SEPM RESEARCH CONFERENCE

The Sedimentary Record of
Meteorite Impacts

Springfield, Missouri
May 21-23, 2005

Abstracts with Program

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PROGRAM

Friday, May 20, 2005

Ice Breaker and Poster Presentations (beginning at 6:00 pm)
Room – Ozark C

The Friday evening poster session is informal, and it will provide the opportunity for extended pre-meeting discussions in a social atmosphere. Refreshments will be available. Poster boards (4 ft by 6 ft) will be placed in Ozark C, on the lower level of the conference hotel, Friday afternoon around 5:00 pm. Presenters are encouraged to set up as soon as possible after this time. Posters will be secured in this room overnight, and they will be made available until Saturday evening, May 21. Please refer to program events for Saturday, May 21 for a list of poster presenters.

Saturday, May 21, 2005

Oral Presentations (8:00 am to 5:30 pm)
Room – Ozark A & B

8:00 am: EVANS, K.R., Introductory Remarks

8:10 am: MELOSH, H.J., The Mechanics of Meteorite Impact Ejection and Sedimentation.

8:50 am: FRENCH, B.M., The Importance of Being Cratered: The New Role of Meteorite Impact as a Normal Geological Process.

9:30 am: MELOSH, H.J., and OSINSKI, G.R., Impact Ejecta Sedimentation Processes.

9:50 am: Break

10:00 am: OSINSKI, G.R., Processes and Products of Meteorite Impacts into Sedimentary Rocks.

10:20 am: BIERHAUS, E.B., and LIPPS, J., Impact Craters on Icy Solar System Bodies as Astrobiological Targets.

10:40 am: BYERLY, G.R., KRULL DAVATZES, A.E., and LOWE, D.R., Petrology and Sedimentology of Mid-Archean Impact-Produced Spherule Beds, Barberton Greenstone Belt, South Africa.

11:00 am: BANET, A.C., A Serendipitous Examination of Well Cores Suggests an Age for the Avak Impact Feature near Barrow, Alaska.

11:20 am: CAMPBELL, C.E., OBOH-IKUENOBE, F.E., and EIFERT, T.L., Is the "Paleocene" Clayton Formation in the southeastern Missouri Portion of the Mississippian Embayment the K/T Boundary Megatsunami Deposit?

11:40 am: SCHULTZ, P.H., ZÁRATE, M., HAMES, W.E., HEIL, C., and KING, J.W., Using the Sedimentary Impact Record in Argentina.

12:00 pm: Lunch break

1:00 pm: LIU, S., and GLASS, B.P., Geographic Distribution of Distal Impact Ejecta Associated with North American Tektite Strewn Field.

1:20 pm: COURTY, M.-A., FEDOROFF, M., GREENWOOD, P., GRICE, K., GUICHARD, F., MERMOUX, M., SCHÄRER, U., SHUKYOLUKOV, A., SMITH, D., and THIEMENS, M., Formative Processes Throughout Lands and Seas of the 4-kyr BP Impact Signal.

1:40 pm: DAVIS, G.H., EVANS, K.R., MILLER, J.F., MULVANY, P.S., and ROVEY, C.W., II, Weaubleau-Osceola, Decaturville, and Crooked Creek: New Aspects of Missouri's 38th Parallel Structures.

2:00 pm: EVANS, K.R., DAVIS, G.H., MICKUS, K.L., MILLER, J.F., and ROVEY, C.W., II, The Weaubleau-Osceola Structure and Weaubleau Breccia–Compiling Evidence of a Marine Impact.

2:20 pm: MILLER, J.F., BOLYARD, S., EVANS, K.R., AUSICH, W.I., ETHINGTON, R.L., THOMPSON, T.L., and WATERS, J.A., Implications of Fossils in the Ejecta Breccia Associated with the Weaubleau-Osceola Structure, St. Clair County, Missouri.

2:40 pm: DULIN, S., and ELMORE, R.D., Paleomagnetism of Impacts in Shallow Water Carbonate Sediments: the Weaubleau-Osceola Impact and the Alamo Breccia.

3:00 pm: Break

3:10 pm: HORTON, J.W., Jr., GOHN, G.S., POWARS, D.S., and EDWARDS, L.E., Origin and Emplacement of Breccias in the Chesapeake Bay Impact Structure, Virginia, USA.

3:30 pm: KING, D.T., Jr., PETRUNY, L.W., and NEATHERY, T.L., Sedimentology of a Late Cretaceous Marine Impact Structure (Gulf Coastal Plain, USA).

3:50 pm: WARME, J.E., and PINTO, J.A., Alamo Enigmas: Too Much Area and Volume, Too Little Crater and Symmetry.

4:10 pm: Break

4:20 pm: DYPVIK, H., WOLBACH, W.S., SHUVALOV, V., and WEAVER, S.L.W., The Barents Sea Floor Ignited by the Late Jurassic Mjølnir Impact.

4:40 pm: KYTE, F.T., GERSONDE, R., and KUHN, G., Detailed Analyses of Deposits of the Eltanin Impact, in Sediment Cores from Polarstern Expedition ANT-XVIII/5a.

5:00 pm: KOEBERL, C., Bosumtwi impact crater, Ghana: Overview of ICDP drilling project.

5:20 pm: Oral presentations conclude. Poster presenters should be available for questions 5:20-6:30 pm.

Poster Presentations (7:30 am to 6:30 pm)
Room – Ozark C

1. AMOR, K., HESSELBO, S., and PORCELLI, D., Geochemical Analysis of a Late Triassic Distal Impact Ejecta Layer From SW England.

2. CONWAY, Z.K., and HASZELDINE, R.S., The Silver Pit North Sea structure, unique or ubiquitous?

3. DAVIS, G.H., The Use of Shallow Geotechnical Drillng to Delineate the Weaubleau-Osceola Impact Structure, St. Clair County, Missouri.

4. DYPVIK, H., MØRK, A., SMELROR, M., TSIKALAS, F., SANDBAKKEN, P.T., BREMER, G.M.A., NAGY, J., and FALEIDE, J.I., The Mjølnir Impact Crater–Core Exhibition.

5. EDWARDS, L.E., Impact Taphonomy: Dinocysts from the Chesapeake Bay Impact Structure, Virginia Coastal Plain.

6. FRISK, Å.M., LINDSTRÖM, M., and HOLMER, L.E., A Marine Impact Crater as an Ordovician Ecosystem; the Tvären Crater.

7. HALDEMANN, A.F.C., KLEINDIENST, M.R., CHURCHER, C.S., SMITH, J.R., SCHWARCZ, H.P., and OSINSKI, G.R., Mapping Impact Modified Sediments: Subtle Remote-Sensing Signatures of the Dakhleh Oasis Catastrophic Event, Western Desert, Egypt.

8. HARRIS, R.S., and SCHULTZ, P.H., Petrographic Signatures of Impacts into Fine-grained, Porous Sedimentary Targets.

9. HARRIS, R.S., RAILSBACK, L.B., RODEN, M.F., and HOLLAND, S.M., Sedimentary Petrology of Upper Eocene Ejecta-Bearing Sands from the Southeastern Coastal Plain.

10. JACKSON, J.C., HORTON, J.W., Jr., CHOU, I-M., and BELKIN, H.E., A Shock-Induced Polymorph of Anatase and Rutile from the Chesapeake Bay Impact Structure, Virginia, USA.

11. JANNETT, P.A., and TERRY, D.O., Jr., A Late Cretaceous Impactite in the Fox Hills Formation of Southwestern South Dakota.

12. KALLESON, E., DYPVIK, H., and NATERSTAD, J., Origin of the Coarse, Clastic Sediments in the Precambrian Gardnos Impact Crater, Norway.

13. KING, D.T., Jr., and PETRUNY, L.W., Sedimentology of Albion Impactoclastic Breccia (Cretaceous-Tertiary boundary section, Belize).

14. MICKUS, K.L., EVANS, K.R., and ROVEY, C.W., II, Gravity and Magnetic Analysis of the Weaubleau-Osceola Structure, Missouri.

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16. POAG, C.W., The Marine Sedimentary Record of Impact Paleoenvironmental Effects: A Field Study at Chesapeake Bay.

17. POWARS, D.S., CATCHINGS, R.D., DANIELS, D.L., PIERCE, H.A., GOHN, G.S., HORTON, J.W., Jr., and EDWARDS, L.E., Anatomy of the Central Crater of the Chesapeake Bay Impact Structure.

18. SANFORD, W.E., Hydrogeology and Hydrochemistry of the Central Crater of the Chesapeake Bay Impact.

19. SELF-TRAIL, J.M., and JUTSON, D.J., Impact Taphonomy: Calcareous Nannofossils From the Silverpit and Chesapeake Bay Impact Structures.

20. STINCHCOMB, B.L., Knob Forming, Distinctive Chert Breccia Boulders of the Central Ozarks, Southern Missouri.

21. WEBER, J.C., POULOS, C., DONELICK, R.A., POPE, M.C., and HELLER, N., An Apatite Fission-Track Age-Determination Attempt at the Kentland Impact Crater, Indiana (USA).

22. WURGLITSH, D.J., ANDERSON, S., and MOSKAL, L.M., Remote Sensing and Geographic Information Systems Technical Workshop: A Hands-On Approach to the Analysis and Potential Discovery of Impact Structures.

Dinner (Buffet) and Reception (6:30 to 7:30 pm)
Room – Ozark A & B

Core and Remote Sensing Workshops (8:00 to 10:00 pm)
Southwest Missouri State University – Temple Hall 335

Sunday, May 22, 2005

Field Trip (Departs 8:00 am from Lamplighter Inn (North))

Geology of the Weaubleau-Osceola Structure, Southwestern Missouri
Field Trip Leaders: Kevin R. Evans and James F. Miller

Monday, May 23, 2005

Field Trip (Optional–$60; Departs 8:00 am from Lamplighter Inn (North))

Geology of the Decaturville and Crooked Creek Impact Structures, Missouri
Field Trip Leaders: Patrick S. Mulvany, George H. Davis, and Kevin R. Evans

Tuesday and Wednesday, May 24-25, 2005

Short Course (Optional–$90; 9:30 am to 4:30 pm)

Traces of Catastrophe: A Course on Impact Shock Metamorphism and Terrestrial Impact Features
Bevan M. French, Smithsonian Institution

ABSTRACTS

GEOCHEMICAL ANALYSIS OF A LATE TRIASSIC DISTAL IMPACT EJECTA LAYER FROM SW ENGLAND

AMOR, Kenneth, HESSELBO, Stephen P., and PORCELLI, Donald

Department of Earth Sciences, University of Oxford, Parks Road, Oxford, OX1 3PR, UK, ken.amor@earth.ox.ac.uk

A distal impactite deposit has recently been reported from a location near Bristol, England. The 0-15 cm thick, discontinuous layer is of Late Triassic age and occurs in a sequence of red calcareous mudstones deposited unconformably on Carboniferous limestone, in a semi-arid, continental environment. It consists of closely packed, millimetre sized green spherules, composed of a green clay surrounding a calcitic or hollow core. They have been inferred to be diagenetically altered type I spherules, formed from quenched impact-melt droplets, deposited aerially from an expanding impact ejecta curtain. The stratum, with a reported ^{39}Ar – ^{40}Ar age of approximately 214 Ma, is coincident with the age of two known impact craters from the Late Triassic, Manicouagan in Canada and Rochechouart in France.

The focus of the present study is to determine if a meteoritic component and projectile type can be identified from this impactoclastic air-fall bed and adjacent strata, using a combination of geochemical analyses - chromium isotope systematics, siderophile and platinum group elemental ratios. In particular, we have developed a new method for the isolation and concentration of chromium, following sample dissolution. Chromium isotope ratios are determined using a multiple collector, inductively coupled plasma, mass spectrometer (MC-ICP-MS) for which the conditions have been established to obtain high precision ratio measurements.

A SERENDIPITOUS EXAMINATION OF WELL CORES SUGGESTS AN AGE FOR THE AVAK IMPACT FEATURE NEAR BARROW, ALASKA

BANET, Arthur C.

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The Avak impact feature near Barrow, Alaska, is located at about N 71° 15’. Exploration wells and interpretations of 2D seismic surveys indicate the Avak feature is at about 1 km. in depth and approximately 20 km. in diameter. The disturbed stratigraphic section encountered by drilling in and peripheral to the crater site results in an estimated age of impact which varies between about 100 (+/-5 my) to as recent as 2 my. The older age coincides with seismically-mapped, massive submarine slumps which occur in the basal portion of the Torok Formation (lower Cretaceous, Aptian to Albian stages). The area of mapped slumps is about 200 km east-southeast of the impact site. However, examinations of core holes from comparatively shallow wells drilled approximately 40 km east of the Avak impact site show there is an assemblage of exotic rock fragments within a section of marine mud and sand. These rock fragments are rounded to angular in shape. They include black shales, red mudstone, chert and quartzite pebbles in sizes up to about 5 cm. These lithologies are representative of the stratigraphic section which was ejected by the Avak event. These exotic rock fragments occur within the marine mudstone of the Seabee Formation (Coniacian and younger) and within poorly sorted, disorganized sands which lack sedimentary structures. The sands may represent chaotic deposition, such as might occur coincidental with a nearby marine impact. Or, the sands may be the upper portion of the Nanushuk Formation (uppermost(?) Albian). If these exotic clasts prove to be ejected debris from the Avak event, then it is younger than the large scale submarine slumps in the basal portion of the Torok Formation.

IMPACT CRATERS ON ICY SOLAR SYSTEM BODIES AS ASTROBIOLOGICAL TARGETS

BIERHAUS, Edward B.[1] and LIPPS, Jere H.[2]

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Impact craters are prime astrobiological targets on icy bodies with oceans below the ice. Craters are natural probes to subsurface materials; hence they may expose fossils, biochemicals, biomarkers, and biotextures, as well as a stratigraphic record of life habitats. Impacts create exposures of the crust in the crater walls, overturned ice, and ejecta. Larger craters excavate deep interior ice in the central peaks, which may rise from between solid ice and liquid water. The largest craters, with concentric rings and flat floors (which may contain frozen water from below the ice), might expose ice, water column, and benthic habitats through the full depth of the ice shell, and perhaps from the liquid ocean.

Craters immediately deliver sub-surface materials to the surface, in contrast to endogenic processes that likely operate over days to thousands or more years. The longer time scales of endogenic processes could allow extant life to migrate from their habitats to other marginal regions or to die and degrade. A sub-surface lens of melt water created by impact may remain for up to thousands of years after the initial crater formation. Life could rapidly exploit and abandon these habitats as they form and disappear, so these sub-surface melt-lenses may serve as locales of biological activity or repositories for fossils as they freeze.

The average surface age of the icy Galilean satellites differ significantly, with consequences for recent exposure of any biological activity. Europa has a dynamic icy crust younger than about 60 million years, whereas Ganymede has regions of cratering that may be billions of years old, while Callisto's surface has craters formed early in solar system history. If Ganymede and Callisto have briny oceans far beneath their thicker icy crusts, excavation to them requires larger, less frequent, and thus generally older impacts. The surfaces of the larger, older craters have been processed by subsequent impacts, tectonic activity, or sputtering, all of which could mask clues to excavated biological signatures. Future missions to icy bodies should explore impact craters – particularly large craters that excavated deeply through icy crusts – as priority targets for astrobiology, using high spatial- and spectral-resolution capability instruments.

PETROLOGY AND SEDIMENTOLOGY OF MID-ARCHEAN IMPACT-PRODUCED SPHERULE BEDS, BARBERTON GREENSTONE BELT, SOUTH AFRICA

BYERLY, Gary R.[1], KRULL DAVATZES, Alexandra E.[2], and LOWE, Donald R.[2]

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At least four unusual sedimentary layers in mid-Archean sequences from South Africa and Australia provide evidence for very large impacts on the early Earth (Lowe and Byerly, Geology, 1986). This evidence includes: (1) a heterogeneous particle assemblage within these layers that have melt droplet shapes and internal quench textures; (2) layers that represent unusually energetic events in otherwise low energy environments; (3) large Ir anomalies, in beds 30 cm thick, that indicate bolides were up to 50 km in diameter (Lowe et al., Science, 1989); (4) Ni-rich spinel and impact layer compositions that suggest chondritic bolides and target that was dominantly oceanic basalt (Byerly and Lowe, GCA, 1994); and (5) chromium isotopic anomalies that confirm an extraterrestrial component in these deposits, and carbonaceous chondrite bolides that were 20-50 km in diameter (Shukolyukov et al., Byerly and others 2002, Science) report precise U-Pb isotopic ages for the oldest impact layers observed in both South Africa and Australia at 3470 +/- 2 Ma, suggesting they were formed by a single global event. A second cluster of at least three large impact events is recognized in South Africa at 3260-3240 Ma (Byerly et al., Precamb. Res. 1996; and Lowe et al., Astrobiology, 2003). Two of these impacts mark major stratigraphic boundaries and abrupt transitions from mafic-ultramafic volcanism of the Onverwacht Group to dacitic volcanism and orogenic sedimentation of the Fig Tree Group. All these impacts were large, comparable to those of Moon's Late Impact Cataclysm (Tera et al., EPSL, 1974; and Ryder, Eos, 1990) at circa 3850 Ma, and likely had a profound influence on the course of early physical and biological evolution. These mid-Archean layers provide examples of a number of important sedimentary phenomena related to large-scale impacts: (1) impact-generated fallout that is spread over a large region and into a variety of very different sedimentary environments; (2) shallow-water settings that display erosional and depositional features likely the result of large impact-tsunamis; and (3) early diagenesis of fallout layers that preserves in remarkable detail textures of impact melt or condensate droplets, but significantly modifies the original mineralogy and chemistry.

IS THE "PALEOCENE" CLAYTON FORMATION IN THE SOUTHEASTERN MISSOURI PORTION OF THE MISSISSIPPI EMBAYMENT THE K/T BOUNDARY MEGATSUNAMI DEPOSIT?

CAMPBELL, Carl E.[1], OBOH-IKUENOBE, Francisca E.[2], and EIFERT, Tambra L.[2]

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Crowleys Ridge in southeastern Missouri preserves Cretaceous to Paleogene marginal marine sediments deposited in the northwest portion of the Mississippi Embayment. Sandwiched between the Paleocene Porters Creek Formation and the uppermost Cretaceous Owl Creek Formation is the "Paleocene" Clayton Formation. We located, excavated four deep trenches, and sampled a complete section of the Clayton Formation at a large kitty litter strip mine in Stoddard County, Missouri. One trench was cut five meters deep through the Clayton Formation, the Owl Creek Formation and into underlying Cretaceous McNairy Formation. The Clayton at this location consists of 180 cm of graded tsunami carbonate deposit, the lower part of which includes large Owl Creek rip-up clasts containing layers of microtektites, invertebrate fossils, and abundant marine dinoflagellate cysts. We also analyzed 50 driller's logs and 23 e-logs covering approximately 3,500 square miles. Well data confirms the consistent thickness and lithology of the Clayton Formation in this part of the Mississippi Embayment. Much work still needs to be done, but we interpret the Clayton formation in northwest Mississippi Embayment to be a megatsunami deposit resulting from post-impact effects associated with the Chicxulub impact event.

THE SILVER PIT NORTH SEA STRUCTURE, UNIQUE OR UBIQUITOUS?

CONWAY, Zana K., and HASZELDINE, R. Stuart

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The origin of the 20 km diameter circular Silverpit structure, southern North Sea offshore basin has been contested since its discovery in 2002. Despite rival explanations of meteorite crater, salt withdrawal, or pull-apart basin with mud diapir, no definitive evidence is available to confirm the origin of the structure. Since there is a lack of rock material to carry out mineralogical and geochemical analysis to confirm the meteorite crater hypothesis, other methods are being developed which, although not conclusive, may bring us closer to an explanation for this structure. A 3D seismic data set, the southern North Sea mega-merge survey, has been used in attempt to test the uniqueness of the structure. Three principal horizons, the Cretaceous top Chalk, the Permian top Zechstein and the top Carboniferous unconformity were mapped and a series of criteria developed to look for similar structures throughout the 7000 km^2 area available on this survey. The criteria included looking for large-scale features such as: synclines of a similar scale and structural setting, as well as smaller scale features such as, ring faults, a missing top Cretaceous reflector and base Cretaceous uplift within the crater. Three similar synclines were identified when the large-scale criteria were applied to the surface maps. However, Silverpit is the only structure which fulfills all of the small-scale criteria and as such can now be considered as a unique structure in the southern North Sea basin. Therefore unlike salt withdrawal synclines, which occur in groups, this implies a unique origin.

FORMATIVE PROCESSES THROUGHOUT LANDS AND SEAS OF THE 4-KYR BP IMPACT SIGNAL

COURTY, Marie-Agnès[1], FEDEROFF, Michel[2], GREENWOOD, Paul[3], GRICE, Kliti[3], GUICHARD, Françios[4], MERMOUX, Michel[5], SCHÄRER, Urs[6], SHUKYOLUKOV, Alex[7], SMITH, David C.[8], THIEMENS, Mark[9]

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The co-occurrence in distant regions of flow-glass debris with similar petrographical and geochemical characteristics, and a distinctive heated soil surface identified the distal dispersion of an impact ejecta at about 4-kyr BP. The aims of the present study are to further elucidate the spatial pattern and related processes of this atypical impact. The facies, petrography and geochemistry of the 4-kyr BP distinguishing features are compared from sedimentary records in soils, ancient habitations, lakes and deep-sea cores in various regions of the Northern and Southern hemisphere. The best-preserved record of the ejecta dispersion is observed in continental deposits at specific locations where the 4kyr-BP impact-related surface were rapidly buried. These nearly intact signals have allowed us to recognize three diagnostic tracers of the 4-kyr BP impact ejecta: (1) glassy to re-crystallized debris produced from melting/vaporisation of mixed mineral sources; (2) a suite of carbonaceous polymorphs produced from melting of terrestrially-sourced organic compounds : nano-sized diamonds, graphitic carbon, amorphous carbon with polycyclic aromatic hydrocarbons (PAHs) species; (3) exotic carbon-linked metallic residues (Cr, Pb, Fe, Ni, Ag), certified to be of terrestrial origin from their isotope ratios. Evidence for heating to selective melting of the host materials appears to result from incorporation along grain boundaries and pore spaces of carbon-rich flow-glass, and interaction of the carbonaceous polymorphs with the local carbonates. The thermal decomposition of organic sources explains the occurrence of a CO_2-rich volatile component in an impact ejecta. Spatial variability of the interaction between the ground surface and the ejecta suggests heterogeneities of the impact fluidised bed, combined with the reactivity of surface materials to flash heating. The erratic abundance of fresh ejecta debris in the marine records that are not altered by bioturbation or secondary transport, is consistent with fallout of the ejecta as distinct hot masses. The similar variability of the 4-kyr BP signal within a micro-region and between distant regions reinforces the hypothesis of a widespread ejecta dispersion, possibly global. A distinctive spatial pattern that would allow locating the potential impact area still remains to be identified.

THE USE OF SHALLOW GEOTECHNICAL DRILLING TO DELINEATE THE WEAUBLEAU-OSCEOLA IMPACT STRUCTURE, ST. CLAIR COUNTY, MISSOURI

DAVIS, George H.

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During the year 2003, geotechnical drill rigs owned by the Missouri Department of Transportation were used to core rock along Missouri state right-of-way in cooperation with Southwest Missouri State University. Information made available from this drilling joint venture allowed researchers to test hypotheses concerning the Weaubleau-Osceola structure, and later to obtain reference cores at the Decaturville Impact Structure. During the course of the investigation, depth to economically valuable asphalt and concrete paving stone was found, the relative overall stability of rock underlying state highways was examined, and representatives of a well-known and internationally respected drilling mud company made themselves available to conduct specialized training for the drilling crews. Cooperative joint ventures of this type are encouraged at other impact sites, if timing allows and funding for researchers is limited. MoDOT used Failing 1500 "Holemaster"–type rigs, which are manufactured by the George E. Failing Company of Enid, Oklahoma.

Two different types of coring methods were used to compare tooling effectiveness. A ten-foot core barrel and a five-foot wire-line core recovery system were used and compared. Three different types of coring bits were used–a triplegrooved, high-speed capable diamond-impregnated coring bit; a standard surface-set diamond impregnated coring bit, and a shale-ripping coring bit. The type of coring bit used depended upon the subsurface conditions encountered. The high-speed bit was most useful for limestones containing chert, the surface-set bit was most useful for general work, and the shale bit was used primarily when shale was encountered, such as at the MoDOT-Vista No. 2 core hole. The five-foot wire-line recovery system with the high-speed bit configuration achieved the greatest productivity. Water was the primary drilling fluid used throughout all coring. Water consumption varied from approximately 600 gallons to over 5000 gallons at a single core hole. Baroid E-Z mud, manufactured by Baroid Industrial Drilling Products, was used in only one of the 8 holes drilled. Drill bit down-pressures were monitored. Boart-Longyear Series 6 and Series 8 diamond bits were used for coring in limestone.

WEAUBLEAU-OSCEOLA, DECATURVILLE, AND CROOKED CREEK: NEW ASPECTS OF MISSOURI'S 38TH PARALLEL STRUCTURES

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Anomalous geological structures along the 38th parallel have a long and controversial history. Proponents of both endogenic and exogenic origins have argued the merits of each structure based on the geologic age constraints, their linear relationship, and presumed common origin. A growing body of literature now documents the criteria for recognizing meteoritic impacts, and two of the 38th parallel structures are regarded as bona fide impact structures. Decaturville and Crooked Creek structures are listed in the Earth Impact Database (EID); both contain shatter cones, and planar deformational features (PDFs) have been reported from Decaturville. The Weaubleau-Osceola structure is not currently part of the EID, but strata in and around the two eccentric circular topographic features have been heavily deformed, brecciated, and uplifted up to 400 m locally. Planar fractures (PFs) and decorated planar deformational features (PDFs) are present in breccias, but they have not yet been thoroughly documented petrographically. One shatter cone has been recovered from core. Evidence clearly supports the hypothesis that this is an impact structure, but much more work is needed to adequately describe and assess the stratigraphic record of this event. Conodont age constraints from breccias in the Weaubleau-Osceola structure indicate that it is latest Osagean in age. Exquisite preservation of articulated fossil specimens and lack of crinoid grainstone clasts in the breccia supports the idea that it was a marine impact. The age of the Decaturville structure is poorly constrained (<300 Ma in EID). Conodont ages indicate that it is post-Silurian in age. Strata younger than Lower Ordovician have mostly been removed by erosion. Recent collection of Mississippian fossils from the Crooked Creek (320 ±80 Ma in EID) structure may place its age in question. Provisional re-mapping and petrographic studies of Crooked Creek also revealed blocks of Lamotte Sandstone, a Cambrian unit which previously was not recognized in the structure. These three structures lie along azimuth 93.1° ± 0.2°. The distance from Weaubleau-Osceola to Decaturville is 85 km, and Decaturville to Crooked Creek is 105 km. The structures are co-linear; at this time, nothing precludes the possibility of their synchronicity.

PALEOMAGNETISM OF IMPACTS IN SHALLOW-WATER CARBONATE SEDIMENTS: THE WEAUBLEAU-OSCEOLA IMPACT AND THE ALAMO BRECCIA

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The objective of this study is to investigate two impact features in carbonate rocks to develop a model that can be used to constrain the age of impacts and provide insights on the sedimentary processes involved during impact events. The Weaubleau-Osceola impact structure contains deformed Mississippian limestones and a fall-back breccia. Its age is stratigraphically constrained between deposition of the deformed Osagean limestones and the overlying undeformed Pennsylvanian (Desmoinesian) units. Paleomagnetic samples were collected from tilted

Burlington Formation inside the structure, the same unit outside the structure, and the fall-back breccia. Demagnetization of tilted limestone samples reveals a characteristic remanent magnetization (ChRM) with southeasterly declinations and shallow positive inclinations that have median destructive field of 20-30 mT, and maximum unblocking temperatures of 450ºC. The ChRM resides in magnetite and is post folding. The pole falls near the Mississippian part of the apparent polar wander path (APWP) and refines the age of the impact compared to the stratigraphic age. Few of the fall-back breccia samples contain the ChRM but most contain a Modern component. Most of the samples from outside the structure contain a Modern component, although some contain a possible late Paleozoic component. The post-deformational ChRM is not a shock magnetization and several models for its origin are being investigated. A chemical remagnetization related to impact-generated hydrothermal activity is not considered likely because the deformed rocks do not have a distinctive geochemical signature compared to other rocks in Missouri. A post-depositional remanent magnetization (pDRM) is possible if the impact occurred in wet sediments with fluid filled pores. A magnetization associated with acoustic fluidization where shock waves that moved through the already deformed sediments caused alignment of the magnetic grains is also possible.

The Late Devonian Alamo Breccia, a mega-breccia located in Nevada, is interpreted as forming during an impact event on the shallow carbonate platform. Preliminary results from the breccia in the Pahranagat Range indicate it contains a ChRM residing in magnetite. The pole for the ChRM is close to the Late Devonian part of the APWP which is consistent with the age of the breccia. This magnetization is interpreted to be a DRM that formed during deposition or a pDRM that formed after deposition.

THE MJØLNIR IMPACT CRATER–CORE EXHIBITION

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The 40 km in diameter impact structure is presently located on the Bjarmeland Platform below a cover of 50 to 150 m of Quaternary beds and 350 m of water. Based on detailed geophysical investigations and more than 2000 km of seismic lines, the geometry from the sea bed and down to 6 km depth has been described and discussed in detail. The Mjølnir Crater is a complex crater with a central peak, annular basin and a modestly developed, partly eroded crater rim. The main features are a 12 km wide outer zone, including a marginal fault zone and a modestly elevate ring, a 4 km wide annular depression and a prominent central peak (250 m above the crater floor) with an 8 km diameter.

The Mjølnir Crater was formed by the impact of a 1.5 to 2 km in diameter bolide into the 300 – 500 m deep paleo-Barents Sea. The impact direction has been indicated from S – SSW. Geophysical studies have shown crater with a lower autochotonous/paraautochtonous breccia of about 2.5 to 3 km thickness and an overlying allocthonous breccia of 1.0 to 1.5 km. These units are overlain by up to 0.5 km of post impact sediments of which ~ 50 m are Quaternary beds.

In 1998 the crater was drilled and a 171 m long core (7329/03-U-01) was retrieved from the central peak of the crater. This core and related detailed geological analyses, formed the base for a series of studies. Based on these studies (macro-, micro-paleontology and palynological analyses), in combination with detailed seismic investigations, the impact has been shown to be of Berriasian age (Berriasella Jacobi Zone), 142 ± 2.6 myr. So far, no well preserved impact glass (for radiometric dating), has been found, as this was most likely altered to smectitic clay minerals. The Mjølnir sedimentary succession, slumps, debris- and suspension- flow deposits, developed as a wedge within the dark grey shales of the Hekkingen Formation, has been named the Ragnarok Formation, parts shown in this exhibition.

Numerical simulations show that the major part of the Mjølnir crater formation took place within 5 minutes and that the pre-impact water level in the crater area was re-established after about 20 minutes. During this time the sea bed was more or less exposed and its highly organic rich, late Jurassic sediments (Hekkingen Formation) were ignited. The central peak formed an island in the paleo-Barents Sea for several hundred years after impact.

THE BARENTS SEA FLOOR IGNITED BY THE LATE JURASSIC MJØLNIR IMPACT

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During Middle and Late Jurassic times, large parts of the present Arctic were covered by a 400 – 600 m deep epicontinental sea, where organic rich clays were deposited below more or less anoxic bottom water conditions. These dark grey, finely laminated shales of to day, the Hekkingen Formation, makes up the main source rock for oil and gas in this part of the Arctic. These shales also formed the sea bed in the target area at the Late Jurassic Mjølnir marine impact. At that time, paleogeographical reconstructions indicate that the closest land areas to be several hundred kilometers away.

The possible 100 to 150 m succession of these organic rich shales were hit by the about 2 km in diameter Mjølnir bolide. Numerical simulations show that the sea floor was probably exposed for about 20 minutes, before the sea water returned permanently to the location. The numerical information in addition shows that a 6-8 km in diameter region reached high enough temperatures for ignition to take place.

We suggest that the richness of organic matter, its dominate composition of type II kerogen and highly volatile components, made it easy to ignite. The result was a short, extreme, and intense fire of the seafloor. This theory is also supported by numerical simulations of heat distribution at the impact site and can explain the large quantities of soot that have been found in samples associated with Mjølnir post-impact sediments. In the studied samples up to 30,000 ppm of soot have been found in the immediate post-impact beds both close to the crater and 500 km away.

IMPACT TAPHONOMY: DINOCYSTS FROM THE CHESAPEAKE BAY IMPACT STRUCTURE, VIRGINIA COASTAL PLAIN

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The taphonomic aspect of the sedimentary record of meteorite impacts has only recently begun to receive attention. In the case of the Chesapeake Bay impact, dinocyst taphonomy includes initial deposition, shock, heat, ejection into the atmosphere, tsunami and resurge transport, secondary deposition, exhumation, transport, and third-time deposition. This impact produced mixed assemblages of fossils that otherwise do not occur together in either time or space. The extreme conditions that produce shocked minerals, tektites, and shatter cones produced bubbled and beaded dinoflagellate cysts and welded organic material that is here informally termed "dino-ignimbrite." Broken (but not melted) dinocysts of mixed ages have confirmed sediment-injection deep in a zone of megablocks.

Dinocysts are composed of a wax-like hydrocarbon called dinosporin. Observed anomalous preservation includes beading, breaking, bubbling, clumping, curling, folding, fusing, melting, and pitting, in various combinations. Some preservation types and combinations of types are unique to impact origins. Other types, while not unique, give clues as to the temperature and pressure regimes under which they formed. Unlike mineral grains, however, dinocysts convey both age and environmental information related to the parent sediments. This information helps to locate the provenance of parent sediments, both laterally and vertically, in the impact excavation. Millions of years later, like the Georgia tektites, impact-damaged dinocysts have also been reworked into younger, postimpact sediments.

For the Chesapeake Bay impact structure, the distinctive mixed-age dinocyst assemblages led directly to the recognition of the areal extent of the sedimentary-clast breccia known as the Exmore beds before the impact origin was confirmed. Anomalous dinocyst preservation, first noted in 1982, was linked to the impact nearly 20 years later.

Distinctively damaged microfossils should be added to the list of impact products in the sedimentary record. Specific types of preservation should be calibrated experimentally and used to indicate temperature, pressure, or other conditions relating to impact history. Age and environmental interpretations of microfossils should be used to relate final depositional sites to original target sources.

THE WEAUBLEAU-OSCEOLA STRUCTURE AND WEAUBLEAU BRECCIA–COMPILING EVIDENCE OF A MARINE IMPACT

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The structural disturbance around Weaubleau Creek in southwestern St. Clair County, Missouri has been known for more than fifty years, but it had not been reexamined until recently. Computer mapping has revealed a circular drainage feature, 19 km in diameter, with a second circular feature in its southwestern part that is 9 km in diameter. The 19-km feature is coincident with the limits of deformed strata. Locally, strata are displaced 5-60 m along peripheral faults, marking the tectonic rim. The small circular feature, which marks "ground-zero" of the structure, coincides with the main outcrop area of the "Weaubleau Breccia".

In surface exposures, this informal stratigraphic unit is a yellow-weathering carbonate-rich polymict breccia. Clasts range from a 0.2-200 mm and are supported by fine carbonate matrix. Clasts include siltstone from the Northview Formation (lower Mississippian, Kinderhookian), dolomitic mudstone from the Cotter Formation (lower Ordovician, Ibexian), angular chert, and abundant echinoderm debris. Spherical chert nodules in the breccia, which formed diagenetically around siltstone clast nuclei, mark the lateral extent of the facies. We interpret this facies as an ejecta and resurge unit.

Fossils from this facies are mixed in age and include excellently preserved Osagean crinoid and blastoid calyces and articulated stem pieces. Conodonts recovered from the breccia are also of mixed ages and include Ibexian, Kinderhookian, early Osagean, and late Osagean forms. Quarry exposures and cores of strata below this upper polymict breccia facies consist of autoclastic and cataclastic breccias that are parautochthonous and mixed with poorly sorted polymict facies that we interpret as injection breccia. Conglomeratic granitic basement and possible melt rock were recovered at 61-76 m depth during core drilling on the margin of the inner circle.

Crystalline basement is typically at 350-450 m depth in this area, so these rocks were uplifted ~300 m locally. Thus far, the strongest evidence supporting an impact origin includes a single shatter cone recovered from drill core. Abundant quartz grains from the breccia contain multiple directions of planar fractures (PFs) and more rarely decorated planar deformational features (PDFs). However, at present these have not been studied in great detail.

THE IMPORTANCE OF BEING CRATERED: THE NEW ROLE OF METEORITE IMPACT AS A NORMAL GEOLOGICAL PROCESS

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The young field of meteorite impact geology has passed through several stages: disregard, controversy, media attention, and gradual acceptance by geologists. Impact geologists no longer have to justify the ideas that meteorite impacts do occur, that such impacts produce major geological and biological effects, or that the resulting impact structures can be unequivocally identified. The challenges today are different: to determine the full range of impact effects preserved in the geological record of the Earth, to continue the merger of impact geology with mainstream geosciences, and to promote communication and education about meteorite impact to the larger geology community and the public.

A particularly exciting trend, especially during the last decade, has been the frequent and unexpected discovery of major impact effects in the geological record, often by traditionally trained geologists doing conventional geological investigations. Examples include: (1) discovery of the 85-km-diameter Chesapeake Bay structure from geophysical and hydrological studies; (2) recognition that the widespread Alamo Breccia (Nevada) reflects the impact-induced collapse of a shallow continental platform; (3) discovery of spherule layers, especially in Precambrian rocks, which may represent ejecta from ancient, distant, and possibly destroyed impact structures.

In related developments, other geologists have begun to use well-constrained and well-studied impact structures as "laboratory experiments" to explore fundamental geological processes: (1) cooling and crystallization of large, instantaneously-generated bodies of igneous melt (at Sudbury, Canada); (2) post-impact hydrothermal activity (e.g., at Haughton, Canada), which has implications for the formation of ore bodies and for the origin of life in suitable warm and sheltered environments.

A personal view of some areas where future impact studies could make major contributions to conventional geological problems include: (1) comparative studies between low-level (<7 GPa) shock deformation of quartz (commonly expressed as multiple cleavage sets) with tectonic deformation of quartz at comparable stress levels; (2) the nature, origin, and significance of bulk organic carbon ("kerogen") in some impact structures (Gardnos, Norway and Sudbury, Canada) and the implications of this material for possible biogenic processes related to meteorite impact events.

The field of impact geology is now at an exciting watershed between its past emphasis on the geology and history of other planets and a new and growing focus on the record of impact events preserved in terrestrial rocks. In addition to continuing impact geology studies, it is essential to improve communications between impact geologists and others and to expand the teaching of impact geology in standard geological curricula (the graduates may unexpectedly run across an impact structure in their future work). As these trends continue, we can look for more exciting and unexpected insights into the history of the Earth to appear.

A MARINE IMPACT CRATER AS AN ORDOVICIAN ECOSYSTEM: THE TVÄREN CRATER

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The Tvären crater was formed as a result of an impact in the Ordovician Baltoscandian epicontinental sea, now situated in the Stockholm Archipelago, Sweden. The bolide impact resulted in an approximately 2 km wide crater and the pre-impact sedimentary sequence consists of Ordovician carbonates resting on non-lithified sands of Early to earliest Middle Cambrian age. After the impact event and the settling of the impact ejecta and resurge material, deposition of carbonates continued (Dalby Limestone). The lithology and thickness of the post-impact Dalby Limestone vary depending on the depositional environment relative to the cratered seascape. The crater itself acted like a sheltering rim for the deposition of sediments, also causing a fairly rapid sedimentation rate compared to the normal sedimentation of the Dalby limestone. The area consequently displayed pure new settings for the marine fauna still living in the surrounding sea, though not affected by the impact, and thus creating a new ecosystem. This particular condition makes it possible to get a good precision of the sedimentation and faunal succession occurring in the crater. Drillings in the Tvären crater were conducted in 1991 resulting in an almost complete drill core through the sedimentary succession in the crater. The base of the core consists of crystalline breccia followed by resurge deposits and then the sedimentation of the Dalby Limestone. The post-impact fossil fauna mostly consists of chitinozoans, graptolites, trilobites, bryozoans, ostracodes, echinoderms, cephalopods and brachiopods. Certain groups are restricted to deeper or lower water levels, varying during the sedimentation, while some occur throughout the succession. A detailed biostratigraphy through the post-impact succession of the drill core is being conducted to understand how the abundance of species changed in relation to the varied environments and how the pre-impact faunal groups recovered gradually as life returned onto a sterile seafloor.

MAPPING IMPACT MODIFIED SEDIMENTS: SUBTLE REMOTE-SENSING SIGNATURES OF THE DAKHLEH OASIS CATASTROPHIC EVENT, WESTERN DESERT, EGYPT

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Over the past decade members of the Dakhleh Oasis Project have studied enigmatic signatures in the Pleistocene geologic record of portions of the Dakhleh oasis and palaeo-oasis. In particular, Ca-Al rich glass melt (Dakhleh Glass) points to a catastrophic event between c. 100,000 - 200,000 years ago in this well-studied African savannah and freshwater lake Middle Stone Age environment. The wide extent of glass deposits, over tens of kilometers, suggest multiple, co-eval impacts or airbursts. Here we report on mapping of remote sensing data (visible, infrared and radar) that is being used to guide wider reconnaissance of the Dakhleh Glass deposits. The remote sensing is anchored on the best-studied element, the Dakhleh Bow Wave Structure (DBWS), where structural elements of a ~400 m cratering event are preserved. These structures are nevertheless highly degraded, and not directly apparent in the remote sensing data. The Dakhleh Glass, while chemically quite unique, is nowhere very extensive, and is thus only a minor constituent in each remote sensing pixel; we attempt to identify its presence by calibrating to the known occurrence locations near the DBWS. Clearly, these subtle remote-sensing signatures of the relatively recent impact(s) into a sedimentary target at Dakhleh, where the erosion rate is estimated at 0.1 mm/yr, underscore the difficulty in accumulating a clear characterization of the range of sedimentary target modifications associated with smaller (100 m - 1 km) terrestrial craters.

SEDIMENTARY PETROLOGY OF UPPER EOCENE EJECTA-BEARING SANDS FROM THE SOUTHEASTERN COASTAL PLAIN

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Traditional sedimentary petrology often utilizes QFL compositional data to infer changes in the sources of sediment to siliciclastic basins through time. In the simplest case, quartz arenites record deposition along a passive continental margin. The appearance of more feldspatho-lithic strata in a succession suggests episodes of increased uplift. A large meteorite impact in or near the hinterland can create circumstances capable of mimicking the effects of tectonism on QFL distributions. In addition to the direct fallout of debris into the basin, such an impact could blanket vast upland areas with a significant volume of sand-sized ejecta susceptible to rapid erosion and redeposition. As a secondary effect, widespread devegetation could boost regional sedimentation rates for a brief time following the collision.

Previously we have demonstrated that a lag deposit near the base of the upper Eocene Dry Branch Formation in east-central Georgia contains ejecta (shocked quartz and possibly shocked zircons) most likely associated with the Chesapeake Bay impact event (~36 Ma). QFL data from this horizon differ from data compiled from other upper Eocene SE Coastal Plain sands, which have quartz arenite compositions. The ejecta-bearing layer contains 15-20% more feldspar and 15-20% more lithic grains but only in the very fine and fine-sand size fractions (65-250 mm) of the sediment–the same fractions in which we find the shocked minerals. Feldspar grains typically show evidence of extreme deformation, but unique shock indicators have not been identified. The lithic components are chiefly zircon and staurolite grains (euhedral grains and broken fragments) with fewer amphiboles (some exhibiting mechanical twinning) and opaque oxides. The QFL data suggest the hypothesis that some of the feldspars and lithic grains in the impact horizon were contributed from the ejecta. The possibility that QFL distributions in thick siliciclastic successions may reflect the influence of some large impact events should be considered by sandstone petrologists and impact stratigraphers.

We also will present updates concerning the general petrology, sedimentology, and stratigraphy of the impact horizon including the possibilities and difficulties associated with connecting the distal and proximal ejecta from the Chesapeake Bay event.

PETROGRAPHIC SIGNATURES OF IMPACTS INTO FINE-GRAINED, POROUS SEDIMENTARY TARGETS

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Deposits of fine-grained, loosely-consolidated, and porous sediments cover significant regions of the Earth's continents and their margins. It is rare that a continental impact does not breach at least a veneer of these materials, and some excavate very thick sequences of detritus. Craters produced in such sediments can be rapidly modified by settling, erosion, and burial beneath materials identical to those in which they were formed. Consequently, the scars of these collisions may be exceedingly difficult to recognize. Therefore, if we seek to read the complete record of terrestrial impacts, it is important that we be capable of recognizing the proximal and distal ejecta from these events where they punctuate the stratigraphy.

Vesicular glasses preserved in the thick loessoid sediments of the Argentine Pampas provide an excellent opportunity to study the products of impacts into fine-grained sedimentary targets. The ages, extents, abundances, and geologic settings of these glasses together with petrographic evidence of extremely high transient temperatures (e.g., baddeleyite and lechatelierite) and rapid quenching support the interpretation that they represent as many as seven impacts occurring since the late Miocene. Unequivocal shock indicators, such as planar deformation features (PDFs), previously have been reported for the most recent Rio Cuarto event (2-6 ka). Here we present additional evidence of shock deformation in mineral grains contained in the 450 ka Centinela del Mar and 3.3 Ma Mar del Plata glasses. We have observed diaplectic glass, PDFs, and other unusual planar features in plagioclase and alkali feldspars. We also report the occurrence of ballen quartz and possible shock-induced mechanical twinning in ilmenite grains. Shocked minerals in these glasses not only give us a way to confirm an impact origin, they also demonstrate the range of deformation we might expect from impacts into similar target materials. These signatures might also be found in loose grains that either escape entrainment in melt breccias or survive the dissolution or alteration of host glass.

We also have performed shock experiments into loess and simulated sedimentary targets. We will present the preliminary results and compare them with the deformation observed in the pampean glasses.

ORIGIN AND EMPLACEMENT OF BRECCIAS IN THE CHESAPEAKE BAY IMPACT STRUCTURE, VIRGINIA, USA

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The buried late Eocene Chesapeake Bay impact structure is the Earth's best-preserved large impact structure formed in a dominantly siliciclastic marine-shelf environment. The 85-km "inverted-sombrero" consists of a central crater and surrounding annular trough formed in a complex layered target of seawater, sediment, and rock. Impactites, including those informally called "Exmore breccia," include: (1) polymict crystalline-clast suevite and monomict brecciated rocks of the central crater, (2) impact-modified autochthonous to parautochthonous sediments of the annular trough, and (3) allogenic sediment-clast breccias deposited over the entire structure and nearby areas.

Suevitic breccia contains metamorphic and igneous rock fragments and less abundant particles of impact-melt rock. Monomict brecciated gneiss occurs as megablocks (some >10 m). The suevite is interpreted as a pre-resurge fallback deposit that contains blocks from the central-uplift basement.

Impact-modified sediments in the outer annular trough include autochthonous to parautochthonous, block-faulted Lower Cretaceous fluvial sediments that are locally fluidized in their upper part. These are overlain by parautochthonous blocks of collapsed Lower and Upper Cretaceous sediment disrupted by faults, fluidized sands, fractured clays, and zones of injected sediments that include exotic particles of disaggregated Upper Cretaceous and lower Tertiary target sediments. Deformation increases upward. This impact-modified section formed in response to acoustic waves (vibrations) and subsequent gravitational collapse.

Allogenic sediment-clast breccias, known informally as the "Exmore beds," consist of mixed-age sediment clasts and minor crystalline-rock clasts in a muddy quartz-glauconite sand matrix. These 8- to 400-m-thick sedimentary breccias overlie the other impactites and pre-impact deposits. They are interpreted to be seawater-resurge deposits influenced by turbulence, current oscillations, and tsunamis. The sediment-clast breccias grade upward into a zone of fine sand and silt, which grades conformably into postimpact marine sediments, indicating no erosion of the impactites since their initial burial. Absence of a proximal ejecta layer beyond the central crater may be due, in part, to resurge erosion.

A SHOCK-INDUCED POLYMORPH OF ANATASE AND RUTILE FROM THE CHESAPEAKE BAY IMPACT STRUCTURE, VIRGINIA, USA

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A shock-induced polymorph of anatase and rutile has been identified in breccias from the late Eocene Chesapeake Bay impact structure. The breccia samples are from a recent, partially cored USGS test hole in the central uplift of the impact structure at Cape Charles, Virginia. The drill cores from 744 m to 823 m depth consist of suevitic crystalline-clast breccia and brecciated cataclastic gneiss in which TiO_2 phases, including anatase and rutile, are common accessory minerals. Electron-microprobe analysis and imaging indicate that the TiO_2 occurs as individual crystals in the matrix, as equant and lenticular inclusions in chlorite, and as patchy inclusions in titanite. Laser micro-Raman spectroscopy on crystals, and powder X-ray diffraction (XRD) of mineral separates, confirm that a rare, high-pressure, α-PbO_2 structured polymorph of TiO_2 is present in these rocks. This polymorph coexists with anatase and rutile in varied proportions in the matrix-hosted crystals and in inclusions within chlorite, but not in the inclusions in titanite. Raman spectra of the high-pressure TiO_2 polymorph include strong bands at wave numbers (cm^{-1}) 236, 259, 281, 312, 338, 352, 422, 531, 569, and 604. Anatase bands at 397, 512, and 634 cm^{-1}, and rutile bands at 441 and 608 cm^{-1} appear with bands of the TiO_2 polymorph in Raman spectra of numerous grains. XRD patterns reveal 12 lines from the polymorph that do not significantly interfere with those of anatase or rutile at the following d-spacings (Å): 2.845, 2.749, 2.455, 2.391, 2.269, 2.160, 2.116, 2.008, 1.829, 1.401, 1.396, and 1.393. The d-spacings and Raman spectra are both consistent with the α-PbO_2 structured TiO_2 polymorph that was first reported to occur naturally as a shock-induced phase in rutile from suevite of the Ries Crater in Germany. This second report of a natural shock-induced occurrence of a TiO_2 polymorph, in the Chesapeake Bay impact structure, appears in anatase as well as rutile.

A LATE CRETACEOUS IMPACTITE IN THE FOX HILLS FORMATION OF SOUTHWESTERN SOUTH DAKOTA

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A zone of intense soft sediment deformation, with associated spherules and shocked quartz grains, has been identified over an area of 1000 km^2 in southwestern South Dakota. This zone of disruption (DZ) is up to 5 m thick and preserved within distal deltaic deposits of the Late Cretaceous Fox Hills Formation. Localized structural development caused thinning and eventual subaerial exposure of several sections within Badlands National Park, whereas sections to the north of the park were unaffected. Although previously interpreted as an intense period of

soil formation under humid, tropical conditions, the degree of ancient soil overprinting of these sections is minimal, with the exception of bright coloration of the strata, and appears not to have had any effect on ejecta preservation. Geochemical analyses of the DZ did not reveal enrichment of meteoritic elements commonly associated with impacts. Instead, this signature appears to have been reworked within the ancient deltaic environment of the Fox Hills Formation. It is also possible that the composition of the impactor was not enriched in platinum group elements (PGE).

Biostratigraphy and preliminary magnetostratigraphy suggest a mid to late Maastrichtian age for the DZ. When compared with other impactites, these study sections in southwestern South Dakota are similar to, and may correlate with, the recently documented 68 Ma impactite within the Vermejo Formation of Berwind Canyon in southeast Colorado. If this correlation is accurate, the size of the ejecta within the Fox Hills and Vermejo Formations suggest that the sections in South Dakota represent distal ejecta deposits.

ORIGIN OF THE COARSE, CLASTIC SEDIMENTS IN THE PRECAMBRIAN GARDNOS IMPACT CRATER, NORWAY

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In the late Precambrian a small (250 m in diameter) asteroid hit the Gardnos area of southern Norway. The excavated crater was approximately 6 km in diameter, with a surrounding 200 m high rim of fragmented target rocks. In the center of the crater, the crater floor rose to a central peak. A 400 m long core was drilled in 1992, penetrating 156 m of sediments, before hitting into the impactites (suevite and breccia). The sedimentary section (having been neglected for many years) has now been analyzed, and together with extensive fieldwork results, reveal parts of the infill history of the crater basin.

The initial post impact sedimentation consists, with coarse grained material deposited directly on the still not solidified suevite. Angular fragments of locally derived bedrock dominates the earliest and coarsest post impact sediments, indicating short clast transport, and a likely origin from excavated material. The conglomeratic sediments studied vary considerably regarding matrix content and clast size distribution. This is believed to reflect different modes of sediment transportation and deposition, with rock avalanches and debris flows being prominent processes of sedimentation. As the bedrock in the area is compounded, the clasts in the conglomerates are of different types. Systematic and considerably variations in clast types reflects composition of source area. The coarse clastic sedimentation probably occurred both from the collapsing central peak and down the steep crater walls.

SEDIMENTOLOGY OF ALBION IMPACTOCLASTIC BRECCIA (CRETACEOUS-TERTIARY BOUNDARY SECTION, BELIZE)

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At Albion Island in northern Belize, KT boundary deposits, also known as the Albion formation, rest upon karsted and fractured Maastrichtian dolostones. These deposits consist of a basal impactoclastic clay layer (~ 1 to 2-m thick) and an upper carbonate-rich, coarse impactoclastic breccia layer (up to 15-m thick).

The Albion impactoclastic breccia shows several important sedimentary structures, including development of discrete sedimentation units (2 to 7-m thick), which are strata that have been enhanced by horizontal shearing, and other sedimentary structures such as normal and reverse size grading, clast imbrication, flow lamination, and isolated and linked aggregates of clasts (i.e., clast clustering).

Most carbonate clasts within the coarse impactoclastic unit show a broad range of angularities and shapes, with the most common being subangular and compact-bladed to compact-elongated, respectively. Surface texture analysis of carbonate clasts shows several types of surface markings, which display a gross sequential order (i.e., facets, polish, striations, cryptographic markings, bruises and pits, and chips).

In-situ, apparent-diameter measurements of the carbonate clasts, which ranged in size from 10 to 300-mm (or -3.3 to -8.2 phi), resulted in cumulative grain-size frequency curves with similar shapes through the interval –3.3 and –6.25 phi (i.e., 10 to 76-mm). Matrix, the total area comprised of less-than-10 mm (< -3.3 phi) particles, ranged from approximately 71 to 82 percent. Modified moment measures of these curves show these breccias are "extremely poorly sorted." The matrix content increases upward, but is slightly lower near its top.

This breccia has sedimentary structures and sedimentologic characteristics suggesting its mode of emplacement during the impact aftermath was similar to that of a very large volcanic debris avalanche. Sedimentation units show evidence of early turbulent flow and a more conspicuous later stage of laminar flow with shearing accompanying emplacement of most breccia units. Clasts within these debris flows are not locally derived for the most part. We speculate that each sedimentation unit at Albion may represent a separate emplacement event during the process of ejecta-curtain collapse, perhaps owing to variations in atmospheric interaction with the debris.

SEDIMENTOLOGY OF A LATE CRETACEOUS MARINE IMPACT STRUCTURE (GULF COASTAL PLAIN, USA)

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An impact event within the shallow epicontinental Gulf of Mexico, which occurred during Late Cretaceous (~80 to 83 million years ago), formed the deeply eroded 7.6 km-diameter Wetumpka impact structure of the U.S. Gulf Coastal Plain (Elmore County, Alabama). Late Cretaceous water depths for the epicenter of this event are estimated to have been 30 to 100 m, and this feature formed within ~ 25 km of the local barrier-island shoreline.

Wetumpka's rim structure, mainly composed of crystalline basement rocks, appears to have been an enduring subaerial feature. Rim height estimates indicate that this crystalline feature (comprised today of a remnant 270^{o} arc of elevated schists and gneisses) was exposed for most of the time since impact. Deep soil development (saprolitization) characterizes most of the higher elevations of the rim, probably attesting to long-term rim exposure since impact.

Based upon coring of the crater interior, the crater-filling sequence appears to have formed in two separate events. Initially, a rapid fall-back of material is followed shortly by violent return of seawater that was pushed away in the contact and early compression phase of impact. Subsequently, this return surge topped the early crater rim and filled the interior with turbulent water flows, which redistributed the fall-back material and target sediments that were either excavated or displaced by the initial impact. Later, after a period of stasis during which sea water was excluded by the crater rim, rim failure apparently led to a subsequent surge of seawater, which washed in much additional sediment.

The lower, "fall-back + return surge" unit contains an impact-related fossil record that was unexpected. In this unit, there is considerably more lignite than we think existed in any of the target strata. This implies that some of the local tropical forest (i.e., coarse biomass) was swept up within the return surge and thus became incorporated into the deeper crater fill.

Further, we theorize that a terrestrial ecosystem could have existed upon the crater floor area during the interval between end of return surge effects and subsequent rim collapse. As we do not know how long this interval was, we cannot easily speculate on the character or extent of development of this local ecosystem.

BOSUMTWI IMPACT CRATER, GHANA: OVERVIEW OF ICDP DRILLING PROJECT

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The Bosumtwi impact crater in Ghana (06°32'N, 01°25'W) is one of 170 meteorite impact craters known on Earth and one of only four known impact craters associated with a tektite strewn field. It is a well-preserved complex impact structure with a pronounced rim and is almost completely filled by the 8 km diameter Lake Bosumtwi. The crater is excavated in 2 Ga metamorphosed and crystalline rocks of the Birimian System. Only limited petrographic studies of rocks found along the crater rim and of ejecta are available so far. Lake Bosumtwi is a closed-basin lake that has wide paleoclimatic significance and a detailed paleo-environmental record. The lake is at an ideal geographical location to provide data on past interannual to orbital-scale variations in the West African monsoon and Sahel drought; it has accumulated a detailed record of varved lake sediments that can be used to monitor both past local and Sahel rainfall variations over the period of 1 million years, since the formation of the crater. In addition, it is one of only two known young craters of this size, and may have a crucial diameter at the changeover between a traditional “complex” crater with a central peak and a crater structure that has a central peak-ring system. Drilling also allows to correlate all the geophysical studies and provides material for geochemical and petrographic correlation studies between basement rocks and crater fill in comparison with tektites and ejected material. The crater was the subject of an interdisciplinary and international drilling effort of the International Continental Scientific Drilling Program (ICDP) from July to October 2004. Sixteen different cores were drilled at six locations within the lake, to a maximum depth of 540 m. Borehole logging as well as vertical seismic profiling (to obtain 3D images of the crater subsurface) were done in the two deep boreholes. A total of about 2.2 km of core material was obtained. This includes ca. 1.8 km of lake sediments and 0.4 km of impactites and fractured crater basement (in the deep crater moat, and on the central uplift). Analyses of samples and geophysical data are currently under way. Acknowledgments: This is the result of work by an interdisciplinary group; thanks to CoPis B. Milkereit, J. Peck, J. Overpeck, C. Scholz, J. King, and several science teams. Funding by ICDP, NSF, FWF, ÖAW, and NSERC.

DETAILED ANALYSES OF DEPOSITS OF THE ELTANIN IMPACT, IN SEDIMENT CORES FROM POLARSTERN EXPEDITION ANT-XVIII/5A

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Deposits of the late Pliocene (2.5 Ma) Eltanin impact are unique: 1) the only example of a km-sized asteroid that impacted a deep-ocean (5 km) basin, and 2) the most meteorite-rich locality on Earth. On March 26 2001, the Polarstern returned to the impact area and, successfully explored ~80,000 km^2, collecting at least 16 new sediment cores of meteoritic ejecta, which is most abundant in cores on the Freeden seamounts and in the basins to the north, where the amount of meteoritic material deposited on the ocean floor was as much as 3 g/cm^2. Despite severe seafloor disturbance which eroded and redeposited sediments as old as Eocene, and possibly Paleocene, there is no indication that the impactor penetrated the ocean floor and formed a crater, and the composition of the melted ejecta is inconsistent with mixing between projectile and terrestrial materials other than the seawater target.

New x-ray radiographs of sediments reveal details not seen in earlier cores. The impact unit is well-preserved in several cores, found as much as 50 km from the seamounts to the east, north, and west of the seamounts where the uppermost, fine grained unit is at least 25 cm thick. These fine-grained sediments are clearly laminated, and show alternating layers of low- and high-density sediments (the latter largely meteoritic). These are consistent with ripple formation in an energetic flow regime during the latter stages of deposition following the impact. 435 samples were analyzed for Ir and 921 samples were sieved and separated into clay, silt, and fractions of >63, 125, 250, 500, 1000, and 2000 microns. All fractions >500 were hand picked and separated into terrestrial, melt rock, and unmelted meteorites, yielding 35 g of meteoritic impact melt rock and 3 g of unmelted meteorite fragments. Additionally a 9 g, 2.2 cm meteorite was found. In a core near the seamount summit, abundant arenaceous forams constructed their shells with meteoritic ejecta. The observation that ~8% of the coarse ejecta is unmelted meteorites is consistent with earlier work.

GEOGRAPHIC DISTRIBUTION OF DISTAL IMPACT EJECTA ASSOCIATED WITH NORTH AMERICAN TEKTITE STREWN FIELD

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It is generally accepted that the North American tektite strewn field (NATS) covers Texas, Georgia, Massachusetts, offshore New Jersey, the Caribbean Sea and Gulf of Mexico, and Barbados (Glass B.P. et al. 1998, *MAPS*, 33, 229), which is probably produced by the Chesapeake Bay Impact Structure (Koeberl C. et al. 1996, *Science*, 271, 1263). To better define the geographic distribution of North American tektite/microtektite layer, upper Eocene samples from several DSDP/ODP sites have been searched for impact ejecta. The result is used to evaluate the distribution pattern of distal impact ejecta associated with NATS.

New impact ejecta information from Site 543 may indicate that the distribution of microtektites is different from the distribution of unmelted impact ejecta as demonstrated by Sites 612, 903, 904, and 1073 off New Jersey (Glass B.P. et al. 1998, *MAPS*, 33, 229).

Both Sites 1073A and 903C only contain unmelted impact ejecta without microtektites, while Sites 612 and 904A contain tektite fragments, microtektites and unmelted impact ejecta. Because the paleo-distance (35 ma years ago) of Sites 1073A, 904A, 903C, 612 to Chesapeake Bay structure were about the same, it is unlikely that the difference of impact ejecta is caused by the slight distance difference. Koeberl (1989) proposed the North American tektite/microtekties were deposited as lobate rays (Koeberl C.,1989, *Proceedings of the LPSC*, 19, 745). It is possible that Sites 612 and 904A are located on a lobate, while Sites 903 and 1073 are not located on lobates. This will explain why only Sites 612 and 904 contain tektite fragments and microtektites.

The NATS covers about ~ 2% of the Earth's surface. Unmelted impact ejecta are recovered from all the marine sites associated with NATS. It was reported that the distribution area of unmelted impact eject is much smaller than the Australasian tektite strewn field defined by the Australasian microtektite layer (Glass and Wu, 1993, *Geology*, 21, 435). Thus we propose that the actual North American tektite strewn field should be at least two times bigger than current known size. We hope future discovery of distal impact ejecta will help us to better define the size of NATS. We thank ODP for the sample. This research was supported by NSF grant EAR-9903811 to BPG.

THE MECHANICS OF METEORITE IMPACT EJECTION AND SEDIMENTATION

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The formation of a meteorite impact crater is sudden and violent by geologic standards. The crater structure and associated impact ejecta deposits form in a geologic instant and, when extensive ejecta deposits can be found, provide an excellent correlation tool. The mechanics of hypervelocity impact crater formation, however, may be unfamiliar to geologists more accustomed to dealing with volcanic eruptions or submarine landslides as a source of extensive deposits. Impact crater excavation is more akin to a powerful explosion than to the low velocity impact of, say, pebbles into water or mud that we experience in everyday life.

The formation of an impact crater begins when a rapidly moving object, a comet or asteroid, strikes the surface of the Earth or another planet. The projectile transforms its kinetic energy into heat and motion in the target over a time interval measured by its diameter divided by its velocity. In the process the target rocks may be raised to temperatures of tens of thousands of degrees while they are compressed to pressures comparable to those at the Earth's core—greatly exceeding pressures reached in even the most violent volcanic eruption. The initial ejected material is ionized plasma containing vaporized projectile and target material that expands away from the impact site and pushes back the ambient atmosphere. This plasma eventually creates a pocket of superheated, low density, gas near the impact site through which the proximal ejecta are deposited almost as if in a vacuum. While these hot gases vent above the atmosphere, solid material from close to the surface is expelled at high speed. Some of this material may even escape the Earth, eventually to fall on the Moon or other planets such as Mars or Venus. Deeper-seated material is melted or highly shocked and expelled at lesser speed. Such material is the source of tektites, microtektites or microkrystites now found in deep-sea cores. The slowest and most voluminous ejecta emerges last and is deposited in thick, chaotic masses resembling glacial till in the vicinity of the crater itself.

The entire duration of the crater formation process is typically less than a minute—a few times a scale factor defined by the square root of the crater diameter divided by the acceleration of gravity. Some ejecta may travel ballistically nearly around the Earth, a process taking only a few hours, with final depositional times controlled by its rate of sedimentation through the air or water columns.

IMPACT EJECTA SEDIMENTATION PROCESSES

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One of the most characteristic, but poorly understood, aspects of hypervelocity impact events is the generation of ejecta deposits. Proximal ejecta deposits are found in the immediate vicinity of an impact crater (i.e., external to the original transient cavity and up to the outer limit of the continuous ejecta blanket); whereas distal ejecta deposits are found distant from the crater (>5 crater radii). It is generally accepted that proximal ejecta deposits on airless bodies, such as the Moon, are emplaced *via* ballistic sedimentation (Oberbeck V. R., 1975, *Rev. Geophys. Space Phys., 13,* 337–362). Studies of the continuous ejecta blanket (Bunte Breccia) at the Ries impact structure, Germany, strongly support the importance of ballistic sedimentation on Earth (Hörz F. et al. 1983, *Rev. Geophys. Space Phys., 21,* 1667–1725). However, a variety of other ejecta types are found at the Ries overlying the Bunte Breccia, including suevites and impact melt rocks. It was generally accepted that these impactites were deposited subaerially from an ejecta plume. However, recently, it has been shown that proximal suevites were emplaced as surface flow(s), either comparable to pyroclastic flows (e.g., Newsom H. E. et al. 1986, *JGR*, 91, 239–251), or as a ground-hugging impact melt-rich flows that were emplaced outwards from the crater center during the final stages of crater formation (Osinski G. R. et al. 2004, *MAPS, 39*, 1655–1683). This has also been suggested for the impact melt rocks at the Ries (Osinski G. R., 2004, *Earth Planet. Sci. Lett., 226,* 529–543). Furthermore, there is a clear temporal hiatus between the ballistically-emplaced Bunte Breccia and the overlying suevites/impact melt flow deposits, which requires a two-stage ejecta emplacement model. This has also been invoked for similar deposits at the Haughton impact structure, Canada (Osinski G. R. et al. in press, *MAPS*). In terms of distal ejecta deposits, it has been suggested that more distal impact ejecta falling into the atmosphere may clump together into density currents that flow to the ground much more rapidly than might be expected for single particles themselves (Melosh H. J., 2004, *MAPS., 39*, A67). This paper will explore various models for the generation and deposition of ejecta deposits using a combination of field and numerical modeling studies of terrestrial impact craters, and volcanic analogues.

GRAVITY AND MAGNETIC ANALYSIS OF THE WEAUBLEAU-OSCEOLA STRUCTURE, MISSOURI

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The general nature of the Late Paleozoic Weaubleau-Osceola structure in southeastern St. Clair County, Missouri has been investigated with detailed field mapping and drilling, and a variety of laboratory studies. The nature of the structure was first recognized by analyzing ten-meter DEM maps that showed a distinctive circular drainage pattern. This pattern marks the location of a ring moat with the uplifted outer rim marking the extent of the tectonic rim.

Evidence that points toward a meteoritic origin of the structure includes highly deformed carbonates that are overlain by undeformed but karstified polymict carbonate breccia. At approximately 200' depth in the ring uplift, granite and carbonate breccia with possible melt material are encountered.

To aid in determining the three-dimensional extent of the structure, a gravity and magnetic analysis was conducted. The existing gravity data are sparse in St. Clair County, so an additional 300 stations were collected within and surrounding the structure. These data were processed into complete Bouguer gravity anomalies using ten-meter DEM models and merged with the existing data. The Bouguer gravity anomaly map indicates a complex pattern of high-frequency minima and maxima with two low-amplitude gravity minima at the suspected point of impact and to the northeast. A gravity maximum coincides with the southern ring uplift. A first-order polynomial trend surface removes the regional northwest-trending anomalies to highlight the minima of approximately 5 mGal that is thought to be related to the impact site and emphasizes high-frequency maximum that occurs over the ring uplift. Aeromagnetic data indicate a more complicated anomaly pattern than is shown by the gravity data but to a first-order it re-emphasizes the Bouguer gravity field. Magnetic maxima occur over and to the northwest of the known ring uplift and along the southern edge of the structure. Two and one-half dimensional gravity models across the structure will be constructed.

IMPLICATION OF FOSSILS IN THE EJECTA BRECCIA ASSOCIATED WITH THE WEAUBLEAU-OSCEOLA STRUCTURE, ST. CLAIR COUNTY, MISSOURI

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The Weaubleau-Osceola Structure probably resulted from a bolide impact. Ejecta form a polymict, unbedded, graded breccia 8.8 m thick. Clasts include angular gray and black chert, green siltstone, and abundant echinoderm debris in a fine buff carbonate matrix. Identified fossils weather from the breccia or are in acid residues. Crinoids are the most common clasts and include perfect calyces up to 22 mm long, stem segments up to 20 mm long, and abundant individual columnals. Crinoids include *Actinocrinites* plates, *Aorocrinus parvus*, *Dorycrinus* spines, *Eretmocrinus*, *Macrocrinus verneulianus*, *Playcrinites* plates, *Uperocrinus hageri*, and *U. pyriformis*, taxa typical of the Osagean Burlington Limestone. Blastoids include *Pentremites conoideus*, known locally from the upper Osagean Keokuk Limestone. Echinoid spines, locally known only in the Keokuk, are broken but up to 22 mm long. Intact horn corals are up to 45 mm long. These fossils weather from breccia matrix but otherwise look just like fossils from Burlington-Keokuk strata. The perfect calyces indicate that at least some Burlington crinoidal sediment was not lithified at the time of presumed impact, and the ejecta breccia has no clasts of crinoidal limestone resembling Burlington-Keokuk strata.

Conodonts include *Calaptoconus quadraplicatus*, probably from the Ibexian (L. Ord.) Cotter Dolomite; *Siphonodella* of Kinderhookian (early Mississippian) age, possibly from the Chouteau Limestone or Northview Formation; common *Gnathodus texanus*, typical of the Keokuk Limestone, and *Taphrognathus*, from the uppermost Keokuk or lower Warsaw formations. *Polygnathus*, *Spathognathodus*, and other species of *Gnathodus* are present. No younger fossils have been found. Conodonts have a Color Alteration Index of ~ 1 (thermally unaltered) and are well preserved.

The mixed ages of fossils in the breccia suggest that the presumed impactor caused ejection of middle and upper Osagean unlithified crinoidal sediment, lithified clasts of Kinderhookian strata and (below a regional unconformity) Lower Ordovician dolomites. Impact probably was in a shallow ocean, and ejecta (including intact and fragmented fossils) were deposited by resurge currents to form the polymict breccia, probably in latest Osagean to early Meramecian time. The crater is too small to be associated with major extinction.

NEW DRILL-CORE DATA FROM THE LOCKNE CRATER, SWEDEN: THE MARINE EXCAVATION AND EJECTION PROCESSES, AND POST-IMPACT ENVIRONMENT.

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Studies of marine-target craters provide information on cratering processes in layered targets. This has implications for the reconstruction of paleoenvironments. At the Lockne crater, Sweden, the target water strongly affected the cratering and, thus, the geology and morphology of the final crater. The impact occurred in an epicontinental sea slightly exceeding the impactor diameter. The water overlaid 80 m of sediments resting on a weathered Precambrian crystalline peneplain. The difference in target strength caused a concentric shape of the transient cavity with a 14 km wide crater in the water mass, and a 7.5 km wide basement crater. A flap of ejected crystalline rock surrounds the crater, but structural rim uplift is absent. The flap rests on top of a surface stripped from much of the sediments by the water cavity excavation flow. The ejecta layer has a distribution reflecting the trajectory of the projectile.

Three core-drillings (7, 8, and 9) were performed in August 2004. The objectives were:

- 7: Massive calc-micrite megalenses ("CMM"). These structures represent a previously unknown carbonate depositional environment in the Ordovician sea, apparently strongly linked to the crater depression in the seafloor. They are exposed in a few locations along the rim of the basement crater, are at least several tens of meters in length and width, but their thickness and stratigraphic position (i.e., the relation with the crater formation) has been hitherto unknown. They lack stratification and are practically empty on fossils. Significant is the high content (up to a few percent) of micro-crystals (< 0.1mm) of quartz and feldspar with surface depressions that indicate growth within the micritic sediment. The formation may be linked to the geochemical environment generated by the impact, and sudden convection of a stratified water body within the crater.
- 8: Ejecta dynamics and energies. Large bodies of crystalline ejecta occur with great thicknesses and clast sizes at great distances. The drilling constrains the volume, the interior stress during ejection, and the effect on the substrate from the deposition of the largest of the known coherent ejecta occurrences outside one crater radius from the basement crater rim.
- 9: Outer crater and overturned rim-flap. The anomalously large overturned flap may indicate a crater excavation different from the standard land-target impact, possibly involving a low shock hydraulic flow.

PROCESSES AND PRODUCTS OF METEORITE IMPACTS INTO SEDIMENTARY ROCKS

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Sedimentary rocks are present in the target sequence of ~70% of the world's known impact structures. In contrast to igneous and metamorphic rocks, sedimentary rocks are typically rich in volatiles (e.g., H_2O, CO_2, SO_2), highly porous, and are typically layered. It is well known that such characteristics exert a considerable influence on the processes and products of meteorite impacts. However, despite the significance of sedimentary rocks in the target sequence of terrestrial impact structures, the response of such lithologies to hypervelocity impact remains poorly understood. In particular, the relative importance and role of impact melting versus decomposition in carbonate- and evaporite-rich targets remains controversial, although a considerable amount of work has been published on this subject in the past few years. Thus, the aim of this paper is two-fold: (1) to provide an up-to-date assessment of our current understanding of impacts into sedimentary-rich targets (carbonates, evaporites, and terrigenous clastic rocks); and (2) to discuss how impact-modified and impact-melted sedimentary rocks may be distinguished from their unshocked counterparts. In summary: (1) It is apparent that impact melting in sedimentary targets is much more common than previously thought (e.g., impact melting of carbonates, evaporites, sandstones, and shales, has now been recognized at a number of impact sites); (2) There is no unequivocal evidence for the decomposition of carbonates or evaporites at any terrestrial impact site; (3) The results of this study suggest that previous assumptions about the response of sedimentary rocks during hypervelocity impact events are incorrect; (4) It is suggested that the apparent "anomaly" between the volume of impact melt generated in sedimentary versus crystalline targets in comparably sized impact structures may be due to a misinterpretation of micro-textures. Textural and chemical evidence for the impact melting of sedimentary rocks during hypervelocity impact is provided by: (1) liquid immiscible textures; (2) quench textures; (3) melt spherules and globules; (4) anomalous chemical composition of various "sedimentary" mineral phases (e.g., SiO_2-rich calcite); (5) crystallization of "new" silicate minerals from sediment-derived melts (e.g., pyroxene, olivine).

THE MARINE SEDIMENTARY RECORD OF IMPACT PALEOENVIRONMENTAL EFFECTS: A FIELD STUDY AT CHESAPEAKE BAY

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Impact craters created on the seafloor, such as that at Chesapeake Bay, provide the unusual opportunity to document local paleoenvironmental perturbations caused by a bolide impact. The intracrater sedimentary record is especially important for documenting paleoenvironmental transitions between synimpact and postimpact deposition. The known synimpact-postimpact paleoenvironmental record from within a submarine impact crater, however, is rare. To date, the only published studies come from two coreholes at Chesapeake Bay. The study presented herein builds on those earlier studies by incorporating new lithological, geochemical, and micropaleontological data from four additional coreholes drilled inside the Chesapeake Bay crater and two drilled less than five kilometers outside the western crater rim. The transition record at Chesapeake Bay starts (at the base) with brecciated tsunami washback deposits (dominantly sand–size quartz and glauconite grains plus pebble-size rock fragments), which form the upper beds of the Exmore breccia. The next highest deposit is notable for cross-stratified quartz sands and silts that contain poorly preserved, reworked microfossils, but no indigenous biota. This unit is interpreted as turbidites or fine debrites, a flowin deposit caused by postimpact storms, which stirred the seabed around the crater depression. Above the flowin deposits at one core site, a thin silt-rich interval (<5 cm thick) contains evidence of microspherules, interpreted to represent a fallout layer. Above the fallout layer, a laminated clay, silt and fine sand interval (<20 cm thick) contains abundant microfossils reworked from the underlying Exmore breccia, but yields no evidence of indigenous microbiota. This deposit is interpreted to represent a dead zone, the result of paleoenvironments hostile to marine biota.

Normal marine paleoenvironmental conditions began to return to the crater depression several thousand years after the impact, and resulted in accumulation of the microfossil-rich, clay-dominant Chickahominy Formation, which represents the final ~2 million years of late Eocene deposition at Chesapeake Bay. A stratigraphic succession of five distinct benthic foraminiferal assemblages within the Chickahominy Formation delineates late Eocene paleoenvironments that evolved within the crater basin.

ANATOMY OF THE CENTRAL CRATER OF THE CHESAPEAKE BAY IMPACT STRUCTURE

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Preliminary analysis of new seismic refraction, seismic reflection, gravity, and magnetotelluric (MT) data, and samples and geophysical logs from a new 823-m-deep, partially cored test hole, reveal the configuration of the central crater of the buried, late Eocene Chesapeake Bay impact structure. The main features are a broad central uplift surrounded by an elliptical moat, a collapsed central-crater margin, and a raised rim. Gravity, MT, seismic-velocity, and seismic-reflection images define a NW-SE-elongate, 12-km-wide (short axis) central uplift that rises about 500 to 800 m above the floor of the surrounding moat. The test hole on the northeastern flank of the central uplift encountered sediment-clast breccia below 355-m depth and polymict crystalline-clast suevitic breccia and monomict brecciated gneiss below 655-m depth.

The moat is about 12 km wide along a new 30-km-long seismic transect that extends NE from the central uplift to about 10 km beyond the central crater margin. The moat corresponds to a gravity minimum, comparatively low electrical resistivities, seismic velocities (Vp) less than 5 km/s above 2,000-m depth, and inward-dipping reflections from synimpact and postimpact sedimentary sections. The postimpact section extends to about 500 m depth and overlies about 550 m of resurge sediments that overlie 600 to 750 m of unknown impactites. Low-amplitude gravity maxima, and MT, seismic-velocity, and seismic-reflection data suggest local structural uplifts within the moat, basement-derived megablocks, uplifted fault blocks, or irregularities in the central-crater margin due to differences in target rock properties. Relatively steep gravity, resistivity, and seismic-velocity gradients, and inward-dipping reflections, mark the central-crater margin. A decrease in the velocity gradient at about 2,000-m depth likely indicates a decrease in fracturing below that depth. MT data suggest fracturing of crystalline rocks to depths of at least 6 km in the central crater.

HYDROGEOLOGY AND HYDROCHEMISTRY OF THE CENTRAL CRATER OF THE CHESAPEAKE BAY IMPACT STRUCTURE

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The late Eocene Chesapeake Bay impact structure consists of an ~85-km-wide annular trough that surrounds a ~38-km-wide central crater that is entirely overlain by post-impact sediment. The annular trough consists of concentric, rotated and down-dropped sediment blocks that are overlain by sediment-clast breccia of the Exmore beds. Analyses of cores and pore waters from drilling have shown the annular trough to be filled with water of near seawater salinity except at the western edge, where it has been partially flushed by meteoric water. Drilling at the central uplift within the central crater in 2004 revealed a 300-m section of the sediment-clast breccia (Exmore Beds) overlying more than 150 meters of hydrothermally altered crystalline-clast breccia. Analysis of permeabilities from cores and wells at the central crater yield values that are low enough ($<10^{-8}$ m/sec), combined with low head gradients ($<10^{-4}$ m/m), to suggest that the groundwater is the original tsunami-resurge water that has been trapped there since the time of impact.

Pore waters squeezed from cores of the crystalline-clast breccia show major-ion chemistry consistent with seawater equilibrated with the host breccia during or after albitization and chloritization. Oxygen-18 values ranging from -3.94 to -0.81 per mil are consistent with a paleoseawater, because some values are similar to those in the sediment-clast breccia while others show enrichment that is consistent with partial rock-water equilibration. The chloride-bromide ratios of the waters in the inner crater range from 72 to 76; these values are substantially different from that of seawater (292), indicate an external source of bromide, and because of their low variability are consistent with a well-mixed hydrothermal convection system. Major ion chemistry in and near a smectite clay clast in the sediment-clast breccia implies that the clay has acted as a very efficient membrane, completely segregating dissolved cations across a distance of less than one meter for tens of millions of years.

USING THE SEDIMENTARY IMPACT RECORD IN ARGENTINA

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The depositional history of the Pampean sediments of Argentina extends into the late Miocene. At least 7 different-age layers of impact glass (locally called "escorias") have been discovered in these sequences, including Holocene (6 ± 2 ka), Pleistocene (114 ± 26 ka, 230 ± 30 ka, and 445 ± 21 ka), Pliocene (3.27 ± 0.08 Ma), and late Miocene (5.33 ± 0.05 and 9.23 ± 0.09 Ma) in age based on $^{40}Ar/^{39}Ar$ dating. These glass horizons are not stacked on top of each other in a given region but occur in exposures within sediments of southern Buenos Aires Province, e.g., along coastal cliffs or river outcrops.

The large number of impacts seems anomalous but is consistent with the expected terrestrial flux rates. Specifically, nearly 20 craters larger than 1 km in diameter should have formed in the area covered by the sedimentary deposits over the last 10 Ma. Two of the occurrences are type localities for important fossils of endemic fauna. And one glass layer (~3.3 Ma) is coincident with the simultaneous disappearance of both large and small endemic fauna. The stratigraphic setting, age (radiometric and magneto-stratigraphic), and petrographic indicators of transient high temperatures and shock within the glasses indicate their origin by impact.

Unmelted clasts (predominantly quartz grains and feldspars) occur with different abundances. Glass fraction ranges from clast free (< 10% vol.) to clast rich (80% vol.). Although they could be classified as melt-matrix breccias, their unique appearance may warrant a new term "pampasites." Such a name would acknowledge their unique origin by impact melting of porous sediments. Embedded clasts in this case are individual mineral grains from the loessoid substrate subjected to various degrees of melting and shock.

The dated glasses establish critical benchmarks for independent ages of their host sediments. Continuous paleomagnetic profiles and detailed allostratigraphy allow extending the chronostratigraphy above and below the glass-bearing horizons. Moreover, small rounded glasses found in horizons above the primary glass layer reveal the role of later reworking, thereby affecting interpretation and timing of recovered fossil fragments. Consequently, the dated impact glasses provide a critical tool for deciphering the sedimentary record.

IMPACT TAPHONOMY: CALCAREOUS NANNOFOSSILS FROM THE SILVERPIT AND CHESAPEAKE BAY IMPACT STRUCTURES

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The study of taphonomic effects on microfossil assemblages due to meteorite impact is a relatively new field and is providing valuable information regarding temperature and pressure conditions during impact events. Calcareous nannofossils from two distinct impact events show evidence of "impact taphonomy": shock-wave induced fracturing and overgrowth of calcareous remains.

The Silverpit crater is a multi-ring wet impact structure that is 20 kilometers wide and is located in the Anglo Dutch Basin in the British Sector of the North Sea. Based on palynomorph and calcareous nannofossil biostratigraphy, the crater is thought to be late Paleocene in age, occurring very near the Paleocene/Eocene boundary. Resurge deposits contain mixed microfossil assemblages of late Maastrichtian and Danian age. Shock-wave induced fracturing has been identified from two genera of calcareous nannofossils: *biscutum* and *prediscosphaera*. Fracturing of elliptical specimens of *biscutum* occurs along the long axis and includes folding along the apex ends. Spiral fracturing of *prediscosphaera* specimens is reminiscent of torque and is unique to the Silverpit crater.

Impact related taphonomy of calcareous nannofossils from the Chesapeake Bay impact structure includes shock-wave induced fracturing and overgrowth and has been identified only from the genus *discoaster*. Fracturing across ray tips of these multi-rayed, round forms produced pentagonal-shaped specimens. Excessive thickening of ray tips and edges is attributed to pressure and temperature-induced overgrowth. Samples from the recently drilled Cape Charles test hole in the center of the Chesapeake Bay crater contain specimens of *Coccolithus pelagicus* that have a very low order birefringence and may be indicative of heat alteration.

Alteration of calcareous nannofossils in an impact breccia may be caused by multiple processes, including excessive heat and pressure. The type of alteration will vary from crater to crater and is most likely dependant on the type of sediment and amount of water present at the impact site. Examination of additional crater sites should lead to a better understanding of the taphonomic responses of calcareous nannofossil assemblages to impact events.

KNOB FORMING DISTINCTIVE CHERT-BRECCIA BOULDERS OF THE CENTRAL OZARKS

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A series of knobs capped with large (4-10 meters in diameter) boulders composed of distinctive chert breccia occur approximately 14 Km southwest of Willow Springs in Howell and Douglas Counties, Missouri. Similar knobs in the area are capped by Mississippian age cherts, however only those of Twin Mts., Nichols Knob and Bear Mt. exhibit these well indurated breccias. These knobs, which are capped by the breccias, are arranged in a linear trend striking N 45 degrees east. The origin of the breccias is suggested to have been from a series extraterrestrial objects impacting in sucessive order to fragment highly cherty carbonates of Mississippian age, possibly sometime during the Mesozoic Era. Secondary silicification, aided by silica solution aided by extensive brecciation and the high surface area of the small chert fragments, produced the solid boulders. Later uplift of the Ozark Plateau removed most traces of Mississippian strata in the area except for these resistant "casehardened" chert breccias. What had originally been medium sized impact craters now became the tops of knobs as the surrounding less resistant rock was removed by weathering and erosion.

ALAMO ENIGMAS: TOO MUCH AREA AND VOLUME, TOO LITTLE CRATER AND SYMMETRY

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The Late Devonian marine Alamo Breccia (AB) is one of the largest impact deposits discovered on Earth. It contains diverse facies that include impactites, seismites, debrites, turbidites, tsunamites, and melt(?), spread across much of Nevada and Utah. Their arrangement creates serious AB enigmas.

1. Crater Size: Only one area with central crater facies is known, excavated into the Upper and Middle Devonian carbonate platform exposed along Tempiute Mountain (TM), Nevada. The exposed crater scale does not match the huge AB area, volume, and impact facies distributions.
2. Asymmetry: east of TM, the AB radially spreads and thins across the platform, as expected. Thickness variations suggest distant tilted terraces. West of TM, AB facies are reworked, far-reaching, deepwater mass flows; the platform with radial facies pattern is missing.
3. Quartz: The AB contains copious loose shocked quartz grains, but the TM crater does not pierce sandstone.
4. Conodont ages: Reworked assemblages from the AB indicate Lower Paleozoic penetration. The TM crater pierced only through Middle Devonian beds of the shallow platform.
5. Conodont bathymetry: Some Devonian forms prescribe a deepwater target, whereas the TM crater is on the shallow platform

These working hypotheses are under test:

- 1'. Crater Size: (A) One or more undiscovered, larger, coeval craters penetrated Lower Paleozoic formations offshore; massive ejecta, waves and currents augmented the effects of the smaller platform crater. (B) The crater is unusually broad, flattened, and terraced because the carbonate target was strongly stratified, cemented and brittle. It was delaminated and shattered from seismic waves and ejecta curtain. The wet impact spawned waves, currents and runoff that widely reworked and spread broken rock.
- 2'. Asymmetry: (A) The western portion of the carbonate platform disintegrated and sloughed into deep water. (B) The undiscovered crater (1'-A) blew away part of the platform. (C) The required western outcrops are buried by volcanics. (D) The missing western platform was compressed by Post-Devonian thrusts, and is buried and/or was uplifted and eroded away.
- 3'. Quartz: (A) See 1'-A; (B) TM crater outcrops represent only the margin of a large mainly unexposed crater that penetrated Lower Paleozoic sandstone formations.
- 4'. Conodont ages: Lower Paleozoic species: see 1'-A.
- 5'. Conodont bathymetry: (A) See 1'-A; (B) The extended crater (3'-B) encompassed the deeper Devonian platform margin or ramp.

To date, none of these alternatives has been disproved.

AN APATITE FISSION-TRACK AGE-DETERMINATION ATTEMPT AT THE KENTLAND IMPACT CRATER, INDIANA (USA)

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We attempted to determine the poorly constrained age of the ≤13 km diameter Kentland impact crater in Indiana, USA (40°45'N, 87° 24'W) through a three-stage fission-track study of the apatite-bearing St. Peter Sandstone (Ordovician) using: 1) three outcrop samples from the Newton County stone quarry in Kentland, in the center of the crater, 2) three subsurface core samples from neighboring Indiana counties, 31-53 km away, and 3) twenty far-field subsurface and outcrop samples from Illinois and Indiana, 138-302 km away. All samples studied have been thermally reset and are significantly younger than the ~460 Ma St. Peter Sandstone depositional age. Modeling fission-track age and track length distributions indicates that the St. Peter Sandstone in the crater was heated to ≥135°C at some unknown time after deposition, and then, 184±13 m.y. ago in the Jurassic, cooled rapidly through 135°C. This Jurassic cooling age is consistent with Mississippian-Pleistocene stratigraphic constraints on the age of the crater, and is significantly older than a Late Cretaceous (< 97±10 Ma) paleomagnetically determined age.

We next tested a working hypothesis that if the reset fission-track ages in the crater are related to impact, uplift, excavation, and exhumation, then additional fission-track ages from more distant samples should decrease to some background age level within a few crater diameter distances away. Three subsurface samples 2 to 4 crater diameter distances away fail the hypothesis test, yielding a model composite cooling age of 185±11 Ma. Of the far-field samples tens of crater diameters (237-251 km) from the crater: eight fail the hypothesis test; one gives an outlier age; and only one gives a significantly older age. We conclude that we have not dated the age of the crater, but rather some regional-scale cooling and exhumation event that either predates or postdates impact.

Empirical relations suggest that 1.0-1.3 km of differential uplift should occur in the center of a 13 km diameter crater. The oldest unit exposed (Shakopee) has, however, been uplifted by only ~600 m above its subsurface position. That the observed stratigraphic uplift is smaller than that predicted may indicate that the diameter of the Kentland crater has been overestimated, perhaps by as much as by a factor of 2.

REMOTE SENSING AND GEOGRAPHIC INFORMATION SYSTEMS TECHNICAL WORKSHOP: A HANDS-ON APPROACH TO THE ANALYSIS AND POTENTIAL DISCOVERY OF IMPACT STRUCTURES

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The Southwest Missouri State University Remote Sensing and Geospatial Analysis Laboratory (RSGAL) recently constructed the Missouri Atlas of Impact and Meteor Sites (MoAIMS) a geospatial database project for the linear swath of meteor impact structures (http://ozarksgeography.smsu.edu/MoAIMS/). The project's study area along the 38th parallel in the southern portion of Missouri was aimed for the analysis of the Decaturville and Crooked-Creek meteor impact sites as well as the Weableau-Osceola area. Since the discovery of impact structures the importance of digital elevation models (DEM) and shuttle radar topography mission (SRTM) data can produce highly beneficial information for the analysis and potential discovery of impact structures. The MoAIMS project will host a hands-on technical workshop to demonstrate how geographical information systems (GIS) and remote sensing technology can be applied to sedimentary geology and impact structure research. The workshop will include a brief history of remote sensing and its applications including information about various sensors and their geospatial data used in the

MoAIMS database as well as how to find websites that contain geospatial data. Remote Sensing and GIS software packages will be briefly discussed and used in a hands-on approach. Software suites such as ESRI's ArcGIS 9.0 (ArcScene, ArcGlobe, and ArcMap), Stereo Photo Maker, and ENVI 4.2 will be displayed in a remote sensing computer laboratory. A "how-to" manual will be included in the workshop discussing geospatial data, its use, and printed screens for step-by-step instructional use for analysis and research.

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