ICDP-USGS Workshop on Deep Drilling in the Central Crater of the Chesapeake Bay Impact Structure, Virginia, USA
September 22-24, 2003
Herndon, Virginia

PROCEEDINGS VOLUME

Lucy E. Edwards, J. Wright Horton, Jr., and Gregory S. Gohn, compilers

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Foreword

This volume contains the proceedings of the "ICDP-USGS Workshop on Deep Drilling in the Central Crater of the Chesapeake Bay Impact Structure, Virginia, USA," which was held September 22-24, 2003, in Herndon, Virginia. This workshop was jointly sponsored by the International Continental Scientific Drilling Program (ICDP) and the U.S. Geological Survey (USGS). The proceedings begin with a brief summary of the workshop followed by the list of participants and a copy of the agenda. This proceedings volume contains two sets of abstracts. The first set of 17 abstracts is based on 29 poster presentations that were displayed at the workshop. The second set of 19 abstracts consists of research proposals that were submitted by members of the scientific community following the workshop. The abstracts are given here as submitted by the authors without further edit, except for the correction of some obvious typographical errors.

Disclaimer

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WORKSHOP SUMMARY.

Gregory S. Gohn[1], J. Wright Horton, Jr.[1], and Lucy E. Edwards[1], [1]U.S. Geological Survey, 926A National Center, Reston, VA 20192, USA (ggohn@usgs.gov).

Introduction. The International Continental Scientific Drilling Program (ICDP) and the U.S. Geological Survey (USGS) sponsored a scientific workshop on "Deep Drilling in the Central Crater of the Chesapeake Bay Impact Structure." The workshop was held September 22-24, 2003, in Herndon, Virginia. The purpose of the workshop was to review the results of previous investigations of the Chesapeake Bay impact structure and to provide a forum for creating scientific and operational plans for deep drilling in the structure's central crater. Over 60 scientists represented 10 countries at the workshop.

The late Eocene Chesapeake Bay impact structure is among the largest and best preserved of the known marine impact craters on Earth. This complex crater lies buried at shallow to moderate depths beneath postimpact Cenozoic sediments of the Virginia Coastal Plain and adjacent Continental Shelf on the U.S. Atlantic continental margin. The diameter of the impact structure typically is cited as about 85 km. Principal subdivisions are a 38-km-wide central crater, which may approximate the location of the impact's transient crater, and a surrounding 24-km-wide annular trough that primarily records late-stage gravitational collapse.

The coreholes and geophysical studies that ultimately led to recognition and characterization of the Chesapeake Bay impact structure began in the late 1980's and continued into the 1990's. Since 2000, the USGS, the Hampton Roads Planning District Commission, the Virginia Department of Environmental Quality, and collaborating institutions have conducted a second phase of multidisciplinary geophysical, corehole, and hydrologic investigations of the impact structure (see summaries in Poag and others, 2004, and Horton and others, in press). Previous investigations have defined the location, size, structure, and inferred origin of the major architectural elements of the Chesapeake Bay impact structure (Powars and Bruce, 1999; Powars, 2000; Poag and others, 2004; Horton and others, in press). Collectively, over 2,000 km of seismic-reflection data have been analyzed (Poag and others, 2004) and 8 new coreholes have been drilled, geophysically logged, and analyzed. However, none of the coreholes were drilled in the central crater.

Workshop Agenda. The workshop began on September 22 with welcoming remarks by Charles G. Groat, Director of the USGS, and P. Patrick Leahy, USGS Associate Director for Geology. The first day of the program featured reviews of previous corehole and geophysical investigations of the Chesapeake Bay impact structure, summaries of the capabilities of the ICDP Support Group and drilling capabilities of DOSECC, Inc. (Drilling, Observation, and Sampling of the Earth's Continental Crust), and discussion of first-order scientific questions that could be addressed by deep drilling in the central crater. The first day concluded with an evening poster session, where voluntary posters by workshop participants and USGS drill cores were examined and discussed.

The second day began with a review of sedimentary, climatic, and tectonic studies of middle Tertiary to Quaternary (postimpact) sediments of the U.S. Mid-Atlantic continental margin. The morning session continued with a lengthy panel and audience discussion of the scientific objectives and experiments, drilling strategy, site selection criteria, funding sources, and logistics of a deep drilling program in the Chesapeake Bay central crater. In the afternoon, participants divided into three working groups: (1) impact processes and products, (2) postimpact geology, and (3) hydrology. The second day concluded with reports from the working groups.

The third day consisted of moderated audience discussions of a variety of issues, including the identification of standing science teams, drilling and logging operations, drill-site and sampling protocols, core storage, and publications.

Identification of Scientific Issues. A significant outcome of the workshop was the identification of scientific goals for the proposed drilling program. The goals were limited to research topics that could be addressed by core drilling in the central crater.

Crater Structure and Morphology

- Determine the crater depth
- Determine the structural character of the cored segment of the central crater

Crater Materials

- Determine target composition and stratigraphy beneath crater
- Determine petrophysical properties of target materials
- Determine target chemistry and mineralogy for comparison with North American tektites
- Search for meteorite component in crater materials to identify projectile type
- Determine isotopic ages for all suitable types of material
- Determine fracture depth and distribution

- Determine the amount and distribution of melt
- Characterize the types of crater breccias and infer their formative processes
- Quantify the volumes of breccia types and melts
- Determine the character of resurge and tsunami sediments
- Determine stratigraphy of the crater fill
- Conduct paleomagnetic studies of shocked rocks and melt
- Document levels and gradients of shock deformation
- Document impact damage in fossils

Borehole Geophysical Studies

- Collect a full suite of borehole geophysical logs for determining petrophysical properties
- Directly measure petrophysical properties of core samples
- Integrate core and log petrophysical data with regional gravity, magnetic, seismic, and electrical conductivity surveys and with numerical models

Impact - Postimpact Transition and Postimpact Events

- Document the impact-produced local biotic crisis and recovery
- Document the physical transition from the high-energy impact environment to the normal shelf environment
- Document the physical stratigraphy, biostratigraphy, and sequence stratigraphy of the postimpact sediments
- Document impact effects on long-term climate
- Determine the postimpact thermal and hydrothermal history and processes

Hydrologic Resources

- Determine the salinity and other chemical attributes of ground water in core samples
- Determine the postimpact hydrogeologic history of the crater area

Modern Deep Biosphere

- Determine the character of deep biota

Workshop participants recommended the creation of standing scientific working groups (science teams) to conduct the analyses of the proposed core and corehole. Seven science teams were defined on the bases of broad research topics and related methodologies: (1) crater materials, (2) regional and borehole geophysics, (3) hydrothermal systems and hydrologic resources, (4) cratering mechanics and modeling, (5) environmental effects of impact and impact-postimpact transition, (6) postimpact sedimentary, climatic, and tectonic history, and (7) deep biosphere.

Deep-drilling Site Selection and Proposal. The workshop participants agreed that a full drilling proposal for the Chesapeake Bay impact structure should be submitted to ICDP in January 2004, and that additional geophysical studies by the USGS were needed to provide adequate site characterization.

Drill-site selection was addressed in several plenary and breakout sessions. These discussions were guided by interpretations of the regional gravity map and the seismic-reflection profiles that cross the central crater. Consideration was given to three general locations characterized by distinctive gravity anomalies. The three locations are (1) the uplifted central peak, (2) the "moat" or deepest part of the central crater that surrounds the central uplift, and (3) the rim of the central crater. Each location addresses a different set of scientific issues with some overlap. After considering the relative merits of each location for addressing the major scientific questions listed above, the "moat" was the consensus first choice for a proposed drill site. The other two locations were consensus scientific choices for a second and (or) third corehole, if possible, to understand the crater.

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LIST OF PARTICIPANTS

Huirong-Anita Ai	(California Institute of Technology)
C.R. "Rick" Berquist	(Virginia Division of Mineral Resources)
John M. Brozena	(Naval Research Laboratory)
T. Scott Bruce	(Virginia Department of Environmental Quality)
Rufus D. Catchings	(USGS-Menlo Park)
Gareth S. Collins	(University of Arizona)
David Crawford	(Sandia National Laboratories)
David L. Daniels	(USGS-Reston)
Alexander Deutsch	(University of Muenster)
Henning Dypvik	(University of Oslo)
Lucy E. Edwards	(USGS-Reston)
Scott R. Emry	(Hampton Roads Planning District Comission)
Robert B. Fraser	(USGS-Reston)
Bevan M. French	(Smithsonian Institution)
Billy P. Glass	(University of Delaware)
Gregory S. Gohn	(USGS-Reston)
Samuel Harvey	(Virginia Polytechnic Institute and State University)
Charles E. Heywood	(USGS-Richmond)
John A. Hole	(Virginia Polytechnic Institute and State University)
J. Wright Horton, Jr.	(USGS-Reston)
David Jutson	(RWE Dea AG-Wietze)
Kunio Kaiho	(Tohoku University)
Thomas Kenkmann	(Humboldt-Universität zu Berlin)
David T. King, Jr.	(Auburn University)
Christian Koeberl	(University of Vienna)
Michael J. Kunk	(USGS-Denver)
Daniel Larsen	(University of Memphis)
Steven M. Lev	(Towson University)
E. Randolph McFarland	(USGS-Richmond)
Susan McGeary	(University of Delaware)
Peter P. McLaughlin	(Delaware Geological Survey)
Sandra Martinka	(U.S. Naval Research Laboratory)
H. Jay Melosh	(University of Arizona)
Kenneth G. Miller	(Rutgers University)
Daniel J. Milton	(USGS-Reston)
Donald H. Monteverde	(Rutgers University)
Roger H. Morin	(USGS-Denver)
Gregory S. Mountain	(Rutgers University)
Dennis L.Nielson	(DOSECC)
Jens Ormö	(Centro de Astrobiologia, INTA/CSIC)
Gordon Osinski	(University of Arizona)
Amanda Palmer-Julson	(Blinn College–Bryan)

Lauri J. Pesonen	(University of Helsinki)
Lucille W. Petruny	(Astra-Terra Research)
Elisabetta Pierazzo	(Planetary Science Institute)
Jeffrey B. Plescia	(USGS-Flagstaff)
C. Wylie Poag	(USGS-Woods Hole)
Jason P. Pope	(USGS-Richmond)
David S. Powars	(USGS-Reston)
Donald G. Queen	(USGS-Reston)
James E. Quick	(USGS-Reston)
Wolf Uwe Reimold	(University of Witwatersrand)
David P. Russ	(USGS-Reston)
Ward E. Sanford	(USGS-Reston)
Jean M. Self-Trail	(USGS-Reston)
Anjana K. Shah	(U.S. Naval Research Laboratory)
Jan Smit	(Vrije Universiteit-Amsterdam)
Peter J. Sugarman	(New Jersey Geological Survey)
Ryuji Tada	(University of Tokyo)
Donald M. Thomas	(University of Hawai'i / DOSECC)
David A. Vanko	(Towson University)
Suzanne D. Weedman	(USGS-Reston)
James Whitehead	(University of New Brunswick)

WORKSHOP PROGRAM WITH LINKS TO POWERPOINT PRESENTATIONS

blue if PowerPoint (R) presentation available

Monday, September 22nd -- Morning

Introduction and Review of Previous Investigations

8:30-8:40	Welcome: Workshop Conveners
8:40-8:50	Opening Remarks Charles Groat (Director, USGS)
8:50-9:00	Opening Remarks Patrick Leahy (Associate Director for Geology, USGS)
9:00-9:15	Meeting Logistics and Agenda Overview Gregory Gohn (USGS)
9:15-9:45	Unresolved Questions about Earth's Marine Impact Craters Jay Melosh (University of Arizona)
9:45-10:15	Review of Marine Seismic-reflection Surveys: Chesapeake Bay Crater Wylie Poag (USGS)
10:15-10:40	BREAK
10:40-11:10	Review of Drilling Programs: Chesapeake Bay Crater David Powars (USGS)
11:10-11:40	Review of Petrography, Geochemistry, and Geochronology: CB Crater Wright Horton (USGS) Christian Koeberl (University of Vienna)
11:40-12:10	Review of Hydrologic Issues and Research: Chesapeake Bay Crater Randy McFarland (USGS)
12:10-1:15	LUNCH

Monday, September 22nd -- Afternoon

Site Characterization: Geophysical Surveys of the Central Crater

1:15-1:45	Gravity and Magnetic Surveys David Daniels (USGS) Anji Shah (U.S. Naval Research Laboratory)
1:45-2:15	On-land Seismic-reflection Surveys Rufus Catchings (USGS)

Operational Issues

2:15-2:45	ICDP Support Group Capabilities Christian Koeberl (ICDP Science Advisory Group)
2:45-3:15	DOSECC Drilling Capabilities Donald Thomas (DOSECC)
3:15-3:40	BREAK

Scientific Issues

3:40-4:00	Drilling at the Chicxulub crater Jan Smit (Vrije Universiteit-Amsterdam)
4:00-5:00	Open Discussion: What are the first-order scientific questions about the inner crater of the Chesapeake Bay impact structure? Will deep drilling provide the answers to these questions? Moderator: Bevan French (Smithsonian Institution)
5:00-5:30	OPEN
5:30-7:30	Poster and Core Examination Session

Tuesday, September 23, 2003

8:30-8:40 Announcements

8:40-9:10 Review of Postimpact Sedimentary, Climatic, and Tectonic History: Kenneth Miller (Rutgers University)

9:10-10:15 *A Scientific Drilling Program for the Central Crater*
Panel and Audience Discussion

Moderator:	James Quick	(USGS)
Panel:	Christian Koeberl	(University of Vienna)
	Jay Melosh	(University of Arizona)
	Kenneth Miller	(Rutgers University)
	Jens Ormö	(Centro de Astrobiología)
Issues:	Scientific objectives	
	Scientific experiments	
	Drilling strategy	
	Site selection	
	Funding	
	Logistics	

10:15-10:45 BREAK

10:45-11:45 Continue Panel and Audience Discussion

11:45-12:00 Organize Working Group Sessions

12:00-1:15 LUNCH

Scientific Working Groups

1:15-3:00 Working Group Sessions

3:00-3:30 BREAK

3:30-4:45 Reports from Working Groups

4:45-5:00 Announcements
Review Wednesday Agenda

Wednesday, September 24, 2003

Discussion Topics

8:30-8:40	Announcements
8:40-10:15	Identification of Science Teams Drilling and Logging - Operational Issues and Strategies
10:15-10:45	BREAK
10:45-12:00	Core Storage Publication Policy Drill-site Protocols Open Discussion
12:00	Adjourned

Committees, ICDP Chesapeake Bay Impact Crater Workshop

Convenors:	Gregory S. Gohn	(USGS-Reston)
	Kenneth G. Miller	(Rutgers University)
	James E. Quick	(USGS-Reston)
Steering Committee:	Alan R. Hildebrand	(University of Calgary)
	Christian Koeberl	(University of Vienna)
	H. Jay Melosh	(University of Arizona)
	Gregory S. Mountain	(Rutgers University)
	C. Wylie Poag	(USGS-Woods Hole)
	Wolf Uwe Reimold	(University of Witwatersrand)
Organizing Committee:	Lucy E. Edwards	(USGS-Reston)
	J. Christine Flynt	(USGS-Reston)
	Gregory S. Gohn	(USGS-Reston)
	J. Wright Horton, Jr.	(USGS-Reston)
	Donna M. Johnstone	(USGS-Reston)
	Colleen T. McCartan	(USGS-Reston)
	Loretta Morris	(USGS-Reston)
	David S. Powars	(USGS-Reston)
	Ellen L. Seefelt	(USGS-Reston)
	Jean M. Self-Trail	(USGS-Reston)

POSTER SESSION

Titles in blue have links to poster abstracts. Titles in black are by title only.

HYDROCODE SIMULATIONS OF THE CHESAPEAKE BAY IMPACT
G. S. Collins and H. J. Melosh

POTENTIAL FIELD GEOPHYSICS OF THE CHESAPEAKE BAY IMPACT SITE
David L. Daniels, Seth D. Tanner, Wilma B. Aleman Gonzalez, Colleen T. McCartan, and James B. Murray

THREE THINGS TO KNOW ABOUT DAMAGED DINOCYSTS, CHESAPEAKE BAY IMPACT STRUCTURE, VIRGINIA
Lucy E. Edwards

STRATIGRAPHIC PALEONTOLOGY OF THE CRATER-FILL DEPOSITS, LANGLEY CORE, CHESAPEAKE BAY IMPACT STRUCTURE, VIRGINIA
Lucy E. Edwards, Norman O. Frederiksen, and Jean M. Self-Trail

CHESAPEAKE BAY IMPACT STRUCTURE - 35 MILLION YEARS AFTER - AND STILL MAKING AN "IMPACT."
Scott R. Emry and Brian Miller

DISTAL IMPACT EJECTA FROM THE CHESAPEAKE BAY IMPACT CRATER.
Billy P. Glass

POSSIBILITY OF OCEAN WATER INVASION INTO THE CHICXULUB CRATER AT THE CRETACEOUS/TERTIARY BOUNDARY
Kazuhisa Goto, Ryuji Tada, Eiichi Tajika, Timothy J. Bralower, Takashi Hasegawa, and Takafumi Matsui

INFLUENCE OF THE CHESAPEAKE BAY IMPACT STRUCTURE ON GROUND-WATER FLOW AND SALINITY IN THE ATLANTIC COASTAL PLAIN AQUIFER SYSTEM OF VIRGINIA
Charles E. Heywood

PROPOSED SEISMIC IMAGING AND NUMERICAL MODELING OF THE 35 MA IMPACT EVENT AT CHESAPEAKE BAY
John A. Hole, Susan McGeary, H. Jay Melosh, and Susan C. Eriksson

PETROGRAPHY, GEOCHEMISTRY, AND GEOCHRONOLOGY OF CRYSTALLINE BASEMENT AND IMPACT-DERIVED CLASTS FROM COREHOLES IN THE WESTERN ANNULAR TROUGH, CHESAPEAKE BAY IMPACT STRUCTURE, VIRGINIA, USA
J. Wright Horton, Jr., Michael J. Kunk, Charles W. Naeser, Nancy D. Naeser, John N. Aleinikoff, and Glen A. Izett

A REVIEW OF MARINE SEISMIC REFLECTION STUDIES OF THE CHESAPEAKE BAY IMPACT CRATER
C. Wylie Poag

"'WET TARGET"' EFFECTS ON THE SYNIMPACT PARTIAL FILLING AND POSTIMPACT BURIAL OF THE CHESAPEAKE BAY IMPACT CRATER, SOUTHEASTERN VIRGINIA
D.P. Powars, L.E. Edwards, T.S. Bruce, and G.H. Johnson

1:24,000 SCALE VISUALIZATION (?MODEL) OF SEISMIC REFLECTION AND GRAVITY DATA INNER BASIN CHESAPEAKE BAY IMPACT CRATER
D.P. Powars, D.L. Daniels, J.W Horton, Jr., L.E. Edwards, and G.S. Gohn

LANGLEY COREHOLE STRATIGRAPHY AND GEOPHYSICAL LOGS: GUIDE TO SEISMIC INTERPRETATIONS
D.P. Powars, G.S. Gohn, L.E., Edwards, J.W. Horton, Jr., and R.D. Catchings

HYDROTHERMAL RESPONSE TO THE CHESAPEAKE BAY BOLIDE IMPACT
Ward E. Sanford

CALCAREOUS NANNOFOSSIL DISTRIBUTION PATTERNS AND SHOCK-INDUCED
TAPHONOMY IN THE CHESAPEAKE BAY IMPACT CRATER
Jean M. Self-Trail

SHIPBOARD GRAVITY AND MAGNETIC FIELD OVER THE CHESAPEAKE BAY IMPACT CRATER
Anjana K. Shah, John Brozena, and Peter Vogt

THE YAXCOPOIL-1 DRILLING IN THE CHICXULUB CRATER: STRATIGRAPHICAL AND GEOCHEMICAL DATA
J Smit., B. Dressler, S. van der Gaastand, and W. Lustenhouwer

FLUID INCLUSION AND MINERALOGICAL EVIDENCE FOR POST-IMPACT CIRCULATION OF SEAWATER-DERIVED HYDROTHERMAL FLUIDS AT THE CHESAPEAKE BAY IMPACT CRATER: A CRITICAL TEST OF THE PHASE SEPARATION MODEL FOR BRINE GENERATION
David A. Vanko [see proposals]

a laptop simulation was presented by David Crawford

HYDROCODE SIMULATIONS OF THE CHESAPEAKE BAY IMPACT. G. S. Collins and H. J. Melosh, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA. (e-mail: gareth@lpl.arizona.edu).

Introduction. The Chesapeake Bay Impact Crater (CBIC) formed about 35 million years ago, in a shallow marine environment (400-600 m water depth). The crater is complex and developed in a multi-layer, rheologically-variable target that comprised 0.4-1 km of soft, water-saturated sediments overlying crystalline basement (Poag and others, 1994).

Seismic reflection data illustrates that the Chesapeake Bay crater morphology—often described as an "inverted sombrero"—is similar to other marine-target impact craters. It consists of a ~1-1.5-km deep, highly disturbed central crater, surrounded by a shallower, less deformed basin (Poag, 1996). The inner crater has a diameter of ~40 km; the edge of the outer basin extends to ~85-km diameter. The morphological divide between the inner and outer crater is termed the inner ring or peak ring. Little is known about the nature of the inner ring. Seismic reflection data show that the underlying basement is modestly uplifted (Powars and Bruce, 1999); however, it is unclear whether the pristine surface expression of the inner ring was elevated above the floor of the outer crater.

The characteristic structure of CBIC and other marine impact craters raises a fundamental question: what is the size of the crater? In other words, which (if either) of the two concentric crater rings relates to the initial cavity (transient crater) formed during the impact process. Answering this question is critical for any assessment of the environmental consequences of the Chesapeake Bay impact, because impact energy can only be reliably estimated from the size of the transient crater.

Three possible models for the formation of the CBIC are proposed (Poag, 1996; Kenkmann, 2003; Hole and others, 2003); each of these implies drastically different impact energies. The first supposes that the inner ring is a peak ring, that CBIC is analogous to lunar peak ring craters such as Schrodinger and that the outer crater ring is the final crater rim. The formation of peak rings is currently believed to involve the collapse of a substantial, transient central uplift (Collins and others, 2002). Therefore, this model implies a large (>40-km diameter) transient crater and zone of deformation. The second model supposes that the inner ring represents the uplifted and overturned flap of brecciated target, which forms the temporary rim of the crater prior to collapse. In this model, the outer ring corresponds to the distal limit of deformation induced by accentuated inward collapse of the weak sediments. The diameter of the transient crater in this model is 30-40 km; however, the amount of collapse must be significantly less than in the first model. The third model supposes that the inner ring marks the boundary between heavily- and weakly-fractured basement material. It defines a rheologic boundary between the damaged basement material, which collapses inwards into the inner basin, and the relatively undamaged basement, which remains essentially undeformed during the impact. As with the second model, the outer ring in this scenario is the most distal evidence for deformation in the weaker sediments above the basement. In this model, the transient crater may be only 20-30 km in diameter. Both the second and the third scenarios rely on the sedimentary cover at Chesapeake Bay being significantly weaker than the underlying basement.

Hydrocode Modeling. We performed some preliminary hydrocode simulations to test the plausibility of the proposed formation kinematics of the CBIC. We used the SALEB hydrocode (Ivanov and Deutsch, 1999), which is a multi-material, multi-rheology extension to the SALE hydrocode (Amsden and others, 1980). We approximated the target lithology at the Chesapeake Bay impact site with a weak, upper layer of water saturated sediments 1-1.5 km in thickness, overlying granite basement. We used the ANEOS equation of state for granite and calcite, and typical rock-strength parameters for granite from experimental work (Lunborg, 1968; Stesky and others 1974). These typical strengths were modified by damage, according to a combined shear and tensile failure algorithm (Collins and others, 2003, in press); by temperature, according to thermal softening relations (Ohnaka, 1995); and by high-frequency pressure vibrations, according to the acoustic fluidization model (Ivanov and Kostuchenko, 1997; Melosh and Ivanov, 1999). To simulate the rheologic difference between the weak sediments and the strong basement, we lowered the strength parameters for the sedimentary unit to values around 0.1-10 MPa, with friction coefficients of 0.0 (Bingham fluid) to 0.5. The collapse of the basement rock was controlled primarily by the acoustic fluidization parameters.

Preliminary Results. The most promising kinetmatic model appears to be the third scenario described above, which supposes that the impact produced a ~25 km diameter transient crater. The more energetic scenarios tend to significantly disturb and uplift the basement rocks beneath the outer basin, which is contradictory to seismic evidence (Poag, 1996; Powars and Bruce, 1999). However, many more simulations spanning the available parameter space must be conducted before firm conclusions can be drawn, and the numerical simulation results must be validated with geologic and geophysical observation.

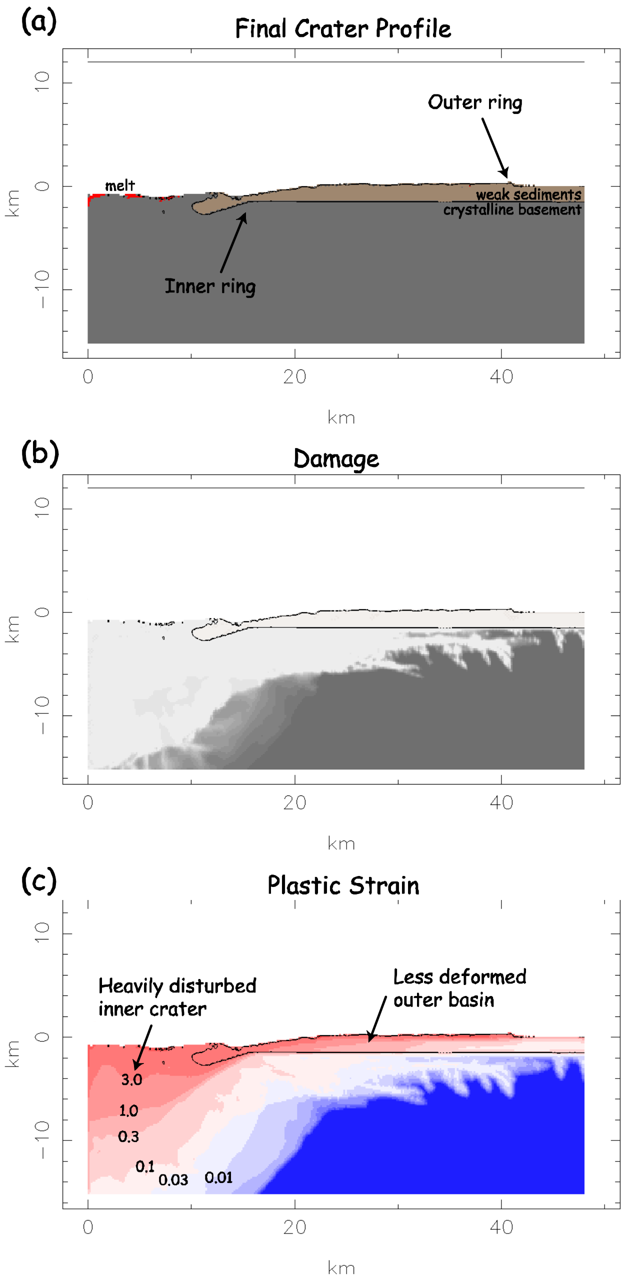

Figure 1: *Final crater cross-section derived from numerical simulations. This simulation tested the third kinematic model described in the text. (a) Final position of the different rock units (red material denotes melt); (b) Damage contours (lighter shading implies more damage); (c) Plastic strain contours (warmer colors imply greater total plastic strain). See text for discussion.*

Figure 1 illustrates the final crater structure from a simulation in which the growing cavity reached a maximum depth of ~6 km and collapse began when the cavity was ~25-km in diameter. The final crater morphology is shallow (<1.5 km). The outermost deformation of significance (see Fig. 1c) defines the outer ring; it is difficult to define surface features from the calculation because of the low resolution used in these preliminary calculations (cell dimension = 150 m). We define the inner ring in this simulation to be the basement material that marks the boundary between the inner, heavily-disturbed crater basin and the outer, less-deformed basin. The basement material within the inner crater is heavily damaged and disturbed; total plastic strains in this region exceed 1 (100 %; total plastic strain is the accumulated plastic strain where the sense of shear is ignored). There is modest uplift of the central crater floor (1-2 km) and a thin melt sheet (<200 m). The only sedimentary material in the inner crater is the collapse deposit, which flanks the inner ring. The sedimentary unit in the outer basin is moderately disturbed (strains >0.1); however, the underlying basement is only weakly deformed (total plastic strain <0.1).

Acknowledgements and References. This work was supported by NASA Grant NAG5-11493.

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POTENTIAL FIELD GEOPHYSICS OF THE CHESAPEAKE BAY IMPACT SITE

David L. Daniels, Seth D. Tanner, Wilma B. Aleman Gonzalez, Colleen T. McCartan, James B. Murray
U.S. Geological Survey, 954 National Center, Reston, VA 20192, USA, (dave@usgs.gov)

Introduction. Potential field data has been used to aid investigations of impact sites around the world (for example, Pilkington and Grieve, 1992; Plescia, 1999). The Chesapeake Bay impact site (Poag, and others, 1999) has a gravity low associated with the inner crater.

Gravity Data. The original gravity data sets for this investigation come from the National Imaging and Mapping Agency (S. Spaunhorst, personal communication, 2001) and the National Oceanic and Atmospheric Administration database (Dater and others, 1999). Data points are mostly on land, collected between 1956 and 1984. The USGS goal was to improve this gravity coverage, mostly in the island area east of the lower Delmarva Peninsula where data points were sparse.

To that end, the USGS team acquired 65 new land gravity stations in the eastern half of the inner crater. Figure 1 shows the gravity anomaly map of the inner crater combining the new and original data. The Bouguer anomaly is used for the land stations corrected to a reduction density of 2.0 gm/cc. The free air anomaly is used for two key surveys that cover Chesapeake Bay and the Atlantic Ocean.

A USGS pontoon boat was used to navigate the very shallow water behind the barrier islands. A conventional v-hull powerboat was used for the surf zone of the barrier islands and the eastern shore of Chesapeake Bay. At low tide, many small beaches with hard-packed sand emerge suitable for placement of a gravity meter. Sand bars and oyster shell bars also emerge at low water to provide additional measurement sites.

In the inner basin part of the gravity map, a 30 km x 35 km gravity low, with significant gradients on three sides, generally coincides with the inner crater rim as interpreted by Powars and Bruce (1999). The missing gradient on the SE edge of the low makes an asymmetric feature and may reflect density distributions existing before the impact. The low may reflect a reduction in density resulting from mixing of the basement impact debris with lower density sedimentary rock debris and seawater. The central area of the low is “lumpy” with four small positive gravity anomalies having 1-2 milligals amplitude. The largest of these occurs at Cape Charles, VA and coincides with the inferred central peak (Poag, and others, 1999).

These anomalies may arise from lateral density variations within a layer or from undulations in a surface separating two layers of differing density.

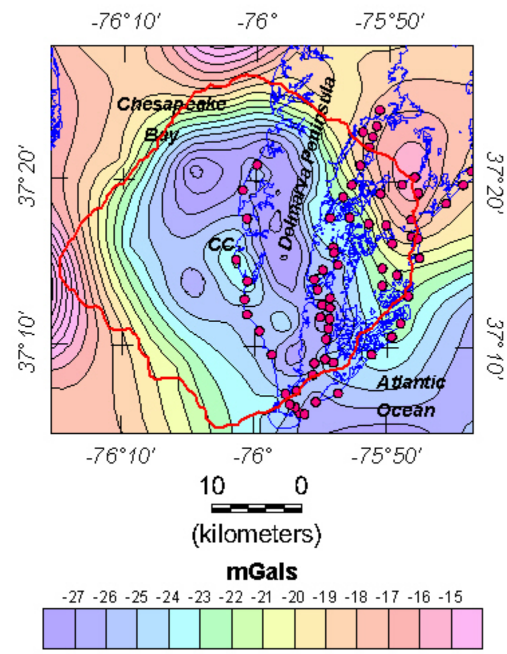

Fig. 1. *Gravity anomaly map of the Inner Chesapeake Bay Crater. Bouguer anomaly is used on land and free air anomaly over water. CC=Cape Charles, VA. Contour interval=1 milligal. Red dots are the new gravity stations; coastline=blue; red line=inner impact crater rim from Powars and Bruce (1999).*

Aeromagnetic Data. In contrast with the gravity data, little correspondence between crater structures and aeromagnetic contours is immediately apparent. This may be, in part, due to lack of resolution of the surveys. The map was constructed from two regional aeromagnetic surveys that nearly cover the lower Chesapeake Bay area. The surveys were flown in 1972 and 1975. Widely spaced flight lines are 3.2 km (2 miles) apart over land and 4.8 km (3 miles) apart over the ocean. The map (Fig. 2) shows the aeromagnetic data in color-shaded relief with an overlay of gravity contour lines. Some magnetic anomalies show a close correspondence with the gravity anomalies; the best example is in the southwest corner of the map, where gravity and magnetic lows result from the subsurface

Portsmouth granite pluton. The northern part of the aeromagnetic map shows distinct northwest trending linear anomalies. Two magnetic anomalies in the southern half of the inner basin also show a hint of northwest trends in general agreement with trends in the gravity contours. This suggests that part of the basement rocks may be intact.

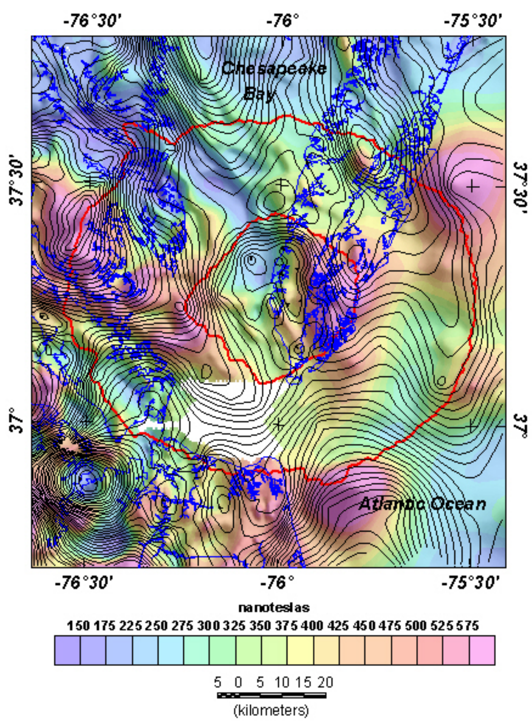

Fig. 2*. Regional aeromagnetic anomaly map of lower Chesapeake Bay. Aeromagnetic data are displayed as color shaded-relief; contour overlay is gravity anomaly. Red line=Impact crater rims; blue=Coastline.*

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THREE THINGS TO KNOW ABOUT DAMAGED DINOCYSTS, CHESAPEAKE BAY IMPACT STRUCTURE, VIRGINIA, USA. Lucy E. Edwards, U.S. Geological Survey, 926A National Center, Reston, VA 20192

Fossil dinoflagellates in impact deposits show impact damage.

Fossil dinoflagellates in impact deposits show a wide variety of kinds of impact-related damage.

Fossil dinoflagellates tell age. Because of the pre-impact shelf setting, age can tell where -- both vertically and laterally -- an individual particle originated.

CHESAPEAKE BAY IMPACT STRUCTURE - 35 MILLION YEARS AFTER - AND STILL MAKING AN "IMPACT." Scott R. Emry, P.G., Regional Senior Geologist; and Brian Miller, Graphics Technician II, Hampton Roads Planning District Commission, 723 Woodlake Drive, Chesapeake, VA 23320, USA (semry@hrpdc.org).

Ground water plays an important role in the economy and quality of life in the Coastal Plain of Virginia. In 2000, the aquifers in the Coastal Plain supplied over 100 million gallons of water per day to the citizens, businesses, and industries in Virginia (DEQ, 2001). Ground water is the primary source of useable water in rural areas of the Coastal Plain and increasingly is being used to support a growing urban population. Ground water levels in the multiple aquifer system are declining due to the increased withdrawals. As a result of the ground water level decline and the potential for saltwater intrusion resulting from the increased uses, the Commonwealth of Virginia created two ground water management areas. These two areas cover more than half of the Coastal Plain Physiographic Province and more than one-third of the state's population.

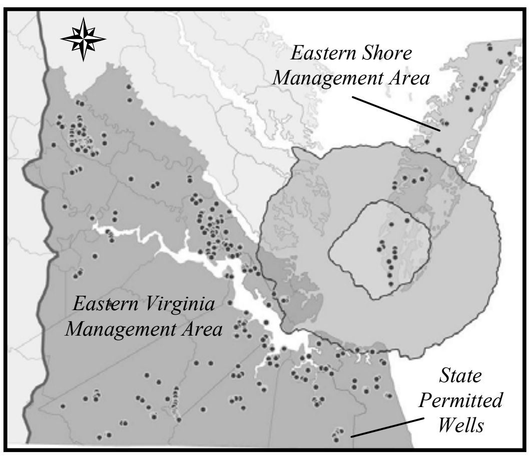

***Fig. 1**. Ground Water Management areas in Virginia and permitted ground water withdrawal locations.*

The Hampton Roads area is situated in the Eastern Virginia Ground Water Management Area. The thirteen public water utilities in Hampton Roads serve approximately 1.6 million people. Due to the relatively low relief of the Coastal Plain Physiographic Province and the increased regulatory obstacles for obtaining a permit to build new reservoirs, the potential for identifying new surface water sources of water to meet the needs of a growing population and expanding economy, the role of ground water resources in sustaining the Hampton Roads area is more critical than ever.

A zone of salty ground water, referred to as the "inland saltwater wedge," is well known to ground water resource planners and scientists, but until recently the phenomenon has not been

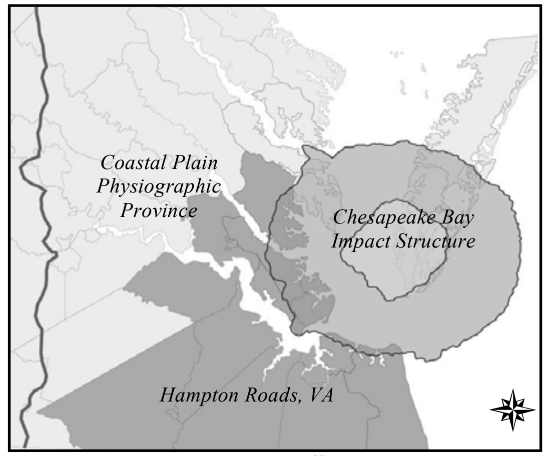

***Fig. 2.**. Hampton Roads, the 31sr largest Metropolitan Service Area in the United States.*

satisfactorily explained (Sanford, 1913; Cederstrom, 1943). In 1996, the Directors of Utilities in Hampton Roads were introduced to the most dramatic geological event that ever took place in the Chesapeake Bay region of Virginia. Geologists for the U.S. Geological Survey (USGS) and the Virginia Department of Environmental Quality (DEQ) provided evidence of a meteor impact that formed a crater over 35 million years ago (Emry, 1999). The contours of the inland saltwater wedge conform well to the shape of the crater's outer rim. Of the five public water utilities in Hampton Roads that currently withdraw and treat brackish ground water, three are located within the "inland saltwater wedge". A new brackish ground water development project within the "wedge" is underway and another project is being proposed.

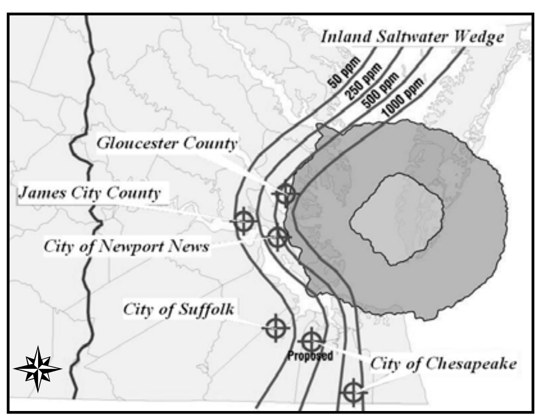

***Fig. 3**. Isocontours of "inland saltwater wedge" and associated municipal brackish ground water systems along crater boundary.*

Prior to the discovery of the impact structure, it was presumed that the ground water flow in the Coastal Plain aquifer system was relatively simple and consistent. The typical description of the aquifer system was "alternating layers of aquifers and confining units gradually dipping and thickening from the west to the east." With the discovery of the impact crater, the rules have changed. Ground water flow can no longer be described in simple terms.

The 1996 briefing led to local government financial support of the USGS research of the impact structure due to implications to the water utilities in Hampton Roads. The cooperative effort became a part of the Hampton Roads Planning District Commission's (HRPDC) comprehensive Regional Water Program. Phase I was entitled *The effects of the Chesapeake Bay Impact Crater on the geologic framework and correlation of hydrogeologic units of the Lower York James Peninsula, Virginia* (Powars and Bruce, 1999). Phase II was entitled *The effects of the Chesapeake Bay impact crater on the geologic framework and the correlation of hydrogeologic units of Southeastern Virginia, south of the James River* (Powars, 2000). Phase III entails study of deep coreholes within the rim of the crater and is scheduled for completion in 2004.

The USGS, HRPDC and DEQ are also working together to replace an aging ground water flow model with a new regional ground water model using the recent knowledge of the Chesapeake Bay Impact Structure's effect on ground water flow. Better modeling tools and a clearer understanding of how the Chesapeake Bay Impact Structure affects ground water movement and quality will assist water resource planners and scientists estimate more accurately the long-term sustainability of the ground water resources of the Coastal Plain aquifer system.

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DISTAL IMPACT EJECTA FROM THE CHESAPEAKE BAY IMPACT CRATER.

Billy P. Glass, Geology Department, University of Delaware, Newark, DE 19716, USA (bglass@udel.edu).

Introduction. North American microtektites have been found on Barbados and in sediment cores from the Gulf of Mexico, Caribbean Sea, and western North Atlantic Ocean (Fig. 1) (e.g., Sanfilippo and others, 1985; Glass and others, 1998). Shocked

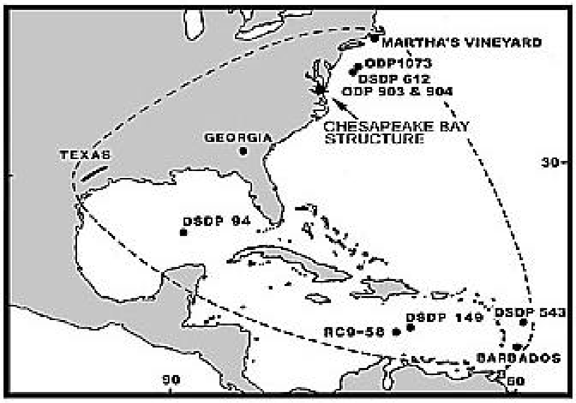

Figure 1. Map of the North American tektite strewn field showing North American tektite locations and sites containing North American microtektites and/or unmelted impact ejecta believed to be from the Chesapeake Bay structure.

quartz and coesite have been found at most of these sites (e.g.,Glass and Wu, 1993; Glass and others, 1998). On Barbados and sites in the Caribbean Sea and Gulf of Mexico there is no discrete layer, but the microtektites and shocked grains are found scattered through 20 cm or more of sediment. At two of the sites off New Jersey there is a discrete ejecta layer of tektite glass and shock metamorphosed grains (Sites 612 and 904). At two other sites the ejecta layer consists of shocked grains, but with no glass (Sites 903 and 1073). At the sites off New Jersey, the ejecta layer contains shocked quartz and feldspar with multiple sets of planar deformation features and large, up to millimeter size grains, containing mixtures of quartz and coesite. Fine-grained ›rock: fragments are also present. They contain mica, coesite, quartz, stishovite, garnet, K-feldspar, and Na-rich feldspar in approximate decreasing order of abundance (Fernandes, 1993). These ›rock: fragments may be shock-lithified sediment (i.e., instant rock).

The ejecta layer at the sites off New Jersey contains a similar suite of heavy minerals including zircon (Glass and others, 1998). Most of the zircons exhibit evidence of shock metamorphism including granular textures, planar features, and X-ray asterism. None were found to have broken down to baddeleyite plus silica, but some of the more heavily shocked zircons have been partially to almost completely converted into a high-pressure $ZrSiO_4$ polymorph with a scheelite-like structure. This phase had earlier been produced in high-pressure laboratory studies by Reid and Ringwood (1969). This is the first time that this phase has been found in naturally-occurring samples. It has been named reidite after Alan F. Reid who first produced this phase in the laboratory (Glass and others, 2002).

The ejecta layer is upper Eocene in age and the tektite fragments have an $^{40}Ar/^{39}Ar$ age of ~35 Ma (Obradovich and others, 1989). These ejecta, including the North American tektites, are believed to be derived from the Chesapeake Bay structure based primarily on geographic location and age (Poag and others, 1994; Koeberl and others, 1996).

Geographic Variations in Ejecta. Assuming that the North American microtektites and associated ejecta are from the Chesapeake Bay impact crater, some general statements can be made about variations in the ejecta with distance from the source crater. As would be expected, the number of microtektites per unit area (or thickness of the ejecta layer) decreases away from the source crater. The percent glass that is in the form of fragments, rather than whole splash forms, increases towards the source crater. The percent glass (microtektites and tektite fragments) increases away from the crater, but there are some exceptions, which may be the result of a ray-like distribution of the glassy portion of the ejecta. Ejecta have been found in four sites NE of the Chesapeake Bay crater: Sites 612, 903, 904, and 1073 (Fig. 1). Site 612 is the closest to the Chesapeake Bay crater. Sites 904 and 903 are ~4 km NW and ~13 km NNW of Site 612, respectively. Site 1073 is ~62 km NNE of Site 612. The ejecta layer is thickest at Site 612 (~8 cm) and thins towards Site 904 (~5 cm) and from Site 904 towards Site 903 (~2 cm). The decrease is due primarily to a decrease in percent glass in the ejecta layer. The thickness of the layer at Site 1073 is not known, but there is not a discrete layer at this site. Like Site 903, there is no glass present. Thus, Sites 612 and 904 may lie along a glass-bearing ray and Sites 903 and 1073 are NW of the ray.

Crater Size. Previous workers have derived equations that relate the thickness of an ejecta blanket to size of, and distance from, the source crater (e.g., Stöffler and others, 1975). These equations can be rearranged and used to calculate the size of the source crater based on the thickness of the ejecta layer and estimated distance from the source crater. This method was used to calculate the size of the source crater for the Ivory Coast microtektite layer assuming that the source crater is located at the Bosumtwi crater site. The size estimated by this method is close to the actual crater size (Glass and Pizzuto, 1994). The thickness of the North American microtektite/ejecta layer and distance from the Chesapeake Bay crater were used to calculate the crater size (Table 1). The estimated crater diameter

Table 1. Estimated Crater Size

SITE	Dist. From CB Crater (km)	Layer Thickness (cm)	Crater Diameter (km)*
612	**322**	**8**	**36**
904	**334**	**5**	**33**
903	**335**	**2**	**27**
94	**1888**	**0.11**	**52**
RC9-58	**2569**	**0.16**	**77**
BARBADOS	**3145**	**0.02**	**50**
			Average 46 ± 18

***Calculated from $t = 0.06\ R\ (r/R)^{-3.3}$ (Stöffler and others, 1975)**

is 46 ± 18 km. This is a little more than half the reported crater size of 85 km (Poag and others, 1994). Thus, the Chesapeake Bay crater may not be the source crater for the North American microtektite/ejecta layer, or the reported crater size is too large, or the equations do not work when the impact occurs in water.

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POSSIBILITY OF OCEAN WATER INVASION INTO THE CHICXULUB CRATER AT THE CRETACEOUS/TERTIARY BOUNDARY. Kazuhisa Goto[1], Ryuji Tada[1], Eiichi Tajika[1], Timothy J. Bralower[2], Takashi Hasegawa[3], Takafumi Matsui[4], [1]Department of Earth and Planetary Sciences, The University of Tokyo (goto@eps.s.u-tokyo.ac.jp); [2]Department of Geosciences, The Pennsylvania State University; [3]Department of Earth Sciences, Kanazawa University; [4]Graduate School of Frontier Sciences, The University of Tokyo.

Introduction. The movement of water rushing into and receding from the Chicxulub crater is considered to have a potential to generate the largest tsunamis caused by the impact at the Cretaceous/Tertiary (K/T) boundary (Matsui and others, 2002). However, no strong evidence for operation of this mechanism has been presented. In this study, samples of the suevite from the YAX-1 site drilled by the Chicxulub Scientific Drilling Program (CSDP), were investigated to test the possibility of the ocean water invasion into the crater and consequent generation of tsunamis immediately after the impact.

Lithology of the YAX-1 core. The YAX-1 core is located approximately 65 km to the south of the center of the Chicxulub crater, on the southern slope the inside the crater. The impactite occurred within the interval between 794.63 m and 894.94 m depth, and is divided into two lithological units; the Impact Melt Breccia Unit (Melt breccia to Polymict melt breccia : 822.86 m to 894.94 m) and the Suevite Unit (Redeposited Suevite to Suevite: 794.63 m to 822.86 m). The Suevite Unit is subdivided into the Lower (Suevite) and Upper (Redeposited Suevite) Subunits based on the grain size of melt fragments.

The Suevite Unit overlies the Impact Melt Breccia Unit with an irregular contact. The Lower Subunit is approximately 15 m thick, poorly-sorted, and shows grain-supported fabric. This subunit is composed of two normally graded beds. This subunit is composed of pebble- to cobble-sized, subangular to rounded, green, black, dark red and brown melt fragments with small amount of limestone, dolostone and basement rock fragments. Large intraclast-like grayish melt fragments of up to 10 cm in diameter occur only in the basal part of this subunit.

Two types of greenish melt fragments are recognized in this subunit: one is vesicular melts, which are common constituent of the underlying impact melt breccia unit, and the other is melt-coated recrystallized calcite, which are similar to the “cored” inclusion type melt that is interpreted as fall-back ejecta (French, 1998). All melt fragments are totally altered and is replaced by clay minerals. Matrix in the suevite is composed of minute carbonate grains, coccolith and partly recrystallized calcite. Poor sorting, grain-supported fabric, and presence of intraclast-like large fragments imply that this subunit is a gravity flow deposit.

The Upper Subunit is approximately 13 m thick, relatively well-sorted, and shows repetition of grain-supported and matrix-supported fabric. Composition of the Upper Subunit is almost the same as of the Lower Subunit but the grain size is much finer (medium sand to pebble size), and the “cored” inclusion type melt becomes abundant. Cross lamination is observed in the uppermost several tens centimeter interval of the Upper Subunit, suggesting the influence of strong current.

Possibility of ocean water invasion. Presence of mono-directional cross lamination in the uppermost part of the Upper Subunit suggests the influence of currents possibly generated by ocean water invasion at least during the deposition of this interval.

Reworked nannofossils of late Campanian to early Maastrichtian age are abundant in the matrix of the Suevite Unit. It is interesting to note that this age range is considerably narrower than the range of the sediments excavated by crater formation. This suggests that nannofossils of late Campanian to early Maastrichtian age were selectively incorporated in the Suevite Unit. Carbonate sediments including late Campanian to early Maastrichtian age deposited in the area of the later crater formation, should have been ejected out and/or vaporized during the crater formation by the impact. Consequently, these reworked nannofossils should have been derived either from the unconsolidated sediments deposited outside the crater or exposed on the rim wall, or the ejecta curtain deposits deposited around the crater.

According to the study of deep-sea impact crater in Sweden, resurge deposit formed by the ocean invasion immediately after the impact was found in the upper part of the impactite (e. g., Ormö & Lindström, 2000). These resurge deposit tends to show the reversed chronology (Ormö & Lindström, 2000). Namely, the lower part of the deposit consists of the sediment with younger age fossils and upper part consists of sediment with older age fossils (Ormö, 1994). In case of the suevite in YAX-1 core, nannofossil assemblage of the major part of the Suevite Unit gives late Campanian to early Maastrichtian age, whereas latest Maastrichtian nannofossil occurs only in the basal part of the Lower Subunit. Consequently, in analogy with the sedimentary process of the resurge deposits in the deep-sea impact crater in Sweden, most probable mechanism Suevite unit deposition is the ocean water invasion.

Sedimentary process of the Upper Subunit. The maximum size of limestone lithics in the Upper Subunit shows oscillatory variation representing repetition of normal grading, whereas the maximum size of greenish vesicular melt fragments shows inverse grading in the lower 3 cycles and normal grading in the upper five cycles. Inverse grading of porous grains such as pumice fragments is formed by the time lag of sedimentation between large and less dense, and small and more dense pumice fragments (Fisher and Schmincke, 1984). Considering the porous nature of greenish vesicular melt fragments in the YAX-1 core that is similar to the pumice grains, formation of inverse grading of greenish vesicular melt fragments in cycles 1 to 3 can be explained by the similar mechanism.

On the other hand, normal grading of greenish vesicular melt fragments in the cycles 4 to 8 could be explained by water infiltration into pores of the large greenish vesicular melt fragments and consequent increase in their bulk densities. The switch from reverse to normal grading of greenish melt fragments between cycles 3 and 4 indicate that water infiltrated into the pores of large greenish melt fragments and increase in their bulk densities enough to settle earlier than small fragments between sedimentation of cycle 3. Oscillations in the bulk chemical composition is also recognized in association with cycles 1 to 8. Oscillations in bulk chemical composition are regarded as representing variation in the ratio of the two components; one is characterized by higher content of Ca and the other is characterized by higher contents of Si, Fe, Ti and Al.

The upward fining character of limestone lithics and upward changes from grain-supported fabric to matrix-supported fabric in each cycle in the Upper Subunit are consistent with the characters of a gravity flow (e. g., Midlleton and Hampton, 1976). Possible trigger was repeated ocean water invasions and/or impact seismic waves, because influence of these processes could have lasted for a few days after the impact and could have enough magnitude to generate gravity flows (Matsui and others, 2002; Boslough and others, 1996). Alternatively, similar lithological features can be formed by reworking of crater-filled sediments by repeated tsunamis.

Conclusion. 1) Presence of cross lamination in the uppermost part of the Suevite Unit suggests the influence of strong current. Abundant occurrence of nannofossils of late Campanian to early Maastrichtian age in the matrix of the Suevite Unit may suggest that the carbonate sediments deposited on the inner rim margin and outside around the crater were eroded and transported into the crater by the ocean water invasion.

2) The maximum grain size of limestone lithics and vesicular melt fragments as well as grain and bulk chemical compositions varied in cyclic manner by more than 8 times in the upper part of the Suevite Unit. The upward fining in grain size and upward changes in fabric from grain-supported to matrix-supported in each cycle are consistent with their gravity flow origin that was triggered either by repeated ocean water invasion or by impact seismic wave. Alternatively, similar lithological features can be formed by reworking of crater-filled sediments by repeated tsunamis.

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PROPOSED SEISMIC IMAGING AND NUMERICAL MODELING OF THE 35 MA IMPACT EVENT AT CHESAPEAKE BAY

John A. Hole[1], Susan McGeary[2], H. Jay Melosh[3], and Susan C. Eriksson[1], [1]Department of Geosciences, MC 0420, Virginia Tech, Blacksburg, VA 24061-0420, USA (hole@vt.edu); [2]Department of Geology, University of Delaware, Newark, DE 19716, USA; [3]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA.

This proposal addresses the important geologic question of how large impact craters are formed through a case study of the 85-km wide Chesapeake Bay, Virginia, impact crater. Fifty years of study of the impact process have failed to produce a predictive, quantitative model of large impact crater formation. A primary reason is the scarcity of subsurface structural and rheologic information – the third dimension. This information is largely unavailable from other planets, and terrestrial impact craters are rapidly changed by erosion, viscous relaxation, metamorphism, and tectonism. Recent work on the K/T-boundary Chicxulub crater in Mexico has shown how deep seismic reflection and seismic velocity images can vastly improve our knowledge of the architecture of a large crater and can prompt improved numerical modeling of the impact process. We propose seismic velocity and reflection imaging of the Chesapeake Bay impact structure and numerical modeling based upon the seismic images. Our primary goal is to investigate the mechanics of and rheologic controls on impact crater formation.

Chesapeake Impact Structure. After Chicxulub, the Chesapeake Bay impact structure is the largest pristinely preserved impact crater on Earth. The impact occurred 35 Ma in what is now the coastal plain of Virginia (Poag and others, 1994; 1999; Poag, 1997). At the time of impact, Late Proterozoic to Paleozoic crystalline rocks at the target site were covered by up to a kilometer of late Jurassic to Eocene unconsolidated, mostly clastic sediments and several hundred meters of seawater. The impact and collapse crater was mostly filled by an impact-triggered tsunami breccia. Subsequent burial in a passive margin setting by up to 500 m of clastic sediment provides excellent preservation. Excellent stratigraphic dating is available for a direct tie to global climate and paleontologic records.

The Chesapeake Bay impact structure has an unusual inverted-sombrero morphology (Poag and others, 1994, 1999). The crater consists of a ~38-km diameter inner crater that disrupts basement inside a ~85-km diameter shallower crater that only disrupts the overlying sediments. The outer crater wall is marked by a slump fault with several hundred meters of relief. The overlying tsunami breccia thickens towards the inner crater to replace the entire pre-impact sedimentary sequence. A strong seismic reflection marking crystalline basement is intact beneath the outer crater, is disrupted upwards at the margins of the inner crater, and is missing within the inner crater. Depth to crystalline rocks (disrupted basement or impact melt) within the inner crater is not well constrained, but is much deeper than surrounding basement.

The unusual crater morphology is presumably due to impact on a layer of weak unconsolidated sediments over a hard crystalline target. This provides an unparalleled opportunity to study the effects of target rheology upon crater formation.

Impact Processes. Impact craters are formed by excavation and subsequent collapse (Melosh, 1989; Melosh and Ivanov, 1999). High-speed bolide impact initially creates a bowl-shaped transient crater by explosive compression and excavation. The transient crater has a diameter:depth ratio of 3:1 to 4:1, and its size is related to impact energy. Subsequent modification by gravity-driven central uplift and marginal collapse creates a broader and shallower crater. The final crater is 1.5 to 2.0 times wider than the transient crater, but much shallower. The target material beneath the crater floor must have been significantly but temporarily weakened to create observed crater collapse structures. Numerical models exist that fairly well explain the hydrodynamics of the compression and excavation stages. However, the collapse stage is more dependent upon target rheology and crater size, and is not as well understood.

We propose three hypotheses to explain the inverted-sombrero morphology of the Chesapeake Bay impact structure. In Hypothesis A, the 38-km wide inner (crystalline) crater represents the transient (explosive) crater and the full 85-km crater is the resulting collapse structure. This implies that the unconsolidated sediments are similar in strength during collapse to the impact-disrupted crystalline basement. In Hypothesis C, the transient crater is much smaller (~20 km) and the inner crater is the collapse crater. The larger outer crater was created by tsunami scour, not collapse of the transient crater. This implies that the sediment is much weaker than the impact-disrupted crystalline basement and plays little role in crater formation. Hypothesis B lies between the above end-members, where the transient crater was 25-32 km wide and both inner and outer crater were created by collapse.

Differentiation between these models requires improved knowledge of the deep structure of the crater, and in particular of the inner, which is poorly constrained at this time. Subsequent numerical modeling can determine the relative contributions of unconsolidated sediments and impact-disrupted crystalline rocks on the collapse process, thus quantifying the rheology of impact collapse.

ICDP Drilling. A team led by Greg Gohn (U. S. Geological Survey, Reston) is currently preparing a proposal to the International Continental Drilling Program (ICDP) to drill a deep borehole into the inner crater at Chesapeake Bay. This follows from a decade of USGS-led studies of the crater, including several recent holes drilled into the crater margin (Powers and Gohn, 2003). The primary goal of the ICDP proposal will be to understand the processes and products of a marine impact through direct sampling of the target rocks, melt lens or melt breccia (if any), tsunami breccia containing impact-derived clasts, and overlying stratigraphy.

In September 2003, the USGS hosted an ICDP-funded workshop to develop a full ICDP proposal. One result of the workshop was strong consensus that the proposed drill site must be characterized by seismic imaging prior to drilling. Participants strongly endorsed the concept that such imaging is required to properly site the drill hole and to properly interpret the drilling results in terms of local and regional geology. Currently, the inner crater is poorly mapped, as existing seismic data either did not penetrate to the base of the Cenozoic sediments or were cut off at basement prior to release from industry. For example, first-order information such as the depth to melt and/or target rocks in the inner crater is poorly known. In addition, there are no deep data on land, where the hole will be located.

Proposed Work. We propose an integrated study of the deep structure and rheology of the Chesapeake Bay impact crater. Our primary goal is a better understanding of the impact process. Our second goal is support of the USGS-ICDP drilling effort through site characterization and local and regional geologic context. Our proposal consists of three components: seismic imaging, numerical modeling, and education outreach.

We propose to illuminate the impact crater through seismic reflection and velocity imaging. A deep, but high-frequency, seismic reflection line across a diameter of the crater on land will map structures within and beneath the sediments, focusing on the inner crater. A cross line (or lines) will be acquired at the proposed drill site(s). Coincident seismic refraction lines will map lithology through seismic velocity. Sub-surface models will be derived from integrated reflectivity structure, seismic velocity, gravity, and drilling contraints. The targets are to identify collapse faulting, pervasive fracturing of crystalline rocks, melt production, transient crater size, and large-scale crater morphology such as a peak ring and central peak.

We propose numerical modeling of the impact process, directly incorporating constraints derived from the seismic data. The models will include a layered rheology – water over sediment over crystalline rocks – to reproduce the observed inverted-sombrero morphology. The results will better quantify the rheology of impact-disrupted rocks and will provide new constraints on marine impacts. In addition, the models will quantify the effects on global climate through vaporization of target rocks.

Finally, we propose an education and outreach effort aimed at secondary-school teachers and the local community. Teachers will participate in the field data acquisition and related outreach lectures. Teachers will then partner with graduate students involved in data analysis and interpretation. They will produce exercises that can be used in the classroom. Web pages and a follow-up workshop will disseminate the scientific results and classroom materials.

It is anticipated that this multi-disciplinary investigation of the Chesapeake Bay structure will greatly improve current understanding of the processes involved in marine impacts and in the formation of large impact craters.

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PETROGRAPHY, GEOCHEMISTRY, AND GEOCHRONOLOGY OF CRYSTALLINE BASEMENT AND IMPACT-DERIVED CLASTS FROM COREHOLES IN THE WESTERN ANNULAR TROUGH, CHESAPEAKE BAY IMPACT STRUCTURE, VIRGINIA, USA. J. Wright Horton, Jr.[1], Michael J. Kunk[2], Charles W. Naeser[1], Nancy D. Naeser[1], John N. Aleinikoff[2], and Glen A. Izett[3], [1]U.S. Geological Survey, 926A National Center, Reston, VA 20192, USA (whorton@usgs.gov); [2]U.S. Geological Survey, MS 963, Denver Federal Center, Denver, CO 80225, USA; [3]Dept. of Geology, College of William and Mary and Emeritus, USGS, 3012 East Whittaker Close, Williamsburg, VA 23285, USA.

Introduction. The Chesapeake Bay impact structure in the Atlantic Coastal Plain of Virginia is an upper Eocene complex crater formed in a continental-shelf environment. The target materials consisted of seawater (~300 m) underlain by lower Tertiary and Cretaceous, poorly consolidated, water-saturated sediments (400 to >750 m) and crystalline basement rocks. An excavated central crater (30-38 km diameter) is surrounded by a flat-floored annular trough that has an outer margin (80-95 km diameter) of collapsed fault blocks. These features are surrounded by concentric faults and underlie 150-400 m of postimpact sediments (Powars and Bruce, 1999; Powars, 2000; Horton and others, 2003). Impact-disrupted sediments in the annular trough were scoured and covered by seawater-resurge deposits of the Exmore beds (Gohn and others, 2002). Recent drill cores from the western annular trough at Bayside, Va. (728.5 m deep), the USGS-NASA Langley site at Hampton, Va. (635.1 m deep), and North, Va. (435.1 m deep), and a core from the outer rim at Watkins School in Newport News (300.3 m deep), are 8, 19, 24, and 27 km, respectively, outside the central crater. All four cores penetrated the Exmore beds. Only the Bayside and USGS-NASA Langley cores sampled complete postimpact and crater sections that include crystalline basement.

Basement Granites and U-Pb Zircon Dates. Crystalline basement below the sedimentary section has been recovered in the USGS-NASA Langley core from 626.3 m (top) to 635.1 m (total depth) and in the Bayside core from 708.9 m (top) to 728.5 m (total depth). Basement rocks in both cores are pale red, medium-grained monzogranites that are non-foliated and pervasively chloritized (Horton, Aleinikoff, and others, 2002). Chlorite is the principal mafic mineral in the granites, and at Bayside traces of relict biotite remain. The top of the granite in each core is weathered but not saprolitized. Features diagnostic of shock metamorphism were not found in the granites. Preliminary SHRIMP U-Pb zircon ages ($\pm 2\sigma$) for the basement granites indicate Neoproterozoic crystallization (625 ± 11 Ma at Bayside and 612 ± 10 Ma at Langley). These dated granites resemble Neoproterozoic granites of peri-Gondwanan volcanic-arc terranes to the south (Horton, Aleinikoff, and others, 2002). This similarity raises doubts about the Chesapeake Bay suture shown on earlier tectonic maps (Horton and others, 1991, and references therein), and suggests an unmapped suture between the terrane sampled in these cores and Mesoproterozoic Laurentian basement beneath the New Jersey Coastal Plain (Horton, Aleinikoff, and others, 2002).

Shocked Quartz Grains. The Exmore beds consist of mixed Lower Cretaceous to upper Eocene sediment clasts (up to boulder size) and minor crystalline-rock clasts in a matrix of glauconitic, quartz-rich, muddy sand that contains Cretaceous, Paleocene, and Eocene fossils (Edwards and Powars, 2003). Planar deformation features (up to 5 intersecting sets) characteristic of shock metamorphism in quartz occur in rare grains or rock fragments from the Exmore of all four cores, confirming earlier evidence that the Exmore beds are of impact origin (Horton, Aleinikoff, and others, 2002; Horton and others, 2003). The proportion of shocked to unshocked quartz grains in the Exmore matrix is very low, indicating that the shocked grains are diluted by an enormous volume of other sediment (Horton and others, 2003). This proportion is consistent with the character of the Exmore beds as a mixed sedimentary deposit that contains ejecta, although a distinct ejecta blanket is not intact in the cores.

Clasts of Impact-derived Crystalline Rock. Most crystalline-rock clasts in the Exmore beds and underlying sediments are rounded, detrital, and essentially undeformed, but a few have angular shapes and cataclastic fabrics. Shocked quartz is an integral part of the cataclastic fabric in some clasts, indicating that this fabric also was produced by the impact event (Horton, Kunk, and others, 2002; Horton and others, 2003). Crystalline rock fragments interpreted to be ejecta include a variety of felsic to mafic plutonic rocks and felsite (Horton, Kunk, and others, 2002; Horton and others, 2003). In the USGS-NASA Langley core, these fragments consist of a single rock type (felsite) in contrast to more diverse assemblages in other cores, indicating that ejecta were distributed unevenly, perhaps in rays (Horton and others, 2003). Microspherulitic matrix in some felsite clasts is evidence of high-temperature devitrification of either impact melt or older volcanic rock (Horton and others, 2001, 2003). The largest impact-derived rock fragments are in the lower part of the Exmore beds, suggesting that, in some areas, the Exmore is crudely size graded (Horton and others, 2003). Shocked quartz in a felsite clast several meters below the Exmore supports other evidence for fluidization and injection of sediment of the Exmore beds into underlying, impact-disrupted material (Horton and others, 2003).

Rock Chemistry. Preliminary chemical analyses of the Langley core indicate that the granite basement rock is slightly peraluminous, and a felsite clast from the Exmore is peraluminous rhyolite. Trace-element discrimination diagrams indicate a volcanic-arc origin for both rocks. The granite and rhyolite are chemically distinct from North American tektites in trace elements as well as major elements.

Argon Geochronology. Colorless mica in a cataclastic leucogranite clast from the Exmore beds (Bayside core) has $^{40}Ar/^{39}Ar$ age-spectrum data consistent with Neoproterozoic U-Pb ages of the other granites. The age spectrum shows no evidence for Paleozoic metamorphism > about 350°C. Potassium feldspar from that clast and from basement granite (USGS-NASA Langley core) have $^{40}Ar/^{39}Ar$ age spectra indicating temperatures > about 250°C until about 346 Ma and 324 Ma, respectively, and final cooling through feldspar closure (~150°C) at about 255 Ma and 245 Ma, respectively, without discernible impact heating (Horton, Kunk, and others, 2002).

Fission-track Dates and Thermal Modeling. Fission-track dates ($\pm 2\sigma$) of zircon (362 ± 49 Ma and 332 ± 44 Ma at Bayside, 375 ± 44 Ma at Langley) and apatite (239 ± 79 Ma and 198 ± 40 Ma at Bayside, 184 ± 32 Ma at Langley) from the basement granites show no impact-related thermal disturbance (Horton, Kunk, and others, 2002). Modeling of the apatite fission-track data indicates that impact-related heating at Langley, if any, probably did not exceed 100°C (Horton, Aleinikoff, and others, 2002).

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A STRUCTURAL COMPARISON BETWEEN THE CHESAPEAKE BAY IMPACT CRATER, USA, AND THE RIES CRATER, GERMANY: HOW DID THE CENTRAL CRATER BASIN FORM?

T. Kenkmann[1], Institut für Mineralogie, Museum für Naturkunde, Humboldt-Universität zu Berlin, Invalidenstr. 43, D-10115 Berlin, Germany, thomas.kenkmann@rz.hu-berlin.de

Ries and Chesapeake Bay–two inverted sombrero craters. The Chesapeake Bay Impact Crater of 85 km diameter has a shape of an inverted sombrero. A deep and highly disturbed central crater of 35 km diameter which is formed in crystalline basement is surrounded by a shallower annular trough in which unconsolidated sediments have been removed and distorted to a suite of megablocks. The crystalline basement is not strongly deformed in this part of the crater. The inner crater is surrounded by a "peak ring", the outer rim is defined by a 300-1000 m escarpment. The floor of the inner crater basin is about 500-1000 m deeper than the peak ring.

The smaller Ries crater, Germany (28 km diameter) shows many similarities to the Chesapeake Bay crater. At the Ries, the central crater basin has 12 km diameter and is also formed in crystalline basement. The gravity anomaly pattern and the thickness of post impact lake deposits clearly outline the deep central crater basin, which is about 600 m deep, when subtracting the post impact infill and the fallback suevite. This inner crater basin is surrounded by a crystalline inner ring which forms some 50 m hills in the landscape. Between the inner ring and the crater rim there is a shallow annular trough, called the megablock zone.

Kinematic considerations. The inverted sombrero shape is probably a consequence of a sharp rheological competence contrast between the crystalline basement and the unconsolidated, water saturated sedimentary cover. However, the formation of this type of multi-layer crater is insufficiently understood with respect to dynamics and kinematics. A key-question appears to be whether (Scenario A, Fig. 1) the "peak ring" represents the remnant of a large collapsing central uplift that flowed radially outward as a consequence of a gravitational instability and which eventually produces a large central crater basin or whether (Scenario B, Fig.1) the

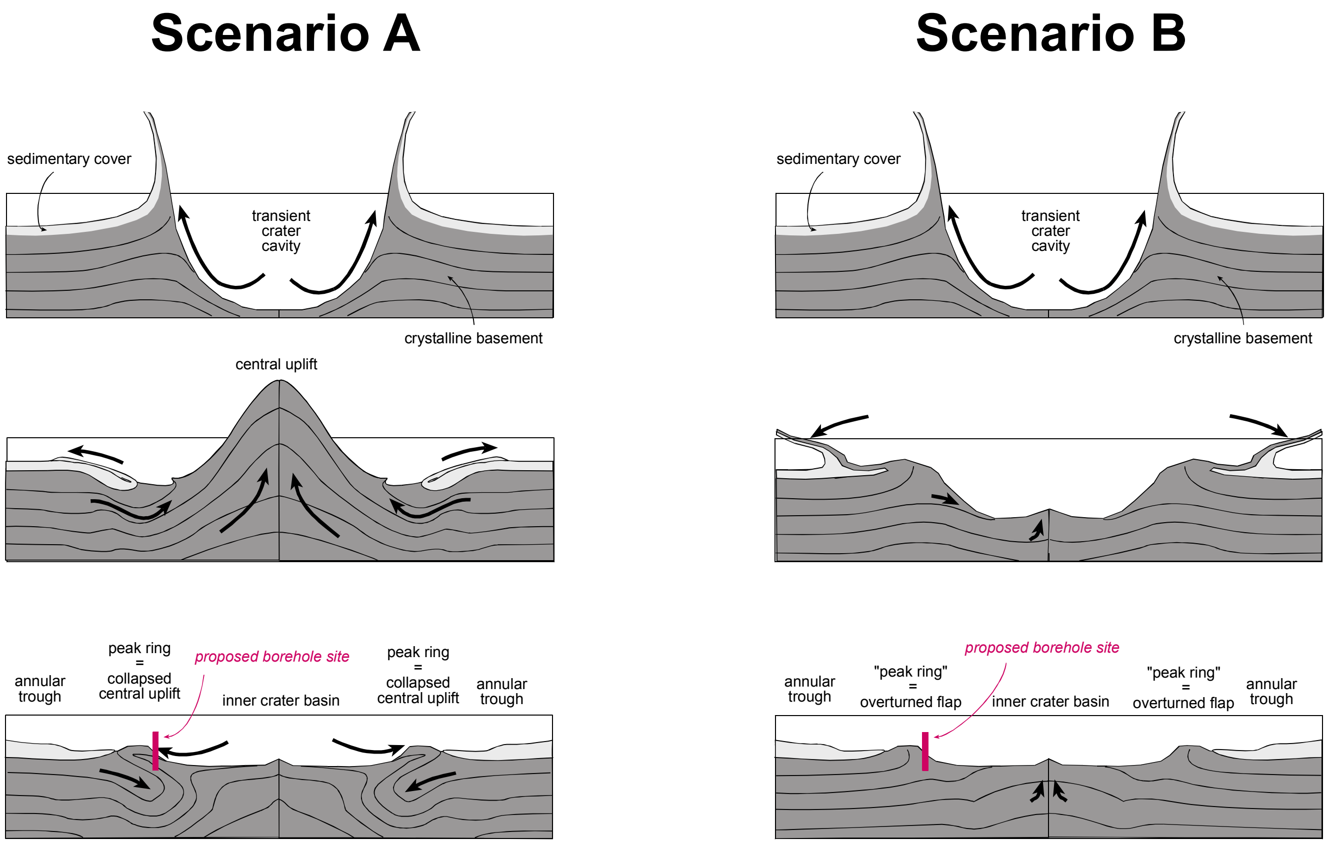

Fig. 1. Sketch showing three potential time steps in the evolution of the crater. The main difference between both models regards the degree of crater floor rebound after the formation of the transient cavity. The sketch is partly based on simulation results of unpublished numerical models by B.A. Ivanov.

transient cavity was only moderately modified and merely produced the small central uplift that is presently documented in the seismic sections. The latter case is in conflict with crater scaling laws. Weak adjustment movements during crater modification are expected for craters near the simple-to-complex transition diameter, that is for crater of 3-5 km diameter. The peak ring in scenario B may be interpreted as the remnant of an overturned flap of the crystalline crater cavity or a step in the crater profile and the inner crater basin represents the moderately modified transient cavity. In this scenario, the unconsolidated sedimentary cover was stripped away from the crystalline basement during crater growth. Due to the different mechanical response, the transient cavity itself may had an inverted sombrero shape instead of the commonly suggested parable-like shape. The solution which of both scenarios is more realistic is of crucial importance to determine energy and size of the impact. In scenario A the crater, in fact, is 85 km in diameter, in scenario B the crater size is about 35 km.

Suggestion for a borehole locality: A borehole located along the rim of the inner crater which is penetrating the "crystalline peak ring" is likely to resolve the questions outlined above. If scenario A (Fig. 1) holds, one should expect heavily deformed crystalline basement of shock stage Ia and Ib recording pressures of up to 25 GPa at the proposed locality. The analysis of shear zone kinematics (oriented drilling is required) would dominantly indicate a shallowly dipping and outward directed flow. In scenario A a decrease in shock metamorphism with increasing depth is suggested. If scenario B holds, the bore hole would probably drill through an overturned flap. This, in turn, would mean that an inverted stratigraphy including relics of the sedimentary cover and a weaker shock metamorphic overprint is found. A bore hole located in the center of the structure near Cape Charles or in the moat is suited to investigate many scientific questions such as the occurrence of a coherent melt rock sheet, a complete section through the tsunami backwash deposits, hydrothermal alteration, etc., but it is not a suited locality to resolve the questions outlined above. A compromise locality along the inner flank of the peak ring/periphery of the central basin (Fig. 1) would probably be able to solve both sets of scientific purposes.

Structure-filling stratigraphy of the marine-target Wetumpka impact structure, Alabama, USA. D. T. King, Jr.[1], L. W. Petruny[2], and T. L. Neathery[3], [1]Department of Geology, Auburn University, Auburn, AL 36849, USA (kingdat@auburn.edu) , [2]Department of Curriculum and Teaching, Auburn University, Auburn, AL 36849, USA and Astra-Terra Research, Auburn, AL 36831-3323, USA, [3]Neathery and Associates, 1212-H Veterans' Parkway, Tuscaloosa, AL 35404, USA.

Introduction. Wetumpka impact structure is a deeply eroded, arcuate, 7.6-km diameter Late Cretaceous feature located within the inner Coastal Plain, Alabama (Fig. 1). This structure was produced by an impact in shallow marine water estimate to have been between 35 and 100 m deep (King and others, 2003). Target stratigraphy included 120 m of unconsolidated Upper Cretaceous sediment (including three formations) and underlying pre-Cretaceous metamorphic crystalline basement rock.

Wetumpka has distinctive exposed, geologic terrains produced by impact-related processes. These exposed terrains include Wetumpka's crystalline rim (**crt**) and two sedimentary terrains: (a) an interior unit (resurge unit, **isu**), and (b) adjacent extra-structure unit (deformed unit, **est**) located outside the rim on the structure's southern side (King and others, 2003; Fig. 2).

Fig. 1. Location of Wetumpka impact crater.

Core drilling. Core drilling near the structure's geographic center revealed that Wetumpka's impact-related fill has two distinctive units: (1) an upper, resurge-deposited unit (~ 100 m thick; same as the "interior unit" above) and (2) a lower, structure-filling breccia unit comprised of fall-back ejecta layers, slumped target-rock blocks, and impact-related sandy breccias and sands (> 130 m thick; same as breccia **b** on Fig. 2; King and others, 2003).

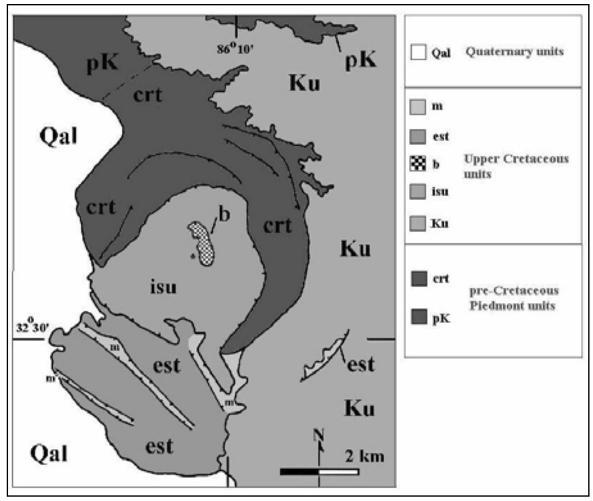

Fig. 2. Geologic map of Wetumpka (from King and others, 2003). Units not noted in text: m = Mooreville Chalk in grabens; pK = pre-Cretaceous metamorphic rocks.

Core drilling, which was accomplished using a truck-mounted drilling rig capable of extracting successive NX cores of ~ 3 m in length at depths of as much as ~ 200 m, took place in July-August 1998. Two boreholes, the Schroeder and Reeves wells, respectively located at N 32° 31.368'; W 086° 10.369' and N 32° 31.303'; W 086° 10.379' (at * on Fig. 2; separation distance = 122 m), penetrated nearly 200 m of weakly consolidated impact-related materials.

Drill-site locations were selected primarily based on two considerations: (1) we wanted proximity to the presumed central region of maximum shock pressure and (2) we needed site availability based on land-owner agreement to access. In addition, we reviewed the limited available geophysical data, a single gravity transect profile that showed considerable relief (10 mGal) within the structure and a central "peak" at the center of the structure. The Schroeder and Reeves drill sites were within a few 100 m of the central "peak" as defined by the gravity profile. A substantial water source was also a practical consideration, and both selected sites were near a lake of size needed for continual water extraction during drilling.

Both drill-site locations were within a few 100 m of a local road-cut outcrop of breccia and were also near exposures of two exotic blocks of target schist, each measuring ~ 10-15 m across. The breccia in outcrop (unit **b**, Fig. 2) was thought to be impact breccia at the time of drilling, and was later confirmed to have shocked quartz in its matrix (Nelson, 2000).

Stratigraphy. As mentioned previously, the upper part of the structure-filling sequence drilled by us is composed of an "interior unit" that is a broken formation or impact mélange. By this, we mean the matrix of the unit is composed of sediments derived from target units mixed together, but blocks and mega-blocks of intact target units are recognizable within the body of the broken formation. This "interior unit" was mapped originally according to the recognizable target mega-blocks within it (Neathery and others, 1976), but has been subsequently recognized as an impact mélange and mapped as a contiguous unit of impact origin (Nelson, 2000).

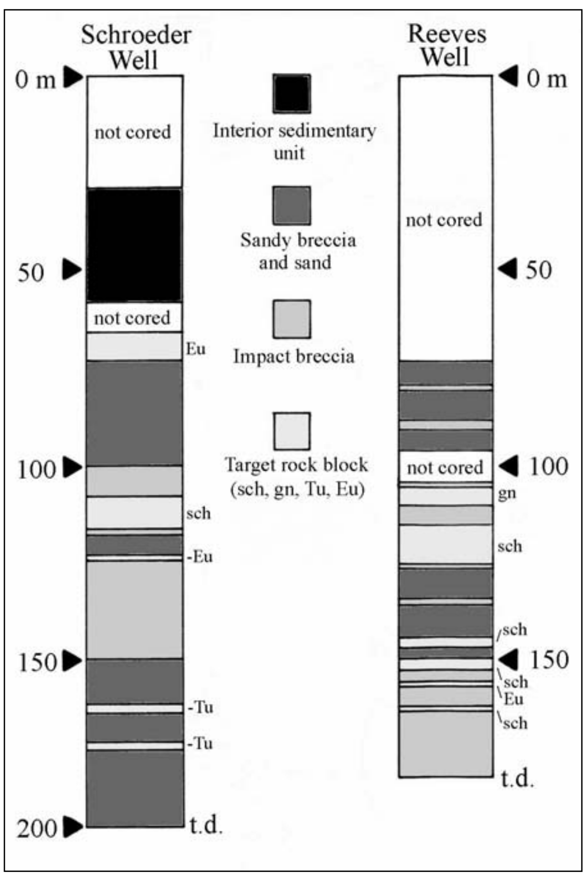

Fig. 3. Stratigraphy drilled at Wetumpka (from King and others, 2003).

Below the "interior unit" (~ 60 m thick), lies an interval, ~ 140 m thick, composed of impact breccia layers intercalated with impactite sands and sandy breccias. This interval also contains target rock blocks up to several m in diamter. The impact breccia is polymict, whereas the impactite sands and sandy breccias are monomict (but clearly of impact origin). Substantial evidence of shocked quartz in the fine matrix of impact breccia was identified from this rock type (see references in King and others, 2003).

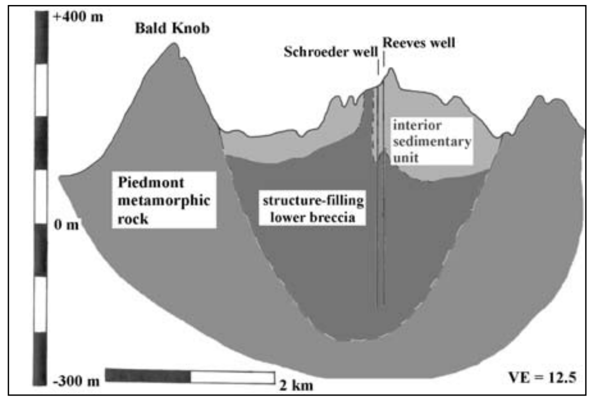

Fig. 4. Inferred cross-section of Wetumpka (from King and others, 2003).

Stratigraphic Analysis. Using a simple statistical technique (upward facies transition analysis; see Selley, 1970), the events in the ideal vertical sequence of impact breccias, impactite sands and sandy breccias, and target rock blocks have been interpreted as (1) fall back of ejecta; (2) slump and related comminution of target-rock blocks (derived from an unstable rim morphology (?); and (3) centrifugal fluid flows within the structure (see King and others, 2003).

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DISTRIBUTION, ORIGIN, AND RESOURCE-MANAGEMENT IMPLICATIONS OF GROUND-WATER SALINITY ALONG THE WESTERN MARGIN OF THE CHESAPEAKE BAY IMPACT STRUCTURE.

E. Randolph McFarland[1] and T. Scott Bruce[2], [1]U.S. Geological Survey, 1730 East Parham Road, Richmond, VA 23228, USA (ermcfarl@usgs.gov), [2]Virginia Department of Environmental Quality, 629 East Main Street, Richmond, VA 23219, USA

Distribution. Stratified unconsolidated sediments that comprise a regionally extensive system of aquifers and confining units across the Coastal Plain of Virginia were severely disrupted within the Chesapeake Bay impact structure and contain salt water approximately 50 km (30 mi) landward of its normally expected position along the coast (Fig. 1).

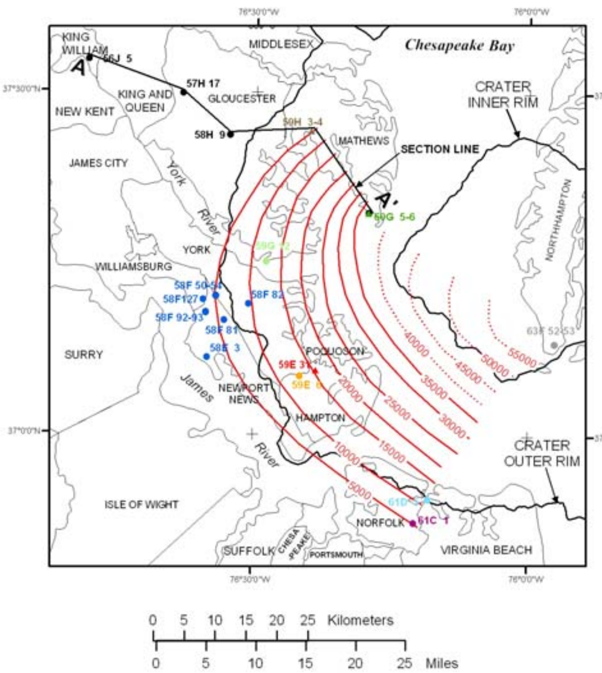

Fig. 1. Locations of sediment-core (triangles) and well (dots) sites along the western margin of the Chesapeake Bay impact structure in the Virginia Coastal Plain. Symbols are color referenced to Figs. 2 and 3. Contours represent specific conductance of ground water in microseimens (µS) near the top of the Exmore beds that fill the crater, and are dotted where approximate.

Origin. The impact structure contains seawater emplaced during regional inundation approximately 2 million years ago, along with much older seawater and evaporative brine emplaced potentially as far back as the impact event 35 million years ago. Bromide-to-chloride ground-water concentration ratios (Fig. 2) largely indicate the source of salinity to be from seawater rather than dissolution of evaporite minerals. (Salinity resulting from membrane filtration is precluded by hydraulic characteristics of the ground-water system.) Enrichment of bromide along with iodide likely resulted from decay of sedimentary organic matter. Some enrichment could also have resulted from evaporation and halite precipitation, possibly associated with hydrothermal activity following the impact event, to form brine which has subsequently been partly re-diluted.

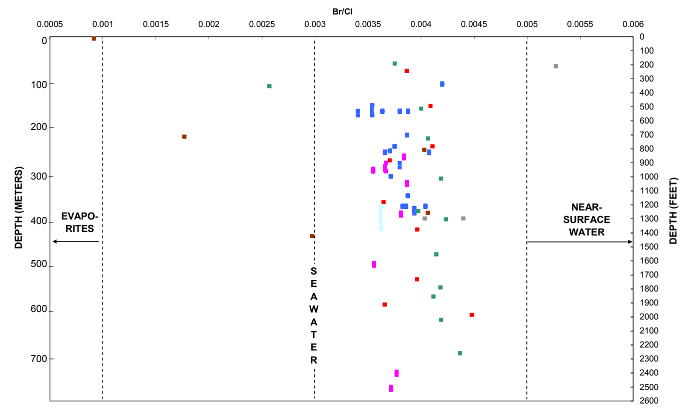

Fig. 2. Relation of the ratios of concentrations of bromide and chloride (Br/Cl) of sediment-core water and well water to depth below land surface. Data points are color referenced to sample locations on Fig. 1.

Ground-water stable hydrogen and oxygen isotopic ratios (Fig. 3) also indicate mixing of fresh water with seawater along a trend of increasing specific conductance approximating the meteoric water line. A second, less steep trend among some of the highest salinity samples possibly results from evaporation. The overall lighter-than-modern isotopic composition indicates the original seawater to predate the Pleistocene epoch of approximately 2 million years ago.

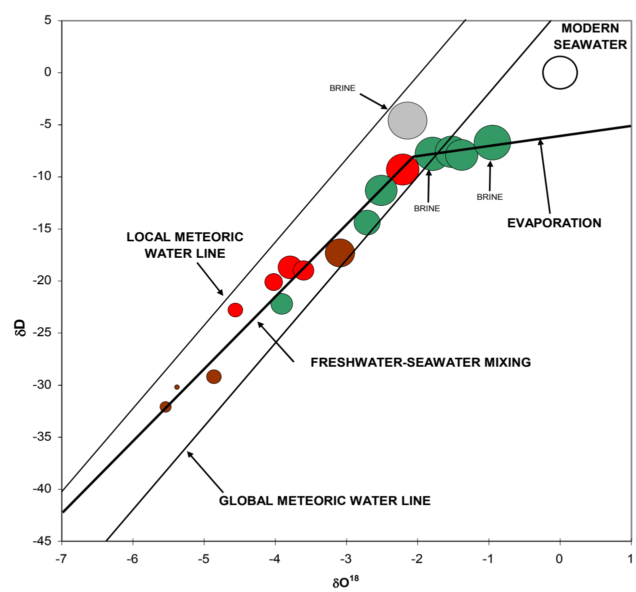

Fig. 3. Relation between hydrogen and oxygen isotopic ratios and specific conductances of sediment-core and well water. Data points are color referenced to sample locations on Fig. 1. Symbol diameter is proportional to specific conductance (modern seawater 45,000 µS).

In addition to the above, carbon 14 concentrations indicate ages of fresh ground water outside of the impact structure as great as 40,000 years. Ratios of chlorine 36 to total chloride in ground water extracted from the USGS-NASA Langley core (59E 31 on Fig. 1) are below the detection limit of 10^{-15} and are consistent with a seawater source. A single value of 12.1x 10^{-15} from well 63F 52, however, suggests a ground-water age toward the center of the impact structure of several million years or more.

With emergence and resumption of ground-water recharge during the past 2 million years, fresh-water flushing displaced residual seawater across the region but was impeded across the impact structure by low-permeability crater-fill sediments and the overlying clayey Chickahominy Formation. Flushing took place laterally along the crater outer rim, followed by upward leakage and surface discharge to areas outside of the crater. Salt water persisted within the impact structure, even as flushing outside of the impact structure extended in places nearly to the edge of the continental shelf during the Pleistocene glacial maximum of 18,000 years ago. Sea level has since risen to its present position, and the residual seawater has merged with the modern ocean. A convoluted and hydrodynamically unstable transition zone along the western margin of the impact structure now separates fresh ground water to the west from salt water to the east (Fig. 4).

Resource-Management Implications. During much of the past century, hydraulic gradients have been greatly increased and flow redirected landward across regional cones of depression centered on industrial pumping centers located outside of the impact structure. Salt-water intrusion across regional distances from the impact structure has not taken place, however, because most of the ground now present was emplaced prior to the onset of heavy pumping. Considering the millennia of fresh-water flushing prior to pumping during which salt water within the impact structure maintained its present position, a potentially very long timeframe could be required for regional salt-water intrusion to occur even under present gradients. By contrast, localized intrusion along the western margin of the impact structure possibly could take place across relatively short distances to municipal withdrawals being made from within the salt-water transition zone. Major increases in withdrawal and desalinization of brackish ground water from the transition zone are being projected to address rapidly growing demands for public supplies during the coming several decades. The feasibility of desalinization is partly dependent, however, on future increases in ground-water salinity that are difficult to estimate because of complex hydrogeologic controls and withdrawal-induced effects within the transition zone. A detailed local-scale characterization of hydrologic conditions along the western margin will be critical to assessment of the potential for salt-water intrusion.

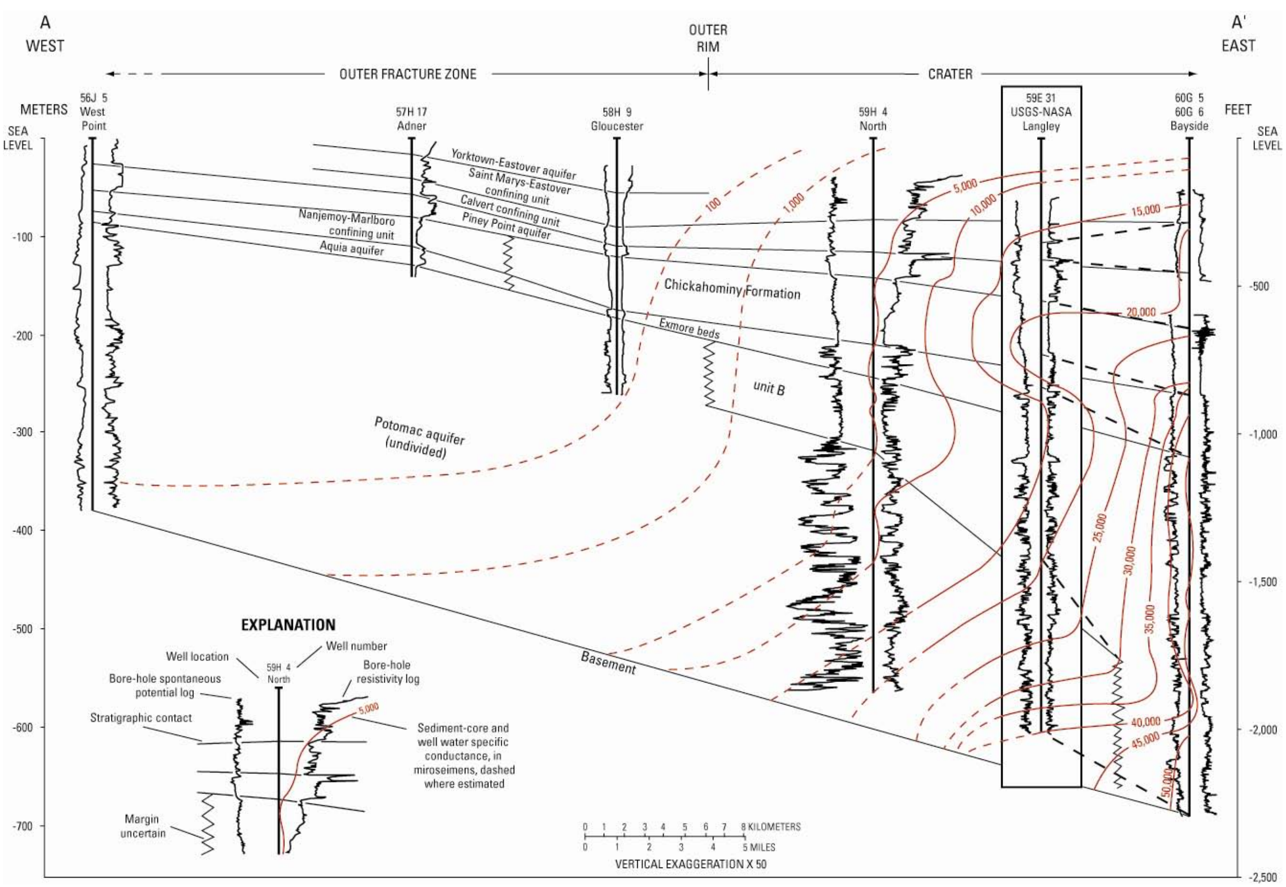

Fig. 4. Simplified preliminary composite section showing the configuration of the salt-water transition zone. Section location is shown on Fig. 1. USGS-NASA Langley core (59E 31) is projected onto section line.

SPATIAL ANALYSIS OF THE HYDROGEOLOGIC FRAMEWORK OF THE VIRGINIA COASTAL PLAIN.

E. Randolph McFarland[1] and Jason P. Pope[1], [1]U.S. Geological Survey, 1730 East Parham Road, Richmond, VA 23228, USA (ermcfarl@usgs.gov)

Introduction. The spatial configurations of 8 confined aquifers and 10 intervening confining units are being delineated across the Virginia Coastal Plain. Geophysical logs and related lithostratigraphic information from a network of several hundred boreholes are being interpreted to estimate the elevations and thicknesses of aquifers and confining units. Borehole data are being used largely from historical site files compiled over a period of several decades, and vary widely in quality. This information is being significantly enhanced, however, by more recent, high quality data obtained from drilling operations associated with the construction of major water-supply wells, and with continuous sediment coring to investigate the Chesapeake Bay impact structure. Published geologic maps also have been drawn on to estimate the elevations of unit surface exposures, and to infer the presence and effects of faults.

Delineation. Different phases have been undertaken beginning with the Northern Neck and Middle Peninsula during 2001, following with the Fall Zone during 2002, and the York-James Peninsula and southeastern Virginia during 2003. Additional refinement is planned during 2004 and beyond, incorporating additional historical information along with new data from on-going drilling operations, to achieve greater spatial resolution of the hydrogeologic-unit configuration. Further refinement in the area of the Chesapeake Bay impact structure is expected to be based on pending results of surface seismic profiling to delineate a complex assemblage of faults that is theorized to encompass the structure margin.

Analyses have been undertaken to synthesize geophysical-log interpretations into a spatially consistent, three-dimensional representation of the confined aquifers and intervening confining units. A series of 13 vertical sections were constructed as part of log interpretation (Fig. 1) to correlate hydrogeologic units across log locations. Hydrogeologic-unit top-surface elevation point data were then used to construct a series of structural-contour maps to represent the configuration of each unit-top surface. The positions of the lateral margins of the units also were estimated.

GIS Analysis. Point-elevation, contour, and margin information were processed using a Geographic Information System (GIS) to generate a series of raster grids representing essentially spatially continuous unit-top surfaces (Fig. 2). Grids initially generated from the contours and other information underwent a series of algebraic operations to further refine the surfaces. Areas of proximity between adjacent surfaces were identified and modified as necessary to ensure that no negative unit thicknesses were generated.

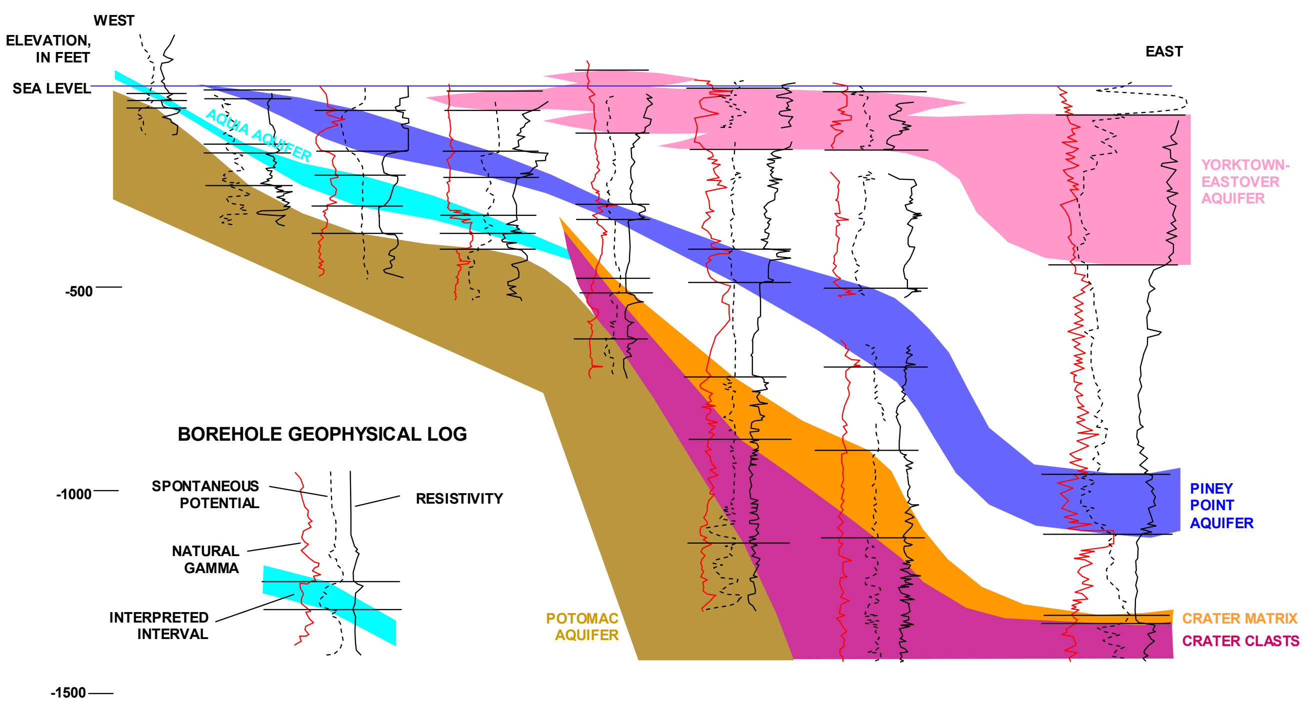

Fig. 1. Hydrogeologic section illustrating correlation of confined aquifers from borehole geophysical logs. Section location approximately across middle of area shown on Fig. 2. Confining units and surficial unconfined aquifer are not shown.

In addition, land-surface digital-elevation model (DEM) data were incorporated to modify unit-top surfaces and margins in proximity to land surface within areas of incision of the units along stream valleys. Unit-top surface elevations were modified where streams have incised only partly through a unit. Where streams have incised entirely through a unit, the margin of the unit was modified. As a result, major stream valleys exhibit a complex array of incised hydrogeologic-unit margins and sequential, valley-wise subcrop belts along which the units are in close hydraulic connection with the overlying unconfined aquifer and surface-water system.

Application. The hydrogeologic framework is being used in conjunction with information on ground-water levels, sediment hydraulic properties, and ground-water withdrawals to support revision of a regional ground-water flow model of the Virginia Coastal Plain. First developed by USGS during the early 1980's under the Regional Aquifer System Analysis (RASA) program, the model has since been adopted by the Virginia Department of Environmental Quality and the Hampton Roads Planning District Commission as a means to manage the ground-water resource. Revision of the model to reflect current understanding of the aquifer system will enable the most viable approach toward evaluating potential regional effects of large and widespread ground-water withdrawals.

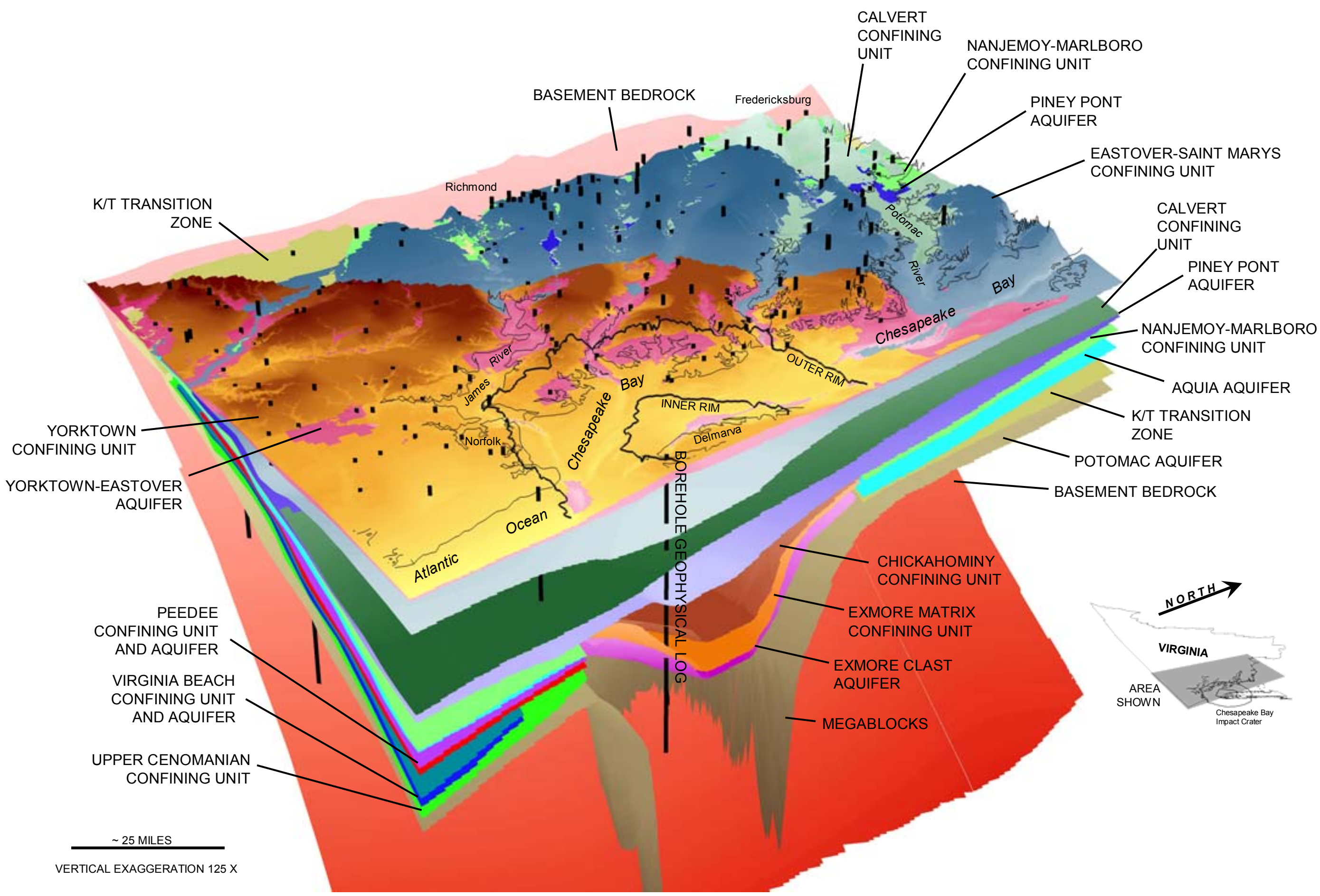

Fig. 2. *Geographic information system (GIS) representation of confined-aquifer and confining-unit top surfaces beneath the surficial unconfined aquifer and channel and bay fill deposits.*

THE INFLUENCE OF A DEEP SHELF SEA ON THE EXCAVATION AND MODIFICATION OF A MARINE-TARGET CRATER, THE LOCKNE CRATER, CENTRAL SWEDEN.. Jens Ormö[1] and Maurits Lindström[2], [1]Centro de Astrobiologia (CAB), Instituto Nacional de Técnica Aeroespacial, Ctra de Torrejón a Ajalvir, km 4, 28850 Torrejón de Ardoz, Madrid, Spain. (ormo@inta.es); [2]Dept. of Geology and Geochemistry Stockholm University 10691 Stockholm, Sweden (maurits.lindstrom@geo.su.se)

Target environment. Comparisons between craters formed at different target water depth and in different strength and configuration of the rocks below the seafloor is a prerequisite for the understanding of the marine impact process. The Lockne crater is a well-preserved and well-exposed example of a crater that was strongly affected by the target water. Geologically well-constrained numerical modeling has shown that the water depth exceeded the impactor diameter: Approximately 800 m water, 600 m impactor diameter (Ormö and others, 2002). Below the water, about 80 m of limestone and loose, bituminous mud rested on the weathered Precambrian crystalline peneplain. Recently, improved outcrop has shown that its ejecta deposits and morphological features are better preserved than hitherto assumed. These new data have improved the interpretation of the formation of the crater.

Crater excavation. The thick layer of target water came to incorporate much of the zones where vaporization and melting normally occur during crater excavation. The difference in strength between the water and the rocks generated a concentric shape of the transient cavity with an at least 14 km wide crater in the water mass, and a 7.5 km wide crater in the basement. A brim with ejected crystalline rock surrounds the crater. There is no obvious uplift of the basement below the ejecta. The brim is about 2.5 km wide on the northern and western sides of the crater, but much smaller on the eastern side. This was previously thought to be due to irregular preservation from erosion, but outcrops exposed by a new forest road extending radially outwards through the eastern brim zone show that the irregularity is due to the obliquity of impact rather than erosion. Shuvalov and others (2003) and Lindström and others (2003) show that the obliquity of impact caused more extensive ejecta downrange (western side) than uprange (eastern side). Interestingly, much of the crystalline ejecta of the brim appear to have been deposited in semi-coherent state as an anomalously wide flap. It rests on top of a surface stripped from much of the sediments by the excavation flow during formation of the water cavity. The target sediments are progressively more complete below the flap outwards from the crater. A combination of weak spallation along the seafloor during passage of the shock wave, the water cavity excavation, and the crushing and shearing during flap deposition have caused a brecciation of the sediments below the flap.

No larger melt bodies have been detected despite intensive studies with drillings, geochemistry (Sturkell and others, 1998), and geophysics (Sturkell and Ormö, 1998). The melt occurs as small fragments incorporated in the upper, arenitic part of the resurge deposit. It is also in this unit that quartz with PDF's has been found so far. The autochthonous breccia within the basement crater, and the coarse clastic ejecta appear to have a remarkably low shock level. This may be due to the circumstance that only a small portion of the basement was within the zone of sufficiently high shock pressures. It is indicated in the models by Shuvalov and others (2003) that most of the basement crater excavation was driven by a high velocity water stream generated by the shock wave propagation through the water. Decimeter-size fragments of granitic ejecta and beds of resurge-affected material with quartz with PDF's are known from up to 45 km from the crater centre (Sturkell and others, 2000).

Crater modification. The water rushing back towards the basement crater during water cavity collapse caused additional strong vibrations and easily eroded the brecciated sediments where they were not protected by the crystalline flap. On the eastern side, where the near absence of a flap gave no protection from the resurge erosion, resurge deposits rest directly on the crystalline peneplain. Preserved Cambro-Ordovician sediments below the small flap near the basement crater rim show that the removal of sediments on this side of the crater most likely was due to the resurge flow rather than the excavation flow. The western side of the crater, on the contrary, has almost no preserved sediments in the same proximal position below the flap. This indicates a stronger excavation flow in this direction prior to flap deposition. The modeling of oblique impact by Shuvalov and others (2003) shows an offset of the water cavity relative to the basement crater supporting the interpretation of a stronger shallow excavation flow downrange. It also shows that a stronger resurge flow can be expected on the uprange side, which appears to correlate well with the indications for a strong erosion, but thin resurge deposits are observed on the eastern side.

The semi-coherent behavior of the ejecta flaps may have caused tangential stresses with resulting wedge-shaped openings in the brim zone. These openings were canalizing the resurge flow so that kilometer long and hundreds of meters wide resurge gullies were formed. There are 4 known resurge gullies at Lockne extending radially out from the crater. The floors of the gullies are covered by resurge deposits and post impact sediments.

Collapse of the basement crater rim during crater modification generated terraces with a few tens of meters width and 5-10 m subsidence. At some locations in the brim zone, ring faults have likewise generated a few tens of meters wide grabens. On the eastern side of the crater, a small graben is filled with resurge breccia. On its sides, resurge arenites rest directly on the Precambrian basement. This may give information on the timing between the faulting and the resurge flow. The relation between the resurge breccia and the resurge arenites may also have been affected by the oscillations in the water movements indicated in the numerical modelings of the water cavity collapse. Evidence for such oscillations are found in repeated beds of coarser and finer resurge deposits on the northern side of the crater.

Summary. Lockne offers the possibility to, in the field, follow the spatial relations between different lithologies. This is valuable in the studies of the influence of water on the crater formation and resurge dynamics at other well-preserved, but less exposed marine-target craters such as Chesapeake Bay crater.

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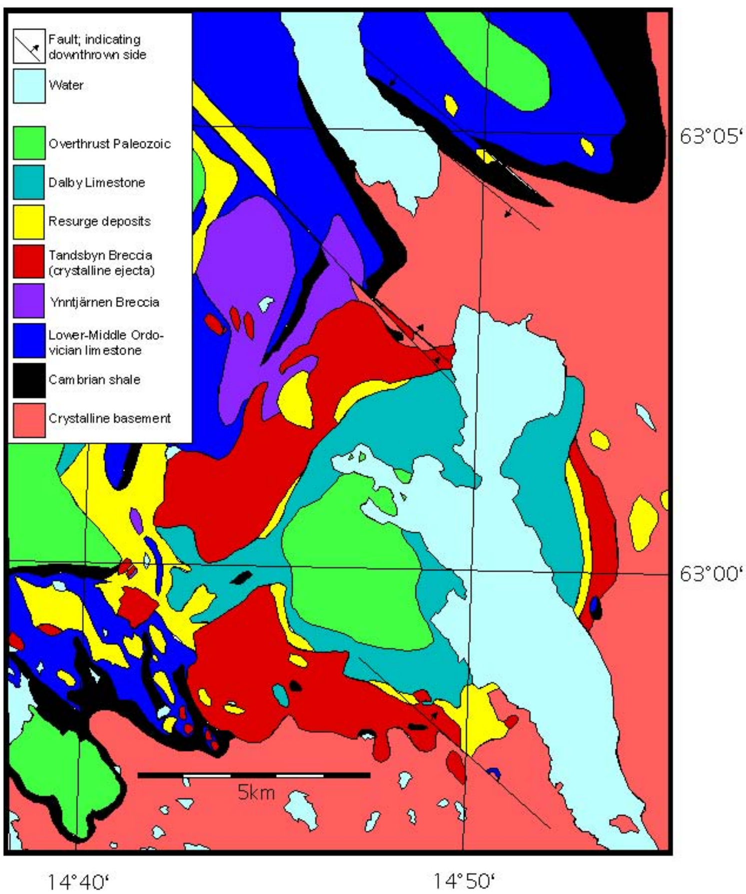

Fig. 1. Geological map of the Lockne crater. Note that the patches of Cambrian shale visible on the south-western flap occur at "windows" through the flap.

A REVIEW OF MARINE SEISMIC REFLECTION STUDIES OF THE CHESAPEAKE BAY IMPACT CRATER. C. Wylie Poag, US Geological Survey, 384 Woods Hole Road, Woods Hole, MA 02543-1598, USA (wpoag@usgs.gov).

Introduction. The structure and morphology of the Chesapeake Bay impact crater are known almost entirely from seismostratigraphic analysis of >2000 km of marine seismic reflection profiles (Poag and others, 1994; 2004). The seismic data base includes multichannel, two-channel, and single-channel data, collected by the US Geological Survey (USGS), the National Geographic Society, the US Minerals Management Service, Lamont-Doherty Earth Observatory, and Texaco, Inc. Depth conversion of two-way traveltime was based primarily on root-mean-square values derived from multichannel data, calibrated with nearby corehole stratigraphy and downhole logging. The principal morphological features identified are the outer rim, annular trough, peak ring, inner basin, and central peak. Important structural and stratigraphic features include faults and compression ridges in the crystalline basement, stratified preimpact nonmarine sediments, displaced sedimentary megablocks, crater-fill breccia, stratified marine postimpact sediments, and postimpact growth faults. All of these features are illustrated in the accompanying PowerPoint files.

Outer Rim. The outer rim is a steep, irregularly circular fault scarp formed by the inward collapse of the sedimentary walls of the crater. The outer rim is clearly expressed on seismic profiles as significant disruption of the horizontal, parallel, discontinuous reflections that normally typify the preimpact sedimentary section. Because the basement surface and preimpact strata slope down to the east, the lip of the outer rim is at -200 m elevation on the west and -400 m on the east. The outer rim averages 85 km in diameter; vertical relief ranges from 300 m on the west side to 1250 m on the east side.

Annular Trough. The annular trough is that part of the crater between the outer rim and the peak ring. The annular trough of the Chesapeake Bay crater varies in width from 15 km to 28 km. The floor of the trough is the surface of crystalline basement, which has been imaged only on the western side of the crater, where multichannel seismic data are available. The trough floor is distinguished by numerous extensional faults and a few compressional faults and ridges. The throw on most faults is 25 m or less, and the compressional ridges are 30 m to 80 m high. If one assumes that each extensional fault with >25 m throw is an individual part of a more extensive fault system, then a pattern of three major radial fault systems emerges in the western part of the annular trough.

Peak Ring. The peak ring of the Chesapeake Bay crater is a raised subcircular ridge of crystalline basement rocks located inside the outer rim. The crest of the peak ring averages 40 km in diameter, and the elevation of its crest varies from -500 m to -950 m. Structural relief is 40-300 m, and width of the ring varies from 4.25 km to 22 km. The eastern side of the peak ring is not imaged by any seismic profiles. The morphology there is extrapolated, using Bouguer gravity data and assuming approximate symmetry with the western side (Poag and others, 2004). The peak ring is quite rugged, and several individual subpeaks and small ridges can be identified on seismic profiles.

Inner Basin. The inner basin is the deepest part of the Chesapeake Bay crater, located inside the peak ring. Its outer wall is indicated on seismic profiles by abrupt truncation of the high-amplitude basement reflection. Approximate diameter of the basin is 28 km. The floor of the basin is not clearly imaged on any seismic profile, but scaling calculations (Grieve and Robertson, 1979) suggest a depth of about 1.3 km from outer rim to inner-basin floor.

Central Peak. The central peak was originally identified on a single-channel profile collected in 1996 at the mouth of Cape Charles Harbor, on the eastern side of Chesapeake Bay (Poag and others, 1999). There, faint diagonal reflections indicate the presence of a poorly defined peak-like feature protruding upward through crater-fill breccia. Subsequent (1998) two-channel surveys and reexamination of several multichannel profiles reveal a series of smaller subpeaks surrounding the main central peak (Poag and others, 2004). The central peak appears to have maximum vertical relief of at least 1 km, and maximum width across the base of 12 km.

Comparison Between Seismic and Gravity Data. Poag and others (2004) found a good match between seismic interpretations of crystalline features of the crater (peak ring, inner basin, and central peak) and residual Bouguer gravity anomalies. A ring of gravity highs distinguishes the peak ring, whereas the inner basin displays a broad gravity low. The central peak also is located over a gravity high. The outer rim, a sedimentary feature, is not distinguished by the gravity data.

Displaced Megablocks. The seismic profiles reveal two types (sedimentary and crystalline) of displaced, km-scale megablocks. The most frequently imaged megablocks consist of sedimentary target rocks that have slumped, slid, and collapsed vertically from the outer crater wall. These megablocks are detached along their bases from the crystalline floor of the annular trough. Some megablocks have rotated and dropped one end as much as 300 m below the other end. These detached sedimentary megablocks appear to be restricted to the annular trough. Downfaulted crystalline megablocks, in contrast, appear to be confined to the walls of the inner basin.

Crater-Fill Breccia. Above the displaced megablocks and inside the inner basin, crater-fill breccia (the Exmore breccia) typically creates a pattern of chaotic, incoherent, or repetitive hyperbolic seismic reflections. The upper surface, however, is manifest as a distinctive, high-amplitude, nearly continuous reflection. The breccia forms a continuous thick blanket over the entire crater. In the annular trough, the breccia is ~200 m thick on the west side of the crater, and ~400 m thick on the east side. The breccia thickens to >1 km in the inner basin, and thins to a feather-edge in a breccia apron (5-50 km across) that encircles the outer rim. The breccia also thins over the principal basement elevations (peak ring, central peak). Due to long-term compaction, the morphology of the upper surface of the breccia mimics the morphology of the basement, but with much subdued relief.

Postimpact Deposits. Most of the postimpact deposits display continuous, horizontal, parallel, medium- to high-amplitude reflections typical of marine sediments. The initial seismically identifiable postimpact deposit is the Chickahominy Formation, a dense marine clay. The impedance contrast at its upper and lower boundaries produces easily recognizable high-amplitude reflections, which can be traced across the entire crater. The Chickahominy interval thickens abruptly at the outer rim and sags into the crater. The sag-and-thicken characteristic allows identification of the outer rim even in parts of the crater where other structural changes are obscured. The Chickahominy Formation also sags and thickens as it crosses from the peak ring or the central peak into the inner basin.

A series of distinct, postimpact normal faults extend from the Chickahominy Formation up as high as the Miocene, Pliocene, and Quaternary sections inside the crater. Some of the faults can be traced to within a few meters of the bay floor. Most of these faults appear to be the result of differential compaction of the underlying breccia.

Future Seismic Surveys. Despite the wealth of seismic data on hand, significant questions remain to be answered by additional seismic reflection surveys. Chief among these is the question of what the basement and outer rim morphology is like under the Delmarva Peninsula and the adjacent continental shelf. It is particularly important to constrain the depth and detailed geometry of these central features in order to choose the optimum location for any future corehole designed to sample the peak ring, inner basin, or central peak.

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HYDROTHERMAL RESPONSE TO THE CHESAPEAKE BAY BOLIDE IMPACT

Ward E. Sanford, U.S. Geological Survey, 431 National Center, Reston, VA 20192, USA (wsanford@usgs.gov)

Introduction. The recently discovered buried impact crater beneath the Chesapeake Bay has been shown to coincide with a previously known inland saltwater wedge (Powars and Bruce, 1999). In addition to an apparently extensive region of near-seawater salinity being co-located with the crater, the only well completed within the inner crater in the tsunami (Exmore) breccia yielded water with a salinity greater than seawater (Cl=23 g/L, McFarland, 2002). Theories to the origin of this water have included osmosis, dissolution of halite, subsequent evaporation in restricted bays during arid climates, and heating during impact (Poag, 1999; Poag and others, 2003). The first three of these theories have been demonstrated to be improbable from other known parameters of the water and sediment (McFarland, 2002). Sanford (2003) argued, based on simple scoping calculations, that the ground water and solutes within the deep inner crater has likely not been flushed out since the time of impact, and the brine may be a residual of hydrothermal boiling that resulted from the heat dissipation that followed the impact. Numerical simulations, which are briefly described here, have been carried out with the USGS code HYDROTHERM (Hayba and Ingebritsen, 1994) to investigate the extent to which a hydrothermal system would have developed in the Exmore breccia following the impact.

Boundary and Initial Conditions. A radial slice of the impact crater extending 40 km out from the center and 8 km downward from the post-impact (mid-Eocene) seawater-sediment interface was considered. Pressure was prescribed at the top boundary to represent 300 m of standing seawater, and temperature was prescribed at 25 °C. The bottom and side boundaries were no-flow conditions. The side boundaries were insulated, and the bottom boundary was assigned a background heat flow of 60 mW/m^2. The inner crater was assumed to be filled with 1.2 km of tsunami breccia and have a central peak rising 500 m from the crater floor.

Initial conditions were assigned to be those estimated from temperature and pressure conditions that would have existed immediately after the crater filled with the Exmore breccia. The initial pressures within the breccia were given a lithostatic gradient to reflect the sudden filling of the crater and lack of ample time for pressures to equilibrate to hydrostatic. The initial temperature of the breccia for the simulation was 25 °C. The initial temperatures for the bedrock were estimated from other high-pressure bolide impact simulations (e.g., Pierazzo and others, 1997) and ranged from background temperatures at 6 km depth up to 1,200 °C at the crater floor. The permeability of the breccia was varied over the ranges estimated from cores and sediment analyses (10^{-14} to 10^{-16} m^2), whereas the permeability of the bedrock was assigned a value significantly lower (10^{-20} m^2). Although extensive fracturing of the bedrock during impact would increase the permeability of the bedrock, subsequent heating and melting would result in healing and closing of fractures in the region beneath the crater floor.

Results. The simulations with HYDROTHERM revealed that an extensive hydrothermal system likely existed in the crater breccia for tens of millennia following the impact. The evolution of this system was controlled predominantly by the permeability of the breccia. The range of permeabilities that were simulated represented two different styles of thermo-pneumatic response of the system. For a breccia permeability of 10^{-16} m^2, fluid cannot escape quickly enough to prevent thermal pressurization from developing. Superlithostatic pressures are the result during early times and would have led to large-scale quick conditions within the breccia and possibly convections cells of sediment-water slurry and/or preferential sinking of large, dense bedrock clasts. Following the dissipation of this high pressure, a super-heated steam-phase develops deep in the breccia but remains relatively distinct from an overlying water phase. For a breccia permeability of 10^{-14} m^2, fluid can move relatively easily and the cooling is characterized by the predominance of hot-water convection cells. For a breccia permeability of 10^{-15} m^2, multiphase convection predominated with the formation of heat pipes (rising steam with descending water) that result in the efficient and rapid cooling of the system.

Certain conditions within the crater could not be simulated using the assumptions currently inherent in HYDROTHERM. First, freshwater conditions are assumed for the phase separation conditions, whereas seawater would have been present in the crater. The presence of dissolved salt in water raises the critical point of water to higher temperatures and pressures (Bischoff and Pitzer, 1989), which would expand the P-T region in the breccia under which multiphase conditions would develop. Second, static permeability conditions are assumed, whereas the permeability of the breccia would have evolved simultaneously with the thermal conditions, responding to changes in pressures and effective stressed that would have changed porosity and permeability over time. Although the hydrothermal conditions under these more realistic conditions would be slightly different, it is believed the current simulations capture the likely features of the hydrothermal system following the impact.

Planned Drilling. In order to test the hydrothermal model of the post-impact conditions, a deep drill hole is currently being planned near the crater center. A 20-cm-diameter hole between 600 and 1000 meters deep has been funded, and drilling is being planned for the spring of 2004 near the town of Cape Charles, Virginia. The plan is to install two 6.35-cm diameter observations wells in the hole--one well near the bottom of the hole and the second well approximately 300 meters above the first one. Water quality samples will be collected from these wells to help determine the extent of the brine within the inner crater, and to look for additional evidence of hydrothermal activity associated with the impact. A variety of environmental isotopes will be analyzed from these samples in addition to dissolved gases and major and minor solute constituents. In-situ permeability tests are being planned for both wells, which will be constructed with 100-ft screens. In addition to drill cuttings being collected over the entire hole depth, a few spot cores are also being planned. Drilling will continue until near refusal, at which point a final core will be taken at the bottom. A wide range of geophysical logs are also being planned for the completed hole. It is possible that the final core may intercept impact lithologies and melt material at the top of the central peak with, but this will depend on the actual depth of the central peak and the difficulty of drilling through the material just above it. Temperature indicators in collected minerals and fluid inclusions should provide information on maximum temperature as a function of depth, which in turn can be used to help constrain future hydrothermal modeling.

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CALCAREOUS NANNOFOSSIL DISTRIBUTION PATTERNS AND SHOCK-INDUCED TAPHONOMY IN THE CHESAPEAKE BAY IMPACT CRATER. Jean M. Self-Trail, U.S. Geological Survey, 926A National Center, Reston, Va 20192 (jstrail@usgs.gov)

The USGS-NASA Langley and Bayside corehole sites are located between the excavated central crater and the slumped outer margin of the western side of the Chesapeake Bay impact crater. Sedimentary samples of both clast and matrix material were collected from the impact-generated Exmore beds and examined for calcareous nannofossil content in these cores. The samples from the Exmore beds contain a mixed assemblage of calcareous nannofossils that range from Santonian to late Eocene in age. The presence of non-reworked *Isthmolithus recurvus* and *Discoaster saipanensis* in both the impact-generated sediments and the post impact Chickahominy Formation constrain the age of impact to approximately 36 Ma using the timescale of Berggren and others (1995).

Matrix. Comparison between depth and the number of Cretaceous versus Tertiary specimens per slide in both cores shows that Cretaceous specimens are common in matrix at the top of the Exmore beds and then rapidly decrease in abundance downcore. They become absent from the Exmore matrix material at ~244.0 m in the Langley core and 310.0 m in the Bayside core. Additionally, the mean size of Cretaceous nannofossils in the Exmore beds decreases downcore at both Bayside and Langley, whereas the mean size of Tertiary calcareous nannofossils remains the same (~4.3µm) throughout. Size sorting of Cretaceous nannofossils in the Exmore beds may indicate the influence of gravity on sediment particles in submarine debris flows that accompanied collapse of the water column and seawater resurge back into the crater immediately following impact.

Clasts. Clast size and composition are contributing factors used to evaluate the amount of contamination by impact-driven allochthonous particles that has occurred in clasts from the Exmore beds. Of 25 clasts examined, 15 were predominantly sandy, 15 were predominantly silty, and the majority (30) consisted of clay. Contamination occurred most commonly in clayey clasts. Comparison of clast width to degree of contamination shows that clast size, not composition, ultimately controlled the contamination. Contamination occurred in all clasts <0.24m in width, regardless of composition. Clasts >0.34m in width were not contaminated, except possibly along rims that were not sampled. Therefore, the forces generated during impact were powerful enough to drive allochthonous particles and microfossils into cohesive sediment clasts of small size, but were unable to penetrate to the center of clasts greater than .30m in diameter.

Fractured Calcareous Nannofossils. Fractured calcareous nannofossils of the genus *Discoaster* are recorded from synimpact sediments within the Chesapeake Bay impact crater (Self-Trail, 2003). Evidence for shock-induced taphonomy includes marginal fracturing of rosette-shaped *Discoaster* species into pentagonal shapes and pressure- and temperature-induced dissolution of ray tips and edges of discoasters. Rotational deformation of individual crystallites may be the mechanism that produces the fracture pattern. Shock wave fractured calcareous nannofossils were recovered from synimpact matrix material in or derived from the Exmore beds. Samples taken from cohesive clasts within the crater rubble show no evidence of shock-induced fracturing. Fracturing of calcareous nannofossils has been recorded from the USGS-NASA Langley core (Self-Trail, 2003), the Bayside core and the Watkins Elementary School core (Self-Trail, unpublished data).

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SHIPBOARD GRAVITY AND MAGNETIC FIELD OVER THE CHESAPEAKE BAY IMPACT CRATER. Anjana K. Shah, John Brozena, and Peter Vogt, Naval Research Laboratory, Marine Physics Branch, Code 7420, 4555 Overlook Ave. SW; Washington, DC 20375, USA (ashah@qur.nrl.navy.mil)

Introduction. We present new shipboard gravity and magnetic field data collected over the Chesapeake Bay Impact Crater. Previous gravity coverage is sparse over the Bay, while magnetic data is limited to older airborne studies with limited navigation and resolution. The new data are used to refine structural characteristics of the crater.

Surveys: Gravity and magnetic field data were collected on board the *R/V Kerhin* during the summer and fall of 2002-2003, yielding maps covering an area of nearly ~800 km^2 over the Chesapeake Bay Impact Crater. USGS workers (e.g. Poag and others, 1994) have previously described the feature as a complex peak-ring crater whose outer edge is marked by the boundary of seismically imaged faults. They also identified an inner ring, within which the crystalline basement was excavated as part of the impact process and later filled with sediment and breccia. The contrast in rock types creates a gravity anomaly low over the excavated region (e.g. Koeberl and others, 1996). *R/V Kerhin* ship tracks were concentrated over the inner ring with track spacing varying from 400 m to 4 km. Previous station data were typically spaced ~9 km apart.

Gravity. The free air anomaly (FAA) over the crater (Fig. 1) shows a low of 12-20 mgal over the inner basin, with sinuous edges following the inner ring. The variation in the gravity anomaly is greatest to the southwest, up to 20 mgal, vs. 12-15 mgal to the northwest and 10-12 mgal to the northeast on the Delmarva peninsula. The gravity contrast to the southwest coincides with larger scale lineations observable in both the gravity and magnetic field, suggesting that this part of the inner rim coincides with orogenic features in the crystalline basement.

The gravity data do not exhibit sharp slopes within the central basin, but instead show a gradual decrease toward the center of the basin over a radial distance of 10-15 km. This gentle slope contrasts the sharper steps observed in seismic reflection data (Poag, 1997; Powars and Bruce, 1999).

Near Cape Charles, the center of the crater, there is a slight increase in the FAA of ~ 4 mgal, suggesting central uplift.

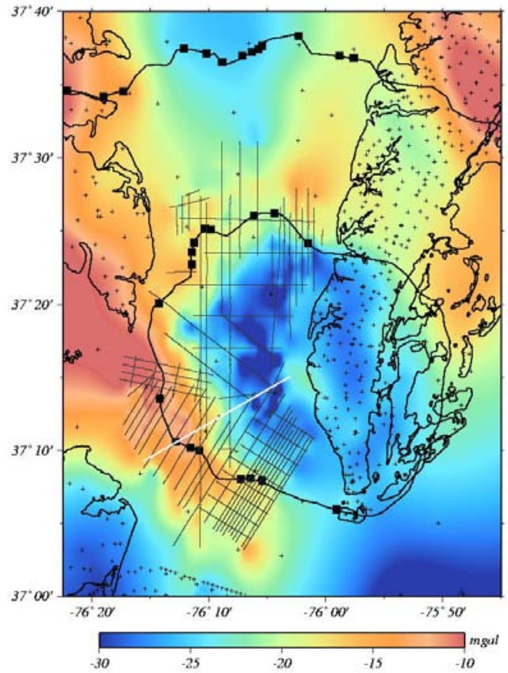

Figure 1. Free Air Anomaly over the Chesapeake Bay Impact Crater. Thin black lines delineate R/V Kerhin shiptracks, crosses mark individual stations (NIMA, USGS). Heavy lines mark the inner and outer rim; squares mark crossings of seismic lines (from Poag and others, 1997). White line extending radially from the town of Cape Charles shows location of modeled profile in Figure 2.

Models. The actual depth to the basement within the inner ring is poorly constrained by currently available data. Seismic lines show rough reflections in some places, but it is difficult to distinguish whether these indicate varying types of breccia or rock which melted during the impact process (Powars and Bruce, 1999; Poag, 1997). The nature of the basement rock is also poorly constrained, allowing only best guesses for density contrasts. We thus consider end-member structure scenarios which are consistent with the observed gravity anomalies.

For example, a 1-km thick layer with density contrast 400 kg/m^3 (assuming the sediments and breccia infill have a bulk density of say ~1900 kg/m^3 and the crystalline basement thus has a bulk density of ~2300 kg/m^3) could produce an ~18 mgal anomaly (Fig 2). Similarly, 2-km thick layer with a density contrast of 200 kg/m^3 could also produce such an anomaly. Such layers, when placed at a depth of 1 km, comparable to the depth to basement outside the inner basin, must have a gradual slope in order to match the observed gravity anomaly. This suggests that either the walls of the inner rim slope gently, or there is a gradual decrease in the density of the basement rock, perhaps due to increases in shock, deformation, brecciation, and/or alteration in the direction of the crater center.

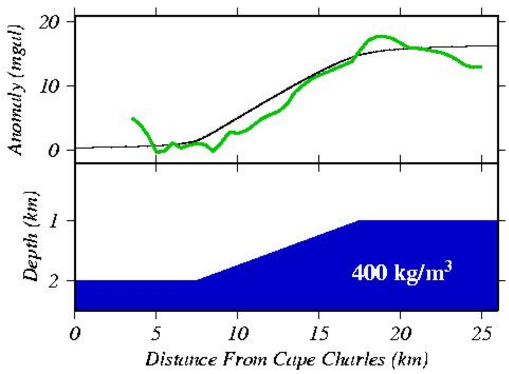

Figure 2. Top: profile of gravity data (green) and model prediction (black) assuming a density contrast of 400 kg/m^3 and the geometry shown below. Bottom: Dimensions and depth of model higher density layer.

The slightly lower gravity slopes to the north can be modeled assuming a 1-km thick layer with density contrast of ~350 kg/m^3, producing a ~14 mgal anomaly. A difference in density of the crystalline rocks to the north could be due to orogenic variation in the basement rock, as larger scale gravity and magnetic field trends suggest. Alternatively, the sedimentary infill layer may be thinner to the north.

The ~4 mgal increase toward the center of the crater can be modeled assuming a 400 kg/m^3 density anomaly reaching a height of ~250 m. Alternatively, the anomaly could be produced assuming 1 km uplift with a density difference of ~95 kg/m^3, a different end-member case of uplifted crystalline rock which is extremely broken, porous, or altered.

Magnetic Field. Shipboard magnetic field data exhibit similar features to previous aeromagnetic data, including a broad 400-nT low over much of the inner basin, surrounded by highly positive anomalies to the east and west. The new data delineate several small (1-2 km wide) patches of 100-nT highs within the inner basin. The low may be due to shock and brecciation reducing the magnetization of the crystalline basement. The smaller highs may indicate large regions of undisturbed basement, or perhaps pockets of impact melt.

Acknowledgments. We are grateful to Captain Rick Younger and Jake Hollinger of the Maryland Geologic Survey and *R/V Kerhin* for their thoughtful and thorough assistance during the surveys. We thank David Daniels of the US Geological Survey for providing gravity station data from NIMA and the USGS. Sandra Martinka of the Naval Research Laboratory (NRL) and David Ball of ITT Industries contributed significantly to the data collection and processing. We also thank Mike Czarnecki, Jim Jarvis, Skip Kovacs, Robert Liang, Clyde Nishimura, Brian Parsons, Barbara Vermillion, and Richard Wilkerson (NRL) for their assistance.

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PROPOSALS FOR FUTURE WORK

Participants were encouraged to submit proposals for future work. The following proposals were received [click on blue name(s) to view proposal]:

RELATING IMPACT DEBRIS IN THE STRATIGRAPHIC RECORD TO THE SOURCE CRATER – THE CHESAPEAKE CASE
A. Deutsch

POSTIMPACT DINOFLAGELLATE AND CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY, LITHOLOGY, SEDIMENTATION ACCUMULATION RATES, AND PATTERNS IN THE FILLING AND REFILLING OF THE CHESAPEAKE BAY IMPACT CRATER
Lucy E. Edwards, David S. Powars, and Jean M. Self-Trail

PALEONTOLOGY OF IMPACT-DERIVED MATERIAL, CHESAPEAKE BAY IMPACT CRATER
Lucy E. Edwards, Jean M. Self-Trail, and U.S. Geological Survey Crater Project team members

THE CHESAPEAKE BAY CRATER CORE – CLAY MINERAL INVESTIGATIONS
Ray E. Ferrell and Henning Dypvik

PROGRESS REPORT AND CONTINUING PROPOSAL FOR COLLABORATIVE RESEARCH ON LITHIC EJECTA, SHOCKED MINERALS, IMPACT MELT, AND CRYSTALLINE BASEMENT IN THE CHESAPEAKE BAY IMPACT STRUCTURE
J. Wright Horton, Jr., Michael J. Kunk, John N. Aleinikoff, Charles W. Naeser, Nancy D. Naeser, and Glen A. Izett

COSMIC IMPACT AND SEQUENCE STRATIGRAPHY
D. T. King, Jr. and L. W. Petruny

IMPACTITE SEQUENCE AND POST-IMPACT ALTERATION/HYDROTHERMAL ACTIVITY: POTENTIAL SCIENTIFIC TARGETS OF AN ICDP BOREHOLE INTO THE CHESAPEAKE BAY IMPACT CRATER
David A. Kring

HOT TIME IN THE CRATER: POST-IMPACT PORE WATERS, HYDROTHERMAL CIRCULATION, AND BIOLOGICAL ACTIVITY IN THE EARLY LATE EOCENE CHESAPEAKE BAY IMPACT CRATER
Dan Larsen and Laura J. Crossey

AN ISOTOPIC AND TRACE ELEMENT INVESTIGATION OF MELT-ROCK AND IMPACT BRECCIA FROM THE CHESAPEAKE BAY IMPACT CRATER TO ESTABLISH THE SOURCE OF THE NORTH AMERICAN TEKTITE STREWN FIELD
Steven M. Lev

CHARACTERIZING THE HYDROGEOLOGIC AND STRUCTURAL PROPERTIES OF AN IMPACT CRATER FROM ANALYSIS OF GEOPHYSICAL LOGS – THE CHESAPEAKE BAY DEEP COREHOLE
Roger H. Morin

PROPOSAL FOR A COMPARATIVE STUDY OF EARLY CRATER MODIFICATION, INCLUDING WATER RESURGE AND HYDROTHERMAL ACTIVITY IN A LARGE MARINE-TARGET IMPACT CRATER, CHESAPEAKE BAY, USA
Jens Ormö, Fernando Ayllón Quevedo, Maurits Lindström, Erik Sturkell, Enrique Díaz Martínez, Jesús Martínez Frías, David S. Powars, and J. Wright Horton, Jr.

PRE- AND POST-IMPACT PALEOCEANOGRAPHIC CONDITIONS ON THE EOCENE MIDATLANTIC CONTINENTAL MARGIN: EVIDENCE FROM RADIOLARIANS
Amanda Palmer-Julson

PHYSICAL PROPERTIES AND PALAEOMAGNETISM OF THE DEEP DRILL CORE FROM THE CHESAPEAKE BAY IMPACT STRUCTURE - A RESEARCH PROPOSAL
Lauri J. Pesonen, Tiiu Elbra, Martti Lehtinen, Johanna M. Salminen and Fabio Donadini

A PROPOSAL TO COLLECT TENSOR MAGNETO-TELLURIC SOUNDINGS ACROSS THE CENTRAL CRATER OF THE CHESAPEAKE BAY IMPACT STRUCTURE
Herbert A. Pierce

A PROPOSAL TO ANALYZE THE STRATIGRAPHIC AND PALEOECOLOGICAL RECORD OF SYNIMPACT TO POSTIMPACT TRANSITION IN THE USGS-ICDP CENTRAL-CRATER CORE, CHESAPEAKE BAY IMPACT CRATER
C. Wylie Poag

PROGRESS REPORT AND CONTINUING PROPOSAL FOR COLLABORATIVE RESEARCH ON LITHOSTRATIGRAPHY, SEISMOSTRATIGRAPHY, AND STRUCTURE OF THE CHESAPEAKE BAY IMPACT STRUCTURE
David S. Powars, Gregory S. Gohn, J. Wright Horton, Jr., and Rufus D. Catchings

ARGUMENT FOR ICDP SCIENTIFIC DRILLING OF THE CHESAPEAKE BAY IMPACT STRUCTURE, EASTERN SEABOARD, UNITED STATES, AND MOTIVATION FOR PARTICIPATION IN THIS PROJECT BY THIS CONSORTIUM
W.U. Reimold, C. Koeberl, I. McDonald, R.L. Gibson, P.J. Hancox, and T.C. Partridge

FLUID INCLUSION AND MINERALOGICAL EVIDENCE FOR POST-IMPACT CIRCULATION OF SEAWATER-DERIVED HYDROTHERMAL FLUIDS AT THE CHESAPEAKE BAY IMPACT CRATER: A CRITICAL TEST OF THE PHASE SEPARATION MODEL FOR BRINE GENERATION
David A. Vanko

SHOCKED BASEMENT ROCKS FROM WITHIN THE PROPOSED CHESAPEAKE BAY IMPACT DRILL CORE
James Whitehead and Richard A. F. Grieve

RELATING IMPACT DEBRIS IN THE STRATIGRAPHIC RECORD TO THE SOURCE CRATER – THE CHESAPEAKE CASE. A. Deutsch[1], [1]Institut für Planetologie, Universität Münster, Wilhelm-Klemm-Str.10, D-48149 Münster, Germany (deutsca@uni-muenster.de).

Distant ejecta. Distant ejecta comprise variably shocked mineral and rock fragments, impact melt glass, high-pressure phases, as well as spherules of widely varying chemical and textural composition and morphology, and the so-called microkrystites. Both the latter, have been discussed to represent high temperature condensates from the vapor plume, expanding over the growing crater. Distant ejecta material may be heavily contaminated by constituents of the impactor, resulting in enhanced abundances of the so-called meteoritic component (mostly PGEs). Exotic chemical components such as, for example, extraterrestrial amino acids have been reported only from the K/T boundary ejecta layer and are still the subject of discussion. Geochemical signals like sharp excursions in the stable isotope record may characterize marine sediments on top of distant ejecta deposits. However, these "anomalies" are secondary consequences of an impact event. They only can be related to the short and long term corollaries of such an event if unambiguous mineralogical evidence for impact metamorphism is documented (*e.g.*, planar deformation features in quartz).

The ejected material having suffered rapid quenching, is either ejected ballistically or suspended and transported by large scale motions in the stratosphere. Distant ejecta can occur up to thousands of kilometers away from the crater; at present roughly 20 horizons of such ejecta have been discovered, their age range from 3.47 Ga to nearly recent (cf. Table 1).

Tektites. Tektites (from τεκτοσ = molten) a subgroup of impact glasses, are characterized by their chemical relatively homogeneous composition and H_2O contents below 0.02 wt-%. The tektite-melt is considered to originate extremely early in a cratering event from near-surface materials, followed by jet ejection of this melt.

Tektites and microtektites with a diameter generally less than 1 mm, are ideal objects for Ar-Ar dating. They occur in four well-constrained major strewn fields, the Australasian, the Ivory Coast, the Central European (Moldavite), and the North American one. Additional discoveries – some of those isolated finds - are listed in Table 1.

Impact debris in the Upper Eocene. Offshore drilling revealed that sediments spanning the Eocene - Oligocene boundary, contain microtektites and microkrystites, for example, in the Caribbean Sea or off New Jersey. At least two layers exist; the impact melt particles display a wide range in chemical composition.

Based on Sr-Nd isotope systematics, one group of this distant ejecta was related to the North American tektite strewn field (e.g., Shaw and Wasserburg, 1982; Ngo and others, 1985; Stecher and others, 1989). The other materials were considered to represent ejecta of the 100-km-sized Popigai impact crater, Siberia (e.g., Langenhorst, 1996; Whitehead and others, 2000; Liu and others, 2001).

Table 1. *Traces of impact events in the geologic record; selected occurrences in the Cenozoic*

known ejecta “horizons” ≤ 20	Age [Ma]	known craters > 165
occurrences of tektites and tektite-like objects		**source crater - diameter**
tektite-like glass?; Argentinean pampas	0.48	unknown
Australasian tektite strewn field	0.784	unknown
Darwin glass?, Tasmania	0.816	unknown
tektite-like glass, Tikal, Belize	0.8	unknown
Ivory Coast tektite strewn field	1.3	Bosumtwi (∅ 10.5) Ghana
S-Ural tektite specimen, Russia	6.4	unknown
Moldavite tektite strewn field	14.34	Ries (∅ 24 km), Germany
Urengoites - 3 tektite specimen, Russia	≈24	unknown
Libyan Desert Glass - Great Sand Sea, W Egypt	28.5	unknown
North American tektite strewn field	35.5	Chesapeake Bay (∅ 90 km), U.S.A.
L. Eocene microtektites, microkrystites, global?	35.7	Popigai (∅ ≤ 100km), Russia
K/T boundary, global	65	Chicxulub (∅ ≤ 200km), Mexico

The Popigai – L. Eocene ejecta connection. Only a detailed Sr, Nd isotope study of various target and impact melt lithologies of the Popigai crater (Kettrup and others, 2003) provided the final proof for the relation of the stratigraphic older microkrystites and associated microtektites to this Siberian crater. The, in comparison to tektites from other strewn fields (e.g., Moldavites; Lange, 1995), surprisingly large geochemical variations, and the unusual spread in isotope compositions and isotope model parameters of these microkrystites and microtektites reflect an origin from the uppermost layers at lithologically different parts of the Popigai target area (Figure 1). The leucocratic microkrystites and microtektites have a high affinity to the post-Proterozoic volcanics and sedimentary rocks that were exposed in the northern part of the target area. The melanocratic microkrystites, in contrast, originated mostly from crystalline basement. The ejecta, which is related to Popigai, is probably distributed globally (Vonhof and Smit, 1999).

Tracking down Chesapeake as the source crater of the North American tektite (NAT) strewn field. On the basis of Nd model ages, it was argued already in the 80ies of the last century that the parent crater of the NATs should be located somewhere at the U.S. east coast (Shaw and Wasserburg, 1982). Hence, the discovery of the impact nature of the Chesapeake structure immediately led to the suggestion that the NATs represent the distant ejecta of the Chesapeake impact event (Koeberl and others, 1996). This proposal seems to be well constrained, although ultimate proof is not available so far due to the lack of isotope data for target rocks at the Chesapeake impact site.

It should be one major objective of a new core hole into the Chesapeake crater to drill various lithologies that may match precursor rocks to the NATs. Such rocks may occur either as lithic clasts in breccias, or in the sub-crater basement.

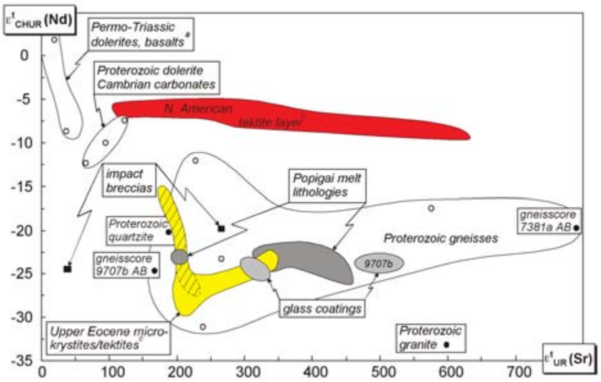

Fig. 1. *Time-corrected ε^t_{UR}(Sr)-ε^t_{CHUR}(Nd) diagram (t = 35.7 Ma) for Popigai impactites, glass coatings of gneiss bombs and target rocks, Upper Eocene microkrystites and microtektites (yellow; Whitehead and others, 2000; Liu and others, 2001) and the North American tektite layer (red; Shaw and Wasserburg, 1982; Ngo and others, 1985; Stecher and others, 1989). [a] = including data of Permo-Triassic basalts from the Putorama region; [b] = the field is defined by data of NAT (Bediasites, Georgiates, Martha's vineyard, Barbados) and DSDP site 612 tektites; [c] = the marked area (diagonal lines) is defined by data of leucocratic microkrystites and microtektites. Circles show data points of target lithologies, squares of impact breccias (modified from Kettrup and others, 2003).*

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POSTIMPACT DINOFLAGELLATE AND CALCAREOUS NANNOFOSSIL BIOSTRATIGRAPHY, LITHOLOGY, SEDIMENTATION ACCUMULATION RATES, AND PATTERNS IN THE FILLING AND REFILLING OF THE CHESAPEAKE BAY IMPACT CRATER.

Lucy E. Edwards, David S. Powars, and Jean M. Self-Trail[1], [1]U.S. Geological Survey, 926A National Center, Reston, VA 20192, U.S.A. (leedward@usgs.gov)

Introduction. The 85-km diameter Chesapeake Bay impact crater is now buried beneath 400-500 m of upper Eocene to Holocene sediments. The upper Eocene to lower Miocene units, unknown or quite poorly known outside the impact structure, are well preserved as a result of the crater setting. Middle Miocene to Holocene units are relatively well known outside the crater but, as a result of continued compaction and structural adjustments, are often more complete stratigraphically where they have been studied inside the crater. The proposed ICDP deep corehole, to be located where the postimpact sedimentation should be the greatest, offers a unique opportunity to study these Eocene and younger deposits.

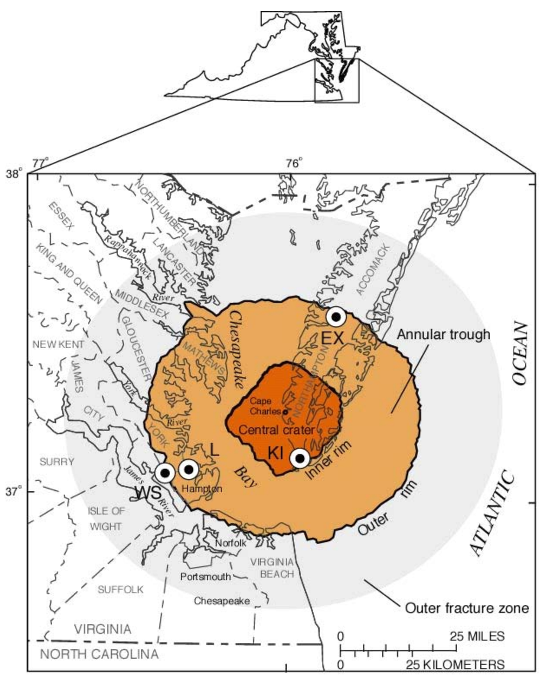

Fig. 1. Index map showing location of four cores in Virginia.

Previous work. Studies of sediment accumulation rates in the USGS-NASA Langley corehole (L, on Fig. 1) show an initial rapid filling of the crater excavation, an unconformity-punctuated series of small sedimentary packages, and a second episode of rapid infilling (Fig. 2). The Exmore core (EX on Fig. 1) was one of several cores used in the Miocene dinocyst zonation of de Verteuil and Norris (1996). The expanded section of the proposed deep corehole should allow refinement of individual species ranges.

Postimpact sediments thicken and dip (sag) into the crater across the inner and outer rims and show variations in thickness and facies of the postimpact units that appear related to directional sources and amounts of sediment supply. (Powars and Bruce, 1999). Within the annular trough faulting and thickening of postimpact units also occurs over four collapse structural rings (Powars and others, 2003).

Proposed study. Here we present a brief summary of the postimpact stratigraphy and some of the questions remaining to be answered.

The *Chickahominy Formation* (upper Eocene), represents nearly continuous deposition over approximately 2 m.y. as the crater filled initially. In the annular trough, this unit shows at least two fining upward sequences. Conspicuous reworking of older material has been found in several cores (L, WS on Fig. 1). Can this reworking be tied to faulting? to patterns of sea-level change? How do thickness and lithology of the unit relate to sediment supply?

The *Delmarva beds* (lower lower Oligocene) were recognized by Powars and others (1992) but, since that time, they were combined with what we now know to be the Drummond Corner beds (Powars and others, in press) by Powars and Bruce (1999) and Powars (2000). The planned deep corehole offers the best chance of recovery of both units and detailed study of their lithostratigraphic and biostratigraphic differences.

The *Drummonds Corner beds* (upper lower Oligocene) were first recognized in the Langley core (Powars and others, in press) and show significant differences both lithostratigraphically and biostratigraphically from the older Delmarva beds, which may be confined to the inner parts of the crater. Again, the planned deep corehole should clarify matters.

The *Old Church Formation* (upper Oligocene) is only 1 m thick at its type section. A much thicker section is found within the crater. Numerous questions remain about its range of age, the presence or absence of significant unconformities within it, and its correlation with other coastal plain Oligocene units.

The *Calvert Formation* (lower and middle Miocene) has several formal and informal members. In the SW part of the annular trough, three very thin members are present, separated by unconformities. The uppermost, the Plum Point, may show paleontological aspects of a confined basin. The Calvert has the widest variation in thickness of all the postimpact units. An expanded section is most likely present in the inner crater.

The *Choptank Formation* (upper middle Miocene) is absent in both the Langley and Exmore cores. Is its absence due to nondeposition or erosion? or to inaccurate correlations?

The *St. Marys Formation* (upper Miocene) is the first postimpact unit that is preserved across the entire region and is finer grained and thicker in the southern part of the annular trough than to the north. An expanded section in the inner crater is also expected. The position of the St. Marys-Eastover boundary relative to the dinocyst DN9-10 boundary will be explored.

The *Eastover Formation* (upper Miocene also may be present in an expanded section. At the Langley core site, named members were difficult to delineate due to stratigraphic completeness.

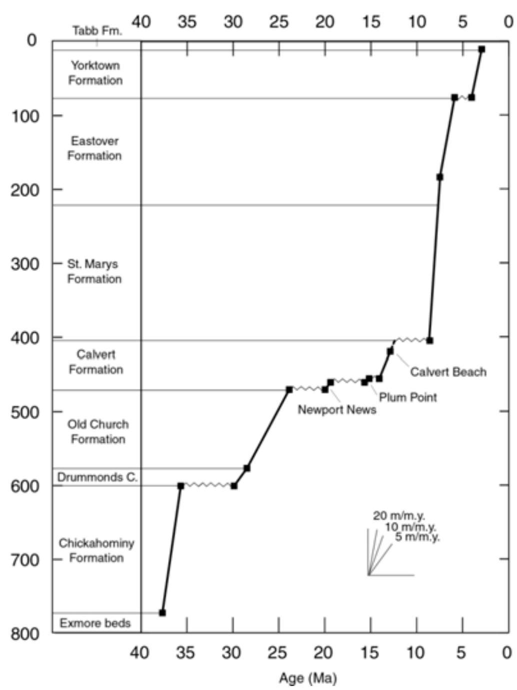

Fig. 2. *Sediment accumulation rates for the postimpact section in the USGS-NASA Langley corehole. From Edwards and others (in press).*

The *Yorktown Formation* (lower and upper Pliocene) has four named members onshore. At the Langley core site, the presence of the lower member is equivocal. The thickest and most complete Yorktown section (including the lower member) was documented in the Kiptopeke core and the deep core should allow an even more complete section.

Various Quaternary formations, where cored, are often cut out by subsequent units.

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PALEONTOLOGY OF IMPACT-DERIVED MATERIAL, CHESAPEAKE BAY IMPACT CRATER

Lucy E. Edwards, Jean M. Self-Trail, and U.S. Geological Survey Crater Project team members, 926A National Center, Reston, VA 20192, U.S.A. (leedward@usgs.gov)

Introduction. The Chesapeake Bay impact crater is one of the Earth's largest and best preserved records of an impact into a primarily siliciclastic, largely unconsolidated, wet, sedimentary target. At the USGS-ICDP Chesapeake Bay workshop in September, 2002, a clear consensus emerged that a deep corehole should be sited in the central crater area away from the central peak, where the impact-derived materials are predicted to be the thickest. Fossils in the proposed core are expected to show the distinctive characteristics seen in previous, shallower cores in terms of mixed stratigraphic ages and a variety of impact-induced damage. We know that as a result of the impact, material from an area over 85-km wide was redistributed. The patterns of sediment redistribution as told by the constituent fossils will be analysed at a variety of scales from the placement of megablocks and boulders to micrometer-sized pockmarks on individual particles. Additionally, the patterns of damage to microfossils will be documented and related to experimental shock and (or) temperature conditions.

Previous Work. The complex mixture of clasts and sediments of mixed ages was noted in the Exmore beds by Poag and others (1992). Partially melted fossil dinoflagellates were noted by Powars and others (2002) and damaged dinocysts and shocked nannofossils were reported by Edwards and Self-Trail (2002), Edwards and Powars (2003), and Self-Trail (2003). Experimental shocking of modern bacterial spores was reported in Horneck and others (2001). Frederiksen and others (in press) report the distribution of clasts and matrix material in the impact related material in the USGS-NASA Langley core. Distinctive patterns in the presence of nonmarine Cretaceous clasts (rare high in the section; exclusive presence low in the section) and select marine Cretaceous and younger microfossils in the matrix (matrix contains younger ages than neighboring clasts; Cretaceous species present only in upper part of the section; ages found that are not known from onshore studies) place constraints on crater history.

Proposed Study.

(1) Biostratigraphic dating and paleoenvironmental interpretations of individual clasts in the impact-derived material, with emphasis on the patterns of clast distribution.

(2) Biostratigraphic dating of the variety of ages in the impact-derived matrix material, with emphasis on the patterns that reveal source location or other aspects crater history.

(3) Biostratigraphic inventories of specific locations (rinds on clasts, suspected injections) to determine or verify infiltration.

(4) Description and documentation of the various kinds of impact-related damage to fossils.

(5) Vertical distribution of microfossils in matrix material, with emphasis on patterns produced by size variation between Cretaceous and Tertiary assemblages.

(6) Documentation of patterns of damage both vertically within a core, and laterally among cores taken within the crater.

(7) Recognition and documentation of reworked damaged specimens in post-impact sediments.

(8) Experimental studies under controlled laboratory conditions to try to reproduce the various kinds of damage observed.

(9) Comparative studies of sediments from outside the crater that are similar to inferred target materials.

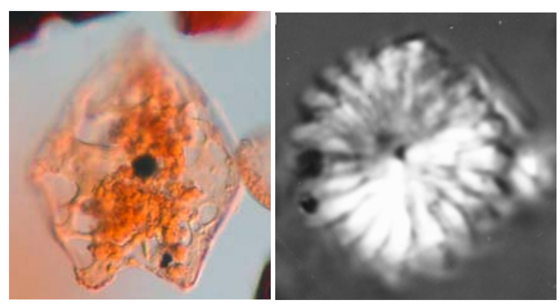

Fig. 1. *Partially melted dinoflagellate cyst (left) and shocked calcareous nannofossil (right) from the Chesapeake Bay impact.*

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THE CHESAPEAKE BAY CRATER CORE – CLAY MINERAL INVESTIGATIONS. Ray E. Ferrell[1], and Henning Dypvik[2], [1] Department of Geosciences, Louisiana State University, Louisiana 70803 4101, USA, 2Department of Geosciences, University of Oslo, P.O.Box 1047 Blindern, N-0316 Oslo, Norway

Introduction. In this study we suggest detailed analyses of the clay mineral composition of syn- and early- post-impact sediments in order recognize aspects of impact crater formation and development, such as; sediment-sources, the presence and alteration of possible melt and melt particles, the degree of weathering in the source area and its general climatic conditions, post impact hydrothermal alteration and diagenetic transformations in the sedimentary succession. In this project we would like to study samples from the Exmore Breccia, combined with possible analyses of weathering crusts from the basement below and analyses of the immediate late post-impact sediments above. The study should be done on core samples and will include sample and core descriptions, grain size separations, and quantitative X-ray diffraction analyses based on simulation of clay mineral diffraction patterns and reference intensity ratios (RIR) for other minerals in the sediments.

Samples. These mineralogical analyses should preferably be done after the first sedimentological and stratigraphical logging of the core has taken place. In this study we need pieces of core-samples of about 10 grams size. The samples will be grain-size separated. The less than 2 µm fraction will be destroyed in the process, while material larger than 2 µm normally will be unharmed, and in part available for other studies. We will need matrix and clast samples. The number of samples and their distribution is difficult to state at the present stage, but up to about 50 samples are anticipated, for the few hundred meters from just below, through and just above the impactite (Exmore Breccia). The number of samples needed is highly dependent on the results of the coring and the nature of the sediments encountered and whether new questions appear. It would be an advantage for this study, of course, if bentonite additives in the drilling mud could be omitted.

Methods. The samples will be separated in two size fractions; particles larger than, and smaller than 2 µm. Each will be examined by quantitative X-ray diffraction methods. The clay fraction will be consumed in this study, while a portion of the coarse fraction can be used by others. The X-ray diffraction analyses will mainly be done in LSU Baton Rouge (LA) and some in UiO (Oslo, Norway) on Siemens (Bruker, D5000) and Philips X-ray (X'Pert) diffraction instruments, respectively. Possible additional electron microscope analyses (TEM, SEM) can also be performed, if necessary. The clay mineralogical simulations will be according to Clay++ (Huang and others, 1993; Aparicio and Ferrell, 2001) and will supply the standard clay mineralogical runs. Some special chemical treatments may be required to further differentiate the clay mineral assemblages (Dypvik and Ferrell, 1998; Dypvik and others, 2003). The initial processing and peak decomposition for qualitative analysis will be accomplished with the latest version of the MacDiff program (Petschick, 2003).

The main goals.

Melt/tektites. In both the Chicxulub and the Mjølnir impactites, altered glasses are commonly found as clay minerals, normally as various modifications of smectite. Such alteration of glass is a fast and common process in nature. Clay mineralogical analyses may be one way of detecting if any glass has been formed in the crater. The clay mineralogical determinations may also be used in correlation between crater deposits and tektites, e.g. from the possibly related North American strewn field.

Tracking hydrothermal and groundwater processes. In relation to the impact event and after, hydrothermal processes may have been active in the crater. During hydrothermal activity clay mineral formation and mineral transformation takes place. It is possible that the clay mineralogical studies may shed some new light on such alteration in the Chesapeake Bay core. Normal circulating groundwater may also produce a distinct mineralogical signature

Impact Mechanisms. It is possible that the timing of the possible glass to clay minerals alterations and synsedimentary glauconite formation can help in timing the impact, in the case pure glass phases are missing. Any possible dating?

Clay minerals in the search for source area characteristics / paleoclimate. In some cases clay minerals can be used to recognize specific source rocks/areas, may be that is possible here? Basement, older sediment units and weathering horizons could all carry their special clay mineralogical fingerprint. Consequently the clay mineralogical composition may give additional information on the mechanisms of crater filling, as well as the paleoclimatic conditions in the surrounding region.

Diagenetic alteration, burial history. The clay minerals can be transformed and altered during increasing burial. They could in this case be used to give information about the burial history of the Chesapeake Bay crater.

Comparison with other craters. Clay mineralogical studies have been performed in the Chicxulub and the Mjølnir core studies (Dypvik and Ferrell, 1998; Dypvik and others, 2003; Oretga-Huertas and others, 2002; Pollastro and Bohor, 1993). In the Chicxulub Crater clay minerals dominate inside the crater, while glass is found outside (Smit, pers.comm., 2003). In the Mjølnir Crater no smectite or glass so far have been found inside the crater, while ejecta 30 km outside the rim have beds highly enriched in smectite, probably derived from altered impact glass (Dypvik and Ferrell, 1998).

Conclusion. This study may contribute to understanding of target composition and paleoclimatic conditions, target stratigraphy, melt recognition and alteration, tektite-melt correlation, hydrothermal evolution as well as the burial history of the structure.

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PROGRESS REPORT AND CONTINUING PROPOSAL FOR COLLABORATIVE RESEARCH ON LITHIC EJECTA, SHOCKED MINERALS, IMPACT MELT, AND CRYSTALLINE BASEMENT IN THE CHESAPEAKE BAY IMPACT STRUCTURE. J. Wright Horton, Jr.[1], Michael J. Kunk[2], John N. Aleinikoff[2], Charles W. Naeser[1], Nancy D. Naeser[1], and Glen A. Izett[3], [1]U.S. Geological Survey, 926A National Center, Reston, VA 20192, USA (whorton@usgs.gov); [2]U.S. Geological Survey, MS 963, Denver Federal Center, Denver, CO 80225, USA; [3]Dept. of Geology, College of William and Mary and Emeritus, USGS, 3012 East Whittaker Close, Williamsburg, VA 23285, USA.

Introduction. The Chesapeake Bay crater is one of the largest and best preserved examples on Earth of a marine impact crater that had a target of thick, poorly consolidated siliciclastic sediments between the water column and the underlying crystalline basement (Earth Impact Database, 2003). The structure has an excavated central crater about 38 km wide surrounded by a flat-floored annular trough about 24 km wide, and the slumped outer margin is about 85 km in diameter (Powars and Bruce, 1999). It is preserved beneath a blanket of postimpact sediments about 150 to 400 m thick and can be sampled only by drilling.

The purpose of current and planned research on lithic ejecta, shocked minerals, impact melt, and crystalline basement from the Chesapeake Bay crater is to understand the character and distribution of materials and their significance to the formative processes of the Chesapeake Bay crater and other marine impact craters. These investigations are part of the U.S. Geological Survey (USGS) Chesapeake Bay Impact Crater Project, which is supported by the National Cooperative Geologic Mapping Program in cooperation with other organizations. Recent studies have focused on samples from four new coreholes in the annular trough on the western side of the structure as summarized below. A deep corehole in the central crater of the Chesapeake Bay impact structure is being proposed to the International Continental Scientific Drilling Program (ICDP) in order to extend this research into other parts of the crater.

Scientific Issues. Current studies are focused on understanding the composition, lithology, age, stratigraphy, and thermochronology of target rocks and crater-fill units in the annular trough. The value of these studies would be enhanced by expanding them to encompass the central crater as well. Expansion of this research into the central crater will allow these investigations to address additional problems such as the amount and location of impact melt, the age of the crater as determined from samples of melt and associated materials, shock-wave attenuation in target rocks, hydrothermal activity, thermal models of the crater, the search for meteorite components for projectile identification, characterization of the target, and process-oriented comparison to other craters.

Current Methods. Current methods include thin-section petrography supplemented by electron microprobe, scanning electron microscope, and X-ray diffraction; universal-stage and spindle-stage studies of shocked minerals; structural analysis of deformational microfabrics as well as macroscopic faults, fractures and veins; geochemistry of major and trace elements (including rare earths and platinum group) by X-ray fluorescence spectroscopy (XRF) and instrumental neutron activation analysis (INAA); ion-microprobe (SHRIMP) U-Pb dating of minerals such as zircon; and thermochronology by the $^{40}Ar/^{39}Ar$ and fission-track methods.

Preliminary Results in the Annular Trough. Our preliminary results from the recent USGS-NASA Langley, Bayside, and North coreholes in the annular trough on the western side of the crater (respectively 19, 8, and 24 km outside the central crater), and from the Watkins School corehole on the outer margin (27 km outside the central crater), are summarized in recent abstracts (Horton, Aleinikoff, and others, 2001, 2002; Horton, Kunk, and others, 2002; Horton, Gohn, and others, 2003; Horton, Kunk, and others, this volume). A lack of evidence for shock metamorphism or discernible impact heating >100°C in crystalline basement from coreholes ≥8 km outside of the central crater implies that these rocks were outside the transient cavity and provides boundary conditions for modeling. An intact ejecta layer is not preserved in the cores. Shocked quartz is found in rock fragments or sand grains from the Exmore beds in all four cores, where it is diluted by a much larger volume of unshocked material in these mixed siliciclastic sediments interpreted as seawater resurge deposits. Rare clasts of possible impact melt from the Exmore beds are being investigated chemically and isotopically, and the search continues for high-pressure minerals such as those reported by Glass (2002) from proposed distal ejecta.

Proposed Collaboration in the Central Crater. In addition to being a logical extension of current research, deep coring in the central crater is likely to recover impact breccias, melt, hydrothermal minerals, and shocked target rocks unlike those studied in the annular trough. New research collaborations are sought to enhance and expand capabilities in areas such as the measurement of physical properties (for example, density, magnetic susceptibility and remanent magnetization, and strength properties), sensitive trace-element analyses by radiochemical neutron activation analysis (RNAA) or inductively coupled plasma mass spectrometry (ICPMS), Nd and Sr isotopes, cosmogenic isotopes, high-pressure mineralogy, fluid inclusions, and thermochronology techniques that complement those described above. Much can be learned about marine craters and processes by comparative studies of impactites from the Chesapeake Bay crater, well studied land-target craters such as the Miocene Ries crater in Germany, and other marine-target craters such as the Ordovician Lockne crater in Sweden. We hope to broaden scientific collaboration with a variety of international crater researchers.

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COSMIC IMPACT AND SEQUENCE STRATIGRAPHY. D. T. King, Jr.[1], and L. W. Petruny[2], [1]Dept. of Geology, Auburn University, Auburn, AL 36849, USA (kingdat@auburn.edu) , [2]Department of Curriculum and Teaching, Auburn University, Auburn, AL 36849, USA and Astra-Terra Research, Auburn, AL 36831-3323, USA.

Introduction. Scientific revolutions of thought concerning cosmic impacts on Earth and about sequence stratigraphy of terrestrial sediments have both come forth as key theories in Earth science during the past 30 years (see Melosh, 1989, for a review of impact geology and Miall, 1997, for a review of sequence stratigraphy). However, not much thought has gone into the joint implications of these theories. One of the axioms of sequence stratigraphy is that sedimentation in general, and its stratal patterns in particular, respond to changes in accommodation space, that is, the space available for sediment accumulation within the depositional realm (Vail and others, 1977).

Where cosmic impacts of size occur, accommodation space is instantly created. In the marine realm, where most sequence stratigraphic studies are focused, this accommodation space would be differentially filled depending upon water depth in the crater area (see Ormö and Lindström, 2000, regarding water depth). The three scenarios considered here are: nearshore impacts, shelfal impacts, and deep marine impacts. We will consider only impacts of large size, such as craters ~ 100 km or more in diameter, in this discussion. We will neglect discussing the variables associtated with impact tectonism, e.g., shelf collapse, and center on sedimentation response to impact-related changes in topography and bathymetry on a passive margin. We will also consider the effect of relative sea-level rise upon impact-related sequence stratigraphy. Implicit in our assumptions is that the target is mainly sedimentary material.

Nearshore impacts. Impacts in which the outer rim of the structure intersects shoreline are considered here as nearshore impacts. After nearshore impacts, previously established drainage and longshore drift patterns must re-establish themselves. In a transgressive phase, this may not be as important as in a regressive phase. Changes in paleogeography of shoreline configuration are to be expected and, on the down-dip side of the impact structure, there is considerable new accommodation space. This space may act as a sediment trap, particularly for clastics, which may otherwise have moved into deeper realms. Down-dip from the structure, a hypothetical "impact-related hiatus" (i.e., condensed section or surface of starvation) may develop due to up-dip trapping of materials (Fig. 1). In carbonate shoreline systems, which may be more sensitive to changes in water depth, temperature, and circulation patterns, local carbonate buildup (reefal) sedimentation may attend the structural rim.

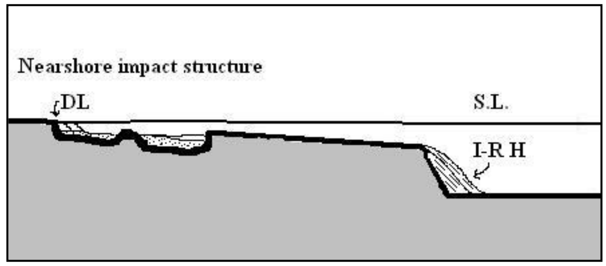

*Fig. 1. Nearshore impact effects.*DL = *downlapping into crater accommodation space*. I-R H = *impact-related hiatus in downlapping deep marine sediments. Impactites stippled; marine slope sediments* = \\\. S.L.= *sea level.*

In addition, nearshore impacts of size will likely have devastating effects upon the adjacent shore and may be related to hemispheric or global catastropies. In these instances, devastated ecosystems, especially those within the local drainage system, may produce copious amounts of organic rich clastic sediment, which could temporarily increase sedimentation rates in the nearshore realm. This effect will rapidly diminish with time, but may be a factor in early-formed sequence stratigraphy within a nearshore impact structure (i.e., development of sequence or parasequence boundaries; terminology of Van Wagoner and others, 1990).

Shelfal impacts. Shelfal impacts produce circular structures of size that do not intersect the shoreline and are formed entirely or almost entirely upon the continental shelf, e.g., Chesapeake Bay crater. Shelfal impacts act more like tectonic features (e.g., strike-oriented grabens) in the way that they potentially disrupt shelfal sedimention patterns. The bowl of the impact structure acts temporarily like a depressed part of the shelf wherein sediments, especially dip-fed clastic sediments, commence filling the depression in a classic downlapping pattern like that seen in deeper water (i.e., along the continental shelf). In deeper shelf settings, it is possible that the equivalent of deep-sea fan systems may develop along the up-dip rim of the structure as dip-fed sediments enter the depression. Coveal sedimentation on the down-dip side of the structure would likely be characterized by slumps and pelagic sedimentation. A similar "impact-realted hiatus" is to be expected within deeper water facies, which are now deprived of dip-fed sediments that would have come to the continental margin were it not for the new accommodation space higher on the shelf. This pattern should continue until the accommodation space is filled, and only at that time will normal sedimentation resume on shelf areas deeper than the structure and on the continental margin within the dip-fed "sedimentation shadow" of the structure. In transgressive phases, filling of crater accommodation space will proceed more slowly than in regressive phases, especially with clastics. With shelfal carbonates, great depth inside the structural bowl may preclude carbonate accumulation at any significant rate.

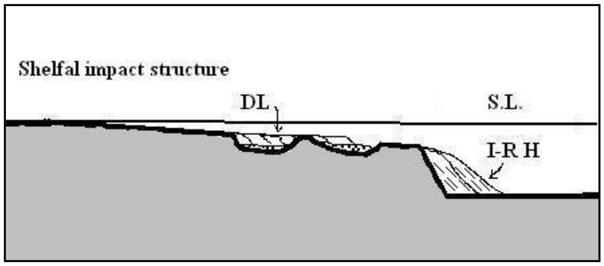

Fig. 2. Shelfal impact effects. Same symbols and abbreviations as in Fig. 1.

In addition, shelfal impact structures of size may be affected to a significant degree by subsequent isostatic adjustment, which is significant because changes in water depth on a shelf can have a profound effect upon sedimentation. This is especially true in carbonate depositional systems, which are quite sensitive to light, temperature, circulation patterns, salinity, etc. (Wilson, 1975).

In order to test the hypotheses presented here, newly proposed ICDP drilling at Chesapeake Bay crater should occur within the up-dip reaches of the crater area. A second well (an ICDP or other well) in deeper water beyond the Atlantic margin shelf break would encounter the envisioned "impact-related hiatus."

Deep marine impacts. Deep marine impacts may produce structures of size on the sea floor, provided that the water is not too deep versus the size of impactor (Ormö and Lindström, 2000; in some scenarios, very deep ocean water may itself form the crater and thus not much of an effect is to be found upon the sea floor itself; Gersonde and others, 1997). Deep marine impacts, as discussed here, do not have any intra-rim area that intersects the continental shelf, but may peripherially involve the continental slope or rise (Fig. 3). The effects of these impacts are (1) to disrupt ongoing sedimentation patterns in the deeper realm, e.g., turbitide flow systems, especially if the impact is adjacent to a significant source of terrestrial clastic sediment and (2) to provide a fresh area for pelagic sedimentation. Sedimentation within such impact structures may be much greater during regressive phases wherein sediment quantities feeding into the deeper realms of the ocean are expected to be greater. Pelagic sedimentation will resume shortly after impact, and thus these early pelagic layers may become a surface upon which downlapping may occur with subsequent progradation, i.e., a sequence boundary.

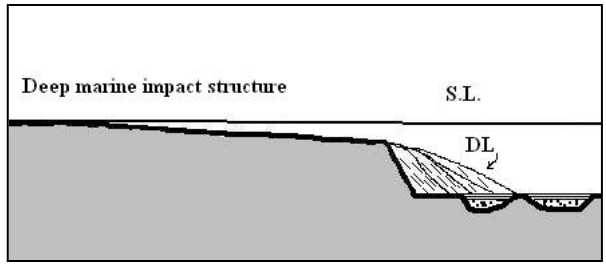

Fig. 3. Deep marine impact effects. Same symbols and abbreviations as in Fig. 1. Pelagic sediments in crater = parallel lines.

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IMPACTITE SEQUENCE AND POST-IMPACT ALTERATION/HYDROTHERMAL ACTIVITY: POTENTIAL SCIENTIFIC TARGETS OF AN ICDP BOREHOLE INTO THE CHESAPEAKE BAY IMPACT CRATER. David A. Kring, Lunar and Planetary Laboratory, University of Arizona, 1629 E. University Blvd., Tucson, AZ 85721 USA (kring@LPL.arizona.edu).

Introduction. The Chesapeake Bay impact crater (Poag and others, 1994; Poag, 1997) is one of only a few surviving complex craters to have been formed on a continental shelf. The crater is also relatively easy to access, despite being buried beneath 300 to 500 m of post-impact sedimentation. This makes the structure a good candidate for a deep borehole project and the recovery of a continuous core through the impact structure.

Science Potential. A deep borehole through the Chesapeake Bay crater would nicely complement a previous ICDP-sponsored borehole project that targeted the Chicxulub impact crater (e.g., Dressler and others, 2003; Kring and others, 2003). Like the Chesapeake Bay crater, Chicxulub was produced on a continental shelf. However, differences in some of the parameters involved may have produced different structures and impact lithologies. The water depth at the Chesapeake Bay impact site was 200 to 500 m, while it was only ~100 m at the Chicxulub site. Both impacts involved a layer of sediments over a granitic continental crust, but the sediment horizon was thinner in the case of Chesapeake Bay (~1 km) than Chicxulub (~3 km). The Chesapeake Bay crater is also much smaller than the Chicxulub crater. These three factors may have produced significant differences in shock-metamorphic conditions and the excavation, transport, and deposition of impact lithologies. In addition, the relative proportions of water depths to rim heights may have influenced the way in which agitated seawater was able to erode the rim and/or rework breccias within each crater and their surrounding impact ejecta blankets.

In the case of the ICDP-sponsored Chicxulub Scientific Drilling Project, continuous core was obtained in the structural trough between the peak ring and final crater rim, augmenting discontinuous borehole samples collected during previous oil exploration projects and several shallow research cores. The project recovered an impactite sequence composed of several melt-rich polymict breccias and a basal melt unit (e.g., Dressler and others, 2003; Kring and others, 2003). The impactite sequence was also altered by an impact-generated hydrothermal system (Zurcher and Kring, 2003; Zurcher and others, 2003).

Chesapeake Bay. To better understand the excavation, transport, and depositional processes involved in the formation of the Chesapeake Bay crater, a similar core through the impactite sequence is needed. Analyses of lithic clasts, their abundances relative to melt fragments and matrix as a function of depth, the range of compositions and textures among melt fragments, etc. would reveal depths of excavation, mixing phenomena during transport, and sorting phenomena that may have occurred during deposition through a water column.

As illustrated at Chicxulub, hydrothermal systems can be generated in large impact craters. A similar system was probably generated in the Chesapeake Bay structure, because such systems can span the entire diameter of a crater and affect material to depths in excess of a kilometer (Kring, 2000). To study the chemical and thermal evolution of the hydrothermal system in the Chesapeake Bay structure, a core sample within the crater is needed, ideally one that penetrates the entire impactite sequence and a portion of the underlying floor of the crater. Analyses of the mineralogy and fabric of the impactite sequence and crater floor, in addition to stable isotope analyses, can be used to infer temperatures in the system, fluid chemistry, and how both evolved with time. Coordinated fluid inclusion studies would further constrain temperatures and fluid chemistry.

The same core sample can conceivably be used to address all of the above issues: (a) shock metamorphism of target materials, (b) excavation, transport, and deposition of impact lithologies, and (c) post-impact hydrothermal activity.

Proposed Borehole Location. The best type of core sample to resolve these scientific issues is from a borehole that penetrates the entire sequence of breccia units, including any melt horizons that may be present (even if discontinuous), and into the fractured basement beneath the impact breccia sequence, in the trough between the central uplift and the outermost modification zone within the final crater rim. This would be located ~10 km radially from the center of the crater. The borehole would need to penetrate 300 to 500 m of post-impact sediments and then at least another 1.5 km to penetrate the previously described "sedimentary breccia," "crystalline breccia," and a significant amount of the underlying crystalline target rocks. This borehole would be modestly deeper than that in the Chicxulub Scientific Drilling Project, which produced continuous core from 404 m to a final depth of 1511 m for a cost of ~$1.5M. A relatively deep borehole of this type would best augment existing data from shallower core samples at larger crater radii around the Chesapeake Bay structure.

A good secondary target would be the central uplifted peak. As studies of the Puchezh-Katunki crater have shown (Pevzner and others, 1992; Naumov, 1992; 1993), extensive hydrothermal activity can alter the central uplift. Studies of shock deformation as a function of depth would also be feasible if a borehole penetrated the central uplift. High numbers of structural faults in the central uplift might, however, decrease the probability for successful core recovery.

Ideally, boreholes in both locations would be recovered. This would facilitate a comparison of the impactite sequence deposited between the central peak and crater rim with that deposited above the central peak, which would further constrain the excavation, transport, and depositional processes in an impact event in a water-covered continental shelf environment. Two boreholes would also allow the spatial extent of any hydrothermal system to be mapped and a better evaluation of the respective roles the central uplift and impactites may have had as heat sources driving post-impact fluid circulation.

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HOT TIME IN THE CRATER: POST-IMPACT PORE WATERS, HYDROTHERMAL CIRCULATION, AND BIOLOGICAL ACTIVITY IN THE EARLY LATE EOCENE CHESAPEAKE BAY IMPACT CRATER.

Dan Larsen[1] and Laura J. Crossey[2], [1]Department of Earth Sciences, University of Memphis, Memphis, Tennessee, 38152 USA (dlarsen@memphis.edu), [2]Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, New Mexico 87131 USA (lcrossey@unm.edu).

Introduction. The early late Eocene-age Chesapeake Bay impact was a first-order convulsive event in Earth history (Poag and others, 1994; Poag and others, 2004). Along with sister Popigai impact in northern Siberia, these events produced a one-two cosmic punch that caused dispersal of widespread ejecta plumes, and potentially enhanced? or accelerated? Late Eocene global cooling (Vonhof and others, 2000). The effects of the Chesapeake Bay event are still evident today in the inland distribution of a saline ground-water wedge, which affects ground water resources to as many 1.8 million people, and localized subsidence in the southern Chesapeake Bay area.

Many aspects of the Chesapeake Bay impact and its effects have become clear through extensive seismic surveys and ground-water related coring studies in the southern Chesapeake Bay area (Poag and others, 2004; Powars, 2000). However, many questions regarding the size and characteristics of the inner crater, degree of melt-rock formation, and post-impact modification remain unanswered. A particularly interesting series of questions pertains to the degree to which hydrothermal circulation and associated thermophilic ecosystems occurred following impact, and whether the current pore waters in the inner crater fill are remnant from the impact event and post-impact hydrothermal activity (Sanford, 2003). Although hydrothermal alteration has been described to some degree in several impact sites (McCarville and Crossey, 1996; Sturkell and others, 1998; Osinski and others, 2001), it has not been described for a geologically young, well-preserved, shallow-marine impact site, such as Chesapeake Bay impact. Furthermore, the potential that the inner crater pore waters are remnant from the impact event provides a unique opportunity to describe and model water-rock interactions in an impact-derived hydrothermal system. Such environments could have been the crucibles of early life on Earth (Farmer, 2000; Kring, 2000); however, no aqueous remnant of an impact-driven hydrothermal system has been sampled.

Post-Impact Hydrothermal Activity. As proposed by Poag and others (2004), the initial impact at the target site vaporized and shattered the marine sediment cover, vaporized an immense quantity of seawater, and potentially melted basement rock. Resurge breccias that were subsequently deposited the crater would thus have immediately encountered hot brine and begun reacting immediately. Assuming only thermal conduction, Sanford (2003) estimated peak temperatures of over 450°C in the breccias after 10,000 yrs. Convective circulation would likely result in higher temperatures, but lower time duration at peak temperatures. Existing core studies from outside the inner crater indicate extensive oxidation in some parts of the breccia and pyrite precipitation in adjacent rock, and common reaction (fusion?) rims on sedimentary clasts (Poag and others, 2004). However, the sedimentary matrix of the breccias is described as containing glauconite, quartz, mica, and calcite, suggesting minimal degrees of post-impact alteration outside the inner crater. Land-based impact structures commonly show evidence of propyllitic alteration at temperatures of as much as 300°C (Koeberl and others, 1989; McCarville and Crossey, 1996; Osinski and others, 2001); however, alteration temperatures might be expected to be proportionally lower for marine impacts because greater ejecta dispersal (Ormö and Lindström, 2000) and vaporization of water. No evidence for post-impact microbiological communities is presently observed in the breccias; however, they might expect to exist based on the presence of organic carbon and likely oxidation-reduction gradients (suggested by iron oxides or hydroxides oxidation and pyrite in close proximity).

Proposed Study. We propose a three-pronged sampling approach to investigate post-impact water-rock-biological interaction system at the Chesapeake Bay impact site: (1) sampling and analysis of pore waters from a proposed inner crater well (Ward Sanford, pers. comm., 2003), (2) sampling of outer and inner crater fill and sub-crater materials for petrological and mineralogical analysis, and (3) sampling of crater-fill materials for evidence of post-impact biological activity. Pore waters will be analyzed for major, minor, and trace elements, as well as a suite of isotopic tracers. The principal objectives of the water analysis are to determine if the pore fluids show evidence of initial impact conditions, the probable mechanisms for attaining high salinity, and the minimum residence time of pore waters in the crater. Outer and inner crater materials will be analyzed to identify secondary mineralogy by light microscopy, scanning electron microscopy (SEM), and X-ray diffraction. Special emphasis will be placed on changes in silica and clay mineralogy, which may be particularly sensitive indicators of low-temperature alteration. Stable carbon and oxygen isotopes of secondary carbonate minerals will also be completed to better constrain fluid composition, temperature conditions, and potential microbial activity. Mineralogical, isotopic, and textural data will be used to establish the sequence of alteration effects and ranges of alteration temperatures, and the distribution of alteration in the crater. The results will be compared with conductive and convective heat-flow/circulation model results in the crater. Pore-water chemistry and mineralogical data will be modeled to determine the probable reaction paths that occurred following impact and evaluate whether the current pore waters are related to the initial impact. Crater-fill materials will be examined in SEM after acid-etching to determine evidence for post-impact microbial activity. In addition, organic fractions from the breccia matrix and post-impact sediments will be separated and analyzed for biomarkers indicative of hydrophilic biological communities. These data along with chemistry and stable oxygen, hydrogen, carbon and nitrogen compositions of pore waters will be used to attempt to reconstruct post-impact biological communities and their relationship to hydrothermal alteration.

The results from our proposed study will coordinate well with hydrologic studies (Ward Sanford), fluid inclusion studies (David Vanko), and other alteration and geochemical studies. The combined results will test several fundamental questions related to impact processes, especially in marine settings: (1) Are impact pore waters persistent in marine impacts? (2) To what degree does hydrothermal alteration occur in marine impacts and how well does heat dissipate by this mechanism? and (3) Is there evidence for post-impact biological activity related to hydrothermal processes?

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An Isotopic and Trace Element Investigation of Melt-rock and Impact Breccia from the Chesapeake Bay Impact Crater to Establish the Source of the North American Tektite Strewn Field. Steven M. Lev, Department of Physics, Astronomy & Geosciences, Towson University, Towson, MD 21252, USA (slev@towson.edu)

The Chesapeake Bay impact structure is thought to be the source of the North American Tektite (NAT) strewn field (Poag et al., 1994; Koeberl et al., 1996; McHugh et al., 1998 and Glass et al., 1998). This correlation is primarily based on the geochemistry of late Eocene tektite samples from as far south as Barbados and north to the New Jersey continental margin. The most compelling geochemical evidence is the isotopic fingerprint derived from the Sr and Nd isotopic composition of the NAT strewn field samples (Shaw and Wasserburg, 1982; Ngo et al., 1985; Stecher et al., 1989 and Glass et al., 1998). The Chesapeake Bay Drilling Project will provide an opportunity to directly test this model. If the Chesapeake Bay crater is truly the source of the NAT then there should be a favorable comparison between the isotopic composition of the NAT samples and melt-rock, impact breccia and the target bedrock, all of which are likely to be encountered during the proposed drilling of the central crater.

The majority of the NAT samples exhibit a narrow range in their Sr and Nd isotopic composition and are thought to be similar to moldavites in that these tektites were derived from melting of homogeneous surface deposits during the initial impact (Stecher et al., 1989). However, there is some heterogeneity when late Eocene tektite samples from DSDP site 612 and ODP site 904A are included (Shaw and Wasserburg, 1982; Stecher et al., 1989 and Glass et al., 1998). The 612 and 904A tektite deposits are geographically closer to the target area than other NAT samples and exhibit evidence of less severe shock (Stecher et al., 1989; McHugh et al., 1998 and Glass et al., 1998). This coupled with the isotopic heterogeneity suggests that these tektites, while still derived from the late Eocene Chesapeake Bay impact, may represent deeper parts of the target area stratigraphy.

Recent work by Kettrup et al. (2003) compared the Sr and Nd isotopic composition of impactites from the Popigai crater in Siberia to the target rocks and previously published data from microkrysites and associated Upper Eocene microtektites. Based on this isotopic comparison the Popigai crater is the likely source of these ejecta. This is a significant result since prior to this investigation the Upper Eocene ejecta, now linked isotopically to the Popigai crater, were thought to be too diverse geochemically to have only one source. The isotopic range, as defined by Kettrup et al. (2003), recorded by the target area lithologies can account for the range in Upper Eocene ejecta.

The range of lithologies present in the Popigai target area are somewhat similar to the range of lithologies in the Chesapeake Bay target area in that the lithology changes with depth from sands, shales and carbonates to crystalline basement rocks. The heterogeneity present in the Popigai target area led to a fairly large range in the Sr and Nd isotopic composition of related ejecta which may also be the case for the NAT-type ejecta including the DSDP 612 and ODP 904A sites. By correlating the geographic distribution of ejecta derived from shallow target area lithologies versus deeper lithologies we may be able to gain insight into such questions as the trajectory of the Chesapeake Bay projectile as well as the extent of melting and mixing that occurred post impact.

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CHARACTERIZING THE HYDROGEOLOGIC AND STRUCTURAL PROPERTIES OF AN IMPACT CRATER FROM ANALYSIS OF GEOPHYSICAL LOGS – THE CHESAPEAKE BAY DEEP COREHOLE. Roger H. Morin, U.S. Geological Survey, MS 403, Denver Federal Center, Denver, Colorado 80225, USA.

Geophysical logging operations are planned in conjunction with continuous coring of the Chesapeake Bay Impact Crater Corehole. A fairly comprehensive suite of logs would consist of caliper, induction, long-short normal resistivity, natural gamma activity, gamma spectral, temperature, fluid conductivity, full-waveform sonic, acoustic televiewer, optical televiewer, neutron porosity, gamma-gamma density, flowmeter, magnetic susceptibility, and formation micro-scanner. Geophysical logs have been an important source of information for lithologic interpretation at various drill sites in the Virginia Coastal Plain (i.e., Powars and Bruce, 1999).

However, it is anticipated that unstable hole conditions, a heavy drilling mud, and possible budget limitations may preclude some of these measurements. Nevertheless, acquisition of data from several of these logging tools should be relatively routine and it is anticipated that some good-quality logs will be successfully recovered. Some of these measurements, such as resistivity and gamma activity, may be directly related to lithology. Others, such as porosity, temperature, and fracture distribution, may infer hydrologic properties and processes. In addition, the combination of sonic and density logs may provide information on the elastic properties of the rocks and on their response to local stress conditions; data derived from these two logs may also be used to refine seismic and gravity surveys, respectively, collected for site characterization (Catchings and others, 2001).

It will be important to plan and integrate complementary laboratory measurements made on core samples with the interpretation of these downhole measurements. Lab results will serve as reference calibration points to improve quantitative estimates of porosity, density, and compressibility computed from logs.

Analysis and interpretation of log data generated from a variety of geophysical tools will help characterize the rheological properties of the rocks cored in this impact structure and provide a continuous vertical profile of changes in these properties as the hole penetrates surficial sediments, breccia, and basement rocks. This general information will be of broad interest to numerous other investigators who will use these data within the context of their own studies.

Finally, logs obtained from this deep corehole will be compared to other logs collected in a nearby pilot hole drilled over the central peak of the crater to examine spatial variability of physical properties and spatial correlation among lithologic sequences.

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PROPOSAL FOR A COMPARATIVE STUDY OF EARLY CRATER MODIFICATION, INCLUDING WATER RESURGE AND HYDROTHERMAL ACTIVITY IN A LARGE MARINE-TARGET IMPACT CRATER, CHESAPEAKE BAY, USA. Jens Ormö[1], Fernando Ayllón Quevedo[1], Maurits Lindström[2], Erik Sturkell[3], Enrique Díaz Martínez[1], Jesús Martínez Frías[1], David S. Powars[4], and J. Wright Horton, Jr.[4], [1]Centro de Astrobiología, INTA/CSIC, Madrid, Spain (ormo@inta.es); [2]Stockholm University, Stockholm, Sweden; Icelandic Meteorological Office, Reykjavík, Iceland, [4]U.S. Geological Survey, 926A National Center, Reston, VA 20192, USA.

Introduction. Drilling a deep corehole in the central part of the Chesapeake Bay impact crater (CBIC) will provide information on several aspects of marine impact cratering. Experience by the team members from other marine-target craters, notably the Lockne crater in central Sweden, indicates that the most complete sequence of impact-generated and postimpact deposits can be found in the inner crater (fig. 1). It is also where most, if not all, of the effects of impact generated heat can be studied. This research proposal is based on comparison of materials from the proposed drilling in the central part of the CBIC, from existing coreholes in outer parts of the crater, and from the well studied Lockne crater. The team is composed of experts on marine-target cratering and modification, the sedimentology of impact craters, and hydrothermal mineralogy.

Crater Modification. The CBIC is a large impact structure that formed in relatively shallow water when compared to other marine impacts such as Eltanin and Lockne (Ormö and Lindström, 2000). At the size and water depth of CBIC, a crater rim too high to allow forceful resurge is expected (Ormö and others, 2002). However, drill cores in the outer slumped zone of the CBIC show that sediments of the Exmore beds resemble the resurge deposit at the Lockne crater. The Lockne resurge probably contained relatively more water than at CBIC. At Lockne, a nearly 14 km wide cavity formed in the about 1 km deep target sea (Ormö and others, 2002). The excavation stripped most of the 80 m thick sedimentary part of the target from a 2-3 km wide zone surrounding a 7.5 km wide, nested, basement crater (fig. 1). Extensive flaps from the crystalline basement crater covered the stripped surface, but were not thick enough to be an obstacle for resurge flow. There is an apparent increase in the relative content of fragments from the deepest part of the target the towards the top of the resurge deposit (i.e. in the coarse clastic Lockne Breccia towards the arenitic Loftarstone). The Loftarstone is also the only unit where melt fragments and shocked quartz have been found. The interpretation is that the lower part of the resurge unit was deposited from a debris flow carrying material ripped up from the disturbed sedimentary part of the target surrounding the crater. Meanwhile, the upper part of the resurge unit carries more high-energy ejecta from deeper parts of the target, laid down from suspension. These beds seem also to have been partly reworked, possibly from oscillation due to collapse of a central peak of water (Fig. 1). The situation at CBIC, with shallower water deepening seaward and underlying target layers of poorly consolidated sediments, may have generated an even more debris-loaded flow than at lockne, with less deposition out of suspension. Comparative studies of the resurge deposits at CBIC and Lockne can give valuable information on the nature of the resurge flows in each crater and of the resurge processes that produced them. Ormö (1994) studied the provenance of the fragments in the resurge breccia of the marine Tvären crater, Sweden, and found a relation between the resurge erosion and clast distribution in the breccia. This technique can be used at CBIC. It will also be possible at CBIC to assess the relative timing of the block slumping and the resurge flow. A deep drill core from the central part of the CBIC can be compared to more distal drill cores, revealing any spatial variations in clast distribution of the resurge deposit. Investigations may also determine if the water was deep enough to oscillate due to collapse of a central peak of water, and how far out in the megablock zone the effects of these oscillations can be traced in the sediments.

Hydrothermal Activity. Studies at Lockne indicate that even a relatively large marine-target crater may lack the melt bodies expected at a similar-sized land-target crater in crystalline rock. At Lockne, 1 km of the upper part of the transient cavity was formed in the water column. This upper part normally includes much of the zones of vaporization and melting in a land-target crater of this size. Impact-generated heat at Lockne only caused a relatively short-lived, low temperature hydrothermal system (Sturkell and others, 1998). The CBIC may be sufficiently large, deep enough into crystalline basement, and formed in sufficiently shallow water, to have got a hot crater floor and melt bodies. Such melt bodies could have had short-term violent interaction with the resurging water and more extended hydrothermal activity after the crater filled with debris. The fluids in these hydrothermal cells may have come both from the resurging seawater (early stage) and from intruding groundwater (later stage with different fluid composition). A deep corehole in the central crater would provide insights into post-impact hydrothermal activity, including possible mineralization and alteration zones, temperature and composition of the mineralizing fluids, timing between seawater and ground-water phases, and duration of the heat flow in both basement and infill.

Inner and Outer Crater Comparisons. In the CBIC, the thin lower Tertiary marine target sediments found outside the crater are missing throughout the crater except as disaggregated, reworked particles (Powars and Bruce, 1999). These thin, easily eroded sediments were either stripped off by the initial, outward excavation flow or by the subsequent inward water resurge. To distinguish between excavation flow and water resurge, we propose to compare materials and structures in the inner and outer parts of the CBIC to those of Lockne and other marine craters by integrating data from coreholes or outcrops and seismic surveys. In the Lockne crater, ejecta flaps were deposited before the resurge (fig. 1), so missing strata below the flaps must be related to the initial excavation flow. However, on the eastern side of the Lockne crater, where a smaller flap suggests less excavation flow, missing sediments were possibly eroded by the water resurge.

Investigations are needed at the CBIC to determine if a flap is present and detectable by seismic surveys or drilling. It is important to compare data from drill core and seismic surveys in the central crater with data from the outer part of the crater, where slumping probably occurred before or during the resurge. Numerical modeling could be used to estimate the amount of excavation that occurred outside the central crater before the water resurge and block slumping.

Suggested Deep Corehole Positions. If possible, the central crater should be drilled in at least two locations. The maximum gain for the hydrothermal study will, most likely, be from a corehole in the deepest moat zone around the putative central peak. The largest melt bodies in a crater of this size are expected to be located in the moat. The moat is also likely to have the most complete resurge sequence. This drilling must reach at least a few hundred meters into the fractured, and possible heated crystalline rocks below the crater infill. The second drill site should be located on top of the crystalline basement crater rim to give information about the excavation and resurge erosion at this position, as well as the formation of the crystalline rim. It is important to test for the existence and possible amount of overturned crystalline material and (or) sediment layers at the rim, and determine if sediments exist under an overturned flap. This information would provide data on excavation flow at a critical location for numerical models.

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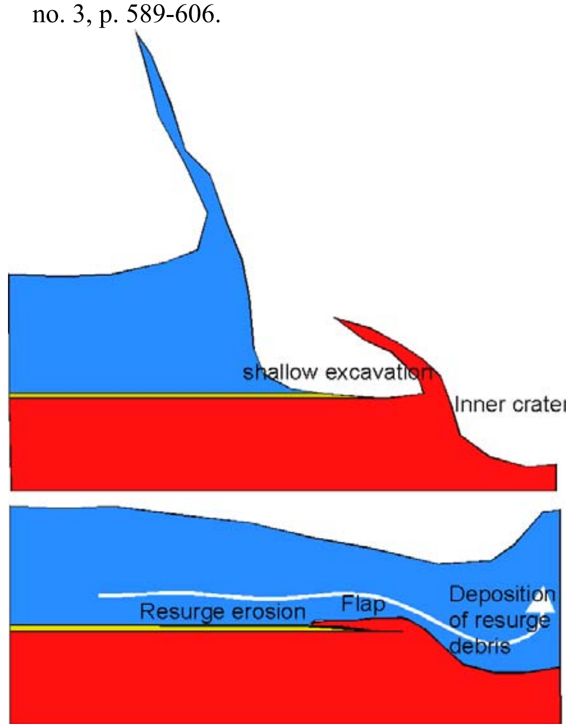

Fig.1. Schematic illustration of the sequence of excavation and resurge at Lockne. Note the concentric shape with a wide water cavity. Blue is water, yellow is sedimentary rock, and red is crystalline basement.

PRE- AND POST-IMPACT PALEOCEANOGRAPHIC CONDITIONS ON THE EOCENE MID-ATLANTIC CONTINENTAL MARGIN: EVIDENCE FROM RADIOLARIANS.

Amanda Palmer-Julson, Natural Sciences Division, Blinn College, Bryan, TX 77805-6030, USA (**ajulson@blinn.edu**).

Introduction. Biostratigraphic and paleoenvironmental analysis of radiolarian assemblages is proposed for material recovered from the planned Chesapeake Bay impact structure central crater corehole and related on- and offshore drill sites.

Previous Studies. Palmer (1987) studied radiolarians from DSDP Leg 95 (Sites 612 and 613, New Jersey Transect) and Atlantic Slope Project Site ASP 15. While less diverse than tropical assemblages, the fauna provided valuable biostratigraphic information. Later work focused on re-investigating the timing of the microtektite layer recovered at DSDP Site 612 (Miller and others, 1991), where once again radiolarians proved valuable in supplementing biostratigraphic results from calcareous microfossils in establishing the nature and timing of the impact event responsible for the Chesapeake Bay crater.

Poag (1997) reported radiolarians in the Chickahominy Formation recovered from the Kiptopeke core (Virginia coastal plain). Based on the presence of radiolarians, Poag interpreted the depositional environment for this post-impact unit as representing high biological productivity in the surface waters.

Palmer (1986) demonstrated in a study of Miocene radiolarians from the mid-Atlantic coastal plain and continental margin that distinct faunal differences allowed recognition of neritic vs. oceanic assemblages. The Eocene radiolarians of the region remain unstudied from this perspective.

Proposed Study. I propose to conduct a thorough analysis of radiolarian assemblages from the Chesapeake Bay central crater corehole and related coastal plain and offshore sites. The biostratigraphic and paleonvironmental data would be a valuable complement to the work of other investigators.

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PHYSICAL PROPERTIES AND PALAEOMAGNETISM OF THE DEEP DRILL CORE FROM THE CHESAPEAKE BAY IMPACT STRUCTURE - A RESEARCH PROPOSAL. Lauri J. Pesonen[1], Tiiu Elbra[1], Martti Lehtinen[2], Johanna M. Salminen[1] and Fabio Donadini[1], [1]Division of Geophysics, University of Helsinki, P.O. Box 64, FIN-00014 Helsinki. (**lauri.pesonen@helsinki.fi**), [2]Department of Geology, University of Helsinki, P.O. Box 64, FIN-00014 Helsinki.

Introduction. Deep drilling has become a powerful tool to test the validities of the geological and geophysical models of large impact structures (Dressler and others, 2003). Drilling has also become important in proving that some of the circular structures are impact structures (Pesonen and others, 1999a,b; Tsikalas and others, 2002). The programme provided by the ICDP (International Continental Scientific Drilling Program) has opened new challenges for drilling through large impact structures, such as the 65 Ma old Chicxulub structure in Yucatan, Mexico (Dressler and others, 2003) and the 1.07 Ma Bosumtwi structure in Ghana (Plado and others, 2000). We describe a project plan where high-resolution paleomagnetic and petrophysical measurements will be carried out of the future deep drill cores through the Chesapeake meteorite impact structure, Virginia, USA. In our project we will use an ultra sensitive DC SQUID magnetometer for paleomagnetic determinations coupled with novel petrophysical techniques recently developed for impact research at the Division of Geophysics and Department of Geology of the University of Helsinki, Finland. Our proposal includes microscopic and X-ray analysis of the samples in order to understand the shock-induced changes in the physical properties of the target rocks. The results will be used for calibrating the geophysical loggings, for dating the post-impact, impact and target rocks and for providing constraints for the 4D geophysical modelings of the Chesapeake structure.

Fig. 1. *A view of the new paleomagnetism and petrophysical laboratory of the Geophysics Division the University of Helsinki.*

Sampling. Chesapeake is a 35 Ma old shallow marine, complex impact structure with a diameter of ca. 85 km. The structure has been mapped with shallow drillings and geophysical data but its horizontal width and vertical depth are poorly known (Poag, 2003). A series of deep drill cores is planned by the joint efforts of ICDP and USGS and other partners. If the drilling will be realized, our aim is to analyze small chips of the core including post-impact, impact and pre-impact (basement) units of the structure. The sampling interval will be dense enough to allow high-resolution paleomagnetic, magnetostratigraphic and paleosecular variation (PSV) data to be extracted from the core. A dense sampling extending through the fractured bedrock down to unfractured bedrock will help to delineate the progressive downward damping of the shock effects on the physical properties of rocks. Petrographic studies (thin section studies with optical microscopy and X-ray analysis; Pesonen and others, 1999a) of the samples will be carried out to determine their degree of shock. Microscopic studies will also provide constraints in estimating the hydrothermal changes in remanent magnetization and in other physical properties. If the drill core is azimuthally oriented, the samples will allow true vector paleomagnetic data. In the case of an unoriented core, the magnetic declination will be measured with respect to a common fiducial line along the core, which provides relative orientation. The possibility to use the viscous remanent magnetization (VRM) technique to reorientate the core will be studied (Järvelä and others, 1996).

Paleomagnetic measurements. Paleomagnetic measurements, including magnetic polarity determinations, will be done using an automated ultra sensitive DC-SQUID magnetometer. Both alternating field (up to 160 mT) and thermal demagnetization (up to 700º C) treatments will be done for each specimen to allow the various remanence components to be isolated. One of them may be a drilling induced remanence, which will be studied with care. Magnetic hysteresis properties will be measured with a VSM in order to determine the relative amount of low coercive force grains, which are relevant to understand the shock remanent magnetization possible present in the impactite units. Hysteresis properties are also used to determine the magnetic domain sizes of the remanence carriers. We will also measure the coercivity spectra of the remanence carriers using new IRM- and ARM-instruments installed in the laboratory of the University of Helsinki (Fig. 1).

Petrophysical measurements. The following physical properties of the drill core samples will be measured. The instruments used are mostly described in Pesonen et al. (1999a).

- dry and wet bulk densities and the grain density using the Archimedean principle
- porosities (effective, total)
- seismic velocities (P and S) and their attenuation using ultrasonic techniques
- magnetic susceptibility and its anisotropy
- natural remanent magnetization (NRM) and its demagnetization characteristics, its nature and origin
- electrical conductivity and inductive conductivity
- thermal conductivity and thermal diffusivity

These measurements are used to calibrate the drill hole geophysical logging data. The knowledge of the physical properties of various rocks are crucial for modeling the gravity, magnetic, electromagnetic and seismic profiles since the geophysical models strongly depend on the contrasts of physical properties between the rocks of the impact structure and those beyond. The physical property data are relevant to study the depth extent of shock on the drill core (Pesonen and others, 1992; Langenhorst and others, 1999; Plado and others, 2000). Measurements of the thermal conductivity and heat capacity will be carried out for understanding the cooling history of the structure.

Other magnetic measurements. To understand the paleomagnetic data and the effects of shock on magnetic properties of the rocks we will carry out:

- magnetic mineral determinations with KLY-3 using both low and high temperature treatments
- magnetic susceptibility anisotropy determinations with KLY-3 device to interprete the paleomagnetic data and to look correlations with shock degree and magnetic anisotropy
- magnetic hysteresis and grain size determinations using VSM magnetometer and IRM and ARM instruments in order to interpret the paleomagnetic data

Summary. We have a plan for a geophysical project where high-resolution paleomagnetic and petrophysical measurements of the future drill cores from the Chesapeake meteorite impact structure will be carried out. Our proposal includes microscopic and X-ray analysis of the samples in order to understand the shock-induced changes in the physical properties of the rocks. The results will be used for calibrating the geophysical loggings, for constructing the magnetostratigraphy of the sequences to get estimates of the ages of the post-impact, impact and fractured target rocks. The data will provide constraints for the 4D geophysical modelings.

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A PROPOSAL TO COLLECT TENSOR MAGNETO-TELLURIC SOUNDINGS ACROSS THE CENTRAL CRATER OF THE CHESAPEAKE BAY IMPACT STRUCTURE. Herbert A. Pierce, U.S. Geological Survey, National Center, MS 954, Reston, VA 20192, USA (hpierce@usgs.gov).

Introduction. During 2000 and 2001 two audio-magnetotelluric (AMT) electrical sections were constructed across the outer margin of the Chesapeake impact crater consisting of a total of 17 stations. The tensor audio-magnetotelluric soundings on the York-James and Middle-Neck Peninsulas demonstrated that electromagnetic soundings could provide electrical data to a depth of 800 meters important to understanding the overall structure of the crater and map the location of the outer margin. The electrical response of the sediments and bedrock coupled with borehole resistivity information allowed interpretations to be extended to the James River from the two coreholes drilled on the NASA Langley Research Center property during 1975 and 2000 (Gohn and others, 2001). AMT stations collected near Mathews and to the northeast allowed an electrical section to be constructed that provided information to a depth of 250-800 meters.

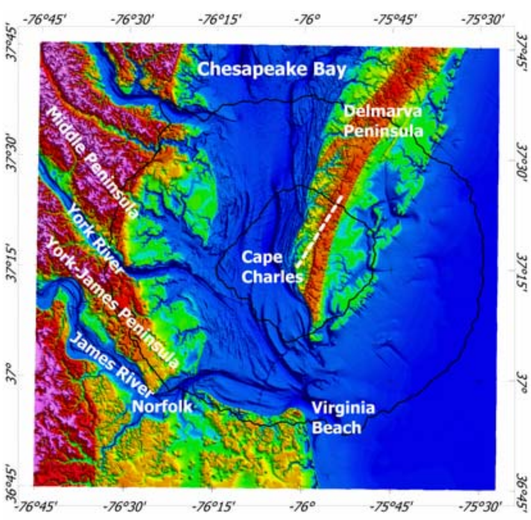

Fig. 1. Location of proposed MT transect indicated by the white dashed line originating northeast of Cape Charles.

Proposal. To map the electrical structure within the central crater I propose an experiment to collect 20-30 of the lower frequency tensor magneto-telluric (MT) soundings and use them to identify depth to basement and geometry from Cape Charles northeast along the axis of the Delmarva Peninsula (figure 1). The location of the soundings would be spaced approximately one kilometer apart starting from Cape Charles and proceeding to the northeast across the central crater of the Chesapeake Bay impact structure. These MT soundings and the electrical sections made from them will have a greater depth of exploration than the AMT soundings because of the much lower frequencies employed. The MT electrical sections will miss the upper 100 meters but will cover depths from 100 meters to more than five kilometers. The technique can collect information routinely to a depth 40 kilometers with a limit of about 100 kilometers for long duration soundings. Stations will use a remote reference to remove noise associated with cultural activity. Interpretations of the electrical sections should provide insight on the structure, geometry, and map depth to bedrock within the central crater of the Chesapeake Bay impact structure.

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A Proposal to Analyze the Stratigraphic and Paleoecological Record of Synimpact to Postimpact Transition in the USGS-ICDP Central-Crater Core, Chesapeake Bay Impact Crater.

C. Wylie Poag, US Geological Survey, 384 Woods Hole Road, Woods Hole, MA 02543-1598, USA (wpoag@usgs.gov)

Introduction. Poag (2002), Poag and others (2004), and Poag and Norris (in press) have documented the transition from synimpact deposition to postimpact deposition in four cores taken from inside the Chesapeake Bay impact crater (Kiptopeke core on southern tip of Delmarva Peninsula; USGS-NASA Langley core on James-York Peninsula; North core and Bayside core on Middle Neck). These authors describe the transition as a complex succession of litho- and biofacies that separates the synimpact Exmore impact breccia (*sensu lato*) from the overlying postimpact Chickahominy Formation. Three stratigraphic units have been identified in the transitional interval.

Flowin Facies. The stratigraphically lowest transitional unit consists of dark, greenish-gray, clayey silt, with centimeter-scale laminae of fine to very fine sand. Nodular concentrations of framboidal pyrite are numerous, and foraminifera reworked from deeper in the Exmore breccia (chalky, leached specimens) are concentrated in the thin, white, horizontal sand laminae, along with concentrations of muscovite flakes. Indigenous microfossils appear to be lacking, however.

At NASA Langley, this silt-rich layer is in sharp contact with the underlying glauconitic quartz sand of the Exmore breccia, but at Bayside and North, the basal contact is transitional. Also, the upper part of the silt-rich layer at Bayside and North is more obviously stratified with white, sandy, micaceous laminae and burrow casts, whose spatial orientations change markedly along the core. Some laminae are horizontal, but others are inclined, with variable angles and directions. The multidirectionality of laminae in this unit has been interpreted to result from successive turbidity currents triggered by impact-generated storms (possibly *hypercanes*). This is the *flowin* lithofacies of Poag and others (2004).

Fallout Layer. The upper ~3 cm of the laminated, silt-rich interval at NASA Langley, contains numerous millimeter-sized, porous, lattices of framboidal pyrite. The key impact-related features of the pyrite lattices are the pore structures. Each pore is nearly perfectly spherical, of uniform ~1-mm diameter, and spatially arranged as if the lattice originally had enveloped a layer of microspherules ~3–4 mm thick. These properties are similar to those of impact-derived layers of glass microspherules reported from other fallout ejecta deposits. Poag (2002), Poag and others (2004), and Poag and Norris (in press) inferred that the pores in the pyrite lattices originally contained glass microspherules ejected from the Chesapeake Bay crater. Over time, the microspherule glass dissolved, or altered to clay. Though a stratigraphically equivalent silt-rich interval is present above the Exmore breccia at the other core sites (where it is inferred to be the final impact-generated deposit), the pyrite lattices have been found only at NASA Langley.

Dead Zone. The initial postimpact deposit is 19-49 cm thick, and composed mainly of fine, horizontal, parallel laminae of fine to very-fine sand, silt, and clay. The clay and silt laminae are disturbed in places by burrows, which are filled with medium to coarse sand and microfossils reworked from the underlying Exmore breccia. Additional reworked microfossils comprise much of the micaceous white sand concentrated in horizontal laminae and lenses. The lack of indigenous microbiota in this interval led Poag (2002) and Poag and others (2004) to interpret this as a *dead zone*, representing paleoenvironments hostile to marine life. The dead zone differs from the silt-rich layer below the fallout layer primarily in having more uniform, horizontal, parallel distribution of laminae, and lacking nodular pyrite. In the Bayside core, the dead zone reaches its maximum known thickness (~49 cm). Since no pyrite-lattice layer has been identified at Bayside, however, the base of the dead zone there can only be approximated by the upward change from multidirectionally inclined, moderately thick laminae, to horizontal, thin laminae.

Chickahominy Formation. The dead zone is succeeded conformably by as much as 220 m of silty marine clay assigned to the Chickahominy Formation. Chickahominy deposition continued for ~2.1 m.y. to the end of the Eocene. The exceptional Chickahominy sedimentary record is a product of relatively deep-water, fine-grained, microfossiliferous deposition within a slowly subsiding, closed basin, which underwent no syndepositional tectonism or synchronous major eustatic sea-level changes. Subsequent Cenozoic sea-level falls and marine transgressions have eroded the top of the Chickahominy Formation, but it has never been subjected to significant tectonic activity.

Planktonic foraminifera and bolboformids document biochronozones P15 and P16-17 of the late Eocene in the Chickahominy Formation (Poag and Aubry, 1995). Coeval benthic foraminferal assemblages constitute a single biozone (*Cibicidoides pippeni* Zone), which is represented by 150 calcareous and agglutinated species. The *Cibicidoides pippeni* Zone can be further divided into five subbiozones. The species represented in the *Cibicidoides pippeni* assemblage indicate a paleodepth of ~300 m for the Chickahominy seafloor, which exhibited oxygen deprivation and high flux rates of organic carbon.

Clearly, understanding the nature and history of the flowin facies, fallout layer, dead zone, and Chickahominy Formation can yield crucial information regarding the age of the impact, the late Eocene paleoenvironments, the resultant marine deposits, and their coeval biota.

Proposed Research. I propose to analyze the mineralogical and micropaleontological record preserved in sediments between the base of the flowin facies and the top of the Chickahominy formation in the new USGS-ICDP core. I will interpret the record in the context of previous studies, and test hypotheses regarding the stratigraphic succession and paleoecological implications of the sediments (and their biota) and determine the genesis of the respective depositional units. The analysis will apply mainly standard micropaleontological techniques, using a binocular stereomicroscope, augmented with scanning electron microscopy. Analyses will determine biozonation, species richness and diversity, predominance, equitability, and microhabitats.

Sample Requirements. Proposed analyses require two different sets of samples: (1) The first set should be quarter-core samples, 2.5 cm long, taken in continuous succession from the top of the sandy Exmore section to the base of the Chickahominy Formation. Such dense sample distribution is required because the section is relatively thin, and some important features (such and the fallout layer) could easily be missed in any sampling gaps. (2) The second sample set is restricted to the Chickahominy Formation. Previous studies cited above show that quarter-core samples, 2.5 cm long, spaced one-meter apart, are sufficient to interpret the biostratigraphic and paleoecological record of the Chickahominy.

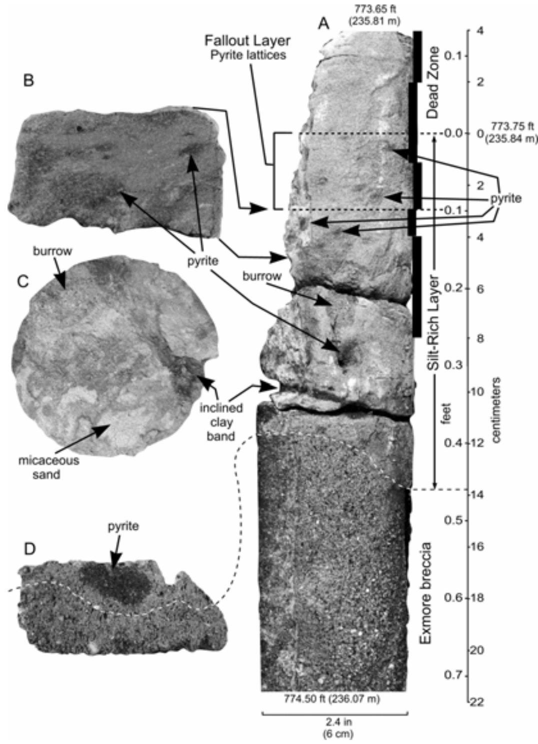

Fig. 1. Segment of USGS-NASA Langley core, showing lithic transition from Exmore breccia (sensu lato) through dead zone. From Poag and others (2004).

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PROGRESS REPORT AND CONTINUING PROPOSAL FOR COLLABORATIVE RESEARCH ON LITHOSTRATIGRAPHY, SEISMOSTRATIGRAPHY, AND STRUCTURE OF THE CHESAPEAKE BAY IMPACT STRUCTURE. David S. Powars[1], Gregory S. Gohn[1], J. Wright Horton, Jr.[1], and Rufus D. Catchings[2], [1]U.S. Geological Survey, 926A National Center, Reston, VA 20192, USA (dspowars@usgs.gov); [2]U.S. Geological Survey, 345 Middlefield Rd, MS 977, Menlo Park, CA 94025-3591, USA.

Introduction. Geologic and geophysical field investigations of the marine, late Eocene Chesapeake Bay impact structure have revealed a buried 85-km-wide complex crater surrounded by a ~35-km-wide outer fracture zone. The impact into an eastward dipping, multi-layered target (crystalline basement overlain by water-saturated, unconsolidated sediments, and seawater) produced a 38-km-wide central crater surrounded by a 21 to 31 km-wide annular trough (see fig 1). The deepest part of the central crater or “moat” excavated crystalline basement to a depth of >2-km, and it encircles a central uplift (fig. 1). The central crater is surrounded by a raised and faulted crystalline basement. The western part of the annular trough consists of locally faulted crystalline basement overlain by impact-modified and impact-generated sediments, and it has an outer margin of slumped, unconsolidated sediment blocks.

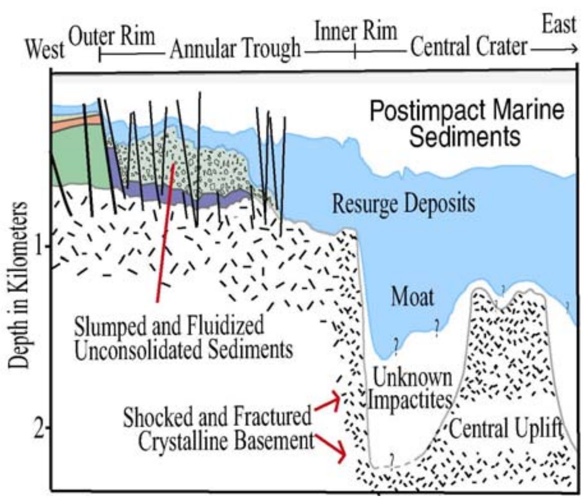

Fig.1 *Interpretive cross section of western side of the Chesapeake Bay impact crater.*

Most of the past studies primarily have focused on the western half of the structure’s annular trough and outer margin. The current and planned integration of data and interpretations from coreholes and geophysical surveys in the Chesapeake Bay impact structure is designed to develop a three-dimensional understanding of the crater’s lithology, stratigraphy, structural geometry, and evolution. These investigations are part of the U.S. Geological Survey (USGS) Chesapeake Bay Impact Crater Project, which is supported by the National Cooperative Geologic Mapping Program in cooperation with other organizations. Extension of this research into the central crater is facilitated by a proposal to the International Continental Scientific Drilling Program (ICDP) for a deep corehole in the central crater of the Chesapeake Bay impact structure.

Scientific Issues. Understanding the crater materials and structure will provide a framework for regional ground-water models as well as constraints for modeling the crater formation and mechanics, including the size of the transient cavity, the energy of impact, morphologic evolution of the crater during its formation, effects of bathymetric and sediment depths and asymmetries, and general implications for terrestrial marine craters. Some questions include structure and composition of the crystalline basement and its influence on crater formation; the nature of the crater’s inner ring, moat, and central peak; and the mechanics of shock compression, gravitational collapse of the transient cavity, seawater resurge, and postimpact settling and slumping.

Current Methods. Results and interpretations based on direct observations, measurements, and analysis of samples from coreholes and water wells are extended laterally by correlation with seismic reflection and refraction surveys. They also provide observed constraints on the geometry and physical properties of rock volumes at depth for more realistic models and interpretations of regional gravity and magnetic surveys.

Preliminary Results. Preliminary results from integrating data from four recent coreholes in the western annular trough, new high-resolution seismic reflection and refraction surveys, and gravity and magnetic surveys in progress are summarized in recent abstracts (Catchings and others, 2002; Gohn and others, 2002; Horton and others, 2002, 2003; Poag and others, 2002; Powars and others, 2002, 2003). Highlights include evidence (from lack of shock and thermal features) that granites from two coreholes to basement in the annular trough were outside the transient cavity, that the outer margin of the annular trough formed by inward extensional collapse, and that the outer to central annular trough consists of a variable pile of highly fractured and fault-bound parautochthonous mega-slump blocks overlain and injected by resurge deposits while the inner 8-km of the annular trough consist mainly (?) of resurge deposits overlying the crystalline basement. The outer to central annular trough appears to have four main concentric zones of extensional collapse structures that are formed by numerous small-offset faults rather than a few major faults. Most of these collapse structures appear to be associated with normal and compressional basement faults and are sites of the greatest postimpact subsidence in the trough. Gravity surveys in progress in the central crater support the existence of a central peak surrounded by an irregularly shaped structurally complex moat. Improved hydrogeologic models are a current and future societal benefit for a region that is increasingly dependent on limited supplies of fresh ground water.

Proposed Collaboration in the Central Crater. Understanding the crater materials and structure require expanding beyond current studies of the annular trough to include the central crater. One or more deep corehole(s) in the central crater will provide constraints for interpreting and modeling seismic reflection and refraction, gravity, and magnetic data to address stratigraphic and structural questions away from the corehole itself.

Current and planned investigations of lithology and stratigraphy of synimpact crater-fill deposits are based on samples from coreholes and correlations of the corehole data with seismic reflection and other geophysical surveys in order to understand the three-dimensional distribution, stratigraphy, and structural relations of crater materials. Planned investigations include sedimentological comparisons of the Exmore beds in the annular trough and central crater to determine the character of seawater resurge and tsunamis. Plans for future research are to extend these studies into the central crater to include presently unknown impact breccias, impact melt rocks, and (or) suevites that may underlie the resurge deposits. Plans for structural analysis includes the study of faults, fractures, and veins, and contrasting features that distinguish contractional deformation due to the initial compression and excavation from extensional structures related to subsequent collapse of the transient cavity.

We propose to build on current collaboration with geophysicists involved in seismic reflection and refraction, gravity, magnetic, and MT surveys, and with numerical modelers. We also invite collaborate with international experts on marine craters in comparative studies to understand the influence of unconsolidated versus consolidated target layers and water depths on formation of resurge deposits, and contrasting processes of fluidization in preimpact target rocks.

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ARGUMENT FOR ICDP SCIENTIFIC DRILLING OF THE CHESAPEAKE BAY IMPACT STRUCTURE, EASTERN SEABOARD, UNITED STATES, AND MOTIVATION FOR PARTICIPATION IN THIS PROJECT BY THIS CONSORTIUM. W.U. Reimold[1], C. Koeberl[2], I. McDonald[3], R.L. Gibson[1], P.J. Hancox[1], and T.C. Partridge[4], [1] Impact Cratering Research Group (ICRG), School of Geosciences, University of the Witwatersrand, Private Bag 3, P.O. Wits 2050, Johannesburg, South Africa (reimoldw@geosciences.wits.ac.za), [2] Department of Geological Sciences, University of Vienna, Althanstr. 14, A-1090 Vienna, Austria (Christian.koeberl@univie.ac.at), [3] School of Earth, Ocean and Planetary Sciences, Cardiff University, P.O. Box 914, CrdiffCF10 3YE, United Kingdom (iain@earth.cf.ac.uk), [4] School of Geography, Archaeology and Environmental Studies, University of the Witwatersrand, private Bag 3, P.O. Wits 2050, Johannesburg, South Africa (tcp@iafrica.com)

Why ICDP drilling of Chesapeake Bay?

Amongst the approximately 170 impact structures known on Earth, all formed in continental (including the continental shelf) environments. A recent compilation by Dypvik and Jansa (2003) lists 7 impact structures that formed in the submarine environment (but on the continental shelf) and have remained located in the marine realm. Further 11 impact structures are known to have formed in the marine realm but are now located on land. Chesapeake Bay, at an assumed diameter of approximately 80 km, represents the second largest of these 18 marine impact structures, only surpassed by the about 200 km Chicxulub impact structure in Mexico that already has been drilled by ICDP earlier this year. The Yaxcopoil-1 drill core is currently the subject of a worldwide investigation and has the potential to make a major contribution to our understanding of the Chicxulub impact event and, consequently, the global environmental effects that this impact at K/T boundary times must have had. However, the single ca. 1500 m long drill core from Chicxulub did not explore the entire crater fill nor did it extend into the crater floor. While this borehole has certainly provided extensive new information about the Chicxulub impact, this project can not solve all remaining problems about this particular impact, per se, and impact cratering in the marine environment, in general.

Chesapeake Bay already has been studied quite extensively, especially by shallow drilling and geophysical analysis (e.g., Poag et al., 2003 – and literature reviewed therein). Thus, much of the groundwork required for successful identification of a drilling location has already been completed. But what are the reasons why Chesapeake Bay should be investigated by comprehensive drilling? The structure represents a relatively young (35 Ma) impact structure that is nearly completely preserved. The sedimentary cover strata are not very thick, so that drilling of the crater interior would not be curtailed by expensive drilling of cover strata. However, the cover strata themselves represent a formidable argument in favor of drilling into Chesapeake Bay, as they represent a complete cross-section through the eastern Coastal Plains of the US, drilling of which would complement the extensive former drilling and sequence stratigraphic investigations of these plains that have been conducted further to the north. The age of the impact crater, as constrained by biostratigraphy and paleomagnetism, seems to coincide with a strong paleo-environmental event that affected much of this planet at that time. Near coincident with the Chesapeake Bay impact is also the Popigai impact into northeastern Siberia, and much effort has been made in identifying the respective global effects of these two impact events. Chesapeake Bay is the most likely source crater for the North American tektite strewnfield, but the currently available materials from this crater have so far not allowed to unambiguously confirm this hypothesis.

Furthermore, Chesapeake Bay is of significant hydrological importance as a water source for some 1.6 million people living in the environs of the structure, with much of the reservoir being brackish. Thus, drilling of the crater could make a major contribution to the knowledge about and hydrogeological modeling of this important water reservoir.

Above all, drilling of this impact structure has the potential to strongly supplement the currently very limited understanding of catastrophic impact into the shallow marine environment and the subsequent evolution of such a large, complex impact structure. In detail, drilling would contribute to the following aspects:

- General understanding of the impact process for cases of impact into shallow marine environment.

- Provide a ground truth basis for improvement of numerical modeling of this process.
- Obtain a full succession of crater fill materials (impactites and post-impact sediment), study of which will contribute to the previous aspects, and will be used to investigate the possible association with the North American tektite strewn-field.
- Hands-on analysis of crater and sub-crater materials is required to provide a basis for geophysical modeling (e.g., gravity modeling).
- Without a full understanding of the crater fill, crater modeling is not possible and the actual crater size can not be scaled at sufficient precision. Once the size of the crater will be better constrained, the impact energy can be scaled, and, thus, inference made regarding the environmental effect that this large-scale event would likely have caused.
- What is the nature of the crater fill – in comparison to the drilling information from Chicxulub?
- What is the nature and deformation of the crater floor and basement below the crater?
- Investigation of the post-impact hydrothermal overprint on the crater and basement below could be investigated.
- What is the nature of the central uplift (mega-breccia?) that has been modeled (see Poag et al., 2003)? How did it form and collapse?
- What is the macro- and micro-deformation of the crater floor and basement rocks? Can shock and thermal zoning be identified?
- The nature of the Exmore Breccia – considered by Poag et al. (2003) the result of post-impact wave and wind action – must be clarified.
- Search for development of life in impactite and deformed impact basement settings could be carried out.
- Is there significant impact melt? In which form (coherent or disseminated) does it occur?
- Is it possible to utilize such melt to obtain absolute age data for the impact event?
- In comparison to Chicxulub and the 10 km Bosumtwi crater, Ghana, that will hopefully be drilled with ICDP support in 2004, the intermediate size Chesapeake Bay structure will provide a medium sized benchmark for comprehensive impact modeling.

In conclusion, drilling of Chesapeake Bay would provide information regarding the pre-impact geological setting, the impact process itself, post-impact sedimentation and biogenic development, and present-day hydrology of the crater.

Participation of this research consortium in the Chesapeake Bay ICDP drilling project.

The members of this team all have extensive expertise in the field of impact cratering studies, and some of them have participated in the investigation of post-impact crater sediment, from a paleo-climatic/-environmental point of view (PJH, TCP and D. Brandt of the ICDP). WUR will concentrate on the mineralogical and, in collaboration with CK and IMcD, geochemical study of impactites of the crater fill and impactite and pseudotachylitic breccia injections into the crater floor. Aims of these studies will include thorough characterization of the target rocks, comparison of these with impactite compositions – also for the purpose of comparison with the North American tektites, possible identification of a meteoritic (projectile) component in impact melt rock (by instrumental neutron activation analysis [CK] and ICP-MS analysis of the platinum group elements [IMcD]), and investigation of hydrothermal overprint on crater fill and basement materials. In addition, detailed study of the mesoscopic (structural) deformation of the crater floor and thermal and shock deformation of the crater floor rocks will be carried out (WUR, Roger Gibson of the ICRG) in order to contribute to our understanding of shock and thermal energy distribution across the central parts of large impact structures (depending on where with respect to a Chesapeake Bay central uplift feature would be drilled, one could compare with results obtained on the central uplift of the Vredefort impact structure – Gibson and Reimold, 2001), also in comparison against the results of numerical modeling of these aspects of impact structures.

Where should be drilled?

It is proposed to drill close to the center, but possibly not directly into the central area, of the impact structure, in order to obtain a comprehensive profile through the entire crater fill, as well as information about the possible central uplift feature. As the nature of the possibly existing central uplift in this crater is entirely unconstrained, it may not be possible to obtain much information about this structural feature from a single borehole. In any case, drilling must extend into the crater floor, in order to constrain the nature of the lower target as well as impact deformation below the crater and hydrothermal alteration on the basement to the crater.

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FLUID INCLUSION AND MINERALOGICAL EVIDENCE FOR POST-IMPACT CIRCULATION OF SEAWATER-DERIVED HYDROTHERMAL FLUIDS AT THE CHESAPEAKE BAY IMPACT CRATER: A CRITICAL TEST OF THE PHASE SEPARATION MODEL FOR BRINE GENERATION.

David A. Vanko, Department of Physics, Astronomy & Geosciences, Towson University, Towson, MD 21252, USA (dvanko@towson.edu)

Introduction. A significant amount of thermal energy is deposited as a result of an impact event. Post-impact heat sources may include impact melt sheets and a potentially significant volume of basement rock beneath the target area. Dissipation of this heat is likely to involve hydrothermal circulation through the permeable crater fill material, particularly when the impact is on a continental shelf. The hydrothermal setting envisioned for the Chesapeake Bay impact crater therefore shares several features of current models for mid-ocean ridge and seamount hydrothermal systems (and has numerous differences as well). Deep core samples from the impact crater can potentially provide information about post-impact hydrothermal conditions recorded in secondary or alteration mineralogy and mineral chemistry and in fluid inclusions.

Background. Post-impact hydrothermal systems have been recognized at several impact sites. In the Chicxulub crater, hydrothermal alteration of crystalline basement materials in the ejection breccias is dominated by pyroxene-quartz-anhydrite, and fluid inclusions in the anhydrite may contain evidence of hot, boiling seawater (Gonzalez-Partida et al., 2000). The Kardla crater in Estonia formed in a shallow Ordovician sea, and hydrothermal convection within crystalline breccia material caused chloritization and secondary quartz, the latter containing 150-300°C fluid inclusions (Kirsimae et al., 2002). Impact breccias of the Haughton structure, Canada, are mineralized with quartz, sulfide, sulfate and carbonate minerals, with presumed formation temperatures from <100°C to >200°C (Osinski et al., 2001). The Lockne marine impact structure in Sweden contains hydrothermal calcite, quartz and sulfides – fluid inclusions in quartz contain either hydrocarbons (chiefly methane and ethane) or saline brines, with maximum temperatures of 210°C (Sturkell et al., 1998a). One geophysical consequence of the large degree of secondary mineralization within the altered Lockne impact breccias is that they exhibit an unusually small density contrast and the structure overall exhibits a rather small negative gravity anomaly relative to other impacts (Sturkell, 1998; Sturkell et al., 1998b).

Brine generation. High fluid salinities, elevated temperatures, and the occurrence of both liquid-dominated and vapor-dominated fluid inclusions in some secondary minerals all suggest that post-impact hydrothermal fluid flow may frequently involve phase separation, or "boiling." At the Chesapeake Bay impact site, Sanford (2003) hypothesizes that hydrothermal activity accompanied by phase separation generated the brine that is still thought to exist today within the Exmore breccia. Sanford (2003) calculates that such a brine, generated 35 Ma ago, would still be present because of low groundwater velocities and minor molecular diffusion effects. Drilling the impact crater will provide specimens from deep within the impact breccia and in the basement that should contain secondary minerals and fluid inclusions. Fluid inclusion investigations can test the hypothesis of hydrothermal brine generation, and provide firm chemical and temperature constraints for the hydrothermal system.

Deep-sea example. Fluid inclusions can provide excellent records of subseafloor boiling in deep-sea hydrothermal systems. One example is the deep-sea PACMANUS system in the eastern Manus Basin back-arc spreading system offshore Papua New Guinea (Vanko et al., in press). An Ocean Drilling Program leg devoted to this location (Leg 193, http://www-odp.tamu.edu/publications/pubs.htm) succeeded in coring directly into the hydrothermal system at two different sites. Core samples were recovered from depths of up to almost 400 m below the seafloor (in over 1600 m of water). The cores contain numerous veins of anhydrite, a secondary mineral that hosts aqueous fluid inclusions. Microthermometric studies of the inclusions shows how fluid temperatures increase with depth, and how the high-temperature fluids apparently intersected the seawater boiling curve and generated both low-salinity vapor and high-salinity brine (Figure 1). Similar investigations of core material from the proposed deep drilling within the Chesapeake Bay impact crater have the potential to define the critical parameters of post-impact hydrothermal activity: fluid temperatures and temperature profiles; fluid chemistry; fluid-rock interaction and secondary mineralogy and mineral chemistry; nature of the heat source driving circulation; and possibly even timing and longevity of the hydrothermal circulation.

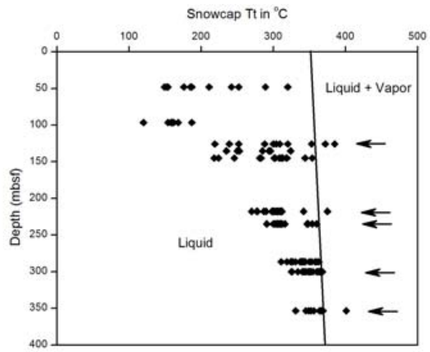

Fig. 1. This is a plot of fluid inclusion trapping temperatures from anhydrite veins beneath the Snowcap area of the PACMANUS deep-sea hydrothermal field (from Vanko et al., in press). Depths are meters below the seafloor (mbsf). The solid line is the boiling curve for seawater-salinity NaCl-H_2O solution, separating the liquid field at lower temperatures from the field of phase separation into liquid plus vapor at higher temperatures. Most of the inclusions are in the liquid field, but some inclusions appear to have been trapped very near or at boiling conditions. The arrows indicate samples that contain additional independent evidence for boiling: vapor-rich low-salinity inclusions, dense saline brine inclusions, or both.

Facilities. The fluid inclusion laboratory at Towson University contains a USGS-type gas-flow heating and freezing stage capable of temperature control between -196° and +700°C. The stage is mounted on a Leitz petrographic microscope with an adjustable coverslip-compensated 40X LWD objective and a Spot Insight digital camera. Sample preparation equipment includes a precision low-speed saw and a polishing unit. Mineral chemical analysis is available using microprobes at the University of Maryland-College Park or the USGS-Reston, and laser-Raman microprobes at the USGS or Virginia Tech can be used to characterize Raman-active fluid inclusion contents such as hydrocarbons and many types of daughter minerals.

Undergraduate Research. Towson University's geology program requires undergraduate majors to carry out a senior research project culminating in a paper and a poster presentation. Sample material from the Chesapeake Bay impact crater would potentially support the research projects for several undergraduate students under the author's direction. Because of the proximity of Towson (near Baltimore) to the Chesapeake Bay, student interest is likely to be very high.

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SHOCKED BASEMENT ROCKS FROM WITHIN THE PROPOSED CHESAPEAKE BAY IMPACT DRILL CORE. James Whitehead[1], and Richard A. F. Grieve[2]. [1]Planetary and Space Science Centre, Department of Geology, University of New Brunswick, 2 Bailey Drive, Fredericton, NB. E3B 5A3 Canada (jwhitehe@unb.ca); [2]Earth Sciences Sector, Natural Resources Canada, Ottawa, ON, K1A OE4, Canada.

Introduction. Despite its 85 km diameter, many facets of the Chesapeake impact structure are poorly understood. The location and depth of the intended ICDP drill core is of paramount importance in determining the types of questions that can be addressed by the drilling programme. Three potential drilling locations within the impact structure were selected by the participants of the ICDP-USGS Workshop. These are: 1) the central uplift; 2) the annular trough, an; 3) the inner rim/overturned flap. Our primary interests are in better understanding the deformation and shock metamorphic features present in the crystalline basement rocks of the structure. The origin of the inner rim/overturned flap is also of interest and, as we outline below, can be indirectly assessed by drilling in the annular trough.

Potential drill sites and goals. The mode in which bulk deformation of the crystalline targets are accommodated during the compression and modification stage of impact is poorly understood, yet has significant ramifications for the formation process of central peaks. The modification stage deformation structures (bulk intracrystalline deformation, intercrystalline slip, microfaults, pseudotachylyte slip horizons, breccia zones, etc.) may be best developed in the region of the basement that has been most affected by modification stage uplift, *i.e.*, the central uplift. A drill site at this location within the Chesapeake Bay impact structure (CBIS) would also afford the greatest thickness of crystalline basement rocks.

The inner nested crater present at the CBIS, may reflect a target in which a weak layer overlies a stronger layer (Melosh, 1989). As such, the edge of the 38 km wide inner crater at Chesapeake, which is located on a mixed sedimentary/crystalline basement target, may be either the margin of the transient cavity, or a peak ring. These two different interpretations have significant implications for the final calculated diameter of the Chesapeake Bay structure. The shock levels present in the target rocks at various inferred transient crater-normalised depths/distances from the centre yield information on the ultimate diameter of the structure and may, indirectly, constrain the diameter of the Chesapeake Bay structure. Although drilling at the central uplift may yield a greater section through the basement lithologies, this region is also the most likely region of structural disturbance, that may thwart attempts to establish the transient crater-normalised shock attenuation rate. Structural disturbance may include bulk rotation of near-horizontal isobars at the impact centre to steeper or vertical dips owing to rotation during upward flow of the central uplift. In addition, structural repetition of marker horizons are evident in central peaks on sedimentary targets (*e.g.*, Red Wing (Brenan *et al.*, 1975); Gosses Bluff (Milton *et al.*, 1996); Cloud Creek (Stone and Therriault, 2003)), and may be apparent impact structures in crystalline targets (e.g., West Clearwater) though more detailed studies are needed. Although establishing if such repetition is present is a worthy goal in itself, the presence of such disturbance could cause difficulties in establishing the shock attenuation rate, the likely diameter of the structure, and thus preclude us from commenting on the most likely origin of the inner crater.

Proposal. Drill core in the annular trough, which appeared to be the site of preference of the bulk of the participants at the ICDP-USGS meeting. We argue that a site in the annular trough, but close to the peak or on the flank of the peak, would be the optimum site for establishing shock attenuation rates in the target, assuming a significant length of drill core in the basement target can be acquired. Such a site would also fulfill the objectives of drilling the annular trough: a large section of crater-fill and post-crater deposits, with low-risk of failing to drill less well-defined features such as the central uplift or the rim of the inner crater.

Shock attenuation rates have been established for only a few other complex craters (Charlevoix and Slate Islands, Canada (Robertson and Grieve, 1977), Puchezh-Katunky, Russia (Ivanov, 1994), Kara, Russia (Basilevsky *et al.* 1983) and Woodleigh (Whitehead *et al.*, 2003). However, the exposure is poor at Charlevoix, precluding an analysis of small- to medium-scale changes in shock with distance, the rate at Woodleigh is poorly constrained, and at Puchezh-Katunky the rate is constrained by five measurement over ~ 5km of core and, thus, would not resolve the effects of structural disturbances in the target. In addition to providing constraints on the size of the Chesapeake Bay impact structure, the characterisation of the shock attenuation in a continuous section of drill core on the edge of the central uplift in the annular trough will provide valuable information on how shock levels diminish with depth in a contiguous section of core, and in the presence of potential structural disturbances.

Samples from such a site should also contain features that may help elucidate the mode in which the flow of the target occurred in response to the impact.

Comparisons. We propose that direct comparisons between the deformation features present in the basement rocks of the Chesapeake Bay drill core with core that is available to us from the central uplift/near central uplift regions of several Canadian impact structures, be performed. These comparisons would contribute to our knowledge of the mode in which the central uplift processes occur, as well as highlight possible differences between the uplift process in craters on crystalline versus mixed targets.

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