by Henning Dypvik¹, Jüri Plado², Claus Heinberg³, Eckart Håkansson⁴, Lauri J. Pesonen⁵, Birger Schmitz⁶, and Selen Raiskila⁵

Impact structures and events – a Nordic perspective

1 Department of Geosciences, University of Oslo, P.O. Box 1047, Blindern, NO 0316 Oslo, Norway. E-mail: henning.dypvik@geo.uio.no

2 Department of Geology, University of Tartu, Vanemuise 46, 51014 Tartu, Estonia.

3 Department of Environmental, Social and Spatial Change, Roskilde University, P.O. Box 260, DK-4000 Roskilde, Denmark.

4 Department of Geography and Geology, University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen, Denmark.

5 Division of Geophysics, University of Helsinki, P.O. Box 64, FIN-00014 Helsinki, Finland.

6 Department of Geology, University of Lund, Sölvegatan 12, SE-22362 Lund, Sweden.

Impact cratering is one of the fundamental processes in the formation of the Earth and our planetary system, as reflected, for example in the surfaces of Mars and the Moon. The Earth has been covered by a comparable number of impact scars, but due to active geological processes, weathering, sea floor spreading etc, the number of preserved and recognized impact craters on the Earth are limited. The study of impact structures is consequently of great importance in our understanding of the formation of the Earth and the planets, and one way we directly, on the Earth, can study planetary geology.

The Nordic-Baltic area have about thirty confirmed impact structures which makes it one of the most densely crater-populated terrains on Earth. The high density of identified craters is due to the level of research activity, coupled with a deterministic view of what we look for. In spite of these results, many Nordic structures are poorly understood due to the lack of 3D-geophysical interpretations, isotope- or other dating efforts and better knowledge of the amount of erosion and subsequent tectonic modifications.

The Nordic and Baltic impact community is closely collaborating in several impact-related projects and the many researchers (about forty) and PhD students (some seventeen) promise that this level will continue for many more years. The main topics of research include geological, geophysical, and geochemical studies in combination with modeling and impact experiments. Moreover, the Nordic and Baltic crust contains some hundred suspect structures which call for detailed analysis to define their origin.

New advanced methods of analyzing geophysical information in combination with detailed geochemical analyses and numerical modeling will be the future basic occupation of the impact scientists of the region. The unique Cretaceous/Tertiary boundary (K-T) occurrences in Denmark form an important source of information in explaining one of the major mass extinctions on Earth.

are the main reason that the Nordic countries are generally well-mapped.

Impact craters came into the focus about 20 years ago and the interest among the Nordic communities has increased during recent years. The small *Kaalijärv* structure of Estonia was the first impact structure to be confirmed in northern Europe (Table 1; Figures 1 and 7). First described in 1794 (Rauch), the meteorite origin of the crater field (presently 9 craters) was proposed much later in 1919 (Kaljuvee, 1933) and proven as an impact crater in 1937 (Reinwald, 1938). As early as in the late 18th century and early 19th century, however, several of the presently recognized Fennoscandian structures were suggested to be of impact origin. Abels et al. (2002) state that the engagement of the two Swedish geologists F.E. Wickman and N.-B. Svensson in the early 1960s have been of great importance. The Nordic participation in impact research has increased through the years, in particular in Sweden, Estonia, and Finland as a consequence of the First Nordic Impact Crater Symposium arranged in Espoo, Finland, 1990. In Norway, the discovery of the Gardnos structure (Naterstad and Dons, 1992; French et al., 1997) triggered some activities, while in Denmark, impact-related research has concentrated on detailed studies of the Cretaceous-Tertiary boundary beds (e.g., at Stevns Klint, Figure 2), including the famous “Fish Clay” (Fiskeler Member in the lithostratigraphy proposed by Surlyk et al., 2006).

During the last 10 years, several important networks were organized through NorFa (coordinator H. Henkel; 1997–1999) and Nordforsk (coordinator H. Dypvik; 2006–2008). Before these Nordic network projects, a Swedish and Finnish initiative (together with French and German groups) for an European Research Group for Terrestrial Impact Phenomena (ERGTRIP) was coordinated by H. Henkel in the period from 1992 to 1995. The Nordic and Baltic countries were also well represented and active in the successful ESF IMPACT-programme (coordinator C. Koeberl) from 1998 to 2003.

In this first period, the international interdisciplinary cooperation of especially Alex Deutsch, Herbert Henkel, Maurtis Lindström, Victor Masaitis, Lauri J. Pesonen, Urs Schärer and Dieter Stöffler was of great importance. Their engagement was crucial for the great success in discovering new impact structures in Fennoscandia in the period between 1990 and 2003. The success reflects the detailed geological and geophysical mapping of the region, mineral and raw material exploration, drilling efforts and general background knowledge and interest of laymen in the theme of impacts. In addition, as in other shield areas such as Canada, the generally high age of the bedrock has implied that the area exposed for asteroid and cometary impacts has existed for a long time. It should also be noted that most parts of the Fennoscandian Shield are easily accessible through well developed networks of roads.

Presently, some 17 PhD students and 40 researchers are involved in impact-related research in the Nordic and Baltic countries.

Introduction

Geological mapping and geoscientific investigation of Fennoscandia and Baltic countries started about two hundred years ago. The first geological maps were made more than 150 years ago. About the same time, national geological surveys and geoscience departments were established in several universities. These long-term activities

In terms of surface geology, Denmark consists essentially of glacial debris, for the most part less than 20 kyrs old. Therefore the study of impact sites has little tradition, and very few circular to sub-circular topographic features have been noted. Mostly, they can be related to sub-surface structures, and in no case has a possible impact origin been investigated. Possible candidates for more recent impact sites are *Harre Vig* in the Limfjord area and *Stavns Fiord* on Samsø.

The classic and most intensely studied boundary succession in the Danish Basin is Stevns Klint (e.g., Alvarez et al., 1980; Hart et al., 2005; Rasmussen et al., 2005; Rosenkrantz, 1966; Surlyk and Håkansson, 1999), easily accessible some 65 km south of Copenhagen (Figures 1 and 2). It represents the marginal basinal setting, exposing the varied sedimentological development of the boundary succession in a sea-cliff over a distance of 12 km. The boundary itself is located at the base of the so-called 'Fish Clay' (Fiskeler Member) at the level of pronounced enrichments in Ir and other elements of the Platinum group (Schmitz et al., 1988). The boundary related features also involve the "Grey Chalk" (Højrup Member) below and the "Cerithium Limestone" (Cerithium Limestone Member) above the "Fish Clay". Due to the basin margin setting, several episodes of sea-floor cementation (hard-grounds) are encountered within the boundary succession of Stevns Klint.

The *Gardnos* structure was the first impact structure recognized in Norway (Figures 1 and 3, Table 1). Though first described in 1945 as a “cryptovolcanic” structure, the discovery of shock metamorphic minerals by Naterstad and Dons (1992) disclosed its impact origin (French et al., 1997). The crater was probably formed at c. 600 Ma ago by an impact into a shallow shelf sea. The 5 km in diameter, complex crater is well exposed, easy accessible and conveniently located along the main road between Oslo and Bergen, just 170 km from Oslo. In addition, its great exposures offer a magnificent section through several different typical impact lithologies. The Gardnos structure is visited annually by about 20,000 tourists and geologists.

Pal.
Fish clay
Cret.

March 2008

The *Mjølner* crater was recognized just a couple of years after Gardnos. *Mjølner* is a 40 km wide structure located offshore northern Norway, below 350 meters of water in the Barents Sea (Figure 1). Most petroleum geologists who studied the geophysical information interpreted this unfamiliar structure as volcano or salt diapir. Gudlaugsson (1993) launched the “crazy” idea that this structure demanded an extraterrestrial explanation (Dypvik et al., 1996). This triggered intense research activity on all available material from the *Mjølner* region, along with the drilling of a new shallow core in the center of the structure in 1998, which confirmed the impact crater interpretation (Sandbakken et al., 2005).

The *Ritland* structure of Hjelmeland, outside Stavanger, has been investigated by geologist F. Riis in recent years. This structure is located in rugged west Norwegian terrain; 2.5 km in circular and 3–400 m deep. The presence of highly altered minerals (quartz, feldspar and mica) together with a good selection of breccias and intense fracture patterns, strongly indicate an impact origin, but no clear-cut impact features have yet been found in samples from the area.

Sweden

The Precambrian Shield of Sweden represents an ideal setting for finding impact craters. Seven confirmed impact structures (Figure 1, Table 1) with diameters from 2 to c. 60 km and ages ranging from 90 to 470 Ma (perhaps 600 Ma, Åvikebukten) are known (Henkel and Pesonen, 1992; Abels et al., 2002). In addition, about 7 probable and 30 possible astroblemes have been proposed for Sweden. In some regions, well preserved lower Paleozoic sedimentary strata display a record of environmental effects of impacts and variations in the flux of extraterrestrial bodies to Earth. Particularly notable has been the discovery (Schmitz et al., 2001) of more than 40 fossil meteorites (up to 20 cm in diameter) in the Ordovician limestones at Kinnekulle, southern Sweden (Figure 4).

The *Siljan* crater located in the Dalarna region of south-central Sweden (Figure 1) is Europe's largest impact crater and was formed in the late Devonian (Reimold et al., 2005). It is represented by a ring-formed lake structure. Its pre-erosional diameter is not well constrained and estimates vary from 65 km (Kenkmann and von Dalwigk, 2000) to as much as 85 km (Henkel and Aaro, 2005). Ar-Ar dating of melt breccias from the crater yielded an age of 377 ± 2 Ma, which is identical, within uncertainties, to the age of 374.5 ± 2.6 Ma for the Frasnian-Famennian boundary (Reimold et al., 2005). The latter coincides with one of the five most severe extinction events of the Phanerozoic, suggesting a possible connection. However, distal ejecta from the *Siljan* impact have not been identified; hence it is difficult to relate the impact event directly to late Devonian bioevents.

Figure 3 The Gardnos crater structure is located in Hallingdal (Norway) and has a probable late Precambrian origin. The 5 km diameter is indicated in this eastward-facing structure. (Photo: H. Dypvik).

Table 1 General characteristics of recognized impact structures in Scandinavia and the Baltic states. Data sources: see text and Abels et al. (1998; 2002), Henkel and Pesonen (1992), Pesonen (1996) and Puura and Plado (2005).

The table gives the age, the maximum present field diameter of the structure and information on crater morphology: C=complex crater, S=simple crater, e=exposed, m=submarine, l=lake, b=bay, tec=tectonically modified, bu=buried under sediment, r=rim exposed, u=central uplift exposed, f=crater field.

Name	Country	Latitude	Longitude	Diameter km	Age Ma	Morphology
Gardnos	Norway	N60°39'	E09°00'	5.0	600±10	C, e, u
Mjølner	.	N73°48'	E29°40'	40.0	142±2.6	C, m, bu
Siljan	Sweden	N61°2'	E14°52'	65.0	377.8±2	C, e, l
Dellen	.	N61°48'	E16°48'	19.0	89.0 ±2.7	C, l, tec, r
Lockne	.	N63°00'	E14°49'	8	455	C, e, l
Granby	.	N58°25'	E14°56'	3.0	~470	S, b
Tvären	.	N58°46'	E17°25'	2.0	~455	S, b
Mien	.	N56°25'	E14°25'	9.0	121±2.3	C, l, r, u
Åvikebukten	.	N62°30'	E17°48'	9.5	600-1200	C, e, b, r, u,
Lappajärvi	Finland	N63°12'	E23°42'	23.0	73.3±5.3	C, l, r, u
Saaksjärvi	.	N61°24'	E22°24'	6.0	602±17	S, l, r
Söderfjärden	.	N63°2'	E21°35'	6.6	~560	C, bu, r
Iso-Naakkima	.	N62°11'	E27°9'	3.0	900-1200	S, tec, bu
Lumparn	.	N60°9'	E20°6'	9.0	~1000	C, tec, bu, r
Suvasvesi N	.	N62°42'	E28°10'	5.0	~260	C, tec, l, r
Karikkoselkä	.	N62°13'	E25°15'	1.5	~230	S, l, r
Saarijärvi	.	N65°17'	E28°23'	1.5	< 500	S, l, r, u
Paasselkä	.	N62°2'	E29°5'	10	<1800	C, l, r
Suvasvesi S	.	N62°40'	E28°10'	4.0	~280?	C, l, tec?
Keuruselkä	.	N62°8'	E24°36'	>20	<1800	C, tec
Kaalijärv	Estonia	N58°24'	E22°40'	0.11	0.004±0.002	S, e, l, r, f
Kärdla	.	N59°1'	E22°46'	4.0	~455	C, bu
Neugrund	.	N59°20'	E23°40'	7.0	~470	C, m, r
Ilumetsa	.	N57°58'	E27°25'	0.08	0.0066	S, e, r, f
Dobele	Latvia	N56°35'	E23°15'	4.5	205±35	C, bu
Mizarai	Lithuania	N54°01'	E23°54'	5.0	500±20	C, bu
Vepriai	.	N55°05'	E24°35'	8.0	160±5	C, bu
Jänisjärvi	Russia	N61°58'	E30°55'	16	700±5	C, l, r, u
Mishina Gora	.	N58°43'	E28°03'	2.5 x 4.0	350-250	C?, e
Suavjärvi	.	N63°07'	E33°23'	16	~2400	C, e

Figure 4 Middle Ordovician (470 Ma) fossil meteorite (6x8 cm) from the Thorsberg Quarry, southern Sweden. The meteorite with relict chondrule structures lies next to a nautiloid shell on a hardground surface. (Photo: B. Schmitz and M. Tassinari).

Both shatter cones and planar deformation features (PDFs) in quartz provide the proof for an impact origin of Siljan (Grieve, 1988). In the 1980s, the crater was drilled (two holes to nearly 7 km depth) in response to a proposal that an impact-induced fracture system below the crater would contain large amounts of “mantle-derived” hydrocarbons (Gold and Soter, 1980); no hydrocarbons of significance were found.

Three craters, namely *Lockne* (8 km), *Granby* (3 km), and *Tvären* (2 km) were formed between c. 470 and 455 Ma. This age clustering of the craters, together with a high abundance of craters of this age worldwide, indicates that they may have been related to an asteroid shower (Schmitz et al., 2001). Abundant relict L chondritic chromite grains dispersed in the mid-Ordovician limestone also provide empirical evidence for a higher flux (up to two orders of magnitude) of extraterrestrial dust and small meteorites at this time (Schmitz et al., 2001; 2003). On theoretical grounds it has been shown that the flux of asteroids may be substantially enhanced for 2–30 million years following a major parent body disruption (Zappalà et al., 1998). Further support for an asteroid shower comes from the discoveries of extremely abundant L chondritic chromite in the resurge deposits of the Lockne crater (Alwmark and Schmitz, 2007).

These three Ordovician craters formed by impacts into a vast epicontinental sea and contain excellently preserved breccia and resurge deposits. These sediments provide detailed information on the processes taking place during and after an impact into a shallow sea, such as tsunami generation, sediment disturbance and biota recolonisation on the sea floor (Lindström et al., 1994; Sturkell, 1998). Lockne hosts a crater museum.

The 19 km in diameter *Dellen* crater in central Sweden was formed at c. 89 Ma in the late Cretaceous (Deutsch et al., 1992). Because of severe post-impact erosion and two lakes filling a large part of the crater depression, impact-related rocks in the Dellen structure are difficult to access.

In the center of the *Mien* crater about 20–25 m of impact melt rocks have been drilled, but no sedimentary fragments are observed in the crater-fill breccias suggesting a continental impact on crystalline rock (Abels et al., 2002).

Recently the complex *Åvikebukten* structure (9.5 km in diameter), of uncertain age (600–1200 Ma?), has been found to contain quartz grains with PDFs (Henkel et al., 2005).

Finland

Eleven proven impact structures have so far been found in Finland (Figure 1, Table 1). These are (with discovery year in parenthesis): Lappajärvi (1967), Sääksjärvi (1969), Söderfjärden (1978), Iso-Naakkima (1993), Lumparn (1992), Suvasvesi North (1993), Karikkoselkä (1996), Saarijärvi (1997), Paasselkä (1999), Suvasvesi South (2001) and Keurusselkä (2003). The ages of formation vary from c. 1200 Ma (Iso-Naakkima) to about 73 Ma (Lappajärvi), but the majority is poorly dated. The present diameters vary from ~23 km in Lappajärvi to 1.4 km in Karikkoselkä (Abels et al., 2002). These diameters, however, are minimum estimates since the structures are moderately to strongly eroded (e.g., Keurusselkä).

Lappajärvi (Figure 1) is the largest impact structure (23 km) in Finland. It is situated in western Finland and Ar-Ar and U-Pb dating resulted in ages of 77.3 ± 4 Ma to 71 Ma (Pesonen et al., 1992). Dark and dense impact melt rock, so-called *kärnaite*, occurs in Lappajärvi's central island Kärnäsaari and nearby smaller islands. The *kärnaite* layer is about 145 m thick and displays enrichments of Ni and Ir, possibly of meteoritic origin. Below the *kärnaite*, the few meters thick layer of suevite rests on a clastic impact breccia. PDFs in quartz are common. Lappajärvi hosts a “meteorite” museum.

Lake *Sääksjärvi* (U-Pb age 602 ± 17 Ma, 6 km diameter) is situated in western Finland and displays a slight elliptical shape along NW-SE direction. In the late 1960s,

shock metamorphic features in quartz were found in suevite boulders from the region. Later petrophysical studies by Elo et al. (1992) of drill core samples revealed abnormally low densities and high porosities consistent with a striking negative and nearly circular gravity anomaly and its second vertical derivative (Figure 5).

The *Söderfjärden* (~560 Ma, 5–6 km diameter) structure forms a distinct geomorphic depression. Drill core samples revealed mica gneissic basement composition, which is covered by 30–40 meters of Quaternary glaciogenic sediments. Topographic and aerial photographs show a somewhat conical structure (man-made), while the geophysical data demonstrate a more circular appearance (Abels et al., 2002).

The *Iso-Naakkima* (900–1200 Ma, 3 km diameter) impact structure is located in central East Finland. It was originally discovered by its distinct circular and negative gravity signature. The geophysical anomalies associated with the structure have a diameter of ~3 km. The basin is covered by 30–40 meters of Quaternary sediments.

The *Lumparn* structure (500–1200 Ma, 9 km diameter) is situated at the main island of the Åland archipelago. The geological studies of drill core samples display a minimum 50 m thick impact breccia unit with PDFs in quartz.

The *Suvasvesi-North* (5 km in diameter) and *Suvasvesi-South* (4 km in diameter) impact structures may form a doublet (Figures 1 and 6). The Suvasvesi-North is probably late Permian (260 Ma) in age, based on paleomagnetism and magnetic modelling (Pesonen et al., 1996), while the age for the Suvasvesi-South has not been determined. The Geological Survey of Finland drilled the Suvasvesi-North structure in 1992 in the center of a circular negative magnetic anomaly. It revealed an 80 m thick layer of impactites, including melt breccias and suevites, with PDFs present in quartz grains.

The small *Karikkoselkä* structure (230–530 Ma, 1.5 km in diameter) is represented by the nearly circular Lake Karikkoselkä. Well-developed shatter cones from a few centimeters to 2 meters occur around the lake. Quartz grains in a breccia boulder carry PDFs.

The *Saarijärvi* impact structure (<500 Ma, 1.5 km in diameter) is a drop-shaped lake located in Archean basement. The drill-core samples revealed PDFs in quartz from the impact breccias.

Figure 5 Gravity anomaly maps of the Lake Sääksjärvi impact structure, SW Finland (Figure 1). (A): Bouguer gravity map as color coded surface presentation. The view is from southwest. Scale is in gravity units (1 gu = 0.1 mGal). (B): the second vertical derivative of the Bouguer anomaly, in units of gu/km^2 . Courtesy: Seppo Elo, Geological Survey of Finland.

Figure 6 Examples of impact rocks in Finnish structures (for locations see Figure 1). A) Suevite-melt boulder from Mannamäki gravel pit, east side of the Suvasvesi South structure, central-east Finland. B) Shatter cone (from boulder) from the Keurusselkä impact structure, central Finland (Figure 1). The scale (5 cm) applies to both figures.

The *Paasselkä* structure (<1800 Ma) is an oval-shaped lake ~8–11 km in diameter, located in southeast Finland. The Geological Survey of Finland drilled two cores through the central magnetic “spikes” in 1999, which showed 20 m thick Quaternary deposits underlain by fractured mica schist down to 252 meters. Quartz grains in the breccia samples revealed well-developed PDFs.

The *Keurusselkä* structure (<1800 Ma) is located 32 km west from Karikkoselkä (Figures 1 and 6). Keurusselkä is most likely a deeply eroded impact structure. The preliminary estimate of the original diameter, based on shatter cone findings, points to >20 km.

The Baltic countries

In contrast to Norway, Sweden and Finland, the Baltic States (Estonia, Latvia, and Lithuania) are located in the Paleozoic platform area of the Svecofennian Crustal Domain. This circumstance is reflected in the ages and preservation of the impact structures; all are Phanerozoic in age and any older structures were likely destroyed during the 1300 to 600 Ma erosional epoch. The relatively well-preserved Paleozoic and Mesozoic impact structures have been preserved from erosion by burial immediately after impact. Most structures, therefore, have been found by indirect methods: drilling and geophysical analysis.

In **Lithuania**, two proven structures: *Mizarai* and *Vepriai* (Figure 1), were reported in 1978 (Motuza and Gailius, 1978). Both structures are complex: 5 and 8 km in diameter, with possible impact ages from 520 to 480 Ma (Middle to Early Ordovician) and 165 to 155 Ma (Jurassic), respectively. The structures are buried and were found by geophysical mapping and proven to be of impact origin by the occurrence of PDFs in quartz, shatter cones and impact glass in drill-core samples.

The *Dobele* structure is located in SE **Latvia**, near the border to Lithuania (Figure 1). The structure is 4.5 km in diameter and late Carboniferous to early Permian in age. It is buried below 75 m of variegated carbonate-terrigenous rocks of late Permian and early Triassic age, and sands and clays of Pleistocene age. The pre-impact sedimentary formations are highly crushed, and shatter cones, as well as PDFs in quartz are observed within the drill-core samples.

Estonia hosts two early Paleozoic (*Kärdla* and *Neugrund*) complex structures and two simple structures (*Kaalijärv* and *Ilumetsa*) which are Pleistocene in age (Figure 1). Applying strict rules of crater identification (see Henkel and Pesonen, 1992) only the *Kaalijärv* structure may represent a “proven” impact structure by the occurrence of meteorite fragments.

Figure 7 Inner view of the *Kaalijärv* impact structure as taken from the rim. The nine structures in Kaali (Estonia) are distributed within an area of 1 km², the photo illustrates the largest structure with a diameter of 105–110 m and height of the rim of 4–7 m. (Photo: J. Plado).

The *Kaalijärv* structure may represent a “proven” impact structure by the occurrence of meteorite fragments. *Kaalijärv* (Figure 7) was described by Pytheas from Massalia (Marseille) in 350–320 BC, and could be linked to Greek Mythology (Phaeton) and Nordic folklore (Finnish Kalevala and Estonian folk poems).

The Early Cambrian *Neugrund* structure (7 km) is located in the Gulf of Finland, about 10 km from the shore of NW Estonia. It was found in the course of integrated geological and geophysical mapping of NW Estonia in 1994–1995, when numerous brecciated erratic boulders were discovered and described in the onshore area by K. Suuroja (Suuroja and Saadre, 1995). This discovery prompted seismic reflection measurements, marine magnetic studies, and submarine sampling of the Neugrund Bank (e.g., with the discovery of shock metamorphic quartz). The shallow offshore plateau of post-impact sedimentary infill was protected against erosion by a well-developed surrounding crystalline rim.

The Ordovician *Kärdla* structure (4 km) was found in 1967 and confirmed in 1980 by identification of fracturing and planar features in feldspar and quartz (Figure 1). It is the most studied crater in Estonia due to an extensive drilling program (>300 wells) in the 1980s (see Puura and Suuroja, 1992). *Kärdla* was formed in a shallow Ordovician sea that covered older sediments and underlying crystalline basement. It is barely visible in the present topography, but displays a well-preserved complex subsurface structure.

The nine *Kaalijärv* craters are located within an area of 1 km². The main crater, which is 105 to 110 m in diameter, is water-filled, whereas the others (12 to 40 m in diameter) are only 1 to 4 m deep and dry. In the vicinity of the smaller structures, a total of about 3.5 kg of projectile remnants (coarse octahedrite iron meteorite) have been collected; the largest single fragment weighs 30 g. The *Kaalijärv* crater has a visitor center and museum of meteoritics, which was established in 2005 and has thousands of visitors each year.

The *Ilumetsa* crater field hosts two structures, 70–80 and 50 m in diameter. Radiocarbon dating of samples from a peat layer with glassy impact spherules from the nearby (6 km) bog have yielded the age of 6,600 yrs BP (Raukas et al., 2001).

Two smaller possible impact structures—*Tsõõrikmäe* (40 m) and *Simuna* (8.9 m) are identified solely by morphological features. Some researchers have also proposed an impact origin of the recently (2004) discovered *Vaidasoo* structure.

Challenges in impact research

Finnish and Baltic challenges

Since the Baltic States are located in the Paleozoic platform area, the search for impact structures needs a slightly different approach compared to the Nordic countries (Figure 1). Analysis of the gravity, magnetic and seismic data, in particular, may give information on buried, circular structures (Figure 5). Studies of the old cores from the extensive Soviet drilling programs may give additional evidence in the search for distal ejecta layers and their host craters.

The most fascinating Baltic impact "mystery" is related to the theories of the age of the Kaalijärvi event (Figure 7). Different researchers have proposed ages ranging from 6720 to 370 B.C. based on ^{14}C analysis of charcoal from within the craters and Ir- and spherule-rich layers in nearby bogs. The inner, unusual structure of Neugrund remains un-drilled; its broad central peak and post-impact sedimentary infill may give information on the age and setting at the time of impact (e.g., was the target wet or dry?).

In order to verify the impact origin of the small Pleistocene structures, unconventional approaches are needed, such as shallow seismic and ground penetrating radar analysis combined with other geophysical and geochemical methods. The first steps were made in 2005 during a summer-school for Nordic-Baltic PhD students focusing on the Ilumetsa structure.

Until 1990, only three impact structures had been found in Finland (Figures 1, 5 and 6). A recent impact search program (headed by L.J. Pesonen) has developed a new strategy with joint efforts involving impact scientists and universities, research institutes, exploration and drilling companies along with amateur geologists. This strategy resulted in the discovery of eight new impact sites during the period 1990–2004. Impact flux calculations suggest that numerous impact structures are still to be discovered. New geophysical techniques, including GIS and DEM analysis and mathematical algorithms, form the modern tools to find hidden structures. Additional problems are the poorly constrained ages of the impact events and the various levels of erosion; more modeling is needed of the impact processes by using sophisticated hydrocode softwares.

The recently founded joint co-operation between the universities of Oslo and Helsinki, the geological surveys of Norway and Finland, and ESA/ESTEC, will provide a new forum for scientific study of impact structures, and the discovery of new impact craters in Fennoscandia. These studies will gather information of interest for later application in extraterrestrial remote sensing analyses of the planets, Mars in particular.

The search for impact structures in Norway

The search for impact structures in Norway has been an important new initiative. Current projects also include: 1) the intensified mapping and the search for impact evidence related to the Ritland structure (headed by F. Riis). 2) The studies of the Mjølner structure (Barents Sea) are progressing smoothly and an international effort to organize an IODP/ICDP coring program of the structure is underway (H. Dypvik). 3) In the Gardnos structure detailed mapping and sedimentological analyses have been finished recently and major efforts concentrate now on both U-Pb and paleontological dating of the impact event (E. Kalleeson).

In 2005, a national program searching for circular structures in Norway was launched, first of all targeting the primary schools of Norway (~10 year olds). Based on the web site (www.geo.uio.no/groper) the students can search their own/home district in order to find possible circular structures with diameters between 2 and 7 km. Instructions on the web-site tell them what to look for and what the succeeding field studies should contain. This pilot project (run by S.O. Krøgli) formed the Norwegian base for the new Finnish, Norwegian, and ESA/ESTEC cooperative program mentioned above.

Understanding the K-T boundary in Denmark

While the biological effects of the K-T boundary event have been clarified to some extent, the sedimentological and geochemical signals still remain somewhat ambiguous.

The up to 4 m of "Grey Chalk" (Højerup Member) underlying the "Fish Clay" (Fiskeler Member) in Stevns Klint (Figure 2) owes its color to finely dispersed elementary carbon, allegedly of the same isotopic composition as the soot in the "Fish Clay" itself (Hansen, 1990), thereby seriously challenging the popular interpretation of the boundary soot as the result of impact-related wild fires.

The post-K-T-boundary "Cerithium Limestone" (Cerithium Limestone Member) has its peculiarities as well, containing an undetermined proportion of possibly chemically precipitated clay to silt-sized, euhedral calcite crystallites. In contrast to the soot mentioned

above, these crystallites are abundant also in the "Cerithium Limestone" equivalents throughout the Danish Basin, whereas there seems to be no reports from other parts of the World.

In view of the apparent 'strangelove' (the alleged adverse ocean existing just after impact) conditions of the "Cerithium Limestone" sea, with basin-wide chemical precipitation of low-magnesium calcite, the changes in skeletal mineralogy of the benthos through the boundary succession becomes very intriguing. The "Grey Chalk", like all chalk, is rich in species with all three varieties of skeletal CaCO_3 (low-Mg calcite [dominant], high-Mg calcite, aragonite). In contrast, the "Cerithium Limestone" and its equivalents in the Danish Basin are essentially devoid of benthic organisms with low-Mg calcite skeletons, in spite of the fact that low-Mg calcite is simultaneously precipitated directly in the sea water (Heinberg and Håkansson, 2000).

The numerous Swedish structures

A major future challenge in Swedish impact research will be to verify or falsify the proposed impact origin for the many structures in Sweden (Wickman, 1988; Henkel and Pesonen, 1992). Priority may be given to drill some of the six probable craters (Skedviken, Björkö, Hummeln, Landsortsdjupe, Trinddjupet, and Ledfat). Further reconnaissance field studies regarding the other 30 possible impact structures should also be given priority. Radiometric and biostratigraphical dating of craters and identification of the impactor types will enhance our overall understanding of the role of impact processes in the history of the solar system and the evolution of life. Analyses of platinum group elements and chromium isotopes and search for relict extraterrestrial minerals in impact melts or resurge deposits may give clues about impactor type.

Another important task will be to find sedimentary sections displaying distal Siljan ejecta (Abels et al., 2002). The large Siljan event has been claimed to be partly responsible for extinction events both in the middle and late Devonian. Consequently, locating ejecta in biostratigraphically dated sections would open up for studies of the effects of a major continental impact on the environment and biosphere.

The confirmed mid-Ordovician craters in Sweden were buried under sedimentary successions and their well-preserved resurge deposits may contain traces of the impactors. Coeval sedimentary strata outside the craters are widely distributed in Baltoscandia and have been studied in great detail during the last two centuries. These craters, consequently, hold a unique potential for studies of sedimentary processes and ejecta transport, and perturbations following marine impacts. The Paleozoic strata may, in addition, contain ejecta layers from impacts for which source-craters are unknown. Because of their condensed nature, they provide a unique flux record of various types of extraterrestrial matter to Earth through time (Schmitz et al., 2003).

Conclusions

It is evident that the field of impact competence is varied in the Nordic countries, underlining the need for close cooperation in order to improve our understanding of the impact events and their post-impact development. The Nordic and Baltic impact community is prospering and the many highly engaged researchers and PhD students promise that this activity level will be retained for many more years.

Impact structures form an important factor in shield research, since these rocks have recorded impacts for billions of years. Detailed geological, geophysical and geochemical studies of those old formations, in combination with modeling experiments and coupled with precise dating will give us a way to study the evolution of the shield in four dimensions.

Such new advanced analyses in combination with deep drilling programs will be the future basic occupation of the impact scientists of the region. In addition, the special K-T boundary occurrences in Denmark form a unique and important source of information in understanding one of the major mass extinctions of the Earth.

Impact structures globally, host economically valuable resources (ores, hydrocarbons, water). They have also become popular tourist attractions. Thus, it is hardly surprising that impact science has found its place in the curriculum of Nordic-Baltic universities.

Acknowledgements

The comments of Christian Koeberl and Alex Deutsch on an earlier draft are highly appreciated.

References

- Abels, A., Pesonen, L.J., Deutsch, A., Bischoff, L., and Lehtinen, M., 1998, A geographic information system-based characterization of the Söderfjärden impact structure, W. Finland: *Meteoritics & Planetary Science* 33 (4) (Supp.), p. A8, 61.
- Abels, A., Plado, J., Pesonen, L.J., and Lehtinen, M., 2002, The impact cratering record of Fennoscandia—A close look at the database, *in* Plado J. and Pesonen L.J., eds, *Impacts in Precambrian Shields*: Springer-Verlag, Berlin Heidelberg New York, pp. 1–58.
- Alvarez, L., Alvarez, W., Asaro, F., and Michel, H.V., 1980, Extraterrestrial cause for the Cretaceous-Tertiary extinction: *Science*, vol 208, pp. 1095–1108.
- Alwmark, C. and Schmitz, B., 2007, Extraterrestrial chromite in the resurge deposits of the early Late Ordovician Lockne crater, central Sweden: *Earth and Planetary Science Letters*, vol. 253, pp. 291–303.
- Bottomley, R.J., York, D., and Grieve, R.A.F., 1978, ⁴⁰Ar-³⁸Ar ages of Scandinavian impact structures: I Mien and Siljan: *Contributions to Mineralogy and Petrology*, vol. 68, pp. 79–84.
- Deutsch, A., Buhl, D., and Langenhorst, F., 1992, On the significance of crater ages: new ages for Dellen (Sweden) and Araguinha (Brazil): *Tectonophysics*, vol 216, pp. 205–218.
- Donadini, F., Salminen, J., Pesonen, L.J., and Lehtinen, M., 2003, The Lake Suvasvesi South Structure: New field evidences supporting impact origin, XXI Finnish Geophysical Days, May 22–23, p. 25–28.
- Dypvik, H., Gudlaugsson, S.T., Tsikalas, F., Attrep, M. Jr., Ferrell, R.E. Jr., Krinsley, D.H., Mørk, A., Faleide, J.I., and Nagy, J., 1996, The Mjølner structure—An impact crater in the Barents Sea: *Geology*, vol 24, pp. 779–782.
- Elo, S., Kivekäs, L., Kujala, H., Lahti, S.I., and Pihlaja, P., 1992, Recent studies of the Lake Sääksjärvi meteorite impact crater, southwestern Finland, *Tectonophysics* 216 (1/2), p. 163–167.
- French, B.M., Koeberl, C., Gilmour, I., Shirey-Steven, B., Dons, J.A., and Naterstad, J., 1997, The Gardnos impact structure, Norway: petrology and geochemistry of target rocks and impactites: *Geochimica et Cosmochimica Acta*, vol. 61, pp 873–904.
- Gold, T. and Soter, S., 1980, The deep-earth gas hypothesis: *Scientific American*, vol. 242, pp. 154–161.
- Grieve, R.A.F., 1988, The formation of large impact structures and constraints on the nature of Siljan, *in* Bodén, A. and Eriksson, K.G, eds, *Deep Drilling in crystalline bedrock; The deep gas drilling in the Siljan impact structure, Sweden and astroblemes*, volume 1, Springer Verlag, Berlin, pp. 328–348.
- Gudlaugsson, S.T., 1993, Large impact crater in the Barents Sea. *Geology*, vol. 21, pp.291–294.
- Hansen, H.J., 1990, Diachronous extinction at the K/T boundary: a scenario, *in* Sharpton V.L. and Ward P.D., eds, *Global catastrophes in Earth history; an interdisciplinary conference on impacts, volcanism, and mass mortality*, Geological Society of America Special Paper, volume 247, pp. 417–423.
- Hart, M.B., Feist, S.E., Håkansson, E., Heinberg, C., Price, D.G., Leng, M.J., and Watkinson, M.P., 2005, The Cretaceous-Paleogene boundary succession at Stevns Klint, Denmark: Foraminifers and stable isotope stratigraphy. *Palaeogeography, Palaeoclimatology, Palaeoecology*, vol. 224, pp. 6–26.
- Heinberg, C. and Håkansson, E., 2000, Selektiv K-T uddøen af organismer med lav-Mg calcit skelet i det Danske Bassin. Nordisk Geologisk Vintermøde, Trondheim, Jan. 2000.
- Henkel, H. and Pesonen, L.J., 1992, Impact craters and craterform structures in Fennoscandia: *Tectonophysics*, vol. 216, pp. 31–40.
- Henkel, H. and Aaro, S., 2005, Geophysical investigation of the Siljan impact structure: A review, *in* Koeberl, C. and Henkel, H., eds, *Impact tectonics*, Springer Verlag, Berlin, pp. 247–283.
- Henkel, H., Puura, V., Flodén, T., Kirs, J., Konsa, M., Preeden, U., Liljequist, R. and Fernlund, J., 2005, Åvike Bay – a 10 km diameter possible impact structure at the Bothnian Sea coast of central Sweden., *in*: Koeberl, C. and Henkel, H., eds, *Impact tectonics*. Springer Verlag, Berlin, pp. 323–340.
- Håkansson, E. and Thomsen, E., 1999, Benthic extinction and recovery patterns at the K/T boundary in shallow water carbonates, Denmark: *Palaeogeography, Palaeoclimatology, Palaeoecology*, vol. 154, pp. 67–85.
- Kaljuvee, J., 1933, *Die Grossprobleme der Geologie*. F. Wassermann, Tallinn (Reval), 162 pp.
- Kenkmann, T. and von Dalwigk I., 2000, Radial transgression ridges: A new structural feature of complex impact craters: *Meteoritics & Planetary Science*, vol. 35, pp. 1189–1201.
- Liiva, A., Aaloe, A., Kessel, H., and Rinne, T., 1979, The age of the Ilumetsa craters (in Estonian): *Eesti Loodus*, vol. 12, 762–764.
- Lindström, M., Flodén, T., Grahn, Y., and Kathol, B., 1994, Post-impact deposits in Tvären, a marine Middle Ordovician crater south of Stockholm, Sweden: *Geological Magazine* vol. 131, pp. 91–103.
- Masaitis, V.L., Danilin, A.N., Mashchak, M.S., Raikhlin, A.I., Selivanovskaya, T.V., and Shadenkov, Ye.M., 1980, *Geologiya astroblem* (in Russian): Nedra, Leningrad, 231 pp.
- Motuza, G.B. and Gailius, R.P., 1978, On the supposed astroblemes in Lithuania (in Russian): *Local Structures of the Byelorussia and Baltic Republics*: Mokslas Press, Vilnius, Lithuania, pp. 91–94.
- Naterstad, J. and Dons, J.A., 1992, The Gardnos impact structure, Norway: *Meteoritics*, vol. 27, pp. 215.
- Pesonen, L.J., 1996, Impact cratering record of Fennoscandia: *Earth, Moon and Planets*, vol. 72, pp. 377–393.
- Pesonen L.J., Marcos, N., and Pipping, F., 1992, Paleomagnetism of the Lappajärvi impact structure, western Finland: *Tectonophysics* 216 (1/2), p. 123–142.
- Pesonen, L.J., Lehtinen, M., Deutsch, A., Elo, S. and Lukkarinen, H., 1996, New geophysical and petrographic results of the Suvasvesi N impact structure, Finland, 27: *Lunar & Planetary Science Conf.*, Houston, p. 1021–1022.
- Pesonen, L.J., Kuivasaari, T., Lehtinen, M., and Elo, S., 1999, Paasselkä – A new meteorite impact structure in eastern Finland, 62. Meteoritical Society Meeting, Johannesburg.
- Pesonen, L.J., Elo, S., Lehtinen, M., Jokinen, T., Puranen, R., and Kivekäs, L., 2000, The Lake Karikkoselkä impact structure, central Finland – New geophysical and petrographic results, *in* Dressler B.O. and Sharpton V.L., *Large Meteorite and Planetary Evolution: Geological Society of America, Special Paper* 339, p. 131–139.
- Puura, V. and Plado J., 2005, Settings of meteorite impact structures in the Svecofennian Crustal Domain, *in* Koeberl, C. and Henkel, H., eds, *Impact Tectonics*: Springer-Verlag, Berlin Heidelberg New York, pp. 211–245.
- Puura, V. and Suuroja, K., 1992, Ordovician impact crater at Kärda, Hiiumaa Island, Estonia: *Tectonophysics* 216, pp. 143–156.
- Puura, V., Lindström, M., Flodén, T., Pipping, F., Motuza, G., Lehtinen, M., Suuroja, K., and Murnicks A., 1994, Structure and stratigraphy of meteorite craters in Fennoscandia and the Baltic region: A first outlook. *Proceedings of the Estonian Academy of Sciences: Geology*, vol. 43, pp. 93–108.
- Rasmussen J.A., Heinberg C. and Håkansson E., 2005, Planctic foraminiferid biostratigraphy of the lowermost Danian strata at Stevns Klint, Denmark: *Bulletin of the Geological Society of Denmark*, vol. 52, pp. 113–132.
- Rauch J.E., 1794, Nachricht von der alten lettischen Burg Pilliskaln, und von mehreren ehemaligen festen Plätzen der Letten und Ehsten; auch von etlichen andern life - und ehstländischen Merkwürdigkeiten: *Neue Nordische Miscellaneen*, vols. 9 and 10, pp. 540–541.
- Raukas A., Tiirmaa R., Kaup E. and Kimmel K., 2001, The age of the Ilumetsa meteorite craters in southeast Estonia: *Meteoritics & Planetary Science*, vol. 36, 1507–1514.
- Reinwald I. A., 1938, The finding of meteoritic iron in Estonian craters. A long search richly rewarded: *The Sky Magazine of Cosmic News*, vol. 2, pp. 6–7.
- Reimold W. U., Kelley S. P., Sherlock, S. C., Henkel H., and Koeberl C., 2005, Laser argon dating of melt breccias from the Siljan impact structure, Sweden: Implications for a possible relationship to Late Devonian extinction events: *Meteoritics & Planetary Science*, vol. 40, 591–607.
- Rosenkrantz, A., 1966, Die Senon/Danien-Grenze in Dänemark. *Berichte der Deutschen Gesellschaft für Geologische Wissenschaften, Reihe A: Geologie und Paläontologie*, vol. 11, pp. 721–727.
- Sandbakken, P.T., Langenhorst, F., and Dypvik, H., 2005, Shock metamorphism of quartz at the submarine Mjølner impact crater, Barents Sea: *Meteoritics and Planetary Science*, 40, 136–1375.
- Schmitz, B., Andersson, P., and Dahl, J., 1988, Iridium, sulfur isotopes and rare earth elements in the Cretaceous-Tertiary boundary clay at Stevns Klint, Denmark: *Geochimica et Cosmochimica Acta*, vol. 52, pp. 229–236.
- Schmitz, B., Tassinari, M., and Peucker-Ehrenbrink, B., 2001, A rain of ordinary chondritic meteorites in the early Ordovician: *Earth and Planetary Science Letters*, vol. 194, pp. 1–15.
- Schmitz, B., Häggström, T., and Tassinari, M., 2003, Sediment-dispersed extraterrestrial chromite traces a major asteroid disruption event: *Science*, vol. 300, pp. 961–964.
- Sturkell, E. F. F., 1998, The marine Lockne impact structure, Jämtland, Sweden: a review: *Geologische Rundschau*, vol. 87, pp. 253–267.
- Surlyk, F. and Håkansson, E., 1999, Maastrichtian and Danian strata in the southeastern part of the Danish Basin. 19th Regional European Meeting of Sedimentology, Copenhagen August 1999: *Excursion Guide*, pp. 29–58.
- Surlyk, F., Damholt, T., and Bjergager M., 2006, Stevns Klint, Denmark: Uppermost Maastrichtian chalk, Cretaceous–Tertiary boundary, and lower Danian bryozoan mound complex: *Bulletin of the Geological Society of Denmark*, vol 54, 1–48.
- Suuroja, K. and Saadre, T., 1995, Gneiss-breccia erratic boulders from northwestern Estonia as witnesses of an unknown impact structure (in Estonian): *Bulletin of Geological Survey of Estonia*, vol. 5/1, pp. 26–28.
- Wickman, F.E., 1988, Possible impact structures in Sweden, *in* Bodén, A. and Eriksson, K.G., eds, *Deep Drilling in crystalline bedrock, volume 1: The deep gas drilling in the Siljan impact structure, Sweden and astroblemes*: Springer Verlag, Berlin, pp. 298–327.
- Zappalà, V., Cellino, A., Gladman B.J., Manley, S., and Miglierini, F., 1998, Asteroid showers on Earth after family break-up events: *Icarus*, vol. 134, pp. 176–179.

Henning Dypvik is professor of geology at the Department of geosciences, University of Oslo. He has been involved in sedimentological and sedimentpetrographical studies of several sedimentary formations from the Arctic, offshore Norway and Tanzania. The last 15 years he has been engaged in planetary geology and impact studies, with particular emphasis on marine cratering and post impact processes. Henning is the coordinator of the Nordic-Baltic NIR (Network on Impact research) program.

Lauri J. Pesonen is professor of geophysics at the Division of Geophysics, Department of Physical Sciences of the University of Helsinki. He has been involved in studies of Precambrian plate movements and supercontinents using paleomagnetic and rock magnetic techniques. The last 20 years he has been engaged in planetary geophysics including research on meteorites, asteroids and impact craters, with a particular emphasis on geophysical aspects of impact cratering. Lauri is a member of the coordinator committee of the Nordic-Baltic NIR (Network on Impact research) program.

Jüri Plado is senior scientist at the Department of Geology, University of Tartu, Estonia. He does research on the geophysical and petrophysical signatures of meteorite impact structures. Currently his main investigation concerns (i) formation and development of small-to-medium size complex impact structures and (ii) geodynamic events on the Fennoscandian Shield in the light of the origin and ages of the magnetic remanence components.

Birger Schmitz is professor of geology at the Department of Geology, University of Lund, Sweden. His research has dealt with climatic and biotic events during the Phanerozoic with focus on the Cretaceous-Tertiary and Paleocene-Eocene boundaries. During the last fifteen years he has become increasingly interested in the possible relation between events in the solar system and on Earth.

Claus Heinberg is geologist-paleontologist and associate professor in environmental science at Roskilde University Center. He is pt. guest scientist at the Department of Geography and Geology, University of Copenhagen. His main subjects of research are: Bivalves from the Cretaceous-Tertiary boundary section, bivalves from the upper Cretaceous white chalk of the Danish Basin and the Anglo-Parish basin.

Selen Raiskila is a PhD-student at the Division of Geophysics, University of Helsinki. She is currently studying Keurusselkä impact structure in central Finland. Her research interests include also paleomagnetic studies of Keuruu dikes and supercontinents.

Eckart Håkansson is professor of geology at the Department of Geography and Geology, University of Copenhagen. He has many years of involvement in the study of the dynamic history of the Arctic as well as the study of evolution and biogeography of cheilostome bryozoans on a global scale. Eckart is president-elect of the International Bryozoology Association.