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Distant ejecta from the Lockne marine-target impact crater, Sweden

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Abstract–The Lockne impact event took place in a Middle Ordovician (455 Ma) epicontinental sea. The impact resulted in an at least 13.5 km wide, concentric crater in the sea floor. Lockne is one of very few locations where parts of an ejecta layer have been preserved outside the crater structure. The ejecta from the Lockne impact rests on progressively higher stratigraphic levels with increasing distance from the crater, hence forming a slightly inclined discontinuity surface in the pre-impact strata. We report on a ~30 cm thick sandy layer at Hallen, 45 km south of the crater centre. This layer has a fining upward sequence in its lower part, followed by low-angle cross-laminations indicating two opposite current directions. It is rich in quartz grains with planar deformation features and contains numerous, up to 15 cm large, granite clasts from the crystalline basement at the Lockne impact site. The layer is within a sequence dated to the *Baltoniodus gerdae* conodont subzone. The dating is corroborated by chitinozoans indicating the latest Kukruse time below and the late Idavere above the impact layer. According to the chitinozoans biostratigraphy, some erosion may have occurred because of deposition of the impact layer. The Hallen outcrop, today 45 km from the centre of the Lockne crater, is at present the most distant accessible occurrence of ejecta from the Lockne impact. It is also the most distant location so far found where the resurge of water towards the crater has affected the bottom sediments.

A greater crater diameter than hitherto assumed, thus representing greater impact energy, might explain the extent of the ejecta blanket. Fluidisation of ejecta, to be expected at a marine-target impact, might furthermore have facilitated the wide distribution of ejecta.

INTRODUCTION

The Lockne impact site is located in Jämtland, central Sweden (Fig. 1). This Middle Ordovician impact event struck a marine target with water and sedimentary rocks covering a crystalline basement (Lindström and Sturkell, 1992; Sturkell, 1998a). Because of the marine environment, a resurge wave filled the newly formed crater. The resurging water eroded the strata it travelled across, the more forcefully the closer to the inner crater. Deep gullies were eroded through the crater rim (Lindström *et al.*, 1996). The impact and the resurge currents generated a distinct marker bed in the surroundings of the crater. This bed marks a prominent local discontinuity that cuts through progressively higher stratigraphic levels outwards from the crater. Thus, the discontinuity forms a wide, very shallow funnel surrounding the inner and deeper 7.5 km wide crater in the crystalline basement (Sturkell, 1998a). In the immediate surroundings of the inner crater, brecciated crystalline basement with a few traces of sedimentary rock forms a 3 km wide zone (Lindström *et al.*, 1996). Ormö and Lindström (2000) interpret this zone as a part of an outer crater in accordance to the concentric crater model presented by Quaide and Oberbeck (1968).

The water depth controls the development of marine impacts (Ormö and Lindström, 2000). If the water depth greatly exceeds the size of the transient crater, no crater can be traced in the seabed, as observed for the Eltanin impact in the Bellingshausen Sea (Gersonde *et al.*, 1997). If the transient crater extends into the seabed, a crater structure will remain, however, with a smaller diameter than the part of the crater formed in the water layer. This circumstance makes it difficult to estimate the crater diameter, because the water depth at such an old impact site is not known precisely. The size of a crater formed in a marine environment is, thus, often underestimated. In addition, impacts in a marine environment produce rock types, which are not formed by impacts on land. These rocks are mainly resurge generated (Lindström and Sturkell, 1992; Lindström *et al.*, 1994; Izett *et al.*, 1998; Smit *et al.*, 1996).

The impact layer around the Lockne crater consists of a mixture of ejecta and rip-up material from the seabed, all mixed when the resurge rushed back to fill the crater. According to Lindström and Sturkell (1992) and Sturkell (1998a), these deposits may be divided in the vicinity of the Lockne crater into two units: (1) clast-supported breccia with clast sizes ranging from less than a centimetre to tens of meters, and (2) sandstone and siltstone representing the final stage of resurge. Locally in the Lockne area, the unit (1) is termed Lockne Breccia and unit (2) Loftarstone (Asklund, 1933; Thorslund, 1940; Lindström and Sturkell, 1992). The clast-supported breccia is greatly dominated by Lower and Middle Ordovician limestone. The smaller limestone clasts (1–10 cm) are often rounded, either because of abrasion, or because they originated as nodules. It is only in its most fine-grained parts that the amount of crystalline components increases to a significant quantity (*i.e.*, ~25 vol%). The transition from the clast-supported breccia to sandstone and siltstone can be either gradational or discontinuous, the latter possibly erosional. In this sequence, sedimentary structures such as graded bedding are common in the lower part; whereas current lineation, cross bedding, and dewatering structures are common in the upper medium- to fine-grained parts.

The grain size of the arenite ranges from coarse sand to silt in a fining upward sequence. The dominant constituent in the arenitic rock is Ordovician carbonate clasts with fossil fragments, making up

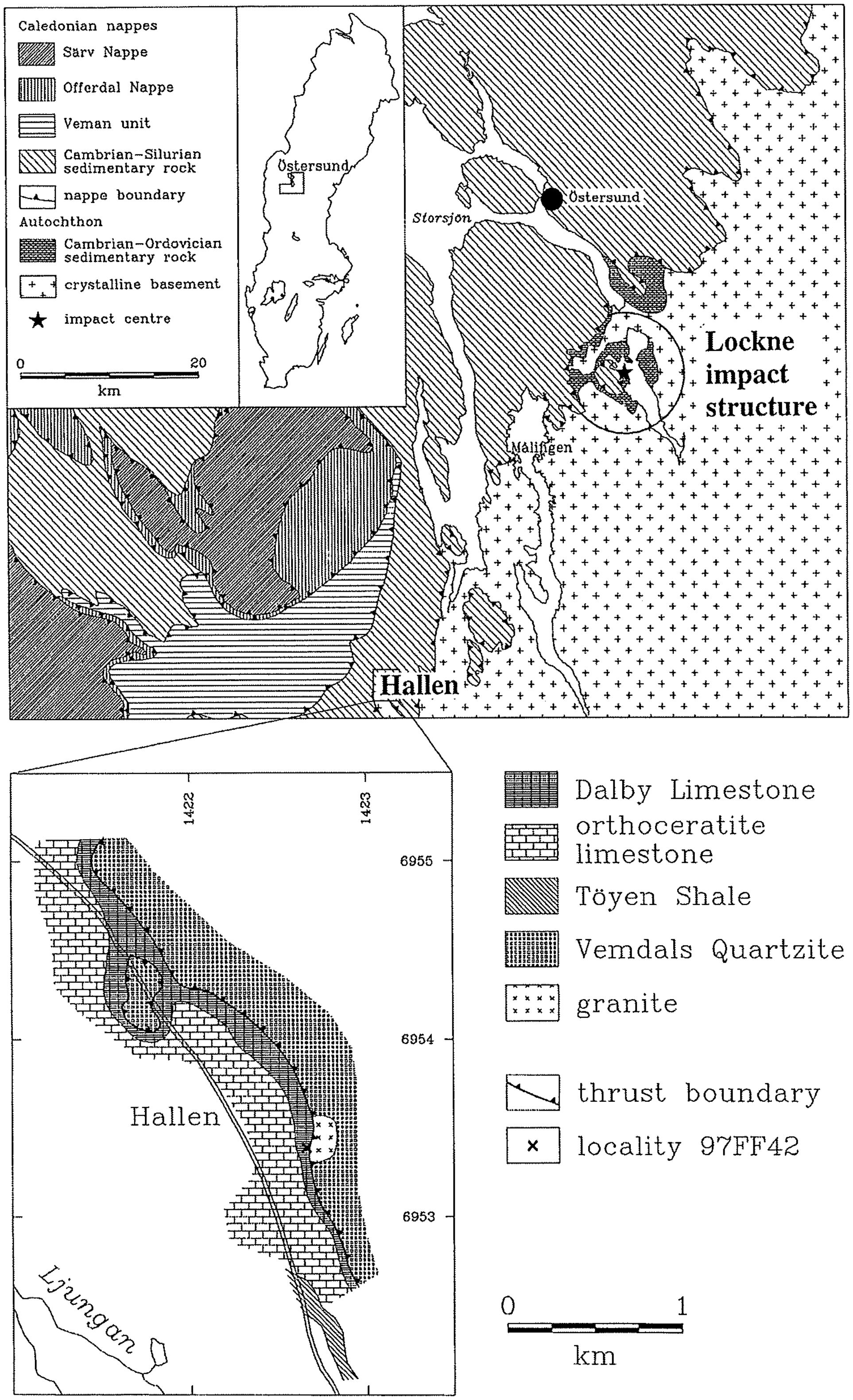

FIG. 1. Geological map of central Sweden with the position of the Lockne crater and the Hallen locality (coordinates 6953370 1422680, Swedish National Grid). The insert map shows details of the Hallen area (modified after Asklund, 1933). This part of central Sweden can be divided into three geological units: the crystalline pre-Cambrian basement, autochthonous Cambrian–Ordovician sedimentary strata, and Caledonian overthrust rocks. The Hallen locality is situated within the lower Caledonian allochthon and has been transported in easterly–east-south-easterly direction. The distance between Hallen and the centre of the Lockne impact is today ~45 km. The circle at Lockne denote the extent of the 13.5 km diameter crater.

~40% of the rock. A carbonate matrix dominates the fine-grained part. Fragments are carbonates, claystone, totally fragmented crystalline rock, and probably solidified melt particles. The amount of lithic crystalline fragments decreases with grain size, whereas the amounts of quartz and monomineralic feldspar particles increase with diminishing grain size. Fragments of crystalline basement (lithic fragments, quartz, and feldspar grains) represent together approximately 20–25% of the rock. In addition, recrystallised impact-melt particles make up 20 vol% of the arenite rock. Simon (1987) reported the presence of pyroclastic material in the arenite. This is today interpreted as impact-generated melt particles. The Cambrian claystone occurs as black shale fragments in all sizes, from coarse sand size to components of the matrix. The shale makes up 10–15% of the rock. The two types of resurge deposits (clast-supported breccia and the arenite) are compositionally alike. However, the arenite has a larger proportion of material originating from the deepest excavated part of the crater, and it contains abundant shocked quartz (Therriault and Lindström, 1995). This sandstone and siltstone unit has an Ir content of up to 4.5 ppb in bulk rock samples from the Lockne area, which further supports the impact origin of the deposit (Sturkell, 1998b).

At the locality Hallen (62°41'04" N, 14°16'50" E), abundant fragments of Proterozoic granite, with clast sizes up to 15 cm, have been found (Thorslund, 1940). These clasts occur in an arenitic layer intercalated in a Middle Ordovician limestone sequence. The aim of this work was to investigate the possibility of this layer being a remainder of an ejecta layer surrounding the Lockne impact crater.

The post-impact sequence and its micropalaeontology have been studied in the crater-filling strata, in drill-core samples, and in outcrops (e.g., Grahn and Nõlvak, 1993; Grahn *et al.*, 1996; Grahn, 1997). The impact layer itself has not been paleontologically dated. However, a precise palaeontological dating of both the youngest pre-impact beds and the oldest post-impact beds in a continuous section will keep the dating error as low as possible. The locality Hallen is very suitable for this purpose. Because of the great distance from the crater, the resurge would have caused only minor erosion of the pre-impact sediments in the footwall of the layer.

GEOLOGICAL SETTING

The Hallen locality is today at 45 km distance from the crater centre. The closest outcrop with the impact layer described is located at Målingen (Fig. 1) that is located 15 km from the centre. Hallen is situated on the south-western slope of the Ljungan river valley ~6 km north-northwest of Åsarna village (Fig. 1). It is located in the lowermost Caledonian allochthonous unit, close to the present-day erosional front of the nappes. According to Asklund (1933), Proterozoic crystalline basement is exposed in the bottom of the river valley. On the crystalline basement with a thrust boundary at its base, follows a sequence of approximately 70 to 80 m of Cambro–Ordovician strata. The Ordovician Dalby Limestone is overthrust by the late Proterozoic Vemdal Quartzite. At Hallen a coarse clastic layer, together with a fining-upward, cross-bedded arenitic layer, is intercalated in the Dalby Limestone ~3 m below the thrust boundary.

The locality studied is what Asklund (1933) refers to as the "southern outcrop" (for location, see Fig. 1). Asklund (1933) used the local term "Loftarstone" when referring to the arenitic layer within the limestone sequence. Jaanusson *et al.* (1982) dated the Dalby bed below the arenitic layer at Hallen, by means of conodonts, as belonging to the *Baltoniodus gerdae* subzone. Simon (1987) came to the same result.

A section consisting of two parts labelled I and II from Asklund's "southern outcrop" was measured and sampled in this study. Acritarchs, chitinozoans, and conodonts were extracted from the samples in order to generate a combined biostratigraphic dating of the event. Both sections were slightly improved by trenching.

RESULTS

The Clastic Layer at Hallen

The logged sections at Hallen, shown in Fig. 2, span together ~3 m of Dalby Limestone with an intercalated clastic bed. The two sections are positioned ~3 m apart; between them, there is a vertical gap of 10–15 cm. The limestone is a grey argillaceous calcilutite in massive as well as nodular beds. The upper part (II) contains three thin bentonite beds. The coarse clastic bed at Hallen, which may correspond to the impact layer at Lockne, can be divided into two parts: a lower coarse-grained clast deposit and an upper part consisting of sandstone and siltstone. The maximum aggregate thickness of the two layers is 40 cm as observed by Thorslund (1940). However, 30 cm is the more common thickness. The coarse-grained layer varies in thickness between a few centimetres and 15–20 cm. The thickness is controlled by the clast sizes. Thorslund (1940) reported granite clasts size of up to 15 cm, but the dominating size of the granite material is 5 cm or less (Fig. 3a). Thorslund also describes clasts of Lower and Middle Ordovician limestone (Fig. 3b) that we did not encounter in our study. The crystalline clasts are embedded in a calcareous matrix and form a continuous layer in the outcrop, and the contact to the arenitic layer is often sharp (Fig. 3a).

The thickness of the overlying arenitic bed is 15–20 cm. The lowermost 1–1.5 cm display a fining upwards sequence, from coarse to fine sand. The remaining part of the arenite displays a low angle cross-lamination with erosion troughs. Several individual sequences can be distinguished, each fining upwards. The grain size varies from fine sand to silt (Fig. 4). Signs of up to six of these flow pulses have been detected at the locality, with two opposite current directions. In the upper part of the arenitic bed, several small slump structures occur. The arenitic bed grades into clay at its top.

Thorslund (1940) described a matrix-supported polymict breccia within the coarse clastic layer, with rounded fragments of varying sizes (Fig. 3b). This breccia is dominated by Lower and Middle Ordovician limestone and may be up to 30 cm thick; however, it is not continuous. Proterozoic granite clasts, that are second most abundant after the limestone, are concentrated at the top of the breccia layer. We did not observe this lithology in Hallen; but as described by Thorslund (1940), this breccia resembles the resurge breccia seen at the Lockne crater.

Thin section analysis of the arenite revealed abundant shocked quartz grains with distinct planar deformation features (PDFs) (Fig. 5). However, most grains have only one easily detectable set. Another common feature of both mineral and lithic components is that they are micro-fractured and later healed with calcite. The fractures can be continuous through several grains. The arenitic bed is composed of calcite (2/3); the remaining lithic clasts and minerals grains are from the crystalline basement. There are also minor amounts of opaque minerals such as pyrite and magnetite. The calcite displays strong and persistent twin lamellation and is occasionally fibrous, all of which indicates tectonisation. All carbonate in the layer at Hallen is recrystallised. A recrystallised bryozoan fragment was observed, but other fossils with less characteristic structure have apparently been rendered unrecognisable through recrystallisation.

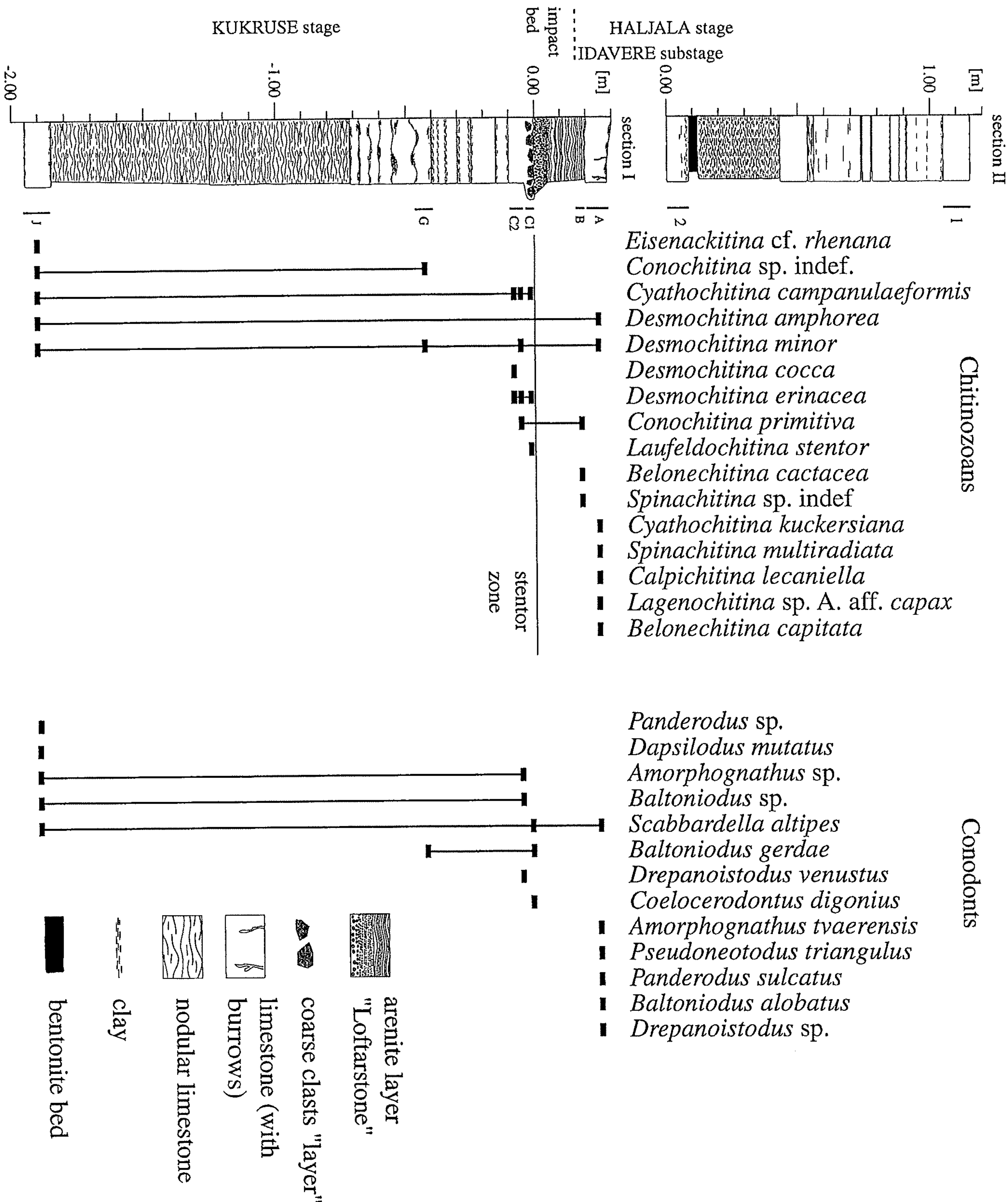

FIG. 2. Lithologic column of sections I and II at the Hallen locality. It shows the Lockne ejecta bed and resurge deposit interlaid in the Ordovician Dalby Limestone. The sample levels for the palaeontological study are indicated, labelled with letters in section I and by numbers in section II. The distribution of chitinozoans and conodonts species for section I is shown. The fossils in section II place it in the upper Idavere Substage of the Haljala Stage, giving it a younger age than section I. The 0.00 level in section I and II do not refer to the same stratigraphic level.

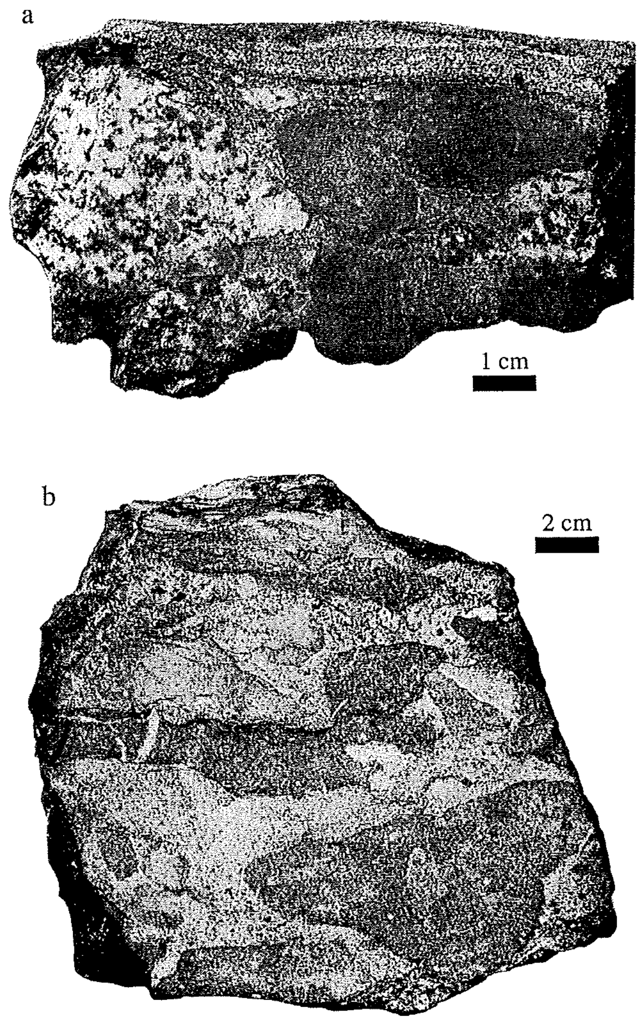

FIG. 3. Polished rock samples from the impact-generated deposit at Hallen. (a) Clast of Proterozoic granite and Lower and Middle Ordovician limestone, which is overlain with a sharp boundary by an arenitic rock, deposited as a result of the resurge. Reproduced photo from Thorslund (1940). (b) Large pebbles of Lower and Middle Ordovician limestone, and small pebbles of granite in a calcareous matrix. The matrix makes up about one-third of the rock. Some rare pieces of black Cambrian shale are also observed. Reproduced photo from Thorslund (1940).

FIG. 4. Etched surface of a polished sample of arenitic rock. The lowermost 1–1.5 cm display a fining upward sequence, from coarse to fine sand. The resurge rock features several flow pulses with two opposite current directions. Scale bar is 2 cm.

FIG. 5. Photomicrograph of a thin section from the lower part of the arenitic rock showing planar deformation features in quartz. One distinct set of deformation features dissects the whole grain. The field of the view is 0.2 mm and taken in plane polarized light.

Preservation State of the Hallen Microfossils

The state of preservation of all acid-resistant organic-walled microfossils was poor or very poor. The majority of the rare specimens found is broken or represented only by fragments. This observation is especially valid for the largest forms among chitinozoans. The walls of almost every chitinozoan specimen are splintered. The best preserved specimens are the small rounded forms, dominated by *Desmochitina*. The mode of preservation is likely to be by silicification of the rock. A likely source of silica is the numerous bentonite beds in the sequence. Silicification is indicated by the ease with which the specimens were reduced to splinters during the preparation of the samples. The chitinozoans and some rare fragments of scolecodonts have a metallic lustre. This lustre is a consequence of thermal alteration and indicates temperature close to 300 °C. This alteration can also be inferred from the colour of the acritarchs. The thermal alteration index of the acritarchs is 4–5 following Traverse (1988). Lighter forms are present, but they are destroyed. The conodonts are dark brown, which gives a conodont alteration index CAI-value of 3–4 (Epstein *et al.*, 1977), indicating a temperature between 110–300 °C. Neither the thermal alteration nor the silicification of these rocks was the result of the impact; instead, they are regarded as secondary changes related to metamorphism.

Biostratigraphy–The amount of acritarchs and their state of preservation were much lower at Hallen than in sediments of about the same age from Tvären on the east coast of Sweden (Wallin and Hagenfeldt, 1996). Most of the specimens are broken and coalified. Recognisable genera are *Baltisphaeridium*, *Goniosphaeridium*, *Multiplicisphaeridium*, and *Ordovicidium*. Other organic microfossils found are scolecodonts.

The analysis of Chitinozoans show that layers belonging to the *Lagenochitina dalbyensis* Zone most probably are absent in section I. In the sample from layer C1, some specimens of *Cyathochitina campanulaeformis* are present. This species has a wide stratigraphic range, but the specific long neck form is restricted to the Kukruse–Idavere boundary beds in the East Baltic and also in the Fjäcka section (Nõlvak *et al.*, 1999). The same is true for *Lagenochitina* sp. A aff. *capax* that is known from upper *Laufeldocitina stentor* Zone to the top of the *Lagenochitina dalbyensis* Zone (Nõlvak and Grahn, 1993; Grahn *et al.*, 1996; Grahn, 1997). From these data, it can be inferred that the bed just below the impact layer belongs to the upper Kukruse, and the chitinozoan *Laufeldochitina stentor* Zone. The two samples from section II (Fig. 2) contained the chitinozoans *Belonechitina hirsuta*, *Belonechitina* cf. *micracantha*, *Desmochitina minor*, and *Cyathochitina campanulaeformis*. This assemblage can be followed in the *Belonechitina hirsuta* Zone in the upper Idavere Substage of the Haljala Stage (Laufeld, 1967; Nõlvak and Grahn, 1993; Nõlvak *et al.*, 1999).

The conodont fauna represented in all samples from section I (Fig. 2) is typical of the *Baltoniodus gerdae* Subzone and from section II of the *Baltoniodus alobatus* Subzone, both of *Amorphognathus tvaerensis* conodont Zone (Bergström, 1971). In section II *Scabbardella altipes*, *Protopanderodus liripipus*, *Baltoniodus alobatus*, and *Amorphognathus* sp. were found in sample 1; and *Scabbardella altipes*, *Baltoniodus* sp., and *Drepanoistodus suberectus* were found in sample 2. All samples yielded conodonts, however, in very low numbers compared with Lower and Middle Ordovician limestone in Jämtland (Zhang and Sturkell, 1998).

DISCUSSION

The currents driven by the distant resurge at Lockne were not strong enough to rip up limestone at the Hallen locality. However, it was able to affect the lime mud on the sea floor. The closer to the crater, the larger the erosional force of the resurge as indicated by the depth of erosion in sedimentary strata. This erosion contributed to a great influx of limestone fragments into the resurge deposit. Hallen is the most distal known locality of recognised impact layer. The greater the distance, the less impact-induced erosion can be observed. Thus, the significance of palaeontolgical dating of the event improves with distance from the crater. The palaeontological investigation shows that a relatively complete section of Dalby Limestone, especially the layers belonging to the *Baltoniodus gerdae* and *B. alobatus* subzones, is preserved at Hallen, but more complete sections are known within the impact structure (see Grahn, 1997). No storm deposit is observed within the Dalby Limestone; and from this, it is assumed that the Dalby Limestone was deposited below the storm wave base. Also, the great distribution of the lithology suggests that no coastline was present in the near surroundings.

The three chitinozoan zones *Armoricochitina granulifera*, *Angochitina curvata*, and *Lagenochitina dalbyensis* are not observed in the section. The first Zone is 18 cm thick, the second is absent, and the third is 1.4 m in the Fjäcka profile in the Siljan district (Nõlvak *et al.*, 1999), ~300 km to the south. We propose that the sediments of those three zones, if present, were not lithified when the ejecta were emplaced at Hallen and probably they were mixed with the impact layer. Dypvik and Attrep (1999) suggest based on drill core data 30 km from the crater rim (*i.e.*, 50 km from the crater center) that a severe seabed erosion took place in the aftermath of the formation of the 40 km wide Mjølnir impact crater. This is analogous to the seabed erosion that took place at Hallen in connection with the Lockne impact. Then about 1–2 m of sediment were eroded and intermixed into the impact layer. The carbonate in the impact layer has been recrystallised. This gives a poor preservation of the microfossils; therefore, we did not search for fossils from the missing zones.

The lower part of the coarse clastic bed at Hallen consists of a layer with granite clasts (up to 15 cm) forming a continuous bed at the Hallen locality. The clasts are petrologically similar to granite found at the impact site and therefore we interpret them as primary ejecta from the Lockne impact. The arenitic layer has abundant quartz grains with PDFs, and the paleontological dating coincides with the Lockne impact event. The crystalline (mineral and lithic grains) content in the arenite exceeds one-third, compared to the crystalline content of the impact generated arenite in the crater itself which is between 20–25% (Simon, 1987). The crystalline material in the impact layer was emplaced as ejecta initially, but almost directly redeposited by the resurging water. The relatively higher crystalline content in the deposit at Hallen indicates that a larger proportion of the material that reached Hallen was emplaced as ejecta.

As the ejecta mainly comes from the upper third of the transient crater (Melosh, 1989), a significant part of the ejected target material at Lockne must have consisted of water. Melosh (1989) describes how such fluidised ejecta on Mars formed a base surge with similarities in behaviour to mudflows. In a marine impact with target water depth as great as at Lockne, the fluidised ejecta would be transported, outside the zone blown dry by the impact, on top of the sea surface. The outgoing ejecta flow would cut down into the seawater, both incorporating water and pushing it forward (Ormö and Lindström, 2000). The matrix supported breccia (Fig. 3b) described by Thorslund (1940) may constitute the part of ejecta that was deposited on the seafloor without being sorted further by passage through the water column. However, it does not form a continuous layer at Hallen; the outcrop in Hallen only displays a few meters laterally of the impact layer.

The continuous ejecta blanket surrounding an impact site is expected to extend about one crater radius from the crater rim, apparently regardless of crater size (Melosh, 1989). The occurrence of impact-related rocks are very patchy outside a one crater radius of the edge of Lockne structure. These occurrences are mostly confined to the area along the Caledonian erosional front. The patchy appearance is probably due to relative scarcity of exposures of the stratigraphic interval and to the circumstance that the Caledonian nappes cut down below the impact layer. The distance between the centre of the Lockne impact and Hallen is today ~45 km. However, Hallen is situated within Caledonian nappes that have been telescoped east to south-southeastward. Lindström *et al.* (1996) estimated the nappe transport in Hallen (Åsarna) to be <20 km. The Caledonian movement has shortened the original distance between the two places. This circumstance makes 45 km the minimum distance for the ejecta emplacement from the Lockne impact event.

Large fragments of target rock are to be expected as a part of the continuous ejecta blanket surrounding the Chicxulub crater out to a few crater radii (Alvarez, 1996). So far only a few sites with large fragments of target rock have been found around the Chicxulub crater. The deposits at Albion Island (northern Belize), which is located 364 km from the centre of the Chicxulub crater, are interpreted by Ocampo *et al.* (1996) to be the most distant part of an ejecta blanket recognised so far from an impact event. They found clasts of Early to Middle Cretaceous limestone resting upon Late Cretaceous dolomite on Albion Island. Using a 195 km diameter for the Chicxulub crater (Morgan *et al.*, 1997), Albion Island is located more than two and a half radii (~245 km) outside the crater rim. This situation, described from Albion Island, is analogous to the occurrence of the Hallen locality, where a layer of Proterozoic granite clasts overlies Middle Ordovician Dalby Limestone.

In the Gulf of Mexico region, a graded unit of sandstone beds often marks the Cretaceous–Tertiary (K/T) boundary with a thickness ranging between 5 cm and 9 m. This is termed the K/T sandstone complex by Smit *et al.* (1996). It can be subdivided into four lithologic units (Smit *et al.*, 1996). The current directions measured in the K/T sandstone complex indicate variable, often 180° different current directions in successive sublayers (Smit *et al.*, 1996). Smit *et al.* (1996) shows unit II from the La Lajilla section in Mexico with climbing ripples and two opposite current directions. Unit II in the K/T sandstone complex displays striking similarities with the impact-generated bed at Hallen (Fig. 4).

The 35 km wide Manson impact structure is dated to ~74 Ma by Izett *et al.* (1998). They suggest that the Crow Creek Member of the Pierre Shale in South Dakota and Nebraska consists of ejecta from the Manson impact event. This was based on the occurrence of shocked quartz in the beds and the time correlation between them. Shocked quartz in the Crow Creek Member is observed up to 500 km from the Manson impact structure and is suggested to be distal ejecta by Izett *et al.* (1998). They also describe blocks that probably originate from the Crow Creek Member and contain hummocky cross-stratification. These beds could also be analogous to the K/T sandstone complex described by Smit *et al.* (1996) and the sandstone bed at Hallen.

The lower part of the clastic layer at Hallen is suggested to contain large fragment ejecta from the Lockne event and can probably be compared to the deposit at Albion Island south of the Chicxulub impact site. The upper part of the Hallen bed is an upward-fining sequence with ripple structures indicating two opposite current directions (Fig. 4). This layer contains fine-grained ejecta, which have been reworked by motions in the watermass caused by the resurge into the Lockne crater. The upper part of the Hallen bed may be compared with the cross-stratificated layers at, for example, La Lajilla section at the Mexican Gulf and the Crow Creek Member close to the Manson impact structure.

It can be concluded that the clastic layer at Hallen is connected to the Lockne impact event and that it has both large fragment ejecta and a bed with reworked fine-grained ejecta. The impact layer in Hallen can be part of an ejecta blanket or the most distal parts of channels formed by the resurge. However, the large amount of material originating from the deepest part of the excavated crater indicates it was first emplaced as ejecta. The Hallen locality is located at a minimum of five crater radii beyond the Lockne crater rim. This might indicate that the ejecta blanket at a marine-target crater may be distributed further than what is found to be the case for impact on land.

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