# CHARACTERISATION OF A SMALL CRATER-LIKE STRUCTURE IN SE BAVARIA, GERMANY


**W. Rösler[(1)], A. Patzelt[(2)], V. Hoffmann[(1)], B. Raeymaekers[(3)]**

*[(1)]Institute for Geoscience, University Tübingen, Sigwartstr. 10, D-72076 Tübingen (Germany), Email: wolfgang.roesler@uni-tuebingen.de, viktor.hoffmann@uni-tuebingen.de*
*[(2)] Terrana Geophysik Zeppelinstr.15, D-72116 Mössingen (Germany), Email: ap@terrana-geophysik.de*
*[(3)] Infraserv Gendorf, D-84504 Burgkirchen (Germany), Email: Bert.Raeymaekers@Gendorf.de*



## ABSTRACT

A small scale crater-like structure, where fused country rocks had been found, was studied in detail. The heated cobbles show a variety of extreme heat effects, but no clear indications for shock metamorphism could be found. For a non-destructive characterisation and for resolving the depth structure, geophysical field methods were used. Magnetic mapping reveals a large number of individual, small scale dipole anomalies associated with the heated crater walls and a negative anomaly in the center of the crater. Ground penetrating radar profiles indicate a continuation of the crater wall morphology into depths of several meters. The crater floor is characterised by strong reflections, indicating significantly different physical properties of the crater floor material compared to the surrounding. The age of the structure is definitely pre-industrial and the signatures can hardly be explained by primitive industrial human activities. At present, an interpretation in terms of a meteoritic or cometary impact is highly speculative and needs more, reliable, data.


## 1. INTRODUCTION

A large number of small, circular, bowl shaped, depressions is found in Holocene and Quaternary glacial and fluviatile gravel beds in SE Bavaria, covering large areas of the Alpine foreland, stretching northward, approximately 50 km to the Inn river. Many of these structures with diameters of a few meters to several tens of meters have been described as features of glacial landscape morphology like buried ice or moraine features [1] or as archaeological structures with ambiguous origin [2]. In a large forest area along the Alz river, between the towns Altötting and Burghausen, north of the maximum extent of glaciation, numerous circular depressions have been described [3]. The crater-like structures attracted our attention when carrying out regional studies on magnetic properties of surface soils for mapping industrial pollution [4] and trace elements in bee honey [5], which both showed anomalous signatures in this area. A brief inspection of some of the suspected crater-like structures could not establish a direct link between the observed anomalous magnetic signatures of top soils or trace elements in bee honey with the circular structures in general. However, at one of the inspected depressions, located at approx. 48°13'N, 12°45'E, considerable amounts of suspicious, fused, cobbles with slag-like appearance, associated with a strong magnetic signal, were found and prompted us to a more detailed characterisation of the structure using macroscopic, microscopic, mineralogical, and geophysical methods. First systematic studies on a few other structures nearby have been undertaken by other investigators but could not yet clarify their origin [6].

Fig. 1. Crater-like structure in beech forest

## 2. GEOLOGICAL SETTING

The landscape surrounding the investigated structure is characterised by late glacial to Early Holocene fluviatile deposits, consisting of unconsolidated glacial gravel and cobble beds, intercalated with fine grained sand and clays, which were deposited at the end of the last, Würm, glaciation period (ca. 12.000 years BP) by rivers draining the melting Salzach and Inn glaciers [7]. The cobble beds are dominated by alpinotype rocks from Northern Alps and crystalline rocks from the Tauern and Engadin window metamorphic series. Typical lithologies are limestones, dolomites, marls, silicatic limestones, quartz and quartzite, gneisses, granitoides, greenstones, amphibolites from the central Alps, clastites, sandstones and others [1]. Soils are of Holocene age, the soil type near the investigated structure is a para-brown earth with a thickness of ca. 10 cm.

## 3. MORPHOLOGY

The investigated structure is found on a gentle NW-SE dipping slope of a terrace of the Alz river, in old beech forest (Fig.1). Trees growing on the structure and dead tree trunks indicate a minimum formation age of more than hundred years, a maximum formation age is given by the deposition of the gravel beds ca. 12.000 years BP. The depression represents an almost perfectly circular, crater-like, structure with a pronounced crater rim with a rim to rim diameter of ca. 11 m and a depth of ca. 1,2 m. At the hill side, the crater rim morphologically merges into the slope and is probably even covered by sediment material transported down the slope. The other parts of the crater rim show almost no sediment or soil cover and form a crater wall with a gently rounded profile.

## 4. EVIDENCE FOR EXTREME HEAT

The rocks of the crater walls appear to have suffered from extreme temperatures. Throughout the crater walls, except the hill side which is covered with finer grained material, the country rocks show a variety of heat effects, ranging from fused, glazed cobble surfaces, partial or complete melting of minerals and thermoplastic deformation of cobbles, to signs of volatilisation of certain mineral phases (Figs. 2&3). Due to extreme metamorphic effects and a wide variety of source rock lithologies, a secure identification of the source rocks from slag-like thermally altered products is hardly possible. At some granite type rocks, the quartz fraction seems to have survived whereas the feldspar fraction is completely molten. Other rock types show lava- or pumice-like appearance with signs of volatilisation of single mineral phases or of the whole rock from one side. At many places, the cobbles are thermo-plastically deformed, indented into each other, and cemented by a brown, silicatic, melt to a solid mass, indicating that the wall structure has been heated as a whole and cannot be explained as a slag deposit. Temperatures exceeding 900 °C are indicated by the lack of carbonaceous rocks, which account for about half of all rocks of the surrounding, in the thermally altered material. Thin sections of selected rocks have been inspected for planar deformation features (PDFs) or high pressure mineral phases but no evidence of shock metamorphism could be observed [8]. X-ray diffraction analysis of quartz phases reveal that a part of the quartz fraction has been transformed to the high temperature polymorphs tridymite (870-1470 °C) and cristobalite (1470-1725 °C; Fig. 4) In fused crusts of a few cobbles, iron silicon crystals and carbon spherules [9] can be observed (Fig. 5), indicating temperatures close to 2000 °C [10].


Fig. 2. Thermally altered cobbles, indented into each other and cemented by silicate melt


Fig. 3. Thermally altered cobble, cut in slices, pumice-like structure with signs of volatilisation

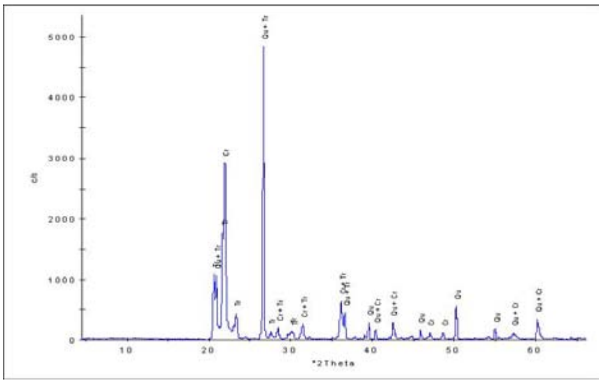


Fig. 4. X-ray diffraction diagram of a thermally altered quartz-type rock fragment. High temperature phases of quartz (Qu; T<870 °C), tridymite (Tr: 870-1470 °C), and cristobalite (Cr; 1470-1725 °C) can be assigned

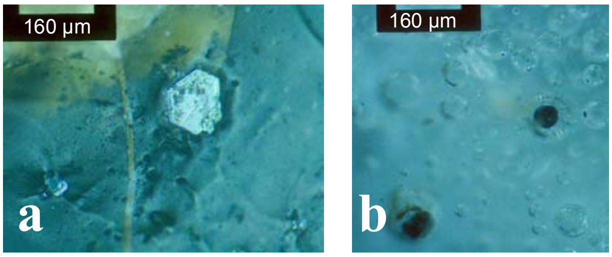


Fig. 5. a: Iron silicon crystal in fused cobble surface
b: Carbon spherules in fused cobble surface

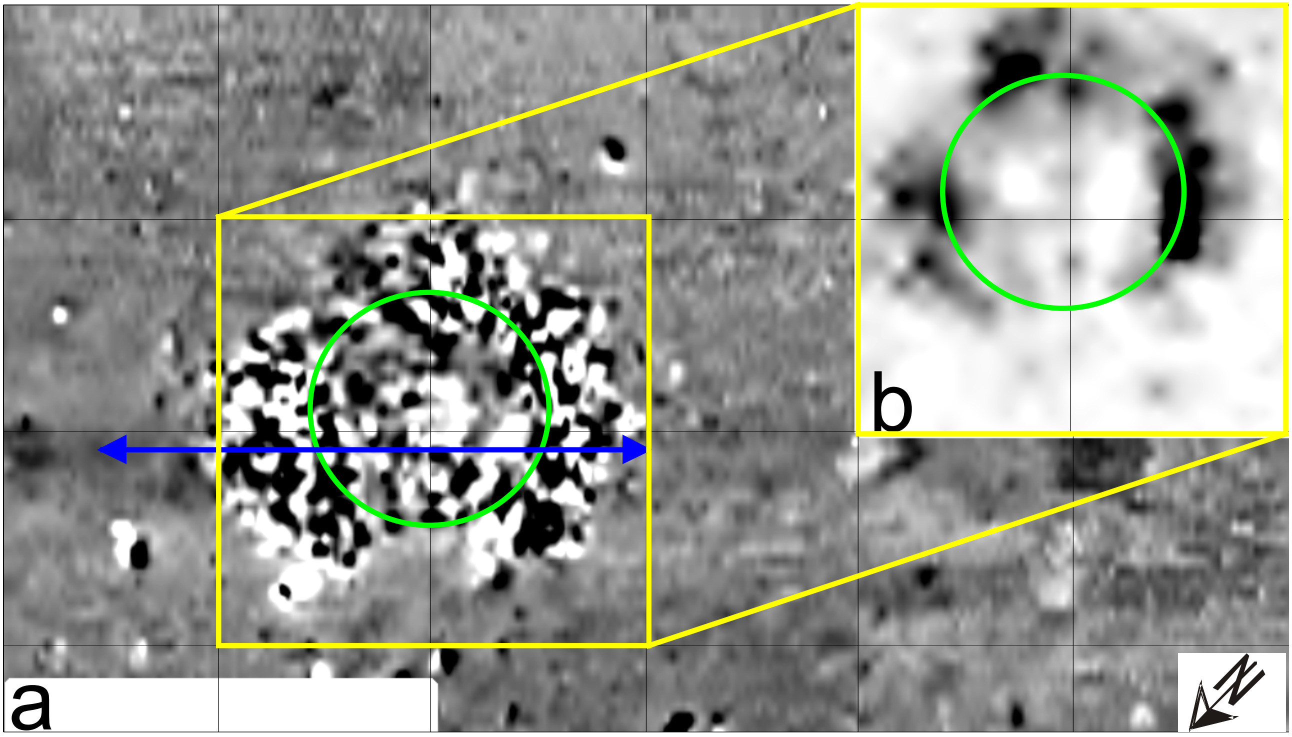


Fig. 6. Magnetic mapping.
a: Gradient of the Earth magnetic field Z component, sampling interval 0.25 m x 0.5 m, dynamics –10 nT (white)/+10 nT(black), 256 greyscales, 10 m grid overlay. The green circle indicates the position of the crater rim, the yellow box the area mapped for magnetic susceptibility, the blue line represents the GPR profile displayed in Fig. 7.
b: Volume specific magnetic susceptibility of the soil surface, sampling interval 1m x 1m, dynamics $10^{-4}$ SI (white) to $10^{-3}$ SI (black), 256 greyscales

## 5. MAGNETIC SURVEY

For a non-invasive characterisation of the crater-like structure, several geophysical field methods have been applied. The observed heat-induced mineralogical changes should also lead to changes in magnetic properties and in magnetization. Moreover, the possible presence of archaeological materials such as tools or meteoritic materials should lead to magnetic anomalies or characteristic patterns. Magnetometry was carried out using a FM36 handheld fluxgate gradiometer (Geoscan Research, UK), a standard system designed for near-surface archaeological applications with a sensor separation of 50 cm, measurement position ca. 30 cm above ground, and a resolution of 0.1 nT in Earth magnetic field Z component gradient. The surrounding of the crater-like structure was mapped in an area larger than 40 m by 30 m with a sampling interval of 0.5 m x 0.25 m. The grey scale plot (Fig. 6a) reveals a calm background with dynamics of generally less than 1 nT in the surrounding of the crater-like structure, indicating generally weakly magnetic country rocks, with a few occasional interspersed dipole anomalies (scrap or highly magnetic individual rocks). The thermally altered crater wall material is characterised by a large number of strong, small scale dipole anomalies, probably representing individual, near surface, re-magnetized, thermally altered country rock cobbles. At the inner crater slopes and at the hill (NW) side of the crater wall, such individual, strong dipole anomalies are partly missing, indicating probably a considerable cover with less magnetic material or the erosion of the strongly magnetised material at some places. Altogether, the resulting image of the gradiometer survey indicates that an area with a diameter of ca. 20 m had been subjected to substantial re-magnetisation. In the centre of the crater-like structure, a negative magnetic anomaly with a diameter of ca. 3 m is visible. Mapping of the volume specific magnetic susceptibility, using a Bartington M2-D loop sensor (Fig. 6b), reveals extremely enhanced magnetic susceptibility values, up to more than 350 $*10^{-5}$ SI associated with the heated crater wall material in contrast to the low background values of less than 10 $*10^{-5}$ SI. Here it is suspected that the increased magnetic susceptibility values may be associated with newly formed highly magnetic mineral phases, such as magnetite or iron silicon phases (Fig. 5a).

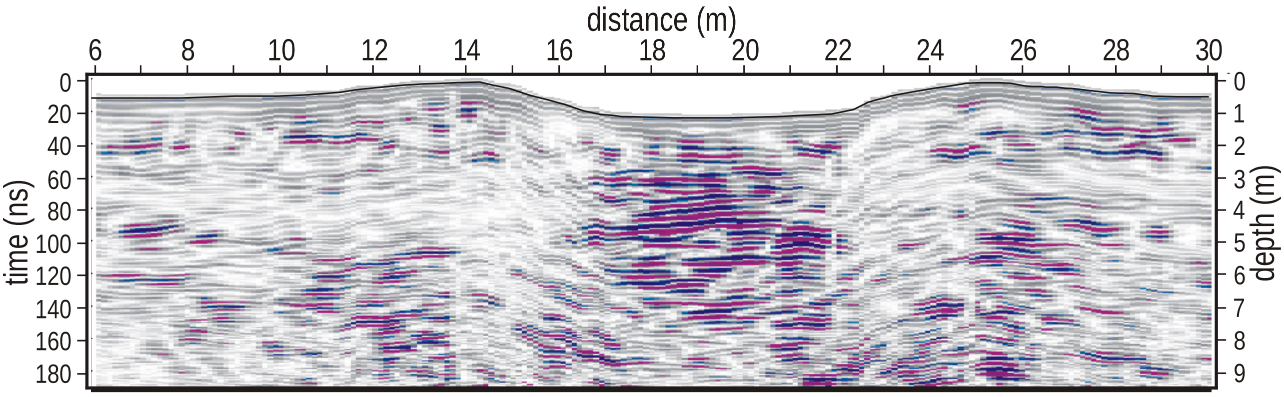


Fig. 7. radargram, 200 MHz antenna

## 6. GROUND PENETRATING RADAR

Ground penetrating radar (GPR) measurements were performed with a RAMAC GPR CU II (Mala Geosciences, Sweden) and an unshielded 200 MHz antenna on lines with 1m separation parallel to the profiles of the magnetic survey. Along a profile every 0.1 m a trace was recorded. Fig. 7 shows exemplaryly a radargram across the centre of the crater-like structure. The position of the radar profile can be seen from Fig. 6a. In this profile and the other radar profiles as well, no significant reflections occur outside the crater. The morphology of the crater wall seems to continue into depths of several meters. Within the crater, strong reflection amplitudes can be observed, indicating significant changes in the physical property ε, the dielectrical constant. Strong reflections start in a depth below ground level of about 2.7 m and last until about 7.5 m. However, the lower limit is not very well constraint, as the maximum penetration depth of the selected antenna is somewhere in that depth range. The shape of the anomaly is not indicative for a larger single body in the subsurface, but points towards a broader zone of massive physical changes.

## 7. DISCUSSION

The main characteristics of the investigated structure can be summarised as follows:

- Crater-like morphology
- Extreme heat effects on crater wall rocks
- No shock indicators yet
- Depth structure of crater walls and fill

$^{14}$C data from other nearby craters [6] and preliminary own data from the investigated structure indicate a date of around 2000 BP, which falls into Roman time. A Roman villa is known nearby, and a possible origin or use of the structure as lime kiln, fire place, or furnace place could be debated. However, the heat effects documented in this study are unparalleled by any pre-industrial or early industrial process. Nevertheless, the structure seems to have parallels to some "vitrified forts" in Scotland or other parts of Europe, but the origin and the purpose of some of such vitrified forts itself is debated ever since their discovery [11]. Unlike at other vitrified forts, no wood remnants or wood casts were found on or between the fused stones. Moreover, a fortification of an 11 m diameter object at a slope, erected with considerable effort, would not make any sense. Until industrial times, ca. 100 years ago, it was extremely difficult to generate temperatures exceeding 1000 °C. Kilns or furnaces for such high temperature applications were generally small and had a distinct morphology. Such temperatures could not be reached using a wood fire, even with ventilation. Early ore smelters used charcoal and could probably reach ca. 1300 °C, typically had diameters of less than 1 m, and produced slags which were usually thrown on a slag heap nearby. From size and morphology the investigated crater-like structure cannot be interpreted as a smelter. Other early furnaces like lime kilns could reach only considerably lower temperatures (ca. 900 °C – 1000 °C) and the observed effects can be hardly explained by a lime kiln gone out of control.

For nearby crater-like structures of similar size without any heat signatures, possible formation mechanisms by meteoritic impacts or human activity have been discussed [6] and an anthropogenic origin has been excluded. The European-wide and regional presence of suspicious carbon materials in soils [9], at a few crater-like structures in considerable quantities, requires a large carbon source and may indicate a carbon rich impactor, probably a comet. The Earth impact record is lacking cometary impacts. It is a paradigm that due to its high velocity and low mechanical strength, a cometary impactor would fractionate in atmosphere and completely vaporise. But there is a lack of data on the nature of cometary matter (dirty snow-ball or snowy dirt ball) and even more on its behaviour during atmospheric entry. Nevertheless, for a few impact events like the Tunguska event [12], carbon anomalies can be found and cometary impacts are taken into account. In order to generate a strewn field of impact craters, exhibiting different effects and stages of shock metamorphism, a progressive break-up of a heterogeneous body, combined with explosive break-up events, could be imagined. Modeling crater sizes and shock effects [13], an impactor of 30-50 cm diameter - irrespective whether ice, stone, or metal - and a velocity of > 12 km/s would be necessary to create a crater with the observed dimensions, melt, and vaporisation.

## 8. INTERPRETATION AND OUTLOOK

The studied crater-like structure seems to have suffered from extreme temperatures which seem unlikely to have been produced by human activity. The regional context with structures of similar shape and size, but without melt may either indicate an yet unknown human use of the structure, or a strewn field of craters with significantly different formation conditions at individual craters. Here the existing data base on different local crater-like structures, on signatures of cometary matter, on break-up of heterogeneous, weak bodies during atmospheric entry, and on the interaction of a cometary gas cloud in the shock front of a bolide are largely unknown and interpretations are highly speculative. Unless accepted signatures for an impact like PDFs or high pressure mineral phases can be found, a careful study of the crater-like structures, also focusing on carbon materials, is proposed.

## 9. ACKNOWLEDGMENTS

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