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STRUCTURE AND STRATIGRAPHY OF METEORITE CRATERS IN FENNOSCANDIA AND THE BALTIC REGION: A FIRST OUTLOOK

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Abstract. A review of 25 most completely studied impact craters in the Fennoscandian—Baltic region, ranging from Neoproterozoic to Holocene in age and from less than 100 m to more than 50 km in diameter, is presented. The craters are located in the crystalline as well as in the sedimentary area of the old East European Craton. The same principal structural zones and impact stratigraphic units can be identified in all the craters. The craters differ in preservation owing to the erosion of structural zones and stratigraphic units. They are usually more complete in sedimentary areas. Post-impact tectonic movements have deformed some of the craters. Some of the impact structures have yielded unique information on the regional geological development.

Key words: meteorite craters, structure, stratigraphy, Fennoscandia, Baltic region.

1. INTRODUCTION

In 1990, a group of European earth scientists dealing with meteorites and cratering initiated a joint study of terrestrial cratering. The European Science Foundation supported the joint research programme and established a Scientific Network devoted to integrated and interdisciplinary research on "The Role of Impact Processes in the Geological and Biological Evolution of Planet Earth" (Stöffler & Deutsch, 1993; Montanari & Smit, 1993). This short paper is a contribution to the Network activities.

Crater studies in Scandinavia and in the Baltic countries have noteworthy traditions. Already in 1937 the origin of the Kaalijärv crater on Saaremaa Island, Estonia, was scientifically determined on the basis of iron meteorite findings (Reinwaldt, 1938). It remained the only truely recognized meteorite crater in Europe for more than two decades. Numerous new findings in Europe followed when the criteria of high pressure impact metamorphism were introduced.

Table 1

STRATIGRAPHIC UNITS AND IMPACT EVIDENCES IN CRATER STRUCTURES
(Ref.:3,6,14,15,17,18,19,24,27,29,30,31,35,36,45,46,47,58,66)

For full names of craters see Fig.1. D=rim-to-rim diameter,(D=)=diameter possible. Environments of cratering and present position: area of sedimentary (**s**) or crystalline (**c**) rocks, and of dry (**d**) (mainland) or underwater (**w**) (marine or lake) conditions. Indicative criteria: S=impact melt, B=breccia, SB=suevitic breccia, BD=breccia dykes, P=shock metamorphic features, F=fragments or geochemical signatures of meteorite material, C=crater fill sediments, G=geophysical criteria. Simple craters are denoted by - for structural zone Ia, indicating the absence of a central uplift.

ESTONIA

No & name, size, age, environm.	Impact strati-graphy: tab. 2	Structural zones						Indicative criteria
		I		II	III			
		IA	IB		IIIA	IIIB	IIIC	
E-1 KAALI	3-2		+					C
D=0.11 km	3-1		+					
0.00395 Ma	2		+		+	+	+	B, F(meteor)
Holocene	1	-	+	+				B, G
s-d-- s-d	Ref.:	(1, 41, 42, 43, 53, 54, 62)						
E-2 KÄRDLA	3-2	+	+	+	+	+	+	C
D=4 km	3-1	+	+	+	+	+	+	C
455 Ma	2	+	+	+	+	+		B, SB
M.Ordovic.	1	+	+	+	+			B, BD, P, G
s-w-- s-d	Ref.:	(27, 39, 64, 65)						
E-3 ILUM.	3-2		+					C
D=0.08 km)	3-1		+					C
0.006 Ma	2		+					B
Holocene.	1	-	+	+				B
s-d-- s-d	Ref.:	(2, 63)						
E-4 TSÔÔR.	3-2		+					C
D=0.04 km	3-1		+					C
0.0095 Ma	2		+					B
Holocene	1	-	+	+				B
s-d-- s-d	Ref.:	(68)						

FINLAND

No & name, size, age, environm.	Impact strati-graphy: tab. 2	IA	IB	II	IIIA	IIIB	IIIC	Indicative criteria
F-1 LAKE LAPPAJÄRVI	3-2							
	3-1							
D=22.5 km	2	+	+					S, P, B, F(Ir)
77 Ma=L.C.	1	+	+	+	depression			P, B, G
c-d-- c-d	Ref.:	(17, 21, 22, 37, 38, 51, 57)						
F-2Lumparn	3-2		+					C
(D=12 km)	3-1							
E.-M.Ordo-	2							
vician	1		+					B, P
c-d-- c-w	Ref.:	(56, 61, Svensson, pers.comm.1993)						
F-3 ISO NAAKKIMA	3-2		+					C
	3-1							
(D= 3 km)	2							B, P
L.Neoprot.	1		+					B, BD, P, G
c-d-- c-d	Ref.:	(9)						
F-4 SÄÄKSJ.	3-2							C
(d>5 km)	3-1							C
560 Ma	2		+					B, SB, P, F(Pt)
E.Cambrian	1		+	+				B, P, BD, G
c-d-- c-d	Ref.:	(8, 32)						
F-5SÖDERFJ.	3-2		+					C
D=6 km	3-1		+?					
~600 Ma	2		+					B
L.Neoprot.	1	+	+	+				B, BD, P
c-d-- c-d	Ref.:	(17, 20, 23, 55)						

LITHUANIA

Table 1 (continued)

L-1 MIZARAI	3-2		+			C
(D=5 km)	3-1		+		+	
L.Neoprot.-	2	+	+			B, S, P
E.Cambrian	1	+	+			B, P, G
c-d-- s-d	Ref.:	(66, 67)				
L-2 VEPRIAI	3-2		+		+? + +	C
(D=7.5 km)	3-1		+			C
455 Ma	2		+	+	+	B, P
M.Ordovic.	1	+—	+	+	uplift	B, P, G
s-w/d--s-d	Ref.:	(66, 67)				

LATVIA

La-1 DOBELE	3-2		+			
(d=3-4 km)	3-1					
post-Trias-	2		+			B
sic	1		+			B,G
s-d--s-d		(Murnieks - unpublished data)				

NORWAY

N-1GARDNOS	3-2		+			C
(D= 5 km)	3-1		+			C
L.Neoprot.	2	+	+	+		B, S, SB, P
	1	+	+	+	+	B
c-w-- c-d	Ref.:	(4, 33, 34)				
N-2 SMÖLA						
(d= 30 km)		(19: unpublished data)				

RUSSIA

R-1 JÄNISJ	3-2					
(D=14 km)	3-1					
698+/-22Ma	2	+	+			B, S, SB, P
M.Neoprot.	1	+	+	+		B, P, G
c-d-- c-d	Ref.:	(32, 40, 66)				
R-2MISHI-NOGORSKAYA	3-2					
	3-1					
(D=4-5 km)	2		+			B, P
L.PZ-CZ	1		+		+ moat	B, P, G
s-d-- s-d	Ref.:	(66, 69)				

SWEDEN

S-1 Åvike	3-2					
D=9 km	3-1					
Phaneroz.?	2		+			P, B
s-d--c-d/w	1	+	+	+		P, B, BD, G
	Ref.:	(17, 18)				
S-2 Björkö	3-2		+			C
D=9 km	3-1					
1210 Ma	2		+			B, S(?)
M.Neoprot.	1	+	+	+		B, G
c-d-- c-d	Ref.:	(13, 17, 18)				
S-3 Dellen	3-2					
(D=19 km)	3-1					
89 Ma	2	(erratic evid.)				S, B, SB, P
L.Cretac.	1		+	+	brecciation	B, P, G
c-d-- c-d	Ref.:	(6, 7, 10, 17, 18, 32, 50, 58)				
S-4 Granby	3-2		+		+	C
D=3 km	3-1		+			C
470 Ma	2		+			B
E.Ordovic.	1	–	+	+		B
s-w-- c-d	Ref.:	(18, 58, 59, 60)				

Table 1 (end)

S-5Hummeln	3-2		+					C
D=1.2 km	3-1							
L.Neoprot.-	2							
E.Cambrian	1	–	+	+				B, G
c-d-- c-d	Ref.:	(18, 49, 64)						
S-6 Lockne	3-2		+		+?	+	+	C
(D=7.5 km)	3-1		+		+?	+	+	C
455 Ma	2		+	+		+		S, B, P
M.Ordovic.	1		+	+				B, P, G
s-w-- c-d	Ref.:	(25, 26, 27, 58)						
S-7 Mien	3-2							
(D=7 km)	3-1							
118 Ma	2	+	+					S, B, P, F(Ir)
E.Cretac.	1	+	+					B, P, G
c-d-- c-d	Ref.:	(16, 17, 18, 52, 58)						
S-8 Siljan	3-2							
(D=52 km)	3-1							
368 Ma	2	+	+					B, P
L.Devonian	1	+	+	+	brecciation			B, P, G
s-d-- c-d	Ref.:	(3, 5, 14, 17, 18, 47, 58)						
S-9 Tvären	3-2		+					C
(D=2 km)	3-1		+					C
455 Ma	2		+					B, P
M.Ordovic	1	-	+	+	brecciation			B, P, G
s-w--c-w/d	(Ref.:	(11, 12, 27, 28, 58)						

In Fennoscandia a large number of crater-shaped structures were investigated by Svensson, Wickman, Lehtinen, Lehtovaara, Henkel, Lindström, and others, and the craters like Siljan, Dellen, Lappajärvi, Söderfjärden, Tvären, Mien, etc. were determined as impact structures (see references in Table 1). Using the complex identification criteria worked out for terrestrial craters, a comprehensive list of 62 crater-shaped structures of identified or suspect impact origin was compiled for Fennoscandia and Estonia (Henkel & Pesonen, 1992). We have included 21 of the craters listed by Henkel and Pesonen (1992, Table 1) for our geological analysis. These 21 craters are the most informative from the geological point of view, and we have added four more craters from the Baltic territory and Russia (Fig. 1 and Table 1). The information provided by Henkel and Pesonen includes geographical position, morphological character, indicative criteria (shock-metamorphic features, impact-generated rocks, topographic features, geophysical features), size, age, and classification (proved, probable, possible, and suspected craters).

The analysis of meteorite craters has developed mainly from studies of well-preserved young craters which are apparent on the surface of the Earth or other planets. Eroded but well-exposed craters have been carefully documented, too. However, descriptions of fossil craters buried beneath covering sediments are rare. Geological and geophysical data from craters in the Fennoscandian—Baltic region have provided material for studying such buried, poorly exposed impact structures. A specific feature of the craters in the Nordic countries is that they underwent a severe process of Pleistocene glaciation, that left imprints of glaciostatic pressure (compaction) as well as glacial erosion.

2. THE STRUCTURAL PROFILE OF CRATERS

Our paper deals with both recent and old, fossil craters. However, only one location of a recent crater which is neither buried nor destroyed through erosion is known in the region. That is the Kaali crater with eight small satellite craters on Saaremaa Island, West Estonia.

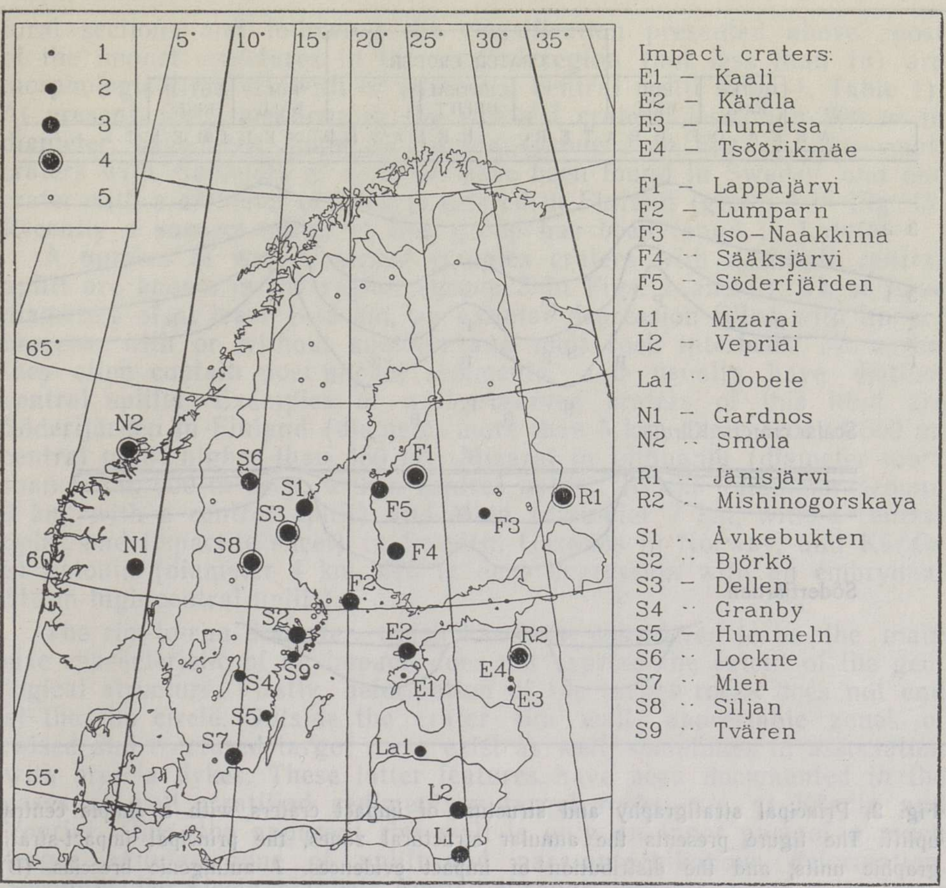

Fig. 1. Location of the 25 geologically most informative of the Fennoscandian—Baltic craters. Numbers and names refer to Table 1. The craters in the map are classified in 5 groups: *1* very small postglacial craters (E1, E3, E4); *2* simple craters larger than 1 km (F3, La1, S4, S5, S9); *3* complex craters with a distinguished or supposed simple central uplift (E2, F2, F4, F5, L1, L2, N1, S1, S2, S6, S7); *4* proved and probable complex crater structures with multiring features (F1, N2, R1, R2, S3, S8); *5* additional unnumbered craters and craterform structures adapted from Henkel and Pesonen, 1992.

The 3 950-year-old Kaali craters are in their early stage of filling and thus well observable in the landscape.

All the known craters of at least 1 km in diameter in the region are pre-Quaternary in age and belong to the group of fossil craters which are buried, deeply eroded, or re-exposed after subsequent burial and erosion. They may or may not contain piles of impact and post-impact rocks.

Traditionally, impact craters are divided into two main groups, namely simple and complex craters. The division is based on essential genetic as well as morphologic criteria. For the geological purposes of this paper we distinguish four different groups of craters on the basis of their size (Fig. 1).

Simple structures (groups 1 and 2 in Fig. 1) resemble proper craters, whereas those of the complex group have a more complicated build-up (groups 3 and 4 in Fig. 1). The apparent annular depressions are partly

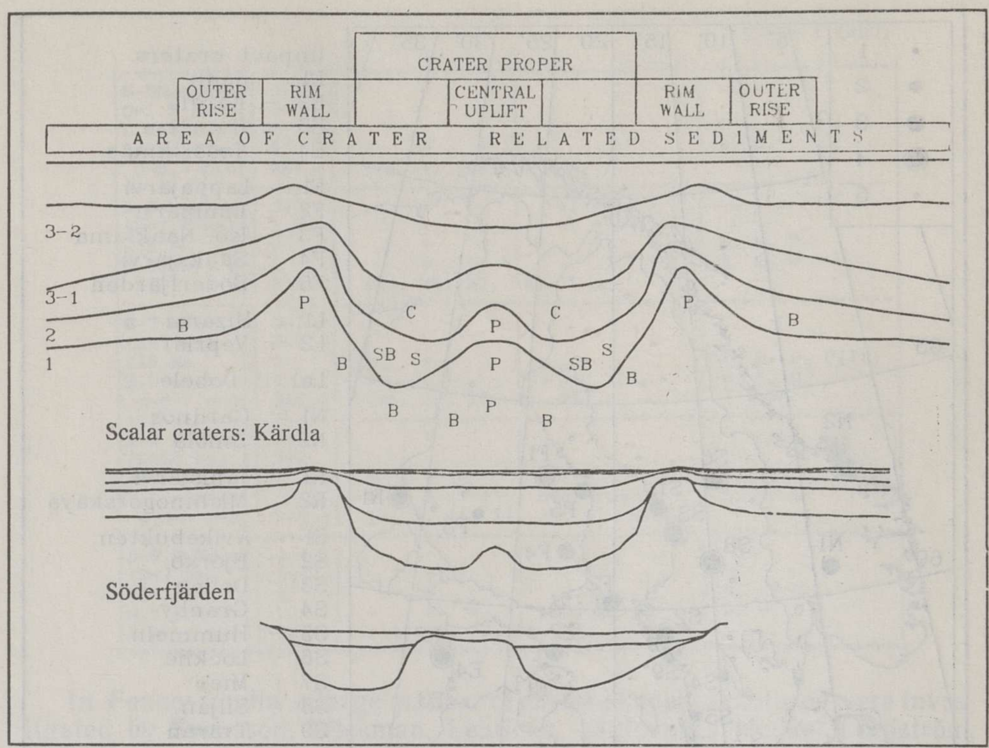

Fig. 2. Principal stratigraphy and structure of impact craters with a simple central uplift. The figure presents the annular structural zones, the principal impact-stratigraphic units, and the distribution of impact evidences. *1* authigenic breccias (B) with evidences of shock metamorphism (P), including shatter cones; *2* allogenic breccias (B) with suevites (SB) and melt rocks (S) and with evidences of shock metamorphism in places (P), inc. shatter cones; *3* crater fill (C) and overlapping sediments: *3—1* strongly crater-dependent sediments, and *3—2* weakly crater-dependent sediments.

or completely filled with stratified sedimentary and impact breccia (including interbeds of suevite and melt rocks, if present) around and above a central uplift (groups 1—3 in Fig. 1; Fig. 2). The largest complex structures (group 4 in Fig. 1) even have no geomorphologic crater. Their distinctive feature is a collapsed central uplift, which usually is a flat raised crater floor built up of a mixture of partly and fully melted rocks. The central uplift is often surrounded by a deformed rim wall or a number of rims in the peripheral part of the impact, and a down-faulted ring structure well on the inside periphery.

Whereas the rim-to-rim diameter is quite a characteristic parameter for simple craters and also for craters with a simple central uplift, the determination criteria for the outer boundary of multiring complex craters with collapsed central uplift are much less distinct and highly dependent on the level of erosion. For example, the largest identified impact in the region, the Siljan structure with a present diameter of 32 km, is estimated to have had an original diameter of approximately 52 km (Grieve, 1988). However, it is quite small in comparison with the largest impacts in the world, e.g. the recently discovered Chicxulub ocean bottom multiring impact basin in the Gulf of Mexico with a diameter of almost 300 km, probably coeval to the worldwide K/T boundary ejecta layer (Sharpton et al., 1994). Considering their structural sections and following the classification presented above, most of the impact structures in the studied region (not less than 15) are morphological craters with or without a central uplift (Fig. 1, Table 1). At present, three locations of the smallest craters, less than 200 m in diameter, have been found in Estonia (group 1 in Fig. 1), four small craters with diameters of 1—3 km have been found in Sweden, and one crater with a diameter of 3 km is located in Finland (group 2 in Fig. 1). Recently a suspect crater of this group has been found in Latvia.

A number of well-preserved complex craters with a simple central uplift are known in the region (group 3 in Figs. 1 and 2). These have diameters of at least 4—5 km, an annular depression filled with impact breccias with or without suevites and melt rock interbeds. Moreover, they often contain post-impact sediments, and usually have distinct central uplifts. Examples of well-preserved craters of this kind are Söderfjärden in Finland (diameter more than 5 km, depth around 500 m, central uplift higher than 450 m), Mizarai in Lithuania (diameter more than 5 km, 300 m deep, with a central uplift), Björkö (diameter around 9 km, with a central uplift) and Mien (diameter 7 km, with a central uplift and impactite sheet) in Sweden, Gardnos in Norway, and Kärdla in Estonia (diameter 4 km, 420 m deep depression with an embryonal 110 m high central uplift).

The rim-to-rim diameter, which has been considered to be the main size characteristic of an impact, does not express the extent of the geological structure. Firstly, deformation of the target rocks does not end at the rim circle. Outside the crater rim wall, appreciable zones of raised and fractured target rocks exist as well, sometimes in association with breccia dykes. These latter features have been documented in the cases of well stratified sedimentary target rocks, e.g. at Kärdla and Vepriai. Thus, the apparent rim wall is only an inner part of a much larger annular zone of uplift and para-autochthonous deformation. Secondly, the ejecta blankets formed through impacts cover quite large areas around the craters. Table 1 presents available data on outside-rim phenomena.

The Siljan ring structure clearly belongs to the largest of the complex impacts in the region (group 4 in Fig. 1). However, also Lappajärvi, Dellen, Jänisjärvi, and even the Mishinogorskaya structure should be studied as suspects of the most complex cratering phenomena as they have no real near-centre sediment-filled depressions. Instead, a complicated mixture of deformed, and in some places melted, rocks occurs in these structures. Pipping has recognized that outside the outer rim heights of the Lappajärvi crater another depressional zone occurs, which again has a chain of wall-shaped heights on its outside. Outside the Dellen ring of heights extensive brecciation of the crystalline target rocks has been reported (Henkel, 1992a). Around the Mishinogorskaya dislocation area, which has been reported (Масайтис et al., 1980) as a crater structure with a diameter of about 4—5 km or even larger, there appears a down-faulted ring structure with a diameter of about 9 km (Шмаенок & Тихомиров, 1974) and the possible outer diameter of the disturbance is around 12 km. The Mishinogorskaya structure may therefore well constitute a smaller version of the Siljan ring. On the shores of Lake Jänisjärvi, outside the accepted crater periphery, tilted shatter cones occur. The Smöla crater is another candidate for this group. However, very little is known about this crater at present.

It is evident that criteria discriminative between comparatively simple and maximally complicated complex craters are not yet firmly established, especially concerning the critical diameter (which is of about 10 km or more) of the structures.

3. PRINCIPAL IMPACT AND POST-IMPACT STRATIGRAPHIES

Studies of meteorite craters in different parts of the world, especially those in the Scandinavian—Baltic region, show that the principal stratigraphy of an impact crater depends on the composition of the target and on the environment during impact and during post-impact time. Thus, marine or continental environments and the rate of sedimentation or erosion as well as post-impact tectonic destruction must be considered. However, despite differences in the conditions of impact and subsequent evolution, the stratigraphical successions are, on the whole, principally similar enough to use a uniform concept of description and classification (Fig. 2, Table 2).

Complete successions of impact and post-impact rocks have been discovered and described from the Kärdla, Tvären, and Lockne craters (Lindström et al., 1992), the Granby crater (Wickman et al., 1980, 1982), and the Mizarai and Vepriai craters (Мотуза & Гайлюс, 1978) within the Scandinavian—Baltic region. The lowermost levels of the crater stratigraphy have been documented from the well-exposed Gardnos crater (Naterstad & Dons, 1993) and from deep drilling data in the cases of the Siljan Ring Structure (Bodén & Eriksson, 1988), and the Lappajärvi crater (Pipping & Lehtinen, 1992). Geophysical measurements, among them gravity, magnetic, wide-band EM and VLF, have contributed to the construction of three-dimensional deep-penetrating images of the crater structures (Grieve & Pesonen, 1992; Henkel & Pesonen, 1992), giving a kind of fundamental background to structural and stratigraphic constraints otherwise based on surface observations and drilling data.

Table 2

LATERAL CORRELATION OF IMPACT STRATIGRAPHIES

-- AREA OF CRATER-RELATED SEDIMENTS --						
	CRATER PROPER		RIM WALL	OUTER RISE	SURROUNDINGS	distant sediments
	CENTRAL UPLIFT					
No	IA	IB	II	IIIA	IIIB	IIIC
UNIT 3: FILLING AND COVERING SEDIMENTS						
Subunit 3-2: Late overlapping sediments, weakly influenced by a crater						
SUBUNIT 3-1: Early overlapping sediments, strongly influenced by crater structure and source material in marine or lake environments						
	thick (fjord-type) succession reduced		reduced or lacking at an early stage		facial changes due to debris inflow and seabottom rise, thinning out	specific distant sediments
UNIT 2: IMPACT-RELATED ALLOGENIC BRECCIAS AND MELTED ROCKS						
	fall-back & resurge allogenic breccias, suevitic breccias & melted rocks		fall-out allogenic breccias thinning out in distal direction			
UNIT 1: IMPACT-RELATED AUTHIGENIC BRECCIAS						
	authigenic breccias max.shock metamorph.		megabreccias		brecciated & fractured target, brecciation distally decreasing	
	breccia dykes					

The most complete stratigraphic sequences are formed by impacts in shelf sea environments. Three major impact stratigraphic units may be distinguished here (Fig. 2 and Table 2):

(1) Fractured, deformed, crushed, and brecciated, impact metamorphosed, and partly melted authigenic and para-authigenic target rocks of any possible pre-impact age, in case of a homogeneous target including "monomict" (Stöffler, 1993) breccias. They are located at the floor and at the rim of the crater, and in near and far surroundings of the crater wall. The occurrence of original near-surface target rocks in the outer megabreccia zone of large structures is extremely important for the crater and paleogeological studies. Examples are the subsided remnants of the pre-impact sedimentary piles in the Siljan Ring and the Lappajärvi structure. As sources of information these megabreccias can be regarded as equal to the clasts of near-surface crystalline and sedimentary rocks in the allochthonous breccias of simple craters, and also of complex craters with a simple central uplift.

(2) Allogenic impact breccias of slump, fall-back, and fall-out origin forming a breccia sheet within the crater, on the walls and in the surroundings. During strong enough impacts, partly or fully melted target rocks occurred forming interbeds in the breccias. Outside the crater the "ejecta blanket" thins with increasing distance to the crater. As one result of impacts in the marine environment resurge breccias and turbiditic coarse to fine-grained sediments form, as e.g. in the Kärdla and Tvären craters. The "allogenic breccias" principally belong to this unit, although allogenic mixtures may form also at the para-autochthonous level.

Theoretically, unit 2 may also include a distant layer of sediments enriched in air-transported impact-related particles or chemical compounds, including extraterrestrial material as in the case of the Cretaceous/Tertiary boundary worldwide event. For example, an area enriched with iron spherules in soils has been discovered and documented around and northeast from the Kaali crater (Symanovich et al., 1993).

(3) Crater fill and overlapping sediments, which can be divided into two subunits:

(3—1): sediments of the early post-impact deposition under the influence of the complex topography and debris inflow from crater heights. The crater depression acts as a sediment trap, surrounded by ring heights, which may function as shoals in the marine environment. These depth-controlled environments cause quite remarkable facies changes, as e.g. at Kärdla, Lockne, and Lumparn. In the basal layers of this subunit, redeposited debris from the "ejecta blanket" and from the crater walls may occur in the central depression as well as outside the crater. Distant crater-related sediments may occasionally occur far away from the impact location, depending on the water current patterns.

(3—2): sediments of the subsequent geological history, during which the crater depression and ring heights may continue to be structures weakly influencing the character of sedimentation. In the case of marine transgression taking place after a long period of erosion, crater structures and debris sources may cause some specific sediments in much younger levels than the real age of the impact. Conventionally, these sediments are assigned to subunit 3—2, although they could have some features of the early post-impact sediments of subunit 3—1. The Lumparn and Iso-Naakkima structures serve as examples of marine transgression after a period of erosion.

4. POST-IMPACT HISTORY AND SURVIVAL OF IMPACT STRATIGRAPHIES AND STRUCTURES

During the post-impact geological history, primary impact structures may have been buried in the course of sedimentation, or exposed by erosional processes, and, sometimes, deformed through tectonic movements. Under the influence of migrating thermal fluids crushed crater rocks may have undergone mineralization processes of metasomatic and/or fracture fill type.

Outside the Caledonian allochthons, the main depositional and erosional processes favoured the survival of craters and their structural elements. Cratering at shelf seas was concurrent to sedimentation and the novel structure was successively buried under sediments as e.g. the Tvären crater. The Kärdla impact took place in a shallow shelf sea environment and sedimentation followed in the crater proper and at some distance outside it, whereas the uplifted rim wall area and the "ejecta blanket" became subject to erosion. Only after some 10 Ma the last elevations were buried under the Middle Ordovician sediments. Also Lockne, Björkö, and other Fennoscandian—Baltic craters were similarly formed in shallow shelf areas. A large number of the craters in the Fennoscandian region have obviously been formed on the mainland of exposed crystalline (Mien, Iso-Naakkima, Lumparn, Söderfjärden, Hummeln, Jänisjärvi, etc.) or sedimentary (Siljan, Mizarai, Vepriai, Mishinogorskaya, etc.) rocks. Subsequent erosion has more or less destroyed the allogenic breccia unit and also parts of the deformed impact target rocks. Partly eroded continental structures may have survived up to Pleistocene glaciations through which they were once more eroded and filled with glacial deposits. In other cases partly eroded craters were submerged and became places of sedimentation during the Neoproterozoic or Phanerozoic (Lumparn, Söderfjärden, Sääksjärvi, Iso-Naakkima, Mizarai, etc.). Depending on differences in the post-impact environment, the impact stratigraphic sequence could be completely formed under marine conditions, with well-developed subunits 3—1 and 3—2, whereas under continental conditions at least subunit 3—2 would be poorly developed.

All the impact structures exposed on the surface, in the area subjected to the Fennoscandian Pleistocene glaciation, have been severely eroded, except for those buried deeply enough under the overlapping Phanerozoic deposits (Mizarai, Kärdla). As a result, the surface morphology of the exposed craters has changed (Lappajärvi, Dellen, Jänisjärvi, etc.).

On the whole, the following different evolution trends of the preglacial crater structures can be distinguished:

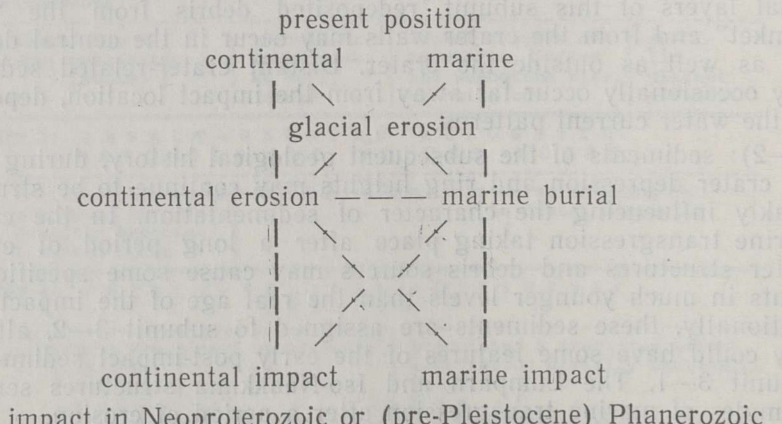

Table 1 characterizes the present stage of erosion of the craters. Only a few craters are of great historical geological interest because of their well-preserved impact stratigraphy. The most informative are those with all or most of the stratigraphic units preserved, inside as well as outside the crater rim wall. This group comprises the Kärdla, Vepriai, Granby, and Lockne craters. Full, or almost full, stratigraphic records are preserved inside the Mizarai, Lumparn, Söderfjärden, Björkö, and Tvären craters.

The Gardnos crater in South Norway represents an extraordinarily good exposure of the lower units of impact stratigraphy—authigenic and allogenic breccias (with melt rocks) and also infill sediments.

A number of craters are represented only by units of allogenic and authigenic breccias, including the largest of them (Siljan, Dellen, Jänisjärvi, Mishinogorskaya), but also medium-sized and small craters Sääksjärvi, Åvikebukten, and Mien.

Two craters in the domain of the Scandinavian Caledonides underwent a weak deformation during the Caledonian orogeny. The Lockne crater is still partly covered with allochthonous tectonic nappes composed of Lower Paleozoic rocks. The Gardnos structure, located in a tectonic window of the pre-Caledonian basement, has undergone low-grade Caledonian metamorphism and deformation. The Dellen structure, formed in the Mesozoic in a stable area of the Fennoscandian Shield, has been deformed by post-impact faulting as reported by Henkel (1992a).

5. CONCLUDING REMARKS

Published reviews on the distribution and structure of craters in the Baltic countries (Кала et al., 1978; Мотуза & Гайлюс, 1978), on the territory of the former Soviet Union (Масайтис et al., 1980), and in Fennoscandia and Estonia (Henkel & Pesonen, 1992) have discussed their location, structure, age, and identification criteria, with a special emphasis on geophysical features of the craters in the paper by Henkel and Pesonen (1992). Our aim was to pay principal attention to the survival of crater structures and stratigraphies. A comparison of the sketch map by Henkel and Pesonen (1992) with our Fig. 1 and Table 1 shows that the majority of craters studied sufficiently enough for our purposes are located in central and southern Fennoscandia and in the Baltic region, which have long traditions of geological investigation. A number of the most completely preserved craters are located in this area. Complete stratigraphies of craters have often survived in or near recent sedimentary areas or in areas where shelf conditions existed in the past. Also those areas which once were covered by Caledonian tectonic nappes yield well-preserved old impact structures, e.g. Lockne and Gardnos.

The principal impact stratigraphy is similar for craters of different ages and also for large as well as small structures. All of these structures contain, unless eroded, the three principal units of authigenic breccias, allogenic breccias, and overlapping sediments. The completeness of the impact stratigraphic sequence depends on the environment at the time of the impact and on post-impact sedimentation and erosion.

The survival of the three stratigraphic units has been very different in the different structural zones of the old craters (Table 1). The most complete sequence, with the inclusion of the uppermost unit 3 has often survived in the proper craters of the small and medium-sized impact structures, whereas large multiring structures usually lack unit 3. In the deeply eroded large structures, the uppermost target rocks have sometimes survived in the subsided outer annular zones. Furthermore, the outer zones of the small and medium-sized craters are often deeply eroded and thus lack the uppermost unit.

It has been acknowledged that rare, and thus very valuable, information on the geological history of the Fennoscandian—Baltic region has been recorded and preserved in crater structures. Thanks to the exposures in the Siljan Ring as well as in other local grabens filled with sedimentary rocks it was long ago accepted that the south and central Swedish areas were once covered by Paleozoic sedimentary rocks. New findings of sedimentary rocks in craters in Finland widen our views, and also indicate that this territory was also once covered by Neoproterozoic—Paleozoic sediments.

Crater sediments represent rich possibilities for detailed paleo-geographic and paleo-ecological studies (Lindström, 1993). As the regularities of the crater build-up in continental and shallow sea environments are gradually understood, new data for the estimation of sedimentary thicknesses and erosional depths in the region become available.

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FENNOSKANDIA JA BALTI REGIOONI METEORIIDIKRAATRITE STRUKTUUR JA STRATIGRAAFIA: ESIALGNE ÜLEVAADE

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On võrreldud regiooni 25-t kõige täielikumalt uuritud kraatrit, mille tekkeaeg ulatub neoproterosoikumist holotseenini. Osa neist on tekkinud kilbi kristalsete kivimite, osa platvormi settekivimite levikualal ning neist mitmete asend on muutunud geoloogilise ajaloo vältel. Kraatrite läbimõõt ulatub vähem kui 100 meetrist enam kui 50 kilomeetrini. Nende struktuur komplitseerub diameetri suurenedes, kuid struktuuriüksused ja impaktstratigraafilised üksused on põhimõtteliselt samalaadsed sõltumata kraatri tekkeajast. Kraatrite erinevused on tingitud eelkõige struktuuri- ja stratigraafiliste üksuste erosiooni sügavusest. Täielikumalt on säilinud platvormialade kraatrid. Osa kraatreid on deformeerunud plahvatusjärgsete tektooniliste liikumiste mõjul. Kraatrites võib sageli leida ainulaadseid tõendusmaterjale ala geoloogilise arenguloo kohta.

ПРЕДВАРИТЕЛЬНЫЙ ОБЗОР СТРУКТУРЫ И СТРАТИГРАФИИ МЕТЕОРИТНЫХ КРАТЕРОВ ФЕННОСКАНДИИ И ПРИБАЛТИКИ

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Рассмотрены 25 метеоритных кратеров Фенноскандии и Прибалтики, возраст которых колеблется от неопротерозоя до голоцена и диаметр — от менее 100 м до более 50 км. Кратеры расположены как на щите, так и на плите в северо-западной части Восточно-Европейской платформы. В строении всех кратеров выделяются однотипные структурные зоны в латеральном профиле и принципиально одинаковые импакт-стратиграфические единицы в вертикальном разрезе. Приведена краткая характеристика тех и других. Больше всего различаются кратеры, образовавшиеся в континентальных и морских условиях. Дополнительное влияние оказали процессы эрозии и седиментации постимпактной истории. Плейстоценовые континентальные ледники глубоко эродировали структуры кратеров, и только погребенные под осадочным чехлом кратеры сохранились полностью. Во многих кратерах собраны данные об истории развития того или другого района.