Meteoritics & Planetary Science 40, Nr 2, 187–194 (2005)
Abstract available online at http://meteoritics.org

A meteorite impact crater field in eastern Bavaria? A preliminary report

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(Received 25 March 2003; revision accepted 12 November 2004)

Abstract–Numerous circular depressions north of Burghausen in eastern Bavaria, with diameters ranging from meters to tens of meters in size and dispersed over an area of at least 11 × 7 km, are suspected to have an extraterrestrial origin since they resemble other small meteorite impact craters. The depressions are bowl-shaped, have high circularity and a characteristic rim. Most of them were formed in unconsolidated glacial gravels and pebbles intermixed with fine-grained sand and clay. Magnetic investigations reveal weak anomalies with amplitudes of less than ±10 nanoTesla (nT). In some cases, the origins of the anomalies are suspected to be due to human activity within the structures. So far, no traces of meteoritic material have been detected. An evident archaeological or local geological explanation for the origin of the craters does not exist. A World War I and II explosive origin can be excluded since trees with ages exceeding 100 years can be found in some craters. One crater was described in 1909. Carbon-14 dating of charcoal found in one crater yielded an age of 1790 ± 60 years. Hence, a formation by meteorite impacts that occurred in Celtic or early medieval times should be considered. A systematic archaeological excavation of some structures and an intensified search for traces of meteoritic material are planned.

INTRODUCTION

During archaeological research on Celtic and Roman remnants in the area of Burghausen in eastern Bavaria, several circular depressions with diameters ranging from meters to tens of meters were noticed by Werner Mayer. Although one of the structures is possibly cut into an archaeological site and others were used for a primitive production of lime and charcoal, evident archaeological explanation for the digging of such large holes in prehistorical or historical times does not exist. In addition, no plausible terrestrial geological process exists which could explain the formation of these crater-like features in this area. This prompted us to consider an extraterrestrial origin of the structures. Subsequently, a research group was formed with members from the Department of Earth and Environmental Sciences of the University of Munich and the Mineralogical State Collection (Munich) in collaboration with the Bavarian Geological Survey and the Bavarian State Department of Historical Monuments and the research group of Werner Mayer.

The aim of this study is to present the first preliminary results of this survey and to discuss morphological, geological, and magnetic investigations. Finally, we will discuss current evidence in favor of an impact origin of these structures.

LOCATION AND GEOLOGICAL SETTING

The investigated craters are located with a distinct south-north distribution in eastern upper Bavaria covering an area of about 11 × 7 km between Burghausen and Marktl.

The area is bounded by 48°11′N and 48°17′N latitude and 12°43′E and 12°49′E longitude (Fig. 1). Presently, 12 craters have been partly investigated and several additional suspected structures have been identified but not yet investigated. The structures south of the Inn river are

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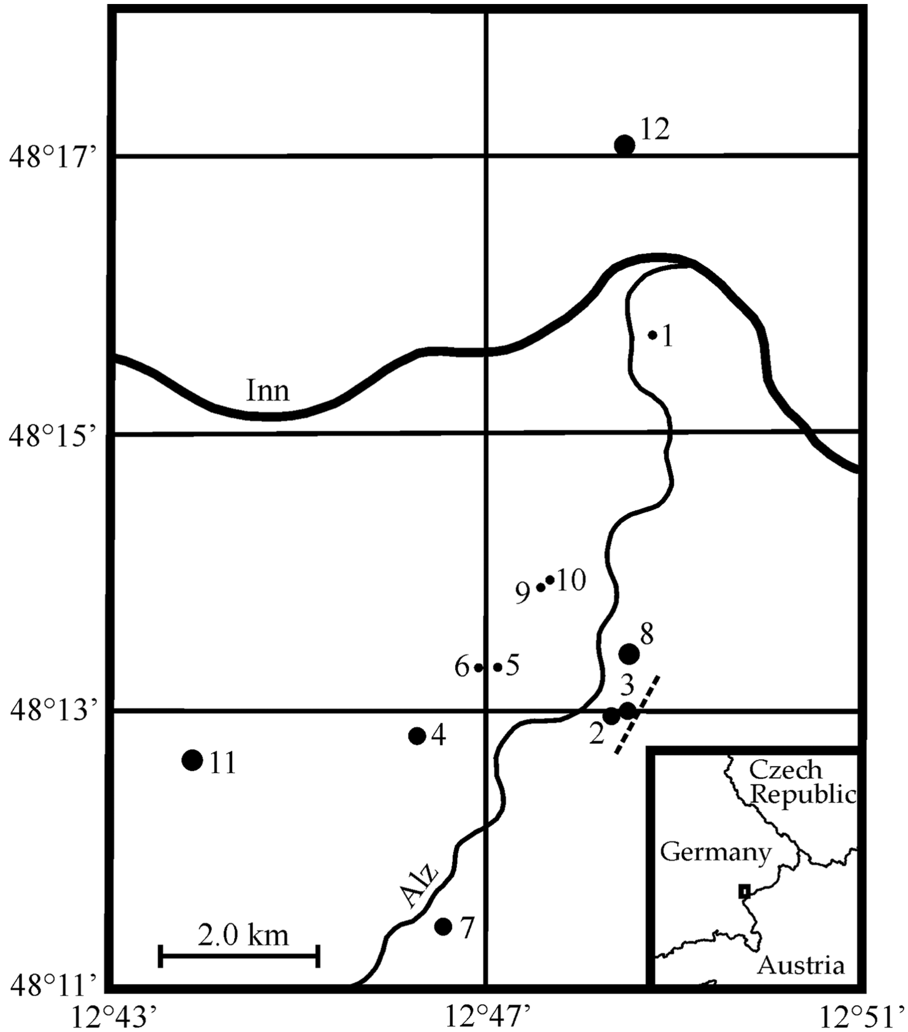

Fig. 1. Location of the Burghausen crater field. The short dashed line indicates the location of part of the “Laubergraben” (see text).

situated in Holocene fluviatile deposits (30–40 m thick) of generally unconsolidated glacial gravels and Würm terraces of the Salzach glacier (Grimm et al. 1979) consisting of pebbles (up to 10–20 cm in size) intermixed with fine-grained sand and clay material. Occasionally, parts of the Würm deposits are consolidated to a kind of conglomerate with the local name Nagelfluh. The Würm period is the youngest ice age activity in this region, which ended 12,000 years ago. The Würm glacier originated in the central Alps, and therefore the gravels consist of various lithologies including sedimentary (limestones, sandstones, shales), metamorphic (schists, gneisses, amphibolites), and magmatic rocks (granites). It is important to note that the area of interest lies beyond the ancient end moraines and that it is characterized by the presence of numerous gravel terraces due to fluviatile activity during the last 12,000 years. Geological mapping is very fragmentary in that region and the only map available is at a scale of 1:500,000. According to Grimm et al. (1979), four to six different terraces exist, but a distinction between late-glacial and post-glacial terraces along the Alz valley (see Fig. 1) has not yet been elaborated. Eleven of the investigated craters are randomly distributed over the different terraces. The fluviatile sediments are covered by a thin humus layer (5–10 cm thick). One crater (#12 in Fig. 1) is located north of the Inn river. This area is characterized by Tertiary sands and loess. The area of interest is mainly covered by forests, and all craters studied were found in wooded areas (Fig. 2).

MORPHOLOGY

All of the investigated structures are bowl-shaped and have a pronounced circularity (e.g., Fig. 2). Some of the structures show a slight asymmetric aspect. This asymmetry could be a primary feature or an effect of the present vegetation since large trees can modify the morphology to a certain extent. The observed rim-to-rim diameters of the circular structures range from 5 m (#6 in Fig. 1) to 18 m (#11 in Fig. 1). The depth-to-diameter ratios range from 0.10–0.19 m.

Fig. 2. Crater #7 with a diameter of about 9 m and a depth of about 1.7 m.

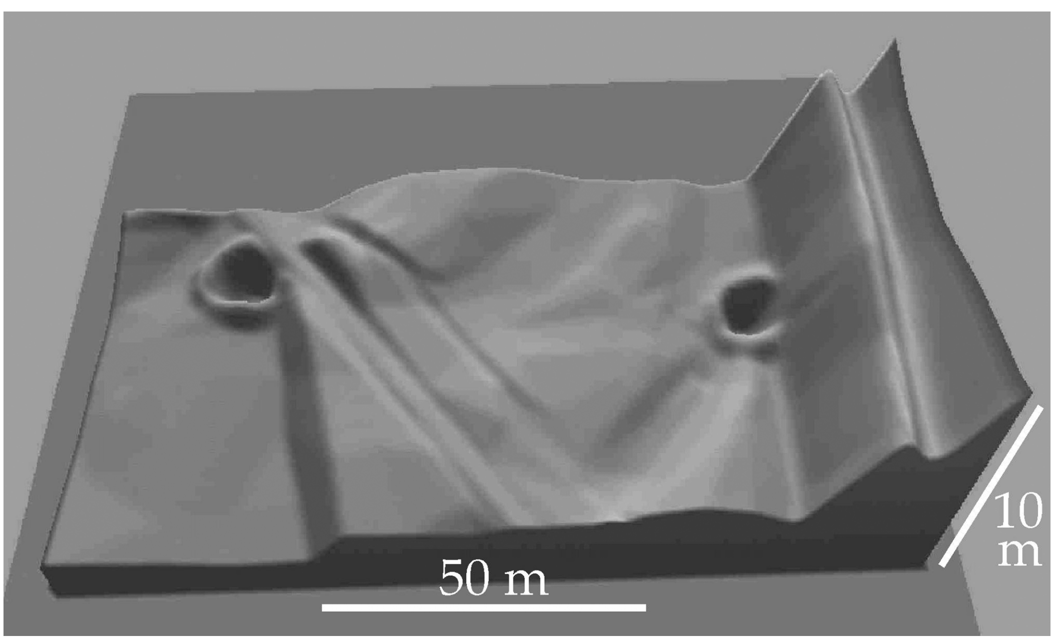

Fig. 3. Morphology of craters #2 (about 12 m in diameter) and #3 (about 10 m in diameter). The distance between the craters is about 80 m. The vertical exaggeration is about 5×. On the right-hand side, the artificial trench called "Laubergraben" can be seen.

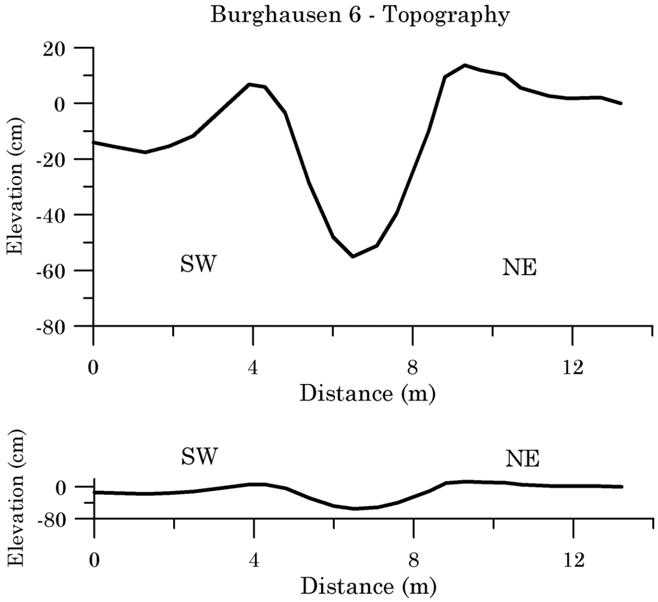

Fig. 4. Normal (lower) and vertically exaggerated (upper) profile across crater #6 (see Fig. 1).

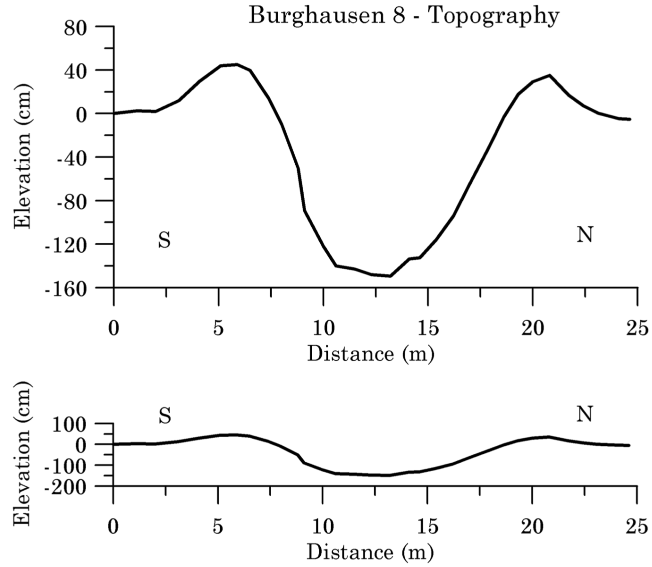

Fig. 5. Normal (lower) and vertically exaggerated (upper) profile across crater #8 (see Fig. 1).

A well-defined rim (0.2–0.9 m in height) surrounds all of the structures, indicating a centrosymmetrical excavation process. The rims of all the craters are more or less complete and are not cut by a sort of entrance point. Figure 3 shows 3D topographic models of the structures #2 (12 m in diameter and #3 (10 m in diameter). The data on which the model is based were obtained with a 0.5 m spatial resolution. The two craters have apparent depths of about 1.2 m and 1.4 m. On the right-side of Fig. 3, an archaeological structure known as "Laubergraben," an excavated ditch of unknown age with a steep wall can be seen. It is possible that crater #3 cuts into the structure, and thus it would be younger.

In several structures, the dense vegetation (Fig. 2) causes problems for determining the morphology of the craters. In these cases, only their profiles were measured by leveling methods at a 0.5 m spatial resolution. Figures 4 and 5 show the topographic profiles of a smaller and a larger crater among those studied (#6 and #8 in Fig. 1). Both figures show a normal and a vertically exaggerated profile. The typical bowl shape of the craters is clearly visible. The craters show a steep inner and a shallow outer slope as demonstrated in the vertically exaggerated profiles of Figs. 4 and 5 in particular.

GEOLOGICAL STRUCTURE

Crater #6 was partly excavated by a small machine excavator to investigate the subsurface of the structure and to search for meteoritic material. The crater has a rim height of about 25 cm and rim diameter of 5 m (Fig. 4). Following the southwest-northeast profile in Fig. 4, a 10 m trench with an approximate width of 1 m and a depth of 1.5 m was dug from outside the wall, through the center of the crater, to the outside of the opposite wall. The trench was excavated in increments of 10 cm. Each level and the excavated material were checked with a metal detector to detect any meteoritic fragments, but none was found during the excavation. The crater lies in a gravel terrace dipping slightly southwest at an angle of approximately 10°. Two different gravel layers occur down to a depth of 1.5 m. The upper layer has a thickness of 1 m and consists of pebbles and intermixed layers of sandy material showing a gradation. In the lower layer, only pebbles without sandy material occur. Below a depth of 60 cm, we only found undisturbed sediments and no hint of a disturbance by an impactor was detected. The uppermost part (20 cm) of the upper layer shows weathering effects as indicated by a more reddish color. From the wall to the center of the crater, a thinning out of the reddish horizon was observed and the weathering horizon is absent in the center. The greatest thickness of this horizon is under the crest of the rim. Beneath the rim, the boundary between the weathered horizon and the underlying gravels shows an upward directed curvature following the shape of the rim as shown in Fig. 4. The whole crater structure is covered by a thin (10 cm max.) humus layer.

MINERALOGICAL INVESTIGATIONS

Samples for magnetic separation and mineralogical studies were taken from subsoil material below the humus layer of the rims and the centers of several of the craters. The material was first washed and the silt and organic fraction were decanted. The residue was separated into different grain size fractions by sieving. Magnetic particles were found mainly in the finest fraction (<0.5 mm). X-ray diffraction analysis showed them to

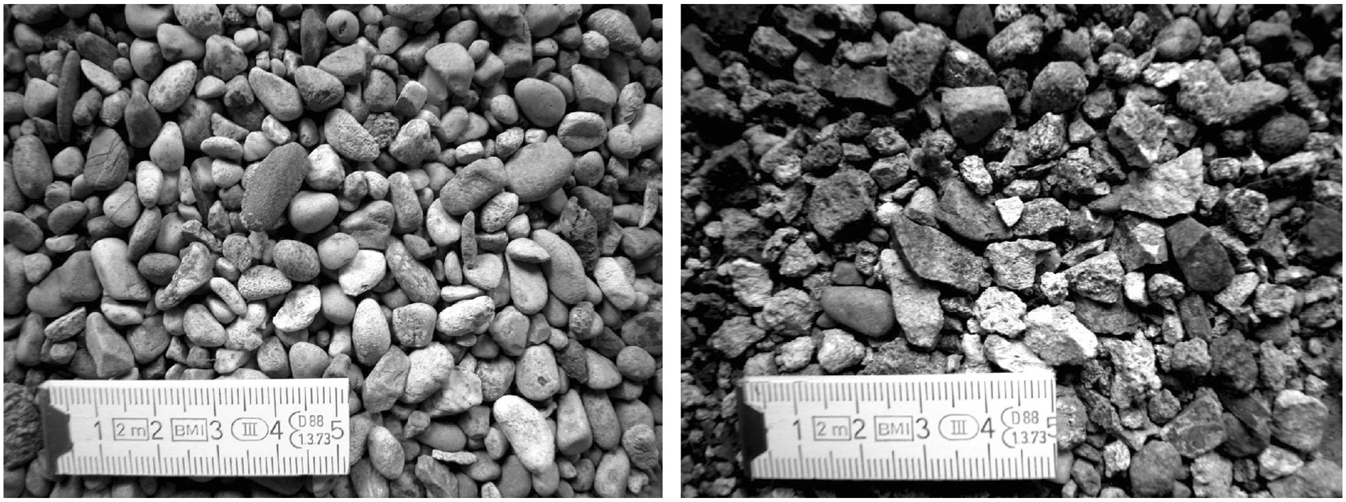

Fig. 6. Unbroken pebbles from the rim (left) and broken pebbles from the center (right) of crater #3 (washed and sieved fraction).

be mostly magnetite. The chemical composition of the soils of the selected craters was determined by X-ray fluorescence analysis (XRF). They display Ni/Fe and Cr/Fe ratios up to 0.00287 and 0.00417, respectively. These values are significantly higher than average values of the continental crust (0.00148 and 0.00262; Taylor and McLennan 1985).

The samples collected from the wall and those from the center have often different shapes, as shown in Fig. 6. Samples from the wall consist of rounded pebbles similar to those found in reference samples from the undisturbed environment outside of the crater sites. Samples from the crater bottom, however, are made up of many broken pebbles with sharp edges. Petrographic analysis showed no difference in material between the rounded pebbles (predominantly limestones) from the rim and the broken ones from the bottom. Frost action is improbable because of the low water table.

MAGNETOMETER SURVEYS

Magnetic anomalies could eventually indicate the presence of magnetic meteoritic material in the craters. Therefore, magnetometry was carried out in several structures using a cesium magnetometer in a sampling interval of 12.5 × 25 cm (12.5 × 12.5 cm in crater #2) at a height of about 30 cm above the ground following the topography of the depression. Additional surveys were carried out using proton magnetometers.

The resulting total intensity disturbances are made visible by a grayscale plot (dynamics ±8.0 nT, 256 grayscales from black [min] to white [max]) of the deviation from the Earth's magnetic field (D = 1.8°, I = 64°). Figure 7 shows an example of the measured anomalies.

In crater #3, a central magnetic anomaly was found with an amplitude of +8.5/−6.5 nT (Fig. 7). This result appears similar to a typical anomaly that occurs above archaeological pits filled by topsoil. The surrounding forest soil shows such a weak magnetic signal that the magnetic effect of the morphological depression (~1.4 m) is not clearly visible in the magnetic grayscale plot. The extended survey around the depression revealed an extraordinarily low noise for the soil (less than ±0.3 nT) indicating that the gravel is dominated by very weakly magnetic rocks such as limestones. The dominance of limestone and other weakly magnetic rocks with low magnetic susceptibility in the target rocks, in this case, facilitates the detection of clear magnetic signatures. In other craters of the Burghausen crater field, the additional occurrence of amphibolites and serpentinites complicates the magnetic signature.

There are several processes that could generate such a magnetic anomaly. First, the anomaly could be ascribed to man-made fire resulting in a transformation of paramagnetic minerals into ferrimagnetic minerals and therefore in an increased magnetization of the soil (Le Borgne 1960). Second, the anomaly could be caused by a pit that is filled with topsoil (enrichment of ferrimagnetic minerals by the pedogenic formation of magnetic minerals in topsoil [Maher and Taylor 1989; Fassbinder et al. 1990]). Third, artificial or extraterrestrial input of fine-grained magnetic minerals could be a possible source of the anomaly. However, no sign of fire (e.g., charcoal or reddening of the soil) is visible in this crater. Furthermore, the amplitude of the magnetic anomaly should be much higher in the case of a thermoremanent magnetization. In the center of the depression, the profile depth of the topsoil is less than in the undisturbed surroundings of the depression. If the anomaly is caused by meteoritic projectile material, it must be assumed that it contained a very small amount of magnetic minerals or that most of the magnetic phases have been destroyed by weathering.

Recently, the occurrence of iron silicide alloys in the Burghausen area was reported on Web sites and newspapers.

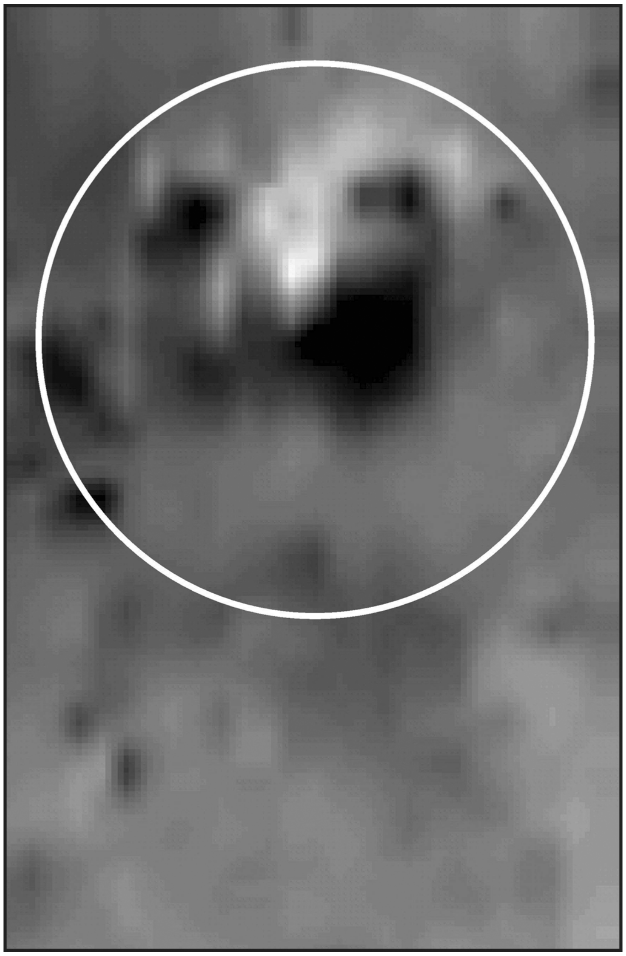

Fig. 7. Magnetogram of crater #3: size 20 × 13 m, sampling interval 12.5 × 25 cm, dynamics ±8.0 nT, 256 greyscales from black (min) to white (max); Earth magnetic field: D = 1.8°, I = 63°. The white circle indicates the location of the 10 m in diameter crater rim.

It was claimed that these materials are of extraterrestrial origin (e.g., Cambridge Conference Network, B. Peiser). Our observations indicate that the iron silicide alloys consist of several phases with varying Fe/Si ratios and display eutectic textures. Furthermore, their lead isotope ratios have a terrestrial signature pointing clearly to an industrial origin (Fehr et al. 2004). The iron silicide alloys have not been found within the investigated craters.

The magnetic survey of crater #2 also revealed no magnetic edge effects due to the topographical depression, indicating similar soil magnetic conditions as those of crater #3. However, a square-shaped anomaly inside the crater suggests the presence of an archaeological structure. Well digging would be a good explanation, but can be rejected because the water of the Alz river is in very close proximity and shares the same topographic level. The dating of the archaeological structure and the purpose of its construction inside the depression remain unclear. A secondary archaeological use of the depression would be one possibility.

AGE

A minimum age is given by the presence of trees within many structures, which are at least 100 years old according to the foresters of the area. A second upper time limit is given by the fact that one of the craters (#11 in Fig. 1) was included in archaeological descriptions of the area in 1909 and 1911 (Weber 1909; Stechele 1911). The authors cited the crater as "spherical cavity of unknown origin without any entrance." Both reports mention that the local population has no knowledge of the origin and purpose of the structures, which indicates an age beyond the memories of the community. Some of the structures that were described at that time are now shallow depressions in agricultural areas, which have been, to a great extent, filled up by the peasants. One of the craters (#3 in Figs. 1 and 3) is located at the foot of the Laubergraben (Fig. 3). This trench is part of a wall system of about 11 km, which is currently undated. Its age is thought to be either medieval (about AD 1000–1200) or Celtic-Roman (~50 BC–AD 50; Harlander 1983). A clarification of the relationship of crater #3 to the Laubergraben could eventually help limit the age of the crater.

No ancient historical record reporting an impact event (which would have caught the attention of the local people and all of southern Germany) exists. A comparable event, the Sikhote-Alin 1947 meteor shower (which covered an area of about 5 × 2 km), was observed by eyewitnesses at distances of up to 400 km from the point of impact (Krinov 1966). Therefore, an early medieval or a pre-Roman age of the structures should be considered. For a much older age, the structures look astonishingly fresh and show almost no weathering effects developed since the supposed impact. Another age limit comes from charcoal dated with ^{14}C and found in crater #5. This crater was used as the base of a primitive lime kiln. The charcoal yielded a ^{14}C age of 1790 ± 60 years (M. Frechen, personal communication) indicating that the crater formation took place before AD 134–202.

DISCUSSION

Several impact craters or crater fields with structures of similar dimensions are known on Earth. They were created mostly by the impact of iron or stony iron (pallasites) meteorite projectiles. Examples for terrestrial crater fields with craters of similar dimensions are Sikhote-Alin in eastern Siberia (e.g., Krinov 1966), Campo del Cielo in Argentina (e.g., Cassidy and Renard 1996), Jilin in Manchuria, China (e.g., Bühler 1988), and the crater fields of Europe: Morasko in Poland (Korpikiewicz 1978; Czegka 1996), Kaali (Tiirmaa and Czegka 1996) and Ilumetsa in Estonia (Czegka 1997; Czegka and Tiirmaa 1998), and most recently, the Sirente strewn field in Italy (Ormö et al. 2002). A single impact crater comparable to the Burghausen craters is, for example, Sterlitamak in

Russia. It has a diameter of ~12 m and formed in 1990 (e.g., Ivanov and Petaev 1992). As far as a comparable impact field area is concerned, the Jilin event with a strewn field of about 67 km × 10 km could be compared to the Burghausen field. The large extent of this field is, however, inconsistent with the atmospheric breakup of a single projectile (e.g., Melosh 1989).

The craters of the above mentioned crater fields are all small, a few meters to tens of meters across, and were created by disrupted projectiles which had retained only a small fraction of their cosmic velocity. A characteristic feature of such small impact craters is the absence of shock metamorphic effects in minerals of the country rocks. The verification of the impact origin is usually based on the morphology and geology, sometimes magnetic anomalies, and in particular, the presence of meteoritic material. Most of these crater fields (exceptions are Ilumetsa and Sirente) have yielded fragments of the meteoritic projectile and therefore are undoubtedly of extraterrestrial origin. In some cases, quite large fragments of meteorites have been found at the bottoms of penetration channels at considerable depth, generally strongly fragmented. Meteorite fragments have also been found at shallow depths in the craters. The fact that many of these craters have been excavated in fine-grained material such as loess makes their investigation much easier.

Although no meteoritic material has been found so far, morphological and geological properties of the structures suggest a possible impact origin for the proposed crater field. Holes or cavities in the ground are often produced by human activity, but there is no historical tradition or record of digging such big structures in the studied region. In addition, no exploitation of mineral deposits is known in the region that could have resulted these structures. About 40 km to the north of the Burghausen area, but in a different geological environment, a well-known area of early medieval iron mining exists ("Trichtergrubenfeld;" Frei 1967). In this area, hundreds of small vertical shafts have been dug into Tertiary sands to gain limonitic iron ores, which left behind numerous funnel shaped pits. Comparative investigations, however, showed significant differences. While the morphology of the so called "Trichtergruben" (ore pits) resembles the smaller structures in the Burghausen area, test measurements showed no indication of a magnetic anomaly, whereas all the structures of the Burghausen area (as far as they have been measured) show weak but clear anomalies. Greater circular structures with diameters up to 10 m are also observed in connection with the mentioned ore mining activities. They are archaeologically determined to be remnants of charcoal piles. However, their depth is generally less than that of structures of comparable diameter in the Burghausen area.

The local peasants' digging for gravel is an alternate explanation. This is usually done at nearby terrace escarpments and would always need entry points through the crater walls, which are missing for all structures under consideration. Bombing during World War II could have caused similar structures, but was excluded based on the well-constrained minimum age limit (Weber 1909; Stechele 1911). With bombing, one would also expect to find metal particles, which is not the case. The usage of such crater-like structures as pitfalls for hunting is not known in southern Germany and seems unlikely, given the shallow depth of the structures. It is also unlikely that the structures were used for storing ice, given their substantial distance from rivers and the elevation of some of the craters. Consequently, on the basis of the current evidence, we exclude an anthropogenic origin of the craters. Nevertheless, we are aware that an unexpected human origin for these structures may be discovered (e.g., Speranza et al. 2004). The area was densely populated during Celtic and Roman times, as shown by numerous archaeological vestiges. However, archaeological signatures (especially metallic objects) in and around the craters are extremely rare finds, unlike at other sites where humans were active.

CONCLUSIONS AND FUTURE WORK

The above discussion indicates that the Burghausen area may host a large impact crater strewn field. To reject or accept this hypothesis, further investigations are needed. These include completing the record and carrying out further systematic morphological and magnetic field measurements, as well as rock magnetic investigations. To substantiate the evidence for an impact origin, a continuation of the excavations of some structures using archaeological techniques and an intensified search for remnants of projectiles are planned. The origins of the magnetic signatures and of possible archaeological features within the craters have to be clarified.

Acknowledgments–We thank the reviewers Herbert Henkel and Jens Ormö for their detailed and constructive comments. We also thank Alex Deutsch and Timothy Jull for their detailed and useful remarks concerning the manuscript.

Editorial Handling—Dr. Alexander Deutsch

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