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# Meteorite Impact "Earthquake" Features (Rock Liquefaction, Surface Wave Deformations, Seismites) from Ground Penetrating Radar (GPR) and Geoelectric Complex Resistivity/Induced Polarization (IP) Measurements, Chiemgau (Alpine Foreland, Southeast Germany)

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### Abstract

Densely spaced GPR and complex resistivity measurements on a 30,000 square meters site in a region of enigmatic sinkhole occurrences in unconsolidated Quaternary sediments have featured unexpected and highlighting results from both a meteorite impact research and an engineering geology point of view. The GPR measurements and a complex resistivity/IP electrical imaging revealed extended subrosion depressions related with a uniformly but in various degrees of intensity deformed loamy and gravelly ground down to at least 10 m depth. Two principle observations could be made from both the GPR high-resolution measurements and the more integrating resistivity and IP soundings with both petrophysical evidences in good complement. Subrosion can be shown to be the result of prominent sandy-gravelly intrusions and extrusions typical of rock liquefaction processes well known to occur during strong earthquakes. Funnel-shaped structures with diameters up to 25 m near the surface and reaching down to the floating ground water level at 10 m depth were measured. GPR radargrams could trace prominent gravelly-material transport bottom-up within the funnels. Seen in both GPR tomography and resistivity/IP sections more or less the whole investigated area is overprinted by wavy deformations of the unconsolidated sediments with wavelengths of the order of 5 - 10 m and amplitudes up to half a meter, likewise down to 10 m depth. Substantial earthquakes are not known in this region. Hence, the observed heavy underground disorder is considered the result of the prominent earthquake shattering that must have occurred during the Holocene (Bronze Age/Celtic era) Chiemgau meteorite impact event that produced a 60 km x 30 km sized crater strewn field directly hosting the investigated site. Depending on depth and size of floating aquifers local concentrations of rock liquefaction and seismic surface waves (probably LOVE waves) to produce the wavy deformations could develop, when the big disintegrated meteoroid (a loosely bound asteroid or a comet of roughly estimated 1 km size) hit the ground. The observations in the Chiemgau area emphasize that studied paleoliquefaction features and wavy deformations (e.g. seismites) need not necessarily have originated solely from paleoseismicity but can provide a recognizable regional impact signature.

# METEORITE IMPACT "EARTHQUAKE" FEATURES (ROCK LIQUEFACTION, SURFACE WAVE DEFORMATIONS, SEISMITES) FROM GROUND PENETRATING RADAR (GPR) AND GEOELECTRIC COMPLEX RESISTIVITY/INDUCED POLARIZATION (IP) MEASUREMENTS, CHIEMGAU (ALPINE FORELAND, SOUTHEAST GERMANY)

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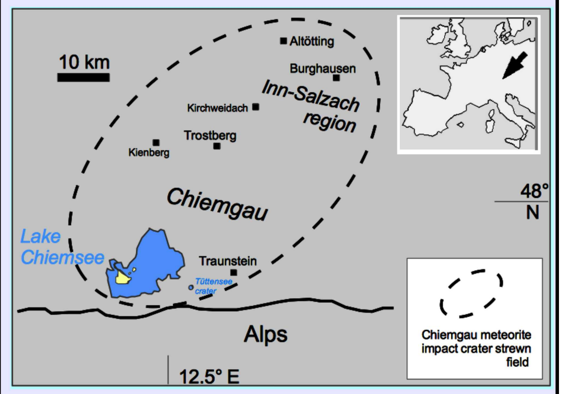
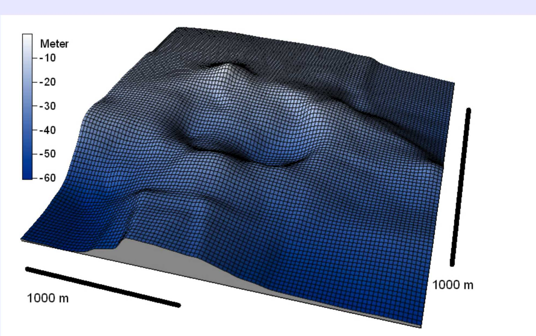



Location map for the Chiemgau meteorite crater strewn field and the impact-induced paleoseismicity features.

### *The Chiemgau Meteorite Impact Event*

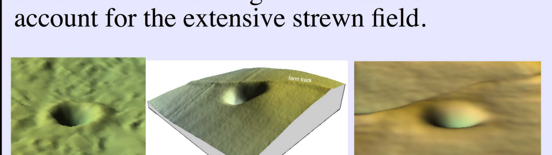
The Chiemgau strewn field discovered in the early new millennium and dated to the Bronze Age/Celtic era comprises as much as 100 mostly rimmed craters scattered in a region of about 60 km length and ca. 30 km width in the very South-East of Germany. The crater diameters range between a few meters and a few hundred meters. The doublet impact at the bottom of Lake Chiemsee is considered to have triggered a giant tsunami evident in widespread tsunami deposits around the lake.


The Tüttensee meteorite impact crater. 600 m rim crest diameter.




The doublet meteorite impact crater at the bottom of Lake Chiemsee. From echosounder measurements.

Geologically, the craters occur in Pleistocene moraine and fluvio-glacial sediments. The craters and surrounding areas are featuring heavy deformations of the Quaternary cobbles and boulders, impact melt rocks and various glasses, strong shock-metamorphic effects, and geophysical (gravity, geomagnetic) anomalies. Impact ejecta deposits in a catastrophic mixture contain polymictic breccias, shocked rocks, melt rocks and artifacts from Bronze Age/Celtic era people. The impact is substantiated by the abundant occurrence of metallic, glass and carbonaceous spherules, accretionary lapilli, microtektites and of strange, probably meteoritic matter in the form of iron silicides like gupeiite, xifengite, hapkeite, naquite and linzhite, various carbides like, e.g., moissanite SiC and khamrabaevite (Ti,V,Fe)C, and calcium-aluminum-rich inclusions (CAI), minerals krotite and dicalcium dialuminate. Physical and archeological dating confines the impact event to have happened most probably between 2,200 and 500 B.C. The impactor is suggested to have been a roughly 1,000 m sized low-density disintegrated, loosely bound asteroid or a disintegrated comet in order to account for the extensive strewn field.



Smaller craters in the Chiemgau impact strewn field: Einsiedeleiche (15 m rim crest diameter), Purkering (75 m), Engelsberg (45 m). Surface plots from Digital Terrain Model (DTM).

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## Introduction

Commonly earthquakes are related to tectonic, volcanic and various collapse processes. Less well known because of their obvious rarity are earthquakes from meteorite impact. Collision of cosmic bodies with the Earth's surface may produce extreme energy release leading to the propagation of strong shock fronts and also elastic seismic waves that may be recorded even by remote seismological stations. The Chelyabinsk meteorite impact event in 2013 of a relatively small object was recorded worldwide as a ~ 3 magnitude earthquake, and for the 1908 famous Tunguska impact event a magnitude of ~ 5 has been estimated. Giant impacts of asteroids and comets in the geological past to have produced big impact craters may have been related with Richter magnitudes up to 13.

Here we report on new observations further strengthening the hypothesis [1] of impact-induced seismic features in the Chiemgau meteorite impact event that happened in the Bronze Age/Celtic era in Southeast Germany.

## The Thunderhole phenomenon and enigma

Within living memory, sudden sinkhole occurences have been a great enigma and a geologically unsettled phenomenon constrained to a relatively small region of roughly 200 km$^2$ with a few isolated occurrences but a clear concentration near the town of Kienberg (location map). According to estimations of the local population roughly one thousand Thunderholes (in German "*Donnerlöcher*") may have formed in the past, and periodically new ones are reported to have occurred.

The "smoking gun" of paleoliquifaction in the past.

Earlier geologic and geophysical field campaigns [1] unravelled the mystery and could show that the sinkhole formation is only the terminal stage of a prominent and complex paleoliquefaction event that featured underground movements and structures well known from very strong earthquakes like the famous 1811/12 New Madrid earthquake in Missouri or the more recent New Zealand and the historical Calabrian earthquakes.

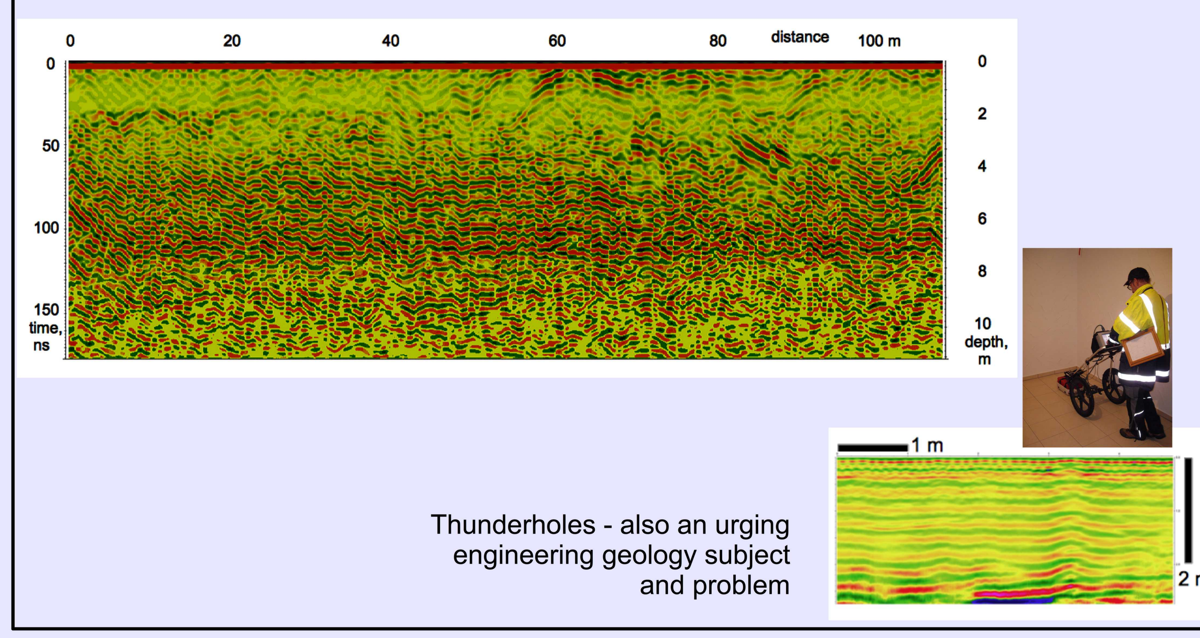
Since the region under discussion lacks any substantial earthquake evidence the big Chiemgau meteorite impact "earthquake" originating from the formation of 100 or more craters in an area of roughly 60 km x 30 km appeared to be the logical trigger mechanism for the massive liquefaction and Thunderhole phenomena.

Meanwhile, the Thunderhole scenario, in the past in general accepted by the population as unavoidable, has attracted increased attention even by the authorities, and engineering geology aspects and near accidents are no longer completely ignored. This change of thinking prompted new geophysical campaigns particularly since more Thunderhole evidence became publicly known from areas east of the town of Trostberg within the impact strewn ellipse (see location map).

## Thunderhole investigation - geophysical measurements

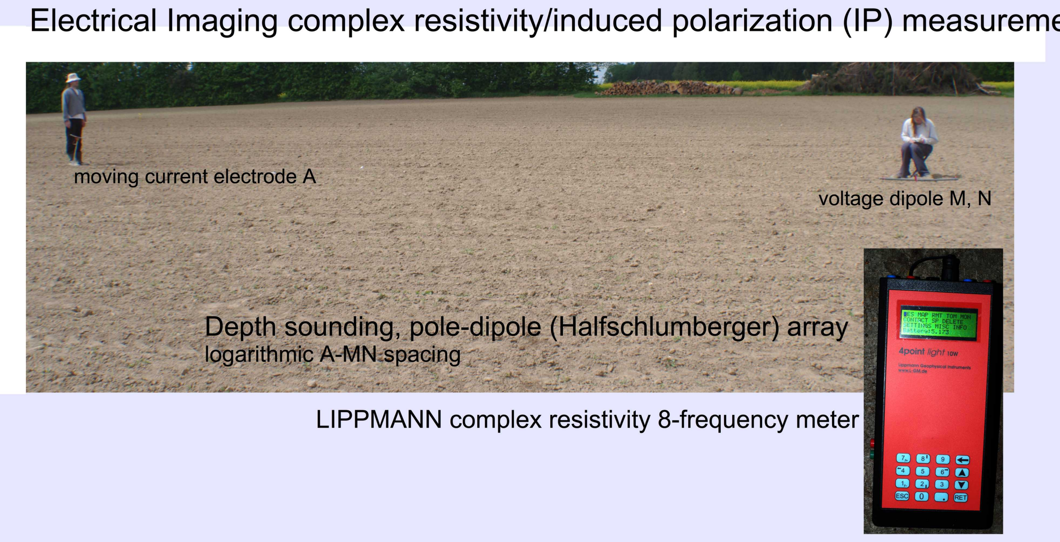
### Ground penetrating radar (GPR)

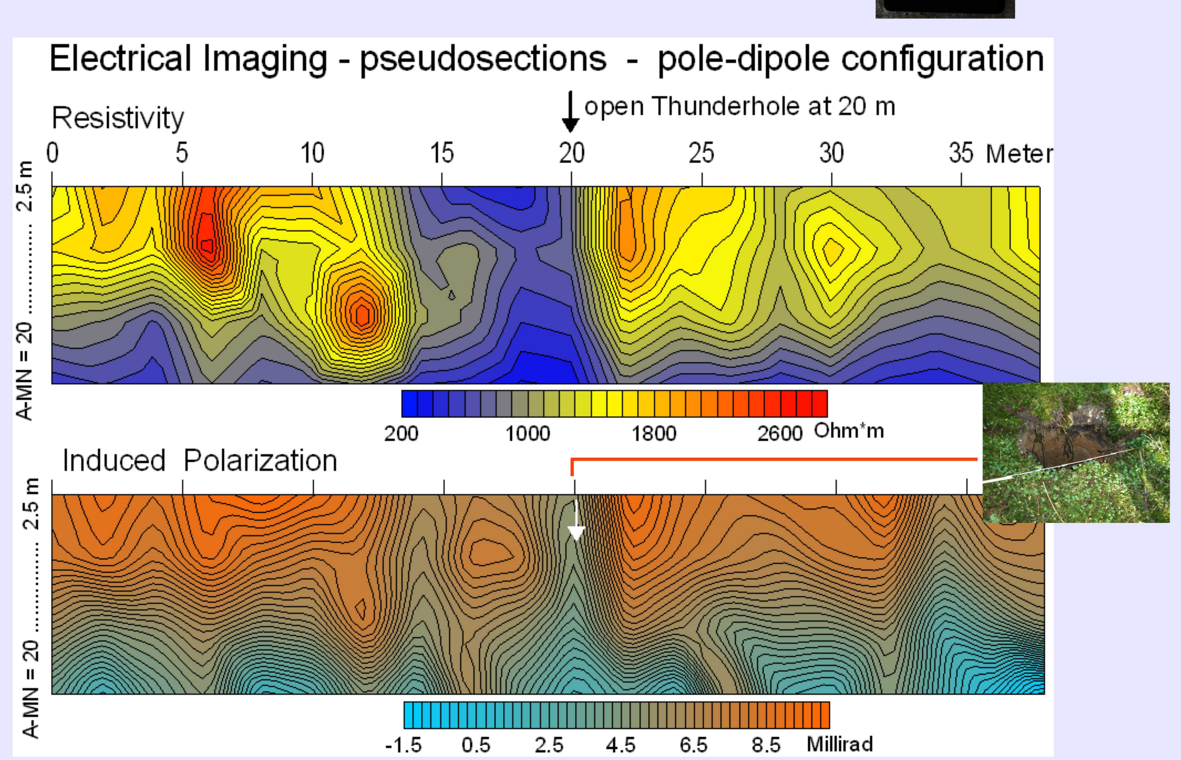
Thunderhole field work with ground penetrating radar (GPR) equipments: GSSI 200 MHz and 400 MHz, VIY3 300 MHz.



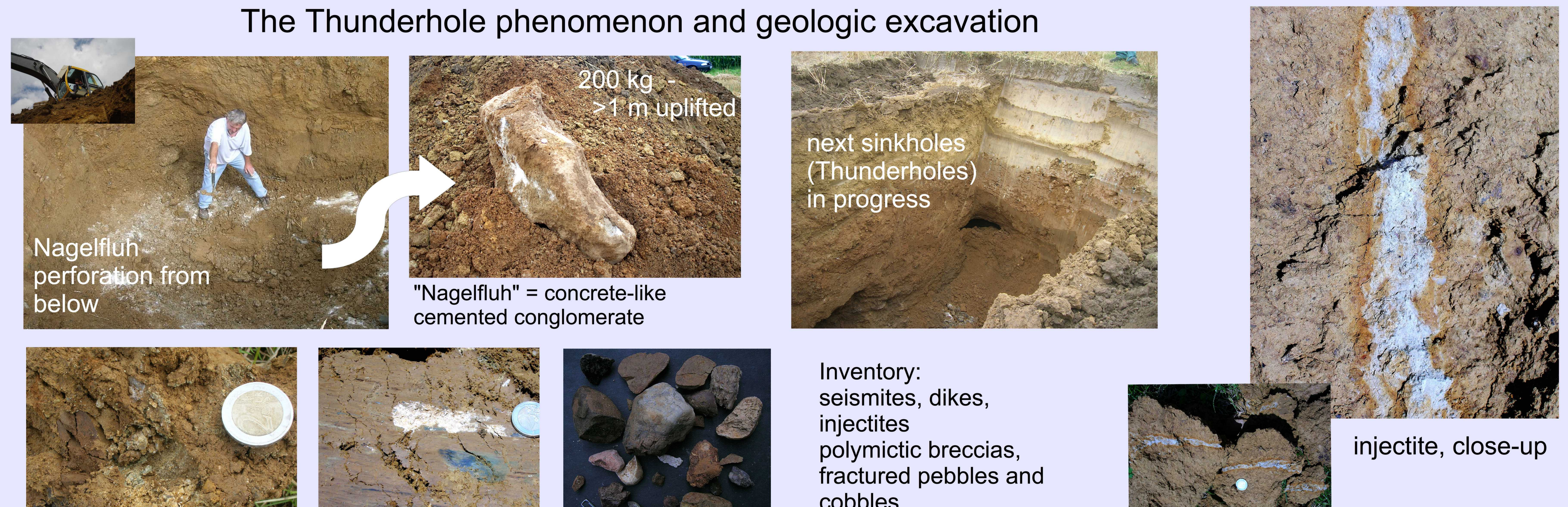

Thunderholes - also an urging engineering geology subject and problem

### Electrical Imaging complex resistivity/induced polarization (IP) measurements

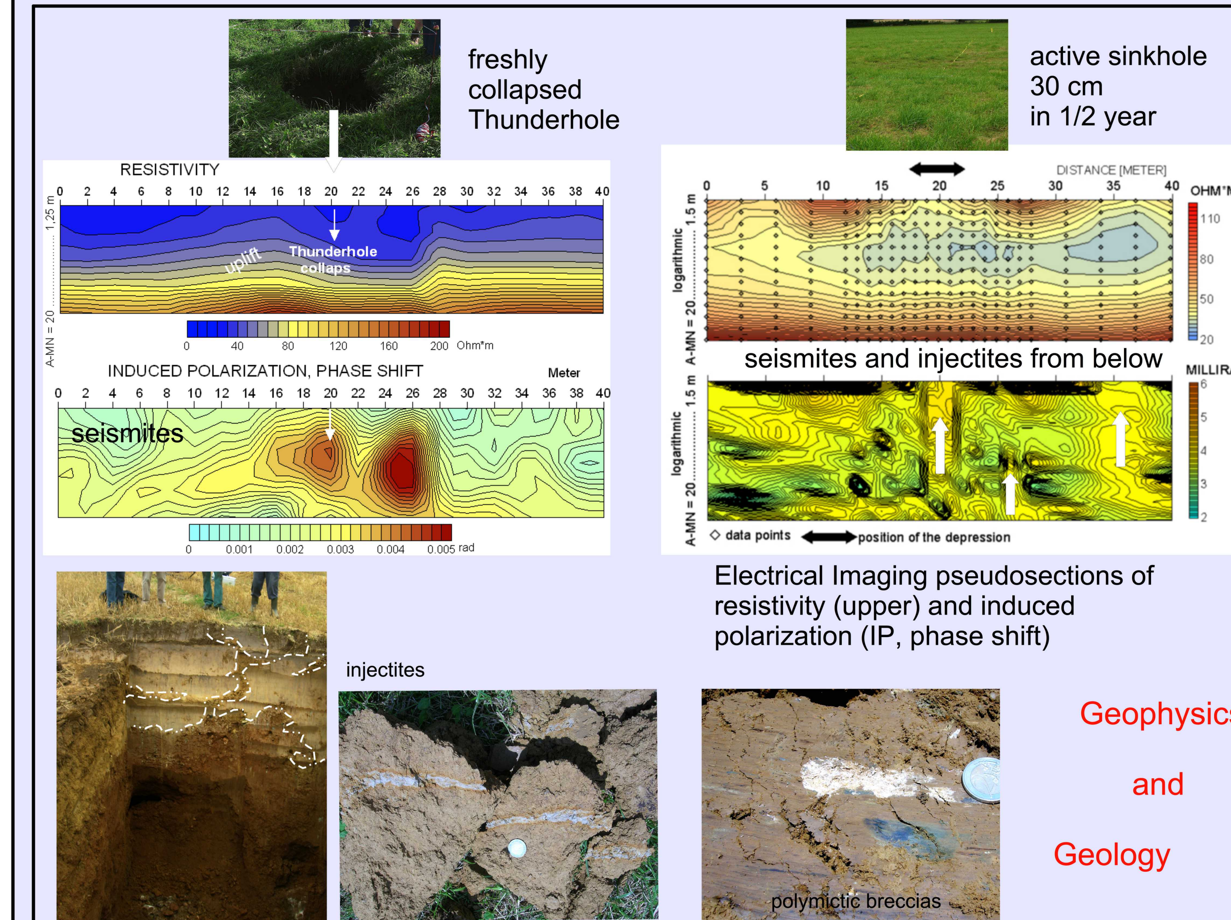


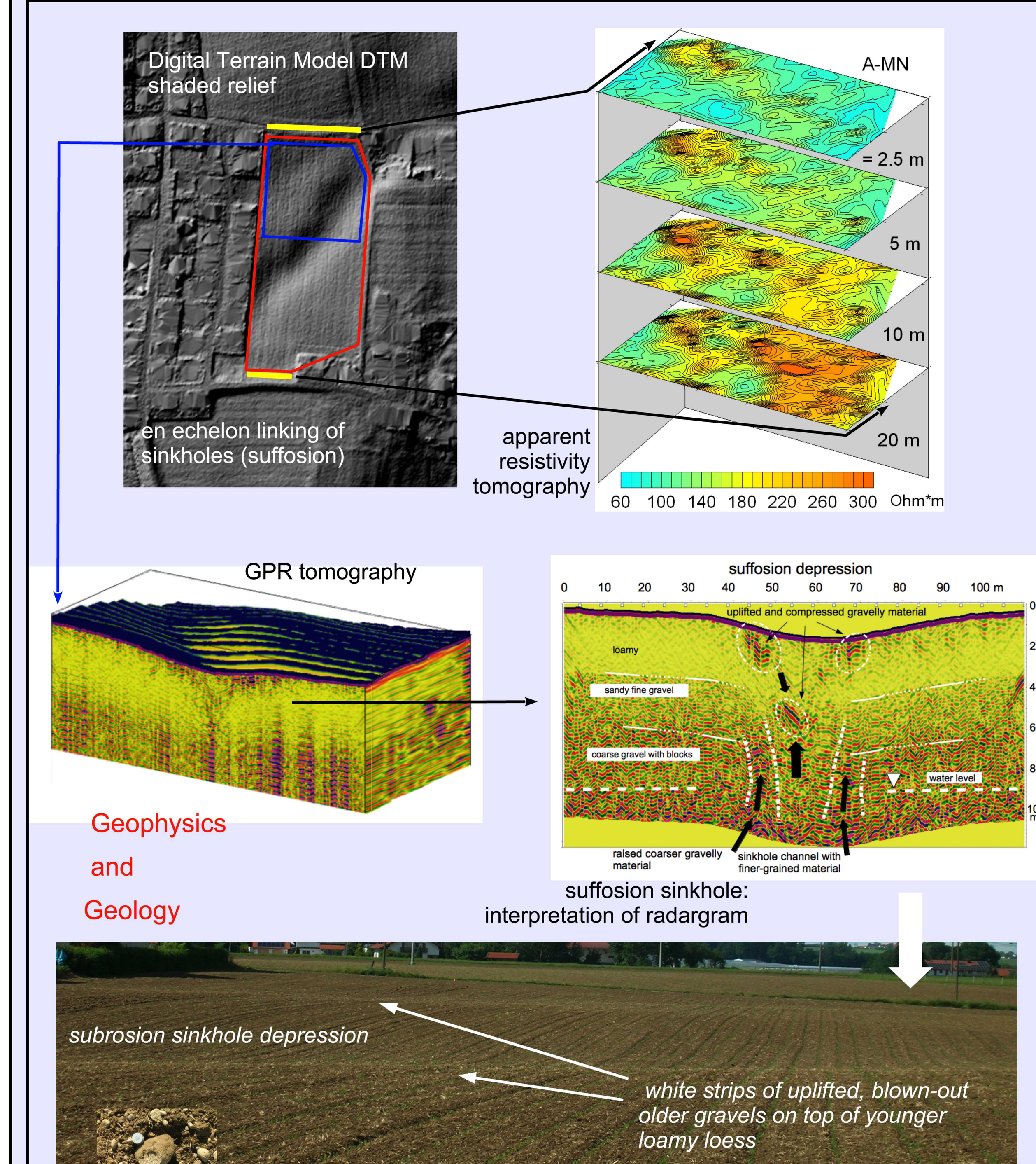

## The Thunderhole phenomenon and geologic excavation




## Paleoseismic features in the Chiemgau impact area

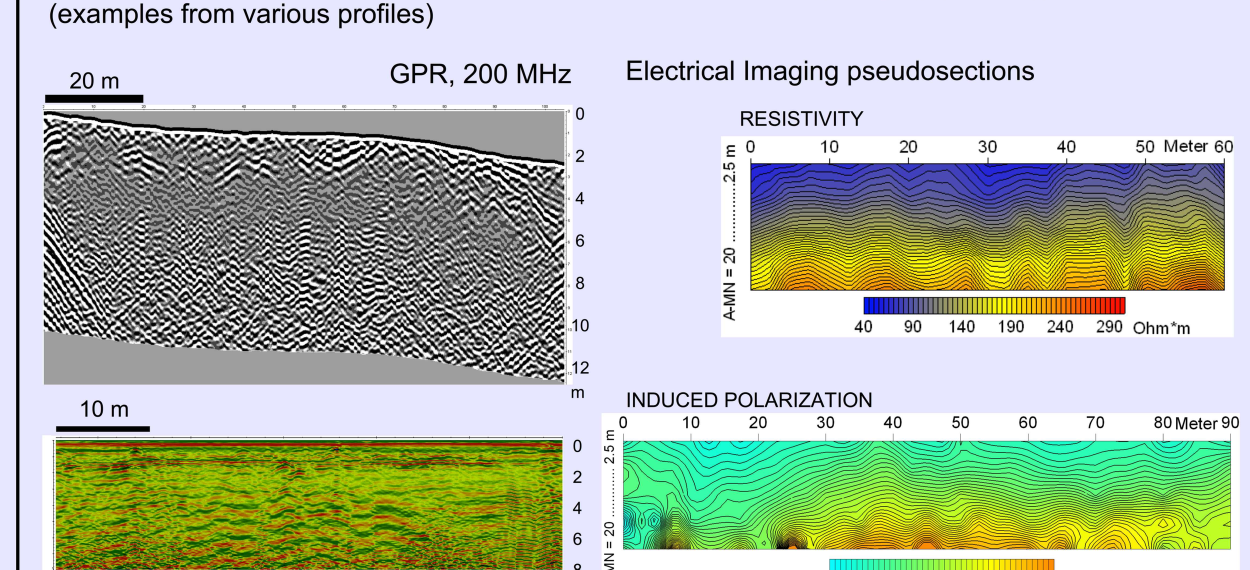



Electrical Imaging pseudosections of resistivity (upper) and induced polarization (IP, phase shift)




### wavy deformations from surface wave (Love, Rayleigh) propagation

(examples from various profiles)




## Summary and conclusions

Strong deformations in the upper 10 - 20 m of the Pleistocene/Holocene ground in the Chiemgau region are related with abundant sinkhole and general suffosion features. They belong to a three-phase process:

-- heavy energy release and material transport bottom-up
-- (in part long-lasting) washout of the fine-grained component with the formation of cavities and depressions
-- collapse of cavities >>> Thunderhole formation

This scenario is accompagnied by significant, in part wavy deformations of the upper soft rock layers. Perched water aquifers appear to play a decisive role.

The observations are well known from very strong earthquakes. They are observed in actual events and are described as

-- rock (soil) liquefaction with the formation of seismites, injectites, clastic dikes.

-- seismic surface wave deformations

They are used to describe and document paleoseismicity.

/ The Chiemgau region lacks any significant earthquake evidence. Strong earthquakes can definitely be excluded in particular with regard to the limited swath of land that has been affected.

/ The Chiemgau big multiple meteorite impact some 2,500 - 4,000 years ago and its giant energy release during the collision of a comet or asteroid with the earth's surface are a reasonable explanation for all intriguing geological observations.

/ Beside the strong impact shock surface waves are considered the most effective process to have caused the strong and frequently wavy deformations, because in an impact event the seismic source is located close to the earth's surface. The contribution of Rayleigh and Love waves may have been complex, but the theoretically required low-velocity layer over a high-velocity halfspace to let Love waves propagate seems to have ideally been fulfilled with a water table in the soft sediments at roughly 10 m depth.

/ In the region there are no young geologic processes known that for example explain the extreme energy release bottom-up. Glacial processes or bog-standard karstification to account for the Thunderhole formation as regularly claimed by local, regional and authority geologists, do not make sense.

/ Meteorite impact-induced "earthquake" features have repeatedly been taken into considerations (e.g., [2, 3]), but the Chiemgau impact appears to be the first event that unmissably relates typical paleoseismic ground deformations with a distinct meteorite impact event.

/ The observations in the Chiemgau area emphasize that studied paleoliquefaction features and wavy deformations (e.g. seismites) need not necessarily have originated solely from paleoseismicity but can provide a recognizable regional impact signature.

/ Geophysical measurements are able to reveal the underground deformations in very detail. In the region under discussion ground GPR measurements with a 200 MHz antenna achieve penetration depths of more than 10 m. Complex resistivity soundings show that induced polarization sections have in general a much greater resolution power with regard to facies and structural features than conventional resistivity measurements, which conforms to our earlier general experience. Both in combination are most helpful.

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