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Sedimentological analysis of resurge deposits at the Lockne and Tvären craters: Clues to flow dynamics

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Abstract–The Lockne and Tvären craters formed about 455 million years ago in an epicontinental sea where seawater and mainly limestones covered a crystalline basement. The target water depth for Tvären (apparent basement crater diameter D = 2 km) was probably not over 150 m, and for Lockne (D = 7.5 km) recent best-fit numerical simulations suggest the target water depth of 500–700 m. Lockne has crystalline ejecta that partly cover an outer crater (14 km diameter) apparent in the target sediments. Tvären is eroded with only the crater infill preserved. We have line-logged cores through the resurge deposits within the craters in order to analyze the resurge flow. The focus was clast lithology, frequencies, and size sorting. We divide the resurge into "resurge proper," with water and debris shooting into the crater and ultimately rising into a central water plume, "anti-resurge," with flow outward from the collapsing plume, and "oscillating resurge" (not covered by the line-logging due to methodological reasons), with decreasing flow in diverse directions. At Lockne, the deposit of the resurge proper is coarse and moderately sorted, whereas the anti-resurge deposit is fining upwards and better sorted. The Tvären crater has a smoothly fining-up section deposited by the resurge proper and may lack anti-resurge deposits. At Lockne, the content of crystalline relative to limestone clasts generally decreases upwards, which is the opposite of Tvären. This may be a consequence of factors such as crater size (i.e., complex versus simple) and the relative target water depth. The mean grain size (i.e., the mean –phi value per meter, φ) and standard deviation, i.e., size sorting (σ) for both craters, can be expressed by the equation $\sigma = 0.60\varphi - 1.25$.

INTRODUCTION

General Description of the Studied Craters

We present results from two Scandinavian Ordovician craters: the Lockne crater (Fig. 1), which represents the deepest target water of all known marine-target craters (Ormö and Lindström 2000), and the considerably smaller Tvären crater (Fig. 2) that formed in a shallower marine environment.

The Lockne crater formed in an epicontinental sea that was at least 500 m deep at the impact site (Ormö et al. 2002; Lindström et al. 2005a). The crater consists today of a 7.5 km wide inner crater in the crystalline basement and an approximately 14 km wide shallow outer crater in the Cambrian and Ordovician shales and limestones that cover the basement (Lindström et al. 2005b).

The Lockne crater has a well-preserved morphology and well-preserved sections of impactites, both within the crater and in its surroundings (Figs. 1, 3a, 3b). This facilitates studies of the provenance of lithic fragments in the resurge deposits. The nested, deeper basement crater (i.e., inner crater) is surrounded by up to 3 km wide overturned flaps of basement ejecta. These flaps form a coherent brim-like structure that is at the most about 50 m thick. The inner crater rim lacks structural uplift (Sturkell and Lindström 2004). The basement ejecta rests on a succession of the sedimentary target rocks that becomes progressively more complete outward from the rim (Lindström et al. 2005b). Preserved sediments that were deposited on top of the flaps immediately after they were laid down constrain the rim height of the fresh crater to have been not more than a few tens of meters (Lindström et al. 2005b). This is much less than the target water depth, and thus it posed no major obstacle to the resurge flow.

In the periphery of the coherent basement ejecta layer, the underlying sediments show signs of strong stirring. This has been suggested to be a result of strong water movements of

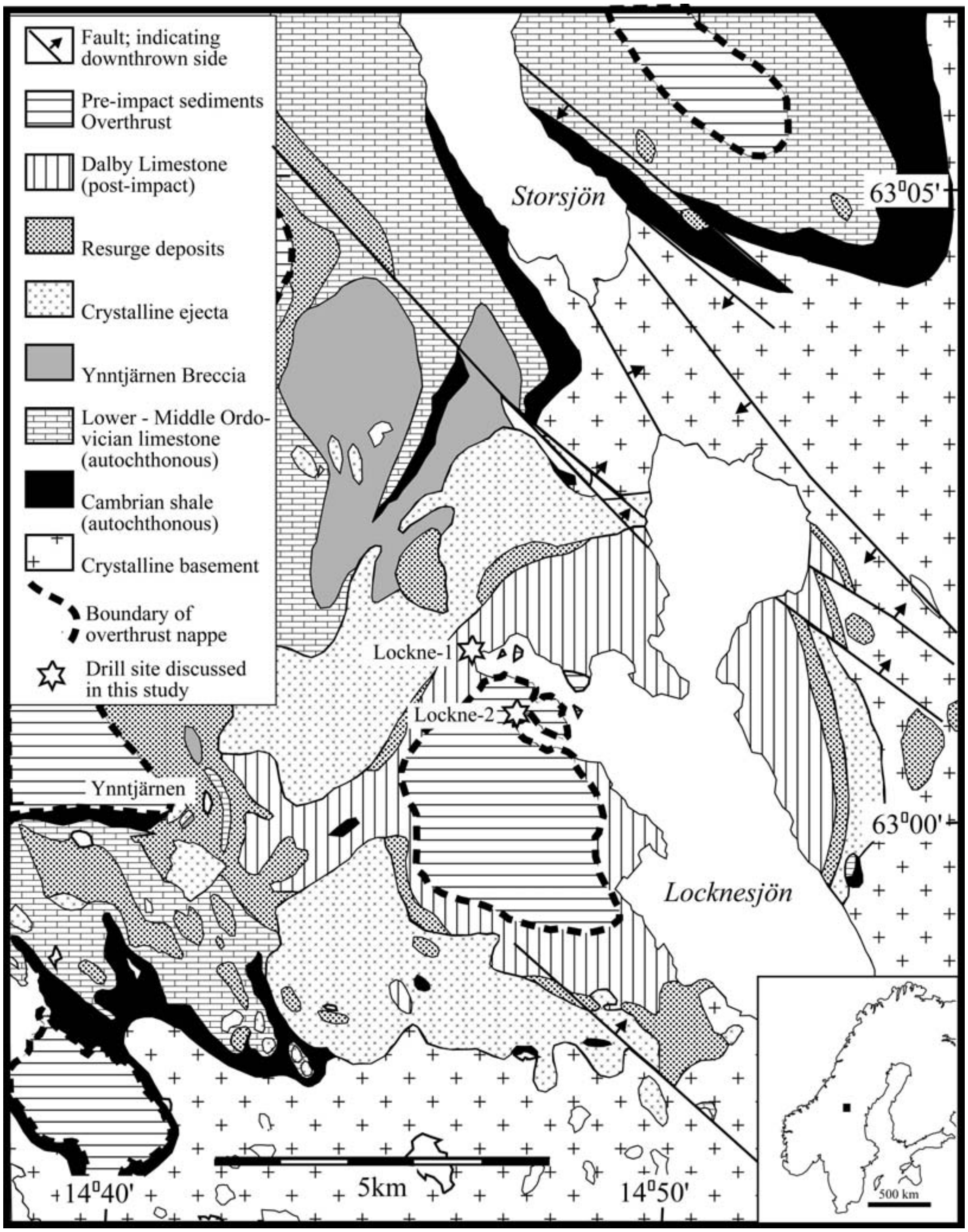

Fig. 1. Map of the Lockne crater with drill core locations (modified after Lindström et al. 2005b). North is at the top of the map.

the outgoing excavation flow along the seafloor when the water cavity was expanding, as well as seismic shaking from the collapsing water wall and percussion during the deposition of basement ejecta (Lindström et al. 2005b; Ormö et al. 2006). The lithology formed by this stirred material has been named Ynntjärnen Breccia after the type locality near Lake Ynntjärnen (Fig. 1). Numerical simulation of the ejecta emplacement and water movements during the formation of the Lockne crater indicate that the Ynntjärnen Breccia may be the primary source of sedimentary clasts for the resurge deposits in the western, presumably downrange, part of the crater, whereas rock fragments in the resurge deposits in the eastern parts primarily originate from ejecta (Lindström et al. 2005b).

The Tvären crater, on the other hand, lacks all traces of the impact outside the rim of the apparent crater. The crater appears on the present seabed as a deep, partially sediment-filled, slightly more than 2 km wide circular depression in the Proterozoic basement (Fig. 2). Later erosion has removed all of the sedimentary rocks of the target

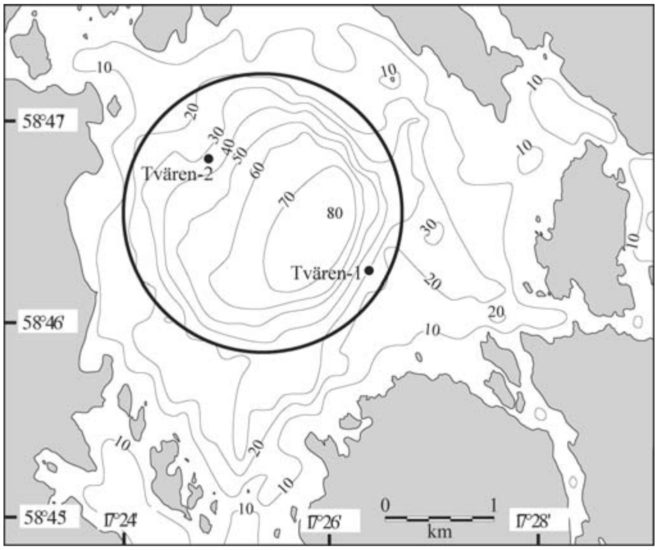

Fig. 2. Map of the Tvären crater with bathymetry and drill core locations (modified after Flodén et al. 1986). The Tvären-1 core did not produce any resurge sediments and is not further discussed here. Land is shown in grey, water is in white. Black circle indicates approximate location of apparent crater rim. North is at the top of the map.

succession as well as any potential topographic crater rim. However, just as Lockne, its interior holds a complete transition from impactites and resurge deposits into the secular sediments deposited after the impact-related processes had ceased (Fig. 3c).

The Tvären crater has been dated to approximately the same age as the Lockne crater (Grahn et al. 1996), and it formed in the same epicontinental sea that covered Baltoscandia at that time (Fig. 4). This sea had its deepest parts to the west of the Lockne impact site where a foredeep was developing in front of the approaching Caledonian orogen. The Tvären impact would have occurred at a location with a water depth estimated to have been about 100–150 m (Ormö and Lindström 2000), possibly in the lower range as discussed in this paper.

The sedimentary target stratigraphy was in part the same at Tvären as at Lockne (Fig. 5), but with the difference that the Cambrian at Tvären was represented by beds of unconsolidated sand (Ormö 1994; Lindström et al. 1994) instead of the shales at Lockne. Also the Ordovician limestones at Tvären were thinner and less consolidated representing a facies closer to that of Estonia and northern Öland (Ormö 1994; Männil 1966).

Resurge Deposits—Definition and General Description

The principal material evidence of a resurge at an impact crater confirmed to have formed in a marine environment (i.e., showing continuous marine sedimentation before and after the impact) consists of a fining-upwards succession of clastic sediment that can be extremely coarse in its basal parts and ends upwards as fine sand to silt at its top. The bulk composition of this deposit is the same from bottom to top, although there may be variations in detail, some of which are the subject of the present study. This succession is the product of erosion and deposition connected with the collapse of the transient crater in the water causing a return of water to the crater excavated in the rocky target (i.e., the seabed) (Fig. 6a). We call the totality of this process "resurge" and its products "resurge sediments" or "resurge deposits," although it includes important outward water and debris movements that may dominate in late stages.

We are in this paper referring to the initial inward rush of water as "resurge proper" (Fig. 6b). The resurge proper culminates in the convergence of the water masses at the crater center, which results in the rise of a central water plume (CWP) at impacts into relatively deep water (Fig. 6c). The subsequent collapse of this plume causes an outward flow called "anti-resurge" (Fig. 6d) followed by a final stage of "oscillating resurge." At craters with target water depths greatly exceeding the height of the rim of the crater forming in the seabed, this anti-resurge may cause an outwards propagating tsunami-wave (Wünnemann et al. 2007). Here we deal with the resurge deposits within and in direct proximity of the crater in the seabed, and not with distal tsunami deposits.

The resurge deposits at Lockne are separated into two parts: the coarse-clastic Lockne Breccia and the arenitic to silty sequence on top, called Loftarstone, most commonly showing a gradual transition to the underlying breccia (von Dalwigk and Ormö 2001). It is the Loftarstone that contains most of the materials with distinguishable shock features such as quartz with planar deformation features and melt fragments (Therriault and Lindström 1995).

At Tvären, the resurge breccia forms a several tens of meters thick, normally graded unit that passes upward into upwards-fining arenite, just like the Lockne Breccia and the Loftarstone inside the Lockne basement crater (Lindström et al. 1994; Ormö 1994).

In the present study we describe and distinguish the deposits from the resurge proper and the outward movements.

MATERIAL AND METHOD

The resurge deposits at the Lockne and Tvären craters were studied in drill cores recovered in the 1990s (Lindström et al. 1994, 1996). At the Lockne crater, the two deepest (Lockne-1 and Lockne-2) of the six cores that were drilled within the basement crater contain Lockne Breccia (Lindström et al. 1996). The Lockne-2 core is situated closer to the crater center than the Lockne-1 core (Fig. 1).

Two cores exist from the Tvären crater (Lindström et al. 1994). The Tvären-1 core was drilled at the rim of the basement crater and only contains about a meter of fractured basement below Quaternary sediments. The Tvären-2 core, however, is located closer to the center and penetrates approximately 140 meters of the crater infill (Figs. 2, 3c).

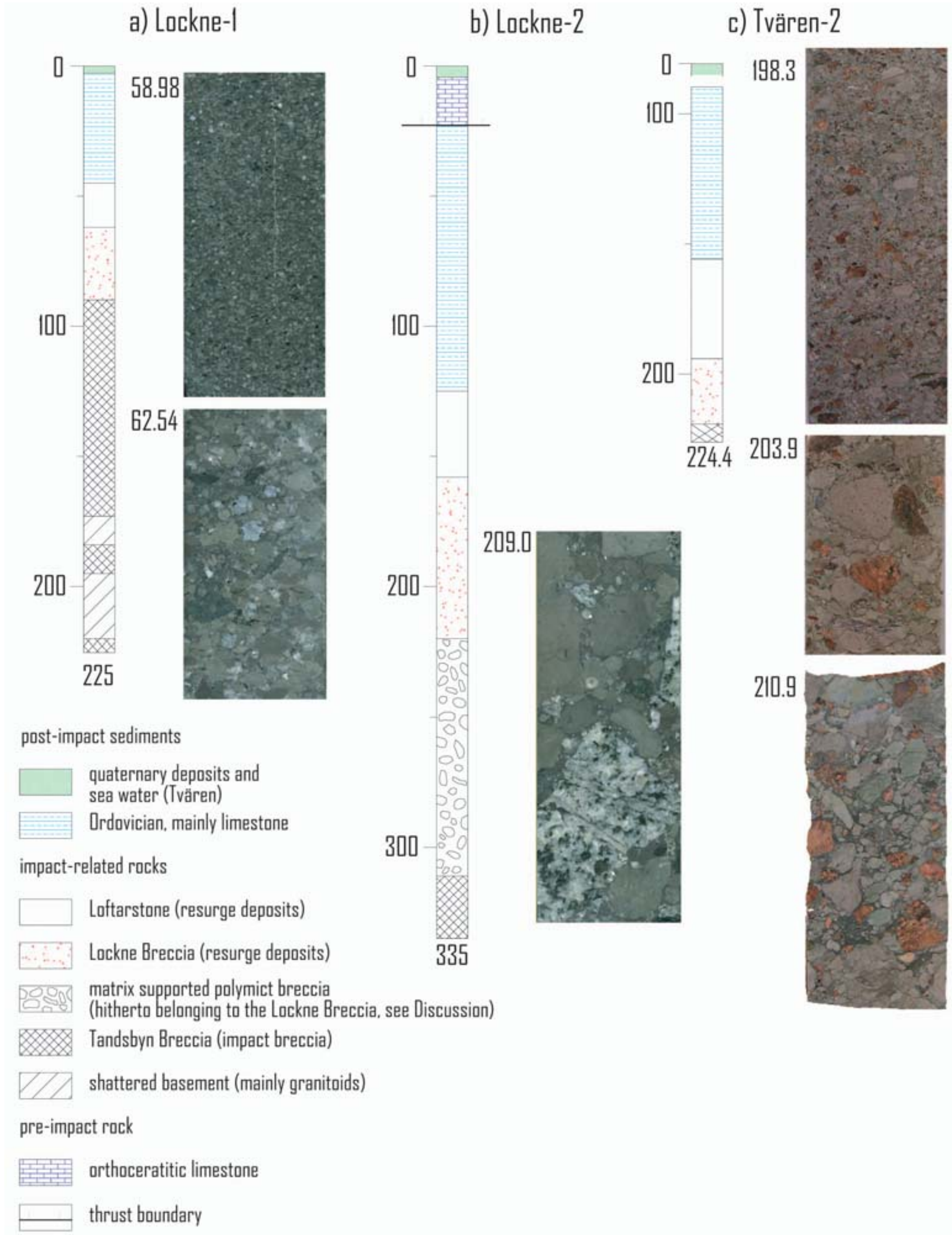

Fig. 3. Schematic core logs of Lockne-1 (a), Lockne-2 (b), and Tvären-2 (c). Insets show representative core photos for the logged interval. The cores are 42 mm wide. Scale is in meters.

For both the Lockne and Tvären coreholes, core recovery was virtually complete. The only part where it was impossible to obtain data (fragmented core) occurred in the Lockne-2 core at 207.88–208.30 m depth. We focused on the parts in the Lockne-1 and Lockne-2 cores logged as Lockne Breccia by Lindström et al. (1996), and on the part logged as coarse to gravelly limestone breccia in the Tvären-2 core by Lindström et al. (1994). The logged sections are overlain in all three cores by carbonate-rich, greywacke-like Loftarstone.

The line-log method (Gohn et al. 2005; Witzke and Anderson 1996) was chosen because it is non-destructive, fast, and economic. It is suited to conglomerates and breccias, where the interesting variables are composition and a proxy for the size of clasts. Other methods, such as point counting, must be used where a principal concern is with composition expressed as percent volume.

The logging was performed along a thin line drawn along the visible “center” of the core when the core boxes were viewed from above. The visible length-axis and the lithology were determined for every clast ($\geq$5 mm length axis) that touched the line. This cutoff size was chosen as it was the minimum grain size for which the clast lithology could be

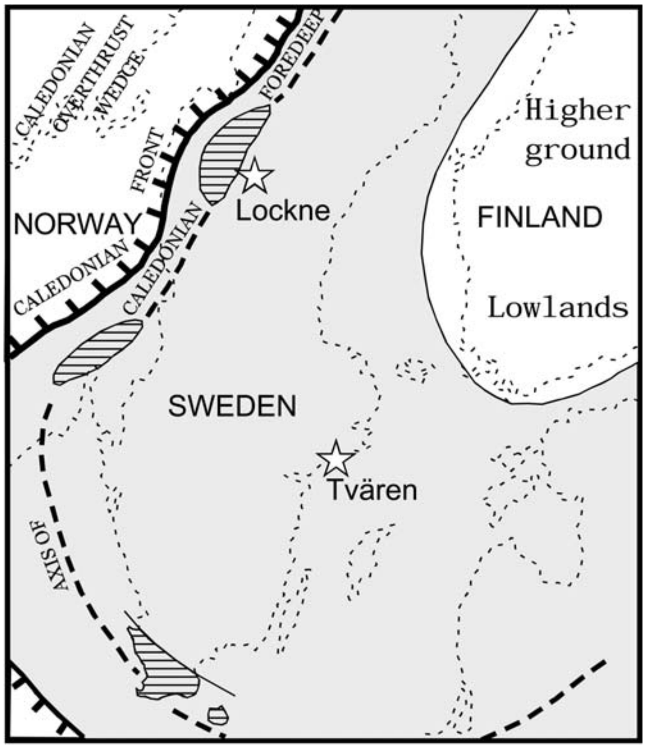

Fig. 4. Paleogeography of Baltoscandia at the time of the impacts, and location of the Tvären and Lockne craters. White is land areas, light grey shade indicates epicontinental sea, and striped pattern are areas with preserved dark mudstones (basin plain facies). Reconstruction based on Männil (1966), Jaanusson (1976), Greiling and Garfunkel (2006), Lindström and Heuwinkel (2006), and Heuwinkel and Lindström (2007).

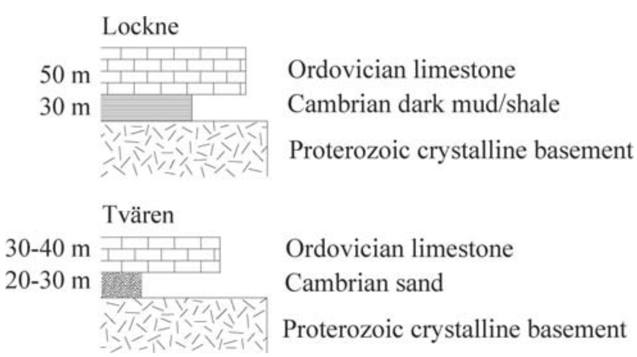

Fig. 5. Simplified lithological profiles of target stratigraphy and relative rigidity of target rocks (length of bar) for Lockne and Tvären.

swiftly determined by the use of a hand lens. Thanks to the relatively simple target stratigraphy of Lockne and Tvären craters, and the insignificant alteration of the clasts, it was fairly easy to determine the lithology of each clast. The depth in the core for each measured clast was set to the depth of the midpoint of the log-line section through the clast. Representative photographs of the logged sections of the Lockne and Tvären cores are given in Figs. 3a–c.

In the Lockne-1 and Lockne-2 cores, we initially divided the clasts into three lithologies: "limestone," "crystalline," and "shale." The "shale" fragments were a quantitatively insignificant component. They were soft and nonlithified during the transport and easily transformed into matrix. Thus, it is not always clear if the logged "shale" is a clast or belongs to the matrix. The sizes of the shale fragments increase downwards towards the matrix-supported breccia that occurs below the logged interval (Fig. 3b). For these reasons the shale was considered as matrix and not included in the numerical clast analysis (see below). In the Tvären-2 core no shale fragments are present.

For Lockne-1 a total of 2817 limestone and crystalline clasts were analyzed between 57.49 m and 83.85 m depth. For Lockne-2 the section between the depths of 158.82 m and 221.69 m yielded 4943 clasts, and for Tvären-2 there were 1407 clasts between the depths of 196.965 m and 219.81 m.

We calculated the total number of clasts per meter as well as the crystalline rock:limestone ratio for each meter in the interval (Figs. 7 to 9). We use phi values when analyzing the clast size distribution. The definition for the phi value is $\Phi = -\log_2 d$, where d is the grain diameter in millimeters (Krumbein 1934). We used positive phi values (i.e., $-1{*}\Phi$) for convenience in our calculations. In order to analyze the clast-size variation, we calculated the mean $-\Phi$ value per meter (here called φ), and the standard deviation (σ) of this value, for "limestone," "crystalline," and "crystalline + limestone" (Figs. 10, 11). Histograms of the clast distribution per meter were created for all cores in order to evaluate the shape of the distributions (not displayed here).

Unlike a point-count of a 2-dimensional section, our line logs cannot yield volume percentages for the components. For instance, the sum of greatest measured dimensions (which are less than the true greatest dimensions) of the clasts occurring within one meter of the log line may easily exceed one meter, although the matrix is not included in the count.

In order to be proven adequate for its purpose, the line-log method should produce consistent results. First, curves based on the line log data should be smooth in alignment and trend over significant numbers of samples. Second, such curves should yield comparable and meaningful results from one drill core and crater to another.

RESULTS

Evaluation of Data

As only clasts ≥5 mm ($-\Phi \approx 2.32$) were measured, the populations plotted in the histograms are artificially skewed, which is most significant in the uppermost parts of the analyzed intervals (colored grey in Figs. 7 to 9). This effect is due to the general upward fining of the sediments in the logged interval. The depth in the core for which the data becomes affected by the cutoff grain size at 5 mm coincides with a drastic drop in clast frequency in all cores (Figs. 7 to 9) as well as in the σ-value (Fig. 10). The drop in σ-value is a consequence of the elimination of grain sizes <5 mm in combination with decreasing real frequency of the sizes ≥5 mm. These parts are neglected in our further analysis. The

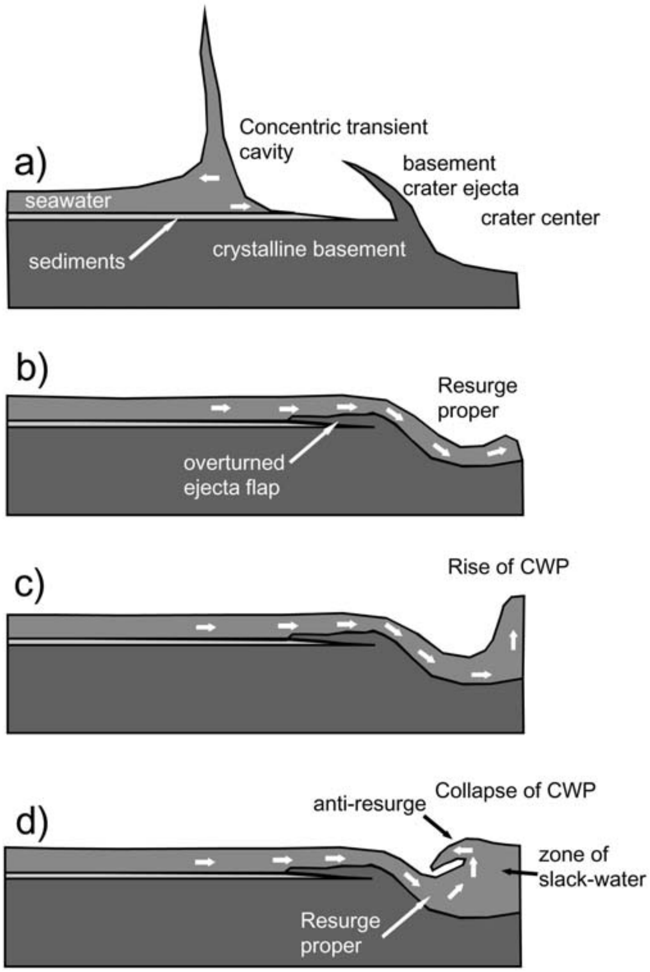

Fig. 6. Half-sections of marine-target crater formation showing principal stages in the development of the resurge in a crater where the target water depth greatly exceeds the height of the rim of the crater in the seabed (e.g., the Lockne crater). CWP = central water plume.

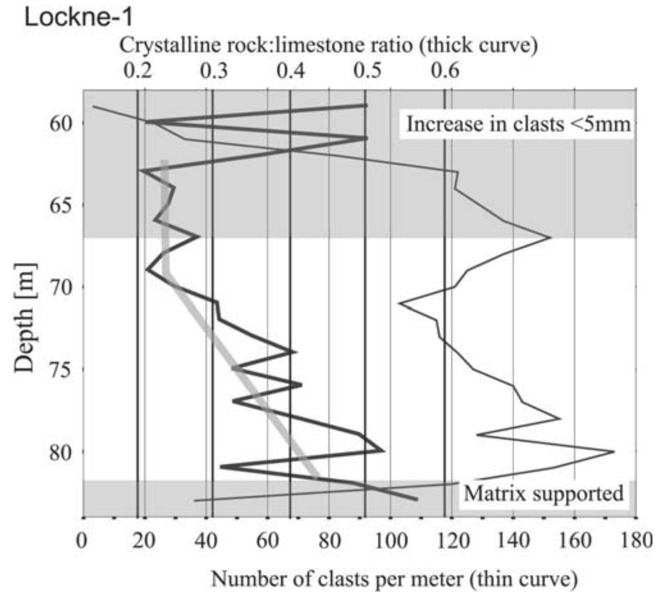

Fig. 7. Clast frequency and ratio between crystalline and limestone fragments in the Lockne-1 core. Gray lines indicate major trends in the crystalline rock:limestone ratio.

lowermost parts of the sampled intervals also show a skewed distribution, likewise with a reduction of clast frequency, which is connected with an observed downward transition from clast-supported to matrix-supported fabric. A contributing, evident reason for the decrease in clast frequency is the increased clast size. These parts are also colored grey in Figs. 7 to 9, but are nevertheless considered in our analysis because the observed effects are not considered artificial.

Clast Frequency and Ratio of Crystalline versus Limestone Clasts

In visual inspection, the investigated interval of the Lockne-1 core appears to have less matrix than the other investigated cores. White calcite spar, rather than matrix, commonly fills the pores between the clasts. The absence of color indicates the calcite is pure spar. If there had been an original filling of matrix, which generally contains a great proportion of greyish silicate matter that is not readily replaced by calcite, this matter would have colored the calcite crystals grey. Therefore we conclude that the now white pores were empty immediately after deposition of the sediment. The presence of empty pores characterizes a water-laid clastic deposit as washed. The alternation with matrix filled pores indicates variations in the density of fine suspension in the water during transport. The relative paucity of matrix results in Lockne-1 (Fig. 7) having at least 50% more clasts per meter than the analogous sections of Lockne-2 (Fig. 8) and Tvären-2 (Fig. 9). The fluctuation in the number of clasts per meter within the Lockne-1 section is, however, considerably greater (Fig. 7). Contrary to the other cores, Lockne-1 has a very high clast frequency in the lower parts (i.e., 76–80 m), and a drastic drop at about 72 m before the clast frequency again increases upwards as expected for a fining-up sequence (Fig. 7). The ratio between crystalline and limestone clasts, however, shows a simpler trend than in the other cores, with a gradual upwards decrease (Fig. 7).

The Lockne-2 core, located nearer to the crater center, has a thicker sequence of Lockne Breccia than Lockne-1 (Figs. 3a, 3b). The ratio between crystalline and limestone clasts shows, with fluctuations, a general increase of crystalline clasts from the top of the core down to a depth of about 185 m where they then decrease downwards again (Fig. 8). There is a noticeable drop in the ratio between crystalline rocks and limestone, as well as in the number of clasts per meter, between 202 m and 210 m. This section is much longer than the parts of the core influenced by the data

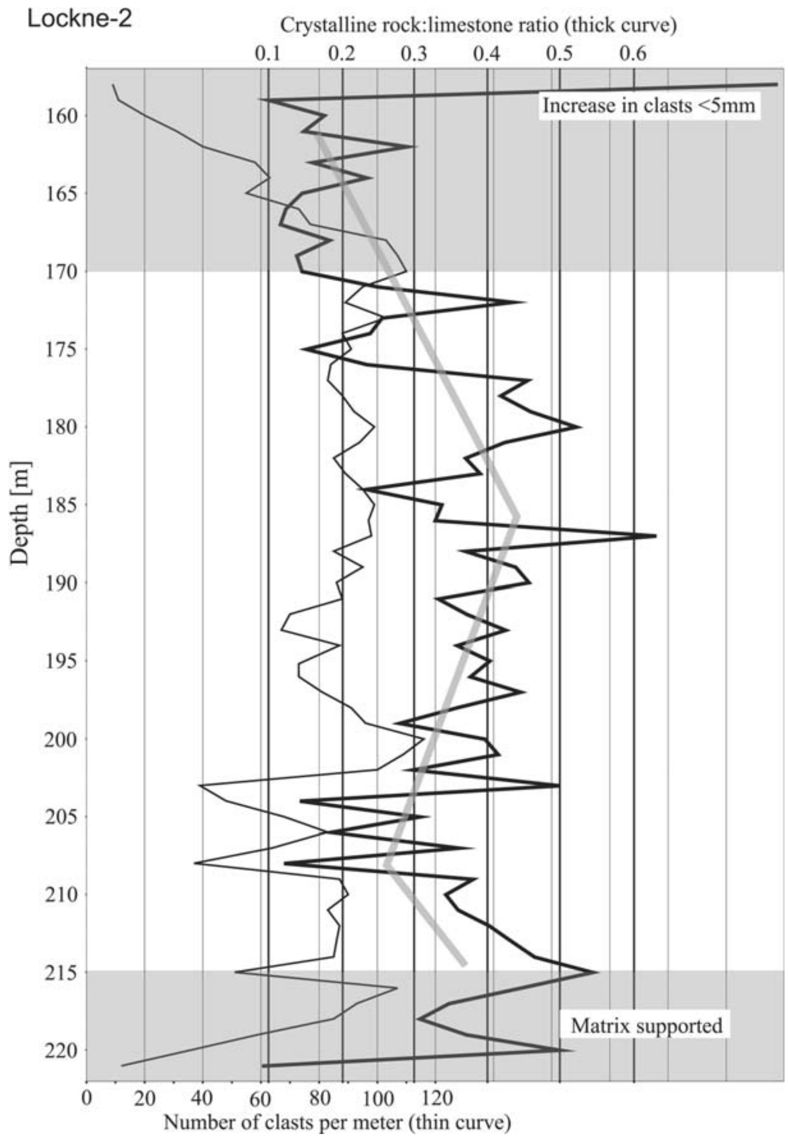

Fig. 8. Clast frequency and ratio between crystalline and limestone fragments in the Lockne-2 core. Gray lines indicate major trends in the crystalline rock:limestone ratio.

loss between 207.88 and 208.30 m mentioned above, and the drop is therefore considered real. Below the drop in the crystalline rock:limestone ratio and clast frequency, there is a last distinct peak in both curves before the number of clasts per meter gets too affected by the increase in matrix content towards the base of the interval (Fig. 8). Above a depth of about 197 m, there is a slight upwards increase in the number of clasts per meter to the top of the statistically useful interval. This increase is not as drastic as in the upper section of Lockne-1 and seems to correlate well with the slow upwards decrease in grain size that is even slower in Lockne-2 than Lockne-1 (Fig. 10a, b).

The investigated breccia interval of the Tvären-2 core (Fig. 9) is thinner than the analogous intervals with Lockne Breccia in the Lockne-1 and 2 cores (Figs. 7, 8). This smaller thickness may be the result of the about 3.5 times smaller size of the Tvären crater compared to the Lockne crater. The number of clasts per meter in Tvären-2 is comparable to Lockne-2, but with a more obvious upwards increase (Figs. 8, 9). This rapid increase is related to the faster fining-up in grain sizes in Tvären-2 than Lockne-2 (Figs. 10b, 10c). Contrary to Lockne-1 (Fig. 7), but as an indication of analogy with Lockne-2 (Fig. 8), there is an upwards increase in the crystalline rock:limestone ratio in the lower part of the analyzed interval, and a decrease in the upper part of the interval (Fig. 9).

With respect to number of clasts per meter and the ratio between crystalline and limestone clasts, Tvären-2 (Fig. 9) and Lockne-2 (Fig. 8) show many similarities, whereas Lockne-1 (Fig. 7) differs with its drastic upwards decline in

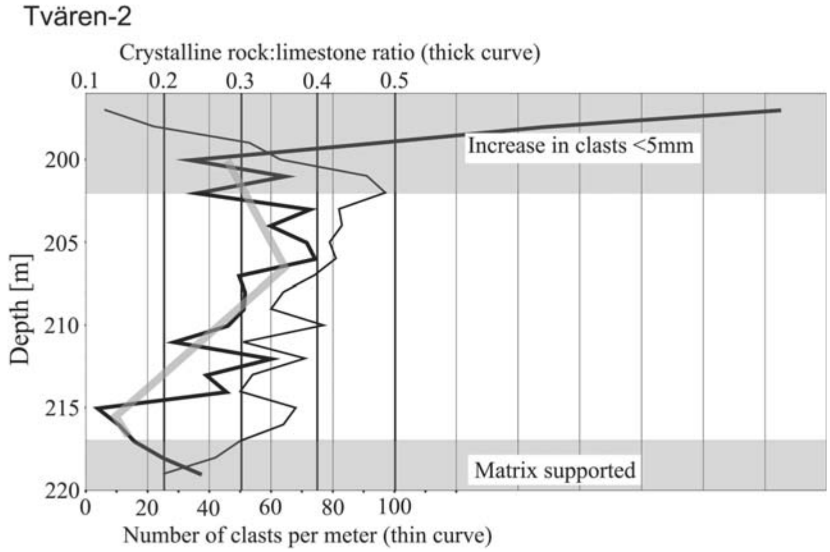

Fig. 9. Clast frequency and ratio between crystalline and limestone fragments in the Tvären-2 core. Gray lines indicate major trends in the crystalline rock:limestone ratio.

Table 1. Linear regression analysis of the relation between standard deviation of the mean clast sizes per meter (σ) and the mean clast size per meter (φ).

	Equation	Square regression coefficient (R^2)
All cores, all lithologies	$\sigma = 0.46\varphi - 0.82$	0.73
All cores, all lithologies (neglecting off line values)	$\sigma = 0.60\varphi - 1.25$	0.86
Lockne-1, all lithologies (neglecting off line values)	$\sigma = 0.53\varphi - 1.09$	0.97
Lockne-2, all lithologies (neglecting off line values)	$\sigma = 0.62\varphi - 1.31$	0.84
Tvären-2, all lithologies (neglecting off line values)	$\sigma = 0.52\varphi - 0.97$	0.89

the ratio between crystalline and limestone clasts, and high and fluctuating clast frequency.

Variations in Mean Clast Size and Size Sorting

The curves of mean clast sizes per meter (φ) are very similar between the cores from both craters. There is a general fining-upwards trend from the bottom to the top of the analyzed interval (Figs. 10a to c). However, in the lowermost part of the interval this trend is broken by a short section of reverse grading and grain size undulations (i.e., below 76 m in Lockne-1, below 206 m in Lockne-2, and below 214 m in Tvären-2). In all cores, the mean-size trend of the crystalline fragments closely follows that of the limestone fragments. However, the crystalline fragments are generally smaller than the limestone fragments possibly due to differences in shape (see Discussion). The size sorting of the clasts is shown by the σ-values (Fig. 10). The higher standard deviation values indicate poorer size sorting of the clasts.

Each of the three studied sections consists of three parts. The lowermost one is thin and characterized by high standard deviations (i.e., poor sorting) that decrease rapidly upwards. The top of this interval is at a sharp low in σ-values at a depth of 81 m in Lockne-1, 217 m in Lockne-2, and 217 m in Tvären-2 (Figs. 10a to c). This is where in Lockne-2 matrix-supported breccia is replaced upward by mainly clast-supported breccia (Fig. 3b).

In the next higher interval the σ-values rise again. Though this is the marked general trend, strong variations occur. The abrupt upper termination and culmination of this trend is at a depth of 72 m in Lockne-1, 203 m in Lockne-2, and 211 m in Tvären-2 (Figs. 10a–c).

The third interval, which forms the upper half of the Lockne-1 section and the major part of the Lockne-2 and Tvären-2 sections, is characterized by improved sorting, expressed by decreasing σ-values. The change is gradual in Lockne-1 (Fig. 10a) and Tvären-2 (Fig. 10c), but in Lockne-2 there is an abrupt drop to lower values that is maintained to about the depth of 182 m, above which the σ-values have a gradually decreasing trend (Fig. 10b). The σ-values are strongly correlated to mean clast size, and the two sets of curves show broadly the same trend, and the same tripartition into intervals (Figs. 10a–c). The clast-size curves are smoother, but the transition from increasing to gradually decreasing values takes place at a lower level than in the curves for standard deviation. It is also noteworthy that both sets of curves for Lockne-1 (Fig. 10a) show lower values than for either Lockne-2 or Tvären-2 (Figs. 10b, 10c). In other words the clasts are generally smaller and their sorting better in Lockne-1 than in the other two cores. Indeed, the major part of the Lockne-1 section above the depth of 75 m, resembles only the uppermost parts (i.e., with rapid fining-up) of Lockne-2 (above 182 m) and Tvären-2 (above 205 m).

When the standard deviation (σ) is plotted against the corresponding mean clast size for each lithology (φ), it is possible to analyze the clast size sorting for each lithology (Figs. 11a to c). The relationship between clast size and standard deviation appears to be linear with a slightly steeper function for crystalline than for limestone clasts. Standard deviations of all clasts in all cores (Fig. 11d) are concentrated mainly in the range 0.5–1.0, which is defined as moderately to moderately well sorted (Folk 1974). The function for standard deviation (σ) against mean clast size (φ) for all clast lithologies together in all one-meter intervals in all three cores (Fig. 11h) is

$$\sigma = 0.46\varphi - 0.82 \quad (1)$$

The square regression coefficient (R^2) is 0.73, which is rather low for the values to distribute along a line. However, after neglecting the four values that fall way off to the right from the main distribution in the graph, then the equation is:

$$\sigma = 0.60\varphi - 1.25 \quad (2)$$

Now the square regression coefficient (R^2) is 0.86, which better supports a linear distribution of the great majority of the values. Applying the same method on Lockne-1, Lockne-2, and Tvären-2 separately (Figs. 11e to f) gives the equations shown in Table 1. The deviation from the linear function increases with increased clast size. This is most apparent in Tvären-2. Here, however, most of the deviation (especially for the limestone clasts) is to the right, which means that the relative increase in standard deviation is not as strongly correlated with increased clast size as in the Lockne cores (i.e., the larger fractions at Tvären are better sorted than at Lockne). This also means that the larger fractions of the limestone clasts at Tvären are better sorted than the same fractions of the crystalline clasts.

DISCUSSION

Stratigraphic and Environmental Setting of the Breccias

The formations located below and above our studied sections of Lockne Breccia are important for the interpretation. In the cases of Lockne-1 and Tvären-2, there is an underlying breccia with crystalline clasts that would readily have served as substratum for the deposition of resurge sediments, and an overlying arenite (Loftarstone) with roughly the bulk composition of the Lockne breccia (Figs. 3a, 3c). This arenite would be the deposits of the oscillatory resurge phase. Indications for oscillating water movements have been reported from as far as 45 km from the crater center in the form of multi-directional ripple structures in Loftarstone deposits (Sturkell et al. 2000). The overlying arenite is present in Lockne-2 as well, but the logged Lockne Breccia of that section is separated from the underlying crystalline breccia by a 91 m thick, polymictic and matrix-supported breccia that previously has been regarded as part of the Lockne Breccia (Lindström et al. 1996) (Fig. 3b). This breccia predominantly contains limestone clasts of gravel to boulder sizes, and subordinate crystalline-rock gravel and cobbles. However, there are also clasts of mud with either non-deformed or contorted lamination and conformable limestone interbeds. This mud clearly would have been disintegrated by the resurge flow and would not have settled as compositionally laminated masses during the same flow. Therefore, we assume that at least the main part of this 91 m thick breccia (i.e., the part that is below the logged section) had formed before the resurge. Nevertheless, it could have covered larger parts of the crater before being eroded by the resurge, for which it would have served as a source of suspension load. The formation of this matrix-supported breccia is enigmatic: we do not consider it to be part of any mega-block slumping. Such a large polymictic deposit would not have had time for the three consecutive steps of piling up, consolidation, and moving bodily in bulk before the water-resurge entered the crater. Possible scenarios include material emplaced but never ejected during crater excavation, or that it is a fall-back from the water cavity ejecta curtain. It is known from both experiments (e.g., Gault and Sonett 1982; Ormö et al. 2006) and numerical simulations (e.g., Melosh 1982) that the ejecta curtain of the water cavity is expanding at a very steep angle, indeed even backwards forming a “dome” above the marine impact site before it collapses almost vertically. The collapsing water mass, charged with solid and semisolid ejecta, would deposit a breccia of the discussed kind irregularly distributed across the area cleared of water. In the inner parts of the crater the deposition would have occurred before these parts were reached by the resurge flow.

There are several differences between the results from the Tvären-2 core and the Lockne cores, but in our opinion the similarities dominate. Both the differences and the similarities are important when trying to reconstruct the formation of the analyzed sediments at the two craters. The most important differentiating factors concerning the Lockne and Tvären craters are the size of the apparent crater, the local depth of the target sea, and the properties of the target bedrock. The resurge and its deposits are furthermore dependent on the volume of the water crater, which in its turn depends on sea depth and is directly correlated with the size of the apparent crater.

The principal circumstantial evidence that can be used for the reconstruction of the target water depth at Tvären consists of (1) the sedimentary succession of the target seabed, (2) the presence of a thick and massive resurge deposit, (3) the occurrence of fossil shallow-water organisms in slumped interlayers in the post-impact sediments within the crater,

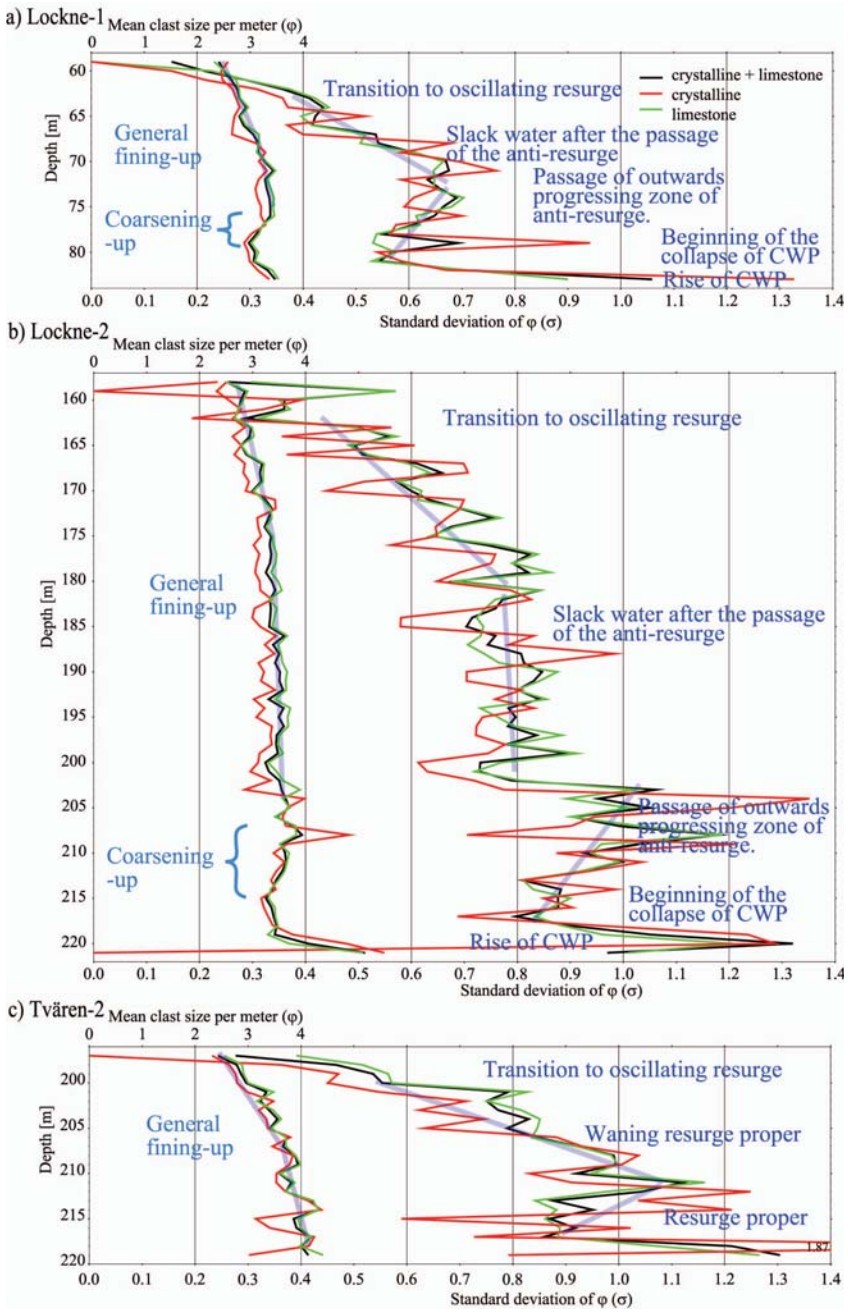

Fig. 10. Graphs showing the mean clast size (φ) distribution and sorting σ (i.e., standard deviation of the mean clast size per meter). a) Lockne-1, b) Lockne-2, and c) Tvären-2. Color code is given at the top (a). Interpretations are given in dark blue color to the right in the figures. CWP = central water plume. Thick light-blue lines indicate major trends in data curves.

(4) the occurrence of clasts of crystalline ejecta in the same slumps, and (5) the absence of ejecta clasts in other post-impact sediments. (1) and (2) indicate a minimum depth of the sea before the impact, whereas (3) and (4) show that the sea was not very deep over the raised rim that formed around the crater. (5) bears on the relation between the height of the rim wall and the water depth.

1. The sediments of the target seabed belonged to a hemipelagic carbonate facies that was deposited extremely slowly with monotony of fauna and sediment. This facies prevailed on the Baltic Shield throughout much of the Ordovician (Lindström 1971, 1984). Although photosynthesizing algae temporarily lived in parts of the sea that were not deeper than 50 m to 100 m (Nordlund 1986), these algal remains were transported and there is no evidence that the sediments in which they occur were deposited at particularly shallow depths. There is structural and stratigraphic evidence that deposition took

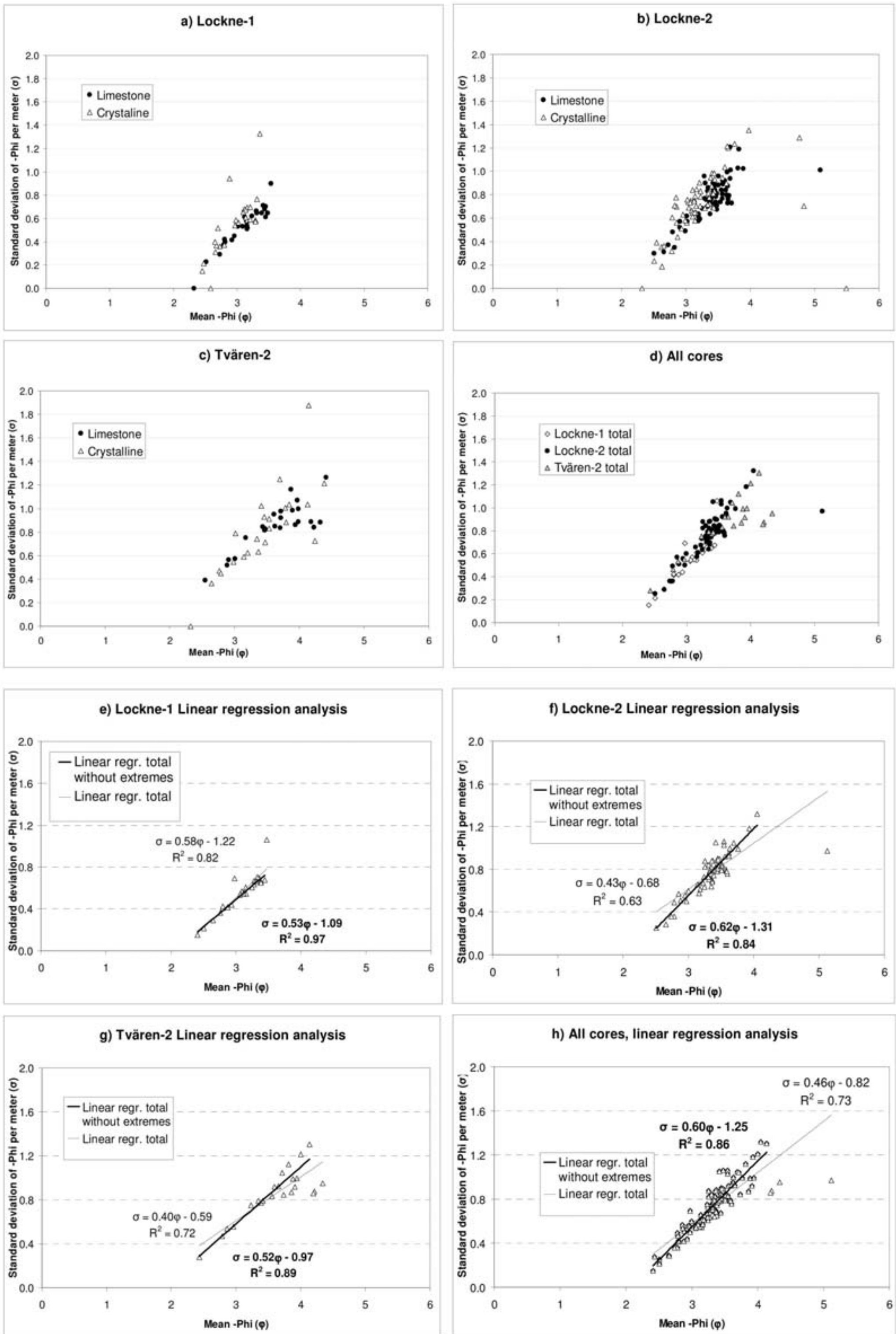

Fig. 11. Plots of mean clast sizes per meter φ versus size sorting σ (i.e., standard deviation of the mean clast size per meter). The upper set of four graphs (a–d) shows values for each lithology in each core, as well as the total for all cores. The lower set of four graphs (e–h) shows linear regression analysis of plots of the total number of clasts for each core, as well as for all cores combined. Two options are given: one that includes all values, and one that excludes a few values that falls way off the main population (bold) in order to avoid influence from extremes (For "Lockne-1" the two single values to the upper left have been excluded. For "Lockne-2" the single value far to the right has been excluded. For "Tvären-2" the group of three values to the right has been excluded. For "All cores" the group of three values to the right of the main population, as well as the single value to the far right have been excluded).

place below hurricane wave base (Lindström 1963, 1971, 1984), which suggests a depth below 100 m.

2. For resurge to have generated a single massive deposit that settled out of suspension, the water depth should have been greater than the order of tens of meters (Ormö and Lindström 2000).
3. There are algal nodules, as well as the remains of a diversified shelly fauna, in the slumped interlayers in the post-impact secular mud deposit inside the crater (Lindström et al. 1994; Frisk and Ormö 2007). These occurrences prove that the highest elevations of the crater rim were shallower than 100 m (i.e., within the photic zone).
4. The presence of crystalline clasts in the slumps proves that minor portions of the crater rim could become unsettled during occasional events, such as severe storms. Therefore, the rim likely extended upward to within several tens of meters of sea level, but not closer.
5. If the rim had risen to near sea level, it would have been substantially eroded, especially during the initial deposition of post-impact secular sediments. However, clasts derived from the rim occur only in a few of the slump horizons.

The approximate height of the rim wall of a 2 km wide crater on land is about 80 m (Pike 1977) and must be considered an uppermost limit for the rim wall of a 2 km crater formed at sea considering that structural uplift is not expected to contribute much to the rim height of a marine-target crater (Ormö and Lindström 2000). A few tens of meters of water can be added to the rim height according to the above arguments, and we arrive at a depth of 100–150 m for the target sea.

Early assessments of the depth of the sea at Lockne at the time determined for the impact were based on the assumption that the Lockne Breccia and Loftarstone are marine shoreline deposits (Thorslund 1940). Only much later (Lindström 1984; Ormö and Lindström 2000) did it become evident that the sea was more likely at least as deep as the deepest reasonable in the case of deposition on a continental shelf of modern type, that is, about 200 m. However, 200 m was taken as a minimum, not as the established depth. The target water depth for Lockne can now be assessed through best-fit numerical models constrained by the geomorphology of the crater (Ormö et al. 2002; Shuvalov et al. 2005; Lindström et al. 2005a). It is determined that 500–700 m is the depth range that allows the impact process to produce most of the observed structures.

Interpretation of the Data

Some of the observations from the statistical treatment of the core logs in this study are obvious upon visual inspection of the cores. For instance, the fining-up sequence is very apparent and is the main reason why the analyzed intervals have been attributed to a forceful resurge in previous work. The statistical method used by us has certain limitations in that a "cutoff" size must be set for the clasts to be logged. Which "cutoff" size to use must be determined by factors such as (i) the aim of the study (i.e., which fractions that need to be included), (ii) the general appearance of the sediments to be analyzed (i.e., to what degree is visual inspection sufficient), and (iii) the time available for the analysis.

The thickest and probably most complete section occurs in Lockne-2, which was drilled 2 km from the center of the crater (Fig. 1). In order to reach this site, the resurge proper passed over about 4 km of crystalline debris (i.e., the ejecta flaps and parts of the interior of the inner crater). It is, however, unknown to what extent this debris was covered by a polymict breccia like the 91 m thick breccia in the Lockne-2 core that was mentioned above. Numerical modeling by Lindström et al. (2005a) shows that rip-up would be the main contributor of sedimentary clasts to the resurge flow, especially on the western, down-range side of the crater where the simulations indicate that crystalline material dominates the ejecta.

Based on our sedimentological results, we propose a scenario where the resurge flow transported the clasts as suspension load along with abundant finer suspended material (i.e., mud-charged flow). The upper part of the resurge flow that carried this load would have been continually shooting past the basal flow that was retarded by bed friction. Upon reaching the front of the resurge flow, this upper flow hits the ground and, losing part of its momentum and carrying capacity, unloads some of the suspended matter. This would, generally, be the larger fractions but also much fines as the flow was mud-charged. When crashing down on crystalline debris, the front of the flow includes much crystalline matter in its first deposit, whereas there might be less of this matter in the sediments deposited in the moments that followed (i.e., the sediment-rich suspension flow).

Numerical simulations of the resurge flow at the Lockne crater indicate that the collapse of the water cavity and the flooding of the whole crater took a few minutes and that the flow entering the inner crater was over a hundred meters deep and moved with a velocity of several tens of meters per second (Ormö and Miyamoto 2002; Shuvalov et al. 2005). As water surged from all directions toward the center an upward-shooting central water plume (CWP) formed. At the site of Lockne-2, the resurge deposition would have been dominated by the build-up of this CWP. Just before the collapse of the CWP, there was a moment of retarded horizontal flow that would have led to sinking grain size of the deposit. We suggest that this is what we see in the core interval just below 215 m. The anti-resurge began with the collapse of the CWP, which caused an increase in flow velocity (now in reveresed direction) that led to upward coarsening to the level about 207 m, above which there is a gradual reduction of mean grain size. That the mean grain size culminates before the standard deviation reaches its greatest values shows that the collapse of the CWP was a complex process including reworking of already deposited material.

The collapse of the CWP was accompanied by a rise in the relative frequency of limestone clasts (i.e., a drop in the crystalline rock:limestone ratio, Fig. 8), because the plume consisted of the upper flow that was particularly rich in limestone clasts.

The anti-resurge stage was a layered flow regime with an outward directed anti-resurge at the top and the continued resurge proper as an inward flow below. The anti-resurge was probably a, relatively speaking, prolonged flow that began as shooting and degraded into turbulent. During this development the sorting of the deposits (i.e., σ) may have become strongly fluctuating, whereas the clast sizes (i.e., φ) remained fairly constant. It may be assumed that the flow velocities of the anti-resurge were lower than the resurge proper. This would cause a dump of material down into the resurge proper that already had all the load of suspended particles that it could carry. This may be visible in the core interval between 215 m and 207 m in Lockne-2.

Behind the contact zone between the continuous resurge proper and the anti-resurge from the collapsing CWP (i.e., a huge vortex similar to a breaking wave, (Fig. 6d), there was a slack water zone that migrated outwards from the center. In this zone, finer components (i.e., the gravel-rich succession between 175 m and 207 m in Lockne-2) were deposited out of the sediment-saturated water.

Lockne-1 was drilled 3.3 km from the center and 0.4 km from the margin of the apparent inner and deeper crater (Fig. 1). The gravel-rich succession is much thinner than at Lockne-2. There the flow of the resurge proper was stronger and lasted longer, and there was less influence of the slack-water zone. The similarity between the Lockne-1 and Lockne-2 drill core sections is best expressed in Figs. 11e, f, where the x and y intercepts are nearly identical. Comparing all graphs for mean grain size (φ) and size sorting (σ) (Figs. 10a, b), the section below 77 m in Lockne-1 resembles the section below 215 m in Lockne-2; the section above 77 m in Lockne-1 resembles the section above 175 m in Lockne-2, which could signify that a succession corresponding to the 215–175 m interval in Lockne-2 is poorly developed (or even missing?), in Lockne-1. The grain size minimum at about 80 m in Figs. 10a could correspond to the slack water moment between resurge proper and anti-resurge similar to that below 215 m in Lockne-2, however with an overall shorter duration at Lockne-1 than Lockne-2. Figure 11f shows that the larger grain sizes and the greatest standard deviations (i.e., poorest sorting) are strongly represented in Lockne-2, where they correspond mainly to samples measured between 215 m and 175 m. In Lockne-1, such large grain sizes and great standard deviations are nearly missing (Fig. 11e). Smaller grain sizes and standard deviations are about equally well represented in both drill cores (Figs. 11e, 11f). This is in agreement with the suggestion that a part of the succession could be missing at Lockne-1. We can not say at this stage if this is due to erosion or different mode of deposition.

Lockne-1 has by far the greatest number of clasts per meter found in any of the drill cores (Fig. 7). The fabric is clast-supported and interclast spaces are frequently filled with cement spar, which indicates that mud was scarce during deposition. This might characterize an anti-resurge regime at some distance from the collapsing CWP. The comparison between Lockne-1 and Lockne-2 suggests that a considerable mud dump formed under the water plume in the central part of the crater, and that this dump did not extend to the marginal parts of the apparent crater.

The total volume of the resurge at Tvären was much smaller than that of Lockne. This is probably reflected in the lower slope of the regression line for mean size versus sorting for Tvären-2 (Fig. 11g). The Tvären-2 section is characterized by few and large clasts in the lower ten meters (Figs. 8, 10c), causing a great variation in standard deviation; in this case it is a sampling artifact rather than an expression of a sedimentary process. The mean grain size decreases fairly smoothly from bottom to top; the grain size drop visible in the lower part of the logged interval in both the Lockne cores, interpreted as characteristic for the CWP, is missing. This may indicate that a CWP did not form at Tvären or that differences in the resurge dynamics did not allow deposition and/or preservation of deposits from a CWP phase. The number of clasts per meter (Fig. 9) is consistently lower at Tvären than in the Lockne sections, which demonstrates that mud played a greater role throughout resurge deposition at Tvären (i.e., higher degree of matrix in the core).

The crystalline rock:limestone ratio in Tvären-2 rises upward from less than 0.2 to over 0.3 (Fig. 8). This rise is unexpected because the first obstacle met by the resurge was the raised rim that was covered by crystalline ejecta (see the model of inverted stratigraphy in the crater rim, summarized by Melosh 1989). Our explanation of the initial relative paucity of crystalline clasts is that the principal components of the resurge front were Paleozoic limestone and sand ripped up from the sediment cover that surrounded the crater. This is consistent with the results by Ormö (1994) who used microfossils to study the age and provenance of sedimentary clasts in the Tvären-2 core. The rip-up material was transported into the crater as suspension load. The raised rim then became an important source of crystalline clast load to the waning resurge.

Figures 10 and 11a–c show the tendency for limestone clasts at both Lockne and Tvären (although less obvious) to be larger than crystalline clasts at all levels. This may reflect a general difference in the shape of the clasts in combination with methodical constraints: The limestone clasts, especially at Lockne, are generally slightly disk-shaped whereas the crystalline clasts may have any shape. The disk shape is due to the origin of many limestone clasts as nodules that were eroded from argillaceous matrix. In the applied method the longest visible axis of each fragment in the core is measured. Thus, the length axis of the limestone clasts is overrepresented in the logging. This effect is further enhanced by the fact that disk-shaped clasts stay longer in suspension than more spherical clasts of equal mass (i.e., giving larger relative clast sizes), and that during deposition there will be a preferred bedding parallel orientation of disk-shaped clasts (i.e., perpendicular to the coring).

CONCLUSIONS

We divide the resurge process into "resurge proper" (water and debris shooting into the crater; in craters with deep enough water relative to the crater rim, culminating in the rise of a central water plume, CWP), "anti-resurge" (collapse of the CWP leading to outward movement of water and debris overriding the resurge proper that prevails in the outer parts of the crater), and "oscillating resurge" (no unique movement direction during waning flow). Behind the outwards moving contact zone between resurge proper and ant-resurge develops a slack-water body with increasing volume.

Line-log data from the Lockne and Tvären marine-target craters are subdivided into characteristic portions, that are correlated with the three principal resurge stages. This is particularly well shown for the Lockne cores by the curves for mean clast size per meter (φ) of drill core (Figs. 10a, 10b). The anti-resurge stage (i.e., the developing slack-water body) in these curves shows the smoothness and consistency of the fining upwards trend required for validation of the method. The other requirement, that the curves can be meaningfully compared between the drill cores, is also fulfilled. Discrepancies between the log results can be explained by factors such as the location of the drill site in relation to the crater center, the crater diameter and rim height in relation to the water depth, and clast morphology.

We note two critical aspects of our method: the necessary cutoff at 5 mm (longest grain dimension), and the rise of standard deviation with grain size. The cutoff at 5 mm turned out to be irrelevant for the discussed results. Because the standard deviation has the number of measurements as divisor, its rise is partly due to the decrease in the number of clasts with rising grain size (there cannot be as many large clasts as there could be small ones in a given unit core length). However, as our graphs also show, there can nevertheless be a considerable spread of standard deviations as the grains get larger. In view of this circumstance, the correlation between average grain size and standard deviation is surprisingly good. If this degree of correlation had been simply inherent in the statistical method, one would expect to find identical slopes of the regression lines for the smaller (Tvären) and the larger (Lockne) crater, which is not the case.

The core Lockne-2 from the central part of the 7.5 km wide inner basement crater contains a relatively complete section of resurge deposits. It shows more mud relative to clasts than the peripheral drill core (Lockne-1). The resurge proper is characterized by large grain sizes and high standard deviations; the beginning collapse of the CWP as well as the consequent initiation of the anti-resurge are signaled by slack water and greatly lowered grain size. The anti-resurge builds up with a strong but gradual rise in both grain size and standard deviation. It passes into oscillating resurge with a decrease in grain size and standard deviation that begins with a fast drop, then a smooth section before again dropping off more rapidly. In the peripheral section of the inner crater (i.e., Lockne-1 core) the effects of the anti-resurge are less conspicuous. Clasts from the sedimentary cover rocks dominate in both sections. They are considered to have been derived mainly through erosion of the outer crater, which formed primarily in the sedimentary target rocks. These clasts were delivered as suspension load by the resurge proper. The content of crystalline clasts in general decreases upward and is thought to have originated mainly as rip-up from the crystalline impact breccia within the inner basement crater.

Contrary to the Lockne crater (500–700 m deep target water), the 2 km wide Tvären crater (100–150 m deep target water) shows no clear granulometric evidence of a CWP. The general fining upward of the resurge deposit is interpreted to reflect a gradual passage from resurge proper to oscillating resurge.

Like Lockne, Tvären shows a dominance of clasts from the sedimentary cover rocks that are interpreted as erosion-derived suspension load. Contrary to the case at Lockne, crystalline clasts increase in frequency upwards. This circumstance is explained as due to the increasing relative importance of erosion of crystalline ejecta of the raised rim as the source of clasts when the resurge slowed down.

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