Meteoritics & Planetary Science 39, Nr 9, 1721–1731 (2004)
Abstract available online at http://meteoritics.org

The target peneplain of the Lockne impact

Erik STURKELL[1*] and Maurits LINDSTRÖM[2]

[1]Icelandic Meteorological Office, Reykjavík, Bústaðavegur 9, 150 Reykjavík, Iceland
[2]Department of Geology and Geochemistry, Stockholm University, 10691 Stockholm, Sweden
[*]Corresponding author. E-mail: erik@vedur.is

(Received 15 July 2003; revision accepted 30 April 2004)

Abstract–The Lockne impact crater in central Sweden, with a diameter of about 7 km, formed in the mid-Ordovician in a marine environment that was deeper than present shelf seas. The present dip of the so-called sub-Cambrian peneplain in the target area of the impact is about 0.85° toward the northwest. The peneplain is cut by a set of northwest-striking, nearly vertical faults with a throw of up to just over 100 m, collectively. The identification of the peneplain and its deformation by faulting allows us to infer that the part of the crater that is exposed to the east of Lake Locknesjön has been lowered by about 100 m relative to parts exposed to the west of the lake and that it has, therefore, been spared from significant erosion. Therefore, the preservation of the whole crater is even better than was assumed in previous work. The peneplain extends to 600–700 m from the rim of the inner crater. Hence, the structural uplift of the rim is quite subdued compared to the craters that formed on land.

INTRODUCTION

The Lockne crater in central Sweden (14°49′30″E, 63°00′20″N; Fig. 1) formed as a result of a meteoritic impact in the middle of the Ordovician period, about 455 Myr ago (Lindström et al. 1996). There is a morphologically well-defined apparent crater (referred to as an "inner crater" in the following text) with a diameter of just over 7 km. The environment of the impact was marine (Sturkell 1998) because the same marine sediments were deposited uniformly throughout the target area immediately before and after the impact. The target consisted of a relatively deep sea (Lindström 1971), about 80 m-thick sediments of middle Cambrian to middle Ordovician age (Sturkell 1998), and a Proterozoic crystalline basement (Lundqvist and Autio 2000). The depth of the target sea was between 500 m and 1,000 m (Ormö et al. 2002; Shuvalov et al. Forthcoming). About half the thickness of the target sediments was argillaceous and mechanically weak; the other half was well-lithified limestone.

A peneplain had formed on the Proterozoic basement before the early Paleozoic marine sedimentation began in the area. This surface, which is the focus of our present paper, is commonly referred to as the sub-Cambrian peneplain. Since this peneplain separates the Cambrian from underlying Proterozoic rocks, it might seem natural to use the term pre-Cambrian instead. However, in an authoritative review of the Cambrian in Scandinavia, Bergström and Gee (1985) use the term sub-Cambrian. This is the appropriate term because, in areas like Lockne where earliest Cambrian sediments are missing, one cannot exclude the possibility that peneplanization continued into the Cambrian.

The inner crater is surrounded by a 1–3 km-wide belt in which most of the pre-impact Paleozoic sediments were stripped away during the growth of a crater in the overlying sea water (Shuvalov et al. Forthcoming). The water crater, and the zone of partial stripping, became more extensive than the inner crater. This belt consists of essentially flat-lying, monomictic breccia with crystalline basement rocks as protolith. The included fragments can attain sizes of over 100 m, but penetrative comminution down to microscopic grain sizes is common throughout the belt and dominant in its outer reaches. Drillings and exposures show that this belt of strongly fractured basement is rootless and, in many cases, is underlain by Cambrian shale (Lindström et al. Forthcoming). For brevity, we refer to this zone as the "brim" because of its likeness to a soup plate.

Exceptionally good outcrops show remnants of Cambrian shale with preserved, sedimentary contact with overlying, fractured basement rocks. Hence, the shale and the overlying basement rocks must be overturned (Lindström and Sturkell 1992). Figure 2 shows an overturned flap of Proterozoic granite with sedimentary contact with underlying Cambrian shale. Both rock units rest on the autochthonous Proterozoic granite of the sub-Cambrian peneplain. Thus, the ejecta of the brim overlie the sub-Cambrian peneplain.

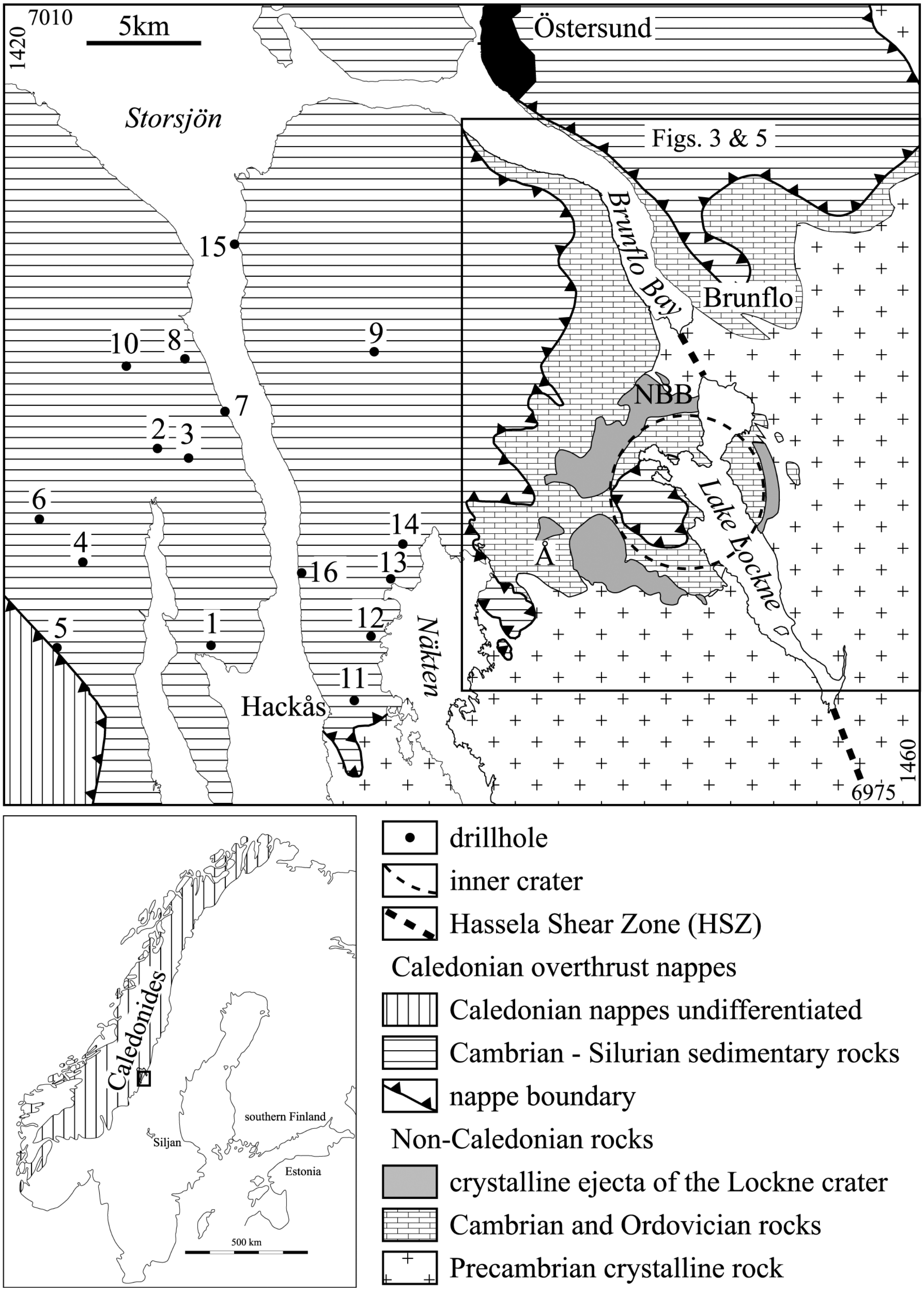

Fig. 1. Overview map of Scandinavia, including Siljan, the southern part of Finland, and Estonia. General geological map of the Lockne area and central Jämtland including Nordanbergsberget (NBB), Åsan (Å), Hackås, Brunflo Bay, and Brunflo. The numbered black dots show the location of the drill cores used in the calculation. The coordinates for the drill sites are given in Table 1.

Fig. 2. View toward the northeast over the sub-Cambrian peneplain forming the bottom of the Skanska quarry at Nordanbergsberget. The wall of the quarry consists of a flap of monomictic and overturned, crystalline ejecta, the sense of ejection being toward the left in the figure. The ejecta sheet is not very far-travelled and contains large segments of crystalline rock with essentially preserved inner structure. At the base of the wall, it rests with preserved, but overturned and locally folded and disrupted, sedimentary contact on a thin sheet of Cambrian shale. The bedrock of the background terrain on the other (northeast) side of the valley is the Paleozoic sedimentary succession of Brunflo that dips slightly toward the northwest in conformity with the underlying peneplain. The base of the wall is identical to the base of the quarry. Reprinted from Lindström and Sturkell (1992) with permission from Elsevier Publishing Company.

At distances of 1–2 km from the margin of the inner crater, Ordovician limestone and Cambrian shale occurs beneath the crystalline ejecta of the brim. As a rule, these Paleozoic sediments are strongly deformed. Outside of the reach of the brim, the Paleozoic cover rocks are mostly well-preserved, unless they were removed by younger erosion. Over large areas in the vicinity of the Lockne crater, erosion has exposed the sub-Cambrian peneplain in an excellent state of preservation.

Since the boundary between the remaining Paleozoic and the exposed peneplain is deeply and irregularly lobate on the map, there are numerous points at which the altitude of the contact between the Cambrian and the Proterozoic basements can be determined. These points are distributed over much of the area. This circumstance facilitated early determinations of the present orientation of the sub-Cambrian peneplain (Asklund 1929; Hjulström 1936; Thorslund 1940). A regional drilling program (Fig. 1) made it possible to reconstruct the westward continuation of the peneplain beneath a cover of Caledonian overthrust nappes that thicken westward (Andersson et al. 1985). These authors found that the peneplain in the areas next to Lockne dip about 1.25% (0.72°) toward the northwest. This orientation of the peneplain has been explained by tilting during, and possibly after, the early to middle Paleozoic Caledonian orogeny (Lindström et al. 1996). The immediate cause of this tilting could have been that the lithosphere was depressed under the load of overthrust nappes that progressed toward the southeast (Roberts and Gee 1985).

Lindström et al. (1996) extrapolated the sub-Cambrian peneplain toward the southeast from its present outcrop west of Locknesjön. In their reconstruction, the peneplain east of Locknesjön would have been at 100–200 m above the present ground level if it had not become eroded. Thus, the reconstruction implied considerable erosion of the eastern part of the Lockne crater. Unfortunately, the outcrop conditions east of Locknesjön at the time in which the Lindström et al. (1996) paper was published did not permit a check of the conditions in the field. However, more data are available now thanks to an improved outcrop. We decided to profit from this situation and make a special investigation of the peneplain to get a better check on the preservation of the crater.

MATERIAL AND METHODS

We will refer to some of the rather extensive literature on the bedrock of the area as well as to our own observations on the geology of the sub-Cambrian peneplain and its overlying rocks, to the extent that these references are relevant to the interpretation of the peneplain and any deformations it has gone through.

We are making use of the drill cores, 16 in all, of the drilling program (Andersson et al. 1985) referred to above that penetrate the sub-Cambrian peneplain. We are also including different outcrops of the peneplain from the literature and our own records. These data include the level at which the peneplain occurs at each particular outcrop. The provenance of the data is shown in Fig. 1. Their geographic coordinates are given in Table 1.

The local level of the peneplain is defined as the altitude above sea level at which Cambrian sediment is found resting on undisturbed crystalline rock. The position in space of any one point on the peneplain is defined with reference to the coordinates x (west-east), y (south-north), and z (up) in the Swedish National Grid (modified UTM). Coordinates for points in the terrain can be obtained from the Geographical Sweden Data (GSD) issued by the Swedish Ordnance Survey. This database gives the altitude of the terrain with a horizontal resolution of 50 m.

The equation for a plane is:

$$ax + by + cz + d = 0 \quad (1)$$

where *a, b, c,* and *d* are specific for the plane, and *x, y,* and *z* define any point on that plane. The data from the 16 drill cores were used for a first approximation of the plane (Table 1).

THE MORPHOLOGY OF THE PENEPLAIN

The peneplain is a mostly flat surface with topographic amplitudes of generally less than 10 m. It is observed to have overlying Cambrian shale along the erosion front of the Phanerozoic rocks, for instance at and south of Hackås (Fig. 1; Table 2), as reported by Karis and Strömberg (1998). In the course of the development of the peneplain, the Proterozoic crystalline basement experienced weathering that mostly left only insignificant traces. At some places, such as Nordanbergsberget (Fig. 1), boulders of practically non-weathered local rock were left as residue when more weathered parts were eroded. Such boulders were included in the basal sediment of the Cambrian.

Another outcrop of the peneplain with excellent preservation of pre-middle Cambrian features of weathering and erosion is southwest of Åsan (Fig. 1; Table 2). This outcrop has irregular rounded depressions that are 10s of cm wide and several cm deep. These depressions were etched in a surface of Proterozoic granite. The depressions contain the remnants of a filling of middle Cambrian bituminous shale. At some places, the shale contains sand and gravel at its base. Karis and Strömberg (1998) described apparently identical structures from other outcrops of the sub-Cambrian peneplain in the region.

Although firm identification of the peneplain is possible only at the sedimentary contact between the Paleozoic and underlying Proterozoic basement, there are large areas in which the basement surface must be close to the peneplain level. Such areas occur to the east of the inner crater east of Locknesjön and to the southwest of the inner crater between

Table 1. The names and coordinates of the drillings. The z-values denote the height of the top of the pre-Cambrian basement (from Gee et al. 1982), and the residual from the best fitting plane are given.

Location	# in Fig. 1	x (m)	y (m)	z (m)	Residuals (m)
Myrviken 78001	1	1429040	6981980	217	13
Myrviken 78004	2	1426700	6990590	116	12
Myrviken 78005	3	1428060	6990170	121	−3
Myrviken 78006	4	1423440	6985620	100	−4
Myrviken 78008	5	1422310	6981880	129	8
Myrviken 79001	6	1421540	6987500	49	−16
Myrviken 79002	7	1429650	6992210	113	−14
Myrviken 79003	8	1427900	6994510	101	14
Måläng 78001	9	1436170	6994820	182	−5
Månsåsen 79001	10	1425340	6994190	66	8
Näkten 78001	11	1435300	6979570	295	−6
Näkten 78002	12	1436030	6982380	282	−5
Näkten 78003	13	1436890	6984890	268	−9
Näkten 78004	14	1437420	6986410	263	−8
Orrviken 78001	15	1430070	6999520	71	−1
Sanne 78001	16	1433000	6985150	223	−4

Table 2. The location and the residual of the peneplain determined by Equation 2. The location for those are given in Figs. 4 and 5.

Location	# in Fig. 5	x (m)	y (m)	z (m)	Residuals (m)
Torkilsttjärnen	A1	1449600	6984400	415	–24
Mörttjärnen	A2	1448550	6984550	413	–12
Handsjö-vägen	A3	1446900	6985500	385	–11
Åsan	A4	1442900	6984950	343	–8
Tandsbyn	A5	1445800	6987700	373	8
Tand	A6	1445500	6989500	340	–6
N Nordanbergsberget	A7	1448330	6994060	365	21
Haga	A8	1453400	6987050	345	–119
Hackås	A9	1434170	6978950	289.5	–3
Hackås	A10	1434820	6976880	325	8
Mon	A11	1442100	6982330	350	–13
Berget	A12	1445300	6984090	380	–8
Farsinberget	A13	1455150	6991930	429.6	–16
Brunflo 1	A14	1451400	6996000	327	–39
Brunflo 2	A15	1453200	6997100	343	–36
Brunflo 3	A16	1450900	6996670	297	–57
Nordanbergsberget 1	A17	1449100	6992950	388	26
Nordanbergsberget 2	A18	1449075	6993250	380	20
Vålbacken	A19	1448150	6996700	293	–27
E Döviken	A20	1454770	6989330	367	–95
Nyckelberg	A21	1446320	6993000	340	12

Locknesjön and Näkten (Fig. 3). They are characterized by low topographic relief in continuity with identified segments of the peneplain.

Other areas are characterized by marked ridges and depressions that are elongated in northwest to southeast directions (Fig. 3). These features are explained by preferential erosion along old tectonic structures in the basement as well as along younger faults that tend to be parallel to the pre-existing structural grain of the basement. The selective erosion along northwest to southeast lineaments was enhanced because the ice movement during the Pleistocene glaciations was largely parallel to the northwest-southeast structural trend (glacial striations in 130–310°; see also Lundqvist 1969). Clearly, areas with these features do not show peneplain morphology.

ORIENTATION AND LOCAL EXTENT OF THE PENEPLAIN

After calculating the factors a, b, c, and d in Equation 1 to their nearest approximation on the basis of drill cores 1–16 (Fig. 1; Table 1), we obtained the following equation:

$$6.353682x - 4.207748y - 512.3452z + 20403144.0 = 0 \quad (2)$$

where *x, y,* and *z* are given in m.

The plane strikes 236° and dips 0.85° (14.9 m/km) to the northwest. The plane, thus defined, could be extended eastward beyond the front of the preserved overthrust nappes through the inclusion of outcrops of Cambrian sediments that are in situ on the Proterozoic basement. The calculated slope of 1.49% is only slightly steeper than the slope of ~1.25% presented by other authors, e.g., Asklund (1929), Hjulström (1936), Thorslund (1940), and Andersson et al. (1985).

The local altitude of the peneplain, z_p, is then subtracted from the observed local altitude of the peneplain, z_l, which gives a residual value showing the amount and sign of the difference from the calculated peneplain. These residuals are given in Table 2 and are shown in Fig. 4. In the Mon-Klockåsen area southwest of the inner crater (Fig. 3), the topographic level of the contact of the Cambrian sediments and Proterozoic crystalline rocks is in good agreement with the calculated peneplain, and the peneplain is preserved to at least 1–2 km south of the contact.

The situation in the area that extends northwest of the inner crater, that is, from Berget to southwest and west of Nordanbergsberget, is more complex because the peneplain is covered by varying thicknesses of ejecta and sedimentary rocks (Lindström et al. Forthcoming). The altitude of the peneplain cannot generally be estimated where the surface rock is crystalline ejecta. However, there are places where the ejecta sheet is penetrated through drilling (Tand, A6; Figs. 4 and 5; Table 2), quarrying (Nordanbergsberget, A18; Figs. 4 and 5; Table 2), or erosion (Nordanbergsberget, A17; Handsjövägen east of Stor-Gårdrolstjärnen, A3; Mörttjärnen, A2; Figs. 4 and 5; Table 2). The Nordanbergsberget quarry extensively exposes how the crystalline ejecta forms a flap that has overturned sedimentary contact with the middle Cambrian at its base. The non-disturbed peneplain (identified by a Cambrian basal conglomerate that rests on it with sedimentary contact) follows underneath and forms the floor of the quarry (Fig. 2).

At other localities (Nyckelberg, A21, and west of

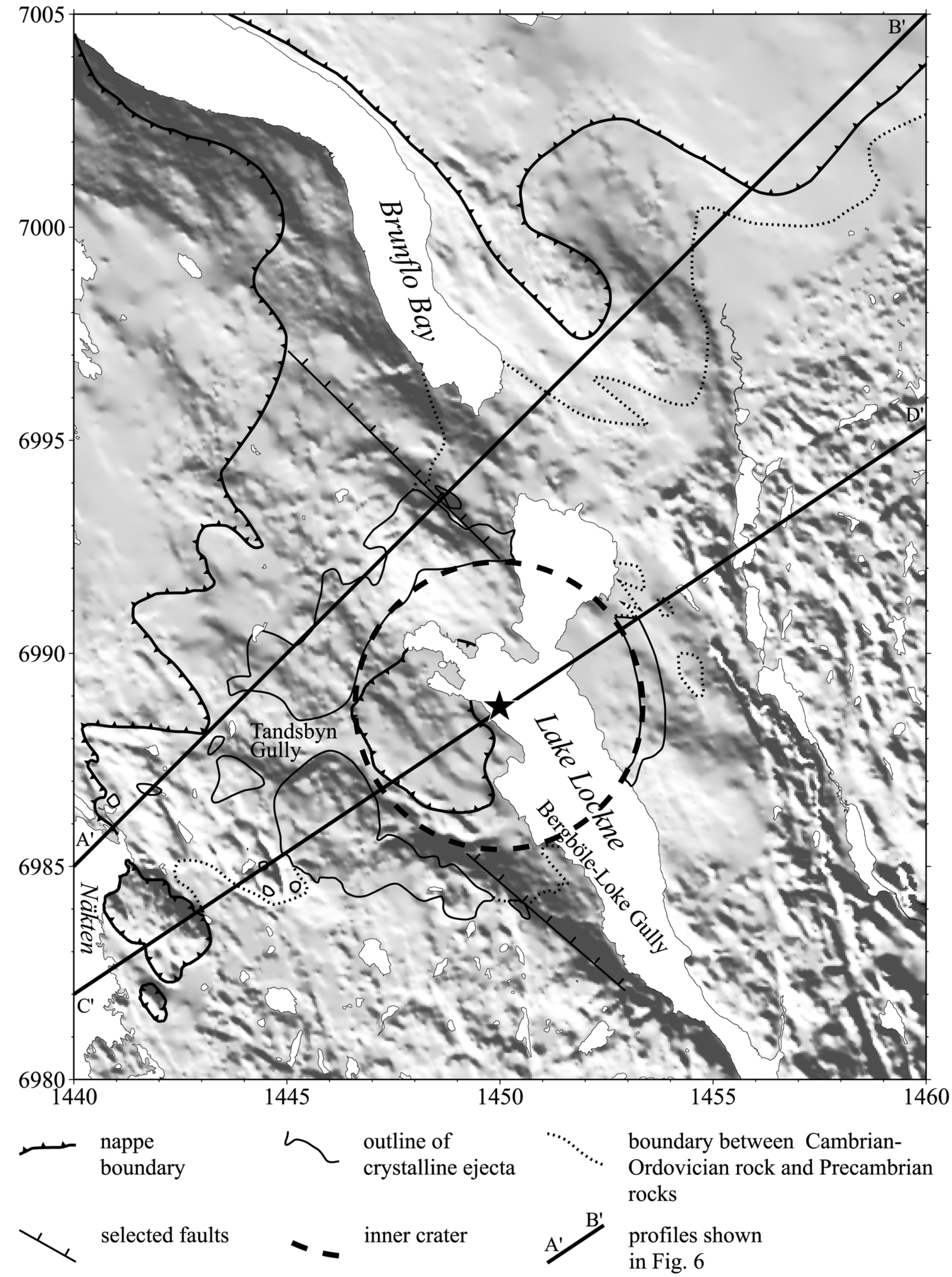

Fig. 3. Digital elevation model of the Lockne area (the geographical data base, GSD). The sub-Cambrian peneplain appears as smooth surfaces southeast of the boundary between the Paleozoic and ejecta on the one hand, and the Proterozoic on the other. The more or less deeply eroded Proterozoic basement southeast of the peneplain has a very hilly small-scale topography. The two northwest to southeast striking fault-zones that run tangentially to the inner crater are prominent in the topography.

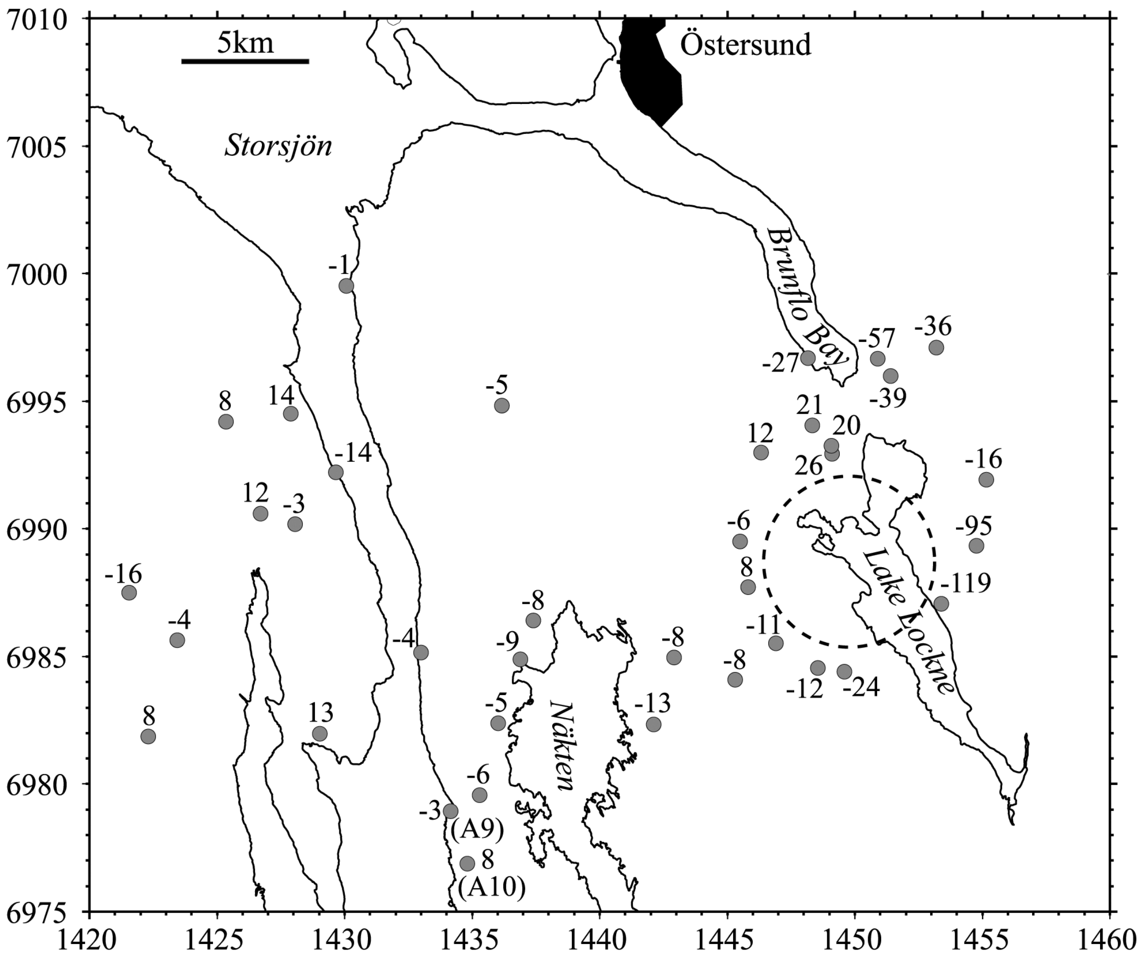

Fig. 4. The calculated residuals for the Cambrian/pre-Cambrian contact (Tables 1 and 2) and for important localities using Equation 2. The residual is given in m.

Tandsbyn, A5; Figs. 4 and 5; Table 2), where the peneplain is buried under Cambrian shale, a lowest probable altitude of the peneplain can be obtained by subtracting the greatest probable thickness of the Cambrian (that is, 30 m) from the altitude of the Cambrian outcrop.

The eastern half of the inner crater is surrounded by localities with reliable determinations of the peneplain altitude but consistently negative residuals. Thus, the peneplain is about 30 m lower than the expected level in the Brunflo area, as exemplified by localities A14–16 (Table 2; Figs. 4 and 5). The greatest documented subsidence of the peneplain is at the Haga locality (A8; Figs. 4 and 5; Table 2), where it is 119 m deeper than expected. The subsidence decreases somewhat northeastward from Haga and becomes negligible at Farsinberget (A13) 2.5 km northeast of the margin of the inner crater (Figs. 4 and 5; Table 2).

At the localities west of Tandsbyn (A5), Nyckelberg (A21), and Haga (A8), as well as north of Nordanbergaberget (A7) (Figs. 4 and 5; Table 2), the observed altitude of the peneplain is a minimum value based on the thickness of the Cambrian shale, which is 30 m. The actual altitude may be higher by less than 30 m than the values given in Fig. 4 and Table 2. The altitude of the peneplain at Farsinberget (Figs. 4 and 5; Table 2) is, likewise, a minimum altitude. It refers to the top of the hill that nearly reaches the level that the peneplain would have had before the later cycles of erosion.

TECTONIC DEFORMATION OF THE PENEPLAIN

The Lockne area is crossed by a set of northwest-southeast striking faults with subvertical displacements on the order of 10s of m (Lindström et al. Forthcoming). The faults were active after the cratering event and were affected particularly at the eastern part of the crater. The northeastern flank of Nordanbergsberget shows evidence of this faulting, in this case with subsidence to the northeast. Another fault escarpment, likewise with subsidence to the northeast, cuts the southern margin of the inner crater southeast of Loke (Fig. 6). The major subsidence of the peneplain documented at Haga and 3 km east of Döviken (A8 and A20; Figs. 4 and 5; Table 2) to the east of Locknesjön is due to a fault with a

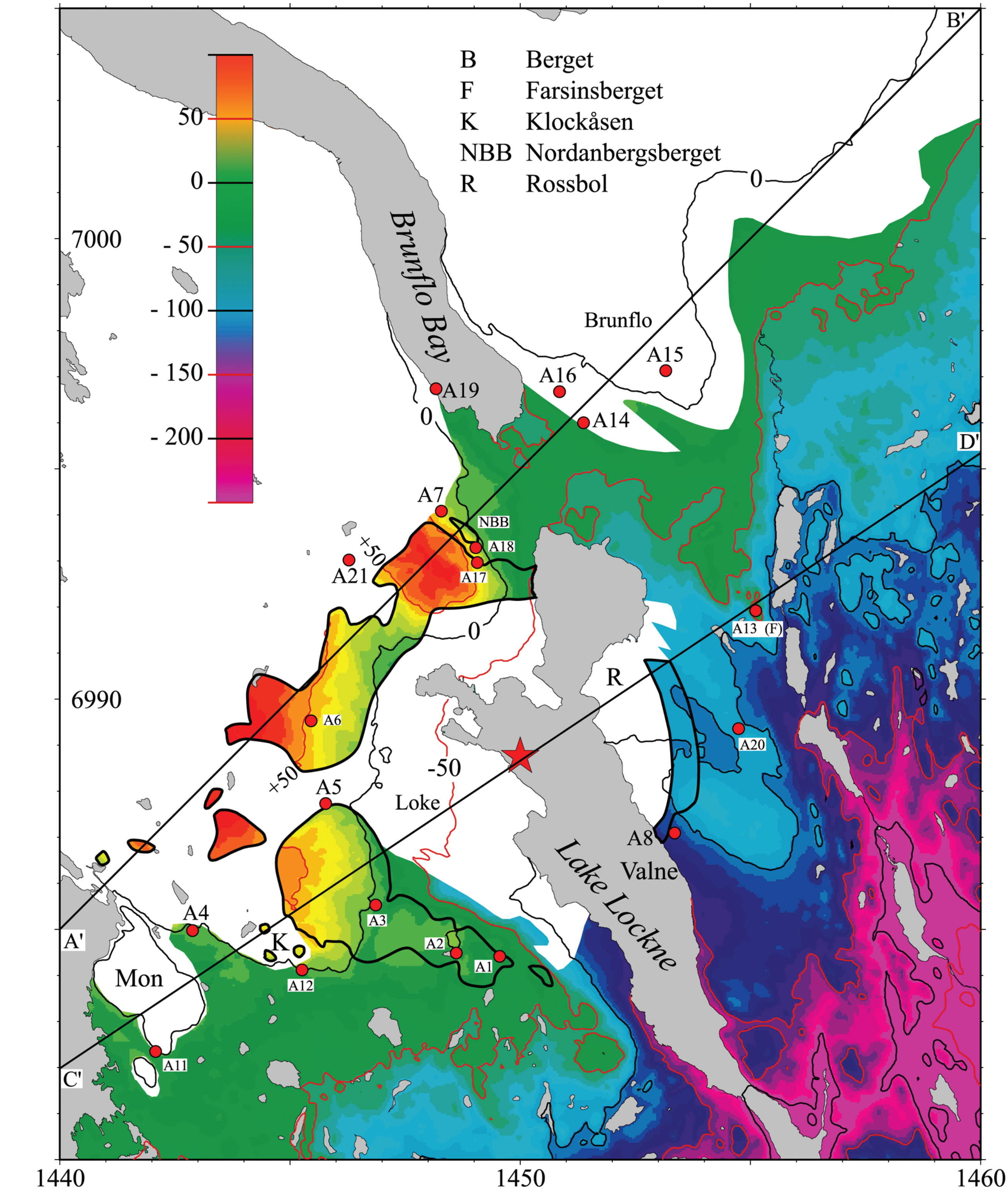

Fig. 5. Peneplain residual map for the pre-Cambrian rock surface in the Lockne and Brunflo areas using the geographical database (GSD). The sedimentary cover rocks are masked out with white. The isolines show the size of the residual from the peneplain at 50 m intervals. The violet red area in the southeast represents residuals larger than 200 m from the peneplain. The star denotes the center of the Lockne impact. The locations of the occurrence of minor alum shale pockets in a predominantly crystalline surrounding are marked A1 to A21 in the figure, and the coordinates are given in Table 2. Locality A13 refers to the top of the hill that nearly reaches the level the peneplain, and the locality 3 km east of Döviken (A20) refers to the peneplain. The thick black lines denote the outlines of the flaps shown in Fig. 1.

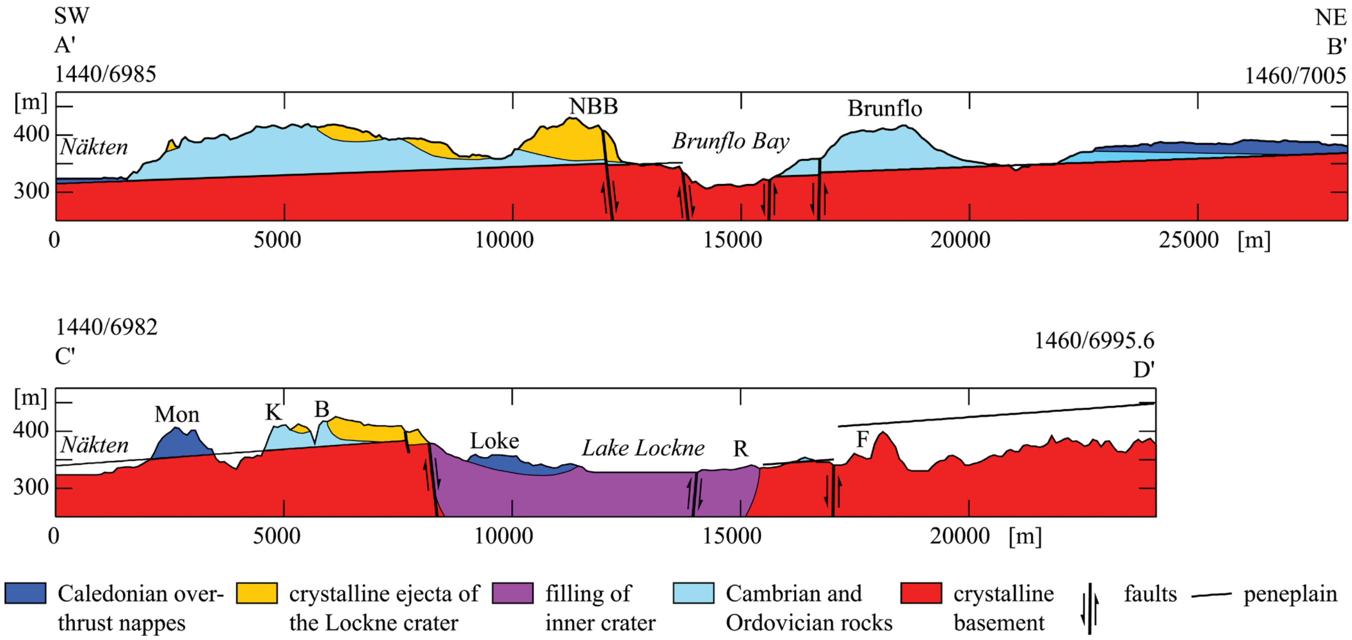

Fig. 6. A profile in the dip direction of the peneplain. The preserved overturned flaps (yellow signature) have positive residuals, and the eroded crystalline rocks generate negative residuals. NBB = Nordanbergsberget; B = Berget; F = Farsinsberget; K = Kloxåsen; R = Rossbol.

northwest-southeast strike that is located at the depth axis of Locknesjön.

Most of the subsidence of the Brunflo area took place along the fault zone on the northeast flank of Nordanbergsberget. Otherwise, the block on which Brunflo is situated shows only minor effects of internal faulting.

The fault-related subsidence on the east side of Locknesjön apparently decreases somewhat toward the northeast, away from the lake. Thus, the subsidence, which might reach 119 m at Haga, is 95 m 3 km east of Döviken on the east shore of Locknesjön (Figs. 4 and 5; Table 2). At Farsinberget, 1.5 km farther northeast, there is no such significant subsidence.

DISCUSSION

According to the *Glossary of geology* (Jackson 1997), a peneplain is a flat or gently undulating surface created by erosion that approached its base level. This means that the slope is much less than 1% (if the slope is 1%, the surface gets 100 m higher every 10 km, which ensures vigorous erosion). The circumstance that the sub-Cambrian peneplain slopes 1.49% in the Lockne area shows that this surface has become reorientated. The question, then, is whether this happened before or after the Lockne impact.

The sub-Cambrian peneplain, which is not unique for the Lockne area, formed through a billion years of denudation, when the entire paleocontinent Baltica was land for most of the time. The invasion of the sea in the early Cambrian began in northern and southern Sweden and in the Baltic basin and was accompanied by sandy deposition in those areas. Central Sweden and adjacent parts of Norway did not get any lasting cover of marine sediments until the middle Cambrian, or even later (Hagenfeldt 1989a, b). Since the Lockne area is in central Sweden, one can conclude that, in the early Cambrian, it was elevated relative to the Baltic basin and those parts of Sweden and Finland that were adjacent to this basin.

The situation was different at the time of the Lockne impact, which happened in sea water that was at least 500 m deep. At the same time, southern Finland must have been land because there can be no other source for the thick coeval deposits of non-marine algae in Estonia (Guy-Ohlson 1992). From the described circumstances, it can be concluded that the sea bed between Finland and the Lockne area acquired a net slope that had come into existence between the middle Cambrian and the mid-Ordovician. This slope was toward the nascent Caledonian orogen. Since the distance from southern Finland to Lockne is over 300 km, the net slope was slight at that time. Although it most likely increased in the direction of the Caledonian orogen, we do not believe that it got as steep as 1.49% anywhere, as we find in the Lockne area at present. Nevertheless, it is clear that the local downwarping of the Earth's crust in the direction of the Caledonides began before the Lockne impact.

The post-impact faults in the basement are parallel to the Hassela shear zone (HSZ) that cuts through the area with a northwest-southeast strike. The HSZ has been dated at a location approximately 15 km south-southeast of the impact center and developed as a ductile shear zone between 1.82 and 1.80 Gyr (Högdahl and Sjöström 2001). The faults are sub-vertical and have not yielded any fabric data from which a sense of movement could be inferred. Any movement in the horizontal sense must have been slight, however. Since the faults are younger than the impact, they might be related to Caledonian tectonism of late Ordovician to Devonian age. Since Caledonian compression was essentially in the west-east and northwest-southeast directions (Roberts and Gee 1985), an assumed Caledonian age of the faults would imply that they are most likely either normal or sinistral transcurrent or, even more likely, normal with a sinistral transcurrent tendency.

As shown in Figs. 5 and 6, the brim of crushed crystalline rock that surrounds the inner crater rises 10s of m above the local level of the peneplain. This circumstance helps to define the extent of the brim. For want of evidence to the contrary, intensely crushed crystalline rocks that occur near the inner crater and rise 10s of m above the local level of the peneplain are, therefore, regarded as ejecta belonging to the brim.

A 7 km-wide impact crater can be expected to be surrounded by a rim wall that is about 280 m high and that extends 2.1 km from the crater rim (Melosh 1989). A significant proportion, probably over half, of its maximum height close to the crater rim consists of ejecta. The lower part of the wall is structural uplift that is quantitatively important in the vicinity of the crater. The regularity of this situation is based on well-preserved terrestrial craters that formed on land, in nearshore waters, and on extraterrestrial craters. Our data indicate that there was little structural uplift around the rim of the inner crater at Lockne (Fig. 2). The level of the sub-Cambrian peneplain within 1 km from the crater rim is either just below or a few m above the reconstructed level of an undisturbed peneplain. The peneplain rise to 26 m above that which is expected in only one place. This is due to upfaulting in a regional fault zone.

CONCLUSIONS

The sub-Cambrian peneplain dips 0.85° toward the northwest and extends up to 5 km from the erosion front of the Caledonian terrain. To the east of this narrow strip of the exposed peneplain, pre-Cambrian rocks are eroded more or less deeply below the level of the peneplain. The Caledonian allochthon has been penetrated by many drillholes that reach through the underlying, autochthonous sediments and the sub-Cambrian peneplain. Information on the three-dimensional position of the peneplain, obtained from the drillholes, allows the peneplain to be defined mathematically. With the aid of this information and the elevation database, we could delimit a zone in which strongly crushed, crystalline basement occurs 10s of m above the mathematically reconstructed peneplain. This zone, here referred to as the brim, surrounds the inner crater. Outcrops and a drilling allow us to conclude that the brim consists of inverted flaps of crystalline ejecta that rest on the preserved sub-Cambrian peneplain and, therefore, rise above the latter.

From the mathematical definition of the peneplain, it was possible to resolve vertical displacements on the faults in the area. Block movements in the Lockne region follow a major Proterozoic shear zone, which has experienced brittle deformation during post-impact Caledonian and/or post-Caledonian time. Vertical block movements up to over 100 m within the Lockne crater are now confirmed, thus showing that the eastern sector of the crater is not deeply eroded but is down-faulted. Reconstruction of the peneplain shows that the impact structure is very well-preserved. Furthermore, the reconstruction indicates that structural uplift is practically absent along the rim of the inner crater. This might be a significant difference between this impact into a several hundred m-deep sea and the well-studied impacts on land.

Acknowledgments–The authors express their gratitude to Mattias Lindman for the mathematical help and to Curt Broman. Matthew J. Roberts commented on earlier versions of this paper. Maurits Lindström thanks the Department of Geology and Geochemistry of Stockholm University for the use of excellent working facilities. The figures were prepared with the public domain GMT software.

Editorial Handling—Dr. Alexander Deutsch

REFERENCES

Andersson A., Dahlman B., Gee D. G., and Snäll S. 1985. The Scandinavian alum shales. *Sveriges Geologiska Undersökning Ca* 56:1–50.

Asklund B. 1929. Norrlands strandflate. *Geologiska Föreningens i Stockholm Förhandlingar* 51:133–152.

Bergström J. and Gee D. G. 1985. The Cambrian in Scandinavia. In *The Caledonide orogen: Scandinavia and related areas,* edited by Gee D. G. and Sturt B. A. Chicester: John Wiley & Sons. pp. 247–271.

Gee D. G., Snäll S., and Stejskal V. 1982. *Alunskifferprojektet—Fjällen, undersökningar mellan Östersund och Svenstavik, Bilaga 1, del 1 och 2, Borrhåls-och analysdata.* Report BRAP 82502. Uppsala: Sveriges Geologiska Undersökning. pp. 1–301.

Guy-Ohlson D. 1992. Botryococcus as an aid in the interpretation of palaeoenvironment and depositional processes. *Review of Palaeobotany and Palynology* 71:1–15.

Hagenfeldt S. E. 1989a. Lower and middle Cambrian acritarchs from the Baltic depression and south-central Sweden: Taxonomy, stratigraphy, and palaeogeographic reconstruction. Ph.D. thesis, Department of Geology, University of Stockholm, Sweden.

Hagenfeldt S. E. 1989b. Lower Cambrian acritarchs from the Baltic depression and south-central Sweden: Taxonomy and biostratigraphy. *Stockholm Contributions in Geology* 41:1–176.

Hjulström F. 1936. Einige morphologische Beobachtungen im südöstlichen Storsjögebiet in Jämtland, Schweden. *Geografiska Annaler* 18:348–362.

Högdahl K. and Sjöström H. 2001. Evidence for 1.82 Ga transpressive shearing in a 1.85 Ga granitoid in central Sweden: Implications for the regional evolution. *Precambrian Research* 105:37–56.

Jackson J. A. 1997. *Glossary of geology,* 4th ed. Alexandria: American Geological Institute. 769 p.

Karis L. and Strömberg A. G. B. 1998. Beskrivning till berggrundskartan över Jämtlands län. Del 2: Fjälldelen. *Sveriges Geologiska Undersökning Ca* 53:2.

Lindström M. 1971. Vom Anfang, Hochstand und Ende eines Epikontinentalmeeres. *Geologische Rundschau* 60:419–438.

Lindström M. and Sturkell E. 1992. Geology of the early palaeozoic Lockne impact structure, central Sweden. *Tectonophysics* 216: 169–185.

Lindström M., Sturkell E., Ormö J., and Törnberg R. 1996. The marine impact crater at Lockne, central Sweden. *Geologiska Föreningens i Stockholm Förhandlingar* 118:193–206.

Lindström M., Ormö J., Sturkell E., and Von Dalwigk I. Forthcoming. The Lockne crater: Revision and reassessment of structure and impact stratigraphy. In *Lecture notes in Earth sciences*. Heidelberg: Springer.

Lundqvist J. 1969. Beskrivning till jordartskarta over Jämtlands län. *Sveriges Geologiska Undersökning Ca* 45. 418 p.

Lundqvist T. and Autio S. 2000. *Description to the bedrock map of central Fennoscandia.* Special Paper 28. Espoo: Geological Survey of Finland. 176 p.

Melosh H. J. 1989. *Impact cratering: A geologic process.* Oxford: Oxford University Press. 245 p.

Ormö J., Shuvalov V. V., and Lindström M. 2002. Numerical modeling for target water depth estimation of marin impact craters. *Journal of Geophysical Research* 107, doi: 10.1029/ 2002JE001865.

Roberts D. and Gee D. G. 1985. An introduction to the structure of the Scandinavian Caledonides. In *The Caledonide orogen: Scandinavia and related areas,* edited by Gee D. G. and Sturt B. A. Chichester: John Wiley & Sons. pp. 55–68.

Shuvalov V., Ormö J., and Lindström M. Forthcoming. Hydrocode simulation of the Lockne marine target impact. In *Lecture notes in Earth sciences.* Heidelberg: Springer.

Sturkell E. F. F. 1998. The marine Lockne impact structure, Jämtland, Sweden: A review. *Geologische Rundschau* 87:253–267.

Thorslund P. 1940. On the Chasmops series of Jemtland and Södermanland (Tvären). *Sveriges Geologiska Undersökning Ca* 436:1–191.