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Candidates for multiple impact craters: popigai and chicxulub as seen by EGM08, a global $5' \times 5'$ gravitational model

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Abstract

In 2008 the new Earth Gravitational Model (EGM08) was released. It contains a complete set of spherical harmonic coefficients of the Earth's gravitational potential (Stokes parameters) to degree 2190 and order 2159 that can be used for evaluation of various potential quantities with both the unprecedented accuracy and high spatial resolution. Two such quantities, the gravity anomaly and second-order radial derivative of the disturbing potential, were computed over selected areas with known impact craters. The displays of these derivatives for two such sites clearly show not only the strong circular-like features known to be associated with them but also other symmetrical structures which appear to make them multiple impact sites. At Popigai, Siberia, the secondary circular features fall in a line from the primary in the SE direction. At Chicxulub, Yucatán, there appears to be one secondary crater close to the primary in the NE direction, as well as possibly others in the vicinity of the main crater. Gravity information alone is not proof of the impact craters but it is useful in identifying candidate sites for further study, for future examination by geologists and geophysicists.

1 Introduction

There are about 175 currently known impact meteoritic craters on the Earth's surface [see Earth Impact Database 2006; EID www.unb.ca/passc/ImpactDatabase and an impact origin for over 600 additional structures has been proposed (Rajmon, 2009). We computed the gravity anomaly and second-order radial derivative of the disturbing gravitational potential at about 30 of the confirmed larger impact crater sites (from EID), and at some other promising places (also from the list of Rajmon, ibid). Here we give two examples of what appears to be double or multiple impact craters at two of those well known locations, namely Popigai in Siberia, Russia, and Chicxulub in North Yucatán, México; for more details and examples see the preparatory study Klokočník et al. (2008a) and (www.asu.cas.cz/~jklokocn).

The novelty of our approach is in: 1 – we use a very detailed Earth Gravitational Model EGM 08 (Pavlis et al., 2008a, b) with theoretical resolution $5' \times 5'$ (arcminutes) or $9 \times 9 \cos\phi$ km on the ground (with ϕ being latitude), and 2 – we computed and analysed two functionals of the disturbing potential, namely the gravity anomaly Δg (1 mGal$=10^{-5}$ m s^{-2}) and the second-order radial derivative T_{rr} (milliEõtvõs, 1 mE$=10^{-12}$ s^{-2}). Note that the latter quantity is not generally available directly from the ground gravity surveys but only as numerical derivatives from measured gravity anomalies in some studies; e.g., Evjen (1936) or Elkins (1951).

The authors of this paper are not geologists (but geodesists), however they know well that circular-like gravitational signals are not proof of an impact origin, they are just one indication. Additional data are needed to confirm an impact origin, such as magnetic anomalies, seismic profiles or deposits of shock-metamorphic minerals, etc. Nevertheless, gravity data together with other geophysical data can establish general criteria that correspond to the geophysical signature of impact craters (Pilkington and Grieve, 1992; French and Koeberl, 2010). Final confirmation of an impact origin remains on geologic evidence. For the two cases considered here, the presence of additional circular structures close to the “primaries” which are known as the impact craters, strongly suggests that these “companions” are also of impact origin.

It is useful to recall history of discovery of Chicxulub or Mjolnir impact craters, where the gravity data played an important role in a first phase of study; such data were and are important for identifying anomalous structures for future examination. It is true that the discovery of gravity and magnetic anomalies associated with suspected structures have lead directly to their confirmation as impact structures (e.g., Pilkington and Grieve, 1992; see details in the recent review paper French and Koeberl, 2010). We do not see the geological verification as a part of our role (and no relevant data are available in the zones of hypothetical “companion” craters Chicxulub II and Popigai II); we have a desire to jump-start geological investigations by others.

For a double crater one scenario could be an impact from a binary asteroid. A binary asteroid can be generated by repeated close encounters with the Earth. It is estimated and observed that 15±4% of the population of near-Earth asteroids larger than 200 m in diameter, are binaries (see Sect. 4.5.). In addition a part of multiple craters might form from the breakup in the Earth's atmosphere.

2 Data and formulae

2.1 EGM08 gravitational field model

EGM08 is a current highly detailed Earth Gravitational Model (Pavlis et al., 2008a) that contains numerical geopotential coefficients $C_{n,m}$ and $S_{n,m}$ of a spherical harmonic expansion complete to degree and order 2159 with additional coefficients complete to degree 2190 but no order higher than 2159. In addition to the satellite data from the mission GRACE (Gravity Recovery and Climate Experiment, NASA satellite active since 2002, see, e.g., www.nasa.gov/missions/, www.csr.utexas.edu/grace/, http://op.gfz-potsdam.de/grace/ and many more), the model was computed by using $5' \times 5'$ area mean free-air gravity anomalies Δg derived from ground gravity surveys and satellite altimetry both compiled nearly worldwide by the US National Geospatial-Intelligence Agency (NGA).

The precision of EGM08 gravity anomaly computations for Popigai or Yucatan and many other places, expressed in terms of its commission error, is at the level of a few miliGals (Fig. 1). But in some localities the precision is worse and can be ~30 mGal, together with much lower resolution, e.g., in Antarctica (because only the GRACE data are available there). This information is used below for the accuracy assessments. We will see for example that the maximum Signal to Noise ratio (S/N) for gravity anomalies at Popigai or Chicxulub is about 30, (from Fig. 1), inevitably smaller for the second derivatives but still large enough in both cases to confirm the additional circular-like features as real and not artifacts (see Sect. 4.2).

For our use we will define and compute $R = S/N$ (to eliminate zero S cases) as follows

$$\begin{aligned} \min R &= (\min(\max|-S|, \max\ +S))/(\max N), \\ \max R &= (\max(\max|-S|, \max\ +S))/(\min N) \end{aligned} \tag{1}$$

for the gravity anomalies and second radial derivatives in the areas of interest, i.e. Ω ($\phi_{\min}$, $\lambda_{\min}$, $\phi_{\max}$, $\lambda_{\max}$), where (ϕ, λ) are geographic latitude and longitude of the center of the area of interest.

Using Fig. 1 (defining N) and 2 (defining S) for Popigai and Chicxulub (the extent of the areas is visible below on Figs. 2–5), we get R (min, max)=8–15 for Popigai and 5–20 for Chicxulub. Statistically, the required minimum R=3.

It should be fully appreciated by readers geologists (who are usually not too familiar with gravity field modeling) how important progress is represented by the EGM 08 as for the accuracy, resolution and homogeneity of the gravity field description (Pavlis et al., 2008a, b). Without EGM 08, our analyses would be impossible (Klokočník et al., 2008a, b).

2.2 Formulae

The following quantities, functionals of the Earth's gravitational potential expressed by EGM 08 can actually be computed for our purposes by using software for the spherical harmonic synthesis (Holmes and Pavlis, 2006):

1. free-air gravity anomaly, more precisely "spherically approximated gravity anomaly", $\Delta g = -\partial T/\partial r - 2T/r$, where T is the disturbing gravitational potential $T = V - U$ with the normal potential U represented by the Geodetic Reference System 1980 (GRS 80, Moritz, 1984);

2. second-order derivatives of T on the main diagonal of the Marussi tensor, i.e. T_{xx},T_{yy} and T_{zz} in the local oriented coordinate frame, namely the second radial

derivative $T_{zz} \approx T_{rr} = \partial^2 T / \partial r^2$, where r is the geocentric radius of a general computation point.

All model computations were evaluated at the surface of the reference ellipsoid (GRS 80) on a grid of ellipsoidal coordinates with equiangular spacing of $5'$.

The gravity anomaly is defined through the fundamental gravimetric equation that reads in the spherical approximation

$$\Delta g(r,\theta,\lambda) = -\left(\frac{\partial}{\partial r} + \frac{2}{r}\right) T(r,\theta,\lambda) = \frac{GM}{a_e^2} \sum_{n=2}^{2190} (n-1) \left(\frac{a_e}{r}\right)^{n+2} T_n(\theta,\lambda) \tag{2}$$

where a_e is the scaling factor of EGM08 (the Earth's mean equatorial radius), and the surface spherical harmonic functions are

$$T_n(\theta,\lambda) = \sum_{m=0}^{n} \left(C_{n,m} \cos m\lambda + S_{n,m} \sin m\lambda\right) P_{n,m}(\cos\theta).$$

Here, $P_{n,m}$ are associated Legendre functions of the first kind, n is degree and m order of the harmonic expansion and (θ, λ) represent spherical co-latitude and longitude. We still use Δg (and not for example the radial gravity disturbances, i.e., the first-order radial derivative of the potential) because sometimes traditional local ground gravity data in the form of Δg (free air or Bouguer's type) are available and might be used for a comparison.

The second-order radial derivative of the disturbing gravitational potential in the spherical approximation is

$$T_{rr}(r,\theta,\lambda) = \frac{\partial^2}{\partial r^2} T(r,\theta,\lambda) = \frac{GM}{a_e^3} \sum_{n=2}^{2190} (n-1)(n+2) \left(\frac{a_e}{r}\right)^{n+3} T_n(\theta,\lambda) \tag{3}$$

3 Preliminary analysis

3.1 Popigai – a multiple crater?

Popigai (ϕ=71° 39′ N, λ=111°11′ E) is a very large impact structure (diameter of about 100 km, age 36 My) located at the Anabar shield, central Arctic Siberia, near the seashore. The main crater at Popigai is partly visible on the surface. The shock pressures from the impact instantaneously transformed graphite in the ground into diamonds near the central zone of the crater (Masaitis, 1998). Coesite and stishovite (strongly indicating an impact origin) are also present there (see Pilkington et al., 2002 for additional references).

Figures 2 and 3 show Δg and T_{rr} for the Popigai area. We think EGM 08 clearly reveals more than one crater, lined up close to the original (visible crater) at Popigai in the NW-SE direction. We label these structures Popigai I, II, III, (and IV?). Our hypothesis is that the Popigai structure is a multiple crater.

A simple geological map of Popigai is available but only for the primary crater "Popigai I" (Pilkington et al., 2002). We have not seen the original terrestrial gravity anomalies (they appear to be "proprietary" of soviet/Russian authorities) but they were evidently used by NGA for EGM 08 (no comment in Pavlis et al., 2008a, b).

3.2 Chicxulub – a double crater?

The Chicxulub structure in the North Yucatán Peninsula, México (ϕ=21°20′ N, λ=270°30′ E) is a multi-ringed impact crater buried partly under a flat surface and partly under a shallow sea (it is not visible on the surface). The crater was discovered (in late 1970s) with the aid of the ground gravity and magnetic anomalies (collected by oil company Petróleos Mexicanos, and others), disclosing concentric, ring-like patterns. This structure is also marked by shock-metamorphosed minerals, sinkholes (cenotes) and a number of seismic profiles revealing its circular nature below ground (e.g., Surendra 2004).

The size of the crater has been discussed intensively. Earlier investigations (e.g., Hildebrand et al., 1995, 1998) found that there were two rings with the diameters of about 80 and 170 km, although others (e.g., Sharpton et al., 1993) identified two more-distant rings in their gravity profiles, and interpreted a 300 km wide crater. The analysis of Espindola et al. (1995) did not support more rings. From the most recent papers we recommend Vermeesch and Morgan (2008) and the review with many references (French and Koebert, 2010).

Bottke et al. (2007) discovered that Chicxulub is a result of an impact of a fragment (of carbonaceous chondrite) from the Baptistina asteroid family, the first such specific identification of an origin among Earth impactors.

One of the older and typical Earth's gravitational models, EGM 96 (Lemoine et al. 1998), providing 50 km half wavelength resolution at latitude of Chicxulub, showed a negative gravity anomaly in the Chicxulub area, but revealed no further details. Newer gravitational models computed with the help of data solely from the recent gravity dedicated satellite missions CHAMP (CHAllenging Minisatellite Payload for geo-science and application) and GRACE (see above) unfortunately did not reveal many more details (Klokočník et al., 2008a and www.asu.cas.cz/~jklokocn), due to their lower spatial resolution (∼100 km).

Figures 4 and 5 show Δg and T_{rr} for the Chicxulub area when the complete EGM08 model is employed. Two circular-like but fragmented structures are clearly visible with negative values of T_{rr}, two central positive parts, and two fragmented rings with positive anomalies. The outer ring has the diameter 160–180 km. Outer "circles" of minimum and maximum gradients with a possible diameter ∼250 km are uncertain being faint and very fragmented.

Moreover, in the NE direction from the Chicxulub impact, we can see a less pronounced circular-like feature (Figs. 4 and 5), partly interfering with the outer ring of the original Chicxulub. This smaller crater-like feature seems to have two rings with the diameter for the outer ring of about 100 km. It is fair to note that the existence of the second crater might have been anticipated (but was not) already from older maps of the ground gravity anomalies, see Fig. 2b in Sharpton et al. (1993) or Fig. 1 in Hildebrandt et al. (2003). Especially the last paper was close to the discovery. But it never have been explicitly expressed, presented and published before in Klokočník et al. (2008a). We will test the hypothesis that Chicxulub is a double (if not a multiple) crater.

4 Further analysis

It is not enough to compute Δg and T_{rr}, identifying circular structures and to claim that we have new candidates for the impact craters. Even geodesists know that many circular structures have nothing to do with the impact craters. We wish to bring more arguments to convince geologists that it is worthy to begin their analyses at suggested localities. We found from many examples with EGM08 of circular-like gravity signals from volcanoes or various tectonic structures look like and we can reliably distinguish them from the signal of a possible impact structure (Klokočník et al., 2008a); in this assessment we always cooperate with geologists. We also detected various artifacts namely in T_{rr} due probably to the Gibbs effect or a consequence of aliasing in the EGM 08 solution, and we are also able to distinguish them from the craters (ibid).

To support the interpretation of our initial survey of Chicxulub and Popigai, here we show comparisons with the DNSC08 database (Andersen et al., 2008), accuracy estimates, filtering of T_{rr}, computations of T_{rrr}, and examples of crater modeling.

4.1 Comparison with the DNSC 08 database, with Russian data for Popigai and terrestrial gravity anomalies for Chicxulub

The DNSC 08 database contains sea surface heights from global altimetry (Andersen et al., 2008). The Danish National Space Center (DNSC) 08 gravitational model uses the same surface gravity anomaly source as EGM 08 but at greater resolution ($2' \times 2'$). Although the two models are not independent, a comparison is useful.

We show examples for Popigai in Fig. 6a and b; the greater detail in DNSC 08 is even more convincing for a multiple crater. The situation is very similar for Chicxulub, see Fig. 7a and b, with interesting details just for the location of the candidate for the impact crater, Chicxulub II.

For Popigai, we also reproduce results from the older soviet gravity data, taken from Fig. 3a of Pilkington et al. (2002), which we have unfortunately in the form of the figures only, see Fig. 6c, d. We can see that the negative gravity anomaly of Popigai I (Fig. 6c) is extended (or "repeated") in the direction of possible location of the candidate crater Popigai II and that the filtering of the anomalies to retain wavelength components <50 km indicates two circular structures on places which we expect for Popigai I and II. This looks promising and supports our hypothesis (compare Figs. 6d to 3 and similarly Fig. 2 in (Hildebrand et al., 2005). On the contrary, the Bouguer anomalies in Fig. 5 of (Masaitis et al., 2005), partly also in the area adjacent to Popigai I, based on various soviet and Russian data (only referenced but not available) do not support our multiple crater conclusion.

The terrestrial gravity anomalies used by Hildebrandt et al. (1995), kindly provided by M. Pilkington, are shown in Fig. 7c (in GPU units, 1 GPU=10 $m^2 s^{-2}$) for Chicxulub and should be compared with Fig. 7a and b. Figure 7c discloses clearly that EGM 08 made use of very similar terrestrial data sets as those of the earlier investigators. The agreement between EGM08 and Pilkington's data in particular is very good on land.

4.2 Input data accuracy assessments

An accuracy assessment for the computed Δg and T_{rr} is not easily obtained since a covariance matrix is only available for the low degree portion of the EGM08 field and integral formulas must be used for the vast number of higher degree terms (Pavlis and Saleh, 2005). This approach, leading to the commission error mentioned above (displayed in detail in Fig. 1), was globally evaluated for the gravity anomaly, geoid undulation and deflections of vertical in EGM 08 (Pavlis et al., 2008a, b).

In the vicinity of these impact structures, do the signals (in Δg and $T_{rr)}$ and their changes (grad(Δg) and grad(T_{rr})) stand out above their estimated precision (or accuracy)? For the gravity anomaly we could use directly the commission error offered by the authors of EGM08 (Fig. 1), while the commission error for the second radial derivative should be somehow estimated. We already know that Δg for Popigai and Chicxulub are robust signals (Figs. 2 and 4) compared to their commission errors (Fig. 1). How do we estimate the errors of the gradient signals?

For this purpose we used the commission error of deflections of vertical. Firstly, T_{rr} as a function of deflections of vertical and some further simplification is needed. We can obtain such relation by the differentiating the basic equation of physical geodesy (Eq. 2) in the spherical approximation (Hofmann-Wellenhof and Moritz, 2003, p. 121), which leads to:

$$\frac{\partial \Delta g}{\partial r} = -\frac{\partial^2 T}{\partial r^2} - \frac{2}{r}\frac{\partial T}{\partial r} + \frac{2}{r^2}T. \tag{4}$$

where all symbols were explained above. Equation (4) connects the radial derivate of the gravity anomaly with the second radial derivative of the disturbing potential. One could find out by numerical evaluation that both quantities are very close to each other. An agreement was checked in terms of RMS for both localities. For Popigai, it was found RMS $\left|\frac{\partial \Delta g}{\partial r} - \frac{\partial^2 T}{\partial r^2}\right| = 0.071$ E while for Chicxulub RMS $\left|\frac{\partial \Delta g}{\partial r} - \frac{\partial^2 T}{\partial r^2}\right| = 0.067$ E what warrants our setting $\frac{\partial \Delta g}{\partial r} \approx -\frac{\partial^2 T}{\partial r^2}$ precise enough for the accuracy assessments. Considering this strong correlation we may use $\frac{\partial \Delta g}{\partial r}$ as a function of the deflections of vertical for the accuracy assessment of T_{rr}. From (ibid, p. 122), the quantity $\frac{\partial \Delta g}{\partial r}$ can be written as follows:

$$\frac{\partial \Delta g}{\partial r} = -\gamma_0 \left(\frac{\partial \xi}{\partial x} + \frac{\partial \eta}{\partial y}\right), \tag{5}$$

where ξ means the north-south component (direction in x axis) and η denotes east-west component of deflection of vertical (direction in y axis) and γ_0 is the normal gravity acceleration (∼10 m/s^2). The commission error of T_{rr} can be approximated via error propagation based on the deflection of vertical commission error as follows:

$$\sigma^2(T_{rr}) \approx \sigma^2\left(\frac{\partial \Delta g}{\partial r}\right) \approx \gamma_0^2\left[\sigma^2\left(\frac{\partial \xi}{\partial x}\right)+\sigma^2\left(\frac{\partial \eta}{\partial y}\right)\right], \tag{6}$$

where the relevant covariances were evidently neglected and error task thus becomes an incorrect one (because the covariances are unknown).

The comparison was performed for Chicxulub (see Fig. 8a, b) and Popigai (Fig. 9a, b). Table 1 yields a summary from these pictures (Figs. 8a and 9a) for the gravity anomalies, where we compare Δg (or grad(Δg)) with the corresponding error estimation. Since "signal" Δg or T_{zz} oscillates around zero, we cannot use the S/N ratio directly, but the range of both (signal and noise) suffices to judge the signal's reliability. We will use R(min, max), defined by Eq. (1) from Sect. 1.

We see from Table 1 that R(min, max) is 3–12 for Chicxulub and 7–11 for Popigai (in fair agreement with estimates from Sect. 1). Similarly Table 2 summarizes range of signal T_{rr} (or grad(T_{rr})) with respect to its estimated error based on Figs. 8b and 9b. Here, R(min, max) is 3 and 7 for the both areas.

So even the second radial derivative T_{rr} yields usually a good proportion between signal and noise, sufficient enough to use EGM08 for our "impact prospecting". It is necessary to recall, however, that such assessments are – due to some assumptions (see Eq. 6) – a rough estimate only rather than correctly done error propagation (Pavlis and Saleh, 2005).

4.3 Filtering the second-order radial derivative

This attempt deals with filtering (removing) of long-wavelength features in Δg and T_{rr} with the goal to support our hypothesis about double/multiple impact craters. We computed T_{rr} again but without terms up to degree and order 36, or 360, leaving only the higher degree/order part as it is in EGM 08, see Fig. 10 a, b. The question is what will remain from the original circular-like features shown in Figs. 2 and 3? We show here the examples for Popigai. We see that the circular-like features "survived" this filtering. Again, we have no proof but a new, additional indication supporting our hypothesis. But more should be done, see the next section.

4.4 Crater modelling

4.4.1 Method

To provide an independent check of our previous findings of the new candidates for the impact craters, we tried to model these putative objects by a point masses model, using accessible geological data as constraints. We compared gravity anomalies from these models with those from EGM 08. In both cases (Chicxulub and Popigai), the hypothetic companion looks like a "twin" of the primary crater.

Gravity anomalies, Δg, and the second radial derivatives, T_{rr}, are obtained by numerical integration over the crater body using the formulas

$$\Delta g = f \int_\tau \sigma r^{-2} \cos z \, d\tau + E, \quad T_{rr} = f \int_\tau \sigma r^{-3} (3 \sin^2 z - 1) \, d\tau + E', \tag{7}$$

where f is the gravitational constant, σ density anomaly relative to the crater surroundings, and r, z are the distance and the zenith distance to the mass element $d\tau$, respectively. The symbols E, E' shift the integrated values to fit numerically to the EGM 08 data.

It is evident that this task is not unique since various mass distributions can produce the same gravity anomalies. To avoid mistakes, we always followed crater models provided by geologists and geophysicists as closely as possible.

4.4.2 Tests of crater modelling

First we modelled Clearwater Lake (Canada) and Ries-Steinheim (Germany) known as double craters to learn from these examples how to do the modelling, which is an improperly posed inverse task. We have only limited geological information (shape of the crater and density contrasts) to define external constraints. The Clearwater Lake craters are supposed to have been created simultaneously by two impactors of a comparable size, while the size-difference for Ries and Steinheim is large. The former can be detected by EGM 08, the latter not.

Here we present an example for the Clearwater craters. The western and eastern craters differ substantially, both in the form and in the gravity anomalies (not in size). This is explained by the timing of the event. First the eastern crater was created in the granite rock. When the second impactor hit the ground, already affected (over a wide area) by the first hit, the shocked granite responded like dry sandstone (Hische, 1994). Using the Hische's profile and density defects ($-0.07\,\mathrm{kg/m^3}$ for the western crater and $-0.40\,\mathrm{kg/m^3}$ for the eastern one), and depth $\sim$2 km, our model yields gravity anomalies as shown in Fig. 11a, as well as of the second radial derivatives (Fig. 11b). The comparison shows a very good agreement between the masses-model and the EGM 08 computations.

4.4.3 Modelling of Popigai and Chixculub

The EGM 08 survey of Popigai shows a series of circular features in addition to the primary crater. Of them the nearest secondary is strongest and shows a structure very similar to the primary. This similarity indicates that, if Popigai is a multiple crater, the system may have been created simultaneously.

Our model is based on the Pilkington's et al. (2002) final crater profile. The diameter is taken as 100 km, depth 6 km, the density contrast varies from $-0.07\,\mathrm{kg/m^3}$ at the bottom to $-0.22\,\mathrm{kg/m^3}$ at the top, and is slightly inclined from NW to SE.

The computed companion is located 95 km SE from the center of the main crater, with the diameter $\sim$80 km. We kept the same structure and density as those of the main crater. Only the depth was decreased to 2.5 km. However, the modelled surface gravity anomalies as well as the second radial derivatives were too detailed to be suitable for a “ground” comparison with EGM08. Thus, they were smoothed by recalculating them at altitude 1.5 km to get the resolution corresponding to that of the EGM 08 (and the results are in Fig. 12a and b).

The model of Chicxulub is based on the Surendra (2004) seismic model, and anomalies are taken from Sharpton et al. (1994) and from EGM 08. Its diameter is about 170 km and depth 8 km. It is buried 2 km beneath the present-day surface. Terraces are modelled by a blunted cone, 80 km in diameter at the bottom and 180 km on its top. Central uplift is represented by a cylinder 50 km in diameter. The density defects are +0.10 kg/m^3 for both the terraces and uplift, −0.15 kg/m^3 for the rest of crater filling, and −0.25 kg/m^3 for the sedimentary cover.

The computed companion of Chicxulub is smaller than the primary crater, some 60 km in diameter, and is located 85 km NE from the center of the primary crater in distance ~85 km. Retaining the same structure, its depth is set to 4 km, sedimentary cover to 1 km, the terrace cone 35–60 km and the uplift diameter 20 km. The model yields gravity anomalies and the second radial derivatives as shown in Fig. 13.

4.5 Notes from astronomy

A fraction of binary systems in the population of near-Earth asteroids is 15±4% (e.g., Pravec et al., 2006). Most binary asteroids are, however, close systems with separations of components so small (see Pravec and Harris, 2007) that they produce typically a single crater when they impact the Earth. A terrestrial impact record of binary asteroids is therefore scarce, with only three double craters identified so far (see Melosh and Stansberry, 1991; Bottke and Melosh, 1996); they could be produced by impacts of less common wide binary systems that are observed in the binary population with a lower frequency.

Table 3 shows some parameters of the binary asteroids (potential impactors) and the impact craters together. For ordinary close and stable binary asteroids the ratio a/D_1 is typically 3 (the symbols are explained at Table 3). But proved double craters on the Earth (Clearwater Lakes and Ries-Steinheim) have a/D_1 ~10. Relevant systems of the binary asteroids are also known, but they are not frequent (Pravec and Harris, 2007), because their lifetime is short; thus there is evolutionary selection effect. For our new candidates for the double/multiple craters, we have $a/D_1 \sim 10$, too. With the help of Pravec and Harris (2007) and other information (e.g., Pravec, personal communication, 2009) we see that astronomers do not exclude the existence of such asteroids which we could use to create our candidates for possible double/multiple impact structures such as Chicxulub or Popigai.

5 Conclusions

Using selected functionals of the disturbing potential (mainly the gravity anomaly and second radial derivative), computed from the recent, accurate and high resolution Earth Gravitational Model (EGM08) provided in a spherical harmonic expansion, we have confirmed the existence of circular or circular-like geopotential structures at all existing larger well known impact craters (with diameter >30 km). This is a useful test of the model EGM08. However, the most interesting inference from this survey and subsequent analysis is the likelihood that at least two of the well known crater sites originally thought to be single are the result of double or multiple impacts (Chicxulub and Popigai). Naturally these findings are tentative pending further (geological and geophysical) surveys of the areas.

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Table 1. Range of Δg, grad(Δg) and its estimated errors for the Chicxulub and Popigai areas.

Area	Δg [mGal]	$\sigma(\Delta g)$ [mGal]	grad(Δg) [mGal]	σ(grad(Δg)) [mGal]
Chicxulub	−20 to +60	2 to 7	−18 to +13	1.5 to 4.5
Popigai	−40 to +65	2 to 5	−20 to +20	1.8 to 3

Table 2. Range of T_{rr}, grad(T_{rr}) and its estimated errors according to Eq. (6) for the Chicxulub and Popigai areas.

Area	T_{rr} [E]	$\sigma(T_{rr})$ [E]	grad(T_{rr}) [E]	σ(grad(T_{rr})) [mGal]
Chicxulub	−30 to +40	4 to 9	−18 to +15	2.5 to 5.5
Popigai	−35 to 30	10 to 14	−25 to 30	4 to 10

Table 3. Impactors and impacts.

name of craters	diameters of craters		a [km]	diameters of impactors		a/D_1
	d_1 [km]	d_2 [km]		D_1 [km]	D_2 [km]	
Clearwater Lakes	36	26	31	2–3	0.7	10–16
Ries Steinheim	24	4	40–50	2–3	?	> 10
Chicxulub I, II	170	60–80	100	10?	?	10?
Popigai I, II	100	80	100–120	10?	?	10–12?

a=distance between geometric centers of the craters

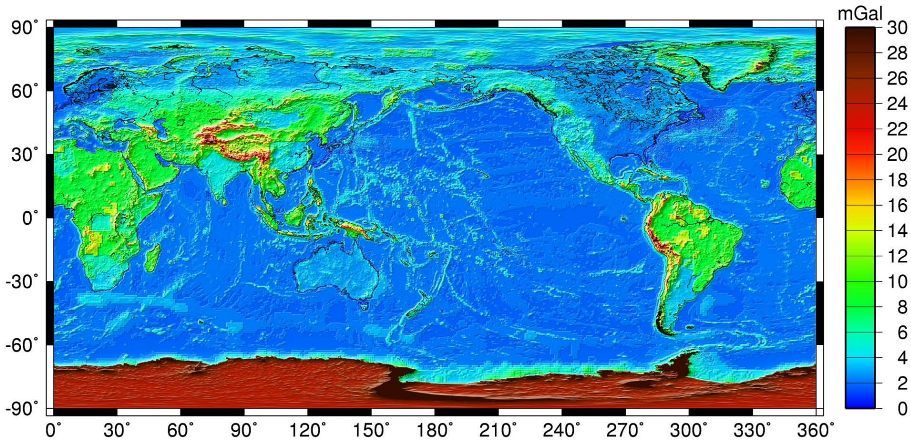

Fig. 1. The commision error of gravity anomalies of EGM 08 (Pavlis et al., 2008a) or standard deviation of free air spherical approximation of the gravity anomalies. Scale in miligals [mGal].

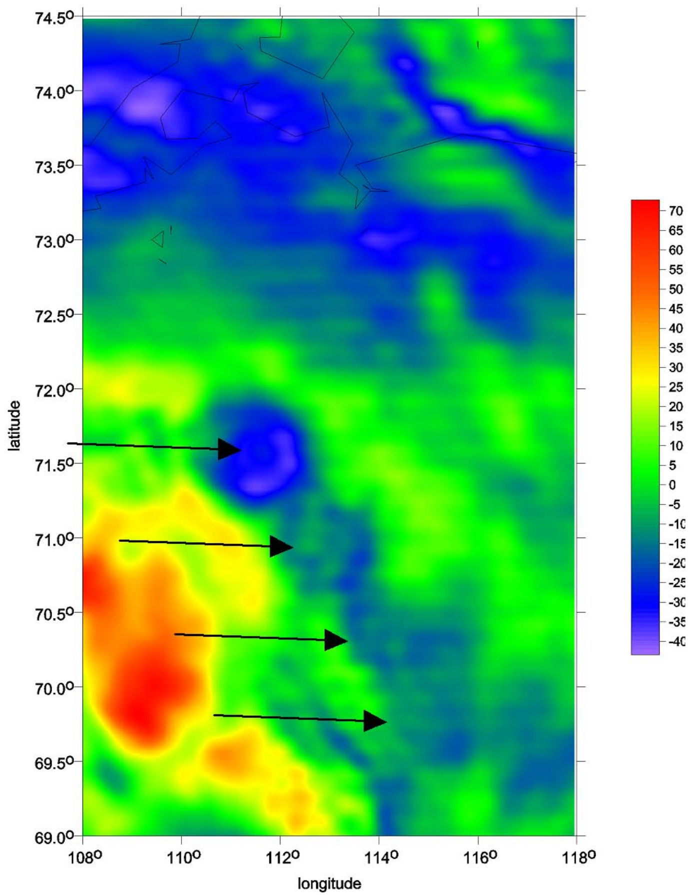

Fig. 2. Gravity anomalies Δg [mGal] computed from the complete EGM 08 at Popigai, Siberia, Russia. Here and everywhere (excluding Figs. 10a, 11 and 12) there is a nonlinear scale with green color at zero. The arrows point to Popigai I, II, II (and IV).

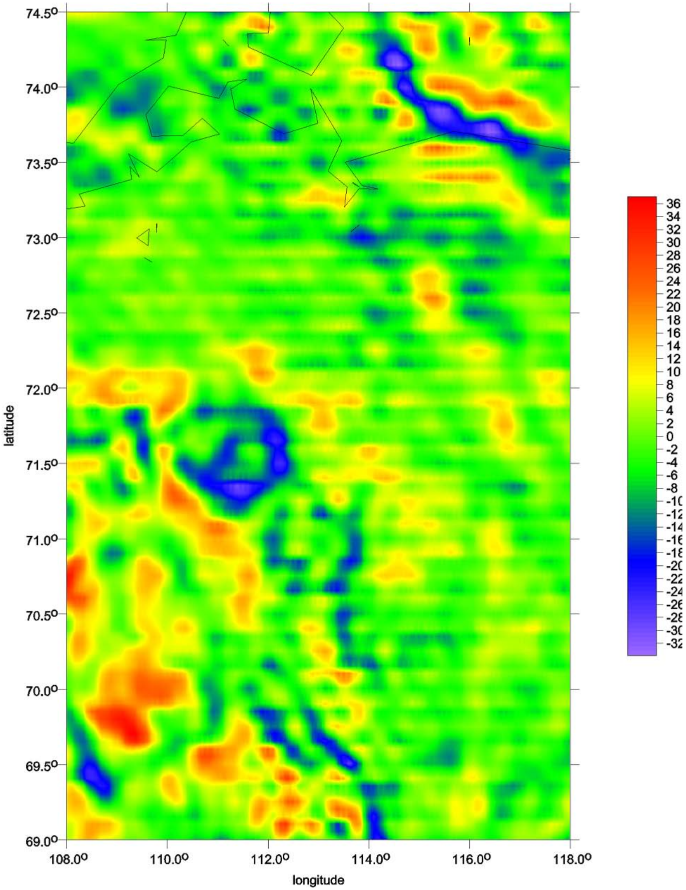

Fig. 3. Second radial derivative T_{zz} [mE] computed from the complete EGM 08 at Popigai (note circular-like candidates for impact craters less pronounced than the original crater but visible in the SE direction from the original one).

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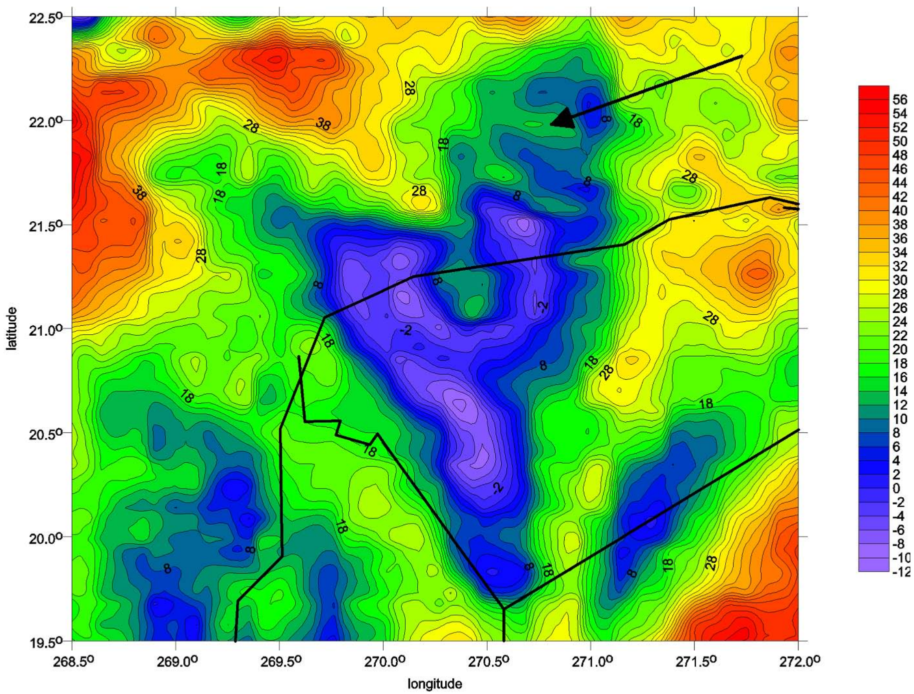

Fig. 4. Gravity anomalies Δg [mGal] based on the complete EGM 08 at Chicxulub (the arrow indicate a possible double crater).

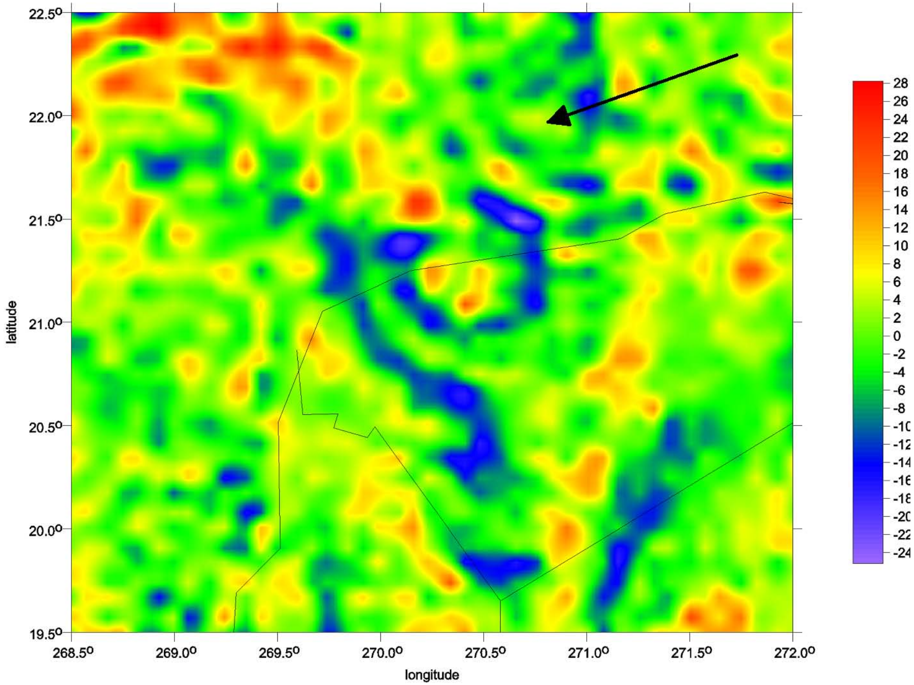

Fig. 5. Second derivatives T_{rr} based on the complete EGM 08 at Chixculub [mE]. To be compared also with Fig. 4 in Espindola et al. (1995).

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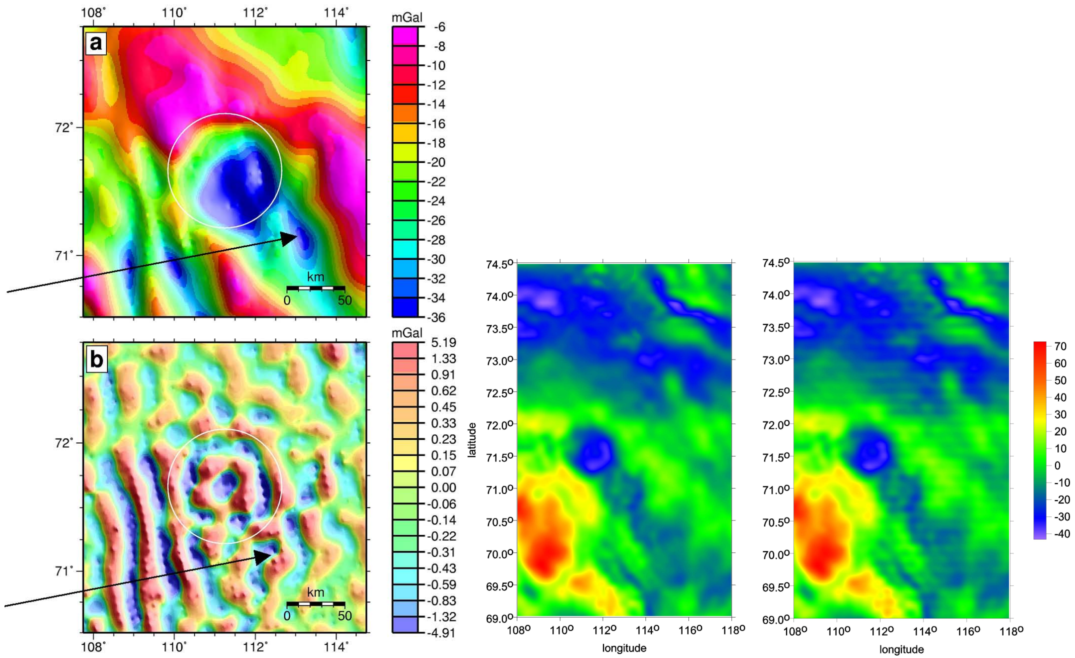

Fig. 6. (a, b) Popigai, Siberia. Gravity anomalies computed with DNSC 08, resolution 2×2′. (left) as compared to those with EGM08, resolution 5×5′ (right, see also Fig. 2). **(c, d)** Gravity anomalies (Bouguer's) over the Popigai region (data courtesy GETECH Ltd); reproduced from Fig. 3a of Pilkington et al. (2002), (c) (top). White circles represent estimated crater at 100 km diameter. The high-pass filtered gravity anomalies to retain wavelength component<50 km, (d) (bottom). The arrows show locations of possible candidate impact crater Popigai II.

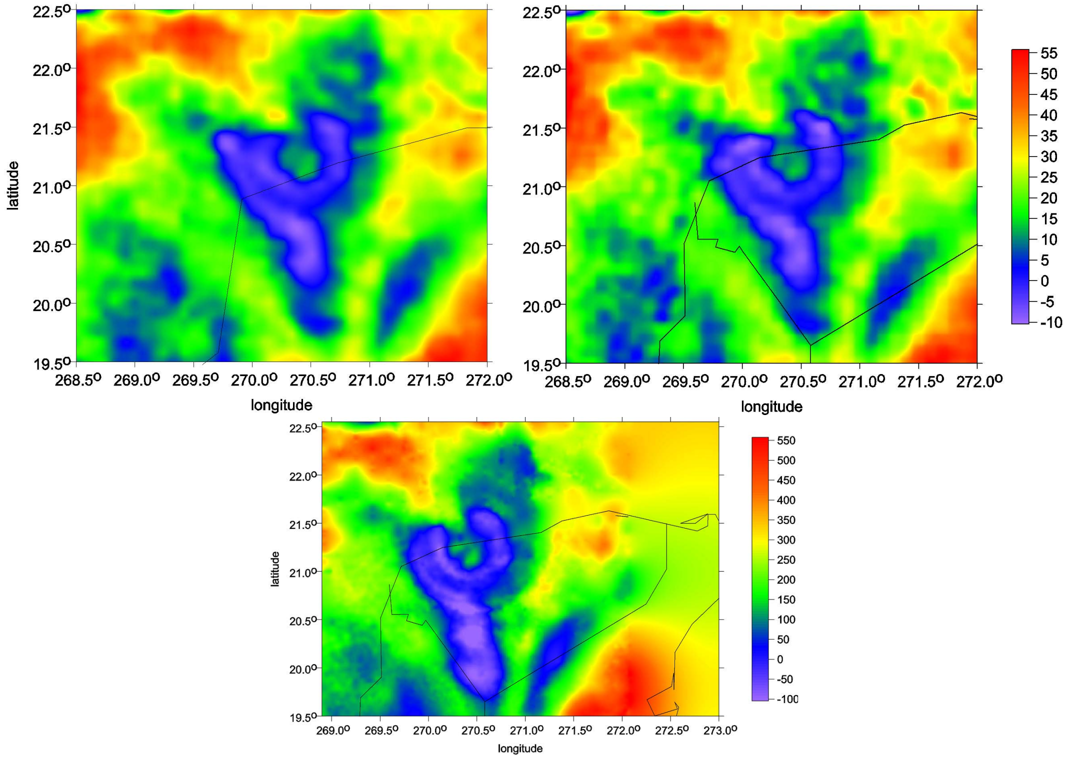

Fig. 7. (a, b) Chicxulub, Yucatán. Gravity anomalies computed with DNSC 08, resolution $2\times2'$ (left) as compared to those with EGM 08, resolution $5\times5'$. **(c)** Chicxulub, Yucatán. Terrestrial gravity anomalies as used, e.g., by Hildebrandt et al. (1995). To be compared to (a) and (b); here the units are "g.u" or "GPU" (geopotential units), $1\,\mathrm{GPU}=10\,\mathrm{m}^2\,\mathrm{s}^{-2}$, in a contrast to miliGals on all other figures with gravity anomalies.

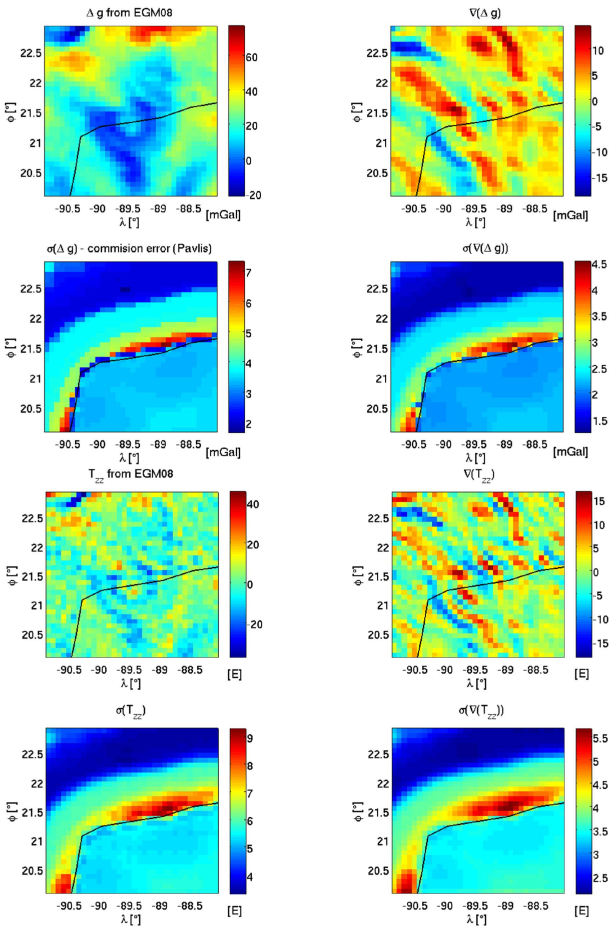

Fig. 8. **(a)** Comparison of the gravity anomaly Δg (upper left) and its gradient (upper right) with relevant $\sigma(\Delta g)$ (lower left) and $\sigma(\text{grad}(\Delta g))$ (lower right) for Chicxulub. **(b)** Comparison of the second radial derivative T_{rr} (upper left) and its gradient (upper right) with relevant $\sigma(T_{rr})$ (lower left) and $\sigma(\text{grad}(T_{rr}))$ (lower right) for Chicxulub.

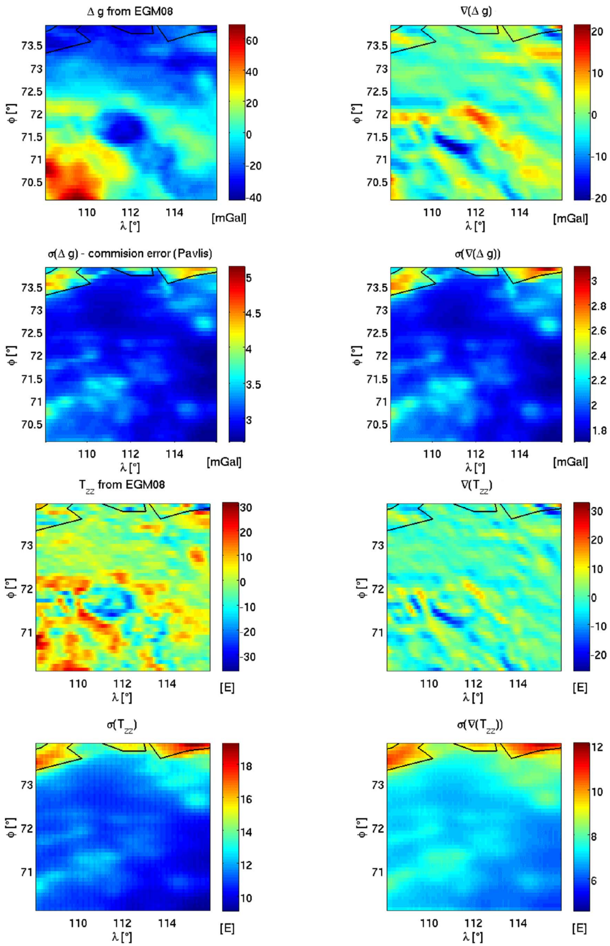

Fig. 9. **(a)** Comparison of the gravity anomaly Δg (upper left) and its gradient (upper right) with relevant $\sigma(\Delta g)$ (lower left) and $\sigma(\mathrm{grad}(\Delta g))$ (lower right) for Popigai. **(b)** Comparison of the second radial derivative T_{rr} (upper left) and its gradient (upper right) with relevant $\sigma(T_{rr})$ (lower left) and $\sigma(\mathrm{grad}(T_{rr}))$ (lower right) for Popigai.

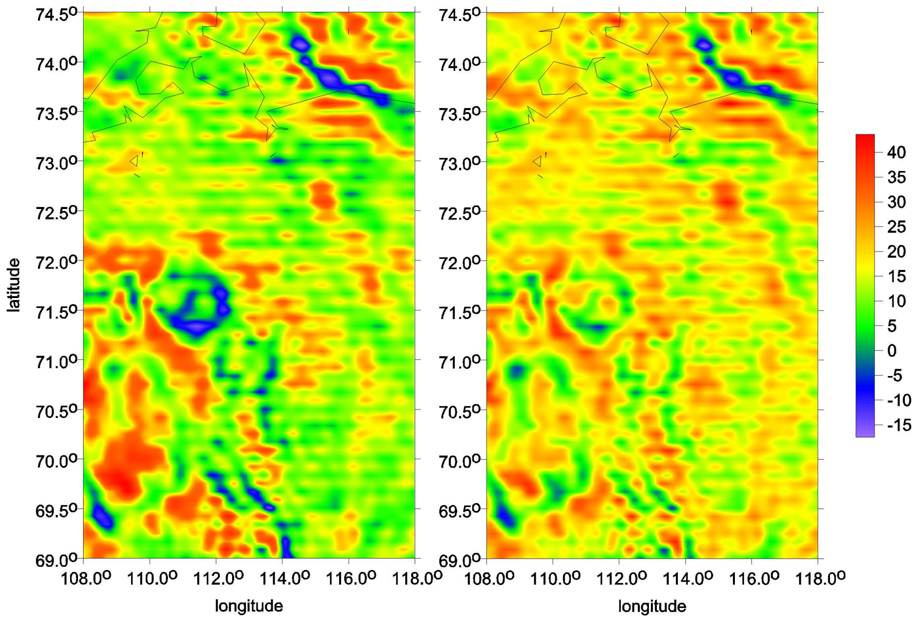

Fig. 10. The second radial derivatives without the low or lower portion of the harmonic coefficients – **(a)** (left) without those coefficients to degree and order 36, **(b)** (right) without those to degree and order 360, based on complete EGM 08.

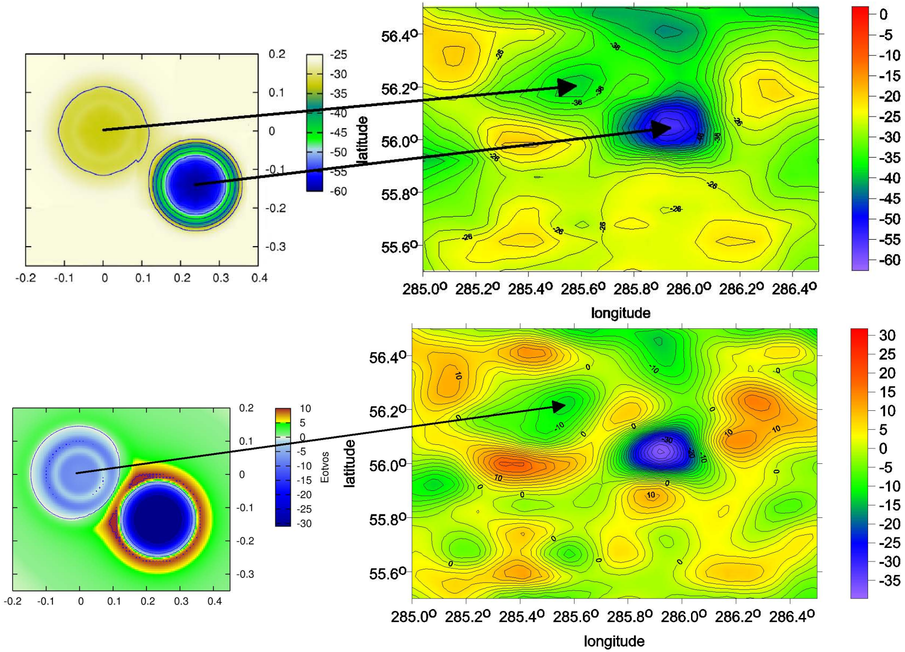

Fig. 11. **(a)** Gravity anomalies of the Clearwater double crater (in mGal) as derived from the crater model (left). Agreement with EGM 08 anomalies (right) is clearly seen. Coordinate axes, x for $\lambda \cos \varphi$ and y for φ are in degrees. **(b)** The second radial derivatives of potential, T_{rr}, of the Clearwater double structure (in mE) as derived from the model (left) and EGM 08 (right).

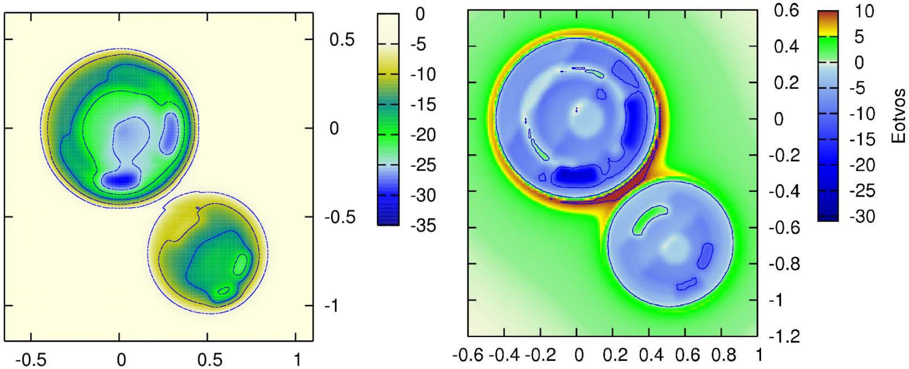

Fig. 12. (a, b) Gravity anomalies (left) and the second radial derivatives, T_{rr}, (right), of Popigai and its possible nearest companion (in mGal and Etvs, respectively) as derived from the craters model. To be comparable with EGM08 (see Figs. 2 and 3), the models were smoothed to the EGM 08 resolution. Coordinate axes, $\lambda \cos \varphi$ and φ are in degrees.

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Candidates for multiple impact craters

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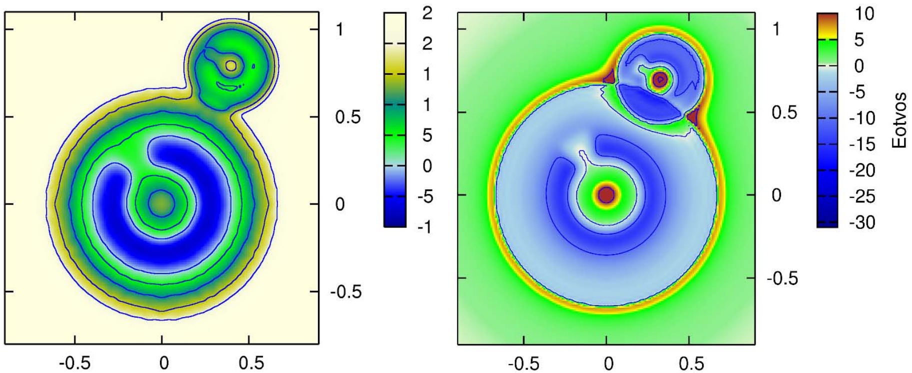

Fig. 13. (a, b) Gravity anomalies (left) and the second radial derivatives, T_{rr} (right), of Chicxulub and its hypothetic companion (in mGal and Eõtvõs, respectively) as derived from the craters model. (For EGM 08 see Figs. 4 and 5).