Rebuttal letter. Reply of the authors to the second review to:

Popigai and Chicxulub craters: multiple impacts and their associated grabens

Jaroslav Klokocnik, Vaclav Cilek, Jan Kostelecky, and Ales Bezdek

Status: final response (author comments only)
Comment types: **AC** – author | **RC** – referee | **CC** – community | **EC** – editor | **CEC** – chief editor |

- **RC1**: 'Comment on egusphere-2024-866', Anonymous Referee #1, 28 May 2024
  - **AC1**: 'Reply on RC1', Jaroslav Klokocnik, 06 Jun 2024
- **CC1**: 'Comment on egusphere-2024-866', Lev Eppelbaum, 07 Jul 2024
  - **AC2**: 'Reply on CC1', Jaroslav Klokocnik, 08 Jul 2024
- **RC2**: 'Comment on egusphere-2024-866', Anonymous Referee #2, 25 Sep 2024.

Thank you for your careful review. We improved our manuscript accordingly. Technical note: Here as well as in the revised manuscript, the replies, comments and corrections are in blue colour and in italics.

The manuscript entitled "Popigai and Chicxulub craters: 2 multiple impacts and their associated grabens" discusses the possibility of Popigai and Chicxulub impact craters being double or multiple craters and the possible reactivation of weak planes in the vicinity of the impact zone resulting in the formation of graben. The authors have conducted a thorough gravitational analysis of the impact craters in great detail using gravity field model EIGEN 6C4 with GOCE gradiometry data. Overall, the volume of work is impressive and the gravitation data expressed in the figures are easily comprehensible. *Thank you.*

However, there are quite a few issues with the discussion and interpretation that needs to be addressed before publication. *Sure, done, the revised text is sent to be posted.*

Major Comments

1. There is a lack of convincing arguments on why the craters are being interpreted as double or multiple craters.

In the case of Popigai, we guess, our arguments are strong enough (3-4 craters lined-up in ES-NW line). It is not so robust for Chicxulub. Principally, it cannot be decisive only with the aid of the gravity data. More below.

The authors have very briefly touched upon how double or multiple craters form, which needs to be explained further.

We guess it is correct to introduce the recent discussion about this topic shortly. Our gravity aspects can, however, say nearly nothing about the formation, meaning whether one or two impact craters will be created by the forthcoming impactor(s). We observe their final gravity record as evolved in long time.

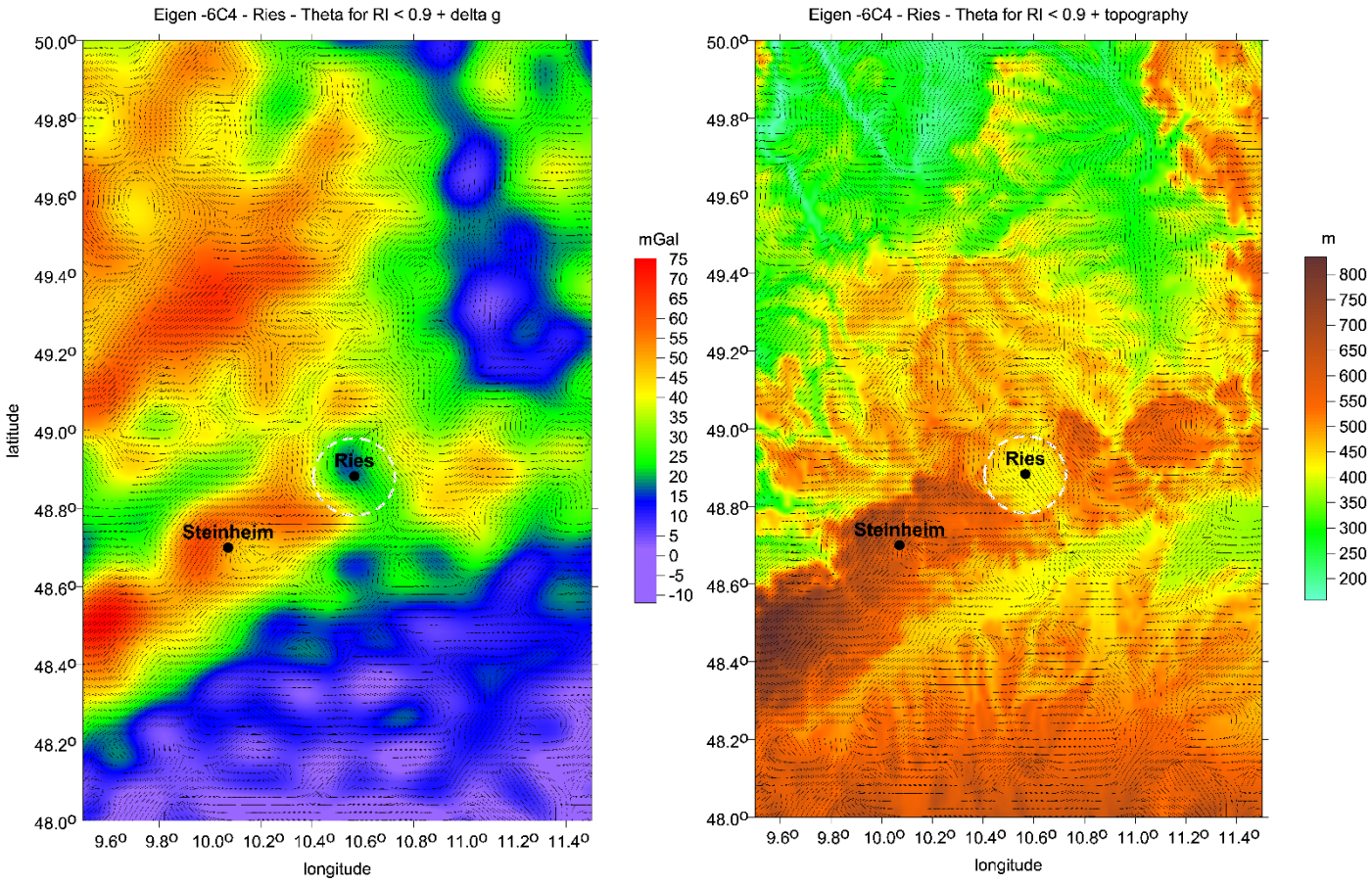
Our text has been extended:
The gravity aspects cannot themselves decide whether the impactor was a single body or a binary asteroid before its impact on the Earth. Both is possible. As noted above (Sect. 5.1.), there is possibility of break-up of one body (a single asteroid) in the atmosphere or a "flying cluster" of bodies encountering the atmosphere. To create a double crater, components of a binary asteroid should have a big distance (hundred kilometres) because velocity of asteroids in the Solar system is much higher than

velocity of a point rotating on the Earth's surface. Thus, close binaries can hit on one and the same place and create one crater only. The binaries with a big distance of their components are difficult to be observed. We do not refer to the relevant literature (e.g., Durda et al., Polishook et al., Pravec et al), because it is out of our main focus.

There needs to be a discussion on why the smaller craters are not secondary craters but rather formed due to binary asteroids or breakup of asteroids into smaller fragments in the atmosphere.

Our opinion:
On the Earth, with a higher gravity than on the Moon, the situation differs from the Moon. On the Earth, catena is a rare feature. On the Moon, catenae (belts of secondary craters, ejecta) are not exceptional.
The ejecta (smaller secondary craters) on the Earth would be formed in another direction than a series of the impact craters originating along-track of the impacting body (bodies). It is always such a „fan" from the impact crater roughly into the opposite direction of the falling asteroid(s).

There is an example of Steinheim-Ries double craters in Germany (double crater in a majority of opinions). Flying roughly from W, two craters were generated (the smaller Steinheim first of all and then the bigger Ries) and finally the ejecta (green glass known as moldavits, vltavins) – it can still be found mainly on the territory of SW part of Czech Republic.



Figures: The strike angles at Steinheim-Ries craters (Germany) together with the gravity anomalies computed with the gravity field model EIGEN6C4 (left) and with ETOPO 1 topography (right). Their trend is from ~W to ~E, with a fragmented halo around Ries.

*Link to Supplement SM2:*https://www.asu.cas.cz/~jklokocn//CHIC-POP24_supplements/

Our text has been modified and extended.

There is also a lack of explanation pertaining to how the authors are interpreting the impact direction. I feel it is important to address and correlate all these points for a more holistic interpretation on the gravity data and its usefulness in deciphering impact phenomenon in planetary bodies.

As for the direction of the impactor: sometime we can deduce this direction from the direction of the gravity strike angles (Klokočník et al., 2020b). As a good guide, we offer Steinheim-Ries (S2:18). Geologists know that the impactor(s) came roughly from west, creating first the smaller Steinheim, than the bigger Ries. We can verify it independently using the strike angles; they are combed in the ~WE direction, they are skirting around both craters, creating a halo around Ries (see the figure above). For Popigai, in an analogy, we can expect the impactor coming in ES-NW, producing the small(er) crater(s) first, and the biggest, already proven one, as the last, final (Figs. 1b-d, S3:6-21).

A general geological note:
Our interpretation is based mainly on the experience with the formation of impact craters on the Moon. In "Atlas of the Gravity and Magnetic Fields on the Moon" (Klokočník et al., 2022), we have studied the gravity characteristics of dozens of impact craters distributed over the lunar surface. Needless to say, lunar craters are not only numerous, but, except for the oldest mascon-type structures, little altered by later processes, whereas on Earth, erosion often results in root-like structures several kilometres deep or, as in the case of Chicxulub, in phenomena buried beneath younger sediments. This means that we have worked mainly with analogies that are additionally obscured by erosional processes on Earth, and the original gravity signal may be overprinted by other processes such as tectonic activity or selective erosion. Therefore, the aim of this paper is not to provide unequivocal evidence for the existence of additional craters, but probability that they exist and that further field research should tell more.

In the case of the Popigai impact, the gravitational anomalies are arranged roughly in a single line, which in our opinion best corresponds to lunar catenae. These structures will be difficult to prove on Earth because the smaller craters in particular were formed with much lower impact energy. Thus, we can expect that the impact structures were of varying depths and the shallower ones were more affected by erosion. They will therefore appear in the gravimetric record with different intensities, or they may have disappeared completely. The uniqueness of Popigai Crater, in our opinion, is that the entire linear structure most closely resembles a catena as we know it on the Moon.

The situation at Chicxulub Crater is far from clear. Our data suggest the existence of another crater with some non-negligible probability, but it is fair to say that any interpretation is speculative at this stage of the research. However, if field, i.e. borehole, exploration proves its existence and at least partially clarifies the conditions of its formation, we will have more basis for speculating on the nature of the impact. We have already pointed out in the article that the gravity aspects indicate possible presence of the second structure.

2. The authors' use of trend and azimuth information is confusing. Some of the trends in the text are hyphenated while others are not. I suggest making all the trend information hyphenated (e.g., N-S, E-W) and azimuth (direction) information non hyphenated (e.g., SE of crater). In that note, I am confused about the SW-SE fault orientation mentioned in the manuscript (pages 8, 14, 19).

Hopefully improved. Not everywhere clear.

Minor Comments

Shortly speaking: we have no objection against these comments, thus we follow your suggestions to correct our text. Thank you.

Page 1

Abstract

Increase the line spacing

Line 19: Rewrite “here the impact craters Chicxulub and Popigai.” as “The improved techniques were applied to study the impact craters Chicxulub and Popigai in this present research.”

Line 21: Both craters are interpreted to be double or multiple craters.

Line 22: Rewrite ‘The both crater formations’ as ‘Formation of both the craters”

Motivation

Line 28: Instead of writing ‘In this journal’ it is better to refer the paper

Lines 28-31: Complex sentence; break the sentence to simpler sentences for better readability

Lines 32-33: Brief description of double and multiple craters needs to be added with references

Page 2

Line 15: Remove ‘indeed’

Line 16: shook → shock

Line 23: If magnetic intensities have not been studied in this paper, please refer publications where it has been studied

Notes on Theoretical Preliminaries

29: remove ’gravity’

Page 3

Lines 8-12: Complex sentence; break the sentence into simpler sentences for better readability

Line 24: Put (Comb) within parenthesis

Line 25: “not combed”

Line 29: Rewrite ‘can shape a halo’ as ‘can take the shape of a halo’

Page 4

Data, computation, and figures

Line 4-5: Refer the theory

Line 10: Rewrite ‘have not access to’ as ‘did not have access to’

Line 14: Rewrite ‘not only a general figure 10 mGal’ as ‘and not only for a general figure of 10 mGal’

Line 16: Mention how worse

Line 19: Mention couple of other measurements within brackets

Line 20: heights → height

Line 21: Bedmap 2 → Bedmap2

Line 26: Remove the exclamation mark

Page 5

Line 4: ‘corresponding to the ground resolution of 9 km’

Line 19: Any significance of plotting θ in black and white?

Page 6

Artefacts

Lines 12-13: Rewrite ‘correct interpreting the’ as ‘the correct interpretation of’

Line 17: with → has

Line 19: unbelievable → unrealistic

Line 22: Rewrite ‘how well by the data is covered the area of our interest’ as ‘how well the data has covered the area of our interest’

Line 30: he → the

Page 7

Line 1: Moons’ → Moon’s

Line 9: “hidden”

Line 16: “lurk”

Line 17: attack and distort → hamper

Popigai

Line 27: Remove ‘it was’

Page 8

Line 6: Please clarify whether ‘it is’ is referring the crater or the shield

Page 9

Lines 6-7: Please add references

Line 10: Rewrite ‘their fig. 3a’ as ‘(cf. Fig. 3a in Pilkington et al., 2002)’

Line15: Section 6.1 does not have any “notes” on binary asteroids, only a brief mention

Line 17: quite remotely area → remote area

Line 19-22: Complex sentence, break the sentence into simpler sentences for better readability

Line 24-25: Why mention beforehand what the authors will argue for?

Page 11

Line 24: Rewrite ‘fragmented now due probably to’ as ‘which is presently fragmented, possibly due to’

Line 25: Rewrite ‘not too intensive’ as ‘not with too much intensity’

Line 27: mark → signature

Line 30: lined → aligned

Page 12

Line 4: Rewrite ‘we had not’ as ‘did not have’

Line 5: Begin a new sentence from “With them now……”

Chicxulub

Lines 14-15: Please clarify ‘external forcing event’

Line 27-28: Add references

Page 13

Line 2: “The impact…….”

Line 8: Rewrite “The literature about the Chicxulub crater is really rich: from Alvarez……” as “The literature about the Chicxulub crater is really rich. To mention a few: Alvarez……”

Line 9: Remove …

Line 11: Remove “This is not a review paper to mention all.”

Line 12: Rewrite “in its study” as “in the study of Chicxulub crater”

Line 14: Rewrite “they did not know” as “they were not aware”

Page 14

Line 3: Remove the

Line 21: Clarify ‘strong on land’

Page 15

Fig. 2a: Point to the semi-circular shadows

Page 17

Line 5: Remove ‘reviving’

Page 19

Discussion

Line 30: “basin”

Page 20

Line 9: “trench modified by impact”

Line 12: Refer the following papers-

Wichman, R. W. (1993). Post-impact modification of craters and multi-ring basins on the Earth and Moon by volcanism and crustal failure. Brown University.

Dasgupta, D., Kundu, A., De, K., & Dasgupta, N. (2019). Polygonal impact craters in the Thaumasia Minor, Mars: role of pre-existing faults in their formation. Journal of the Indian Society of Remote Sensing, 47, 257-265.

Zhang, F., Pizzi, A., Ruj, T., Komatsu, G., Yin, A., Dang, Y., ... & Zou, Y. (2023). Evidence for structural control of mare volcanism in lunar compressional tectonic settings. Nature communications, 14(1), 2892.

Line 30: central peak as the first ring

Page 21
Line 16: Meantime → In the meantime

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The End of rebuttal letter.
Jaroslav Klokočník with co-authors

The End of message