The Decorah Impact Structure, Iowa: A Case study for Assessing Target Water Depth and Paleoenvironment for past Marine Target Impacts in Presently Non-Marine Locations.

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ABSTRACT

Reconstructing paleoenvironments—particularly aquatic ones—is essential for identifying potential habitats for life, both on early Earth and early Mars. Impact craters often serve as effective sediment traps that are relatively shielded from erosion. In aquatic settings—most commonly in shallow marine environments—where seafloor craters can form, the return flow of water during the early stages of crater modification can produce distinctive "resurge deposits." Analyses of such deposits from drill cores at various marine-target impact structures, including the Decorah structure examined in this study, reveal a direct correlation between average clast frequency per meter, impact event magnitude (i.e., projectile diameter), and the depth of the target water. If two of these parameters are known, the third can be inferred. In this study, we analysed two drill cores obtained from the interior of the Decorah impact structure to gain insights into the paleoenvironment at the time of impact. Applying the aforementioned relationship yields

an estimated target water depth of 40–90 meters, thereby situating the Decorah paleoenvironment within a defined range of the ancient marine realm.

INTRODUCTION

Sedimentary strata is a primary source for information on past depositional environments, be it aeolian, fluvial, lacustrine, marine or other. However, most commonly the current environment is completely different from the one that prevailed during the deposition of the sediment. For instance, marine sediments cover today large land areas of our continents and their variations in facies, fossil content and other parameters have helped us reconstruct not only the local paleoenvironment, but also the regional, or even global, paleogeography. Nevertheless, it may be difficult to ascertain, for instance, other than maximum or minimum water depths for certain marine sediments. For this, impact craters have proven very useful. This is because many parameters regarding the cratering process and the resulting crater can be calculable in a way that is not allowed by other geological processes. One of the more well-known of the defined relations is that of the depth to diameter ratio of the impact crater. For instance, this proved useful when establishing the paleo-water depth at the time of the formation of the Ordovician Tvären Crater, Sweden. The occurrence of certain algae in the sediments that had been deposited on the elevated crater indicated a depositional depth within the photic zone, but calculations of the fresh crater rim height gave a more exact span of the water depth (Frisk and Ormö, 2007).

In addition to being relatively predictable in shape, impact craters also offer efficient sediment traps relatively protected from erosion. In aquatic ("marine") environments, water may rush back into the crater during early modification generating "resurge deposits" (Ormö et al., 2007). Studies of resurge deposits in drill cores from several impact structures show a direct relation between average clast frequency per meter (<N>), event magnitude (projectile diameter d) and target water depth (H) as

$$\langle N \rangle = -15(d/H) + 100 \quad (1)$$

for a "lower" (e.g. moat) location, or

$$\langle N \rangle = -13(d/H) + 150 \quad (2)$$

for a "higher," more turbulent ("washed") position where fines are kept in suspension longer (e.g., near rim or central uplift) (Ormö et al., 2021; Herreros and Ormö, 2022). These equations show us that unknown factors can be calculated, if the other two factors are known. This method of calculation was successfully applied on the Rochechouart impact structure, which had been the subject of debate as to whether it was marine-target or not due to lack of marine sediments in the area (Schmieder et al., 2010; Ormö et al., 2023). Here, we study two drill cores from the interior of the presently buried Decorah impact structure, Iowa (43.3136111000, -91.7719444444) (Fig. 1), so as to learn more about its paleoenvironment and how it affected the crater modification.

The 5.6 km Decorah impact structure is mostly buried under up to 26 m of the post-impact (i.e., post-resurge, cf. Ormö et al., 2010) Winneshiek Shale (Briggs et al., 2018), and also of up to about 100 m of younger sediments (See Fig. 3 in French et al., 2018). Except for some local deformation along the perimeter the impact structure (French et al., 2018), it has today no obvious topographic expression on the ground surface (Fig. 1), and there is no indication for a preserved elevated rim although this can be a result of later erosion (French et al., 2018). Likewise, Decorah seemingly lacks a central uplift, as might be expected for its size and sedimentary target in current crater-model scheme (e.g., Grieve, 1991). The sedimentary target's stratigraphic sequence, the graded beds within the crater infill, and the immediate post-impact deposition of the overlying, marine sediments (Winneshiek Shale) led French et al. (2018) to suggest the impact to have occurred in a shallow sea. The target was an Upper Cambrian and Lower Ordovician sedimentary succession of mainly sandstones and dolomites (French et al., 2018; Wolter et al., 2011). Briggs et al. (2018) estimate that there was also a cover by shallow seawater in a target area forming a near-

shore embayment of the Middle Ordovician epicontinental sea. Earliest post-impact infill of the overlying Winneshiek Shale places the impact in the Darriwilian (Bergström et al., 2018). Decorah is extensively drilled, but only two drill sites yielded cores useful for this study; the ~33 m "H2" core (43.3057160000, -91.7430820000), and the ~28 m "CS1" core (43.3051610000, -91.7965310000), both drilled only a few hundred meters inside the approximate location of the crater rim (Fig. 1).

MATERIAL AND METHODS

Only the two drill sites "Steve Hildebrand H2" and "Carl Selland Wayside Park CS1" (hereafter H2 and CS1) at Decorah offer enough core material to allow the type of logging technique applied in this study. We logged the polymict breccias of these 5-cm diameter cores because their observed grading (French et al., 2018) suggests the presence of marine resurge deposits within Decorah (cf. Ormö et al., 2007). The logged section of H2 spans 9.6 m from the bottom of the core at 33.19 m until the depth 23.59 m where the clast sizes become too small (<5 mm) for use in the line-logging method. Similarly, the CS1 core was logged from the bottom of the core at 80.47 m depth up to 58.52 m depth (~22 m logged length) for the same reason. However, for the topmost 1.5 m of the logged section of CS1, the clasts with sizes 5 mm or larger were too few to generate useful data. The remainder of both cores, above the logged sections, are comprised of post-impact Winneshiek Shale.

We adapted the line-logging technique previously used for the following craters -- Lockne, Tvären, Chesapeake Bay, Wetumpka, Chicxulub, Rochechouart, and Flynn Creek, (cf. Ormö et al, 2007, 2009, 2021, 2023; DeMarchi et al., 2019). For most of these craters, it was possible to work directly with the cores, but in this instance, similar to the Chicxulub study (Ormö et al., 2021), we used high-quality digital core photos and the software JMicroVision 1.2.7. Regarding the cores, it should be noted that core recovery in the logged intervals of H2 and CS1 was greater than 97%. As with other studies cited above, our data

were expressed as averages per length unit. In most of the previous studies cited above, that unit length was usually one meter, but in this instance, it is half a meter. This unit length was chosen in order to reveal more detail within the resulting graphs with regard to the relatively short intervals being logged. In the line logging method, size sorting calculates as the standard deviation of the clast size per unit length, and roundness is estimated with a grain shape comparator (cf. Mazzullo et al., 1988). Matrix-support versus clast-support in each instance is based on contact with adjacent clasts and plotted as a ratio per length unit. Clasts smaller than the 5-mm size cut-off are considered as part of the matrix. A noteworthy drop in number of clasts per meter, coupled with an equally notable increase in calculated matrix support of the grains despite a fine-grained, clast-supported visual appearance of the sediment, indicates the influence of the 5-mm cut-off. This influence reduces the reliability of the clast-size and matrix-support data above this level (cf. Ormö et al., 2007). This effect usually happens where the resurge deposits grade into post-impact secular sediments. One should bear in mind that the plotted values are intended to show relative variations indicating trends, and are not specifically about absolute values. It should be also noted that the depths given here generally refers to depths in the graphs of the logged sections, which merely are data points for the average number per half meter unless otherwise indicated.

In addition to the data on granulometry (e.g. size, shape) and sedimentology (e.g. grading, sorting, matrix support), clast colors were determined to enable an association with the target stratigraphy (cf. Ormö et al., 2021, 2023). Previous loggings of other craters have taught us that it is best to begin with a larger number of clast categories with as detailed descriptions as possible, and then later group them together into fewer clast categories, preferably supported by published descriptions of the target lithologies.

RESULTS

In the H2 core 416 clasts were examined, and in CS1 695 clasts. The mean clast size in H2 is 14 mm, and in CS1 27 mm. A selection of representative clasts, mainly from H2 that was logged first, is shown in Figure 2. There is no single clast category that completely dominates in the cores. However, there are four categories that stand out as having a huge difference in abundance between the cores. Clast categories 2 ("terracotta"), 4 ("white") and 9 ("dark green") are much more common in H2, but category 3 ("dark brown-gray") is more abundant in CS1 (Fig. 2). Figure 3 illustrates the transition in core H2 from the graded breccia into the overlying, post-impact Winneshiek Shale. The transition in grain size is very gradual, but approximately at depth 17.85 m there is an abrupt change from the pale color of the silt to the dark color of the shale. Figure 4 shows the plotted results from the logging of H2, and Figure 5 from CS1.

Whereas clasts of the colors that we term "terracotta" and "light gray" in H2 dominate in the drill core below 30.25 m (exact level 30.43 m, erosional contact, Fig. 6A), there is also an obvious change in clast lithologies within the interval 29.25–30.25 m (Fig. 4). In that interval, "white" clasts dominate but are then succeeded by dominant clast colors "dark green," "dark brown-red," "dark gray" and "light brown." On the other hand, "terracotta," "light tan-gray" and "light gray" clasts appear throughout the logged sequence.

The clast categories in CS1 have a more homogeneous distribution than in H2 except where it appears that there has been disintegration of a larger clast, thus causing a localized dominance of a single clast category. However, in general, it can be seen in Figure 5 how "dark brown-gray" clasts dominate below 68.8 m in the logged interval. At 73.5 m it is clear how a disintegrating block probably resulted in a nearly monomict breccia of "dark brown-gray" rock (Fig. 6B). This disintegration of larger blocks is probably the reason why the "dark brown-gray" clast category is three times more common in CS1 than in H2 (Fig. 2). Likewise, the abundance-curves of "light-tan gray" and "light brown" clasts show peaks at 73 m and 69 m respectively at locations of probable disintegrating blocks. Ultimately, the "dark brown-gray" gradually decreases towards the top. Similarly to H2, the "light tan-gray" and "light gray" are relatively continuous. However,

in this group the "white" and "terracotta" clasts are mysteriously absent (Figs. 2 and 5). Likewise, "dark green" is rarely present in CS1. The "dark brown-red" clast count increases upwards, as it does in H2, but the "dark gray" and "light brown" are instead categories with more continuous occurrence throughout the logged interval.

In Figures 4 and 5, the vertical trends in roundness (and thus angularity) are plotted. In both cores, the roundness-angularity scale measurements vary from about 1 to 2, with only one small exception around 29.2 m in H2. Figure 7 shows the roundness-angularity data for all the clast categories. In overview, among nearly all clast categories, core CS1 appears to have slightly more angular clasts than does H2. This is especially evident in the categories "light tan-gray," "light brown," and "terracotta." In addition to the here observed lithic clasts there is also the observation of French et al. (2018) of numerous rounded, sometimes shock metamorphosed, single quartz grains (≤2 mm), feldspar grains, and glauconite grains in the matrix of the cored breccia. These grains are too small to be observed in the photos used in this study, but are nevertheless important for our reconstruction of material provenance.

DISCUSSION

Reconstruction of the Mode of Deposition

In both cores, the logged intervals show a gradual grain-size decrease moving upward towards the transition to the overlying, post-impact Winneshiek Shale. Even so, there is a sharp color difference between the lighter colored resurge sand and the overlying shale, especially obvious at 17.85 m in the H2 core (Fig. 3). The abrupt change from the pale color of the silt to the dark color of the shale may, in addition to a darker color as a possible effect of finer grain size, also indicate a compositional change (e.g., organic carbon content) between resurge and post-impact secular sedimentation, which is similar to what has been observed and interpreted at the Lockne impact structure (Ormö et al., 2010). The plots of H2 in Figure 4 support the

observation of a general normally graded character of the breccia as noted by French et al., (2018). However, in CS1, this is mainly evident in the uppermost two meters of the logged interval (Fig. 5). When comparing with logs from other, aforementioned craters, where cores have reached through resurge deposits into underlying slump and avalanche breccias (e.g., Ormö et al., 2007, 2009, 2023; DeMarchi et al., 2019; Sturkell et al., 2013), it is evident that both H2 and CS1 end within resurge deposits. The transition into underlying avalanche breccias have been shown in other craters to stand out clearly in the graphs as a combination of extremely poor sorting, occurrence of conspicuously large blocks (i.e., -phi-values greatly exceeding the average), and commonly dominated by one lithology (e.g., Sturkell et al., 2013; Ormö et al., 2023). This is not seen in the two Decorah cores examined for this study.

For interpreting Decorah core H2, we need to compare with the data from previously investigated craters using the same method (see summary in Ormö et al. 2021, and Ormö et al. 2023). Of these craters we find Flynn Creek (DeMarchi et al., 2019) and Rochechouart (Ormö et al., 2023) to be the best analogs due to their similar clast frequencies indicating similar modes of transport and deposition, i.e., a domination of a very mud-rich hyperconcentrated flow (cf. Vallance, 2000). The clast frequency (<N>) for the Decorah CS1, and H2 is 32 and 43 respectively, to compare with 32 and 40 for the two analysed cores at Flynn Creek (DeMarchi et al., 2019), as well as 58 for Rochechouart (Ormö et al., 2023). The impact structures with lower clast frequency, like Chesapeake Bay and Wetumpka, show debris flow or mudflow -like deposits (Ormö et al., 2021). Important for the comparative analysis are also similarities in the shapes of the plotted graphs (Figs. 4 and 5). Ormö et al. (2023) compared with the Lockne-2 core from the Lockne impact structure in their analysis of Rochechouart. For Decorah, we find that of Flynn Creek and Rochechouart, it is Rochechouart that shows most similarities in the fluctuations expressed by the graphs, which, thus, imply also similarities in transport and deposition with the Lockne impact structure (Ormö et al., 2007; 2023).

In the Rochechouart core, the resurge sequence is subdivided into 6 intervals beginning with interval 1 at the bottom of the core (see Fig. 4 in Ormö et al., 2023). In particular, intervals 3–6 in Rochechouart show the greatest apparent similarities to H2, whereas the Decorah equivalents of the lowermost intervals at Rochechourart (intervals 1 and 2) were not cored at Decorah. However, we think that these intervals are likely present at Decorah below the cored part of the crater infill, because they represent the inevitable initial stages of the resurge. The subsequent upwards intervals 3 and 4 at Rochechouart ("outwards passage of anti-resurge" followed by development of "body of standing water") are characterized by slight upwards increase in clast frequency (up to 32 m in H2) followed by slight decrease (32 to 30.25 m in H2). In the same interval at Rochechouart, the clast size and size sorting remained stable, but is accompanied by an increase in clast angularity (as noted from 32 to 30.25 m in H2). With interval 5 at Rochechouart, a new pulse in transport energy is interpreted to have caused a notable increase in clast size and coeval drop in size sorting, as well as slight increase in roundness (as also noted between 29.25–30.25 m in H2). In H2, there is an erosional contact at 30.43 m supporting the notion of a new pulse in the flow (Figs. 4 and 6A). Likewise, the obvious change in clast categories at this level may be due to material ripped-up in another part of the zone of damage surrounding the crater and transported by the new pulse of resurge. In Rochechouart, resurge interval 5 is followed by resurge interval 6, which includes an increase in clast frequency and size sorting, and a generally normal grading towards the top (as in 29.2 m and upwards in H2). In Rochechouart, there is also a general upwards decrease in roundness similar to H2. This interval is interpreted to represent settling of material in what would have been at that point in time a nearly water-filled crater, but also with seiches causing minor repeated beds (e.g., at 26 m and 27 m in H2). Whereas roundness in Rochechouart is strongly related to the presence of angular melt clasts, and noting here that melt is absent in the Decorah cores, there may still be a common effect of angular clasts being kept longer in suspension as seen at Rochechouart (Ormö et al., 2023) and noted for Chicxulub as well (Ormö et al., 2021). The deposits in H2 show clear signs of suspension flow (e.g., normal grading. Fig. 4), the angularity

205 is generally increasing towards the top, and indeed some of the lithologies that increase closer to the top
206 are relatively angular, e.g. “dark brown-gray” and “light gray” (Figs. 4 and 7).

207 The CS1 has fewer clasts per meter (<N> = 32) than H2, but as the level of matrix support is similar between
208 the two cores (i.e., a higher matrix content often results in fewer clasts), CS1’s characteristics are instead
209 more likely due to the effect of the in general larger average clast size in (27 mm) than in H2 (14 mm). The
210 large blocks in CS1 (>0.5m, mainly located at ~ 69 m and 73-75 m, Fig. 5) commonly show internal
211 brecciation but with good fitting, a sign of having begun to disintegrate during the transport, thus there was
212 likely a less turbulent transport in CS1 than in H2 for equal lithologies. Except for the obvious normal
213 grading in the uppermost two meters, the generally poorer sorting (compared to H2) throughout the logged
214 interval, the occurrence of larger blocks, and the overall less structured trends in the graphs in Figure 5
215 place the deposits in CS1 closer to that of debris flows rather than the apparent suspension flows of H2.

216 The graphs for CS1 indicate a separation of the logged deposits into three parts (Fig. 5). Notwithstanding
217 the closer appearance to debris flows of CS1, there is a lowermost part that despite a relatively poor sorting
218 sees the initiation of a fining upward trend. As it is coupled with an increase in number of clasts it is possible
219 that it was deposited out of suspension. Angularity of clasts also increases upwards within this part of the
220 core, which may suggest a suspension deposit with angular clasts being kept longer in suspension. However,
221 there is a jump to slightly less angularity at 77 m. Above ~ 76 m begins a second part that is strongly
222 influenced by disintegrating blocks in a higher degree of matrix content. One such block is of the “light
223 tan- gray” lithology at 73.5 m, and a second is of “dark brown-gray” at 73.5-75m (Fig. 6B). The blocks
224 cause stronger fluctuations of the graphs, noticeably a relatively poorer sorting.

225 The last of the three parts of the logged interval begins just above ~ 69 m. At ~ 67 m the higher number of
226 clasts of less than the cut-off size helps boost the extent of matrix support. This tends to indicate material
227 being deposited out of suspension. Likewise, the number of clasts continue to increase slightly towards the

top, whereas clast size remains rather equal. An increase in clast frequency for a constant clast size means that matrix must decrease, which can be seen for the interval. For a suspension deposition, we would also expect to see an increase in sorting. However, levels with larger clasts cause significant decrease in sorting, which affects the general sorting trend negatively. A clear suspension deposit is not evident until above ~ 61 m where an obvious normal grading is present (see inset core photo in Figure 5). Higher up, this uppermost part of the graded deposit has a gradual transition into the overlying Winneshiek Shale.

Of the previously studied craters (see references cited above), it is difficult to find one with a core log that perfectly resembles that of CS1. Ormö et. al. (2009) characterized the resurge deposits of the "upper unit" in their log of the Eyreville A core from the moat at the Chesapeake Bay Impact Structure (CBIS) as being mainly debris flows. However, they noted a normally graded suspension deposit in the uppermost one-third of the resurge interval. The graph trends for CS1 show some similarities with CBIS in the overall poor sorting that only improves just at the top, the generally equal number of clasts per meter except for higher amounts in the lowermost (in CS1, ~ 77 m depth) and uppermost (in CS1, the upper ~ 2 m) parts, as well as a clast size trend that is rather stable except for a noticeable drop in the topmost part. These characteristics of the trends were also noticed at the Flynn Creek impact structure that, likewise, has a low average number of clasts per meter (<N> = 32-40 for the two investigated cores at Flynn Creek. DeMarchi et al., 2019). However, at Flynn Creek the trends were interpreted to show a suspension flow causing a lower "traction flow" when passing over slump breccias. The CS1 core may not go deeply enough into the Decorah resurge deposits to reveal this relationship.

Provenance of Clasts

The variation in occurrence of clast categories between the cores and within the cores can provide clues to where in the target stratigraphy they originate, if they have been emplaced as ejecta before being transported

by the resurge, or if they have been ripped up from the rim and the vicinity of the crater. For instance, categories that appear throughout the logged sequence may, possibly, be playing the same part as the basement clasts at Rochechouart that Ormö et al. (2023) considered to be ejecta fragments more equally mixed in the whole resurge sequence, whereas other can be connected to certain pulses of the flow causing rip-up of strata at the elevated rim or the surroundings of the crater (Ormö et al., 2021). The clast categories "light tan-gray" and "light gray" occur relatively evenly distributed throughout both cores, maybe indicating an origin as ejecta. In H2 this more even distribution is also noted for the "terracotta". However, interestingly this category is nearly absent in CS1, which could speak against the ejecta hypothesis. There instead, the "dark brown-gray" dominates due to the disintegration of larger blocks, which could support the suggested debris flow transport of more locally derived material. Possibly, H2 with its higher clast content, more obvious grading, and potentially higher ejecta contribution, suggest a more proper resurge at this location, whereas CS1 with its more locally derived material and debris flow deposits could indicate a stronger contribution from a collapsing crater rim at this location.

Possibly, two stratigraphic intervals in the target can be correlated closely (primarily) with two clast types in the examined cores; The Upper Cambrian Lone Rock and St. Lawrence formations, which contain glauconitic and feldspathic sandstone and beds of dolomite and green-gray shale, respectively, and the Lower Ordovician Shakopee Formation, which includes beds that may have been stained red ("terracotta") owing to their underlying relationship to the truncating, inter-regional unconformity at the base of the directly overlying St. Peter Sandstone (Fig. 8. Stratigraphy from Wolter et al., 2011). These two intervals produce the more easily (primarily) traceable greenish and "terracotta" clasts. In consultation with the Iowa Geological Survey, the following clast lithologies and constituent grains seem to their staff, and to us as well, to be likely sourced (primarily or secondarily) from the following stratigraphic units (in parentheses): "terracotta" dolomite (Shakopee Formation), gray and brown dolostone clasts (Oneota Formation, darker shades the lower in the sequence); white tripolitic chert clasts (chert-bearing beds of the middle and upper

parts of the Oneota Formation); and green silty dolostone (Lone Rock Formation or St. Lawrence Formation).

French et al. (2018) suggest that the well-rounded, moderately poorly sorted quartz grains could be sourced from any quartzose sandstone units in the sedimentary section, e.g., the Ordovician basal Shakopee Fm., or the Cambrian Jordan Fm., or possibly even from units deeper than the Lone Rock Fm. As we have not observed any clasts that unequivocally can be connected to the Jordan Fm., and that these sandstones are known to be poorly consolidated (Witzke and McKay, 1987), makes us favor an origin from the Jordan Fm. Likewise, the glauconite grains in the breccia matrix likely could be connected with the St. Lawrence Fm (cf. Witzke and McKay, 1987).

In the following analysis, we have attempted to interpret where several of the more distinctive types (i.e., color categories) of clasts have originated within the target section (Fig. 8) and what their presence in the resurge deposits means with regard to impact and related resurge processes. However, to translate the not always certain stratigraphic clast provenance into an interpretation of the mechanism of their dislocation (e.g., as ejecta or rip-up) can, thus, become speculative. Nevertheless, if we assume certain clast categories to originate from the upper target, and others from lower parts in the target, and combine this with what we have concluded above regarding the mode of the resurge flow in the two cores, then we might get a picture of the material origin and mechanism of deposition at the two respective drill core locations within the crater. The deposition in H2 is clearly affected by upper target "terracotta." The "new pulse" brings in upper target (middle and upper Oneota) chert ("white"), but also lower target Lone Rock/St. Lawrence ("dark green"). In addition, in H2 the "dark brown-red" appears higher up, which may also relate to the new pulse (Fig. 4). The clast provenance in H2 could support a the more mixed (turbulent) resurge assumed from its sedimentology/granulometry (see above) where upper target ejecta is then more likely to occur in the deposits, e.g., "terracotta" and "white."

On the other hand, do the debris flow deposits and primarily middle target clast provenance in CS1 suggest rip-up and reworking of slumps from a collapsing rim area as suggested above? An overturned rim would provide less access to upper target material ("terracotta") that would be sandwiched inside the rim, and maybe also the less turbulent resurge (more debris flow) does not bring in such material from more distal ejecta that landed in the seawater. Likewise, lower target ("dark green") may not have been any major constituent of the uplifted rim, although maybe occurring in ejecta that more affected the deposits in H2.

Unfortunately, both H2 and CS1 are located near the rim, so one cannot argue about much "high vs. low" position influence (i.e., "washed" vs "muddy") as for e.g., Lockne (cf. Ormö et al., 2021; Herreros and Ormö, 2022). More likely, in Decorah we see a difference between a location of rim-collapse (CS1, debris flow -like deposits) and more water-rich resurge (H2, suspension deposits).

Target Water Depth Estimation

As the diameter of the Decorah impact structure is well defined (5.6 km), and now also the average number of clasts per meter (<N>) of the resurge deposits, it should be possible to calculate the target water depth based on the aforementioned relations (see equations in the Introduction section). However, a complication remains because we are not sure that the H2 and CS1 core locations should be considered to be in a "moat" or in a more "washed" high position just inside the crater rim, i.e., a position with more prolonged turbulence (cf., Ormö et al., 2021; Herreros and Ormö, 2022). It is possible that the higher clast content in H2 is a reflection of its position slightly closer to the crater rim than the CS1 (Fig. 1) in analogy with the Lockne-1 (near rim) and Lockne-2 (moat) cores at the Lockne impact structure (Ormö et al., 2007, 2021).

The calculated <N> for the H2 core is 43, and for CS1 it is 32. The online "Earth impact effects program" calculator (Marcus et al., 2010) gives a 350 m projectile diameter (d) regarding a final crater diameter of 5.6 km. We think this is a reasonable projectile diameter for the purposes of this discussion. If assuming

the cores are in low ("moat") position, Equation 1 gives a calculated target water depth based on H2 to be ~ 92 m, and based on CS1 it would be ~ 77 m. This also seems reasonable considering that resurge must have been able to overcome an elevated rim of ~ 230 m height, if calculated using the commonly cited equation by Pike (1977). But considering that crater rims in sedimentary target rocks, especially if in aquatic setting, may be highly unstable, e.g., the similar-sized Wetumpka Crater, Alabama has a collapse rim section (King et al., 2006), therefore an even shallower water could be plausible. If we consider that the near-rim locations of the two core holes (shown in Fig. 1), which may have caused them to be in more high-energy, and thus have more "washed" positions during resurge (cf. Ormö et al., 2021), then the Equation 2 gives a calculated target water depths of ~ 42 m (H2) and ~ 39 m (CS1). One caveat - At Decorah we cannot know if there are even muddier parts nearer to the crater center.

These latter two water-depth estimates are near to the estimated target water depth of 50 m for the Flynn Creek impact structure, which we already noted shows similarities to the deposits at Decorah, especially for the CS1. For a more certain target water-depth calculation, we would have needed a core located closer to the crater center for comparison. Generally, in support of our water-depth interpretations, we note that certain benthic fossils in the Winneshiek Shale indicate a deposition within the photic zone (i.e., < 200 m; Liu et al., 2006; see also Briggs et al., 2018), which fit to the span of the calculated depths just discussed (i.e., 40-90 m). Briggs et al. (2018) describe the target environment as a shallow marine embayment, which was populated by eurypterids, conodonts, jawless fish, arthropods, and crustaceans. Interestingly, they note that linguloid brachiopods, gastropods, and benthic algae are also present and thus suggest water shallow enough to be entirely consistent with our interpretations.

CONCLUSIONS

The comparison between graded deposits in two cores from locations inside the apparent rim of the buried Decorah impact structure with published descriptions of resurge deposits from known marine-target impact structures confirms a shallow marine target environment at Decorah as suggested by French et al. (2018) and Briggs et al. (2018). The resurge deposits at Decorah also confirm a relatively shallow target water depth compared to the size of the impact structure. An established relation between calculated projectile size (i.e., event magnitude), clast frequency and target water depth suggests the water depth to have been 40-90 m, which is consistent with the estimated depth of deposition of the youngest target sediments. The shallow water depth relative to the standard rim height for an impact structure of this size suggests the rim to have been unstable due to high content of poorly consolidated target sediments allowing the resurge to, nevertheless, enter the crater.

This study shows how useful the sedimentology of marine-target impact craters can be when establishing the paleoenvironments in today completely different environmental settings, e.g. subaerial terrestrial. If we widen our perspective to beyond Earth to our neighbour planet Mars the reconstruction of paleoenvironments, especially aquatic, is important in search for potential life habitats,. Remote sensing can give us information on tell-tale geochemistry and landforms. However, remote sensing may be hampered by extensive surface erosion, volcanism, etc. Future access to imagery of cross-sections of resurge deposits such as those suggested for the Gale Crater (Dohm et al., 2023), or preferably even from core drillings, would maybe allow the here applied method also on Martian marine-target craters.

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FIGURE CAPTIONS

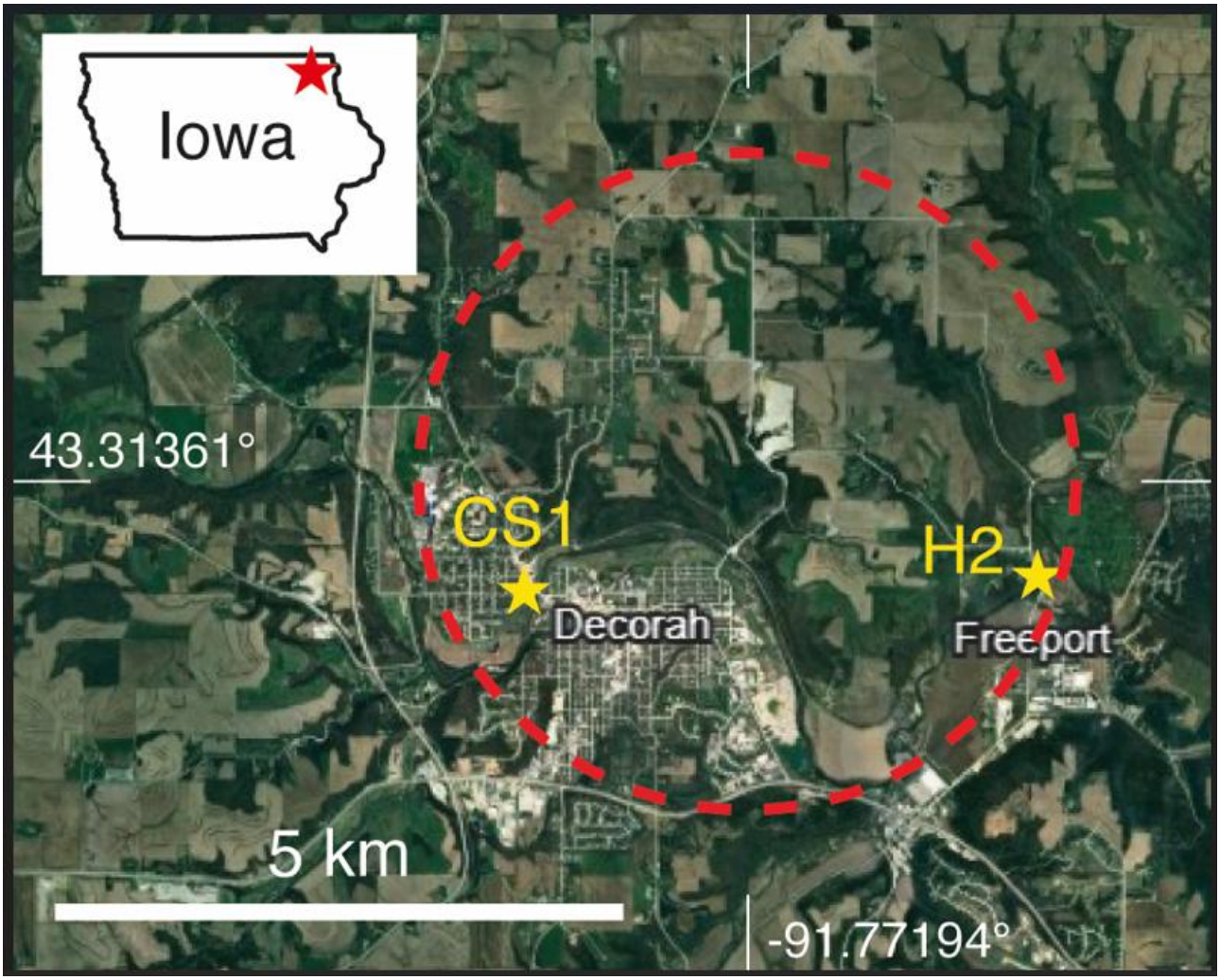


Figure 1. Location of the Decorah impact structure (red star in inset), the crater rim (red stippled line), and the drill sites of the here investigated cores (yellow stars). The buried impact structure has no topographic expression, nor obvious influence on the drainage pattern. Imagery from Google Earth (Imagery ©2025 Airbus, CNES / Airbus, Landsat / Copernicus, Maxar Technologies).

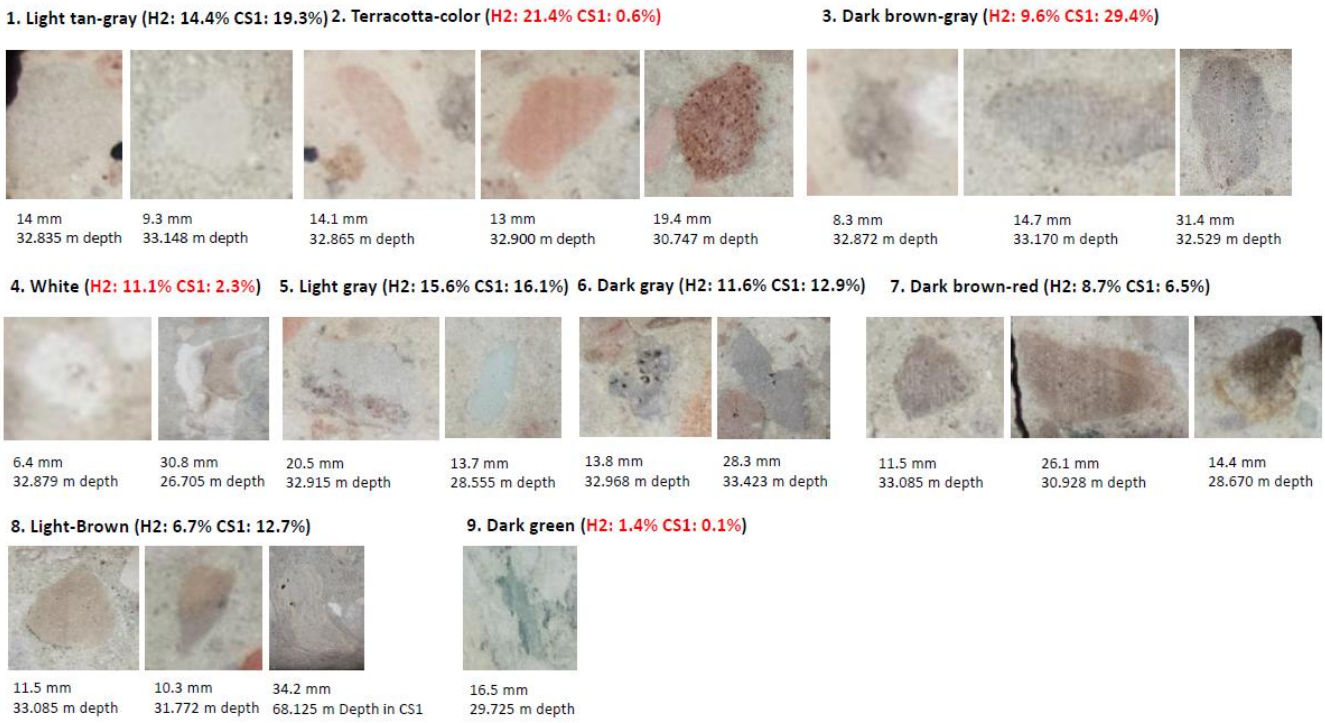
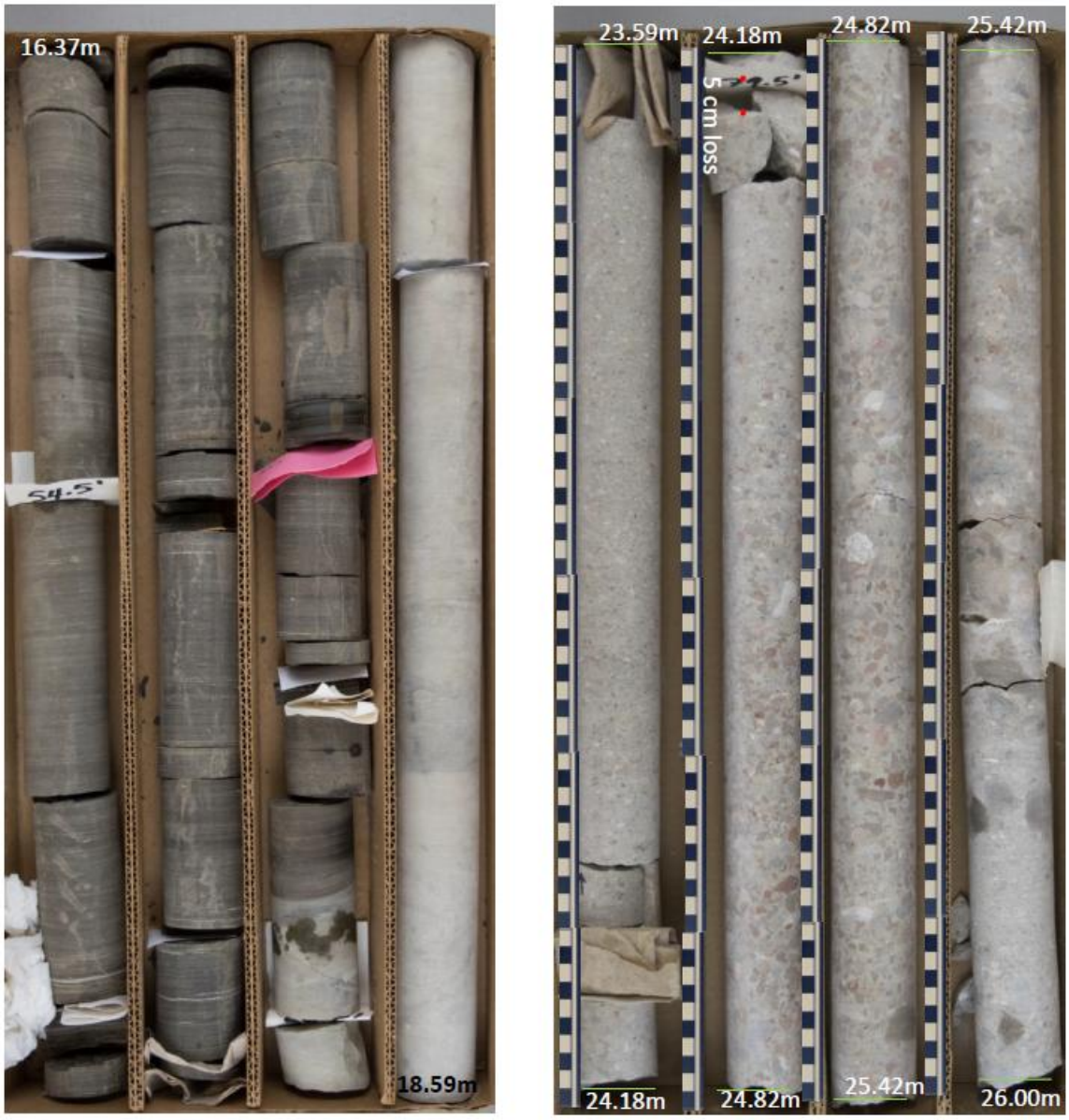


Figure 2. Representative examples of the clast categories also indicating the color span of the category. All photos from H2, unless otherwise indicated. Clast categories with a more than three times difference in abundance between H2 and CS1 are highlighted in red font. Images were extracted and enlarged from core photos provided by the Iowa Geological Survey, used with permission.



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477 *Figure 3. The transition from graded breccia (right panel) into overlying Winneshiek Shale (left panel) in*
478 *core H2. Between the two boxes are 5 m of pale sand and silt not shown here. The right panel shows the*
479 *topmost part of the logged section above which the method cut-off size (<5 mm) did not allow the recording*
480 *of more clasts. Photos from the Iowa Geological Survey, used with permission.*

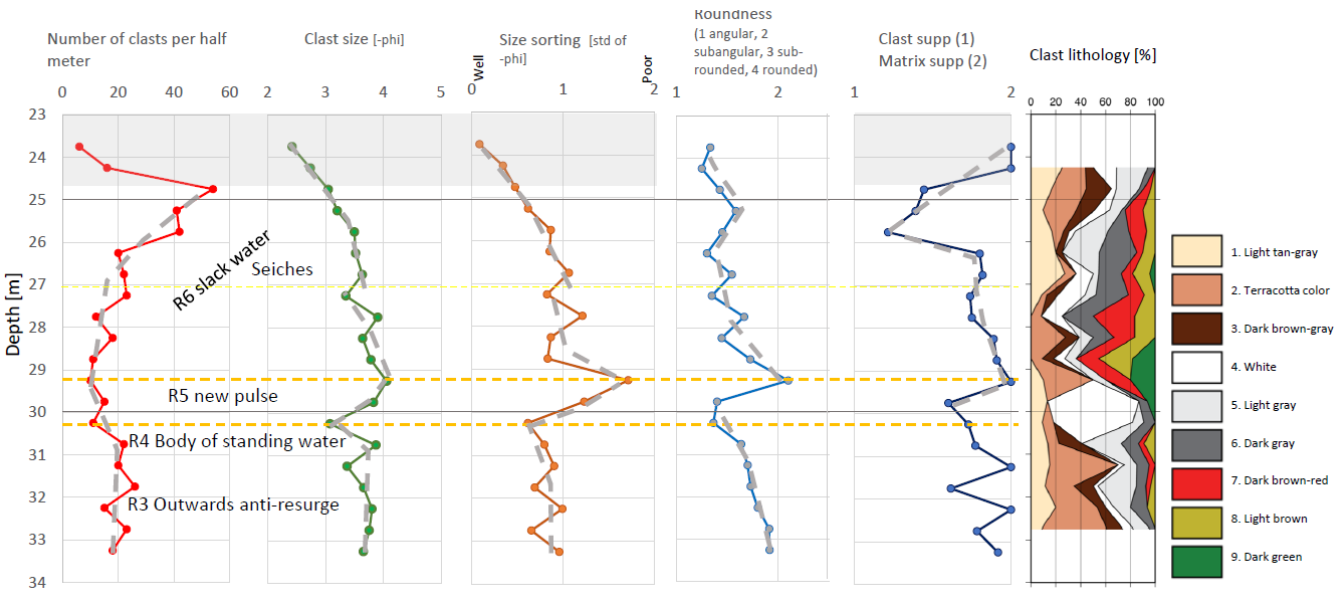


Figure 4. Graphs showing variations in the sedimentology, as well as clast granulometry and clast color for the graded breccia within the Decorah H2 core. On the left side, a comparison with the interpretations of similar-appearing intervals in the Rochechouart core log (Ormö et al., 2023) are noted (Rochechouart intervals R3-6). Gray stippled lines indicate subjectively generalized trends. Yellow stippled lines indicate levels of significant shift in the trends. Light gray shaded area indicates area where data are affected by the 5 mm cut-off size of the method.

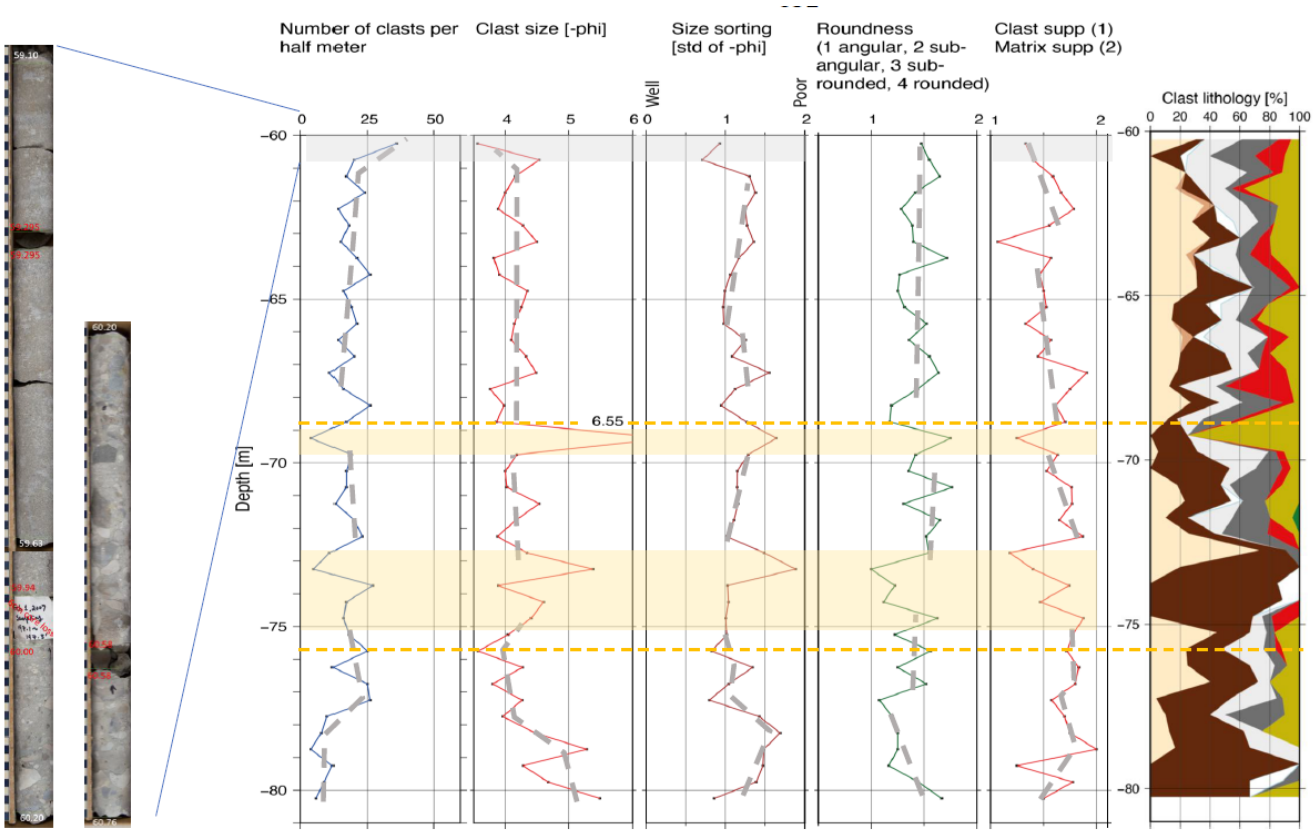


Figure 5. Graphs showing variations in sedimentology, as well as clast granulometry and clast color for the graded breccia in the Decorah CS1 core. Inset core photos show the uppermost 2 meters wherein lies the most obvious normal grading of the resurge breccia as it transitions into overlying, finer resurge sands. Scale in cm is left of the core. For other information, see the figure legend of Figure 4. In addition to the gray-shaded upper part where data are affected by the 5 mm cut-off, there are here also two levels indicated in yellow shade where disintegrating blocks strongly affect the trends. This does, however, not affect the reliability of the data. Core photos from the Iowa Geological Survey, used with permission.

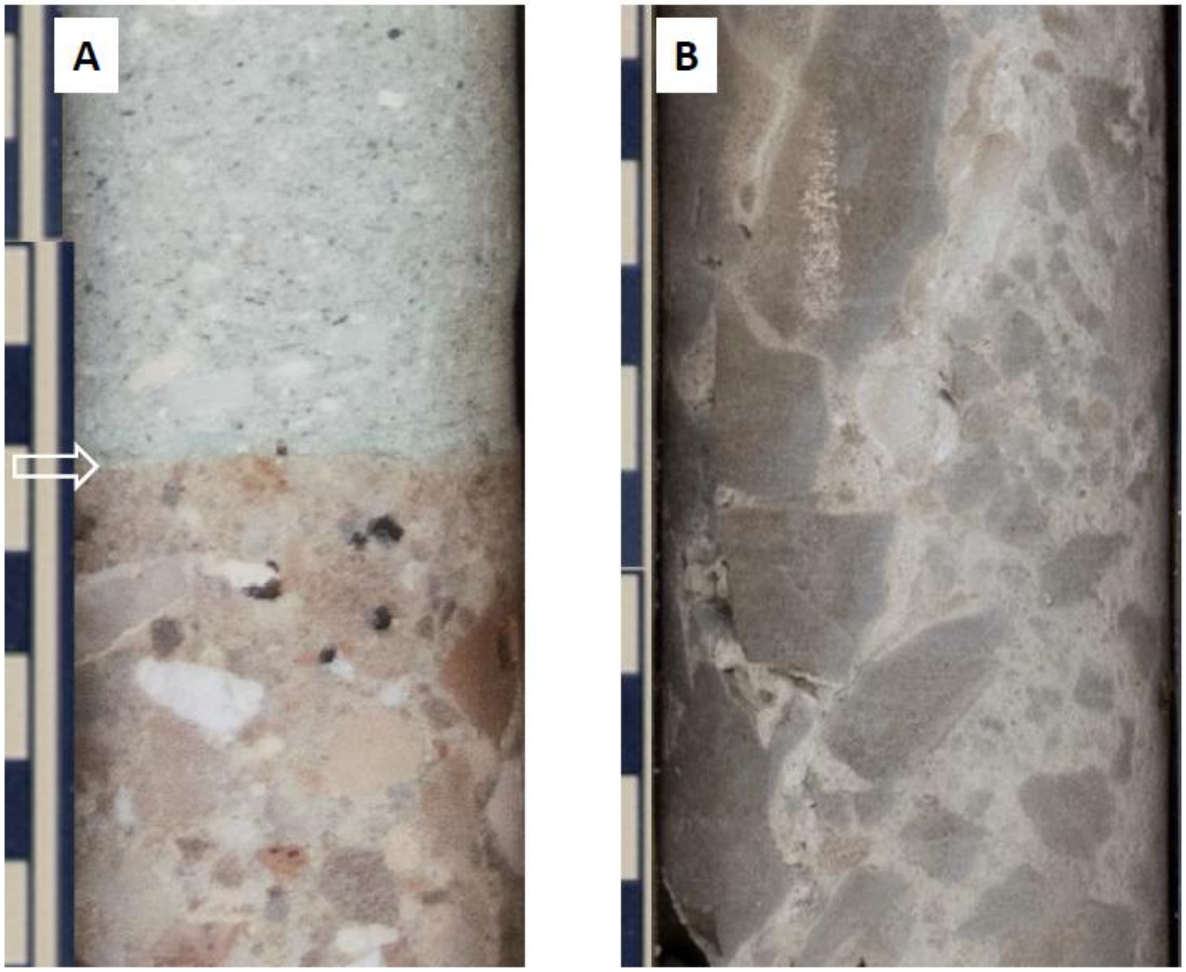
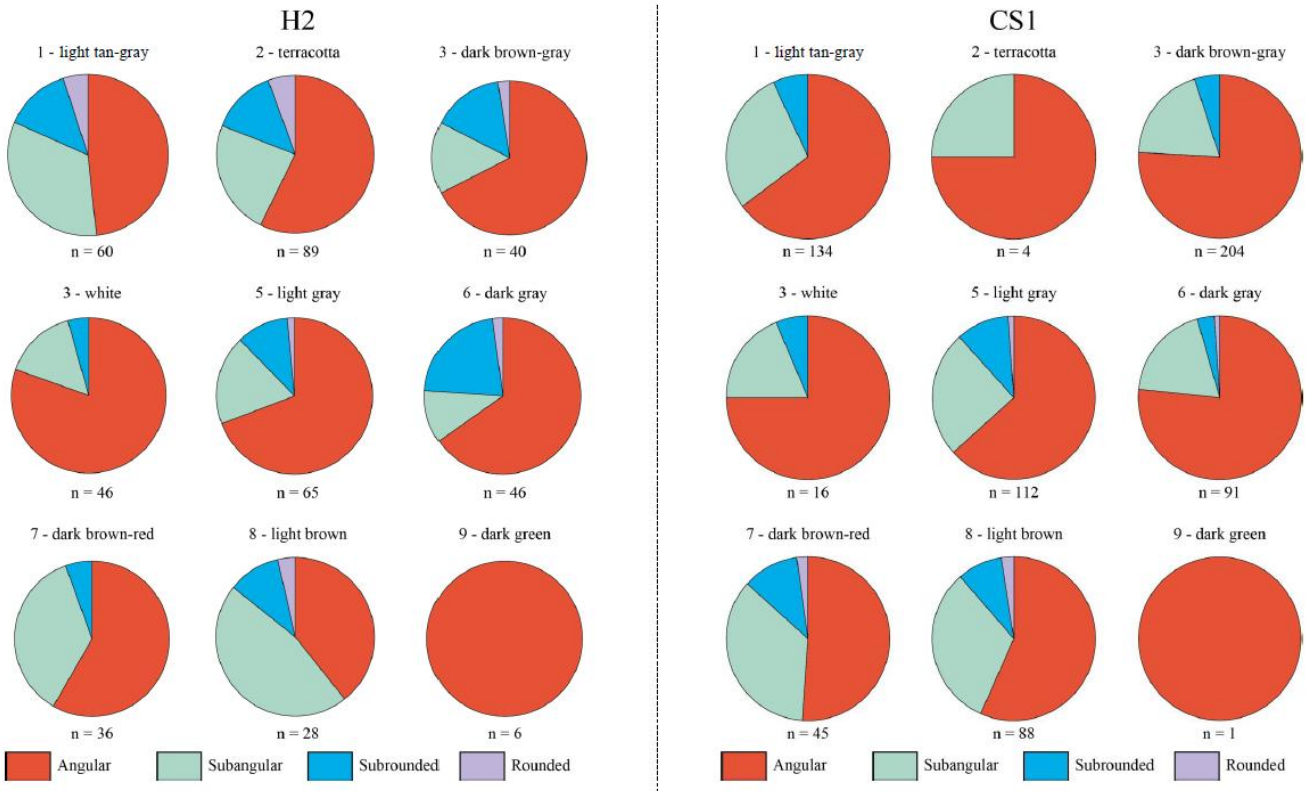


Figure 6. Photos of noteworthy intervals within the two cores. A) Erosional contact at level 30.43 m in H2 indicating a possible new pulse in the flow. B) A nearly monomict breccia of "dark brown-gray" lithology at 73.5 m in CS1, which may indicate disintegration of an originally larger block.



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501 *Figure 7. Degree of angularity for the logged clast categories in the H2 and CS1 cores.*

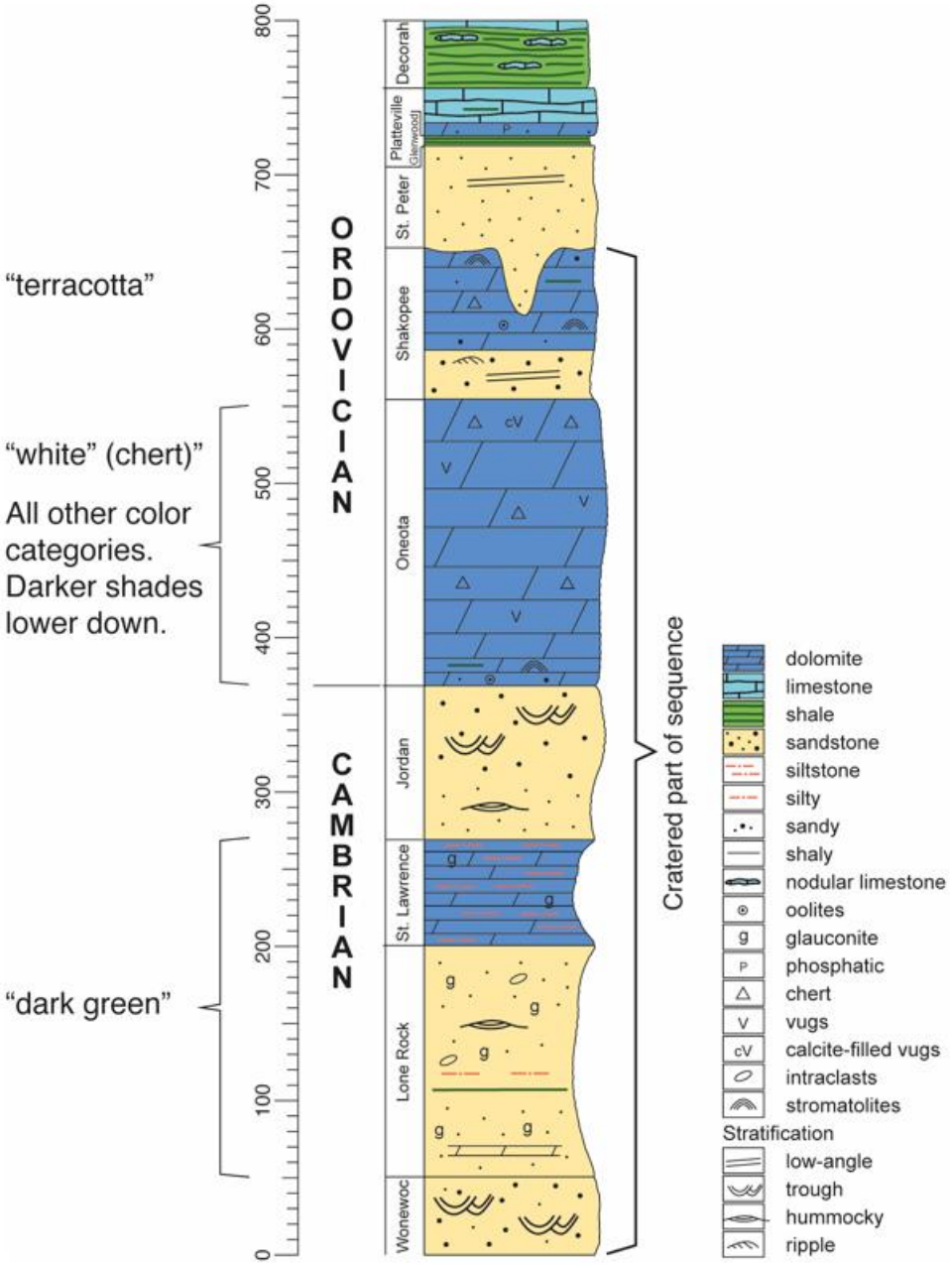


Figure 8. Stratigraphy of the here relevant part of the Decorah target section. As the lithologic column is adapted from Wolter et al. (2011) the thickness is also here given in feet in the linear scale on the left of the stratigraphic column. Stratigraphic systems (Cambrian, etc.) are indicated to the left of the lithologic column, as are the names of the stratigraphic units as well as the suggested provenance of our clast color categories. Details of the petrology are shown in the key to symbols on the lower right part of the figure.

Target formations are mentioned in the text by names given herein. Note that the post-impact Winneshiek Shale lies on the unconformity below the St. Peter Sandstone only within the Decorah impact structure and is not specifically shown here. Modified from Wolter et al. (2011); used with permission of the Iowa Geological and Water Survey.