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Multiple fluvial reworking of impact ejecta—A case study from the Ries crater, southern Germany

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Abstract–Impact ejecta eroded and transported by gravity flows, tsunamis, or glaciers have been reported from a number of impact structures on Earth. Impact ejecta reworked by fluvial processes, however, are sparsely mentioned in the literature. This suggests that shocked mineral grains and impact glasses are unstable when eroded and transported in a fluvial system. As a case study, we here present a report of impact ejecta affected by multiple fluvial reworking including rounded quartz grains with planar deformation features and diaplectic quartz and feldspar glass in pebbles of fluvial sandstones from the "Monheimer Höhensande" ~10 km east of the Ries crater in southern Germany.

INTRODUCTION

The 14.4 Ma (e.g., Buchner et al. 2003) Ries crater in southern Germany is unique in terms of the state of preservation of its impact ejecta blanket (Fig. 1). Proximal Ries ejecta are subdivided as follows (e.g., Hörz et al. 1983; Hüttner and Schmidt-Kaler 1999): 1. "Bunte Breccia," a lithic impact breccia containing clasts of the sedimentary cover of the target area. Clasts in Bunte Breccia commonly lack signs of shock metamorphism exceeding shock pressures of 10 GPa (von Engelhardt and Graup 1984). 2. "Kristallinbreccie," a lithic impact breccia with slightly to intensely shocked clasts from the deeper parts of the sedimentary cover and the Variscan crystalline basement. 3) Suevite, a melt-bearing impact breccia thought to originate from the collapsing cloud of rock fragments in all stages of shock metamorphism, molten rocks, and rock vapor (e.g., von Engelhardt et al. 1967; von Engelhardt and Graup 1984). Bunte Breccia originally surrounded the Ries crater up to a distance of ~40 km, whereas Kristallinbreccie was deposited in isolated patches on top of the Bunte Breccia. Suevite overlies these ejecta types in and outside the crater up to a distance of ~20 km from the crater rim. Distal Ries ejecta are subdivided in: 1. "Ries-Brockhorizont," isolated blocks or layers of mainly Upper Jurassic limestones distributed in Middle Miocene sediments of the North Alpine foreland basin up to a distance of ~200 km from the Ries crater (Buchner et al. 2007). These blocks are considered distal Ries ejecta suggesting ballistic and subsequent short-range fluvial transport. 2. Central European tektites (Moldavites) are distributed as a strewn field that extends ~200–450 km from the center of the Ries crater to the east (Stöffler et al. 2002). In addition, reworked material (mainly shocked quartz grains) eroded from the Ries ejecta blanket and swamped into a paleovalley south of the crater were described by Buchner et al. (2003). Gall et al. (1977) documented lithic components of the Bunte Breccia in fluvial sediments east of the Ries crater that are locally known as "Monheimer Höhensande" (Fig. 1).

Impact ejecta reworked in marine environments (e.g., tsunami deposits, turbidites) or transported and redeposited by glaciers are frequently documented in the literature. In contrast, impact ejecta reworked by fluvial processes are sparsely reported. We here give a brief review of reworked impact ejecta in diverse terrestrial environments and report the first recognition of impact ejecta that underwent multiple fluvial reworking in the Monheimer Höhensande.

GEOLOGICAL SETTING

Today, the occurrence of Monheimer Höhensande is restricted to a comparatively small area east of the Ries crater (Fig. 1). The Monheimer Höhensande (maximum thickness of ~8 m) comprise silt and fine- to coarse-grained sands with intercalated pebbly layers. Mudstones with a maximum thickness of 1 m (Borger 1993) predominantly occur near the basis of the sediment body (Gall et al. 1977; Schmidt-Kaler 1997). In contact with mudstones and sandstones, ferruginous layers up to 30 cm thick are incorporated (Borger 1993), each interpreted as relicts of a fossil surface area. Monheimer Höhensande exhibit planar and cross bedding, which indicates transport and deposition within a braided river system (Borger 1993). Lithic clasts and mineral grains of the

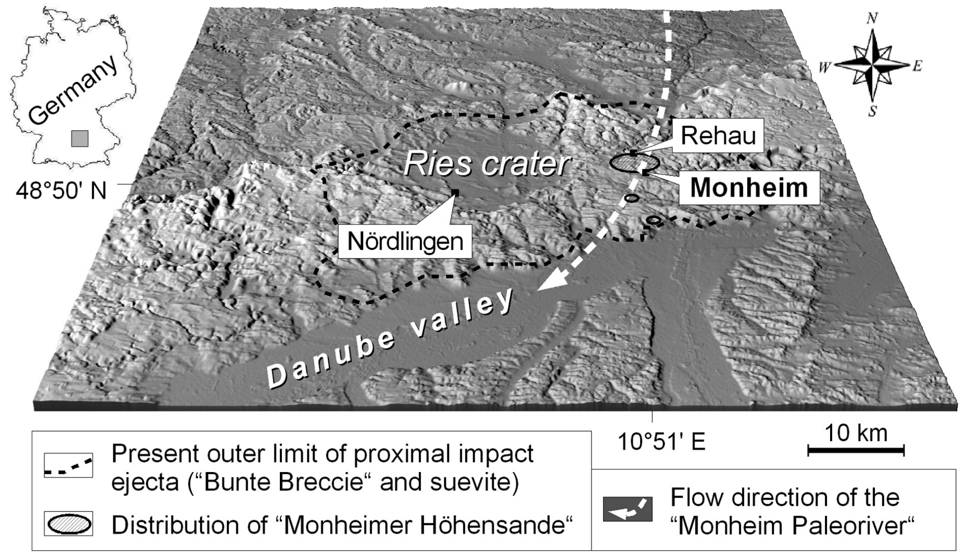

Fig. 1. Relief map of southern Germany with the position of the Ries crater and distribution of the Monheimer Höhensande. Shaded relief terrain image computed from NASA Shuttle Radar Topographic Mission (SRTM) data.

Monheimer Höhensande are largely derived from the Paleozoic (Variscan) basement northeast, as well as from Mesozoic to Cenozoic sediments north of the Ries area (Borger 1993) that have been eroded since the Cretaceous. Mesozoic to Cenozoic constituents comprise siliciclastics from the North Alpine foreland basin. Subsequent to the Ries event, a fluvial system (the “Monheim Paleoriver”) reworked Cretaceous-Miocene sandstones, as well as fragments of Bunte Breccia redeposited in the lowest parts of the Monheimer Höhensande (Schmidt-Kaler 1974). Reworked Ries ejecta are restricted to mudstone layers near the basis of the sediment body (Gall et al. 1977).

The Monheimer Höhensande were carried by a roughly N–S trending fluvial system (the “Monheim Paleoriver”) and deposited in a paleovalley that run ≥10 km east of the Ries crater rim (Fig. 1). Whereas Birzer (1969) postulated that these sediments were deposited prior to the Ries impact event, Gall and Müller (1970) and Schmidt-Kaler (1974) recognized that the Monheimer Höhensande overlie Ries ejecta and, thus, are post-impact deposits. According to Bader and Schmidt-Kaler (1977), a pre-impact drainage system was filled by Ries ejecta. In the aftermath of the 14.4 Ma Ries event, a fluvial system cut the ejecta blanket following the flow path of the inherited drainage system; however, Ries ejecta were not completely eroded in the pre-Ries valley. The Monheimer Höhensande were finally deposited in Middle to Upper Miocene times. Monheimer Höhensande still cover 140 m of Bunte Breccia in the surroundings of Monheim (Bader and Schmidt-Kaler 1977).

SAMPLE LOCATION AND MATERIAL

The sandstone pebbles discussed in this study were sampled in 1999 in a sand pit (“Sandgrube Rehau;” 48°52′26″/10°51′05″) about halfway between the villages of Monheim and Rehau (~10 km east of the Ries crater rim; Fig. 1). Since the early 1990s, this (sporadically operated) sand pit has represented the sole outcrop of the Monheimer Höhensande, providing small temporary outcrops. A detailed geological description of the Monheimer Höhensande is given by Gall and Müller (1970), Schmidt-Kaler (1974), and Borger (1993). The simplified geological profile (Fig. 2) shows the stratigraphic relations between the Bunte Breccia, Upper Freshwater Molasse, and Monheimer Höhensande as compiled from our own field investigations in the sandpit Rehau and a core drilling at Monheim/Stickelberg (Schmidt-Kaler 1974), ~4 km south of the sandpit Rehau. In the study area, mudstones of the Upper Freshwater Molasse that inclose components of reworked suevite are intercalated between the underlying Bunte Breccia and the overlying stratum of Monheimer Höhensande. We collected three pebbles as single and isolated components (~3–4 cm in size; Figs. 3A and 3B) within a mudstone layer ~30 cm thick, near the base of the Monheimer Höhensande (Fig. 2) in the sandpit Rehau. Polished thin sections of the sandstone pebbles were investigated by optical microscopy, and the geochemical analyses on sandstone clasts and clay minerals in the sandstone matrix were carried out using a CamScan™ SC44 scanning electron microscope (SEM)—EDAX™ PV 9723/10 energy dispersive X-Ray (EDX) system (Institut für Planetologie, Universität Stuttgart).

PETROGRAPHIC OBSERVATIONS

Macroscopically, the pebbles are well-rounded (Figs. 3A and 3B); one of the pebbles is perfectly rounded and shows distinguishable layering and grading (Fig. 3A). The three sandstone pebbles are relatively well-sorted and the grain size

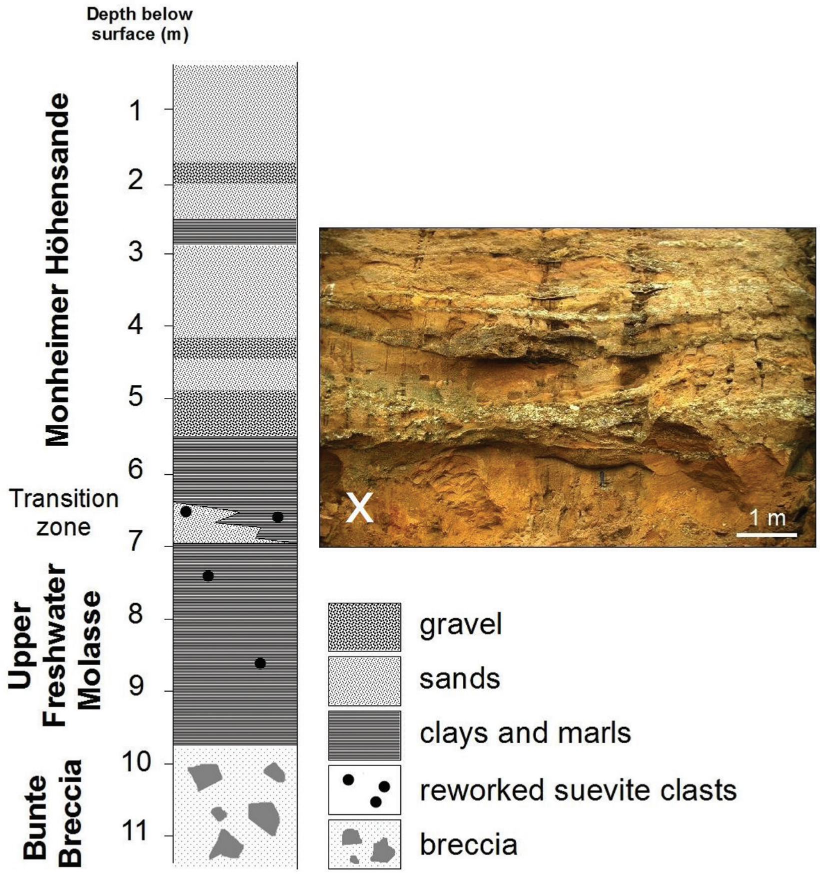

Fig. 2. Simplified geological profile showing the stratigraphic relation between Bunte Breccia, Upper Freshwater Molasse, and Monheimer Höhensande in the study area, determined by a drilling at Monheim/Stickelberg near the sandpit Rehau. The photograph shows the sample location (sandpit Rehau; 48°52′26″N/10°51′05′E) with mudstone layers (clays and marls) near the basis overlain by planar- and cross-bedded Monheimer Höhensande with interbedded pebble layers; pebbles discussed in this study were obtained from the mudstone layers at the base (white cross).

of the components ranges from fine- to coarse-grained including subordinate fine gravel components (Figs. 3A and 3B); coarser- and finer-grained layers are interbedded. The components are angular, poorly rounded, or well-rounded (Figs. 4A–F). Due to their textural features, the pebbles exhibit characteristics typical for sedimentary rocks.

At the microscopic scale, the sandstone is grain-supported (Fig. 4A) and the matrix is composed of Fe-Mn oxides (predominantly goethite) and clay minerals. According to Borger (1993), the dominant clay mineral in the matrix of the Monheimer Höhensande is kaolinite; illite occurs as a minor constituent. Most components in the pebbles are single mineral grains of quartz (Figs. 4B and 4C), feldspar, biotite, and muscovite. The mineral grains are unshocked or affected by various stages of shock metamorphism (Figs. 4B–F). In accordance with Ries suevite, crystalline lithic clasts in the sandstone pebbles comprise biotite granite, gneiss, amphibolite, and sandstone (Fig. 4A). In the crystalline clasts, quartz and feldspar grains commonly exhibit planar deformation features (PDFs), whereas biotite shows distinct kink bands. These components are generally angular to poorly rounded; the majority of sandstone components are well rounded and lack unequivocal signs of shock metamorphism. However, some sandstone clasts contain shocked quartz grains with PDFs (sets in up to 5 directions) and/or diaplectic quartz and feldspar glass (Figs. 4B–F) with relict shock features. Diaplectic glass frequently occurs as angular, poorly or well-rounded grains (Figs. 4D and 4E), either as fresh glass components (Figs. 4D and 4E), aggregates of recrystallized feldspar glass, or altered masses transformed to sheet silicates (Fig. 4F). We did not observe fluidal impact glass in our rock samples. Most rock fragments, single mineral grains, and glass particles exhibit distinct alteration rims (Figs. 4B–F).

REWORKED IMPACT EJECTA—A BRIEF REVIEW

Some examples of reworked impact ejecta through geologic time and in various terrestrial environments are given in the following (compare Table 1). Glacial reworking of considerable amounts of melt-bearing impact ejecta has been reported from various impact structures in Canada (e.g., Grieve 2006; Fig. 5A) and Scandinavia (e.g., Abels

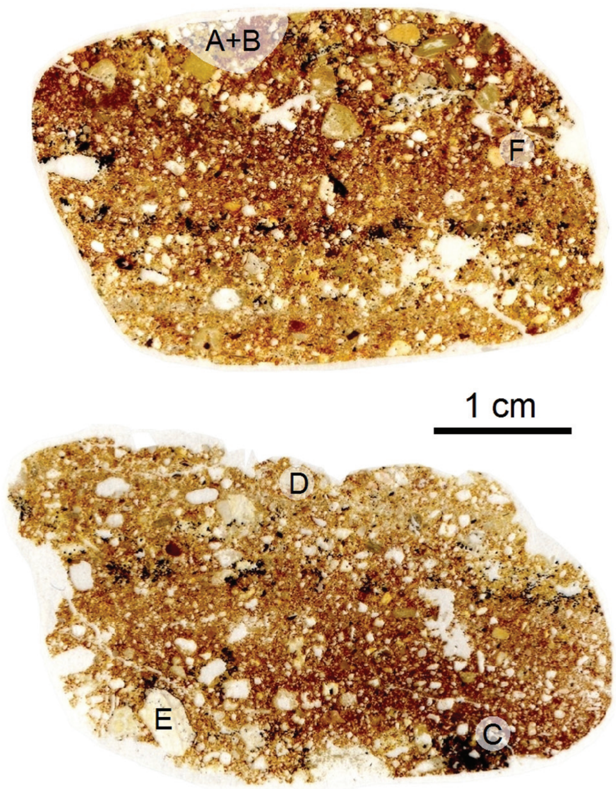

Fig. 3. Sections of rounded sandstone pebble from the Monheimer Höhensande that exhibits layering and grading of well-sorted components. A) The pebble exhibits layering and grading and is well sorted. B) Layering, grading, and sorting are less distinct; for description of single components see Fig. 4.

et al. 2002; Figs. 5B and 5C). Allochthonous impact melt rocks from the ~229 Ma Paasselkä impact crater (Finland) recently described by Schmieder et al. (2008) were sampled in glacial till south of the crater. Furthermore, allochthonous cobbles of impact melt rock were recently collected by the authors in Quaternary till several kilometers southeast of the Manicouagan impact structure (Québec, Canada).

Simonson and Glass (2004) provide a summary of depositional processes associated with the formation of terrestrial spherule layers. Ejecta layers rich in impact spherules, shocked minerals, and glass particles have been described from the Cretaceous-Paleogene boundary all over the world and interpreted as a fireball layer proximal to the ~200 km Chicxulub crater (Yucatán, Mexico) and as distal ejecta at distances >5 crater radii. Submarine reworked ejecta of the Cretaceous-Paleogene boundary with shocked mineral grains and glass fragments have been interpreted as tsunami deposits (e.g., Maurrasse and Sen 1991; Smit 1999) or as transported and deposited in turbiditic gravity flows triggered by the Chicxulub impact (Bralower et al. 1996). King and Petruny (2008) reported gravity-driven resedimentation of reworked impact spherule-bearing sands of the marine Shell Creek section (Cretaceous-Paleogene boundary) in Alabama, USA. At the ~455 Ma old marine Lockne impact structure (Sweden), reworked impact ejecta are distributed within turbiditic resurge deposits (regionally referred to as "Loftarsten;" Fig. 5D; see Sturkell 1998). The Archean spherule layers in the Barberton Greenstone Belt (South Africa) and the Hamersley Basin (Australia) were interpreted as deposits of an impact-generated tsunami and subsequent wave reworking (e.g. Hassler and Simonson 2001; Hofmann et al. 2006). Reworked impact ejecta with shocked mineral grains in the Officer Basin (Australia) derived from the ~590 Ma old Acraman crater are most likely of wind-borne and mass-flow origin (Arouri et al. 2000). Weber and Watkins (2007) stated that the sedimentary Crow Creek Member (South Dakota and Nebraska, USA) contains reworked ejecta that indicate a resuspension event associated with the ~74 Ma old Manson (Iowa, USA) impact. At the <190 Ma old Viewfield impact structure (Saskatchewan, Canada), well-rounded shocked quartz grains are obviously detrital and were washed into their present location (Grieve 2006). Osinski and Lee (2005) described shocked quartz grains reworked from impact melt breccias in fluvioglacial post-impact sandstones of the ~39 Ma old Haughton impact structure (Nunavut, Canada). Glidden et al. (2004) reported reworked, sub-angular shocked quartz grains with PDFs, as well as fragments of probably altered glass or recrystallized glassy impactites in uppermost Eocene fluvial sandstones from the coastal plain of Texas. Reworked impact ejecta were also reported from Upper Eocene coastal plain sediments in Georgia, linked with the ~35.7 Ma old Chesapeake Bay impact (Harris et al. 2004). Schultz et al. (1998) described enigmatic glasses ("Chapadmalal escorias") subjected to fluvial reworking, ascribed to a postulated mid-Pliocene impact in the Argentine Pampas. Anyway, there is neither a candidate structure as source for these ejecta nor any information on transport distances of the reworked material. An ~214 Ma old (probably Manicouagan-derived) Upper Triassic impact ejecta layer in southwestern Britain also exhibits sedimentological signs of reworking (Walkden et al. 2002).

Reworked impact glass in the form of tektites, however, has been described from several tektite strewn fields on Earth. These coarse grained impact glass bodies, often centimeters in size or even larger (e.g., indochinites, Haines et al. 2004), may be incorporated into sand and gravel of tsunami flood deposits (Haines et al. 2004). Tektites of the Central European strewn field (Fig. 6) that even survived multiple fluvial reworking have been reported from the Czech Republic (moldavites) Bouška (1964, 1988) and from Lusatia (Lusatian tektites) by Lange (1996).

DISCUSSION

Impact ejecta reworked by glacial erosion and transported over significant distances have been often

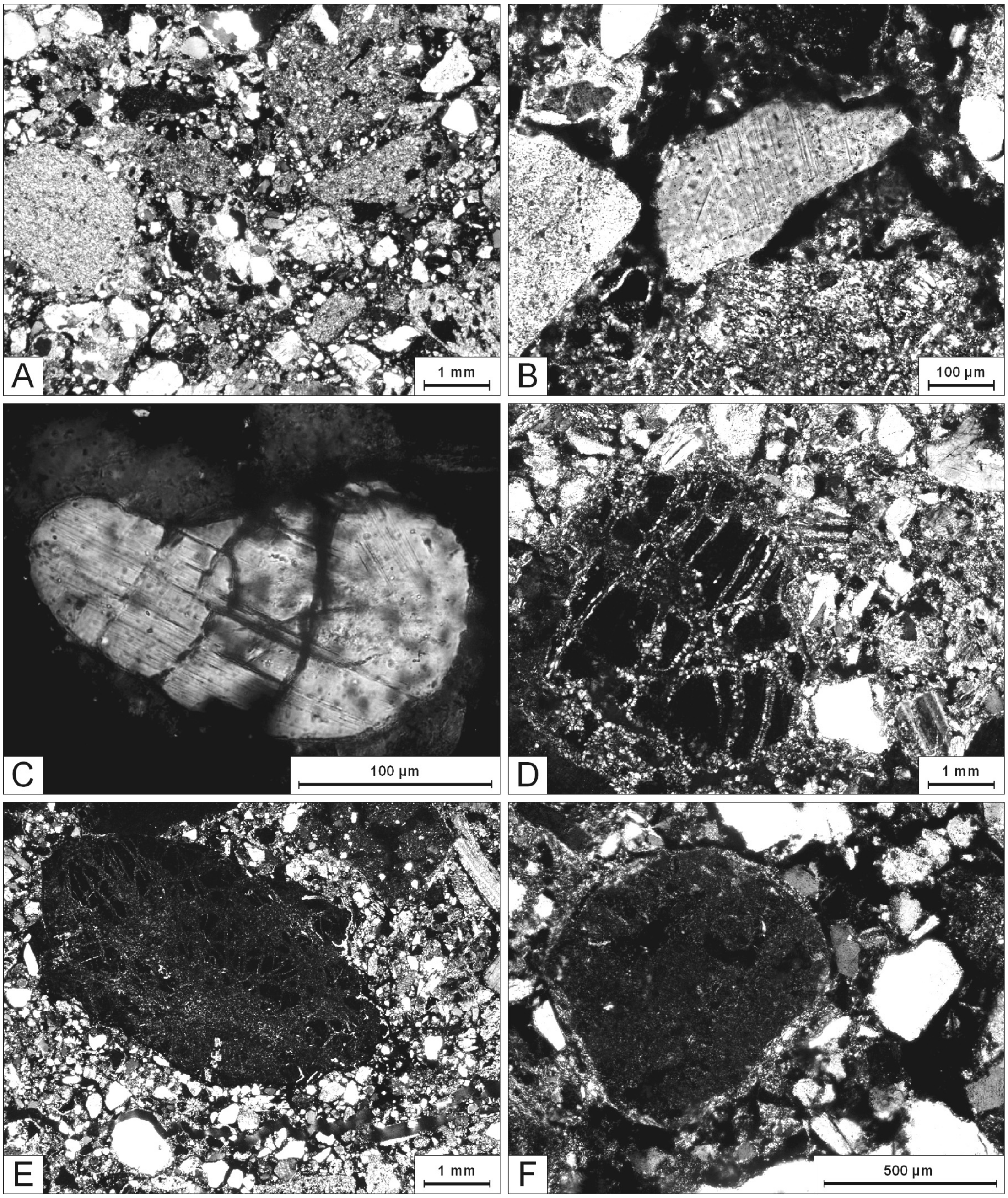

Fig. 4. Photomicrographs (cross polarized light) showing components in sandstone pebbles of Monheimer Höhensande. A) Mineral grains (angular to well-rounded) and well-rounded sedimentary detritus (intra-sandstone pebbles). Most components show weathered rims; the sandstone is grain-supported. B) Poorly rounded shocked quartz grain surrounded by goethitic groundmass. C) Well-rounded shocked quartz grain with planar fractures and planar deformation features. D) Roundish grain of diaplectic feldspar glass partially recrystallized. E) Rounded grain of diaplectic quartz glass (center) and sub-angular suevite fragment (top right). F) Well-rounded, altered glass particle with distinct alteration rim; see Fig. 3 for location of A–F.

described in the literature; the ejecta components may exhibit shocked mineral grains and glass particles in pebbles and cobbles of suevites and impact melt rocks (e.g., Abels et al. 2002; Grieve 2006; Schmieder et al. 2008). Fine-grained and rounded components of fresh impact glass have not been reported in glacial deposits. Sediments derived from impact ejecta reworked and redeposited by tsunamis or turbidites commonly contain angular to sub-angular shocked mineral grains, as well as impact spherules and, occasionally, fresh impact glass (e.g., Smit 1999). Wave reworking may cause mechanical rounding of shocked quartz grains. Sediments reworked by fluvial processes or wave action are unlikely to contain unaltered glass particles. Shocked quartz grains are thought to become fragmented along planar fractures and,

Table 1. Synopsis of the occurrence of reworked impact ejecta compiled from the literature and the present study.

Locality	Reworked material	Reworking process	Associated impact structure	Age of the impact event	References
Till southeast off site the crater (Québec, Canada)	Melt rock boulders	Glacial	Manicouagan (Québec, Canada)	~214 Ma	e.g., Grieve (2006); this study (Fig. 5A)
Till at the Massey Bay area south of the Lake Wanapitei (Ontario, Canada)	Suevite boulders	Glacial	Wanapitei (Ontario, Canada)	~37 Ma	e.g., Grieve (2006); this study (Fig. 5B)
Hietakangas sand and gravel pit several kilometers south of the crater (Finland)	Suevite boulders	Glacial	Lappajärvi (Finland)	~73.3 Ma	Abels et al. (2002); this study (Fig. 5C)
Till at the Sikosärkät pit southeast of the crater	Melt rock boulders	Glacial	Paasselkä	~229 Ma	Schmieder et al. (2008)
Barberton Greenstone Belt (South Africa), Hamersley Basin (Australia)	Archean spherule layers	Tsunami and subsequent wave reworking	?	?	e.g., Hassler and Simonson (2001); Hofmann et al. (2006)
Several localities in the Lockne impact crater	Shocked mineral grains, glass fragments ('Loftarsten')	Marine turbiditic resurge deposits	Lockne (Sweden)	~455 Ma	e.g., Sturkell (1998); this study (Fig. 5B)
C/P boundary, Gulf of Mexico region (Mexico, Belize) and Haiti	Shocked mineral grains, glass fragments, spherules	Tsunami	Chicxulub (Mexico)	~65 Ma	e.g., Maurasse and Sen (1991); Smit (1999)
C/P boundary, Gulf of Mexico and Caribbean region	Shocked mineral grains, glass fragments, spherules	Marine turbiditic gravity flow	Chicxulub (Mexico)	~65 Ma	Bralower et al. (1996)
C/P boundary, Shell Creek section (Alabama, USA)	Spherule-bearing sands	Marine gravity flow	Chicxulub (Mexico)	~65 Ma	King and Petruny (2008)
Crow Creek Member (South Dakota and Nebraska, USA)	Shocked mineral grains	Marine resuspension	Manson (Iowa, USA)	~74 Ma	Weber and Watkins (2007)
Officer Basin (Australia)	Shocked mineral grains	Mass-flow	Acraman (Australia)	~590 Ma	Arouri et al. (2000)
Haughton crater (Nunavut, Canada)	Shocked quartz grains	Fluvioglacial	Haughton crater (Nunavut, Canada)	~39 Ma	Osinski and Lee (2005)
Coastal plain sediments (Texas and Georgia, USA)	Shocked quartz grains, altered or recrystallized glass particles	Fluvial	Chesapeake Bay (Virginia, USA)	~35.7 Ma	Glidden et al. (2004); Harris et al. (2004)
Viewfield crater (Saskatchewan, Canada)	Shocked quartz grains	Fluvial	Viewfield crater (Saskatchewan, Canada)	<190 Ma	Grieve (2006)
Bristol and Warwick (England)	Spherules, shocked mineral grains	Fluvial?	Manicouagan (Québec, Canada)?	~214 Ma	Walkden et al. (2002)
NE Thailand	Indochinites (Australasian tektites)	Tsunami	?	~0.8 Ma	Haines et al. (2004)
Several localities in the Czech Republic	Moldavite tektites (Central European tektites)	Fluvial	Nördlinger Ries (Germany)	~14.4 Ma	e.g., Bouška (1964, 1988); this study (Fig. 6)
Several localities in the Lusatia area (Germany)	Lusatian tektites (Central European tektites)	Fluvial	Nördlinger Ries (Germany)	~14.4 Ma	e.g., Lange (1996)

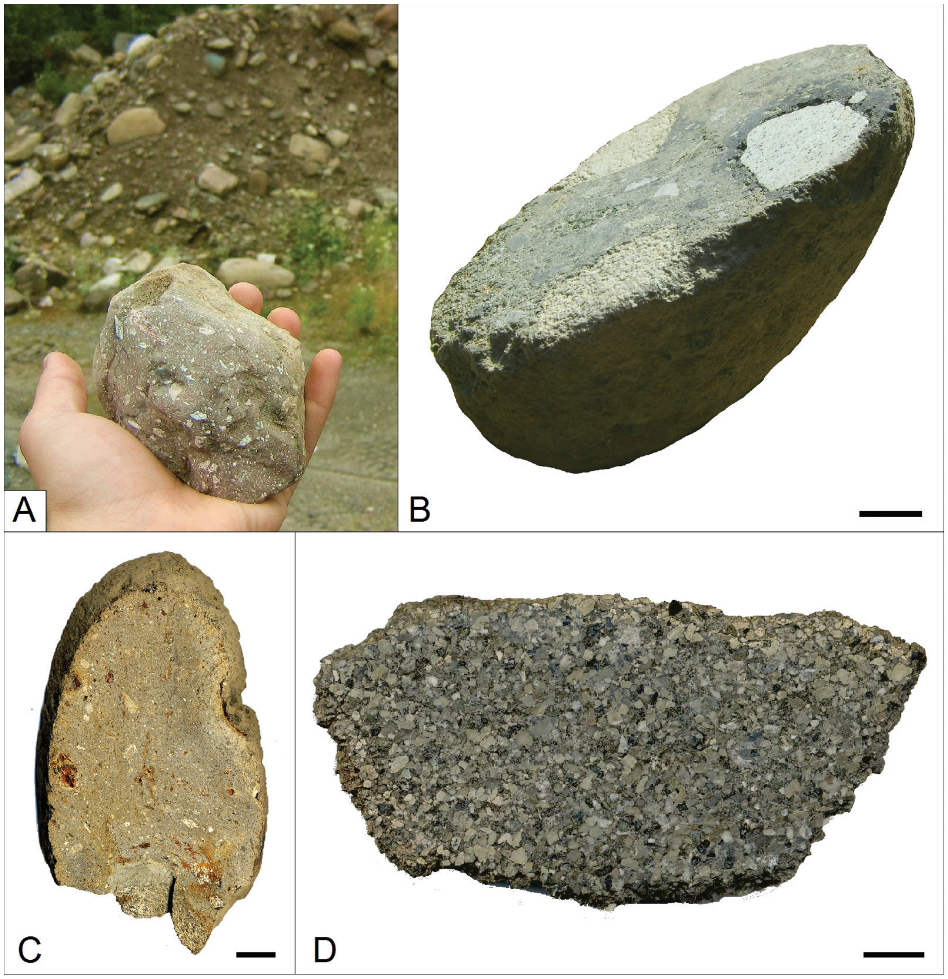

Fig. 5. A) Poorly rounded melt rock boulder from the Manicouagan impact structure (Québec, Canada), removed from glacial till southeast off site the crater. B) Well-rounded suevite boulder from the Lake Wanapitei impact structure (Ontario, Canada), recovered from glacial till in the Massey Bay area south of the crater. C) Slice of a well-rounded suevite boulder from the Lappajärvi impact structure (Finland), taken from glacial till of the Hietakangas sand and gravel pit several kilometers south of the crater. D) Marine "resurge arenite" (Loftarsten) from the Lockne impact structure (Sweden); scale bar is 1 cm.

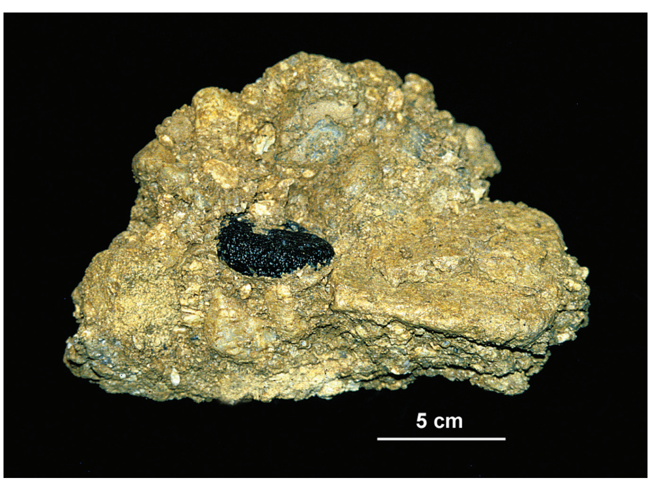

Fig. 6. Reworked moldavite (Ries tektite) embedded in a coarse-grained fluvial conglomerate from Chlum and Malse, a locality in the Chech Republic (Central European tektite strewn field).

thus, considered to be unstable when eroded and transported in a fluvial system; impact glass in contact to fluids tends to alter to clay minerals. Impact ejecta modified by post-impact fluvial processes (i.e., reworked fresh impact glass in fluvial sediments) are only sparsely mentioned in the literature (e.g., Glidden et al. 2004).

Except for multiply reworked tektites (e.g., moldavites; Bouška 1988 and others), this is the first petrographic description and sedimentologic interpretation of impact glass-bearing ejecta that show evidence of multiple fluvial reworking. Compared to primary suevite, the most obvious difference is the occurrence of clast-supported and commonly well-rounded components in the sandstone pebbles studied. Further strong arguments for the sedimentary origin of the pebbles is layering and grading, as well as the presence of a goethite matrix and weathered rims around clasts. A high content of sedimentary rocks would be atypical for suevite but further supports the assumption that reworked Bunte Breccia

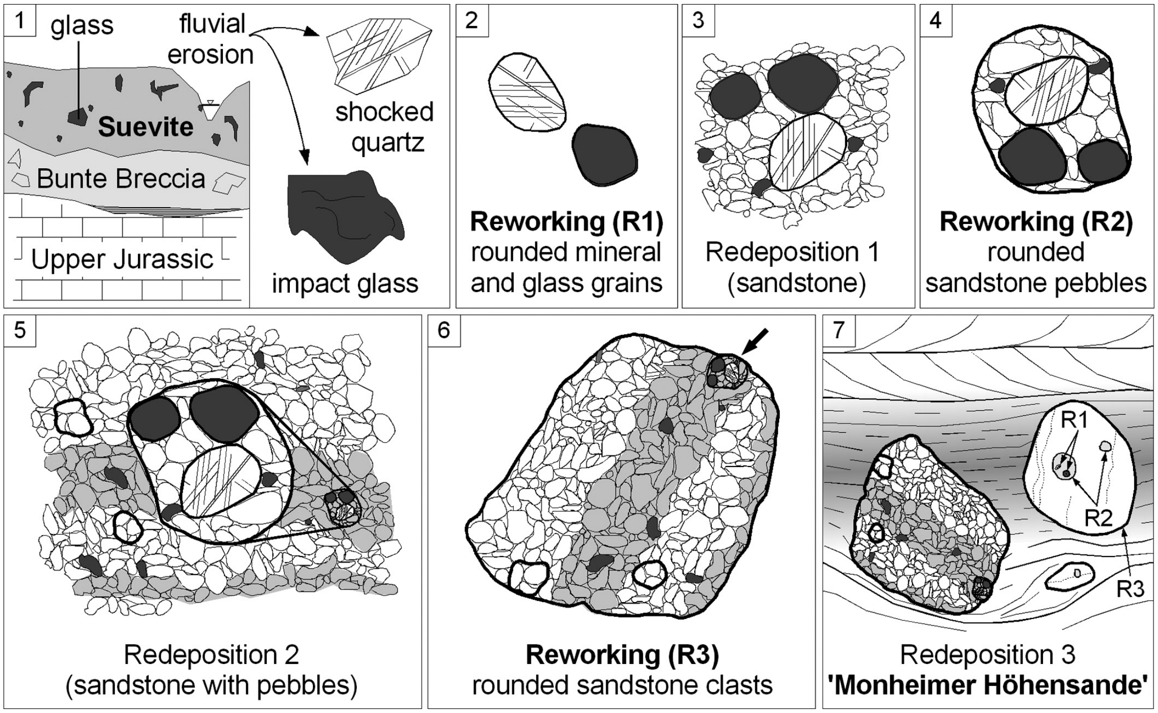

Fig. 7. Depositional history of sandstone pebbles in Monheimer Höhensande. 1–3) Suevite was eroded and redeposited together with detritus of Bunte Breccia and Mesozoic-Cenozoic sedimentary components (R1). 4–5) Sandstone with shocked mineral grains and suevite fragments was eroded and redeposited (R2). 6–7) Sandstone was eroded and pebbles were transported by the "Monheim Paleoriver," finally deposited within the Monheimer Höhensande (R3).

is admixed. In addition, well-rounded and unshocked components could originate from reworked pre-Ries sediments eroded and transported in Cretaceous to Miocene times.

Well-rounded lithic clasts with subordinate shocked mineral grains (in particular grains of diaplectic quartz and feldspar glass; Figs. 4D–F) in the sandstone pebbles suggest the following: 1) due to the high-stage shock metamorphic features, these clasts most likely do not originate from Bunte Breccia but from suevite; 2) as some grains are highly shocked whereas most grains in the same intra-sandstone pebble are unshocked, these components do not represent shocked sedimentary rock clasts inherited from suevite; 3) we exclusively detected diaplectic quartz and feldspar glass (no fluidal impact glass) in the sandstone pebbles, which suggests that fluidal impact glass is less resistant to erosion during fluvial transport compared to diaplectic glass. It remains speculative whether diaplectic glasses are more stable to (fluvial) erosion and transport in general; a possible explanation could be the specific physical properties of diaplectic compared to normal impact glass (i.e., a crystallographic "memory effect" responsible for preferential internal recrystallization of diaplectic glass as earlier suggested by Stöffler and Langenhorst 1994); 4) the sandstone pebbles deposited in the fluvial Monheimer Höhensande contain components of reworked Ries suevite and, in addition, host reworked intra-sandstone clasts with suevite particles, diluted by non-impact material. Thus, our observations indicate multiple fluvial reworking of Ries suevite. We exclude that the shocked quartz grains stem from sandstones rounded prior to shock-metamorphism, due to the fact that most of the sedimentary cover of the target area was incorporated into the Bunte Breccia and remained widely unshocked (e.g., von Engelhardt and Graup 1984).

The depositional history of the sandstone pebbles can be reconstructed as follows: suevite and Bunte Breccia were a) eroded and reworked subsequent to the Ries impact event. Shocked and unshocked rock clasts and mineral grains were mixed and redeposited together (compare to Fig. 7, steps 1–3). Diagenesis produced a first-generation sandstone which was b) eroded, reworked and again consolidated (Fig. 7, steps 3–4). Rounded clasts of this second-generation sandstone together with additional debris of suevite, Bunte Breccia, and Mesozoic to Cenozoic sedimentary rocks were c) reworked once again and formed a third-generation sandstone deposit (Fig. 7, steps 5–6). A braided river system (the "Monheim Paleoriver") d) eroded parts of this sandstone, reworked, and finally deposited the sandstone pebbles together with the fluvial sediments of the Monheimer Höhensande (Fig. 7, steps 6–7).

The proximity between the areas of erosion and resedimentation can be considered as one of the main reasons for the survival of highly shocked quartz grains and glassy ejecta components. The scenario of multiple (minimum three-fold) fluvial reworking of ejecta-bearing sediments probably took place in a limited area of some tens of square kilometers; short-range (probably a few km) and comparatively steep gradients of erosion and transport can be assumed for each reworking step (R1–R3, compare to Figs. 1 and 7). Multiple fluvial reworking of impact ejecta is the expression of a water distribution network that initially developed in a landscape strongly shaped by the Ries impact event and concomitant emplacement of proximal ejecta. A high groundwater level coupled with warm "subtropical" climatic conditions in the Miocene (Böhme et al. 2001) gave rise to the formation of the Ries crater lake and further lakes (e.g., the large Miocene Rezat-Altmühl lake) dammed by Ries ejecta, as well as to the recovery of the pre-impact drainage system (i.e., the N-S trending Paleo-Main river in the area of the Monheimer Höhensande; Hüttner and Schmidt-Kaler 1999). The ejecta blanket (mainly Bunte Breccia and suevite) was initially affected by small watercourses and/or torrential rain events leading to incipient erosion of small portions of ejecta that, in turn, were resedimented nearby. Subsequent incision of southward-directed major drainage systems followed. One of these fluvial systems eroded a considerable portion of the ejecta blanket and suevite-bearing sandstones east of the Ries crater in multiple steps and finally deposited the Monheimer Höhensande including reworked impact ejecta. Incorporation of the sandstone pebbles into a thick mudstone layer provided the conditions for excellent preservation of these pebbles.

The maximum distribution of suevite reach to a distance of ~22 km from the Ries crater rim (e.g., Hüttner and Schmidt-Kaler 1999); today, only a few single and isolated patches of suevite are conserved in the Monheim area (~10 km east of the crater; Gall et al. 1977). As components of Bunte Breccia, as well as of suevite, are incorporated into Monheimer Höhensande, the suevite blanket originally covered the Monheim area after the impact event.

CONCLUSIONS

Soon after the Ries impact event, an initial water distribution network developed in a landscape shaped by the Ries ejecta blanket. Proximal impact ejecta (Bunte Breccia and suevite) became eroded, transported, and redeposited by local watercourses, in multiple steps. The "Monheim Paleoriver" finally incised into Ries ejecta and ejecta-bearing sandstone bodies. Lithic clasts of Bunte Breccia, suevite, as well as sandstones that host rounded particles of diaplectic glass and shocked minerals were incorporated as pebbles into mudstones of the Monheimer Höhensande; a minimum of three steps of fluvial reworking can be retraced. Due to notably short-range reworking and redeposition, sandstone pebbles of various generations exhibit an exceptionally fresh state of preservation. The occurrence of single rounded impact glass fragments in fluvial deposits that were initially eroded from suevite and repeatedly reworked, shows that impact glass fragments can, under ideal circumstances, survive multiple fluvial erosion and redeposition.

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