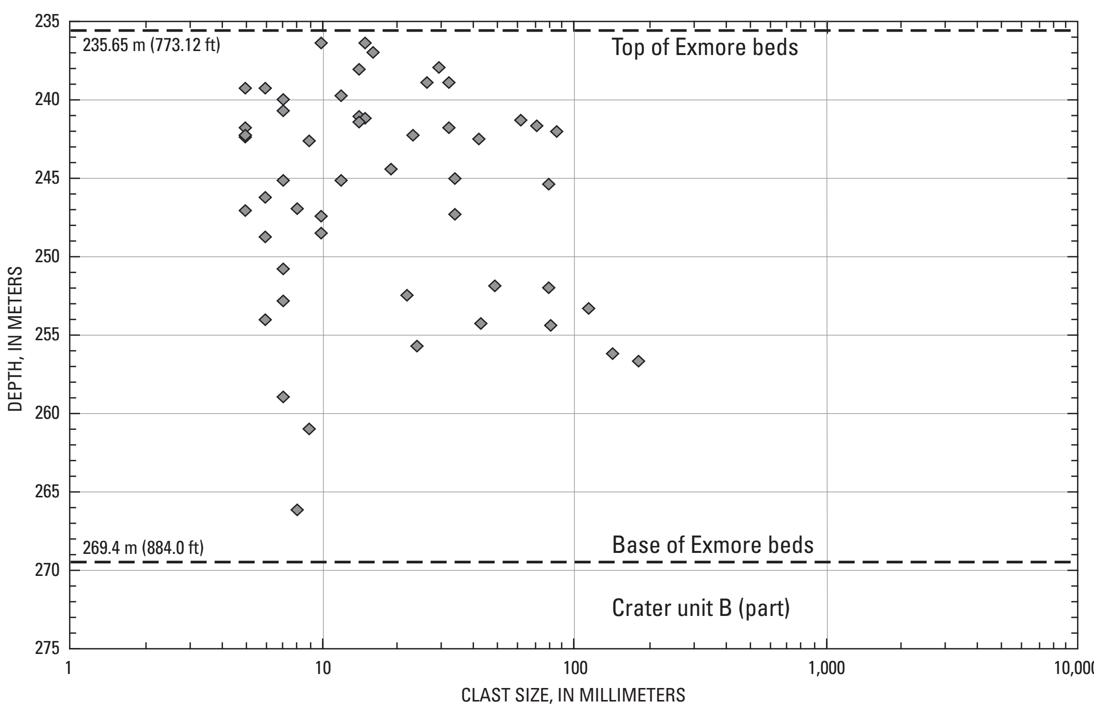


Figure C14. Graph of the distribution and size of limestone clasts (>4 mm (>0.16 in.)) of categories 16 and 17 (table C1) in the Exmore beds in the USGS-NASA Langley core. Clasts were identified in the line count as explained in the text.

the preimpact sedimentary section. Melt rock is absent from these units as well. In addition, no shock deformation or thermal effects were detected in the granite at the base of the Langley core (Horton and others, this volume, chap. B).

The basement granite, crater unit A, and the lower beds of crater unit B, all below a depth of 427.7 m (1,403.3 ft), are autochthonous materials retained at moderate depths within the annular trough and outside the zone of shock deformation and excavation flow. Significant impact deformation in this interval is limited to local in situ fluidization of sands, faulting, and fracturing. The stratigraphic order of the preimpact sediments is largely retained below 427.7 m (1,403.3 ft). Exotic sediments are present only in a single thin interval (0.3 m (1.0 ft) thick) at the boundary between crater units A and B (fig. C7*A*).

The Potomac Formation sediments in the upper beds of crater unit B above a depth of 427.7 m (1,403.3 ft) are parautochthonous materials retained at shallow depths within the annular trough and outside the zone of shock deformation and excavation flow. Fracturing, slumping, and rotation of Potomac Formation sediment blocks and megablocks, fluidization of Potomac Formation sands, and injection or infiltration of exotic sediments are widespread in this interval, and the primary stratigraphic ordering of the preimpact Potomac Formation sediments is retained only within megablocks.

Principal Impact Processes in the Annular Trough

Fracturing and Faulting

Faults and fractures are pervasive features in crater units A and B. Fractures and slickensided faults with small or uncertain displacements dip at all angles from horizontal to nearly vertical and occur in all sediment types in crater units A and B of the Langley core. These structures are irregularly spaced, although observed fault spacing generally decreases upsection. Short faults having centimeter-scale displacements are abundant in megablocks of the upper beds in crater unit B.

A complex system of short faults (tens of meters) with small, dominantly normal displacements (meters) in crater units A and B is interpreted from the migrated depth image for the Langley seismic survey adjacent to the corehole (Catchings and others, this volume, chap. I). Numerous diffractions on the unmigrated images for that survey also indicate the presence of discontinuities in this sedimentary section.

Mineralized faults, fractures, and veins are common in the granite of the Langley core; however, most of these structures probably are Mesozoic or older (Horton and others, this volume, chap. B). Partially healed, quartz-lined fractures are the best candidates for impact fractures in the cored granite, although their age remains equivocal. Catchings and others (this volume, chap. I) suggest that common diffractions on the unmigrated seismic-reflection images indicate significant numbers of discontinuities in the granite. High-angle faults that displace the contact between the granite and overlying sediments also are interpreted from the seismic images (Catchings and others, this volume, chap. I).

Two mechanisms probably account for the fracturing and faulting observed in the core and seismic images. Relatively early in the cratering process, a tensile wave moves downward into the target materials (those affected by the impact). This rarefaction results from the reflection of the direct compressive stress wave at the target's free surface**,** the sea floor (Melosh, 1984, 1989). The low tensile strength of most geologic materials suggests that extensive fracturing should occur by this process.

The second mechanism is the late-stage collapse of a crater. Temporary strength reduction of target materials by tensile fragmentation and (or) other mechanisms, including pore-pressure or acoustic fluidization, results in late-stage gravitational collapse of complex craters across a wide area (Melosh, 1989; Melosh and Ivanov, 1999; Collins and Melosh, 2002).

Collapse deformation in the Langley area was not uniformly distributed, however. The main feature of the Langley seismic survey is a 550-m-wide (1,805-ft-wide), stratabound collapse structure developed within the upper beds of crater unit A and crater unit B (Catchings and others, this volume, chap. I); the Langley corehole penetrated this structure near its center. Deformation within the collapse structure is distributed along the small-displacement faults noted on the seismic images rather than along bounding large-displacement normal faults. The seismic images indicate that the relatively intense deformation observed in the upper beds of crater unit B was restricted to the collapse structure to a significant extent. Hence, the pattern of deformation that characterizes crater unit A may extend closer to the surface in areas away from the collapse structure and the Langley corehole.

We were unable to distinguish faults and fractures in the Langley core produced by early tensile fracturing from faults and fractures produced during late-stage gravitational collapse. However, given the location of the corehole within the extensional collapse structure seen on the seismic images, we infer that most of the faults seen in crater units A and B of the Langley core resulted from gravitational collapse.

Fluidization of Sands

We interpret the numerous layers of structureless sand present above 558.1 m (1,831.0 ft) depth in the upper beds of crater unit A and in crater unit B as fluidized beds. Two possible mechanisms for this fluidization are increased pore-water pressure in these water-saturated sands and acoustic fluidization (Melosh, 1979, 1989; Collins and Melosh, 2002). Temporary compressive strain (densification) produced in water-saturated sands by impact-stress-wave compression would increase pore-water pressures, thereby reducing the overburden pressure and the internal friction in the sands and allowing the sand-water mixtures to flow as viscous fluids. During acoustic fluidization, alternating compressions and rarefactions in acoustic waves produced by the impact temporarily and locally reduce the overburden pressure and thereby reduce the internal frictional strength of the sand layers, allowing fluid flow (Melosh, 1979, 1989; Melosh and Ivanov, 1999; Collins and Melosh, 2002).

In either case, the widespread preservation of primary Cretaceous sedimentary structures in the sands below 558.1 m (1,831.0 ft) depth suggests that the overburden pressure remained sufficiently high to prevent fluidization below that depth near the Langley corehole. The loss of primary sedimentary structures in the fluidized sands is directly attributed to the fluid flow.

The reduction in target strength produced by fluidization in the Langley area was lithology dependent. The most susceptible sands liquefied, whereas less susceptible sands and finer grained beds remained more competent. The temporary reduction of bearing strength in the fluidized sand layers almost certainly contributed to the general collapse of beds at higher stratigraphic levels in crater unit B, particularly the fracturing, slumping, and rotation of the more competent beds. Impact-produced fractures probably acted as dewatering conduits that allowed the upward loss of pressurized pore water, thereby providing the volume accommodation required for the structural collapse of crater unit B.

Injection and Infiltration of Exotic Sediments

The matrix zones in crater unit B consist of mixed native and exotic sediments. The most obvious exotic component is the abundant glauconite sand between blocks in the matrix zones. The source of the glauconite is inferred to be the pre-impact Upper Cretaceous and lower Tertiary marine sediments that are present regionally above the Potomac Formation (fig. C3).

A parautochthonous section of these marine sediments similar to the Potomac Formation sediments of crater unit B is not present in the Langley core, nor are such sections present in other cores that penetrated below the Exmore beds within the annular trough (Powars and others, 1992; Powars and Bruce, 1999). Instead, the Exmore beds routinely overlie impact-disrupted sections of the Potomac Formation.

We infer from these observations that the near-surface Cretaceous and Tertiary marine sediments, and perhaps the uppermost part of the Potomac Formation, were disaggregated into their constituent particles by the same reflected tensile wave described above as a cause of target fracturing (Melosh, 1984, 1989). The downward passage of this rarefaction also pulled apart the underlying Potomac Formation strata and allowed the downward injection of the disaggregated glauconitic sediments into the underpressured Potomac section. Sturkell and Ormö (1997) invoked this same process for the injection of clastic dikes and sills in strata adjacent to the Ordovician Lockne crater (Sweden).

In addition, some amount of disaggregated marine sediment may have been ejected as dissociated spall material due to stress wave interference in the near-surface area (Melosh, 1984, 1989), and part may have been scoured and entrained by oceanic resurge currents flowing into the collapsing crater (see the following section on the "Exmore Beds").

Exmore Beds

The diamicton section of the Exmore beds of the Langley core consists of a polymict assemblage of sediment and rock clasts suspended in an unstratified, unsorted, glauconitic, muddy and sandy matrix. The unit is dominantly matrix supported, and coarse-tail size grading of clasts is present. These textures and structures suggest sediment transport and deposition by cohesive, subaqueous debris flows (Middleton, 1967; Middleton and Hampton, 1973; Postma, 1986; Mulder and Cochonat, 1996).

The observed pattern of coarse-tail grading suggests that the diamicton of the Exmore beds consists of two debris-flow units in the Langley core (fig. C12). The core section can be divided into (1) a thick, normal coarse-tail-graded unit from the base of the Exmore to about 244 m (800 ft) depth and (2) a thinner, normal coarse-tail-graded unit from about 244 m (about 800 ft) to the top of the diamicton at 235.92 m (774.03 ft) depth. Size variations within individual lithologic categories of clasts also suggest the presence of a boundary at 244 m (800 ft) depth (fig. C13).

Frederiksen and others (this volume, chap. D) note that reworked Cretaceous calcareous nannofossils are present in diamicton matrix samples from 242.2 m (794.7 ft) depth and above but are absent from samples from 244.3 m (801.5 ft) depth and below. The nannofossil distribution indicates a change in sediment provenance and supports the presence of a depositional boundary at about 244 m (about 800 ft) depth.

Smaller scale variations in lithology also are observed in the diamicton. Figure C12 shows intervals 1 to 3 m (3.3 to 9.8 ft) thick in which maximum clast size either fines or coarsens upward. There also is a tendency for clasts to be concentrated in roughly 10-cm-thick (3.9-in.-thick) intervals within the upper part of the diamicton (fig. C10*D*). These lithologic variations likely indicate variations in flow conditions within the debris flows.

Catchings and others (this volume, chap. I) mapped four Exmore subunits (debris flows) in the vicinity of the Langley corehole on their seismic-reflection images. The three older subunits successively overstep toward the crater's center, producing a shingled appearance. Hence these three units have limited lateral distributions. The youngest subunit extends entirely across the seismic survey. Only seismic subunits Ex2 and Ex4 of Catchings and others (this volume, chap. I) are present at the Langley corehole location, where they apparently represent the two Exmore debris flows defined in the core.

We attribute the origin of the Exmore debris flows to ocean-resurge currents produced by crater collapse. During impacts on continental shelves, the collapse of the transient crater (including the water-column crater) typically includes a catastrophic collapse and resurge of the water column back into the crater (Ormö and Lindström, 2000). This process can result in severe erosion of the proximal ejecta field, the preimpact shelf deposits that underlie the ejecta field, and the crater rim, followed by deposition of the eroded materials within the collapsing crater (Lindström, 1999; Ormö and Lindström, 1999, 2000; von Dalwigk and Ormö, 1999; Shuvalov and others, 2002; Tsikalas and Faleide, 2002).

Clasts in the Exmore beds of the Langley core include shocked cataclastic crystalline-rock fragments ejected from significant depths (Horton and Izett, this volume, chap. E) and coherent, unshocked Cretaceous and Tertiary sediment clasts that represent most, if not all, of the sedimentary units in the target section. The shocked ejecta likely were derived by current scour of the proximal ejecta blanket outside the collapsing crater and from direct ejecta fallback. The Tertiary sediment clasts suggest scour of the ocean floor below the level of the proximal ejecta blanket and perhaps resedimentation or direct fallback of unshocked sediment clasts ejected from the top of the preimpact sedimentary section (spall of Melosh, 1984). The Cretaceous sediment clasts likely resulted from erosion of the collapsing outer crater margin and perhaps from deep (channelized?) scouring of the adjacent shelf.

The presence of a single piece of shocked crystalline ejecta and two fossiliferous matrix samples in the upper 30 m (98.4 ft) of crater unit B suggests mixing of material from the Exmore beds and crater unit B. This mixing could represent passive infiltration of Exmore sediments into the top of crater unit B. It also could represent entrainment of blocks and megablocks of crater unit B into the base of the lowest Exmore debris flow. A third possibility is that the upper 30 m (98.4 ft) of crater unit B represents additional debris flows, perhaps generated at the collapsing outer crater margin, as suggested by the strong dominance of Potomac Formation sediment clasts (blocks) in this interval.

Wave swash during re-equilibration of sea level and the return of degraded, impact-induced tsunamis (tsunami washback) from the nearby North American shoreline may have reworked the Exmore sediments within the crater and swept fine-grained sediments from the adjacent shelf into the crater (for nonimpact examples of similar processes, see Pickering and others, 1991, and Cita and others, 1996). Possible large bedforms at the top of the Exmore section, postulated by Catchings and others (this volume, chap. I) on the basis of their seismic survey, may represent this sediment reworking.

The transition sediments at the top of the Exmore beds represent postimpact settling of fine-grained sediments suspended in the water column by impact processes. Poag (2002) and Poag and Norris (this volume, chap. F) interpret the presence of microspherules (microtektites) in a fallout layer within this section. Although microtektites were not observed directly in the Langley core, their former presence was inferred by these authors from the hemispherical molds within the pyrite lattices.

Poag (2002) and Poag and Norris (this volume, chap. F) interpret the thin interval of laminated clayey silt and very fine sand at the top of the transition sediments in the Langley core to be a biological dead zone. They base this interpretation on the absence of an indigenous microfauna in this interval (Poag and Norris, this volume, chap. F). Sparse pyritic sand-filled burrows in the dead zone may indicate the presence of a limited infauna in the dead-zone sediments, or they may represent later burrowing initiated at higher stratigraphic levels. The transition sediments represent the final stage of impact-related sedimentation before the return to normal marine-shelf sedimentation represented by the upper Eocene Chickahominy Formation.

Summary

The continuously sampled USGS-NASA Langley core and the Langley seismic-reflection survey provide a basis for describing and interpreting the impact-modified and impact-generated Cretaceous and Tertiary sediments within the outer annular trough of the Chesapeake Bay impact structure. Above the basement granite, crater unit A and the lower beds of crater unit B constitute an autochthonous section of Cretaceous sediments (Potomac Formation) that were faulted, fractured, and locally fluidized during the impact. The lowest occurrence of impact-induced fluidization of water-saturated sands is at the base of the upper beds of unit A at 558.1 m (1,831.0 ft) depth, and the lowest occurrence of injected exotic sediments is the thin matrix zone at the contact between crater units A and B at 442.5 m (1,451.7 ft) depth. The upper beds of crater unit B consist of faulted, fractured, and rotated blocks and megablocks of the Potomac Formation, fluidized sands, and matrix zones consisting of Potomac Formation blocks suspended in a finer grained matrix of mixed native and exotic sediments. The lowest occurrence of abundant injected exotic sediments is at the base of the upper beds of crater unit B at 427.7 m (1,403.3 ft) depth.

The Exmore beds consist of unshocked, preimpact Cretaceous and Tertiary sediment clasts and minor shocked and (or) cataclastic igneous-rock clasts suspended in a finer calcareous, muddy, quartz-glauconite matrix. The Exmore beds are interpreted as ocean-resurge sediments deposited by multiple debris flows as a result of the late-stage catastrophic collapse of the oceanic water column. The thin transitional beds at the top of the Exmore section record the return to normal continental shelf sedimentation.

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