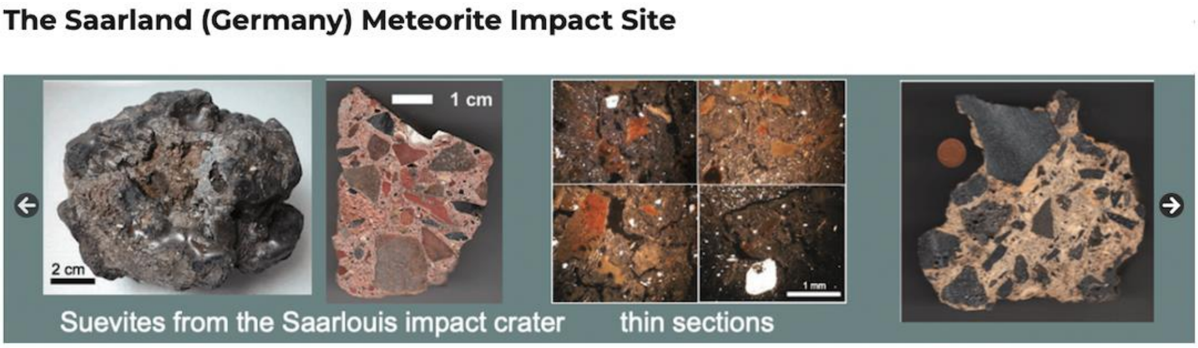

Rayleigh-Taylor and Kelvin-Helmholtz instability structures in the Saarland impact event

The "touchdown" airburst impact and the extremely high-resolution digital terrain models

Kord Ernstson[1] **and Jens Poßekel**[2]

Abstract. - The Saarland impact in Germany, with a scatter field at least 15 km in size, has been recognized for over 10 years as possessing all impact-specific features acknowledged by research (crater, pronounced shock metamorphism, shatter cones, impact breccias such as suevite, impact glasses, and impact melt rocks) as a remarkable, presumably Holocene impact event. Given the compelling evidence of a near-surface airburst impact, the detection of Rayleigh-Taylor and Kelvin-Helmholtz instability structures—first described in the Chiemgau impact—is also documented in the Saarland impact through analyses of the extremely high-resolution digital terrain model. Since geological processes and anthropogenic constructs can be ruled out, this provides further evidence of a significant Saarland impact event, which is still regarded as non-existent by the established impact "community."

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1 **Introduction**

Distinctive features in impact craters, which are frequently observed in laboratory experiments, can be caused by Rayleigh-Taylor (RT) and Kelvin-Helmholtz (KH) fluid instabilities, which are related to differences in viscosity, inertia, density, and velocity (overview Google AI 2006).

In the laboratory: RTI occurs during a density inversion during impact deceleration and forms diapirs, while KHI occurs during velocity shear and generates wave-like deformations. Both phenomena lead to complex mixing layers. RTI during impacts (mushrooming) occurs when a denser liquid or solid ejecta material strikes a less dense landing material, and the deceleration destabilizes the interface, causing the less dense material to be pushed upward and the denser material downward. This creates mushroom-shaped diapirs or fingers that grow outward from the impact site.

In terrestrial craters: While this process is frequently observed in laboratory experiments with liquid impacts, it is rarely found in large terrestrial craters, where it may occur due to other physical processes such as vaporization or shock waves. KHI occurs at the interface between two rock layers moving at different speeds and generates a velocity shear that forms wave-like patterns. While RTI can lead to diapir (mushroom) formation and central elevations during impacts (alongside, for example, elastic rebound), KHI can occur in turbulent impact ejecta or mixing zones and contribute to complex dynamics. Therefore, RTI generates mushroom and derived finger structures (Fig. 1), while KH instability is velocity-dependent and can induce wave-like impact phenomena (Fig. 2).

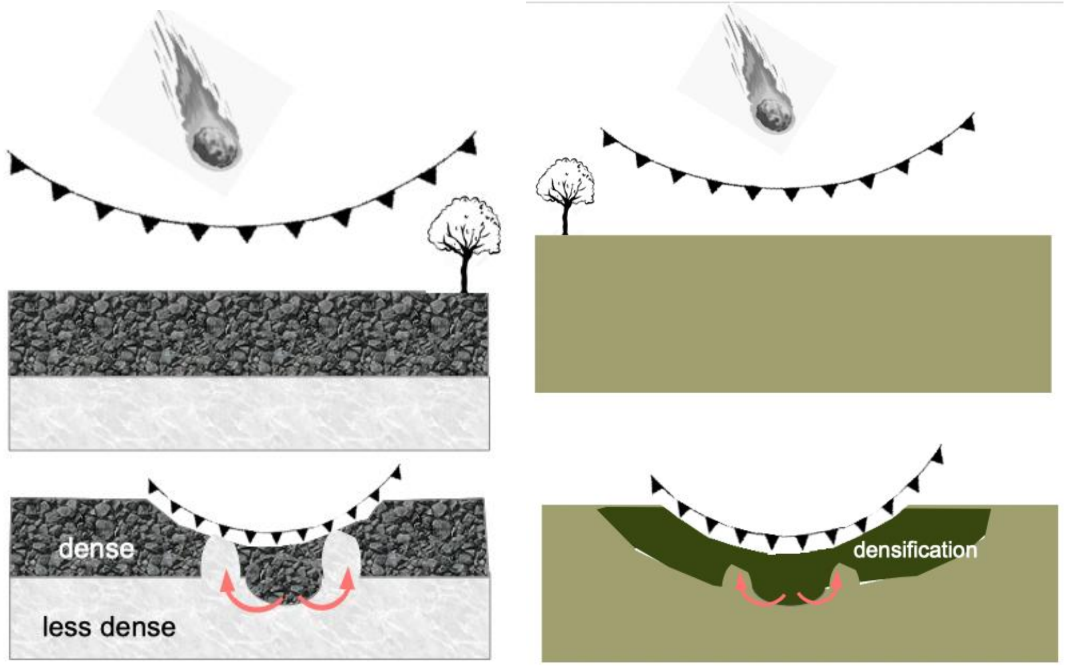

Fig. 1. Simple models for the formation of RTI mushroom and finger structures. Left: The shock front pushes the higher-density layer downward into the lower-density layer, causing the mushrooms and fingers to rise upward in response. Right: The shock front compresses the upper region, and the compressed material pushes downward while the underlying material rises upward in mushroom- and finger-like shapes.

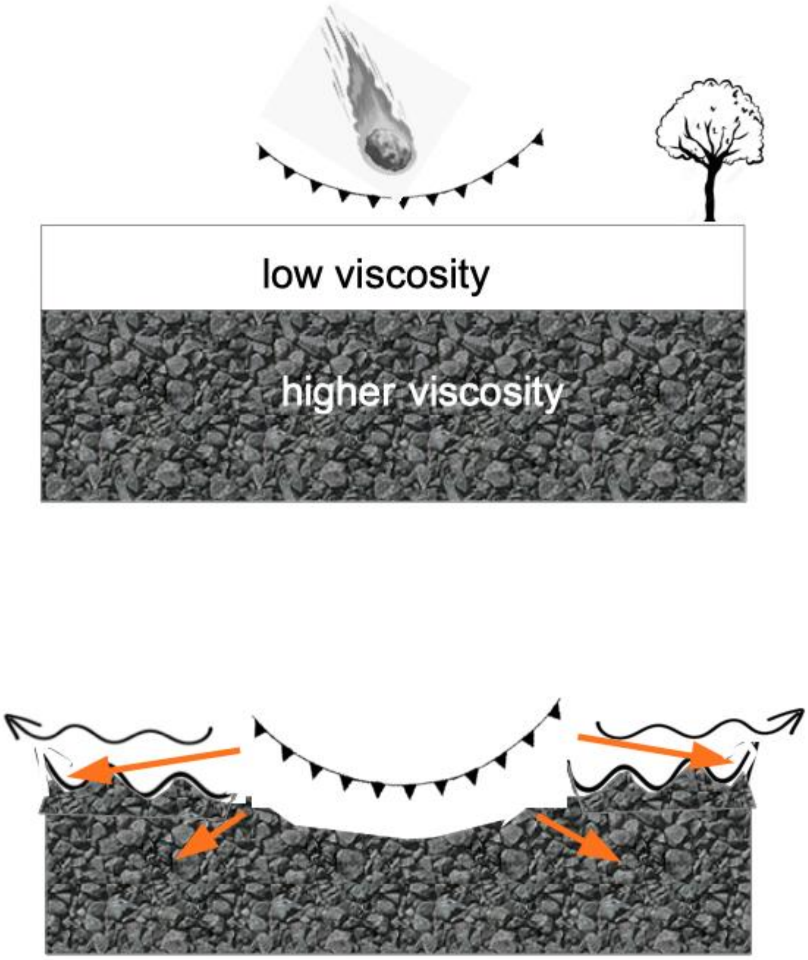

Fig. 2. Model for the formation of wave structures during KH instability. Upon impact, the lower-viscosity layer is pushed outward more easily and at a higher speed than the higher-viscosity, tougher layer.

It is understandable that both processes can interact in the formation of impact structures. Here we report on apparent RT and KH instabilities that can be observed in the extremely high-resolution digital terrain models with the aforementioned crater features (fingers, mushrooms, waves, block formations) from the airburst impact of the Saarland Impact Area.

2 The Saarland Impact [11, and contributions therein]

Based on the initial discoveries of impact traces by Werner Müller [7, 8], field investigations and material analyses evolved into what is now referred to as the "Saarland impact," which now encompasses two craters with diameters of 250 m and 2.3 km, respectively (Fig. 3). Surface finds of various impactites, including suevites, impact melt rocks, impact glasses, as well as monomictic and polymictic impact breccias with multiple impact-specific breccia generations, extend across an approximately elliptical area with an axis length of about 15 km and accompanying smaller impact zones, which has led to discussions and ultimately to the acceptance of a large near-surface airburst impact [2–5].

Clear evidence of the impact is provided by the widespread, intense shock effects (shock metamorphism) observed in the impactites, which encompass virtually all the evidence documented in impact research: planar deformation features (PDF) in quartz and other minerals, multiple sets of planar fractures (PF) in quartz, quartzite pebbles that have been completely transformed into diaplectic glass, diaplectic feldspars, ball-like structures associated with cristobalite and tridymite, toasted quartz, extremely deformed e mica with multiple sets of planar deformation features and multiple sets of closely spaced kink bands, as well as intense shock spallation in quartzite boulders and individual quartz grains [1]. Shattercones in quartzites further support the clear evidence of an impact [9].

Finally, this inventory includes the very special carbon impactite Chiemit, which—apart from the first discovery at the Chiemgau impact site—has been previously unknown in impact research [10].

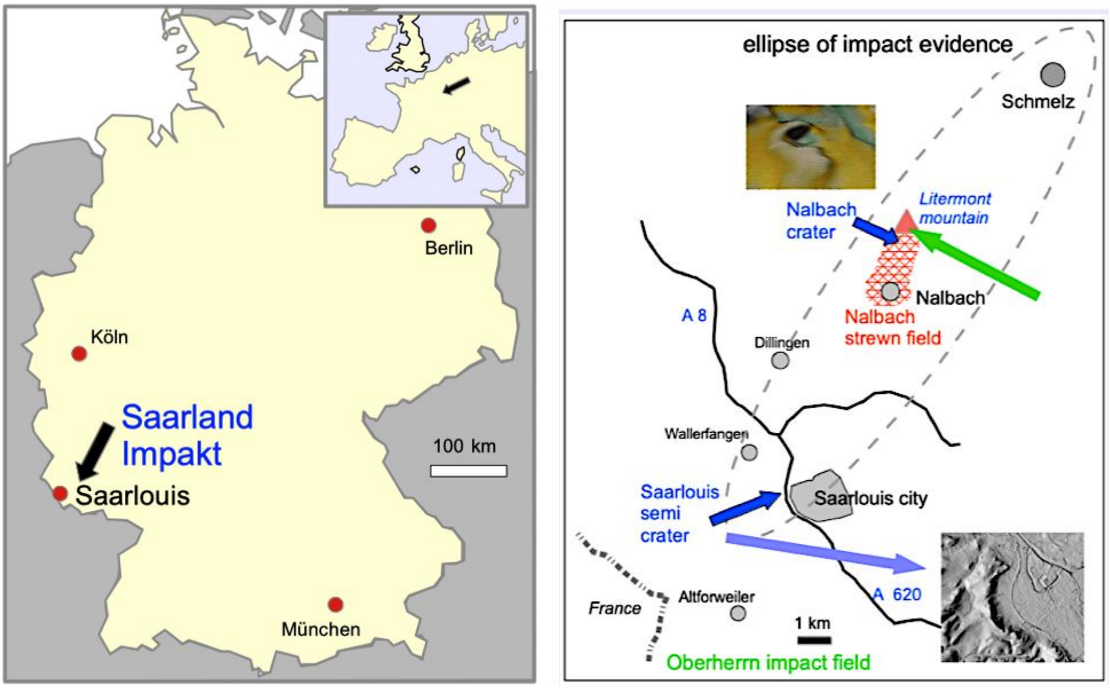

Fig. 3. Site maps. The associated crater field at Überherrn is characterized by dense clusters of smaller crater and hump structures.

3 The Digital Terrain Model (DGM 1)

The Digital Terrain Model (DGM) is based on aerial LiDAR data of the Earth's surface in a regular meter grid with extremely high elevation resolution. This allows for the precise identification of distinctive features, particularly in young meteorite craters and impact structures in general, that would never be discovered during fieldwork or on topographic maps. The bare earth surface is depicted independently of buildings and vegetation, even in dense forests. (X,Y,Z) files are made available for download online by the relevant authorities and can be used with data processing programs (filtering, gradient generation, etc., SURFER program) to create various map displays and terrain profiles. With the SURFER program, it is also possible to reduce the already extreme resolution through interpolation down to the decimeter and centimeter range.

A significant advantage of DGM mapping is that the extremely high-resolution morphology of the structures, due to their mostly perfect symmetry, excludes geogenic and anthropogenic origins down to the centimeter range , whereas point-like explosions of an airburst with spherical shock propagation down to the Earth's surface produce precisely what also forms an essential basis for the following explanations.

Regarding the following DGM 1 figures (maps and profiles), it should be noted that (with a few exceptions) a long-wavelength terrain trend was subtracted from the original morphological data in the SURFER program (extreme low-pass filter with 2D moving average), which means centering on a zero level. and the finer details of the impact structures are documented more precisely.

Source of DGM 1 data: Saarland - State Office for Surveying, Geoinformation, and Land Development

4 Topography and Geology

The topography of the impact area can be roughly divided into the regions of the two larger craters at Saarlouis and Nalbach and the widespread smaller structures, the latter of which in turn appear as clusters of craters and mounds (pockmarked and pustular) of varying sizes, primarily in the Überherrn impact field (Figs. 1, 3).

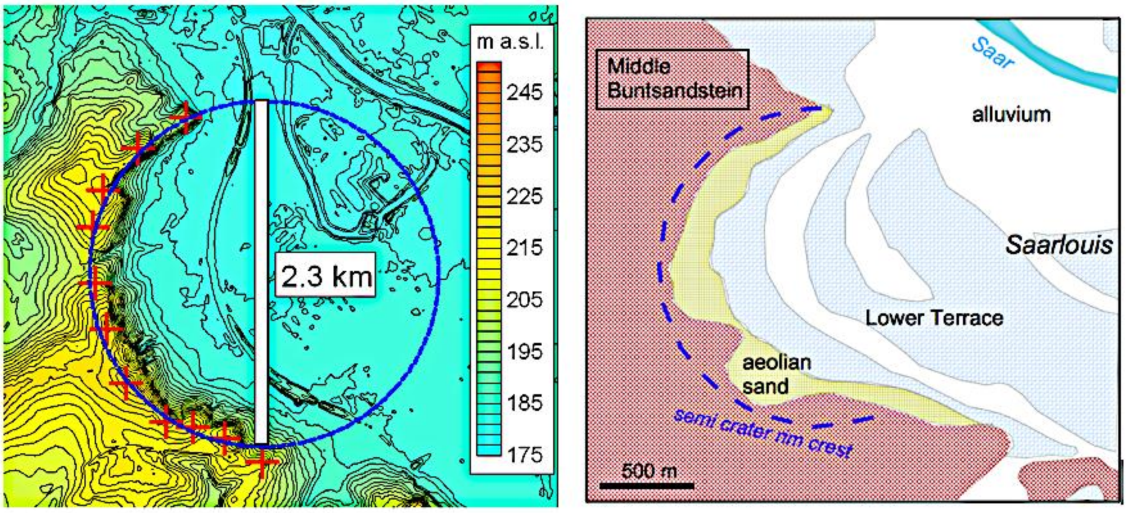

Fig. 4. The DGM 1 (contour interval 2 m) of the Saarlouis impact half-crater. The red crosses mark the rim of a perfect circular segment with an associated crater diameter of 2.3 km. Right: The corresponding section of the simplified geological map (geoportal.saarland.de).

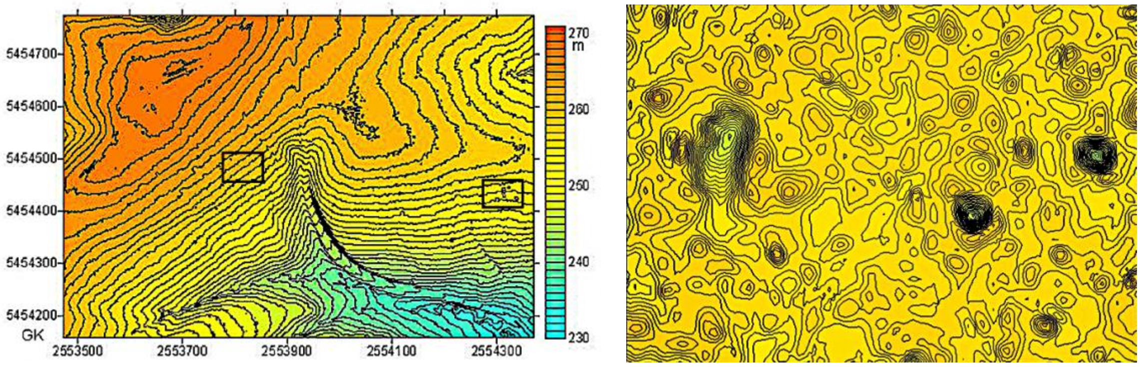

Fig. 5. The digital elevation model of the Überherrn impact area; contour interval 1 m, the map scale is in meters. Right: the eastern section of the map showing craters and a dense cluster of dome structures; contour interval 5 cm.

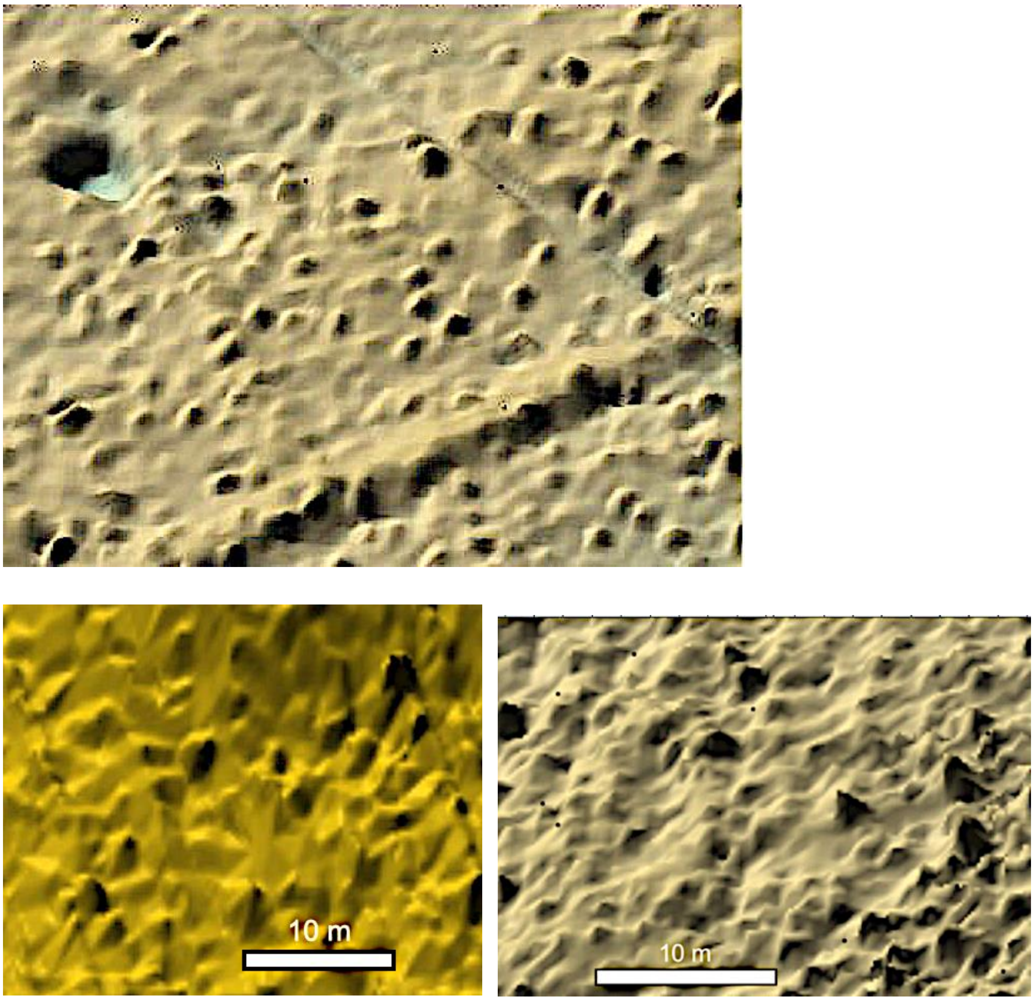

Fig. 6. Pockmarked and pustular impact terrain at the Saarland impact site (Überherrn, top; western section shown in Fig. 5), at the Chiemgau impact site (Vogelöd, bottom left), and at a Czech impact scatter field. Such distinctive morphological features are evidently characteristic of near-surface airburst impacts with falling explosion debris. Note the pronounced elevation in the DGM 1 block models: The heights of the humps are usually only a few decimeters (see the following profile figures) and are not visible to the naked eye.

3 Rocks and parameters relevant to KHI and RTI at the Saarland impact

Typical Quaternary sedimentary deposits, which play a decisive role near the surface during the airburst “touchdown,” consist of loess, loam, silt, clay, sand, gravel, and various mixtures of these fractions, e.g., sandy loam, sandy silt, clayey sand, and sandy gravel.

Densities: The densities of the affected rocks can vary considerably and range (in g/cm^3) from 1.5–1.6 for dry sand, 1.3–1.7 for dry gravel, 1.9–2.0 for groundwater-saturated sand, 1.9–2.2 for clay, and up to 1.0–1.2 for dry silt.

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

4 Selection of RTI and KHI features in the Saarland impact structures

4.1 Rayleigh-Taylor Instabilities: Mushroom Structures

As described above in section 3, RTI instabilities form primarily when, in layered media, density differences under pressure (in the simplest case due to gravity, with denser liquids above less dense ones) lead to vertical mixing and the formation of characteristic structures (mushrooms, fingers). During the impact with the airburst shock wave and the explosion debris striking the Earth’s surface, this situation arises due to a spontaneous, strong compaction of the uppermost layers, which are accelerated against the uncompacted loose sediments and lead to the RTI structures (Fig. 1). It is easy to understand that in this process, the subsurface layering with varying rock densities and viscosities leads to very specific shapes, as illustrated below.

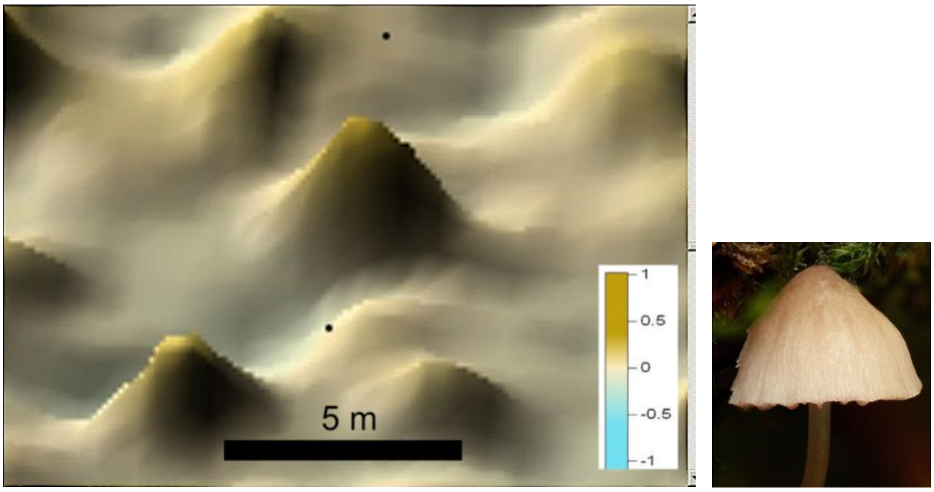

Fig. 7. RTI mushrooms; DGM 1, 3D surface block model, slight oblique view, and the eponymous mushroom. Note the pronounced DGM 1 elevation.

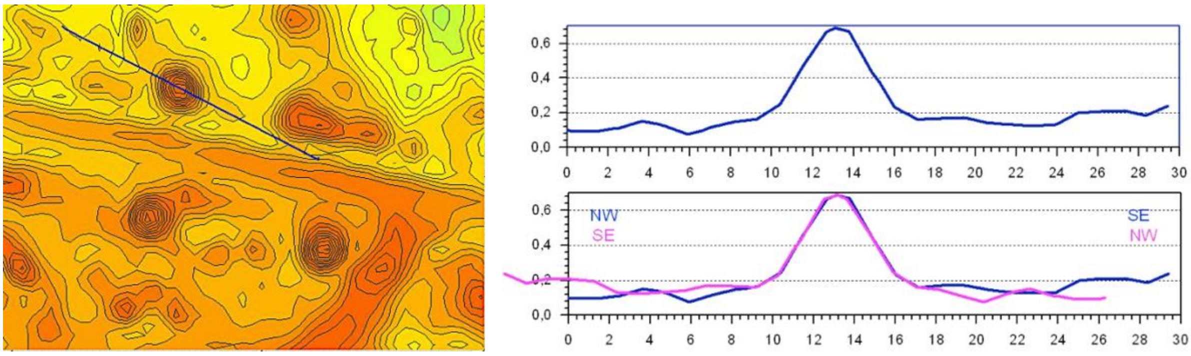

Fig. 8. Ensemble of RTI mushrooms. DGM 1, contour interval 5 cm. Profile in blue and trace (pink). Centimeter-precise superimposition over 10 m of the hump rules out geological and anthropogenic origins.

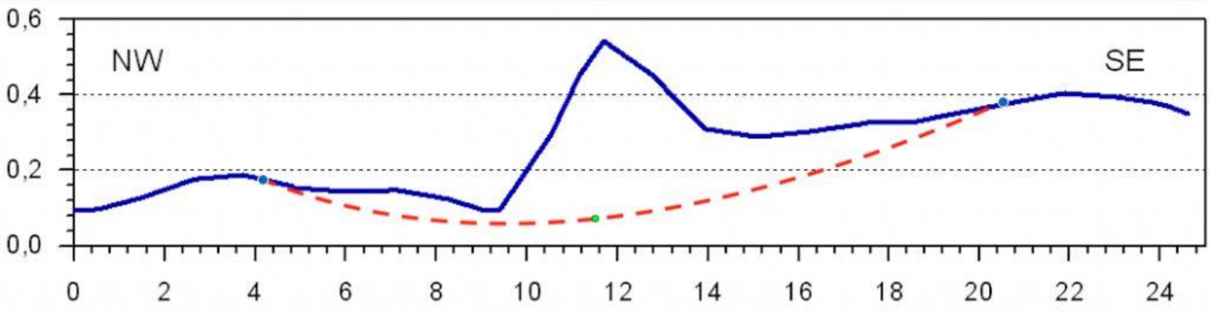

Fig. 9. RTI mushroom in a shallow depression.

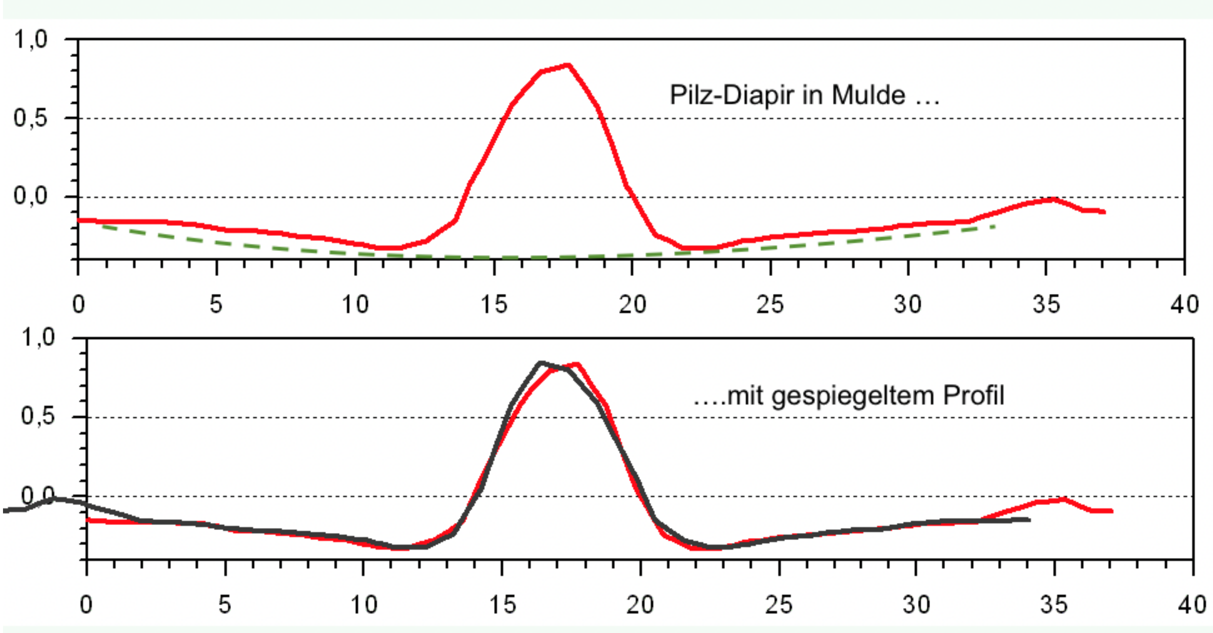

Fig. 10. RTI mushroom in a depression. Centimeter-level accuracy of the mirrored profile over 35 m.

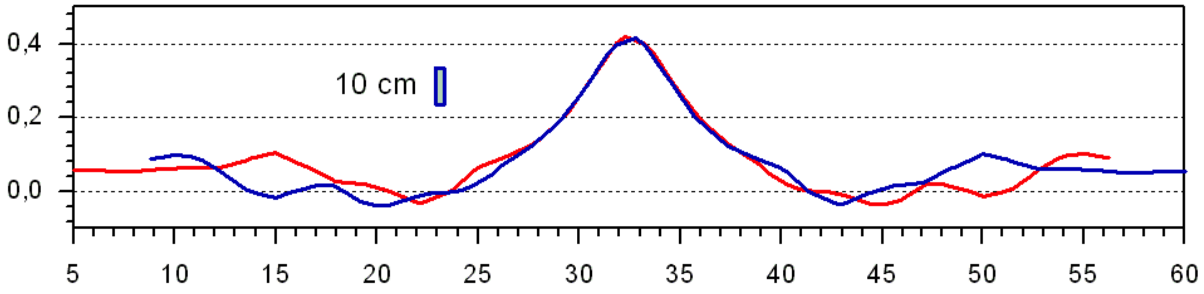

Fig. 11. Slightly terraced RTI mushroom in a shallow depression with a mirror superposition of the profile.

4.2 Rayleigh-Taylor Instabilities: Finger Structures

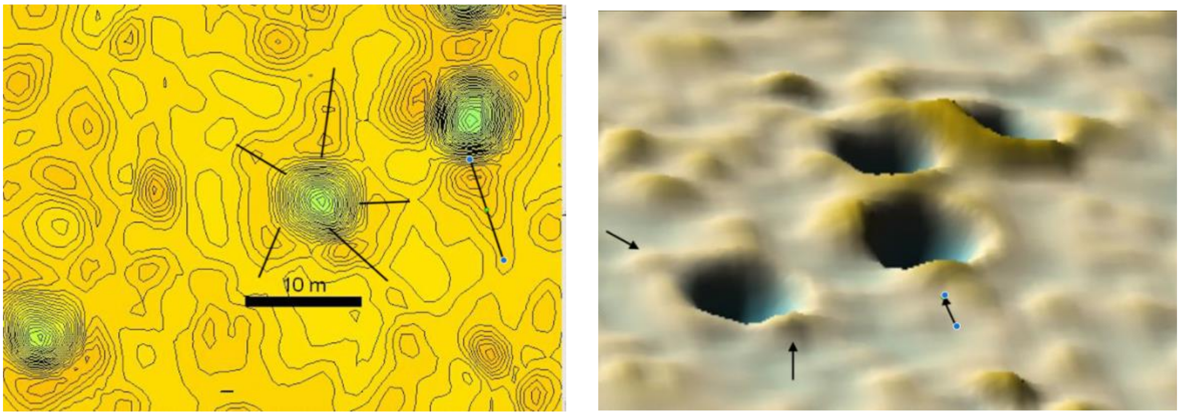

Fig. 12. DGM 1 of crater ensemble, topographic map (contour interval 5 cm), and 3D block model. RTI fingers as protrusions of the crater rim.

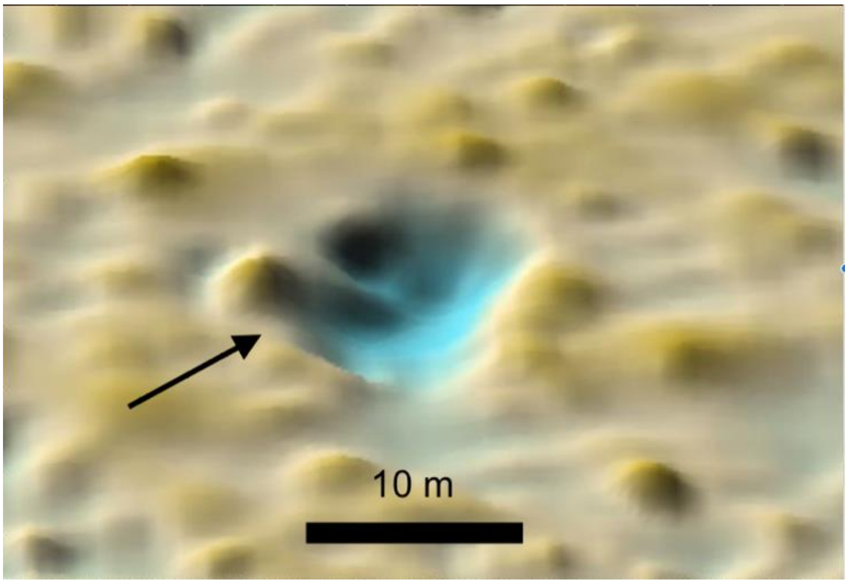

Fig. 13. DGM 1 block model of a crater; protrusion of the rim as an overlay of mushroom and finger structures.

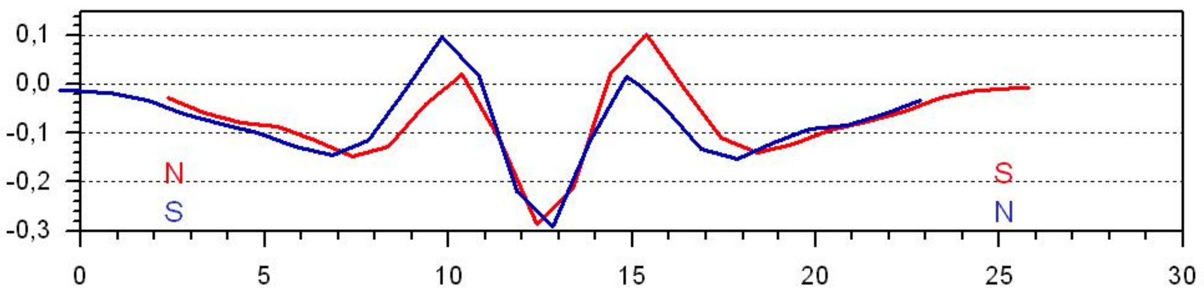

Fig. 14. Presumably collapsed RTI mushroom or finger formation in a crater basin with pronounced mirror symmetry over a profile length of more than 25 m.

4.3 Kelvin-Helmholtz Instabilities: Wave Structures

KHI instabilities with wave structures arise in shear layers between two materials moving at different speeds (Fig. 2). It is evident that this is precisely what occurs during an impact, particularly in layered loose sediments, where the impact shock front penetrating the subsurface leads to concentric or lateral layer displacements with, under certain circumstances, significant velocity differences, especially in the presence of substantial changes in viscosity.

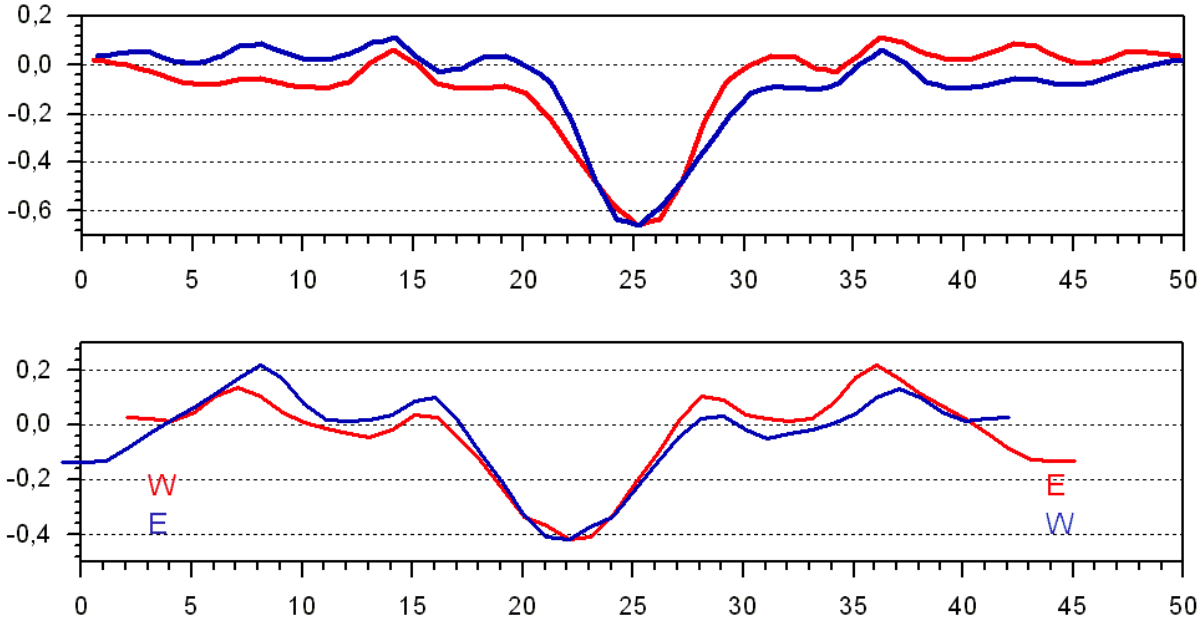

Fig. 15. Impressive wave structures with pronounced, centrally induced mirror symmetry over 40–50 m.

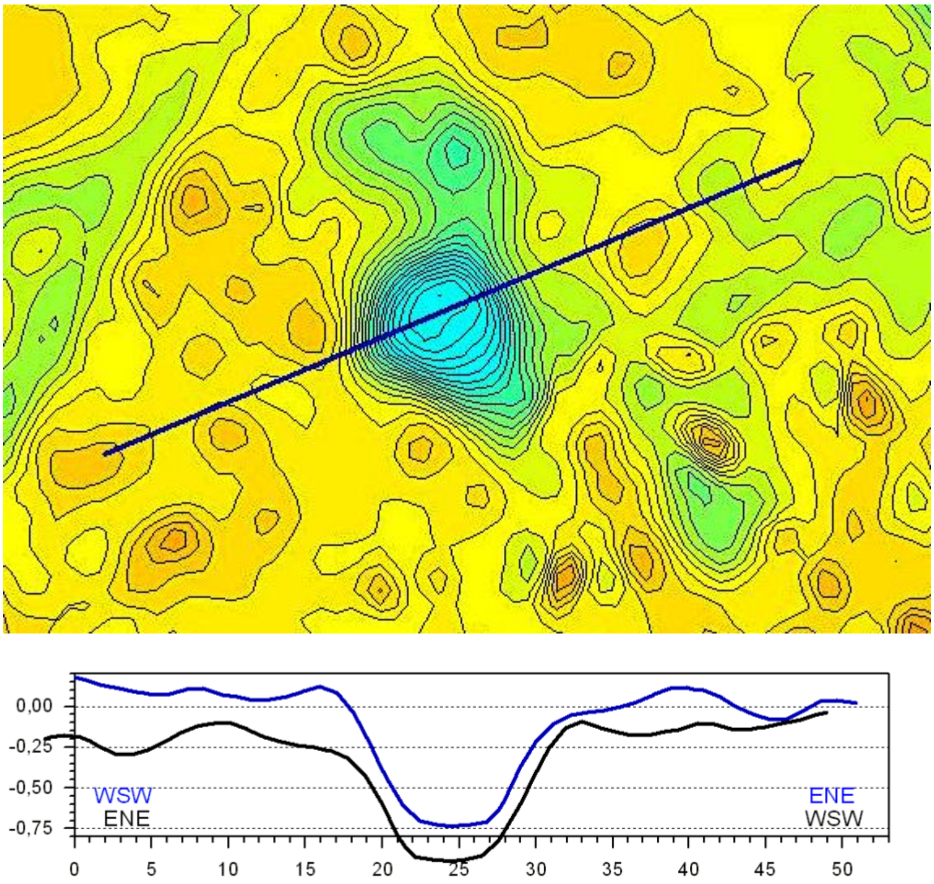

Fig. 16. Wave structure consisting of ring-shaped mushrooms.

4.4 Combined structures resulting from Kelvin–Helmholtz and Rayleigh–Taylor instabilities

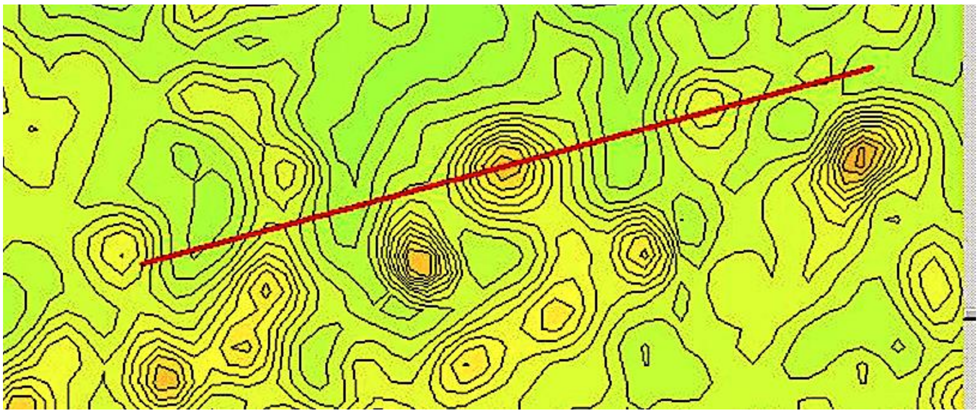

Fig. 17 A. RTI vortices with KHI-wavy framing. Profile in Fig. 17 B.

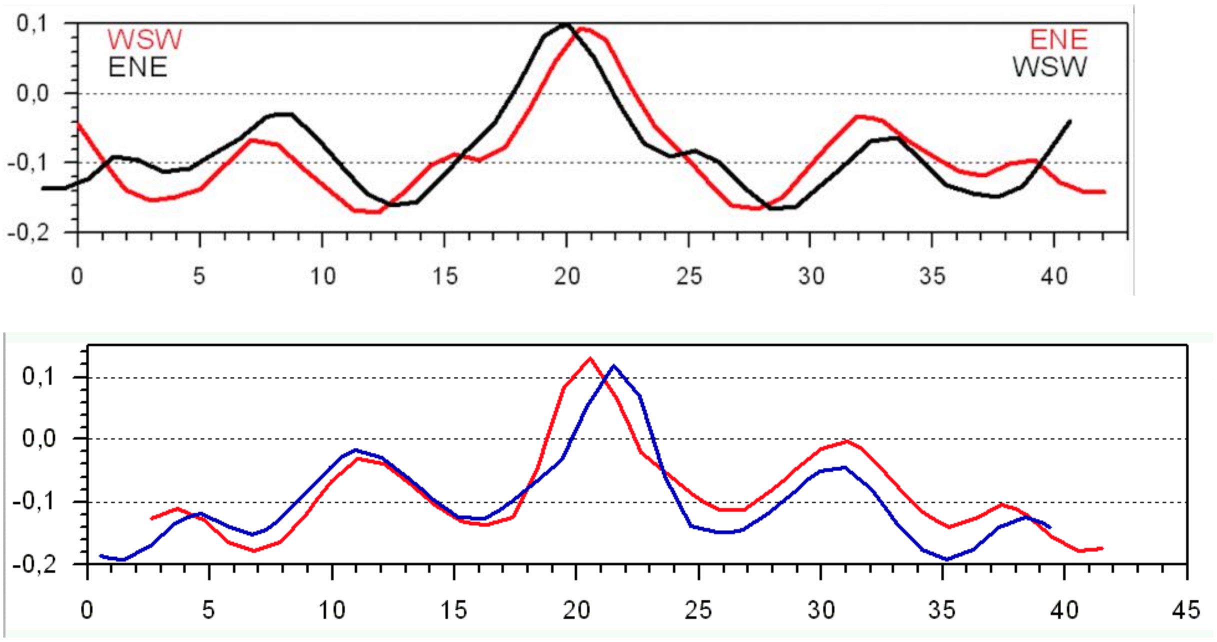

Fig. 17 B. RTI vortices with KHI-wavy framing. DGM 1 topography (17 A) and profile above, and a strikingly similar profile below, each with mirrored traces. Upside-down versions of the profiles in Fig. 15 come to mind. An explanation lies in strongly differing density and/or viscosity profiles of the underlying layers.

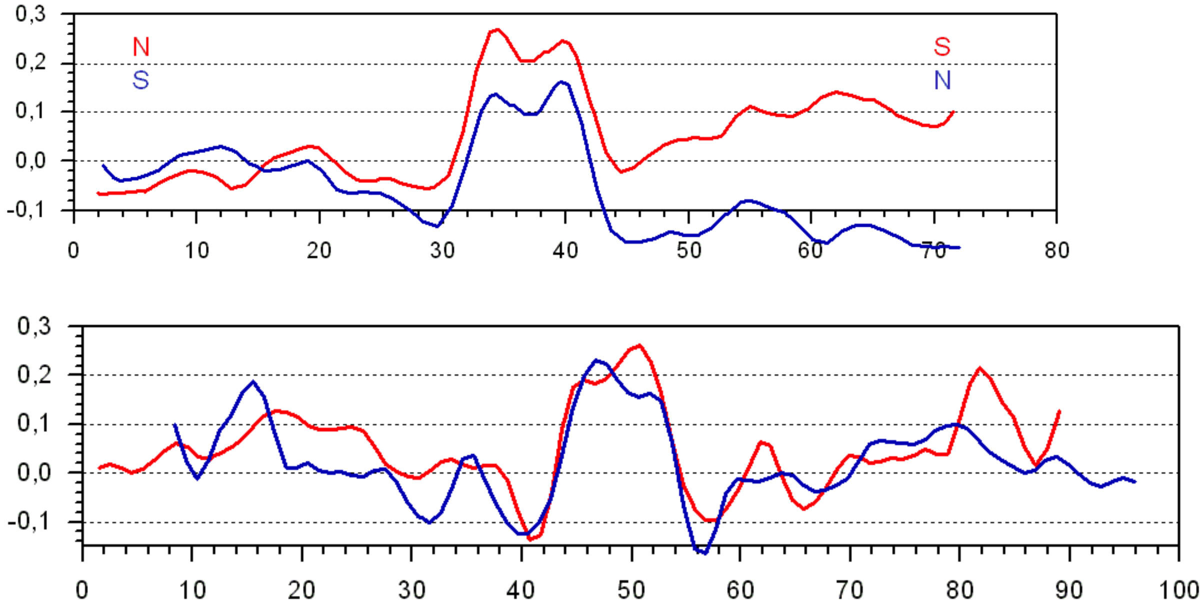

Fig. 18. DGM 1. Incipient collapse of RTI mushrooms in KHI-wavy depressions (with respective trace reflections).

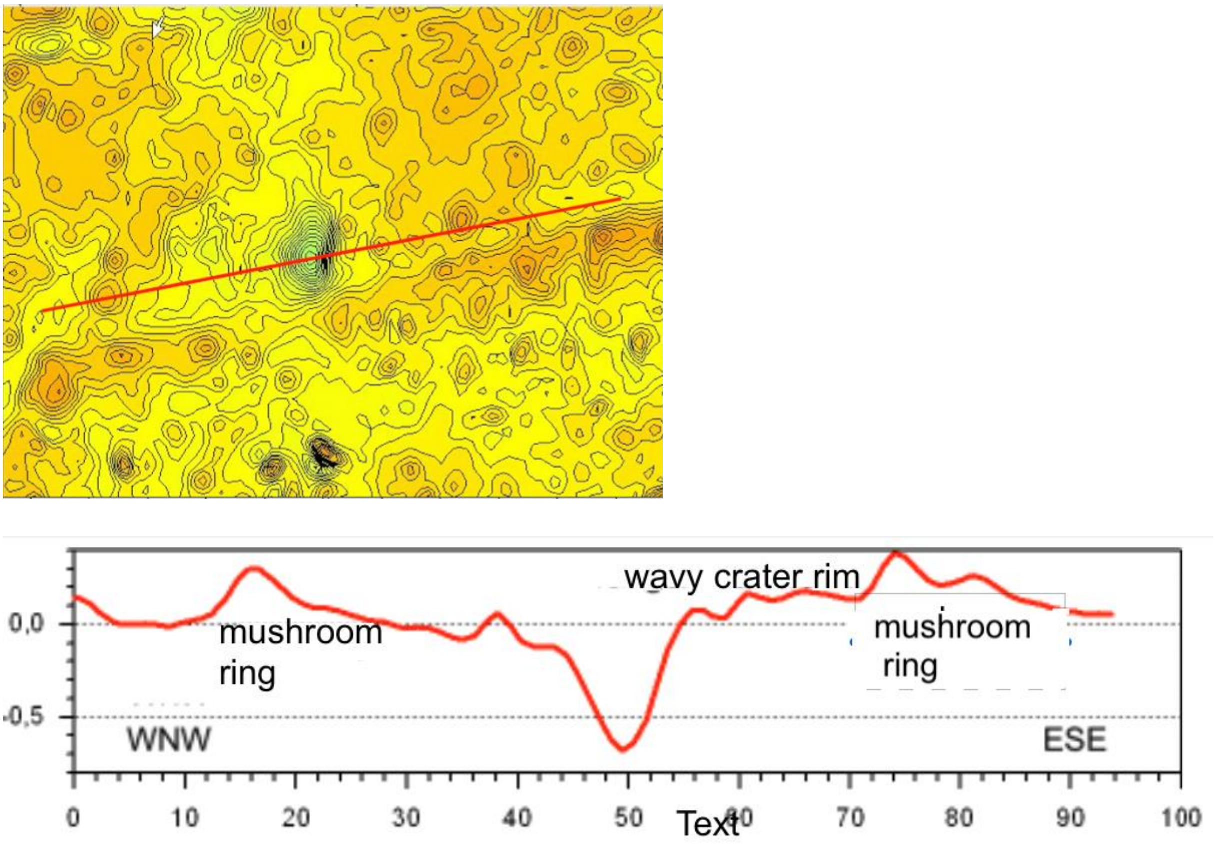

Fig. 19. DGM 1: Crater with a KHI-undulating rim zone in a shallow basin with an outer ring of RTI mushrooms. Similar to Fig. 16.

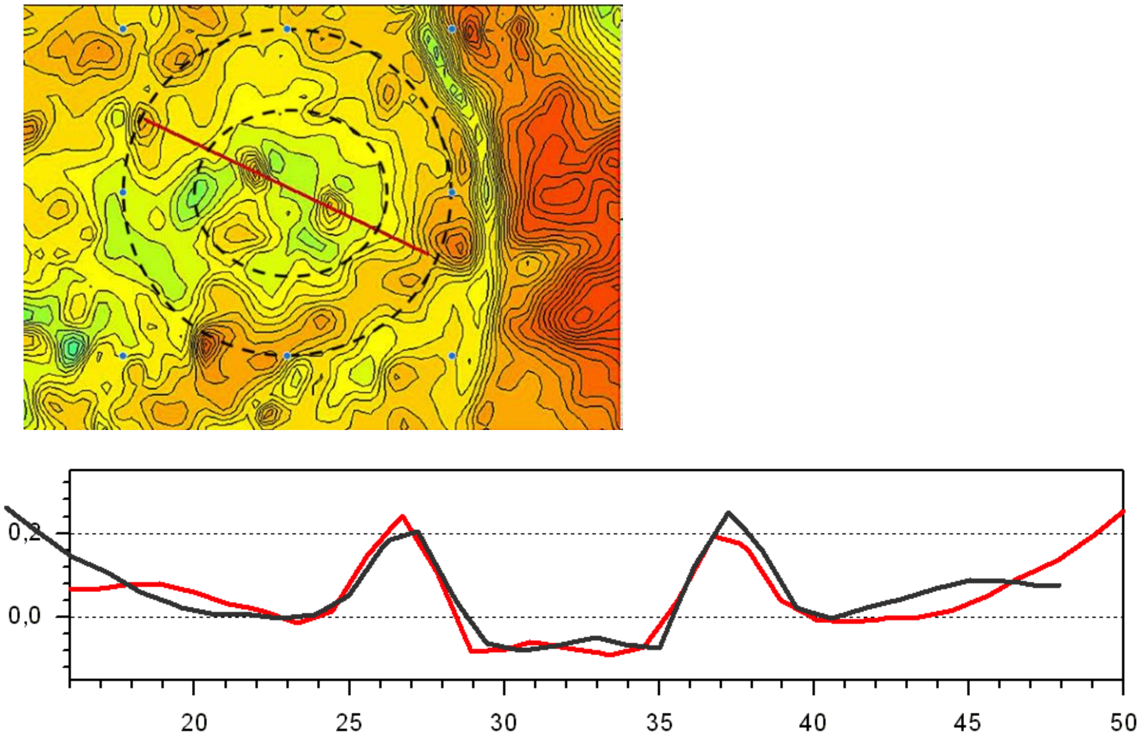

Fig. 20. RTI mushrooms as part of a complex ring structure with diametrical trace symmetry.

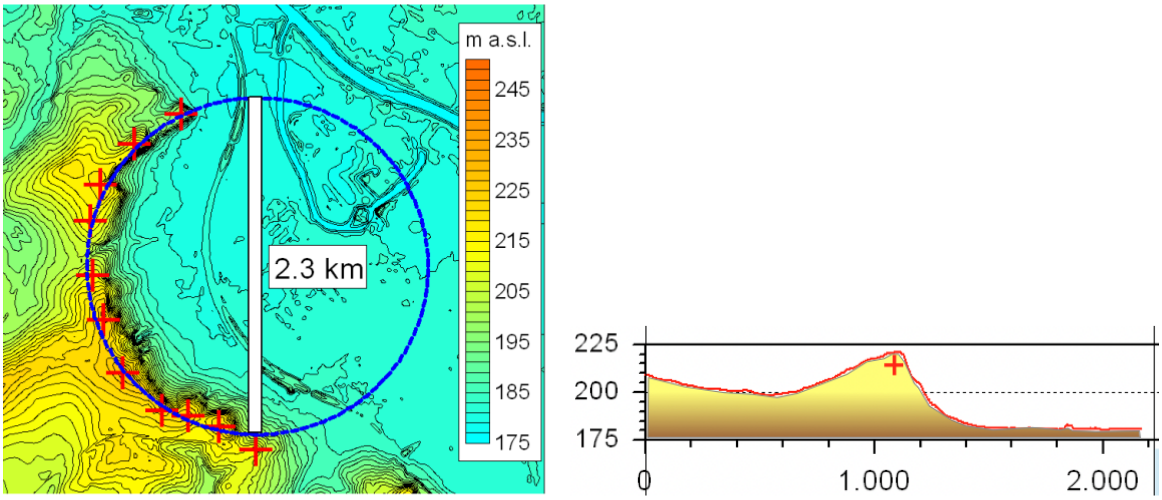

Fig. 21. DGM 1 of the Saarlouis semi-crater: Despite the perfect semicircular signature of the ring wall (the red crosses mark the wall crest on radial profiles), the wall itself is highly structured, which we explain by RT and KH instabilities during crater formation. Density and viscosity contrasts in the Quaternary loose sediments overlying the Buntsandstein bedrock would correspond to the model concepts shown in Figs. 1 and 2.

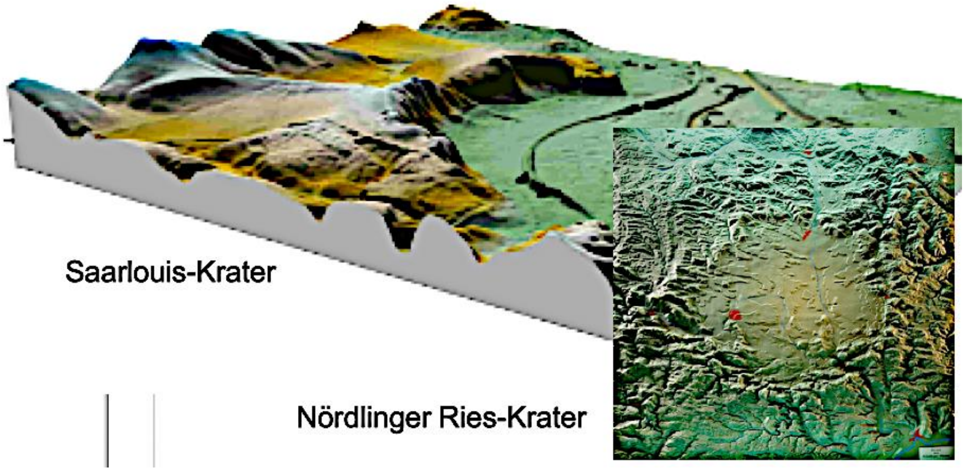

Fig. 22. The same as the DGM 1 terrain surface in a 3D block model. Despite the perfect semicircular signature of the Saarlouis crater wall (Fig. 21), the DGM 1 shows a morphologically highly structured configuration reminiscent of the wall of the Nördlinger Ries crater.

Fig. 23. The 3D block model of the Saarlouis crater rim reveals a complex structure composed of RTI and KHI elements (fingers, block formations, and ridges).

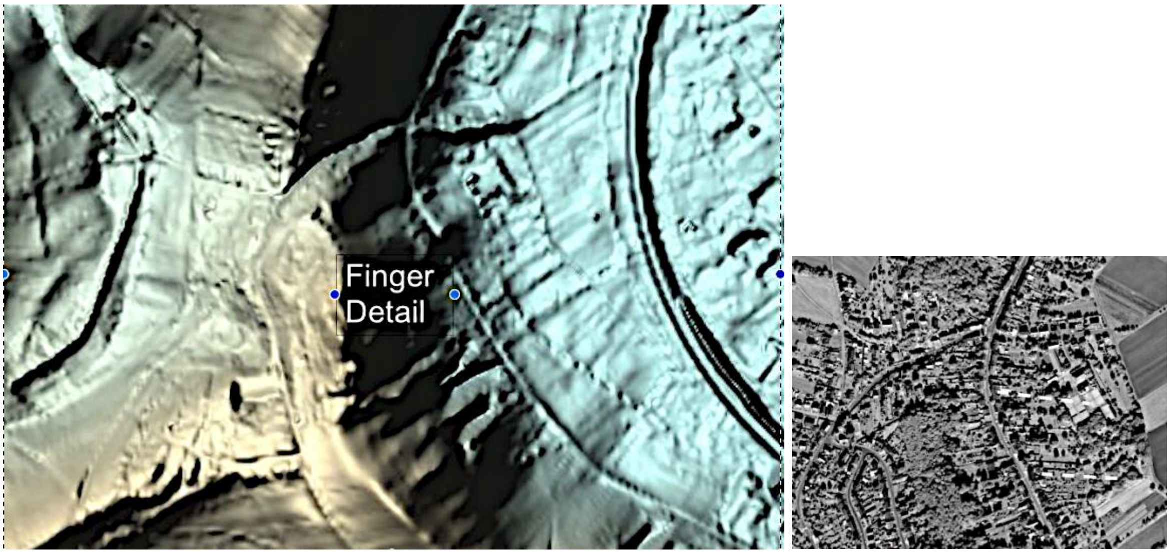

Fig. 24. Detailed view in which the finger-to wave-like structure is particularly striking. The area of the fingers/waves extending down from the rim does not appear to follow property lines, as the adjacent Google Earth image suggests (the white lines).

5 Similarities and Confusions (?) with Bomb Craters

At first glance, the ensemble of six craters in the Überherrn impact field (Fig. 25; already mentioned in Fig. 12) bears an undeniable resemblance to a bomb drop and its craters (Fig. 26). This is not surprising, as the physical processes involved are similar. In individual cases, especially with more heavily weathered craters, a definitive classification may be difficult, but in the case of bomb craters, they can be identified through the discovery of shrapnel or historical documents.

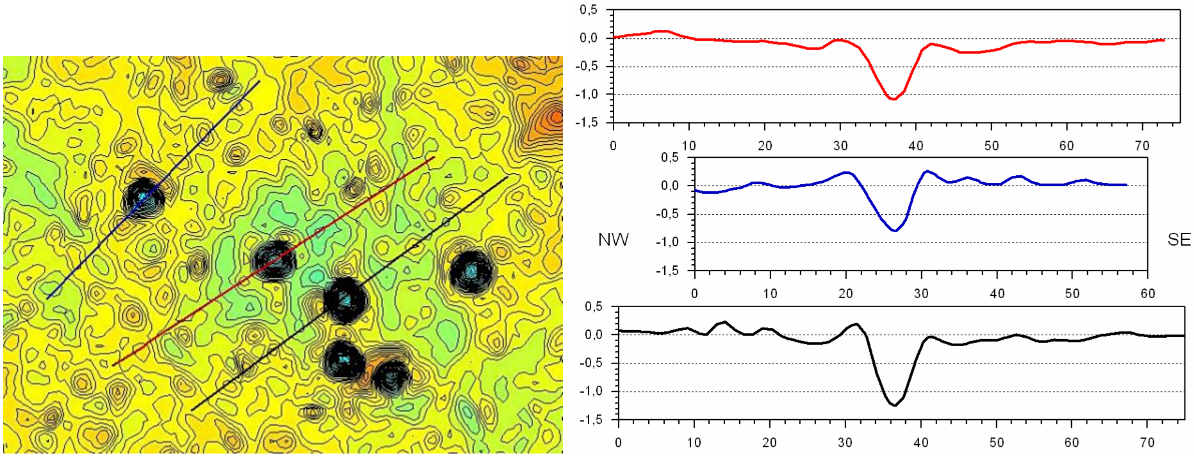

Fig. 25. Group of Saarland impact craters surrounded by partially marginal depressions as well as mushroom and finger structures.

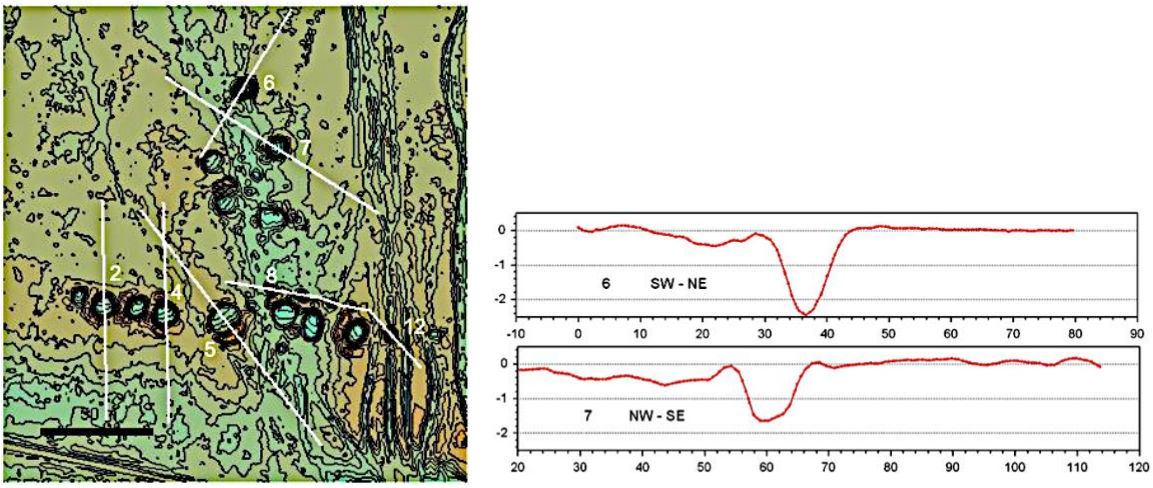

Fig. 26. DGM 1 map of a bomb drop in a forested area of Upper Bavaria.

6 Discussion and Conclusion

- The Saarland impact area is an impact crater field with an extent of at least 15 km, featuring two larger craters (2.3 km and 250 m in diameter) and a multitude of smaller impact structures, as well as a separate nearby impact area on a substrate of loose Quaternary sediments overlying a Mesozoic substrate of red sandstone and shell limestone.
- Based on all findings and results from over 10 years of research, a near-surface "touchdown" airburst impact is assumed to have occurred, which, due to the impact rocks appearing directly at the surface and archaeological excavations, is believed to have taken place in the Holocene, with a possible synchrony with the Chiemgau impact already having been discussed [6].
- The discovery and documentation of this new, very large number of impact structures is attributable to the new capabilities of the LiDAR Digital Elevation Model (DEM) 1, which, with an extremely high resolution of 1 m (interpolated to decimeters) in the horizontal direction and 0.1 m (interpolated to centimeters) in the vertical direction, it

can even detect craters in dense vegetation (e.g., in forests) and reveal complex impact morphologies with the highest possible level of detail.

- The DGM 1 shows that the impact produced not only craters but also many highly complex structures such as mushroom shapes, finger-like patterns, multiple rings, wave patterns, and fragmented rim zones.
- The formation of such complex shapes can be explained—as the central point of this article—by impacts, a phenomenon primarily known from experiments with liquids, specifically through so-called Rayleigh-Taylor (RTI) and Kelvin-Helmholtz (KHI) instabilities.
- We apply these RTI and KHI processes to the layers in the Saarland impact area, which consist of alternating layers of loose sediments with widely varying densities and viscosities of the constituent rocks.
- Based on these highly complex crater shapes, we conclude that they rule out a normal geological origin such as sinkholes or other collapse structures.
- Anthropogenic origin must also be ruled out in the vast majority of cases due to the morphological characteristics, which include strictly circular and structurally symmetrical forms, some of which are of considerable size and often extend down to the decimeter and centimeter range.
- The large concentration of these very distinctive, sometimes exotic crater structures within the roughly elliptical impact field of the Chiemgau impact once again proves the reality of a Saarland impact event involving a near-surface "touchdown" airburst impact.
- It also shows that databases and statistics on currently recognized terrestrial impacts, to which the impact literature consistently refers, are no longer relevant. Naturally, the Saarland impact and the other new Holocene impact scatter fields in Central Europe do not fit into this current “worldview” of impacts.

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