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PEOPLE EXPERIENCED THE PREHISTORIC CHIEMGAU METEORITE IMPACT – GEOARCHAEOLOGICAL EVIDENCE FROM SOUTHEASTERN GERMANY: A REVIEW

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ABSTRACT

Archaeological sites undoubtedly destroyed by a meteorite impact had not been identified so far. For such a proof, both a meteorite impact and its definite effects on an archaeological site would have to be evidenced. This review article reports on geoarchaeological investigations, involving mineralogy, petrography, and geophysics, which established evidence that two prehistoric human settlements have been affected by the Late Bronze Age/Early Iron Age (ca. 900-600 BC) Chiemgau meteorite impact in southeastern Germany. One site, the Mühlbach area, was affected by the ejecta from the 600 m Ø-Tüttensee crater, one of the largest craters in a crater strewn field measuring about 60 x 30 km. At the other site, Stöttham close to Lake Chiemsee, the catastrophic layer of the impact was found embedded in the archaeological stratigraphy of a settlement, which had been repeatedly occupated from the Neolithic to the Roman era. At both sites, artifacts have become components of impact rocks, establishing a hitherto unknown form of an impact rock, an artifact-in-impactite. The immediate coexistence of rocks, which exhibit impact-diagnostic shock metamorphism, with relicts of metallic artifacts, as encountered in finds from Stöttham, are unprecedented evidence of human experience of a meteorite impact.

KEYWORDS: prehistoric meteorite impact, Holocene meteorite impact, Bronze Age/Iron Age meteorite impact, crater strewn field, airburst, artifact-in-impactite, catastrophe, disaster

1. INTRODUCTION

Evidence that a cosmic event such as a meteorite impact or a meteoritic airburst directly affected human settlements is extremely rare. The only unquestionably documented example is the Chelyabinsk meteor with its airburst in 2013 (Popova et al., 2013), which caused major damage in several cities. Hundreds of people were injured by side effects, e. g. by splintering glass. For the period 616 to 1997 AD 15 events have been listed (Gritzner, 1997), collected from written sources, in which people were killed or at least injured by meteorites; settlements or individual dwellings were accordingly affected in four cases. As for antiquity, the biblical account of the destruction of the cities of Sodom and Gomorrah has repeatedly been interpreted as describing a meteorite impact. Various archaeological sites and dates have been suggested as the place and time of the alleged event, but without any proof (Rappenglück, B., 2013 and literature therein). In recent years, geoarchaeological results have been presented which argue for the destruction of the settlement Tall el-Hammam in Jordan by an airburst (Bunch et al., 2021).

It has now been geoarchaeologically substantiated that two prehistoric settlements in southern Germany were directly affected by the Chiemgau meteorite impact, one of the largest impacts of the Holocene known so far. This impact, named after the mainly hit region, occurred during the Central European Late Bronze/Early Iron Age (ca. 900-600 BC). A strewn field of craters extends north of the Alps between 47.8° and 48.4° N, 12.3° and 13.0° E (Fig. 1). More than 100 craters ranging from 5 m to 1.3 km Ø are scattered over an approximately elliptical area of about 60 km length and 30 km width (Fig. 1, 2). At two sites in the target area, settlements were directly involved in this catastrophic event. Here we report on the corresponding research and results.

For the verification of the claim that an archaeological site was affected by a hypervelocity impact, two challenges exist: the impact itself must be proven, and effects on the archaeological site must be clearly attributable to this event. This review article brings together the answers to both challenges for the two archaeological sites in Chiemgau region: For the first time, it compiles the many different individual results achieved by various research groups over the course of more than twenty years, which contribute to the proof of a hypervelocity impact in the Chiemgau region, thereby taking up latest discussions. For both archaeological sites concerned, it presents for the first time the entire wealth of impact evidence obtained with a wide variety of methods, and explains how they are intertwined with the archaeological finds.

1.1. Geological setting and archaeological overview

The topographical and geological framework for the Chiemgau impact is the Alpine foothill shaped by the last (Würm) glaciation. Apart from the northernmost part of the strewn field, where Miocene gravels, sands and marls are exposed in the hilly terrain, the target area is mainly composed of Pleistocene and Holocene moraine sediments and fluvial deposits (Bayerisches Geologisches Landesamt, 1996). Pebbles, cobbles and boulders up to the size of 30 cm, representative alpine material, are intermixed with sands, clays and loamy material. Occasionally blocks of cemented conglomerates (Nagelfluh) are encountered. Locally, lacustrine clays, peat, loess and loamy soils contribute to the target layers.

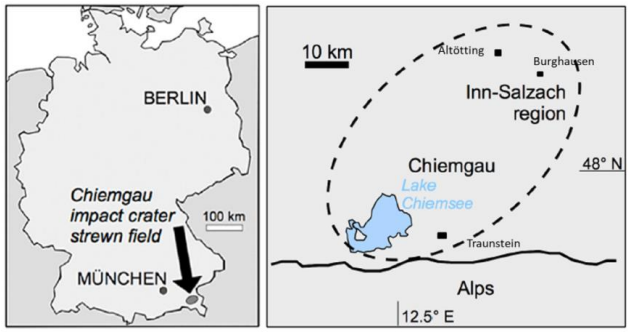

Figure 1. Localization of the Chiemgau Impact crater strewn field.

First settlements have been documented up from the late Neolithic (Münchshöfener culture, ca. 4500-3800 BC) (Bayerisches Landesamt für Denkmalpflege). From the Bronze Age onwards, the river valleys of the region, heading from the Alps northwards to the Danube, were parts of important routes for the trade of Alpine ores and salt, as well as Baltic amber (Melheim and Sand-Eriksen, 2020; Navarro, 1925). Settlement evidence can be found for all subsequent cultural periods, but the database for the pre-Roman cultures (Roman occupation began in 15 BC) is of limited informative value, as many archaeological finds are only generally classified as "prehistoric" (Bayerisches Landesamt für Denkmalpflege). Even when the time period is mentioned (e.g. Hallstatt, ca. 750-480 BC, or Latène culture, ca. 480-15 BC), these periods cover several hundred years each and the data add up to only a superficial picture.

Figure 2. Craters, from left to right: 001 "Schatzgrube", Ø 13 m; Purkering, Ø 75 m; Tüttensee, Ø 600 m.

1.2. *The meteorite impact (overview)*

The craters of the strewn field are located in a fluvio-glacial, hilly landscape, where craters can be distinguished from sink- and pit-like landforms of other origin only with the aid of mineralogical and geophysical methods. Due to this fact they were for a long time hidden even from geologists, and at times prompt contrary interpretations (Darga and Wierer, 2009; Doppler et al., 2011; Huber et al., 2020). First scientific investigations (geomagnetics, ground penetrating radar, SEM and TEM) (Hoffmann et al., 2004; Schryvers and Raeymakers, 2004; Fehr et al., 2005; Hoffmann et al., 2005; Rösler et al., 2005; Hoffmann et al., 2006; Rösler et al., 2006; Yang et al., 2008) concentrated on small hollow forms in the Altötting/Burghausen area (see map Fig. 1). They found numerous anomalies, e.g. thermo-plastically deformed rocks, indications of heating close to 2000° C, strong magnetic anomalies, nano- and microdiamonds in the glassy melt crust of cobbles. Considered in a comprehensive overview, all the observed phenomena could be explained neither by anthropogenic influences nor by glacial processes, and prompted to discuss an impact-related origin of the investigated structure (Hoffmann et al., 2005; Rösler et al., 2006) and the existence of a large impact crater strewn field (Fehr et al., 2005). But unambiguous evidence of a hypervelocity impact, such as shock metamorphism or extraterrestrial material as a relic of the impactor (French, 1998; Ferrière and Osinski, 2013) had not yet been achieved in this early phase of research. In addition, it was considered very unlikely that shock phenomena could have occurred at craters as small as those ones in the Chiemgau area (Fehr et al., 2005).

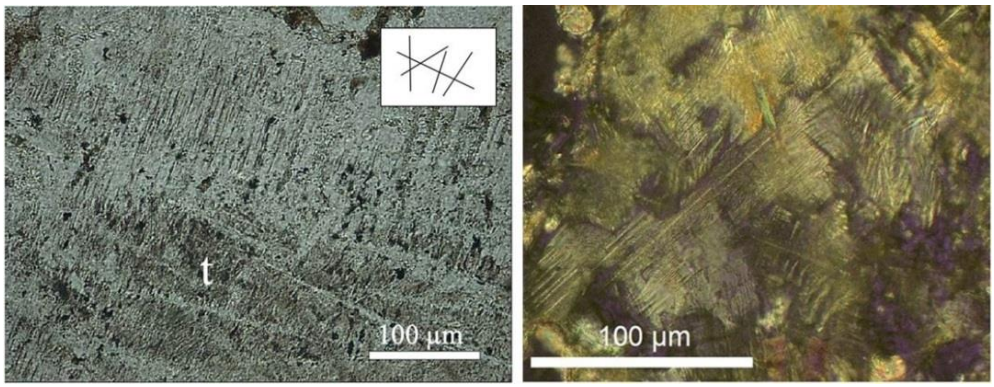

Figure 3. Shock features in cobbles from the Tüttensee wall. Photomicrographs. Left: Multiple (5) sets of PDF in quartz. The sets (see insertion) become evident by rotation of the universal stage (crossed polarizers). t = „toasted" quartz from tiny fluid inclusions, frequently observed in shocked grains (Whitehead et al., 2002). Right: Twin lamellae, multiple sets of PDF in feldspar, and spots of diaplectic feldspar glass (crossed polarizers). Note the characteristic "ladder" texture (French, 1998: 56).

However, impact-diagnostic shock metamorphism has meanwhile been detected at various comparably small craters around the world (Gurov and Gurova, 1998; Fazio et al., 2014), and also at small craters in the Chiemgau area. Shock metamorphism produces characteristic changes in rocks and minerals (macroscopic: shatter cones; microscopic: planar deformation features [PDFs] in quartz, diaplectic glass by the collapse of the crystal lattice (Ferrière and Osinski, 2013)). It is triggered by the extremely high P/T conditions (P > 2 GPa) within very short time, which occur in nature only in meteorite impacts, and is hence one of the few criteria accepted in impact research as evidence of a meteorite impact (French and Koeberl, 2010). Such evidence - PDFs in quartz, diaplectic glass, shock mosaicism, ballen structures - has been found in samples from different locations in the Chiemgau area (Fig. 3, 14; see also e.g. Ernstson et al., 2010, Fig. 4 left; Rappenglück et al., 2010, Fig. 3), and attests a hypervelocity impact event which created a crater strewn field.

Scientific investigations were not only applied at crater-like structures, but also at some metallic shiny,

barely corroded material, encountered in the same area in the subsoil down to 45-50 cm (Fehr et al., 2004; Schryvers and Raeymakers, 2004; Rappenglück, M. A. et al., 2005; Hoffmann et al., 2006; Ernstson, 2023). Varying in sizes (1-60 mm), weight (0.2-167 g; one outstanding sample 8 kg), and shapes (Fig. 4), it was analyzed to be iron silicides, which originate only in a highly reducing environment. Therefore, they naturally arise on earth rarely and only under extreme conditions (fulgurites, Earth mantle material); the other natural occurrence of iron silicides is known from some meteorites and extraterrestrial dust. Artificial production of some iron silicide phases started at the end of the 19th century (Rappenglück, M. A., 2022). Results of first analyses of three samples from Burghausen were interpreted to indicate a non-meteoritic, industrial origin (Fehr et al., 2004) and prompted conjectures that the material had been spread as fertilizer (Darga and Wierer, 2009; Huber et al., 2017). However, find situations (e.g. beneath an early modern coin hoard or in peat bogs) (Ernstson, 2023), analyses (by microprobe, SEM-EDS, TEM, EBSD) of samples from many different locations of the area, and finally new scientific insights into the natural formation of iron silicides and their differentiation from technically synthetically produced ones, clearly speak for a natural genesis (Rappenglück, M. A., 2022).

Figure 4. Impact-related material from the Chiemgau impact crater strewn field. From left to right: 8 kg chunk found at the municipality of Grabenstätt; regmaglyptic shape; splash shape (mm-scale); smaller fraction.

Different iron silicide phases have been proven (Bauer et al., 2019; Bauer et al., 2013; Hiltl et al., 2011; Rappenglück, M. A. et al., 2013; Rappenglück, M. A. et al., 2014; Rappenglück, M.A., 2022; Ernstson, 2023): Fersilicite/naquite (FeSi), ferdisilicite/linzhiite ($FeSi_2$), hapkeite (Fe_2Si) in two variants (cubic [hapkeite-1C] and trigonal [hapkeite-1T]), gupeiite (Fe_3Si), xifengite (Fe_5Si_3), and suessite ($(Fe,Ni)_3Si$) (with Ni ~ 0.8 wt%). The iron silicides, intertwined, form a matrix for other very rare mineral inclusions phases as cubic moissanite (β-SiC), and khamrabaevite ((Ti,V,Fe)C) (Rappenglück, M. A., 2022; Ernstson, 2023), whose extremely rare occurrences have also been proven in meteorites (e.g. khamrabaevite in the Allende meteorite (mindat.org)). In the 8 kg chunk calcium-aluminium-rich inclusions (CAIs) are embedded in a matrix of iron silicides. CAIs are a mineralogically and chemically diverse group of structures mainly known from carbonaceous chondrites (Rappenglück, M. A. et al., 2013). Crotite ($CaAl_2O_4$), which is a high temperature (>1,773 K)/low-pressure mineral, and dicalcium dialuminate ($Ca_2Al_2O_5$) which is a high-pressure mineral, coexist in samples examined. An industrial production would be contradictory to the exotic mixture encountered in the samples and to the depicted extreme and partly conflicting conditions of formation. Instead, a formation before or during an impact suggests itself, whereby both extraterrestrial material delivered by the impactor and terrestrial material incorporated during the impact may be involved. The microstructure of some samples which shows signs of very intense mechanical overload and also rimmed microcraters (10-20 µm) points to the former (Ernstson, 2023).

The association of the material with an impact is substantially corroborated by the interlocking, mutually supporting findings at crater #004 (48°13′ N, 12°45′ E; 11 m Ø, rim wall of 0.5 m height, ca. 1,2 m depth). There the following peculiarities were found: thermo-plastically deformed rocks, partly fused and/or glazed at the rim wall, indicating complete heating of the rim wall (Rösler et al., 2006; Ernstson et al., 2010); indications of temperatures close to 2000° C (Rösler et al., 2006); strong magnetic anomalies associated with the thermally altered wall material (Rösler et al., 2006); superparamagnetic nanoparticles in limestones (Prochazka and Kletetschka, 2016); carbon spherules containing nano- and microdiamonds (Rösler et al., 2006; Yang et al., 2008), partly together with iron silicides (Schryvers and Raeymakers, 2004) in the melt crust of cobbles (Rösler et al., 2006); Kamacite, indicating a meteorite fragment (Prochazka, 2023); GPR data pointing to massive physical changes of the underground and indicating that the morphology of the crater wall continues into a depth of several meters (Rösler et al., 2006; Poßekel and Ernstson, 2019; Ernstson and Poßekel, 2020); impact-diagnostic shock metamorphism in cobbles from this crater (Ernstson et al., 2010, Fig. 18 left; Rappenglück et al., 2010, Fig. 3). The synopsis of these findings strongly suggests that "the crater formation must have been accompanied by a discrete strong thermal event independent of impact shock" (Ernstson et al., 2010: 93). Crater 004 is the best explored crater in the crater

strewn field and combines outstandingly the evidence of required impact criteria - shock metamorphism and impact-related material - as well as secondary (impact-related, but not impact-diagnostic) phenomena.

The crater strewn field was probably caused by a rather porous object consisting of various components that broke apart in the atmosphere. Indications of extreme heating of the underground, found at many locations in the strewn field (Rösler et al., 2006; Shumilova et al., 2018), suggest that the impacts of the different parts were accompanied by airbursts with extreme heat jets. Archaeological finds allow dating to 900-600 BC (see below section 3.2.).

Figure 5. Sites mentioned in the article. Scale: Ø of the Tüttensee crater (= yellow circle): 600 m. Based on Google maps.

2. SETTLEMENT STRUCTURES AFFECTED BY THE METEORITE IMPACT: THE MÜHLBACH LOCATION AND THE STÖTTHAM SITE

At two sites in the southwest of the crater strewn field settlement structures were affected by the meteorite impact (Fig. 5). The corresponding archaeological finds and features, and the mineralogical, petrographic and geophysical investigations that were applied are presented and discussed here.

2.1. *The Mühlbach site*

The Mühlbach location, a meadow area, is very close to the Tüttensee crater, one of the biggest craters in the crater strewn field (Fig. 2, Fig. 5). For understanding the Mühlbach site it is essential to shortly introduce this crater.

2.1.1. TheTüttensee crater

The Tüttensee basin (47° 50' 48'' N, 12° 34' 6'' E) is characterised by a kettle-shaped depression of about 600 m Ø, nowadays largely occupied by a lake of ca. 17-30 m depth. It is surrounded by hills up to 8 m high, the crest of which has been artificially levelled in the southwestern area. Likewise, the breakthroughs in the W and E are artificial (personal communication Baron Dieter Freiherr von Wrede†, owner of Lake Tüttensee). The Tüttensee basin was usually referred to as a kettle hole (Ganss, 1977).

Our interpretation of the Tüttensee basin as an impact crater is based on the evidence of impact-diagnostic shock metamorphism, namely PDFs in quartz, and PDFs and diaplectic glass in feldspar, occurring in cobbles from the wall and from an area of up to 1,5 km radius (Fig. 3, Fig. 14). The 8 kg chunk of iron silicides (Fig. 4 left) with its unusual composition (see section 1.2.), found about 1.5 km west of the Tüttensee crater, may be addressed as an impact-related material (Bauer et al., 2019; Ernstson 2023).

Results of geophysical surveys support the interpretation of the Tüttensee basin as a crater. Gravimetric data obtained during a measurement campaign covering an area of approx. 3 km² around Lake Tüttensee with 115 measurement points (40 of which were on the frozen Lake Tüttensee) revealed a broad ring of relatively positive anomalies surrounding the negative anomaly of the lake and the crater mass deficit (Ernstson et al., 2010). From well understood impact cratering effects (e.g., Melosh 1989), it is assumed that shock-wave densification of the Quaternary target loose-rock sediments produced the gravity positive ring anomaly.

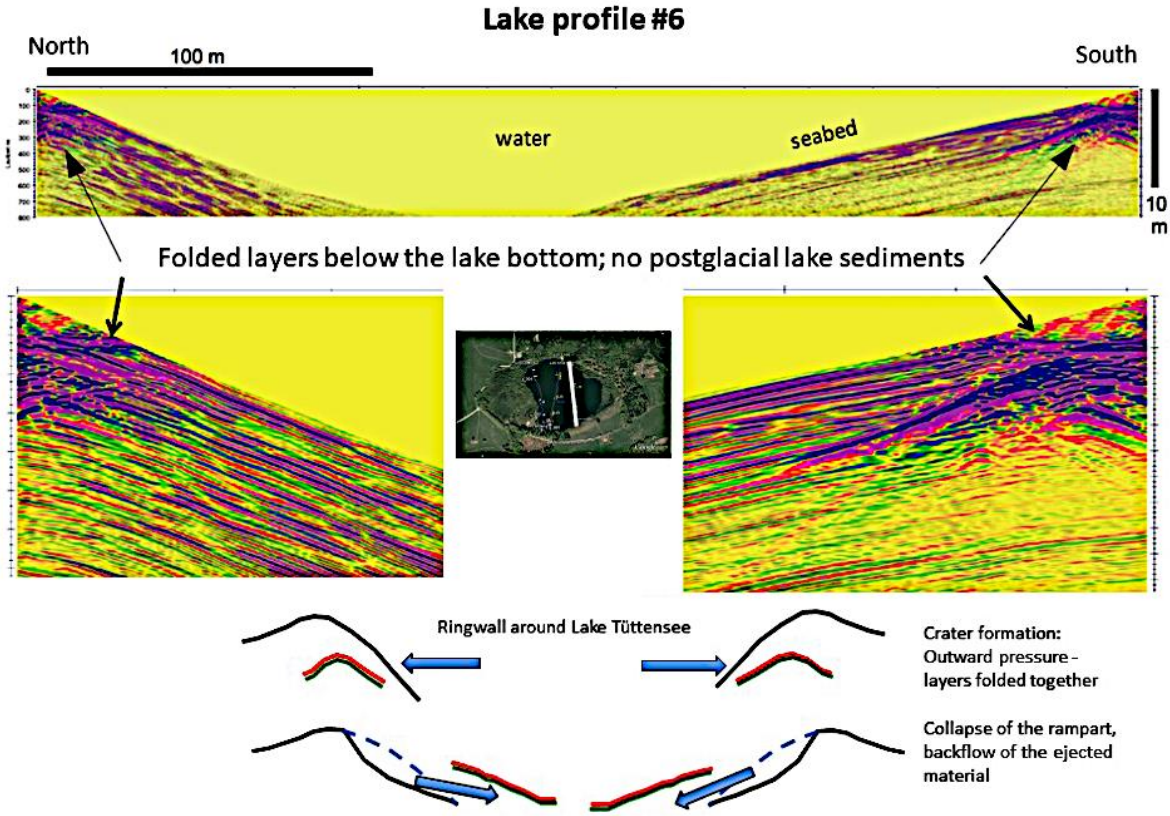

Figure 6. Tüttensee, GPR lake profile #6; folded layers below the lake bottom exclude postglacial lake sediments, as also indicated by the results of a seismic survey (Ernstson, 2014).

Ground penetrating radar (GPR) measurements in different frequency ranges (25 MHz antenna bistatic; 200 MHz antenna monostatic; 300 MHz antenna monostatic) on Lake Tüttensee, around the lake and in numerous profiles across the wall provided information about its internal structure: The wall has internally dipping layers rising and descending outwards from the crater (Fig. 6). This clearly distinguishes its structure from a kame (Götz et al., 2018) and illustrates how the successive ejection of material, including slipping back, produced a "roof tile" layering during the formation of the crater. Also visible is the folding of the bedrock and the lateral deviation of the fold apex under the pressure coming from the crater (Fig. 7).

In addition to the explicit impact-diagnostic shock metamorphism these results are incompatible with a dead ice hole, but are coherent products and concomitants of a hypervelocity impact.

Doppler et al. (2011) and Rösch et al. (2021) drilled boreholes on the northern shore of the Tüttensee and concluded from the discovery of undisturbed postglacial sediments that they had disproved the impact genesis of the Tüttensee basin. Their fallacy to drill inside the crater is based on a confusion of the "true", much smaller transient crater (French, 1998) and the apparent crater suggested by the rim wall. This error we have already pointed out years ago in a reply (Rappenglück, B. et al., 2011) and it makes their considerations regarding the impact obsolete.

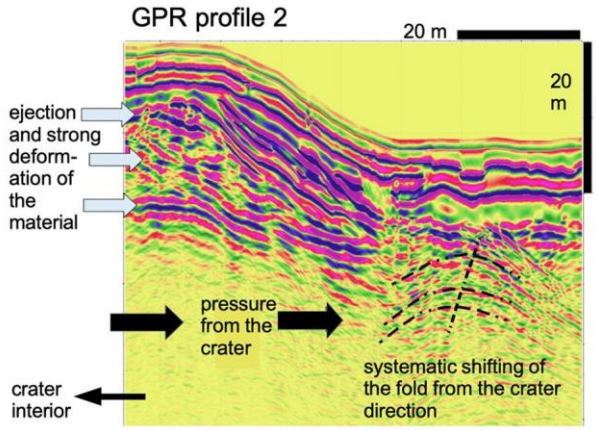

Figure 7. Tüttensee rim wall: ground penetrating radar profile. The systematic shifting of the fold apex (broken line) suggests simultaneity of folding and lateral displacement in the excavation process.

In general, the proponents of the kettle hole hypothesis (Doppler et al., 2011; Huber et al., 2020; Rösch et al., 2021) apply inappropriate methods for the detection of a hypervelocity impact, e.g. using sedimentological methods (Huber et al., 2020), and ignore the evidence of shock metamorphism at Tüttensee crater. This is probably due to a misunderstanding

by one of Huber's co-authors who in an earlier paper formulated (translation from German by B. Rappenglück): "a 'shocked' (i.e. already provided with open and 'uncemented' fissures) boulder ..." (Darga and Wierer, 2009: 176). Shock metamorphism however has nothing to do with macroscopic fissures in boulders. Planar deformation features (PDFs) in quartz, as one of the main manifestations of shock metamorphism, are very narrow (spacing < 1-10 µm) and very narrow (fractions of a µm) isotropic lamellae aligned with the crystallographic directions of the crystal. Isotropic means that the fine lamellae behave optically like glass. The lamellae can be homogeneous, but also decorated with the finest inclusions. PDF detection requires the preparation of a thin section, which is then examined with a polarising microscope.

Based on all the evidence we address the Tüttensee basin as an impact crater with a rim-to-rim diameter of about 600 m. From impact scaling laws (Wünnemann et al., 2011) it is estimated that the projectile that created the crater was about 25-50 m in size.

2.1.2. Description of the stratigraphy at the Mühlbach location

For investigating the extension and structure of a suspected ejecta blanket, approximately 80 trenches (1-3 m depth, up to 3,5 m length, 2,1 m breadth) were excavated (Fig. 8). At a distance of up to 1100 m to Tüttensee crater a sequence of generally (modifications included) four layers was encountered, e.g. to the west in an excavation pit near Grabenstätt, to the east in numerous diggings at the Mühlbach location. This meadow area extends 500-1000 m east of the Tüttensee crater and is one of the sites of geoarchaeological interest.

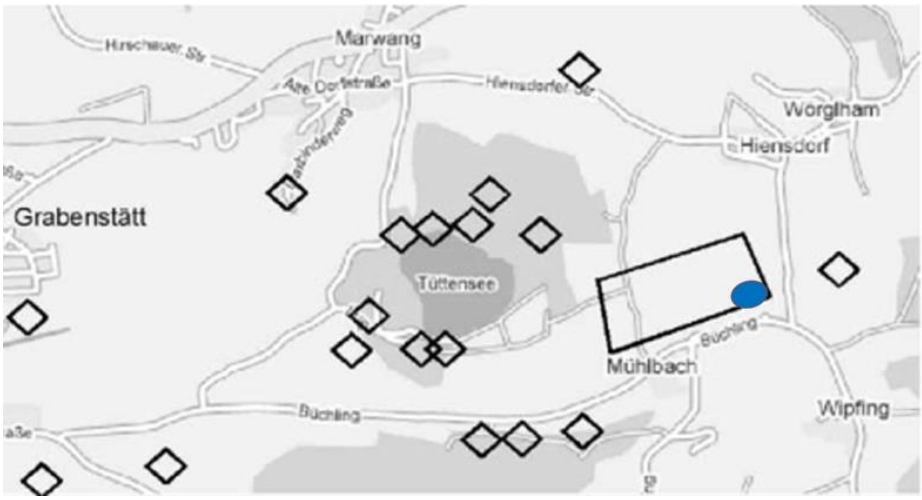

Figure 8. Areas where test trenches have been excavated (width of map section 3 km).

The stratigraphy at the Mühlbach location was studied macroscopically and, as far as individual rock components are concerned, also microscopically. The layers encountered have the following characteristics: 1. At 1-2 m depth (depending on the topographic situation) an undisturbed Pleistocene or Holocene rock representing a lacustrine clay or loamy gravel composed of well-rounded cobbles of Alpine lithologies is encountered. 2. Over that, a decimeter thick horizon represents a fossil soil sometimes containing excellently preserved organic material (wood, blades of reed, tufts of animal and/or human hair). 3. This fossil soil horizon is overlaid by an up to one meter thick diamictite. The basal diamictite is dominated by subangular carbonate and silicate boulders in a muddy matrix which are in part strongly deformed plastically and are abundantly corroded down to a skeletal sculpture (Fig. 9). An intermediate bed, not always present, has the character of a polymictic, multi-coloured, matrix-rich breccia composed of heavily fractured, sharp-edged cobbles and boulders of Alpine lithology (Fig. 10-12), while the uppermost part of the diamictite is especially enriched in humus material. The whole diamictite is characterized by clasts which in spite of strongest smashing are encountered coherent in the clayey matrix (Fig. 12 A). Stones of all lithologies show an extreme corrosion to the point of rock skeletons (Fig. 13). Seemingly intact gneiss and amphibolite cobbles can be broken and grinded with the bare hand. Abundant splinters of wood, partly extremely twisted, charcoal, fractured animal bones (one of them from cattle) and teeth contribute to the diamictite; some artifacts will be addressed below (see section 2.1.4.). 4. The diamictite is overlaid either by a gravel layer of completely untouched cobbles and recent soil formation, or immediately by recent soil.

For search for shock effects, samples from Quaternary crystalline and sedimentary Alpine cobbles were selectively taken from this layer. The moderate shock

effects discovered repeatedly display planar deformation features (PDFs) in quartz (Fig. 14).

2.1.3. Interpretation of the geological/mineralogical/petrographic observations at the Mühlbach location

"Diamictite" is a purely descriptive term. The possibilities of formation include, among others, glacial processes as well as impacts. By exhibiting abundant evidence of shock metamorphism, the diamictites of the Mühlbach location and at Grabenstätt bear the distinct traces of a hypervelocity impact.

Knowledge about impact processes (Melosh, 1989) and the petrographic observations on the diamictite allow interpreting the described layer as ejecta blanket of the Tüttensee crater. The sequence of layers encountered may be explained as follows: At the time of the impact, the target is made up of lacustrine clay and Pleistocene and/or Holocene banks of loamy gravel including a (nowadays fossil) soil with organic material. In the contact and compression stage of the impact process, shock waves propagate into the projectile being vaporized and into the target rocks that experience shock metamorphism. 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 must have rapidly become oxygen sealed enabling the excellent preservation.

The highly crushed rock fragments in the soft, clayey breccia matrix at the Mühlbach location can be explained by high confining pressure (Collins et al., 2004) applied to the ejecta during excavation and landing. The quartzite boulders (compressive strength of quartzite 100-300 MPa) in particular are through and through crushed into smaller, but nevertheless still coherent and perfectly fitting fragments. But also many of the other countless, highly fragmented components, originally alpine boulders, must have been deformed *in situ* - presumably when the ejecta landed at high speed -, because of the coherence of the fragments. Any further transport must have led to complete disintegration. The coherence indicates that the boulders were subject to high confining pressure during the fracturing process. A conceivable fragmentation during a landslide is not applicable due to the lack of relief; frost blasting can be ruled out.

Figure 9. Corrosion down to skeletal sculpture: limestone (left). Deep channels and the contrasting protruding small column (encircled red) exclude any transport and are incompatible with normal weathering. Sandstone (right).

Figure 10. Polymictic breccia.

Figure 11. Sharp-edged and partly etched Alpine cobbles.

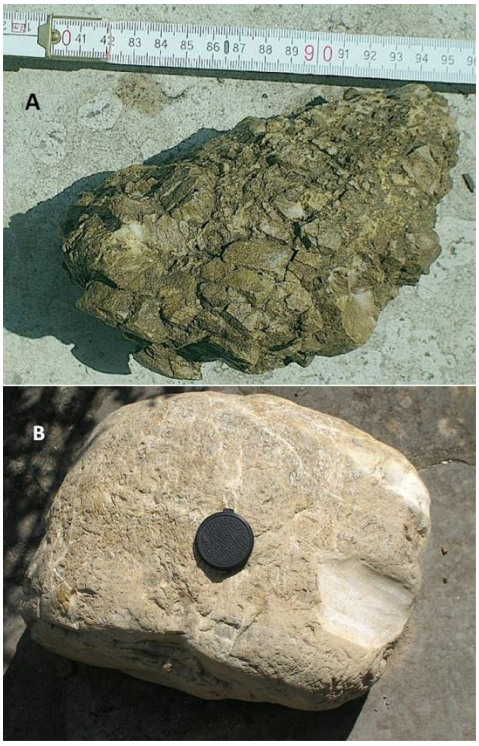

Figure 12. A: Shattered and deformed but coherent quartzite boulder; B: Quartzite block scraped (at the right edge) while it was plastically deformable under extreme pressure. Photo cap as scale.

The extreme corrosion of many components is attributed either to strong heat overprint, in particular due to decarbonization of carbonate rocks (Osinski and Spray, 2001), to chemical solution, or to both. The causative agent of the chemical solution, especially of the carbonate, is considered an acid precipitate (nitric acid) emanating from the impact cloud, a phenomenon also known from other impacts (Prinn and Fegley, 1987). As a result rocks are sculptured due to the different solubility of their components (Fig. 13). Carbonate clasts, when removed from the embedding site leave in many cases a white mantle of detached carbonate in the matrix of the ejecta. Crystalline rocks are also encountered in a highly decomposed state. The extremely friable components would not have survived further transport. All these observations indicate that processes (chemical solution, exposure to heat) have taken place *in situ* here.

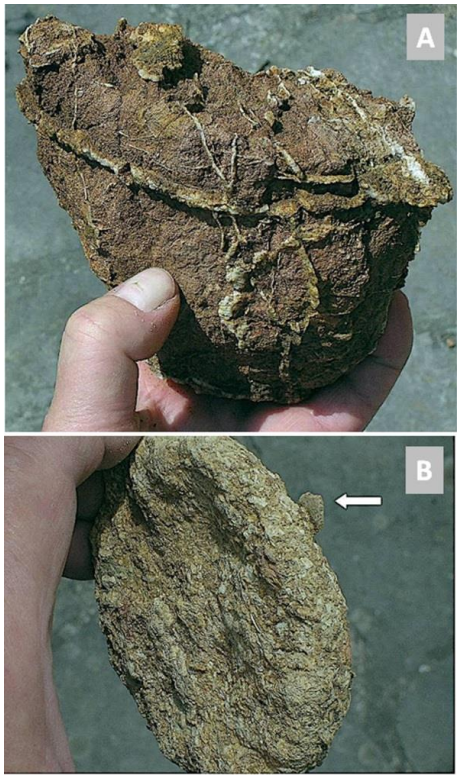

Figure 13. A: Drastically corroded sandstone clast with protruding whitish quartz veins. B: The fossil-rich limestone cobble heavily etched all around shows a protruding quartzite platelet (arrow). The size of the platelet suggests a thickness of at least 8 mm of the dissolved layer.

The uppermost, strongly humic part of the diamictite suggests that the ejecta layer was finally in part overprinted and/or reworked by muddy, tidal (tsunami) waves emerging from companion impacts into close by Lake Chiemsee, where a double crater structure had been detected with sonar sounding (Ernstson, 2016).

In sum, the diamictite exhibits numerous characteristics of an impact ejecta layer.

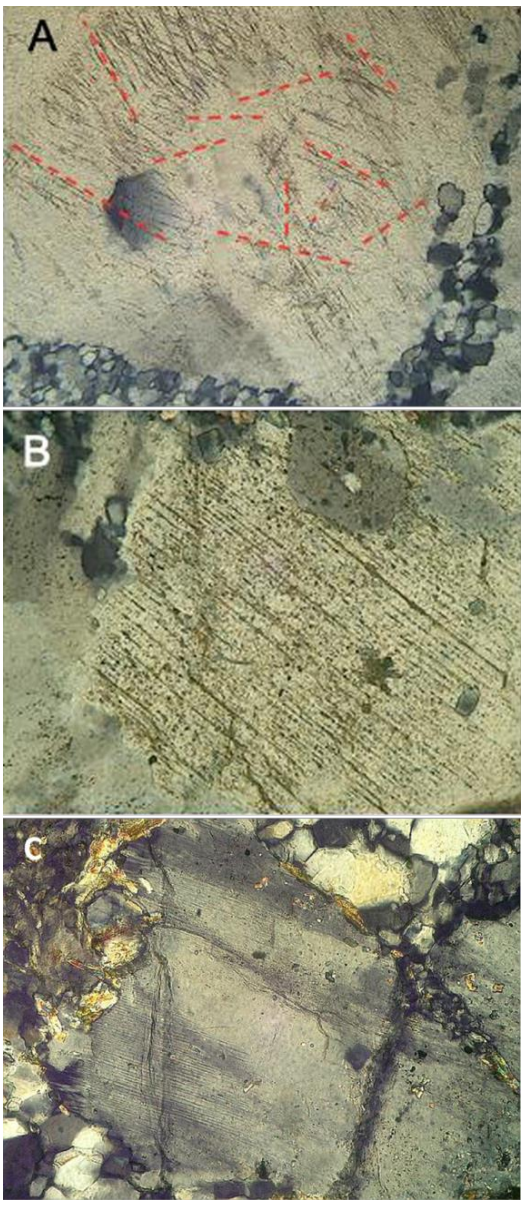

Figure 14. Photomicrographs of shock metamorphism in cobbles from the ejecta layer at the Mühlbach site. A: Multiple (11 at least as indicated) sets of PDFs in a quartz grain, quartzite, pit 11. Crossed polarizers; field width 1100 µm. B: Quartz grain with strongly decorated PDF, mica quartzite, pit 21. Crossed polarizers, field with 260 µm. C: A set of nondecorated PDFs in quartz from quartzose mica schist, pit no. 10. Crossed polarizers, field width 480 µm.

2.1.4. Archaeological finds in the Mühlbach

A number of artifacts were found in the diamictite of some closely spaced excavation pits, concentrated in the southeastern corner of the Mühlbach area (see blue ellipse in Fig. 8). The finds included a processed quartzite boulder (17.6 x 8.6 cm) (Fig. 15 A, B), from a depth of 1 m, dating to the Neolithic or Bronze Age. A dozen sherds were found in several ditches as components of the polymictic breccia, in depths between 1-1,30 m. The sherds, the largest of them measuring roughly 4 x 3 cm, are coarsely tempered with clasts up to 3 mm (Fig. 15 D). They are without any specific characteristics of shape or décor, and can therefore only roughly be attributed to the Central European Bronze Age or Iron Age (personal communication Kurt Zeller†, former director of the Celts Museum Hallein, Austria). A further find (depth 1 m) was an unidentifiable, slightly bent iron pin of 2 cm length and 1,5 mm Ø (Fig. 15 C).

Five small pieces of sherds of the type mentioned were discovered beneath in the lacustrine clay (depth 1,60 m), and a graphited sherd dating to the Middle or Late Latène culture in the topsoil above the diamictite (depth 30 cm).

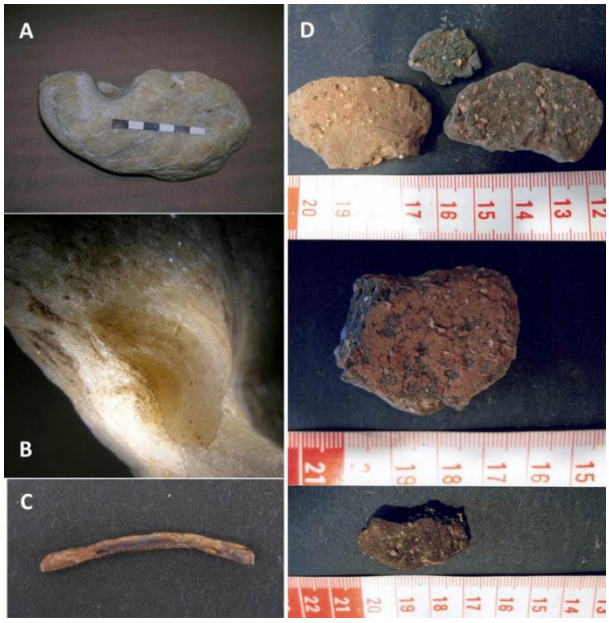

Figure 15. Archaeological finds from the Mühlbach ejecta layer. A: processed quartzite boulder; B: detail of A, drill-hole; C: iron pin (length 2 cm); D: sherds.

The accumulation of the finds in a small area and the potsherds in particular prompted suspicion that there might have been some kind of settlement that was destroyed by the impact. In order to test this assumption, preliminary geophysical investigations were carried out on partial areas of the Mühlbach site. A pulse electromagnetic (TDEM) survey and a ground-penetrating radar campaign revealed conspicuous geometric structures that might possibly be

interpreted as settlement traces. However, further, much more detailed measurement campaigns are necessary and planned in order to be able to make reliable statements.

2.1.5. Interpretation of the archaeological finds in the Mühlbach impact layer in their geological context

The findings at the Mühlbach indicate that the impact involved a settlement site. So far, it cannot be said whether the presumed settlement was inhabited or already abandoned at the time of the impact. Nor do the animal bones and teeth found - of which at least a cattle's second phalange (toe bone) bone certainly belonged to a domestic animal - answer this question. They may be relics of animals that died during the event, but they may also have existed before.

The archaeological finds at the Mühlbach are, outwardly, distinctly unremarkable. Nevertheless, their significance lies in three aspects. First, they indicate that the diamictic layer was deposited in a period far after the end of the last ice age, earliest in the Bronze Age. Secondly, they indicate that a settlement was affected by the meteorite impact. Third, they were the first archaeological finds found as components of an impact layer. This aspect will be further discussed (section 3.1.)

2.2. *The Stöttham site*

The second site of interest here is at Chieming-Stöttham, a village on the eastern shore of Lake Chiemsee, ca. 7 km NNE of the Tüttensee crater (see Fig. 5). A rescue excavation had to be carried out in Stöttham in 2007/2008. A distinct diamictite (Fig. 16: stratum Bef. 143 [all 'Bef.' ascriptions of findings hereafter are terminology of the excavating archaeologist Möslein, 2009]) caught our attention, but geological monitoring of the excavation and investigations by our team was only possible to a limited extent, due to the time pressure caused by the planned construction project. Concerning the archaeological situation, we got an overview of and access to the finds only after the excavation was finished. Our comments on the overall archaeological situation and the finding situation of individual archaeological artifacts therefore refer to a meticulous study of the excavation report (Möslein, 2009).

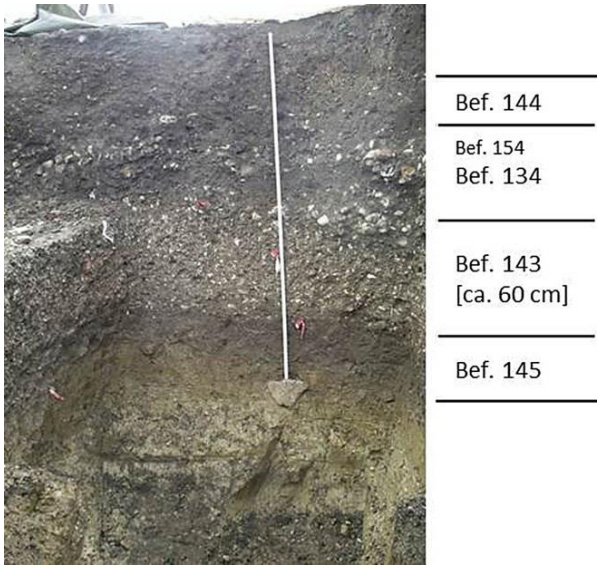

Figure 16. Profile at the Stöttham site with indications of the archaeological layers.

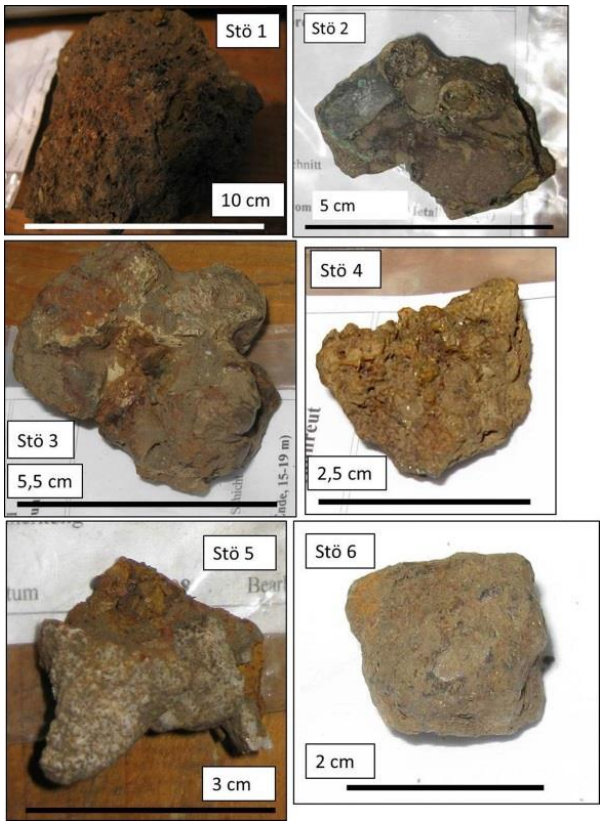

Figure 17. Samples Stö 1-6.

At the now built-up site (47°54´26´´ N, 12°31´29´´ E, ca. 530 m a.s.l., ca. 700 m afar and ca. 13 m above the current lake level; total of the investigated area ca. 1150 m²) the partial excavation of subarea 2 (Möslein, 2009) covered a sloped area of roughly 300 m², digging down into deposits of Holocene fluvio-glacial gravel and till, and partly reaching Würmian glacial sediments. It revealed finds from the Neolithic, the Bronze Age, Late Bronze Age and the Roman period.

The Early Iron Age Hallstatt period, however, is represented by very scarce finds only, and finds from the Latène period are completely missing (information extracted from Möslein, 2009).

The stratigraphy with the distribution of archaeological finds and features in these strata has been presented and discussed in detail (Rappenglück et al., 2020a; Rappenglück et al., 2020b) as well as the C14 and OSL dating, from the bottom of the stratigraphy up to layer Bef. 134 (Liritzis et al., 2010; Völkel et al., 2012). The studies found that the complex stratigraphy is not as simple and undisturbed as Völkel et al. depict it (Völkel et al., 2012) neither in terms of archaeological finds nor in terms of radiometric dating.

The following is concentrated on the impact evidence we found, and about which we have gained new insights as our investigations have progressed.

Table 1. Stöttham excavation site: impact shock features (French, 1998; Ferriére and Osinski, 2013; Engelhardt and Stöffler, 1969; Stöffler et al., 2017; Stöffler and Langenhorst, 1994) in archaeological finds.

shock features	sample	required pressure (at least)	definition
planar deformation features (PDF)	Stö 1 in hornblende Stö3 in quartz Stö 4 in hornblende amphibolite Stö 6 in amphibole	> 5-10 GPa	Planar Deformation Features (PDF) are closely spaced (1-10 µm apart) isotropic lamellae following crystallographic planes; according to current knowledge they are unknown from any endogenetic geological process.
diaplectic glass	Stö 2	> 5 GPa	Diaplectic glass is formed not by melting but by shock damage of quartz or feldspar minerals. It is optically isotropic and x-ray amorphous.
ballen structures	Stö 2	≈ 15 Gpa [Chanou et al., 2015]	Ballen structures are mostly spherical formations of SiO_2. They are considered to form by solid phase transformation in diaplectic silica or lechatelierite involving high-temperature cristobalite phases. A different model [Smith et al., 1999] proposes a formation of ballen in quartz in an extreme thermal shock event.
shock mosaicism	Stö 4	> 10 GPa	Mosaicism is a common feature of plastic deformation of minerals by dynamic compression. Under the microscope it shows as a strongly irregular extinction pattern (mottled extinction pattern) originating from the formation of differently orientated blocks within the crystal structure.
shock melt glass	Stö 1, Stö 3	50-60 GPa >60-200 GPa	e.g., feldspar glass complete melting of all mineral phases

2.2.1. Mineralogical-petrographical evidence of a meteorite impact

First indications of a connection between the Stöttham site and a meteorite impact were found in the diamictic stratum Bef. 143 (Fig. 16; Ernstson et al., 2012). Here we summarize important points: The layer comprised heavily shattered and extremely corroded cobbles in a clayey-silty, slightly sandy matrix intermixed with splintered wood, charcoal, fractured bones and teeth, as well as sherds. Thin sections show impact-diagnostic shock metamorphism in the form of PDFs and diaplectic spots in quartz. Brecciated, but still coherent clasts indicate high confining pressure upon deposition. Elutriation of the diamictite matrix revealed carbonaceous, glassy and metallic spherules. Evidence of strong heating was frequent. More considerations will be given to this later (see section 3.1.).

Meanwhile, the evidence of a meteorite impact has been significantly expanded. Six finds (Bef. 133 [from Bef. 144], 51, 181, 142, 283, 282 [from Bef. 134] = Stö 1-6 in our nomenclature) (Fig. 17), combinations of rocks and metal, were investigated. Sections were studied with the naked eye; polished thin sections were examined with the polarizing microscope, and metal components were additionally analyzed with SEM-EDS (Bruker).

These samples exhibit a rich inventory of shock phenomena and textures typical of impactites. The shock phenomena encountered, which form under extremely high P/T conditions within very short time, are summarized in Table 1 and illustrated in Fig. 18-20.

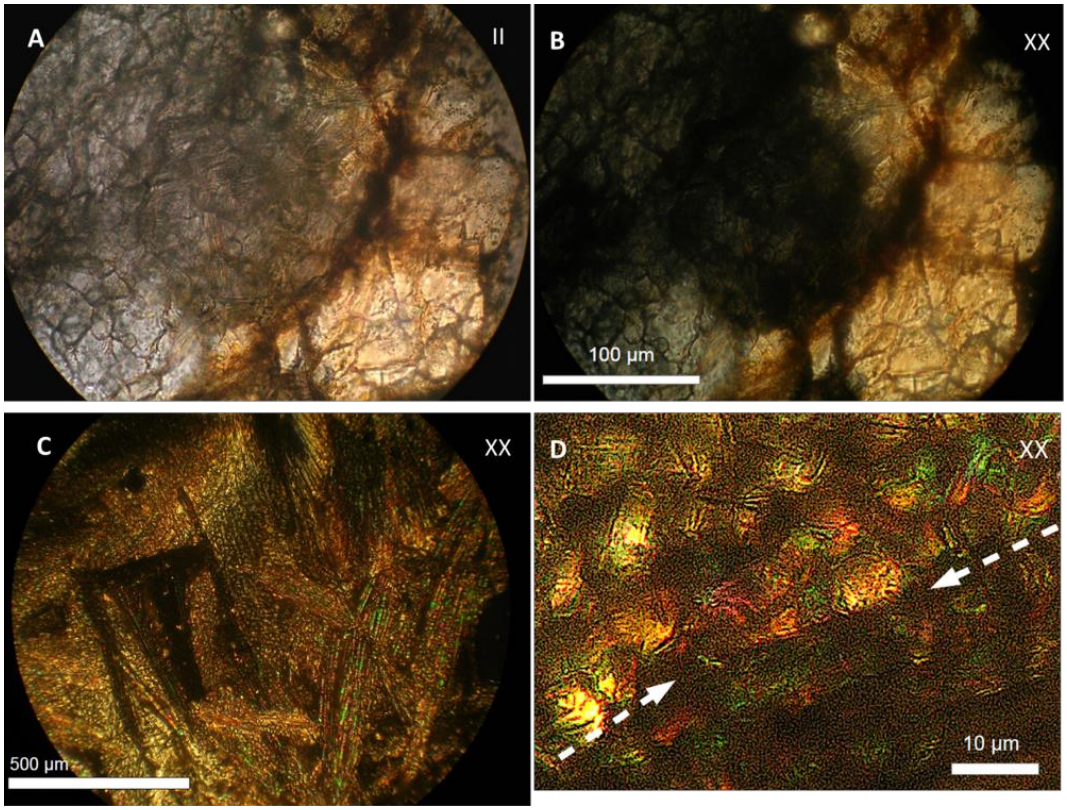

Figure 18. Photomicrographs of shock features in sample Stö 3, 4. A + B: Stö 3, multiple sets of PDF in quartz; C: Stö 4, strongly shocked hornblende amphibolite with mosaicism and PDF. Shock mosaicism is a structural disorder in mineral grains (French, 1998: 36), here shown by the granular texture alternating with multiple sets of crossing PDF lamellae. D: Stö 4, high magnification shows the mosaic particles of the two adjacent crystals practically without exception with PDF. Arrows mark ghostly crystal boundary. Crossed polarizers.

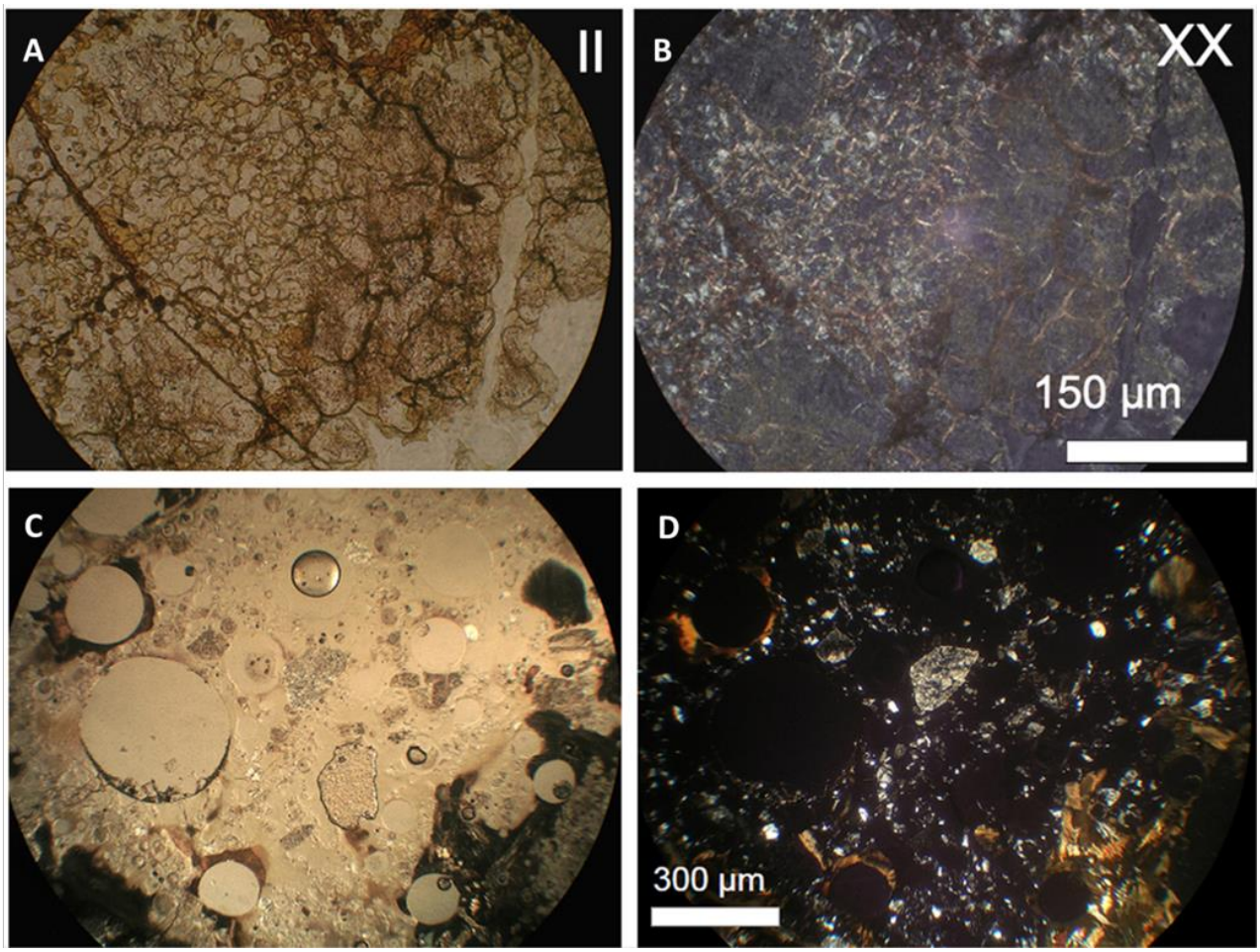

Figure 19. Photomicrographs of shock features in samples Stö 2, 1. A + B Stö 2, ballen structures in diaplectic glass. Ballen structures in silica form a characteristic texture in shocked quartz that in general is considered a result from various stages of phase transformation and recrystallization (Ferrière, Koeberl and Reimold, 2009). C + D Stö 1: vesicular glass (black at XX) with small quartz- (and feldspar-?) fragments, (C) parallel, (D) crossed polarizers. Under crossed polarizers glass becomes optically isotropic.

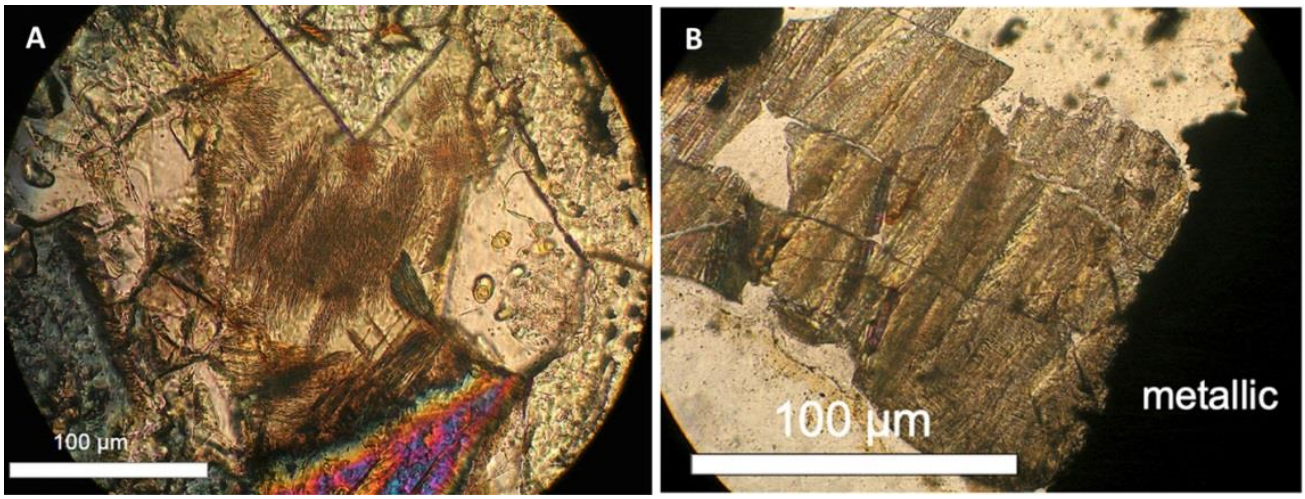

Figure 20. Photomicrographs of shock features in samples Stö 1, 6. A: Stö 1, PDF in hornblende (grain in the middle), parallel polarizers; B: Stö 6, PDF in amphibole, parallel polarizers. The multiple sets of closely spaced and crossing PDF in A and B must not be confused with the clearly established planar fractures in the grains.

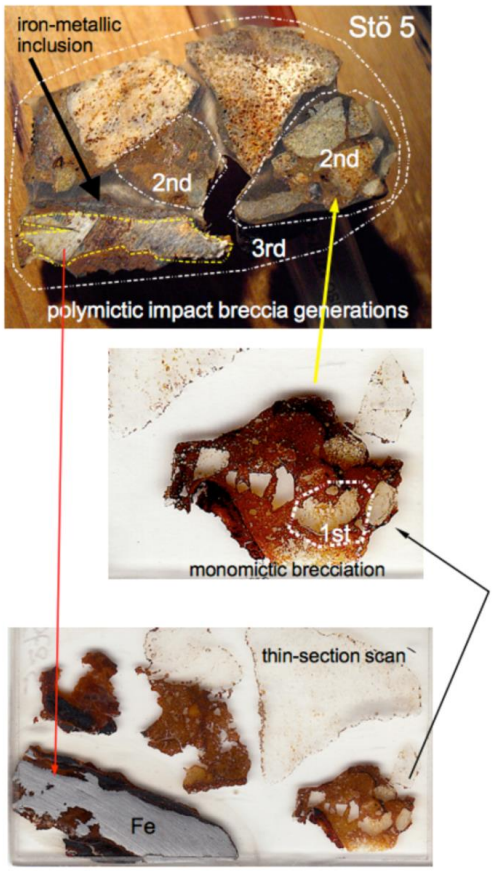

Figure 21. Multiple generations of breccia in sample Stö 5 (length of the sample: 3 cm). Cut and thin sections. In the middle thin section, a white, dashed circle surrounds a large lightish piece. This piece, which represents the first generation of breccia, is monomictically broken in itself and the fragments are surrounded by brownish matrix. The lower thin section shows a large iron fragment for which Table 2 shows the results of SEM-EDS.

Besides the described shock features, indicating impact shock between about 5 and >50 GPa, the samples under examination display textures typical of impactites:

- Multiple generations of breccia: Sample Stö 5 exemplarily exhibits three generations of breccia (Fig. 21). The first one is a monomictic breccia, which subsequently became part of a polymictic breccia. The third generation additionally integrates fragments of a highly heated silica limestone as well as a piece of iron, which will be discussed in more detail later (section 2.2.2.). Multiple generations of breccia, rarely occurring in "normal" geology, can successively form during the different stages of an impact event and constitute a typical product of impact processes (Lambert, 1980).

- Suevite/Suevite breccia is a "polymict impact breccia with particulate matrix containing lithic and mineral clasts in all stages of shock metamorphism including cogenetic impact melt particles which are in a glassy or crystallized state" (Stöffler and Grieve, 2007: 198). Stö 2 (Fig. 17, 22) mainly consists of a vesicular amphibolite with gas bubbles. The rock joins up with a fine matrix containing smaller pieces of rock, countless tiny metallic particles, and a metallic flow structure. The largest metallic piece visible (analysis see Table 2) measures roughly 4 x 4 mm. Microscopically, the sample shows ballen structures and diaplectic glass as impact shock features (Fig. 19 A, B), indicating the exposure to shock pressure of ≈ 15 GPa. This composition corresponds to a suevite/suevite breccia.

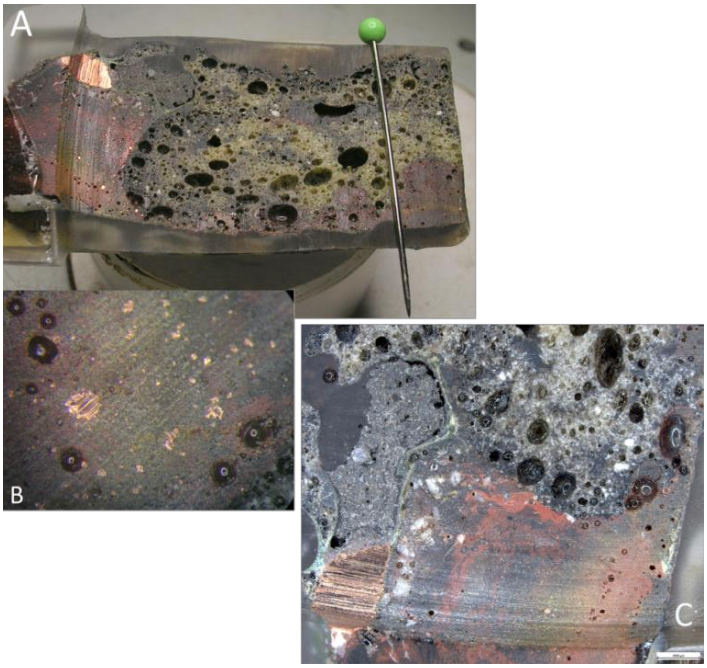

Figure 22. Suevite breccia Stö 2. A: cut (pinhead 2,5 mm); B: close-up of tiny metallic particles; C: metallic flow structure (optical microscope). The scale bar equates to 3000 mμ. The small particles in B and the flow structures in C show the same phenomenology in the optical microscope as the large piece in A analysed with SEM-EDS (Table 2).

The same applies to sample Stö 3 (Fig. 17, 23) which is a polymictic breccia with dominating amphibolite components. A strongly decomposed, silvery bright to rusty, strongly magnetic fragment, visually classified to be iron (analysis by SEM-EDS pending), makes up another large part of the breccia and partially disintegrated into finest particles within the silicate accompanying material. Strongly shocked quartz fragments contribute to the polymictic breccia with glass particles, which in turn form a polymictic breccia (breccia-within-breccia) (Fig. 24). The characterization as suevitic breccia applies equally to sample Stö 1 and 4 (Fig. 25, 26).

The various impact features (shock features, textures) described characterize the studied samples as impactites and underpin that the site at Stöttham was involved in a meteorite impact.

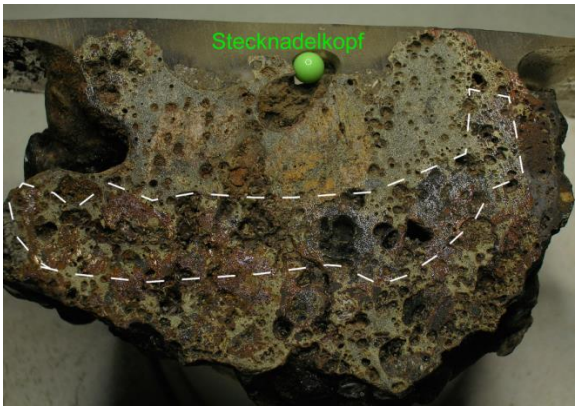

Figure 23. Sample Stö 3. Cut (pinhead 2,5 mm), polymictic melt rock breccia (mostly amphibolite) with metallic inclusions (encircled white dashed), most probably iron according to their magnetism and their partly shiny, partly rusty appearance.

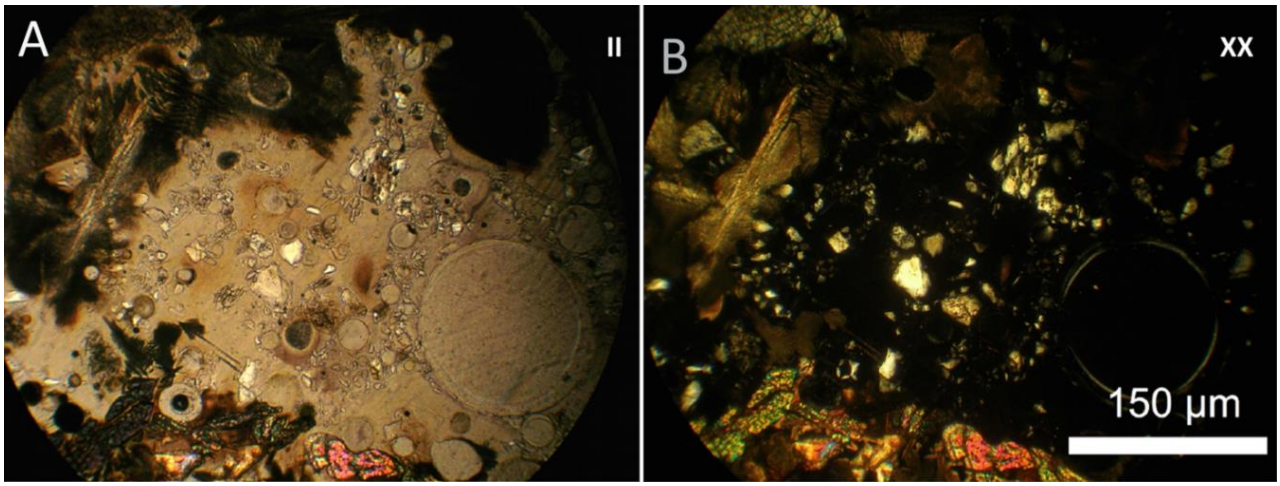

Figure 24. Sample Stö 3. Photomicrographs, parallel (A) and crossed (B) polarizers: glass with quartz fragments.

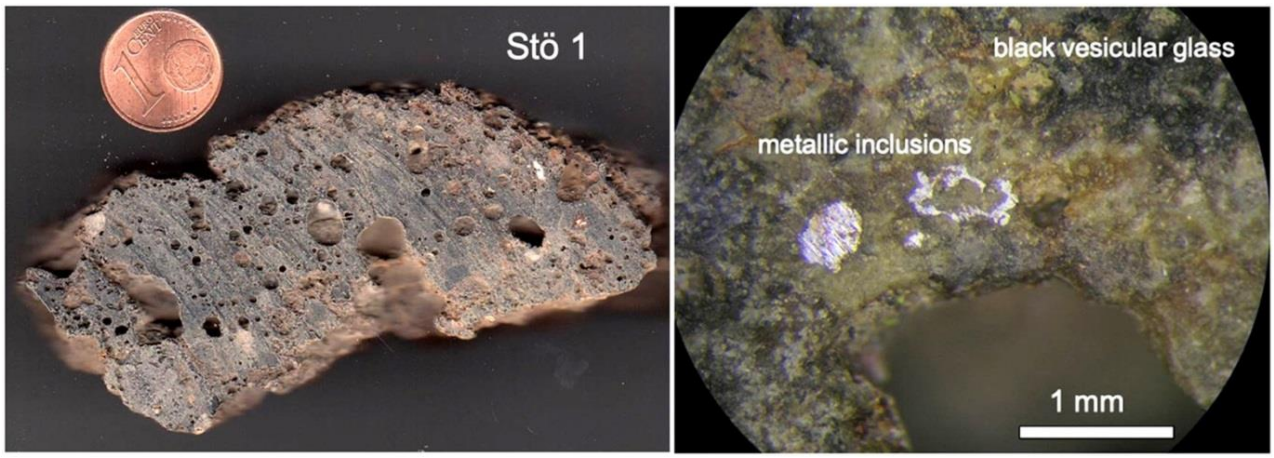

Figure 25. Stö 1: polymictic melt breccia of fused, vesicular amphibolite with glass particles, indeterminable rock particles, and sporadic metal particles.

Table 2. Stöttham samples: EDS results of Stö 2, 4-6.

EDS of Stöttham samples	["ca.": data are taken from the diagrams]															
Sample (Spectrum X) wt%	Cu	Pb	Sn	Fe	C	O	Si	Al	Ca	Mg	Na	K	Sb	Cl	Mo	As
Stö 2 (Spectrum 1)	47,29	26,12		0,93	7,11	11,16	3,64	0,99	1,08	0,43	1,01	0,23				
Stö 2 (Spectrum 2)	51,87	34,04			7,01	6,2							0,87			
Stö 2 (Spectrum 3)	7,32	44,35	5,28	2,04	6,69	20,24	8,11	1,57	3,56	0,85						
Stö 2 (Spectrum 4)	2,88	36,44	3,88	2,97	6,98	24,97	11,72	2,2	6,61	1,35						
Stö 2 (Spectrum 5)	10,24	44,16	4,53	1,78	5,82	19,39	8,84	1,66	3,17	0,78						
Stö 2 (Spectrum 6)	5,84	38,41	5,53	2,37	7,82	24,52	9,18	2,23	3,19	0,81						
Stö 2 (2nd meas. Spectrum 1)	5,57	27,36	10,12	2,26	10,72	24,63	11,44	2,44	3,27	0,77						1,41
Stö 2 (2nd meas. Spectrum 2)	6,14	31,58	1,98	2,83	11,6	24,64	12,86	2,66	3,74	0,8						1,13
Stö 2 (2nd meas. Spectrum 3)	4,8	31,07	3,9	2,75	11,16	25,08	12,84	2,77	3,62	0,86						1,15
				Fe	C	O										
Stö 4 (Spectrum 5)				90,4	9,1		0,2	0,3								
Stö 4 (Spectrum 6 (ca.)				95		5	minor	minor								
Stö 4 (Spectrum 7 (ca.)				97		3	minor	minor								
Stö 4 (Spectrum 8 (ca.)				95		5	minor	minor								
Stö 4 map sum spectrum ((ca.)				76	8	16	minor	minor	minor					minor	minor	
Stö 5 (Spectrum 1)				95,16	4,84											
Stö 5 (Spectrum 2)				95,87	4,13											
Stö 5 (Spectrum 3)				95,18	4,82											
Stö 6 (1st meas. Spectrum 1)				90,3	7,2	2,5										
Stö 6 (Spectrum 1 (ca.)				99		1										
Stö 6 (Spectrum 2 (ca.)				88	10	2										
Stö 6 (Spectrum 3 (ca.)				98		1,5	minor	minor								
Stö 6 (Spectrum 4 (ca.)				98		2		minor								

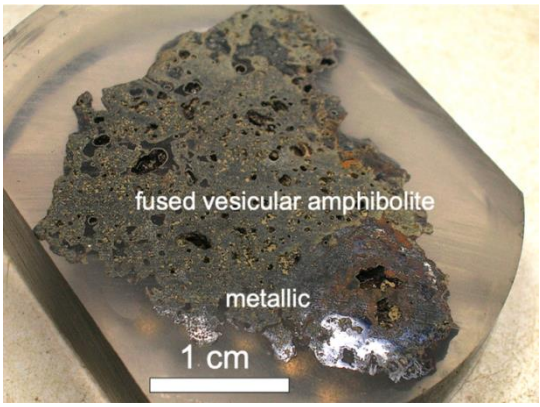

Figure 26. Stö 4: Cut.

All the samples exhibit macroscopically recognizable metallic components. For analyzing these components, four of the samples (Stö 2, 4-6) have so far been investigated by SEM-EDS.

The results for the samples Stö 2 and 4-6 are presented in Table 2. "The fact that the metallic components are mainly of iron with so minimal contaminations excludes them to be unprocessed iron ore and suggests an anthropogenic origin, i.e. some kind of processing. However, in view of the ratio of iron to oxygen, a meteoric origin could also be considered for the Stö 4 and Stö 6 samples, as new studies have shown that pure iron together with similar proportions of oxygen can also be found in meteorites (Pechersky et al., 2015, p. 61; Pechersky et al., 2012: 653). Ultimately, however, the proportion of carbon in the samples suggests an anthropogenic origin not only for Stö 5, but also for Stö 4 and Stö 6. Möslein had suspected that sample Stö 5 is an iron nail that has been baked with gravel (Möslein, 2009)." (Rappenglück et al., 2020b: 337) This interpretation is suggested by the external view of the specimen, from which the presumed nail emerges at the bottom right (see Fig. 17). The EDS analyses support this assumption and indicate that not only this sample but also the samples Stö 4 and 6 are remnants of some iron processing.

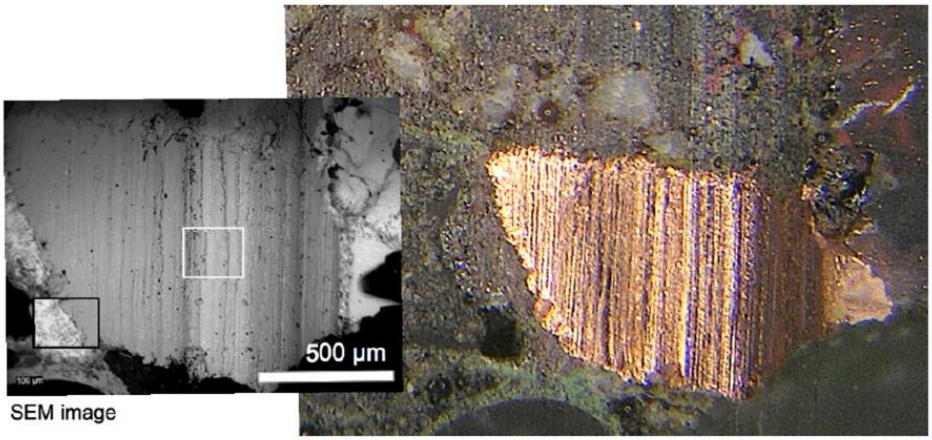

Figure 27. Stö 2: (right) close-up of the ca. 4 x 4 mm metallic particle; (left) SEM image.

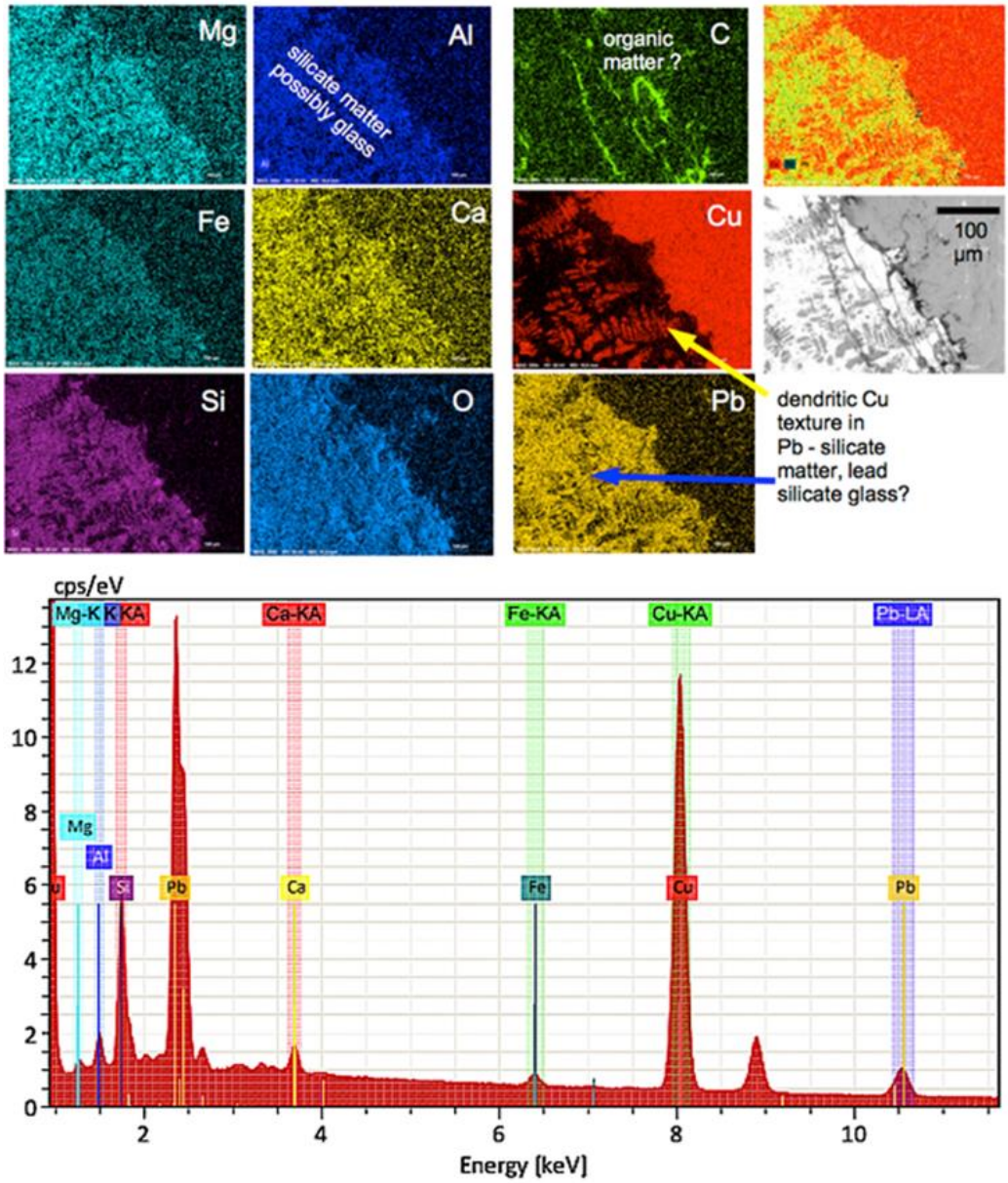

Figure 28. Metallic particle in sample Stö 2: EDS of the contact area with the matrix.

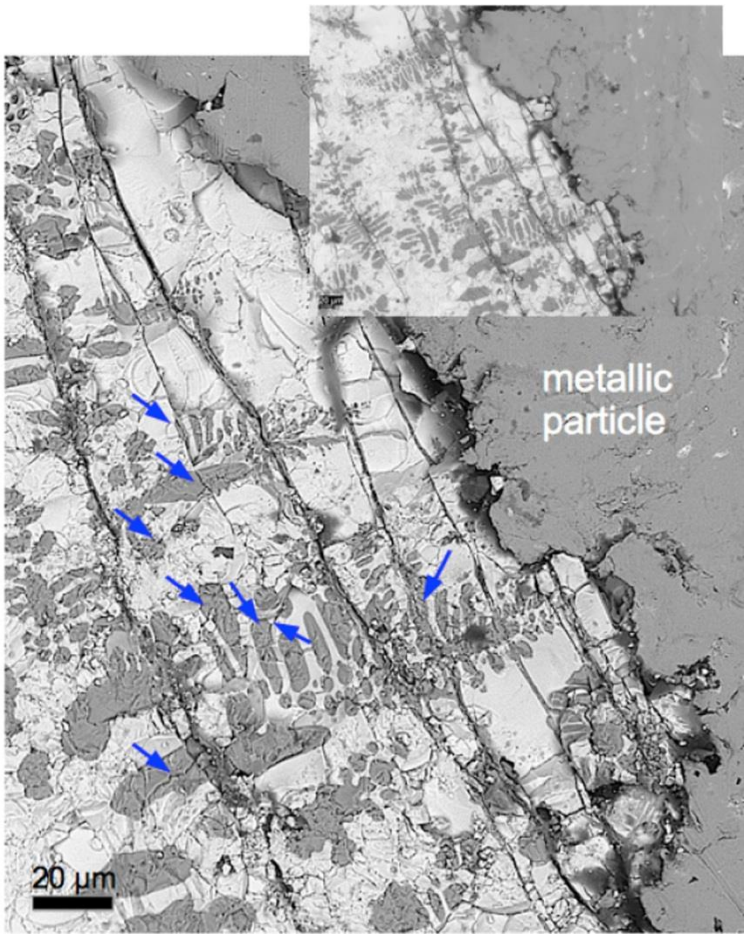

Figure 29. Metallic particle in sample Stö 2: SEM image, close-up of the Pb - silicate matter with dendritic Cu texture. The upper small rectangle corresponds to the black rectangle in Figure 26. Subparallel fracturing and fractures are cutting through the Cu dendrites (blue arrows).

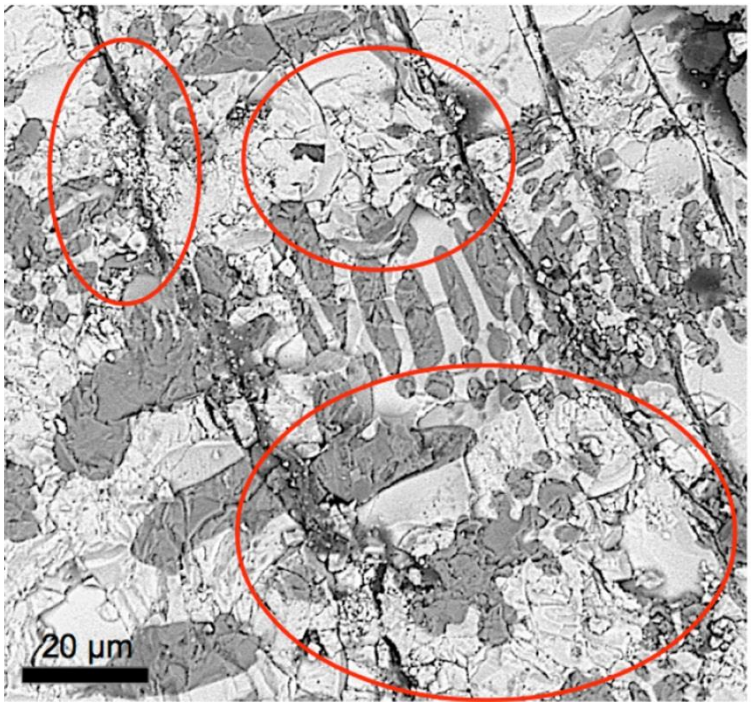

Figure 30. SEM image, close-up of the Pb - silicate matter with dendritic Cu texture. Partly intense fracturing with resulting micro-brecciation (Hippertt et al., 2014, pp. 288–290) is encircled red.

In sample Stö 2 the aforementioned piece of metal measuring approximately 4 x 4 mm was examined (Fig. 27; all results in Table 2). SEM-EDS analysis of the center (white rectangle in Fig. 27) reveals a largely homogeneous mixing of mainly copper and lead. Analyses of the contact area with the matrix (black rectangle in Fig. 27) present a more complex result (Fig. 28): Contrasting with the northeast area of dominantly Cu, the southwest area shows a mixed Pb - silicate distribution, possibly a lead - silicate glass. Dendritic Cu texture can be observed within the Pb – silicate matter. Close-ups reveal subparallel fracturing and fractures cutting through the Cu dendrites (Fig. 29) and partly intense fracturing with resulting microbrecciation (Fig. 30).

The metallic piece under examination being characterized by predominant copper, lead and minor tin admixtures can be excluded to be a natural product but must have originated from human production as an artifact of whatever degree of processing and purpose (Rappenglück, et al., 2020a). When looking for artifacts characterized by a comparable mixture of copper, a considerable amount of lead, and tin, artifacts made of highly leaded copper alloys, known from European Late Bronze Age and Early Iron Age, offer the closest parallel (Rappenglück, et al., 2020a), but it is not yet possible to establish a direct link. In view of the copper content of Stö 2, it offers itself to at least make a comparison with the nearest prehistoric copper mining areas. These were the fahlore deposits in the Inn valley and the chalcopyrite deposits near Salzburg and Kitzbühl (Möslein and Winhart, 2002). Fahlore is concisely characterized by high proportions of antimony, arsenic, silver and bismuth, and the chalcopyrites contain mainly arsenic and nickel as trace elements (Möslein and Winhart, 2002). Of these elements antimony and arsenic were detected in the sample studied, but these are too minor indications, and to trace the provenance encounters considerable methodological problems (Radivojević et al., 2019). Nothing can be said about the origin of the artifact in sample Stö 2 with the methods applied so far, except to note the said parallel.

The sample Stö 2 enables to get an idea of the formation of the suevitic breccia with its metallic components. The observations concerning the texture, made in the contact zone of the metal piece with the surrounding matrix, point to a very complex process, which must have led to the partial separation of the metal components and their mobilization within the silicate rock components and possibly enabled the formation of a kind of lead glass. Obviously, after the copper dendrite implantation, there was still a high-pressure overprint that produced the fractures and possibly also the micro-fracturing marked in Fig. 29 and 30. The complex combination of metallic and stony components in these samples could not have been produced by prehistoric or ancient technology, but required a highest-energy process typical of a meteorite impact. This applies not only for Stö 2, but also for the other samples which all exhibit artificial metallic relicts as components of impactites.

3. DISCUSSION

3.1. Artifacts-in-impactites

At two sites in the area of the Chiemgau Impact artifacts have been discovered as components of impact rocks. At the Mühlbach location, different kinds of artifacts had become part of the diamictite which corresponds to the impact ejecta blanket, at the Stöttham site some kinds of metallic artifacts contribute to the polymictic impact breccia. Human artifacts and impact shock bearing stones are intimately intertwined; they form "artifacts-in-impactites".

Finds of shocked mineral grains, melt glass and presumed cosmic spherules are reported from the context of few archaeological excavations elsewhere (Courty, 1998; Moore et al., 2020), and they are discussed to attest cosmic airbursts. But the occurrence of "artifacts-in-impactites" is to our knowledge so far not known from any other meteorite impact and/or cosmic airburst.

At the Mühlbach location the formation process of the "artifact-in-impactite" can be imagined in a comparatively simple model. Landing ejecta masses excavate and incorporate material of the subsurface (Hoerz et al., 1977). At the Mühlbach artifacts have been taken up and integrated by the ejecta mass of the Tüttensee, resulting in "artifacts-in-impactites".

For the Stöttham site a massive projectile impact in place can be excluded. The stony components, which show shock metamorphism, could have arrived here - as at the Mühlbach - as ejecta of a crater. Here the ca. 3 km distant double crater (900 x 400 m) in Lake Chiemsee comes into question. However, enormous heat must also have been involved on site in order to put the metallic components of the samples into the described state of being. We consider a local, impact-accompanying airburst with hot jet streams. We developed the conceivable scenario in Rappenglück et al. (2020a) as an approximate hypothesis. The described limited geological investigation possibilities during the excavation, the fact that the site is built on today, the fact that the site is located on a slope, which in itself favours uncontrolled mass movements, and the uniqueness of the described finds make a more precise reconstruction of the processes almost impossible at the time being.

3.2. *The finds in the context of the archaeological inventory of the area*

The findings of "artifacts-in-impactites" attest that the Chiemgau meteorite impact and its concomitants affected settlements. The latest artifacts contained in the impactites - the iron artifacts - allow establishing the *terminus post quem* of the event. While very few and small iron artifacts turned up in Central Europe from the early Urnfield culture (Bz D, ca. 1300-1140 BC), in the last period of the Urnfield culture (Ha B3, ca. 900-800 BC) the number of iron artifacts increased sharply (Miketta, 2017). 900 BC can reasonably be assumed to be the *terminus post quem*. The numerous finds from the Urnfield period, and the few ones dating either to the Urnfield or the Hallstatt culture in the excavation of Stöttham, and the sherds in the impact layer at the Mühlbach location, which date either to the Central European Bronze Age or Iron Age, fit easily into this scenario.

This inevitably raises the question of whether a decline in settlement can be observed in the region after 900 BC. As far as the excavation in Stöttham is concerned, there were only very few single finds from the Hallstatt period and none at all from the following Latène period (Möslein, 2009), suggesting a gap in occupation. But how deceptive it can be to draw far-reaching conclusions from apparently missing finds at a single site is shown by the fact that there are quite a number of Hallstatt period finds in the area of the impact, be it single artifacts or burial mounds (Bayerisches Landesamt für Denkmalpflege). On the other hand, their more exact dating into this period of about 400 years is usually not known, as already mentioned above (1.1.). An exception is the site of Nußdorf (either a settlement or a sacrificial site (Hauser, 2011)), where finds testify to a use from about 600 BC. Due to its location (47°54′15″ N, 12°35′9″ E), 4.5 km from Stöttham, 4 km from the shore of Lake Chiemsee and situated at the rim of the largest crater in the crater strewn field, it gives the *terminus ante quem* for the Chiemgau impact (Rappenglück, et al., 2020a). But about the settlement history of the region between 900-600 BC and its possible connection with the meteorite impact no statement can be made on the basis of the available archaeological data.

If we assume that an event like the Chiemgau impact resulted in a decline or even cessation of settlement activity of unknown duration and of unknown territorial extent, pollen diagrams from the region might provide clues. Pollen analyses and radiocarbon dating have been performed on two drill cores pulled from the bottom of Lake Chiemsee (Voigt, 1996). Voigt (1996: 177) concluded that there had been a decline in settlement at Lake Chiemsee in the early Hallstatt period between "cal 810 BC (interpolated)" and "cal 610 BC (interpolated)", and she also mentioned that archaeological relicts of the Hallstatt period are found in a distance of at least 3 km to the lake shore. This seems to fit the lack of occupation at Stöttham and the finds at Nußdorf. However, here again caution is required: 1. It is not clear which region (immediate Chiemsee shore, areas 5 km, 10 km or even more away?) Voigt actually considers when she tries to reconstruct the settlement history. 2. One of the drill cores had collapsed just at the depth of Neolithic time and above (Voigt, 1996) and was not usable for the periods of interest here. 3. Both cores carried sparse datable organic material so that only 6 datings could be obtained from a total of 14 m of core length (Voigt, 1996). Furthermore, the pollen diagram from Lake Chiemsee could not be correlated (Voigt, 1996) with another one established in the 1960s (Schmeidl and Kossack, 1967/68) from the Rottauer Filzen, a moorland area immediately south of Lake Chiemsee. The two previously mentioned (section 2.1.1.) drillings at the northern shore of Lake Tüttensee were, as described, unsuitable to disprove the impact. Furthermore, the first drill core could give just as little information about the settlement history, since the uppermost 50 cm encountered decomposed peat. The most recent dating of this core at a depth of 60 cm is 4580-4420 BP (Doppler et al., 2011), i.e. much older than the period under discussion here. The second core (Rösch et al., 2021), however, interestingly shows periods when higher percentages of *Betula* pollen and of other pioneers indicate land use interruption and reforestation (Rösch et al., 2021). Two such peaks occurred around 900 and 720 BC, probably indicating only local changes. This result reinforces our pronounced reluctance to speculate about extended and long-standing catastrophic effects of the Chiemgau impact on settlement history. We have detailed the methodological problems that stand in the way of such speculation elsewhere (Rappenglück, et al., 2021).

Despite unique finds and comparably good dating, the serious methodological problems (Rappenglück, et al., 2021) to be overcome in assessing the effects of prehistoric meteorite impacts on settlement activity and other cultural expressions have not been solved as yet. The only cultural effect presumed so far is the processing of the experience of this monstrous event into a myth: the Greco-Roman myth of Phaethon crashing with the Sun-charriot might reflect the Chiemgau meteorite impact event (Rappenglück and Rappenglück 2009; Rappenglück et al., 2010).

3.3. *The finds in the context of previous radiometric dating*

Determining the *terminus post quem* for the Chiemgau impact on the basis of the iron artifacts in

the investigated samples resulted in ca. 900 BC, but in view of the clear presence of iron, actually even a somewhat younger date might be considered. This is in tension with both the OSL dating of the corresponding layer determined by Völkel et al. (Völkel et al., 2012, p. 375) (7.4 +/- 0.4 ka; 3.7 +/- 0.8 ka; 3.0 +/- 0.2 ka) and that of Liritzis et al. (Liritzis et al., 2010, p. 22) (1130 +/- 370 BC [bOSL: 1120 +/- 300]). Liritzis et al. (Liritzis et al., 2010, pp. 29–30) had already mooted that the OSL dates might have yielded an age that was somewhat too high. They had pondered what this might mean for OSL dating of impact rocks. The results presented here confirm that this caution was appropriate and may stimulate further research into this problem.

4. CONCLUSIONS

The Chiemgau meteorite impact in southeastern Germany has been confirmed according to impact diagnostic criteria with evidence of shock metamorphism. Numerous further research in the disciplines of geophysics, petrography and mineralogy have yielded much detailed knowledge about the impact, its accompanying circumstances and its effects. That this impact, one of the largest of the Holocene, was experienced by people in the Late Bronze Age/Early Iron Age (900-600 BC) is evident at two sites. A catastrophic layer bearing explicit traces of the meteorite impact was found as part of the archaeological stratigraphy during the excavation of a settlement. The application of petrographic and mineralogical methods led to the discovery of prehistoric metallic artifacts in impact rocks. These finds represent a previously unknown type of impact rock, an artifact-in-impactite. At another site, sherds were found, also as part of an impact rock. They indicate, as geophysical investigations additionally suggest, that also here a settlement was affected by the catastrophe. Due to serious methodological problems to evaluate the cultural effects of a prehistoric meteorite impact, no well-founded statement can be made so far about conceivable consequences regarding the occupation history of the affected region nor of regions even beyond that. Nevertheless, these two Late Bronze Age/Early Iron Age sites with the described finds are exceptional evidence for human settlements affected by a meteorite impact.

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