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Facies distribution of post-impact sediments in the Ordovician Lockne and Tvären impact craters: Indications for unique impact-generated environments

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Abstract–The Lockne and Tvären craters formed in the Late Ordovician Baltoscandian epicontinental sea. Both craters demonstrate similarities concerning near-synchronous age, target seabed, and succeeding resurge deposits; however, the water depths at the impact sites and the sizes of the craters were not alike. The post-impact sedimentary succession of carbonates, i.e., the Dalby Limestone, deposited on top of the resurge sediments in the two craters, is nevertheless similar. At least three main facies of the Dalby Limestone were established in the Lockne crater, depending on sea-floor topography, location with respect to the crater, and local water currents. The dominating nodular argillaceous facies, showing low values of inorganic carbon (IC), was distributed foremost in the deeper and quiet areas of the crater floor and depressions. At the crater rim, consisting of crushed crystalline basement ejecta, a rim facies with a reef-like fauna was established, most certainly due to topographical highs and substrate-derived nutrients. Between these facies are occurrences of a relatively thick-bedded calcilutite rich in cephalopods (cephalopod facies).

In Tvären, the lower part of the succession consists of an analogous argillaceous facies, also showing similar low IC values as in Lockne, followed by calcareous mudstones with an increase of IC. Occasionally biocalcarenites with a distinctive fauna occur in the Tvären succession, probably originating as detritus from a facies developed on the rim. They are evident as peaks in IC and lows in organic carbon (Corg). The fauna in these biocalcarenites corresponds very well with those of erratic boulders derived from Tvären; moreover, they correspond to the rim facies of Lockne except for the inclusion of photosynthesizing algae, indicating shallower water at Tvären than Lockne. Consequently, we suggest equivalent distribution patterns for the carbonates of the Dalby Limestone in Lockne and Tvären.

INTRODUCTION

In the Ordovician period, several cosmic impacts occurred in the moderately shallow epicontinental Baltoscandian sea. In Baltoscandia, five craters have been proposed to have formed in this sea, comprising about one-third of the known marine-target craters on Earth listed by Ormö and Lindström (2000).

These impact craters almost certainly had a significant influence on the local sedimentation. Immigration of the surrounding fauna occurred almost immediately on the post-impact ocean floor (Lindström et al. 1994; Grahn et al. 1996). The geological history of the marine-target Baltoscandian craters is described in earlier works (e.g., Tvären crater [Lindström et al. 1994; Ormö 1994]; Lockne crater [Lindström et al. 1996; Sturkell 1998; Dalwigk and Ormö 2001; Lindström et al. 2005a; Kärdla crater: Puura and Suuroja 1992; Puura et al. 2004]; Granby crater [Bruun and Dahlman, 1982]; the probable Hummeln crater [Lindström et al. 1999; Ormö et al. 1999]).

Marine-target craters like Lockne and Tvären offer a significant opportunity to investigate how paleoenvironments were affected by impact events. Although Lockne and Tvären are different in crater size and actual water depth, at the target site they demonstrate similarities in age (Lindström et al. 1994; Grahn et al. 1996; Grahn 1997), resurge sediments (Ormö et al. 2007), and post-impact secular depositional patterns. The understanding of the craters' influence on the post-impact sedimentation and biofacies development is important for understanding other marine-target craters such as Chicxulub

(Mexico), Chesapeake Bay (USA), and Mjølnir (Norwegian Barents Sea).

The location of the target areas with respect to the Baltoscandian epicontinental sea (e.g., Ainsaar et al. 2004) is shown in Fig. 4 in Ormö et al. (2007). The target seabed at Lockne was located on the western margin of the sea that extended over southern Scandinavia and the Baltic (Männil 1966; Jaanusson 1973). To the west, the area was transitional to a slope environment. Sedimentological and paleoecological evidence favors a relatively deep shelf position, rather than shallow water at the Lockne impact site (Lindström et al. 1996, 2005a, 2005b; Ormö et al. 2007). Deposition at this time was characterized by very slow and, on average, constant sedimentation rates. This situation was controlled by the tectonic stability of the Baltic Shield.

In this study we have examined post-impact secular deposits belonging to the Dalby Limestone at the Lockne and Tvären craters to determine the distribution patterns of different litho- and bio-facies. The aim is to analyze the post-impact infill histories of the crater structures and paleoenvironmental implications of the impacts. Factors controlling depositional environments of carbonatic sediments in the Lockne and Tvären craters are discussed and compared.

GEOLOGICAL SETTING

Lockne Crater

The impact at Lockne (Fig. 1) took place at a water depth of about 500–700 m (see summary of the water depth discussion in Ormö et al. 2007) at the time of carbonate sedimentation. A crystalline granitic basement overlain by about 30 m of Cambrian shale (commonly referred to as “alum shale”) and 50 m of Ordovician limestones constitute the target rocks, the youngest sediments being the Dalby Limestone, during which deposition the impact occurred. The inner crater in the basement is about 7.5 km wide and is surrounded by a 3 km wide brim, i.e., a zone of ejected crystalline basement (Lindström et al. 2005a). Fractured and brecciated basement of the inner crater together with the crystalline ejecta constitute the Tandsbyn breccia. Coarse clastic resurge deposits (Lockne breccia) were the first sediments to enter and partially fill the inner crater. The Lockne breccia has a gradual transition into sandstones and siltstones (Loftarstone), representing the waning stages of the resurge. The Loftarstone is followed by secular deposits belonging to the continued sedimentation of the Dalby Limestone. In some areas the Dalby Limestone is succeeded by the Örå Shale. The resurging water was channeled by openings in the brim that may have been initiated during crater excavation and ejecta emplacement (von Dalwigk and Ormö 2001; Lindström et al. 2005a). In this study, we provide further sedimentological evidence for the gullies being primary features existing before the deposition of their infill. At Lockne, the resurge gullies are tens of meters deep, up to a kilometer wide, and partially filled by resurge and post-impact secular deposits. Two of the resurge gullies are central for preservation of post-impact secular deposits and fossils in the crater; the best preserved are the Tandsbyn gully situated at the western margin of the crater and the Bergböle-Loke gully to the south, which is of similar size, but which has its western margin distorted by later tectonics. The influence on the Lockne crater, and in particular on the sediments of the Tandsbyn gully, by the Caledonian Orogeny has been discussed in a number of previous publications (e.g., Lindström et al. 2005a). We consider this tectonic influence of minor importance for the facies distributions presented in this study. Nevertheless, the crater owes its fine preservation to the protection of Caledonian nappes, now almost completely removed except for a small outlier covering parts of the central crater.

Tvären Crater

The Tvären crater has for long periods been exposed to subaerial erosion, and lately also to glacial erosion, but today it is situated underwater in the Tvären Bay on the Swedish east coast (Fig. 2). The crater is located in a region now dominated by Precambrian crystalline rocks and comprises a partially sediment-filled circular depression approximately 2 km wide. Its impactites and post-impact infill are accessible only in drill cores and glacial erratic boulders. Fossiliferous boulders of Ordovician age are fairly abundant in a restricted area on islands south of the Tvären Bay. Investigations on the island of Ringsö by Thorslund (1940), Strachan (1959), and Bergström (1962) led to the conclusion that the limestone boulders are glacial erratics of the Upper Ordovician Dalby Formation. Geophysical investigations by Flodén et al. (1986) led Wickman (1988) to suggest the Tvären Bay as an impact crater. Later, two cores, Tvären 1 and 2, were drilled (Fig. 2b). Tvären 1 struck crystalline basement at the rim, but Tvären 2 yielded a 140 m sequence of impactites and secular sediments (Lindström and Sturkell 1992; Lindström et al. 1994). The target sequence at Tvären consisted of Ordovician carbonates resting on non-lithified sands of Early to earliest Middle Cambrian age covering a crystalline basement (see Fig. 5 in Ormö et al. 2007). Drillings in the structure showed a similar succession as at Lockne with a crystalline breccia overlain by 60 m of fining-upward resurge deposits, and 80 m of secular sediments of carbonate mudstone representing the Dalby Limestone (Lindström et al. 1994; Ormö et al. 2007). Based on conodonts and chitinozoans, the age of the impact event is determined to be in the late Kukruse Stage (Ormö 1994; Grahn et al. 1996), which also indicates that infilling of the structure was completed before the end of the stage.

As at Lockne, the Dalby Limestone deposition occurred both before and after the impact event. Pre-impact sediments of Dalby age are now only preserved in the resurge deposits, but post-impact Dalby beds overlie the resurge deposits with a gradual transition. The impact occurred at a sea depth of 100 to 150 m, although most likely in the lower end of this range, as is discussed in this paper.

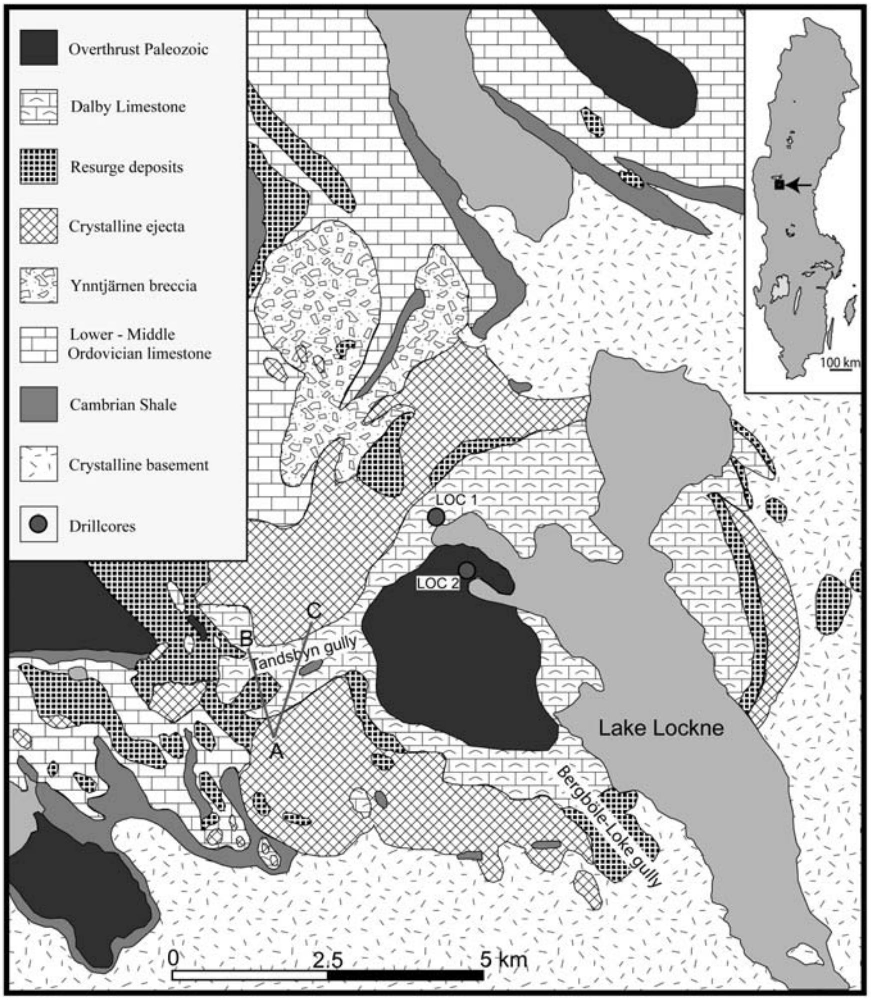

Fig. 1. Geological map of the Lockne area with the Tandsbyn gully and the Lockne 1 and Lockne 2 drill cores marked. Modified from Lindström et al. 1996. A–C refer to the location of profiles given in Fig. 6.

Dalby Limestone

In the Late Ordovician (Caradoc) period, deposition of carbonates constituting the Dalby Limestone was characterized by very slow sedimentation rates and a uniform fauna. A bedded or slightly nodular calcarenite signifies the Dalby Limestone succession at the type locality in Fjäcka (Siljan area), Sweden. There it comprises the chitinozoan *Laufeldochitina stentor* Zone and *Belonechitina hirsuta* Zone (Fig. 3). The Dalby Limestone reaches its greatest thicknesses within the inner crater and the resurge gullies in Lockne, although it is also preserved in a wider area around the crater (Fig. 1). It belongs to the *Lagenochitina dalbyensis* and *B. hirsuta* chitinozoan zones (Grahn et al. 1996) (Fig. 3). The impact event is documented in beds corresponding to the *L. dalbyensis* chitinozoan Zone. In Tvären the post-impact secular deposits, belonging to the Dalby Limestone, are confined entirely to the chitinozoan *L. stentor* Zone (Grahn et al. 1996) (Fig. 3). The post-impact sequences of the Dalby Limestone overlie the resurge deposits in the craters and correspond to the time when deposition had returned to more normal conditions, and when the organisms began to populate the craters. Facies and thickness distribution of the Dalby Limestone are influenced by the crater morphology. In the central part of the Lockne structure, the Dalby sediments are more than than 88 m thick (Lindström et al. 1996, 2005a). Investigations by Grahn (1997) of four drill cores from the central part of the impact structure produced chitinozoans; however, the abundance of other fossil groups from the cores is low. Close to the rim of the inner crater, the thickness of the Dalby Limestone is reduced, comprising only about 10 m. At some localities in the Lockne area the Dalby Limestone is succeeded by the Örå Shale, corresponding to the *B. hirsuta* Zone (Grahn 1997); the limestone is therefore most probably restricted to the upper part of this zone (Fig. 3). The total thickness of the post-impact part of the Dalby Limestone inside the Lockne and Tvären craters exceeds by several times the thickness of coeval limestones in Sweden, which are generally 15–20 m thick.

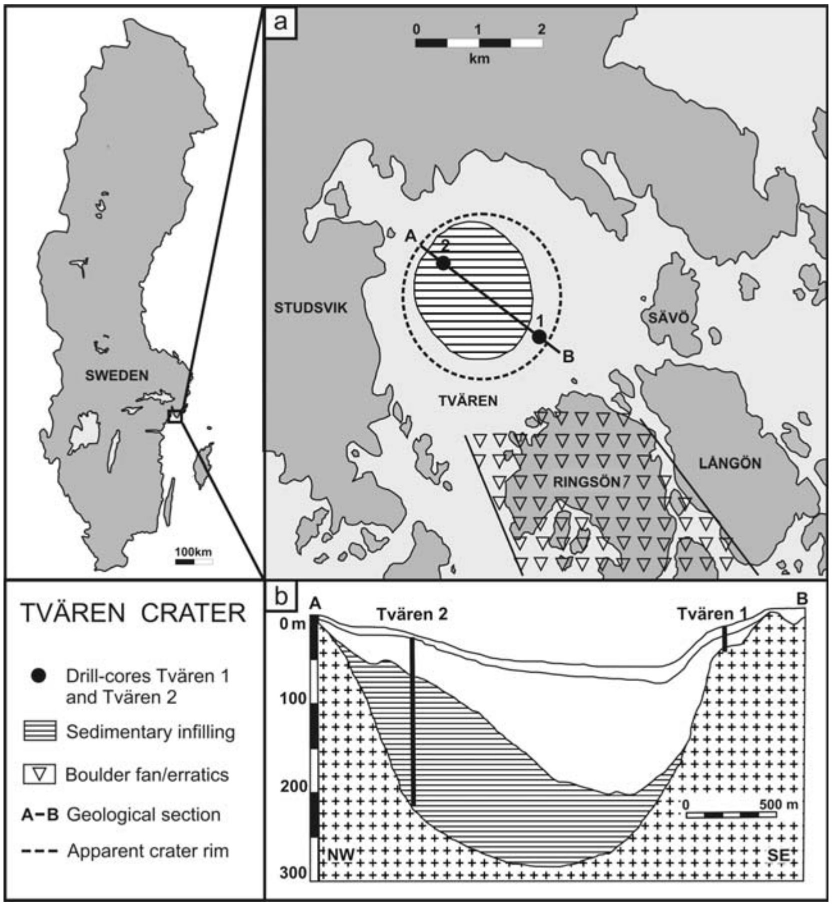

Fig. 2. a) Map of the Tvären crater showing the location of the two drill cores in the structure. The fan of glacial erratic Dalby Limestone boulders found on the islands south of the crater is marked with triangles. b) Cross section based on drillings and seismic profiles. The second drill core (Tvären 2) penetrated through the entire Dalby Limestone succession and the resurge deposits down to the crystalline impact breccia. Modified from Lindström et al. (1994).

MATERIAL AND METHODS

We have investigated the Dalby Limestone in the Lockne crater through comprehensive fieldwork, mainly in the Tandsbyn gully (Fig. 1), and through material from the Lockne 1 and Lockne 2 drill cores (Lindström et al. 1996). Deposits of the equivalent post-impact secular deposits in the Tvären crater are available through the Tvären 2 drill core and glacial erratic boulders (Lindström et al. 1994). The studied material includes previously unpublished geochemical and thin section analyses done by J. Ormö shortly after the recovery of the Lockne and Tvären drill cores in the mid-1990s. In 1996, Tvären glacial erratics were collected by J. Ormö by kayak in the Ringsön area (Fig. 2a). The three drill cores were sampled and investigated in thin sections, and further analyzed for weight percent of organic carbon (Corg) (Tvären 2) and inorganic carbon (IC) (Lockne 1, Lockne 2, and Tvären 2). The geochemical results are listed in Table 1 and plotted in Figs. 5a–c next to lithological logs based on the thin section and visual inspections. Samples are numbered from top to bottom of the analyzed interval of each core. Nine samples (L1_1 through L1_9) from the Lockne 1 drill core from depths between 2.9 m and 33.6 m were examined for IC content and inspected in thin sections. The Lockne 2 drill core was sampled from 22.2 m down to 126.76 m, providing 22 samples (L2_1 to L2_22), of which 20 were analyzed for their IC content. No IC data are available for samples L2_2 and L2_17. When possible, the samples in Lockne 1 and 2 were taken from calcareous nodules. A total of 22 samples from the Tvären 2 core at depths from 82.4 m down to 160.5 m were lithologically determined; 19 of these samples were processed for organic carbon (Corg) and inorganic carbon (IC). No chemical data is available for samples TV3, TV17, and TV18. In addition, one sample from the Tvären erratics ("Ringsön 2") was analyzed. It is a biocalcarenite with a Corg value of 0.33% and an IC value of 11.17%. The geochemical analyses were carried out during 1997–98 with a LECO CHN-900 elemental analyzer at the Department of Geology and Geochemistry, Stockholm University, Sweden. The instrument's detection limit for carbon for samples in the analyzed size range is 0.002% and the precision is <1% relative standard deviation (RSD) (LECO Corporation 2005). The analytical results are, thus, about four orders of magnitude greater than the detection limit, and the variation between the samples is well above the precision. The quality control of the analysis was performed by running a control sample five times throughout the analysis. The error can be expressed as half the variation (10.65–10.17 = 0.48) in percent of the median value (10.28), thus ±2.33% or as the sample standard deviation. Calculating the sample standard deviation to be $\sigma = 0.19$, we find that all reference samples lie within the confidence interval $2\sigma = 0.38$ around the arithmetic mean value of 10.33.

At the Lockne crater, macrofossils were collected from the different facies in the Tandsbyn gully. The Tvären 2 drill core was examined for macrofossils by splitting the core. In addition, fossils from the rim facies of Tvären were examined through the glacial erratics. Rock samples from the different facies from Lockne, the Tvären 2 drill core, and the Tvären erratics were dissolved by using acetic acid (7%) to recover phosphatic fossils like conodonts. Sample residues were washed, dried, and sieved, and fossils were recovered by hand-picking.

RESULTS AND DISCUSSION

Facies Distribution in the Lockne Crater

This study shows that the occurrence of fossils in the Dalby Limestone is fairly common, but diversity and abundance (i.e., the facies) differ considerably depending on the topographical position in the crater. The distribution patterns of the carbonates, their composition, and changes of facies depend on irregularities in sea-floor topography, differences in local water movements, and actual position in the crater. Here we subdivide the post-impact secular deposits of Dalby age in the Lockne crater into at least three distinct facies based on lithology and distinctive fauna. The different facies range from argillaceous to clean carbonates, depending on conditions of sedimentation, and document a wide spectrum of depositional environments: a) rim facies, b) cephalopod facies, and c) argillaceous facies. Facies a–c are best exposed at the "crater trail" in the Tandsbyn gully close to Tandsbyn (Fig. 6); consequently, the following descriptions are mainly based on outcrops in this area. Sporadic occurrences of a micritic, fossil-poor facies are known as well, forming what has been described as calc-micrite megalenses near the western rim of the basement crater as well as in the Tandsbyn gully (Ormö and Lindström 2005). The micritic facies is the subject of a separate study and is not further discussed here.

Facies A: Rim Facies

Description: In the general stratigraphic succession of the crater and the resurge gullies, underlying resurge deposits wedge out toward the crater rim where, consequently, the rim facies of the Dalby Limestone is found with direct sedimentary contact on the Tandsbyn basement breccia. Figure 6 illustrates these stratigraphic relations along the profiles crossing the Tandsbyn gully (for location of the profiles, see Fig. 1). The initial post-impact secular deposit of this facies is a pure, light gray, and thick-bedded biocalcarenite, presumably indicating a non-pulsating deposition. The clayey material has either been rinsed away or did not accumulate in the relatively high-energy environment on the crater rim. The lowermost parts of this deposit consist of thin argillaceous layers intercalated between thin- to medium-bedded skeletal limestones. This biocalcarenite is highly fossiliferous and skeletal fragments are dominant components throughout. Within the lowermost 0–4 m, coarse and angular fragments of crystalline rock, ranging in size from fine pebbles to cobbles, are sparsely and randomly distributed in the succession (Fig. 4a). These crystalline fragments most likely derive from the Tandsbyn breccia of the substrate where meter-scale topographic irregularities could produce fragments that slid out on the surrounding unconsolidated sediments. The preserved sections have a maximum thickness of 5–6 m.

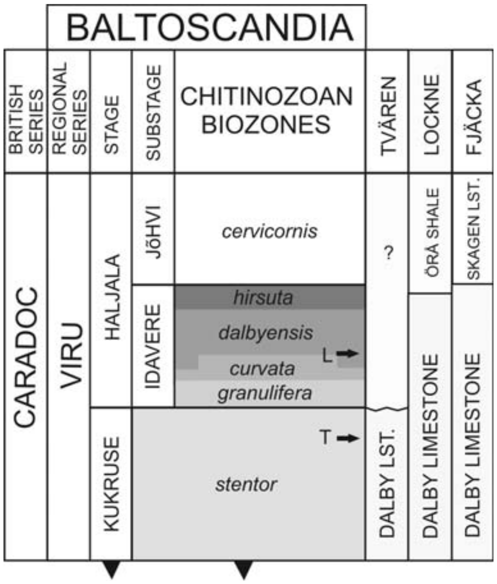

Fig. 3. Stratigraphic chart for the investigated Upper Ordovician Dalby Limestone in Lockne and Tvären, based on chitinozoan biostratigraphy (Grahn 1996; Grahn et al. 1997). L and T indicate the time of impact in Lockne and Tvären, respectively.

The faunal assemblages are quite different from the facies of the general seafloor and within the crater and gully depressions. The limestone abounds in skeletons of echinoderms, large rhynchonelliformean brachiopods, bryozoans, trilobites, and ostracodes. The non-calcareous microfossil fauna mostly consists of diverse conodonts and lingulate brachiopods. In the upper part of the successions, orthoid brachiopod shells are exceedingly abundant and locally form coquina beds in a skeletal calcarenite (Fig. 4b).

The contact between the rim facies and the Tandsbyn breccia of the ejecta flap is especially well-exposed along the southern side of the Tandsbyn gully in the higher terrain passed by the "crater trail." It is a sedimentary contact where

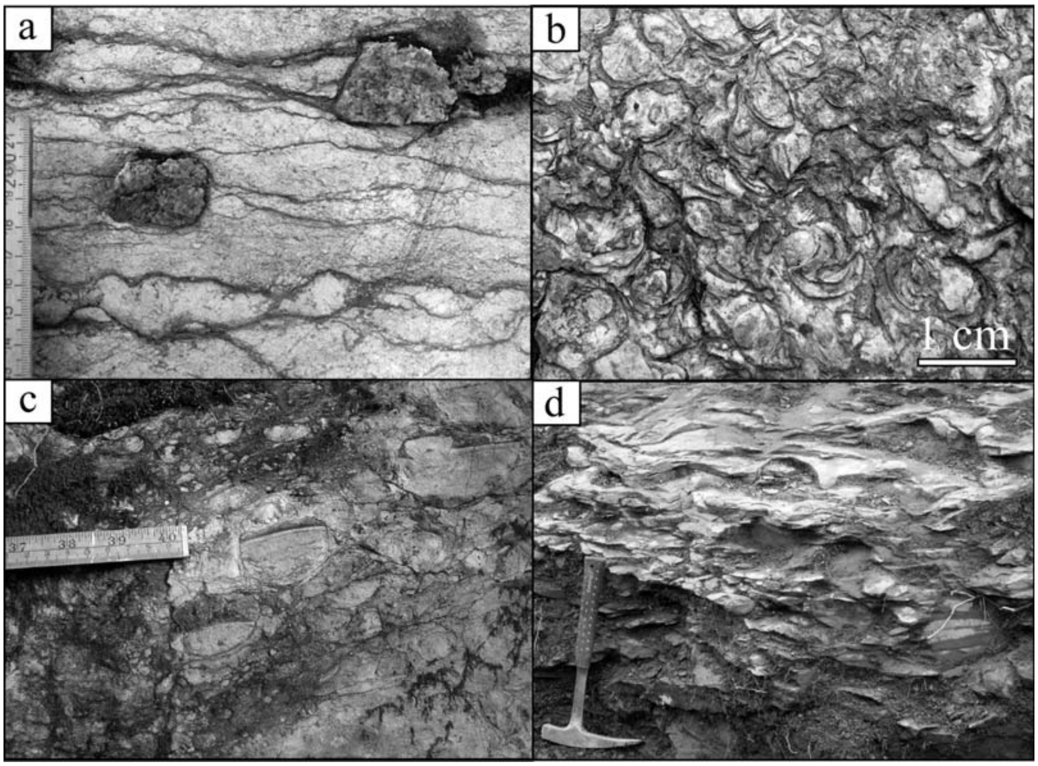

Fig. 4. Outcrops at the Tandsbyn gully, Lockne crater. a) Lithology of the rim facies. A light gray biocalcarenite containing crystalline clasts of the brecciated basement found only on the crater rim. b) Part of the brachiopod coquina bed found in the upper layers in the rim facies. c) The cephalopod facies, a thick-bedded calcilutite with a high abundance of nautiloid conchs. d) The argillaceous facies at the bottom of the Tandsbyn gully characterized by argillaceous limestone nodules set in a hard, slightly fractured mudstone.

it can be seen how the calcareous sediment at its base is filling the space between the crystalline clasts of the brecciated substrate. Well-preserved contacts between the breccia and the overlying Dalby Limestone, with abundant nautiloid conchs and angular crystalline clasts, are frequent on this side of the gully toward the northeast. No sediments overlying this Dalby Limestone rim facies have been documented.

Interpretation: The crater rim facies is evidence of a localized marine environment that developed consistently on the topographic highs. This very distinct facies was obviously aided by the topographic relief created by the rim, although it was low compared to the estimated water depth (i.e., below the photic zone). Nevertheless, the rim provided a relatively firm substrate as well as abundant nutrients for the organisms (i.e., chemical instability of fine-crushed basement rocks). The higher topography seems to have also been a location with significantly less deposition of mud than the gullies and the crater depression. A low sedimentation rate of fine particles favors the observed fauna of the rim facies, which indeed indicates a reef-like environment. The rim height has been estimated to have been a few tens of meters (Sturkell and Lindström 2004). However, we should not ignore the possibility that the original topography of the ejecta sheet around the inner crater may have been considerably smoothed in parts and thus lowered by the scraping off of protruding parts through the Caledonian overthrusting to which the whole region was subjected, as well as by the land ices of the Pleistocene. Nevertheless, localized occurrences of resurge sediments as well as Dalby Limestone resting with direct sedimentary contact on the crystalline rim ejecta support the idea that the present rim height is, at least in parts, near to the original (e.g., Lindström et al. 2005a).

The absence of organisms typical of the photic zone (e.g., calcareous algae) supports the relatively deep water suggested by the crater geomorphology and numerical simulations (Ormö et al. 2002; Lindström et al. 2005a, 2006b; Shuvalov et al. 2005).

The reef-like community of the rim facies at Lockne, which consists mostly of echinoderm detritus and brachiopods, is unique for the Dalby Limestone and has not been documented elsewhere in other coeval successions, apart from the Tvären crater (Lindström et al. 1994).

The fact that basal beds of the facies were deposited directly on the crushed crystalline basement at the flanks of the Tandsbyn gully and that coeval beds of Dalby Limestone rest conformably on resurge deposits further down the slope of the gully and on its floor indicate that the gully existed prior to the deposition of the Dalby Limestone (Figs. 6 and 7).

Table 1. Inorganic carbon (IC) and organic carbon (Corg) values for material from the Lockne 1 core (L_1-9), Lockne 2 core (L2_1-20), and Tvären 2 core (TV1-22). Values from a control sample and a sample from a glacial erratic (Ringsön 2) from the Tvären crater are also listed.

Sample number	Sample description	Depth in core (m)	IC (% by weight)	Corg (% by weight)
Control samples				
96LO34J	Calcilutite		10.17	
96LO34J	Calcilutite		10.21	
96LO34J	Calcilutite		10.28	
96LO34J	Calcilutite		10.36	
96LO34J	Calcilutite		10.65	
Mean ±2σ			10.33 ± 0.38 (2σ)	
Lockne 1				
L1_1	Gray calcilutite with light gray nodules	2.90	0.52	
L1_2	Dark gray calcilutite with light gray nodules	6.80	0.18	
L1_3	Dark gray calcilutite with light gray nodules	10.95	4.66	
L1_4	Dark gray calcilutite with light gray nodules	15.45	0.45	
L1_5	Gray calcilutite	19.85	0.69	
L1_6	Gray calcilutite with sporadic light gray nodules	24.85	1.75	
L1_7	Gray calcilutite with light gray nodules	28.63	1.86	
L1_8	Gray calcilutite with light gray nodules	31.93	2.01	
L1_9	Dark gray claystone	33.60	2.96	
Lockne 2				
L2_1	Calcilutite with light gray limestone nodules	22.20	3.22	
L2_3	Calcilutite with light gray limestone nodules	30.27	5.98	
L2_4	Calcilutite with light gray limestone nodules	34.37	1.86	
L2_5	Calcilutite with light gray limestone nodules	40.45	3.74	
L2_6	Calcilutite with light gray limestone nodules	48.15	8.17	
L2_7	Black claystone with mica (bentonite?)	51.83	0	
L2_8	Calcilutite with light gray limestone nodules	57.30	8.16	
L2_9	Calcilutite with light gray limestone nodules	64.17	7.70	
L2_10	Calcilutite with light gray limestone nodules	69.67	8.96	
L2_11	Calcilutite with light gray limestone nodules	74.77	6.36	
L2_12	Calcilutite with light gray limestone nodules	81.80	4.78	
L2_13	Calcilutite with light gray limestone nodules	86.52	8.07	
L2_14	Calcilutite with light gray limestone nodules	91.37	9.41	
L2_15	Calcilutite with light gray limestone nodules	96.70	9.05	
L2_16	Dark gray claystone, light gray laminations	101.70	0.56	
L2_18	Gray claystone	114.54	2.86	
L2_19	Gray claystone	119.37	4.72	
L2_20	Gray siltstone	126.64	5.77	
L2_21	Dark gray siltstone	126.70	5.73	
L2_22	Gray siltstone	126.76	5.77	
Tvären 2				
TV1	Light gray mudstone	82.40	5.68	2.62
TV2	Gray mudstone with biocalcarenite	85.10	8.16	1.86
TV4	Light gray mudstone with thin biocalcarenite	95.30	7.40	2.08
TV5	Light gray mudstone	98.30	6.31	2.70
TV6	Biocalcarenite	98.50	10.24	0.98
TV7	Gray mudstone with thin biocalcarenite	105.10	6.22	2.57
TV8	Light brown-gray mudstone	110.00	3.79	3.07
TV9	Light gray mudstone with biocalcarenite	115.00	8.29	1.69
TV10	Brown-gray mudstone (graptolitic shale)	120.00	2.16	4.13
TV11	Light gray mudstone	125.10	5.950	2.26
TV12	Light gray mudstone	130.00	5.69	2.34
TV13	Gray mudstone	130.20	6.47	1.97

Table 1. *Continued.* Inorganic carbon (IC) and organic carbon (Corg) values for material from the Lockne 1 core (L_1-9), Lockne 2 core (L2_1-20), and Tvären 2 core (TV1-22). Values from a control sample and a sample from a glacial erratic (Ringsön 2) from the Tvären crater are also listed.

Sample number	Sample description	Depth in core (m)	IC (% by weight)	Corg (% by weight)
TV14	Light gray mudstone with thin biocalcarenite	135.30	4.89	1.97
TV15	Light gray mudstone	140.00	8.52	1.47
TV16	Light gray mudstone with thin biocalcarenite	145.10	5.99	2.22
TV19	Gray mudstone with thin biocalcarenite	147.20	5.54	2.74
TV20	Gray silty mudstone	148.20	3.84	2.16
TV21	Light gray mudstone with fine sand laminations	148.90	3.03	1.70
TV22	Light gray mudstone	160.50	4.85	1.30
Ringsön 2	Brown biocalcarenite (coarse)	Glacial erratic	11.17	0.33

Facies B: Cephalopod Facies

Description: This facies is a thick-bedded, light gray, moderately pure calcilutite with occasional very thin argillaceous layers. It is distributed in a limited area near the bottom of the Tandsbyn gully and is especially rich in nautiloid conchs that characterize the facies (Fig. 4c). As a result of the richness in nautiloids, this facies has occasionally been mistaken for orthoceratite limestone, although Thorslund (1940) has already mapped it as the Dalby Limestone based on its fossil contents. The facies is exposed in several north-dipping outcrops throughout the topographical middle parts of the gully (Fig. 6). Thicknesses of the Dalby Limestone in these locations exceed 4 m. No sedimentary units directly overlying this Dalby Limestone facies have been documented. Endoceratid nautiloids, up to 1 m long, are the dominant element preserved in the low-diversity macrofauna. A large coiled nautiloid was also found. The conchs have diameters up to 7–8 cm and lie in sub-parallel arrangement, with average numbers of specimens per square meter ranging between ten to several tens. A majority of the specimens on two investigated bedding planes (around 120 specimens per bedding plane) are oriented with their apices in approximately the same direction (NNW-SSE, 149°). The mean apex orientation points up the slope of the gully. Several nautiloid shells have chambers with spar-filled geopetal voids, mostly oriented in the same direction, thus demonstrating that they were only partially filled with mud. This calcilutite limestone is moreover fairly rich in cystoids, but otherwise rather poor in macrofossils, although crinoids and brachiopods are evident in the successions. Up the slope of the Tandsbyn gully, cephalopods are less common and instead cystoids become the dominant elements. The microfossil fauna mostly consists of conodonts, inarticulate brachiopods, and ostracodes.

Interpretation: The extremely abundant nautiloids point toward a shift in the depositional environment, not necessarily reflecting where they lived as much as where they accumulated after their death. Nautiloids also occur in the argillaceous facies, although other macrofossils are also common. The cephalopod facies has a mud-supported rock fabric, indicating deposition under rather low-energy conditions. Nevertheless, the fact that many of the nautiloid conchs are found with parallel orientation may indicate current alignment by water movements from the same direction, and/or topographic control (i.e., slight rolling and rotation downslope). In the case of preferred orientation due to water movements, the apices of the nautiloid shells point upstream, making them very good current indicators (Reyment 1968; Wendt 1995). The strong association of the accumulations of nautiloid conchs with the lower flanks of the Tandsbyn gully indicates that cratering-generated topography of the area may have influenced the deposition of the nautiloids, thus supporting the gully as a primary feature. The slopes of the gully would have had a gentle dip, as illustrated by the profiles in Fig. 6. Nevertheless, previously documented small-scale Caledonian folding of the sediments within the Tandsbyn gully may have caused a later, localized tilting of strata (Lindström et al. 2005).

Facies C: Argillaceous Facies

Description: The cephalopod facies of the slope of the Tandsbyn gully is toward the lower parts of the gully, replaced by an argillaceous facies. This facies consists of nodules of argillaceous limestone set in gray, hard, and slightly cleaved mudstone (Fig. 4d). The 5–30 cm wide and 2–15 cm thick nodules take ellipsoidal to irregularly rounded forms and consist mainly of a massive, light gray, hard calcilutite. The facies rests with gradational conformable contact on fine-grained Loftarstone. No overlying strata have been documented.

Strata of the argillaceous facies have been studied primarily at a richly fossiliferous locality at Grubban, where the underlying, fining upward Loftarstone has a moderate dip to the northeast. Such sedimentary structures as nodules and trace fossils are common. The unit appears to get less clayey upward. The interbedded shales display a moderate amount of bioturbation as vertical traces cutting the bedding planes. Microfossils include inarticulate brachiopods, chitinozoans, and conodonts. Macrofossils start to occur more frequently above the lowermost 30 cm of less nodular sediments in the

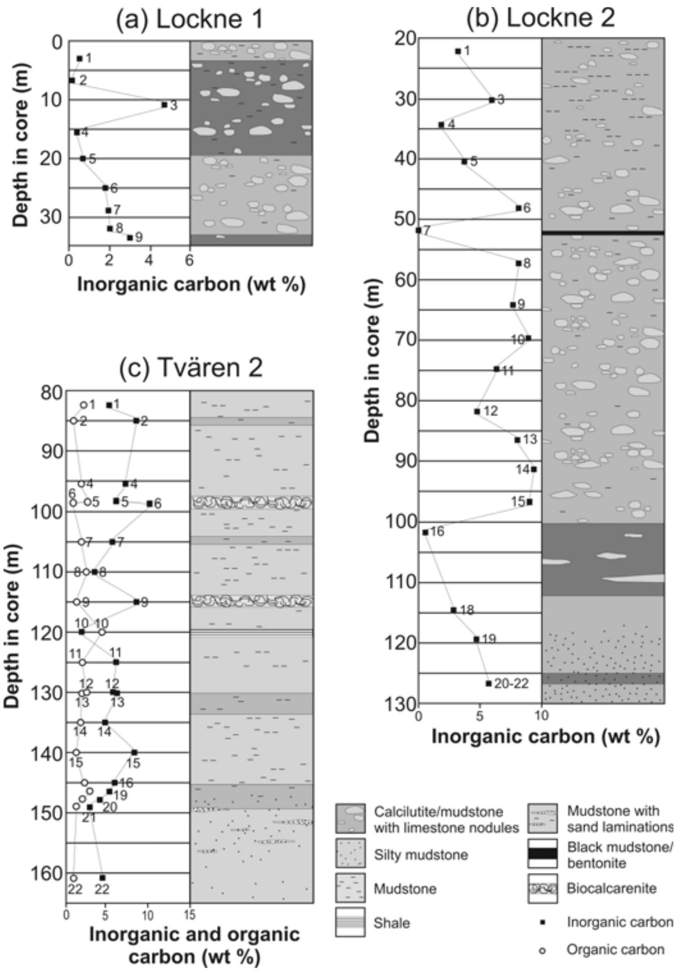

Fig. 5. Lithoprofiles and carbon contents of the Dalby Limestone succession from (a) the Lockne 1 drill core, (b) the Lockne 2 drill core, and (c) the Tvären 2 drill core. Different shades of gray represent color differences; depths in meters below ground surface (Lockne) and sea level (Tvären).

succession. Trilobites, mainly *Neoasaphus ludibundus*, cephalopods, and occasional cystoids of *Echinosphaerites* type constitute the macrofauna. Large and well-preserved conularids have been observed but lost (M. Lindström, personal communication).

Interpretation: Based on the fossils and bioturbation, this is an open marine facies; the predominantly fine-grained deposits indicate a calm, stable, and reducing depositional environment located in the deeper parts of the crater and the Tandsbyn gully. Sediments deposited in relatively deep and quiet environments with clay contents around 50% or more can develop into nodular limestones during diagenesis (Möller and Kvingan 1988). This depends on the amount of detrital clay, which could only have been deposited in quiet depositional environments below the fair-weather wave base. The environment in the lower parts of the Tandsbyn gully contains faunal groups that are consistent throughout similar facies in the crater. This facies is comparable with contemporaneous Dalby Limestone occurrences elsewhere in Baltoscandia.

One of the most abundant faunal members in these sediments are Asaphida trilobites, mostly *Neoasaphus ludibundus*, which are already occurring abundantly in an early stage. This trilobite is extremely frequent and appears to be very tolerant to changes in the environment; it is found throughout the post-impact secular deposits, and in Tvären, even in different facies.

The Lockne 1 Drill Core

The Lockne 1 drill site is located inside the margin of the inner crater (Fig. 1), penetrating the crater infill all the way down into the Tandsbyn breccia, where it ends at a depth of 225.15 m (Lindström et al. 1996). The uppermost approximately 40 m of the core consists of post-impact Dalby Limestone overlying sandy and silty deposits of the Loftarstone (see Fig. 3 in Ormö et al. 2007). Grahn (1997) assigned the Dalby succession in this core to the *dalbyensis* chitinozoan Zone. Generally the core is very poor in both microfossils and macrofossils.

The lithology is mainly calcilutitic, but it gets increasingly clayey toward the bottom of the analyzed interval where there is a gradual transition into Loftarstone. The stratigraphically

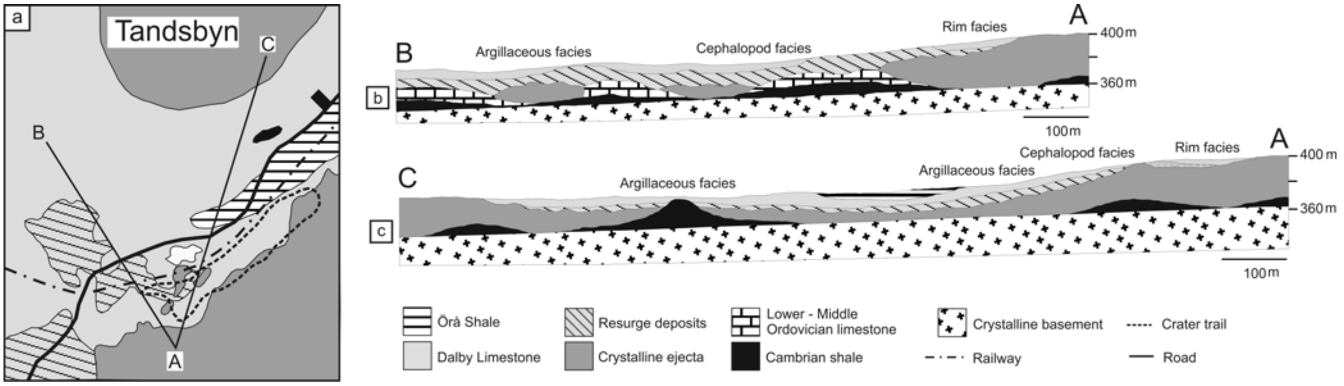

Fig. 6. Geological map (a) and profiles (b, c) of the Tandsbyn gully based on mapping by Thorslund (1940) while the area was being extensively quarried and before it became overgrown, by Lindström et al. (1996, 2005a), and by the authors. Thorslund's map could be followed as far as rock assignments allow it, and where it is not contradicted by fresh exposures. The southern one-third and northern ends of the sections are based on exposure and information from drillings adjacent to the profiles (Sturkell and Lindström 2004; Ormö and Lindström 2005), the rest is hypothetic and schematic. The profiles are crossing the Tandsbyn gully as indicated in the map. They show the general stratigraphic relationships of the sediment infill of the gully as well as the distribution of the different facies of the Dalby Limestone.

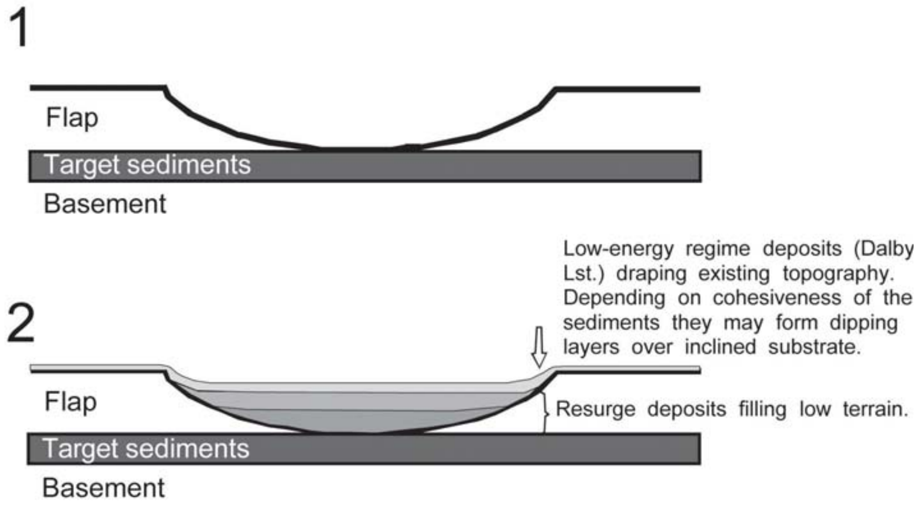

Fig. 7. Schematic profile showing stratigraphic relationships in an existing depression (compare with the profiles of the Tandsbyn gully in Figs. 6b and 6c).

lowest sample, L1_9, is a claystone resembling the topmost part of the Loftarstone (Fig. 5a).

Samples L1_8, L1_7, and L1_6 show moderate IC values (Table 1; Fig. 5a); these samples are defined as gray calcilutites. A slight drop in IC content occurs at sample L1_5 and continues upward, indicating a decrease in carbonate content that is verified by a change to more argillaceous dark gray nodular calcilutites. A high peak in IC content is noted for sample L1_3. Although this suggests high carbonate contents, it has, surprisingly, the same visual appearance as the adjacent samples. Above the solitary peak value the succession continues with low IC values. Overall, the IC content (Table 1; Fig. 5a) displays a relationship with the depth in the core where the carbonate content decrease from the Loftarstone upward through the Dalby Limestone, possibly as a result of a relative increase in the clay content.

The Lockne 2 Drill Core

The Lockne 2 drill core is situated in the central part of the Lockne crater (Fig. 1), ending in the Tandsbyn breccia at a depth of 335 m (Lindström et al. 1996). The location closer to the center of the crater than Lockne 1 provides a thicker succession of post-impact sediments. The Dalby Limestone has, similar to Lockne 1, a gradual transition downwards into the Loftarstone.

The IC content is generally significantly higher than for Lockne 1 (Table 1; Fig. 5b), but shows the same decreasing trend at the transition from Loftarstone toward the secular sediments (i.e., from the bottom of the analyzed interval until a depth of about 100 m). Above 100 m there is a strong jump to much higher values, which with some minor fluctuations remain high until a depth of about 48 m, above which the IC content again decreases, possibly in a stepped fashion with a second rise at a depth of 30 m.

The lowermost samples L2_16 to L2_22 have low to moderate IC values and are gray, silty, and argillaceous, but get increasingly darker and more clayey upward. They probably represent the later stages of the Loftarstone sedimentation. The samples L2_20 to L2_22 are from almost exactly the same depth in the core, and thus plot in same region in the diagram (Fig. 5b). The clear increase in IC content from sample L2_15 upward indicates an increase in carbonate content, which is also visible in the presence of light gray limestone nodules. Sample L2_7 is a black mica-bearing mudstone that lacks inorganic carbon. This sample is most likely a bentonite, which are fairly common in the Dalby Limestone of the Lockne area (Sturkell et al. 2000). The core continues upward with nodular calcilutites showing low to moderate IC values. Sample L2_3 is a more nodular calcilutite, which is reflected in the increase in IC. The uppermost sample (L2_1) is more argillaceous and, hence, a lower IC value is recorded.

It is clear that this method can help to distinguish the transition from resurge-related sedimentation to “normal” sedimentation in the area where this is not obvious in thin sections and visual inspection of hand specimens. Based on our results, we confine the Dalby Limestone in the Lockne core to the interval above a depth of approximately 100 m. The strong upward decrease in carbonate content encountered in the Dalby Limestone in Lockne 1 is not equally obvious in Lockne 2, although a slight decrease is noted above 48 m depth.

Facies Distribution in the Tvären Crater

The post-impact secular sequence of Dalby age in the Tvären 2 drill core (Figs. 2a–b) consists of beds of argillaceous limestone set in gray mudstone. Occasional calcarenitic turbidites appear in the core (Lindström et al. 1994), pointing toward transportation from a different setting in the crater. The fossils found in the turbidites are similar to those occurring in glacial erratics on islands south of the crater (e.g., the island Ringsön) also deriving from the Tvären crater. Many of the erratics are bioclastic calcarenites with coarse sparitic overgrowths on mainly echinoderm fragments (Ormö 1994). Large brachiopods, bryozoans, trilobites, and calcareous algae represent the general life assemblage. The biota found in the turbidites of the drill core is likewise characterized by skeletons of small echinoderms, bryozoan colonies, large brachiopods, trilobites, ostracodes, and calcareous algae (Lindström et al. 1994), linking the introduced material to the same source as the erratics. The occurrence of the material in thin turbiditic horizons within the deeper part of the crater indicates their provenance from the raised rim. This suggests that a reef-like environment developed on the crystalline crater rim some time after its formation. Algal fragments are fairly abundant in the calcarenites, indicating a formation within the photic zone. Therefore the crater bottom seems unlikely to be the source area for these sediments since it was situated too deep for photosynthesis.

The claystones and calcareous mudstones dominate the lower part of the core, whereas the biocalcarenite horizons become increasingly frequent higher up in the stratigraphy. This increase of biocalcarenites is clearly visible in Fig. 5c, evidenced by peaks in IC content coupled with marked lows in Corg content. The high IC values and low Corg values of all the calcarenitic turbidites from the Tvären 2 core coincide very well with the Ringsön 2 sample, supporting a similar origin in relation to the crater.

COMPARISON OF FACIES DISTRIBUTIONS IN LOCKNE AND TVÄREN

During the cratering at Lockne, seawater, sediments, and basement rocks were excavated and ejected. The seawater surged back into the crater, bringing with it both excavated material and rip-up material from the crater’s surroundings (e.g., Ormö et al. 2007). The rather well-sorted uppermost part of the resurge deposit (i.e., Loftarstone) thins out ascending the crater rim, where only sporadic deposits can be found. This is evident in the parts of the Tandsbyn gully described in this study (Fig. 6). Deposition of carbonates (i.e., Dalby Limestone) continued after the impact and covered the Loftarstone. In the quiet and deeper parts of the crater depression and the Tandsbyn gully, the Dalby Limestone is represented by an argillaceous facies (Fig. 6). A restricted diversity of macrofossils occurs in this facies (Fig. 4d), dominated by large asaphids, cephalopods, and less frequent cystoids. The relatively lower carbonate content of the argillaceous facies is reflected in the low IC values (Table 1; Figs. 5a and 5b). Subsequent sediments in the studied cores from the Lockne crater are calcilutites with different quantities of limestone nodules and a higher IC content. There is, however, a decrease in the IC values toward the top coupled with a darkening of the sediments. This may indicate an increased terrigenous component due to both eolian and aquatic supply from the approaching Caledonides (Lindström 1971; Bjørlykke 1974; Heuwinkel and Lindström 2007).

At higher topographic positions within the crater, and especially along the flanks of the Tandsbyn gully, the argillaceous facies is replaced by calcilutites with abundant cephalopod conchs, herein the cephalopod facies (Figs. 4c and 6), which contains only thin layers of argillaceous material.

The bioclastic content in the limestone increases toward the upper part of the rim, where the cephalopod facies is replaced by the biocalcarenitic rim facies (Figs. 4a, 4b, and 6) containing abundant echinoderm columnals. These beds were deposited on the topographically elevated rim but still below the storm wave base. In the parts of the rim where Dalby Limestone is found resting directly on the Tandsbyn breccia, the otherwise underlying Loftarstone can be seen wedging out toward the slope of the topographic rim (Fig. 6). The reef-like environment on the rim may have been established after some period of time in analogy with the reef facies at Tvären. It is possible that bottom currents kept the higher parts of the rim relatively free from deposition of finer sediments prior to the immigration of reef-building organisms. The existence of bottom currents, possibly in combination with variations in the seafloor topography, is indicated by unidirectional deposition of cephalopod conchs in the nearby cephalopod facies. The facies distribution and sedimentary relationships within the Tandsbyn gully (Fig. 6) indicate that it was already a topographic feature at the onset of the sediment deposition (Fig. 7). At the flanks of the gully, the sediments would have been deposited on a slightly sloping surface (Figs. 6 and 7). The fundamental structural feature of our sections in Fig. 6 is the sub-Cambrian peneplain. We base its reconstruction on the following observations: first, the peneplain is a regionally extensive, planar surface with a constant rise of about 12.5 m/km toward the northeast, except for where it is offset as a part of a major fault block (Sturkell and Lindström 2004). Second, there are several controls on the depth and orientation of the peneplain in the area. They consist of water-well drillings 1 km north of Tandsbyn (Sturkell and Lindström 2004), a research drilling at coordinates 6986100/1446470 (Ormö and Lindström 2005), and exposures of the peneplain as well as stratigraphic controls through sedimentary successions with preserved horizontal orientations and known thickness at neighbor localities in the area. Third, the sheet of crystalline ejecta preserved to the north and south of the Tandsbyn gully has its upper surface constantly at a level about 50 m above the reconstructed peneplain. We assume that the peneplain remained as smooth beneath the Tandsbyn gully as in other parts of the Storsjön area (Sturkell and Lindström 2004) because the crystalline basement was too rigid to yield plastically within the relatively small space beneath the gully and because there is no local fault offset that would have proven the presence of brittle deformation of adequate magnitude (for a different view, see Kenkmann et al. 2007). Nevertheless, it is documented that Caledonian tectonic movements have caused folding of sediments within the Tandsbyn gully (Lindström et al. 2005a). This would have locally altered the bedding planes of the Dalby sediments. However, it is clear from the sedimentary contacts between the Dalby sediments and underlying units at the investigated sections that the tectonic movements have not significantly affected the observed facies distribution.

In the Tvären 2 core from the deeper parts of the crater, argillaceous deposits overlay the silty and sandy deposits of the Loftarstone, as in Lockne. The beginning of the Dalby sedimentation was generally muddy and clayey (low to moderate Corg and IC values) but changed slowly to become more calcareous (higher IC values). Upward, the dominant calcareous mudstones are intercalated increasingly with distinct fossiliferous calcarenites probably derived from the rim. Apart from the obvious change in fauna and lithology, the biocalcarenites display different values of IC and Corg than the mudstones. They have the highest contents in IC coupled with low Corg values, reflecting the higher carbonate contents indicated by the richness in fossil remains. These trends are furthermore shared with erratics (“Ringsön 2”) from the islands to the south of the Tvären Bay. Frequent faunal members in the Tvären 2 drill core biocalcarenites are brachiopods, ostracodes, and echinoderms, and the biota is similar to that of the erratics of Tvären, as well as the Lockne rim facies to some extent.

In both the Tvären and Lockne craters, echinoderms, large rhynchonelliformean brachiopods, bryozoans, trilobites, and ostracodes were responsible for building up the reef-like deposits on the rim. Contrary to Lockne, algal remains also constitute the rim fauna at Tvären, requiring much shallower water at Tvären than at Lockne to allow photosynthetic organisms to thrive on the rim. If the target water depth was 100–150 m, a rim height of even a few tens of meters could be quite significant. A more complete discussion of the target water depth at Tvären is provided by Ormö et al. (2007), who argue based on the sedimentology of the resurge sediments for a water depth of not more than, but also not much less than 100 m. This is consistent with our results. The inner flank of the crater rims at both craters was most certainly covered by debris from the rim facies that occasionally collapsed and was transported into the deeper parts of the crater.

Whereas the rim facies at the eroded Tvären crater is only evident as turbidites in the crater interior and as erratics brought up from this cratered area, there are actual outcrops of this facies on the Lockne crater rim on the southern side of the Tandsbyn gully. The similarities of fauna and lithology in the present in situ rim facies of Lockne and the calcarenitic turbidites in the Tvären infill indicate that analogous depositional facies occurred in the craters. At Lockne, crystalline breccia clasts (Fig. 4a) are frequent in the rim facies and demonstrate the close proximity to the crystalline ejecta substrate that was still unstable during the deposition of the carbonates.

It is evident that very small topographical differences at the sea bottom can cause obvious variations in facies. A few tens of meters rise in altitude can give a considerable change in both lithofacies and biofacies even at water depths well below the photic zone and storm wave base (e.g., Lockne). This can be explained with higher energy levels (i.e., currents) occurring over the crater rim keeping the deposition of mud particles to a minimum, which favors the establishment of reef-like organisms. Indeed, Ainsaar et al. (2002) reported on an equivalent reef-like environment on the crater rim of the almost coeval, Late Ordovician, 4 km wide, marine-target Kärdla crater in Estonia. The rim wall of the Kärdla crater, however, most certainly reached over the breaker regime.

CONCLUSIONS

- Three main facies (rim facies, cephalopod facies, and argillaceous facies) of the post-impact Dalby Limestone were recognized at the Lockne crater, with different faunal assemblages characterizing each facies. Similar facies occur at the Tvären crater.
- The argillaceous facies dominates the lowermost part of the Tvären 2 core, much of the Lockne 1 and 2 cores, and outcrops in the Tandsbyn gully at the Lockne structure.
- The facies distribution in the Tandsbyn gully and the stratigraphic relationships shows that the gully existed as impact-induced topographic feature prior to the deposition of the Dalby Limestone. However, the structural inhomogeneity caused by this feature would inevitably attract its amplification by Caledonian tectonic forces.
- At the Lockne crater, variations in the carbonate content (i.e., IC values) can be used to trace the end of the resurge deposition (Loftarstone) and the beginning of secular sedimentation (i.e., Dalby Limestone), as well as possibly a change toward increased terrigenous contribution from the approaching Caledonides.
- Turbidites with skeletal debris in the Dalby Limestone succession at Tvären are distinguished by having much lower Corg and higher IC than the rest of the succession. This circumstance points to an origin from the crater rim. These turbidites show a close resemblance in biota, lithology, and Corg and IC values with glacial erratics from the vicinity of the crater area. A similar facies occurs in situ at the rim of the Lockne crater.
- For the post-impact secular Dalby Limestone deposits in Tvären and Lockne, we suggest comparable distribution patterns of the facies despite differences in depth of the impacted sea and crater size.

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