A gravity survey of the Holocene Lake Tüttensee meteorite impact crater (Chiemgau impact event).

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Abstract

The 600 m-diameter Lake Tüttensee structure is so far considered the largest meteorite crater in the strewn field of the Holocene Chiemgau impact, although there is strong evidence of a 900 m x 400 m rimmed doublet crater at the bottom of Lake Chiemsee. Shape and depth of the water body of Lake Tüttensee have been controversially disputed, which is probably related with the deposit of a layer of thick consolidated organic material. A gravity survey on the frozen lake and in its surroundings had the principal aim to get knowledge of the crater shape. The maximum gravity anomaly of Lake Tüttensee is about -0,8 milligals mainly resulting from the density contrast of water/organic material and rock. Modeling of the gravity anomaly with respect to the water (plus organic material) body, however, reveals unsatisfactory results related with a complex density distribution in the target rocks. Gravity also shows that the true crater is smaller than the lake extent. Surprisingly, a ring of relatively positive anomalies is measured surrounding the Tüttensee negative anomaly. The positive anomalies are modeled by a 1000 m-diameter flat lens of slightly enhanced density. It is explained by a model of soil liquefaction and post-liquefaction densification well known from large earthquakes. Moreover, mass flow behind the impact shock front could have contributed to the compaction of the unconsolidated, highly porous and water-saturated target rocks. In addition to impact melt rocks, shock metamorphism (PDFs), high pressure/short term deformations in rocks from the Tüttensee ring wall, and a catastrophic impact ejecta layer, the geophysical measurements provide a further argument against the hitherto favored origin of Lake Tüttensee from glacial dead-ice melting. Further studies of impact shock liquefaction may be interesting for the understanding of impact cratering in targets composed of loose and extremely water-rich rocks as has been discussed for near-surface sediments on Mars.

1 Introduction

Within the frame of the Holocene Chiemgau impact event (CIRT 2004, Ernstson et al. 2010) the Lake Tüttensee near the town of Grabenstätt (Fig. 2) is a distinct issue. Located in the southwesterly end range of the impact strewn ellipse, it is currently considered the largest meteorite crater in the field exhibiting a rim-to-rim diameter of 600 m. However, detailed echo sounding measurements on Lake Chiemsee have revealed a further (doublet) crater sized roughly 900 m x 400 m (Ernstson 2010, Rappenglück et al. 2010). The Lake Tüttensee crater that formed in a target of moraine and fluvio-glacial material has a distinct ring wall (Fig. 1), and the impact nature is established by impact melt rocks (the pumice-like so-called swim stones), shock metamorphism (e.g. PDFs in quartz; Schüssler et al. 2005), characteristic high-pressure/short term deformations, and an extended ejecta layer of polymictic breccias containing abundant organic matter like splintered wood, charcoal, fractured animal bones and teeth (Ernstson et al. 2010).

Before the discovery of the Chiemgau impact Lake Tüttensee was generally considered a relic from the Würm glacial period, a so-called dead-ice kettle. This interpretation is still maintained by a few local and regional geologists (Doppler & Geiß 2005, Darga & Wierer 2009, Doppler et al. 2010), although the arguments have clay feet (CIRT 2005, Ernstson et al. 2010, Rappenglück et al. 2011; also see the discussion of the geologists' *dead-ice speculations and lacking proofs* by Martin [2007]).

A hitherto unsettled quantity was the depth of the Tüttensee kettle. While official data sheets mention 14 m on average and 17 m maximum water depth (meanwhile confirmed by a sediment echosounder survey [Daut 2008]), divers have allegedly plumbed about 70 m. Since Lake Tüttensee carries plenty of organic material and, according to divers reports, numerous tree trunks, inconsistent statements about the depth are plausible. In fact, this organic material hampers information about the deeper structure, which understandably is important for considerations about the impact cratering process of the Lake Tüttensee crater. Thus, the idea came up to get an estimate of the crater depth by the aid of a gravity survey.

Gravity reacts on underground density contrasts, and hence the large density contrast between the lake water (the low-density organic material included) and the embedding rock was the basis to "see" the crater in the gravity field and to enable a computer modeling of the crater shape. Instruments for the measurements of gravity are highly sensitive gravimeters that can work only on a solid underground. Therefore, a measuring campaign on a frozen, walk-on-able Lake Tüttensee was a prerequisite.

Normally, gravity surveys are a prominent tool in the geophysical investigation of impact structures, because the extreme kinetic energy of the impacting projectile transferred to the target may lead to enormous density changes within a large underground volume. Consequently, impact structures are in general featuring distinct gravity anomalies, which are in many cases roughly circular.

However, in the case of small meteorite craters the respective effects are also small, and for the Lake Tüttensee crater a gravity signature was though to be at the limit of detectable effects especially with regard to the strong negative gravity anomaly of the lake water body.

The present article (which is a reworking of a former version in German [Ernstson 2005]) reports on the gravity survey on the frozen Lake Tüttensee and in its environs. It outlines the many steps of the data processing and shows computed models of the underground density distribution, which are interpreted in terms of the formation of the Lake Tüttensee crater.

Fig. 1. Gravity measurements on the frozen Lake Tüttensee. In the background the ring wall of the crater.

2 Execution of the survey

Fig. 2 shows the survey map with an outline of the measuring area. The survey comprised 115 gravity stations, 40 of which were apportioned to the icy surface of Lake Tüttensee.

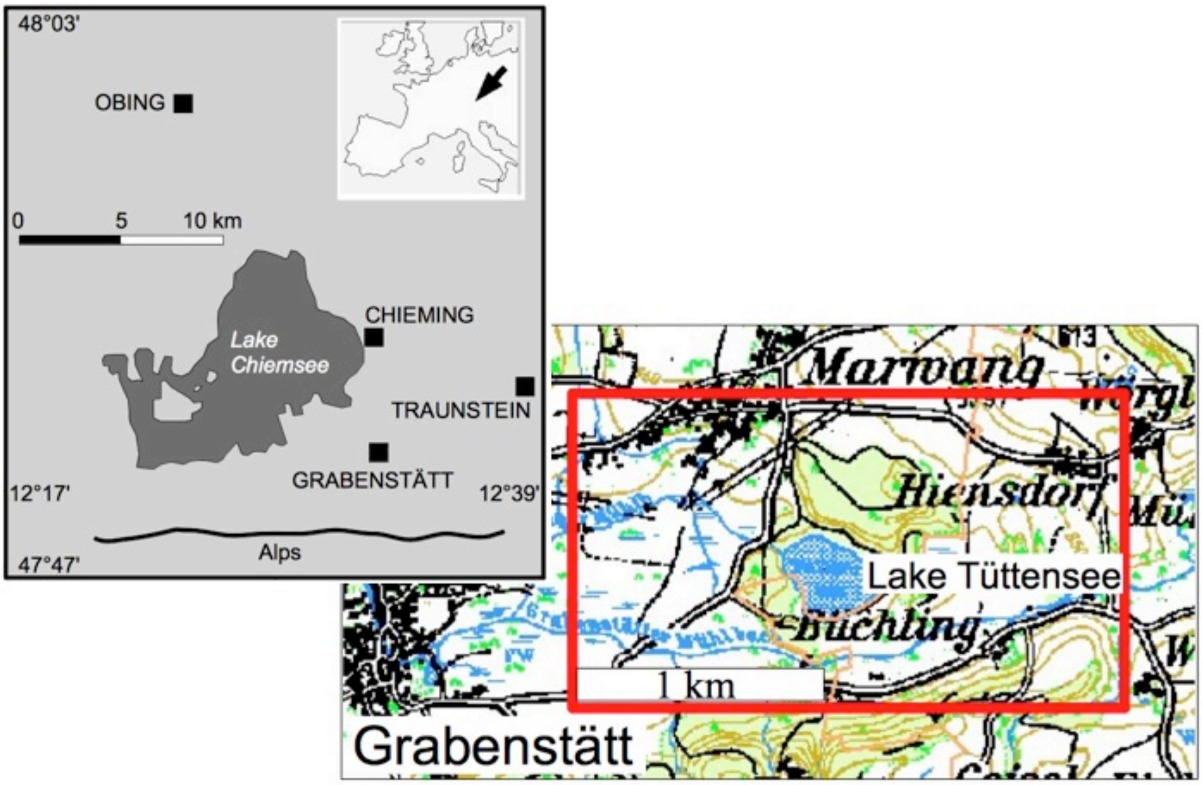

Fig. 2. Location map of the survey area.

A LaCoste-Romberg gravimeter, G type, was used. The temporal variations due to earth tides and instrument drift were recorded by repeated readings at a base station. Since gravity readings sensitively depend on altitude, each gravity station, even those on ice, had precisely to be leveled. Recording topography for terrain reduction purposes had also to be performed, although the effects were in most cases negligible.

3 Data processing and visualization

The standard corrections (Bouguer plate, free air, tidal, latitude, terrain) were applied to the data resulting in a map of Bouguer gravity anomalies (Fig. 3). The scaling of the values around 20 mgals must not irritate because of the relative character of the gravity data. A scaling in terms of existing gravity networks was not aimed at.

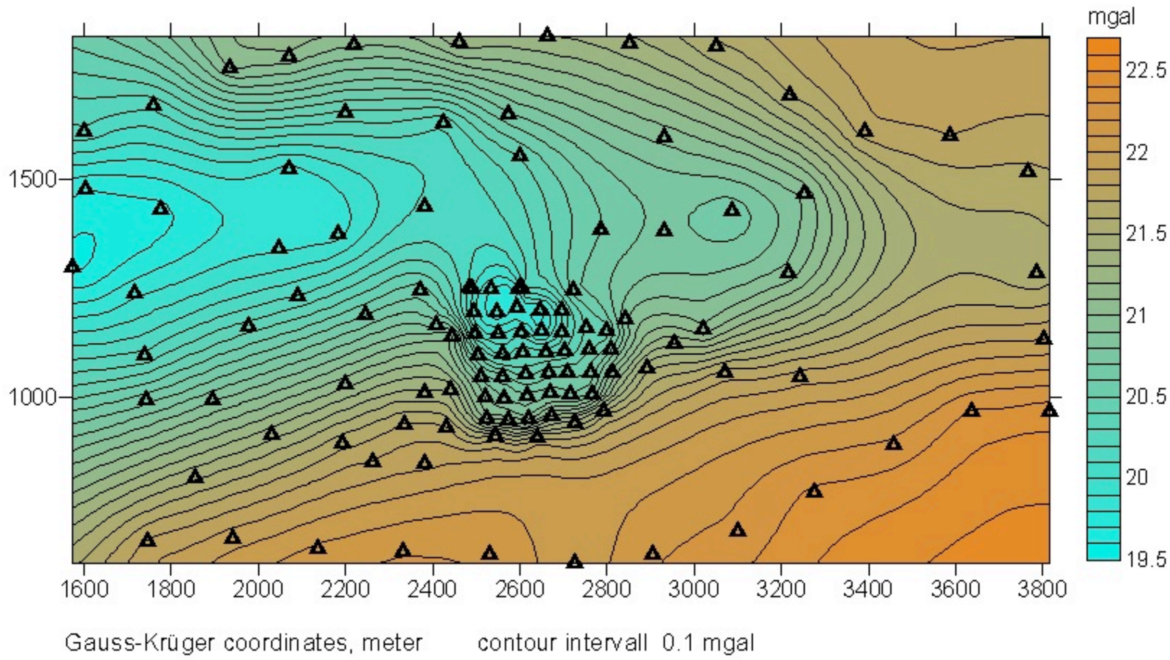

Fig. 3. Map of measured Bouguer anomalies. Triangles are gravity stations.

As with all fields of geophysical data, further processing may be useful, and gravity interpretation may profit from various filter procedures. In the present case, the Bouguer anomalies in a first step were subjected to a slight smoothing by low-pass filtering. The resulting field (Fig. 4). is the basis of all following processing stages and related visualizations.

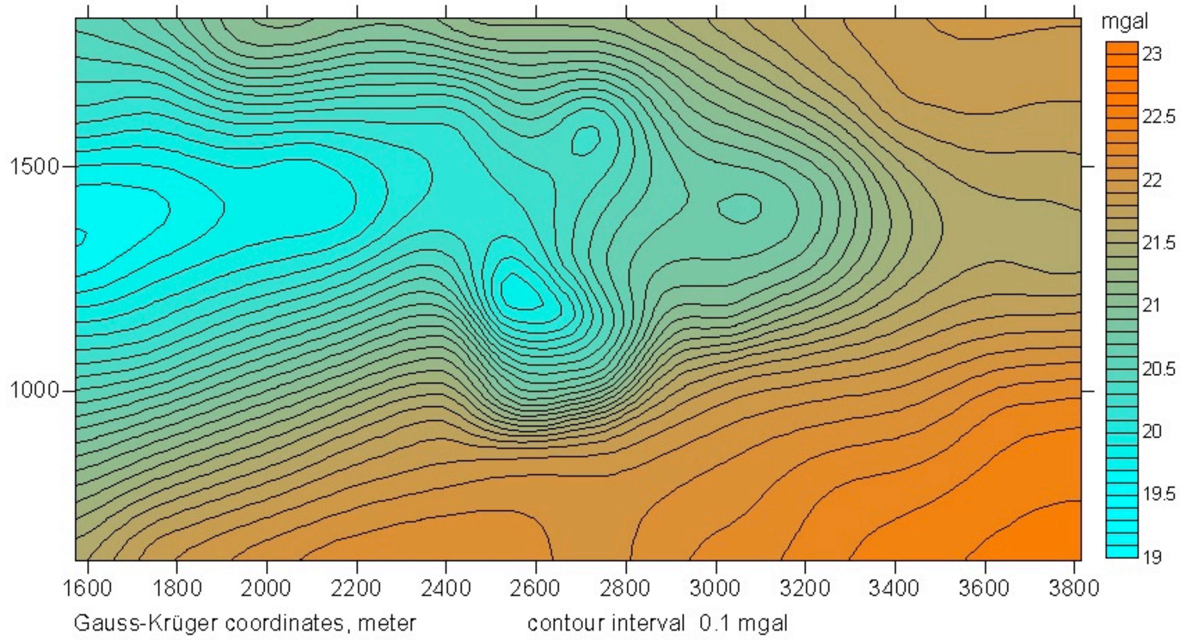

Fig. 4. Bouguer anomalies after slight low-pass filtering.

4 Regional field und residual field

Measured gravity fields are basically a superposition (addition) of various parts that may be attributed to different density bodies. Focusing on one of these portions in more detail, its gravity must be separated from that of the other ones. In the present case of the Lake Tüttensee gravity survey this property is especially evident as can be seen in Fig. 5 A. We recognize the small-scale Lake Tüttensee anomaly marked by a circle (the local anomaly) exactly in the edge region of an elongated large-scale anomaly widening to the west. Investigating the effect of the lake Tüttensee (the residual field) only, requires knowledge of the effect of the large anomaly (the regional field) here. This of course is not the case, and mathematically we may speak of an equation with two unknowns, which is not solvable unambiguously:

measured field = regional field + residual field

Hence, we need assumptions about the *regional field* in order to solve the equation for the *residual field* equivalent to calculating the difference *measured field - regional field*.

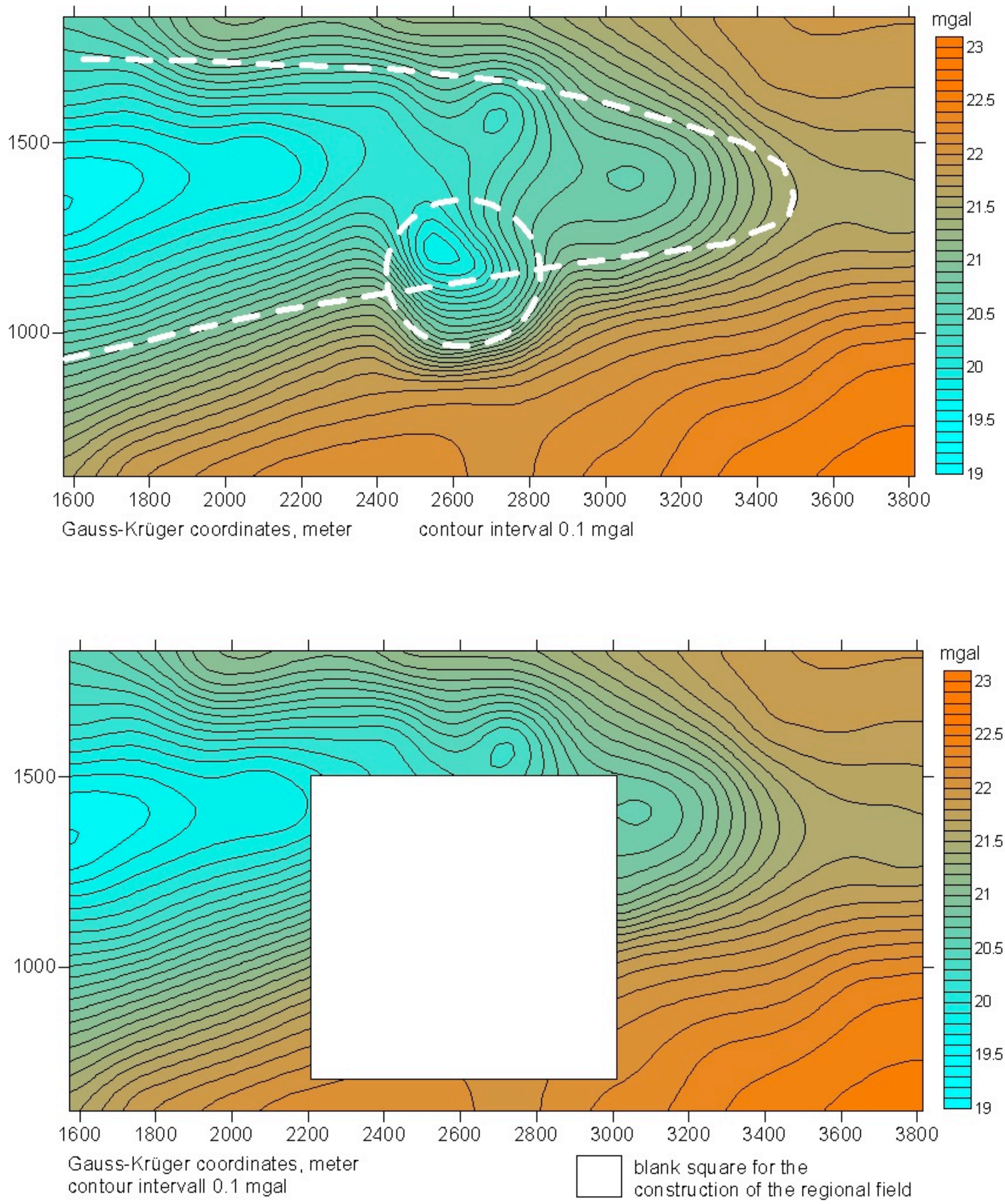

Fig. 5. A. Superposition of the Lake Tüttensee anomaly (encircled) and an extensive relatively negative anomaly. B. Square cutting for regional field construction.

In the case of the Tüttensee anomaly a 800 m x 800 m blank square was positioned over the local anomaly (Fig. 5 B) to allow the construction of a regional field using a computer-aided interpolation program the result of which is shown in Fig. 6.

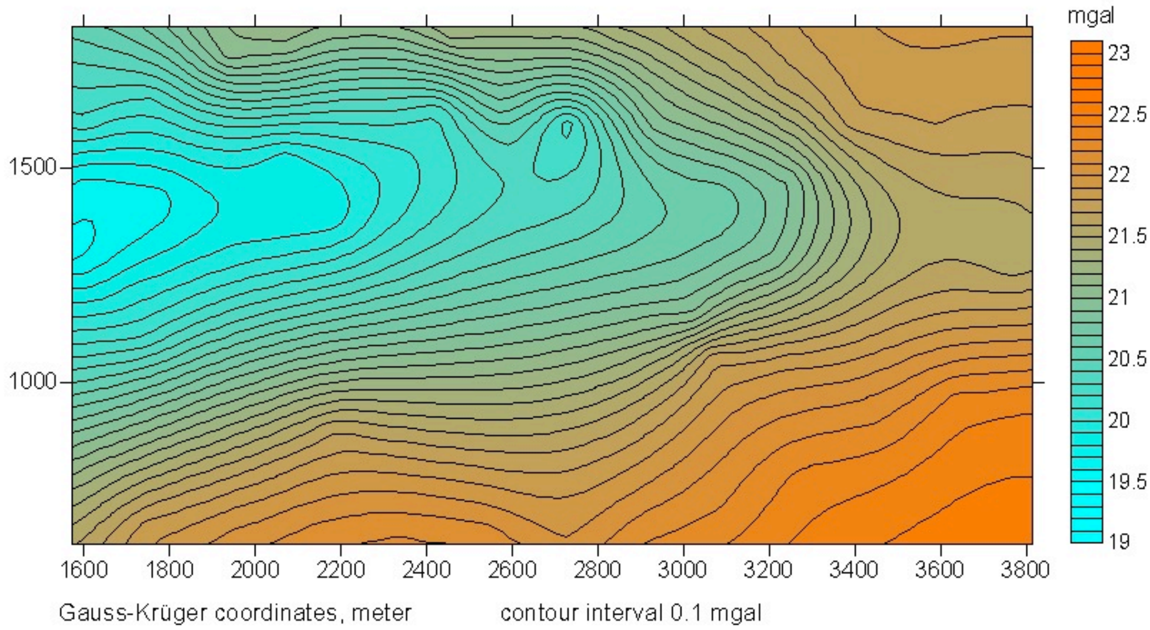

Fig. 6. Regional field.

Subtracting this regional field from the measured field (Figs. 4, 5 A) the difference corresponds to the residual field (Fig. 7). We have to realize that there is no unambiguous solution of this procedure, and uncertainties of the regional-field construction are to be found as uncertainties in the residual field again.

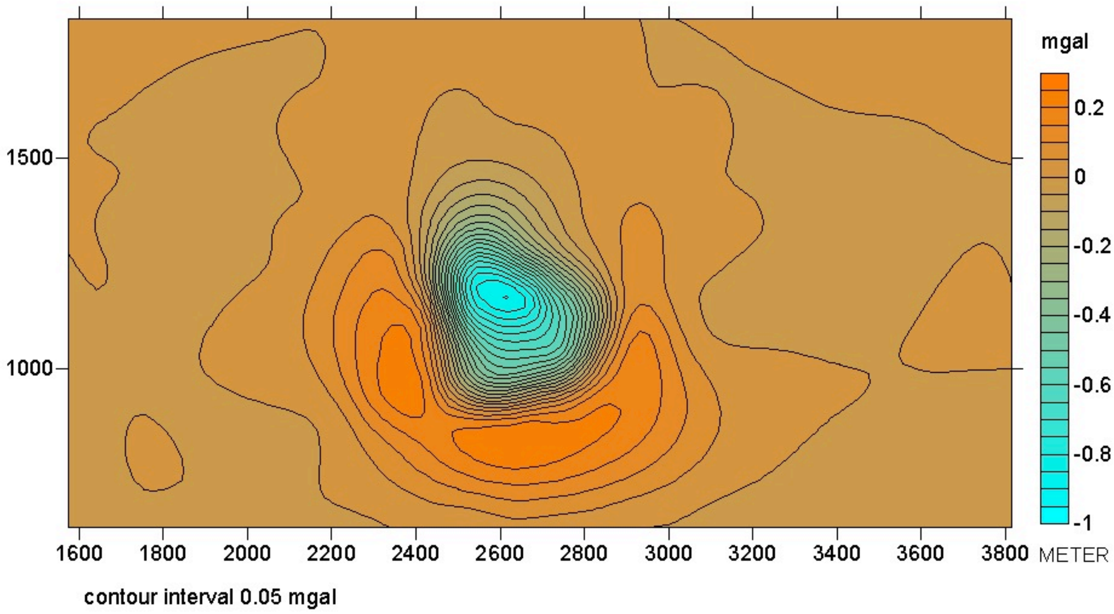

Fig. 7. Residual anomaly of Lake Tüttensee.

5 Gradient fields

5.1 Horizontal gradient of the gravity field

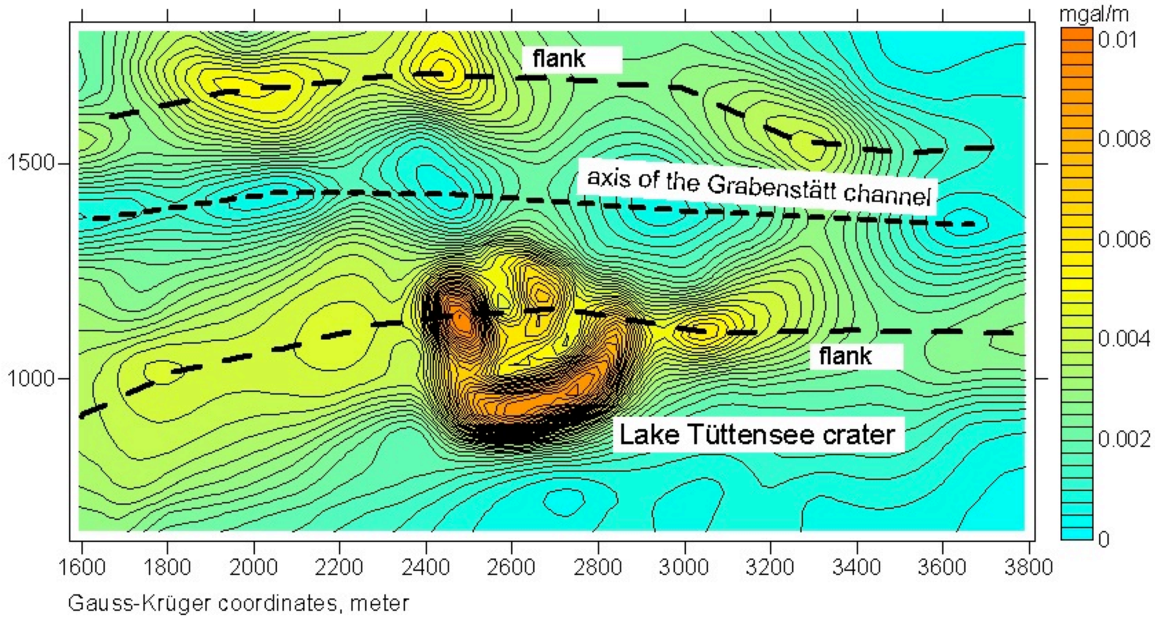

Fig. 8. Map of the horizontal gradient of the Bouguer anomalies.

Filtering procedures applied to geophysical fields also comprise calculations of various derivatives (gradient fields). In these fields, computed and visualized, certain structures frequently become illustrated more clearly than in the original field. An important quantity that can be deduced mathematically from the Bouguer field is the horizontal gradient. For each point of the data grid it quantifies the maximum horizontal gravity variation (unit mgal/m). The relevance of the horizontal gradient are locally confined maxima corresponding with sites of maximum gravity variation that for their part are related with lateral density contrasts. Frequently, geologic boundaries, e.g., tectonic displacements, are thus accentuated.

In Fig. 8 the field of the horizontal gradient as computed from the Bouguer field has been plotted. The Lake Tüttensee shows especially pronounced exhibiting a distinct ring-like maximum. It will be shown later that this ring of maximum gradient does not correspond with the shoreline of the lake. In the map of the horizontal gradient both the flanks and the axis of the Grabenstätt channel become clearly evident conveying the strong influence of the channel anomaly on the northern part of the Lake Tüttensee anomaly.

5.2 Horizontal second derivative of the residual field

Focusing on the Lake Tüttensee it is interesting to apply higher-gradient computations to the residual anomaly. Computing the horizontal gradient of the gradient field, the result features the field of the so-called horizontal second derivative accentuating the resolution of the field even more. Starting with the residual anomaly from Fig. 7, Fig. 9 visualizes the corresponding horizontal second derivative. The circularity of the gravity field becomes more evident, while the relevance of the anomaly "rings" in terms of the crater structure will be discussed later.

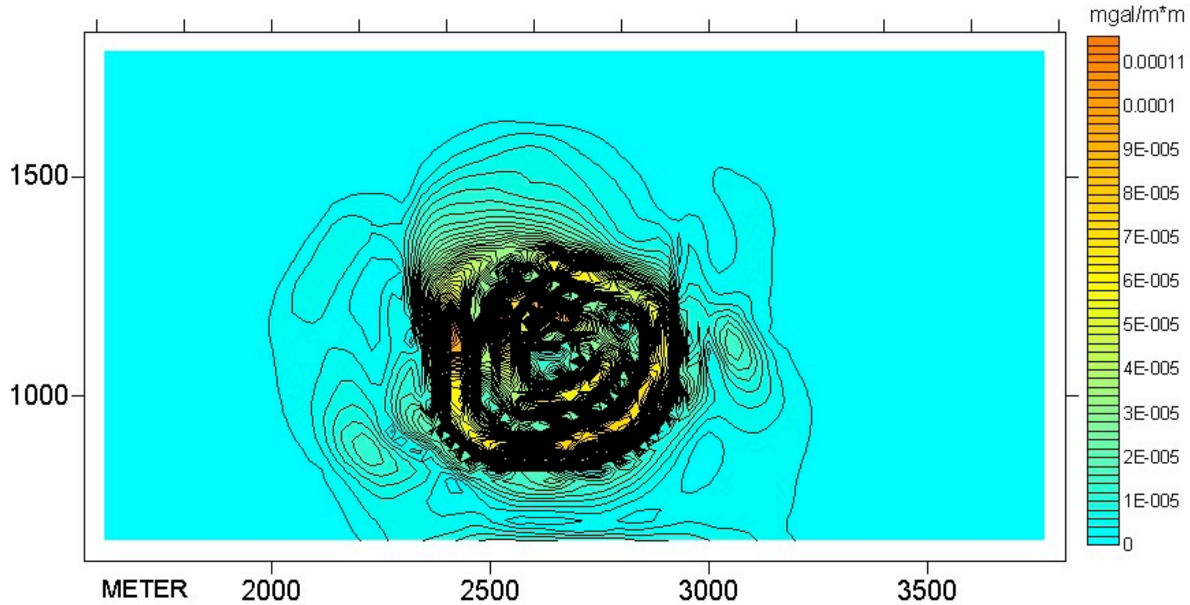

Fig. 9. Horizontal second derivative of the Lake Tüttensee residual anomaly.

6 Results

6.1 The Bouguer gravity map

6.1.1 The Grabenstätt channel

From the preceding discussion it has become evident that the Bouguer gravity field (Fig. 4) apart from the local Lake Tüttensee anomaly reveals a further very distinct anomaly. The elongated anomaly is relatively negative corresponding with a mass deficiency tunneling the underground. The anomaly is running west - east widening to the west towards Grabenstätt, and that is why we would like to call it the Grabenstätt channel. A geologic interpretation remains undone.

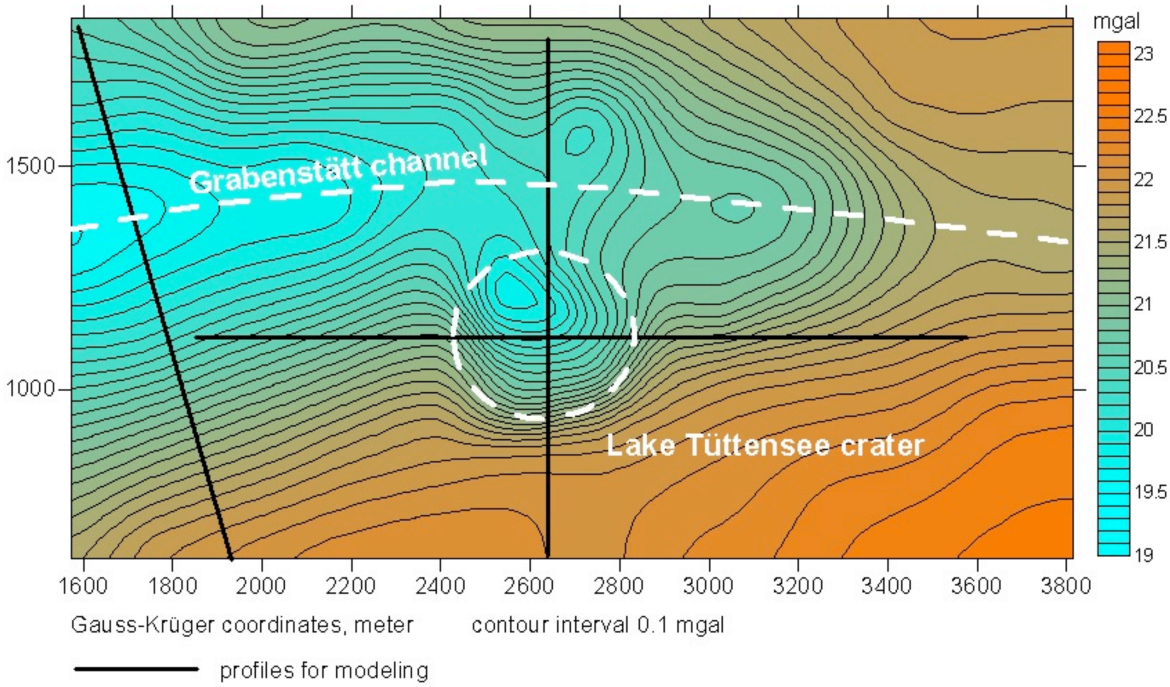

Fig. 10. Location of profiles for model calculations of the Grabenstätt channel and the Lake Tüttensee anomaly.

Since this extended anomaly superimposes the Lake Tüttensee area, model calculations for a more detailed investigation were performed. A gravity profile perpendicular to the channel axis was taken (Fig. 10), and the resulting curve together with the calculated model is shown in Fig. 11.

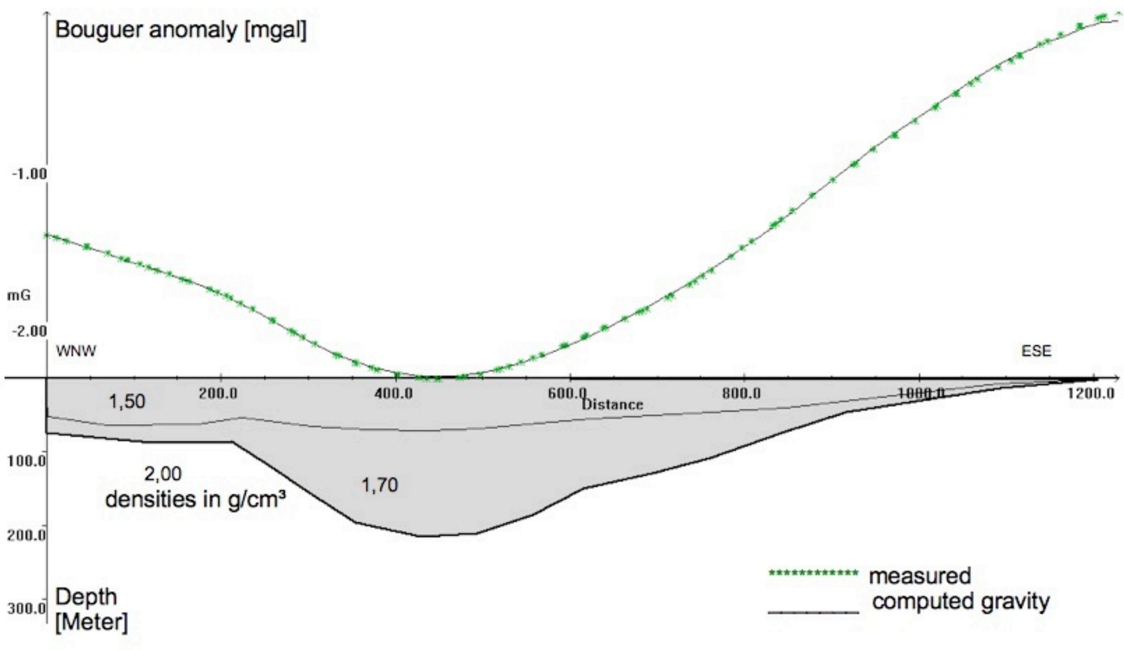

Fig. 11. Modeling of the regional-field anomaly.

Measured and computed gravity fit well corresponding with an up to 200 m thick causative body of considerably reduced density at the western edge of the survey area. The body itself is subdivided in an upper layer (density 1.5 g/cm^3) and a bottom layer (density 1.7 g/cm^3) deepened into a host rock of density 2.0 g/cm^3.

The calculation has featured a possible model; somewhat differing body coordinates and densities may also apply, but it is important to note the very low densities of the channel material playing a certain role when the Lake Tüttensee anomaly is discussed.

6.1.2 The Lake Tüttensee gravity anomaly

As already expected, the Lake Tüttensee has a distinct gravity negative anomaly due to the low densities of the water and the embedded organic matter, which is expressed also in two gravity profiles extracted from the field in Fig. 10.

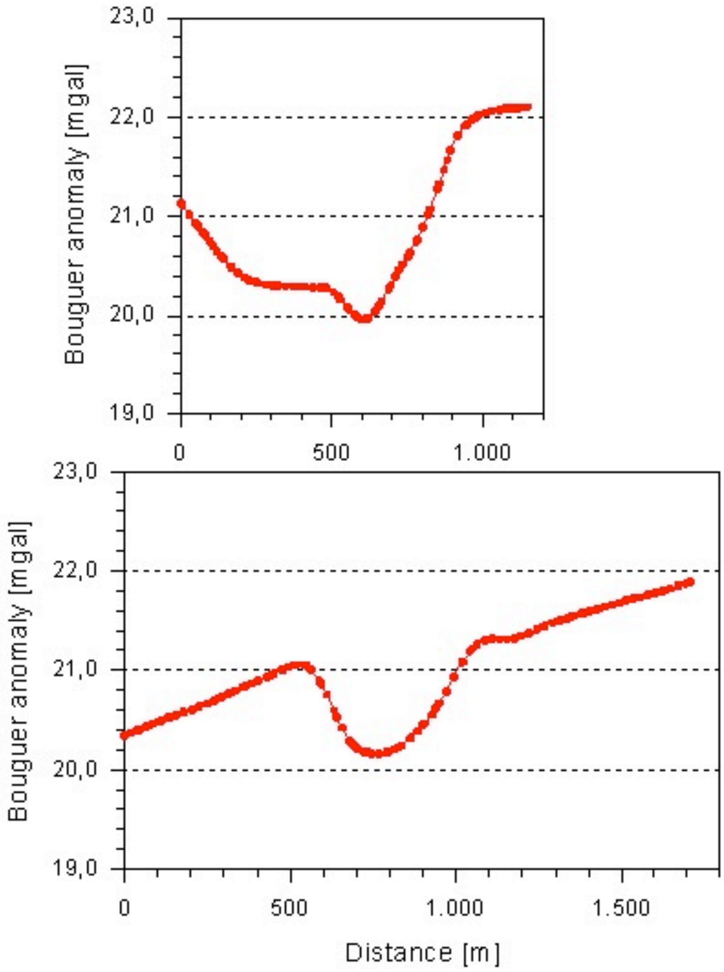

Fig. 12. Bouguer gravity profiles across the Tüttensee anomaly.

Both profiles have different character, which has primarily to do with the strong influence of the regional field. Especially the west-east running profile reveals faint, relatively positive anomalies peripheral to the central negative anomaly. This is even more evident in perspective, pseudo-3D illustrations of the gravity surfaces (Bouguer field, Fig. 13, and residual field, Fig. 14).

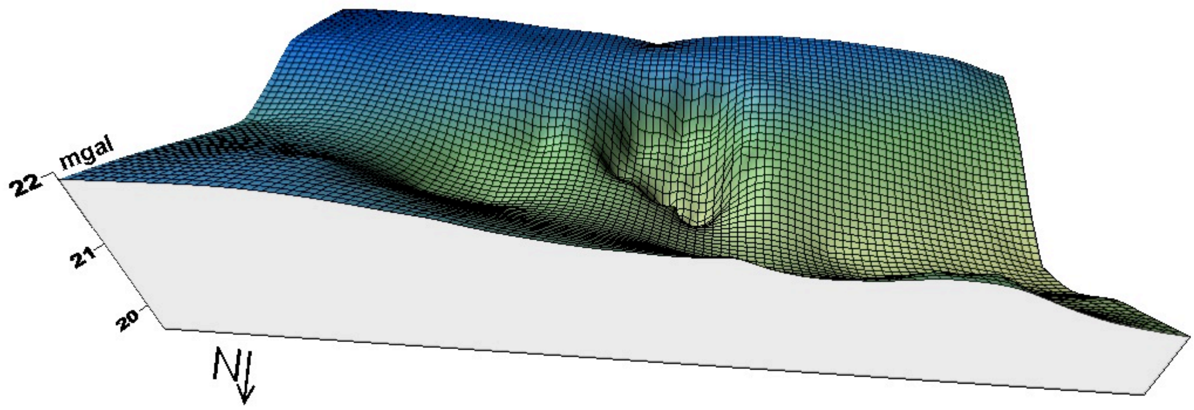

Fig. 13. 3-D plot of the Bouguer anomalies. Note the ring of relatively positive anomalies surrounding the local Lake Tüttensee negative anomaly.

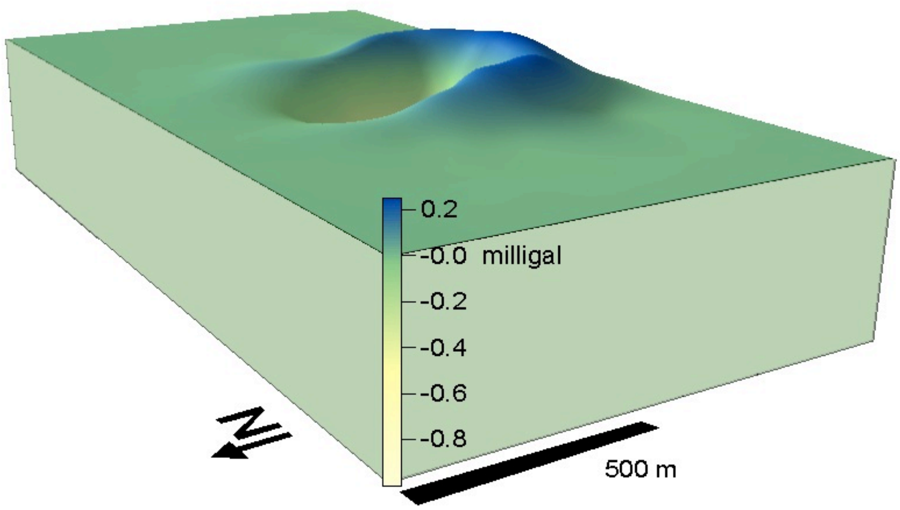

Fig. 14. 3-D plot of the Bouguer residual anomaly.

It is pointed out that this ring of positive anomalies is already to be seen in the original Bouguer map (Fig. 13) and not possibly an "artifact" from data processing (e.g. from the construction of the regional field). The obvious gap in the northern part will be addressed in the Discussion chapter.

6.2 The Lake Tüttensee residual anomaly and model calculation

In Fig. 15 a gravity profile is plotted that as a basis for model calculations has been taken from the residual anomaly (Fig. 15, upper). The profile has been chosen to run approximately midway through Lake Tüttensee thus avoiding local extremes of the gravity contours.

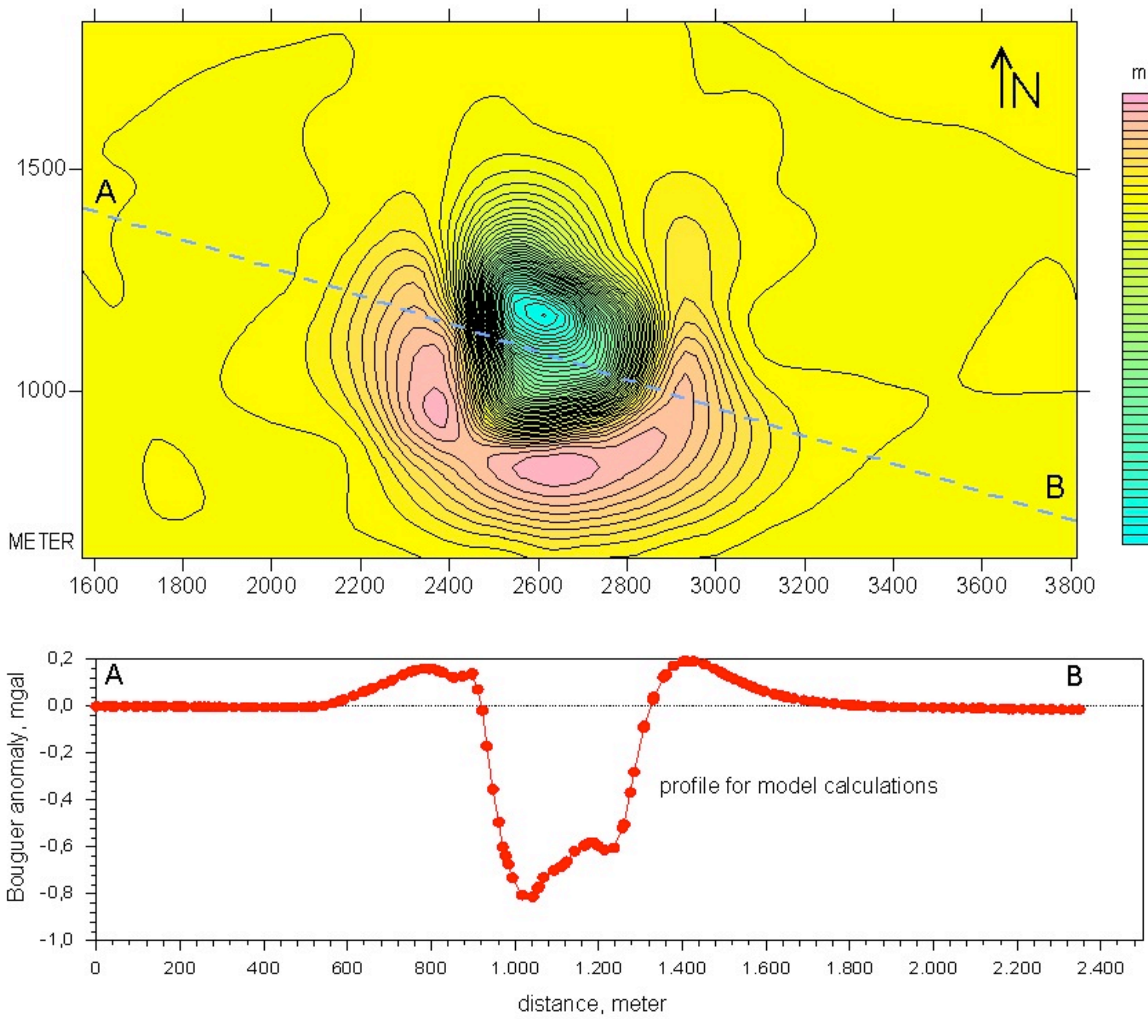

Fig. 15. Lake Tüttensee residual anomaly and gravity profile for model calculations.

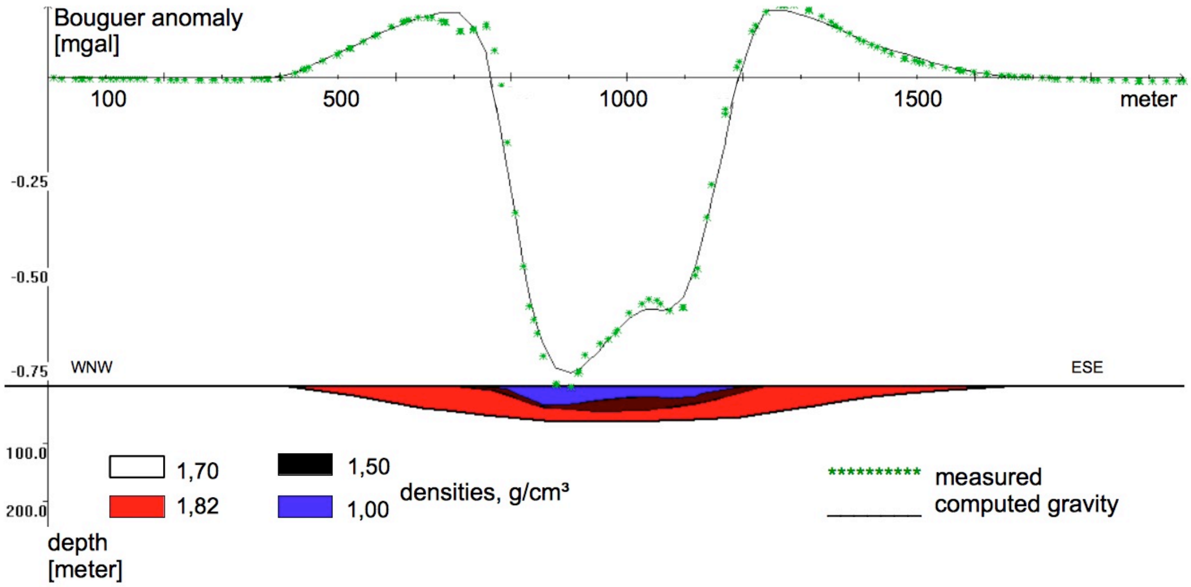

Fig. 16. 2.5D gravity modeling and density model for the Lake Tüttensee anomaly. Without exaggeration. Note the lens of increased density (red color).

The gravity modeling (Fig. 16) used a program for 2.5-D structures. I did not aim at an exceedingly precise matching but instead tried to point out more general aspects. Accordingly, the model (that is not exaggerated in Fig. 16) consists of the lake's water body and organic matter (density 1.0 g/cm^3) about 20 - 30 m deep, which is embedded in a shell of a low-density material (1.5 g/cm^3). An extended flat lens-like body (about 1,000 m diameter) of increased density (1.82 g/cm^3) accounts for the peripheral relatively positive anomalies. It is assumed that these density bodies were formed in the impact cratering process that took place in a surrounding material of density 1.7 g/cm^3.

It is pointed out that the model may considerably be varied with regard to densities and geometries without lowering the fitting of measured and calculated curves. In particular, an inaccurate knowledge of the densities corresponds with an inaccurate geometry of the model. However, the reality of a body of increased density that obviously was formed in the impact cratering process cannot be questioned. The density increase has nothing to do with the visible ring wall.

6.3 Gravity and the rim of the Lake Tüttensee crater

While details of the crater structure geometry cannot unambiguously be determined from gravity, the crater rim can fairly well be outlined by the maximum density contrast, which finds best expression in the horizontal gradient fields and is especially accentuated in the horizontal second derivative (Fig. 9). In Fig. 17, the red dashed line corresponds to a sharp minimum in the second derivative that mathematically in turn traces the maximum horizontal gradient thus delineating the crater rim as position of maximum density contrast. This red line is copied to an oblique aerial photograph of Lake Tüttensee (Fig. 18), and it is evident that the crater and its rim are not synonymous to Lake Tüttensee.

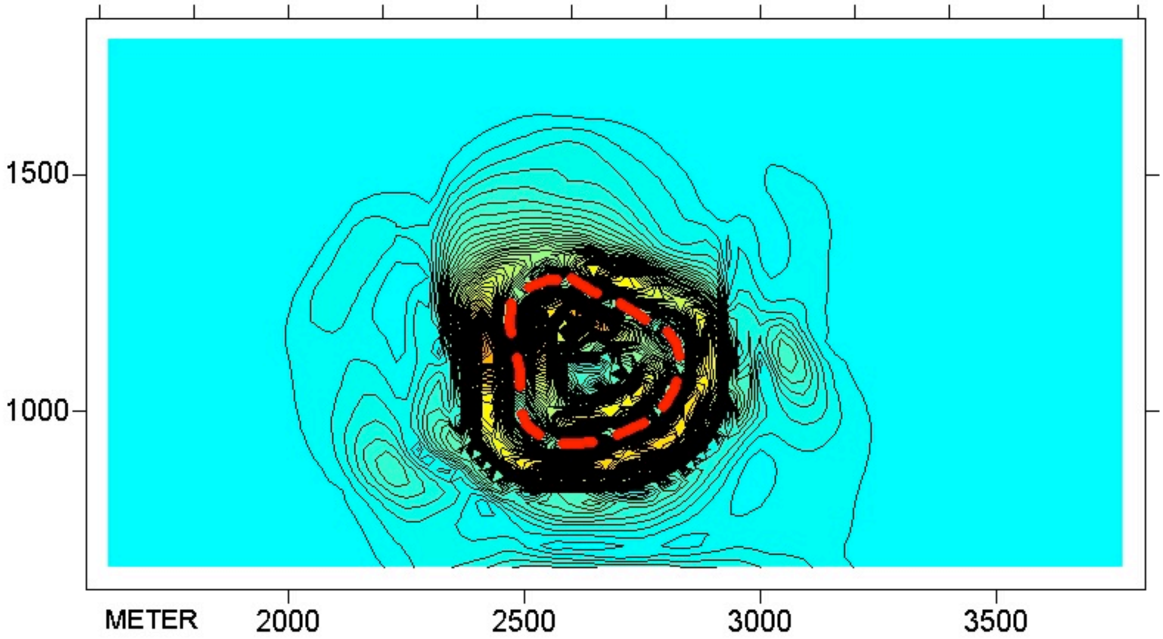

Fig. 17. Horizontal second derivative of the residual anomaly establishing the ring-like maximum density contrast (red line) at the crater rim.

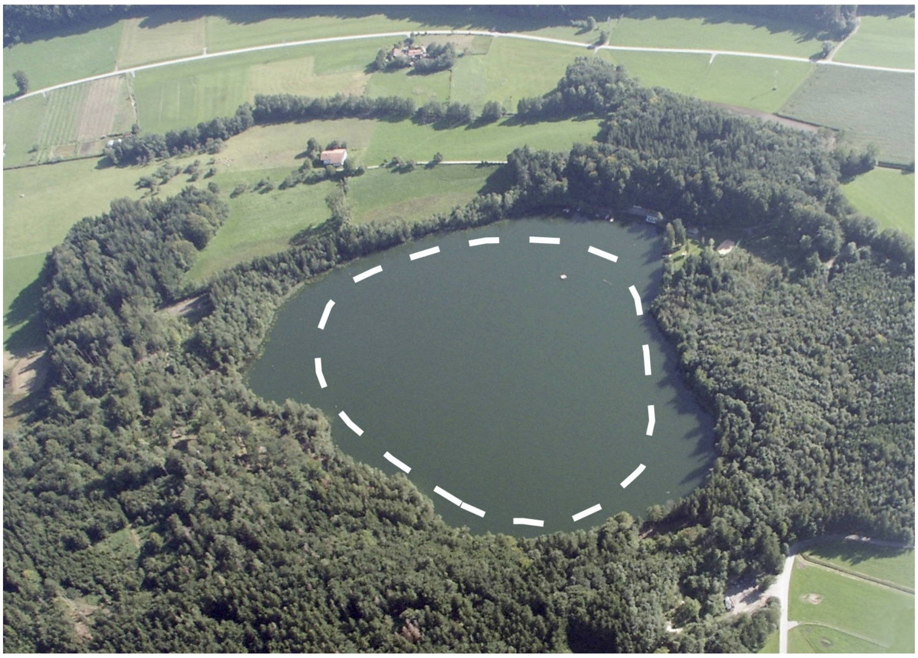

Fig. 18. The crater rim deduced from the gravity second derivative in Fig. 17. Note that the photograph is rotated by approximately 180° with respect to the map in Fig 17.

Meanwhile, results of a few sediment echo sounder profiles across Lake Tüttensee (Daut 2008, unpublished data and report) have shown (Ernstson, internal report) that pre-impact sediment layering abruptly breaks exactly at the gravity-deduced line in Fig. 18 taken up again in the discussion chapter.

6 Discussion

The gravity campaign results in the measurement of the expected Lake Tüttensee negative gravity anomaly. It superimposes a distinct elongated negative anomaly ascribed to a deeply indented channel-like structure - not exactly to be expected. Likewise not to be expected was the verification of a roughly ring-like anomaly of relatively positive gravity around Lake Tüttensee.

According to the starting situation the distinct negative anomaly over Lake Tüttensee with -0.8 mgal amplitude must primarily be attributed to the water body of maximum 17 m depth and a suspected body of organic material of unknown thickness. Simple gravity modeling of this combined low-density body shows that it is impossible to arrive at convincing data for the depth to the crater bottom which is basically due to the unknown densities of the surrounding embedding Quaternary sediments and which could not be eliminated by the regional field modeling (Fig. 11). However, both the officially plumbed and seismically confirmed water depth and the diver's putative 70 m value (see the Introduction) require modeled densities for the Quaternary that are either far to low or far too high for these sediments. A value somewhere lying in-between and modeled to 20 - 30 m crater depth in Fig. 16 may reasonably apply, and the true crater depth must be left to assumptions for the time being.

This assessment concerns also the layer of density 1.5 g/cm^3 at the bottom of the crater that has been inserted in the model of Fig. 16. It is uncertain whether this layer exists but it would be compatible with strongly shattered rock material that in the impact process was deposited at the floor of the cavity as a breccia lens well known from small meteorite craters.

Amazing at first is the laterally considerably extended body of increased density, which has to be assumed due to the annulus of relatively positive gravity anomalies and which, in the gravity model, forms the substratum of Lake Tüttensee. Peripheral gravity positive anomalies like that are unknown from impact structures. This is comprehensible since shock waves, rarefaction waves and divergent mass flow behind the shock front break up and loosen the rock even outside the structural crater. Gravity positive anomalies are found within very large impact structures when in the modification stage of impact cratering (Melosh 1989) on elastic rebound and collapse of the transient cavity denser rocks are uplifted from depth.

The positive anomalies at Lake Tüttensee require a different explanation, and a model is presented that follows processes during strong earthquakes: soil or rock liquefaction and post-liquefaction densification. Earthquake liquefaction may lead to enormous modifications of the earth's surface and immense damage. Liquefaction occurs when in water-saturated unconsolidated sediments the earthquake shock pressure exceeds the pore internal pressure, which may result in a breakdown of the framework, in a complete loss of strength and finally in a liquefaction of the rock ([1]). Due to the breakdown and liquefaction the pore water can be expelled on a grand scale leading to densification with significant volume reduction (Lee & Albaisa 1974, Tokimatsu & Seed 1987, Montgomery et al. 2003, and others). Soil subsidence on a meter scale after earthquakes as consequence of this densification is not unusual.

Similar processes possibly implying more far-reaching strong effects must have occurred in the impact with the formation of the Lake Tüttensee crater. The postulated giant explosion of the impacting projectile and the formation of 100 craters or more (the Lake Tüttensee crater included) within the impact strewn field (Rappenglück et al. 2004, Ernstson et al. 2010) may have touched the effects of most heavily earthquakes and possibly may have even topped them. And also the second prerequisite seems to be fulfilled: At the time of the impact an unconsolidated, porous and water-saturated sediment occupied the area of the today's Lake Tüttensee. Provided the densities of 1.7 and 1.5 g/cm^3 used in the modeling of the Grabenstätt channel are accurate, these values on water saturation involve c. 50 % - 65 % porosity (2.5 g/cm^3 matrix density) corresponding to respective large water quantities in the rock. Thus, greatest precondition for extreme shock liquefaction must have existed, probably far beyond the developing Lake Tüttensee crater.

In the gravity model for the Lake Tüttensee anomaly a density increase of 0.12 g/cm^3 (from 1.7 to 1.82 g/cm^3) is assumed. In a model of soil densification following soil liquefaction, this density increase leads to the computation of a c. 8 % volume reduction. This corresponds to an 80 cm compaction of a 10 m thick sediment layer, which is a plausible quantity and of the order of compaction observed in earthquakes, all the more in an earthquake only the rock framework breaks down expelling the pore water. A meteorite impact implying energetic mass flow behind the shock front should be even far more effective with regard to compaction of water-saturated rocks of high porosity.

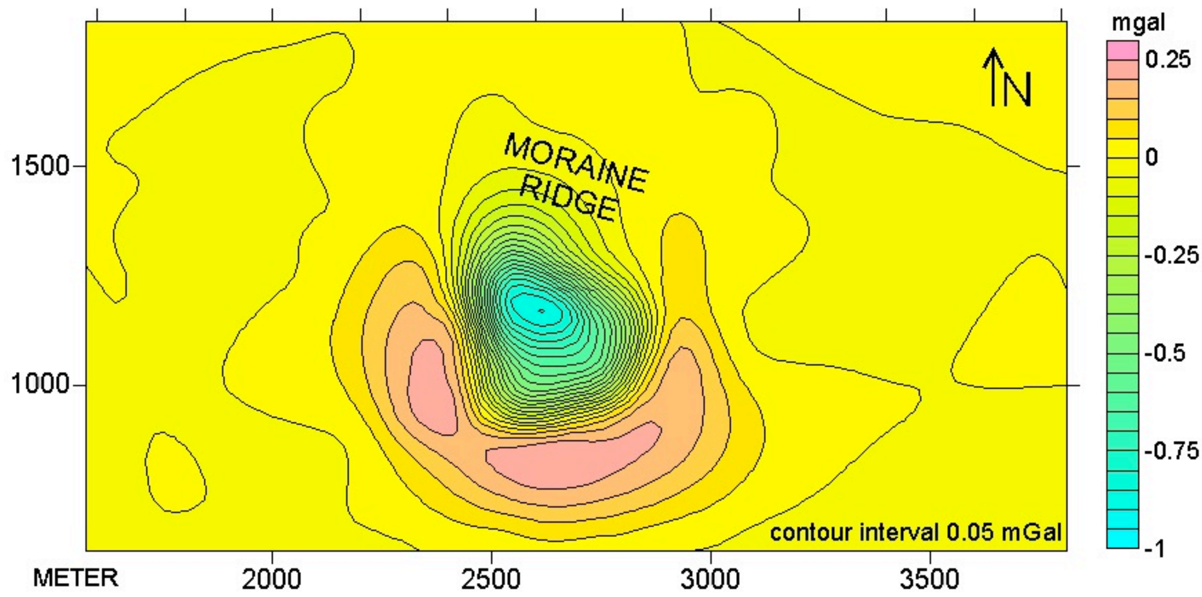

Fig. 19. The Lake Tüttensee gravity residual field and the moraine ridge corresponding with a gap in the positive ring anomaly.

The obvious gap in the positive ring anomaly (Fig. 19) may indirectly support the model of liquefaction and densification. As designated in the figure, the northern part of Lake Tüttensee is geologically different from the rest of the field. A ridge of relatively dense moraine material contrasts with the fluvio-glacial sands and gravels otherwise exposed everywhere. Hence, the shock front must have come across the already existing solidification of the moraine that possibly became rather loosened than compacted.

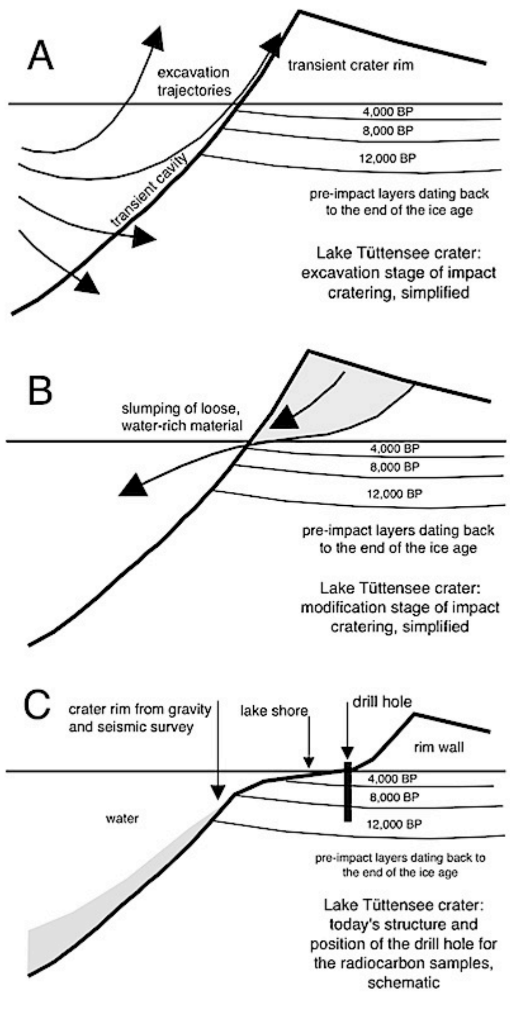

Fig. 20. Schematic diagram (not to scale) showing the formation of the Lake Tüttensee crater and the location of the drill hole cited by Doppler et al. (2011). A) formation of the crater B) subsequent slumping of the rim C) the situation today. The drill hole is positioned over the largely undisturbed pre-impact layering. Figure first published in Antiquity, 85, 2011, p. 279.

A further outcome of the gravity survey is worth being discussed, which is the crater rim diameter and configuration. As outlined in Fig. 18, the true meteorite crater as deduced from the gravity horizontal second derivative is smaller than the Lake Tüttensee and much smaller than the 600 m-diameter ring wall of the impact structure (meanwhile confirmed by sediment echo sounder profiles across Lake Tüttensee, see above). This has led to some confusion and misinterpretation when a borehole drilled onshore by opponents of the meteorite impact origin had encountered a sequence of peat and lake sediments obviously largely undisturbed and, from radiocarbon dating, older than the postulated impact event (Doppler et al. 2011). In their opinion, peat and sediments at the location of the drill hole within the ring wall must appear extremely wrecked and heated from the impact. This attests an amateurish comprehension of impact processes. Outside the original cavity of the crater, shock intensities are already lowered to such a degree (a few kbars maximum pressure) that minor deformations are not possibly to be seen in a few-centimeter diameter sized drill core, not to mention the absence of any detectable enhanced temperature signature. Therefore, the arguments of Doppler et al. (2011) who further on maintain a glacial origin of Lake Tüttensee have been rejected by Rappenglück et al. (2011) pointing to the development of the Lake Tüttensee crater in the cratering process and the utterly unsuited location of the borehole for dating the impact event (Fig. 20).

One more feature of the gravity image in Fig. 17 and the crater rim outline in Fig. 18 is pointed out. Although the gravity second-derivative anomaly proves to be quite circular on the whole, a kind of triple bulge is conspicuous. This may be attributed to a superposition of the impact of a disintegrated projectile as is considered the case for other asymmetrical meteorite craters like e.g. the largest crater in the Henbury, Australia, strewn field. Moreover, the doublet crater structure in Lake Chiemsee mentioned in the Introduction points to a twin impact into the lake. Altogether, these multiple-impact craters are most compatible with the model of a very large disintegrated, loosely bound cosmic projectile (a comet or a *rubble pile* asteroid) to have produced the extensive Chiemgau impact strewn field (Rappenglück et al. 2004, Ernstson et al. 2010).

7 Conclusions

The gravity measurements at Lake Tüttensee have shown that the original purpose of determining the crater depth by modeling the water (and organic matter) body was not achieved. The reason is the to this degree unforeseen complex density distribution in the surrounding rocks. At least, the gravity modeling shows that neither the official water depth nor the diver's alleged 70 m define the true impact crater. A depth between 20 m and 30 m seems to be most plausible, although the maximum depth of the transient crater in the excavation stage was probably much larger. As shown in Fig. 20, due to the extremely unconsolidated excavated material full of water, large masses must have slumped from a transient crater rim wall widely backfilling the cavity. This scenario explains the unusual discrepancy between the today's ring wall diameter (600 m) and the crater true diameter (300 m).

Perhaps the most intriguing result of the gravity survey is the existence of a broad ring-like zone of increased density around Lake Tüttensee (and possibly below it). A fully consistent model considers the impact shock causing a rock densification in the wake of liquefaction and an additional compaction in the course of highly energetic mass flow behind the shock front starting from the impact point. Thus, the impact origin for the Lake Tüttensee kettle is also strengthened from geophysical investigations. By contrast, a formation as a glacial dead-ice depression initiated by the melting of glacier ice and subsequent subsidence of fluvio-glacial material (Doppler & Geiß 2005, Darga & Wierer 2009, Doppler et al. 2010) meets insurmountable problems to explain the densification.

If the model remains valid, more detailed investigations within the frame of impact research would be a worthwhile task, because hitherto on Earth comparable situations have not been recognized and studied. Further studies may be interesting for the understanding of impact cratering in targets composed of unconsolidated and extremely water-rich rocks. On Mars, liquefaction due to impact events is considered to be possible (Clifford 2004, Wang et al. 2005) based on the comparison with terrestrial earthquake-induced liquefaction, and Komatsu et al. (2007) suggest that layered ejecta structures and small mounds in the vicinity of impact craters in high northern latitudes of Mars could be explained by this mechanism.

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