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Gravity field aspects for identification of cosmic impact structures on Earth

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ABSTRACT

We studied the following proven as well as hypothetical impact craters (among others), and some of the relevant results are reviewed in this chapter: (1) a hypothetical impact structure in Saginaw Bay, Great Lakes, Michigan; (2) a putative impact crater basin under the ice of Antarctica in Wilkes Land; (3) two recently discovered subglacial impact craters in Greenland; (4) a possible huge impact crater in Kotuykanskaya in a remote area of Siberia near the proven impact crater Popigai; and (5) a hypothetical impact object Burckle on the bottom of the Indian Ocean. They were tested using the gravity data derived from the recent gravity field model EIGEN 6C4 (with ground resolution of ~9 km). Our method is novel; we introduce gravity aspects (descriptors) to augment traditional gravity anomalies. The following gravity aspects were used: (a) gravity disturbances/anomalies, (b) second derivatives of the disturbing potential (the Marussi tensor), (c) two of three gravity invariants, (d) their specific ratio (known as 2D factor), (e) strike angles, and (f) virtual deformations. These gravity aspects are sensitive in various ways to the underground density contrasts. They describe the underground structures (not only the craters) more carefully and in more detail than the traditional gravity anomalies could do alone. Our results support geological evidence of the impact craters found by others in many cases or suggest new impact places for further study.

INTRODUCTION

More than 200 meteoritic (extraterrestrial) impact craters are confirmed as impact structures on Earth (Rajmon, 2010), and there are another ~600 structures that are possibly of impact origin. A compilation of proven impact structures is available from the Earth Impact Database (collated by the Planetary and Space Science Centre, University of New Brunswick, Canada; http://www.passc.net/-EarthImpactDatabase/index.html), and unconfirmed impact craters have been summarized by Rajmon (2010)

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in the previous Suspected Earth Impact Sites (SEIS) catalogue. Another inventory has been published by Mikheeva (2014, http://labmpg.sscc.ru/impact/index1.html, last updated 24 September 2021).

Many of the proven impact craters and some of the putative impact structures with diameter >20 km have been tested by our method using gravity aspects (functions of geopotential) with recent gravity field models. The results have been presented, e.g., in Klokočník et al. (2010, 2017a, 2017b, 2018a, 2018b, 2019). In Mizera et al. (2016, this volume), our method contributed to identification of a parent crater according to its ejecta (tektites). Most craters selected for this section are not visible on the surface because they are hidden under ice, sand, water, or younger deposits, but they are detectable via their gravity and magnetic signals.

Gravity studies applied to geoscience usually employ only the traditional gravity anomalies (via gravimeters), and sometimes also some of the second derivatives (via gradiometers) of the disturbing gravitational potential. Gradiometers are now on airplanes, and one is on board the European Space Agency's *GOCE* (Gravity and Ocean Circulation Explorer) satellite. A wider set of functions of the disturbing gravitational potential, the "gravity aspects," is used here; these "descriptors" are sensitive in various ways to the underground density contrasts (variations) due to causative bodies. They provide much more complete (but more complicated) information about the causative body (density variations) than the gravity anomalies can do alone.

COMMENTS ON THEORY

The theory comes mainly from Pedersen and Rasmussen (1990) and Beiki and Pedersen (2010). The theory, geophysical interpretation, and examples for the gravity aspects are summarized in our books (Klokočník et al., 2017a, 2020c) and cannot be repeated here (due to space constraints), so the reader is referred to our earlier work for the full details.

The gravity aspects include: the gravity anomaly (or disturbance) Δg, the Marussi tensor (Γ) of the second derivatives of the disturbing potential (T_{ij}), two gravity invariants (I_j), their specific ratio (I), the strike angles (θ), and the virtual deformation (*vd*). This set of gravity aspects provides information about the location, shape, orientation, the tendency of the causative body in two and three dimensions, and stress tendencies, and it can simulate tensions, although the input data are always the same—the harmonic geopotential coefficients (Stokes parameters) of a static gravity field model.

A set of these coefficients defines a static global, comprehensive gravitational (gravity) field model. These models are computed from worldwide diverse satellite and terrestrial data and then provided to the scientific community for various applications. The spherical harmonic expansion goes theoretically to infinity; in the real world, there is always some maximum degree and order (d/o) relevant to the data available. Generally, the satellite data dominantly provide the harmonic coefficients of low and lower degrees and orders, whereas the terrestrial data (e.g., the anomalies measured by gravimeters) provide the higher degrees and orders (Klokočník et al., 2020d).

The identification of density variations (causative body location) or target deposits like groundwater, oil and gas, minerals, metals, salt, and coal only by means of the gravity data/aspects cannot be unique—we always need additional (geological, geophysical, magnetic, and other) data (Klokočník et al., 2020d). A field survey of various types is required to obtain definitive proof of the impact origin. Drilling into the structure is not, however, always feasible. Geologists look for shatter cones, high-shock-pressure metamorphism, high-pressure dense polymorphs (coesite, stishovite), quartz grains, iridium enrichment, or various ore deposits (see, e.g., French and Koeberl, 2010).

NOTES ON DATA

We made use of a high-resolution, recent European Improved Gravity model of Earth by New techniques (EIGEN 6C4; Foerste et al., 2014), expanded to d/o = 2190, corresponding to ~10 km resolution on the ground. The gravity aspects over many regions of the world were computed and plotted with a step of 5 × 5 arcmin in latitude and longitude.

The color figures here have nonlinear scales to emphasize various features and details. The gravity disturbances are in milligals [mGal], and the second-order derivatives are in Eötvös [E], where 1 mGal = 10^{-5} ms^{-2}, and 1 E ≡ 1 Eötvös = 10^{-9} s^{-2}. The invariants have units I_1 [s^{-4}] and I_2 [s^{-6}]. The strike angle, θ [deg, °], is expressed in degrees, red means north of east, and blue means south of east. The virtual deformation *vd* is shown as dilatation (in red color) or compression (blue).

It is important to emphasize that the resolution of EIGEN 6C4 is ~10 km on the ground. This is not a defect of our method, but a given fact about the input data; in turn, for smaller craters, say below 30 km, we can detect them, but we cannot expect to "see" many details in them, for example, a possible central peak.

TYPICAL GRAVITY SIGNAL OF PROVEN IMPACT CRATERS

Impact craters on Earth can be hidden and not visible on the surface, but their gravity signal can still be revealed. First, we have to learn what the gravity aspects of various geological features look like. The most common and conspicuous signature is a circular gravity low in the floor of the crater. For simple bowl-shaped craters, gravity data indicate that the anomaly is largely due to the presence of an interior allochthonous breccia lens. In big complex craters, the main contribution is from fractured parautochthonous rocks. The magnetic signature of craters is more varied, with the main effect being a magnetic low due to a reduction of magnetic susceptibility after the impact (Pilkington and Grieve, 1992).

Taking into account all the gravity aspects available now, the values of Δg and T_{zz} are negative inside a crater and change to positive and negative values for the rim(s) and areas in between, respectively. The gravity invariants have extreme values inside and around the crater, and they are concentrated in the rim(s). The strike angles often exhibit orientation in one prevailing direction near the crater and encircle the crater as a halo (they are "combed"). The virtual deformation inside the crater shows compression, and the rim(s) is(are) surrounded by dilatation (and the space between the rims again shows compression). If the crater is large and has a central peak, we can detect it by positive T_{zz}; if the crater is huge (crater basin), then the central peak can "grow" to a mascon caused by upward motion of the regional material.

EXAMPLES

Saginaw Bay, Great Lakes, Michigan

The Saginaw Bay object is a hypothetical impact locality in Lake Huron, Michigan, suggested by Davias and Harris (2015, 2019, this volume). Davias and Harris posited a highly oblique impact into hydrated sedimentary strata shielded by continental ice during marine isotope stage 20 (MIS 20), which excavated a landform commonly attributed to the Saginaw glacial lobe. Such impact conditions would be expected to produce an unconventional signature (Stickle and Schultz, 2012; Kenkmann et al., 2011). The explosion may have happened in the atmosphere (Wittke et al., 2013) or on the ice cover (Wolbach et al., 2018).

Our initial findings (Klokočník et al., 2019) indicated that there is no impact crater (a hole), because nothing interesting was found by analyzing Δg or T_{ij}. However, when analyzing the pattern of the strike angles, which are combed in a SW–S-SE direction (Fig. 1), the picture looks different. These data (see references concerning the Saginaw Bay case in Klokočník et al., 2019) suggest that there was an impact and that the impactor direction was NE-SW. This agrees well with the combed θ from our computations, which are organized into an arch and mostly in the NW-SE direction (rectangular to the incoming stress due to the impact): see Figure 1.

Burckle

Burckle is a candidate for an undersea impact crater with diameter of ~30 km, probably only 5000 yr old, at the bottom (~3.8 km) of the Indian Ocean ESE of Madagascar. It is situated in a fracture zone along the SE arm of the Indian oceanic ridge, centered at 30°52′S, 61°22′E, which was drilled and surveyed during a search for oil (e.g., Klokočník et al., 2020d; Abbott et al., 2007, 2009, and references therein). The impactor was supposed to be an iron asteroid. The formation was dated by Abbott et al. (2007, 2009) to 3000–2500 B.C.

The crater is a round hole 30 ± 1 km wide; its bottom is deeper in the SE part, while the foreground of its NW rim is topographically smoothed due to an ejecta layer in this direction. These features indicate that the impacting body came from the SE. In the crater rim, Abbott et al. (2007, 2009) proposed an occurrence of resurge gullies, and at the top of a borehole outside the crater, a 25-cm-thick layer with high magnetic susceptibility was documented, which contains numerous rock fragments coated by Mn oxide that do not resemble common

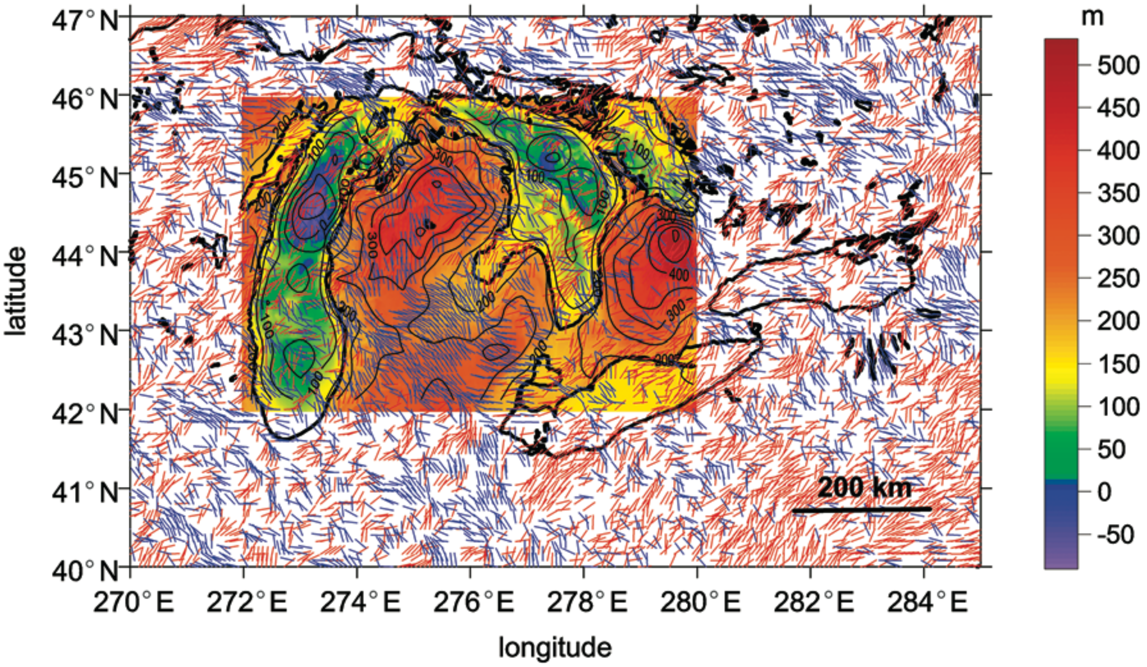

Figure 1. Great Lakes area, United States and Canada, showing the strike angles, θ [°], at Saginaw Bay, Lake Huron, using EIGEN 6C4, gravity invariant (I) <0.3, with added surface topography in the colored rectangle.

Mn/Fe nodules. Abbott et al. (2007, 2009) found a grain of NiC (size = 200 μm; possibly a fragment of the impactor) that has an ablation rind in the form of surface drops. The list of the findings inside the impact ejecta contains suspected meteorite fragments, suspected impact glass, oceanic mantle fragments and impact spherules. The impact glass does not contain any K, so a continental origin is not likely. The crater could be associated with chevron (V-shaped) dunes on the coasts of the Indian Ocean in Western Australia, India, and Madagascar. A megatsunami resulting from the impact might have reached a height of ~200 m at Madagascar, penetrating up to 45 km inland. Some authors state (we refer the reader to Klokočník et al., 2020c, and a set of citations therein) that there is insufficient or unreliable geological, petrographic, or geochemical evidence. Others state that there is a very small probability of occurrence of an impactor of that size in the last 5000 yr. The dunes might have been produced by other mechanisms, including floods, perhaps associated with a caldera collapse on Reunion Island (newly claimed by Abbott, 2020, personal commun.). However, as discussed below, our new modeling approach for this region supports the impact origin.

Here, we show the results from analysis of T_{zz} and *vd* (Figs. 2B and 2C). Figure 2B shows small T_{zz} values inside the crater and semi-annular positive values around the crater, which are stronger on the N, NW, and W. Figure 2C shows *vd* values that repeat the same pattern. Additional results (not reproduced here) indicate an evident change in the direction of the combed strike angles. We infer that the impactor for this crater came from SE or E. This agrees with geological evidence and with analysis of magnetic anomalies (demagnetization due to the iron material).

Note about the diameter of ~30 km versus the data resolution of ~10 km: One cannot ask for too much gravity detail in such a case. Without our "navigation" to the place where the crater should be, based on evidence other than the gravity data, we never would discover such a small object.

Hiawatha and Paterson, Greenland

These are recently discovered impact craters (Kjær et al., 2018; MacGregor et al., 2019) with diameters of 30–36 km; they are not exposed, and only partly drilled, centered in NW Greenland at 78°40′N, 293°40′E (the Hiawatha crater is nearly completely covered by the Hiawatha Glacier) and 78°20′N, 301°30′E (the Paterson crater is covered by an ice layer thicker than at the Hiawatha crater). The age is not known.

Kjær et al. (2018) did not use any gravity or magnetic data (see p. 8 of their paper); thus, we tested their discoveries using our method (Klokočník et al., 2020a). Here, we show T_{zz} for Hiawatha in Figure 3B; it has an evident negative value inside the crater as expected; an asymmetry of ejecta is outlined by the variable intensity of positive T_{zz} values around the crater (similar but weaker T_{zz} values were found for the Paterson crater; see Klokočník et al., 2020a, 2020c). These results independently support those of Kjær et al. (2018) and MacGregor et al. (2019).

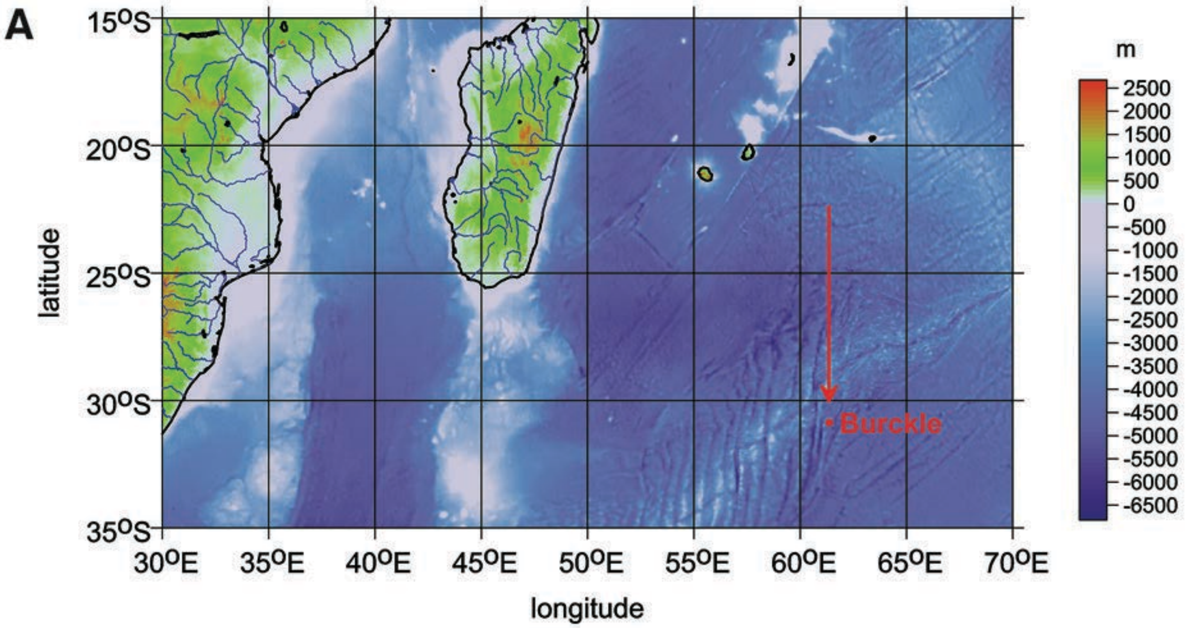

Figure 2. (A) Map showing location of Burckle structure on the bottom of the Indian Ocean. (B) T_{zz} [E] and (C) *vd* [–] for the Burckle structure (modified from Klokočník et al., 2020c; used with author permission). For more figures, see Klokočník et al. (2020c, chap. 6). Note the diameter of ~30 km vs. the data resolution of ~10 km; one cannot ask for too much gravity detail. (*Continued on facing page.*)

Wilkes Land, Antarctica

The definitive existence of a giant impact crater (or a crater basin with mascon), two times larger than the Chicxulub crater in the Yucatan Peninsula, beneath Wilkes Land, East Antarctica, has remained controversial. The U.S. authors von Frese et al. (2006, 2009) based their discovery on the gravity anomalies derived from *GRACE* (Gravity Recovery and Climate Experiment) satellite data, the best data of that time. Their discovery has been discussed for a decade without any clear conclusion. We have available new and more precise data with higher resolution, including spaceborne gradiometry from the *GOCE* satellite mission, and the gravity aspects derived from EIGEN 6C4 (Klokočník et al., 2018b, 2020c).

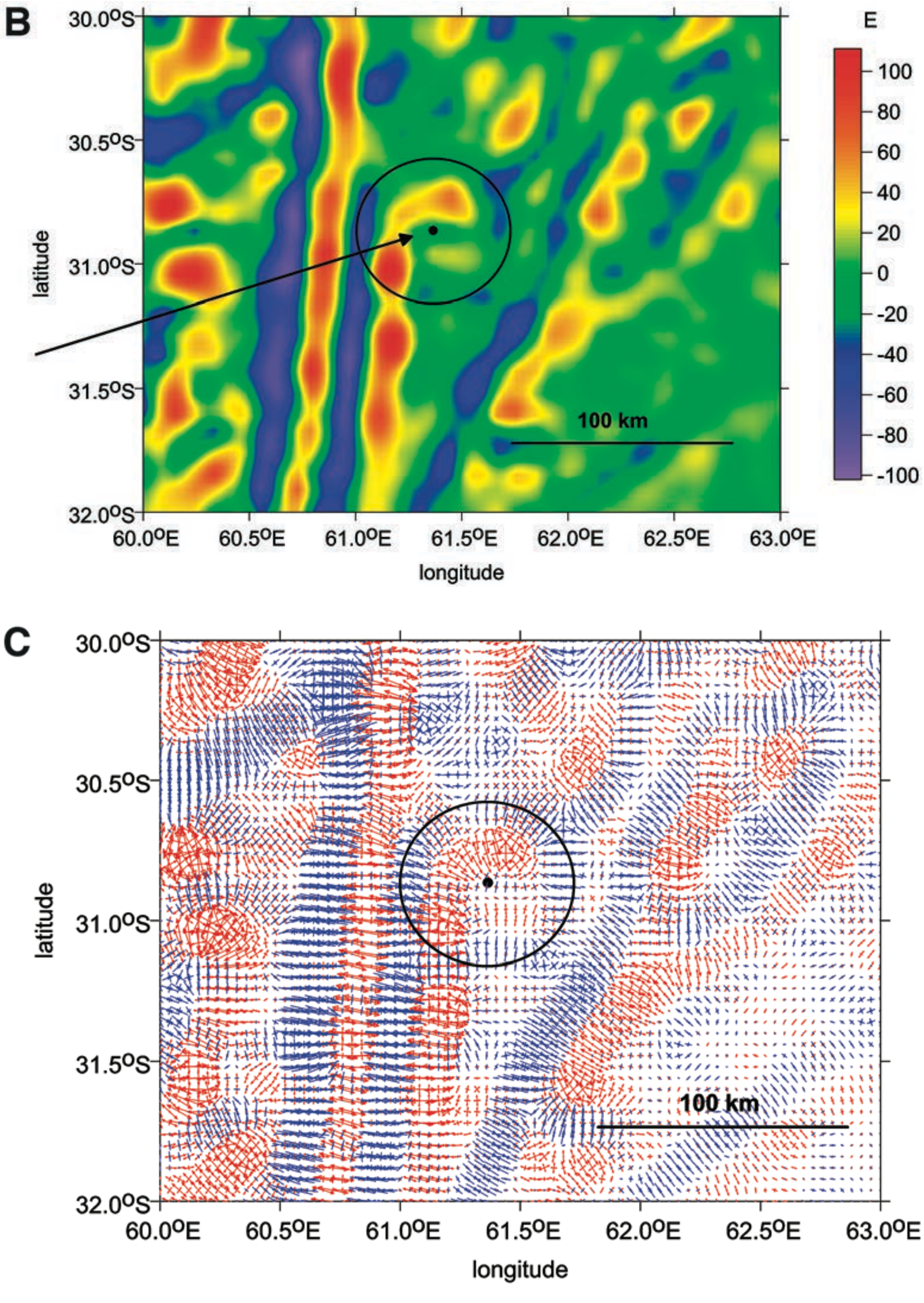

Figure 2 (*Continued*).

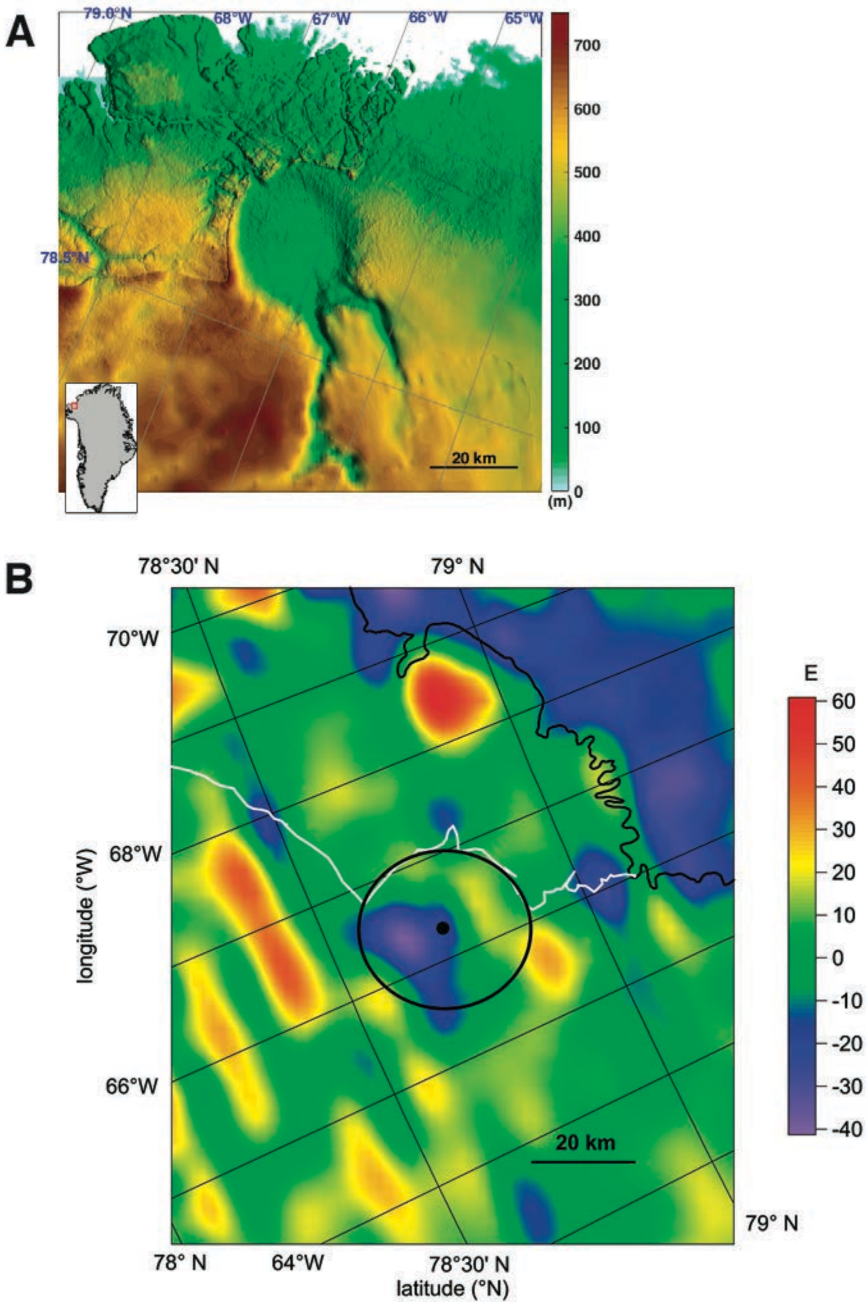

Figure 3. (A) Bedrock topography (from Bedmachine data, Morlighem et al., 2017) and (B) T_{zz} [E] for Hiawatha Glacier, Greenland, using EIGEN 6C4, gravity invariant (I) <0.3. Note the diameter of ~30 km versus the data resolution of ~10 km; one cannot ask for too much gravity detail. Figures modified from Klokočník et al. (2020a; used with permission).

Figure 4A shows Δ*g* for the whole continent of Antarctica and introduces the location of Wilkes Land. Figure 4B shows *vd* values. The crater's rim and the mascon inside are well depicted. There are also significant Δ*g* values more than 100 mGal and T_{zz} reaching 150° E (from Klokočník et al., 2017a).

The putative basin and its mascon have a U-shape, where the northern part is disrupted and fragmented. According to von Frese et al. (2013, their fig. 2), it is appropriate to check the gravity aspects near southern Australia, too. The gravity aspects really indicate a continuation of the Wilkes Land anomaly from Antarctica to Australia (Klokočník et al., 2018b).

This crater basin is probably the largest known crater of all or the only such crater basin on our planet. Our observations support the interpretation of von Frese et al. (2013), who suggested that separation of Antarctica from Australia was triggered by that enormous impact event probably ~250 m.y. ago (see Klokočník et al., 2018b, and references therein).

Kotuykanskaya, Siberia

There is a candidate for a huge impact crater with a diameter around 200 km (without geological evidence in open literature;

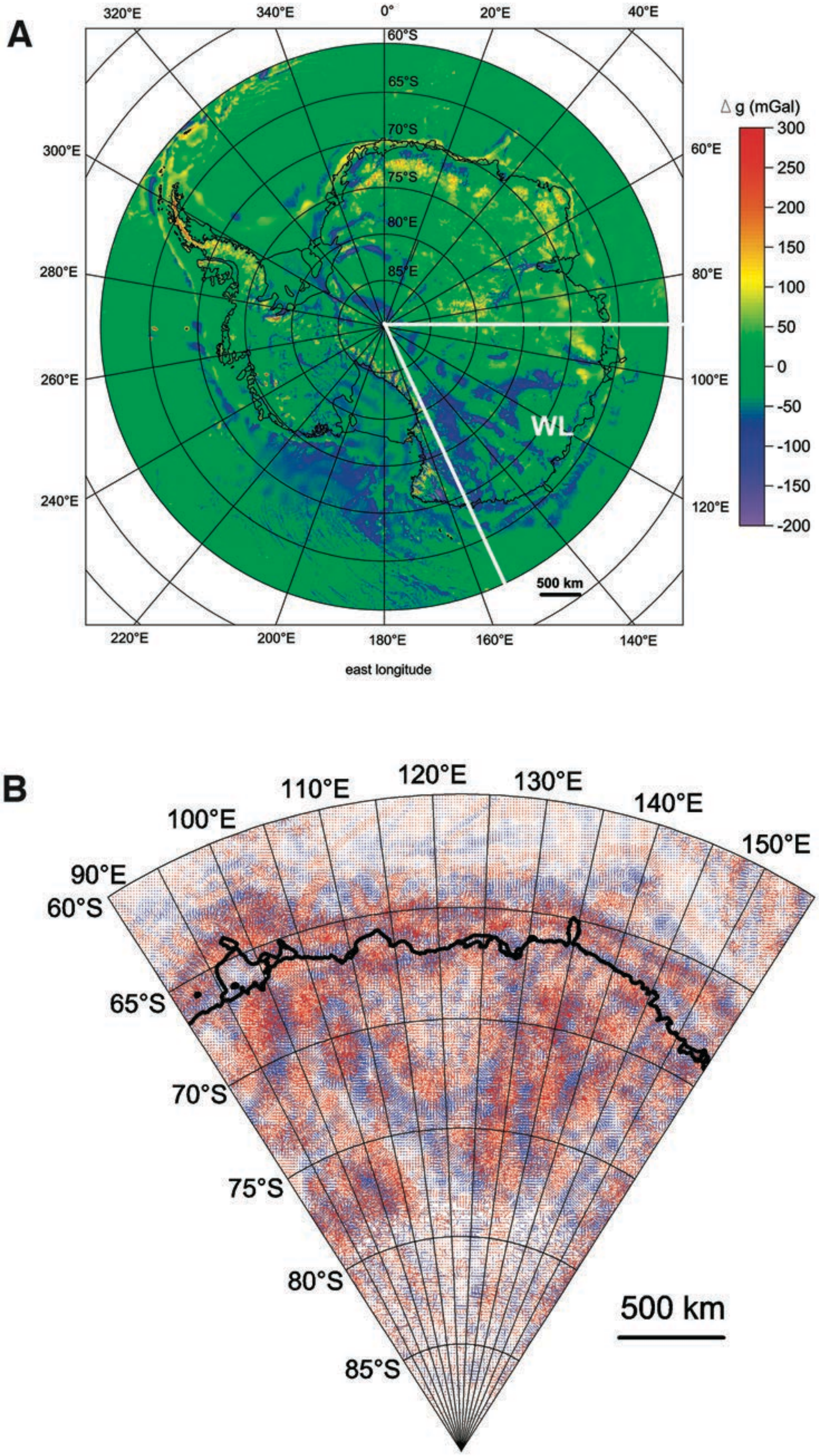

Figure 4. (A) Δg for the whole continent of Antarctica (WL—Wilkes Land). Modified from Klokočník et al. (2018b; http://creativecommons.org/licenses/by/4.0/). (B) Virtual deformation, *vd* [–], in Wilkes Land (red for dilatation and blue for compression; here, north is up). Modified from Klokočník et al. (2018b; http://creativecommons.org/licenses/by/4.0/).

Khazanovitch-Wulff et al., 2013; Mikheeva, 2014) in Siberia near the known crater Popigai.

We found (Klokočník et al., 2020b) that Δg and T_{zz} values are negative and circular inside the Kotuykanskaya structure and show a large central peak, namely, in the second derivative. The craters Popigai II–IV, predicted in Klokočník et al. (2010), are also well visible, and they are lined up in a NW-SE direction from the most intensive Popigai (I) structure on the NW side (see T_{zz} in Klokočník et al., 2010, 2020b). Kotuykanskaya seems to have a crater inside the crater in its southern part, also with a central peak shown by T_{zz}. The rim around Kotuykanskaya is very fragmented and partly missing on the eastern side. In our very limited selection for this report, Figure 5B presents *vd* values that show clear dilatation at the rims (and around the central

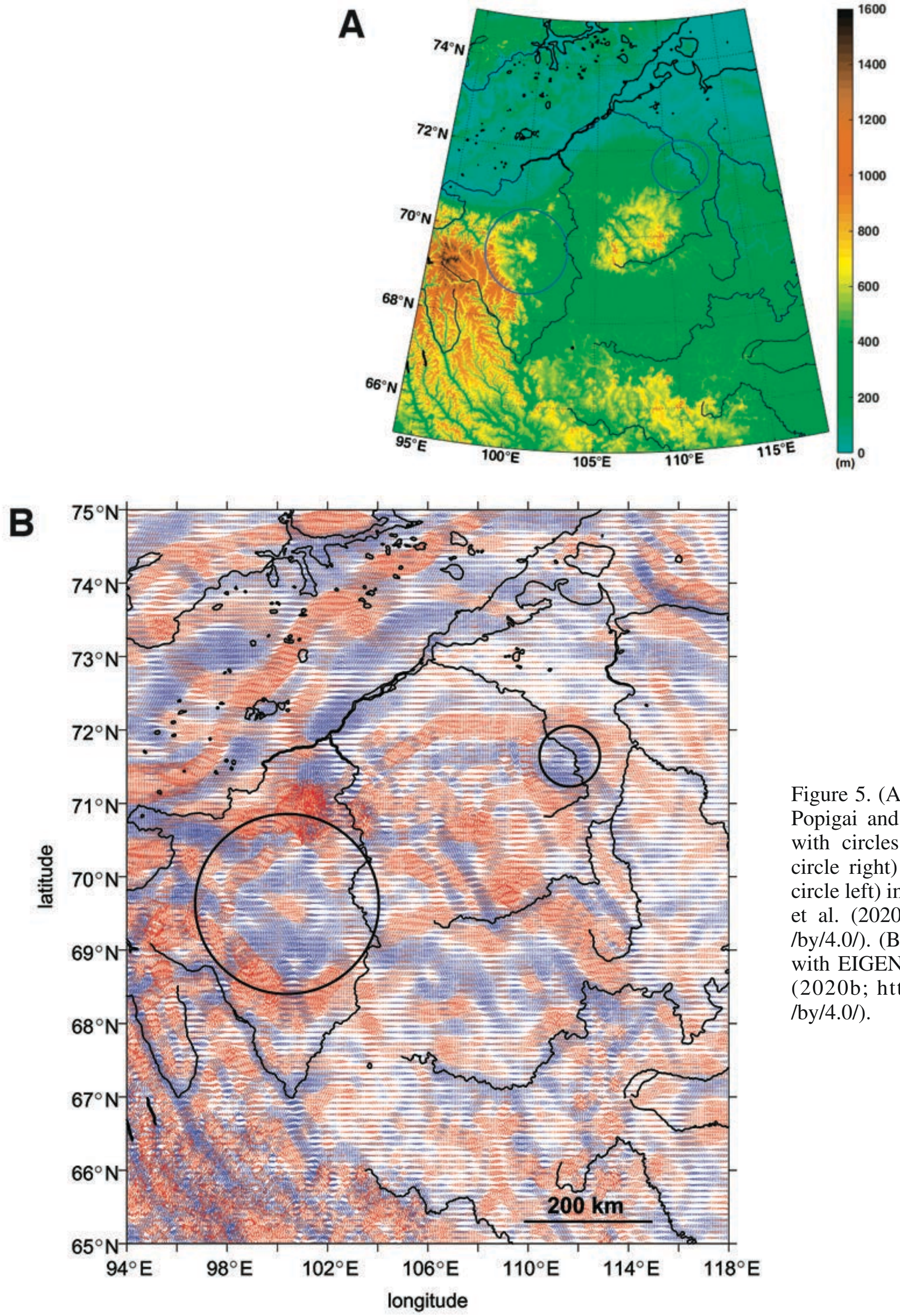

Figure 5. (A) ETOPO 1 surface topography for the Popigai and Kotuykanskaya area, Siberia, Russia, with circles around the proven Popigai (smaller circle right) and suspected Kotuykanskaya (larger circle left) impact craters. Modified from Klokočník et al. (2020b; http://creativecommons.org/licenses/by/4.0/). (B) Virtual deformation, *vd* [–], obtained with EIGEN 6C4. Modified from Klokočník et al. (2020b; http://creativecommons.org/licenses/by/4.0/).

peak) and compression inside the craters. Also, here we can see very well the central peak inside Kotuykanskaya, as is expected for any large and complex crater. All these results support the hypothesis about the impact origin of Kotuykanskaya (together with the magnetic data and results not presented here), but they provide no direct proof.

CONCLUSION

Gravity and magnetic data have proven to be useful in the study of meteoritic impact craters on Earth (e.g., Hildebrand et al., 1995, 1998; Pilkington and Grieve, 1992). Here, we used such modern data as EIGEN 6C4 and surface or bedrock topography to study suspected impact craters in Saginaw Bay (Great Lakes, Michigan), Burckle (the Indian Ocean), Hiawatha and Paterson (Greenland), Wilkes Land (Antarctica), and Kotuykanskaya (Siberia). This is a review of our recent results, summarized in one place. In all these cases, we support the impact origin, but we cannot provide direct proof.

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