Meteoritics & Planetary Science 40, Nr 4, 639–651 (2005)
Abstract available online at http://meteoritics.org

Density and magnetic susceptibility of rocks from the Lockne and Tvären marine impact structures

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(Received 01 April 2004; revision accepted 09 March 2005)

Abstract–The Lockne and Tvären impact craters in Sweden formed in a marine environment during the Ordovician. The contrast in density between the impact breccias and the surrounding target rock of these two craters is significantly lower than what has been found in craters formed in crystalline targets on land. Another marine-target structure, the Estonian Kärdla structure, demonstrates intermediate contrast in impact breccia and target rock, which we attribute to the interpreted shallowness of the sea at the Kärdla impact site. We conclude that the main cause for these low-density contrasts is pore and fracture filling of calcite with subordinate quartz and fluorite. Calcite is the most abundant cement, and its density differs most from that of fractured and brecciated bedrock with a low degree of cementation. Furthermore, from the studied cases, it is concluded that the target rock to impact rock contrast is generally the highest in craters formed on land in crystalline targets and the lowest in craters formed at sea, while craters formed on land in sedimentary targets are intermediate. The low density contrasts should decrease the negative gravity anomalies of marine craters.

INTRODUCTION

The original purpose of this study was to supply petrophysical data for gravity and magnetic modelling of the Lockne structure (Sturkell et al. 1998a; Sturkell and Ormö 1998), to which was later added the petrophysical study of the Tvären structure.

Comparisons with similar investigations (Pilkington and Grieve 1992; Henkel 1992) indicated that our study supplied hitherto missing knowledge on the petrophysical properties of impact-related rocks. This knowledge particularly concerns the relationship between impact-related rocks in craters formed on land and at sea. Pilkington and Grieve (1992) noted the lack of knowledge concerning the petrophysical relationship between impact-related rocks and undisturbed target rocks. Our data are relevant to this problem.

GEOLOGICAL BACKGROUND

The Lockne and the Tvären structures (Fig. 1) are the results of impact events which occurred in an epeiric sea (Lindström and Sturkell 1992; Lindström et al. 1994; Ormö and Lindström 2000; Lindström et al. 2005) during the Caradocian (Middle Ordovician) age (Grahn et al. 1996).

Marine-Target Impact Craters

A general introduction to impact craters formed on land is given by Grieve and Pesonen (1992) and Melosh (1989). However, impact-related rocks in craters formed at sea are different from those in craters created on land. Here these craters are called "marine craters," in agreement with Lindström et al. (1994) and Sturkell and Ormö (1998).

The allochthonous breccia lens and the fractured rocks are, as are craters created on land, primarily derived from the deeper parts of the target. In the Tvären and Lockne structures, the allochthonous breccia lens and the fractured rocks are dominated by crystalline rock fragments (Lindström et al. 1994; Lindström et al. 1996; Lindström et al. 2005). In this study, these rocks have been classified as fractured granitoids, granitoid breccias, and mafic breccias. Crystalline rock breccia implies a breccia of crystalline rocks in general. Compared to rock breccias, fractured rocks show little or no clast rotation and matrix is more or less absent.

The greatest differences between craters formed on land and at sea are found among the allochthonous units. The ejecta curtain is deposited in conjunction with strong water movements eroding and redepositing target surface material. It is therefore often difficult to differentiate between poorly

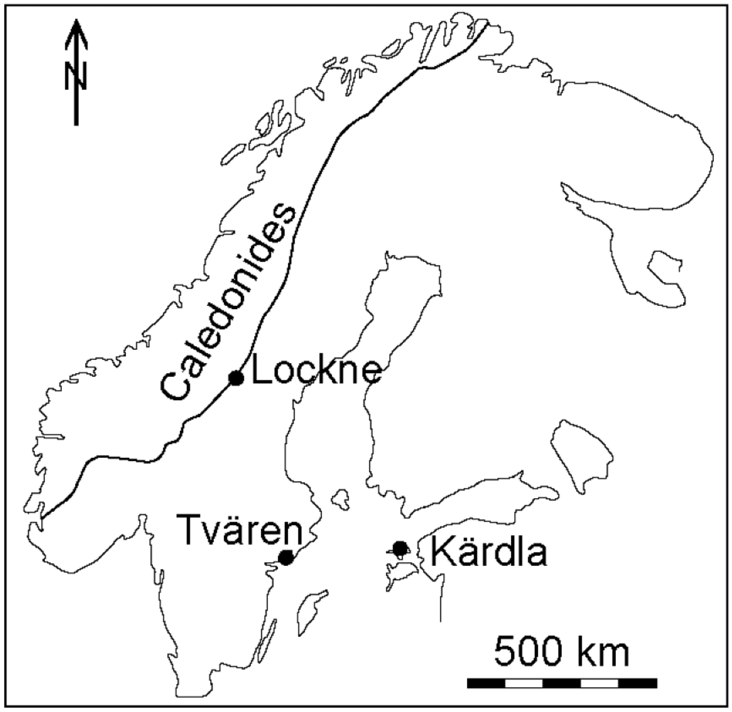

Fig. 1. Location of the three Middle Ordovician (Lower Caradocian) impact craters of Lockne, Tvären and Kärdla.

sorted, coarse-grained resurge deposits and ejecta deposits. The resurge sediments are deposited both inside and outside the crater depression as the sea rushes back into the crater basin (Lindström et al. 1994; Lindström et al. 1996; Törnberg 1996; Ormö and Lindström 2000).

In the Tvären and Lockne structures, the resurge deposits are dominated by sedimentary target rocks (Lindström et al. 1994; Lindström et al. 1996). The resurge deposit commonly consists of a matrix-supported lower unit and a clast-supported upper unit. Grain sizes in both the upper and lower unit vary from clay to blocks of many hundred cubic meters. The upper part is better sorted and exhibits fining upwards, from breccia through arenite to mud, and has been deposited from watery suspension. The uppermost part of the resurge deposit (gravelly to muddy resurge deposits) is well graded, fairly well sorted, and fine-grained (Lindström et al. 1996). It also contains water-related sedimentary structures such as cross-bedding, water escape structures, and parallel lamination (Simon 1987). As no universally applicable terms for the different parts of the resurge deposits have yet been accepted, we have chosen to use the descriptive terms "matrix-supported resurge breccia," "clast-supported resurge breccia," "resurge arenites," and "resurge lutites" to identify the sequential units.

It is noteworthy that melt has only been found as tiny fragments, with no macroscopic impact melt bodies observed in either of the two craters (Lindström et al. 1994; Sturkell and Ormö 1998; Mansfeld et al. 2002).

Geology of the Lockne Structure

The 7 km diameter Lockne structure is situated 20 km south of Östersund in central Sweden (Lindström and Sturkell 1992; Lindström et al. 1996; Lindström et al. 2005). Today, it is located at the erosional front of the Caledonian thrusts. The center of the structure is partly covered by an isolated nappe. The Lockne meteorite hit crystalline Proterozoic basement consisting of granitoids (predominant), dolerites, and metavolcanic rocks overlain by a nearly 80 m thick sequence of Lower Paleozoic sediments predominated by Cambrian dark gray bituminous shales (so-called "alum" shales) and Ordovician (Orthoceratite) limestone.

The northwestern part of the Lockne area is covered by Cambrian and Ordovician rocks with numerous Caledonian folds and fractures. The central part of the Lockne structure proper is covered by an erosional remnant of allochthonous Orthoceratite limestone. Hence, prior to erosion, the Lockne structure was covered by nappes of the Caledonian orogen (Lindström et al. 1996).

The impact-related rocks consist of an authigenic impact breccia, termed the Tandsbyn breccia, the fractured basement, and resurge deposits (Lindström and Sturkell 1992; Lindström et al. 1996). The Tandsbyn breccia is a mainly monomictic, autochthonous breccia composed of clasts predominantly originating from the local Proterozoic basement rocks. The limestone-dominated resurge deposits of the Lockne structure have been divided into Lockne breccia (Lindström et al. 1983;

Simon 1987) and Loftarstone (a local vernacular name). The Lockne breccia is a coarse clastic deposit, with clast sizes varying from clay to many hundred cubic meters. Both matrix-supported and clast-supported varieties occur, though the latter is undoubtedly the most common. The Loftarstone comprises the uppermost sandy to muddy part of the resurge deposits. It has both sharp and gradational contacts with the underlying Lockne breccia. Drilling into the resurge deposits of the annular depression revealed a sequence of matrix-supported non-graded breccias with a thickness of up to 100 m, overlain by about 70 m of graded clast and clast-supported deposits (Lindström et al. 1996).

The post-impact rocks mainly consist of the Dalby limestone. The lowest part of the Dalby limestone belongs to the chitinozoan zone of Lagenochtina dalbyensis which corresponds to the middle part of the Lower Caradoc conodont subzone of Baltoniodus gerdae. This is the same biostratigraphical age as the youngest beds that pre-date the impact event (Simon 1987; Grahn et al. 1996).

Geology of the Tvären Bay Structure

The 2 km diameter Tvären Bay structure is situated 72 km SSW of Stockholm in an area of Proterozoic gneisses and granitoids (Lindström et al. 1994). At the time of impact the crystalline target rocks were covered by Orthoceratite limestone and underlying, non-lithified sand (Lindström et al. 1994).

The crater infill consists of allochthonous and suballochthonous breccias, resurge deposits, and secular mudstones, siltstones, and carbonates. Tvären has a 60 m thick graded and clast-supported resurge deposit without the matrix-supported type of deposits found in the Lockne structure. No Phanerozoic deposits have been preserved in the area outside the impact structure. The area where the structure is located has not been affected by the Caledonian orogeny.

METHODOLOGY

We have studied two Lockne drill cores (LOC 1 and 2), two Tvären drill cores (Tvären 1 and 2), and a number of samples from the surroundings of the Lockne and Tvären craters. The distances from the centers of the structures to the different boreholes is 2.9 and 1.8 km, respectively, for the LOC 1 and 2 drill cores; and 1.3 and 0.45 km for the Tvären 1 and 2 drill cores (see The Lockne and Tvären Drill Core Measurements section for more details of drill core stratigraphy). About 150 of the density and susceptibility values for the area surrounding the Lockne structure have been kindly supplied from the petrophysics data base of the Geological Survey of Sweden. Our own magnetic susceptibility data was produced with a Geoinstruments JH-8 susceptibility meter. The scale of the panel meter is divided in twenty parts, which gives 5×10^{-5} SI resolution on the most sensitive measuring range. It has a coil of about 25 mm in diameter that senses a few cubic centimeters of volume and the drill core only has a diameter of 42 mm. In order to make the resulting data more comparable, we choose to use the same susceptibility meter for all samples. According to the manufacturers' operation manual, calibration is done for a half-space. Therefore, readings of drill cores should be multiplied with a correction factor. Accordingly, all of our drill core readings were multiplied by a factor of two, as the drill core diameter is 42 mm. The irregular surfaces of the samples of the surrounding lithologies were made up for by locating flat and less weathered surfaces for measurements. All samples were measured 10 times and the mode value, as well as the minimum and maximum values, was noted. The measurements provided by the Geological Survey do, however, have a higher resolution and precision in susceptibility than our data. The wet bulk densities were derived with a scale with an accuracy of 0.1 g. The sample masses ranged from 500–6000 g. The wet density was calculated by comparing the weight of water saturated samples in water and the weight in air after the surface of the sample had dried. Fracturing and dissolving of clay-rich samples was a problem during the density measurements of some of the secular sediments, the resurge lutites, the alum shale, and the alum shale-rich parts of the matrix-supported breccias. Measurements on core samples give a better representation (at least for the density) as compared to surface samples, where the weathering results in skewing in favor of better preserved (less fractured) samples.

RESULTS

The Lockne Impact Structure

A total of 703 samples from the LOC 1 and 2 drill cores and the crater surroundings were analyzed for mean wet bulk density and magnetic susceptibility (Table 1 and Fig. 2), and the ranges of these values are quite narrow. The granites in the area have lower mean densities than the most common sedimentary rocks, the Orthoceratite limestone and the Dalby limestone. Furthermore, the densities and susceptibilities of the resurge deposits and crystalline impact rocks are very similar to those of the respective target rocks, i.e., Orthoceratite limestone and granite. Open fractures and pore spaces are rare in the crystalline breccias and absent in the resurge deposit. The open spaces that were once present have been filled with calcite and, subordinately, by quartz. This feature is most obvious in the authigenic impact breccias (Fig. 3). Fluorite has also been locally observed to be an important pore-filling mineral.

The density values obtained for the matrix-dominated resurge deposit are likely too high because the measurements were difficult to make due to disintegration of the samples. Many of the more coherent samples contained unusually high concentrations of pyrite, which probably originates from the pre-impact dark gray alum shale. The alum shale is one of the

Table 1. Average densities and susceptibilities for the Lockne samples. Standard deviation is not given for the susceptibility values as the measurements are at the detection limit.

Rock type	Density (g/cm^3)	Standard deviation	Susceptibility (SI)	Standard deviation	N
Dalby limestone	2.703	0.006	2.49E-04	n/a	74
Resurge lutites	2.701	0.004	2.49E-04	n/a	41
Resurge arenites	2.687	0.020	2.41E-04	n/a	31
Clast-supported resurge breccia	2.695	0.026	2.03E-04	n/a	86
Matrix-supported resurge breccia	2.705	0.013	2.29E-04	n/a	43
Matrix-dominated resurge breccia	2.743	0.105	2.71E-04	n/a	9
Resurge breccia of crystalline rocks	2.648	0.002	3.00E-04	n/a	2
Breccia of granitoids	2.629	0.043	1.80E-04	n/a	124
Breccia of mafic rocks	2.717	0.029	5.06E-04	n/a	9
Fractured granite	2.623	0.030	1.61E-04	n/a	36
Orthoceratitic limestone	2.704	0.013	1.29E-04	n/a	26
"Alum" shale	2.664	0.033	1.59E-04	n/a	3
Åsby dolerite	3.020	0.020	1.42E-03	n/a	118
Granite	2.660	0.041	1.09E-04	n/a	84
Meta-volcanic rocks	2.819	0.118	5.10E-04	n/a	17
Total					703

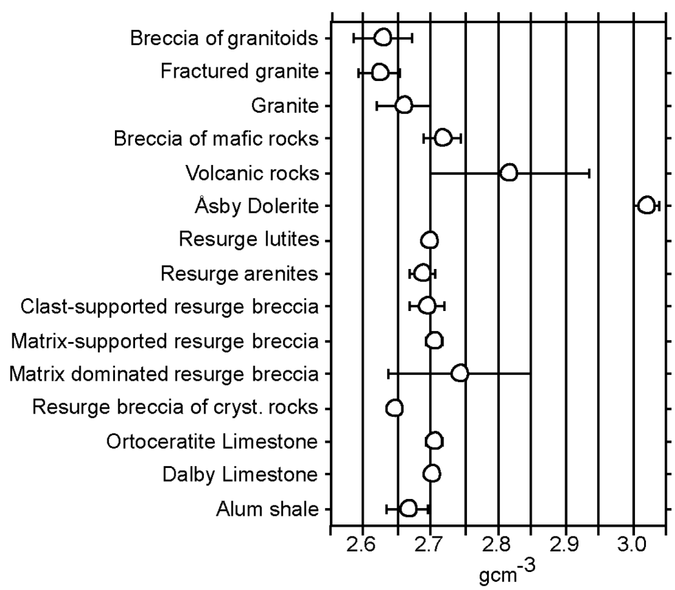

Fig. 2. Density diagram for the Lockne samples showing average values for each rock type and one standard deviation wide error bars.

most important constituents of the matrix-dominated resurge deposit; it contains pyrite in the groundmass as laminae and as scattered larger aggregates (Thickpenny 1984).

The Tvären Impact Structure

Ninety-four samples from the Tvären crater from both drill cores and the surrounding area have been investigated (Table 2). The Tvären 1 drill core penetrated fractured Precambrian basement rocks on the crater edge and Tvären 2 was drilled halfway between the crater wall and the crater center. As in the breccias of the Lockne structure, calcite infill of open fractures was observed.

The Lockne and Tvären Drill Core Measurements

Density and susceptibility versus depth plots have been produced for the LOC 1 and 2 and Tvären 2 drill cores (Figs. 5 and 6). The density plots show a clear correlation to rock type. The susceptibility plot is not as clear because of the limited range of values (see section Interpretation of the Susceptibility Data), but a comparison with the density plot demonstrates similar trends. These relationships are best visible in the LOC 1 drill core, where drilling penetrated deeper into the brecciated and fractured basement.

In the Lockne drill cores, the pre-impact allochthonous Orthoceratite limestone and the secular Dalby limestone have

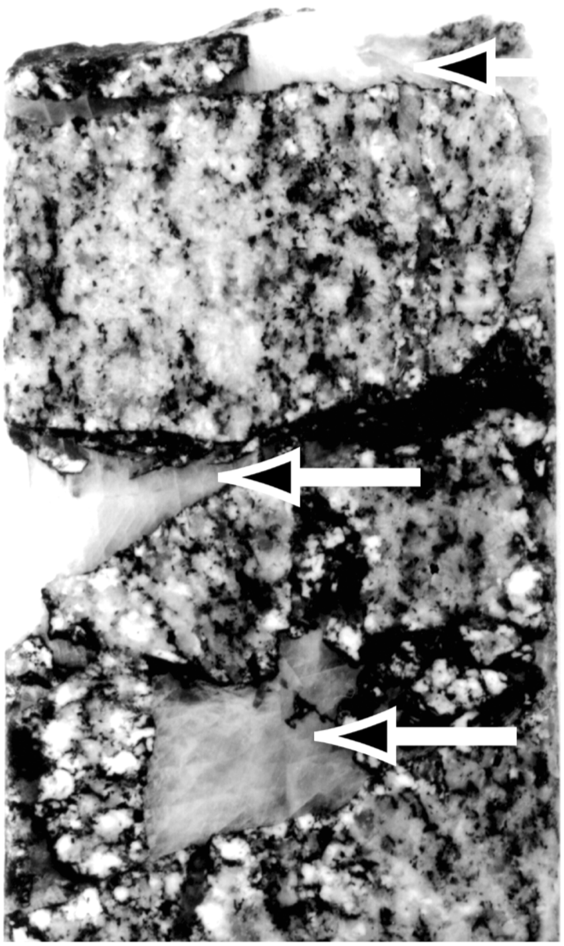

Fig. 3. Calcite filled fractures in autochthonous crystalline breccia in the LOC 1 drill core at 167.5 m. The drill core diameter is 4.2 cm. From an original photo by Uno Samuelsson.

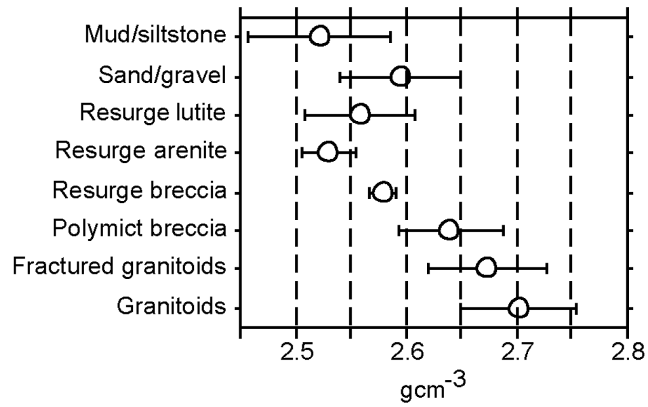

Fig. 4. Density diagram for the Tvären samples showing average values for each rock type and one standard deviation wide error bars.

small density variations. At 20–40 m depth in the LOC 2 drill core, there is a tectonic discontinuity between the Orthoceratite limestone and the Dalby limestone, which has resulted in reduced density. Here, Caledonian overthrusting has mobilized carbonate solutions and thereby caused precipitation of a late generation of calcite cement.

There is a similarity in density between the relatively fine-grained resurge sediments and the Orthoceratite and Dalby limestones. However, the deeper, more coarse-grained resurge deposits show increasing variability because of increasing clast size and crystalline clast content. This increase in the content of crystalline basement clasts with increasing grain size in the Loftarstone was noticed by Simon (1987).

The crystalline rock breccia shows a density increase toward the less crushed deeper parts. This general trend is broken up by two larger drill core sections, at 175 m and below 190 m in LOC 1, where brecciation has been less intense. The density of the uppermost part of the crystalline breccias is relatively high. This uppermost part is relatively rich in calcite-filled fractures. Strong positive and negative anomalies are due to small occurrences of lithologies with different densities, such as high density and susceptibility dolerite, pyrite, or biotite-rich granite clasts, or low density pegmatite. Drill core sections with such higher susceptibility lithologies occur at, for example, 160–170 m and below 200 m in LOC 1, and at 245 m and 300–320 m in LOC 2.

The depth versus density and susceptibility plots for the Tvären 2 drill core (Fig. 6) show a clear correlation between grain size and density in the resurge deposits. The top of the resurge sediments in the Tvären 2 drill core are pyrite-rich, which explains the presence of a rise in the density curve just below 160 m. However, in the main part of the underlying resurge sediments, the density correlates with the amounts of relatively dense crystalline basement clasts. Likewise, the susceptibility reflects the content of granitic material with higher susceptibility. An increase in granite clasts in coarser grained samples was the visual impression we had working with the material. Törnberg (1994) made a quantitative thin section study on samples from the Tvären 2 drill core which also suggests an increase in the content of crystalline basement clasts with increasing grain size in the resurge deposits.

A slight but clearly noticeable decrease in susceptibility exists in the crystalline rock breccia at Tvären compared to the above resurge deposits.

DISCUSSION

Interpretation of the Density Data

An explanation for the small differences in density between impact related rocks and undisturbed target rocks is the near absence of open fractures in the breccias and the fractured target rocks we observed in the Lockne and Tvären structures compared to what has been observed in craters created on land. Open fractures and increased pore space are

Table 2. Average densities and susceptibilities for the Tvären samples. Standard deviation is not given for the susceptibility values as the measurements are at the detection limit. Values have also been for all granitoids, as well as separated for the western and eastern part of the target (see discussion in the text).

Rock type	Density (g/cm^3)	Standard deviation	Susceptibility (SI)	Standard deviation	N
Mud/siltstone	2.523	0.064	1.04E-04	n/a	19
Sand/gravel	2.595	0.055	1.00E-04	n/a	8
Resurge lutite	2.558	0.050	2.00E-04	n/a	11
Resurge arenite	2.530	0.024	3.11E-04	n/a	12
Resurge breccia	2.579	0.012	4.78E-04	n/a	11
Brecciated granitoids	2.641	0.048	3.40E-04	n/a	10
Fractured granitoids	2.674	0.053	7.78E-04	n/a	10
Granitoids all	2.702	0.052	5.48E-04	n/a	13
Total					94
Granitoids (western)	2.667	0.055	2.37E-04	n/a	5
Granitoids (eastern)	2.724	0.030	9.26E-04	n/a	8

common features and the main reason for density decreases in impact breccias and fractured target rocks (Pilkington and Grieve 1992).

Most fractures and pores in Tvären and Lockne have been closed by calcite and subordinately quartz and fluorite. Sturkell et al. (1998b) established that there was an impact related phase of hydrothermal activity after the Lockne impact event that resulted in precipitation of calcite, quartz, and other low-temperature minerals. Calcite is the most important because it is more mobile and its density differs the most from that of brecciated or fractured rocks with a low degree of cementation. We suggest that the process of porosity decrease by calcite precipitation is most effective in targets where a great deal of water and carbonates are present and that this is a process characteristic of impact structures formed at sea.

The variation in density with different volume percent calcite per unit total pore volume for a hypothetical impact formed rock can be modelled. The density D of an impact-formed rock sample is dependent on the density of the original rock D_0, the pore volume V_p, the volume V_f, and density D_f of the fill material, and the density of ground water, as given below:

$$D = D_0(1 - V_p) + V_p \times D_f \times V_f \quad (1)$$

If ground water is present and fills open pore space, the density D_v and amount of water must also be accounted for:

$$D = D_0(1 - V_p) + V_p(D_v(1 - V_f) + D_f \times V_f) \quad (2)$$

From the above formulas and from Fig. 7, which is based on the second formula, it follows that the density D is strongly dependent on the amount and type of infill. Furthermore, in extreme cases (see enlargement to Fig. 7), when the infilling material has a higher density than the original target rock, the post-impact density can even exceed the original density. The density of pure calcite is 2.710 g/cm^{-3} and the density of fluorite is 3.179 g/cm^{-3} (Carmichael 1989), whereas the mean density of the undisturbed granitoid part of the crystalline target rocks is 2.660 g/cm^{-3} in Lockne and 2.702 g/cm^{-3} in Tvären.

The densities of the resurge deposits are remarkably close to the densities of the most common source rock, i.e., the Orthoceratite limestone. The difference amounts to 0.01 g/cm^{-3} (Table 3), or less than 0.5%. This is rather surprising, considering that the resurge deposits almost always have some (seldom major) amount of less dense crystalline rocks. It follows that the calcite and matrix infill into fractures and other cavities must be particularly extensive in the resurge deposits.

Comparison of the Lockne and the Tvären depth versus density graphs (Figs. 5 and 6) reveals that the Tvären density signature is more variable than the Lockne signature in the post-impact secular sediments. This is a result of the circumstance that the secular deposits of clay and limestone are repeatedly interrupted by crater-wall-derived, silty to coarse sandy slump sheets containing shocked target rocks and crystalline clasts (Törnberg 1994), possibly owing to a shorter distance to the crater wall in the Tvären 2 drill core compared to the Lockne drill cores. However, the Lockne structure has been subjected to compaction under a considerable load of Caledonian nappes, which probably led to closure of some of the pore space, resulting in a smoother density curve. Locally, however, tectonic discontinuities have resulted in lower density, as exemplified by the discontinuity at 20–40 m depth in LOC2.

Interpretation of the Susceptibility Data

Though it is often possible to see trends in the susceptibility data that are similar to those observed in the density data, the susceptibilities are more difficult to interpret. Many of the readings are at the detection limit of the susceptibility meter, which made it hard to resolve readings to a better resolution than in steps of 5, 10, and 15 × 10^{-5} SI, respectively. The lowest readings are only indicative of low susceptibility.

In Tvären there is a fairly clear relationship between the

Table 3. Comparison of the contrast between target rocks and rocks with impact-related deformation in craters formed on land and at sea. The numbers in parentheses refer to the labels in Fig. 8.

Structure	Type of impact deformation	Environment, target rocks	Contrast (g/cm^3)	Reference
Lockne, Sweden	Fractured	Marine, mixed	0.04	This study
Tvären, Sweden	Fractured	Marine, mixed	0.03	This study
Kärdla, Estonia	Fractured	Marine, mixed	0.12	Plado et al. 1996
Manicouagan, Canada	Fractured	Land, crystalline	0.13	Pilkington and Grieve 1992
Gosses Bluff, Australia	Fractured	Land, sedimentary	0.15	Pilkington and Grieve 1992
Söderfjärden, Finland	Fractured	Land, crystalline	0.16	Pilkington and Grieve 1992
Clearwater Lake, Canada	Fractured	Land, crystalline	0.17	Pilkington and Grieve 1992
Holleford, Canada	Fractured	Land, crystalline	0.24	Pilkington and Grieve 1992
Average (1)	Fractured	Marine	0.06	This study
Average (2)	Fractured	Land, crystalline	0.18	Pilkington and Grieve 1992
Lockne, Sweden	Brecciated	Marine, mixed	0.03	This study
Tvären, Sweden	Brecciated	Marine, mixed	0.06	This study
Kärdla, Estonia	Brecciated	Marine, mixed	0.24	Plado et al. 1996
Dellen, Sweden	Brecciated	Land, crystalline	0.26	Henkel 1992
Jänisjärvi, Russia	Brecciated	Land, crystalline	0.33	Henkel 1992
Lappajärvi, Finland	Brecciated	Land, crystalline	0.34	Henkel 1992
Average (3)	Brecciated	Marine	0.11	This study
Average (4)	Brecciated	Land	0.31	This study
Lockne, Sweden	Resurge arenite	Marine, mixed	0.01	This study
Lockne, Sweden	Resurge breccia	Marine, mixed	0.01	This study

Table 4. Variation of the maximum negative residual gravity anomalies with diameter for impact structures of sizes similar to the Lockne and Tvären structures in Fennoscandia.

Crater	Country	Diameter (km)	Gravity anomaly (mGal)	Reference
Dellen	Sweden	15	−7	Pilkington and Grieve 1992
Janisjärvi	Russia	14	−13	Pilkington and Grieve 1992
Lappajärvi	Finland	17	−10	Pilkington and Grieve 1992
Mien	Sweden	9	−5	Pilkington and Grieve 1992
Sääksjärvi	Finland	5	−6.5	Pilkington and Grieve 1992
Söderfjärden	Finland	6	−6	Pilkington and Grieve 1992
Lockne	Sweden	7.5	−2.5	Sturkell et al. 1998
Karikkoselkä	Finland	1.3	−4	Pesonen et al. 1997
Iso-Naakama	Finland	3	−4	Elo et al. 1993
Kärdla	Estonia	4	−3	Puura and Suuroja 1992
Suvasvesi North	Finland	3.5	−2.8	Werner et al. 2002
Saarijärvi	Finland	2	−1.5	Pesonen et al. 1998
Paaselkä	Finland	10	−8	Pesonen et al. 1999

increase in crystalline rock fragments and the increase in susceptibility. The slight decrease in susceptibility in the crystalline rock breccia at Tvären may be due to the circumstance that the clasts originate from another source than the granitic components in the resurge breccia. The local aeromagnetic map by Lundström (1976) shows that the eastern part of the basement outside the structure has a greater magnetic anomaly than the western part. Unpublished magnetic susceptibility values supplied by Herbert Henkel to Ormö and Blomqvist (1996) show that the eastern part of the basement outside the structure has higher magnetic susceptibility than the western part. This is also apparent in our data (Table 2). Lindström et al. (1994) noted, as did we, bleached outer zones of many crystalline clasts in which biotite appears to have been altered to other minerals, such as chlorite. Hence, greater oxidation of magnetite due to more extensive water circulation (Henkel 1992) and possibly owing to less cementation in the crystalline rock breccia than in the resurge deposits might also be the reason for the decrease in susceptibility. We did not, however, notice any difference in cementation between the crystalline rock breccia and the resurge deposits.

As mentioned, in Lockne, possibly pre-impact inhomogeneities within the crystalline basement rocks play an important role for anomalies in the drill cores. In both Lockne and Tvären, the crystalline impact-related rocks have a smaller variation than their undisturbed counterparts. Susceptibility is known to decrease in impact breccias and

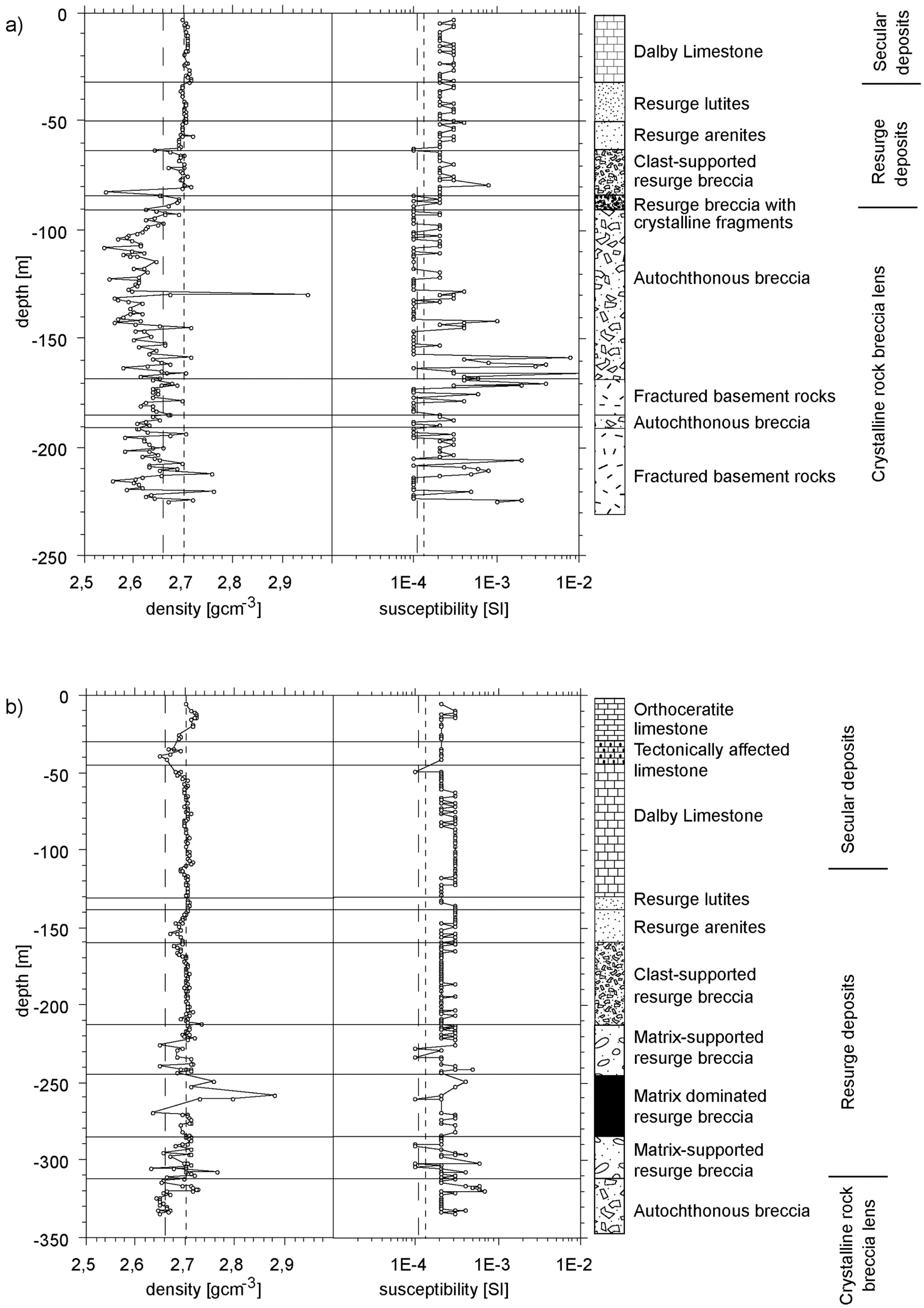

Fig. 5. Density and susceptibility versus depth in the a) LOC 1 and b) LOC 2 drill cores. The dashed lines represent the density and susceptibility of the target granite (long dashes) and limestone (short dashes), respectively.

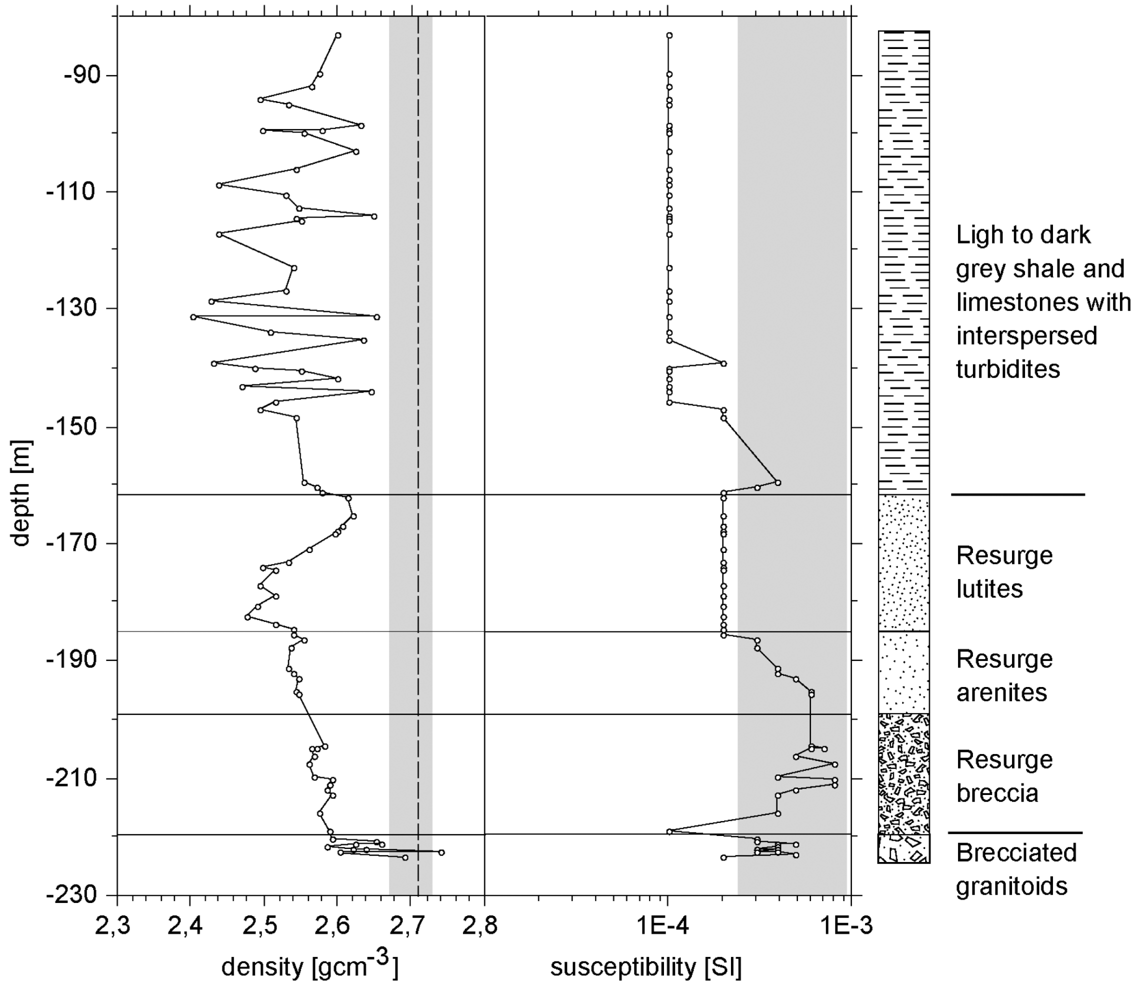

Fig. 6. Density and susceptibility versus depth in the Tvären 2 drill core. The gray area indicates the density and susceptibility range for the western and eastern target granites shown in Table 2. The density of calcite (from Carmichael 1989) is marked with a dashed line.

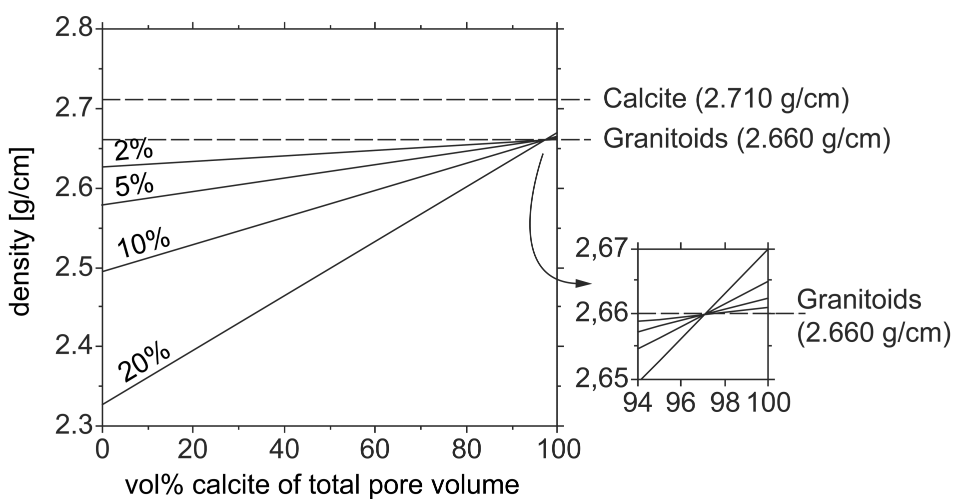

Fig. 7. Variation of density with different volume percents of calcite of total pore volume modelled for fractured and brecciated granitoid rocks from the Lockne area. Whenever the pores are not completely filled with calcite, water occupies the remaining pore space. The average density of the undisturbed granitoids in Lockne, 2.660 g/cm^{-3}, the density of pure calcite is 2.710 g/cm^{-3} (Carmichael 1989), and a water density of 1.000 g/cm^{-3} were used and are indicated by the dashed lines. The numbers at each line represent the pore volume prior to calcite infill. The arrow indicates the origin of the enlargement to the right.

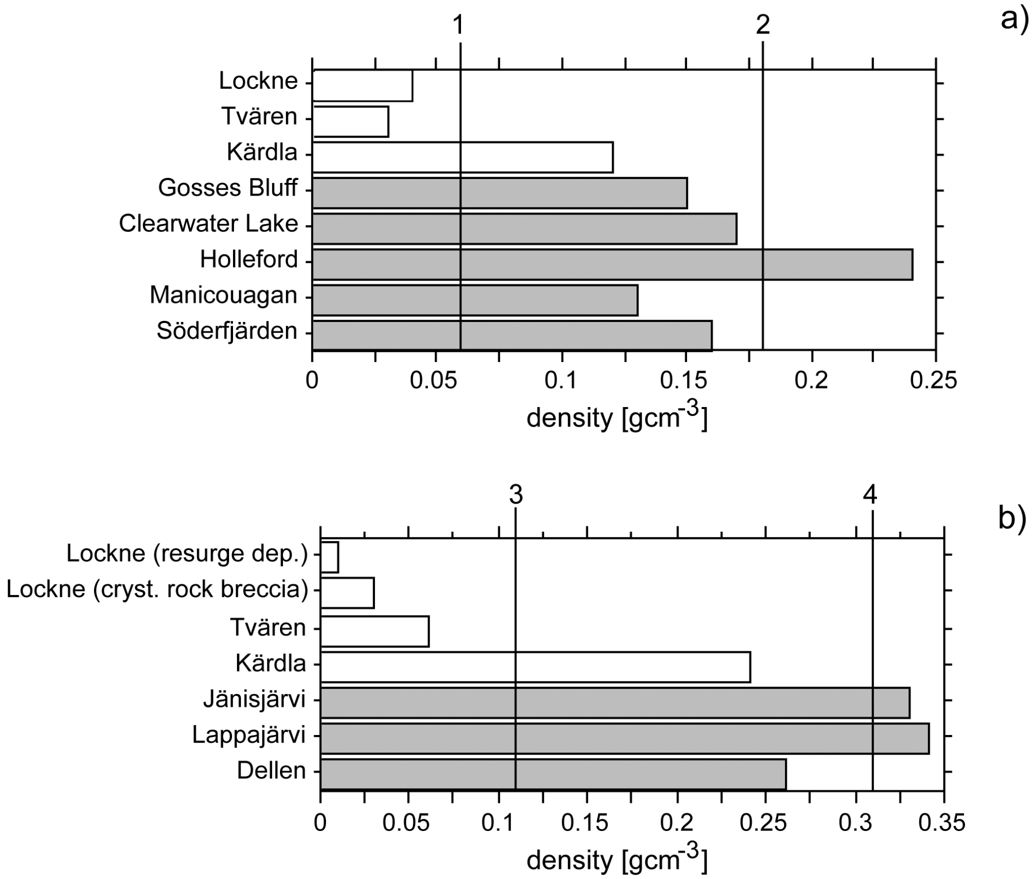

Fig. 8. Comparison of the contrast between target rocks and rocks with impact-related deformation in craters formed on land (gray) and in marine targets (white). Craters formed in a marine environment show a lower density contrast for both the fractured rocks and the brecciated. The data used and their references are given in Table 3. a) The contrasts for fractured crystalline target rocks. b) The contrasts for brecciated target rocks. The vertical lines show the average density contrast for marine craters (1 and 3) and for craters formed on land (2 and 4).

fractured rocks compared to the non-deformed target rocks (Pilkington and Grieve 1992; Pohl 1994). Impact-induced remanent magnetization occurs in some cases, but is nonetheless not a rule nor a common feature (Table 1 in Henkel 1992; Pilkington and Grieve 1992; Pohl 1994). The strongest anomalies are associated with masses of strongly shock-metamorphosed target rocks and suevite-type impact formations. Massive impact melt bodies mostly have weak magnetic anomalies (Pohl 1994).

Comparisons to Other Impact Craters

Density data from a number of craters have been compared with the data obtained in this investigation. The craters were created in several different environments: both on land and at sea and in both crystalline and sedimentary targets. We have found some common features that seem to be dependent on the nature of the target rock and on the environment of impact, whether in a marine environment or on land. Like Pilkington and Grieve (1992), we have chosen to compare density data from impact structures by looking at the density contrasts in different rocks. The contrast is defined as the density of the rock with impact-related deformation subtracted from the density of the undisturbed target rock. We have chosen this definition for clarity. Table 3 and Fig. 8 show the contrasts between the crystalline impact-related rocks and the original crystalline target rocks for some different craters. Apparently, the contrast between target rock and impact-deformed rock is the highest in targets on land, whereas the lowest values occur in marine targets. The mean values of the density contrasts in marine craters are on the order of one-third to one-half of those for craters formed on land and none of the marine craters have higher values than the lowest value of the craters created on land. Observations of rocks from the Lockne and Tvären structures have shown that precipitate of calcite is an important fracture and pore-filling material, which, as shown, can increase the densities of the impact-related rocks.

The Estonian Kärdla impact structure has many similarities to the Lockne and Tvären structures. Like those, it is of Caradocian (Middle Ordovician) age (Grahn et al. 1996). The target had a 140 m thick sedimentary cover of Cambro-Ordovician limestone, shale, and sandstone (Puura and Suuroja 1992). The water depth at Kärdla was probably less

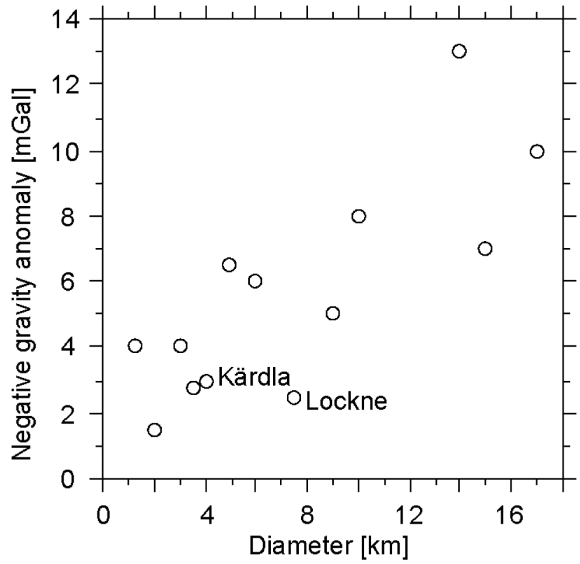

Fig. 9. Variation of the maximum negative residual gravity anomalies with diameter for impact structures of sizes similar to the Lockne and Tvären structures in Fennoscandia. This figure is based on data from Table 4.

than 100 m (Puura et al. 2004), whereas Tvären and Lockne formed in a water depth of at least 100 m (Ormö and Lindström 2000). From our observations of drill cores from the Kärdla structure, we conclude that open fractures here are rather rare, but not as rare as in Lockne and Tvären. Accordingly, the density contrasts are not as low for the Kärdla samples as compared to the samples from the Lockne and Tvären structures. Although the contrasts are lower than in all of the structures formed on land, the relatively large contrast might be due to smaller amounts of water circulating in the impact-related rocks, which resulted in less calcite precipitation and thus larger contrasts. Another reason might be that the calcite has been dissolved by ground water, for example, after its precipitation.

For comparison, the density contrast between the resurge deposit and the Orthoceratite limestone from Lockne has been included in Table 3 and Fig. 8.

A lower density contrast for sedimentary targets compared to crystalline targets was proposed by Pilkington and Grieve (1992), because the same amount of porosity in less dense sedimentary rocks and more dense crystalline rocks should result in a higher density contrast for the crystalline rocks. This hypothesis was supported by a comparison between separate populations of craters formed in sedimentary and crystalline lithologies. The craters formed in crystalline environment have greater negative gravity anomalies for a given crater diameter. Further support for the hypothesis came from a single breccia value from a sedimentary crater having a relatively low contrast compared to those found in crystalline targets. We concur with the hypothesis of Pilkington and Grieve (1992), especially in view of our observation that marine craters generally will plot on the lower end when contrasts between target and impactites are compared.

It appears that the target rock to impact rock contrast is generally the highest in craters formed in crystalline targets on land and the lowest in craters formed at sea, while craters formed in sediments on land are intermediate.

Implications for Gravity Modelling

Consequently, the marine structures, in which easily mobile carbonates are more common than in craters formed on land, should generally have smaller gravity anomalies than impact structures of the same size in similar targets on land. Comparing the 2.5 mGal maximum negative anomaly found by Sturkell et al. (1998a) and the 3 mGal reported by Puura and Suuroja (1992) in their studies of the Lockne and Kärdla structures to the anomaly data for similarly sized craters formed on land as presented in Table 4 and Fig. 9 definitely places these marine structures in the lower range. The state of preservation of the Lockne and Kärdla structures is good, as ejecta and resurge deposits are partly preserved outside of the crater and very well preserved within the crater (Lindström et al. 1996; Sturkell et al. 1998a; Puura and Suuroja 1992). Therefore the subdued characters of these two gravity anomalies should not be interpreted as a feature that is due to poor preservation. The impact structures formed on land most often have little or no preserved crater fill and some even have crater floor removed. This places them in the categories of deepest erosional level as used by Pilkington and Grieve (1992).

CONCLUSIONS

In both Tvären and Lockne, a fairly clear and opposite relationship exists between the increase in crystalline rock fragments and the change in susceptibility. There is an increase in Tvären and a decrease in Lockne. The slight decrease in susceptibility in the crystalline rock breccia at Tvären may be due to either inhomogeneities in the target granitoids or oxidation due to post-impact circulation of fluids. Strong positive and negative anomalies in the Lockne drill cores are due to minor occurrences of lithologies with different susceptibility.

The small difference in density between target rocks and authigenic breccias and the resurge deposits in marine impact structures is due to healing of fractures and pores by calcite and subordinately quartz and fluorite. Calcite is the most important because it is more mobile and denser than average (crystalline) granitic rocks. We suggest this is a process characteristic of impact structures formed at sea and where carbonates are available. We have also noted that tectonic discontinuities, such as shear zones, can cause a local decrease in density.

Our results, combined with data from other studies, give us reason to suspect that contrasts in density between the impact-related rocks and the original target rocks are significantly smaller in craters formed in marine environments than in craters formed on land because (mobile) carbonates are more frequently available.

Acknowledgments–Access to density and susceptibility data for the Lockne impact structure surroundings from Lutz Kübler at the Geological Survey of Sweden is gratefully acknowledged. We also want to thank Maurits Lindström, Herbert Henkel, and Eve Arnold for valuable critical remarks and discussions during the preparation of the manuscript. We are also thankful to the reviewers Herbert Henkel, Mark Pilkington, Uwe Reimold, and Dattatray Parasnis.

Editorial Handling—Dr. Richard Grieve

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