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Commentary

Commentary on Klokočník, J., Kostelecký, and Bezděk, A. 2019. The putative Saginaw impact structure, Michigan, Lake Huron, in the light of gravity aspects derived from recent EIGEN 6C4 gravity field model. Journal of Great Lakes Research 45:12–20

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Introduction and background

In the decades since the beginning of space exploration, the geological and astrophysical communities have come to appreciate the importance of impact cratering as a major process in the formation and modification of the Earth's surface and its biosphere. Impacts lead to major crustal deformation and deposit extensive blankets of ejecta; they can form important deposits of economic minerals and even hydrocarbons (Donofrio, 1998; Reimold et al., 2005); and perhaps most importantly, they can lead to dramatic biological and ecological changes - and even mass extinctions - through their impact on regional or global climate (Alvarez et al., 1980). As a result, locating and confirming meteorite impact structures have become keen areas of interest for many. Unfortunately, this has also led to the identification and naming of putative impact structures, sometimes without proper adherence to established criteria, i.e., direct solid or chemical evidence of either the impacting projectile or of the structural deformation and shock metamorphism of the impacted target (Reimold, 2007; French and Koerberl, 2010; Reimold et al., 2018).

One of the more recent discussions on the possible role of meteorite impacts on past climates has focused on the global cooling known as the Younger Dryas event, at ≈12.9 to 11.7 ka (Dansgaard et al., 1989). Evidence for this climate event has been recorded widely across the Northern Hemisphere in ice cores, in oceanic sediment, and on land, e.g., Broecker et al. (1988), Dansgaard et al. (1989), Fairbanks (1990), Rasmussen et al. (2006). Some even go so far as to link this cooling event to faunal extinctions, especially of some megafauna, and the apparent demise of the Clovis human culture of North America (Haynes Jr., 2005, 2008).

Early causal linkages between the Younger Dryas event (YD) and a meteorite impact were sparked by a non-peer reviewed publication by Firestone and Topping (2001, p. 10). In this article, they argued for a major cosmic episode with multiple airbursts and impacts at ≈12.5 ka BP, which then presumably led to a variety of cataclysms across the planet, including abrupt climate change, widespread burning, and extinctions of fauna and early human cultures. (See Holliday et al., 2016 for a rebuttal.) Firestone and Topping (2001) concluded that the Great Lakes region - at ca. 43°N and 85°W - was the focal point of such an impact. (The date of the impact event proposed by Firestone et al. (2007) has recently been revised to 12.8 ka BP by Kennett et al. (2015).) An impact of this size and location would have affected climate across the region, the hemisphere, and possibly globally. Hence, linkages between such an impact and the YD continue to be discussed, e.g., Firestone et al. (2007), Israde-Alcantara et al. (2012), Kletetschka et al. (2018), even though many researchers have questioned much of the field and laboratory data upon which this hypothesis and its many ramifications are based (Surovell et al., 2009; Pinter et al., 2011; Boslough et al., 2012; Holliday et al., 2016).

Our purpose is not to debate the possible linkages between an extraterrestrial impact and the onset of the YD. Instead, we object to claims that there is evidence that an impact occurred in southern Michigan near Saginaw Bay at the end of the Pleistocene, as suggested by Klokočník et al. (2019). In this paper, published in the *Journal of Great*

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Lakes Research, Klokočník et al. (2019) present geophysical interpretations for an impact structure in southern Michigan. The authors suggest that the "Putative Saginaw Impact Structure" could be the "smoking gun", which could have triggered the YD. They hypothesize that a meteorite impact onto the margin of the Laurentide Ice Sheet, in the vicinity of present-day Saginaw Bay, formed a large glacial lake that subsequently drained catastrophically, excavating Saginaw Bay and therefore forming the gravity anomalies that they use as evidence for this impact.

In this commentary, we question the conclusions of Klokočník et al. (2019) by pointing out the low resolution of the gravity data input to the model for their Michigan study area, the errors in how the authors derive and interpret the their new data, and the complete lack of geological evidence for a meteorite impact during or after the YD in the Saginaw Bay region – an area that was ice-free when their "putative" impact was to have happened. In summary, there exists little to no physical evidence for the impact that they purport to have occurred in the Saginaw Bay region, and the authors' interpretations of the gravity data they present are highly questionable.

Refutation based upon geophysics

We do not question the overall geophysical approach taken by Klokočník et al. (2019). Indeed, spherical harmonic coefficient "models" are standard ways of fitting observed data to a spherical coordinate system, e.g., the Earth for magnetic, gravity, heat flow data, or at the other scale extreme, in physics to describe the electron charge distribution around an atom.

In this method, a complicated modeling process is applied to the observed data, to convert them to a set of coefficients, such that each has an associated degree and order (latitude and longitude indices, or subscripts). The magnitude of each number, i.e., its spherical harmonic coefficient (SHC), relates to the amplitude of a sine or cosine wave (of gravity anomalies) of that wavelength plotted around the globe in either the latitudinal or longitudinal sense. The irregularly spaced data points around the globe are fitted to a numerical model that is, in effect, a table of numbers (SHCs). The actual degree or order (subscripts of the SHC) indicates the number of cycles in that wave going around the Earth, e.g., a degree or order (d/o) index of 90 implies wavelengths of 4 degrees (360 degrees/90 = 4 degrees), or wavelengths of about 444 km along a great circle path.

Klokočník et al. (2019) refer to a recent "model" (EIGEN 6C4) with maximum d/o of 2190. The basic principle here is that the measured gravity (or other) field or its potential can then be reconstituted (calculated) at any latitude/longitude position from these SHCs by summing the amplitudes of the superposed sine/cosine waves for all wavelengths included in the model for that point. This approach is not dissimilar to the process of Fourier synthesis to generate any waveform by summation of many different wavelengths and phases. Thus, a gravity profile around the earth (1-D) can be constructed by adding sine or cosine waves of the maximum degree/order and all lower terms of the "model", each wavelength of wave with its specified amplitude (the value of the SHC). Using the calculations in both directions (deg/order ≥ lat/long) allows one to reconstruct the 2-D gravity field surface ("model") over the Earth, or for any given subarea.

It is important to note that extending the "model" to a very high d/o, such as 2190, requires that the data used to generate this "model" be very dense, with station spacing less than half the smallest wavelength of the model (recall spatial aliasing and the Nyquist sampling frequency). Dividing 360 degrees by 2190, and then multiplying the result by 111 km/great-circle degree, yields 18.24 km for the smallest wavelength for that EIGEN 6C4 "model". The narrowest gravity high or low describable by that set of SHCs would then be 9.12 km. Most areas on the Earth do not have gravity data at such close spacing, especially areas beneath oceans and large lakes. Although satellite-based gravity data included in the EIGEN 6C4 model from GRACE and GOCE missions resolutions. Saginaw Bay has only a few widely-spaced ship tracks of gravity data, whereas much of central Michigan, particularly the area southwest of Saginaw Bay, has gravity station spacings of 10 km, and more often closer to 20 km. The satellite based data included in the EIGEN 6C4 model used by the authors does nothing to improve the resolution of the existing, low resolution gravity data in the Saginaw Bay region.

Key to our argument is the fact that, where data with the requisite close spacing are lacking, the model will generate fictitious "data" or SHC values by extrapolation/interpolation of the sine/cosine waves through the areas that lack sufficient data, e.g., Manicouagan, Chicxulub (offshore), Popigai, and much of the lower peninsula of Michigan (and especially beneath Saginaw Bay). There exist small areas of the Earth's surface where ground-based gravity data are of adequate density to allow such a "model" to be valid, e.g., parts of Europe and North America, and a few other areas that have been covered by low-flying aircraft with gradiometer equipment, done at close line spacings. Our point here is simple: applying such a "model" anywhere on the Earth's surface will likely produce very questionable results. The errors implicit in such an approach would then be greatly compounded by making a series of higher-order calculations such as those introduced by Klokočník et al. (2019). Mathematically, the calculations from such a "model" are probably very accurate, but that fact must not be confused with whether the data used to build the "model" had the requisite spacing densities in the area where it was applied. In sum, we believe the data used by Klokočník et al. (2019) in their gravity model were not dense enough for the areas discussed in their paper.

Of the calculated parameters used in the paper, Tzz is a fairly well known, 2nd vertical derivative (their 'radial' derivative). However, the 'theta', 'comb', 'I2', 'I3', and 'virtual deformation vd' parameters of Klokočník et al. (2019) are all outside of mainstream analyses of gravity data used by geophysicists, and certainly involve further multiple and derivative calculations that only enhance any errors or artifacts in the starting "model". The 'vd' parameter is actually fairly fanciful, in that the authors refer to a 'compression' signal somehow locked into the Earth by impacts, or dilatations over geoid highs. The Earth's gravity field does not record the state of compression or dilatation of the crust in this manner. Additionally, the "combed strike angles" shown on many of the maps in their paper are apparently a representation of gravity lineaments - elongated anomalies and parallel linear contour lines. However, unlike their representation, such geological and geophysical lineaments are never of a constant or identical length, and neither are they separated by uniform distances. To suggest as much is simply geologically unreasonable. In fact, the zone of "combed" linear features that they emphasize in the ellipse on their Fig. 2a as indicative of an impact near Saginaw Bay are most certainly due to the long parallel linear and sigmoidal contour lines associated with the mid-Michigan gravity high and its flanking elongate lows that dominate most of the Lower Peninsula of Michigan (Hinze et al., 1992). Although all these parallel contours may make their "theta" value very high, that pattern in no way indicates the presence of an impact structure. This pattern is likely just an artifact of the ≈1.1 Ga old Midcontinent Rift that occurs in southern Michigan, e.g., Dickas et al. (1992), Ma et al. (2009), Stein et al. (2016), where it is buried by thousands of meters of Paleozoic bedrock.

One can also question their statement on page 4 that "The second order derivatives and the invariants provide evidence about the details of near-surface (not deep) structures". The elliptical area (Their Fig. 2a) SW of Saginaw Bay includes the deepest parts of the Michigan Basin, where the igneous/metamorphic basement rocks occur at >4.8 km depth.

Klokočník et al. (2019) cite data from one of their previous papers (Klokočník et al., 2010) in support of their Saginaw Bay interpretations. They refer to strike angles θi for the Popigai crater in Siberia, where the data are combed but located asymmetrically around the crater's center. However, their inclusion of the Popigai crater map (their Fig. 6) does not, in fact, support their arguments. First, the location of the crater is not shown on the map. Secondly, the map is severely contaminated by W-E artifacts, probably originating from the survey itself or by processing of the gravity data. Additionally, the maps of the Chicxulub crater area (their Fig. 3) are not nearly as convincing as is the conventional, and more easily calculated, horizontal derivative of the Bouguer Gravity anomaly data. Such data are, for example, very apparent on the cover illustration of the Aug. 3, 1995 edition of *Nature* (Hildebrand et al., 1995); this image shows an impact structure much more clearly than any provided in the Klokočník et al. (2019) paper. In this case, the authors' confusion about why their results are "better" for the on-land area is explained simply by the fact that there are more data on land, versus the sparse offshore gravimetry from a few ship tracks offshore of Chicxulub (and in Lake Huron). Hence, their "model" is not adequate for medium to small sized features in the offshore areas.

Finally, the authors' mention in several places that this technique has revealed many oil, gas, and water concentrations, as well as features hidden beneath ice sheets. They seem to imply that the anomalies are due to the presence of the oil, gas, or water. However, in almost every case the gravity data indicate only geologic structures (anticlines, faults, salt domes, etc.), any of which may occasionally house concentrations of these fluids. Most such structures do not. In sum, the gravity anomalies are not due to gas, oil, or water contained within.

Refutation based upon geology

Research on the glacial geology of the Saginaw Bay region, now spanning over a century (e.g. Leverett and Taylor, 1915 and much work since then), has repeatedly advocated for a glacial erosional origin for Saginaw Bay, as influenced by the underlying Paleozoic sedimentary bedrock and the Michigan Basin structure. The Saginaw Lobe – a sublobe of the Huron Lobe of the Laurentide Ice Sheet – flowed to the southwest, into Lower Michigan, and scoured out the area that today is flooded with Saginaw Bay (Bergquist and MacLachlan, 1951; Bretz, 1951; Kehew et al., 2012, 2018; Blewett et al., 2017). As the ice receded from the region between ≈22,000 and 13,600 BP, a series of proglacial lakes formed between the ice margin and the higher landscapes that rim the lake plain (Larson and Schaetzl, 2001; Kincare and Larson, 2009; Connallon and Schaetzl, 2017), helping to document the pattern and timing of ice retreat from the Saginaw Lowlands.

One fact is clear: the Saginaw Bay region lacks any clear, topographical or geological evidence of an impact structure, and certainly lacks any kind of crater with a raised rim or not. A detailed physiographic study of the Saginaw Lowlands by Schaetzl et al. (2013) identified subtle, generally undisturbed shorelines of former proglacial lakes and small sand dune fields set amidst a generally featureless, very low-relief lake plain. Many of these features pre-date (or formed during) the YD, the time when the putative impact would have occurred. Indeed, none of the diagnostic features and conditions listed as requisite for the identification of a meteorite impact structure by French and Koerberl (2010), Klokočník et al. (2019) and Davias and Harris (2015), along with Davias' self-published web site cited in their paper, can be found in the Saginaw Lowlands (Table 1). In short, unlike almost all other studies of meteorite impacts, Klokočník et al. (2019) fail to present any field evidence for a clear, circular depression or rim and associated subsurface deformation – normally taken as necessary evidence for an impact structure. Subtle older features like shorelines and dunes that are present in the area would surely show cross-cutting relationships caused by disturbance of even a small meteorite impact, had it occurred.

The explanation Klokočník et al. (2019) use for the lack of on-the-ground evidence for a Saginaw area impact revolves around their assumption that the meteorite landed on top of an existing ice sheet (Klokočník et al., 2019), or that the meteorite broke up in the atmosphere, i.e., as Tunguska-like comets. Unfortunately, Klokočník et al. (2019) lack a clear understanding of the glacial chronology of this re-

Table 1
Features and geologic characteristics commonly used to identify impact structures on the Earth's surface[a].

1: Circular pattern/form with central depression and sometimes, a central uplift area
2. Extensive fracturing and brecciation of bedrock
3. Circular gravity and magnetic anomalies
4. Presence of large units of igneous rocks
5. Preserved meteorite fragments
6. High-pressure mineral glasses and melts
7. Traces of impacting projectiles
8. Shatter cones

[a] After French and Koerberl (2010).

Sheet had retreated from the Saginaw Bay region well before 12.9 ka (11,100 ^{14}C yrs BP). By this time, most of ancestral Lake Huron was ice-free, and had become part of Glacial Lake Algonquin (Larsen, 1987; Larson and Schaetzl, 2001; Schaetzl et al., 2002; Kincare and Larson, 2009). Certainly, the Saginaw Lowlands would have been open water and/or dry land at this time. A meteorite impact onto an ice sheet in the Saginaw Bay area would have been simply impossible, based on this timeline. In short, ice did not occupy the Saginaw Bay region – or even any part of the Saginaw Lowlands - at the time that this putative impact could have occurred; this is the crux of the argument given by Klokočník et al. (2019) for the lack of an impact structure. And thus, such an impact could not have dislodged "ice boulders" that could then have been ejected to great distance to form features such as the Carolina Bays (Zamora, 2017).

Summary

Early suggestions of a meteorite impact in the Great Lakes region were mainly from Firestone et al. (2007). Most of the interpretations and some of the data in that paper have not held up to subsequent scientific scrutiny; see critiques by Boslough et al. (2012), Holliday et al. (2014), and Meltzer et al. (2014), among others. Regardless, the Firestone et al. (2007) paper provided the launch point for the paper by Klokočník et al. (2019). They used highly interpretive and questionable gravity-based arguments for an extraterrestrial impact in the Saginaw Bay region of Michigan at ≈12.9 ka. The authors explain the lack of evidence for an impact structure by suggesting that any such meteorite would have impacted an ice sheet that covered the region at that time. However, the Laurentide Ice had long-since retreated from the region, rendering this explanation moot.

Geophysical interpretations of gravity data used by the authors fail to support their conclusions of an impact in the Saginaw Bay region. The authors state that "We present a new approach, based on recent, high quality gravity data and…" (p. 9). We disagree with this statement; this part of Michigan and Saginaw Bay do not have any public-domain, high quality data younger than at least 50 years, besides satellite-based GRACE-COGE mission gravity data, which are very low resolution data. It appears that the authors seem to have confused "new data" with "new model".

There exists no documented chemical, geophysical, or geomorphic evidence in the Saginaw Bay region for a meteorite impact, or even an airburst of a meteorite, before or during the YD, and Klokočník et al. (2019) acknowledge this (p. 20). Yet, there is plentiful and detailed geomorphic evidence for post-glacial, lacustrine, eolian, and stream processes across the region, many of which occurred during (and even before) the YD.

Lastly, we object that the editors of the *Journal of Great Lakes Research* allowed the citation of a dubious web site. Cited in the Introduction of the Klokočník et al. (2019) paper, this web site is filled with non-peer reviewed information, spurious material, and opinionated statements. The *Journal of Great Lakes Research* should not give credence to web sites of this type, because it only adds to their legitimization and spurs on others to create (and cite) web pages of similar credibility. Klokočník et al. (2019) do cite peer-reviewed work done by glacial geologists and others, but out of context and in ways that would seem to support their version of the YD impact hypothesis.

Although we support the notion that, sometimes, bold and even outrageous hypotheses can challenge existing science and add to it, e.g., Alvarez et al., 1980, because this is good for science, we feel this paper presents an "outrageous hypothesis" without the necessary physical evidence to support it. We believe that the paper is an example of application of complicated mathematical techniques without comparison or insight gained from field geoscientists; it is clearly incompatible with the well-documented geologic and glacial history of the area under study.

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