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Density current origin of a melt-bearing impact ejecta blanket (Ries suevite, Germany)

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ABSTRACT

Melt-bearing clastic deposits (suevites) at impact craters have traditionally been regarded as plume fallout deposits. We present new field, textural, and chemical evidence that the subcircular blanket of suevite at the type locality, the Ries impact crater, Germany, was emplaced by a radial, granular fluid–based particulate density current, analogous to those that form ignimbrites of volcanic origin. Newly mapped chemical zoning patterns in the blanket record the response of the current to changing topography during the earliest modification stages of impact crater formation. The eastern sector of the suevite blanket has a different high field strength element composition than the western sector. The crater-fill facies also shows vertical gradational zoning that records changes in the composition of suevite deposited with time. The lateral zoning is best explained by radial outflow of the density currents, but changes in the crater topography caused the flow directions of the melt-bearing density current to change (return flow). The later convergence of flow paths allowed more thorough mixing in the crater, and is recorded by the more uniform composition of the later deposited upper parts of the crater-fill suevite. Emplacement by density currents is indicated by (1) topography-influenced (ponded) thickness variations of the suevite sheet, (2) very poor sorting, (3) matrix support, (4) massive nature, (5) subtle coarse-tail grading, (6) abundant elutriation pipes, (7) abundance of broken and whole matrix-supported concentric-laminated accretionary lapilli in uppermost parts, and (8) an inverse-graded basal layer with low-angle cross-stratification. These are classic features of deposits from granular fluid–based density currents, such as ignimbrites deposited by pyroclastic density currents at explosive caldera volcanoes, but differ markedly from fallout deposits worldwide.

INTRODUCTION

Melt-bearing impact breccias (suevites) are one of the most important records of impact cratering, which is a fundamental geological process in the solar system. This rock type records various aspects of impact-induced rock comminution, different degrees of shock-metamorphism including melting, and the dynamics of crater formation (e.g., Stöffler et al., 2013). The way in which suevites (including the type example at Ries crater, Germany) are formed and deposited is not well understood, despite their petrogenetic importance (e.g., Meyer et al., 2011; Stöffler et al., 2013). Previous hypotheses for the origin and/or emplacement of the Ries suevite are (1) collapse of an ejecta plume (e.g., Engelhardt, 1997), (2) deposition via a density flow (Newsom et al., 1990) or lateral flow (Bringemeier, 1994; Meyer et al., 2011), (3) deposition from an impact melt flow (Osinski, 2004), and (4) collapse of post-impact phreatomagmatic plume or plumes caused by fuel-coolant interaction (FCI) of an impact melt sheet with water or an aquifer (Stöffler et al., 2013; Artemieva et al., 2013).

This paper presents the results of a study to investigate how the Ries suevite was emplaced, using geochemistry and techniques adapted from physical volcanology. Deposit-scale chemical zoning patterns through the suevite blanket are documented, along with the depositional structures and particle textures. This new approach of combining geochemical zoning and field and textural data facilitates a new interpretation for the emplacement of the Ries suevite. This has implications for our understanding of impact deposits elsewhere.

FIELD AND TEXTURAL CHARACTERIZATION OF THE RIES SUEVITE

The ca. 15 Ma impact crater at Nördlingen (Ries) in Germany is 26 km in diameter and has features typical of moderate-sized craters (e.g., Wünnemann et al., 2005). The target rocks are a varied crystalline basement overlain by a sedimentary cover as much as 600 m thick. The impact ejecta comprises a lower layer of lithic breccia (the Bunte Breccia) sharply overlain by a clastic deposit (here termed suevite) that contains former melt particles and target-rock lithic clasts. The suevite blanket extends from within to beyond the crater (crater suevite to outer suevite; Stöffler et al., 2013; Fig. 1A). The lower part of the impact melt–bearing deposit in the crater is a coarser grained proximal facies (impact melt breccia) with a remnant vitrophyric matrix between large fluidal-shaped clasts (Reimold et al., 2013), interpreted here to be a welded, coarse-grained proximal facies of the suevite, similar to coarse welded scoria agglomerates in proximal facies of some large ignimbrite sheets (Branney and Kokelaar, 2002, their figure 5.4).

The thickness of the suevite ranges from 10 to 400 m, according to the underlying inner ring and central crater basin topography (Pohl et al., 1977). Thickness variations of the outer suevite also correspond with the underlying topography, from 90 m in the megablock zone between the inner ring and the crater rim, and from 20 to 2 m beyond the crater rim. Most of the suevite is massive and nongraded, with former melt particles and angular rock fragments supported in a poorly sorted fine-grained matrix (Fig. 1B). There are local subtle vertical and lateral coarse-tail grading patterns (Branney and Kokelaar, 2002, their figure 5.6). Well-developed subvertical elutriation pipes are abundant in the upper parts (Fig. 1D; Engelhardt et al., 1995), and the lowest 4 cm are locally inverse graded and exhibit diffuse low-angle splay-and-fade cross-lamination (Fig. 1F). Abundant accretionary lapilli occur within the uppermost parts of crater suevite (Graup, 1981; Newsom et al., 1990).

CHEMICAL ZONING PATTERNS OF BULK SUEVITE AND CONSTITUENT CLASTS

We present the first detailed trace element study of Ries suevite and its various components (Item DR1 in the GSA Data Repository[1]). The major element composition of the suevite predominantly reflects the crystalline basement

[1]GSA Data Repository item 2017285, Item DR1 (outer suevite chemical data), Item DR2 (Ce, Zr suevite whole-rock versus suevite components diagrams), Item DR3 (Th-Nb diagram analogous to Fig. 3), Item DR4 (crater suevite chemical data), Item DR5 (Ce, Zr histograms of Ries impact target lithologies), and Item DR6 (photo locations Fig. 1), is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

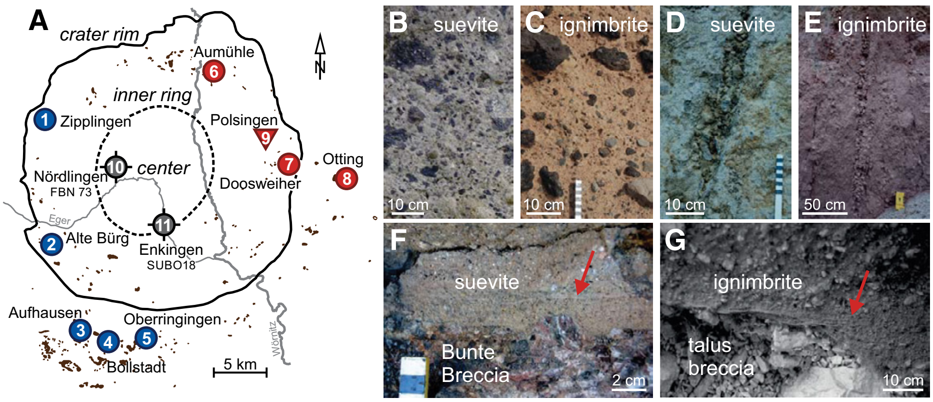

Figure 1. A: Simplified geological map of the Ries crater, Germany (48°53′N, 10°37′E) displaying outer suevite exposures (in brown). Sample locations: 1–5—outer suevite in the western part; 6–8—outer suevite in the eastern part; 9—impact melt breccia; 10 and 11—crater suevite drill cores. B: The very poorly sorted, matrix-supported massive nature of the Ries suevite is strongly indicative of deposition from a granular fluid–based density current. It closely resembles the deposit shown in C. C: Typical ignimbrite deposited from pyroclastic density currents at volcanoes. D: Subvertical elutriation pipes of the Ries suevite; they are similar to the pipes shown in E. E: Subvertical elutriation pipes common in ignimbrite deposited by fluid-escape-dominated deposition from pyroclastic density currents. F: The sharp base of the Ries suevite with inverse grading and diffuse low-angle cross-stratification with splay-and-fade lamination (arrow) records deposition from lateral density currents. It is very similar to the deposit shown in G. G: Low-angle splay-and-fade stratified ash (arrow) that coarsens upward to massive lapilli tuff, seen widely in ignimbrites deposited from pyroclastic density currents (Item DR6; see footnote 1).

lithologies (Stöffler et al., 2013). Major elements may have been affected by post-impact hydrothermal alteration (e.g., Osinski et al., 2001), so we focus on the less mobile trace elements. The whole-rock composition of suevite depends upon the relative proportions of the diverse constituent lithic and former melt clasts, including those making up the matrix. To distinguish the effects of clast composition versus the relative proportions of the components, we have analyzed both the whole rock and the individual components of the suevite at several locations (Item DR1). The study reveals the following new features.

1. Former melt particles, matrix, and whole-rock data of the outer suevite exhibit similar compositional ranges of immobile trace elements at each individual location. The chemical similarity of the vitric clasts and the matrix in a sample suggests that they represent the same origin (Item DR2). This indicates that the whole-rock immobile trace element data of the suevite are not significantly affected by the proportions of the constituent particles, and faithfully record the compositions of the target rock components that contributed to its formation.

2. The most pronounced deposit-wide variations in suevite chemistry, least affected by hydrothermal alteration, occur in the least mobile trace high field strength elements (HFSEs), including the light rare earth elements (LREEs). We selected Zr and Ce, the most commonly analyzed and suitable representatives of HFSEs (see other chemical data in Items DR1–DR4). Ce and Zr contents also are reasonable proxies for how evolved the crustal target rocks are. The crystalline target rocks display a wide spectrum of trace element compositions (Schmitt et al., 2017; e.g., 32–583 ppm Zr, 11–293 ppm Ce), whereas the suevite samples have a more restricted range of whole-rock compositions due to mixing (Figs. 2 and 3; Item DR3), although they still preserve significant variations (86–285 ppm Zr and 26–118 ppm Ce).

3. The composition of the suevite ejecta blanket varies geographically around the impact crater in a systematic, asymmetric way; in the east, the outer suevite and lower crater suevite have higher Zr and Ce values than in the west (Fig. 3).

4. Within the crater the suevite also shows systematic gradational vertical compositional zoning (Fig. 2; Item DR4). Zirconium values increase with height in the west of the inner crater, whereas they decrease with height in the southeast of the inner crater. Thus, the uppermost parts of the crater suevite are closer in composition to each other than are the lower parts (Fig. 3).

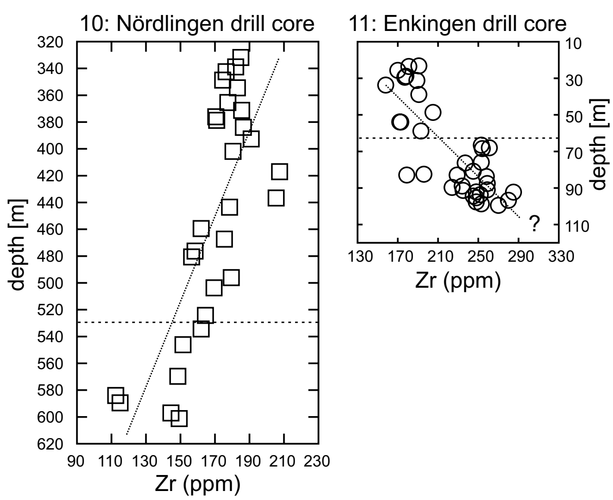

Figure 2. The crater suevite of the drill cores Nördlingen (10) and Enkingen (11) shows vertical trace element zoning exemplified by Zr contents. The dashed lines subdivide the drill cores into bottom and top parts used for averages shown in Figure 3. Question mark at Enkingen location indicates that drilling ended before contact to crystalline basement was reached (data from Reimold et al., 2013).

DISCUSSION: EMPLACEMENT OF SUEVITE

Any robust model of suevite emplacement must be consistent with the textural, field, and chemical data described here. A suevite origin via fallout from an impact-generated or subsequent FCI-induced plume is incompatible with the following six features. (1) The marked thickness variations that correspond to the underlying topography contrast markedly with fallout deposits, which drape topographic irregularities and decay in thickness systematically with distance from source (Cioni et al., 2015). (2) The local presence of low-angle cross-lamination (Fig. 1F) indicates tractional processes at the base of a particulate current (Branney and Kokelaar, 2002); fallout deposits lack cross-lamination. (3) The very poor sorting and the matrix support (Fig. 1B) are in marked contrast with typical fallout deposits, which are well sorted with framework support (Cioni et al., 2015). (4) Abundant elutriation pipes (Fig. 1D) do not occur in fallout deposits. (5) Whole and broken fragments of accretionary lapilli are supported in the suevite matrix. These contrast with aggregates in fallout deposits, which typically comprise framework-supported dust pellets that do not exhibit brittle breakage (Brown et al., 2010). (6) Modeling (Artemieva et al., 2013) suggests that the mass of the Ries suevite is too great to be reconciled with fallback from an initial impact-generated buoyant ejecta plume.

We propose that topographic ponding within a crater, very poor sorting, matrix support, and elutriation pipes are all classic characteristics of deposits derived from ground-hugging particle-bearing gaseous density currents, such as radial pyroclastic density currents that deposit ignimbrite sheets (Branney and Kokelaar, 2002). The massive, very poorly sorted nature of the

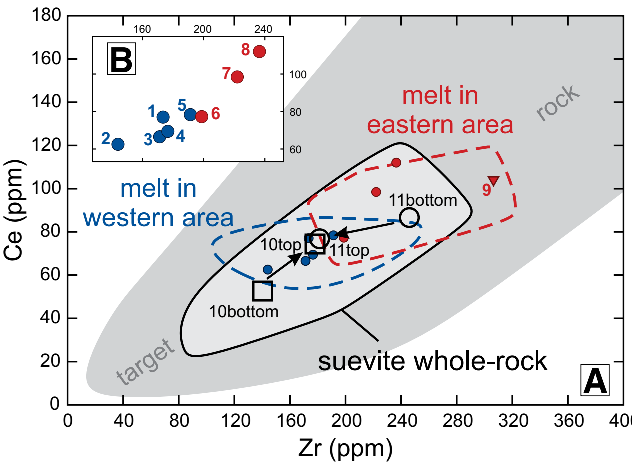

Figure 3. A: Zr-Ce diagram of Ries target rock (gray field, top right shortened), suevite whole-rock (solid line), and impact melt (dashed lines). Blue dots show average outer suevite whole-rock of each locality in the western area; red dots are average outer suevite whole-rock of locality in the eastern area; red triangle shows average impact melt rock at Polsingen with numbering from Figure 1. Open squares and circles with arrows represent the chemical trend from bottom (average) to top (average) of suevite whole-rock of both drill cores, with subdivision as shown in Figure 2 and numbering of localities as shown in Figure 1A. B: Detail of A; sample localities as in Figure 1A.

suevite and local coarse-tail grading indicate that deposition was from a granular fluid–based density current in which particle segregation, fluid turbulence, and associated tractional processes were suppressed by high particle concentrations within the current lower flow boundary zone (Branney and Kokelaar, 2002). This interpretation is supported by the presence of abundant subvertical elutriation pipes (Fig. 1E), also a characteristic of ignimbrites deposited by granular fluid–based pyroclastic density currents (Druitt, 1995). Thin inverse-graded basal layers with local, low-angle splay-and-fade cross-lamination (Fig. 1G) are widespread features of otherwise massive deposits of pyroclastic density currents (Branney and Kokelaar, 2002, their figure 6.16). Locally scattered, discontinuous concentrations of matrix-supported accretionary lapilli with angular broken fragments are common in the upper parts of deposits of pyroclastic density currents (Brown et al., 2010) where the breakage is by attrition from high-velocity particle impacts in the current. In summary, the textural and field characteristics of the Ries suevite strongly suggest deposition from radial, granular fluid–based density currents.

There is no evidence in the Ries suevite sheet for deposition of successive, smaller FCI-induced secondary explosion plumes (Osinski et al., 2016), as has been suggested (Artemieva et al., 2013; Stöffler et al., 2013). Successions of discrete fallout events generally leave distinctive evidence in the form of multiple fallout layers bounded by bedding planes.

The chemical zoning patterns in the suevite are best explained by deposition from a sustained density current (Williams et al., 2014; Fedele et al., 2016), in which the flow directions changed with time in response to a rapidly evolving crater topography. The consistent trace element chemistry of the suevite components at individual sites indicates that thorough mixing of particles occurred on a local scale during ejection and emplacement. However, the west-east chemical asymmetry across the sheet is thought to reflect heterogeneous basement target rocks; i.e., the target rocks in the west had lower HFSE (e.g., Zr, Hf, Th, Nb, LREEs) contents than those in the east. This chemical heterogeneity is documented by 185 analyses of target-rock fragments (Schmitt et al., 2017; Fig. 3; Items DR3 and DR5).

We propose that initial ejection of the suevitic material rapidly formed a gas-particle density current during the early excavation stage of the crater. This ejection may have been enhanced by degassing of volatile-bearing target lithologies (Thompson and Spray, 2017) and substantially enhanced by the very rapid post-impact pressure release (Collins et al., 2012). The ejected dispersion of gas and particles was too dense to loft through the atmosphere so it fountained, collapsing and dispersing outward as a radial density current (t$_1$ in Fig. 4). This happens at large explosive volcanic eruptions where ingestion and thermal expansion of atmospheric air are insufficient to enable the entire erupting dispersion to loft buoyantly (Sparks et al., 1978). Within the density current mixing occurred on a local scale, but the divergent flow paths meant that parts of the current flowing east did not completely homogenize with the westward-flowing parts of the current. Thus, opposite sectors of the suevite blanket partly retained their original signatures (e.g., higher Zr and Ce values in the east and lower Zr and Ce values in the west) that arose from asymmetry in the target-rock lithologies (t$_1$ in Fig. 4).

As the current flowed, the crater morphology was rapidly changing (t$_2$ in Fig. 4) with sagging of transient crater walls, movement of brecciated material around the transient crater cavity into the crater, and simultaneous collapse and outward flow of the gravitationally unstable central peak (e.g., Kenkmann et al., 2014). The density current responded to this changing topography by changing flow direction (return flow) such that centrally converging flow paths within the crater resulted in increased mixing during the later phases of the current. Uppermost parts of the crater suevite were deposited from this later, better mixed part of the density current, so its composition is laterally more uniform, and close to that of average Ries suevite (Fig. 3).

Our density current model for suevite emplacement finds additional support from fabric studies of the Ries outer suevite, where lateral transport is indicated by radial and concentric preferred orientations of elongate particles (Bringemeier, 1994; Meyer et al., 2011), and from granulometric data that plot in the pyroclastic density current field

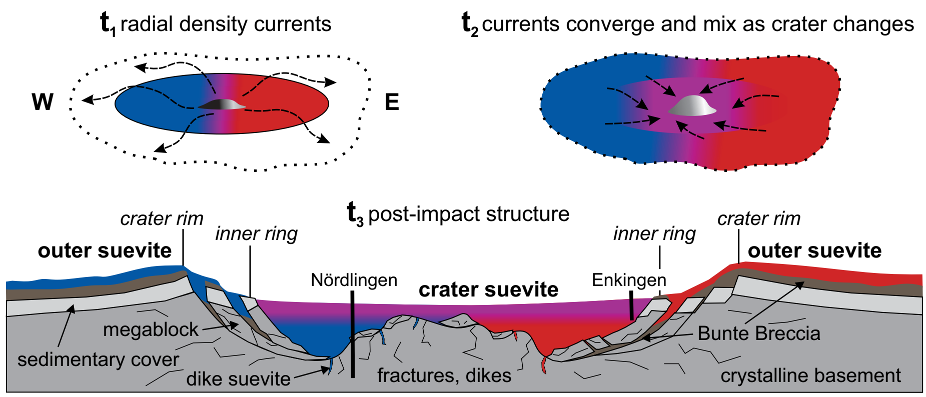

Figure 4. Model of origin and emplacement of Ries suevite. t$_1$: Initial radial outflow of suevite material at the excavation to early modification stage (supported by central peak uplift), preserving chemistry of western (blue) and eastern (red) target rock heterogeneities. t$_2$: Mixing within the crater (purple) during crater modification stage (central peak collapse). t$_3$: Schematic cross section of Ries impact crater after the impact (modified after Kenkmann et al., 2014) with positions of drill holes Nördlingen and Enkingen (dark gray is crystalline basement, light gray is sedimentary rock, brown is the Bunte Breccia, a polymict impact breccia). The outer suevite deposits and the lower part of crater suevite keep their original target lithology heterogeneities. The top of crater suevite (purple) represents the best mixed suevite (t$_2$) with a chemical composition close to average Ries suevite (Fig. 3).

of a sorting versus grain-size diagram (Meyer et al., 2008). It is also consistent with evidence from other suevite occurrences where deposition from impactoclastic density currents (Branney and Brown, 2011), debris flows (Kalleson et al., 2010), and horizontal movement (Välja et al., 2013) has been invoked.

CONCLUSIONS

Textural, field, and deposit-scale trace element zoning data indicate that the Ries suevite blanket was emplaced from a radial impactoclastic density current rather than by fallout or ballistic processes. High basal particle concentrations in the current suppressed tractional processes and resulted in the very poorly sorted and largely massive nature of the deposit. The high particle and ash contents in the lower flow boundary zone of the current may have helped maintain high fluid pressures by partly trapping interstitial gas, which aided mobility. During deposition, the interstitial gas was displaced up through the hindered settling dispersion, forming vertical elutriation pipes similar to those in ignimbrites. The density current was initially radial, preserving sectorial differences in composition, reflecting a heterogeneous target-rock basement. However, as the crater topography rapidly evolved, the flow directions of the current changed. Convergent return flow allowed improved homogenization of the current with time, recorded by vertical zoning of the crater-fill suevite, with more uniform compositions of the later deposited uppermost parts.

Melt-bearing deposits with similar textural characteristics at other impact craters may also have been emplaced by impactoclastic density currents, similar to the pyroclastic density currents of ignimbrite-forming volcanic eruptions (Branney and Brown, 2011). This has far-reaching implications for the way we model suevite emplacement during impact cratering events.

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