GEOELECTRIC COMPLEX RESISTIVITY MEASUREMENTS OF SOIL LIQUEFACTION FEATURES IN QUATERNARY SEDIMENTS OF THE ALPINE FORELAND, GERMANY NS23A-1555

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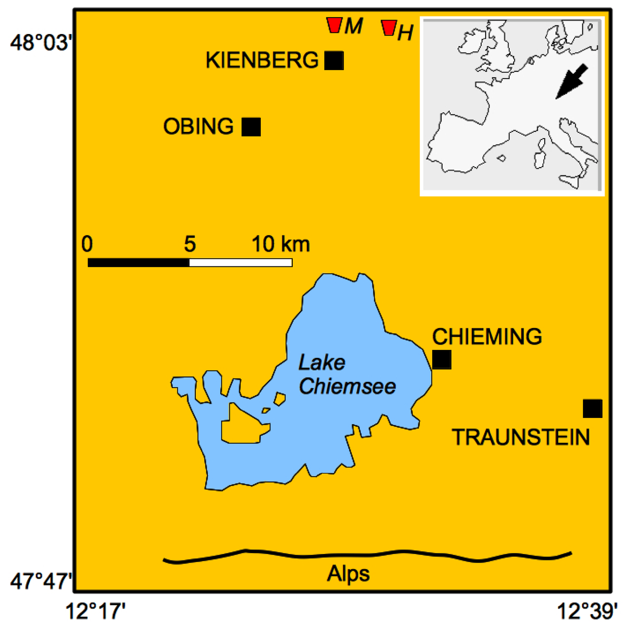


Fig. 1. Location map for the area of the rock liquefaction features. M = Mörn active depression; H = Heretsham Thunderhole.

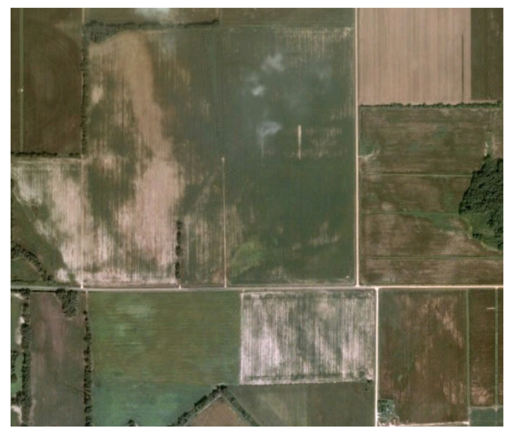
Fig. 2. A sinkhole collapsed during construction works, and a typical sinkhole in a forest.

Introduction

Within living memory, the formation of sinkholes (so-called Thunderholes; in German: Donnerloch) has been a peculiar natural phenomenon constrained to an area of roughly 200 km² near the town of Kienberg north of Lake Chiemsee (Fig. 1). These Thunderholes are sudden cave-ins in a Quaternary sandy-gravelly and loamy underground (Fig. 2). The surface diameter of the frequently circular holes ranges between about one meter and ten meters, and their depth may reach to several meters. The cause of the Thunderhole formation has been a great enigma until today even for geologists who have sometimes been claiming an undefined relation with glacial processes.

With regard to their engineering geology aspects so far only hesitantly admitted by the local authorities, we developed new ideas about their formation motivated by studies of rock/soil liquefaction features and especially by comparison with liquefaction effects of the famous 1811/1812 New Madrid, Missouri, strong earthquake series [1, 2, 3]. When we compared satellite imagery from both the New Madrid area and the Thunderhole-affected area in Germany, we were stunned by the amazingly similar surface features (Fig. 3).

This observation initiated a campaign of geophysical measurements and large-scale excavations in the area of the Thunderholes, and here we report on this new approach to the Thunderhole phenomenon leading to a model that may explain all observed Thunderhole features.



Liquefaction features near New Madrid, Missouri

Probable liquefaction features in the Lake Chiemsee region, Germany

Fig. 3. Rock liquefaction from space: amazingly similar.

Excavation

So far, two Thunderholes near Heretsham (Fig. 1) that had been sealed by sand immediately after their collapse were excavated some months later. In both cases the excavator revealed a complex geologic scenario completely different from the normally well-bedded Quaternary sediments known from numerous gravel pits in the region. Below a few meters of loamy loess and loam the excavator found a nagelfluh layer of strongly cemented conglomerates and in each case a c.1m-diameter hole punched into the nagelfluh bed. The holes served as vents for intrusions of sandy-gravelly material obviously originating from deeper layers. The intrusions must have been highly energetic because heavyweight blocks of nagelfluh had been uplifted, and strongly fractured pebbles and cobbles were observed to contribute to real breccia zones of the intruded material (Fig. 4). Moreover, the process of intrusion from below must have been very rapid with regard to the sharp contact to the loamy host rock and to the significant uplift of layers above the nagelfluh plate.

The Heretsham Thunderhole #2 excavation revealed prominent caverns (Fig. 4) at once establishing a connection to the surficial Thunderhole collapses.

Before Thunderhole #2 was excavated, a geophysical survey in the form of a 20 m electrical imaging profile across the sealed hole was performed.

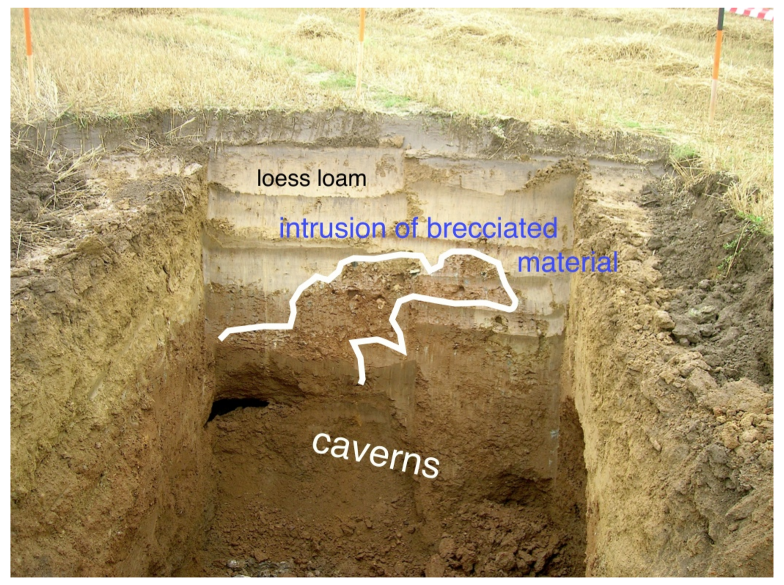
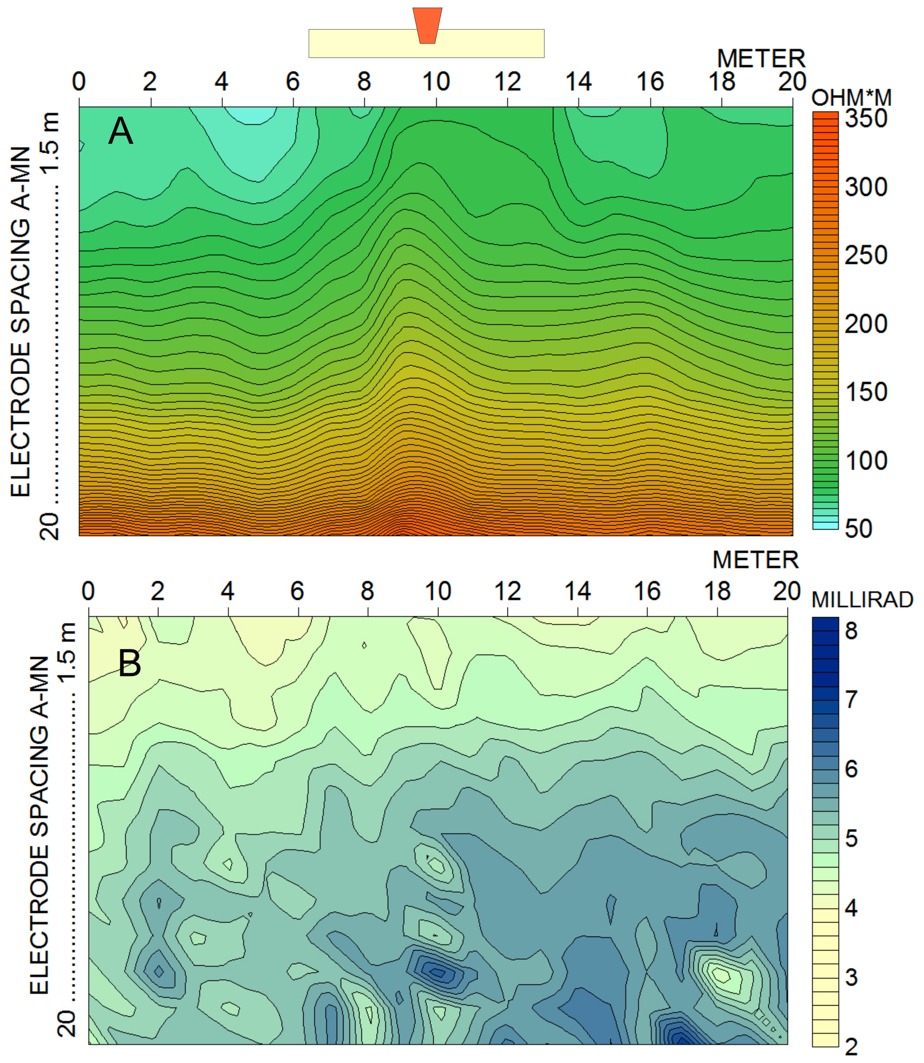


Fig. 4. 7 m x 7 m excavation around the Thunderhole #2 collapse.

Geophysical measurements

Fig. 5. Setup of pole-dipole electrical imaging over an active sinkhole.

The geophysical measurements comprised complex resistivity soundings in the form of an electrical imaging on profiles that crossed a recently collapsed and sealed sinkhole (the Heretsham #2 Thunderhole), and an active depression at the Mörn farmhouse obviously preceding a future collapse. Resistivity and induced polarization (IP) data were recorded in a pole-dipole configuration at 8,33 Hz frequency, 0° and 90° phase, resulting in the phase shift as relevant IP parameter. On the profiles, the individual soundings with electrode layout perpendicular to profile strike were measured every 1 m at each point taking apparent resistivity and IP data for electrode spacings of A-MN = 1.5, 2, 2.5, 3, 4, 5, 6, 7, 8, 10, 12, 15 and 20 m. The *Lippmann Earth Resistivity Meter 4-Point light hp* was used (Fig. 5). From the data apparent resistivity and apparent IP pseudosections were produced (Fig. 6, Fig. 7). In Figs. 6, 7, also the grids of data points for constructing the pseudosections are shown. They point to a larger 3 m station spacing at the ends of the Heretsham profile (Fig. 7) and a gap at 10 m profile station where data have been omitted because of a possible static shift of the apparent resistivities due to the sealing material of the Thunderhole.



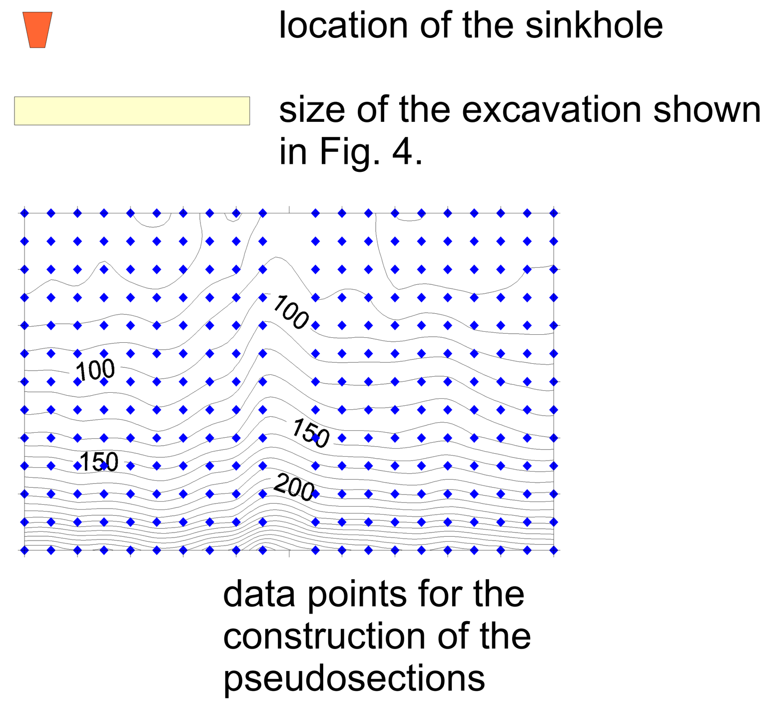


Fig. 6. Heretsham Thunderhole #2: pseudosections of apparent resistivity (A) and induced polarization (B); pole-dipole configuration

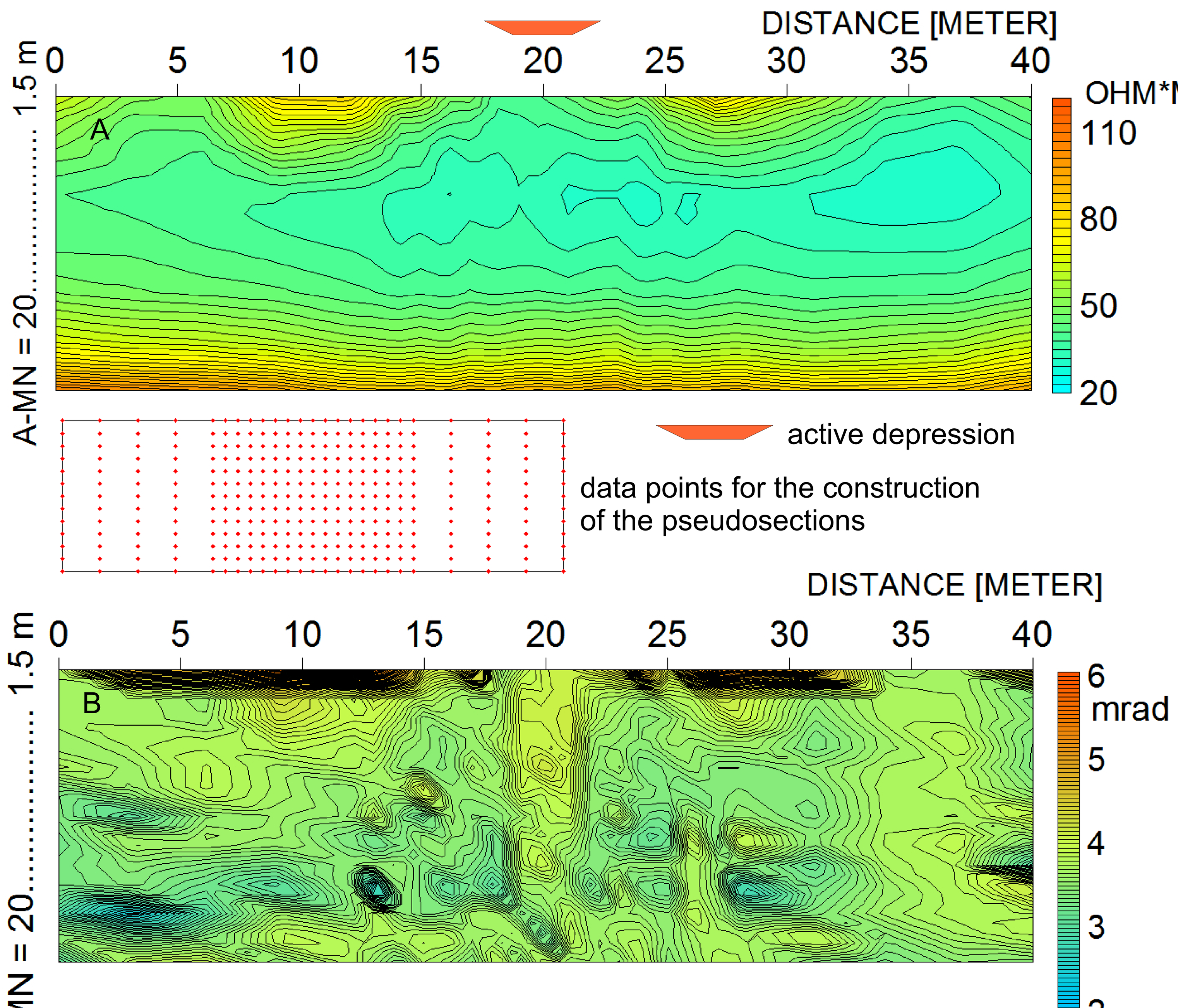


Fig. 7. Mörn active depression: pseudosections of apparent resistivity (A) and induced polarization (B); pole-dipole configuration

Results and Discussion

The complex resistivity pseudosections of Fig. 6 and Fig. 7 reveal underground structures that are fully compatible with rock liquefaction. They give evidence of forces and movements having acted from below, as seen in the uplifted isoohms in Fig. 6, which was later confirmed by the excavation of the Heretsham Thunderhole # 2. From resistivity modeling, the upper loamy layers (50-70 Ohm*m) contrast sharply with the sands and gravels at dept (> 1,000 Ohm*m) easily explaining the general pseudosection contours. Interestingly, the IP pseudosection contours in Fig. 6 differ considerably from the isoohm contours characterizing a rather ransacked geologic underground also in detail documented by the excavation. The same holds true for the pseudosections for the Mörn farmhouse active depression with strongly contrasting resistivity and IP contours (Fig. 7). First, more or less symmetrical to the surface depression over a distance of c. 40 m, the resistivity section suggests that the observable subsidence is only a small-scale snapshot in time of a much larger geologic scenario running in the subsurface as likewise seen in the case of the Heretsham Thunderhole. For two reasons, the IP section in Fig. 7 is especially highlighting. Even more evident than in the Heretsham case, the IP contours reflect an extremely detailed picture of high resolution of underground structures which the resistivity section is unable to provide. And although not confirmed by geologic excavation so far, the IP contours seem to speak for themselves, and the interpretation in Fig. 8 is pointing to nearly perfect parallels between the liquefaction models for the New Madrid intrusions and extrusions and the geophysical observation.

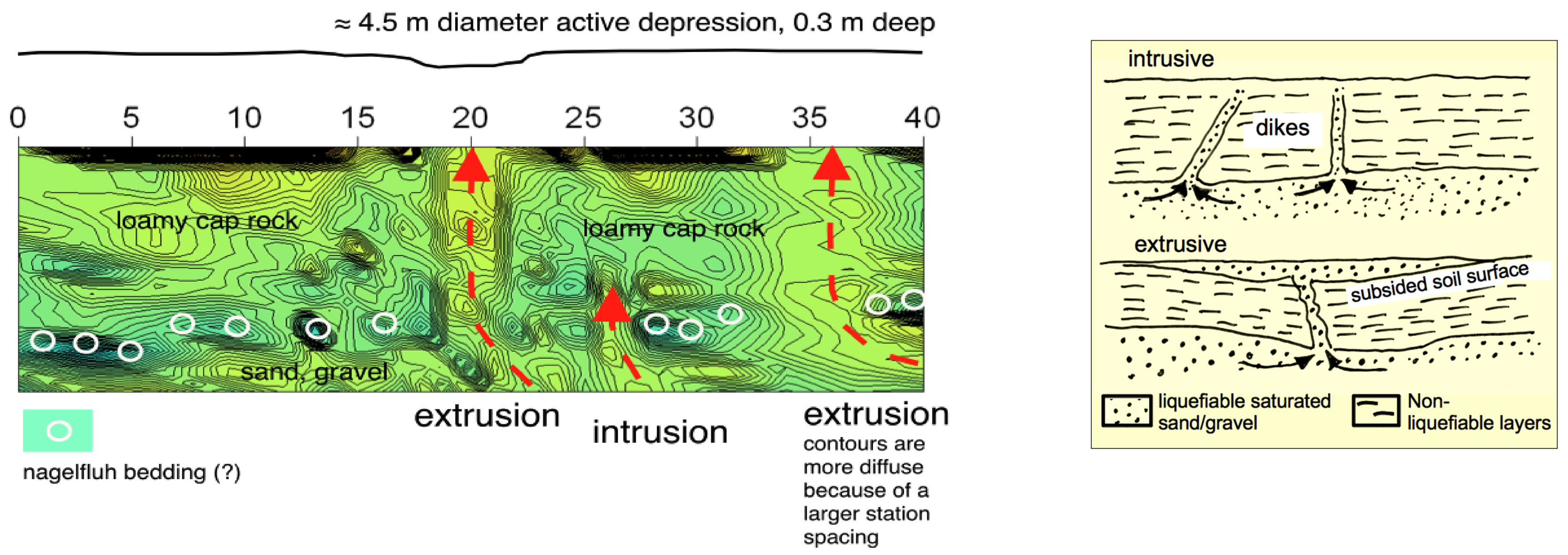


Fig. 8. Interpretation of the induced polarization pseudosection from Fig. 7 (left) and models of liquefaction features as seen in the New Madrid, Missouri, earthquake region (right; modified from [3]).

Excavation and geophysical measurements give clear evidence of a geologic process connected with a highly energetic mass transport bottom up followed by later sinkhole formation due to partial collapse of uplifted layers. The observations exclude any kind of dissolution (karst) sinkholes and eliminate any consideration of a glaciation context but are clearly speaking in favor of rock/soil liquefaction well known from strong earthquakes. Since strong earthquakes can reasonably be excluded for the limited area under consideration, we suggest that the recently proposed Holocene large meteorite impact event, the so-called Chiemgau impact [4] was the driving force, and we point to the fact that impact energy release in the form of spreading shock waves has a lot in common with earthquake shock. The Chiemgau impact in the Bronze Age/Celtic era produced an extended crater field with the 600 m-diameter Lake Tüttensee crater located at a distance of c. 20 km and a doublet crater in Lake Chiemsee (see Fig. 1) sized about 900 m x 400 m. Shock release from both nearby craters must have been enough for extreme rock liquefaction and related effects [5].

Although the purely scientific aspects of meteorite impact and liquefaction are highlighting enough [5], the Thunderhole phenomenon has some practical aspects. In general, the local population has considered the sudden and sometimes drastic Thunderhole collapses, due to unknown causes, as a fate. Caverns encountered during construction works had to be filled with huge amounts of cement, farmers found their cows looking irritated down into a Thunderhole that had formed in the cowshed, and lawsuits are said to have been filed reproaching the contractor with badly done work although geology had simply piped up. As we have seen, geophysical measurements in the form of complex resistivity soundings seem to be best adapted to this special underground scenario.

Summary and conclusions

◆ In the Lake Chiemsee region there is abundant and strong evidence of rock liquefaction features in Quaternary sediments. ◆ Acute evidence are sinkholes ("Thunderholes", "Donnerlöcher") that collapse all of a sudden. The phenomenon totaling roughly several hundred to one thousand sinkholes to have occurred in the past in a relatively small area is known as long as anyone can remember but has so far lacked any reasonable explanation. ◆ Excavations and geophysical measurements in the form of complex resistivity (resistivity and induced polarization) electrical imaging over a freshly formed Thunderhole and an active depression, probably preceding a future sinkhole collapse, reveal the clue to understanding the geologic scenario. ◆ The geologic scenario reflects prominent rock liquefaction well known from strong earthquake shocks and shows remarkable similarity to the intense rock liquefaction features in the large area affected by the strong 1811/1812 New Madrid (Missouri) earthquake series. ◆ Strong earthquakes to have produced the heavy rock liquefaction can be excluded for the small Kienberg/Trostberg area under discussion. ◆ A reasonable cause for the rock liquefaction are local reactions to the recently proposed Holocene large Chiemgau meteorite impact event having produced a crater strewn field including nearby impact craters of the size of several hundred meters. ◆ The rock liquefaction was induced by impact shock. ◆ The engineering geology aspect for the region is important but has so far only hesitantly been considered. ◆ Geophysical measurements are a useful tool to investigate the underground for substructure purposes threatened by sinkhole collapse. ◆ Complex resistivity soundings with a focus on induced polarization (IP) measurements prove to be especially suited to provide a high-resolution picture of a possibly disturbed underground.

References

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