Support for two subglacial impact craters in northwest Greenland from Earth gravity model EIGEN 6C4 and other data

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1. Introduction

There are now nearly 200 proven impact craters known on the Earth and many other features not yet confirmed (but suspected) as impact craters (Rajmon, 2017). Two new possible impact craters buried under the ice of Greenland have been discovered very recently.

Kjær et al. (2018) reported the discovery of an impact crater in NW Greenland under Hiawatha Glacier (in the depth 0–2 km beneath the surface); here we call this crater “Hiawatha”. The bedrock topography from a special scanning radar carried aboard airplanes (known as the radio echo sounding) shows (i) a flat depression with a diameter 31.1 ± 0.3 km, (ii) a rim-to-floor depth 320 ± 70 m and (iii) a central uplift. We reproduce their result in our Fig. 1 with coordinate system of geodetic latitudes and longitudes added. The crater is slightly asymmetrical, with a gentler slope towards the southwest and maximum depth in the southeast of the structure (Kjær et al., 2018). From their geological and related findings, we quote that investigations of the deglaciated foreland identified overprinted structures within Precambrian bedrock along the ice margin, that glacioluvial sediment from the largest river draining the crater contains shocked quartz and other impact related grains or that geochemical analysis indicates that the impactor was a fractionated iron asteroid.

The age of the object is not clear but probably from Pleistocene allowing it to be at the onset of Younger Dryas (Kletetschka et al., 2018; Wittke et al., 2013; Wolbach et al., 2018a, 2018b). It looks like that Kjær et al. (2018) did not use gravity data.

MacGregor et al. (2019) reported the discovery of a second impact crater in NW Greenland near Hiawatha Glacier, SE of the Hiawatha crater, in Humboldt Glacier. They call this crater Paterson (so here we label it also “Paterson”). The bedrock topography shows a similar
The gravity aspects (gravity anomalies/disturbances $\Delta g$, second radial derivatives $T_{rr}$) as a part of the Marussi tensor, the gravity invariants $I_i$ and their specific ratio, known also as a “2D indicator”, the strike angles $\theta$ and virtual deformations $v_d$ were computed from the global, static gravity field model $EIGEN 6C4$ (Foerste et al., 2014) combined from satellite and terrestrial data. The model is expanded in spherical harmonics (geopotential harmonic coefficients, also known as Stokes parameters) to degree of order 2190 and yields the ground resolution of about 9 km and typical precision 10 mGal. The input data to compute all the gravity aspects are – in our method – always the geopotential harmonic coefficients of a gravity field model (of the $EIGEN 6C4$ gravity model in our case).

All the gravity aspects together provide much more complex view about the causative (underground) density variations than the traditional gravity anomalies only. The reader may find theory in our book *Gravitational Atlas of Antarctica* (Klokočník et al., 2017a). The examples of applications of our methodology for Sahara or Antarctica or the Indian Ocean’s bottom (for features beneath the sand or ice or water) are, e.g., in (Klokočník et al., 2017b, 2017c, 2018a, 2018b).

The gravity gradient tensor $\Gamma$ (Marussi tensor) is a tensor of the second derivatives of the disturbing potential of the particular gravitational field model. Marussi tensor was considered the centrepiece of traditional differential geodesy; up to second order this tensor systematically synthesizes all of the dynamical and geometric properties of the Earth’s gravity field. The tensor $\Gamma$ is symmetric and harmonic; it contains nine components, but just five linearly independent components. The values of $\Gamma$ are measured by gradiometers, recently by space-borne instrument on the GOCE mission (2009–2013).

The importance of the second derivatives was recognized already by Elkins (1951, p. 29) who stated: “the double differentiation with respect to depth tends to emphasize the smaller, shallower geologic anomalies at the expense of larger, regional features”... and that they provide “often a clearer and better resolved picture ... important in oil or mineral exploration than is the original gravity (anomaly) picture”. The full Marussi tensor is a rich source of information about the density anomalies providing useful details about the target objects located shallowly beneath the Earth’s surface. The tensor components are used at local scales to identify and to map the geological contact information, either the edges of the source targets or the structural/stratigraphic contact information. The Marussi tensor has been used locally (it means in areas of a few per few kilometres) for petroleum, metal, diamond, groundwater and other explorations. For references see e.g. (Klokočník et al., 2017b, 2017c, 2018a, 2018b).

Under arbitrary coordinate transformation, any gravity field and any $\Gamma$ has just three global gravity invariants which remain constant. They can be looked upon as non-linear filters enhancing sources with big volumes (Pedersen and Rasmussen, 1990). They discriminate major density anomalies into separate units.

From the gradient tensor $\Gamma$ we take advantage of deriving subsurface strike (stress) directions (Pedersen and Rasmussen, 1990) and call them strike angle $\theta$ as a main direction of $\Gamma$. It consists from a non-linear combination of the components of $\Gamma$. This is a mathematical definition; from geophysical point of view, it is a direction important for the ground structure that may indicate areas with a lower porosity or “stress directions”. A typical situation is that $\theta$ has diverse directions. The combed strike angles are the strike angles oriented roughly in one and the same direction in the given area. The relevant theory for the “combed” strike angles was explained, together with statistics, in Klokočník et al. (2019) and cannot be repeated here. Klokočník et al. (2014) have defined “virtual deformation”, shortly $v_d$. It is an analogy to the tidal deflections of vertical; one can imagine directions of such a deformation due to “erosion” brought about solely from gravity. The derivatives of the disturbing geopotential as directional quantities are transformed to small deformations – planes of weaknesses along which the rock can slip. But basically, the information content of the Marussi tensor (five components, five figures) can shortly be represented by “one” $v_d$ as it contains the same information (Klokočník et al., 2017a).

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**Fig. 1.** The area of our study, the bedrock topography of a large impact crater beneath Hiawatha Glacier in NW Greenland ($\varphi = 78^\circ 40'N, \lambda = 66^\circ 45'W$) and its surrounding terrain; the figure is based on Bedmachine v3 data (Morlighem et al., 2017; Greene et al. 2017), cf. Fig. 1d of Kjær et al. (2018), with geodetic coordinate system (latitude and longitude) in a polar projection implemented in the gravity aspects or descriptors (Klokočník et al. 2019).

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2. Method and data

2.1. Method

Classical gravity anomalies $\Delta g$ provide only a limited information about the stress state of the rocks causing them. In order to broaden the potential information about the state of rocks we compute specific novel gravity functions of the disturbing gravitational potential called the gravity aspects or descriptors (Klokočník et al., 2017a).

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2.2. Data

The gravity data consist of the Stokes parameters of the gravity field model EIGEN 6C4 (Foerste et al., 2014) mentioned above. We are well aware that the gravity data alone (Fig. 2a–d), even so complex as are the gravity aspects, do not provide unambiguous results; thus other data types are always needed (Kjær et al., 2018; MacGregor et al., 2019) – the geological data. Further, in Fig. 3 we add magnetic anomalies from the EMAG 2 global model, which is a global 2-arc-minute resolution grid of the anomaly of the magnetic intensity at an altitude of 4 km above mean sea level, compiled from satellite, marine, aeromagnetic and ground magnetic surveys (Bankey et al., 2002; Ravat et al., 2002; Maus et al., 2009). MacGregor et al. (2019) used also certain local gravity and magnetic data (see Table 1 of MacGregor et al., 2019) and both groups of authors relied upon the bedrock topography (Bedmachine 3 and radar sounder) received from aeroplanes with ice penetrating radars (to the ground rocks or water level, known also as the radar echo sounding). They did not use the set of the gravity aspects derived from a gravity field model. Finally let us recall that the gravity data can say nothing about a possible age of the craters.

Fig. 2. a–d. The gravity aspects: (a) gravity disturbances $\Delta g$ [milligals, mGal], (b) the radial component of the Marussi tensor of the second derivatives $T_{zz}$ [Eötvös, E]), (c) the gravity invariant $I_2$ [s$^{-2}$], and (d) the virtual deformations $v_d$ [dimensionless, blue for zones with the compression, red for the dilatation], all computed from the full static global Earth gravity field model EIGEN 6C4 (complete till degree and order 2190) with the ground half-wavelength resolution about 9 km and precision 10 mGal.

Fig. 3. Magnetic anomalies [nT] from the global combined EMAG2 data set plotted over Hiawatha crater boundary as identified by (Kjær et al. 2018).
3. Results and discussion

First let us recall how the typical gravity aspects for impact craters look like; this has many times been verified for proven impact craters on the Earth and the Moon (see some examples in the references to our works mentioned above).

For an impact crater, it is expected that $Δg$ and $T_{zz}$ will be negative inside the crater (missing masses), changing to positive and to negative values for the respective rims and space between them. For a very large crater, or crater basin or mare, inside the feature, there may be a hole topographically, but $Δg$ and $T_{zz}$ are there positive – due to the abundant masses. The gravity invariants have extreme values inside and around the crater concentrated to local extrema in the rim(s). The strike angles $θ$ are often significantly combed along the rings around the crater and in another way inside the crater. We speculate (another study) that the direction of $θ$ is a indication, trace, symptom of the impactor direction. The virtual deformations $vd$ show compression inside the crater and dilatation around it.

Fig. 1 shows the area of Hiawatha; it is a copy of Fig. 1d from Kjær et al. (2018), with a coordinate system implemented (in a polar projection). Then we present a choice of our figures with the gravity aspects computed with EIGEIN 6C4, namely the gravity disturbances $Δg$ (in milligals), Fig. 2a, the second radial derivative $T_{zz}$ (in Eötvös), Fig. 2b, one of the gravity invariants $I_2$ (in $s^{-2}$), Fig. 2c, and the virtual deformations $vd$ (dimensionless, blue for zones with compression, red for dilation), Fig. 2d.

We add $T_{nn}$ for both Hiawatha and Paterson together in Fig. 4a and $θ$ for both craters in Fig. 4b. Fig. 3 shows the magnetic anomalies for Hiawatha from EMAG 2 with clear negative anomaly at the crater, Fig. 4c the magnetic anomalies for both craters. The discussion follows.

The values of $Δg$ and $T_{zz}$ are negative inside the craters (Figs. 2a, b, 4a). As for Hiawatha and $T_{nn}$, one can see a fragmented rim (recalling our resolution, we understand that we cannot see too many details). The invariant $I_2$ is negative inside the crater (Fig. 2c). All this was expected. The virtual deformations $vd$ do not exhibit a clear compression inside and a dilatation around the crater, as is usual, but two lobes W and E of the centre (Fig. 2d). We speculate that both the craters are too small and “weak” in comparison with forces controlling the ice cover and thus their gravity signal (compression inside, dilatation around) is overwriten by the ice masses.

The gravity signal for Hiawatha is in general stronger, for example in $T_{nn}$ than for Paterson; the reason is that Paterson is located under a thicker ice cover (Fig. 1 and text above). This makes a small difference in $Δg$ but the difference is up to tens percent of the relevant surface signal in the case of $T_{nn}$ (we investigated such a signal attenuation under the ice or in water in Klokočník et al., 2017c). How such an attenuation of the gravity signal looks like, the reader can see in fig. 2.1 in Klokočník et al. (2017a).

We note that the geometric centres of the surface and the bed toponography derived from Fig. 1c, d in Kjær et al. (2018) and the centre of the features shown by the gravity aspects in our Fig. 2a–d have a significant offset. The gravity aspects show a shift to the south by about 25 km. We speculate that this may be due to a slant angle of the impacting asteroid (impactor) or due to a subsequent geological evolution on the spot or both. The former variant is also admitted by Kjær et al. (2018) and in the following, by us by analysing magnetic data.

The strike angles $θ$ are combed in NS direction for both the craters. This agrees with the direction of an impactor deduced by Kjær et al. (2018). We are however a little bit sceptical to the claim that Fig. 4b exhibits the impactor direction; rather it shows the tensions in the ice masses.

Our results independently support the findings in Kjær et al. (2018) and in MacGregor et al. (2019). We do not see, however, any central uplift because of an insufficient resolution of EIGEN 6C4 for this goal. It is good to repeat that the ground resolution of EIGEN 6C4 is ~9 km and the diameters of the craters about 30–35 km, so we cannot expect too many details.

We do not overestimate our possibilities; we are aware that with the gravity data only we would never be able to make the discovery like this, but we can effectively confirm it. This confirmation is independent on all the ways used by the quoted authors, thus it is important. We also used the magnetic anomalies.

Note that the magnetic anomaly maps show (Figs. 3, 4c) large negative anomaly centred towards north from the centre of the impact crater (the effect of impact demagnetisation).

The distribution of the magnetic anomalies in this area is dictated by the underlying geology and in this part of Precambrian shield negative magnetic anomalies often indicate presence of underlying allochthonous crustal blocks with reversed magnetizations (Kletetschka and Stout, 1998, 1999). However, in terms of meteorite impact, the negative anomaly could also originate as a result of the shock delivered to the Proterozoic gneiss sheet. This sheet contains magnetic carriers that in general include both induced and remanent magnetic expression [Kletetschka and Stout, 1998]. Impact demagnetizes this crust to a shock pressure wave that decays away from the impact structure depending on the nature of magnetic carrier (Adachi and Kletetschka, 2008; Kletetschka et al., 2004). The crust acquires a demagnetized volume that is concentrated within the crater boundaries but it generally extends an additional crater diameter distance outside the rim (Kletetschka et al., 2004). This causes the return flux from the neighbouring magnetized crust to go through this magnetic gap and contributes to a negative magnetic expression. However, this impactor contained iron and a significant component of the impactor material distributes according to the angle of the impact (Pierazzo and Melosh, 2000). Then, the asymmetry of the negative magnetic anomaly, from south-west to north-east of the crater, is consistent with an overwhelming presence of the iron rich impactor material south-west from the crater centre. This is illustrated in Fig. 3 where the negative magnetic anomaly does not go all the way to the south-western rim of the crater. Positive magnetic flux coming through this part of the crater is consistent with the gravity data that the impact angle may have been coming from the north direction towards the south. The iron rich breccia (Arizona Crater is an example (Artemieva and Pierazzo, 2009), incorporated in the southern portion of the crater, contributes with the overall induced positive magnetic flux that is consistent with the gravity asymmetry. Thus, both gravity and magnetic data over the Hiawatha crater in northwest Greenland suggest that a southward directed impact may have contributed to the southward generation of ejecta material, some of which may have converted into iron rich micrometeorites observed in the lake sediments of central Europe and north America (Kletetschka et al., 2018; Wittke et al., 2013). It is good to recall that the ground resolution of EMAG 2 is ~5 km.

4. Conclusions

We independently support discovery by Kjær et al. (2018) and MacGregor et al. (2019) of two possible subglacial impact craters in NW Greenland. We used the gravity aspects computed from the harmonic geopotential models of the global static gravity field model EIGEN 6C4 and our previous experience from analyses of other similar phenomena like volcanoes, lakes, paleolakes and impact craters (e.g., Klokočník et al., 2017a, b, c, 2018a, 2018b). Magnetic anomalies from the EMAG 2 model are in the case of Hiawatha Glacier crater consistent with the impact direction, as is the gravity signal. Such an analysis is feasible owing to iron nature of the impactor, which has been recognized by geologists (Kjær et al. 2018). Both the gravity aspects and magnetic data indicate that the impactor (in the case of Hiawatha) was moving southward over the region at the time of impact.

We contributed by analysis of independent gravity aspects and magnetic anomalies. A conclusive identification of these structures as impact craters, however, awaits further research, including direct sampling.
CRediT authorship contribution statement

Jaroslav Klokočník: Conceptualization, Methodology, Writing - original draft, Writing - review & editing. Jan Kostelecký: Software, Data curation, Visualization. Aleš Bezděk: Writing - original draft, Writing - review & editing, Software, Data curation, Visualization, Validation. Václav Cílek: Formal analysis, Investigation. Gunther Kletetschka: Investigation, Writing - original draft, Writing - review & editing, Validation. Hana Staňková: Software, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Fig. 4. a, b, c. The radial second derivatives $T_{zz}$ [Eötvös], the strike angles $\theta$ [deg] and magnetic anomalies [nT] for Hiawatha and Paterson area, computed with EIGEN 6C4. The strike angles $\theta$ are expressed in degrees with respect to the local meridian and its red colour means its direction to the east and blue to the west of the meridian. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
request.

References


