The Holocene Tüttensee meteorite impact crater in southeast Germany

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Abstract. The 400 m-diameter Lake Tüttensee in southeast Germany is the largest crater in the strewn field of meteorite craters that formed in the Holocene Chiemgau impact event possibly in the 6th or 5th century BC. The crater was excavated from a Quaternary target of predominantly moraine and fluvioglacial material and is surrounded by an 8 m-height rim wall and an extensive ejecta blanket. The up to 1 m thick ejecta layer is a polymictic breccia containing heavily fractured cobbles and boulders of Alpine lithologies and is rich in organic material like wood, charcoal, animal bones and teeth. Extremely corroded silicate and carbonate clasts in the breccia point to carbonate melting/decarbonization and/or dissolution by nitric acid. The ejecta layer has conserved an underlying fossil soil rich in organic material, too. A gravity survey reveals a zone of relatively positive anomalies around Lake Tüttensee interpreted by impact shock densification of the highly porous target rocks. Abundant, although moderate, shock metamorphism is observed to occur in clasts from the

rim wall and the ejecta layer. An impact cratering process is able to explain all observed features that are completely inconsistent with a formation of Lake Tüttensee by glacial processes.

Zusammenfassung. Der im Durchmesser etwa 400 m große Tüttensee in Südostdeutschland ist der größte Krater innerhalb des Streufeldes, das sich beim Chiemgau-Impakt - möglicherweise im 6. oder 5.Jh. vor Chr. - gebildet hat. Der Krater ist in überwiegend quartärem Moränen- und Fluvioglazial-Material angelegt und von einem 8 m hohen Ringwall und einer ausgedehnten Decke aus Auswurfmassen umgeben. Die bis zu 1 m mächtige Ejektalage ist eine polymikte Brekzie, die heftig zertrümmerte Gerölle aus alpinem Gesteinsmaterial enthält. Sie ist zudem reich an organischem Material (Holz, Holzkohle, Tierknochen und -zähne). Extrem korrodierte und tief zerfressene Karbonat- und Silikatklasten in der Brekzie deuten auf Karbonat-Schmelzen/Dekarbonisierung und/oder Lösung durch Salpetersäure. Die Ejektalage hat im Liegenden einen fossilen Bodenhorizont konserviert, der ebenfalls reichlich frisches organisches Material enthält. Eine Gravimetrie-Kampagne zeigt eine Zone relativ positiver Schwereanomalien um den Tüttensee herum auf, die durch Schockverdichtung des extrem porösen Untergrundmaterials erklärt wird. Moderate, dennoch reichlich Schockeffekte zeigen sich in Gesteinen vom Ringwall und in Klasten der Ejektaschicht. Alle beobachteten Merkmale können zwanglos durch einen Impaktprozeß erklärt werden, aber sie sind absolut unverträglich mit einer Bildung der Tüttenseestruktur durch Prozesse der Eiszeit.

1 Introduction

The 400 m-diameter Lake Tüttensee near Lake Chiemsee in Bavaria (southeast Germany) defines the largest meteorite crater so far proposed for the strewn field of the Holocene Chiemgau impact event (CIRT 2004, 2005, Rappenglück et al., 2004, 2005) that has been and is still controversially debated (CIRT 2006 a, b; Hoffmann et al. 2004 a, b, c, 2005 a, b, 2006 a, b; Raeymaekers & Schryvers 2004; Raeymaekers 2005; Rösler et al. 2004, 2005 a, b, 2006 a, b; Schryvers & Rösler 2004; Ernstson 2005; Fehr et al. 2004, 2005; Schryvers & Raeymaekers 2005; Schüssler 2005 a, b; Schüssler et al. 2005; Doppler & Geiss 2005; Reimold et al. 2006, Rappenglück & Rappenglück 2006).

The strewn field comprises more than 80 individual craters with diameters exceeding 3 m spread over an area of roughly 60 km x 30 km. Compared with other impact strewn fields (Wabar, Henbury, Macha, Morasko, Sikhote Alin and others; Hodge [1994], Krinov [1963], Gurov & Gurova [1998]), the impact documentation on the ground is unusually impressive (although the Gibeon meteorite strewn field with a size of 390 x 120 km², but without craters, is much larger) and has led to the model of the impact of a disintegrated comet (Rappenglück et al. 2004).

According to radiocarbon data (CEDAD 2006) and archeological finds, the impact is younger than 2,500 BC and happened before the Roman occupation around 15 BC, possibly in the 6th or 5th century BC (Rappenglück & Rappenglück 2006).

After the discovery of the Chiemgau strewn field, much work has been done on the Lake Tüttensee crater and its surroundings comprising geological field work, geophysical measurements and petrographic analyses. Reports on these investigations have repeatedly been published in the Internet in German language with English abstracts and figure captions (web [1, 2, 3, 4, 5]). Now and here, we give a summary of these contributions also focusing on the criticism of the impact model.

2 Lake Tüttensee - topography and target rocks

Lake Tüttensee is located a few kilometers east-southeast of Lake Chiemsee and north of the Foothills of the Alps (Fig. 1). The maximum size of the lake (Fig. 2) is roughly 400 m, and, according to official data, 17 m deep on average. A gravity survey on the frozen lake (Ernstson 2005; also see below) suggests 17 m to be water depth, however roughly 30 m total depth including a thick layer of organic material seem to be more realistic.

The lake is surrounded by a rim wall merging in the southeast into a glacial moraine (Fig. 2). About one hundred years ago, the 8 m-height rim wall continuously encircled the lake (Fig.3, Fig. 4) but now exhibits three artificial gaps (Fig. 5). The rim crest diameter amounts to roughly 500 m, which therefore is the diameter of the proposed meteorite impact crater. Apart from the artificial gaps, the rim and crater area have sustained significant morphological modifications probably beginning already in Roman times.

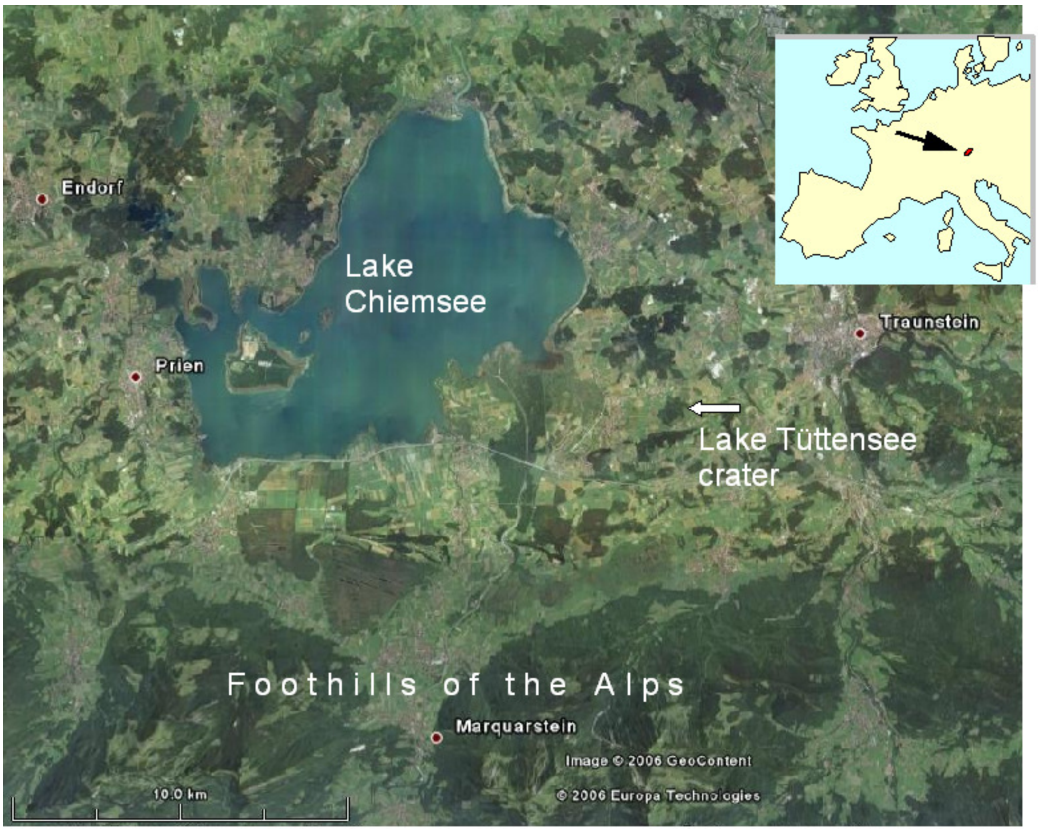


Fig. 1. Lake Tüttensee near Lake Chiemsee and the Foothills of the Alps. Image courtesy of Google Earth. The coordinates of Lake Tüttensee are 47°50'48'' N; 12°34'05'' E.

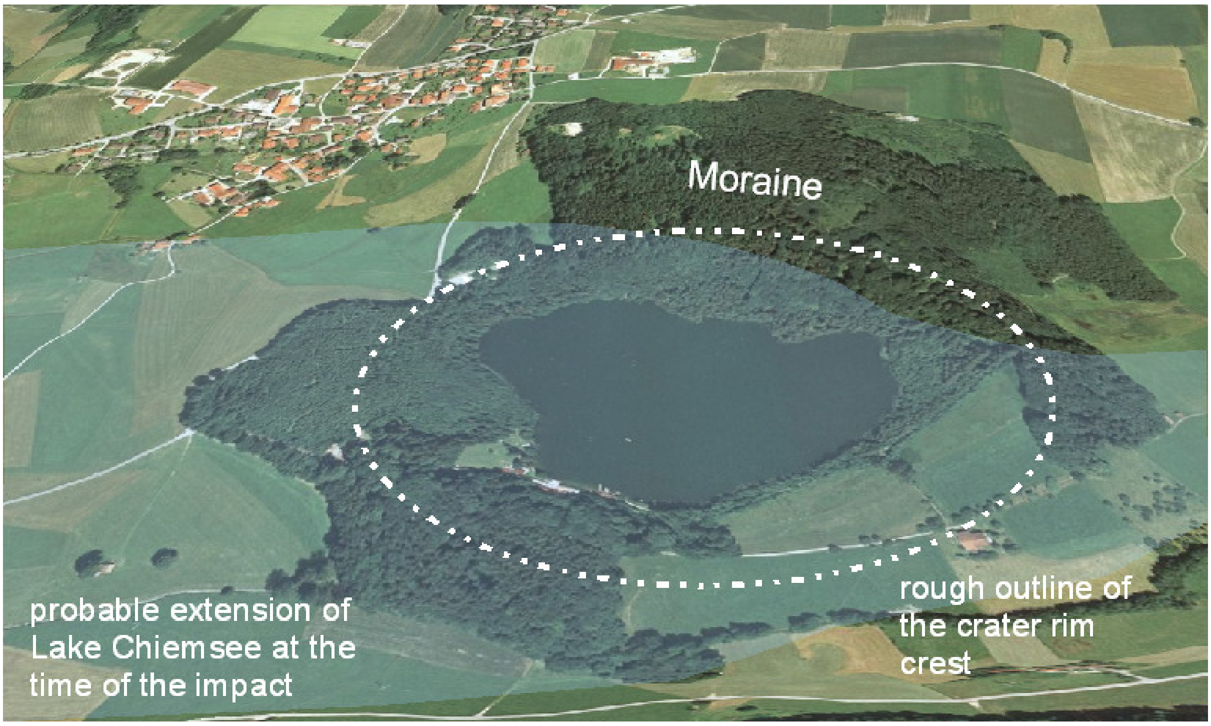


Fig. 2. Oblique view (exaggerated) of Lake Tüttensee. The probable extension of Lake Chiemsee is marked by the transparent overlay. Image courtesy of Google Earth.

Fig. 3. Lake Tüttensee rim wall (arrows) seen from the south.

Fig. 4. The 8 m-height Lake Tüttensee rim wall seen from inside during a gravity survey on the frozen lake.

Fig. 5. One of three artificial gaps in the Lake Tüttensee rim wall.

The target is predominantly composed of Quaternary moraine sediments and fluvio-glacial gravels (Fig. 6). Pebbles, cobbles and boulders up to the size of 20 cm are intermixed with sands and clays. The components represent Alpine material in the form of sediments (mostly limestones and sandstones), magmatic rocks (mostly granitoids) and metamorphic rocks (mostly quartzites, gneisses, amphibolites, serpentinites and schists). Occasionally, larger blocks of cemented conglomerates (Nagelfluh) are observed. Locally, Holocene gravels, loess and loamy soils may contribute to the uppermost target layers. The lithologic variety of the target contributes to a considerable diversity of impact features in the affected rocks.

Fig. 6. Typical Quaternary target rocks exposed in a foundation pit a few kilometers north of Lake Tüttensee. The peculiar non-anthropogenic bowl filled with brownish material and cut by the excavation wall requires further investigation because it may possibly be related with the impact and may have originated from secondary cratering.

A peculiarity of the impact target certainly was the circumstance that the projectile that formed the Tüttensee crater probably crashed into the extension of the at that time much larger Lake Chiemsee (Fig. 2) leading to cratering processes and possibly to a crater morphology and impact rocks different from otherwise well-known cases. In connection with Lake Chiemsee, lacustrine clays must also have contributed to the multifaceted target rocks.

3 Geologic setting

Because of the lake and reeds around it, geological investigations of the Tüttensee crater are limited to the rim region and the surrounding area. The study of the rim wall is mostly restricted to the outcrops of the artificial gaps with in general poor insight into its structure and material, the latter in principle being Quaternary moraine and gravel material. From the gaps, and especially from quite a few additional superficial excavations into the rim wall, we sampled lots of pebbles, cobbles and boulders that attracted attention because of unusual deformations and peculiar textures (Fig. 7) in more detail described in Rappenglück (2004) and web [6].

Fig. 7. Unusually deformed cobbles from the Tüttensee rim wall. The strongly fractured however coherent clasts extracted from an unconsolidated soft matrix prove high-pressure/short-term deformation typical of impact. A deformation from Alpidic tectonics as suggested by Doppler & Geiss (2005) can totally be excluded since the cobbles would not have survived any transport. The discoloring of the cobble, lower left, points to enhanced temperatures.

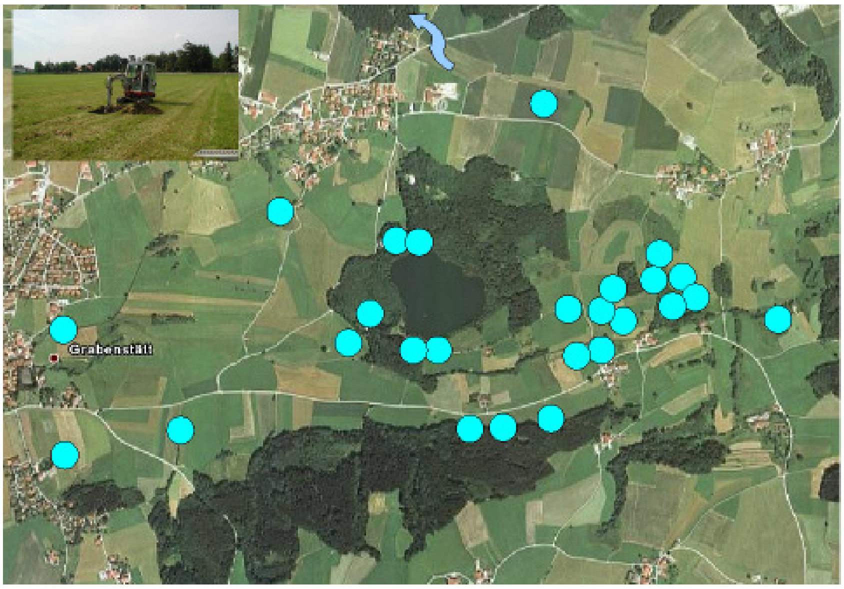


Fig. 8. Excavation pits around Lake Tüttensee and location for soil magnetic susceptibility measurements (arrow). Image courtesy of Google Earth.

The Tüttensee ejecta layer

The most striking geological evidence of the Tüttensee impact cratering process, however, has been supplied by more than 20 excavation pits around Lake Tüttensee (Fig. 8). Modifications included, they exhibit in general a four-layer sequence of autochthonous target rocks, a fossil soil, an ejecta layer, and subrecent to recent gravelly soil (Fig. 9). It is interesting to note that a very similar situation is met with the impact ejecta layer of crater No.2 of the Holocene Macha meteorite crater field in Yakutia (Gurov & Gurova 1998; Fig. 10).

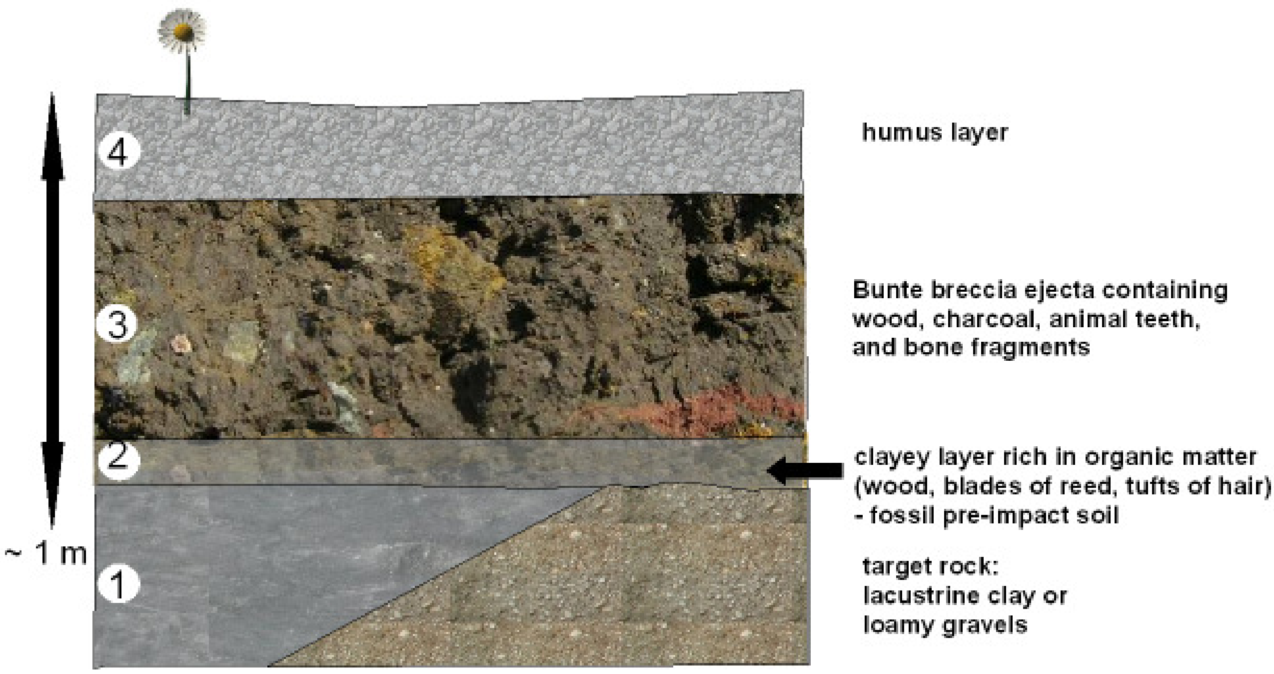


Fig. 9. Generalized sketch of layering around the Lake Tüttensee crater.

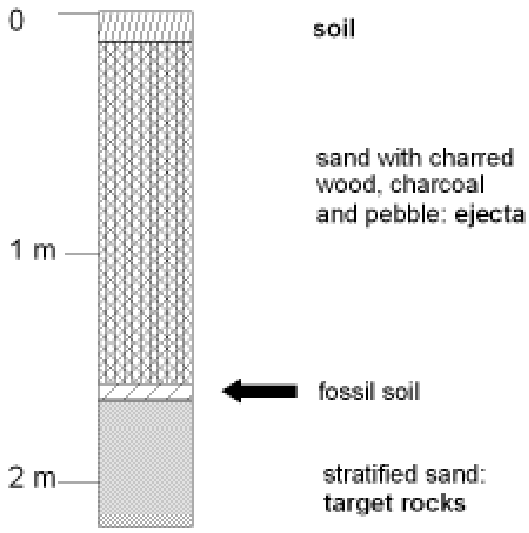


Fig. 10. For comparison: cross-section of the ejecta layer of Macha crater No. 2. Modified from Gurov & Gurova (1998). The similarity to the Tüttensee ejecta layer (Fig. 9) is evident.

In more detail, we encounter

1. at 1 - 2 m depth (depending on the topographic situation) an undisturbed Pleistocene or Holocene rock representing a pure lacustrine clay (Fig. 11) of the previously larger Lake Chiemsee or well-known loamy gravel composed of well-rounded cobbles of Alpine lithologies.

2. over that, a decimeter thick horizon representing a fossil soil. This fossil soil horizon contains excellently preserved organic material in the form of wood, fresh blades of reed and tufts of animal and/or human hair (Fig. 12). Pushed in this fossil horizon and partly breaching it, we find individual clasts (Fig. 11) among them heavily shattered however coherent clasts of quartzite, limestone, dolostone and crystalline rocks (Fig. 13).

Fig. 11. Excavation pit No. 5: individual clasts sticking in the fossil soil horizon over the autochthonous target rocks (lacustrine clay, see the extra hole to the lower right). The larger clasts are sized about 20 cm.

Fig. 12. Excellently preserved reed and tufts of hair at the base of the ejecta layer.

Fig. 13. A strongly shattered however coherent quartzite clast from the fossil soil horizon at the base of the ejecta layer.

3. This fossil soil horizon is overlaid by an up to one meter thick polymictic breccia (Fig. 14) that in part exhibits the same facies as shows the Bunte breccia of the Nördlinger Ries impact structure (Pohl et al. 1977) (Fig. 15). The Tüttensee Bunte breccia contains multicolored sharp-edged rock fragments representing a complete grain size spectrum from Alpine lithologies. The Bunte breccia is rich in organic material in the form of fragmented wood (Fig. 16), charcoal (Fig. 15), bones, bone fragments (Fig. 17) and well-preserved animal teeth (Fig. 17). The Tüttensee Bunte breccia contains brecciated clasts exhibiting grit brecciation and mortar texture and the peculiarity that the clasts in spite of strongest smashing are encountered coherent in the clayey matrix (Fig. 18) like those shattered clasts found at depth with the underlying fossil soil.

Radiocarbon dating (CEDAD 2006) of a wood and a charcoal fragment from two different excavation pits reveal ages around 2,500 BC (depending on the calibration curve) that is, geologically speaking, clearly a Holocene age.

Fig. 14. Polymictic breccia of the Tüttensee impact ejecta horizon.

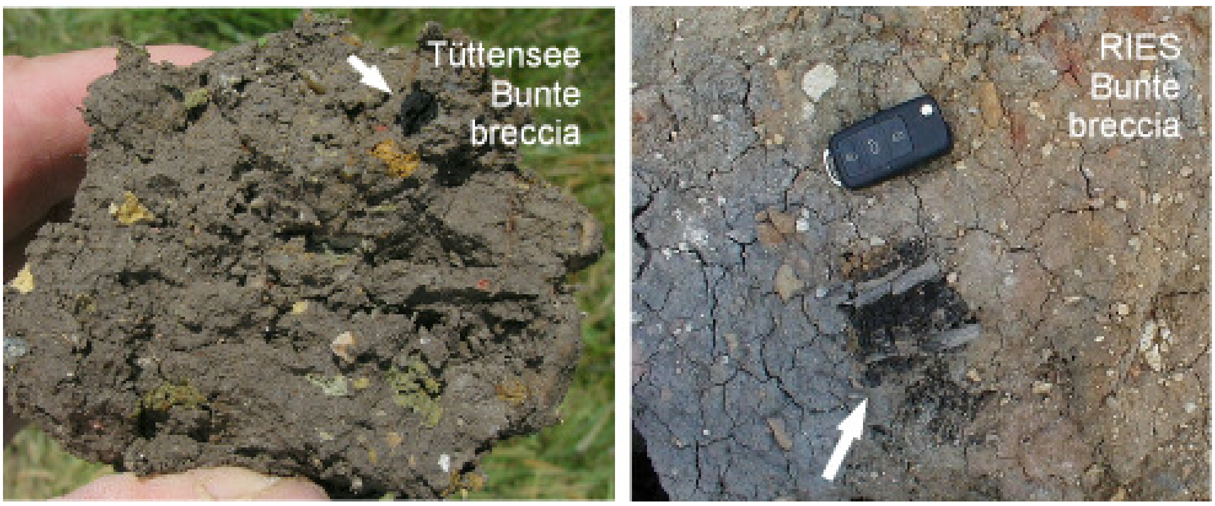


Fig. 15. Comparison of the Tüttensee Bunte breccia and a sample taken from the Ries crater Bunte breccia. Arrows point to charcoal contained in both ejecta breccias

Fig. 16. Wood embedded in the Tüttensee Bunte breccia layer.

Fig. 17. Bones and teeth embedded in the Tüttensee Bunte breccia layer.

Fig. 18. Heavily shattered however coherent clasts (limestone, to the left, and quartzite) in the Tüttensee Bunte breccia.

Clasts of all lithologies (thus also silicate rocks like sandstones or amphibolites) from the Tüttensee Bunte breccia show an extremely deep-reaching corrosion to the point of residual rock skeletons (Fig. 19).

Fig. 19. Deeply corroded clasts from the Tüttensee impact layer. Limestone clasts, upper left and lower right, a sandstone clast, upper right, and an amphibolite cobble from the impact layer that could be powdered with the bare hand (lower left).

4. The Tüttensee Bunte breccia is overlaid either by a fresh, probably Holocene gravel layer of completely untouched cobbles and recent soil formation, or immediately by recent soil.

4 Geophysics

Gravity survey

A gravity survey of Lake Tüttensee has been performed to get some knowledge about the craterform structure. The measurements were carried out on the frozen lake in winter 2005, and quite a few gravity stations were also placed in the environs enabling the construction of a Bouguer map (see Ernstson 2005). In Fig. 20 the Bouguer residual map is shown. It exhibits a roughly circular anomaly of maximum -0.8 mgal mostly related with the low density of the water and organic material of the lake.

Surprisingly, a ring of relatively positive anomalies is measured surrounding the Tüttensee negative anomaly (Fig. 20). The positive anomalies are modeled by a 1000 m-diameter flat lens of slightly enhanced density (Fig. 21). It is explained (Ernstson 2005) by a model of soil liquefaction and post-liquefaction densification well known from large earthquakes (e.g., Lee & Albaisa 1974, Montgomery et al. 2003). Moreover, mass flow behind the impact shock front could have contributed to the compaction of the loose, highly porous and water-saturated target rocks.

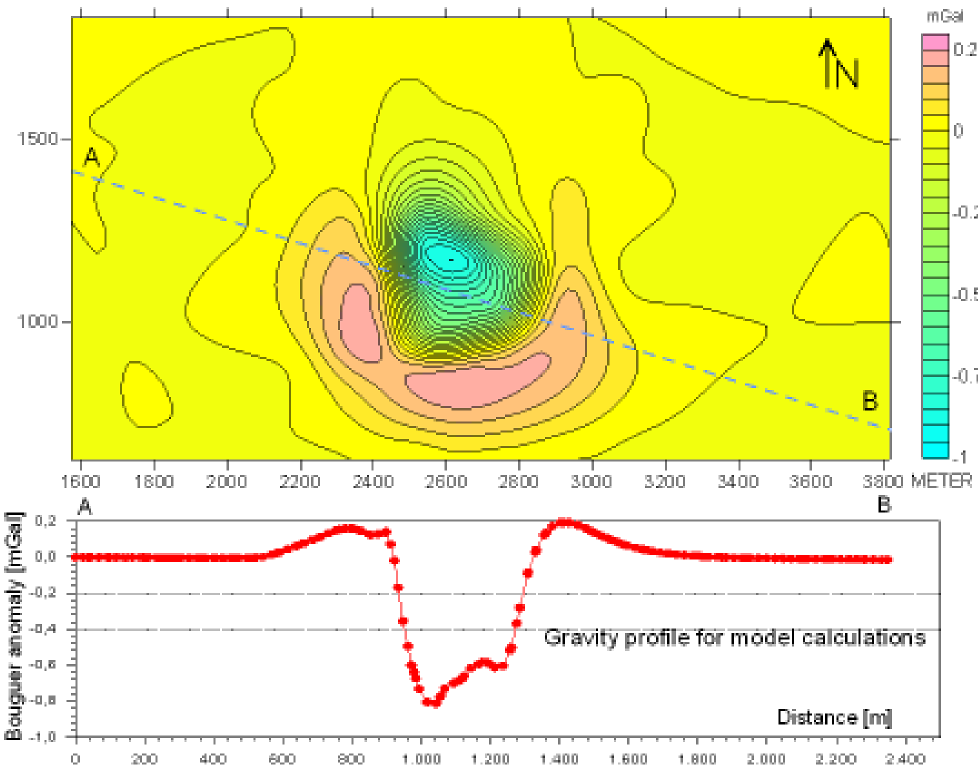


Fig. 20. Gravity Bouguer residual anomaly for Lake Tüttensee and environs. For model calculations a gravity profile A - B has been taken from the map.

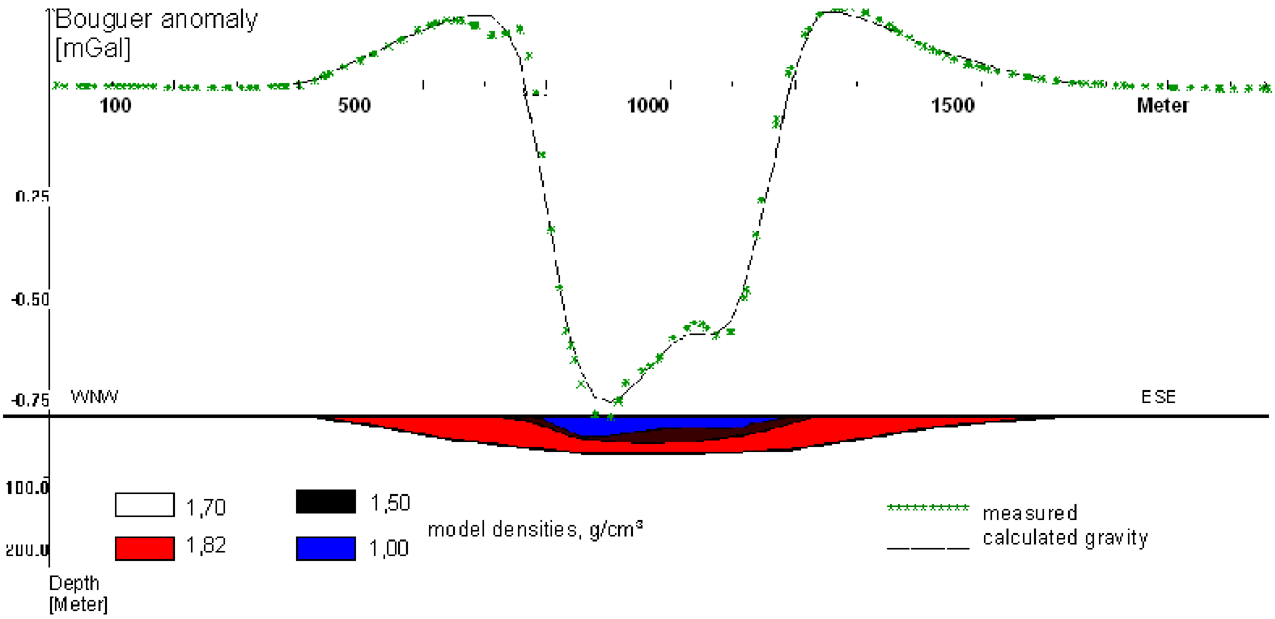


Fig. 21. 2.5D gravity modeling and density model for the Lake Tüttensee anomaly. Without exaggeration. Note the lens of increased density (red color).

Soil magnetic susceptibility measurements

Initiated by the results of soil magnetic susceptibility (MS) measurements in the northern part of the Chiemgau impact strewn field in the Burghausen area (Hoffmann et al. 2004), we carried out own soil susceptibility investigations in a forest near Lake Tüttensee (see Fig. 8). In large undisturbed forest areas, Hoffmann et al. (2004) found an anomalous soil magnetic signature with a more or less regular substantial increase of MS at 10 - 20 cm depth different from enhanced MS values in the uppermost soil centimeters otherwise found in industrial regions (also see Magiera et al. 2006). Hoffmann et al. (2004) exclude industrial contamination as well as a geogenetic origin of this MS anomaly, but they also avoid to discuss a third explanation.

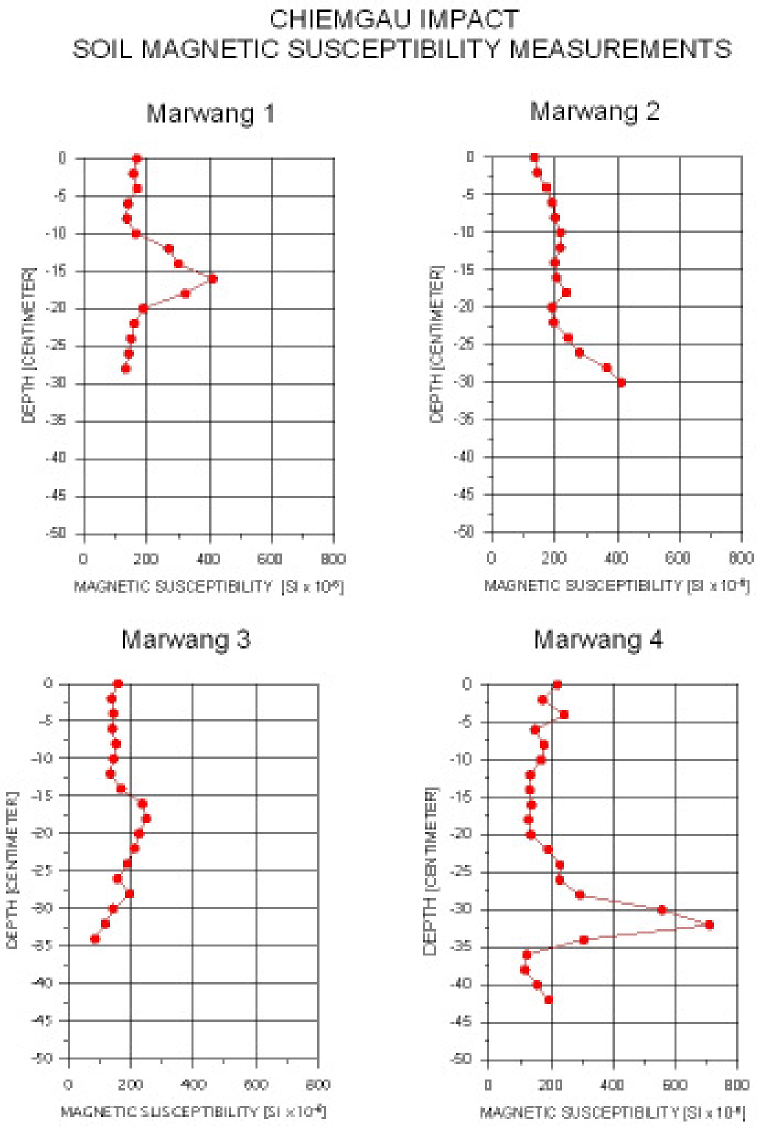


Fig. 22. Soil magnetic susceptibility profiles in a forest near Lake Tüttensee.

Interestingly, we found a corresponding, even more pronounced MS anomaly in the soil profiles measured near Lake Tüttensee in part displaying prominent peaks at 15 - 35 cm depth (Fig. 22). A possible relation with the Chiemgau impact is suggested, however, more measurements and detailed investigations of the respective horizon are needed.

5 Shock metamorphism

Shock in the Tüttensee rim wall

It is generally accepted that shock metamorphism in rocks must be considered as in proof of meteorite impact (French 1998, and others).

Depending on their intensity, shock waves leave quite different traces in a mineral. Planar deformation features (PDFs) belong to the most important ones. Fig. 23 (to the left) shows a photomicrograph of such PDFs in quartz. Under the microscope, at least five sets with varying orientation can be seen. These peculiar structures are closely spaced parallel, optically isotropic lamellae following crystallographic planes in the quartz grain.

According to current knowledge (e.g., Stöffler & Langenhorst 1994), multiple sets of these closely spaced isotropic lamellae can only originate from extreme shock pressures. PDFs in quartz have been shown to exist in several samples from the Lake Tüttensee rim wall and in rocks from the Tüttensee Bunte breccia ejecta layer (see in detail web [3, 4]).

Another shock effect, however of reduced intensity, is shown in Fig. 23 (to the right). In the photomicrograph we see multiple sets of planar fractures (PFs) following crystallographic planes in a quartz grain. Normally, quartz does not exhibit such a cleavage, and only in rare cases, under extreme tectonic pressures in the strongest stages of regional metamorphism, quartz may acquire planar fractures. In impact structures, however, shock-produced planar fractures belong to the regular inventory.

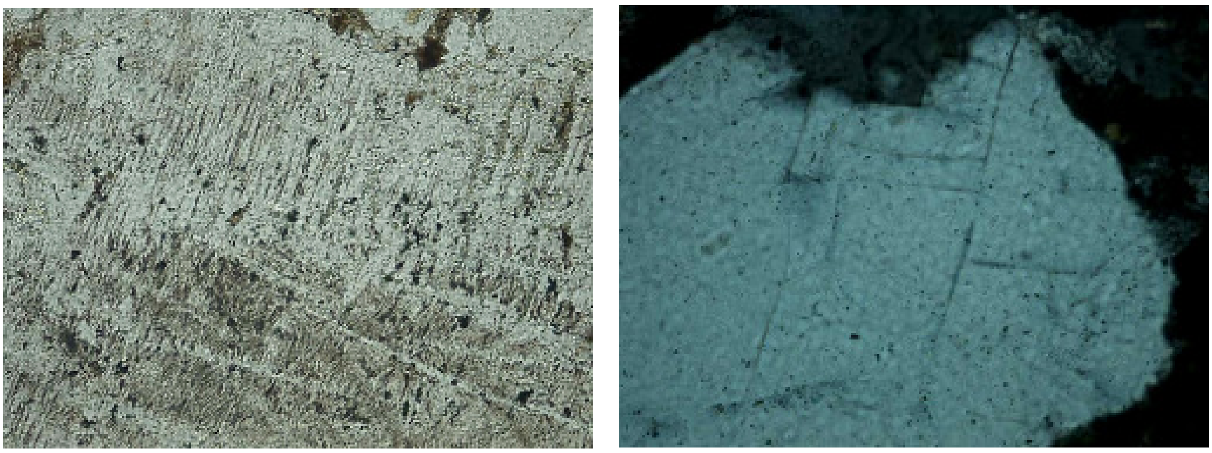
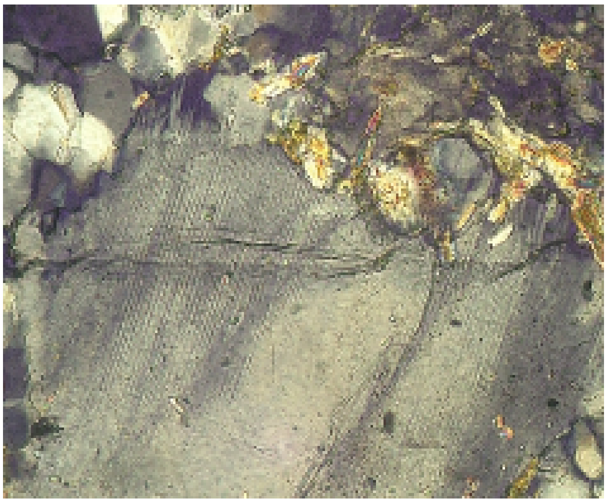


Fig. 23. Shock effects in rocks from the Tüttensee rim wall. Photomicrographs, crossed polarizers; width of images about 500 µm. To the left: Five sets of planar deformation features (PDFs) in quartz. Not all sets can be seen on the image, but they become visible on rotation of the thin section on the microscope stage. To the right: Sets of planar fractures (PFs; cleavage) in quartz.

Shock in the Tüttensee Bunte breccia ejecta layer

While clasts from the Tüttensee rim wall have only cursory been studied for shock metamorphism, rocks from the Tüttensee Bunte breccia have been analyzed for shock effects more systematically. For it, samples from Quaternary crystalline and sedimentary Alpine cobbles were selectively taken from this ejecta layer.



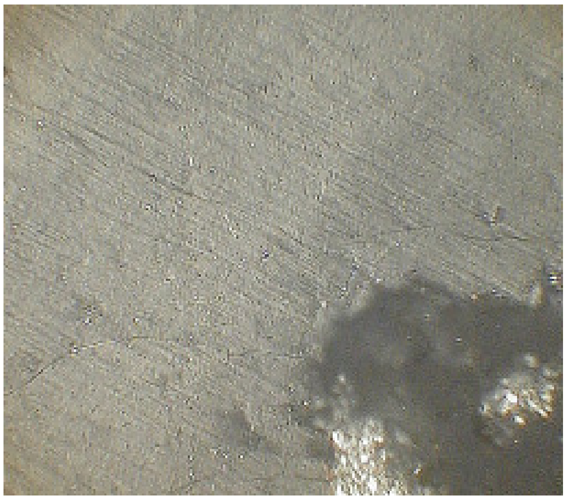


Fig. 24. PDFs in quartz from the Bunte breccia ejecta layer. To the left: quartzose mica schist, excavation pit No. 10. To the right: mica quartzite, excavation pit No. 21. Photomicrographs, crossed polarizers; the fields are 380 µm and 400 µm wide.

The study of thin sections from 31 rock samples taken from 7 different excavations establishes a rich inventory of mineral deformations (web [4]) that with reasonable certainty or with great likeliness have originated from shock load. The shock effects are moderate and comprise planar deformation features (PDFs) in quartz (Fig. 24), extreme and abundant kinking in mica (Fig. 25) (see e.g., Hörz 1970, French 1998), and regularly occurring multiple sets of microtwinning in calcite (Fig. 26) (see e.g., Metzler et al. 1988). With regard to the relatively small impact crater, the frequency of occurrence of the presumed shock deformations, although of moderate intensity, is conspicuous. Therefore, the special target conditions, that is hard and dense cobbles and boulders in an uncemented soft matrix, are discussed to have enabled a focusing of shock intensity as has earlier been considered for the Coconino sandstone (Kieffer 1971) and for a shocked conglomerate (Ernstson et al. 2001; also see web [7]).

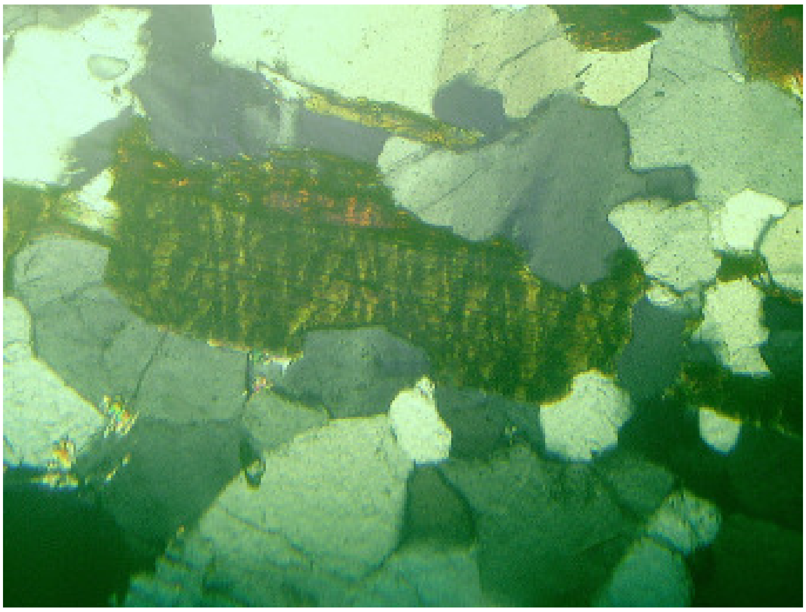


Fig. 24. Two sets of dense kink-banding ("NNW - SSE" and "NNE - SSW" trending) in biotite. Gneiss, Tüttensee excavation pit No. 10. Photomicrograph, crossed polarizers; the field is about 1mm wide.

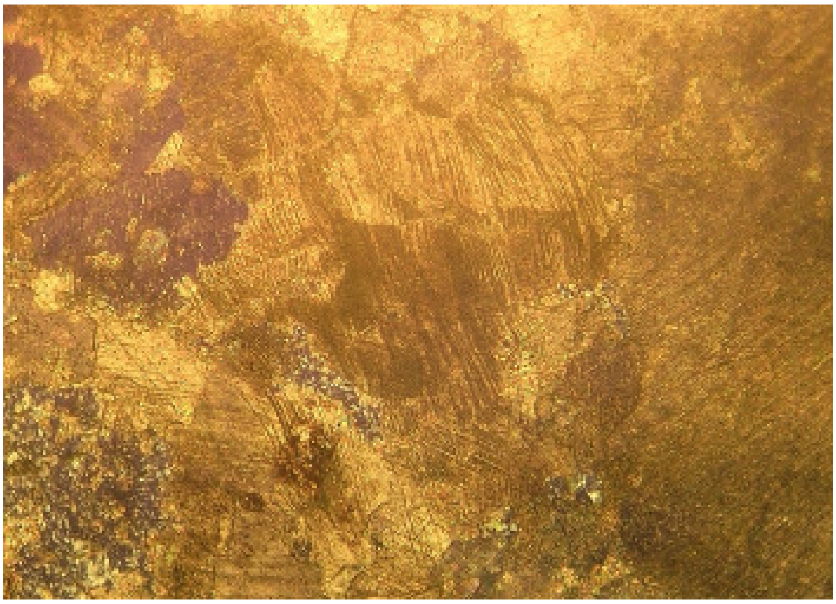


Fig. 25. Strongly deformed calcite exhibiting multiple sets of microtwins and a few kink bands. Calcite dikelet in quartzite, Stefanutti excavation pit at Grabenstätt village. Photomicrograph, crossed polarizers; the field is about 1 mm wide.

The microscopic shock deformations in rocks from the Tüttensee rim wall - apart from the significant high-pressure/short-term deformations - clearly speak in favor of an impact origin for Lake Tüttensee, while these petrographic observations are hardly if at all to be understood with regard to a dead-ice formation (Doppler & Geiss 2005).

6 Summary and the Tüttensee impact cratering process

In ***summary*** we state:

-- The Lake Tüttensee structure is surrounded by an originally continuous and closed rim wall.

-- The rim wall contains large quantities of strongly deformed pebbles, cobbles and boulders pointing to short-term/high-pressure load typical of impact cratering.

-- Clasts from the Tüttensee rim wall give clear evidence of shock metamorphism in the form of multiple sets of planar deformation features (PDFs) in quartz requiring shock pressures of the order of 10 GPa (100 kbar) or more.

-- The Tüttensee rim wall is surrounded by a blanket of a polymictic breccia in part similar to the Bunte breccia of the Nördlinger Ries impact structure. The Tüttensee Bunte breccia contains brecciated clasts exhibiting grit brecciation and mortar texture and the peculiarity that the clasts in spite of strongest smashing are encountered coherent in the clayey matrix. The breccia is rich in organic material like wood and charcoal, and it contains animal bones and teeth.

--The breccia overlies a fossil soil also rich in organic material (wood, blades of excellently conserved reed, tufts of human or/and animal hair). Individual, frequently shattered but coherent clasts of competent rocks are observed to stick in the fossil soil horizon.

-- Clasts from the Bunte breccia layer show abundant although moderate shock metamorphism like PDFs in quartz, very strong kink-banding in mica and intense microtwinning in calcite.

-- Clasts of all lithologies (thus also silicate rocks like sandstones or amphibolites) from the Tüttensee Bunte breccia show an extremely deep-reaching corrosion to the point of residual rock skeletons.

-- The Tüttensee Bunte breccia is overlaid either by a fresh, probably Holocene gravel layer of completely untouched cobbles and recent soil formation, or immediately by recent soil.

-- Radiocarbon dating of organic material from the polymictic breccia (CEDAD 2006) proves that the breccia layer is younger than 2,500 BC and thus cannot have resulted from any glacial process.

The cratering process

The geological setting as presented can without constraint be explained by well-known impact cratering processes (Melosh 1989). At the time of the impact some 2500 years ago, the target is made up of lacustrine clay of Lake Chiemsee and Pleistocene and/or Holocene banks of loamy gravel including a (nowadays fossil) soil with organic material (wood, reed, tufts of hair possibly from a bird's nest). In the contact and compression stage, shock waves propagate into the projectile being vaporized and into the target rocks that experience shock metamorphism. The high pressure of the impact explosion, shock waves and shock-wave-induced mass flow compact unconsolidated, highly porous and water-saturated target rocks leading to densification and the now observed peculiar zone of positive gravity anomalies around Lake Tüttensee.

On excavation of the impact-induced growing Tüttensee crater (excavation stage), ejecta are forming the rim wall of the Tüttensee, and a blanket of crushed rock material and mud extends over the soil. Since the crater-forming process acts catastrophically, the organic matter in the soil is supposed to have rapidly been blanketed and thus to have become oxygen sealed enabling the excellent preservation until today.

The fragmented and heavily crushed however completely coherent clasts within the soft clayey breccia matrix and sampled from the Tüttensee rim wall are explained by high confining pressure having acted on excavation and landing of ejecta well known from many other impact structures (e.g., Ries, Germany, Azuara/Rubielos de la Cérida, Spain [Claudin et al. 2001, Ernstson et al. 2002]).

The deep-reaching skeletal corrosion of many clasts is explained by decarbonization/melting and/or nitric-acid dissolution of carbonate rocks (limestones, dolostones) and by nitric-acid corrosion of silicate rocks. The production of considerable amounts of nitric acid (and other acids) in the explosion cloud of large impacts has repeatedly been proposed (Lewis et al., 1982; Prinn and Fegley, 1987;

Zahnle, 1990, Maruoca & Koeberl 2003, and others). We suggest the deeply corroded carbonate and silicate clasts in the Tüttensee area to be the first real evidence of this process in terrestrial impacts.

Finally, younger flooding has buried the Tüttensee Bunte breccia ejecta by gravel layers of untouched cobbles, and in part the recent soil has formed immediately over the breccia horizon.

So far unclear is the possible modification of the rim wall and the ejecta layer immediately after the impact. From echo sounding/sonar measurements on Lake Chiemsee, there is ample evidence of rimmed circular structures with diameters of the order of 100 - 200 m that could have originated from impacts of separate projectiles in the Chiemgau impact event. Tsunami-like tidal waves from these suggested impacts could have run over the just formed Tüttensee crater and ejecta blanket implying the formation of additional erosive and sedimentary features. In the excavation pits located between Lake Tüttensee and Lake Chiemsee (see Fig. 8), especially in the excavation pit at Grabenstätt village, there is evidence of such processes that, however, need closer examination.

7 Discussion

According to current impact research and knowledge (e.g., French 1998, Norton 2002), the following criteria serve for the identification of an impact structure:

-- the observation of the impact
-- the find of fragments of the impactor or geochemical signature of the projectile
-- crater morphology
-- geological features (e.g., breccias, breccia dikes, high-pressure/short-term deformations of rocks, exotic horizons in rocks)
-- geophysical anomalies
- shock metamorphism in rocks and minerals (planar deformation features, diaplectic glass, shatter cones in rocks).

Up to now authentic reports of the event have not been found, even when it might be reflected in ancient traditions (Rappenglück & Rappenglück 2006). No fragments of the Tüttensee impactor have so far been found, but they may be buried beneath the Lake Tüttensee water and thick organic material. The same holds for geochemical signature.

Morphologically conspicuous is the rim wall originally having continuously surrounded the lake. Although its shape is rather untypical for a glacial moraine, morphology is little meaningful when a possible impact crater is addressed.

The post-glacial polymictic breccia (Bunte breccia) surrounding the Tüttensee structure as a blanket has all criteria of an impact breccia and, with regard to the depositional features, all those of an impact ejecta layer. Reasonably, there is no "normal" geologic process responsible for the formation of this extensive peculiar Holocene polymictic breccia. All requisites for a large landslide or rock fall (relief, source of the material) imaginable at most are absolutely missing. An origin from impact and as ejecta seems to be the sole logic explanation. The many strong deformations of cobbles from the Tüttensee rim wall pointing to high-pressure/short-term *in situ* load (Claudin et al. 2001; Ernstson et al. 2002) also substantiate an impact cratering process. Even non-geologists are convinced that these shattered clasts could never have survived a fluvio-glacial transport from the Alps. Such a transport, however, must be assumed if the deformations are derived from Alpine tectonics as suggested by Doppler & Geiss (2005).

Although geophysical anomalies may be very significant in impact structures (e.g. the great gravity anomaly of the Chicxulub impact structure [Hildebrand et al. 1995] or the extensive geomagnetic anomalies over the Ries crater central suevite layer [Pohl et al. 1977]), they are not enough to speak against a possible endogenetic origin of the structures. With regard to gravity anomalies of smaller impact structures that, as a general rule, are negative due to density reduction by rock brecciation, excavation and microfracturing (see, e.g., Innes 1961, Ernstson 1984), the zone of relatively positive anomalies around Lake Tüttensee is conspicuous, because it implies rock densification. While such a densification can easily be explained by impact shock compaction roughly comparable to soil liquefaction and post-liquefaction densification well known from large earthquakes, an increased density around a dead-ice moraine is rather difficult to explain.

Apart from the direct observation of an impact and disregarding the find of projectile relics, shock metamorphism in rocks from a structure under suspicion is generally considered unambiguously diagnostic of an impact event (French 1998, Langenhorst & Stöffler 1994, Grieve et al. 1996, and others). Correspondingly, the verification of shock effects in rocks from the Tüttensee rim wall and the Bunte breccia layer alone must be considered as in proof of an impact event.

Competing glacial model

The establishment of new terrestrial impact structures has almost always come along with emphatic refusal by local and regional geologists, and in many cases long-lasting fierce controversies followed, and we remind, among many others, of the cases of the Nördlinger Ries crater (Dehm 1969), the Vredefort (e.g., Nicolaysen & Reimold 1985) and Sudbury (Pye et al. 1984) impact structures, and the Spanish Azuara multiple impact event (Ernstson et al. 2001, 2002; Aurell 1994, Cortés et al. 2002). The in general urged argument is the regional geological setting allegedly not compatible with an impact origin of the structure under discussion. Although the crash of a celestial body with the earth is a purely statistical event with respect to the target, regional geologists don't tire to play the regional-geology card.

The same is true for the Tüttensee proposed meteorite impact crater. In this case the regional geologic argument is the location of Lake Tüttensee in the Quaternary glacial landscape of the Alpine foreland, and the craterform structure is said, as has always been done previously, to be a dead-ice moraine (Doppler & Geiss 2005). Apart from a cursory reconnaissance of the Tüttensee area (Doppler & Geiss 2005), the authors don't procure any substantial evidence for a glacial origin as has in detail been discussed by CIRT (2005). Also the argument of Schieber (2006, written comm.) he has observed typical fluvio-glacial texture in one of the Tüttensee rim wall artificial exposures is by no means conclusive. We wonder if he is able to make a clear distinction between a fluvio-glacial deposition and a deposition controlled by impact excavation from the underwater Chiemsee target and possibly modified by post-impact tsunami-like erosional and sedimentary overprint.

Counter-arguments raised by the critics to refuse the Chiemgau impact and to substantiate the glacial hypothesis are soil formation processes and dissolution by sour soils to explain the deformations and deep-reaching skeletal corrosion of rocks in the impact layer (Geiss 2006, TV and radio interviews). Here we remind of the observation that the clasts under discussion are part of a rock, namely the impact breccia, and are found neither in a recent nor in a fossil soil. If the critics intend to argue with frost shattering to have produced the breccia clasts, we as a precaution point to the fact that frost shouldn't have acted at 1.5 m depth 2,000 BC, and with regard to Figs. 14, 15, the sharp-edged fragments in the breccia obviously lack their counterparts to be expected with frost decomposition.

In a new statement by critics of the Chiemgau impact event (Reimold et al. 2006), the glacial argument has again been claimed completely ignoring and suppressing the ample impact evidence presented in a couple of previous publications (see CIRT 2006, and the compilation therein). Instead, Reimold et al. (2006) argue with (cit) "*Overwhelming scientific evidence suggests that the larger structures referred by CIRT, in particular the largest one, Tüttensee, are kettle holes.*"

We wonder if this is the new style of a scientific debate to replace data, documents, analyses, detailed descriptions etc by the pure and completely unfounded assertion that there is *overwhelming evidence.*

8 Conclusions

Opposing the results of our Tüttensee research to the arguments of the critics of the proposed impact scenario, we conclude that there is ample evidence to establish Lake Tüttensee as a confirmed impact crater and that the counter-arguments based on a competing glacial origin are extremely poor only (Doppler & Geiss 2005, Schieber, written comm.) or simply lack any substance (Reimold et al. 2006).

The acceptance of lake Tüttensee as an authentic meteorite impact crater substantiates the proposed large crater strewn field (Rappenglück et al (2004) that is assumed to have formed in the Chiemgau impact event, and implies more credit for the work of those authors (Fehr et al. 2005 , Hoffmann et al. 2004 c, 2005 a, b, 2006 a, b, Rösler et al. 2005 a, b, 2006 a) who consider the numerous craterform structures in the northern part of the strewn field to be only possibly impact-related.

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