Petrographic Studies of Rocks from The Chesapeake Bay Impact Structure (USA): Implication for Moderate Shock Pressures in Sedimentary Breccias

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ABSTRACT

Shock petrographic investigations were carried out on samples collected from drill cores from the Chesapeake Bay impact structure (USA). The late Eocene Chesapeake impact structure is, at 85 km diameter, currently the largest impact structure known in the United States, buried at shallow to moderate depths beneath continental margin sediments underneath southeastern Virginia. To better define the variety of the samples collected from the shallow drill cores and the shock degrees experienced by the target rocks and breccias in the Chesapeake impact crater, thin section analyses were conducted on more than 50 samples from the various zones of the impact structure. The study involves measurements of the orientations of planar deformation features (PDFs) using a universal stage attached to a petrographic microscope. The aim of this study is to determine the shock pressures of various clasts in the shallow breccia fill of the crater. As a result, we note that the overwhelming numbers of shocked grains, which are now present in the sedimentary breccia, are derived from the basement granitoids. Our studies involved samples from four shallow drill cores (Exmore, Windmill Point, Kiptopeke, and Newsport News).The breccia fill is termed the Exmore breccia, which is dominated by particulates of silt, shocked and unshocked granitic fragments, shale, clay, and free shocked quartz grains. The Kiptopke and Windmill Point samples contained rare fragments showing a variety of different shock effects, whereas the Newporte News samples, show several fragments and impact melt with the evidence shock metamorphism was noted. The most abundantly observed shock indicators are shock fracturing, indicative of shock pressures of less than about 10 GPa, as well as 1-2 sets of PDFs in quartz grains, which is indicative of moderate shock pressures of up to about 20 or 25 GPa.

Key words: Chesapeake Bay Crater, PDFs, Shock pressure, Universal stage, Impact structure.

1. INTRODUCTION

Impact cratering is a rapid surface-modification process, which happens when a large meteoroid (asteroid or comet) hits a planet or a satellite (e.g., Koeberl, 1998). Besides, it is a unique geological process in which vast amounts of energy are released in a small area in a very short time (e.g., Grieve, 1990). Impact craters on Earth are produced by the hypervelocity impact of asteroids and comets at a velocity between 11 and 72 km/s and the magnitude of the energy release depends mainly on the speed and size of the impacting body (Grieve, 1991). As a result, impact events have generated large crustal disturbances, produced huge volume of igneous rocks, formed major ore deposits, and participated in at least one major biological extinction event (e.g., French, 1998; Montanari and Koeberl, 2000).

Today, it has been realized that the terrestrial impact structures are more abundant, larger, older, more geologically complex and economically important and even more biologically significant than anyone would have predicated a few decades ago (e.g., Grieve, 1991; French, 1998). In addition, impact processes are now considered to have played a vital role in planetary formation, through accretion of large bodies (the protoplanets) as the result of collisions between smaller bodies, the so-called planetesimals (e.g., Melosh, 1989; Taylor, 1992). About 175 terrestrial impact craters have been discovered so far (2009) and several new craters are discovered each year (Grieve, 1991, See also Earth Impact Database, 2010:www.unb.ca/passc/Impact Database/). The impact craters on Earth range in age from a few thousands to almost two billion years (Grieve, 1990, 1991; French, 1998). The known impact structures ranges from circular bowls only a few kilometers in diameter to a large complex structure more than 200 km in diameter and as old as 2 Ga. Some of the preserved terrestrial craters on Earth show varying stages of preservation and exposure, ranging from deeply eroded, e.g., Vredefort, South Africa, to those that have well preserved ejecta deposits outside the crater rim, e.g., at the Bosumtwi, Ghana, and Ries, Germany, impact craters.

The Chesapeake Bay crater is one of the largest impact craters that have been recently discovered. It is centered at 36^0 75’ to 37°61’ 30’’ N and 76° 42’ to $75^0$30’ W, near the town of Cape Charles on Virginia’s segment of the Delmarva Peninsula (Fig.1). The crater is a complex peak ring structure buried about 300 to 500 m beneath the lower Chesapeake Bay, its surrounding Peninsulas and the adjacent inner continental shelf (Koeberl et al., 1996). The Chesapeake Bay impact crater was formed when a large comet or meteorite crashed in to shallow-shelf waters of the western Atlantic ocean approximately 35 million years ago (Powars et al., 2000; Poag et al., 1994; Poag et al., 2004). The impact structure has an age of about 35.5 million years, which places it in the late Eocene, a time of an enhanced impact flux onto the Earth (cf. Koeberl and Montanari, 2009; Montanari and Koeberl, 2000).

The 85-km-wide crater includes the Virginia Coastal plain sediments, the southern part of the Chesapeake Bay, and a small part of the Atlantic Ocean (Fig.2). It includes an inner basin surrounded by a ring of raised basement rock, as well as a flat-floored terrace zone that is bounded along the outer rim by a zone of concentric faulting. Cross-sections of the crater were constructed based on 10 multi-channel seismic reflection profiles transecting the bay and the 3 single-channel profiles on the inner continental shelf, as well as 56 boreholes drilled inside and outside the crater rim (Poag et al., 1994). The seismic profiles define the outer rim structure of the crater (e.g., Koeberl et al., 1996; Poag et al., 2004).

Much of the shallow part of the crater is filled with a chaotic sedimentary deposit known as the Exmore breccia. The Exmore breccia contains angular clasts of older sedimentary material, and granite to metamorphic basement rocks in sandy matrix. A first petrographic and geochemical study of samples from the Exmore breccia (imaged on seismic profiles in the environs of the central uplift with a maximum thickness of 1.2 km) showed that the breccia is composed of a range of clastic components (the various pre-impact sediments and crystalline granitoid basement) set in to fine-grained clastic- matrix of the same components. The first evidence for an impact crater came from the morphology and the occurrence of breccia (Poag et al., 1994). Final confirmation came from the identification in cores of partially melted basement rocks and multiple sets of planar deformation features in quartz and feldspar basement clasts (Koeberl et al., 1996).

The relatively recent discovery of the crater (Powars et al., 1993; Poag et al., 2004) has contributed to a better understanding of the geological framework of the middle and outer Virginia Coastal Plain. Moreover, the existence and location of the crater helps to explain the structure, stratigraphy and ground-water quality in the area.

The Chesapeake Bay impact structure is also the source crater for the North American tektites – glassy distal ejecta that are found in a geographically extended strewn field along the eastern and central part of the North American continent (e.g., Koeberl et al., 1996; Deutsch and Koeberl, 2006).

Recently, the Chesapeake Bay impact structure was the subject of a large international and interdisciplinary deep drilling project; the goal was to obtain a deep, continuously cored hole into the central part of the structure. Drilling funds were provided by the International Continental Scientific Drilling Program (ICDP), the U.S. Geological Survey (USGS), and the NASA Science Mission Directorate. Field operations were conducted at Eyreville Farm, Northampton County, Va., a few kilometers from Cape Charles. Drilling was performed during September-December 2005, resulting in two continuously cored, deep holes. The USGS and Rutgers University cored a shallow hole to 140 m in April-May 2006 to complete the recovered section from land surface to 1766 m depth. Details are described by Gohn et al. (2006, 2008, 2009).

Figure 1. Location map of the Chesapeake Bay impact crater, showing the crater rim, solid dots are drill core locations [***Note***: N, Newport News; W, Windmill point; E, Exmore; O, Eyreville and K, Kiptopeke (from Gregory Gohn, 1996)].

As noted by Gohn et al. (2008), the recovered section consists of 1322 m of crater materials and 444 m of overlying post-impact Eocene to Pleistocene sediments. The crater section consists, from base to top, of: basement-derived blocks of crystalline rocks (215 m); a section of suevite, impact melt rock, lithic breccia, and cataclasites (154 m); a thin interval of quartz sand and lithic blocks (26 m); a granite mega-block (275 m); and sediment blocks and boulders, polymict, sediment-clast-dominated sedimentary breccias, and a thin upper section of stratified sediments (652 m). The results from the deep drillcore supplement the information that has been obtained from the sampling of the shallow drillcores (including those described in the present manuscript).

2. GENERAL GEOLOGY

The geological cross section of the Chesapeake Bay impact crater and its circular features was derived from seismic surveys and detailed examination of sedimentary cores (Fig. 2). The

Chesapeake Bay impact structure lies beneath the shallow waters of the Chesapeake Bay and a thin veneer of coastal plain sediment (Powers and Bruce, 1999; Poag et al., 1994; Poag et al., 2004). The structure includes an inner basin surrounded by a ring of raised basement rock, encircled by a flat-floored terrace zone and bounded by the outer rim by a zone of concentric faulting (Powars and Bruce, 1999; Koeberl et al., 1996). The crater is overlain by up to 650 m of Early Cretaceous to late Eocene sedimentary material and underlain by granodioritic basement rocks The pre-impact coastal plain rocks consisted of a seaward-thickening wedge of mainly lower Cretaceous to upper Eocene age, poorly lithified, and mainly silicic-clastic sedimentary rocks (Fig. 2).

Information from borehole samples indicates that the structure of the Chesapeake Bay crater is partially filled with the so-called Exmore breccia, which is mainly composed of autochthonous sedimentary material and granitic to metamorphic, with minor basement rock clasts in a sandy matrix (e.g., Poag et al., 1994; Koeberl et al., 1996). After the formation of the crater, younger marine and non-marine sediments deposited on the coastal plain completely buried the structure. The crystalline basement (interior structure) of the Chesapeake Bay crater is expressed in the structure and thickness of the overlying breccia and of the post-impact sedimentary section. In particular, both the breccia and the post-impact section are notably thinner and structurally raised where they cross the peak ring and central peak (Fig. 2). During the impact process, the impactor penetrated through the water column, the full thickness of the existing Coastal Plain sediments, slammed in to the basement rock, and vaporized, creating a catastrophic explosion and ejected material into the atmosphere (e.g., Poag et al., 2004; Powars and Bruce, 1999). The basement rocks lining the crater cavity were melted, and the basement rocks in the region beneath and around the crater were faulted and fractured. The impact produced an inverted sombrero-shaped 85-km-wide complex crater that was immediately filled with sediments and rim collapse material and eventually buried by younger sedimentary deposits (Powars and Bruce, 1999). From geophysical and geological data, the Chesapeake Bay crater has been reported as one of the best-preserved complex peak-ring structures documented on Earth (Poag et al., 1994, 2004).

3. METHODOLOGY

The samples for this study of shock metamorphism of the clastic sediments were collected by Poag (2004) (US Geological Survey) from cores drilled earlier into the Chesapeake Bay crater. For the present study, 50 samples that are representative of the different lithological types exhibited in the shallow drill cores were taken from various depths throughout the length of cores. Petrographic thin sections were prepared from the samples and they were studied using a standard optical petrographic microscope.

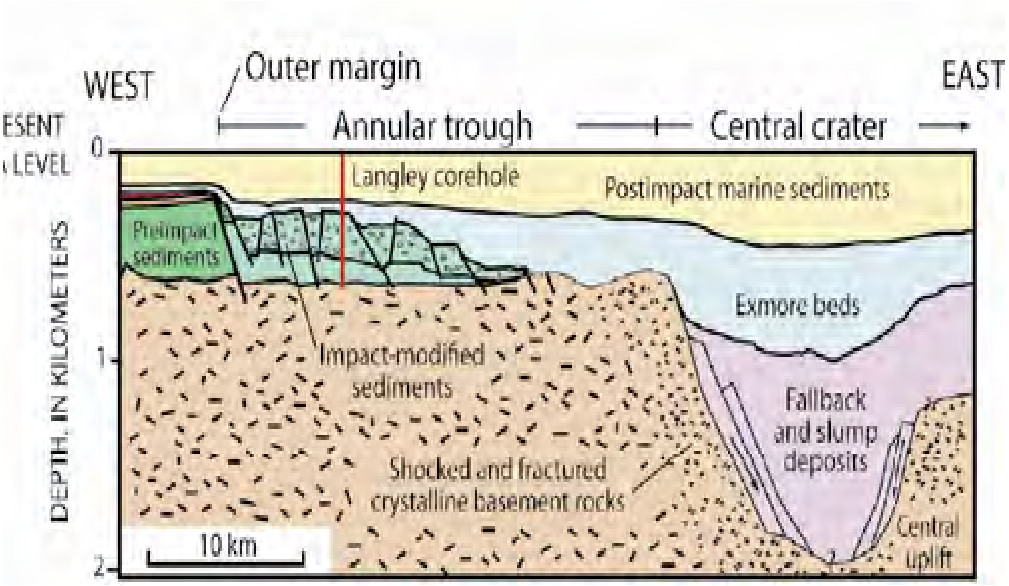

Figure 2. Schematic radial cross section showing half of "inverted sombrero" shape of the Chesapeake Bay impact crater, constructed from drill core and seismic data (from Gohn et.al 2006). The location of the cross-section is indicated in Fig. 1.

The measurements of the planar deformation features (PDFs) were conducted using universal stage (e.g., Emmons, 1943). More precisely, this method allows the determinations of the angle between the c-axis of a quartz grain and the poles of the planes of the planar deformation features. The data obtained from the universal stage measurements are then plotted with the aid of a stereographic equal-area net projection. After measuring the orientations of the PDFs in quartz grains, the data are arranged in table form to provide information about the axis of orientation and plane of orientation of each quartz grains in thin section. From the data, a histogram is plotted, with the X-axis representing the polar angle and the frequency on the Y-axis.

4. RESULTS AND DISCUSSION

4.1. Petrographic Observations

About 50 samples from four different drill cores were examined for their petrographic characteristics. Table 1 lists the most characteristic products of shock metamorphism, as well as the associated diagnostic features. The best diagnostic indicators for shock metamorphism are features that can be studied easily by using the polarizing microscope. They include planar micro-deformation features; optical mosaicism; changes in refractive index; optical axis angle; isotropization and phase changes. These samples were taken from the following cores: Exmore, Windmill Point, Kiptopeke, and Newport News; all of these have penetrated into the Exmore breccia, but not into the deeper crater filling, which was recently intersected by the 2005/6 ICDP-USGS project (Gohn et al., 2006, 2008, 2009). About 50 of the samples which represent the Exmore breccia in the interval between 1210.2 and 1388.2 feet (368.2 and 423.12 m), were taken from the Exmore core. In addition 4 samples from the Kiptopeke core between 1329.2 and 1332.25 feet (405.14 and 405.65 m) and 10 samples from Windmill Point core between 539.80 and 566.4 m depths were analyzed. The Windmill Point samples are dominated by sandy material with minor carbonate and crystalline basement lithologies. On the other hand, the three samples from Newporte News core samples contained a comparatively higher amount of crystalline basement fragments and sediment materials.

The Kiptopeke section contains sediment and crystalline basement rocks, as well as a significant silt component, in addition to the sand and carbonate. The proportion of the shocked fragments as derived from the thin sections is relatively variable in each of the samples, where a limited number of shocked grains were identified from all the analyzed samples of this study.

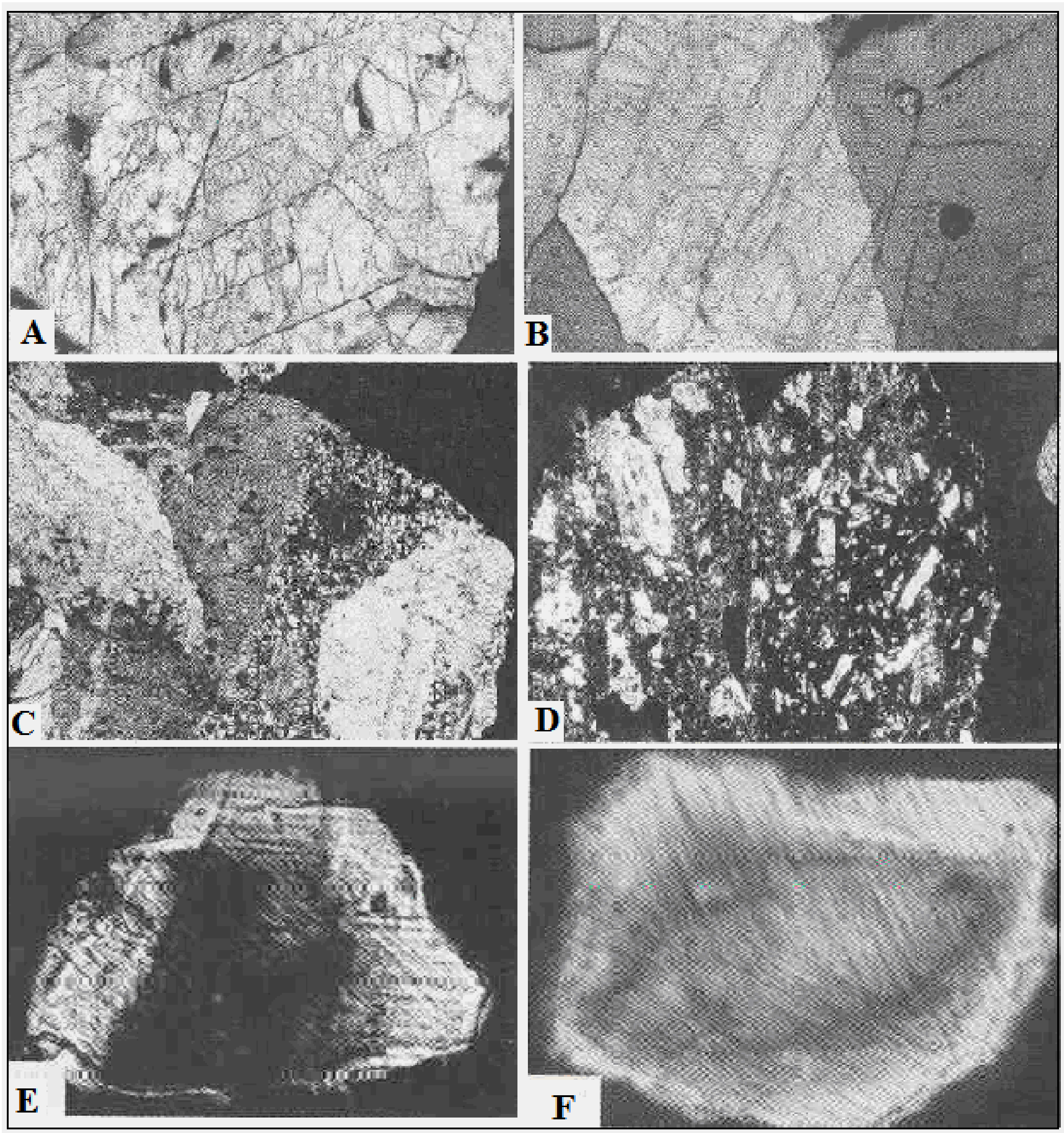

Figure 3. Photomicrographs of thin sections showing typical fractures patterns resulting from low-pressure (~8 GPa) shock metamorphism in clasts of crystalline basement from Exmore breccia. (A) Sample no. Ex 1280.78 (390.4 m depth), shock fractures in feldspar, width of field 2.2 mm, plane polarized light. (B) sample no., Ex 1290.d (393.4m depth); typical shock fractures in quartz with granitoid fragment or vein, plane polarized light; width of field 1.1 mm. (C) sample no., Ex 1323.82 (403.5 m depth); granite fragment with annealed melt vein; width of field 3.4 mm; crossed polarizer. (D) sample no., Ex 1341.4 (408.9 m); aphanitic impact melt with K-feldspar clasts; width of field 3.4 m, crossed polarizer. (E) and (F) sample no., K 1332.25 (406. 1 m depth), and NL 820.6 (250.12 m); quartz grains from matrix of Exmore breccia (cross-polarized light), each showing two sets of PDFs, width of field ~0.2 mm. K= Kiptopeke corehole; NL= NASA Langley core hole.

Table 1. Petrographic observations of individual clasts of samples from the thin section of the Chesapeake Bay impact crater.

Sample no.	***Description***
Ex- 1235.43 -.67	Shock fracturing and incipient melting of quartz along fractures. Particulate sample; glauconite in carbonate matrix, shale, shocked quartz fragments contain single set of PDF and silt derived fragments with shocked quartz 1235.43 -.67 feet (376.56 to 376.65 m).
Ex- 1237	Particulate clay, silt, and centimeter sized K-feldspar with some quartz clasts. Both K-feldspar and quartz contains up to two sets of PDFs 1237 feet (377.04 m) depth.
Ex- 1290.60- 76	Particulate sample: a breccia particle containing shocked quartz, unshocked granite, and granite derived fragments , pegmatite-or vein quartz, clay and sand. The shocked minerals in the lithic fragments are derived from crystalline basement lithologies. No shocked sediment particles were observed, except some rare shocked quartz grains in carbonate. Some of the carbonate veins are cutting across the granite 1290.60- 76 feet (393.37 to 393.42 m) depth.
Ex- 1320	Clay and quartzite fragments mostly unshocked, brecciated. One quartzite fragment has shock fractures 1320 feet (402.34) depth.
Ex-1329.20- .40	Carbonate, chert, granite with fractured quartz. Shocked granite with plenty sets of PDFs; & unshocked granite fragments 1329.20-.40 ft (405.14 to 405.20 m) depth.
Ex- 1341.5 - .67	Unshocked microcline, partially altered impact melt, silt, & shocked quartzite and sand. Myrmekite has developed from melting of feldspar 1341.5 - .67 ft (408.89 to 408.94 m) depth.
Ex- 1356.8	Shocked quartz in a granitoid fragments, showing multiple sets of PDFs 1356.8 feet (413.55 m) depth.
Ex-1240.85-1241.0	Granite fragments, silt microcline and shocked granite fragments with shock fractures and 1-set of PDF. Reddish type breccia with annealed quartz clasts and shocked granite-derived clasts (quartz feldspar with shock fracturing and one set of PDF, 1240.85 -1241.0 feet (378.21 to 378.26 m) depth.
Ex- 1210.2	Silt with abundant fine grained quartz, calcite, magnetite and biotite. Feldspar and muscovite are less abundant. The matrix consists of calcite. No shock deformation noted 1210.2 feet (368.87 m) depth.
Ex- 1286.7	Clasts, medium to sub angular grain and lithic clasts, often showing minerals with reduced birefringence. Most of the micas are kink banded. Enhanced cleavage in some feldspar grains: no PDFs or other shock features 1286.7 ft (392.19m) depth.
Ex- 1337.6	Quartz, microcline and plagioclase are the abundant clast phase. They are mostly medium to coarse grained. Poorly sorted, with rounded to angular fragments. Fragments are set into a fine-grained matrix of similar mineralogical composition, but with calcite as most abundant mineral. In places, magnetite alteration has caused Fe-oxide staining on the matrix. No shock deformation features 1337.6 feet (407.7 m) depth.
Ex- 1331.0	Dominated by quartz, microcline and some plagioclase fragments, mudstone, siltstone and carbonate clasts. Over 90% granite derived material and 10 % vol sediment; no shock effects 1331.0 feet (405.69 m) depth.
NN- 433.8	Fractured and brecciated granite, fine grained melts rock that could represent impact melt rock and unshocked granite clasts and fine grained melt rock with angular and well rounded quart clasts in an altered matrix 433.8feet (132.22 m) depth.
WP- 552.11	Medium grained sand with fine grained carbonate clasts. Some folded, mica clasts, unshocked 552.11 m (168.28 m) depth.

Ex= Exmore; NN= Newport News; WP= Windmill Point.

Table 2: Preliminary composite geologic section for the Eyreville boreholes (from Gohn et al., 2006; Reimold, et al., 2006).

0 to 444 m	Post-impact sediments
444 to 1,096 m	Sediment-clast breccia and sediment megablocks
1,096 to 1,371 m	Granitic megablock(s)
1,371 to 1,393 m	Lithic blocks in sediment
1,393 to 1,550 m	Suevitic and lithic breccia
1,550 to 1,766 m	Schist and pegmatite; breccia veins

The overwhelming number of shocked grains is derived from basement granitoids. Only rarely it was possible to observe weak to moderate shock deformation in sediment-derived particles. Granitoids are widely present, even though the clastic sedimentary components are important throughout the drilled breccia sequences, carbonates are relatively rare. On the other hand, mafic components are also extremely rare (Poag et al., 2004). Most thin sections contained 10 to 15 mineral fragments, but fine grained material (<1 mm grain size) may have contained several grains. Exmore samples do frequently contain very small proportions of shock particles, but here too, very weak and weak shock degrees are dominant.

Table 3. Thin-section samples and numbers with those that have only shocked quartz grains from the Chesapeake Bay crater, USA.

No.	***Sample number***	***Number of grains***
1	Ex 1235.43-.67	3
2	EX1237	3
3	EX 1280.78	3
4	Ex 1290.60-.76	2
5	EX 1312.0-.14	3
6	Ex 1329.20-.40	3
7	Ex 1341.5-.67	4
8	EX 1356.8	1
	Total	**22**

Overall, the Exmore breccia is dominated by particulates of silt, shocked and unshocked granitic fragments, shale, clay with very rare shocked quartz grains, fractured and locally melted granite, unshocked microcline, sandstone and opaque mineral fragments. To generalize, the shocked grains identified in the Exmore breccia are far less than 2 % of all grains studied. With regard to Kiptopeke samples, none of them exhibited any shock deformation. Windmill Point samples showed rare fragments with a wide variety of different shock effects, including shock fracturing only or impact melt breccia. In Newport News samples, several fragments and impact melt with evidence of shock metamorphism were noted.

4.2. Planar deformation feature (PDF) measurements

Confirmation of an impact origin requires conclusive evidence that the rocks and minerals have undergone shock metamorphism, which is defined by high pressures and temperatures (up to 100 GPa and 1000 ^{0}c), and strain rates associated with impact cratering (from 5 GPa to > 50 GPa). The type of metamorphism depends on the shock pressure experienced. Planar deformation features (PDFs) is the designation currently used for distinctive and shock produced microstructures that were formerly given a variety of names (e.g. “planar features”, “shock lamella”). In contrast to planar features, with which they may occur, PDFs are not open cracks. Instead they are sets of closed, extremely narrow , parallel planar regions (Fig. 3e, f).

Most of the information from impact structures comes from dense, coherent quartz bearing crystalline rocks (French, 1998). There is a relatively little information about the effects of shock deformation in other kinds of quartz-bearing rocks, e.g. porous sandstone or fine grained shale. Several studies have demonstrated that shocked sandstones and shale’s also develop PDF in quartz, and even diapeletic quartz and feldspar glasses, similar to those observed in other craters in shocked crystalline rocks (Fig.3). Despite These similarities a growing amount of data now indicate that sedimentary rocks respond differently to shock pressure than do crystalline rocks (Greive et. al., 1996). The more important difference between the sedimentary porous rocks and crystalline rocks is that a shock wave passing through sediments will generate more heat than in passing through crystalline rocks. extremely narrow , parallel planar regions (Fig. 3e, f).

Evidence of shock metamorphism is abundant in rocks and mineral clasts from the Exmore breccia in the Chesapeake Bay impact structure was described earlier by Koeberl et al. (1996) and Poag et al. (2004). A first petrographic study from the Exmore breccia showed that the breccia is composed of a range of clastic components, such as various pre-impact sediments and crystalline granitoid basement set in to fine-grained clastic matrix of the same components. More than 50 specimens from four boreholes (Exmore, Windmill Point, Kiptopeke, and Newporte News) into the shallow outer annulus of the Chesapeake Bay crater were examined for the presence of distinctive mineral deformation features. Most of the samples analyzed did not show any significant deformation features at all. A specimen from Windmill Point and Newport News revealed only micro-deformation features limited to the development of rather wide-spaced fractures and in some parts shows undulatory extinction (Table 1).

Besides, the Chesapeake Bay Impact Structure Deep Drilling Project (CBIS Project) was completed its coring operations during September–December 2005 and April–May 2006. Cores were collected continuously to a total depth of 1766 m. The recovered section consists of 1322 m of impactites beneath444 m of post-impact continental shelf sediments (Table 2).

Out of 50 thin sections analyzed only 8 shows PDF characteristics in the Exmore breccia samples from depths of 1210.2 to 1388.2 feet (Table 3). These samples are mainly shocked granite fragments with quartz and rarely shocked quartz grains in a carbonate matrix. Some shocked alkali feldspars were also observed, which showed up to two sets of PDFs (Fig.3). Because shocked-produced PDFs in a given quartz grain are parallel to only few specific crystallographic planes, the angles measured between the quartz c-axis and the poles to to the PDF tends to concentrate at a few specific values (French, 1998). In a histogram plot, the poles appear as sharp concentrations at specific angles, and each of which belongs to a particular plan. This sharply peaked pattern of PDF orientations, typically characterized by peaks at c (0001) (0^0), ($10\bar{1}3$) (23^0), and π ($10\bar{1}2$) (32^0) is one of the most useful and used for indicating characteristics of shock metamorphism (Fig.4).

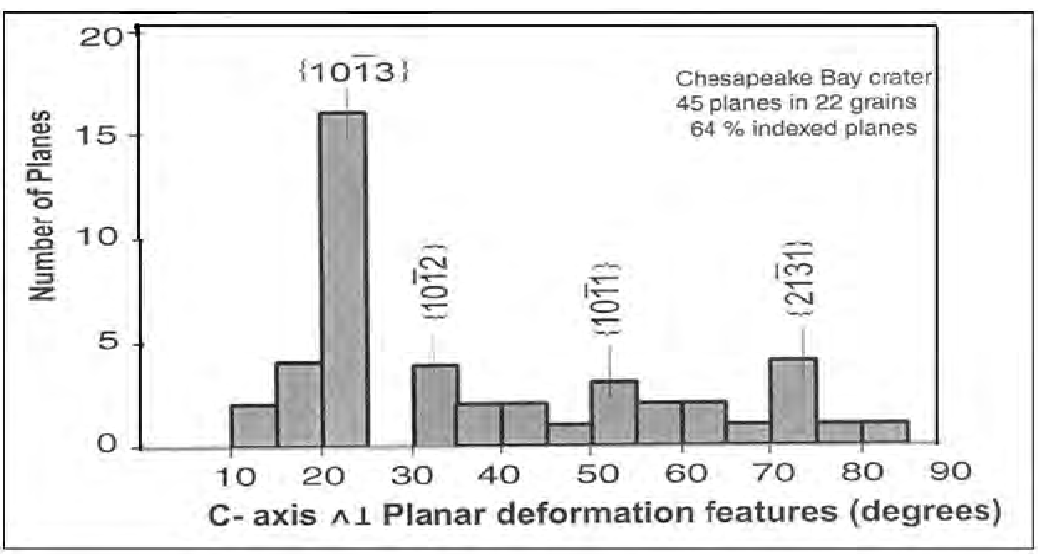

Figure 4. Histogram showing orientations of PDFs in quartz from Chesapeake Bay crater (from Exmore breccia). In the diagram, the angle between the quartz C-axis and the pole to the planar features is plotted on the x-axis; on the y-axis the frequency is given for each angle.

Shock metamorphism in these samples is manifested by a number of quartz grains with single occasionally with multiple sets of planar deformation features (Table 4). The overall percentage of PDF-bearing quartz grains in the investigated core samples is far less than 1 vol%. The results include data for 2 grains with 1 sets of PDFs, 17 grains with two sets each and 3 grains with three sets (Table 3) each, and also the data showings the frequency of the angles between the quartz C-axes and the poles to the planes of PDFs in degrees. Figure 4 shows a histogram with orientations of the poles to the planes of PDFs relative to the C-axis of the quartz grains.

The orientation of 45 sets of PDFs was determined in 22 quartz grains from the Exmore breccia. Approximately 35 % of the sets conform with $\omega\{10\bar{1}3\}$ and 10 % to $\pi\{10\bar{1}2\}$ orientations. Most of the remaining sets are oriented parallel to r $\{10\bar{1}1\}$ and $\{21\bar{3}1\}$, and basal the plane is absent. Seventeen grains with 2 sets could be reliably indexed at shock diagnostic orientations. Most abundantly observed PDFs in the Exmore breccia in the quartz grains are one to two sets of planes, which are indicative of moderate degrees of shock. Mainly $\{10\bar{1}3\}$ and $\{10\bar{1}2\}$ are the dominant orientation, which provide conclusive evidence that the rocks and minerals have undergone shock metamorphism; that is, subjected pressures of 10-25) (Fig 4).

Table 4. Number of quartz grains with a number of sets of PDF planes and orientations from the Chesapeake Bay impact structure, USA.

Set of planes	***Orientations***	***Number of grains***
1 set	$11\bar{2}1$, (0001- $10\bar{1}3$)	2
2 sets	$51\bar{6}1$, $10\bar{1}2$	1
	(0001- $10\bar{1}3$), $10\bar{1}1$	1
	$11\bar{2}2$, $21\bar{3}1$	1
	$10\bar{1}3$, $10\bar{1}3$	2
	$21\bar{3}1$, $21\bar{3}1$	1
	$10\bar{1}3$, ($10\bar{1}2$- $11\bar{2}2$)	4
	$10\bar{1}3$, $10\bar{1}1$	2
	$11\bar{2}1$, $22\bar{4}1$	1
	(0001-$10\bar{1}3$)	1
	$10\bar{1}3$, $10\bar{1}2$	1
	$10\bar{1}3$, $11\bar{2}2$	1
	$10\bar{1}3$, $11\bar{2}1$	1
3 sets	$21\bar{3}1$, $10\bar{1}2$, $10\bar{1}3$	
	(0001- $10\bar{1}3$), (0001- $10\bar{1}3$), $10\bar{1}1$	
	$10\bar{1}1$, $11\bar{2}2$, $10\bar{1}3$	

<u>*Note:*</u> (0001-10$\bar{1}$3) means between 0 to 23° and (10$\bar{1}$2- 11$\bar{2}$2), 28° to 48°. From 22 Grains, 14 grains were indexed, i.e., 63.6%.

Shock metamorphism is not a thermodynamically reversible process and most of the structural and phase changes in mineral structures associated with impact are uniquely characteristic of the high pressures (5 to >50 GPa) with extreme strain rates (10^6 to 10^8 s^{-1}) (Koeberl, 1997). These conditions are in sharp contrast to the conditions for endogenic metamorphism of crustal rocks, with maximum temperature of 1,200 ^{0}C and pressures of usually <2 GPa (Fig. 5).

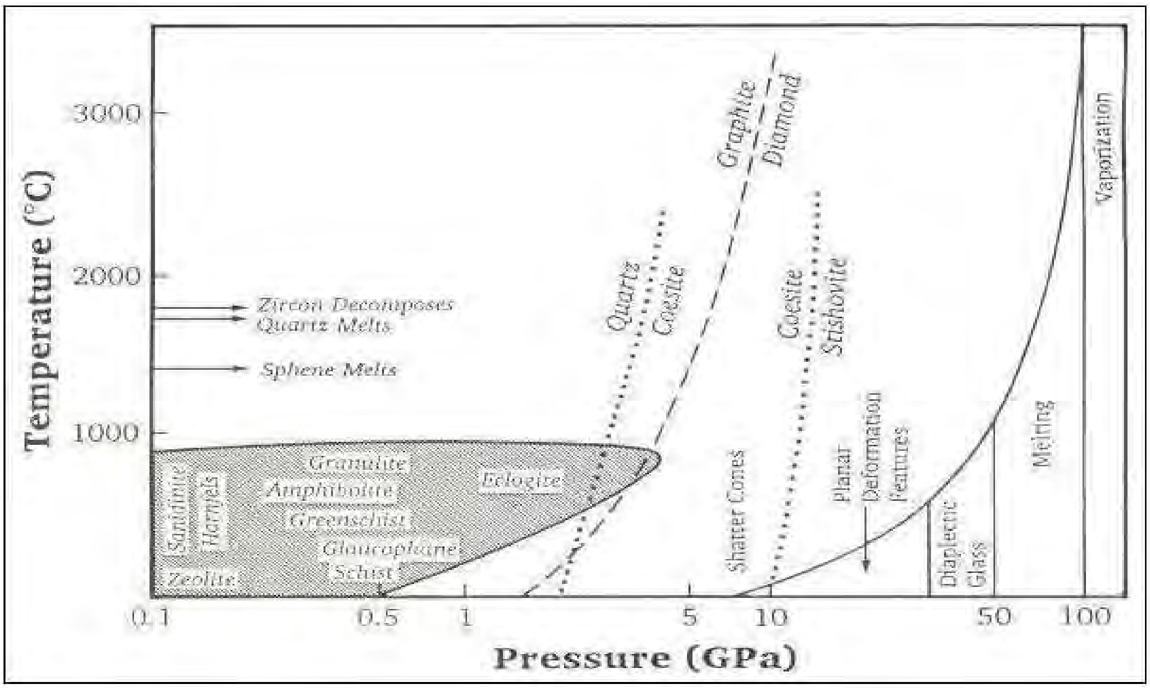

Figure 5. Comparison of pressure-temperature fields of endogenic metamorphism and shock metamorphism. Besides, onset pressures of various irreversible structural changes in the rocks due to shock metamorphism are indicated. The curve on the right side of the diagram shows the relationship between pressures and post-shock temperature for shock metamorphism of granitic rocks. (from Grieve, 1987, Montanari and Koeberl, 2000).

5. CONCLUSIONS

The Chesapeake impact structure is a large complex crater of late Eocene age and 85 km diameter, which is hidden beneath the shallow waters of the coastal plain sediments. It is the largest impact crater currently known in the USA. For petrographic analysis of the Exmore breccia, samples were mainly collected from drill cores from the Exmore core and from three other shallow cores. The Exmore breccia contains angular clasts of older sedimentary material and minor granitic to metamorphic basement rocks. Shock clasts are very rare and most of the shock effects include shock fracturing in quartz, PDFs in both quartz and feldspar, and rare impact melt and glass fragments. Shock effects were recognized only in crystalline rock fragments or clasts, but not in sedimentary material. Evidence for shock metamorphism comes from Exmore breccia samples from depths of 1210.2 to 1388.2 feet (368.2 and 423.12 m).

The results showed a very small component of shocked material, in the form of shock-deformed quartz, and to an even lesser degree feldspar, and somewhat less abundant altered melt particles, throughout the section. The proper PDFs was found in only 8 samples of Exmore breccia, which were then analyzed for the orientations of the PDFs in quartz grains by a universal stage. In quartz and feldspar, up to three sets of PDFs with shock-characteristic crystallographic orientations were found. The PDFs in shocked quartz were found to occur in intersecting sets of planes corresponding to specific crystallographic orientations with {1013}, {1012}, {1011}, and {2131}. Most abundantly observed shock fractures are shock fracturing indicative of shock pressures <15 GPa and 1-2 sets of PDFs in quartz, which is indicative of moderate degree of shock. However, between 408.89 to 408.94 m depths granite fragment with annealed melt vein and Myrmekite has developed from melting of feldspar.

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