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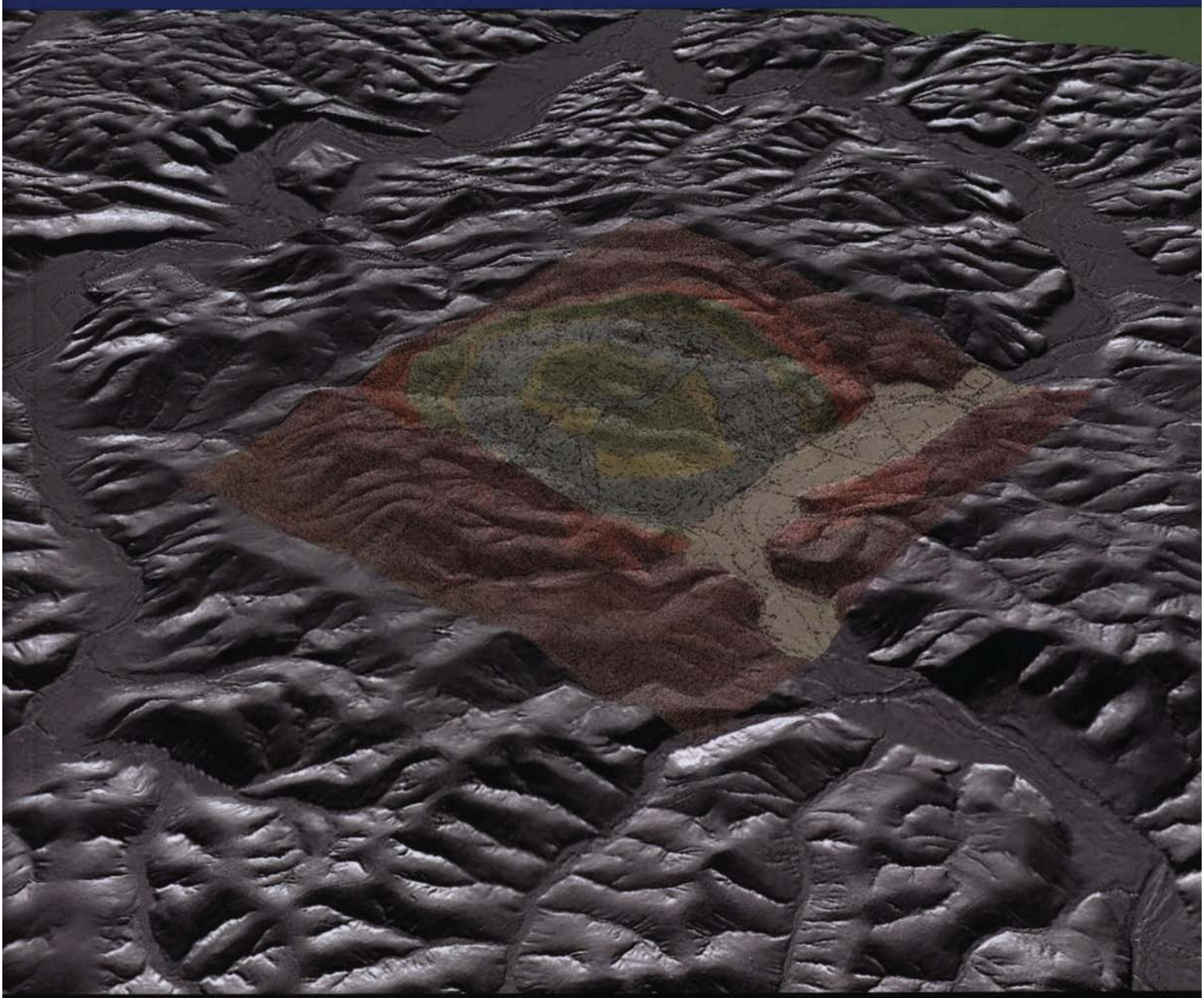

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Visualizing Impact Structures Using High-Resolution LiDAR-Derived DEMs: A Case Study of Two Structures in Missouri

Michael P. Finn, Gary W. Krizanich, Kevin R. Evans, Melissa R. Cox, and Kristina H. Yamamoto

ABSTRACT: Evidence suggests that a crypto-explosive hypothesis and a meteorite impact hypothesis may be partly correct in explaining several anomalous geological features in the middle of the United States. We used a primary geographic information science (GIScience) technique of creating a digital elevation model (DEM) of two of these features that occur in Missouri. The DEMs were derived from airborne light detection and ranging, or LiDAR. Using these DEMs, we characterized the Crooked Creek structure in southern Crawford County and the Weaubleau structure in southeastern St. Clair County, Missouri. The mensuration and study of exposed and buried impact craters implies that the craters may have intrinsic dimensions which could only be produced by collision. The results show elevations varying between 276 and 348 m for Crooked Creek and between 220 and 290 m for Weaubleau structure. These new high- resolution DEMs are accurate enough to allow for precise measurements and better interpretations of geological structures, particularly jointing in the carbonate rocks, and they show greater definition of the central uplift area in the Weaubleau structure than publicly available DEMs.

KEYWORDS: Impact structure, crater, DEM, meteorite, elevation model, LiDAR, light detection and ranging, GIScience

Introduction

In the middle of the United States there is an alignment of several anomalous geological features that have alternately been interpreted as crypto-explosive structures or meteorite impacts (Snyder 1964; Snyder and Gerdeman 1965; Unklesbay and Vineyard, 1992; Rampino and Volk 1996; Luczaj 1998; Kenkmann 2001; Plymate 2004; Evans et al. 2005a; 2005b; Planetary and Space Science Centre 2012). Crypto-explosive structures are generally assumed to have a volcanic origin. Viewed from a meteorite impact perspective, the nearly linear arrangement of the features is an argument for serial impact, comparable to the Shoemaker-Levy 9 impacts on Jupiter in 1994 (Rampino and Volk 1996). However, for this argument to hold, the age of the disturbances with respect to one another must be the same. Evidence suggests that both hypotheses may be partly correct (Dulin and Elmore 2008). A predominance of the evidence, however, seems to lean more towards the impact origin for three of the structures, Crooked Creek, Decaturville, and Weaubleau (Miller et al. 2008; Planetary and Space Science Centre 2012). Others have a variety of igneous, structural, or spurious features with enigmatic affinities (Evans et al. 2010).

We have used a primary geographic information science (GIScience) technique of creating a digital elevation model (DEM) of two of these features that both occur in Missouri–the Crooked Creek and Weaubleau structures (Figures 1 and 2). Specifically, we used DEMs created from LiDAR because the high-resolution capabilities of LiDAR-derived DEM far exceed the capabilities of other DEM sources, such as image-based photogrammetry as commonly practiced in the mapping industry. The current generation of Airborne Laser Swath Mapping systems are capable of laser pulse rates in excess of 150,000 pulses per second, and

Michael P. Finn, U.S. Geological Survey (USGS), Center of Excellence for Geospatial Information Science (CEGIS), Denver, CO. Email: <mfinn@usgs.gov>. **Gary W. Krizanich,** University of Central Missouri, Department of Biology and Earth Science, Warrenburg, MO. Email: <gkrizanich@ucmo.edu>. **Kevin R. Evans,** Missouri State University, Department of Geography, Geology, and Planning, Springfield, MO. Email: <kevinevans@missouristate.edu. **Melissa R. Cox,** Green Building Certificate Institute, Springfield, MO. **Kristina H. Yamamoto,** USGS, CEGIS, Denver, CO. <khyamamoto@usgs.gov>.

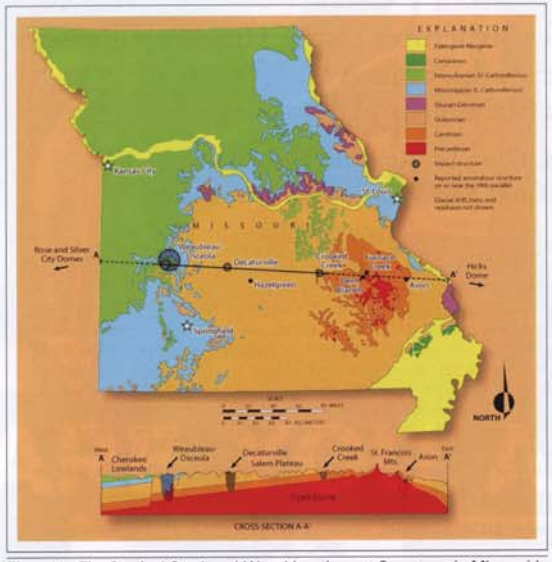

Figure 1. The Crooked Creek and Weaubleau Impact Structures in Missouri in relation to other similar structures (from Evans and others, 2005a).

with higher pulse rates comes denser point spacing, which allows finer terrain features to resolved (Slatton et al. 2007).

One of the most common applications for LiDAR data is evaluating forest characteristics. Tree height (Clark et al. 2004), diameter of stems (Lefsky and McHale 2008), and canopy and trunk volume (Omasa et al. 2008), which are difficult to measure in the field, can now be obtained more quickly, and likely more accurately, using LiDAR data. LiDAR data have also been used to quantify glacial downwasting (Hopkinson and Demuth 2006) and soil loss from gully erosion (Perroy et al. 2010). Baruch and Filin (2008) were able to detect and extract paleo shorelines using LiDAR. Further, Filin et al. (2007) extracted terrain and a road network from LiDAR data for the purpose of generalizing three-dimensional landscapes. Urban characteristics such as roof structure (Alexander et al. 2009) and building shape and size (Goodwin et al. 2009) are also possible to identify with LiDAR. Therefore, LiDAR DEMs are a good option for visualizing impact structures, as their fine spatial resolution may highlight details not visible with coarser spatial resolution datasets.

Study Area

The Crooked Creek structure is approximately 7 km in diameter and has a ring-like morphology; the exposed target material in the structure

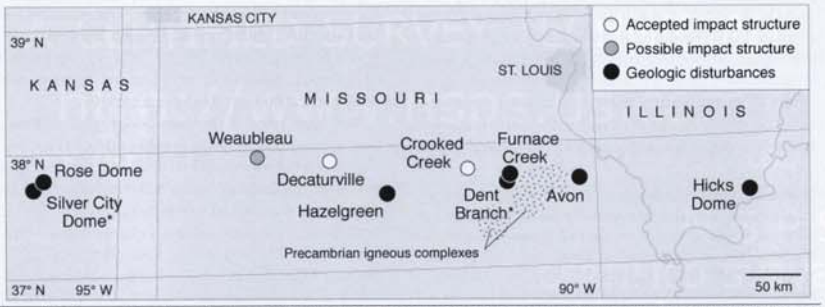

Figure 2. These midcontinent features (circles) collectively were referred to as the 38th parallel structures by Snyder and Gerdemann (1965) and Rampino and Volk (1996). [Asterisks indicate two additional structures that lie along this trend (McCracken, 1971). Decaturville and Crooked Creek are accepted impact structures (Planetary and Space Science Centre, 2012). Evidence of shocked quartz from Weaubleau indicates that it too is an impact structure (Morrow and Evans, 2007).]

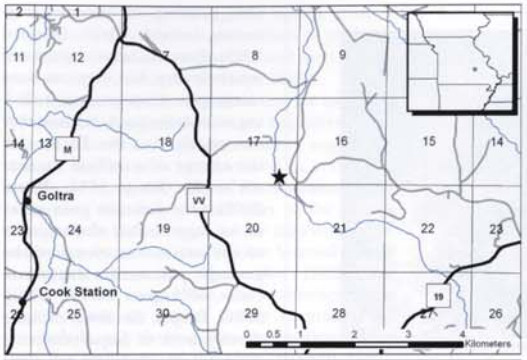

Figure 3. Location of the Crooked Creek structure in southern Crawford County, Mo, marked by a star.

includes Cambrian and Ordovician strata. It is located in southern Crawford County, Missouri, approximately 5 km northeast of Cook Station on Missouri State Highway VV and is centered at approximately 37°50′ N and 91°23′ W, Township 36N, Range 14W, Section 17 (Figure 3). The Weaubleau structure is approximately 18 km in diameter, and the structure comprises deformed Mississippian limestones and breccia that partially are buried below undeformed Pennsylvanian strata. The Weaubleau structure is located in southeastern St. Clair County, Missouri, centered approximately 3 km south of Vista, Missouri at 37°58′N and 93°40′ W (Beveridge 1978; Unklesbay and Vineyard 1992) in Township 37N, Range 25W (Figure 4).

The Crooked Creek structure has an intensely deformed central uplift area that includes displaced blocks of sandstone, dolomite, and bedded chert (Figure 5, top). Crooked Creek has eroded into the eastern margin of the central uplift and flows northward into the Meramec River. The central uplift, which consists mostly of Potosi Dolomite (Phanerozoic | Paleozoic | Cambrian-Furongian [Croixian]), exposes formations approximately 300 m higher than their stratigraphic position and is surrounded by peripheral normal faults. The surrounding moat region consists of an encircling synclinal depression in an area otherwise identified by flat top ridges that divide drainage basins with narrow flood plains (Kiilsgaard et al. 1963; Hodge 1994). The central part of the Crooked Creek structure has been eroded more rapidly than the surrounding area (Hendricks 1954; Kenkmann 2001). The uplifted rocks are exceedingly brecciated (Kiilsgaard et al. 1963). Older craters are generally too eroded to easily confirm an impact origin, but here, Dietz and Lambert (1980) found shatter cones and planar deformation features in quartz from the Lamotte Sandstone (Phanerozoic | Paleozoic | Cambrian-Furongian [Croixian]), thus providing diagnostic evidence of impact.

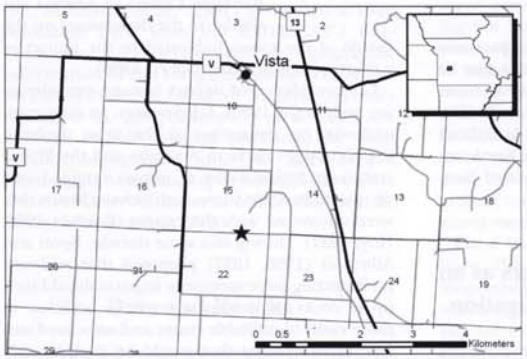

Figure 4. Location of the Weaubleau structure in southeastern St. Clair County, Missouri, marked by a star.

The Weaubleau structure lies on the northwestern margin of the Ozarks, in a dissected upland area where fairly small divides separate abundant tributaries in the Weaubleau, Coon, Bear, and Brush Creek watersheds (Figure 5, bottom). These watersheds join the Osage drainage system near the confluence of the Sac and Osage Rivers; in this area of Missouri, Mississippian strata generally dip gently at less than 1° to the northwest. Near the Weaubleau structure, however, many of the rocks are fractured, faulted, and folded. Such intense deformation makes tracing faults extremely difficult and demonstrates the mostly horizontal compressive forces acting on the Mississippian and older rocks (Beveridge 1951). The Weaubleau

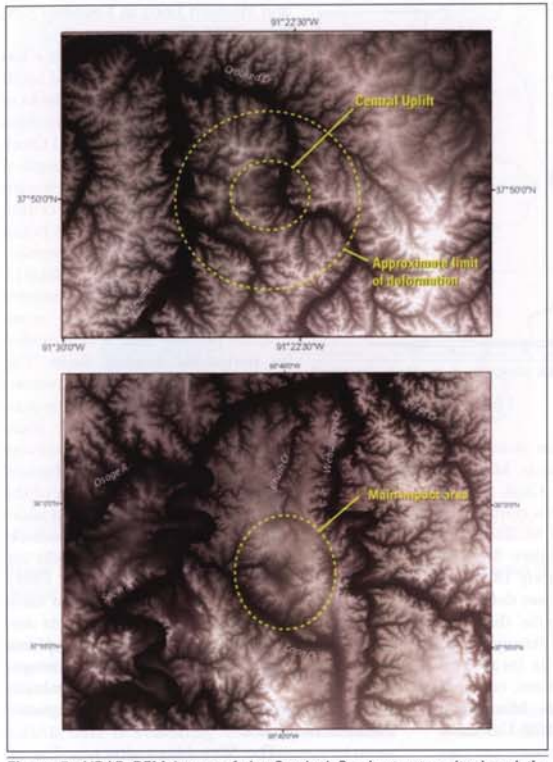

Figure 5. LiDAR DEM image of the Crooked Creek structure (top) and the Weaubleau structure (bottom).

structure is unusual in that the main impact area and tectonic rim are not concentric; this may be due to oblique impact and relatively weak material strengths in the shallow target rock. The eccentricity of the Weaubleau impact is difficult to explain, but the incompetence of the Northview Formation allowed strain to be transmitted laterally away from the main impact.

Impact Cratering and Craters as an Object of Scientific Investigation

An apparent spike in impact frequency occurred roughly 500 million years ago when it is thought that two asteroids collided, sending a considerable number of asteroid fragments toward Earth (Bogard 1995). Even so, large impacts are relatively rare, but they can have catastrophic consequences, including mass extinctions, because they can smash into the Earth with the energy of a million nuclear warheads (Raup 1991; Wood 2004). One estimate goes so far as to suggest that the majority of the extinction events of the geologic past were a direct outcome of impact events (Raup 1991). Despite the slowly evolving development of impact-cratering theories, scientists now recognize more than 170 terrestrial craters (Shoemaker and Shoemaker 1999).

In the 1870s, Grove Karl Gilbert became an affiliate of the U.S. Army's Geographical Survey West of the 100th Meridian and, in the process of this work, made wide-ranging studies in Utah, Arizona, and New Mexico which led to his explanations of distinguishing landforms of the Basin and Range Province (Dupree 1957; Pyne 1980; Hoyt 1987). In the 1890s, while acknowledging similar predecessor suggestions, Gilbert suggested that the crater at Canyon Diablo (also known as Coon Butte, Coon Mountain, Meteor Crater, and, ultimately, Barringer Crater) in Arizona was similar to the depressions on the facade of the moon fashioned by the impact of a giant meteoritic mass (Gilbert 1896).

Later, evidence of impact became overwhelming and, in the 1930s, L.J. Spencer, an important authority on meteorites at the time, declared the Henbury craters in Australia and the Wabar craters in Arabia to be of impact origin, based on the meteoritic irons and lechaterlierite that were uncovered with the craters (Baldwin 1963; Hoyt 1987). During this same decade, Boon and Albritton (1936; 1937) proposed that evidence for detecting large meteorite impacts should turn up in rocks underlying a crater in addition to more easily identifiable crater and associated surface disfigurement that would be decipherable after erosion removed all surficial evidence of the impact event. Subsequently, Baldwin (1949) listed

10 craters (or groups of craters) known to be of meteoritic origin and a dozen others as probably having been formed by impact, and soon his list grew to 48 (Baldwin, 1963; Hoyt, 1987).

Shoemaker (1983) extended the list to nearly 80 after challenging Baldwin's hypothesis that impact craters are explosion craters, suggesting that an explosion is not involved in crater formation of meteorite craters. Rather, Shoemaker contended that only a small part of the kinetic energy of the meteorite is in the meteorite itself, and only a fraction of this leftover internal energy is trapped thermally (Shoemaker 1962; Hoyt 1987). By the early 1960s, the conversion from cryptovolcanic to impact theory essentially was concluded, only lacking the explanation rather than the legitimacy of the idea (Baldwin 1965). Impact craters occur on all the terrestrial planets and their satellites as well as on the vast majority of satellites of the outer planets (Shoemaker 1984; Hoyt 1987).

The mensuration and study of exposed and buried impact craters as well as volcanoes, pull-apart basins, diapirs, and similar circular features implies that impact craters may have intrinsic dimensions that could only be produced by collision (Stewart 2003). For example, it has been hypothesized that a depth-to-diameter aspect ratio of 0.05-0.3 would be more consistent with an origin other than volcanic, i.e., an impact crater (Stewart 2003). The interpretation of high-resolution DEM derived from airborne light detection and ranging, or LiDAR, can potentially contribute to the study of impacts as well as other enigmatic circular structures, and benefit scientists who study them. Similar approaches, with coarse resolution data, have been used; for example, Mahmood et al. (2001) generated a 10-m resolution DEM from the RADARSAT-1 fine-beam data to generate accurate topographic information of the Haughton impact crater site on Devon Island in Canada's Nunavut Territory (Rosen et al. 2001; Mahmood et al. 2003). In addition to laser ranging on Earth, the most detailed topographic survey of Mars used a nonimaging laser-ranging device called the Mars Observer Laser Altimeter or MOLA (Zuber et al. 1992; Mahmood et al. 2003).

Data and Results

For the United States, the nominal, publicly available DEM is based on a 1 arc second posting of latitude and longitude, with some higher resolutions available at 1/3-arc second and a few at 1/9-arc second. These DEMs have nominal postings of 30-, 10-, and 3-m, respectively (Gesch et al. 2002; U.S. Geological Survey 2006). We acquired airborne LiDAR data at nominal 1.4-m pulse ground-sample distance (nominal because LiDAR has a non-gridded character) and processed these data to a DEM with 1.6-m post spacing. These data represent a statistically rigid solution based on samples collected in two directions at 90 percent of the final post spacing as follows:

$$CI = 0.9 * PS \quad (1)$$

where CI equals the collection interval and PS equals the post spacing. So, for these data, we used the following equation:

$$1.4m = 0.9 * PS \quad (2)$$

$$1.5555m = PS \quad (3)$$

The result was rounded up to 1.6 m (ceiling function). This provided for even more redundancy for the Inverse Distance Weighting interpolation.

The LiDAR data were collected between 30 November and 05 December 2005 to provide a high-accuracy, bare-earth ground-surface model. We defined an area of interest (AOI) for both collection targets as a bounding rectangle. The AOI for the Crooked Creek structure was 280 km^2 and for the Weaubleau structure 736 km^2 (Figure 5). These data were processed to the North American Datum 1983 and the North American Vertical Datum of 1988. LiDAR calibrations were performed to eliminate systematic biases that occurred within the hardware. A base survey network was established for each AOI, utilizing five National Geodetic Survey (NGS) monuments (Figure 6), and survey data were processed to adjust the network to first order in terms of internal accuracy with constraints as shown in Table 1. As this project was focused on the identification of impact structures through visualization there was no further ground truth testing other than the tying of the bare-earth DEM to the ground control, as opposed to obtaining absolute survey measurements.

Fixed bias solutions were found for all baselines. The broadcast ephemeris was used. The loop misclosures are outlined in Table 2. The misclosures in each component are given in millimeters and parts per million (ppm) in an Earth-Centered, Earth-Fixed (ECEF) Cartesian coordinate system. Every station in the network occurs at least once in a loop. All loops meet

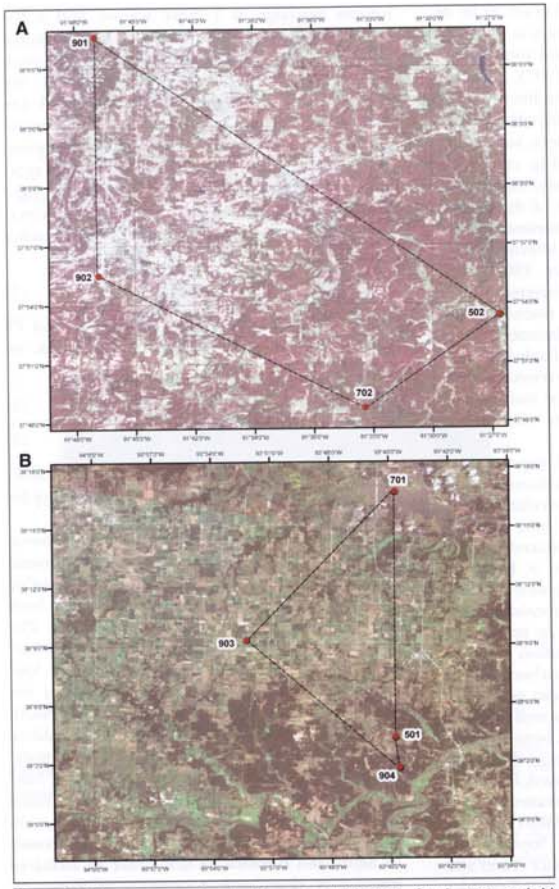

Figure 6. The survey network diagram: a) Crooked Creek area and b) Weaubleau area. Numbers refer to the NGS Station Name as shown in Table 1.

with GPS guidelines for first order work: in any component (X, Y, Z),

- the maximum misclosure does not exceed 250 mm;
- the maximum misclosure in terms of the loop length does not exceed 12.5 ppm; and- the average misclosure in terms of the loop length does not exceed 8 ppm.

The geodetic latitude, longitude, and elevation of one existing control point were held fixed, and an adjustment comprising of four stations and 12 baseline vector components was performed. *A priori* weights for the observations were based on the variance–covariance submatrices from solutions from Trimble Navigation's GPSurvey™ software. The relative confidence regions and the associated relative horizontal and vertical precisions were computed for all pairs of points that were directly connected by vectors. All station pairings meet the horizontal positioning standard for *first order* surveys. The network is therefore classified as *first order* in terms of its *internal* accuracy.

To complete fully constrained adjustments, the network for the Crooked Creek area was horizontally constrained to control points 901 and 902 and vertically by orthometric elevation to 90. For the Weaubleau area, the network was horizontally constrained to control points 701 and 903 and vertically by orthometric elevation to 903 and 904. (See Table 1 for associated orders and assigned standard deviations.) None of the 12 vector components were flagged for possible rejection under the τMAX - test at the 0.05 level of significance. None of the horizontal or vertical constraints were flagged. The slight change in the *a posteriori* variance factors ($\sigma_o^2 = 1.0505$ for Crooked Creek area) and ($\sigma_o^2 = 1.0559$ for Weaubleau area) from the minimally constrained adjustment indicates that the network is not being unduly distorted by the imposition of the constraints.

Next, we took the LiDAR data–which had been delivered in an ASCII (comma separated) file of X, Y, and Z coordinates–and created the 1.6-m DEMs. We manipulated and analyzed the DEMs separately and in conjunction with other digital geospatial datasets including raster topographic and geologic maps. The results show elevations varying between 276 and 348 m for Crooked Creek and between 220 and 290 m for the Weaubleau structure on models compiled to

Code	NGS Station Name	Order	Latitude	Longitude	Height
Horizontal					
701	CLINTPORT	B	0.03	0.03	
901	ROLLA NATL PORT	B	0.03	0.03	
902	PH 03	1	0.03	0.03	
903	APPLETON EAST BASE	2	0.03	0.03	
Vertical					
901	ROLLA NATL PORT	1-II			0.001
903	APPLETON EAST BASE	2-0			0.005
904	VISTA	2-0			0.005

Notes: Order is the survey order for the stations; standard deviations in meters; "Code" refers to station numbers shown in Figure 6).

Table 1. Network adjustment constraints.

Loop	dX (cm)	dY (cm)	dZ (cm)	Dist. (m)	ppm
Crooked Creek Area					
901-502-702-902-901	0.4	1.8	1.6	99985	0.24
Weaubleau Area					
701-501-904-903-701	0.4	0.2	0.0	94971	0.04

Table 2. Survey loop closure summary.

meet vertical accuracy of not greater than 0.12 m and horizontal accuracy of not greater than 0.03 m, based on values in Table 1 and performance flights over a runway test field (Federal Geographic Data Committee 1998; Minnesota Planning 1999).

In addition to many other potential uses, these new high-resolution DEMs are accurate enough to allow for precise measurements and better interpretations of geological structures (such as shape and extent), particularly for jointing in the carbonate rocks. The use of such DEMs may ultimately stimulate advancements in knowledge of these meteorite impact structures (Figures 7 and 8).

Figure 9 shows the DEM of the Crooked Creek area with a geo-registered geologic map draped over the terrain. Figure 10 shows a shaded relief rendering of the LiDAR DEM (top) of a portion of the main impact area of the Weaubleau structure, which illustrates the striking level of detail

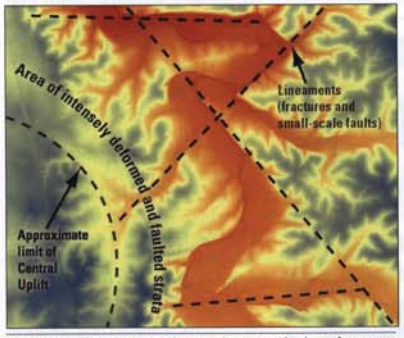

Figure 7. This image shows the complexity of stream meandering in an area that has extensive fracture control for the Weaubleau structure. Amstutz (1965) recognized the polygonal nature of these sorts of features.

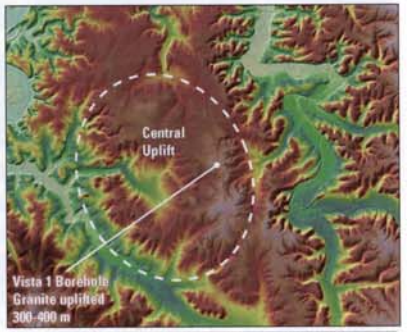

Figure 8. The ring-like drainage feature in this LiDAR image is the central uplift area of the Weaubleau structure.

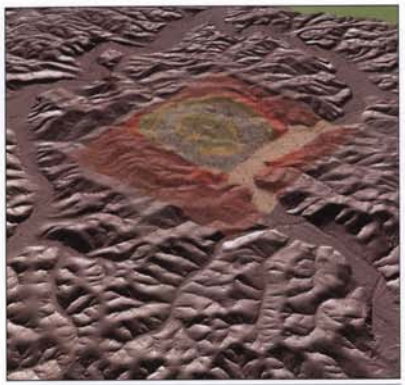

Figure 9. Crooked Creek area – with geologic map draped (Hendricks, 1954). Vertical exaggeration 5X.

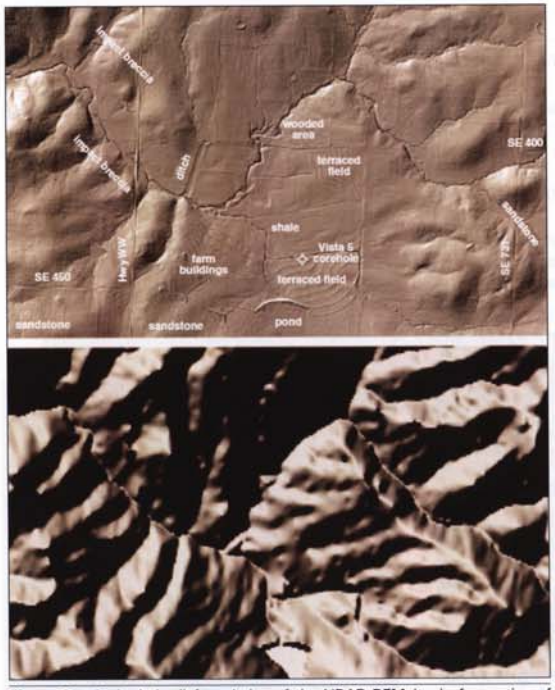

Figure 10. A shaded relief rendering of the LiDAR DEM (top) of a portion of the main impact area of the Weaubleau structure illustrates the striking level of detail that cannot be achieved with the standard 30 m DEM (bottom).

that cannot be achieved with the standard 30 m DEM (bottom). As can be seen in Figure 10, buildings, berms from terraced agricultural fields, roads, and ponds are clearly visible. The topography of this area is a product of weathering of crater fill materials as well as deposition and erosion of overlying undeformed strata above the impact breccia (broken and deformed rock). The low area in the central part of this image (location of Vista 5 corehole) is near the center of the main impact area. Core-drilling encountered 52 ft (15.8 m) of undeformed shale before reaching impact breccias that are exposed in nearby creeks and hillsides. Undeformed sandstone that postdates the impact is exposed on the higher hills surrounding the center. Shocked quartz grains recovered from the breccias are diagnostic of an impact origin for the Weaubleau structure. Shocked quartz includes microscopic planar deformational features and other planar microstructures that form as a response to shock pressures greater than 5 gigapascals (GPa).

Figure 11 shows a shaded relief image of a portion of the Crooked Creek structure. Vertical beds bordering the central uplift are visible near the center of the image The area of the central uplift is characterized by low-lying topography where the target rocks were essentially crushed and broken (brecciated). Shatter cones, which also are diagnostic of an impact, have been found in creeks that cut across the central uplift. Shatter cones are macroscopic conical rock forms that show characteristic "horse-tailing" striations on their surfaces.

Discussions and Conclusions

We have brought a new data set (LiDAR) to investigate a geomorphic problem. The objective was to see if a new (very) high-resolution DEM would have the effect of making hypothesized ancient impact sites easily recognizable (i.e., jump out at the viewer) from the rest of the terrain. Utilizing denser point spacing than was available in the past we are now able to resolve very fine terrain features. LiDAR provides geologists and terrain analysts a new tool in a high-resolution DEM that traditional DEMs do not.

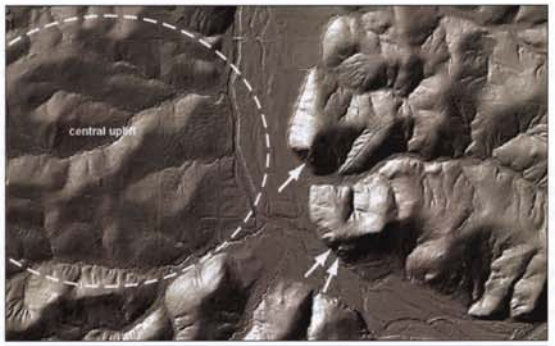

Figure 11. A shaded relief image of a portion of the Crooked Creek structure. Arrows indicate vertical and near-vertical beds bordering the central uplift near the center of the image.

LiDAR data show greater definition of the central uplift area in the Weaubleau structure than do the traditional 30-m DEMs. LiDAR has much higher resolution and assists by helping to identify areas of interest that can be visited for field mapping (for example, 8 m high road cuts along Highway 13 are clearly visible as are some vertical beds along Coon Creek). LiDAR alone cannot be used to positively identify impact structures. This still requires identification of shock metamorphic features or other proxy evidence from impactors.

For this investigation, we acquired airborne LiDAR data at nominal 1.4-m pulse ground-sample distance in 2005, which is roughly less than 1 point per meter squared. Due to technological advances, more recent LiDAR systems are able to measure a more dense point cloud. However, we doubt that using a more dense point cloud would have improved our results, primarily because of the amount of erosion present. Although the data collection for this study cost less than U.S. $40,000 in 2005, we presume that our LiDAR flight is still much more cost-effective than a ground survey. Ground surveys are not feasible for creating DEMs, and the alternative would be a photogrammetrically derived DEM, which is more costly (Petzold at al. 1999). Therefore, survey-grade work would not add great benefits to this study, other than to increase the density of a ground-control network for the quantitative accuracy assessment of the finished DEM. However, field surveying work with a geological aim, instead of surveying or positioning, may be of use for future studies to add additional information about crater identification. Further digital processing may also help the identification, as well as adding the benefit of a likely lower cost than an absolute survey. This digital processing would unfortunately also increase the cost and time of the data analysis, but this could be implemented in future work. Additionally, although there was no quantitative accuracy testing against the 30 m DEM, visual inspection (Figure 10) indicates that the accuracy was much greater in the 1.6 m LiDAR data than the 30 m DEM). Previous comparisons done between LiDAR-derived DEMs and photogrammetrically derived DEMs have consistently shown the LiDAR DEMs to be more accurate (see for example, Adams and Chandler 2002; Murphy et al. 2008).

The emphasis of this study was to see how LiDAR data can help visualize crater impacts. Studies that can expand on the methods utilized from this work are potentially numerous, including comparisons of surface roughness of the crater and non-crater areas, and the use of edge detection to highlight the crater boundaries. In addition, Fourier analysis of periodicity can be done to illustrate the surface's dome tendency. These analyses may help further characterize the impact structures and assist in delineating craters from the surrounding landscapes. Such delineations could assist in the defining of many like geomorphic features in a feature-oriented geospatial data model, for example. The results from this study also help define further areas of interest when using LiDAR data with impacted surfaces.

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comment that made the manuscript better. Any use of trade, product, or firm names in this paper is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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