High-resolution digital terrain models DTM: Rayleigh-Taylor and Kelvin-Helmholtz instabilities and impact cratering in unhardened loose sediments - the Holocene Chiemgau airburst impact case

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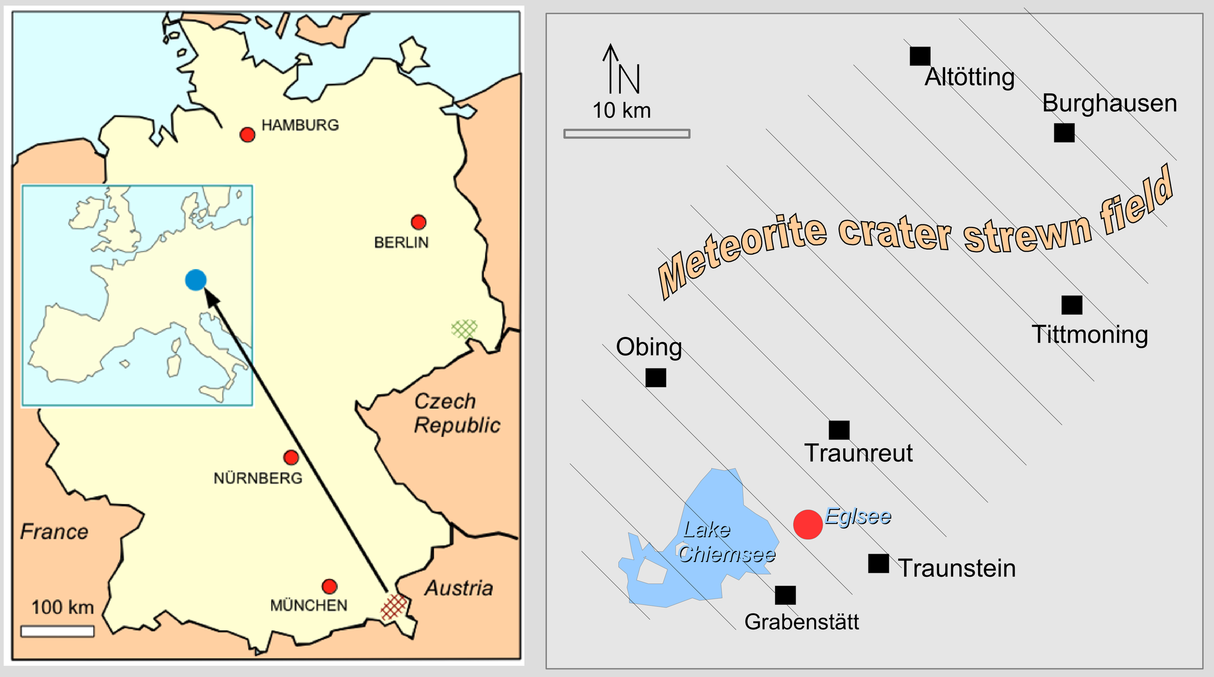
Introduction: Special features in impact craters, often seen in lab experiments, may be caused by Rayleigh-Taylor (RT) and Kelvin-Helmholtz (KH) fluid instability related to viscosity/inertia/density/velocity differences, with RTI occurring from density inversion during deceleration, forming plumes, while KHI happens with velocity shear creating wave-like deformations, both generating complex mixing layers. RTI in impact cratering (mushrooming) happens when a denser impacting liquid or solid ejecta hits a less dense target fluid or surface, and the deceleration causes the interface to become unstable, lifting the denser matter up and pushing the lighter matter down. This creates mushroom-shaped plumes or fingers growing outward from the impact site. While this process is commonly observed in lab experiments of liquid impacts, it is less common in large terrestrial craters where it may happen due to different physics like vaporization or shock waves. KHI occurs at the interface between two layers with different velocities, creating a velocity shear forming wave-like patterns. While RTI may drive the mushroom shape in impacts to form central uplifts (besides e.g., rebound) KHI can occur in turbulent impact ejecta or mixing zones, contributing to complex dynamics. Hence, RT produces mushroom and finger structures, while KHI instability is velocity-driven and may produce wavy impact phenomena.[1]. It is understandable that both processes can interact in the formation of impact structures. Here we report on obvious RTI and KHI instabilities that can be observed regularly in the extremely high-resolution digital terrain models with the aforementioned crater features (fingers, mushrooms, waves, splashing) related to the low-altitude touchdown airburst impact of the Chiemgau impact strewn field.



Location maps

The Chiemgau impact and the DTM

The Chiemgau meteorite impact, suggested some 20 years ago, is now established as the world's currently largest Holocene impact site, which has been dated to 900-600 B.C. in the Bronze Age/Celtic era. The Digital Terrain Model DTM (in Germany the DGM 1 [2]) maps the topography of the earth's surface with a dense data network obtained from laser scanning (LiDAR) from an airplane. The DTM data used here for a 1 m x 1 m grid at a vertical resolution of 10 cm (even lower with interpolation) capture the bare ground without buildings and vegetation, even in dense forests and swamps. We have been using the DGM 1 for several years to systematically search the Chiemgau impact strewn field for new impact findings applying this extremely high-resolution method, which has now led to well over 100 new structures with diameters up to 1,300 m [3-6]. In addition, the DTM has led to the Chiemgau crater strewn field being now understood as the result of a low-altitude "touchdown" airburst impact with associated crater shapes, some of which are highly complex [4].

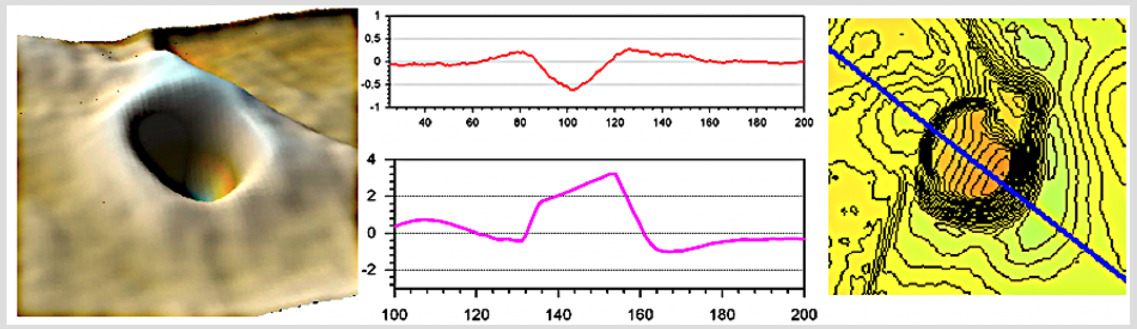
KHI and RTI relevant Chiemgau impact target rocks

Typical Quaternary layered deposits consist of loess loam, silt, clay, sand, gravel, and any mixture of these fractions, e.g., sandy loam, sandy silt, clayey sand, sandy gravel, in addition to special formations such as interbedded layers of highly consolidated conglomerates (Nagelfluh).

Densities: Densities of involved rocks may vary considerably and are (in g/cm3) dry sand 1.5-1.6, dry gravel 1.3-1.7, groundwater-saturated sand 1.9-2.0, clay 1.9-2.2, Nagelfluh 2.4, dry silt down to 1,0-1,2.

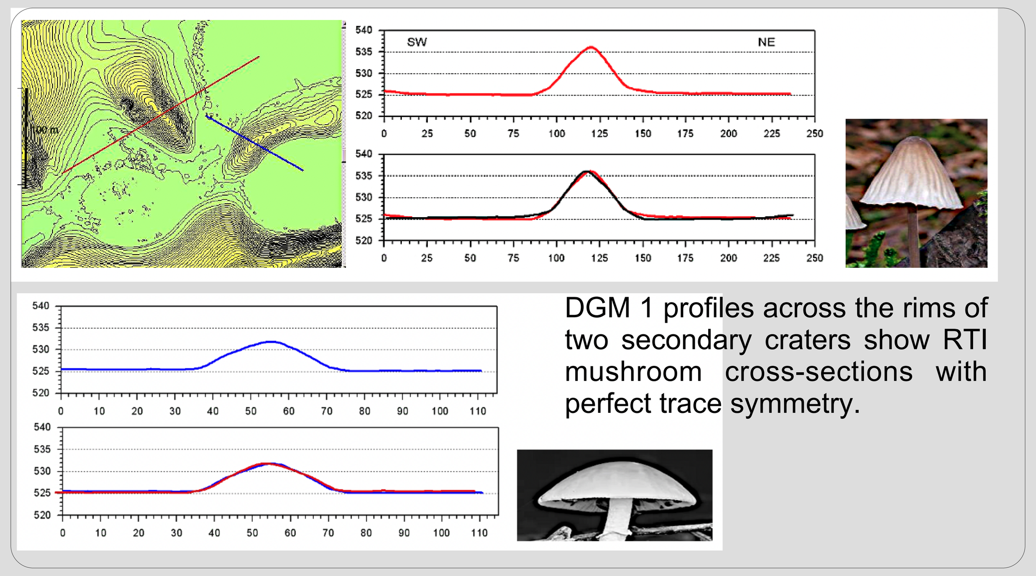
Viscosities: The viscosities of the unconsolidated rocks affected by the touchdown impact differ by many orders of magnitude, with the pre-impact viscosities of the target rock, such as composition, grain size, texture, and water content, but also the impact parameters, such as temperature, pressure, and strain rate, are playing an important role.

Selection of RTI and KHI features in Chiemgau impact structures

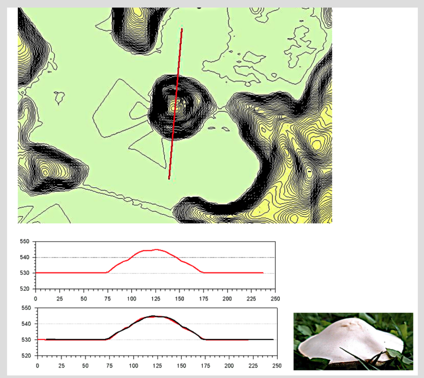


In the case of the Chiemgau impact, we generally contrast the predominant number of simpler, walled, bowl-shaped craters with the complex structures (Fig. 2), for which we show the RT and KH instabilities in maps and profiles (meter scales; some after removal of a trend field)..

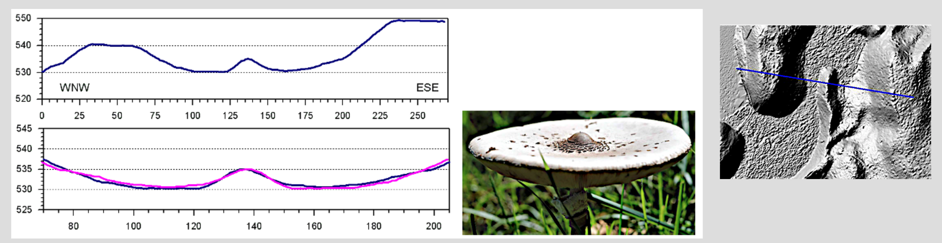
Rayleigh-Taylor instabilities: Mushroom structures



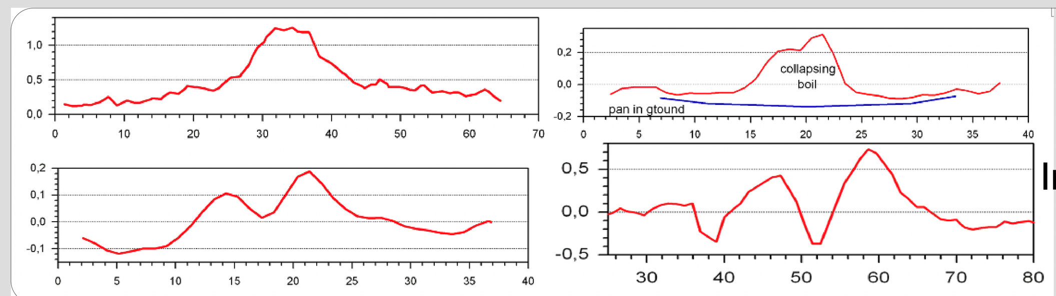
DGM 1 profiles across the rims of two secondary craters show RTI mushroom cross-sections with perfect trace symmetry.



A 100-meter-wide, 15-meter-high, gently terraced mushroom-shaped hill, as described by RTI, with perfect symmetry at the decimeter scale over a 100-meter span and a black-mirrored profile.

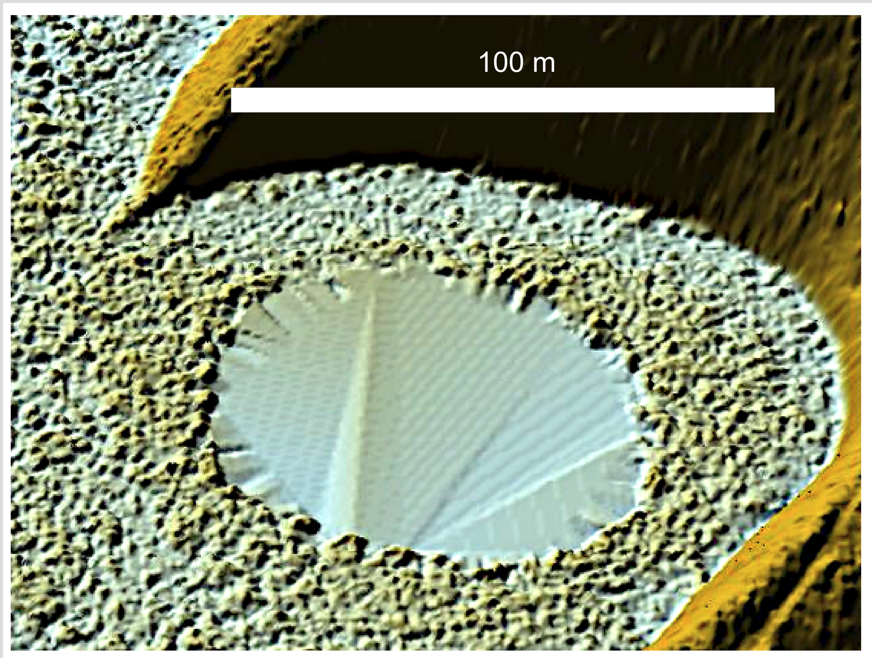


Eastern edge of Lake Kesselsee crater. Rib-like RTI finger structure with a distinctive mushroom-shaped cross-section and perfect trace symmetry.

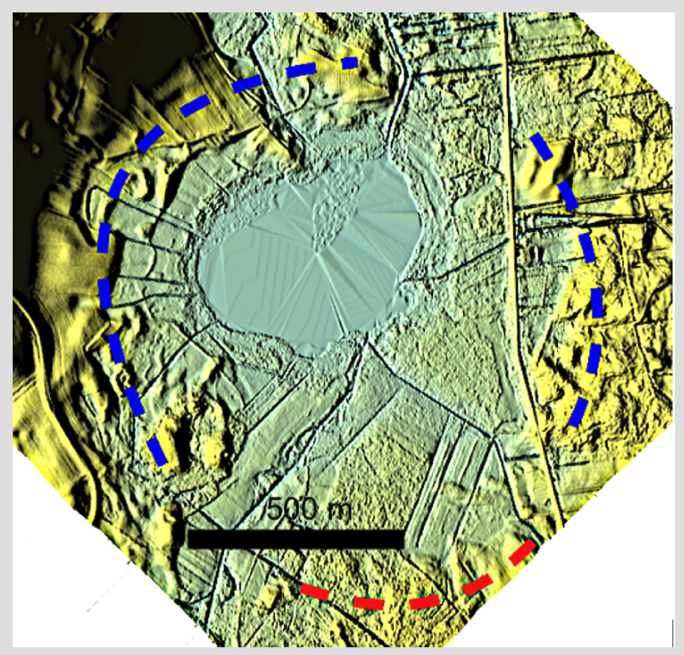


Increasing collapse of mushroom impacts.

Rayleigh-Taylor instabilities: Splashing of crater rims

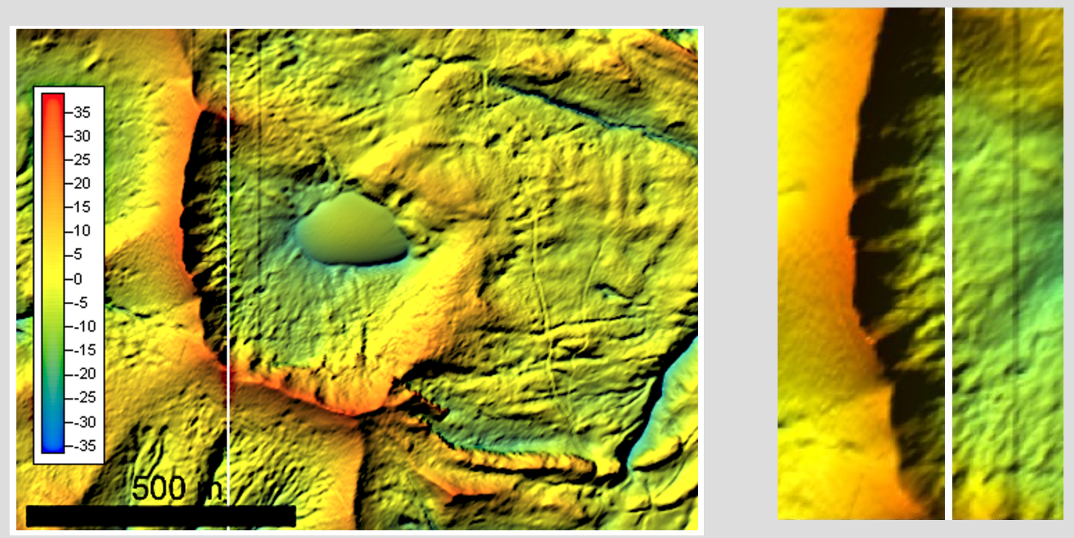


The Schernsee Crater as a DGM 1 3D block model of the terrain surface, viewed at a slight angle. The sawtooth pattern along the lake's edge turns out to be a circumferentially periodic arrangement of roughly equidistant, roughly equal-sized boulders, which almost perfectly document a KTI movement structure that originated from a central circular impact load.



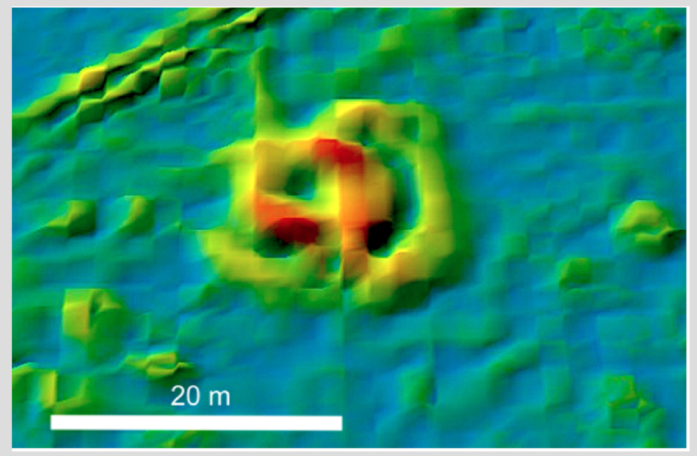
Lake Eschenau crater, DGM 1 surface. Blue: splashed crater rim; red: fingered crater rim.

Rayleigh-Taylor instabilities: Finger structures

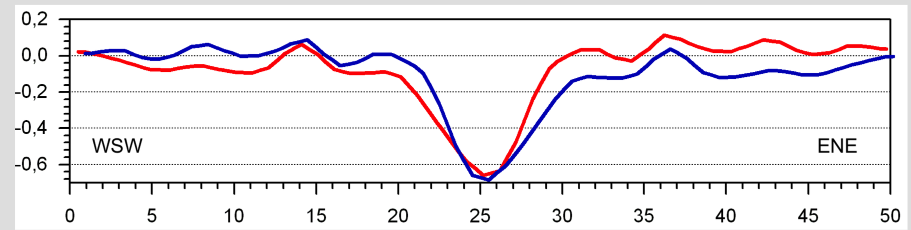


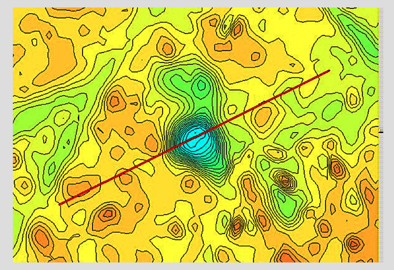
Lake Grünsee crater, DGM 1 surface. RTI crater fingering, sawtooth-like rim wall.

Kelvin-Helmholtz instabilities: Wavy structures



Emmerting 004 crater, DGM 1 surface. Wavy crater rim-





Crater with significant broad wavy rim wall zone. Note the roughly concentric mushrooming around the crater bowl. The superposition of the red profile and its blue mirror shows remarkable trace symmetry over 50 m

Discussion and Conclusions

The Chiemgau impact is an impact crater field measuring at least 60 km x 30 km with well over 100 craters in a Quaternary loose sediment substrate.

<>The discovery of this new, very large number of craters is thanks to the new possibilities offered by the LiDAR Digital Terrain Model DGM 1, which, with an extremely high resolution of 1 m (interpolated decimeter) horizontally and 0.1 m (interpolated centimeter) vertically, even detects craters in dense vegetation (e.g., in forests) and reveals complex crater morphologies in the highest possible detail.

<>The DGM 1 show that the craters created by the impact are largely bowl-shaped with walls, but also have some very complex structures such as mushroom shapes, finger shapes, multiple rings, wave patterns, and fragmented edge zones.

<>The formation of such complex shapes can be explained, as here, by impacts known primarily from experiments with liquids, through so-called Rayleigh-Taylor (RTI) and Kelvin-Helmholtz (KHI) instabilities.

<>We apply these RTI and KHI processes to the layers in the Chiemgau impact area, which consist of alternating beds of loose sediment with greatly varying densities and viscosities of the rocks involved.

<>Based on these very complex crater shapes, we conclude that they rule out a normal geological origin such as sinkholes or other collapse structures, as well as relics of the last ice age in the form of dead ice holes, as is still claimed by some people, even by official sources.

<>The large accumulation of these very special, sometimes exotic crater structures in the roughly elliptical strewn field of the Chiemgau impact proves once again the reality of the existence of this currently largest Holocene impact event worldwide.

<>It also shows that databases and statistics on currently established terrestrial impacts, to which the impact literature consistently refers, are no longer relevant.

References: [1] Modified and shortened from Google Chrome AI [2] Geodaten Bayerische Vermessungsverwaltung. [3] Ernstson K. and Poßekel J. (2025) MetSoc. Meeting 2025, Abstract #5312. [4] Ernstson K. and Poßekel J. (2024) LPSC 2024, Abstract #1658. [5] Ernstson K. and Poßekel J. (2020) 11th PPC 2020, Abstract #2019. [6] Ernstson K. and Poßekel J. (2024) AGU 2024, Abstract #EP01-29.