UDC 550.83; 551.3; 551.794; 552.5: 523.681.8

Václav PROCHÁZKA[1*], Petr MARTINEC[2], Pavel KALENDA[3], Lenka THINOVÁ[1], Kamil SOUČEK[2], Richard ŠTORC[4], Jan ADÁMEK[5], Jiří MIZERA[6], Tomáš TROJEK[1], Günther KLETETSCHKA[4, 7]

[1] Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, Břehová, 7, Praha 1, 11519, Czech Republic, e-mail: vaclav.prochazka@fjfi.cvut.cz, lenka.thinova@fjfi.cvut.cz, tomas.trojek@fjfi.cvut.cz, https://orcid.org/ 0000-0003-4320-7266, https://orcid.org/0000-0001-8277-1121, https://orcid.org/0000-0002-2136-4503
[2] Institute of Geonics, Czech Academy of Sciences, Studentská, 1768, Ostrava-Poruba, 70800, Czech Republic, e-mail: martinec@ugn.cas.cz, https://orcid.org/0009-0000-5084-6053
[3] CoalExp, Pražmo 129, 73904, Czech Republic, e-mail: pkalenda@volny.cz, https://orcid.org/0000-0003-4351-9593
[4] Institute of Hydrogeology, Engineering Geology and Applied Geophysics, Faculty of Science, Charles University, Prague 12843, Czech Republic, e-mail: gunther.kletetschka@natur.cuni.cz, https://orcid.org/0000-0002-0645-9037
[5] Czech Technical University in Prague, Faculty of Nuclear Sciences and Physical Engineering, Trojanova, 13, Praha, 2, 12003, Czech Republic
[6] Nuclear Physics Institute, Czech Academy of Sciences, Husinec-Řež 130, 25068, Czech Republic, e-mail: mizera@ujf.cas.cz, https://orcid.org/0000-0002-8926-6213
[7] Geophysical Institute, University of Alaska – Fairbanks, AK 99709 Fairbanks 903, N Koyukuk Drive, AK, USA, e-mail: gunther.kletetschka@natur.cuni.cz, https://orcid.org/0000-0002-0645-9037

https://doi.org/10.23939/jgd2025.01.005

TWO HOLOCENE IMPACT CRATERS AT EMMERTING, GERMANY. DEFORMATION, FRACTURING, AND THEIR RELATIONSHIPS TO THE MELTING AND DECARBONIZATION

In two craters near Emmerting, three major processes which variably affected the original pebbles are documented in the following order: 1. Deposition of hot material which solidified to glass (usually thin and transparent) or reacted with carbonate to form expanded “pumice” on the surface of pebbles. 2. Ductile deformation of variable intensity (with limited fragile deformation but intense fracturing of mineral grains), using older as well as newly formed discontinuities; in some cases this deformation had to be associated with extreme strain, excluding interpretation of the crater formation by any plausible human activity. The largely ductile character of deformation points to a high temperature, but it was not necessarily accompanied by melting. 3. Solidification of melts generated within pebbles or derived from secondary projectiles. These disequilibrium melts were hot enough to have very low viscosity (in some cases, they may have also been injected by high pressure / strain, or sucked in), which enabled them to fill even thin fractures in individual mineral grains; gas expansion also formed extrusions resembling miniature volcanic features on the surface of some pebbles. In one zircon grain baddeleyite was observed, probably formed by shock metamorphism. However, no additional evidence was found to suggest pressures exceeding the threshold typically required for shock-induced melting (~8 GPa or more). Nevertheless, the energy transformed during repeated mutual collisions may have heated the interior of pebbles sufficiently. Origin of the depression at Grabenstätt – Kaltenbach is unclear, the disequilibrium melting and decarbonization may also be explained by anthropogenic processes.

Key words: holocene craters, impact, Emmerting, deformation, fracturing, injections.

Introduction

In this contribution we present mainly the in-situ deformation and its relation to disequilibrium melting in the pebbles from three sites in eastern Bavaria, Germany: two craters at Emmerting and one similar depression at Grabenstätt-Kaltenbach. The sites were investigated mainly by Rösler et al. [2006], Fehr et al. [2005], Ernstson et al. [2010], and Neumair et al. [2016]. In previous contribution [Kalenda et al., 2024], we presented field observations and field geophysical data (completed with laboratory gamma-ray spectrometry and some laboratory magnetometric results). These results, especially the presence of a compact body below the bottom of Crater No. 4 (already suggested by Rösler et al. [2006] are consistent with impact origin of the craters, which is evidenced mainly by findings of meteoritic matter (preliminary presented by Procházka [2023]).

Here we demonstrate that in-situ thermal- and pressure / deformation effects in the rocks are difficult to explain unless a catastrophic event like impact took place. The craters developed in unconsolidated Quarternary terraces formed mainly by coarse pebbles and cobbles. Criteria for shock metamorphism in such target material have not been established yet.

Material and methods

In 2015, we collected ca. 25 pebbles or their large fragments in the Kaltenbach depression and at least 30 pebbles in Crater No. 4 at Emmerting (see also Table 1 in Kalenda et al. [2024]). Samples were taken from shallow, decimeter depths from soil within the craters. Exact sample positions could not be determined due to repeated prior excavation at the site. Nevertheless, the presence of soil-filled fractures and root penetration shows that the pebbles have not been introduced recently. In 2016, we collected dozens of samples in profiles in Crater No. 4. We had to break off a few of them from the glass-rich area near the crater floor (which may represent a transition to the compact layer indicated geophysically). No correlation was observed between thermal or deformation effects and sample position within the profiles. Nevertheless, numbers of samples referring to their position in profiles are preserved, e. g. 4/1/–3 means: Crater No. 4 / Profile 1 / –3 m. In addition, samples 5/1/0 (a, b) were collected from the center of Crater No. 5 (position 0 m in Profile No. 1).

After soft cleaning from recent soil and macroscopic photo documentation, magnetic susceptibility of bulk samples from Crater No. 4 and Kaltenbach was measured (see also Procházka and Kletetschka, 2016, Kalenda et al., 2024). A binocular stereomicroscope was used for observation of the surface of original samples or sections, and photographs using one optical pathway were made. Selected samples were partly cut and investigated in sections. For both original surfaces (especially thin glass layers) and sections also XRF-analyses and spatial mapping of elements were performed. Thin-sections and polished sections from selected samples were investigated with petrographic microscope and scanning electron microscope (SEM). SEM included back-scattered electron (BSE) and secondary electron (SE) imaging and electron micro-probe analyses.

Computer tomography (CT) was performed in the Institute of Geonics, Ostrava, with the X-ray computer tomograph Nikon XTH 225 ST. Software *CT Pro 3D* was used for reconstruction of CT data (set of the radiographic images). CT volume and tomographic slices were evaluated by the *VGStudio Max* software (versions 2.2 and 3.3.2).

Bulk soil, small pebbles (usually 1–3 cm in size) and fine fractions of soil/sediment from Crater No. 4 were also investigated to assess material balance and potential meteoritic contamination. Most results will be presented in a separate publication. Here we only compare minerals in deformed and partially molten pebbles with isolate grains of the same minerals in the finer filling fractions.

Results

Fracturing and deformation of rocks

Deformation of pebbles, which must have proceeded after their transport to the present site, is observed mainly in the Crater No. 4. Open fractures are characteristic mainly for silicate pebbles from Crater No. 4 (Fig. 1). Their formation was often accompanied by extreme ductile strain, as evidenced by stretched bridges spanning the fractures (Figs. 1, 2). Only one sample (No. 422) exhibited such deformation without any melting inside of the rock (Fig. 2). In other cases, samples were more- or less melted (Figs. 1, 3, 4). Fractures are often partly or fully infilled with meltglass. Importantly, this does not hold for thin transparent glass coatings which do not cover the walls of young fractures.

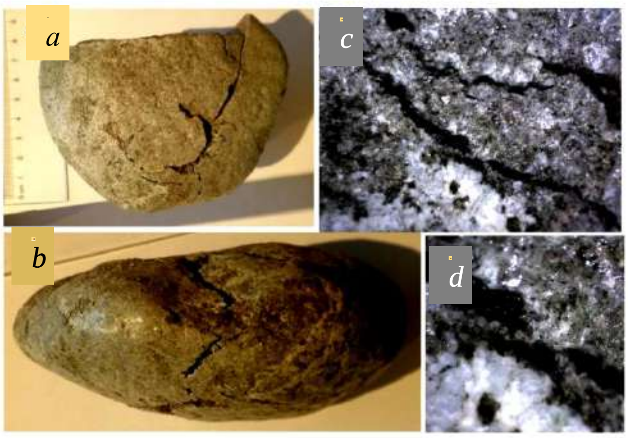

Fig. 1. A part of a fractured and deformed pebble with thin glass coating (sandstone, Crater No. 4, No. 415):

a – a view from the probable original upper side with glass; part of the original pebble (top) was broken-off along an older crack (with limonite) after the strike; b – a view from the narrow side; c – two skew bridges formed by extension of a fracture (image 12×16 mm); d – a detail of c.

The highly fractured and deformed sample No. 422 (Fig. 2) was also investigated with CT. Results indicate little distinctive orientation of mineral grains askew to the pebble's long axis. The open fissures formed perpendicularly to the propagation of pressure shock wave after the compression ceased and correspond to failure by tensile stress.

Fissures at the end which was partly broken off reach to the surface and are more opened than those at the opposite end. The fractures in two dominant directions may have formed by combination of the incident shock wave and waves reflected from the opposite surface (Fig. 2, *d*). The morphology and spatial arrangement of fractures resemble rocks after an explosively driven dynamic tensile test.

Melting inside of pebbles and cobbles

The typical partially molten rocks are quartz-rich (mainly quartzites to gneisses) (Figs. 4, 5). Inside of carbonate pebbles, the mineral composition has not significantly changed during the crater-forming process. In contrast, the basic or mafic rocks often underwent very intense to complete melting (Fig. 6, *a*).

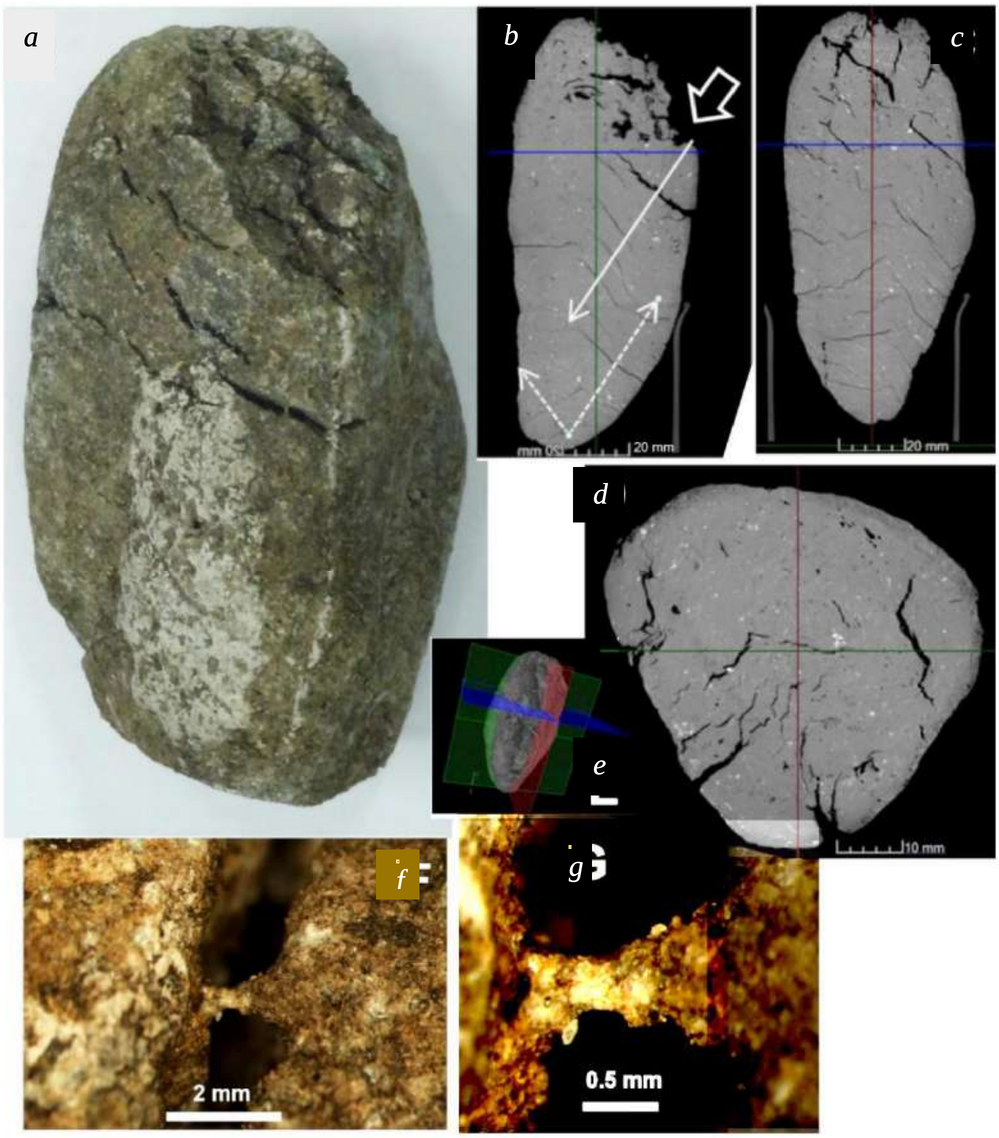

Fig. 2. A fractured pebble (Crater No. 4, No. 422) of quartzitic or granitic rock with stretched bridges in open fractures:

a – overview; note that no movement along fractures can be observed. Sample length 12 cm; b–e – CT of the pebble in three perpendicular sections and scheme of the sections. Regular fractures are distinctive especially in the longitudinal sections. The upper arrow marks the direction of incident pressure, the bottom dashed ones mark the pressure waves reflected from the pebble's surface; f, g – details of a bridge crossing an open fracture; it is formed by unmolten quartz and other minerals like the surrounding rock.

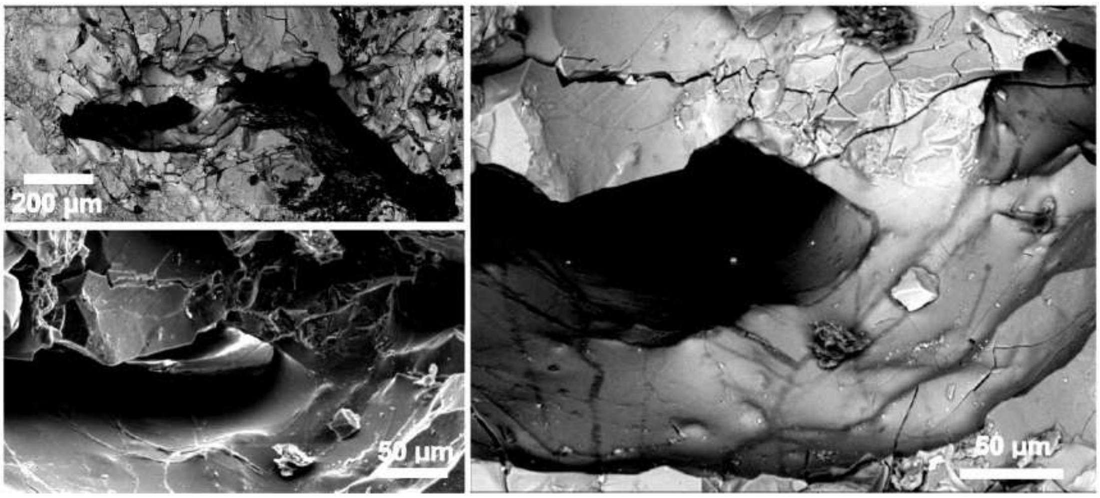

Fig. 3. A stretched bridge in a *K*-feldspar rich rock (Crater No. 4, granitic / syenitic? rock, No. 16133). Left top: overview in BSE (the irregular dark stainings are from a pencil), left bottom: detail in SE, right: detail in BSE (slightly darker quartz veinlets in the glass of *K*-feldspar composition).

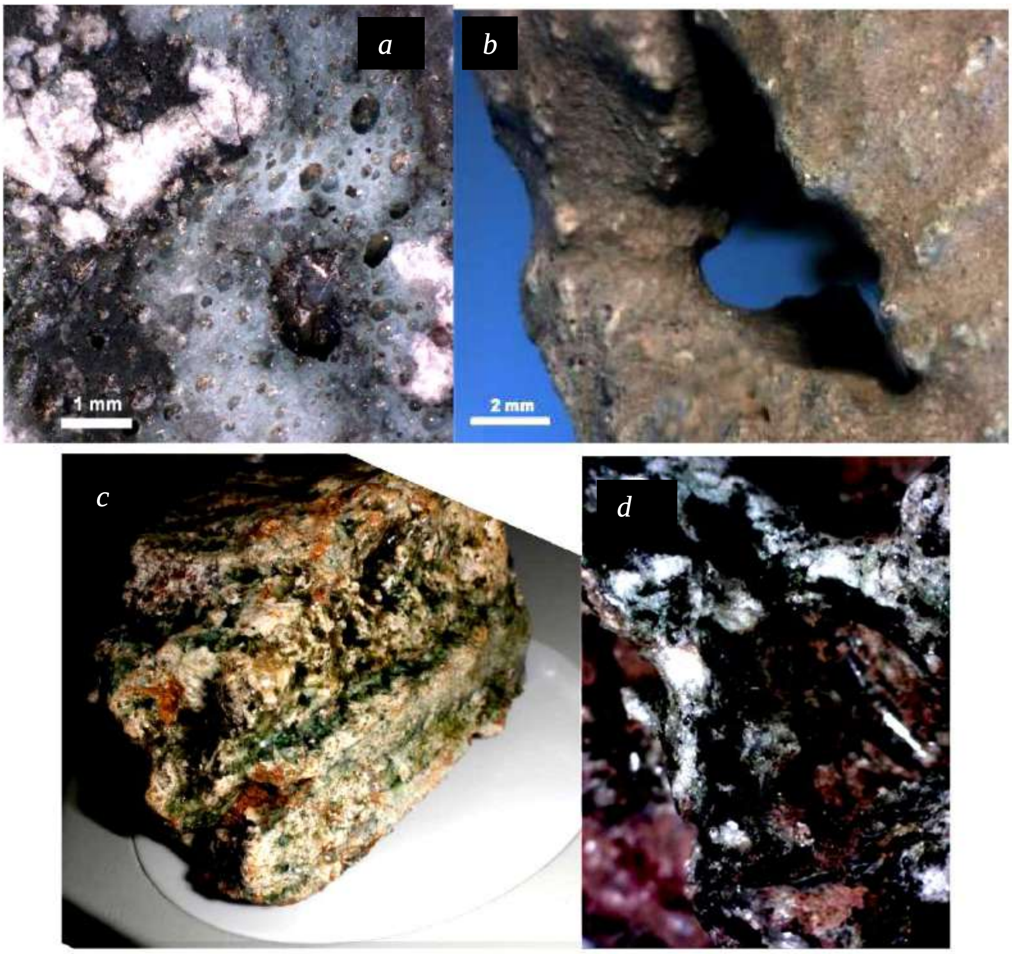

Fig. 4. Examples of moderate deformation of stones affected by melting:

a – “folding” of blue-green porous melt (chemically corresponding to biotite); also sharp boundaries of white quartz and green / black melt with no mutual reactions are visible (Crater No. 4, No. 407); b – a “window“ formed in molten and deformed rock with relics of quartz crystals (Crater No. 5, No. 5/1/0a); c – ductile deformation of glass and probably of the unmolten stone surface too (orthogneiss, Kaltenbach; diameter of the white circle is 10 cm); d – detail of the surface deformation shown in c) (image 12×16 mm).

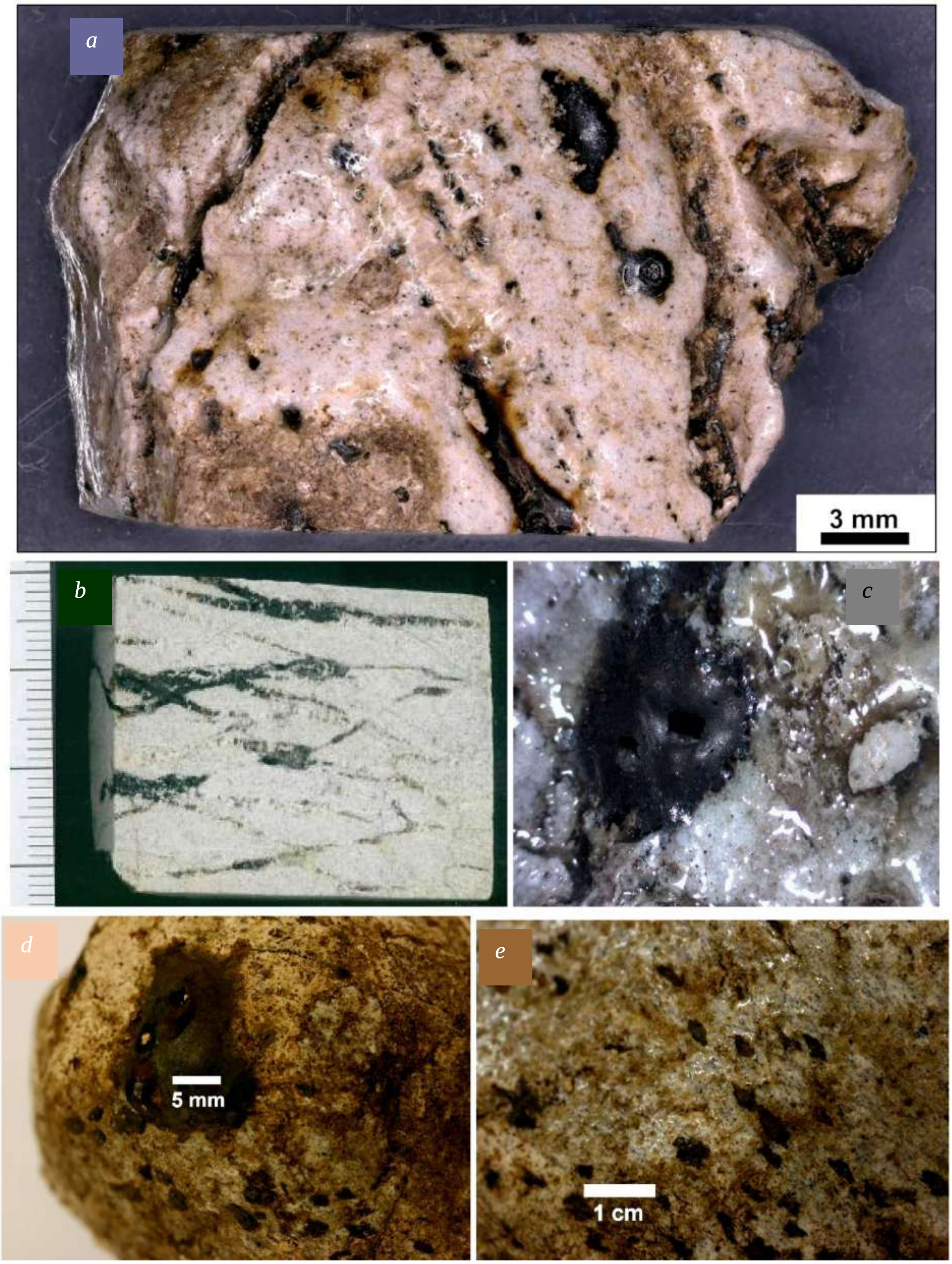

Fig. 5. Extrusions of dark melt from impure quartzites
(a–c – crater No. 4, No. 421; d–e – crater No. 5, No. 5/1/0a):

a – parallel extrusions, perhaps oriented along original foliation; b – dark melt veinlets and white tectonic quartz veinlets in unpolished section; c – detail of the surface formed by colorless and yellow glass with abundant bubbles (image width 16 mm); d – the largest extrusion on the cobble's surface; e – smaller pieces of dark melt, on the pebble's surface with thin transparent glass.

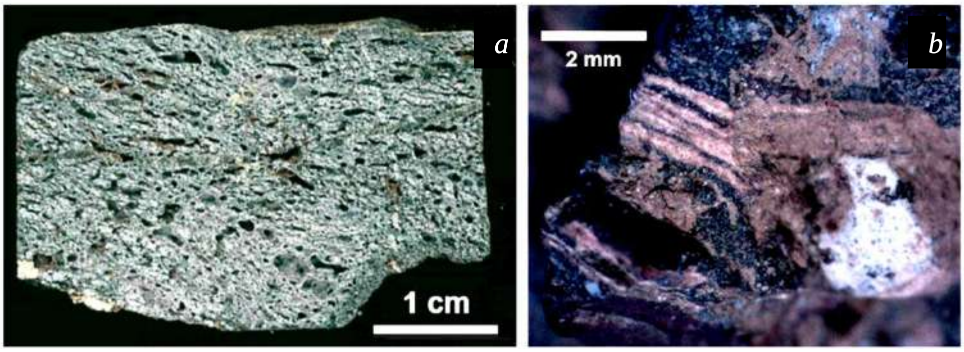

Fig. 6. Melting-affected natural rocks partly similar to metallurgic slags:

a – almost completely melted and expanded basic rock (Crater No. 4, No. 419); note the quartz (?) veinlet crossing the whole specimen on the right which is partly disturbed by the expansion; b – preserved relics of layering of the original sedimentary rock (Kaltenbach, No. 124).

Black melt forms extrusions on the surface of a quartzite pebble (No. 421) from Crater No. 4 (Fig. 5, *a*–*c*). Similar extrusions are also observed on an originally micaceous quartzite pebble (No. 5/1/0a, Crater No. 5): dark porous melt, which resembles miniature volcanoes, or is flat and seemingly similar to lichen, was expelled from veinlets (Fig. 5, *d, e*). The transparent glass coatings never cover the porous dark melt (including the melt attributed to secondary projectiles). It follows that the mafic melts were still very hot (or even not yet covered the surface of pebbles) when the thin, usually colorless glass coatings were already solidifying after they had been deposited. This interpretation is also supported by the chemical composition of the glass coatings, which is probably strongly influenced by biomass but almost unrelated to chemical composition of the pebble’s rock (see also Procházka and Trojek, 2017).

The quartzite sample No. 421 exemplifies pr-olonged exposure to elevated temperatures (probably due to a high amount of melt at the crater floor), enabling crystallization of various minerals from the melt (e. g., skeletal magnetite, various forms of clinopyroxene and tridymite), which does not contradict quick and disequilibrium melting. Also pebbles welded by melt, without significant mutual deformation, were found at the crater floor.

In the Kaltenbach structure only three partially molten samples were found. The surface of the sample No. 123 with relatively thick glass in some places does show some deformation during or after melting (Fig. 4, *c*, *d*); inside of the pebble, however, significant deformation is uncertain, except for expansion of water vapor liberated mainly from micas. Nevertheless, interesting glass-filled fractures were observed in this sample (Fig. 7).

Stones seemingly similar to slags occur, however, they have preserved original calcite or quartz veinlets from the rock, and even original layering (Fig. 6). Their composition (e. g., low Mn content) is also incomparable to slags from old iron metallurgy [Piatak and Ettler, 2021; Strassburger and Wieser, 2014].

Melt injections and secondary projectiles

Melt intrusions from external sources into pebbles were observed in Crater No. 4. In the sample No. 16132, the original quartzite was contaminated by dark basic melt which not only forms part of the surface but also intruded into open fractures (Fig. 8). Some of these fractures were formed or at least expanded due to high strain prior to the melt intrusion, and stretched bridges can be observed again. As a result, there are abundant planar cavities in two directions, one probably corresponding to foliation; they intersect older tectonic quartz veinlets. The same sample is coated in places with thin transparent glass which, however, never covers the dark melt.

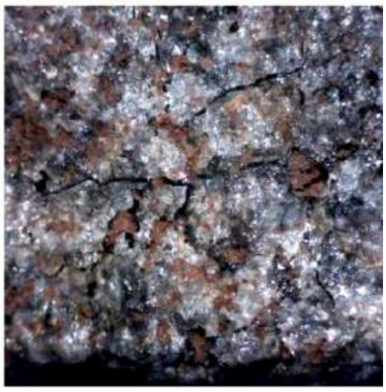

Fig. 7. Relatively thin fractures filled with glass (orthogneiss, Kaltenbach, No. 123; see also Fig. 4, *c*) at the sheltered side which lacks any significant glass coating; surface depressions are filled with soil (image width 8 mm).

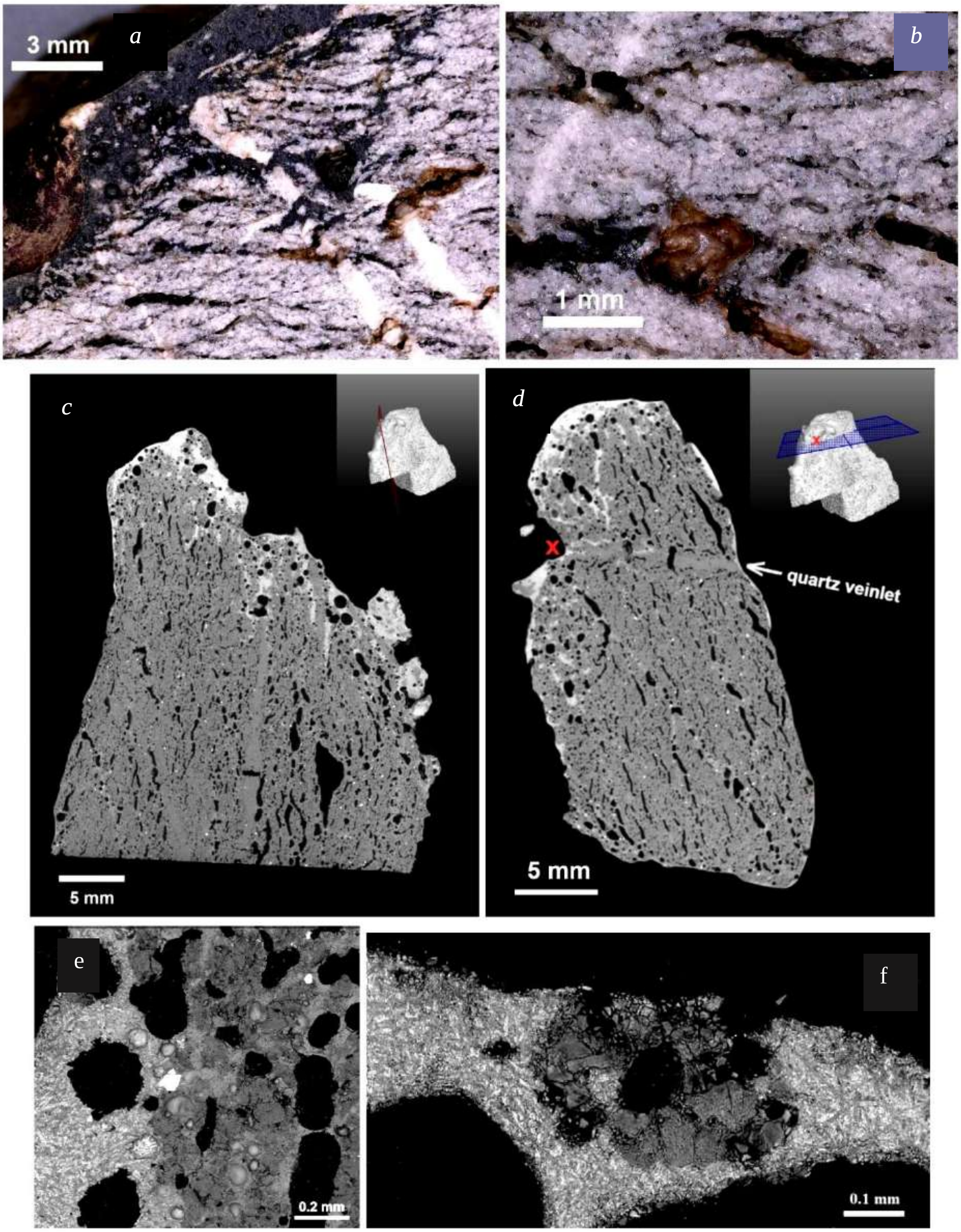

Fig. 8.

Injection of dark melt into a quartzite pebble (No. 16132) (a); isolated quartz remnants in the dark melt are visible; abundant bridges crossing open fractures (see one obviously stretched in the upper left) (b); CT shows injection of the basic melt (bright); note the relatively undisturbed quartz veinlets which partly act as barriers (c, d); BSE image: the basic melt (bright – on the left) with sharp boundary with the original rock (with prevailing gray quartz, somewhat brighter glass, and bright zircon); the melt layer also contains isometric cavities partly filled with crystals (e); (BSE) Crushed quartz (gray) enclosed in the basic melt on the pebble rim (see also bubbles in the bottom); melt with bright columnar crystals (clinopyroxene etc.) surrounds the quartz (f).

Out of probable original rock-forming minerals in the secondary projectiles, only an Fe-Mg-Ti oxide (probably Mg-rich titanomagnetite) was identified; it is also heavily crushed and has complicated spatial relations to the melt. Note that basic rocks, likely altered and hydrated by weathering, may have undergone nearly complete melting, whereas melting of quartz would require much higher temperature (due to insufficient time for eutectic reactions). For the melt injections into individual mineral grains see below.

Secondary projectiles whose impact has not led to significant injections of melt were also observed in Crater No. 4. These projectiles strongly deformed the partially molten surface (Fig. 9), and may have even significantly deformed smaller pebbles (Fig. 10).

Evaporation

Expansion of micas or chlorite due to water vapor release is observed in many other pebbles from all three sites. Evidence for evaporation of silicates was observed in Crater No. 4. The sample No. 4/2/–1b (originally perhaps granitic or dioritic rock) is very strongly expanded, with a mass less than 600 g despite a size of approximatey 8–13 cm (Fig. 10). It also displays significant strain and deformation, possibly due to impact of a secondary projectile.

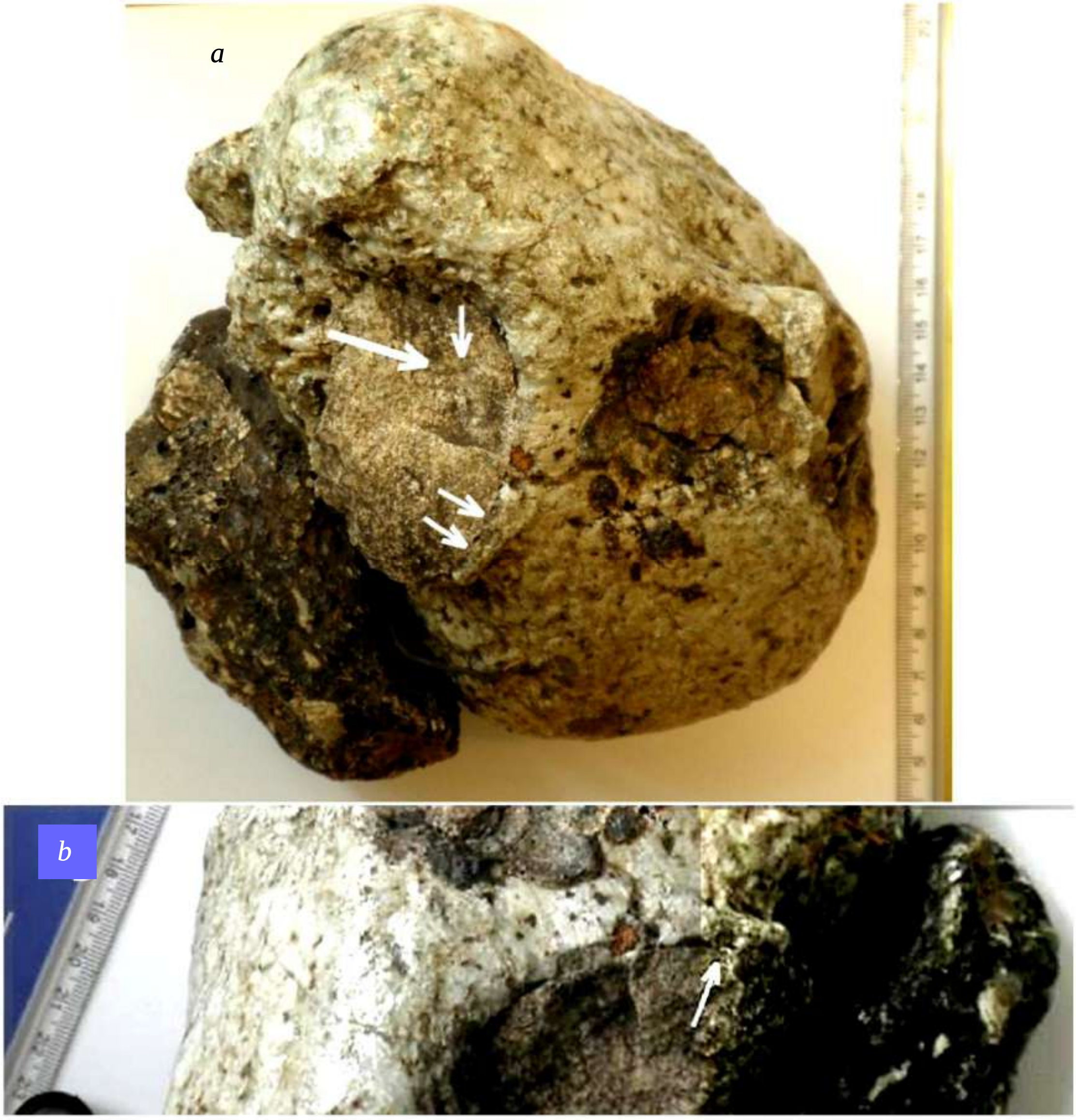

Fig. 9.

Partially molten silicate cobble (No. 4/2/1/a1), "welded" with a gneiss pebble (rich in dark melt) on the left, and hit by a secondary projectile (calcareous sandstone?). Note the pushing away of the partially molten surface by the projectile (two small arrows), and the furrows behind the projectile (large and one small arrow) (a); view from another side: rolling up of the partially molten surface by the secondary projectile (arrow) (b).

Processes at the level of single mineral grains

Quartz and some accessory minerals, mainly zircon and less frequently monazite, rutile, and rarely xenotime are the primary minerals preserved in glasses in various partially melted samples. In the unmelted but injected or glass-coated samples, also primary albite, micas, and rarely apatite were found. Very intense but rather irregular fracturing of quartz is common. Primary cristobalite, i. e. scale-like cristobalite which forms by long-term high-temperature solid phase transformation of quartz (see also Bartuška, [2001]) was not observed.

The remarkably deformed (possibly partly mylonitic) sample No. 422 (Fig 2), containing mainly quartz and albite, shows no melting (the thin surface glass has an external source); the only possible thermally induced mineral transformations are decomposition of chlorite (which is relatively opaque) and dehydration of limonite, which perhaps formed opaque rims at some grain boundaries. Strong fracturing of both quartz and albite is observed, including some planar fractures in quartz and highly intense cleavage of albite (Fig. 11). These features have not proved shock metamorphism yet, nevertheless, intense impact-induced fracturing is common at pressures lower than necessary for diagnostic shock effects, like the planar deformation features (PDF) [French, 1998].

Within some zircon grains baddeleyite (ZrO_2) associated with glass was found (Fig. 12). Such baddeleyite can be a high-temperature product of zircon decomposition, which would have to be caused by shock wave because in case of external heating, baddeleyite would form an outer rim of zircon first. The temperature of the zircon-to-baddeleyite transition in long-lasting industrial processes is about 1550 °C [Bartuška et al., 2001]; however, for shock metamorphism, temperatures up to 1800 °C are reported [French, 1998]. The glass associated with the baddeleyite found is not pure silica, which would result from a simple decomposition of zircon (unless the zircon was heavily metamictized and altered), but it has high content of Al_2O_3, CaO and FeO, and significant admixtures of alkalis and MgO. Therefore, the zircon decomposition may have been promoted (or the reverse reaction of baddeleyite to zircon prevented) by an inclusion of other mineral which subsequently reacted with the silica liberated. Some melt or fluid injected into fractures (see below) may have also played a role. An alternative explanation to the shock decomposition of zircon, i. e. a detrital baddeleyite in the sedimentary protolith of the present quartzite which would react with silica to form zircon, is highly improbable due to tiny size and complicated morphology (i. e., relatively high surface) of the baddeleyite grains.

Feldspars and micas were frequently completely melted in Crater No. 4 samples, forming mostly glasses of mixed composition where microscopic minerals commonly crystallized from melt (mainly magnetite in the dark-mica derived glasses).

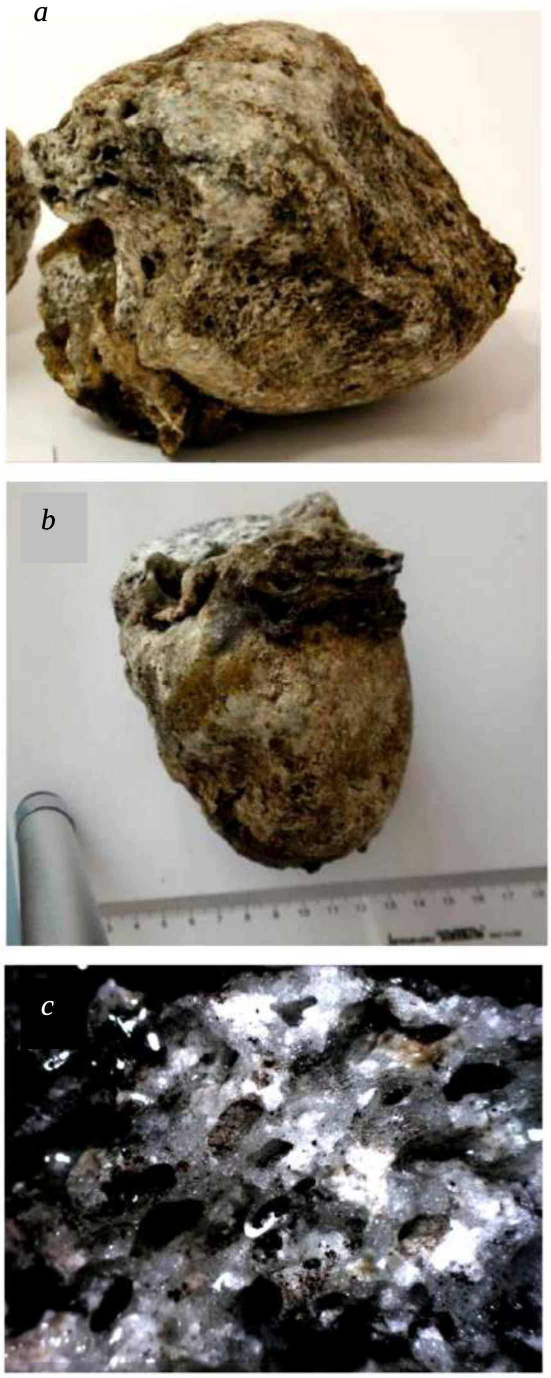

Fig. 10. Strongly expanded pebble (No. 4/2/–1):

a, b – general view; see also the dark melt which is strongly deformed – possibly a secondary projectile: in *a* in the left bottom, in *b* in the top; c – original surface (relatively thin split on black background, 12×16 mm).

Examples of glass derived from a single mineral are the glass pseudomorphs after *K*-feldspar (with abundant bubbles) and after albite exsolutions in the sample No. 16133 (Fig. 3, 13). In the sample No. 16133, the original *K*-feldspar had been penetrated by quartz veinlets which have been preserved without any reaction with the feldspathic melt (solidified to glass) (Fig. 3, 13).

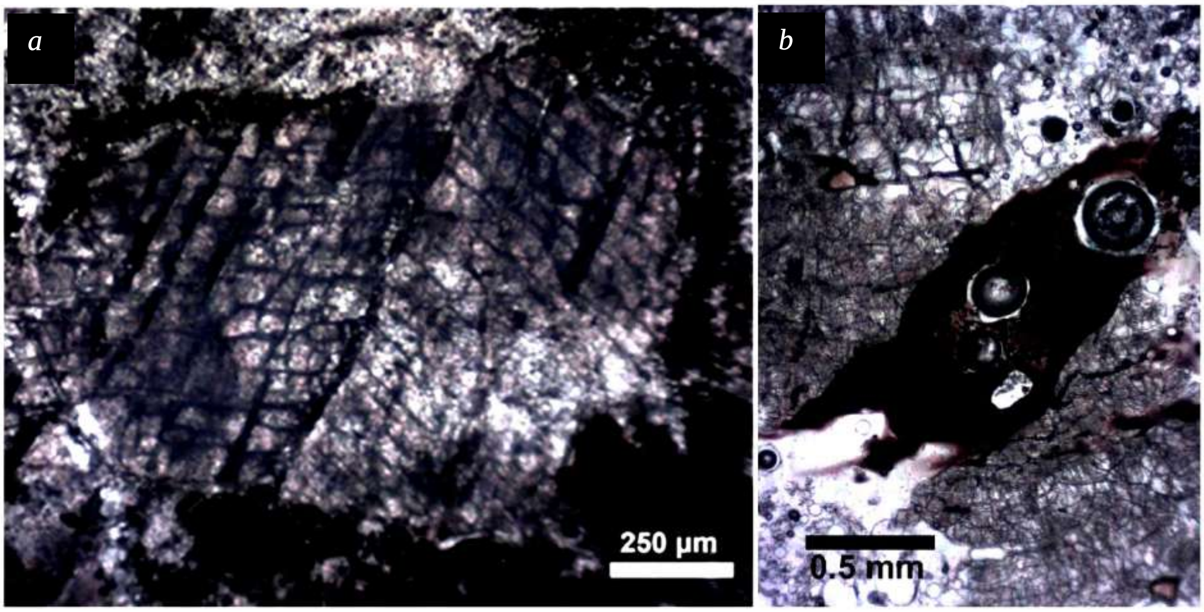

Fig. 11. Fracturing in transmitted light, Crater No. 4:

a – intensely cleaved albite (No. 422); b – abundant post-tectonic fractures in quartz veinlet, interstected by a dark porous glass veinlet (with black magnetite dendrites surrounded by translucent, Fe-depleted glass) (No. 421).

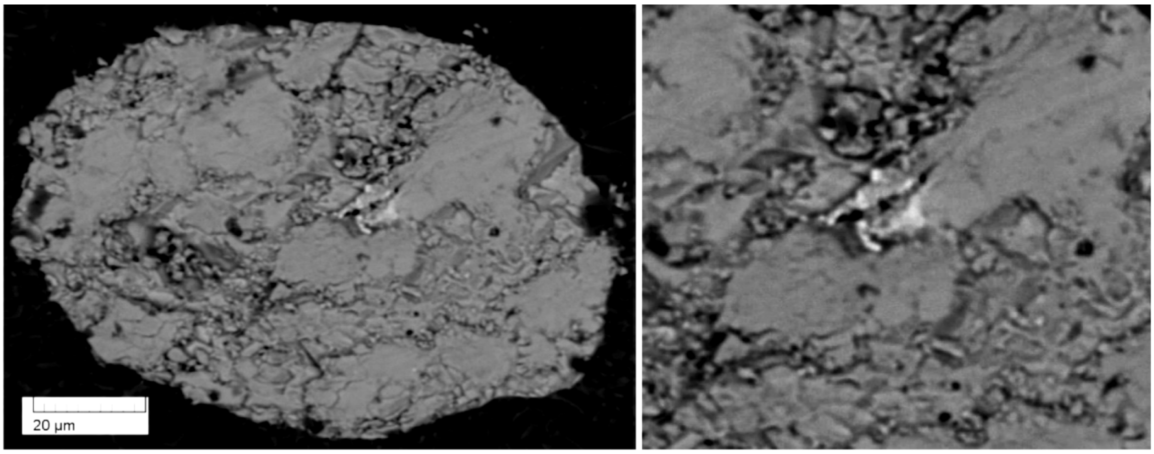

Fig. 12. Zircon with inclusions of baddeleyite (brighter) associated with Zr-poor silicate glass (darker), both on the right from the center. Crater No. 4 (No. 16132), BSE image (detail on the right).

Melt (regardless to its origin) also penetrated into fractures in individual mineral grains, mainly quartz and zircon, and solidified as a glass there (Figs. 14–16). The injections into fractured crystals were observed in both craters No. 4 and No. 5. It follows that the melt in several samples must have had very low viscosity due to high temperature, or was pushed by high pressure / strain (or alternatively, sucked-in during expansion of the just compressed rock), or both. Note that in the sample 5/1/0a, the melt could not be injected from any source outside of the cobble (instead, melt extrusions are observed).

In the fine-grained crater filling, the disturbance of zircon and monazite is minimal (Fig. 17). This can be explained by two causes: 1. minerals not included in a rock pebble or cobble could more easily escape the pressure waves, 2. some portion of the crater filling has been deposited only after the crater formation.

Surface glasses

Thin, usually transparent or greenish glass coating of large domains of individual cobbles and pebbles larger than ca. 4 cm is typical for both craters at Emmerting. At Kaltenbach, the green glass covering the partially melted orthogneiss (Fig. 4, *c*, *d*) is relatively thick and likely related to the bands of green glass (former phyllosilicates) inside. The sample No. 15240 (quartzite with biotite, Crater No. 4) is an example of pebble with some fracturing, insignificant deformation, no melting inside, but with a thin glass coating (transparent, green-yellow). Neither significant reaction of the melt (glass) with mineral grains, nor thermally induced fracturing of quartz was observed (Fig. 18, *a*). Two glass layers were identified (Fig. 18, *b*) but with a similar chemical composition. The glass sometimes covers old weathered or even moss / lichen-covered surface. It follows that the glass-forming "external" material reacted with the pebble surfaces minimally.

Note that in places thin glass also covers vein quartz (which again supports external origin of the glass, unless temperature 1700 °C was exceeded).

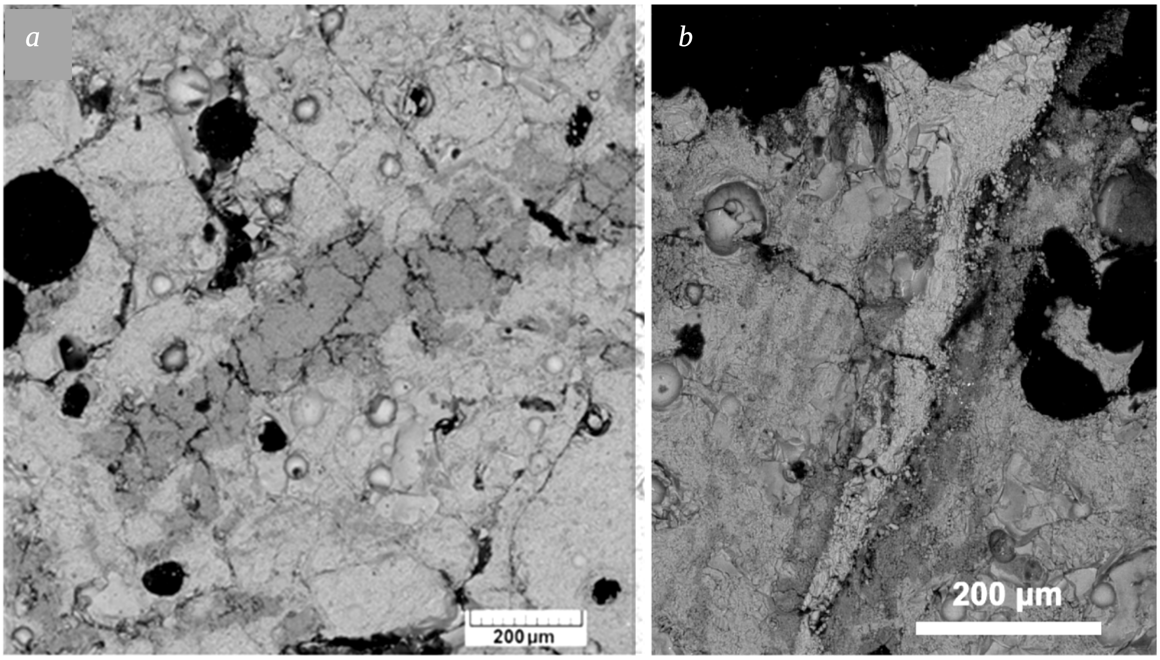

Fig. 13. Glasses of pure feldspar composition, Crater No. 4 (No. 16133, BSE images):

a – quartz veinlet (medium grey) in a glass pseudomorph after *K*-feldspar (light grey, rich in bubbles); b – glass pseudomorph after *K*-feldspar (medium grey) with parallel pseudomorphs after exsolved albite (dark grey) and injection of a basic melt (bright).

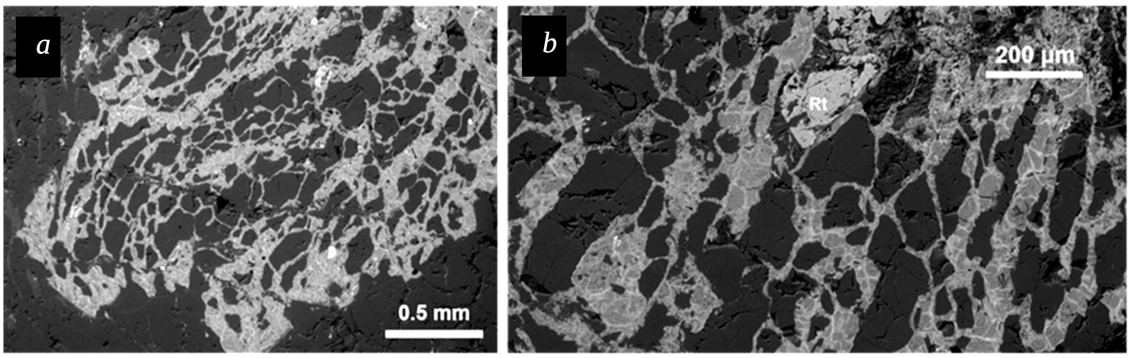

Fig. 14. Melt penetrations in quartzitic rock (Crater No. 5, No. 5/1/0a; BSE images):

a – injections of melt chemically similar to a mafic silicate (chlorite, tourmaline or amphibole, containing Al, Fe, Mg, Na and little Ca) into fractured quartz; b – detail of other injected quartz (dark gray); Rt – rutile, possibly deformed; the melt separated into very fine, usually acicular Fe-oxides (bright) and silicate glass (medium gray), also crystallization of fine cristobalite is possible.

Decarbonization

Probable remnants of re-carbonized lime are found at all three sites. Importantly, in some samples evidence of in situ decarbonization can be observed. Part of the surface of the sample No. 5/1/0a, especially near the crossing of two fractures (former calcite veinlets?), is covered with a white "mortar", containing stuck grains of, e. g., quartz from the surrounding soil / sediment (Fig. 19, *a*, b).

The mortar formed naturally from re-carbonizing lime, and it is younger than the glass coating.

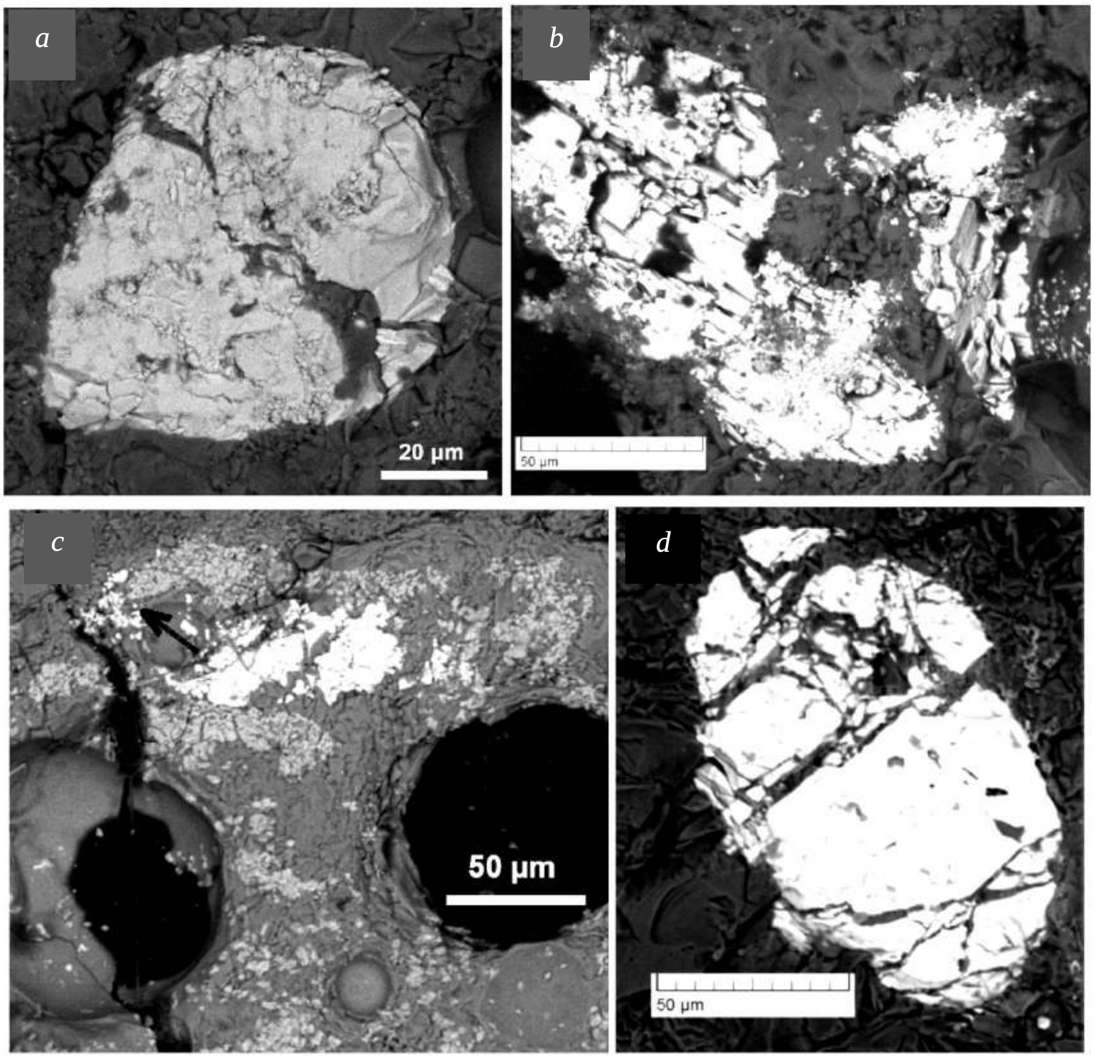

Fig. 15. Melt penetration into accessory minerals (unpolished sections, BSE images):

a – zircon with injections of glass (No. 16132); b – monazite – probably originally one grain, penetrated and somewhat divided by melt (No. 16132); c – zircon (white) and rutile (or anatase; light gray) in glass of *K*-feldspar composition; the zircon had been likely a single crystal whose part was shifted away by an expanding bubble (arrow); d – crushed zircon with several fragments somewhat torn away (mainly in the upper part) and glass-filled fractures, in places with small crystals in the glass (No. 5/1/0a).

Unusually complicated morphology, rough surface and easy disintegration are typical for many small (several-cm sized) carbonate fragments, especially in Crater No. 4, and similar crust also covers a dolomite pebble (Fig. 19, *c*). We suggest that the decarbonization took place, which could also explain the bright white, soft, chalk-like surface of many pebbles of Crater No. 4 and the Kaltenbach structure. Nevertheless, many limestone samples (including large ones) do not display such an effect.

No glass that would cover carbonates has been observed. It seems that the pressure of escaping gas (CO_2) prevented formation of any continuous coating at high temperature; nevertheless, glass sometimes formed on older weathering crusts of carbonate pebbles. Possible product of reaction of an external hot material with carbonate is the matter similar to pumice observed in Crater No. 4 (No. 417 – sandy limestone; Fig. 19, *d*) and perhaps in Crater No. 5, partly filling open fractures and/or covering pebble's surface. Its bright colors and relatively hard and inflexible consistency exclude organic character (also XRF, where applicable, shows a silicate composition). This "pumice" could be a product of a reaction of glowing fluid, melt or aerosol from outside with the original surface, strongly influenced by escaping gas (especially on calcite veinlets or carbonate surfaces). Charred, obviously burnt relics of moss were also found on relatively sheltered surface of the sample No. 417 (Fig. 19, *e*).

In the sample No. 105 from the Kaltenbach structure, residual lime (portlandite) was identified. Its partial re-carbonization formed a macroscopically distinct crust; in addition, matter similar to man-made mortar occurs on the sample surface. Similar to limekilns, gas released from decarbonation may have contributed to expansion of Ca-rich silicate rocks (No. 419, Crater No. 4; see also Fig. 6). No burnt fine-grained material, like clay or loam, which would be necessary for any furnace construction, has been found in the craters at Emmerting (however, the presence of such material at Kaltenbach is possible).

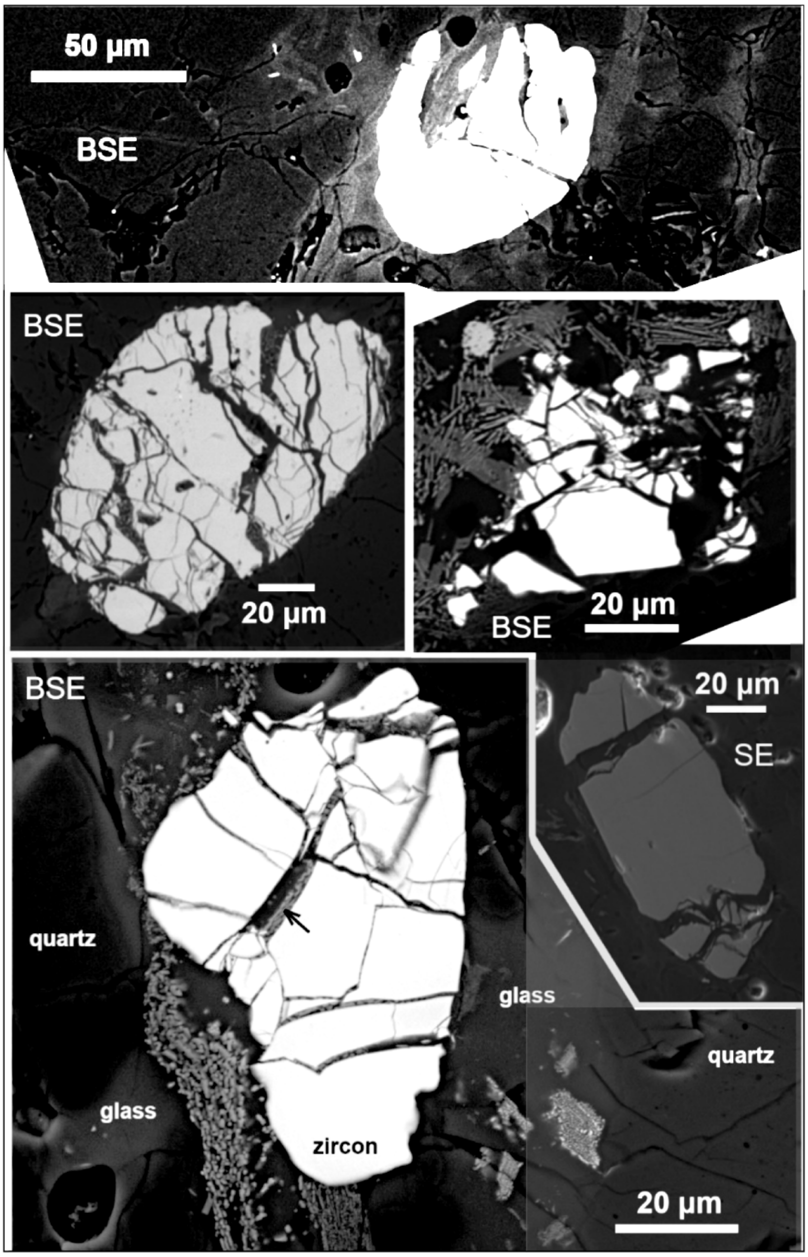

Fig. 16. Melt penetrations in zircon in polished specimen (5/1/0a). Zircon is allways the brightest phase in the image. Composition of the melt veinlets in zircon varies from Al-rich silicate glass, in places with tiny crystals (arrow in the bottom image points to Fe-Al oxides), to silica (lechatelierite?). Also Ti(-Fe) oxides may have crystallized from melt, similar to the surrounding glasses.

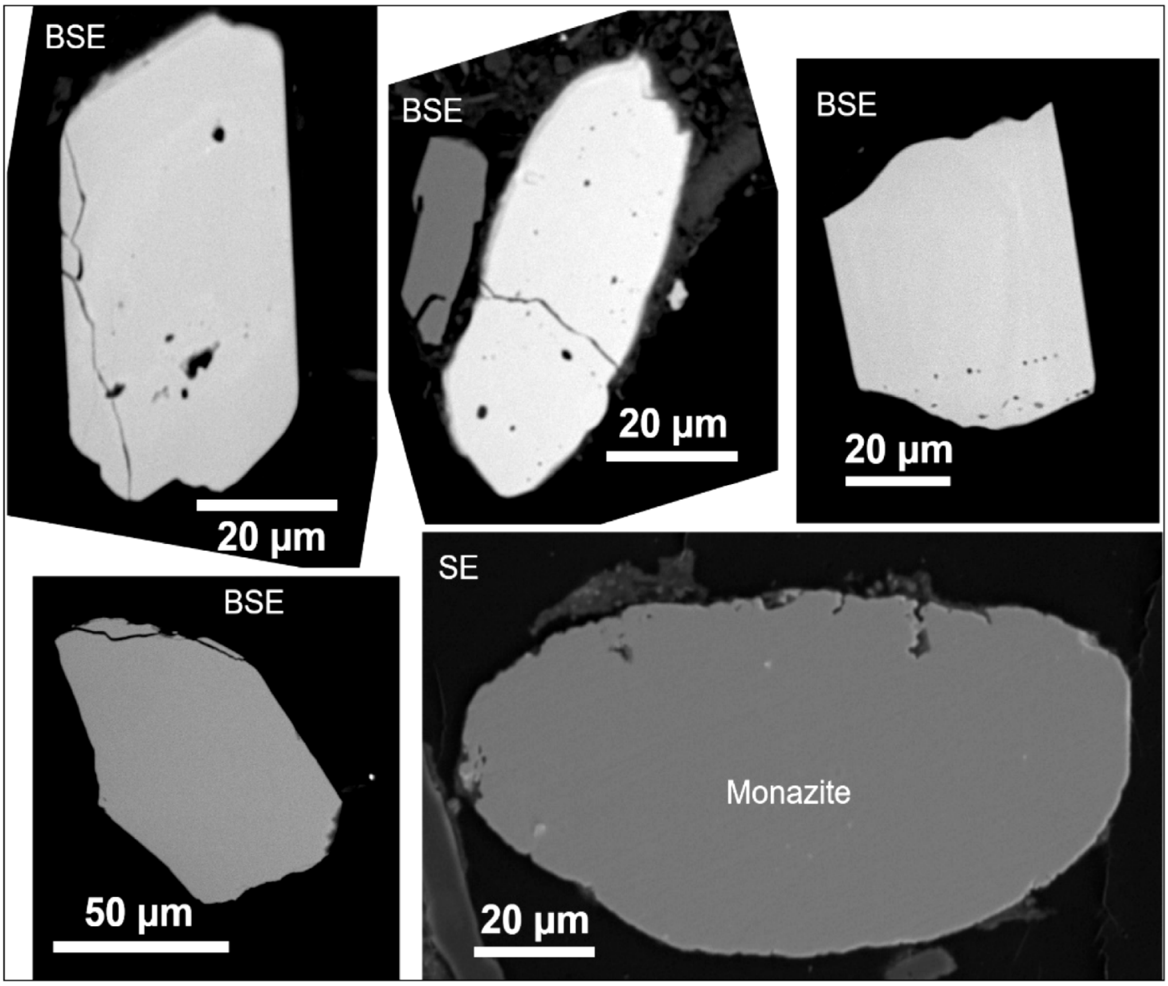

Fig. 17. Examples of free zircon grains and a free monazite grain from the fine-grained filling of Crater No. 4, with inabundant fractures (not filled) and inclusions or pores, not penetrated by melt.

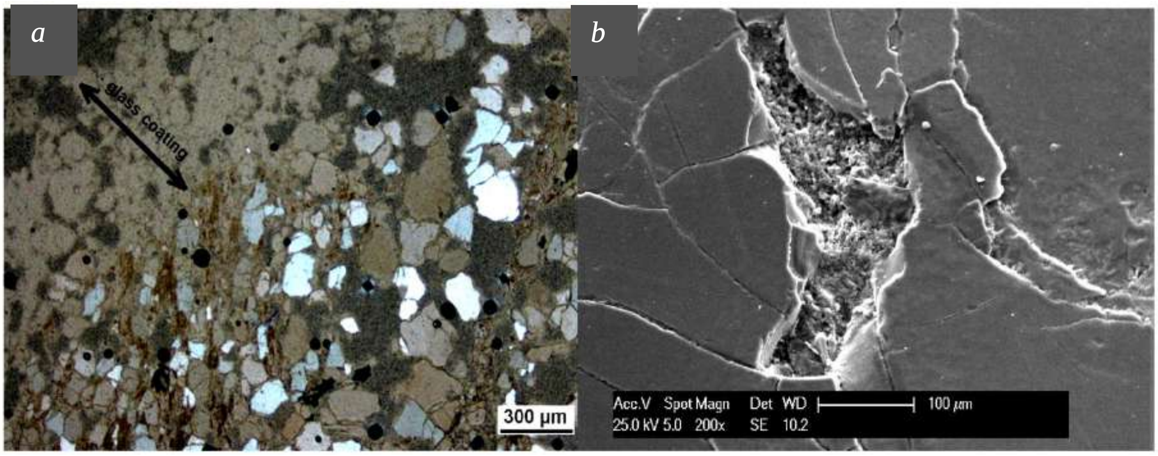

Fig. 18. A quartzite pebble (Crater No. 4, No. 715240) containing altered biotite and organic matter, with glass coating (independent on the foliation):

a – transmitted light, askew-crossed polars (hollows in the section are greenish gray);
b – SEM image of the surface: a flat upper glass layer (left, lower right), lower glass layer (upper right) and rugged older weathered surface of the pebble (middle).

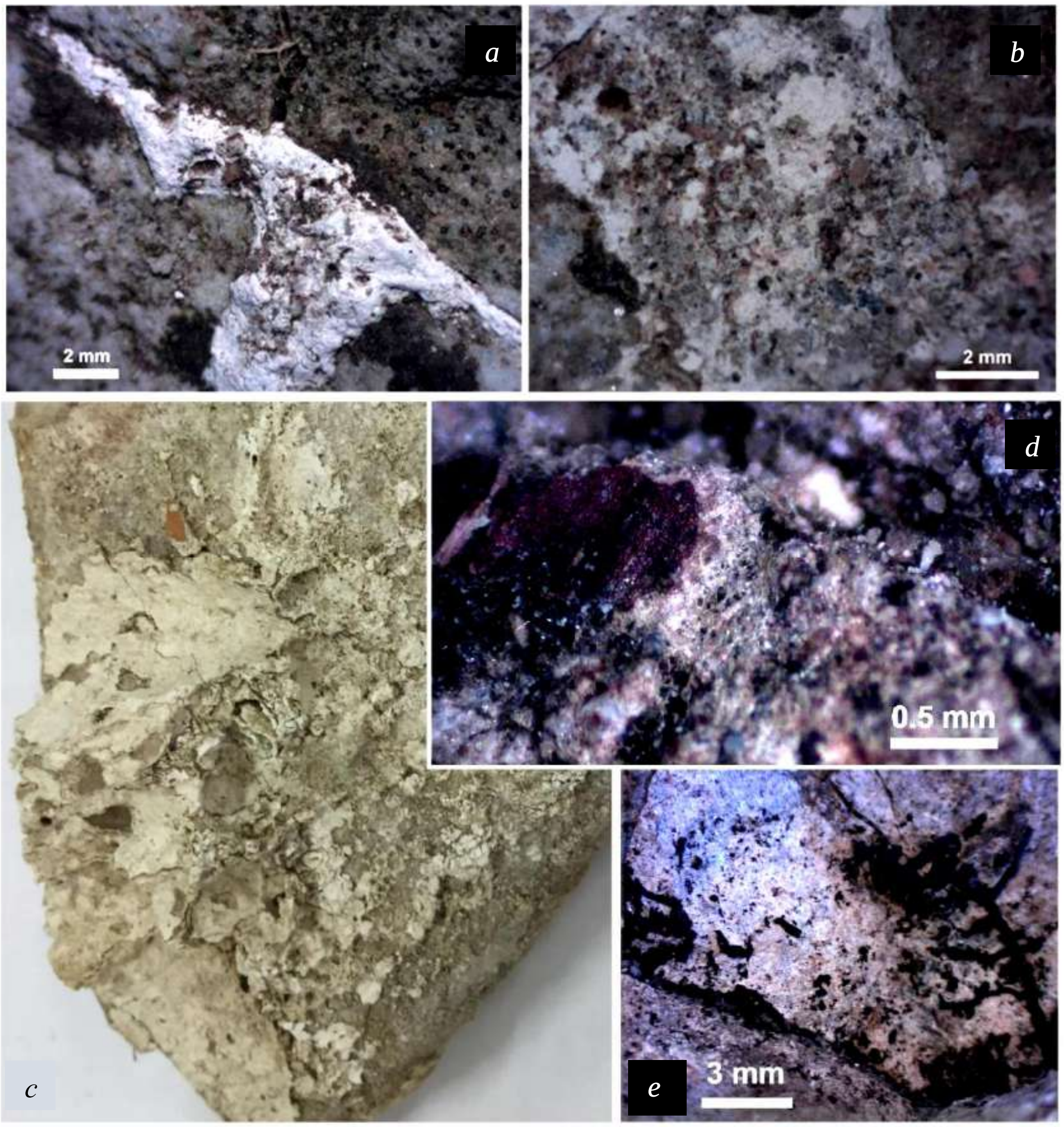

Fig. 19.

white “mortar”, i. e., small mineral (e. g., quartz) and perhaps organic grains stuck on the original lime on two intersecting cracks (Crater No. 5, No. 5/1/0a) (a); a detail of mortar with stuck grains, on the bottom left and upper right also (older) thin glass coating is visible (b); “flourishing” of dolomite surface, perhaps due to gas expansion during decarbonization (Crater No. 4, No. 406, image height 4.5 cm) (c); a leaf remnant (rusty) stuck on yellow porous glass(?) layer (“pumice”) on an impure carbonate pebble (Crater No. 4, No. 417) (d); charred moss at another site of the same sample (e).

Discussion

Possible anthropogenic processes and origin of the Kaltenbach structure

Limestone pebbles in the Alpine foreland, including the surroundings of Grabenstätt [Freude, 2007 and references therein], may have conspicuous morphology and structures due to dissolution in acidic soils and formation of corrosion layers (we observed these phenomena mainly in Crater No. 4). However, nothing similar to the decarbonized, i. e. expanded or chalk-like, surfaces (Fig. 19) was presented [Freude, 2007].

Many human activities may cause disequilibrium melting. All the glass-coated pebbles of anthropogenic origin shown by several authors (e. g., Doppler and Geiss [2005]) have a smooth surface and show no deformation during or after melting. Darga and Weiler [2009] argued that stones could have been coated with glass, softened and even deformed in an old limekiln thank to temperatures reaching up to 1200 °C. However, this would explain neither melt injections into very thin fractures, nor extensive evaporation of minerals in some samples. Detailed research of partially melted stones from old limekilns (including the area mentioned by Doppler and Geiss [2005]) is the subject of a separate study. Nevertheless, even preliminary comparison [Procházka, 2023] clearly shows that in limekilns the melt was much less deformed and the glass layers are relatively thick and rather not clearly delimited, which is rather comparable to the Kaltenbach site but not to craters of Emmerting.

Finally, placement of a limekiln (or any other device demanding for fuel feeding) in poorly drained and frequently wet alluvium (Crater No. 5) would be illogical. Note that the situation was not better in the past due to proximity of fossil side channels of the Alz river, as displayed in a historical map [Anonymus]. Fehr et al. [2005] suggested that Crater No. 5 was secondary used (as a natural depression) for a limekiln, but neither presented nor cited any evidence for that.

Man-made fires partially melted walls of many prehistoric to early mediaeval hillforts in Europe, forming so-called vitrified forts, especially in Scotland. Stones in these walls, however, had been intercalated with wood and possibly other combustibles (see also Childe and Thorneycroft [1938]). This would be impossible in the depressions investigated. Some authors [Friend et al., 2007] suggested relatively low temperatures (< 900 °C) as sufficient for vitrification of the walls but they assumed eutectic melting of biotite and quartz, i. e., a long-lasting equilibrium process.

The morphology of the depression at Kaltenbach corresponds to an impact crater, not a limekiln. However, the owners may have partly recultivated and hidden their limekilns after usage to escape taxation. The superparamagnetism (most likely caused by nanoparticles) of stones from the Crater No. 4 and Kaltenbach [Procházka and Kletetschka, 2016] indicates a rather short heating. In limestones, however, the nanoparticles may also simply reflect submicroscopic grain size of the original iron hydroxides / hydrated oxides (and in the only silicate sample of Kaltenbach measured, magnetometry did not indicate significant presence of nanoparticles).

Formation of the craters at Emmerting: the role of a specific target

Shock metamorphism has also been proven in small impact craters: it was significant even in the Kamil crater with a diameter of 45 m [Fazio et al., 2016]. In the Carancas crater with a 13.5 m diameter (i. e., comparable to the craters at Emmerting), small-scale melting of the projectile with melt injections into the target sediments was documented and weak shock effects were found in the ejecta [Tancredi et al., 2009]. So the shock effects could be, in principle, found even in very small impact craters, but in such a case the shocked material usually has small volume and is dispersed in relatively large area. High-temperature and shock phenomena and even small craters can be also produced by airbursts, i. e. explosions of the projectile in a relatively high altitude [LeCompte et al., 2025; Fitzenreiter et al., 2025].

The energy necessary to form the craters at Emmerting was larger than for a crater of similar size in a compact and even in a sandy target. The porosity significantly reduces pressure and the compression of pore space leads to a greater temperature enhancement [Love et al., 1993]. In sands and sandstones the porosity can locally enhance the pressure at grain rims [Kowitz et al., 2013]. While this effect could be somewhat different in the coarse-grained target at Emmerting, the finding of baddeleyite as a probable shock product points to inhomogeneity of the peak pressure and temperature. We have not observed other evidence for shock pressure greater than ca. 8 GPa (nevertheless, PDFs and spallation were mentioned by Schüssler [2005]). The formation of PDFs is dominant in compact rock massifs, while in a porous environment, it is relatively suppressed and temperature effects are more important [Osinski et al., 2022 and references therein]; note that most of the terrestrial porous rocks investigated for shock metamorphism were sandstones [Kowitz et al., 2013] which are still very compact targets in comparison to the coarse terrace sediments.

The projectile may have exploded above the ground yet. The porous target would be efficient in transfer and absorption of heat from the explosion and potentially from thermal radiation of the projectile (in case of subvertical impact). An ignition of aboveground biomass and leaf litter prior to the projectile arrival (see also [Řanda et al., 2008]) could lead to formation of a fluid rich in K and other biogenic metals which could form the glass coatings rich in these elements.

Mutual collisions of cobbles and pebbles heated them strongly and led to complicated relations of melting and deformation (see also [Procházka, 2023]. In the pebbles interior, the melting was mainly caused by the pressure wave and subsequent decompression when more compressible (i. e., relatively soft and/or porous) matter, like alterered mafic minerals, micas or feldspars, melts first, while eutectic melting (e. g., feldspars with quartz) is very limited. Shock pressure in tens of GPa is considered to melt minerals [French, 1998 and references therein], albeit for very local melting 5 GPa was sufficient in experiments with sandstone [Kowitz et al., 2013]. Nevertheless, due to repeated collisions, the peak pressure could be much lower than necessary for “one-shot” melting.

Secondary projectiles are little documented in literature, but they should be significant in case of impact into target dominated by large pebbles or boulders. Anfinogenov et al. [2014] described a stone several meters in size and several tons in weight which formed a furrow in the permafrost near the epicenter of the Tunguska explosion. The boulder, formed by sandstone (or conglomerate), and its fragments collected in the soil, were partly coated with thin glass. Anfinogenov et al. [2014] calculated that the stone had to hit the ground with velocity higher than 500 m/s (they suggested that it was a meteorite, which however is inconsistent with its chemical and isotopic composition [Haack et al., 2016]). Therefore, this stone may represent a secondary project-tile. Note that smaller stones could have been accelerated to much higher velocity. Fehr et al. [2005] also documented probable effects of secondary projecttiles, but with very low velocity, around several craters near Emmerting.

Fine-grained fractions of the original target sediments appear poorly preserved in the crater infill. They were partly lost during the impact by the effects of gas pressure (due to projectile explosion, water evaporation, and possibly explosive fire of organic matter). The role of impact-vaporized pore water which removed preferentially fine particles was documented in nature [Pietrek and Kenkmann, 2016] as well as experimentally [Buhl et al., 2013]. Downward transport of fine particles and fragments was also significant (as supposed for highly porous targets, like some asteroids [Housen et al., 2018]), which could explain formation of the compact bodies below the craters No. 4 and 5 indicated geophysically [Kalenda et al., 2024]. A potential sintering was limited by abovementioned processes causing depletion in fine particles, and (in Crater No. 4) low clay content in the original sediment. The present fine material was also influenced by soil formation and transport of particles (by groundwater, gravity, and bioturbation) through the skeleton of large clasts all the time after crater formation. While the heating of the target was quick, the cooling was locally slow for several reasons: i) many pebbles have been heated inside; ii) after water evaporation, fire from organic matter has persisted for some time; iii) cooling effect of liquid water which reached the site soon after the crater formation would be prevented by its exothermic reaction with quicklime burned from carbonates.

Originality

The craters at Emmerting are unique by the combination of small size and strong HT-metamorphism probably including shock effects. Due to poor preservation of the stony projectile material, the documented extreme deformations and penetrations of melt even into thin fractures in crushed mineral grains are important evidence of impact.

Practical significance

Our results may be useful to interpret hitherto as well as future discoveries of potential impact craters in coarse unconsolidated sediments. In addition, the assumption that many small asteroids have a relatively loose, “rubble-pile” like consistence, is being confirmed by spacecraft missions (e. g., [Fujiwara et al., 2006]). Thus, knowledge of the behavior of such targets during impact is important for space activities, including potential planetary defense.

Conclusions

In the craters No. 4 and 5 at Emmerting, three major phases have been documented:

1. Deposition of hot material which solidified to glass (usually thin and transparent) or reacted with carbonate to form expanded “pumice” on the surface of pebbles (usually bottom side was sheltered). The surface glass coatings may have started to form by thermal wave shortly before the impact.
2. Ductile deformation of variable intensity (accompanied by intense fracturing of mineral grains but with very limited movements along fractures); in some cases this deformation proves extreme strain, excluding explanation by any realistically possible human activity. The ductile character of the deformation points to a high temperature, which however did not always cause melting.
3. Solidification of melts formed inside the pebbles or from secondary projectiles. These melts were also able to fill even thin fractures in individual mineral grains (perhaps owing to underpressure during rebound of the compressed rock); expansion of gases also lead to extrusions and formation of miniature “volcanoes” on the surface of some pebbles. The strongly expanded Ca-poor pebble and abundant bubbles in feldspar-derived glasses point to evaporation of silicates in Crater No. 4. The role of underpressure in the melt evaporation is also possible.

The character of melts in most samples from craters proves quick heating with minimum of eutectic melting. Typical highly porous “internal” melt formed likely from micas (like chloritized biotite). Feldspars melted in many samples and they formed mixed feldspar glass, and even glass pseudomorphs after *K*-feldspar and albite without any eutectic reaction.

The formation of baddeleyite in zircon was very likely caused by the shock wave with a pressure in the order of tens of GPa. However, presssures greater than ca. 8 GPa were generally rare (quartz was typically strongly fractured but for now, we cannot confirm the PDFs reported by some authors). The heating sufficient for melting and evaporation was possible at relatively low shock pressures in the rocks thanks to porosity of the target and mutual interaction of pebbles.

The role of natural and anthropogenic processes in formation of the Kaltenbach structure remains open. Anthropogenic contamination is probable (but possibly after the depression's formation). Some fracturing of pebbles and deformation of partially molten rocks, dominated by gravity and gas expansion, do not prove impact event, although the filling (injection?) of some fractures by glass is remarkable.

Several samples may macroscopically resemble metallurgical slags, but their composition and relics of original rock's textures, including quartz and calcite veinlets, exclude such comparison.

Acknowledgments

The work was funded by the Ministry of Education, Youth and Sports of the Czech Republic within the projects LM2023073 and RVO: 68145535, and by the Czech Science Foundation (Project No. 23-06075S). We thank two anonymous reviewers for comments which helped to improve the manuscript.

References

Anfinogenov, J., Budaeva, L., Kuznetsov, D., Anfinogenova, Y. (2014). John's Stone: A possible fragment of the 1908 Tunguska meteorite. *Icarus*, 243, 139–147. https://doi.org/10.1016/j.icarus.2014.09.006

Anonymus. UmweltAtlas Bayern. (Web version: https://www.lfu.bayern.de/geologie/geo_karten_schriften/gk500/index.htm). Bayerisches Landesamt für Umwelt, Augsburg, Germany (accessed in 2023).

Bartuška, M. (ed., 2001). Vady skla (Glass defects). Práh. Prague, Czech Republic; 606 p.

Buhl, E., Poelchau, M. H., Dresen, G., Kenkmann, T. (2013). Deformation of dry and wet sandstone targets during hypervelocity impact experiments, as revealed from the MEMIN Program. *Meteor. Planet. Sci*., 48, 71–86. https://doi.org/10.1111/j.1945-5100.2012.01431.x

Childe, V. G., Thorneycroft, W. (1938). The experimental production of the phenomena distinctive of vitrified forts. *Proc. Soc. Antiq. Scot*., 72, 44–55. https://doi.org/10.9750/PSAS.072.44.55

Darga, R., Wierer, J. F. (2009). Der Chiemgau-Impakt – eine Spekulationsblase – Oder: Der Tüttensee ist KEIN Kometenkrater. in: Auf den Spuren des Inn-Chiemsee-Gletschers – 2. Exkursionen, pp. 174–185. München (Pfeil), ISBN 978-3-89937-104-8.

Doppler, G., Geiss, E. (2005): Der Tüttensee im Chiemgau – Toteiskessel statt Impaktkrater. Bayerisches Landesamt für Umwelt, Germany. Available online: https://www.lfu.bayern.de/ geologie/meteorite/bayern/doc/tuettensee.pdf

Ernstsson, K., Mayer, W., Neumair, A., Rappenglück, B., Rappenglück, M. A., Sudhaus, D., Zeller, K. W. (2010). The Chiemgau crater strewn field: evidence of a Holocene large impact event in southeast Bavaria, Germany. J. Sib. Federal Univ., *Eng. Technol.*, 1, 72–103.

Fazio, A., D'Orazio, M., Cordier, C., Folco, L. (2016). Target-projectile interaction during impact melting at Kamil Crater, Egypt. Geochim. Cosmochim. *Acta*, 180, 33–50. https://doi.org/10.1016/j.gca.2016.02.003

Fehr, K. T., Pohl, J., Mayer, W., Hochleitner, R., Faßbinder, J., Geiß, E., Kerscher, Y. (2005). A meteorite impact crater field in eastern Bavaria? A preliminary report. *Meteor. Planet. Sci*., 40, 187–194. https://doi.org/10.1111/j.1945-5100.2005.tb00374.x

Fitzenreiter, R. et al. (24 co-authors) (2025): Evidence of a 12,800-year-old Shallow Airburst Depression in Louisiana with Large Deposits of Shocked Quartz and Melted Materials. *Airbursts and Cratering Impacts*, 3, 47 p., https://doi.org/10.14293/ACI.2025.0004.

French, B. M. (1998). Traces of catastrophe. A handbook of shock-metamorphic effects in terrestrial meteorite impact structures. LPI Contribution No. 954, Lunar and Planetary Institute, Houston, 120 p.

Freude, F. (2007). Strukturgeologisch-petrographische Untersuchungen an Karbonatgeröllen einer Schotterterrasse im Chiemgau und Diskussion der Ergebnisse im Rahmen der Impakt-Streufeld-Hypothese. – Master thesis, Friedrich-Alexander-Universität, Erlangen, 64 p.

Friend, C., Dye, J., & Fowler, M. (2007). New field and geochemical evidence from vitrified forts in South Morar and Moidart, NW Scotland: Further insight into melting and the process of vitrification. *Journal of Archaeological Science*, 34, 1685–1701. https://doi.org/10.1016/j.jas.2006.12.007

Fujiwara, A. et al. (2006). The rubble-pile asteroid Itokawa as observed by Hayabusa. *Science*, 312, 1330–1334. https://doi.org/10.1126/science.1125841

Haack, H., Greenwood, R. C., Busemann, H. (2016): Comment on "John's stone: A possible fragment of the 1908 Tunguska meteorite". *Icarus*, 265, 238–240. https://doi.org/10.1016/j.icarus.2015.09.018

Housen, K. R., Sweet, W. J., Holsapple, K. A. (2018). Impacts into porous asteroids. *Icarus*, 300, 72–96. https://doi.org/10.1016/j.icarus.2017.08.019

Kalenda, P., Thinová, L., Tengler, R., Procházka, V., Mizera, J., Martinec, P., Kletetscka, G., Trojek, T. (2024). Two impact craters at Emmerting, Germany: field documentation and geophysics. *Geodynamics*, 37, 27–44. https://doi.org/10.23939/jgd2024.02.027

Kowitz, A., Güldemeister, N., Reimold, W. U., Schmitt, R. T., Wünnemann, K. (2013). Diaplectic quartz glass and SiO_2 melt experimentally generated at only 5 GPa shock pressure in porous sandstone: laboratory observations and meso-scale numerical modeling. *Earth Planet. Sci. Lett.*, 384, 17–26. https://doi.org/10.1016/j.epsl.2013.09.021

LeCompte, M. A. et al. (2025): A Tunguska sized airburst destroyed Tall el-Hammam, a Middle Bronze Age city in the Jordan Valley near the Dead Sea (Expanded). *Airbursts and Cratering Impacts*, 3, 87 p., https://doi.org/10.14293/ACI.2025.0003.

Love, S. G.; Hörz, F.; Brownlee, D. E. (1993). Target porosity effects in impact cratering and collisional disruption. *Icarus*, 105, 216–224. https://doi.org/10.1006/icar.1993.1119

Neumair, A., Waitzinger, M., Finger, F. (2016). Interesting glass coatings on cobbles and rock fragments from the Alpine foreland, SE-Bavaria, Germany, and their possible origin. GeoTirol 2016, A233.

Osinski, G. R. et al. (11 co-authors) (2022). Impact Earth: A review of the terrestrial impact record. *Earth-Sci. Rev.*, 232, 104112, 48 p. https://doi.org/10.1016/j.earscirev.2022.104112

Piatak, N., Ettler, V. (2021). Metallurgical Slags: Environmental Geochemistry and Resource Potential. Royal Society of Chemistry: Cambridge, UK, 305 pp. https://doi.org/10.1039/9781839164576

Pietrek, A.; & Kenkmann, T. (2016). Ries Bunte Breccia revisited: Indications for the presence of water in Itzing and Otting drill cores and implications for the emplacement process. *Meteorit. Planet. Sci.*, 51, 1203–1222. https://doi.org/10.1111/maps.12656

Procházka V., & Kletetschka G. (2016). Evidence for superparamagnetic nanoparticles in limestones from Chiemgau crater field, SE Germany. 47th LPSC, Abstract No. 2763.

Procházka V., & Trojek T. (2017): XRF- and EMP-investigation of glass coatings and melted domains of pebbles from craters in Chiemgau, Germany. 48th LPSC, Abstract No. 2401.

Procházka, V. (2023). Melt behavior in two impact craters at Emmerting, Germany: Deformation, expansion, injections, and the role of under-pressure and mutual collisions of pebbles. 54th LPSC, Abstract No. 2102.

Řanda, Z., Mizera, J., Frána, J., & Kučera, J. (2008). Geochemical characterization of moldavites from a new locality, the Cheb Basin, Czech Republic. Meteorit. *Planet. Sci.*, 43, 461–477. https://doi.org/10.1111/j.1945-5100.2008.tb00666.x

Rösler, W., Patzelt, A., Hoffmann, V., & Raeymaekers, B. (2006). Characterization of a small crater-like structure in S.E. Bavaria, Germany. Proc. 1st Int. Conf. on Impact Cratering in the Solar System, Noordwijk, pp. 67–71. European Space Agency.

Schüssler, U. (2005). Chiemgau-Impakt: Petrographie und Geochemie von Geröllen mit Deformationsmerkmalen und starker thermischer Beanspruchung aus dem nördlichen Bereich des Impakt-Areals (research report, 28 p.). https://nbn-resolving.org/urn: nbn:de:101:1-201005228993.

Strassburger, M., Wieser, J. (2014). Early and high medieval iron production in the Grubet near Aichach. *Acta Rer. Natur.*, 16, 33–50.

Tancredi, G. et al. (15 co-authors) (2009). A meteorite crater on Earth formed on September 15, 2007: The Carancas hypervelocity impact. *Meteorit. Planet. Sci.*, 44, 1967–1984. https://doi.org/10.1111/j.1945-5100.2009.tb02006.x

Вацлав ПРОХАЗКА[1]*, Петр МАРТІНЕЦ[2], Павел КАЛЕНДА[3], Ленка ТІНОВА[1], Каміль СОУЧЕК[2], Річард ШТОРЦ[4], Ян АДАМЕК[5], Їржі МІЗЕРА[6], Томаш ТРОЙЕК[1], Гюнтер КЛЕТЕЧКА[4, 7]

[1] Чеський технічний університет, Бржехова, 7, Прага 1, 11519, Чехія, ел. пошта: vaclav.prochazka@fjfi.cvut.cz, lenka.thinova@fjfi.cvut.cz, tomas.trojek@fjfi.cvut.cz, https://orcid.org/ 0000-0003-4320-7266, https://orcid.org/0000-0001-8277-1121, https://orcid.org/0000-0002-2136-4503;

[2] Інститут геоніки Чеської академії наук, Студентська, 1768, Острава-Поруба, 70800, Чехія, ел. пошта: martinec@ugn.cas.cz, https://orcid.org/0009-0000-5084-6053;

[3] CoalExp, Пражмо, 129, Пражмо, 73904, Чехія, ел. пошта: pkalenda@volny.cz, https://orcid.org/0000-0003-4351-9593;

[4] Інститут гідрогеології, інженерної геології та прикладної геофізики, факультет природничих наук, Карлів університет, Альбертов, 6, Прага 2, 12843, Чехія, ел. пошта: gunther.kletetschka@natur.cuni.cz, https://orcid.org/0000- 0002-0645-9037;

[5] Чеський технічний університет у Празі, факультет ядерних наук та фізичної інженерії, Троянова, 13, Прага 2, 12003, Чехія;

[6] Інститут ядерної фізики Чеської академії наук, Husinec-Řež, 130, 25068, Чехія, ел. пошта: mizera@ujf.cas.cz, https://orcid.org/0000-0002-8926-6213;

[7] Геофізичний інститут, Університет Аляски – Фербенкс, 2156 N Коюкук Драйв, Фербенкс, Аляска, 99775, США, ел. пошта: gunther.kletetschka@natur.cuni.cz, https://orcid.org/0000- 0002-0645-9037

.

ДВА ГОЛОЦЕНОВІ УДАРНІ КРАТЕРИ В ЕММЕРТІНГУ, НІМЕЧЧИНА. ДЕФОРМАЦІЯ, РУЙНУВАННЯ ТА ЇХ ЗВ’ЯЗОК ІЗ ПЛАВЛЕННЯМ ТА ДЕКАРБОНІЗАЦІЄЮ

У двох кратерах поблизу Еммертінга задокументовано три основні процеси, які по-різному вплинули на первинну гальку, в такій послідовності: 1. Осадження гарячого матеріалу, який затвердів, перетворившись на скло (зазвичай тонке та прозоре), або прореагував із карбонатом, утворивши пухирчасту “пемзу” на поверхні гальки. 2. Пластична деформація змінної інтенсивності (з обмеженою крихкою деформацією, але інтенсивним розтріскуванням мінеральних зерен), із використанням як старіших, так і новоутворених розривів; у деяких випадках ця деформація відповідає екстремальному стисканню, що робить її антропогенне походження дуже малоймовірним. Переважала пластична деформація, що вказує на високу температуру, але вона не обов’язково супроводжувалася плавленням. 3. Затвердіння розплавів, що утворилися всередині гальки або походили від “вторинних снарядів” (викинутих ударом розплавлених порід). Ці нерівноважні розплави були достатньо гарячими, щоб їхня в’язкість була дуже низькою (у деяких випадках вони також могли бути ін’єктовані під високим тиском / напруженням або всмоктані), завдяки чому заповнювали навіть тонкі тріщини в окремих мінеральних зернах; розширення газів також утворювало екструзії, що нагадують мініатюрні вулканічні утворення на поверхні деяких шматочків гальки. У деяких зернах циркону спостерігався бадделеїт, ймовірно, утворений внаслідок ударного метаморфізму. Однак не було знайдено ніяких додаткових доказів, які б свідчили про тиск, що перевищує поріг, зазвичай необхідний для ударно-індукованого плавлення (8 ГПа або більше). Проте енергія, перетворюючись під час повторних взаємних зіткнень, могла достатньо нагріти внутрішню частину шматочків гальки. Походження западини у Грабенштет – Кальтенбах не з’ясоване, нерівноважні плавлення та декарбонізацію тут можна також пояснити антропогенними процесами.

Ключові слова: голоценові кратери, удар, Еммертінг, деформація, тріщинуватість, ін’єкції.

Received 10.12.2024