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DETECTION OF EARTH IMPACT CRATERS AIDED BY THE DETAILED GLOBAL GRAVITATIONAL MODEL EGM2008

Jaroslav KLOKOČNÍK [1)] *, Jan KOSTELECKÝ [2,3)], Pavel NOVÁK [2, 4)] and Carl A. WAGNER [5)]

[1)] *Astronomical Institute, Academy of Sciences of the Czech Republic, CZ-251 65 Ondřejov Observatory, Czech Republic*
[2)] *Research Institute for Geodesy, Topography and Cartography, CZ-250 66 Zdiby 98, Czech Republic*
[3)] *Department of Advanced Geodesy, Czech Technical University, CZ-166 29 Praha 6, Thákurova 7, Czech Republic*
[4)] *Department of Mathematics, Faculty of Applied Sciences, University of West Bohemia, CZ-306 14 Plzeň (Pilsen), Univerzitní 8, Czech Republic*
[5)] *NOAA, Lab. Satel. Altim., Silver Spring, MD 20910-3226, USA*
**Corresponding author's e-mail:* jklokocn@asu.cas.cz

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ABSTRACT
We have surveyed the Earth's surface using gravity anomalies and second-order radial derivatives of the disturbing gravitational potential computed from the gravitational model EGM2008 complete to degree and order 2159 (for selected degrees up to 2190). It corresponds to 5 arcmin resolution on the ground. Over most well known impact crater sites on the Earth we found the second-order derivatives (not available from ordinary gravity surveys) offered finer discrimination of circular features than the gravity anomalies themselves. We also discovered that some of the sites show evidence of double or multiple craters which will need further ground verification. Some of these signatures (in hilly or mountainous terrain) may also need to be corrected for the gravitational effect of topography to sharpen their hidden features.

KEYWORDS: global gravitational model, gravity anomaly, second-order derivative of the disturbing potential, impact craters on the Earth

1. INTRODUCTION

There are now about 175 impact meteoritic craters (also called „astroblems“ known on Earth; see, e.g., the diabase [http://www.unb.ca/passc/ImpactDatabase] of the *P*lanetary *A*nd *S*pace *S*cience *C*enter (PASSC), University of New Brunswick, Canada, where the craters are sorted by size, age, name or continent, including much additional information. PASSC presents also principal criteria for determining if a geological feature is an impact structure formed by the hypervelocity impact of a meteorite or comet (the „impactor“). There are also up to 600 other potential impact crater sites according to some authorities, see SEIS [*S*uspected *E*arth *I*mpact *S*ites; http://web.eps.utk.edu/ifsg.htm]. The largest of the data base at PASSC are listed in Table 1.

We have computed gravitational signals (gravity anomalies and second-order potential derivatives) at all localities mentioned in Table 1 and at some other promising places (see also a catalogue on www.asu.cas.cz/~jklokocn). We also compared and contrasted these signals for different volcanic areas attempting to establish some rules for impact craters in other localities (Sect. 4.3). Some of these other structures are still of uncertain origin (e.g., *Bangui* in Central Africa).

Specifically, at the selected localities we computed the free air gravity anomaly Δg and the second derivatives of the disturbing gravitational potential in the radial direction T_{rr}, (Sect. 2.2.). In some cases we computed other second derivatives (of the main diagonal of the Marussi tensor), but we usually do not present them here, because the most interesting results are seen in Δg and T_{rr} (see theory, e.g., in Sünkel, 2002, and the formulae below). In mountainous areas these parameters may require correction for topographic effects to reveal the hidden structure of the crater.

The novelty of our approach, promising new results not obtainable by scattered ground gravity surveys, is *(i)* the use of a very detailed global gravitational model EGM2008 (Pavlis et al., 2008a,b) with the spatial resolution 9 km on the equator and *(ii)* computing two anomalous parameters of the gravitational field, namely the gravity anomaly Δg and the second-order radial derivative T_{rr} of the disturbing potential (the latter is not available directly

Table 1 The largest known impact craters on the Earth. *D* is diameter of the crater (typically an estimate of original rim diameter) and *t* is its estimated age, given in millions of years B.C.E. *[My]*.
Source: www.unb.ca/passc/ImpactDatabase.

Name	**Location**	**D** *[km]*	**t** *[My]*
Vredefort	South Africa	300	2020
Sudbury	Ontario, Canada	250	1850
Chicxulub	Yucatán, Mexico	170	65
Popigai	Siberia, Russia	100	35.7
Manicouagan	Quebec, Canada	100	214
Beaverhead	Idaho, United States	100	900
Acraman	South Australia, Australia	90	590
Chesapeake Bay	Virginia, United States	90	35.5
Puchezh-Katunki	Nizhny Novgorod, Russia	80	167
Morokweng	Kalahari Desert, South Africa	70	145
Kara	Nenetsia, Russia	65	70
Woodleigh	Western Australia, Australia	60-120	364
Tookoonooka	Queensland, Australia	55	128
Charlevoix	Quebec, Canada	54	342
Siljan	Dalarna, Sweden	52	377
Kara-Kul	Pamir Mountains, Tajikistan	52	5
Montagnais	Nova Scotia, Canada	45	50
Araguainha	Central Brazil	40	244
Mjølnir	Barents Sea, Norway	40	142
Saint Martin	Manitoba, Canada	40	220
Carswell	Saskatchewan, Canada	39	115
Clearwater West	Quebec, Canada	36	290
Manson	Iowa, United States	35	73.8

from ground surveys). The second-order derivative has increased sensitivity to smaller features of the gravitational field showing greater details over the area of interest. However, it also amplifies the short-wavelength noise associated with the global gravitational model's commission errors (currently under investigation).

The gravitational signal itself may show circular or ring-like structures including changing positive and negative values of Δg or T_{rr}, but this is merely one of the indicators of an impact origin at that site. Geologic and geophysical data is needed to confirm or deny most of our suggested impact sites, such as magnetic anomalies, seismic profiles and deposits of shock-metamorphic minerals (stishovite, coesite, diamond, etc.), shatter cones, impact breccias, and shocked quartz.

2. DATA AND METHOD

2.1. DATA

The NGA (*N*ational *G*eospatial-Intelligence *A*gency) of the USA has developed the *E*arth *G*ravitational *M*odel 2008 (EGM2008, Pavlis et al. 2008a,b) intended to replace the previous solution EGM 96 (Lemoine et al., 1998). EGM2008 was developed complete to degree and order 2159 in ellipsoidal harmonic coefficients and to degree 2190 in spherical harmonics. The complete model was used to avoid problems in computations at high latitudes. A half-wavelength resolution of EGM2008 on the grand (about 9 km) is a large improvement of a combination model EGM 96 or about 150 km of recent gravitational models based solely on CHAMP (*Cha*llenging *M*inisatellite *P*ayload for geophysical research and application) and/or GRACE (*G*ravity *R*ecovery *A*nd *C*limate *E*xperiment) satellite data. The effective resolution of EGM2008 is not homogeneous around the world. It depends on the quality and resolution of available data used for its development. For example, the Antarctic region is based solely on the GRACE satellite-to-satellite data of much lower spatial resolution. In other words, the precision of the functionals of the EGM2008 coefficients is not homogeneous, as was demonstrated by figures showing commission errors for geoidal undulations and gravity anomalies in (Pavlis et al., 2008b).

To summarize, EGM2008 is a combined gravitational model: the low-frequency portion of which is due spaceborne data (from the GRACE mission) and the high-frequency part (most interesting for us) from a global gravity grid based on ground gravity and altimetry data (5 arcmin *x* 5 arcmin mean free-air gravity anomalies based on ground gravity observations over dry land and derived from satellite altimetry over the oceans). Their precision is usually (excluding a few mountainous areas and tropical and polar regions such as Antarctica) at the mGal level

(Huang et al., 2007; Pavlis et al., 2008a,b). This is also true for the commission error of the gravity anomaly computed from the EGM2008 coefficients [see methodology in Pavlis and Sale (2005)] for all localities tested in this article, excluding Antarctica. More information about the Signal-to-Noise ratio (S/N) for gravity anomalies and second-order derivatives will be presented elsewhere.

The *S*huttle *R*adar *T*opography *M*ission (SRTM) with resolution of 3 arcsec *x* 3 arcsec (and 1 arsec *x* 1 arcsec for USA and Canada) has improved tremendously our knowledge of the global topography covering about 80% of the Earth's land surface (Rabus et al., 2003). This progress in the data, satellite as well as ground, goes together with the refinement of data processing algorithms. The result is that the EGM2008 performs in some cases equally well as (or better than) detailed gravimetric products based on local ground gravity surveys thus providing a new paradigm for a variety of geosciences applications [Pavlis et al. (2008b) giving the results of the IAG evaluation team on PGM 2007 and EGM2008, in press].

2.2. METHOD

We made use of generic software for 'gravity synthesis' (Holmes and Pavlis, 2006); the program computes (among other quantities) the gravity anomalies and second derivatives of the gravitational potential. We focused on the *radial* derivatives of the disturbing gravitational potential T_{rr} that show more detail than the gravity anomaly itself (and the other second derivatives). This quantity is proportional to the mean curvature of the geoid (here represented by the set of the EGM2008 harmonic geopotential coefficients/ Stokes parameters).

The following quantities are actually computed for our applications: (1) "free-air gravity anomaly", more precisely "the spherically approximated gravity anomaly" $\Delta g = -\partial T/\partial r - 2T/r$, where T is the disturbing gravitational potential $T = V\text{-}U$ with the normal potential U represented by Geodetic Reference System 1980 (Moritz, 1984), and (2) the second derivatives of T on the main diagonal of the Marussi tensor, i.e. T_{xx}, T_{yy} and T_{rr} - namely the second radial derivative $T_{rr} = \partial^2 T/\partial r^2$, where r is the geocentric radius of a general computation point. All presented results were computed on the reference ellipsoid and on a 5 arcmin *x* 5 arcmin angular grid.

Note about the units: 1 mGal (gravity anomaly) = 10^{-5} ms^{-2}; 1 E = 1 Eötvös (second order potential derivative) = 10^{-9} s^{-2}. These units are used in all our figures for Δg and T_{rr}.

The gravity anomaly Δg is approximately equal to the first radial derivative of the disturbing gravitational potential, thus T_{rr} is approximately equal to the first-order radial derivative (radial gradient) of the gravity anomaly.

The gravity anomaly is defined through the fundamental gravimetric equation and in spherical approximation reads as follows

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

where R is radius of the Earth and $T_n(\theta,\lambda)$ is approximation of T_n (component of T) by spherical functions, n is degree of the harmonic expansion, (θ, λ) are co-latitude and longitude. $T_n(\theta, \lambda)$ are surface spherical harmonics of T:

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

where $C_{n,m}$ and $S_{n,m}$ are harmonic geopotential coefficients (Stokes parameters) from EGM2008 and $P_{n,m}$ are associated Legendre functions. Here, for EGM2008, n_{max}= 2190.

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

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

3. CHICXULUB – OUR TEST AREA

Chicxulub has an "epicenter" hidden beneath the surface at φ = 21° 20' N and λ = 270° 30' East of Greenwich, in north Yucatán, Mexico. While Hildebrand et al. (1995, 1998) estimated its diameter as 170 km based on measured gravity profiles (available at that time) and by the location of rings of cenotes, Sharpton et al. (1993) identified two more distant rings in their gravity profiles and interpreted also a 300 km-diameter crater. Figure 1a reproduces the result of Sharpton et al. (1993), in contoured Δg from the Chicxulub area. The original data came from a 1:200,000 map of gravity anomalies of Mexico; offshore data of lower precision are from the US National Oceanic and Atmospheric Administration (NOAA), onshore data from the US Defense Mapping Agency (DMA, now NGA), and Mexico's Instituto Nacional de Estadistica, Geografica e Informatica, 1990-2. These sources were not available to us so we could only compare our results from EGM2008 with those in Fig. 1a.

Figure 1b shows Δg's computed from the harmonic expansion of the complete EGM2008 with the spatial resolution of about 9 km. They compare fairly well with ground gravity data used by Hildebrand or Sharpton *(ibid)* but the new results from EGM2008 are now available worldwide with a homogeneous resolution and fairly uniform precision. Furthermore, we show the components T_{rr} (Fig. 2). The second-order derivatives T_{rr} on the ground actually disclosed many more details than the gravity anomalies and led us to the hypothesis of a double-crater. For a better perspective we also computed T_{rr} over all Mesoamerica; for T_{rr} - see Figure 3.

Figure 2 shows T_{rr} for the Chicxulub area. Two circular-like features of the Chicxulub crater are clearly visible with strong negative values of T_{rr}, a central positive part and two rings with positive anomalies. The outer ring has a diameter of 160 - 180 km. Larger but fainter and fragmented are outer "circles" of minimum and maximum gradient with a possible diameter of about 250 km. The crater is not perfectly circular.

Moreover, north-east (NE) of this main Chicxulub impact we can see a less pronounced circular-like feature, partly interfering with its outer ring. This smaller crater seems to have two rings with the diameter for the outer ring reaching approximately 100 km. It is fair to note that the existence of the second crater might have been anticipated already (but was not) in older maps of the gravity anomalies from Sharpton's paper (1993), p. 1565 (here Fig. 1a).

Figure 3 shows the radial gradient of gravity (T_{rr}) over the whole of the Yucatán (to Guatemala and Belize). The ring structures Chicxulub "I" and "II" are visible here as well, but in many places the gradient signal is much stronger than in these crater areas and is not related to any impact. Note the "waves" or "ringing" close to the sea-shore near Villahermosa may be an artifact of the spherical harmonic expansion truncated here at degree 2190 (maybe the "Gibb's effect" at sharp boundaries of a finite truncation of the infinite harmonic series of the geopotential). They can easily be distinguished from the circular features.

It is interesting and educational to compare the Chicxulub gravity signal to that of a confirmed double impact crater, namely the Clearwater Lakes in Canada. Thus we show the topographic and gravitational signals of this actual double crater in Figure 4. First, Figure 4a shows the area of the double-crater Clearwater Lakes from the Digital Elevation Model (DEM), easily visible on the surface. Then, Figure 4b displays its surface gravity gradient signal T_{rr}. The two craters are detected by EGM2008 without any problem but there are more circular structures in the area. The west crater is bigger but has an inner rim with a total signal smaller than that of the east crater. The Clearwater Lakes craters are much smaller than Chicxulub, about 30 km in diameter each; here they serve as a further test of the EGM2008 abilities and as a guide to other double or multiple impact structures.

To conclude this section: aided by the new detailed global gravitational model EGM2008, we find that the Chicxulub crater is probably larger than 170 km in diameter (that is in agreement with Sharpton and others and in disagreement with Hildebrand and others) and that it may be a double crater, as shown in Figures 1, 2, and 3; this "Chicxulub II" is a new candidate for an impact structure and we suggest an additional study (by geologists and other specialists). A detailed statistical comparison of older ground gravity anomalies (Hildebrand or Sharpton, *ibid*) with our EGM2008 results would be very beneficial to this analysis. But such a comparison requires access to older ground gravity data (in a digital form) not available to us.

4. TESTS OF SENSITIVITY OF EGM2008

4.1. METEOR CRATER IN ARIZONA AND OTHER SMALL CRATERS

We tested EGM2008 on small structures which are theoretically below its resolution. It is about 7 km for the latitude of the *Meteor (Barringer's) crater* in Arizona near Flagstaff (its diameter is only 1.2 km) and around 4 km for the crater called New Quebec (diameter 3.5 km, next example).

Our computations of the gravity anomalies Δg and of the second radial derivatives T_{rr} with EGM2008 yield (among others) the results in Figures 5a,b for the Meteor crater in Arizona. There is no anomaly at the crater itself, but there are large negative anomalies and negative values of T_{rr} (to 50 mE) west of the crater (among others). These are related to the general geology of the area so that it is very probable that the impact did not create them.

We also performed several similar tests in different parts of the world. Let us consider for example the small and young impact crater called *New Quebec* ($\varphi = 61^0 17'$N, $\lambda = 286^0\ 20'$ E), diameter only 3.5 km, age about 1.4 My and the much older crater *Couture* ($\varphi = 60^0\ 08'$ N, $\lambda = 284^0\ 20'$E), diameter 8 km, age 430 My. The smaller crater is below the EGM2008 resolution, while *Couture* is detectable (as a negative anomaly of the order of 30 E) – not shown here.

4.2. NARROW STRUCTURES - GRAND CANYON

The famous Grand Canyon (in Arizona, USA) is easily seen by EGM2008 and is in Figures 6 a,b with Δg and T_{rr}, despite being very narrow; its gravity signal is very strong.

4.3. EXAMPLE OF VOLCANOES

From various tests with volcanoes around the world, the volcanoes Popocatepetl (see arrow P) and Iztaccihuatl (I), and others near Mexico City ($\varphi = 19^0\ 22'$ N, $\lambda = 260^0\ 53'$ E) are shown in Figures 7 a,b. There are positive second derivatives T_{rr} located "in" the volcanoes, surrounded by "belts" or "rings" around them with negative T_{rr}. There are also clear differences from impact craters (generally); although both features are circular we usually see a positive anomaly at the „center" of a (raised) volcano but a negative anomaly at the (gouged out) „epicenter" of an impact crater.

4.4. NEOTECTONIC PATTERN OF LAKE BAIKAL

We can observe - in Figures 8 - the Lake Baikal area as a strong and prolonged negative anomaly. There is an interesting feature NW of the Lake Baikal; it is a circular-like structure diameter about 120 km.

5. GRAVITY SIGNAL OF OTHER KNOWN IMPACT CRATERS AS REVEALED BY EGM2008 AND NEW CANDIDATES FOR IMPACT CRATERS

5.1. VREDEFORT AND SUDBURY – VERY LARGE AND VERY OLD

Vredefort (Fig. 9) and *Sudbury* (Fig. 10) belong to the largest but also the oldest impact craters (Table 1). They have been severely altered by Earth processes so we can expect that the present-day gravitational information will reflect the result of these processes as well (e.g. fragmented or incomplete rings). The second-order derivatives T_{rr} for the *Vredefort Dome* (φ = 270° 01' S, λ = 270° 30' E) are shown in Figure 9, those for the *Sudbury Basin* on the Canadian Shield (φ = 46° 36′ N, λ = 278° 49′ E) in Figure 10.

There are more circular-like structures in the area of Sudbury which might be (without additional geo-information) misinterpreted as "craters". Adjacent to the main oval, NE of it, is a smaller and much younger *Lake Wanapitei Meteorite Crater*. The close proximity of these two impact features is strictly coincidental (www.meteoritelabels.com/Astrobleme.html).

5.2. POPIGAI

Popigai (φ = 71°39'N, λ = 111°11'E) is a very large impact structure, (diameter about 100 km and age only 36 My) located in Siberia near a seashore, on an old Siberian platform. Popigai is the best example yet of the formation of an impact crater of this type visible on the surface, (Fig. 11a). Three other craters are larger, but they are either buried (Chicxulub), strongly deformed (Sudbury), or deformed and severely eroded (Vredefort). At Popigai the shock pressures from the impact instantaneously transformed graphite in the ground into diamonds within a 13.6 km radius of ground zero. Coesite and stishovite are also present there (www.mines.edu/academic/geology/faculty/klee).

We present Δg (Fig. 11b) and T_{rr} (Fig. 11c) as computed with EGM2008. The crater Popigai is clearly visible as a negative anomaly with a small central peak; moreover, in the SE direction there appears to be one or more slightly smaller circular structures which may also be impact craters. We label the original Popigai as "Popigai I" and the new candidates for impact craters as "Popigai II", "III", and "IV".

Maps with terrestrial gravity anomalies for Popigai, but only covering its nearest surroundings, can be found in Masaitis et al. (2005) and Pilkington et al. (2002). The existence of the second crater SE of „Popigai I" might have been anticipated (but was not) already from these older terrestrial data, which do not show the sites we label as Popigai II, III and IV from the EGM2008 survey.

5.3. MANICOUAGAN – A DOUBLE CRATER?

This is one of many large craters on the territory of Canada. It is very large, a diameter of about 100 km, and its age is approximately 214 My. *Manicouagan Reservoir (*also *Lake Manicouagan*) is an annular lake in central Quebec (φ = 51° 23' N, λ = 291° 18' E), see Figure 12a. Mount Babel is interpreted as the central peak of the crater (see the web page below).

Figures 12 c, d exhibit Δg and T_{rr} as computed by EGM2008 for Manicouagan over a wider area, where two other impact craters are known. Zoomed-in images of Manicouagan are shown in Figures 12b and 12e.

The crater Manicouagan is perfectly modeled by the gravity anomalies and second-order derivatives from EGM2008 with negative values at a river valley surrounding the central part of the impact structure, then positive inward and outward from the valley. It is possible that an additional crater is located north of the original Manicouagan. Without having additional geological and geophysical data, this is a hypothesis only. We take "Manicouagan II" as a crater candidate and postulate a *double crater Manicouagan I and II.*

The impact craters *Charlevoix* (φ = 47°32'N, λ = 289°42'E) and *Montagnais* (φ = 42° 53'N, λ = 296° 47' E) are smaller than Manicouagan, the former, located in Quebec, is exposed at a river bank, the latter in Nova Scotia is below the surface, with ~ 54 km and 45 km diameters, and ages 342 and 50 My, respectively. In both localities drilling took place (confirming their impact nature). We do not know why Charlevoix is easily visible in the EGM2008 gravitational data while Mantagnais is not.

5.4. PUCHEZH-KATUNKI - A DOUBLE CRATER?

The crater at *Puchezh-Katunki,* Russia (φ = 56° 58'N, λ = 43° 43' E), Fig. 13a, is not exposed at the surface (it appears as a variation in the vegetation). It has a diameter of about 80 km and the age is estimated to be 167 My. Its gravitational signals are shown in Figures 13 b,c. The crater is visible but hardly would be detectable without having additional geoinformation. It appears to be a good candidate for another double crater.

5.5. CHESAPEAKE BAY

The *Chesapeake Bay* (φ = 37° 17' N, λ = 283° 59' E) impact structure in Virginia, USA, is not visible on the ground; it is buried 300-500 m beneath the lower part of the Chesapeake Bay and its peninsulas (e.g., Powars, 2000). It has a total diameter of about 90 km and an age of only 35.5 My. One of the most unusual features associated with this submarine structure is a field of 23 inferred secondary craters. In age, size, and morphology, the Chesapeake Bay complex is very similar to Popigai's.

Figures 14 a,b,c exhibit Δg (Fig. 14a with EGM2008 anomalies compared to Fig. 14b with ground anomalies) and T_{rr} (Fig. 14c) based on the complete EGM2008 model of that area. There are stronger anomalies in the close surroundings than those due to the crater itself. The gravity anomalies are not too distinct. This buried crater-structure and many others (see Sect. 5.8. and further text) will need a more detailed inspection including the removal of the topographic effects from the signals.

5.6. KARA – ONE CRATER CONFIRMED

Kara is located in Nenetsia, Russia (φ = 69° 06' N, λ = 64° 09' E), at the seashore, almost buried in the flat tundra topography (Fig. 15a), diameter about 65 km, age about 70 My. Actually, two craters have been suggested (see references in Raitala et al. (2003)). However, ground gravity data (Raitala et al., 2003) support only one crater with a positive central anomaly surrounded by a negative anomaly circle which coincides with many of the impact outcrops. Using EGM2008, we confirm one crater, see Figures 15 b,c.

5.7. ARAGUAINHA

The impact crater *Araguainha* can be found in Central Brazil, South America (φ = 16° 47′ S, λ = 307° 01′ E), diameter about 40 km, age about 244 My. It is a complex crater with annular and radial faults, exposed to the surface and eroded, and crossed by the Araguaia River. Figures 16 a,b show our EGM2008 results (T_{rr} on the right). We can recognize the central uplifted core as a small positive anomaly surrounded by a fragmented negative inner and positive outer ring.

5.8. OTHER EXAMPLES

At some localities the gravitational signal due to the impacts (at known crater sites) is too weak or disturbed to be convincing. Without knowledge we would not be able to discover a crater there just from T_{rr} or even only from Δg.

Beaverhead (φ = 44° 36'N, λ = 113° 00'W). We compared a Bouguer gravity anomaly map of the region (www.unb.ca/passc/ImpactDatabase) with our EGM2008 values of Δg and T_{rr}. We do not see the crater in the "right place", but shifted southwest; the crater looks much larger with our results (Fig. 17). There are also interesting "strips" of Δg and T_{rr} in the area due to mountains and valleys.

Acraman (φ = 32° 01' S, λ = 135° 27' E), *Tookoonooka* (φ = 27° 07' S, λ = 142° 50' E) and *Woodleigh* (φ = 26° 03' S, λ = 114° 39' E), are three examples from around twenty five impact craters known in *Australia.* The deeply eroded crater *Acraman* in South Australia is outstanding in the EGM2008 gravitational signal. On the contrary Tookoonooka and Woodleigh (which is entirely underground) are faint.

The *Bedout* structure in the Canning Basin off the coast of Western Australia, has been cited as one of the *possible impacts* that contributed to one of the greatest extinction events known in the world (http://home.alphalink.com.au/~dannj). This area needs more detailed inspection using EGM2008 as well as topographic corrections.

The *Morokweng* impal crater (φ = 26° 28′ S, λ = 23° 32' E) is buried beneath the Kalahari Desert near the town of Morokweng in the Northwest Province of South Africa. Its 70 km diameter would be easily detected if the gravitational signal were not obscured by other effects. We confirm that it exhibits as a negative anomaly or negative second-order derivatives surrounded by positive circular-like features (see Fig. 18). However, the rims cannot be distinguished.

The crater *Kara-Kul* in Tajikistan (φ = 39° 01'N, λ = 73° 27'E) with the lake and complicated surrounding mountains has a negative anomaly clearly correlating with the area of the lake, a positive central „peak“ and a positive outer rim.

The impact crater *Siljan Ring (Siljansringen)* in Dalarna, Sweden (φ = 61° 02' N, λ = 14° 52' E), is one of many impact craters in Northern Europe (22 structures of an impact origin and about 50 others which lack sufficient impact evidence are located in Fennoscandia), see Pesonen (1996). Siljan is seen as a negative Δg and T_{rr} field with a small positive central peak. Two huge structures are proposed to be the impact craters, *Lycksele* in northern Sweden, diameter 120 km, and *Valga* in Latvia/Estonia, diameter ~ 180 km (Pesonen, 1996). Our EGM2008 computations were not too successful in supporting their existence. Topographic corrections will be applied in further investigations.

The crater *Mjolnir* (φ = 73° 48' N, λ = 29° 40' E) is hidden under the bottom of the Barents Sea, Norway; its diameter is about 40 km. This crater was discovered by oil prospectors, like Chicxulub was. With EGM2008, it exhibits a faint "gravitational signal".

6. SOME SUSPECTED IMPACT CRATERS

6.1. BANGUI (Φ = 6° N, Λ = 18° E)

There is a long-term discussion about the *Bangui* structure in Central Africa, famous for its enormously large magnetic anomaly (described by data from satellite missions Magsat and CHAMP). For the first time *Bangui* was recognized as an impact crater by Gindler et al. (1992). However, since that time opinions have varied such as: "The Bangui magnetic anomaly is not of impact origin" (DeCarli et al., 2002) or "The large meteorite impact origin of the satellite-altitude Bangui magnetic anomaly: additional evidence" (Ravat et al., 2002). Our computations of Δg and T_{rr} with the complete EGM2008 (Figs. 19 a,b) point to an impact crater, because there is a tendency to circularity namely in Figure 19b and a trend to (fragmented) rings, as at some other (old) impact sites.

6.2. SUSPECTED IMPACT CRATER AT WILKES LAND, ANTARCTICA (Φ = 70° S, Λ = 120° E)

Ralf von Frese reported in 2006 of a hypothetical giant crater beneath the *Wilkes Land* ice sheet in Antarctica as a *mascon* (mass concentration). The team from Ohio State University based this hypothesis on gravity measurements derived from the GRACE data, identified a 300 km wide mascon and noted that this mass anomaly is centered within a larger ring-like structure visible in radar images. There are alternative explanations for this mascon, such as formation by a mantle plume or other large-scale volcanic activity.

With EGM2008, we cannot decide this question because this model for the region of continental Antarctica is based only on the GRACE data, without any ground or altimetry-based anomalies (Pavlis et al., 2008 b). The half-wavelength resolution there is about 40 km but precision much lower than in many other parts of the world.

Figure 20a shows where the Wilkes Land is in Antarctica and Figures 20 b,c show the relevant gravity signal based on EGM2008. Indeed, in the vicinity of φ = 70° S, λ = 118° E, there is a positive anomaly surrounded by inner negative and outer positive rings, both fragmented. There are, however, many such places where the gravity signal indicates quasi-circular structures which are not of impact origin.

7. CONCLUSIONS AND PROSPECTS

We contributed to an evaluation of the quality, accuracy and reliability of EGM2008 (Pavlis et al., 2008 a,b) with a 5-arcmin angular resolution derived from satellite (GRACE and altimetry) and ground gravity data. We rely mainly on the second-order derivatives of the disturbing gravitational potential those are not available from ground surveys. With these values we see the signatures of some well known impact craters on the Earth where in some cases only scattered ground gravity anomalies were available in the past. We have not made a statistical evaluation of our results with ground survey data because currently we have only limited access to most of it.

EGM2008 makes prospecting for new impact (or other) craters on Earth a promising 'virtual' activity. With this prospect, in a preliminary and empirical survey, we suggest some new candidates for impact craters which should be further studied by geologists to prove or reject our suggestions. In some cases they are seen by EGM2008 as multiple craters closely connected to the well known sites (of proved impact craters). These suggested 'multiples' are: *Chicxulub, Manicouagan,* and *Puchezh-Katunki*, where we propose double craters, and *Popigai*, where more craters might be the case. We also favor an impact origin at the suspected crater sites in Bangui (central Africa).

The apparent tendency towards terrestrial "double craters" should stimulate astronomers to explain them due either to the disintegration of the impactor near the Earth (from internal weakness under the forces of atmospheric drag) or alternatively due to the impactors travelling in tandem or close groups.

In the future, with data from the ESA gradiometric mission GOCE (Gravity field and steady-state Ocean Circulation Explorer) and new ground gravity data, further improvement of the detailed geopotential models can be expected to enhance the quality of this crater search.

ACKNOWLEDGMENTS

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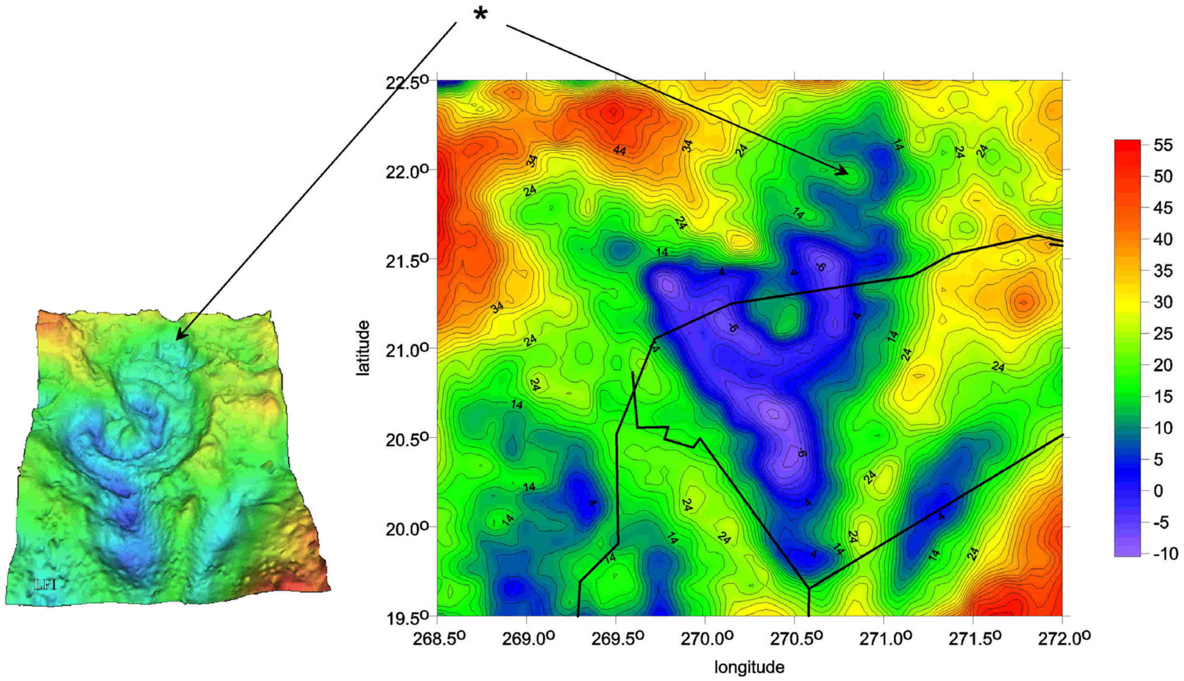


Figs. 1a,b The gravity anomalies Δg *[mGal]* from terrestrial data (left, reproduced from Sharpton et al. (1993), the gravity anomalies Δg *[mGal]* (right) based on complete EGM2008 model for the area of Chicxulub. Possible second crater (see the arrow above for position of Chicxulub II *).

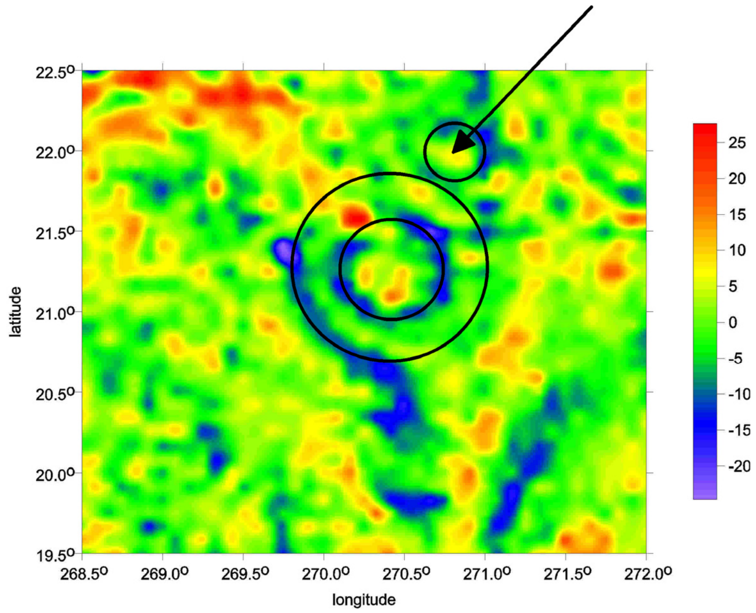


Fig. 2 Second derivatives T_{rr} computed by complete EGM2008 for $h = 0$ km; scale *[E]*. Arrow shows center of possible second crater.

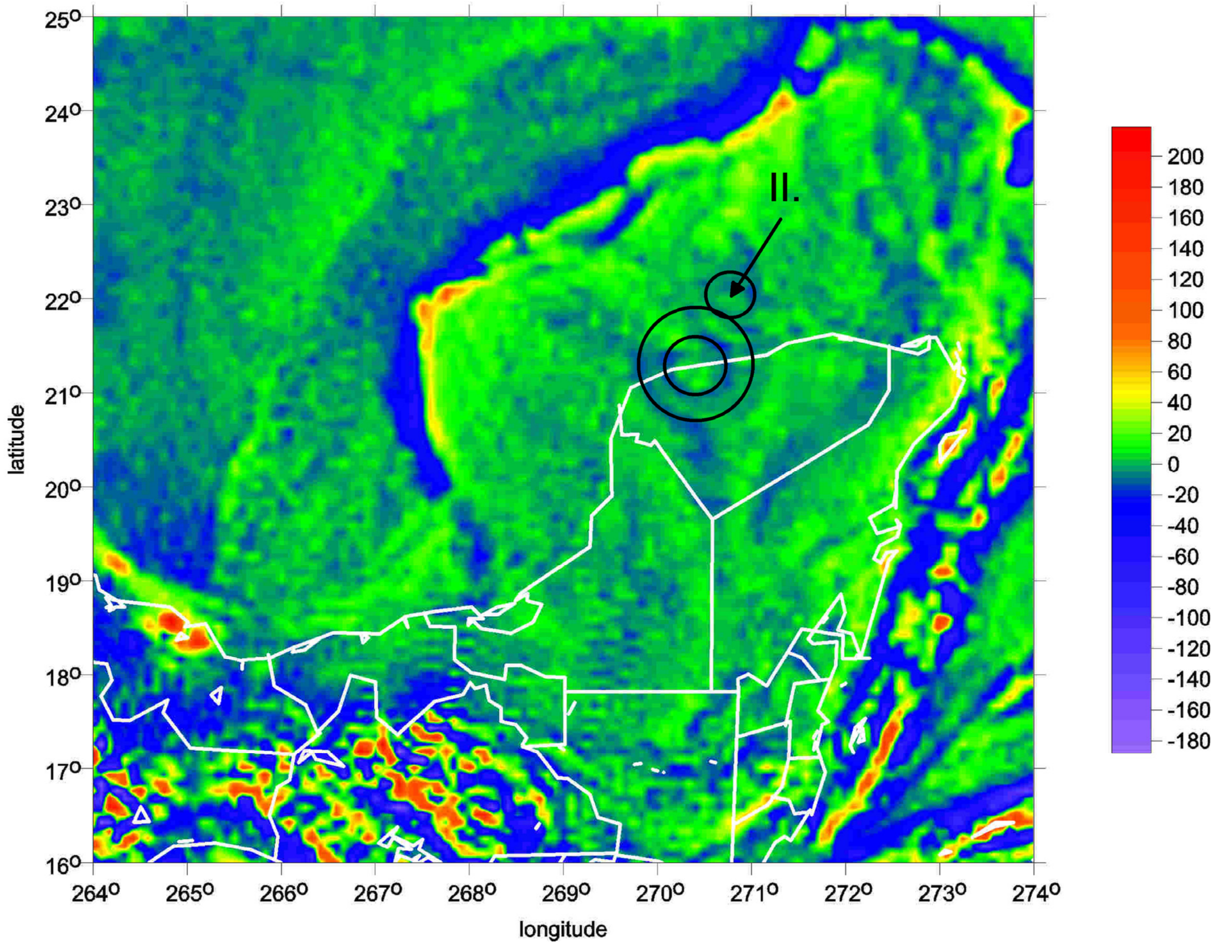
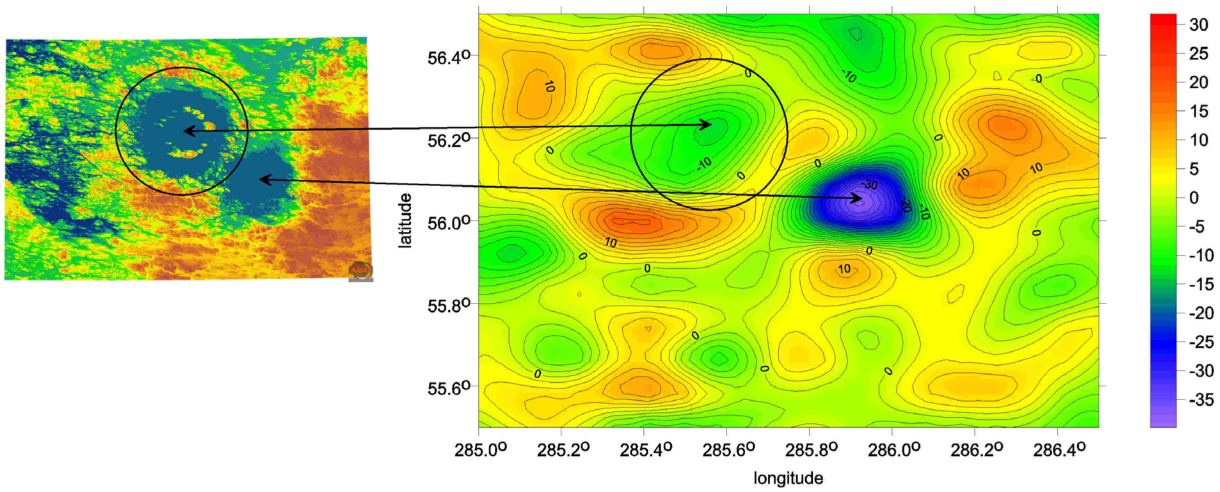
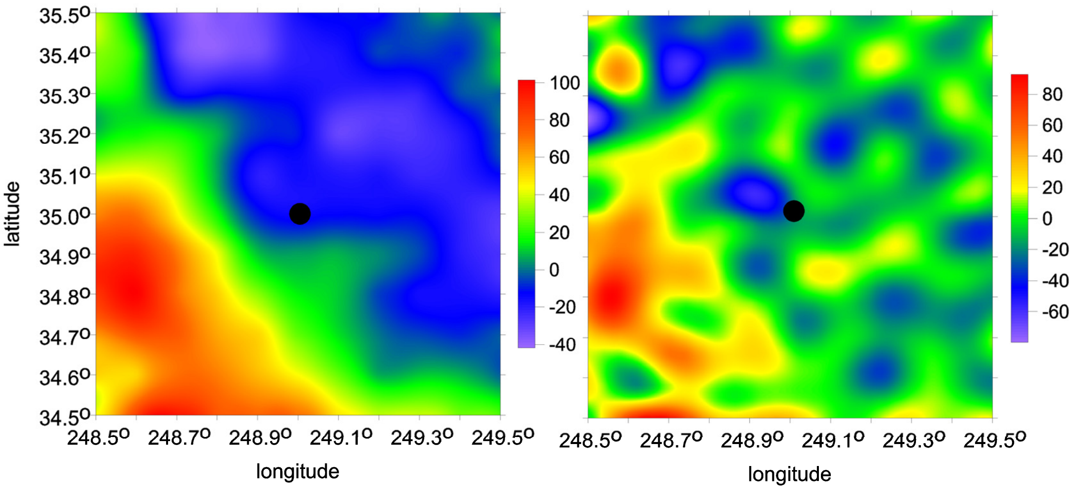


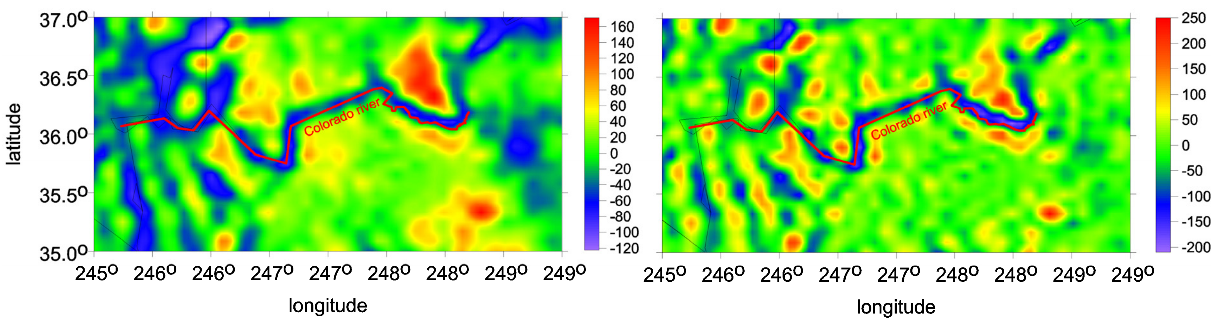
Fig. 3 Second derivatives of the geopotential represented by EGM2008 in the vertical direction, T_{rr} *[E]* in parts of Exico, Belize and Guatemala. Note the crater or a double-crater Chixculub on north Yucatán, Campeche Bank with pronounced gravity anomalies north and east of Yucatán, and the artifacts of EGM2008 ("waves" or "ring-like" patterns between the mountains on the soouth and the sea shore near Villahermosa).



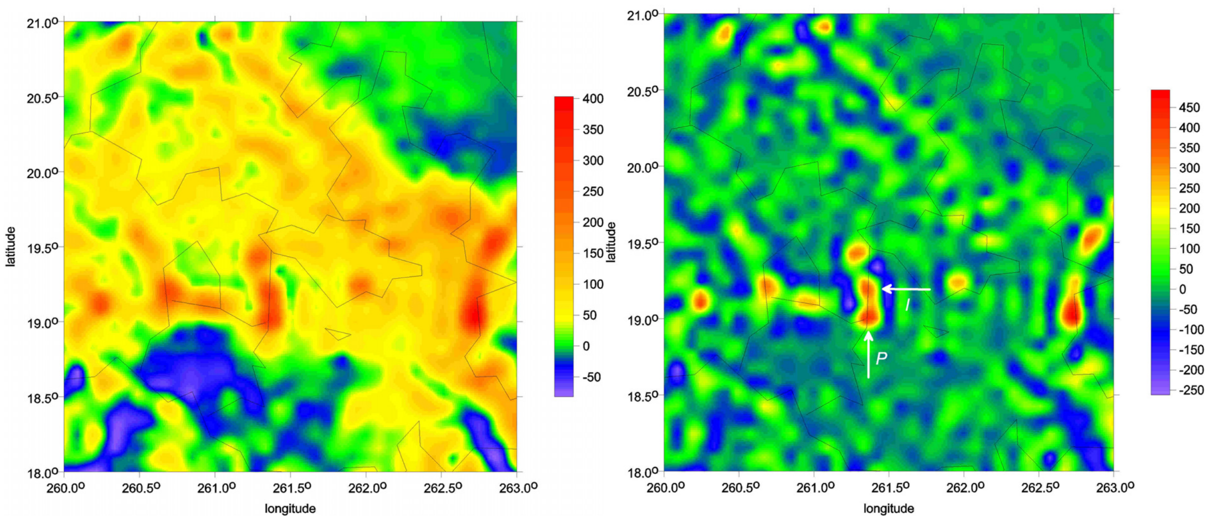
Figs. 4 a,b Double-crater Clearwater Lakes (left) as seen from Space Shuttle. Location: Quebec, Canada (φ = 56° 08′ N, λ = 285° 42′ E), surface area 1383 km², second derivatives of the geopotential (right) represented by EGM2008 in the vertical direction T_{rr} *[E]*.



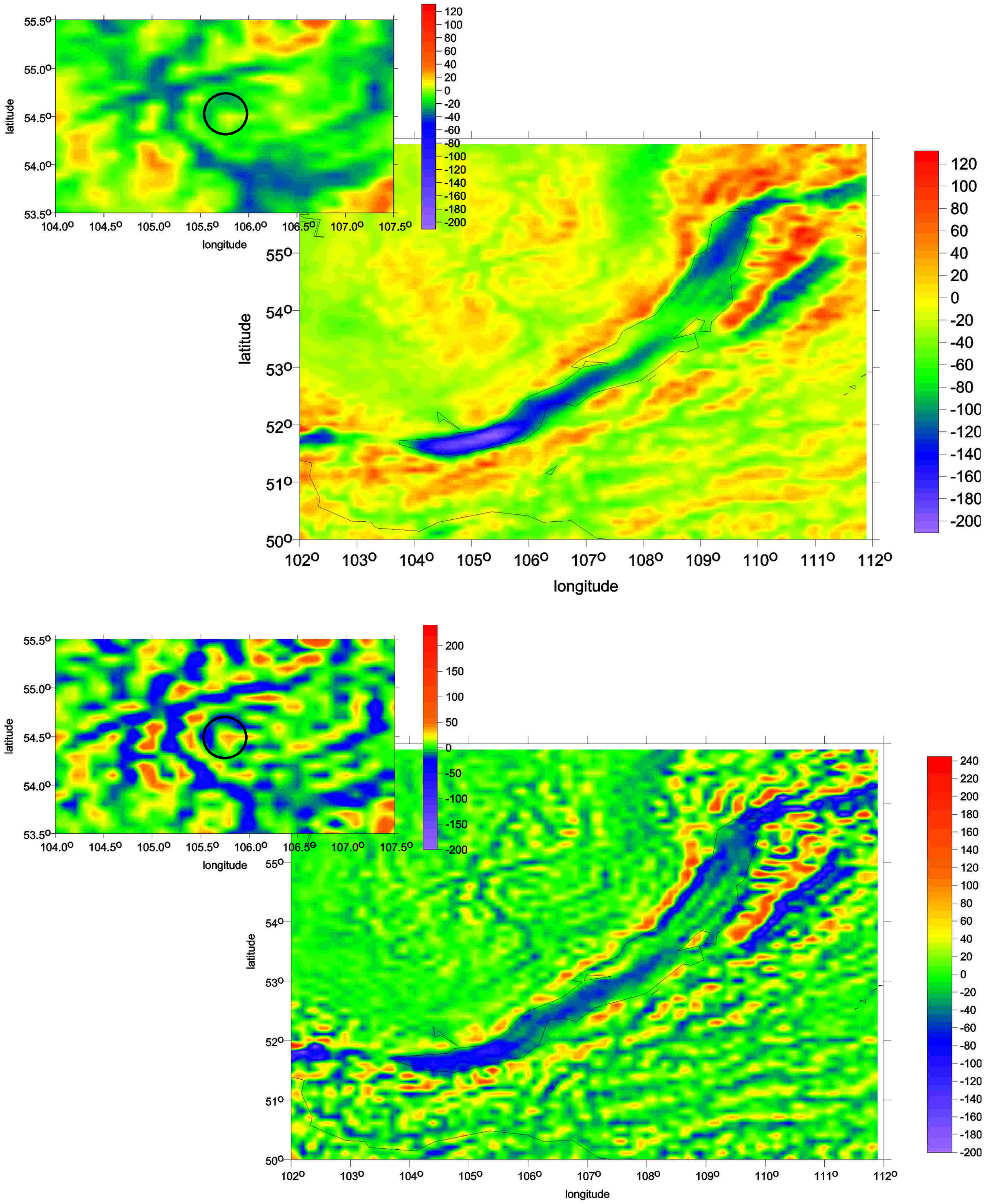
Figs. 5 a,b The gravity anomalies Δg *[mGal]* (left) and of the radial second derivatives T_{rr} *[E]* (right) with EGM2008 around the Meteoritic crater in Arizona.



Figs. 6 a,b Gravity anomalies Δg *[mGal]* (left) and the radial second derivatives T_{rr} *[E]* (right) with model EGM2008 to degree and order 2190 for the area of the Grand Canyon, AZ, USA.(Colorado river is shown by red lines).



Figs. 7 a,b Gravity anomalies Δg *[mGal]* (left) and the radial second derivatives T_{rr} *[E]* (right) with EGM2008 for the area of the volcanoes Popocatepetl (5426 m), Iztaccihuatl (5230 m), Matlalcueitl (4412 m) and Citlalepec (5636 m) - all stand 2000-3000 metres above Mexico City and are 30-40 km across.



Figs. 8 a-d showing Δg *[mGal]* (upper) and T_{rr} *[E]* (down) in the Lake Baikal area, Irkutsk, Russia, with an interesting circular-like structures west of the lake.

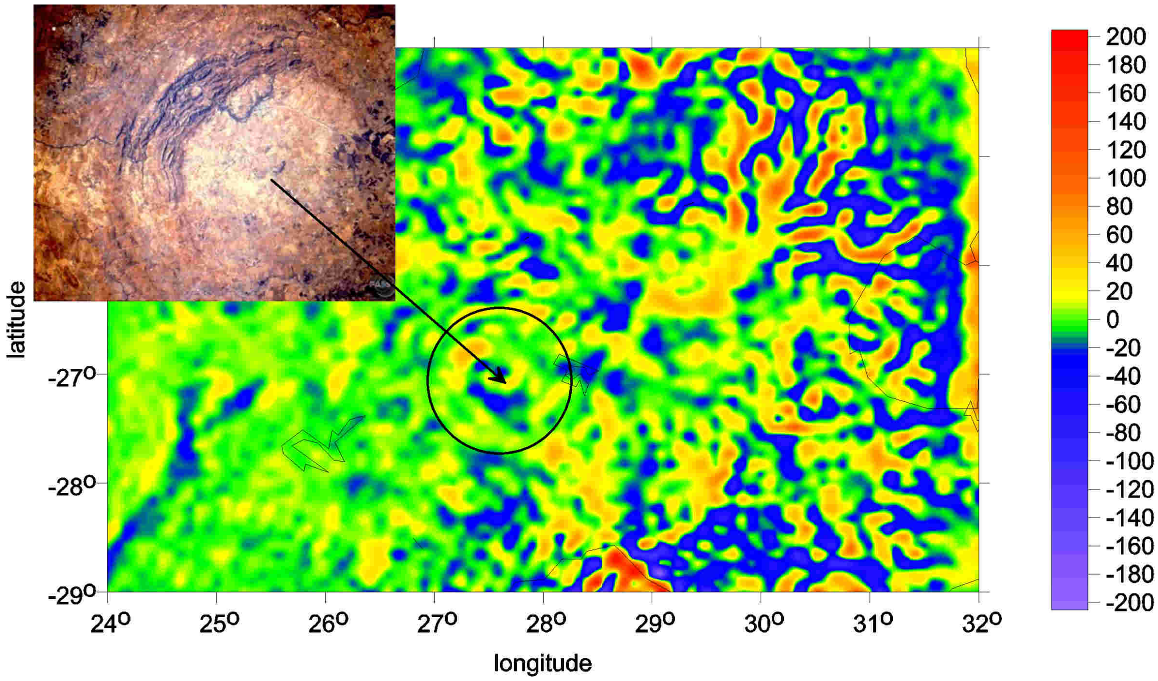


Fig. 9 Information about Vredefort from http://geology.com/articles/vredefort-dome.shtml and www.unb.ca/passc/ImpactDatabase/. Image on left: NASA Landsat. and the radial second derivatives T_{rr} *[E]* with EGM2008 in the area of the Vredefort Dome in South Africa.

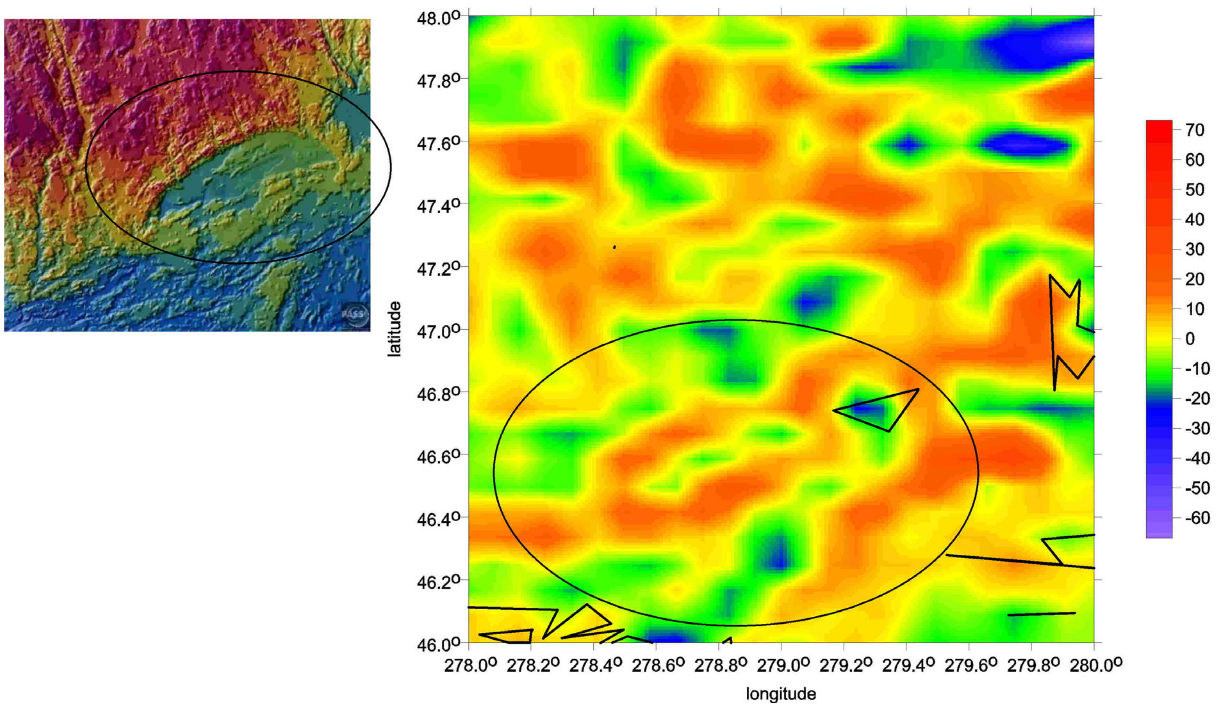
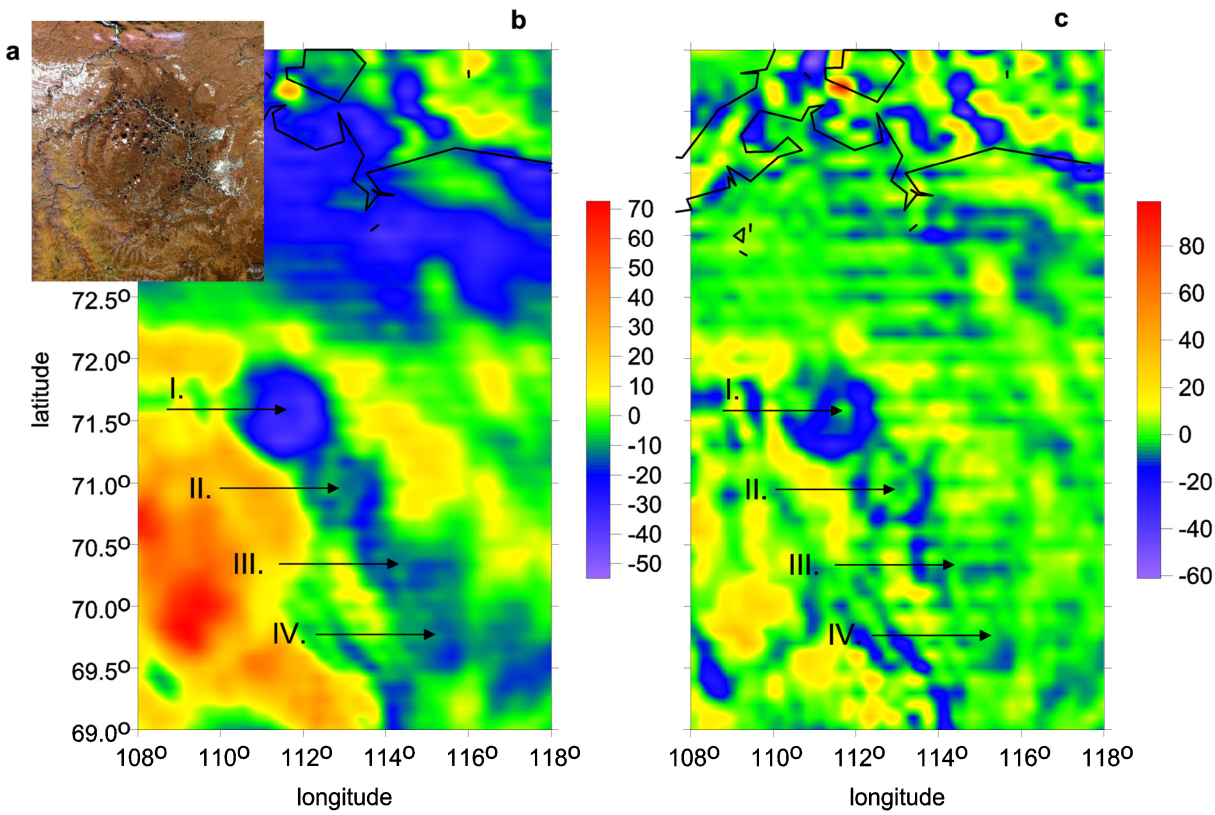


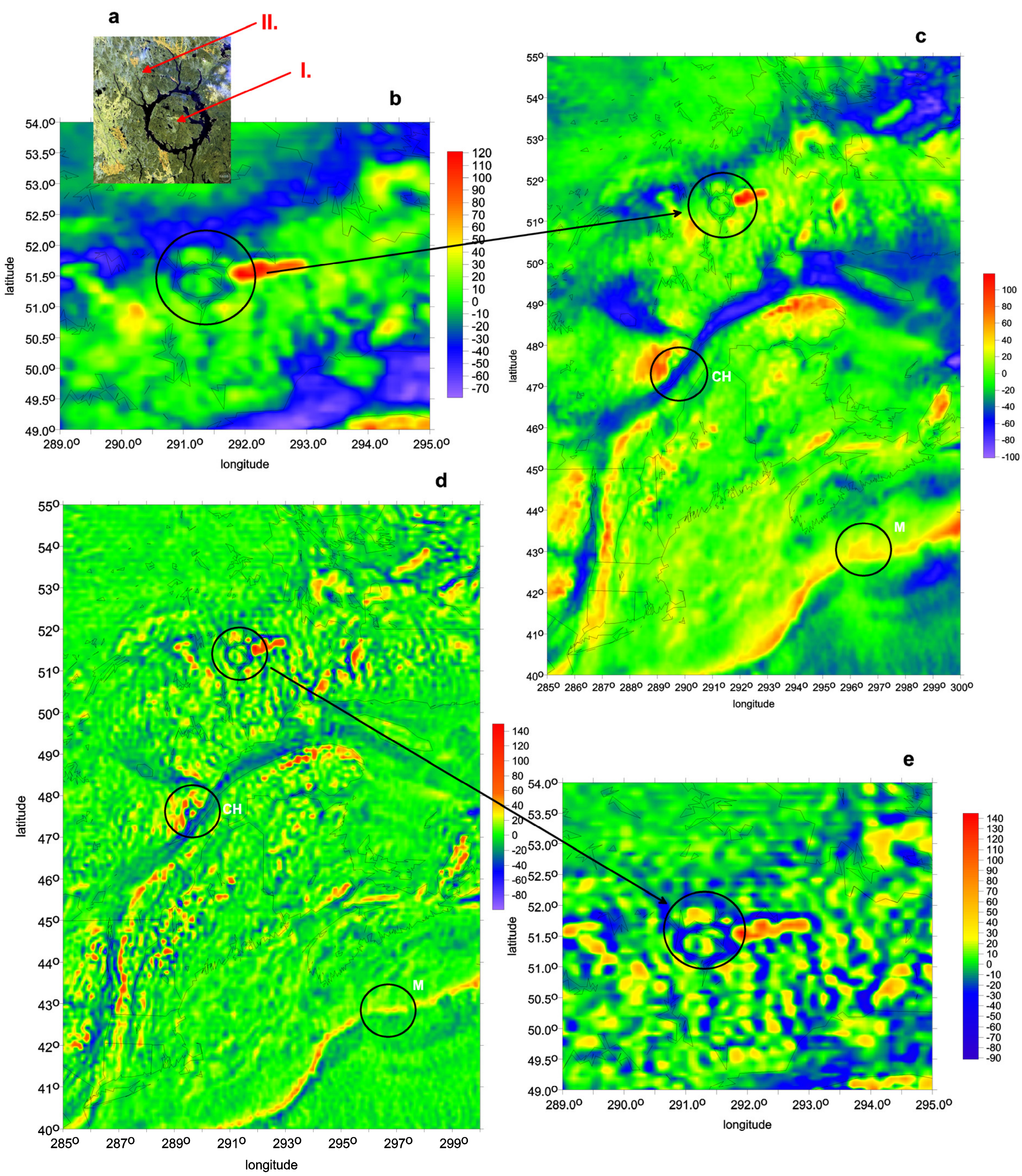
Fig. 10 Information about Sudbury from www.unb.ca/passc/ImpactDatabase/ and the radial second derivatives T_{rr} *[E]* with EGM2008 in the area of Sudbury, Ontario, Canada. (Polygons mean simplified boundaries of lakes).



Figs. 11 a-c a) Popigai impact structure, Siberia, Russia, www.unb.ca/passc/ImpactDatabase/, Landsat image.

b) The gravity anomalies Δg *[mGal]* modelled by EGM2008 at Popigai, Siberia, Russia. The original crater Popigai I, plus possible other impact craters II, III, IV connected with it, lined up from NW to SE.

c) The radial second derivatives T_{rr} *[E]* using EGM2008 at Popigai, Siberia, Russia. Not only one crater is seen, but more circular-like structures II, III, IV, candidates for impact craters, less pronounced than the original crater, but visible in the SE direction from the original one.



Figs. 12 a-e a) Manicouagan impact crater and the annular lake from Landsat 7, by R.W.Hayes, USGS, www.unb.ca/passc/ImpactDatabase, b) and c) the gravity anomalies Δg *[mGal]* and d) and e) the radial second derivatives T_{rr} *[E]* with the complete EGM2008, around the Manicouagan impact zone, Ontario, east Canada. The hypothesis is that this is a double impact crater. The other craters in this area are Charlevoix (CH) and Montagnais (M).

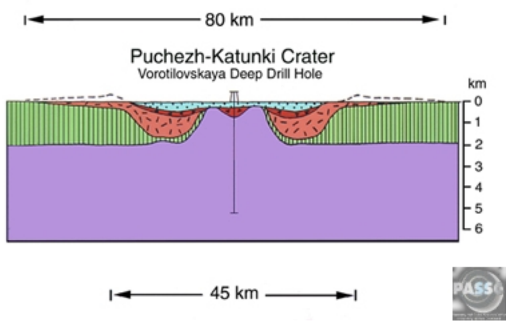
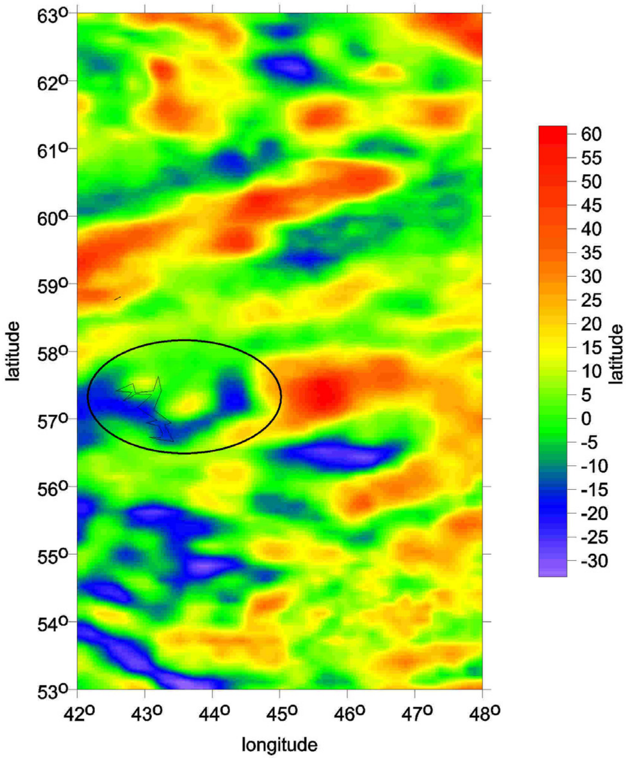
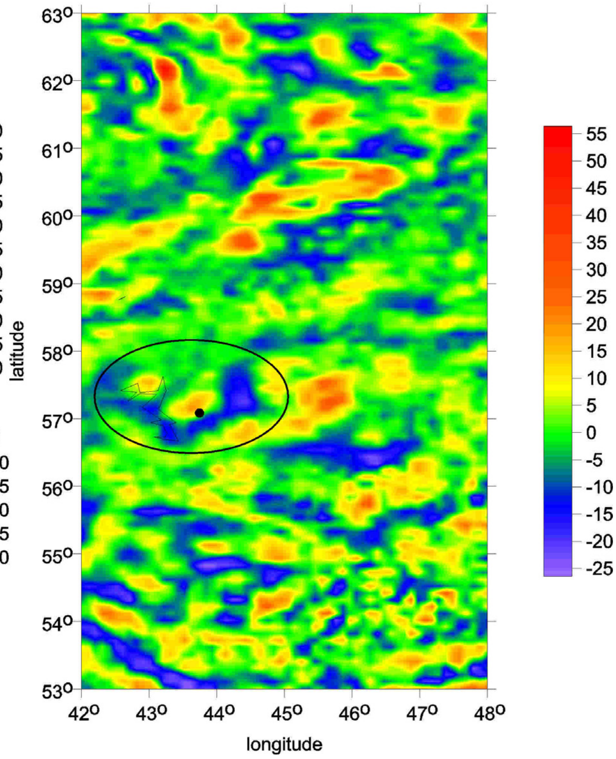


Fig. 13 a Information about the locality Puchezh-Katunki (Nizhny Novgorod, Russia) from www.unb.ca/passc/ImpactDatabase/.

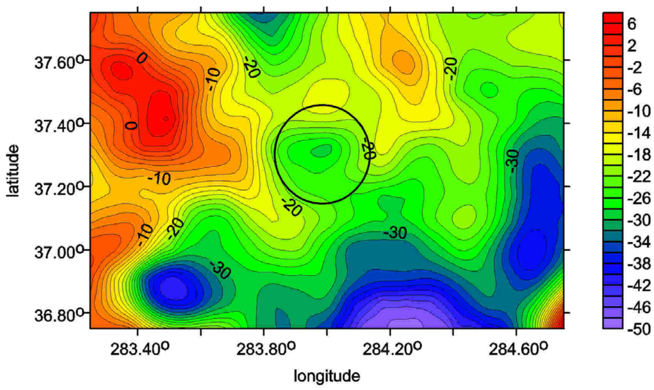


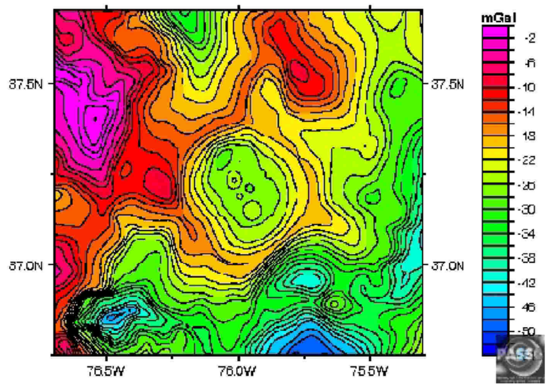
b



c

Figs. 13 b,c The gravity anomalies Δg *[mGal]* (left) and the radial second derivatives T_{rr} *[E]* (right) with EGM2008 for the impact crater(s') at Puchezh-Katunki (Russia). May be there are two craters together.





Figs. 14 a,b Comparison of Δg from EGM2008 (left) with terrestrial Δg, both in mGals, for the Chesapeake Bay complex, the latter are from www.unb.ca/passc/ImpactDatabase/images/chesapeake.html.

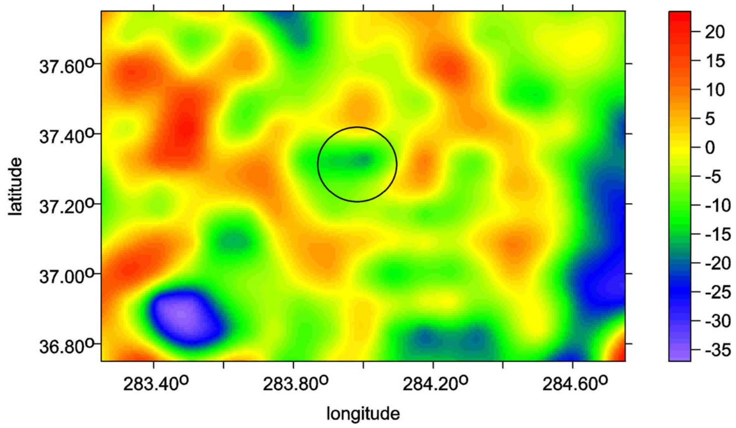
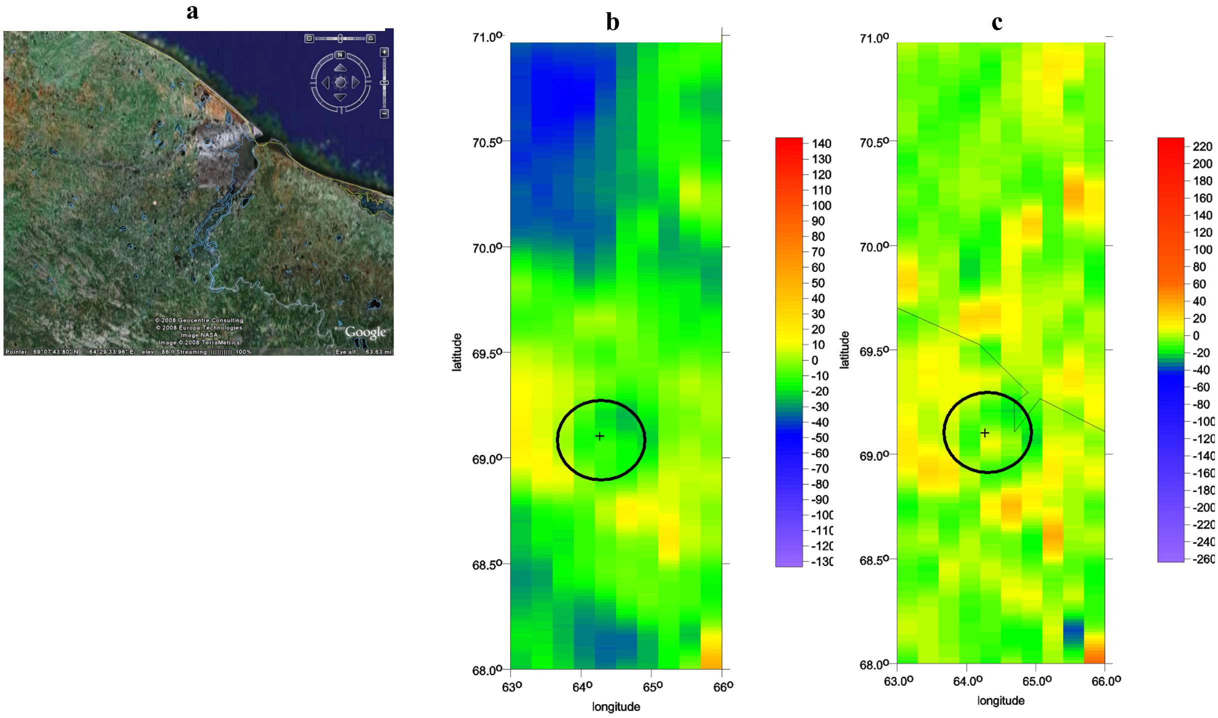
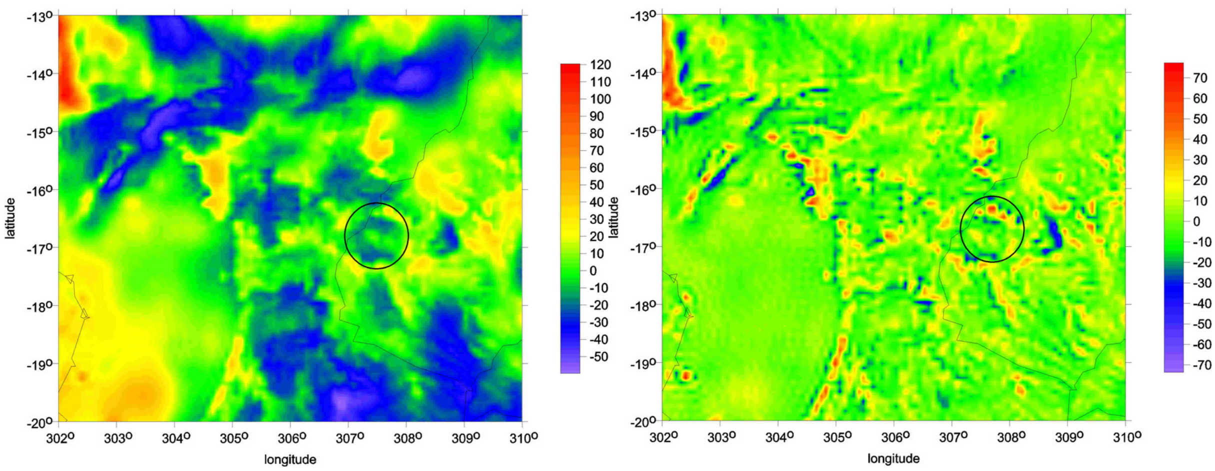


Fig. 14 c The radial second derivatives T_{rr} *[E]* with EGM2008 for the hidden impact crater in Chesapeake Bay, VA, USA.



Figs. 15 a-c Locality Kara, Russia, from Google Earth (left). The gravity anomalies Δ*g [mGal]* (middle) and T_{rr} *[E]* (right) with complete EGM2008 for the impact crater Kara.



Figs. 16 a,b The gravity anomalies Δ*g [mGal]* (left) and T_{rr} *[E]* with EGM2008 for the impact crater *Araguainha* (right).

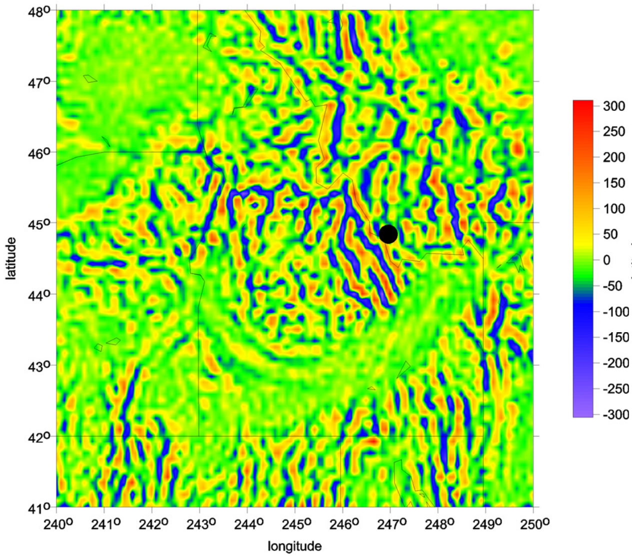


Fig. 17 The values of T_{rr} computed by EGM2008 for the area of Beaverhead, Idaho, USA.

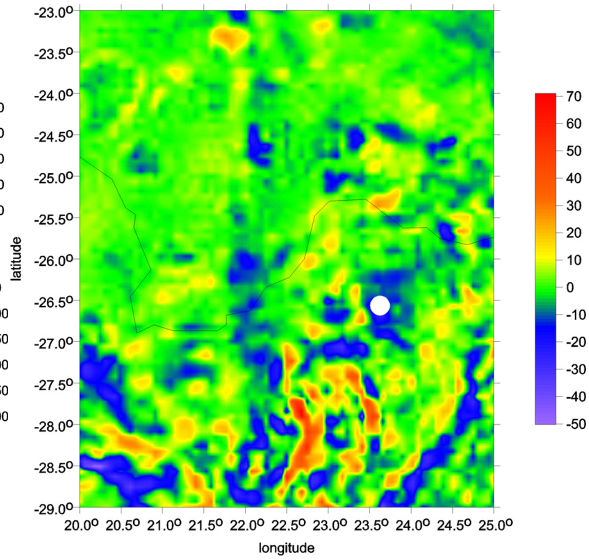
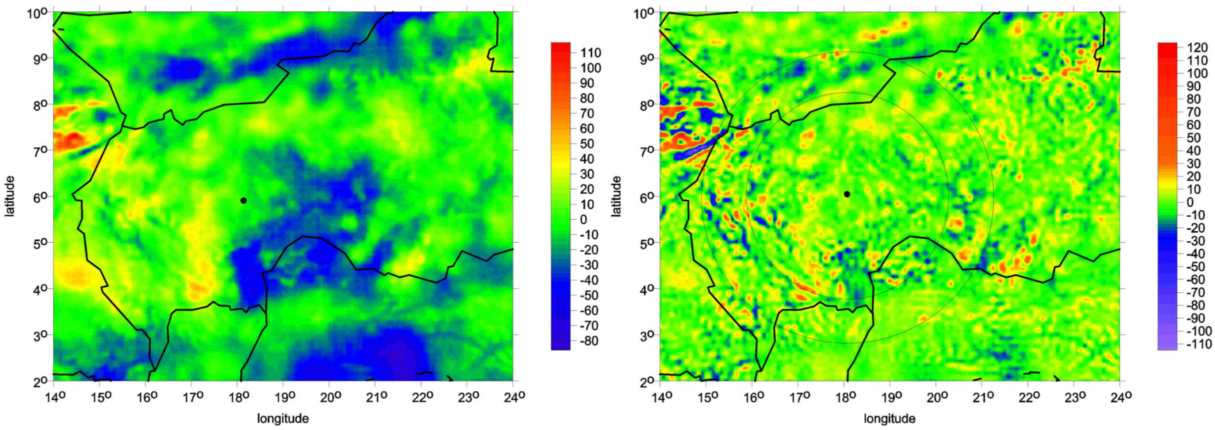


Fig. 18 The values of T_{rr} with EGM2008 for the impact crater at Morokweng (φ = 26° 28′ S, λ = 23° 32’ E), the Kalahari Desert, South Africa. Scales in *[E]*.



Figs. 19 a,b The gravity anomalies Δ*g [mGal]* (left) and T_{rr} *[E]* with EGM2008 (right) for the area of the Bangui magnetic anomaly, Central Africa.

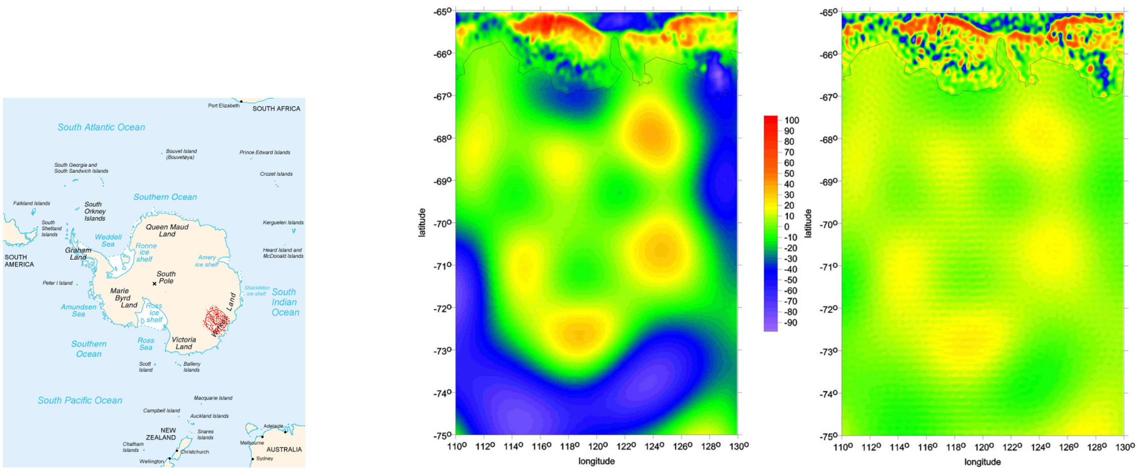


Fig. 20 a-c Location of Wilkes Land in Antarctica. (left) the gravity anomalies Δ*g [mGal]* (middle) and T_{rr} *[E]* (right) with the complete EGM2008 for the area of Wilkes Land, Antarctica.