The Sedimentary Record of Meteorite Impacts:
An SEPM Research Conference

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ABSTRACT
Large meteorite impacts are important agents of sedimentation and sediment modification that vary according to geologic settings, ranging from marine to non-marine. Impact structures and deposits that they generate are hosts for hydrocarbons and ore deposits, and influence water quality and availability. By preserving a record of ancient meteorite impacts, rocks and sediments provide insight into the distribution of these resources as well as modern risks for life and civilization. SEPM is sponsoring a research conference to address the sedimentary record of meteorite impacts around the world using multidisciplinary approaches.

INTRODUCTION
Large meteorite impacts generate shock-metamorphic fabric in rocks, and they are also bona fide agents of sedimentation. Impacts generate, transport, and deposit sedimentary particles in marine and non-marine settings, and deform and alter pre-existing rocks and sediments. Until the 1960s, the geologic community largely relegated studies of meteorite impacts to geologic sidelights and curiosities, which were inherently controversial. Today, it is widely recognized that large impacts have played a pivotal role in the evolution of Earth's biota and sculpted the surface of the planet. Although impacts are even rarer than large-scale earthquakes, volcanic eruptions, and tsunamis on human time scales, the probability of a future impact is a certainty in geologic time. This should remind us of our perpetual exposure to natural catastrophes of all sorts. Stratigraphers can play an essential role in documentation and evaluation of impact structures for the benefit of all.

IMPACT PROCESSES AND PRODUCTS
Impacts of large meteorites on Earth are beyond the scope of normal human experience. Even so, studies of conventional and thermonuclear explosions, experiments with high-velocity projectiles, and computer modeling have helped to develop our understanding of impact processes. Melosh (1989) recognized three stages of impact cratering: contact and compression, excavation, and modification.

The contact and compression stage entails generation of the shock wave that instantaneously provides extreme pressure and disruption of the target material. Typically, this stage lasts only a fraction of a second, but the shock pressures pass through the target well into the excavation stage. Shock pressure and the release from such pressure forms three of the four diagnostic features associated with meteorite impacts: high-pressure mineral species such as coesite and stishovite, diaplectic glasses and planar deformational features (PDFs) in shocked minerals such as quartz, and shatter cones (French, 1998; Koeberl and Martinez-Ruiz, 2003). The fourth diagnostic criterion is a geochemical signature of highly siderophile elements (HSEs) associated with the impactor.

The excavation stage involves the formation of the transient crater, where the impactor penetrates the target, deforms, vaporizes, and explodes, creating a balloon-like cavity within the surrounding rock. An enormous amount of material is displaced downward, outward, and upward during excavation. This leads to a "space-problem" in strata surrounding the transient crater. Folding of strata and motion along reverse and transpressive faults accommodate the en masse lateral displacement and emplacement of flow material. Ultimately, the explosive forces breach the roof of the tran-

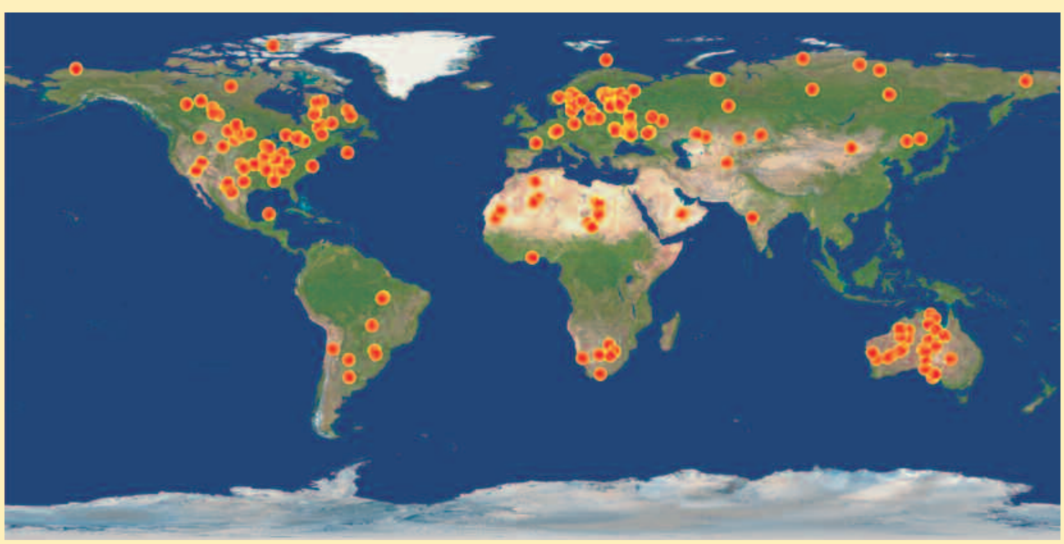


Figure 1: At this time, 172 impact structures are recognized in the Earth Impact Database (2005). The vast majority are located on landmasses. Many marine impacts have likely been destroyed by subduction. Despite this skewed pattern of occurrences, several impacts in the Balto-Scandia region of Europe and North America were impacts in shallow seas (see Dypvik et al. 2004). Impact locations and map modified from Earth Impact Database (2005). "Blue Marble" image courtesy of NASA (http://earthobservatory.nasa.gov/Newsroom/BlueMarble/).

Figure 2: Map of continental United States showing confirmed and proposed impact structures. Most exposed structures are located on stable cratonic platforms in Paleozoic strata in the mid-continent. Map modified from Earth Impact Database (2005).

sient cavity, and a curtain of ejecta is expelled from the crater.

During the modification stage, the compression wave has passed and rarefaction causes relaxation and inward flow of disrupted material. Normal faults develop around the periphery of the structure, forming a tectonic rim. Ultimately, crater morphology is a function of the size of the impactor, the angle of incidence, and properties of the target material. Simple craters generally form bowl-shaped depressions with crater rims that are elevated above the original land surface. Complex craters are generated by larger impacts, where, during the modification stage, rocks rebound to form central uplifts or peak ring structures within craters. Crater rims are rarely preserved in ancient impacts, so the eroded remains of impact cratering are commonly referred to as impact structures. Currently, 172 impacts are recognized in the Earth Impact Database (2005; Fig. 1). Roughly 30 accepted or plausible impact structures are located in the continental United States (Fig. 2).

Impacts on continental "dry" targets and those on oceanic "wet" targets show significant variation, although water is present in dry targets where the rocks are saturated with ground water (Fig. 3). The principal differences are related to the mitigating effects of variable water depths, deposition from the violent resurge of seawater back into the crater, a variety of post-impact crater-fill deposits, and possible distal tsunami deposits (French, 2004). Distal deposits from both wet and dry impacts include ejecta such as microkrystites, microspherules, and tektites.

IMPACTITES

Shock-metamorphosed rocks, including breccias and melt rocks, are called impactites. Evidence for shock metamorphism is based on criteria such as microscopic planar deformation features within grains or shatter cones. A proposed international classification of impactites (Stöffler and Grieve, 2003) was recently endorsed with slight modifications by the North American Geologic-map Data Model Science Language Technical Team (2004). The three main classes of impactites are shocked rock, impact melt rock, and impact breccia. Shocked rock is non-brecciated rock that shows unequivocal effects of shock metamorphism exclusive of whole-rock melting. Impact melt rock is a rock (crystalline or glassy) in which ≥50% of the rock volume is solidified from impact melt. Impact breccia is breccia in the general sense that has unequivocal evidence of shock metamorphism. The three subclasses of impact breccia are suevite (containing impact melt particles), polymict impact breccia (containing fragments of different composition and free of impact-melt particles), and monomict impact breccia (containing fragments of essentially the same composition and free of impact melt particles). The field identification of impactites can be difficult because of their similarity to other breccias and fragmental rocks of sedimentary, volcanic, and tectonic origin, and field interpretations can be subject to debate.

RISK OR RESOURCE

Although the future holds risks of impact, ancient impact structures may be viewed as resources, where breccia bodies and peripheral strata host accumulations of ore deposits, hydrocarbons, and ground water. An estimated 25% of the world's impact structures are associated with mineral production (Mory et al., 2000). Sudbury in Ontario hosts the world's richest nickel deposit. Vredefort in South Africa, at 300 km diameter, is the world's largest impact structure and also host to the world's largest gold deposit.

The evolution of porosity in the target rocks, fault networks, subsequent burial, and up-dip migration of hydrocarbons are important factors in impact-related petroleum accumulations. Petroleum production is associated with impact structures at Ames, Oklahoma; Calvin, Michigan; Newporte and Red Wing, North Dakota; and Marquez and Sierra Madera, Texas (Fig. 2). At 50 MMBO, Ames has the largest estimated reserves among impacts in the continental United States (Donofrio, 1997). A major oil field in Mexico appears to be associated with the Chicxulub impact (Grajales-Nishimura et al., 2000). Two enigmatic structures in Texas, at Lyle Ranch and Viewfield, have oil and gas accumulations that may or may not be impact related (Donofrio, 1997). Oil and gas production near Middlesboro, Kentucky, is mostly related to thrust plays (Kuehn et al., 2003). The Avak structure near Barrow, Alaska, hosts three gas accumulations (Kumar et al., 2001).

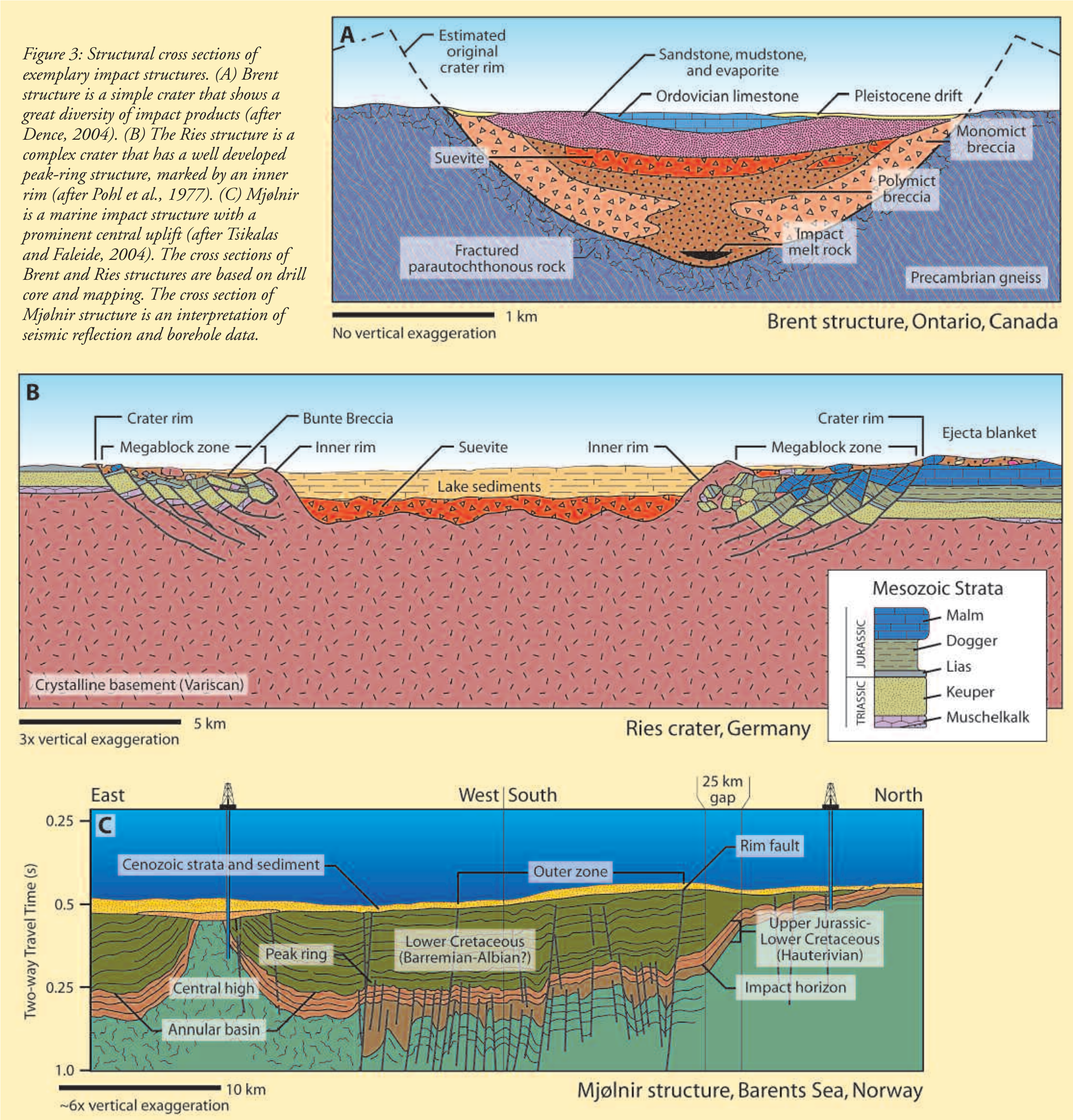
RESEARCH CONFERENCE

SEPM is hosting a Research Conference on The Sedimentary Record of Meteorite Impacts, May 21-22, 2005, in Springfield, Missouri. The conference will feature talks and posters on the sedimentary aspects of impact structures around the world. It includes a field trip to the Weaubleau-Osceola structure and an optional field trip to the well known Decaturville and Crooked Creek impact structures. The co-conveners of the Research Conference are Kevin Evans (Southwest Missouri State University), Wright Horton (U.S. Geological Survey), Mark F. Thompson (Kentucky Geological Survey), and John Warme (Colorado School of Mines). The sedimentary record of meteorite impacts will be addressed using multidisciplinary approaches, which include scientific drilling, geologic mapping, sedimentology, stratigraphy, paleoecology, paleontology, petrology, mineralogy, hydrology, geophysics, remote sensing, and astrobiology.

PRESENTATIONS

Keynote speakers for the Research Conference are Jay Melosh (University of Arizona) and

Figure 3: Structural cross sections of exemplary impact structures. (A) Brent structure is a simple crater that shows a great diversity of impact products (after Dence, 2004). (B) The Ries structure is a complex crater that has a well developed peak-ring structure, marked by an inner rim (after Pohl et al., 1977). (C) Mjølnir is a marine impact structure with a prominent central uplift (after Tsikalas and Faleide, 2004). The cross sections of Brent and Ries structures are based on drill core and mapping. The cross section of Mjølnir structure is an interpretation of seismic reflection and borehole data.



Bevan French (Smithsonian Institution). Jay Melosh, author of Impact Cratering, A Geologic Process (Melosh, 1989), is an expert on numerical modeling of impact processes who will present information on the generation of particles and stratigraphic significance of distal ejecta. Bevan French, author of the book *Traces of Catastrophe, A Handbook of Shock-Metamorphic Effects in Terrestrial Meteorite Impact Structures* (French, 1998), has had a long career investigating impact products and will discuss the importance of these geologic structures.

Oral and poster presentations will feature studies from several impacts, including:

- K/T impact breccia, Belize; multiple debris-flow units up to 7 m thick record variations in turbulent and laminar flow in the aftermath of this Earth-shattering impact.
- Alamo Breccia, Nevada; why is this deposit asymmetrical, and why does it show only shallow disturbance over a huge area? Alternative solutions include impact directly on the Devonian continental margin, a massive impact in deep water, or multiple impacts.
- Avak structure, Alaska; distal ejecta in core may provide tighter age constraints for the age of impact.
- Bosumtwi crater, Ghana; drilling in the 8 km diameter lake that fills this structure is providing valuable information on orbital-scale climatic variations of monsoons and droughts.
- Chesapeake Bay structure, Virginia; studies

Figure 4: NX core from the MoDOT-SMSU Vista 1 borehole penetrated nearly 220 ft (~67 m) of breccia. Each core segment is five ft (~1.5 m) in length. Top is at upper left and bottom at lower right. Total depth (TD) reached 247.8 ft. The yellow-brown polymict breccia in the upper part of the core contains angular clasts of dolomite, siltstone, sand grains, chert, and chert concretions supported by a fine-grained limestone matrix. This unit is interpreted as ejecta or a resurge deposit. Rounded crystalline basement clasts were recovered at approximately 200 ft (61 m), and the lower 20 ft (4.5 m) of core contains crystalline basement clasts. Drilling records from this area indicate crystalline basement at a depth of about 1,400 ft.

of drill core and geophysical surveys provide insights into the sedimentology, mineralogy, petrology, paleontology, paleoecology, morphology, and hydrology of this 85-km diameter marine impact structure.

- Crooked Creek, Decaturville, and Weaubleau-Osceola structures, Missouri; compelling sedimentological and geophysical evidence suggest that the latter may become the third impact structure recognized among the 38th parallel structures. Why are they in a row, and what are their ages? Faunal studies of the "Weaubleau breccia" give a tightly constrained age of latest Osagean (middle Mississippian).
- Mjølnir structure, Barents Sea; sooty remains in breccia from this Late Jurassic marine structure suggest that the impact ignited petroleum-rich material on the seafloor target. Slumps and debris flows later blanketed the crater with sediment. A display of drill cores from the structure will provide for lively discussion.
- Gardnos structure, Norway; drill core is providing a new look at avalanche and debris flow processes that record the collapse of the central peak and crater walls. A segment of drill core will be available for examination.
- Silverpit structure, North Sea; "impact taphonomy" is a new approach looking at impact-damaged microfossils. In this late Paleocene structure, microfossils provide information on the temperature and pressure conditions.
- Tvären structure, Sweden; after the impact event, marine craters can provide a sheltered ecosystem for pioneer species. This Ordovician impact crater contains a richly diverse assemblage of post-impact fauna.
- Lockne crater, Sweden; core drilling is providing information on the processes associated with excavation and ejection in marine impacts.
- Wetumpka structure, Alabama; sedimentology based on drill cores suggests two crater-filling episodes; a rapid fallback of material followed by the violent return of seawater.

Other presentations will focus on distal ejecta in areas such as the North American tektite strewn field, the Barberton greenstone belt of South Africa, and the Western Desert of Egypt, and the widespread stratigraphic record of a 4 kyr BP impact of uncertain location.

Following presentations, a workshop will feature core from the Weaubleau-Osceola structure of Missouri (Fig. 4). The MoDOT-SMSU Vista 1 core features more than 200 feet (~60 m) of breccia to a TD of 247.8 ft (67 m); it includes rocks that are interpreted as carbonate ejecta or resurge breccia, as well as crystalline basement breccia that has been uplifted approximately 1,200 ft (360 m). Other cores from Weaubleau-Osceola and Decaturville will tie into the field trip stops.

FIELD TRIPS

Weaubleau-Osceola, Crooked Creek and Decaturville are three of the "cryptoexplosive" structures that have been proposed along the 38th parallel (Fig. 5). The field trip to the Weaubleau-Osceola structure, led by Kevin Evans and Charles Rovey, Southwest Missouri State University, will feature roadcuts and quarry exposures, where the rocks are folded and brecciated (Fig. 6 and cover). Structural complexity around the Weaubleau Creek area has been known for more than half a century, but digital-map images in 2002 revealed a much broader, 19-km diameter, circular area of deformation. The age of the Weaubleau-Osceola structure is tightly constrained by the youngest ages from mixed faunas recovered from the breccia (middle Mississippian, latest Osagean). Features of the Weaubleau-Osceola structure that have been reported as evidence of an impact origin include a circular outline, brecciation, intense laterally-directed folding and thrust faulting, peripheral normal faults, circular Bouguer gravity anomaly low, basement ring(?) uplift, a possible shatter cone recovered from core, and preliminary petrographic evidence for planar fractures and planar deformational features in quartz (Evans et al., 2003).

An optional Monday field trip (May 23), led by George Davis, Missouri Department of Transportation, and Pat Mulvany, Missouri Department of Natural Resources, will feature the well known Crooked Creek and Decaturville impact structures. Shatter cones and shocked quartz have been reported from both structures (Fig. 7; Dietz and Lambert, 1980; Hendriks, 1954; Offield and Pohn, 1979).

SCHEDULE OF EVENTS

Saturday, May 21:	Daytime talks and posters Evening reception and workshops (core, remote sensing)
Sunday, May 22:	Field trip to Weaubleau-Osceola structure
Monday, May 23:	Optional field trip to Decaturville and Crooked Creek structures
Tues.-Wed., May 24-25:	Short course "Traces of Catastrophe" by Bevan M. French* *This short course, although not affiliated with SEPM or the Research Conference, will be offered at Southwest Missouri State University for a nominal fee.

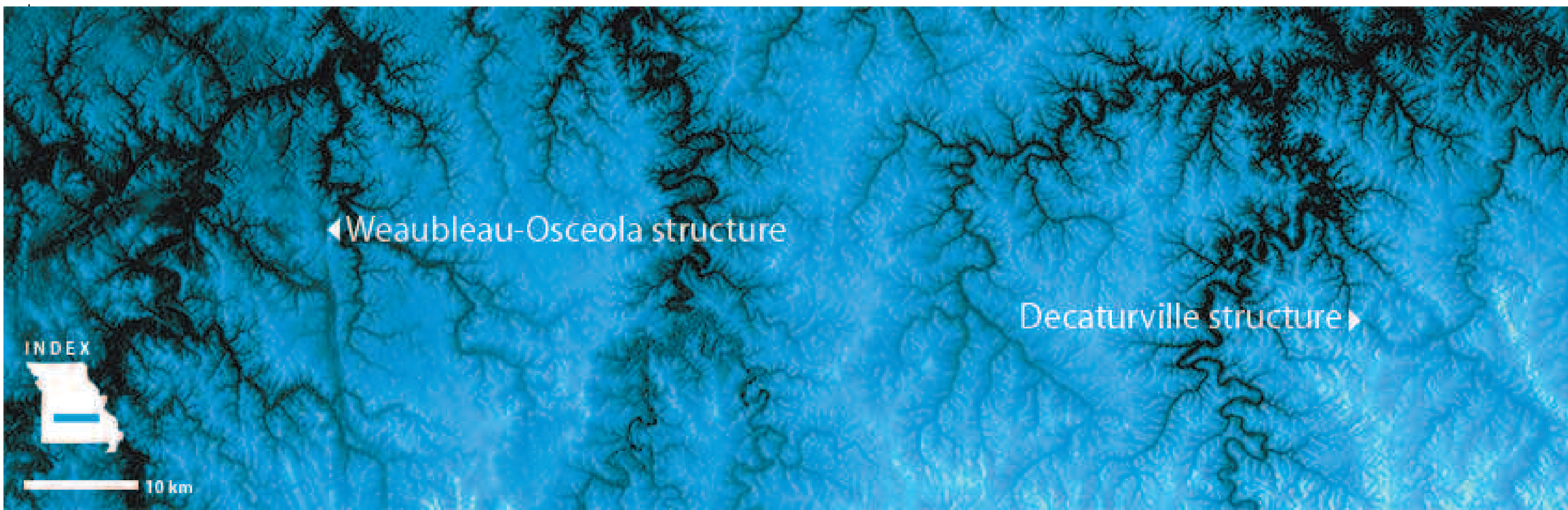


Figure 5. Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) image across central Missouri shows circular features associated with the Weaubleau-Osceola, Decaturville, and Crooked Creek structures. This DEM is in shaded relief, where dark blue and black indicate low elevations (~700 ft), and light blue indicates higher elevations (~1,200 ft). DEMs, such as this, led to the discovery of new features of the Weaubleau-Osceola structure (Evans et al., 2003). SRTM data obtained from USGS EROS Data Center in 2004 (<http://seamless.usgs.gov.).

Figure 6. Recumbent fold and thrust fault in Mississippian carbonates are overlain by brittlely fractured rocks and paleo-karst at the Ash Grove Aggregates quarry near Osceola, Missouri.

Figure 7. Shatter cones are well developed in the Potosi Formation (Cambrian) in the central uplift area of the Crooked Creek structure. Knife is 90 mm.

REGISTRATION AND INFORMATION

Information on the Research Conference, including details such as registration and accommodations, is available online at: http://www.sepm.org/events/research-conferences/rconferencehome.htm

Any additional questions can be addressed to Kevin Evans [e-mail: kre787f@smsu.edu].

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