Crystalline-Rock Ejecta and Shocked Minerals of the Chesapeake Bay Impact Structure, USGS-NASA Langley Core, Hampton, Virginia, with Supplemental Constraints on the Age of Impact

By J. Wright Horton, Jr., and Glen A. Izett

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

Edited by J. Wright Horton, Jr., David S. Powars, and Gregory S. Gohn

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By J. Wright Horton, Jr.,[1] and Glen A. Izett[2]

Abstract

The USGS-NASA Langley corehole at Hampton, Va., was drilled in 2000 as the first in a series of new coreholes drilled in the late Eocene Chesapeake Bay impact structure to gain a comprehensive understanding of its three-dimensional character. This understanding is important for assessing ground-water resources in the region, as well as for learning about marine impacts on Earth. We studied crystalline-rock ejecta and shock-metamorphosed minerals from the Langley core to determine what they reveal about the geology of crystalline rocks beneath the Atlantic Coastal Plain and how those rocks were affected by the impact.

An unusual polymict diamicton, informally called the Exmore beds (upper Eocene), is 33.8 meters (m; 110.9 feet (ft)) thick and lies at a depth of 269.4 to 235.65 m (884.0 to 773.12 ft) in the core. This matrix-supported sedimentary deposit contains clasts of Tertiary and Cretaceous sediment (ranging up to boulder size) and sparse pebbles of crystalline rock. The matrix consists of muddy sand that contains abundant quartz grains and minor glauconite and potassium feldspar.

Significantly, the sandy matrix of the Exmore beds contains sparse quartz grains (0.1 to 0.3 millimeter (0.004 to 0.012 inch) in diameter) that contain multiple sets of intersecting planar deformation features formerly referred to as shock lamellae. As many as five different sets have been observed in some quartz grains. Planar deformation features also occur in quartz grains in reworked crystalline-rock clasts in the Exmore beds. Such grains are clearly of shock-metamorphic origin. The presence of these features indicates that the quartz grains have experienced pressures greater than 6 gigapascals (GPa) and strain rates greater than 10^6/second. Thus, the shock-metamorphosed quartz grains, although rare, provide clear and convincing evidence that the Exmore beds are of hybrid impact origin. Identification of shocked quartz grains in the Langley core adds to the number of sites in the structure where their presence is confirmed.

Most of the clasts of crystalline rock that are in and just below the Exmore beds are rounded, detrital, and typical of coastal plain sediments. However, a few have angular shapes and consist of cataclastically deformed felsite having aphanitic-porphyritic to aphanitic texture and peraluminous rhyolite composition. Three of these clasts contain quartz grains that display two sets of planar deformation features of shock-metamorphic origin. Shock-metamorphosed quartz is an integral part of the cataclastic fabric in these three clasts, indicating that both the fabric and the shocked quartz were produced by the same high-energy impact event. Some felsite clasts have spherulitic textures that may be features either of an impact melt or of preimpact volcanic rocks.

A weighted-mean total-fusion $^{40}Ar/^{39}Ar$ age of 35.3±0.1 Ma (±1σ) for 19 analyses of 4 North American tektites records the age of the late Eocene Chesapeake Bay impact event.

Introduction

Purpose and Scope

The USGS-NASA Langley corehole at Hampton, Va., was drilled in 2000 as the first in a series of new coreholes drilled in the late Eocene Chesapeake Bay impact structure to gain a comprehensive understanding of its three-dimensional structure and stratigraphic framework and its influence on regional ground-water resources. We studied crystalline-rock ejecta and shock-metamorphosed minerals from the Langley core to determine what they reveal about the regional geology of crystalline rocks beneath the Atlantic Coastal Plain and how those rocks were affected by the impact. Research is in progress to expand this initial investigation to encompass samples from three coreholes completed in 2001 and 2002—the North, Bayside, and Watkins School coreholes (fig. E1).

The main purpose of this chapter is to present the results of our study of samples from the Langley core. A secondary pur-

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pose is to present new constraints on the age of the Chesapeake Bay impact metamorphism based on argon geochronology of North American tektites.

Study Area and Geologic Setting of the Chesapeake Bay Impact Structure

The Chesapeake Bay impact structure is near the mouth of Chesapeake Bay, where it lies buried beneath approximately 150 to 400 meters (m; 492 to 1,312 feet (ft)) of postimpact sediments of the Atlantic Coastal Plain (fig. E1); it was described in earlier reports (Poag and others, 1992, 1994; Poag, 1996, 1997, 1999; Powars and Bruce, 1999; Powars, 2000). The Chesapeake Bay impact structure is one of the largest on Earth and is one of the few fully marine impact structures that have been extensively studied by seismic reflection and drilling (Reimold and others, 2002).

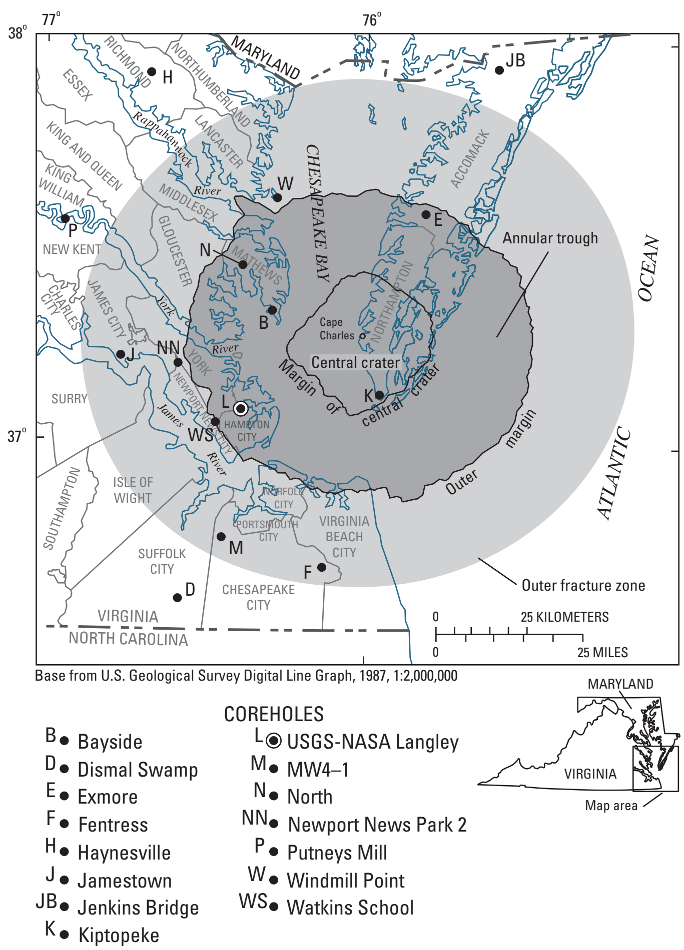


Figure E1. Regional map showing the location of the Chesapeake Bay impact structure, the USGS-NASA Langley corehole at Hampton, Va., and some other coreholes in southeastern Virginia. Locations of the central crater and outer margin are from Powars and Bruce (1999). The extent of the outer fracture zone (light gray) is based on Powars (2000) and Johnson and others (2001); the eastern part is speculative. Illustration modified from Powars, Johnson, and others (2002) and Edwards and Powars (2003).

These studies reveal that the buried structure is a complex impact crater 85 kilometers (km; 53 miles (mi)) wide. It consists of an excavated central crater, which is 30–38 km (18–24 mi) wide and 1–2 km (0.6–1.2 mi) deep, surrounded by a flat-floored annular trough, which is 21–31 km (13–19 mi) wide and contains disrupted sediments, a slumped terrace zone, and a steep gullied escarpment (Poag, 2002a; Powars, Gohn, and others, 2002; Powars, Johnson, and others, 2002). This annular trough is encircled by a 35-km-wide (22-mi-wide) outer fracture zone of concentric faults (Powars, Gohn, and others, 2002; Powars, Johnson, and others, 2002).

The innermost part of the annular trough is interpreted by some workers (Poag, Hutchinson, and others, 1999; Poag, 2002a) to be underlain by a crystalline-rock peak ring that surrounds the central crater. Geophysical interpretations suggest that the floor of the central crater contains a central peak of uplifted crystalline rock overlain by crater-fill sediments (Poag, Hutchinson, and others, 1999; Poag, Plescia, and Molzer, 1999; Poag, 2002a).

The USGS-NASA Langley corehole is located 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. It is on the York-James Peninsula at the National Aeronautics and Space Administration (NASA) Langley Research Center in Hampton, Va., about 19 km (12 mi) outside the margin of the central crater and about 8 km (5 mi) inside the outer margin of the annular trough (fig. E1). The hole was drilled by the U.S. Geological Survey (USGS) and cooperators (see "Acknowledgments"). Preliminary descriptions of the core are available in Gohn, Clark, and others (2001), Gohn, Powars, and others (2001), Horton and others (2001), and Powars and others (2001).

The core contains weathered Neoproterozoic granite below 626.3 m (2,054.7 ft) depth (Horton and others, this volume, chap. B). The granite is overlain by weakly to strongly disturbed preimpact sediments (crater units A and B of Gohn and others, this volume, chap. C), followed by a polymict diamicton (the Exmore beds) and by postimpact sediments (Powars and others, this volume, chap. G).

The impact-disturbed sediments include a basal crater unit A, consisting of autochthonous, block-faulted sediments of the Cretaceous Potomac Formation, which Gohn and others (this volume, chap. C) divide into lower beds (nonfluidized) and upper beds (variably fluidized). Crater unit A is present in the Langley core between depths of 626.3 and 442.5 m (2,054.7 and 1,451.7 ft) and is 183.8 m (603.0 ft) thick.

The overlying crater unit B consists of blocks of Lower Cretaceous sediments disrupted by zones of extensive fluidization, injection, and mixing (Powars, Gohn, and others, 2002; Gohn and others, 2002 and this volume, chap. C). The base of crater unit B in the core, defined by the deepest occurrence of glauconite, is interpreted to represent the lowest zone of injection by Tertiary marine sediment from above (Gohn and others, this volume, chap. C). Crater unit B is present in the Langley core between depths of 442.5 and 269.4 m (1,451.7 and 884.0 ft) and is 173.0 m (567.7 ft) thick.

The crater-fill unit informally known as the Exmore beds (Powars and others, 1992) is a matrix-supported sedimentary deposit and contains clasts of Tertiary and Cretaceous sediment (ranging up to boulder size) and sparse pebbles of crystalline rock; the matrix consists of muddy sand that contains abundant quartz grains and minor glauconite and potassium feldspar (Gohn and others, 2002 and this volume, chap. C; Powars, Gohn, and others, 2002; this study). The unit consists mainly of rounded clasts, rather than angular fragments, in a detrital matrix and is more accurately characterized as a polymict diamicton (Gohn and others, this volume, chap. C) than a breccia (see the glossary for this chapter).

The Exmore beds have also been called the Exmore boulder bed (Poag and others, 1992), the Exmore breccia (Powars and others, 1993; Poag and others, 1994; Poag, 1996, 1997), and the Exmore tsunami-breccia (Powars and Bruce, 1999; Powars, 2000). The mixed sediments of the Exmore beds were previously interpreted as tsunami deposits (Powars and Bruce, 1999; Powars, 2000) and were reinterpreted as mainly seawater-resurge deposits (Gohn and others, this volume, chap. C).

Microfossils in the Exmore beds have mixed Cretaceous, Paleocene, and Eocene ages (Edwards and others, 2002; Frederiksen and others, this volume, chap. D). In the USGS-NASA Langley core, the Exmore beds have a thickness of 33.8 m (110.9 ft); they extend from the base of glauconitic marine sediments at 269.4 m (884.0 ft) depth to the uppermost synimpact fallout layer at 235.65 m (773.12 ft) depth (Gohn and others, this volume, chap. C).

In this chapter, we discuss shock-metamorphosed minerals and crystalline-rock clasts in and just below the Exmore beds in the USGS-NASA Langley core. Initial results of this study and related studies of other cores are summarized in several abstracts (Horton and others, 2001; Horton, Aleinikoff, and others, 2002; Horton, Kunk, and others, 2002; Horton, Gohn, and others, 2003).

General Criteria for Shock Metamorphism

Grains of quartz and other silicate minerals that contain multiple intersecting sets of closely spaced planar deformation features are commonly called "shocked" or "shock metamorphosed." They are interpreted to be formed in target rocks during hypervelocity impacts of asteroids or comet nuclei with the Earth (Grieve and others, 1996). These microstructures have been observed in rocks at known impact sites, in rocks that have undergone a high strain rate during hypervelocity shock metamorphism in laboratory experiments (Chao, 1967, 1968), and in rocks at high-yield chemical and nuclear explosion sites (Short, 1968). Quartz and feldspar in volcanic rocks produced by giant silicic pyroclastic eruptions lack these multiple sets of planar deformation features (Izett, 1990, p. 74).

Shock-metamorphic features in quartz share the following characteristics (Alexopoulos and others, 1988; French, 1998):

1. Features are planar, well to very well defined, and sharp.
2. Within each set, the planar deformation features are parallel, are generally continuous, and extend across a minimum of 75 percent of the grain.
3. Spacing between the individual planar deformation features is typically about 1 to 4 micrometers.
4. Approximately 80 percent of these features are oriented (±3° variance in orientation measurement) parallel to the basal plane c{0001} and to the rhombohedral planes $\omega\{10\bar{1}3\}$ and $\{10\bar{1}2\}$, which have poles inclined at angles of approximately 23° and 32°, respectively, to the *c* axis. The $\omega\{10\bar{1}3\}$ orientation is important because it is not a normal cleavage, twin, or growth plane and because it does not correspond to deformation features produced in low-strain-rate experiments (Alexopoulos and others, 1988).

Transmission-electron-microscopic (TEM) studies have shown that individual planar deformation features in quartz grains that have experienced low shock pressures consist mainly of planar open microfractures, dislocation bands, microgranulated laminae, and tiny voids (Chao, 1976; Chao and Goresy, 1977; Xie and Chao, 1985). Planar deformation features in quartz grains that have experienced moderate to high shock pressures consist of submicrometer-thick silica glass (Chao and Goresy, 1977; Xie and Chao, 1985).

The features characteristic of shock-deformed minerals have been variously termed "shock lamellae" (Chao, 1967), "planar features" (Carter, 1965), "planar elements" (Stöffler, 1972), "microfractures" (Chao and Goresy, 1977, p. 291), and "planar deformation features (PDFs)" (Koeberl and others, 1996). The International Union of Geological Sciences (IUGS) Subcommission on the Systematics of Metamorphic Rocks has released a proposal (Stöffler and Grieve, 2003) to standardize use of the term "planar deformation features" and to discard synonymous terms such as "shock lamellae" and "planar elements."

It has long been recognized that the presence of multiple intersecting sets of planar deformation features is the most diagnostic criterion for identifying shock metamorphism in silicate minerals. This recognition is based on extensive experimental and empirical mineralogy of impact materials (Wackerle, 1962; Carter and others, 1964; Carter, 1965, 1971; Chao, 1967, 1968; Ahrens and Rosenberg, 1968; Bunch, 1968; Engelhardt and others, 1968; McIntyre, 1968; Robertson and others, 1968; Short, 1968; Engelhardt and Bertsch, 1969; Stöffler, 1971, 1972; Grieve and others, 1996). Other important evidence of shock metamorphism can include optical mosaicism, isotropization, high-pressure mineral polymorphs such as coesite and stishovite, and macroscopic features such as shatter cones (Chao, 1968; French and Short, 1968; Grieve and others, 1977, 1996; Alexopoulos and others, 1988; Grieve, 1991).

Previous Evidence of Impact Metamorphism near Chesapeake Bay

Poag and others (1992) first reported the presence of shock-metamorphosed quartz grains in the Exmore beds in samples from the Newport News Park 2 corehole, Va. (fig. E1). Prior to publication in 1992, Larry Poppe (USGS) and Wylie Poag (USGS) sent one of us (Izett) three smear slides from the Newport News Park 2 corehole that they believed to contain shock-metamorphosed quartz grains. Izett found only two quartz grains in the three slides that contained multiple intersecting sets of planar deformation features. Neither grain was a textbook example of shocked quartz.

Subsequent studies of the Newport News Park 2 core by Izett (unpub. data, 1993) revealed clear and convincing evidence that shock-metamorphosed quartz grains, containing multiple intersecting sets of planar deformation features, were present in some samples of the Exmore beds at Newport News but in very low abundance, far less than 1 percent. Izett examined 30 immersion-oil mounts containing silicate mineral grains from the Exmore beds and found only one quartz grain that contained multiple intersecting sets of planar deformation features.

The evidence of shock metamorphism presented by Poag and others (1992), although meager, provided important physical confirmation that an asteroid or comet nucleus struck the Earth in the general region and generated the Exmore beds near the mouth of the present Chesapeake Bay. Since then, Koeberl and others (1996) presented corroborating evidence of shock metamorphism in samples from the corehole at Exmore, Va. (fig. E1). This evidence included quartz having up to six sets of planar deformation features and crystallographic orientations consistent with shock pressures of 20 to about 30 gigapascals (GPa), as well as shock-metamorphosed feldspar having as many as three sets and having microfracture patterns consistent with shock pressures of 5 to 10 GPa (Koeberl and others, 1996). Reimold and others (2002), in a continuation of that study, estimated shock pressures of 10 to 20 GPa from a small data set on the orientations and relative frequencies of planar deformation features in quartz.

Poag and others (1992) reported but did not illustrate vesicular tektite glass in samples from the Exmore, Va., corehole. More recently, Poag (2002b, p. 997) and Poag, Koeberl, and Reimold (2004, fig. 6.32) illustrated material identified as "intact glass microspherules" in thin sections of the Exmore beds from the Exmore and Newport News Park 2 coreholes. Reimold and others (2002) referred to these spherules as proximal microtektites. Further tests that are needed to confirm and characterize the suspected glass include index of refraction measurement, chemical analysis, and $^{40}Ar/^{39}Ar$ isotopic analysis. Such material has not been found in our own studies of cores from the Chesapeake Bay impact structure.

In addition to shocked minerals, marine microfossils that are interpreted to be impact damaged were recently discovered in samples of the Exmore beds from the Langley core (Edwards and Self-Trail, 2002; Edwards and others, 2002; Edwards and Powars, 2003; Self-Trail, 2003; Frederiksen and others, this volume, chap. D).

Distal impact ejecta that are inferred to be from the Chesapeake Bay impact structure include tektites and microtektites (impact glass), shocked quartz and zircon, the high-pressure silica polymorphs coesite and stishovite, and the high-pressure zircon polymorph reidite (Glass and Liu, 2001; Glass, 2002; Glass and others, 2002; Kamo and others, 2002).

Crystalline-Rock Ejecta and Shocked Minerals in the USGS-NASA Langley Core

Methods

Preparation and microscopic study of matrix samples.—Sandy matrix of the Exmore beds was sampled in the USGS-NASA Langley core at depths of 236.9 m (777.3 ft) and 250.1 m (820.6 ft). These samples were sieved, and grains having diameters less than 0.5 millimeter (mm; 0.02 inch (in.)) were prepared for microscopic examination by disaggregating the sediment in a 10-percent hydrochloric acid solution in an ultrasonic cleaning bath for at least an hour. Suspended material, consisting mostly of clay minerals, was decanted from the slurry. The residuum again was placed in an ultrasonic cleaning bath, but this time in an aqueous solution of household bleach (~30 percent). It was then treated in 5-percent hydrofluoric acid for 30 seconds to clean and enhance the visibility of any planar deformation features. Immersion-oil mounts were prepared by placing several hundred of the dried grains in 1.544 index oil without a cover glass.

Individual grains in the immersion-oil mounts that were suspected to be shock metamorphic because of their appearance under a binocular microscope were nudged out of the oil and pushed aside with a sharpened steel spindle. A selected grain was transferred into a drop of water and agitated. After the water evaporated, the grain was glue mounted (by using a mixture of 50 percent white carpenter's glue and 50 percent molasses) on the tip of a steel-wire spindle. The mounted grains were inserted into the immersion cell of a spindle stage (Wilcox, 1959).

A spindle stage is ideal for the study of shock-metamorphic features in mineral grains because planar deformation features can be rotated to the vertical, and their orientations in relation to optical directions can be measured and plotted on a stereonet. The spindle stage is also ideally suited for the measurement of the principal indices of refraction of shocked minerals. When a spindle stage is used, the precision of measuring planar features and optical directions is about ±2° (Wilcox, 1959). Techniques for preparing and manipulating quartz grains on the spindle stage and for estimating the relative abundance (percentage) of shocked grains per sample were described by Wilcox (1959) and by Izett (1990).

Preparation and microscopic study of clast samples.—The Langley core was also examined for lithic clasts composed of crystalline rock. Most of those in and just below the Exmore beds were rounded detrital pebbles. Thin sections of these rounded pebbles revealed no unusual high-strain-rate fabrics or shock-induced features (appendix E1, samples NL854.0, NL864.05).

A much smaller population of crystalline-rock clasts has angular shapes or cataclastic fabrics, and these clasts were examined in thin section (appendix E1). A standard microprobe polish was used to eliminate surface scratches in most thin sections. In other thin sections, a yellow stain (sodium cobaltinitrite) was used to distinguish potassium feldspar. Quartz grains were separated from several clasts, were processed as described in the section above, and were rotated on a spindle stage to further verify the presence or absence of shock-induced planar deformation features.

The planar deformation features can be seen readily by using a petrographic microscope and plane-polarized light, and they give the quartz grains a remarkable appearance that is very different from normal unshocked quartz. The planar microstructures are best seen when they are oriented nearly parallel to the axis of a microscope. In this orientation, they appear as parallel bright lines commonly bordered by dark lines. These closely spaced parallel planar deformation features differ from twin lamellae in that adjacent crystallographic domains do not go to extinction at different angles during rotation of the stage of a petrographic microscope. In contrast, curved discontinuous planar features (termed Böhm lamellae) that occur in quartz grains of tectonites have a much different appearance than the planar deformation features in shock-metamorphosed quartz at impact sites.

Chemical analysis of rocks.—Chemical analyses of two rock samples (discussed below) used several methods (Arbogast, 1996), including the following: wavelength-dispersive X-ray fluorescence (WDXRF) spectrometry for 10 major elements (Taggart and others, 1987; Mee and others, 1996), energy-dispersive X-ray fluorescence (EDXRF) spectrometry for 30 trace elements (Siems, 2000, 2002), instrumental-neutron-activation analysis (INAA; Baedecker and McKown, 1987) using a long-count procedure for 44 elements including rare-earth elements (Wandless, 1996), and individual determination of FeO, forms of H_2O, C as CO_2, F, and S as described by Jackson and others (1987).

Results

Shocked Quartz Grains

Quartz and potassium feldspar are the chief components of the clastic mineral grains in the Exmore beds. Most of the grains appear structureless and show normal sharp extinction when examined with a petrographic microscope using cross-polarized light. Some grains show anomalous extinction, and others exhibit Böhm lamellae. Of special importance is the fact that rare quartz grains contain multiple sets of planar deformation features. As many as five sets occur in some quartz grains. The grains are subangular, commonly 0.1 to 0.3 mm (0.004 to 0.012 in.) in diameter, and generally colorless. Spindle-stage measurements show that the planar deformation features we studied most commonly have poles inclined at about 23° to the *c* axis. This is the rhombohedral planar orientation, or the ω direction $\{10\bar{1}3\}$ in quartz.

Quartz is the only mineral in these sediment samples that has convincing shock-induced planar deformation features. No shocked feldspar grains were found, and no attempt was made to separate and examine heavy minerals such as zircon for evidence of shock metamorphism. Figure E2 and the cover of this volume show examples of shock-metamorphosed quartz grains from the Langley core.

Shock-metamorphosed quartz is scarce in samples from the Langley core. We estimate the relative abundance to be no more than one shocked grain in several thousand quartz grains, on the basis of the number of immersion-oil slides per sample and the numbers of total grains and shocked grains per slide. Consequently, point counting of grains to obtain meaningful statistics on their abundance would be impractical. Although the abundance of shocked grains is insufficient for a statistically meaningful assessment of crystallographic orientations, the orientations of planar deformation features that we measured on a spindle stage are consistent with shock metamorphism. The individual quartz grains that have confirmed shock-induced deformation features are mostly subangular and lack the rounded shapes that would indicate derivation from a detrital sedimentary target. This lack of rounding suggests that they are mainly particles of crystalline basement, or possibly fragments of smashed detrital grains, that were excavated by the impact.

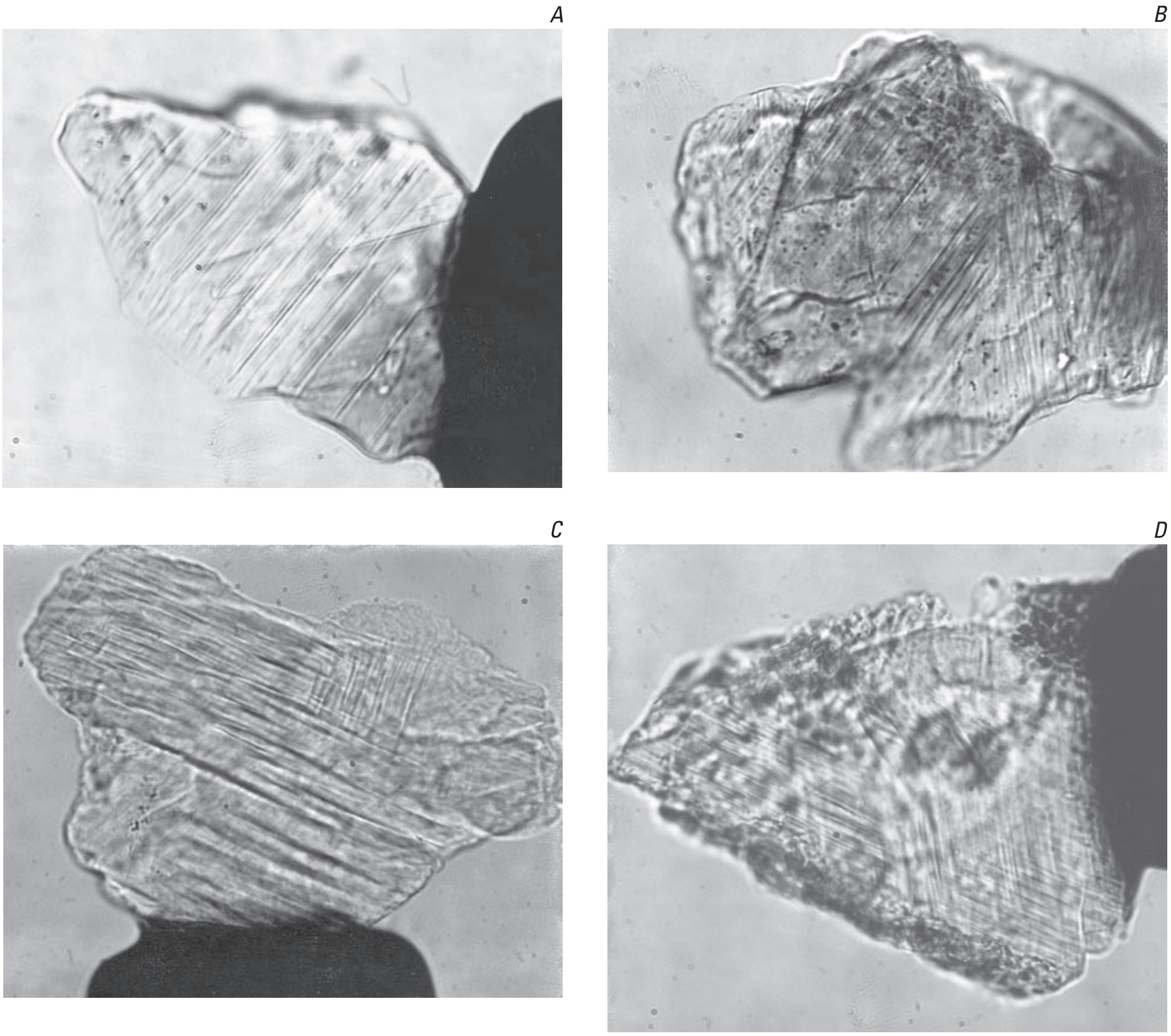
Impact-Derived Clasts of Crystalline Rock

Cataclastic Fabrics and Planar Deformation Features

Cataclastic rocks are high-strain-rate rocks produced by mechanical crushing, faulting, and fracturing of existing rocks. Those found in impact structures are identical in many respects to those found in fault zones (Snoke and Tullis, 1998). They are not diagnostic as criteria for an impact origin, but they may be impact related where associated with features such as shock-metamorphosed minerals or a crater.

Lithic clasts of crystalline rock that have angular shapes or cataclastic fabrics were distributed throughout the Exmore beds in the Langley core, and one was found in the core below the Exmore beds in the upper part of crater unit B (fig. E3). Clasts larger than the nominal core diameter of 6.4 centimeters (cm; 2.5 in.) were found only in the lower half of the Exmore beds and below. Figure E4 shows some of the crystalline-rock clasts, and figure E5 shows the cataclastic microfabrics.

Figure E4*A* shows the jagged edges of a brecciated felsite clast in contact with matrix sediment of the Exmore beds, and figure E4*B* shows a clast of cataclasite (deformed felsite) with thin calcite veins along fault surfaces. Primary igneous textures are preserved in less deformed felsite clasts from the Exmore



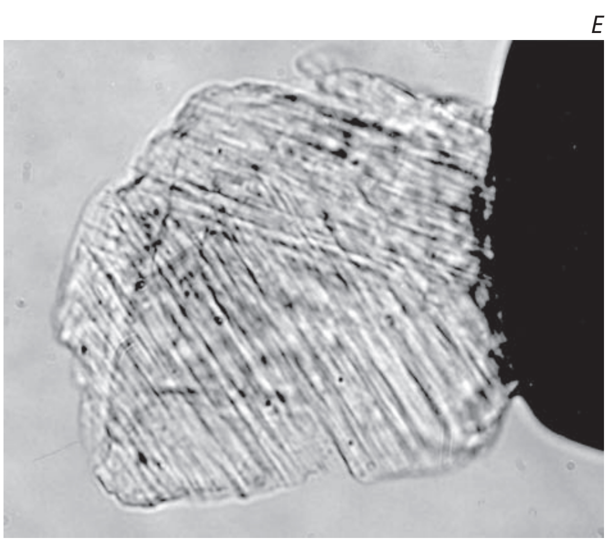


Figure E2. Photomicrographs of selected individual quartz grains from matrix samples of the Exmore beds in the USGS-NASA Langley core showing multiple sets of shock-induced planar deformation features (PDFs). All grains were photographed on a spindle stage in plane-polarized light. *A*, Grain #3, 0.13 mm (0.005 in.) in diameter, showing two sets of PDFs; sample NL777.3, from 236.9 m (777.3 ft) depth. *B*, Grain #1, 0.23 mm (0.009 in.) in diameter, showing two sets of PDFs; sample NL820.6, from 250.1 m (820.6 ft) depth. *C*, Grain #2, 0.26 mm (0.010 in.) in diameter, showing at least two sets of PDFs; sample NL820.6. *D*, Grain #5, 0.25 mm (0.010 in.) in diameter, showing at least two sets of PDFs; sample NL820.6. *E*, Grain #6, 0.13 mm (0.005 in.) in diameter, showing two sets of PDFs; sample NL820.6. Another view of grain #6 is shown on the front cover of this volume.

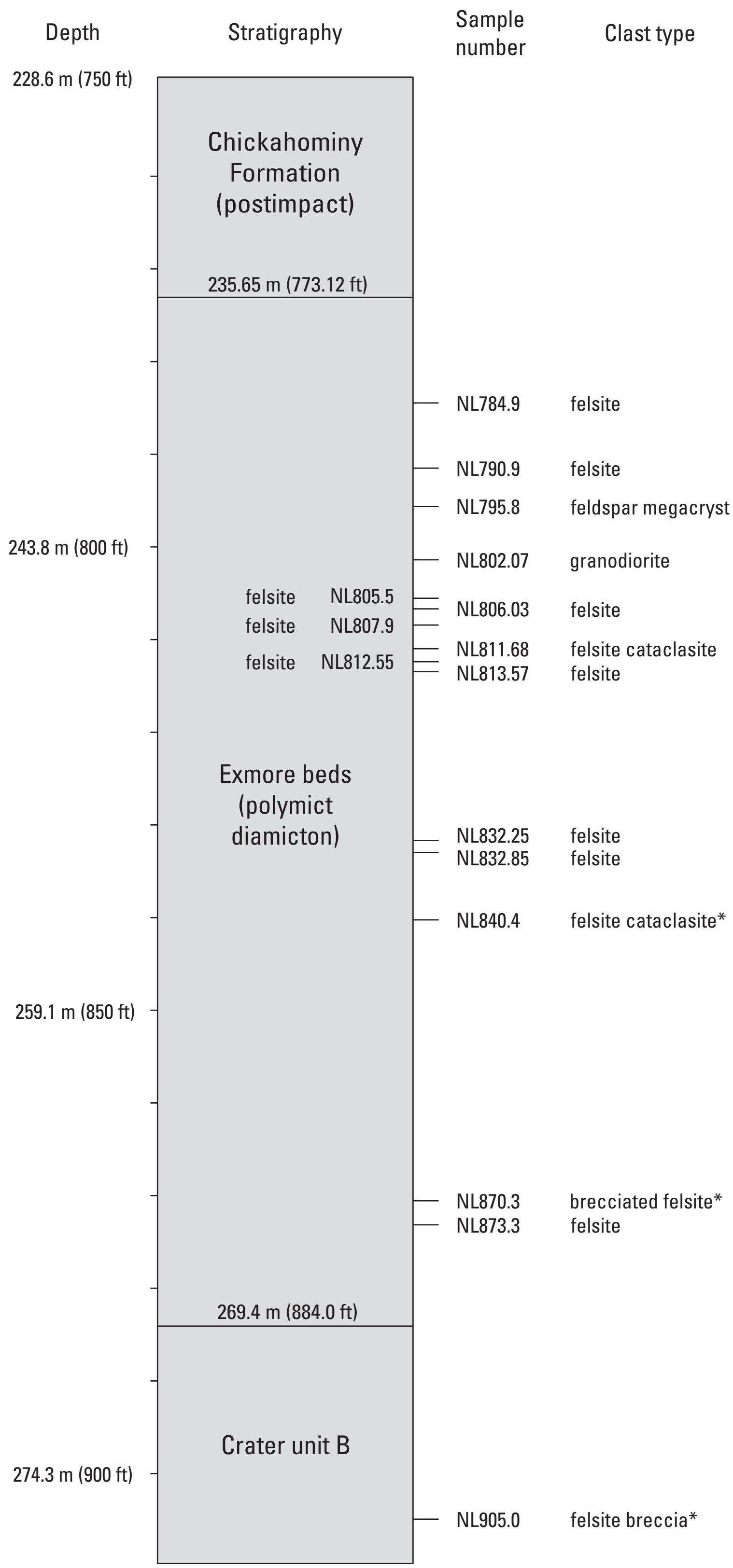
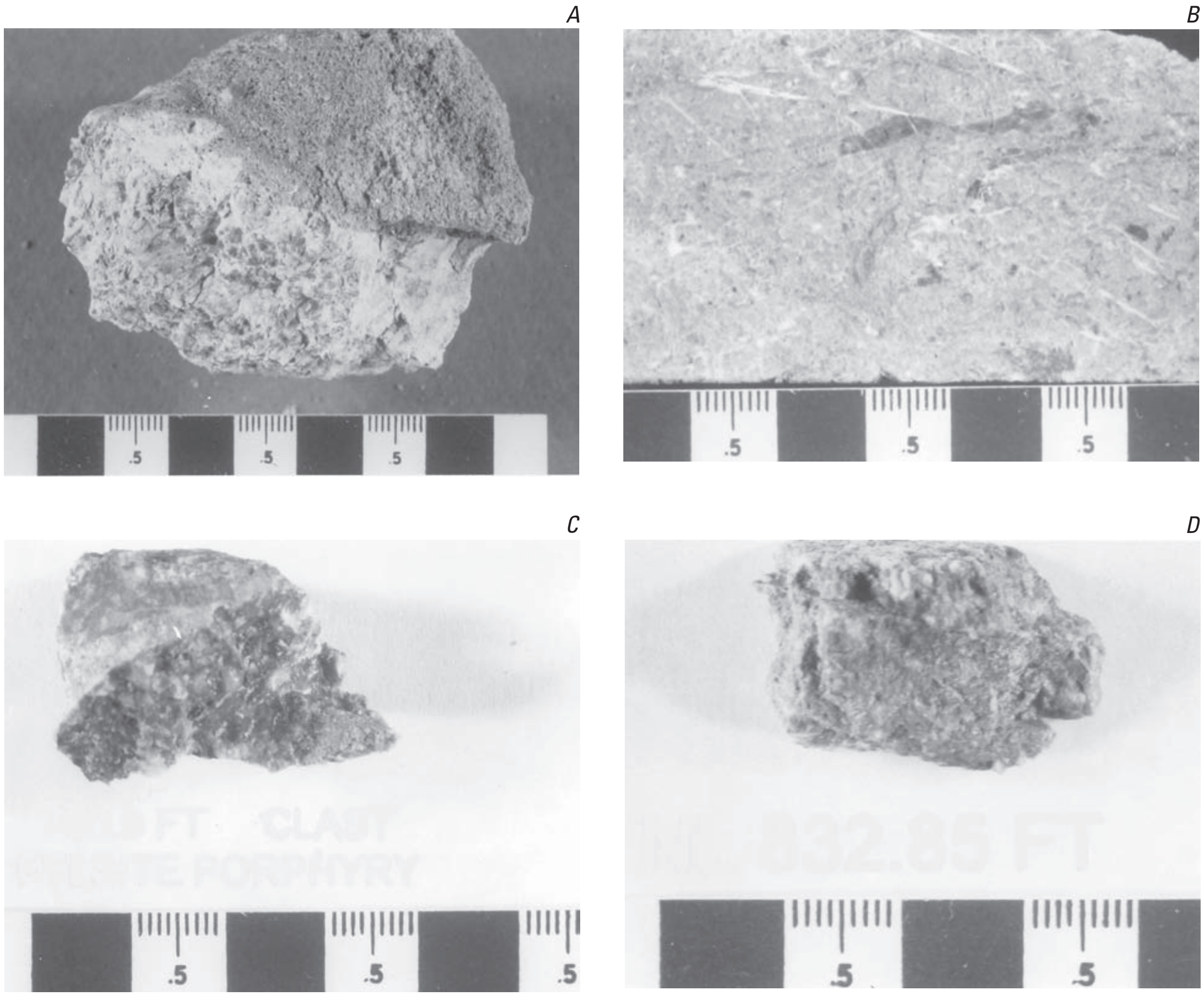


Figure E3. Stratigraphic column of part of the USGS-NASA Langley corehole showing positions of selected lithic clasts of crystalline rock. All samples interpreted as impact ejecta are from the Exmore beds, with one exception; sample NL905.0 is from crater unit B. An asterisk (*) indicates clasts larger than the nominal core diameter of 6.4 cm (2.5 in.). Sample numbers indicate depths in feet; sample descriptions are in appendix E1.



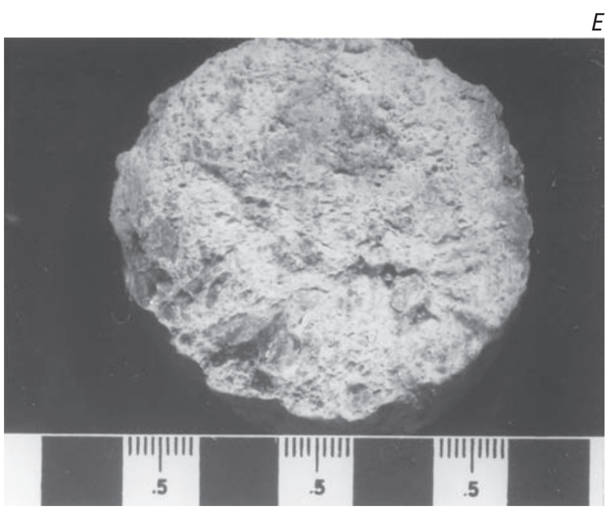


Figure E4. Photographs of selected lithic clasts of crystalline rock from the Exmore beds (*A*–*D*) and from the upper part of crater unit B (*E*) in the USGS-NASA Langley core. Scale bars in centimeters have millimeter subdivisions. *A*, Brecciated porphyritic felsite (NL870.3) having jagged edge and angular crevices filled with darker sediment; striated surfaces (not shown) are inconclusive evidence that the sample may have been part of a shatter cone. *B*, Felsite cataclasite (NL840.4) having shocked quartz and interpreted as impact breccia is weakly cohesive; white streaks on cut surface are calcite veins along faults. *C*, Porphyritic felsite (rhyolite) (NL790.9) used for chemical analyses (tables E2, E3, and E4). *D,* Porphyritic felsite (NL832.85). *E*, Impact breccia (NL905.0) having shocked quartz consists of angular fragments of microcrystalline felsite in gougelike clay matrix.

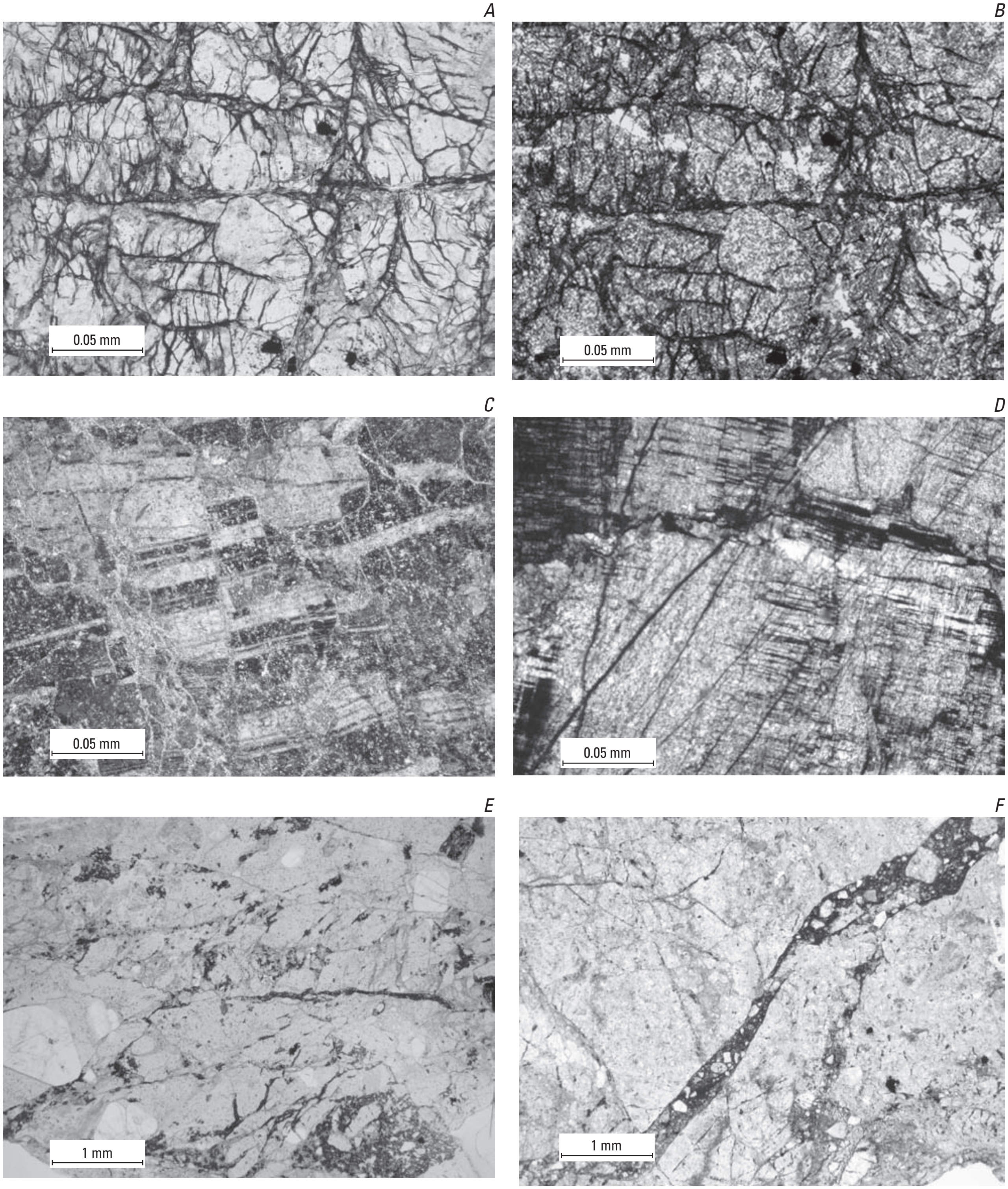


Figure E5. Photomicrographs showing cataclastic microfabrics in lithic clasts of crystalline rock from the Exmore beds in the USGS-NASA Langley core. *A*, Felsite cataclasite (NL811.68) having pervasive orthogonal sets of throughgoing microfaults and fractures, viewed in plane-polarized light. *B*, Same view as in *A* but in cross-polarized light, showing that fracture lengths greatly exceed grain size. *C*, Microfaults offsetting polysynthetic twins in plagioclase phenocryst in porphyritic felsite (NL784.9) that contains shocked quartz (fig. E6*D*), viewed in cross-polarized light. *D*, Microcline megacryst (NL795.8) crosscut by closely spaced planar microfaults oblique to perthitic exsolution lamellae, viewed in cross-polarized light. *E*, Dark microbreccia veinlets along fractures in porphyritic felsite (NL790.9), viewed in plane-polarized light. *F*, Dark vein interpreted as pseudotachylyte (frictional melt?) containing broken crystals and fragments of brecciated porphyritic felsite host (NL870.3); quartz fragments in the vein appear clean and free of planar deformation features; viewed in plane-polarized light.

beds as shown in figures E4*C* and E4*D*. The clast shown in figure E4*E* is from the upper part of crater unit B and is a brecciated felsite loosely held together by gougelike clay.

Figures E5*A* and E5*B* show a cataclasite having pervasive orthogonal sets of throughgoing microfaults and fractures. Figures E5*C* and E5*D* show examples of microfaults cutting feldspar phenocrysts (plagioclase and microcline) in clasts of igneous rock. Dark veinlets of microbreccia (fig. E5*E*) are visible in a few thin sections of porphyritic felsite. The vein in figure E5*F* appears to be a pseudotachylyte (frictional melt?), containing broken crystals and fragments of the felsite host rock.

Clasts of crystalline rock that contain shock-metamorphosed quartz are sparse in the Langley core, and three are described in appendix E1 (samples NL784.9, NL840.4, NL905.0). All of these clasts have cataclastic fabrics of which the shock-metamorphosed quartz is an integral part. Within these clasts, only a few quartz grains in any thin section have multiple sets of intersecting planar deformation features, and none were found to have more than two well-developed sets. Selected quartz grains in lithic clasts of crystalline rock are shown in figure E6. All of these have intersecting sets of parallel planar deformation features that are interpreted to be shock induced. Planar deformation features viewed in thin sections on a flat stage, as in figure E6, tend to be oblique to the microscope axis and thus not as clear in photographs as those oriented on a spindle stage (fig. E2).

Table E1 summarizes the features of clasts considered likely to be impact ejecta. Deformational features include brecciation, microfaults, shock-induced planar deformation features in quartz, and veins of pseudotachylyte or microbreccia. Some felsite clasts have porphyritic and spherulitic igneous textures.

Clast Composition

The three lithic clasts found to contain shock-induced planar deformation features in quartz consist of cataclastically deformed felsite having aphanitic-porphyritic to aphanitic texture (appendix E1). Moreover, except for one granodiorite clast (NL802.07), all of the lithic clasts having cataclastic fabrics without confirmed shocked minerals in the Langley core consist of felsite having the same characteristics (appendix E1). Thus, all of the crystalline-rock fragments confirmed or interpreted to be impact ejecta are composed of variably porphyritic felsite such as the example in figure E7. Most of the felsite clasts were considered unsuitable for chemical analyses because of calcite-filled fractures or secondary alteration.

Some of the felsite clasts have a spherulitic texture (fig. E8). Each spherulite consists of a spherical cluster of plagioclase crystals radiating from a central point, and some have potassium-feldspar-rich outer rims (yellow in stained thin sections). Spherulitic textures commonly form in volcanic glasses by devitrification (Ross and Smith, 1961) and are locally preserved in metamorphosed volcanic rocks of the southeastern United States (Allen and Wilson, 1968). Of the four felsite clasts having spherulitic devitrification texture observed in this study, only one (NL905.0) has shocked quartz (appendix E1).

Unaltered porphyritic felsite from the clast shown in figure E4*C* and figure E7 (NL790.9) and a sample of the Langley Granite (NL2083.1; Horton and others, this volume, chap. B) were chemically analyzed. The results are shown in tables E2, E3, and E4.

In LeBas and others' (1986) chemical classification of volcanic rocks based on the total alkali-silica diagram, the porphyritic felsite is classified as a rhyolite. The aphanitic matrix of the felsite is too fine grained to allow a classification based on petrographic determination of mineral percentages. The Langley Granite sample is a monzogranite in Streckeisen's (1973, 1976) classification (Horton and others, this volume, chap. B). Both the rhyolite clast and the Langley Granite sample are slightly peraluminous. They have essentially identical alumina saturation indices (A/CNK = Al_2O_3/[CaO+Na_2O+K_2O], mol proportion) of 1.1 and 1.1, respectively, as well as corundum in the CIPW norms (Horton and others, this volume, chap. B). On the basis of the analytical results, the rhyolite sample NL790.9 has these minerals in the CIPW norm (weight percent): 37.7 percent quartz, 15.9 percent orthoclase, 34.8 percent albite, 3.8 percent anorthite, 2.4 percent hypersthene, 1.2 percent magnetite, 0.5 percent ilmenite, 1.7 percent corundum, and 0.25 percent apatite.

Where we have measurements of some of the same trace elements by EDXRF (table E2) and INAA (table E3), they vary in agreement. For example, concentrations of Rb agree within ~2 percent and those of Ba, Sr, and Zn agree within <20 percent. The INAA data are considered to be more accurate for the rare-earth elements and for elements in these samples that are near or below the detection limits of EDXRF, including As, Cs, Ni, Sb, U, and W.

Trace-element concentrations in the rhyolite fragment and in the Langley Granite are similar in other respects, and discrimination diagrams (not shown) for identifying the tectonic settings of granite emplacement consistently indicate a volcanic arc setting for both rocks. These include Pearce and others' (1984) diagrams for Rb and Y+Nb, for Nb and Y, for Rb and Yb+Ta, and for Ta and Yb, and Harris and others' (1986) Hf-Rb-Ta diagram.

A plot (fig. E9) of rare-earth elements (REEs) in the two samples normalized to average REE abundances in chondrites from Nakamura (1974) shows that the rhyolite (NL790.9) is lower in REEs than the Langley Granite (NL2083.1). Otherwise, the rhyolite and granite have very similar REE patterns characterized by enrichment in light REEs (rhyolite La/Lu = 10.5 x chondrite; granite La/Lu = 4.6 x chondrite), negative europium anomalies (Eu/Eu* of 0.60 and 0.63, respectively), and flat distributions of heavy REEs.

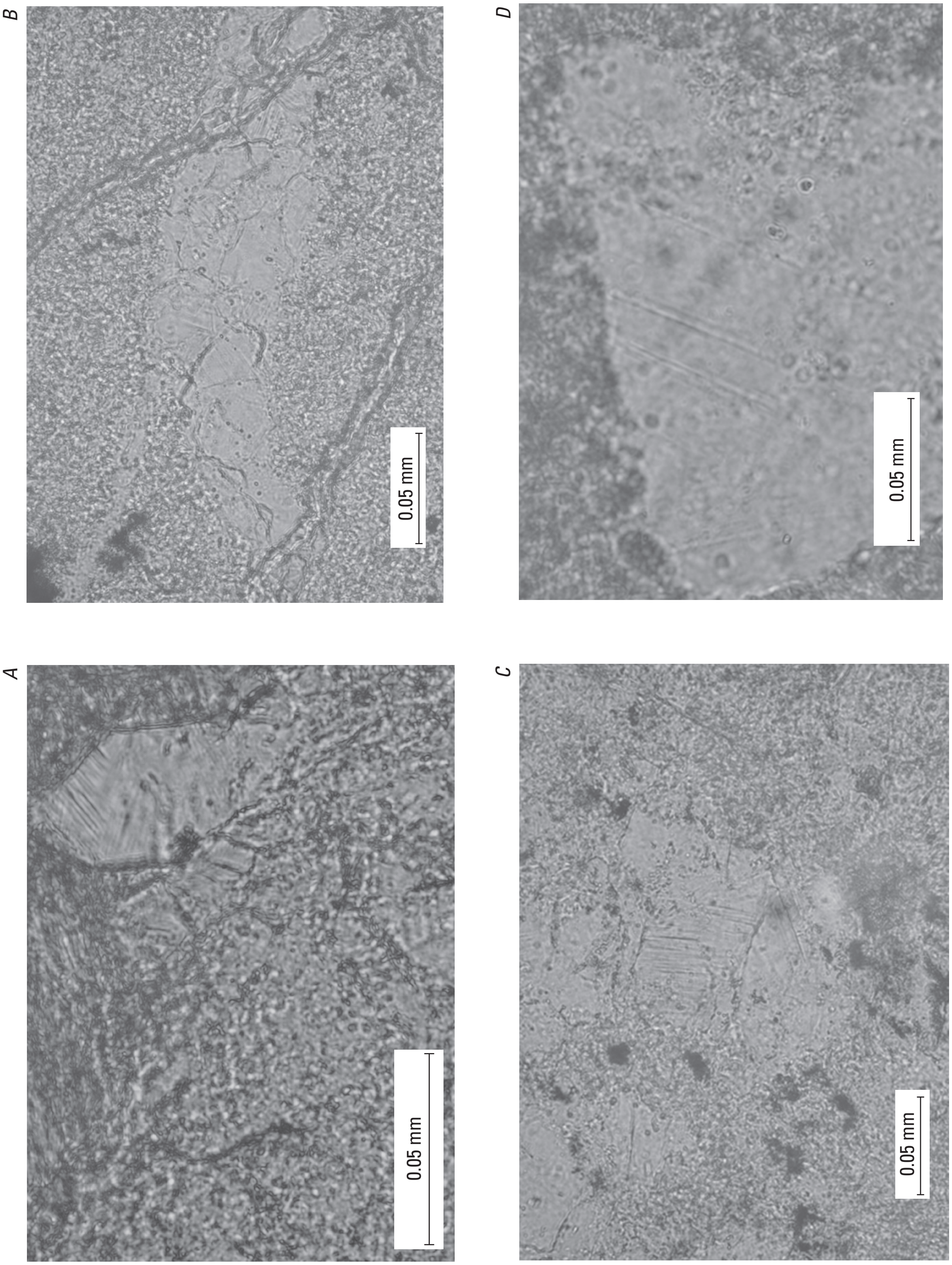


Figure E6. Photomicrographs of quartz showing intersecting sets of shock-induced planar deformation features in lithic clasts of crystalline rock from the Exmore beds in the USGS-NASA Langley core. Thin sections were photographed on a flat stage in plane-polarized light. *A*, Quartz crystal (in upper right corner) having two well-developed sets, in felsite cataclasite (NL840.4, thin section 1). *B* and *C*, Multiple quartz crystals having intersecting sets in same felsite cataclasite (NL840.4, thin section 1). *D*, Quartz phenocryst having two sets, one well developed and one poorly developed, in porphyritic felsite (NL784.9).

Table E1. Features of selected crystalline-rock clasts from the USGS-NASA Langley core that are interpreted to be possible impact ejecta.

[Samples are described in appendix E1. All samples but one are from the Exmore beds; sample NL905.0 is from crater unit B. Igneous textures: FF, flow foliation; P, porphyritic; S, spherulitic; —, none. Cataclastic or shock-induced features: B, brecciated; F, microfaults; N, not highly strained; Q, shocked quartz; V, veins of pseudotachylyte or microbreccia]

Sample number	Depth in core		Rock type	Igneous textures	Cataclastic or shock-induced features
	(meters)	(feet)			
NL784.9	239.2	784.9	Felsite	P	F, Q
NL790.9	241.1	790.9	Felsite	P	F, V
NL795.8	242.6	795.8	Feldspar megacryst	—	F
NL802.07	244.47	802.07	Granodiorite	—	N
NL805.5	245.5	805.5	Felsite	P	F
NL806.03	245.68	806.03	Felsite	P, S	N
NL807.9	246.2	807.9	Felsite	P	N
NL811.68	247.40	811.68	Felsite cataclasite	—	B, F
NL812.55	247.67	812.55	Felsite	P, S	N
NL813.57	247.98	813.57	Felsite	P	F
NL832.25	253.67	832.25	Felsite	P	N
NL832.85	253.85	832.85	Felsite	P, S	N
NL840.4	256.06–256.26	840.1–840.75	Felsite cataclasite	P	B, F, Q
NL870.3	265.27–265.36	870.3–870.6	Brecciated felsite	P	B, V
NL873.3	266.2	873.3	Felsite	FF	N
NL905.0	275.71–275.93	904.60–905.33	Felsite breccia	S	B, F, Q

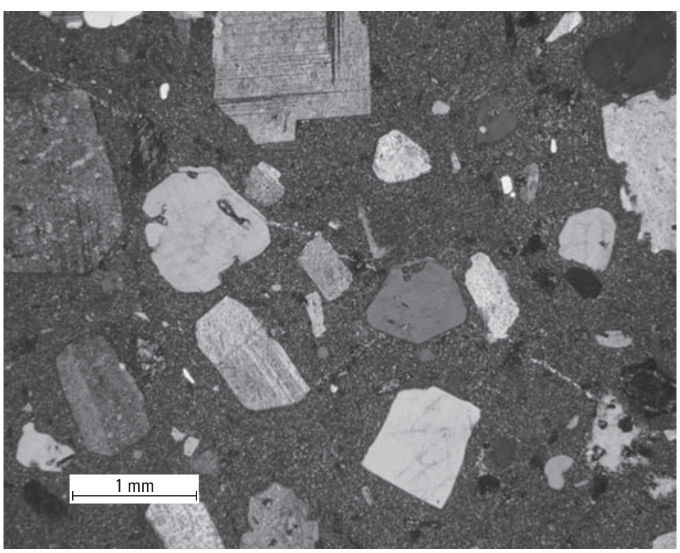


Figure E7. Photomicrograph showing the porphyritic texture in felsite (rhyolite) sample NL790.9 from the Exmore beds in the USGS-NASA Langley core; tables E2, E3, and E4 show the results of chemical analyses of this sample. Feldspar phenocrysts are euhedral to subhedral; some have embayed margins indicating magmatic corrosion. Photographed in cross-polarized light.

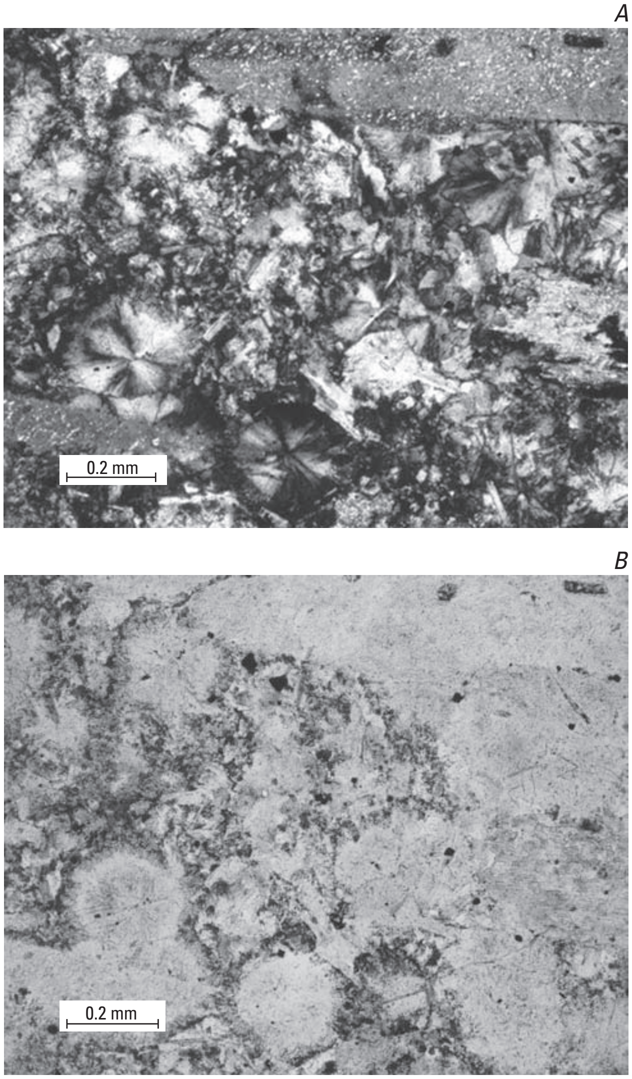


Figure E8. Photomicrographs showing spherulitic devitrification texture in felsite (NL812.55) from the Exmore beds in the USGS-NASA Langley core. *A*, Thin section in cross-polarized light. *B*, Thin section in plane-polarized light. Each spherulite is a spherical cluster of plagioclase crystals radiating from a central point as shown in *A*. Outer rims are rich in fine-grained potassium feldspar and appear gray in *B* because of a yellow sodium cobaltinitrite stain in the thin section.

Table E2. Results of X-ray fluorescence spectrometry analyses of two samples from the USGS-NASA Langley core.

[Analysts: D.F. Siems and J.E. Taggart, Jr., both of the U.S. Geological Survey. Samples are described in appendix E1]

Sample number....	NL790.9	NL2083.1
Rock type...........	rhyolite clast	monzogranite
Unit..................	Exmore beds	Langley Granite
Major oxide composition and loss on ignition (LOI) at 900°C, in weight percent [Method used: wavelength-dispersive X-ray fluorescence spectrometry (Taggart and others, 1987; Mee and others, 1996)]		
SiO_2..........................	74.9	71.0
Al_2O_3........................	12.8	14.2
Fe_2O_3T*...................	1.80	2.93
MgO..........................	.64	.77
CaO..........................	.91	1.29
Na_2O........................	4.11	3.98
K_2O..........................	2.69	3.48
TiO_2..........................	.25	.38
P_2O_5..........................	.11	.13
MnO..........................	.06	.06
LOI...........................	.99	1.24
Trace-element abundances, in parts per million [Method used: energy-dispersive X-ray fluorescence spectrometry (Siems, 2000, 2002)]		
Ag............................	<1	<1
As.............................	<2	<2
Ba.............................	902	668
Bi..............................	<5	<5
Br..............................	<1	2
Cd.............................	2	<1
Ce**..........................	47	61
Cr..............................	7	7
Cs.............................	<5	6
Cu.............................	41	145
Ga.............................	13	14
Ge.............................	<2	<2
La**..........................	29	30
Mo............................	4	4
Nb.............................	8	12
Nd**.........................	33	39
Ni.............................	<2	4
Pb.............................	28	60
Rb.............................	89	123
Sb.............................	<2	<2
Se.............................	<1	<1
Sn.............................	<2	3
Sr..............................	176	156
Th.............................	4	10
U..............................	<4	<4
V...............................	25	23
W***........................	<5	<5
Y...............................	10	28
Zn.............................	459	218
Zr..............................	110	166

* Fe_2O_3T, total iron calculated as Fe_2O_3.
**See more accurate rare-earth-element abundances in table E3.
***W values probably reflect sample preparation procedure.

Table E3. Results of long-count instrumental-neutron-activation analyses (INAA) of two samples from the USGS-NASA Langley core.

[Analyst: J.R. Budahn of the U.S. Geological Survey. The method was described by Wandless (1996). Samples are described in appendix E1]

Sample number.....	NL790.9	NL2083.1
Rock type...............	rhyolite clast	monzogranite
Unit..........................	Exmore beds	Langley Granite
Trace-element abundances, in parts per million		
As.............................	1.21	0.75
Au.............................	.0072	.0286
Ba.............................	779	580
Co.............................	2.66	3.65
Cr.............................	2.88	1.78
Cs.............................	1.15	1.14
Hf.............................	2.99	5.23
Ni.............................	2.2	3.6
Rb.............................	87	121
Sb.............................	.24	.18
Sc.............................	3.19	5.78
Sr.............................	177	185
Ta.............................	.68	1.11
Th.............................	6.89	9.95
U.............................	1.5	2.1
W.............................	1.0	.5
Zn.............................	539	182
Zr.............................	102	204
Rare-earth-element (REE) abundances, in parts per million		
La.............................	20.3	20.4
Ce.............................	38.3	50.1
Nd.............................	14.7	24.0
Sm.............................	2.57	5.46
Eu.............................	.5	1.1
Gd.............................	2.4	5.0
Tb.............................	.30	.87
Ho.............................	.44	1.26
Tm.............................	.20	.59
Yb.............................	1.27	3.8
Lu.............................	.20	.55
Chondrite-normalized REE abundances (rock/chondrite) and the Eu/Eu* ratio[1]		
La.............................	65.3	78.5
Ce.............................	47.1	61.6
Nd.............................	24.3	39.7
Sm.............................	13.1	27.9
Eu.............................	6.74	14.9
Gd.............................	9.27	19.2
Tb.............................	6.40	18.4
Ho.............................	6.13	17.6
Tm.............................	6.10	18.2
Yb.............................	6.05	18.1
Lu.............................	6.19	16.9
Eu/Eu*.....................	.60	.63

[1]Eu/Eu* is the size of the europium anomaly, where Eu* is the europium concentration interpolated from surrounding elements in the REE pattern.

Table E4. Results of individual chemical analyses of two samples from the USGS-NASA Langley core.

[Analyses were done by a contractor for the U.S. Geological Survey using methods described by Jackson and others (1987). Samples are described in appendix E1. Contents of each constituent are reported in weight percent (%) except that F is in parts per million (ppm)]

Sample number..........	NL790.9	NL2083.1
Rock type....................	rhyolite clast	monzogranite
Unit...............................	Exmore beds	Langley Granite
FeO (%)........................	0.97	1.03
CO_2 (%)........................	0.11	<0.01
CO_2 as carbonate (%)....	0.03	<0.003
S (%).............................	0.18	0.42
F (ppm).........................	212	358
H_20^- (%).......................	0.1	0.1
H_2O^+ (%)......................	0.8	0.9

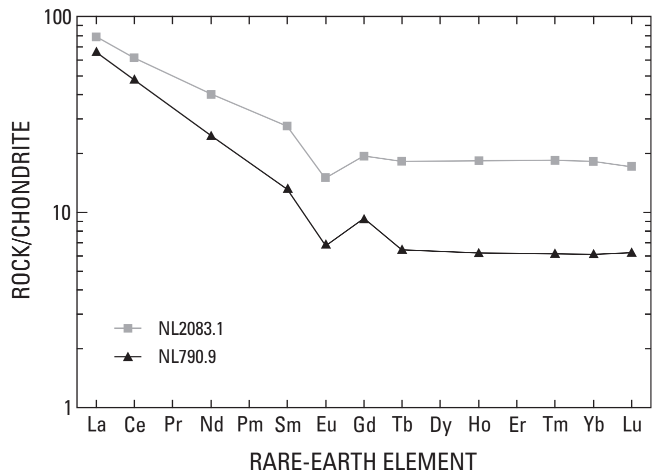


Figure E9. Rare-earth-element (REE) abundances normalized to chondrite abundances (rock/chondrite) for two samples from the USGS-NASA Langley core. The samples are a rhyolite clast (NL790.9) from the Exmore beds and a piece of the Langley Granite (NL2083.1). REE values are from table E3.

Discussion

Implications for the Chesapeake Bay Impact Event

The conclusion that multiple sets of planar deformation features in rare quartz grains from the Exmore beds are of shock-metamorphic origin is unambiguous. The presence of these features indicates that the quartz grains have experienced pressures greater than 6 GPa (Short, 1968) and strain rates greater than 10^6/second (Chao and Goresy, 1977, p. 291).

The relative proportion of shocked to unshocked quartz grains in the sediment is very low in comparison to the proportion in some other impact-related deposits (for example, see Izett, 1990, table 9), indicating that the shock-metamorphosed grains are mixed into and diluted by an enormous volume of unshocked material. This observation is consistent with the character of the Exmore beds as a mixed sedimentary deposit (Gohn and others, this volume, chap. C). The individual shocked quartz grains are mostly subangular, and they lack the rounded shapes that would indicate derivation from clastic sedimentary target deposits. Hence, we interpret them to be derived from crystalline rocks that underlie thick preimpact clastic sediments in the target region.

Although the possibility cannot be ruled out that some clasts of cataclastic rock in the Langley core could be derived from a faulted Piedmont source terrain, transported, and deposited in the outer coastal plain by purely sedimentary processes, such long-distance transport seems unlikely for clasts that are angular, internally fragmented, crumbly, and in some cases only weakly cohesive. Furthermore, shock-metamorphosed quartz is an integral part of the cataclastic fabric in some clasts. Shock metamorphism is not required to produce most of the high-strain-rate fabrics observed, but the occurrence of these fabrics together with shocked quartz strongly suggests that they were impact generated.

Using samples from earlier drill cores in the Chesapeake Bay impact structure, Reimold and others (2002) estimated shock pressures of 10–20 GPa from a small data set on the orientations and relative frequencies of planar deformation features in quartz. The Langley core has not produced enough quartz grains containing planar deformation features, or enough of these features per grain, to support a statistical study of their crystallographic orientations and relative frequencies or to estimate shock pressures by using the methods reviewed and critiqued by Grieve and others (1996).

The spherulitic texture observed in some felsite clasts (fig. E8), including one that has shocked quartz, is attributed to devitrification. Koeberl and others (1996, fig. 4B) interpreted a similar spherulitic texture as impact melt because the spherulitic matrix contained "clasts" of shocked quartz and feldspar. Alternatively, this texture could be a preimpact feature of volcanic target rocks similar to those described by Allen and Wilson (1968) in the North Carolina Piedmont. Isotopic dating of the spherulites may allow discrimination between these hypotheses.

Ejecta-derived rock fragments in the core are sparsely disseminated throughout the Exmore beds, and the largest are found near the base of the unit (fig. E3 and appendix E1). This distribution is consistent with evidence that the Exmore at this location was deposited as crudely size-graded units (Gohn and others, this volume, chap. C). We found one crystalline rock fragment containing shock-metamorphosed quartz below the Exmore beds (sample NL905.0; figs. E3 and E4*E* and appendix E1); it was in a zone of mixing about 6.4 m (21.0 ft) below the base of the Exmore. We interpret this isolated occurrence as evidence for downward injection or infiltration of sediment from the Exmore beds into the upper part of crater unit B.

Preimpact target rocks of the Chesapeake Bay impact structure are widely inferred to be the source of impact glass in tektites of the North American strewn field (Poag and others, 1994; Koeberl and others, 1996; Glass, 2002). Evidence from other strewn fields suggests that only the upper ~200 m (~650 ft) of target material was involved in the formation of tektites (Koeberl, 1994); thus, crystalline basement in the Chesapeake Bay impact structure is not as likely as the overlying preimpact sediments to be a source of the North American tektites.

The chemical compositions of tektites, including bediasites, georgiaites, and microtektites, from the North American strewn field were summarized in Koeberl (1990), Albin and others, (2000), and Koeberl and others (2001). The bulk major-element composition of the rhyolite clast (NL790.9) most closely resembles that of bediasites; it is similar in Si, Al, Mg, and Ca, lower in Ti and Fe, and higher in K and Na (volatile).

We compared the REE patterns in figure E9 with those of tektites from the North American strewn field (Albin and others, 2000, fig. 5; Huber and others, 2000, fig. 1). The REE distribution for the Langley Granite (NL2083.1) is within the range of REE distributions determined for tektites, and the rhyolite (NL790.9) is slightly depleted in REEs relative to the tektites. Both the rhyolite and the granite have patterns of light REE enrichment similar to those of the tektites, as well as flatter distributions of heavy REEs and larger negative europium anomalies than most tektites. Both the rhyolite and the Langley Granite have other trace-element concentrations (tables E2 and E3) that are clearly lower (Co, Cr, and Ni) or higher (Cu and Zn) than concentrations in the North American tektites (Koeberl, 1990, table 2; Koeberl and others, 2001, table 1).

Tektites of the North American strewn field are composed mainly of SiO_2 (microtektites averaging 70.7 percent, bediasites averaging 76.4 percent, and georgiaites averaging 81.5 percent) and Al_2O_3 (microtektites averaging 15.4 percent, bediasites averaging 13.8 percent, and georgiaites averaging 10.7 percent). Middle Eocene to Paleocene sediments in the area of the Chesapeake Bay impact structure tend to be lower in both (Koeberl, 1990, table 1; Koeberl and others, 2001, table 1). The rhyolite and granite in table E2 are comparable to the tektites in Al_2O_3 and are slightly lower in SiO_2.

Geochemical studies of these tektites show triangular arrays in oxide-oxide variation diagrams that indicate mixing of at least three source components, including a silica-rich (~90 weight percent) material such as quartz-rich sand and two components higher in Al_2O_3 (about 16 to 18 weight percent) and in FeO (about 5.5 to 6.5 weight percent) such as shale or graywacke (Albin and others, 2000). The rhyolite and granite have intermediate compositions within the range defined by these hypothetical end members. Albin and others (2000) suggested that a crystalline basement component might explain some unusual La-Th-Sc characteristics and high Rb/Cs ratios in georgiaites. The rhyolite fragment (NL790.9) has La/Th (=2.9), Th/Sc (=2.2), and La/Sc (=6.4) ratios in the range of ratios for North American tektites and a Rb/Cs (=76) ratio higher than the ratio for the tektites. At this stage, the rhyolite is neither confirmed nor ruled out as a source for some tektites. Further geochemical studies of preimpact sediments, as well as crystalline basement and basement-derived ejecta, will be needed to link the chemistry of tektites to potential source materials.

Crystalline Terrane beneath the Coastal Plain

The crystalline rocks concealed beneath thick sedimentary deposits of the Atlantic Coastal Plain are poorly known and are considered to be one of the last frontiers of regional geology in the United States. The impact event served as a remarkable sampling tool that excavated an enormous volume of coastal plain basement rocks and scattered the fragments where they can be sampled at shallower levels.

All of the lithic clasts in the Langley core that were confirmed or suspected to be impact ejecta consist of the same rock type, a variably porphyritic felsite of rhyolitic composition. Although this felsite is petrographically distinct from the Langley Granite (Horton and others, this volume, chap. B), both rocks have similar, slightly peraluminous, bulk compositions. Similarities in REE patterns (fig. E9) and other trace-element concentrations (tables E2, E3, and E4) suggest that the rhyolite and granite magmas originated in the same volcanic arc setting. We thus infer that the undated rhyolite fragment is about the same age as the Neoproterozoic Langley Granite, which was dated at 612±10 Ma (Horton and others, this volume, chap. B). Working hypotheses for the age of spherulitic devitrification texture range from as old as Neoproterozoic (if formed in preimpact volcanic rock) to as young as late Eocene (if formed in impact glass).

The trace-element concentrations and discrimination diagrams discussed above consistently indicate that the rhyolite fragment and the Langley Granite originated in a volcanic arc setting. Thus, they are chemically distinct from Neoproterozoic granitoids that intruded Mesoproterozoic basement of the Goochland terrane in the Piedmont (see table B6 and fig. B11 of Horton and others, this volume, chap. B), which have higher concentrations of alkalis (Na_2O+K_2O >8.6 percent), Ga (>30 parts per million; ppm), Nb (>70 ppm), and Y (>89 ppm) typical of A-type granites (Owens and Tucker, 2003). Testing specific petrologic and tectonic correlations with Neoproterozoic magmatic arc terranes of the southeastern United States and studying implications for the Chesapeake Bay tectonic indenter of Archean crust proposed by Lefort and Max (1991) would require further investigation, as discussed by Horton and others (this volume, chap. B).

The relatively uniform composition of impact-derived rock fragments at the Langley corehole differs from the distribution of clast compositions at other sites in the western annular trough, where such fragments include a variety of felsic to mafic plutonic rocks as well as felsite (Horton, Aleinikoff, and others, 2002; Horton, Kunk, and others, 2002). The distinctive population of impact-derived clasts at this site suggests that the original impact ejecta were distributed unevenly, perhaps in rays. If so, the geographic distribution of impact-derived rock fragments may provide clues to the preimpact distribution of rock types and their relations in the target area.

Age of Impact Metamorphism based on Argon Dating of Tektites

Background

Estimates of the age of the Chesapeake Bay impact structure based on isotopic dating of North American tektites are widely cited (for example, by Koeberl and others, 1996). An $^{40}Ar/^{39}Ar$ geochronological study to improve the dating of those tektites, although outside the main focus of this chapter on data from the USGS-NASA Langley core, is discussed here to make the results available.

Tektites and microtektites that constitute the North American strewn field are thought to have originated by melting of near-surface sediments in the Chesapeake Bay area of Virginia, when a large asteroid or comet nucleus struck that area (Poag and others, 1994; Koeberl and others, 1996) about 35.2 to 35.8 million years ago (Obradovich and others, 1989). Tektites of this strewn field have been found mainly in upper Cenozoic gravel deposits derived from erosion of upper Eocene deposits in Georgia (georgiaites) and Texas (bediasites). Tektites less than 1.0 mm (0.039 in.) in diameter, termed microtektites, have been found in upper Eocene marine sediments in the Atlantic Ocean and Caribbean Sea.

Suess (1900) proposed the term “tektite” for small, corroded silicate glass nodules found near the Moldau River in southern Bohemia, Czechoslovakia. He suggested that the glass objects, similar in some aspects to obsidian, formed by melting of meteoritic material. Since that time, many different definitions have been proposed, emphasizing different aspects of these curious glass nodules.

Baker (1959, p. 11) defined tektites as “natural objects of impure silica glass found in thousands on the surface of certain parts of the earth, and in places buried several feet beneath surficial deposits.” He noted that they occur in widely separated regions and show minor chemical composition and physical variations from place to place.

In the “Glossary of Geology” (Jackson, 1997, p. 653), a tektite was defined as “A rounded pitted jet-black to greenish or yellowish body of silicate glass of nonvolcanic origin, usually walnut-sized, found in groups in several widely separated areas of the Earth’s surface [so-called strewn fields] and generally bearing no relation to the associated [underlying] geologic formations." The definition indicated that some "have shapes strongly suggesting aerodynamic ablation during hypersonic flight."

Tektites have been studied for more than a century, and considerable physical and chemical information has been gathered (see references in O'Keefe, 1976). Chao (1963) studied several thousand tektites and noted three of their main features: (1) distinctive shapes (flanged buttons, cores, dumbbells, and elongated teardrops), (2) unique surface sculpture, and (3) color and luster. He also observed that tektites have three diagnostic microscopic characteristics: (1) universal presence of flow structure and associated strain birefringence, (2) general presence of siliceous glass inclusions (see Barnes, 1940), and (3) general absence of microlites. Ross (1962) observed that obsidians are rarely without microlites, crystallites, trichites, and Fe-oxide dust. In contrast, tektites are devoid of such materials. Aghassi (1962) and Chao (1963, p. 63) noted that tektites nearly always contain widely disseminated bubble cavities or vesicles.

Isotopic ages reported previously for the different tektite groups (Cretaceous-Tertiary (K-T) boundary, North American, Moldavite, Ivory Coast, and Australasian) were obtained in different laboratories using several different techniques (K-Ar, $^{40}Ar/^{39}Ar$, and fission track) and using diverse standards and decay constants. Fleischer and Price (1964) obtained fission-track ages (35.4, 35.3, and 27.2 Ma) for three bediasites from Texas. Albin and Wampler (1996) measured conventional K-Ar ages of georgiaites and calculated a mean age of 35.2±0.3 Ma. For North American tektites and microtektites, $^{40}Ar/^{39}Ar$ ages have been reported by Glass and others (1986, 35.4±0.6 Ma), Obradovich and others (1989, 35.5±0.3 Ma), and Glass and others (1995, 35.0±0.1 Ma). U-Pb zircon geochronology of shocked and unshocked zircons from several sites, although "not straightforward" (Kamo and others, 2002), is compatible with these results.

Argon Dating Methods

Total-fusion $^{40}Ar/^{39}Ar$ ages were determined for 19 analyses of 4 North American tektites as part of a larger $^{40}Ar/^{39}Ar$ study of all known tektite types by one of us (Izett) using the same mass spectrometer, methods, fluence monitors, and decay constants. The analytical data and ages presented in table E5 were determined in the USGS laboratory in Menlo Park, Calif., by using procedures described by Dalrymple and Lanphere (1971), Dalrymple and Duffield (1988), and Dalrymple (1989).

A technical feature of the $^{40}Ar/^{39}Ar$ method is that geologic materials of unknown age such as tektites are irradiated with fast neutrons next to a fluence-monitor mineral, or standard, having an accepted isotopic age. Thus, the method is a relative one; ages of unknown materials are relative to ages of a selected fluence-monitor mineral. The measured $^{40}Ar/^{39}Ar$ ratios of the fluence-monitor mineral are used with its known age to calculate a conversion factor, J, which is a measure of the fraction of ^{39}K converted to ^{39}Ar by the fast neutron reaction ($^{39}K(n,p)^{39}Ar$). The factor J is then used in the age equation to calculate ages for materials of unknown age. The precision of the fluence-monitor mineral calibration has a significant effect on the precision of the ages calculated for materials of unknown age.

For the North American tektites, $^{40}Ar/^{39}Ar$ ages were determined by using single fragments about 0.3 mm (0.12 in.) in diameter. The tektite fragments were irradiated in the core of the USGS TRIGA reactor. A typical irradiation packet consisted of the tektite fragments loaded into a 9-mm-diameter (0.35-in.-diameter) aluminum-foil cup and covered by a 9-mm aluminum-foil cap. The flattened pancakelike packets were sandwiched between similar packets of the neutron fluence monitor and arranged in a vertical stack in a 10-mm-diameter (0.39-in.-diameter) quartz glass tube; the position of the packets was measured. The distance between adjacent packet centers typically was about 0.3 mm (0.012 in.). The neutron fluence within the radiation package was measured by analyzing five to seven lots of two to three sanidine crystals for the fluence monitor.

We used sanidine from the Taylor Creek Rhyolite of New Mexico (Dalrymple and Duffield, 1988) as a fluence-monitor mineral because it has been shown to be uniform in K and Ar content and its isotopic age is within an acceptable range of ages for North American tektites. Dalrymple and others (1993) gave reasons for using an age of 27.92 Ma for sanidine from the Taylor Creek Rhyolite. Lanphere and Dalrymple (2000) measured an age of 513.9±2.3 Ma for the widely used MMhb–1 hornblende, which is 1.26 percent younger than the internationally adopted mean value of 520.4 Ma (Samson and Alexander, 1987). Ages reported in this chapter were first calculated using an age of 27.92 Ma for sanidine from the Taylor Creek Rhyolite of New Mexico; they were then recalculated by using an age of 28.32 Ma for sanidine from the Taylor Creek Rhyolite, which is based on the internationally adopted mean value of 520.4 Ma for MMhb–1 hornblende. All ages reported herein were calculated by using decay constants recommended by the Subcommission on Geochronology of the IUGS (Steiger and Jäger, 1977).

Results of Argon Geochronology

The individual tektite ages in table E5 are given to two decimal places, and the composite, final age is rounded to one decimal place. Errors given for individual $^{40}Ar/^{39}Ar$ ages are estimates of the analytical precision at the 1σ level and include a conservative error of 0.5 percent in J. The final composite age is a weighted mean $\pm\sigma_{best}$, where weighting is by the inverse of the variance (Taylor, 1982). The result is a weighted-mean total-fusion $^{40}Ar/^{39}Ar$ age of 35.3±0.1 Ma (±1 σ) for 19 analyses of 4 North American tektites. We interpret this age as recording the age of the late Eocene Chesapeake Bay impact event.

Age Constraints for the Chesapeake Bay Impact

Previous estimates of the age of the Chesapeake Bay impact structure have been based either on micropaleontology

Table E5. Total-fusion $^{40}Ar/^{39}Ar$ ages of North American tektites from Washington County, Ga., and Lee County, Tex.

[Analyses by Glen A. Izett in the U.S. Geological Survey (USGS) laboratory, Menlo Park, Calif., as described in the text. Procedures used were described by Dalrymple and Lanphere (1971), Dalrymple and Duffield (1988), and Dalrymple (1989). *J*, conversion factor discussed in text; *, radiogenic]

Location	Experiment number	Catalog number[1]	J	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{40}Ar/^{39}Ar^*$	$^{40}Ar^*$ (%)	Age (Ma)	Error (σ)
Georgia	94Z0379	MNGaTek	6.94E-03	0.0504	0.0015	2.7843	86.0	34.53	0.22
Georgia	94Z0380	MNGaTek	6.94E-03	0.0639	0.0012	2.7826	88.7	34.51	0.22
Georgia	94Z0382	MNGaTek	6.94E-03	0.0542	0.0002	2.7961	98.0	34.67	0.21
Georgia	94Z0383	MNGaTek	6.94E-03	0.0597	0.0035	2.7731	72.6	34.39	0.23
Georgia	94Z0384	MNGaTek	6.94E-03	0.0614	0.0022	2.7821	81.0	34.50	0.22
Texas	93Z0441	B–97	6.20E-03	0.1042	0.0003	3.1135	97.3	34.46	0.26
Texas	93Z0442	B–97	6.20E-03	0.1039	0.0003	3.1223	97.3	34.56	0.24
Texas	94Z0365	B–97	6.94E-03	0.1050	0.0001	2.7906	98.8	34.60	0.21
Texas	94Z0366	B–97	6.94E-03	0.1039	0.0001	2.8060	98.9	34.79	0.24
Texas	94Z0367	B–97	6.94E-03	0.1064	0.0001	2.7931	99.1	34.63	0.23
Texas	94Z0368	B–97	6.94E-03	0.1037	0.0001	2.8004	99.0	34.72	0.22
Texas	96Z0194	30773	7.07E-03	0.1049	0.0002	2.7590	98.3	34.83	0.21
Texas	96Z0195	30773	7.07E-03	0.1050	0.0002	2.7494	98.2	34.71	0.21
Texas	96Z0196	30773	7.07E-03	0.1062	0.0001	2.7496	98.4	34.71	0.21
Texas	97Z0516	B–74	7.09E-03	0.1348	0.0000	2.7671	99.8	35.04	0.24
Texas	97Z0517	B–74	7.09E-03	0.1386	0.0001	2.7579	99.2	34.93	0.22
Texas	97Z0518	B–74	7.09E-03	0.1396	0.0001	2.7538	99.1	34.88	0.24
Texas	97Z0519	B–74	7.09E-03	0.1365	0.0002	2.7552	97.4	34.90	0.21
Texas	97Z0520	B–74	7.09E-03	0.1384	0.0001	2.7444	98.7	34.76	0.22
					Initial weighted mean age[2]			34.8	0.1
					Recalculated weighted mean age[2]			35.3	0.1

[1]All four tektites are now in the collection of the Denver Museum of Natural History. Tektite MNGaTek was collected by R.L. Strange. Tektite 30773 came from the University of Texas Museum in Austin. Tektites B–74 and B–97 were sent by V.E. Barnes (USGS) to E.C.T. Chao (USGS).

[2]The initial weighted mean age of 34.8 Ma was calculated relative to a fluence-monitor age of 27.92 Ma for sanidine from the Taylor Creek Rhyolite; the sanidine age was based on an age for MMhb–1 hornblende of 513.9 Ma. The recalculated mean age of 35.3 Ma was determined relative to a fluence-monitor age for MMhb–1 hornblende of 520.4 Ma. The error for individual ages is ±1σ and includes a conservative error of 0.5 percent in *J;* the group error is $\pm 1\sigma_{best}$ of Taylor (1982).

within the structure or on geochronology of North American tektites from outside the structure. Studies of micropaleontology within the structure indicate that the impact event occurred in the late Eocene biochronozones P15 of planktonic foraminifera and NP 19/20 of calcareous nannofossils (Poag and Aubry, 1995; Poag, 1996, 1997). A layer of impact ejecta offshore of New Jersey at Deep Sea Drilling Project (DSDP) Site 612, although somewhat reworked, is in the same biochronozones (Poag and Aubry, 1995; Poag, 1997), and tektite material from that layer is considered to be part of the North American strewn field on the basis of geochemistry (Stecher and others, 1989). Most of the previously cited argon and fission-track dates of tektites and microtektites from the North American strewn field, including those from the DSDP 612 layer, are consistent with the biochronological data, have overlapping uncertainties, and cluster in the range of ~35 Ma to ~36 Ma. The weighted mean $^{40}Ar/^{39}Ar$ age of 35.3±0.1 Ma (±1σ) presented here for the North American tektite material is interpreted to date the late Eocene Chesapeake Bay impact event.

Conclusions

The Chesapeake Bay impact excavated unknown coastal plain basement rocks and scattered the fragments where we can sample them at shallower levels. This study of shock-metamorphosed minerals and impact-derived crystalline rock fragments in the USGS-NASA Langley core produced the following conclusions:

1. The sandy matrix of the Exmore beds contains sparse quartz grains (0.1 to 0.3 mm (0.004 to 0.012 in.) in diameter) that contain multiple sets of intersecting planar deformation features, commonly referred to as shock lamellae. As many as five different sets have been observed in some quartz grains. Planar deformation features also occur in quartz grains in reworked crystalline-rock clasts in and just below the Exmore beds. The presence of these features indicates that the quartz grains have experienced pressures greater than 6 GPa and strain rates greater than 10^6/second. The conclusion that such grains are of shock-metamorphic impact origin is unambiguous.

2. The shock-metamorphosed quartz grains, although rare, provide clear and convincing evidence that the Exmore beds are of hybrid impact origin. The identification of shocked quartz grains in the Langley core adds to the number of drill sites in Virginia where their presence in the structure is confirmed.

3. The proportion of shocked to unshocked quartz grains in the sedimentary matrix is very low in comparison to the proportion in some other impact-related deposits, indicating that the shock-metamorphosed grains are mixed into and diluted by an

enormous volume of unshocked sedimentary material. This observation is consistent with the character of the Exmore beds as a mixed sediment, which Gohn and others (this volume, chap. C) interpret as a seawater-resurge deposit.

4. Individual shock-metamorphosed quartz grains lack the rounded shapes that would indicate derivation from a clastic sedimentary target and are inferred to be mainly particles of excavated crystalline basement, or possibly smashed detrital grains.

5. Shock-metamorphosed quartz is an integral part of the cataclastic fabric in some clasts, indicating that both the fabric and the shocked quartz were produced by the same hypervelocity impact event. All of the crystalline rock fragments that contain shocked quartz also have cataclastic fabrics.

6. In this core, all of the rock fragments that are confirmed or interpreted to be reworked impact ejecta consist of variably porphyritic felsite. The chemical analysis of one sample shows it to be peraluminous rhyolite from a volcanic arc setting. The undated felsite is inferred to be Neoproterozoic in age on the basis of geochemical similarities to the dated Langley Granite of Horton and others (this volume, chap. B).

7. The monotonous population of impact-derived crystalline-rock clasts at the Langley site, in contrast to the varied populations at other sites in the western annular trough, suggests that the original impact ejecta were distributed unevenly, perhaps in rays. If so, the geographic distribution of impact-derived fragments may provide clues to the original distribution of rock types in the target area.

8. Some felsite clasts contain spherulites that are interpreted to be devitrification products, either of an Eocene impact melt or of older preimpact volcanic rock in the target area.

9. Impact-derived rock fragments are sparsely disseminated throughout the Exmore beds section of the core. Those larger than the core diameter were found in the lower half of the unit, suggesting that the Exmore at this location may consist of crudely size-graded deposits.

10. The presence of shock-metamorphosed quartz in a rock fragment several meters below the Exmore beds suggests injection or infiltration of resurge sediments from the Exmore beds (or particles from an ejecta blanket removed by resurge erosion?) into the upper part of crater unit B.

11. Trace-element geochemistry of a rhyolite fragment that is interpreted to be impact derived and a sample of the granite basement from the Langley core neither confirms nor rules out crystalline basement in the Chesapeake Bay impact structure as a partial source for some tektites of the North American strewn field.

12. A weighted-mean total-fusion $^{40}Ar/^{39}Ar$ age of 35.3±0.1 Ma (±1σ) for 19 analyses of 4 North American tektites records the age of the late Eocene Chesapeake Bay impact event.

Questions raised by this research are being addressed as our efforts expand to include samples from other coreholes (Horton, Aleinikoff, and others, 2002; Horton, Kunk, and others, 2002). Continued studies should provide insight into the character, age, and origin of rocks excavated by the impact and their relations to basement rocks sampled by deep drilling. They can provide valuable information on the regional geology of crystalline terranes beneath the Atlantic Coastal Plain, a context for understanding the Eocene impact structure, and a test of hypothetical models such as the proposed Chesapeake Bay tectonic indenter of Archean crust (Lefort and Max, 1991; Horton and others, this volume, chap. B). Isotopic dating of minerals from impact-derived clasts may yield information on thermal effects of the impact.

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Glossary

A

allochthonous impact breccia "Impact breccia in which component materials have been displaced from their point of origin." (Stöffler and Grieve, 2003, p. 5)

B

breccia "A coarse-grained clastic rock, composed of angular broken rock fragments held together by a mineral cement or in a fine-grained matrix . . . " (Jackson, 1997, p. 82)

C

cataclasite "A fine-grained, cohesive cataclastic rock, normally lacking a penetrative foliation or microfabric, formed during fault movement. The fracture of rock and mineral components is a significant factor in the generation of a cataclasite, and it may play a significant role in the continued deformation of the rock." (Jackson, 1997, p. 99)

cataclastic "Pertaining to the structure produced in a rock by the action of severe mechanical stress during dynamic metamorphism; characteristic features include the bending, breaking, and granulation of the minerals." (Jackson, 1997, p. 100)

cataclastic rock "A rock . . . containing angular fragments that have been produced by the crushing and fracturing of preexisting rocks as a result of mechanical forces in the crust." (Jackson, 1997, p. 100)

D

diamictite "A comprehensive, nongenetic term . . . for a nonsorted or poorly sorted, noncalcareous, terrigenous sedimentary rock that contains a wide range of particle sizes." (Jackson, 1997, p. 175)

diamicton "A general term . . . for the nonlithified equivalent of a diamictite." (Jackson, 1997, p. 175)

E

ejecta *See* impact ejecta.

F

fabric "The complete spatial and geometrical configuration of all those components that make up the rock. It covers terms such as texture, structure, and preferred orientation." (Hobbs and others, 1976, p. 73)

G

gouge "Non-consolidated fractured rock, commonly very fine-grained, formed by brittle deformation at a shallow crustal level along a fault." (Passchier and Trouw, 1996, p. 259)

H

hypervelocity impact "The impact of a projectile onto a surface at a velocity such that the stress waves produced on contact are orders of magnitude greater than the static bulk compressive strength of the target material. The minimum required velocities vary for different materials, but are generally 1–10 km/sec, and about 4–5 km/sec for most crystalline rocks." (Jackson, 1997, p. 312)

I

impact breccia "Monomict or polymict breccia, which occurs around, inside, and below impact craters." (Stöffler and Grieve, 2003, p. 5)

impact ejecta "Solid, liquid, and vaporized rock ejected ballistically from an impact crater." (Stöffler and Grieve, 2003, p. 4)

impact pseudotachylyte "Pseudotachylite [sic] produced by impact metamorphism; dike-like breccia formed by frictional melting in the basement of impact craters; may contain unshocked and shocked mineral and lithic clasts in a fine-grained aphanitic matrix." (Stöffler and Grieve, 2003, p. 6)

"Some workers attribute impact-related pseudotachylyte formation to shock melting . . . whereas others believe it is primarily the product of frictional melting incurred during gravitational collapse of the impact-generated transient cavity . . . Regardless of origin, all pseudotachylytes are high-strain-rate features." (Snoke and Tullis, 1998, p. 9)

M

microfabric "The fabric of a rock as seen under a microscope." (Jackson, 1977, p. 406)

monomict impact breccia "Cataclasite produced by impact and generally displaying weak or no shock metamorphism; occurs in the (par)autochthonous floor of an impact crater or as clast (up to the size of blocks and megablocks) within allochthonous impact breccias." (Stöffler and Grieve, 2003, p. 5)

P

planar deformation features "Submicroscopic amorphous lamellae occurring in shocked minerals as multiple sets of planar lamellae (optical discontinuities under the petrographic microscope) parallel to rational crystallographic planes; indicative of shock metamorphism; synonymous with the terms "planar elements" and "shock lamellae" which should be discarded." (Stöffler and Grieve, 2003, p. 7)

planar fractures "Fractures occurring in shocked minerals as multiple sets of planar fissures parallel to rational crystallographic planes, which are not usually observed as cleavage planes under normal geological (non-shock) conditions." (Stöffler and Grieve, 2003, p. 7)

planar microstructures "Collective term comprising shock-induced planar fractures and planar deformation features." (Stöffler and Grieve, 2003, p. 7)

polymict "Said of a clastic sedimentary rock composed of many mineral or rock types." (Jackson, 1997, p. 501)

polymict impact breccia "Breccia with clastic matrix or crystalline matrix (derived from the crystallization of impact melt) containing lithic and mineral clasts of different degree of shock metamorphism excavated by an impact from different regions of the target rock section, transported, mixed, and deposited inside or around an impact crater or injected into the target rocks as dikes." (Stöffler and Grieve, 2003, p. 5)

pseudotachylyte "Dark brittle fault rock occurring in veins and fractures in host rocks with low porosity. Pseudotachylyte is thought to form by local melting of a host rock along a fault in response to seismic activity on the fault and associated local generation of frictional heat." (Passchier and Trouw, 1996, p. 262)
Also spelled pseudotachylite. *See* impact pseudotachylyte.

S

shock metamorphism "Metamorphism of rocks or minerals caused by shock wave compression due to impact of a solid body or due to the detonation of high-energy chemical or nuclear explosives." (Stöffler and Grieve, 2003, p. 3)

shocked Term used for brevity in places for "shock metamorphosed." (Izett, 1990, p. 3)

spherulite "A rounded or spherical mass of acicular crystals, commonly of feldspar, radiating from a central point. Spherulites may range in size from microscopic to several centimeters in diameter . . . Most commonly formed by the devitrification of volcanic glass." (Jackson, 1997, p. 612)

spherulitic "Volcanic igneous texture dominated by spherulites or spherical bodies of radiating mineral fibers." (Jackson, 1997, p. 612)

T

target rocks "Rock(s) exposed at the site of an impact before crater formation." (Stöffler and Grieve, 2003, p. 4)

tektite "Impact glass formed at terrestrial impact craters from melt ejected ballistically and deposited sometimes as aerodynamically shaped bodies in a strewn field outside the continuous ejecta blanket; the size of tektites ranges from the submillimeter range (MICROTEKTITES, generally found in deep sea sediments) to the subdecimeter range, rarely to decimeters." (Stöffler and Grieve, 2003, p. 6)

Appendix E1. Descriptions of Matrix and Clast Samples from the Exmore Beds and Crater Unit B in the USGS-NASA Langley Core

Samples from the USGS-NASA Langley core that are described in this chapter are identified by the letters NL followed by a number indicating depth in feet. The clasts examined are nonlineated and nonfoliated except in sparse, very narrow shear zones and in one clast (NL873.3) where oriented grains are interpreted as igneous flow foliation. Positions of selected clasts are plotted on the stratigraphic column in figure E3. Sample descriptions in this appendix are ordered from highest to lowest sample depth.

Sample NL777.3

[About 10 immersion-oil slides + quartz on spindle stage (fig. E2*A*)]

Depth.—236.9 m (777.3 ft); core box 87.

Sample type.—Sandy sediment of the matrix.

Host unit.—Exmore beds (polymict diamicton).

Description.—About 10 immersion-oil slides, each containing several hundred grains, were examined of residue from the core at 236.9 m (777.3 ft) depth by using an optical petrographic microscope**.** Three shocked quartz grains were examined by using a spindle stage. One grain (0.23 mm (0.009 in.) in diameter, not photographed) showed five sets of intersecting planar deformation features on rotation through 180º. A second grain, 0.24 mm (0.009 in.) in diameter, had three sets of intersecting planar deformation features. A third grain, 0.13 mm (0.005 in.) in diameter, had two sets of intersecting planar deformation features (fig. E2*A*). Two of these grains with multiple planar deformation features were photographed, and optic measurements were made. No feldspar grains showed convincing planar deformation features.

Sample NL784.9

[1 thin section (figs. E5*C* and E6*D*) + quartz on spindle stage]

Depth.—239.2 m (784.9 ft); core box 87.

Rock type.—Porphyritic felsite, containing microfaults.

Host unit.—Exmore beds (polymict diamicton).

Dimensions.—4.0x1.8x2.5 cm (1.6x0.71x0.98 in.), whole clast.

Description.—The subangular clast of porphyritic felsite is medium light gray to greenish gray and nonfoliated. It consists of feldspar phenocrysts (~25 percent) in a microcrystalline matrix (~75 percent). Feldspar phenocrysts are medium to coarse grained (2–7 mm (0.079–0.28 in.) long). In thin section, plagioclase phenocrysts appear euhedral to subhedral, and some are highly fractured and internally faulted. Twinning and grain boundaries of some phenocrysts are offset by abundant microfaults. One large quartz grain (near the label end of the thin section) has two sets of intersecting planar deformation features, a strong set and a weaker set, which does not extend across the whole grain (fig. E6*D*). Other grains show no evidence of shock metamorphism. Quartz grains from the residue of this sample were examined in immersion-oil slides and on a spindle stage; one grain was discovered to have two sets of planar deformation features.

Sample NL790.9

[1 thin section (figs. E5*E* and E7) + chemical analysis (tables E2, E3, and E4)]

Depth.—241.1 m (790.9 ft); core box 88.

Rock type.—Porphyritic felsite (rhyolite), with faults and microbreccia veins.

Host unit.—Exmore beds (polymict diamicton).

Dimensions.—3.0x2.0x1.5 cm (1.2x0.79x0.59 in.), whole clast (fig. E4*C*).

Description.—The angular clast of porphyritic felsite is greenish gray and nonfoliated. It consists of feldspar phenocrysts in an aphanitic matrix. In thin section, feldspar phenocrysts appear euhedral to subhedral, and some have embayed margins (fig. E7) or matrix-filled pits indicating magmatic corrosion. A throughgoing fault (near the center of the thin section) and smaller anastomosing faults contain narrow microbreccia veins. One quartz phenocryst has a single set of Böhm lamellae, which are not highly planar or uniform. No planar deformation features were found, but some quartz phenocrysts have mosaic texture.

Sample NL795.8

[1 thin section (fig. E5*D*)]

Depth.—242.6 m (795.8 ft); core box 88.

Rock type.—Microcline megacryst, strained and microfaulted.

Host unit.—Exmore beds (polymict diamicton).

Dimensions.—2.4x1.3x1.0 cm (0.94x0.51x0.39 in.), partial clast bounded by core.

Description.—The subangular clast is very light gray, and a single feldspar crystal extends the full length of the clast. The thin section shows a large microcline crystal, which is internally microfaulted and highly strained.

Sample NL802.07

[1 thin section]

Depth.—244.47 m (802.07 ft); core box 89.

Rock type.—Granodiorite.

Host unit.—Exmore beds (polymict diamicton).

Dimensions.—2.3x2.3x1.4 cm (0.91x0.91x0.55 in.), whole clast.

Description.—The angular clast is granodiorite according to the classification of Streckeisen (1976); it is fine to medium grained, pale red, and nonfoliated. In thin section, the rock is nonfoliated, inequigranular to porphyritic having euhedral to subhedral plagioclase phenocrysts; the thin section is composed of plagioclase (~55 percent), quartz (~30 percent), potassium feldspar (~10 percent), clinozoisite (<1 percent), magnetite (<1 percent), secondary chlorite (~5 percent), and secondary carbonate. The potassium feldspar occurs mainly as granophyric intergrowths with quartz and plagioclase. Clinozoisite and chlorite indicate metamorphic or hydrothermal (deuteric?) alteration. Euhedral comb quartz crystals occur along the edge of a small cavity now filled with secondary calcite. Evidence of high strain is limited to a narrow ductile shear zone along the edge of the sample (in thin section) and to a parallel veinlet of strained quartz grains. No evidence of shock metamorphism is seen.

Sample NL805.5

[1 thin section]

Depth.—245.5 m (805.5 ft); core box 90.

Rock type.—Porphyritic felsite, containing microfaults.

Host unit.—Exmore beds (polymict diamicton).

Dimensions.—2.0x1.3x1.3 cm (0.79x0.51x0.51 in.), clast.

Description.—The angular clast of weathered porphyritic felsite is nonfoliated and consists of medium-grained, subhedral to angular, white feldspar phenocrysts in an aphanitic, pale-red clayey matrix. In thin section, feldspar megacrysts are internally microfaulted; some have mosaic texture and extreme undulatory extinction.

Sample NL806.03

[1 thin section]

Depth.—245.68 m (806.03 ft); core box 90.

Rock type.—Porphyritic felsite having spherulitic texture.

Host unit.—Exmore beds (polymict diamicton).

Dimensions.—2.4x1.5x1.0 cm (0.94x0.59x0.39 in.), whole clast.

Description.—The subangular clast of porphyritic felsite is fine grained, light brownish gray, and nonfoliated. In thin section, the felsite has a pervasive spherulitic texture composed mainly of plagioclase and quartz, with secondary clay minerals having a spotty potassium stain.

Sample NL807.9

[1 thin section]

Depth.—246.2 m (807.9 ft); core box 90.

Rock type.— Porphyritic felsite.

Host unit.—Exmore beds (polymict diamicton).

Dimensions.—1.7x1.5x0.9 cm (0.67x0.59x0.35 in.), clast.

Description.—The angular clast of porphyritic felsite is fine grained, grayish red, and nonfoliated. In thin section, the felsite consists of plagioclase phenocrysts 1–2 mm (0.039–0.079 in.) long in an aphanitic matrix. The yellow sodium cobaltinitrite stain indicates that fine-grained potassium feldspar makes up about 25 percent of the matrix. Minor constituents include an epidote mineral (~2 percent) and opaque minerals (~1 percent). No high-strain fabrics are evident.

Sample NL811.68

[3 thin sections (fig. E5*A*,*B*) + quartz on spindle stage]

Depth.—247.40 m (811.68 ft); core box 90.

Rock type.—Cataclasite (deformed felsite).

Host unit.—Exmore beds (polymict diamicton).

Dimensions.—3.2x2.0x1.1 cm (1.3x0.79x0.43 in.), whole clast.

Description.—The subangular clast of fine-grained cataclasite formed by deformation of felsite is leucocratic, light gray, and nonfoliated, and it has disseminated sulfide crystals. Striated surfaces are inconclusive evidence that the sample may have been part of a shatter cone (Daniel J. Milton, USGS Emeritus, oral commun., 2001). Thin sections show highly microfaulted and brecciated but cohesive felsite consisting of plagioclase phenocrysts in an aphanitic feldspar-quartz matrix. Plagioclase phenocrysts are crosscut by microfaults and have highly undulatory extinction and mosaic texture. Calcite-filled fractures are abundant. A few quartz grains have a suspicious brown color in thin section but lack planar deformation features. One potassium feldspar crystal has weak, nonthroughgoing lamellae, which are interesting but inconclusive.

Sample NL812.55

[1 thin section (fig. E8)]

Depth.—247.67 m (812.55 ft); core box 90.

Rock type.—Porphyritic felsite having spherulitic texture.

Host unit.—Exmore beds (polymict diamicton).

Dimensions.—1.9x0.9x0.4 cm (0.75x0.35x0.16 in.), whole clast.

Description.—The angular clast of porphyritic felsite is grayish red and nonfoliated. Calcite-filled fractures are visible in hand sample. In thin section, the felsite consists of euhedral plagioclase phenocrysts (~30 percent) in a finer grained matrix dominated by feldspar-quartz spherulites. The yellow stain for potassium is concentrated in the outer margins of spherulites and in mesostasis. Some clear, euhedral plagioclase laths appear to have grown across earlier spherulites. Minor constituents include opaque minerals (~2 percent), secondary calcite (~5 percent) and chlorite (~5 percent). The thin section does not contain the calcite-filled fractures, and no other cataclastic features were observed.

Sample NL813.57

[1 thin section]

Depth.—247.98 m (813.57 ft); core box 90.

Rock type.—Porphyritic felsite.

Host unit.—Exmore beds (polymict diamicton).

Dimensions.—1.2x1.0x0.8 cm (0.47x0.39x0.31 in.), whole clast.

Description.—The angular clast of porphyritic felsite has tiny disseminated sulfide (pyrite?) crystals and secondary calcite in fractures. In thin section, the felsite consists of plagioclase phenocrysts in an aphanitic feldspar-quartz matrix. Embayed margins of some feldspar phenocrysts indicate magmatic corrosion. Microfaults and fractures are filled by polygonal quartz and by calcite.

Sample NL820.6

[About 10 immersion-oil slides + quartz on spindle stage (fig. E2*B*, *C*,*D*,*E*)]

Depth.—250.1 m (820.6 ft); core box 91.

Sample type.—Sandy sediment of the matrix.

Host unit.—Exmore beds (polymict diamicton).

Description.—About 10 immersion-oil slides, each containing several hundred grains, were examined of residue from the core at 250.1 m (820.6 ft) by using an optical petrographic microscope. Six of the quartz grains examined by using a spindle stage were observed to have two or more sets of intersecting planar deformation features (fig. E2*B,C,D,E*), indicating that the grains had experienced shock metamorphism. These grains ranged in diameter from 0.13 to 0.26 mm (0.005 to 0.010 in.).

Sample NL832.25

[1 thin section]

Depth.—253.67 m (832.25 ft); core box 92.

Rock type.—Porphyritic felsite.

Host unit.—Exmore beds (polymict diamicton).

Dimensions.—1.7x1.2x1.0 cm (0.67x0.47x0.39 in.), clast.

Description.—The angular clast of porphyritic felsite is grayish red and nonfoliated. In thin section, it consists of euhedral to subhedral plagioclase phenocrysts in an aphanitic quartz-feldspar matrix. The yellow sodium cobaltinitrite stain indicates that potassium feldspar is disseminated in the groundmass. Many euhedral plagioclase phenocrysts are rimmed by potassium feldspar coronas. A volcaniclastic origin is suggested by the possible contained igneous rock fragment as well as by the angularity of grains in the groundmass. No high-strain fabrics were observed.

Sample NL832.85

[1 thin section]

Depth.—253.85 m (832.85 ft); core box 92.

Rock type.—Porphyritic felsite.

Host unit.—Exmore beds (polymict diamicton).

Dimensions.—3.4x2.2x1.7 cm (1.3x0.87x0.67 in.), partial clast bounded by core (fig. E4*D*).

Description.—The angular clast of porphyritic felsite is porphyritic-aphanitic, mottled grayish red and grayish green, and nonfoliated. The thin section shows phenocrysts of plagioclase and quartz, and the aphanitic matrix has a mild yellow sodium cobaltinitrite stain, indicating that it contains disseminated potassium feldspar. Minor constituents include opaque minerals and secondary calcite, both disseminated and in veinlets. Some of the matrix has a spherulitic texture. No high-strain fabrics were observed.

Sample NL840.4

[2 thin sections (fig. E6*A,B,C*) + quartz on spindle stage]

Depth (entire clast).—256.06–256.26 m (840.1–840.75 ft) (ends were left in the core box).

Depth (sampled part).—256.11–256.23 m (840.25–840.65 ft); core box 94. The depth in the sample number, 840.4 ft, is within the sampled part of the clast.

Rock type.—Cataclasite (deformed felsite), pervasively microfaulted, brecciated, and weakly cohesive (fig. E4*B*).

Host unit.—Exmore beds (polymict diamicton).

Dimensions.—12-cm-long (4.7-in.-long) central part of clast bounded by the core having a nominal diameter of 6.4 cm (2.5 in.).

Description.—The very light gray, very fine grained clast is larger than the core diameter, and so its shape is undetermined; the top and bottom of the clast are irregular. It consists of porphyritic-aphanitic felsite, which is pervasively microfaulted, brecciated, and weakly cohesive. Two thin sections show that the rock consists mainly of euhedral to subhedral plagioclase phenocrysts in a matrix of aphanitic quartz and plagioclase, and they show very little of the yellow sodium cobaltinitrite stain indicating potassium. Some plagioclase phenocrysts are offset by crosscutting microfaults. Secondary calcite (about 5 percent) is disseminated through the rock and also commonly fills fractures. A sulfide mineral (pyrite?) occurs as tiny disseminated crystals. Numerous crosscutting microfaults and fractures extend short distances and disappear in the microcrystalline groundmass. Calcite-filled fractures up to 1 mm (0.039 in.) thick are conspicuous; some of this calcite is strained, suggesting continued fault slip. Many quartz grains in thin section 1 have at least two sets of intersecting planar deformation features, indicating shock metamorphism.

Sample NL854.0

[1 thin section]

Depth.—260.3 m (854.0 ft); core box 95.

Rock type.—Diabase pebble (detrital).

Host unit.—Exmore beds (polymict diamicton).

Dimensions.—4.5x3.5x2.8 cm (1.8x1.4x1.1 in.), whole clast.

Description.—The subrounded pebble of fine-grained diabase (Early Jurassic?) is medium gray and nonfoliated. It has randomly oriented plagioclase laths and an intergranular texture. It resembles typical Early Jurassic diabases in the Appalachian Piedmont, except that it contains 1–2 percent magnetite as equant megacrysts 1.0–1.5 mm (0.039–0.059 in.) across. In thin section, the diabase consists of plagioclase (~60 percent), orthopyroxene (relict and chemically weathered to clay, ~25 percent), miscellaneous clay weathering products (~15 percent), and a secondary carbonate mineral (<1 percent); no relict olivine was found. No high-strain fabrics or possible impact effects were observed.

Sample NL864.05

[1 thin section]

Depth.—263.36 m (864.05 ft); core box 96.

Rock type.—Quartz pebble (detrital).

Host unit.—Exmore beds (polymict diamicton).

Dimensions.—2.3x1.7x1.3 cm (0.91x0.67x0.51 in.), whole clast.

Description.—The well-rounded quartz pebble is very light gray and nonfoliated. The quartz is polycrystalline. In thin section, the quartz grains have irregular interlocking grain boundaries, no obvious preferred orientation, and no unusual undulatory extinction or any other evidence of high strain.

Sample NL870.3

[1 thin section (fig. E5*F*)]

Depth (entire clast).—265.27–265.36 m (870.3–870.6 ft); core box 97.

Depth (sample).—265.27–265.33 m (870.3–870.5 ft) (the remainder was left in the core box).

Rock type.—Brecciated porphyritic felsite containing pseudotachylyte(?).

Host unit.—Exmore beds (polymict diamicton).

Dimensions.— 8.0-cm-long (3.1-in.-long) partial clast (fig. E4*A*) bounded by the core having a nominal diameter of 6.4 cm (2.5 in.).

Description.—The partial clast of brecciated porphyritic felsite is very fine grained, light gray, nonfoliated, and crumbly; it appears weathered. The clast is larger than the core diameter, and so its shape is undetermined; the top is subhorizontal, and the bottom dips about 60º. Striated fractures on the top surface (in the core box) are inconclusive evidence that the sample may have been part of a shatter cone (Daniel J. Milton, USGS Emeritus, oral commun., 2001). The thin section shows a highly brecciated porphyritic felsite having abundant microfractures, including some offsetting twins in plagioclase phenocrysts. A pseudotachylyte(?) vein (about 0.2 mm (0.0079 in.) thick) was injected into a tension fracture having matching grain fragments on opposite walls. The vein contains some large clean quartz grains. Even quartz in and adjacent to the pseudotachylyte(?) vein appears clean and free of planar deformation features. No shock-metamorphosed minerals were found.

Sample NL873.3

[1 thin section]

Depth.—266.2 m (873.3 ft); core box 97.

Rock type.—Felsite having igneous flow foliation.

Host unit.—Exmore beds (polymict diamicton).

Dimensions.—2.3x1.4x1.1 cm (0.91x0.55x0.43 in.), whole clast.

Description.—The angular clast of felsite is grayish black, appears flinty, and does not fizz in hydrochloric acid. The thin section shows sparse, matrix-supported feldspar phenocrysts in a very fine grained groundmass of feldspar and quartz with diffuse spots of opaque oxide. Alignment of tiny plagioclase laths in the matrix may be an igneous flow foliation. No cataclastic fabrics were observed.

Sample NL905.0

[5 thin sections + quartz on spindle stage]

Depth (entire clast).—275.71–275.93 m (904.60–905.33 ft); core box 101.

Depth (sample).—275.80– 275.84 m (904.85–905.00 ft) (the remainder was left in the core box).

Rock type.—Monomict felsite breccia (impact breccia).

Host unit.—Crater unit B (upper part) of Gohn and others (this volume, chap. C).

Dimensions.—22-cm-long (8.7-in.-long) clast bounded by the core having a nominal diameter of 6.4 cm (2.5 in.).

Description.—The clast is larger than the core diameter, and so its shape is undetermined; the top surface dips ~10º, and the bottom dips ~50º. It is a monomict breccia composed of angular, grayish-red, cherty microcrystalline felsite fragments separated by white gougelike clay between the fragments and in fractures. The clay matrix lacks primary cohesion and crumbles when wet. Thin sections show pervasive brecciation. Angular fragments of microcrystalline felsite resemble chert and consist mainly of very fine grained plagioclase and quartz; the yellow stain for potassium is dispersed on clay-sized particles. Some spherulitic texture is present. Microfaults offset twins in plagioclase. The clay matrix contains a few round, green glauconite pellets along the margins and in cracks, indicating some mixing with coastal plain sedimentary material. A few quartz grains in thin section 3 and thin section 5 have two convincing sets of intersecting shock-induced planar deformation features; some other quartz grains have one visible set of parallel planar deformation features.