Serendipity: A search for lineaments finds impact craters?

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Abstract

In exploration for oil and gas, potential fields provide a cost-effective way to explore large areas. Euler deconvolution is an established algorithm to extract features from potential fields. We use an enhancement to the conventional Euler deconvolution process designed to identify lineaments typically associated with faults, fractures, etc. In examining these data, it was surprising to observe circular features, in particular a very large feature in the Texas Panhandle. Since the observed pattern was suggestive of an impact site, known impact craters are examined to look for similar expressions in the gravity field. Gravity measurements are often used in analyzing impact sites due to changes in geology, which can be quite varied and complex. The ability of this process to extract small coherent signals from the data and to operate on large areas makes it a useful tool in identifying impact sites and other large circular features such as salt domes, calderas, etc. All of these types of structures can be of scientific and economic interest. The examination here is focused on impact structures.

Introduction

Several authors have written on the relevance of impact craters to economic production of hydrocarbons and minerals, motivating this study. "Nearly one quarter of all known terrestrial impact craters are associated with economic deposits of some kind whether they are mineral ores, hydrocarbons, evaporite minerals, or even fresh water" (Mazur et al., 1997). Writing about the importance and difficulty of identifying impact sites, Donofrio concludes: "The known and potential dimensions of impact events need to be realized. Large scale impact structures (or their remnants) approach linearity relative to regional geologic and geophysical coverage used in an exploration program. Recognition of a feature such as a rim arc is a challenge to explorationists, and the basinward flank of a large scale rim segment is one of the crater areas where a giant field awaits discovery" (Donofrio, 1998). This linearity, which makes them difficult for explorationists to identify, is what enables our lineament process to detect large circular features. The ability to cover a large area in a cost-effective way makes this process well suited to identify features that might otherwise go unnoticed. Examples shown here are based on regional gravity grids, available from the U.S. Geological Survey (USGS). Lineament analysis will not provide direct evidence of hydrocarbons or minerals, but it may yield a better understanding of the geologic history and be useful in locating geology analogous to existing production.

EASI: Euler angle stack imaging

The Euler angle stack imaging (EASI) process used here originated at Amoco Production Company as an enhancement to the Euler deconvolution algorithm first described by Thompson (1982). As a deconvolution process, it takes a gridded field of data (Bouguer gravity or total magnetic intensity) and identifies points satisfying the Euler equation (Thompson equation 1). From Thompson, Euler's equation is expressed as

$$x\frac{\partial f}{\partial x}+y\frac{\partial f}{\partial y}+z\frac{\partial f}{\partial z}=nf\ . \qquad (1)$$

For a point source located at x_0, y_0, z_0 relative to the plane of measurement, the total field intensity I will be of the form

$$\Delta I(x,y)=f\left[(x-x_0),(y-y_0),z_0\right]. \qquad (2)$$

Euler's equation for this can be written as

$$(x-x_0)\frac{\partial \Delta I}{\partial x}+(y-y_0)\frac{\partial \Delta I}{\partial y}-z_0\frac{\partial \Delta I}{\partial z}=-N\Delta I(x,y), \qquad (3)$$

where N represents a structural index dependent on the geometry of the source of the field. Solving equation 3 for (x_0, y_0, z_0) in a least-squares sense using vertical and horizontal gradients of the field at each input-grid position yields an estimate of the anomaly's location and depth. The EASI implementation extends Thompson's approach into three dimensions.

Development of the process has continued at Flamingo Seismic Solutions. The enhancement to the process filters the data to bring out linear features and is typically used for locating faults, fractures, etc. As illustrated in Figure 1, the gridded input field is first transformed into the spatial frequency domain. A high-cut spatial filter is typically applied to remove noise. In the frequency domain, the data is divided into ranges of azimuths, with each range then transformed back to the spatial domain for Euler deconvolution. These azimuthally separated fields more closely approximate the 2D case. Iterating over the field will produce multiple solutions in close proximity to each other. These results are then averaged (stacked) in the spatial domain. As with seismic data, this stacking process reduces noise from the Euler solution considerably. These point features are plotted using a color scale based on the pseudo-depth value which comes from the frequency content of the field. Figure 2a shows an example input Bouguer gravity field (U.S. Geological Survey, 1995), and the EASI results from the field are shown in Figure 2b. In displaying the results, each color dot represents an average of the projected solutions of Euler's equation over an area of the input field to a point in x, y, z space. The points are colored by the pseudo-depth z value from red (shallow) to blue (deep). This example shows the linear nature expected from the process.

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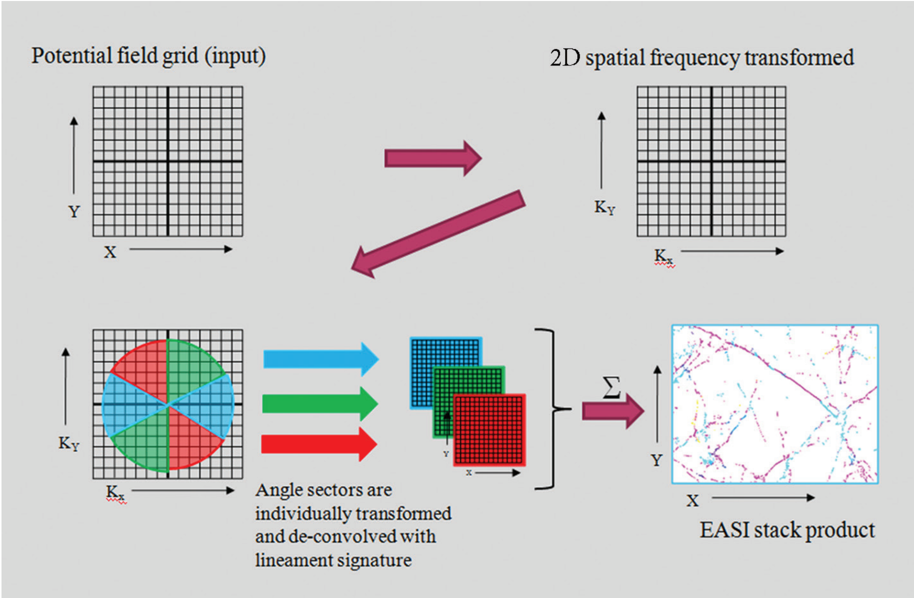

Figure 1. Depiction of the Euler angle stack imaging (EASI) process.

Texas Panhandle/western Oklahoma

Since EASI is designed to identify linear features, it came as a surprise to see what looked like large circular features in the results. The gravity field published by the USGS for the Texas Panhandle and surrounding areas is shown in Figure 3a. Lineaments computed from this field are shown in Figure 3b. A regional study of this area is where large circular features were first observed, as interpreted in Figure 4. The Bouguer gravity field that was used for the lineament calculations is shown again in Figure 5a, with the interpreted circular features in Figure 5b. Hints of these circular features can be seen on the raw Bouguer field, although not as clearly defined as they are by the EASI process.

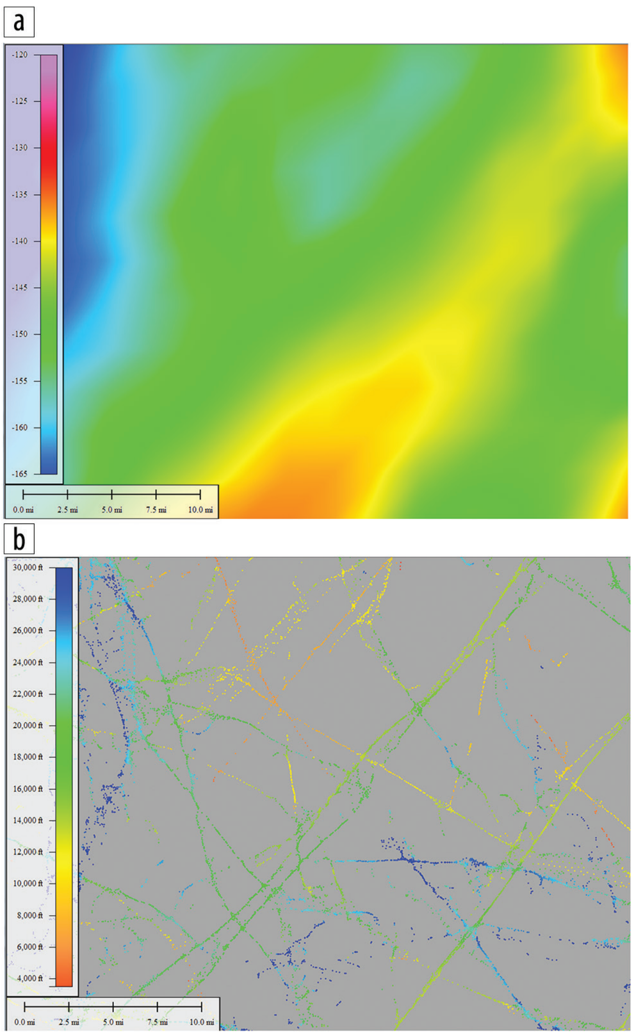

Figure 2. Example of (a) input Bouguer gravity field (USGS) and (b) computed EASI lineaments.

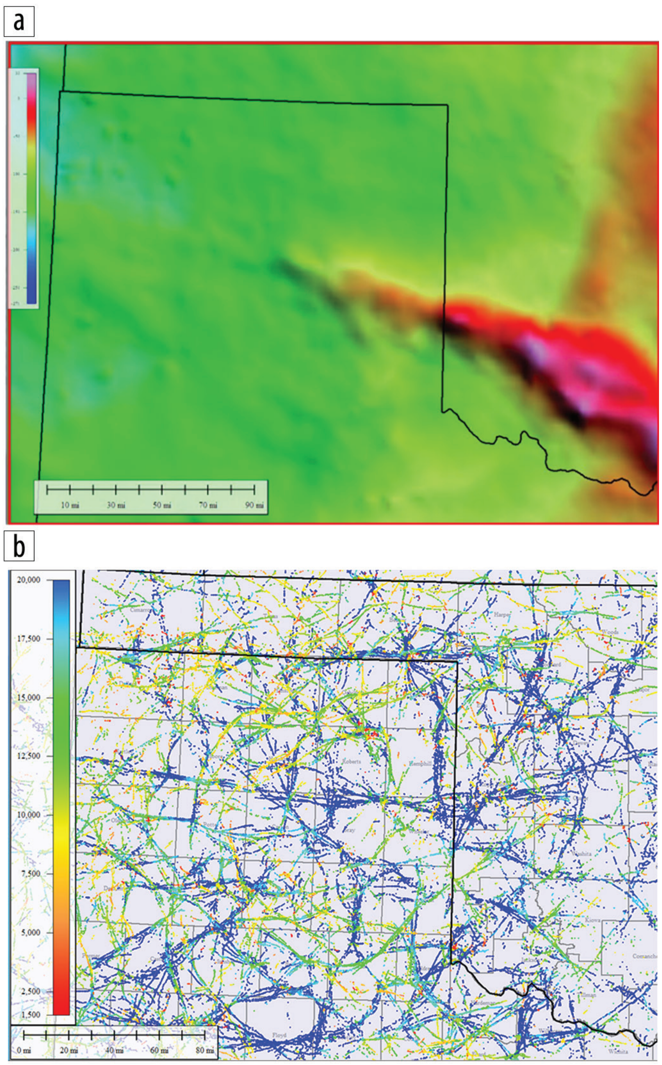

Figure 3. Texas Panhandle and Oklahoma (a) Bouguer gravity field (USGS) and (b) EASI lineaments.

The largest of these features is approximately 320 km across. Also clearly visible are bounding features along the Wichita Mountains cutting through some of the circular features. This would suggest the Wichita Mountains (~575 million years old) (Perry, 1989) are younger than the event creating the circular features. The area has long been a source of hydrocarbon production, and this may provide additional insight to its geologic history and production. Observation of these circular features led to the question of whether this could be a valid tool to aid in identifying impact sites. In an effort to validate the possibility, we examined cases of known impact sites.

Example: Ames, Oklahoma

A well-known subsurface impact site was examined near Ames, Oklahoma, (Table 1) where oil production has exceeded 17 million barrels (American Oil & Gas Historical Society, n.d.). Figure 6 shows a subsurface view of the Ames astrobleme, depicted based on well control and 3D seismic coverage (Donofrio, 2007). There is no visible surface expression of the Ames structure.

The EASI process applied to the USGS regional gravity field over the same area produces the lineaments shown in Figure 7a. The crater site is marked with a black circle and has been reported as 16 km in diameter. An interpretation of a circular feature about 145 km in diameter around the Ames impact site is identified in Figure 7b in pink.

Example: Kentland, Indiana

Another known impact site over which we had EASI data computed is a carbonate quarry near Kentland, Indiana, (Table 2) that has been identified as an impact site (Laney and Van Schmus, 1978). Figure 8 shows a map view of the bedrock geology, with the carbonate quarry indicated by a blackened section near the structure's center. In Figure 9, the cross section shows the rebound effect attributed to a large impact. It is important to note that this depiction was based on a number of studies, including reflection and refraction seismic, detailed gravity, bedrock drilling, and quarrying.

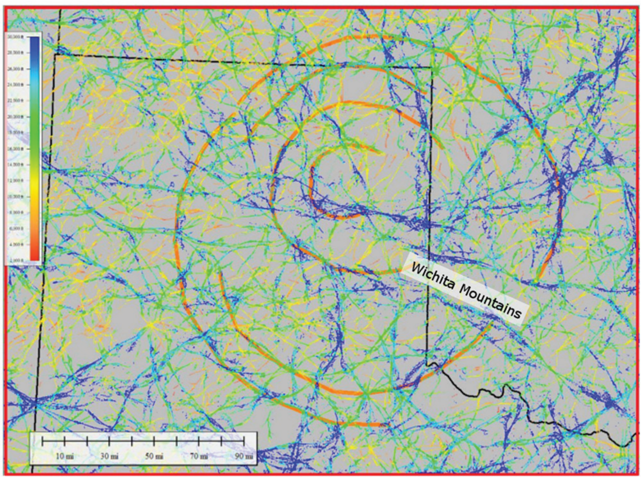

Figure 4. EASI lineaments from gravity field in Texas Panhandle and Oklahoma, with interpreted circular features.

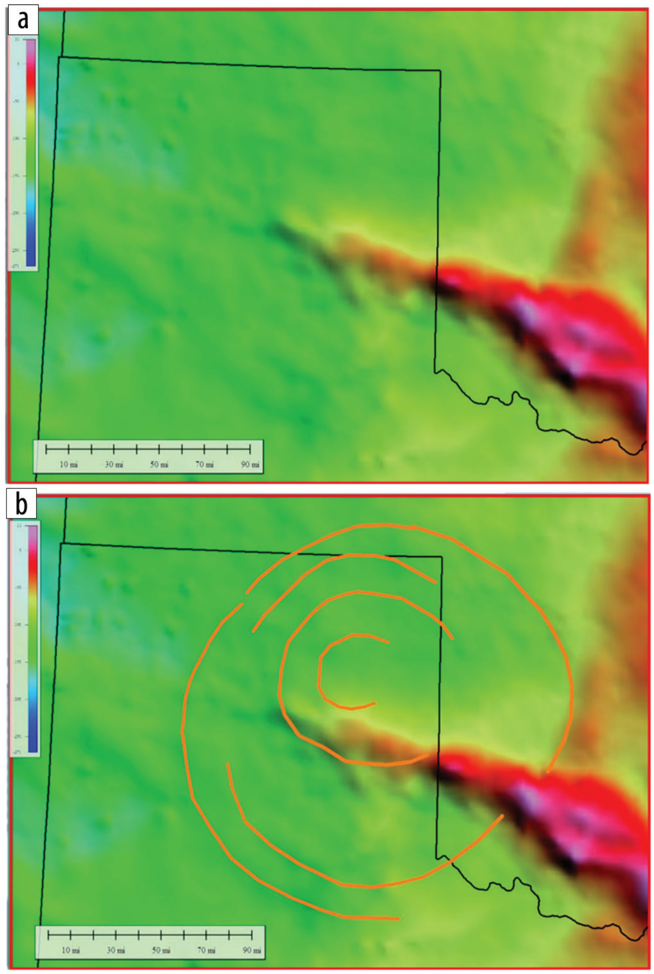

Figure 5. (a) Bouguer gravity field (USGS) shown in Figure 3a, and (b) the same field with circular features interpreted from lineaments in Figure 4.

Table 1. Crater information for Ames, Oklahoma, from Earth Impact Database (Planetary and Space Science Centre, n.d.a).

Crater Name	Location	Latitude	Longitude	Diameter	Age (Ma)	Exposed	Drilled
Ames	Oklahoma, USA	N 36° 15’	W 98° 12’	16	470 ± 30	N	Y

Table 2. Crater information for Kentland, Indiana, from Earth Impact Database (Planetary and Space Science Centre, n.d.b).

Crater Name	Location	Latitude	Longitude	Diameter	Age (Ma)	Exposed	Drilled
Kentland	Indiana, USA	N 40° 45’	W 87° 24’	13	< 97	Y	Y

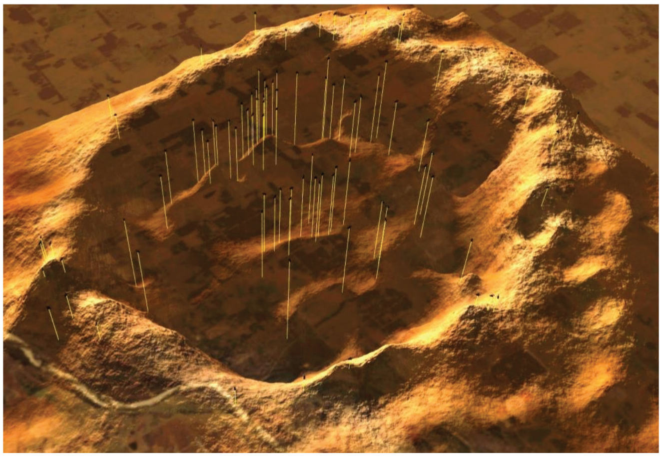

Figure 6. Ames astrobleme subsurface structure from seismic and well control (from Donofrio, 2007; image courtesy of NHK and Parwest Land Exploration).

The EASI process applied to the USGS regional gravity field over the Kentland area produces the lineaments shown in Figure 10a. In this display, shallower features (less that 15,000 ft. estimated depth) have been removed to better see the deeper features. An interpretation of a circular feature around the Kentland site is drawn in orange in Figure 10b, with a diameter of approximately 115 km. Also interpreted is another set of rings drawn in yellow showing a possible impact site to the northeast of the rings around the Kentland site. Since these rings appear to truncate the Kentland rings, this would suggest the rings to the northeast are younger.

Example: Yilgarn, Australia

The size of the Ames and Kentland features are significantly smaller than the new feature observed in the Texas Panhandle. A previously published feature in Australia is of a similar scale and supports the conclusion that these circular features are not an artifact of the EASI process, through an independent observation of circular features directly from a gravity field. Watchorn (2013a, 2013b) identified gold and nickel mines associated with circular features on gravity and Landsat images in the Eastern Yilgarn area of southwest Australia. He concludes: "The WIS (Watchorn impact site) rings also have an empirical megascopic and field correlation with the largest nickel, gold, copper, silver–lead– zinc and rare earth deposits. ... This observed relationship means a paradigm shift is needed for studying the genesis of mineralisation in the Yilgarn and targeting requirements for exploration success. *This might apply to the very similar Archaean Cratons worldwide and perhaps the same impact cratering mechanism has operated right up to the present?*" (emphasis added) (Watchorn, 2013b).

Figure 11 shows the gravitational field over the WIS alongside interpreted ring features. The largest of these is approximately 560 km in the north-south direction (Watchorn, 2013a). The rings found in the Texas Panhandle, an area of known hydrocarbon production, are similar in scale to those identified by Watchorn at the WIS. The two areas are shown side by side in Figure 12 for comparison.

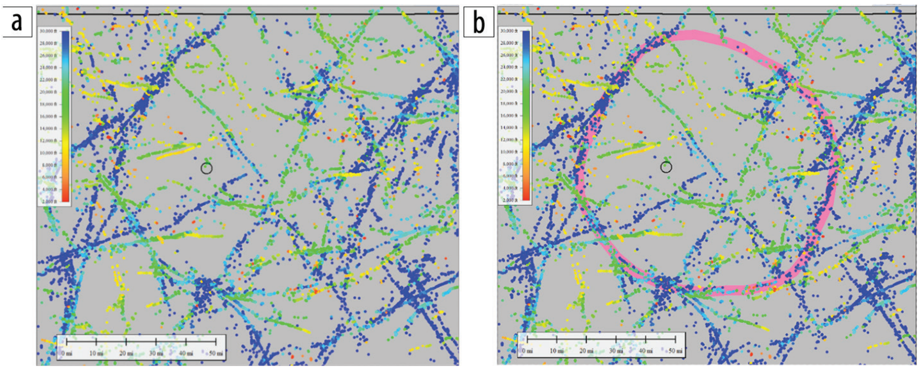

Figure 7. (a) Ames impact site approximate location at the small black circle; lineaments from USGS gravity as color dots; (b) interpreted circular features in pink.

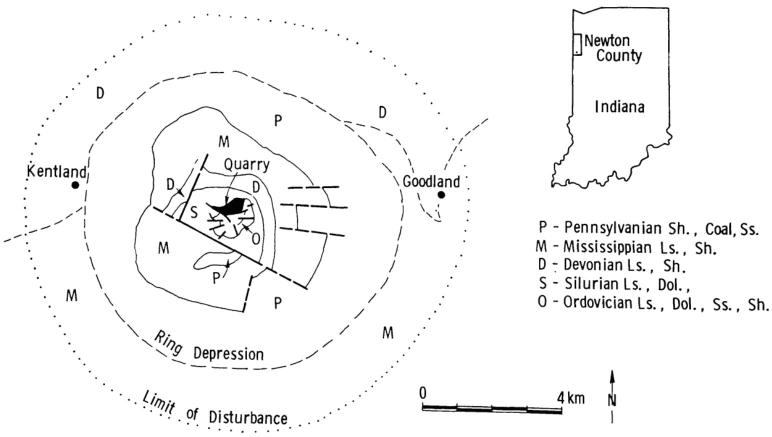

Figure 8. Map view of the Kentland impact site (from Laney and Van Schmus, 1978).

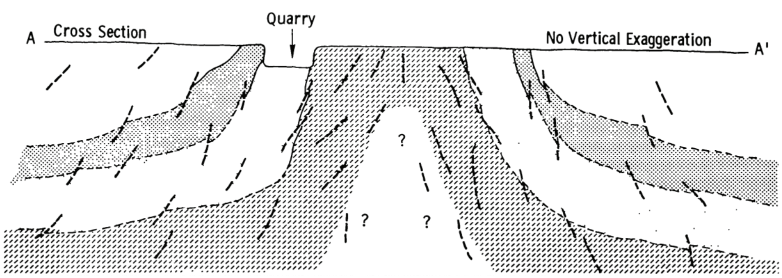

Figure 9. Cross section of Kentland impact site (from Laney and Van Schmus, 1978).

Discussion

The size of the rings observed in the EASI data in the Texas Panhandle imply that if they are caused by an impact event, they are outer rings of large complex craters (Ernston and Claudin, 2016). The spatial sampling of the input grid (~4 km) is likely too coarse to image a central peak uplift. With such sampling, a typical operator size is about 20 km for the derivative calculations, so an anomaly would need to approach linearity over that distance to be detected with this method. It is difficult to quantify a relationship between grid sampling and the minimum size of a circle that could be detected, in part because of the interpretive nature of identifying the circles. Confirmation of this being an impact site would require higher resolution data of some type. Each of the known impact sites examined here were confirmed with multiple independent sources of data such as gravity, seismic, wells, and surface data. Some of these technologies would be needed to determine whether the observed Texas Panhandle features are related to an impact event.

A number of authors, including Taylor (1982), have speculated on the likelihood of many more Earth impact sites than have been identified, based on their prevalence on other planets and moons. If the Texas Panhandle rings are the result of an impact event, the large scale might have kept it from being recognized on existing higher resolution data such as seismic.

The ring structure of an impact crater is a natural geometry to provide a horizontal density contrast that can be detected by the Euler method. Different models have been developed for the formation of rings from impact events of different sizes. Models developed from the study of lunar impacts, in which the sites remain unburied, are shown in Figure 13 (Taylor, 1982). Here it is seen that the center of the structure could be a basin (as in Wollaston and Orientale) or a peak (as in Lalande, Tycho, and Compton). In addition to the complexity of the initial structure, burial and ongoing geologic forces would complicate the structure further. The Euler depth estimates for the rings around the Ames structure are consistently deep (~25,000 ft or more), which puts them into the basement. The rings in the Texas Panhandle vary considerably in their Euler depth estimates, tending to be deeper (~25,000-plus ft) in the east and more shallow (~12,000–20,000 ft) to the west, which would put them nearer the top of basement (Ball et al., 1991). Characteristic features of some impact craters, such as radial faulting, might not be imaged by the Euler method if there is no density contrast across the faults. Full evaluation of the Texas Panhandle ring structure, incorporating multiple fields of study, provides an opportunity for additional analysis.

Summary

An algorithm designed to identify linear features from potential fields is shown to detect circular features such as those associated with impact sites, salt domes, calderas, etc., which often correlate with economic production. While existence of a circular feature is not sufficient to determine an impact site, lineament identification through a process such as EASI appears to be a useful tool in identifying and studying impact structures. The availability of large-scale data sets and the low cost of the process make it well suited for this task. A large (~320 km diameter) circular feature in west Texas has been found that could be an area of further investigation. Further work is needed to identify the origins of this phenomena and establish whether the outer rings are correlated with economic opportunities. TLE

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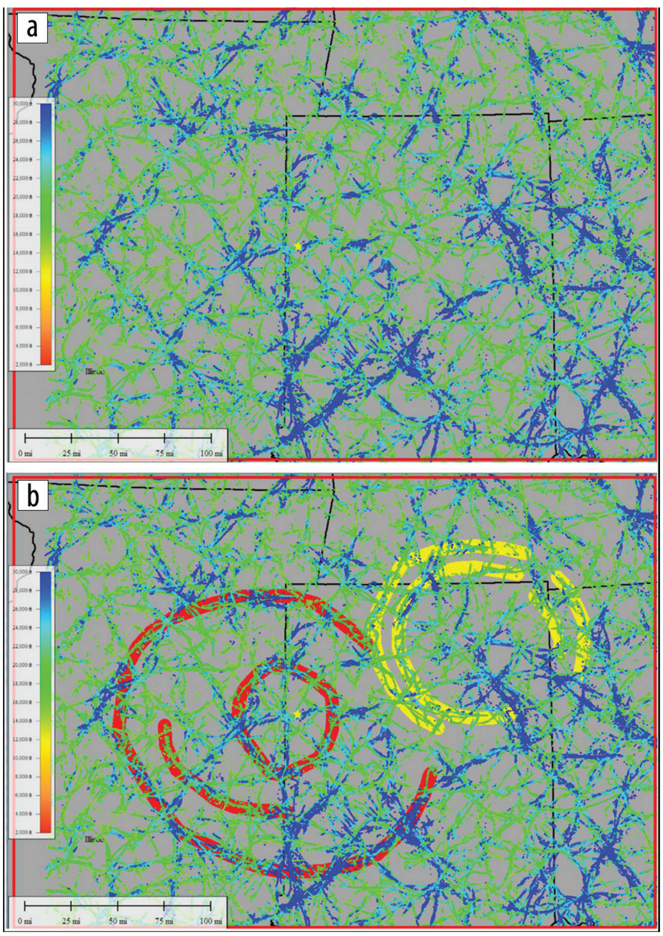

Figure 10. (a) Kentland crater located at yellow star; EASI lineaments from gravity and (b) interpreted circular features around Kentland in orange. Note a secondary set of rings in yellow, which seem to terminate a ring around Kentland.

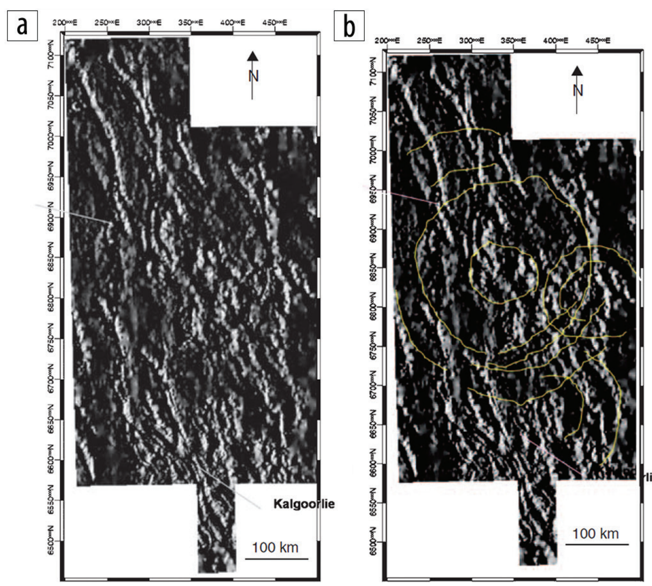

Figure 11. (a) Gravity field over Watchorn impact site and (b) with interpreted rings (from Watchorn, 2013a).

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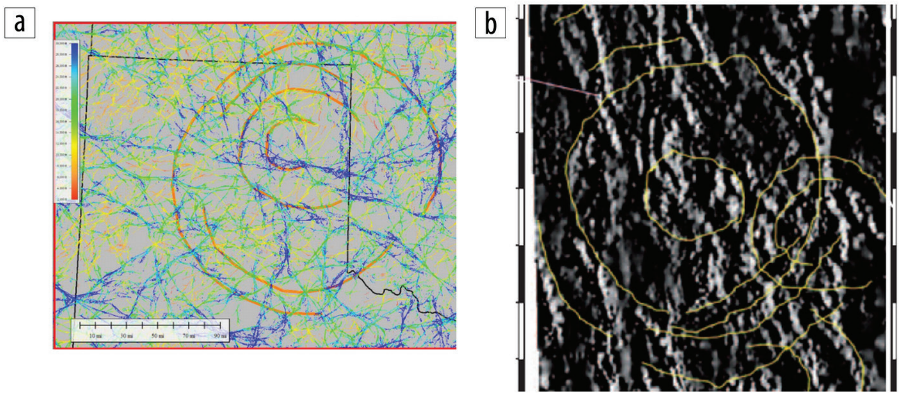

Figure 12. (a) Texas Panhandle lineaments with circular interpretations; (b) Watchorn impact site and circular interpretation (from Watchorn, 2013a). Images have been adjusted to approximately the same scale.

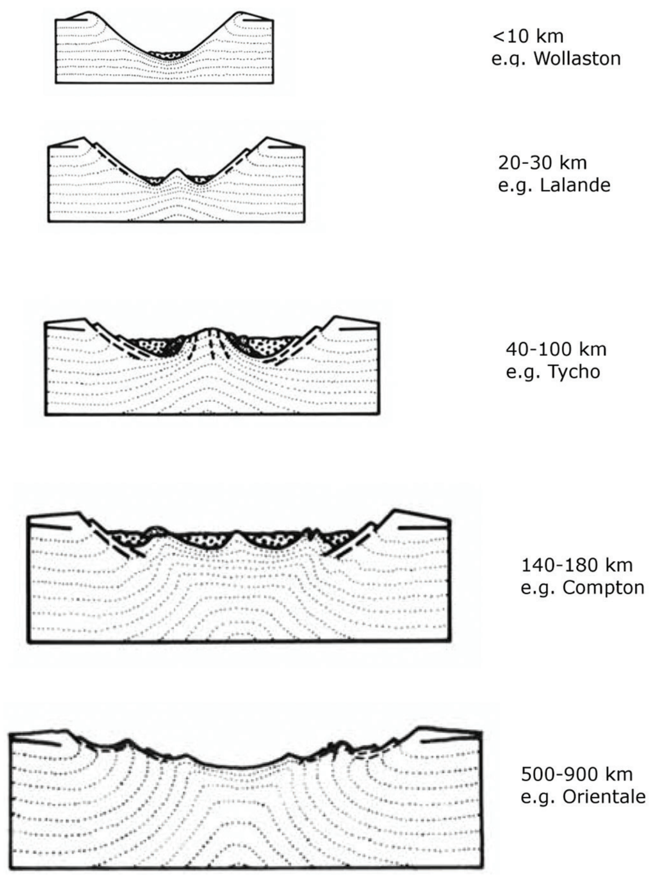

Figure 13. Models of impact craters of increasing size and complexity (from Taylor, 1982).