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The Neugrund meteorite crater on the seafloor of the Gulf of Finland, Estonia

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Abstract The Neugrund marine impact structure is located on the southern coast of the entrance to the Gulf of Finland (59°20' N, 23°31' E), straight eastward of the Osmussaar Island (Odensholm, *Swed.;* Odin's Grave, *Engl.).* The structure is very well preserved and the only one with morphological units, visible and easily accessible for the researchers and skin–divers. The Neugrund is a complex meteorite crater about 20 km in diameter. In the centre of the structure emerges the inner crater with a two–ridged rim wall having approximately 7 km rim–to–rim diameter: an inner ridge of about 6 km and an outer ridge of about 8 km. The presence of a central peak (uplift) of about 5.5 km diameter in the deep part of the crater is not proven. A 4–5 km wide terrace or zone of dislocations surrounds the inner crater. The Neugrund impact structure formed in the Early Cambrian (ca. 535 Ma ago) as the result of impact of an asteroid about 1 km in diameter.

Keywords *Estonia, Gulf of Finland, Osmussaar, Odensholm, meteorite impact, impact structure, complex impact structure, inner crater, outer crater.*

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INTRODUCTION

The Neugrund impact structure (meteorite crater) is located in the southern part of the entrance to the Gulf of Finland (59°20´N, 23°31´E), straight eastward of the Osmussaar Island (Fig. 1). Rather, Osmussaar is situated at the outer boundary of the impact structure. During WWII a large granite erratic boulder known as Odenstain (Odin's Stone), according to a legend marking the grave of Odin, was demolished in course of establishing fortifications.

The Neugrund impact structure is probably one of the best–preserved marine impact structures in the World Ocean and the only one those most morphological units are visible and easily accessible. Most of the 176 recognized hypervelocity meteorite impact sites around the Earth are located on land and only ten (Bedout, Eltanin, Ewing, Lumparn, Mjölnir, Montagnais, Neugrund, Shiva, Silverpit, Tvären) completely and five (Charlevoix, Chesapeak Bay, Chicxulub, Kara, Kärdla) partially on a sea floor (Table 1).

The geological section of the target is well documented by the data obtained mainly from the nearest to the impact centre drill hole on the Osmussaar Island. The borehole is located at the outer boundary of the structure (10 km west of the centre) and penetrates a thick section of the pre–impact target rocks. In the core sections of the five wells drilled on the mainland 10–25 km southward of the impact centre (F-331, F-331A, F-332, F-334, F-335) the action of the meteorite impact related disturbances were followed (Fig. 2).

The Neugrund impact took place in a shallow sea, where at that time fine– and medium–grained quartz sand with interlayer of silt and clayey silt were deposited (Suuroja *et al.* 1997). The water depth at the impact site is estimated to about 50–100 m (Suuroja, Suuroja 2000) or even more than 100 m (Suuroja, Suuroja 2004). By numerical modelling of the impacts in shallow sea (Shuvalov 2002) the depth of water in such cases should have been 100 m or more.

At the moment of the impact about 150 m of unconsolidated or weakly lithified siliciclastic deposits covered the Precambrian metamorphic rocks. Presently the compacted ca. 100 m thick pre–impact succession is composed by Fortunian (Lower Cambrian) sandstones, siltstones and clays of the Lontova Fm. (ca. 40 m) on the top of a complex of Neoproterozoic Ediacaran weakly lithified quartzose sandstones (about 60 m) (Suuroja, Suuroja 2000). In the Palaeoproterozoic (Orosirian) Svecofennian basement strongly folded migmatite granites, gneisses and amphibolites dominate. The basement is covered by a 5–10 m thick illite–rich weathered crust (Põldvere, Suuroja 2002).

The stratigraphical extent of the covering sedimentary rocks of the impact crater, which is preserved from post–Devonian erosion, reaches the Late Ordovician limestone's of Keila Regional Stage.

METHODS AND MATERIALS

The impact (meteorite) origin of the circular Neugrund structure was predicted by a hypothesis raised by K. Suuroja and T. Saadre (1995). They paid an attention to the gneiss–breccias erratic boulders encountered in the north–western coastal area of Estonia and on the Osmussaar Island (Figs 3, 4, 5). These rocks (gneiss–breccias) (Öpik 1927) were macroscopically very similar to impact breccias from the Kärdla crater. The authors supposed that a glacier move these erratic boulders from a submarine impact structure hidden under the circular Neugrund Bank.

A. Öpik (1927) first described gigantic erratic boulders consisting of breccias–like crystalline rocks (gneiss–breccias) on the Osmussaar Island. N. Thamm (1933) studied more detail the mineral composition of these gneiss–breccias boulders in Spithamn (Põõsaspea) and Toomanina capes. K. Orviku (1935) and J. Viiding (1955) somewhat later described additional gneiss–breccias erratic boulders, but none of them tried to explain their origin.

In 1970-1980s, important results were obtained in a course of geological mapping (at a scale 1:200 000 and 1:50 000) of north–western Estonia[1]. First, disturbed and tilted beds in the Ediacaran (Vendian) and Early Cambrian clays and sandstones were drilled in a borehole 410 on the Osmussaar

[1] The manuscript reports are stored in the geological archive of the Geological Survey of Estonia.

Fig. 1. Location of the Neugrund and other partially or completely marine impact structures, known in the north of Europe.

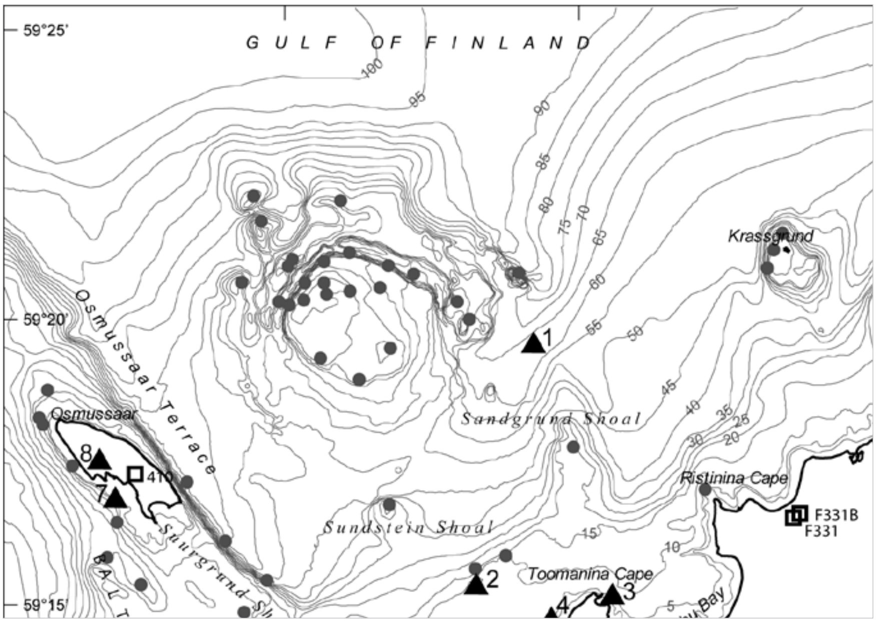

Fig. 2. Bottom topography of Neugrund impact crater area. *Triangles:* remarkable Neugrund Breccia erratic boulders: 1 – Gigantic Boulder of Osmussaar Deep, ca. 10000 m^3; 2 – Toodrikivi, ca. 1200 m^3; 3 – Toomanina Suurkivi, ca. 400 m^3; 4 – Toomanina Üksiklane (Solitary), ca. 150 m^3; 5 – Dirham Boulder, ca. 100 m^3; 6 – Gahona, ca. 400 m^3; 7 – Skarvan, ca. 400 m^3; 8 – Osmussaar Twins, ca. 100 m^3. *Circles:* deep drill holes and their number. *Dots:* sites of diving carried out in 1998–2003.

Table 1. Proved and problematic impact structures located completely on the seabed.

No.	Name of the structure (location)	Status of the structure	Diameter of struc–ture, km	Age, Ma	Appearing of the impact structure on seabed	Remarks	Reference
1.	Bedout (north-western continental margin of Australia)	Proved by findings of shocked minerals	200	250	Semicircular Bedout High as about 40-km-diameter central uplift cropped out	Candidate for an end–Permian impact event connected with the biggest mass extinction	Becker *et al.* 2004
2.	Eltanin (Bellingshausen Sea, 5000 m below sea level)	Proved by findings of shocked minerals and asteroidal debris in the core	130	2.1	Structures of the impact crater are not followed in seabed	The previously proposed size was of 24 to 80 km	Gersonde *et al.* 2003
3.	Ewing (Central Equatorial Pacific)	Proved by findings of shocked minerals and impact spherules and microtectites	150	7–11	Structures of the impact crater are not followed in seabed		Leung, Abbott 2003
4.	Lumparn (Baltic Sea, Main Island of Åland)	Problematic, shatter cones have been found in rapakivi granites	9	1000	The strongly eroded hollow in rapakivi granites is filled with Pleistocene sediments and Ordovician limestones		Svensson 1993
5.	Mjölnir (Barents Sea, Bjarmeland Platform)	Proved by findings of shocked minerals (quartz)	40	142	The crater is buried beneath Quternary deposits and on relief of seabed not expressed	Mjölir is the name of Thor's mythological hammer	Dypvik *et al.* 2006
6.	Montagnais (North-America, Canada, Nova Scotia shelf area)	Proved by findings of shocked minerals (quartz)	45	50	Is buried beneath marine sediments and on relief of seabed not expressed	Has been established by geophysical methods	Pilkinton *et al.* 1995
7.	Neugrund (Baltic Sea, Estonia, Gulf of Finland)	Proved by findings of shocked minerals (quartz)	20	535	The rim wall surroundings of the inner crater cropped partially out in seabed		K. Suuroja, S. Suuroja 2000
8.	Shiva (Indian Ocean, west of Mumbai)	Problematic, connected with of sea floor	600 x 400	65	The shape of the structure is rectangular and mostly buried	The same time as the K/T mass extinction event. Shiva, the Hindu god of destruction and renewal.	Chattarje 2002
9.	Silverpit (North Sea off the coast of the UK)	Problematic, supposedly connected with salt mobility	10	74–45	The structure lies below up to 1500 m thick bed of sediments and about 40 m thick water layer	The crater–like form Silver Pit a nearby sea–floor valley recognized by generations of fisherman	Stewart, Allen 2002
10.	Tvären (Baltic Sea, Sweden, Studsvik Bay)	Proved by findings of shocked minerals (quartz) in the drill core	2	455	The crater expressed as is a ring shaped and is covered with Ordovician limestones		Lindström *et al.* 1994

Fig. 3. Skarvan is the gigantic erratic boulder consisting of Neugrund Breccia in the shallow sea near the western coast of Osmussaar Island, Estonia. Photo by K. Suuroja, 2005.

Fig. 4. Smaller (ca. 1 m in diameter) Neugrund Breccia erratic boulder is found on Ruhnu Island (about 170 km further south). Photo by S. Suuroja, 2005.

Fig. 5. Gahona is a pile of Neugrund Breccia erratic boulders on western coast of Dirham Peninsula (Gahona – Swedish name, meaning is unknown). Photo by K. Suuroja, 2009.

Island. Later on, brecciate clays– and sandstones in the upper part of the Early Cambrian (Lontova Stage) were found in the drill cores F-331 (Ristna), F-332 (Vihterpalu), F-334 (Dirhami), and F-335 (Metsküla). The submarine ring–shaped walls around the Neugrund Bank were observed on the seismic reflection profiles during marine geological mapping (at a scale 1:200 000). The walls were interpreted as glacial moraine walls (Lutt, Raukas 1993). Summarizing results of the geological mapping of the north–western Estonia, the impact hypothesis of the Neugrund Bank was postulated (Suuroja, Saadre 1995). The most disturbances and appearances of the gneiss–brecciate erratic boulders were explained as an unknown impact structure, possible hidden under the Neugrund Bank (Suuroja *et al.* 1998).

In 1996, a seismic reflection profiling of the seabed in the surroundings of the Neugrund Bank was carried out by the Geology Department at Stockholm University on the research vessel *Strombus*. These investigations surveyed an about 9 km rim–to–rim diameter crater–like structure (Suuroja 1996 a, b). A specific pattern of the seabed—the Neugrund Bank––was suggested likely to represent the impact structure (meteorite crater). At the same time shocked quartz grains with PDFs (Planar Deformation Features) was found in the quartz grains from erratic blocks of gneiss–breccias (Suuroja *et al.* 1997).

In 1998, the Geological Survey of Estonia and Estonian Maritime Museum carried out a marine expedition on R/V *Mare*. Divers, geologists and submarine archaeologists took samples from the submarine outcrops along the rim wall, consisting of brecciate Precambrian metamorphic rocks. The samples macroscopically resembled the impact breccias from the erratic boulders and in addition contained shocked quartz grains with PDFs (Fig. 6). Therefore, the impact origin of the Neugrund structure was proven (Suuroja, Suuroja 1999, 2000; Suuroja *et al.* 1999).

Examination of the submarine outcrops by skin–diving has been a new method used for geological survey of the impact structures. Afterwards diving was used to study sedimentary rocks inside the crater. In 1998–2003, the Neugrund structure area was studied in details by several marine expeditions commonly during 30 days. Skin–divers geologists have discover 21 different location (see Fig. 2), and collected samples from 12 sites. Depth of sampling points varies from two to 42 m. Simultaneously; the exposures were recorded by the Sony Camcorder TR 810E-Hi8 accommodated with underwater housing system. Outcrop records on videotape allowed decode the submarine sections, whereas the results of sampling were evaluated.

Seismic reflection profiling (SRP) was one of the most commonly applied methods for the submarine Neugrund structure investigations. It was first cleared up the elements of the partially buried impact structure (Flodén 1981; Kearey *et al.* 2002). 560 km of SRP were shot altogether on the Neugrund structure area of ca. 250 km^2, most of them by *Marina* (Fig. 7; Table 2). SRP on *Marina* was carried out using single channel equipment of Sparker–type working at frequencies 0–450 Hz. Profiling on *Strombus* was performed by using single channel air–gun PAR–600 at 12 MP wave generator, and record signals were filtered by two frequency bands at 100–200 and 250–500 Hz. Simultaneously a mud–penetrator sounder at 4 kHz was used to obtain the high–resolution records of Quaternary deposits. Similar survey equipment was used on R/V *Skagerak.* In addition to the paper tapes, the data were recorded digitally. SRP survey by R/V *Littorina* and *Humboldt* were made using spark wave generator with recording frequencies 1.2–5 kHz.

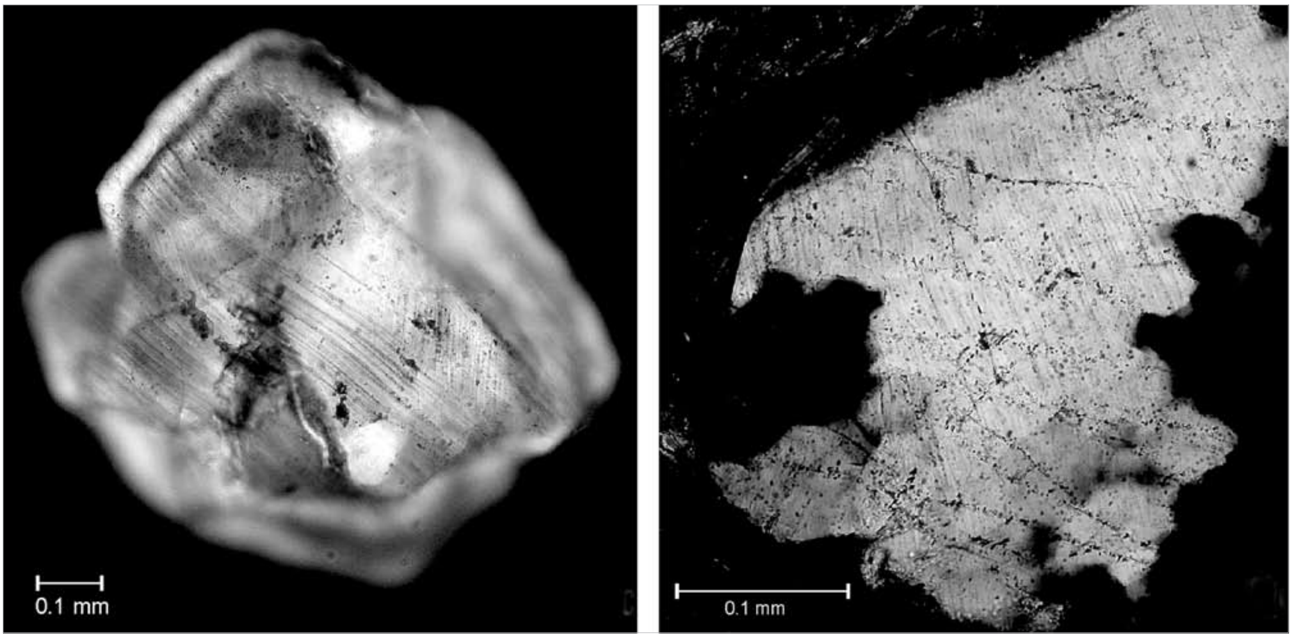

Fig. 6. Shock–metamorphosed quartz grains with PDFs from the impact related rocks of the Neugrund structure. *Left:* sub–rounded quartz grain with two sets of decorated PDFs, taken from the distal ejecta layer at a distance 15 km from the impact center (drill core F-331–Ristna at a depth 90.8 m); immersion liquid, cross–polarized light. *Right:* Quartz grain with three sets of slightly decorated PDFs; the sample is taken from a vein of polymictic impact breccia from the brecciated metamorphic rocks of the rim wall at a depth 24.2 m; thin section, cross–polarized light. Photo by S. Suuroja, 2005.

Table 2. The marine expeditions carried out in Neugrund impact structure area.

No.	Year	Participation countries	Research vessel	Used methods of investigation
1.	1985	Estonia	Marina	SRP, SBR
2.	1989	Estonia	Marina	SRP, SBR
3.	1996	Sweden, Estonia	Strombus	SRP, MP
4.	1996	Germany, Estonia	Humboldt	SRP, SBD
5.	1996	Germany, Estonia	Littorina	SRP, SBD
6.	1998	Estonia	Mare	SRP, SSSP, SBR, D, VR
7.	1999	Estonia	Mare	SRP, SSSP, SBR, D, VR
8.	2000	Estonia	Mare	SRP, SSSP, SBR, D, VR
9.	2001	Estonia	Mare	SRP, SSSP, SBR, D, VR
10.	2002	Estonia	Mare	SRP, SSSP, SBR, D, VR
10.	2002	Sweden, Estonia	Skagerak	SRP
11.	2003	Estonia	Mare	SRP, SSSP, SBR, D, VR
12.	2006	Estonia	Mare	SRP

SRP – seismic reflection profiling of different span frequencies; SSSP – side scan sonar profiling; MP – magnetometric profiling; VR – observing submarine outcrops by a video robot; SBD – sampling of bottom deposits and rocks with gravity corer and scarp; D – sampling of bottom rocks in course of the diving's.

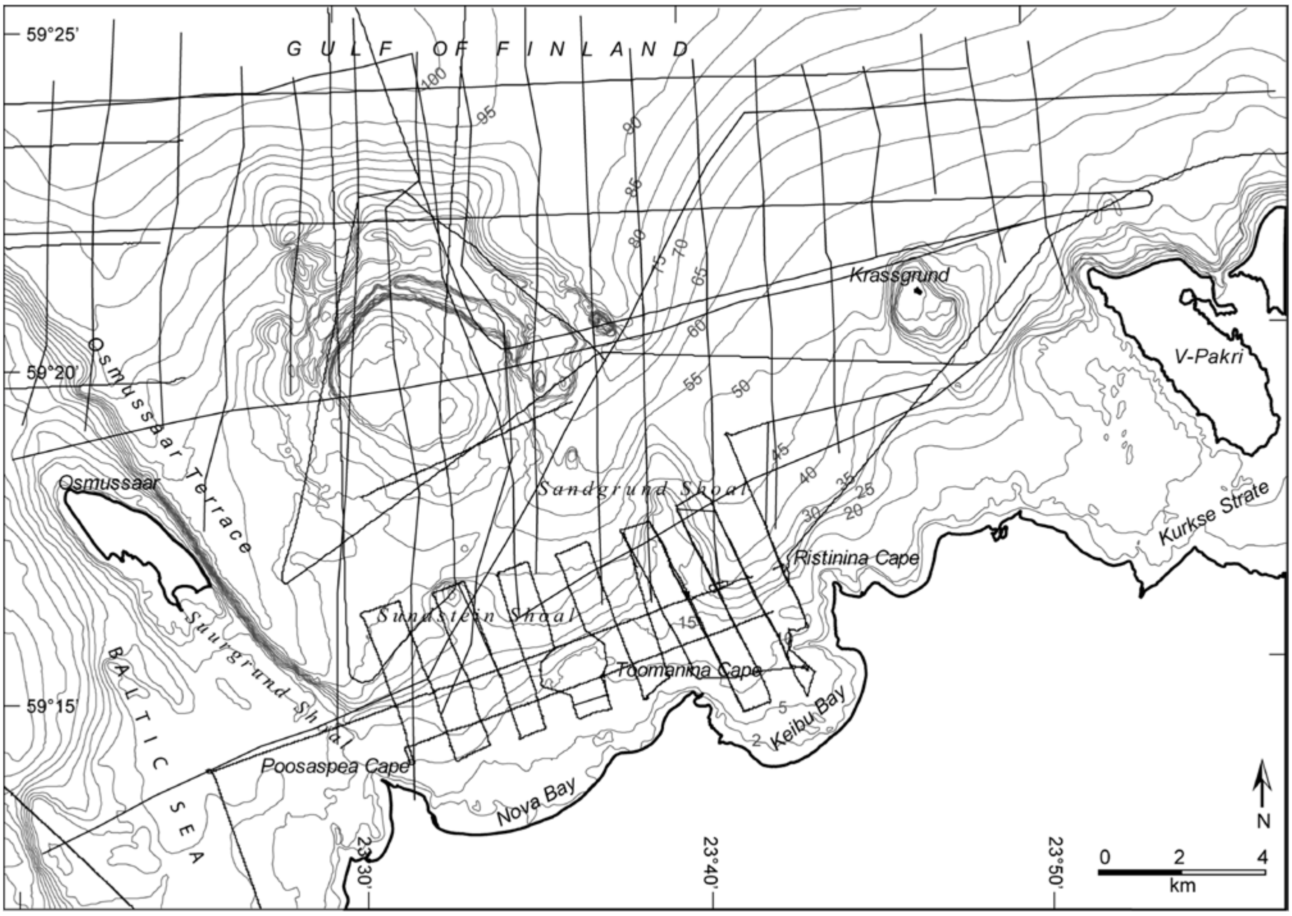

Fig. 7. Location of seismic reflection profiles shot in 1996–2001 in the area of Neugrund impact structure.

The digital metadata of all these records are stored in the Euroseismic database and the diagram records – at the Geological Survey of Estonia. The recorded diagrams shot by *Strombus* (1996) and *Skagerak* (2001) were interpreted by S. Suuroja using the following seismic velocity values (Flodèn 1981; Tuuling, Flodén 2001): seawater 1440 m/s; Quaternary deposits 1750 m/s; Ordovician limestone's 3500 m/s; Cambrian silt– and sandstones 2725 m/s; Palaeoproterozoic crystalline rocks 5500 m/s. The filtered bands of 250–500 Hz were more suitable for revealing deep buried bedrock layers and for surface of crystalline basement, while filtered band of 4 kHz was used for observing the buried bedrock surface under the Quaternary deposits and for revealing details inside the latter. Disturbing circumstance was presence of thicker layers of Quaternary deposits containing gas (especially varved clays), which could not be penetrated by the wave of higher frequency bands (4 kHz).

Side–scan sonar (SSS) profiling was carried out mostly by *Mare* (altogether ca. 120 km) and to lesser extent by *Marina* and *Littorina*. The sea floor topography and a certain amount of sediments composition was surveyed within 100–400 m wide band. Origin mega–blocks and giant erratic boulders were established by the SSS earlier discovered in rather deep (more than 50 m) sea within the Osmussaar Deep westwards the Neugrund Bank and on other sites. The intensity of rebounded beam made possible deciphering of rocks composition on the seabed (Fig. 8).

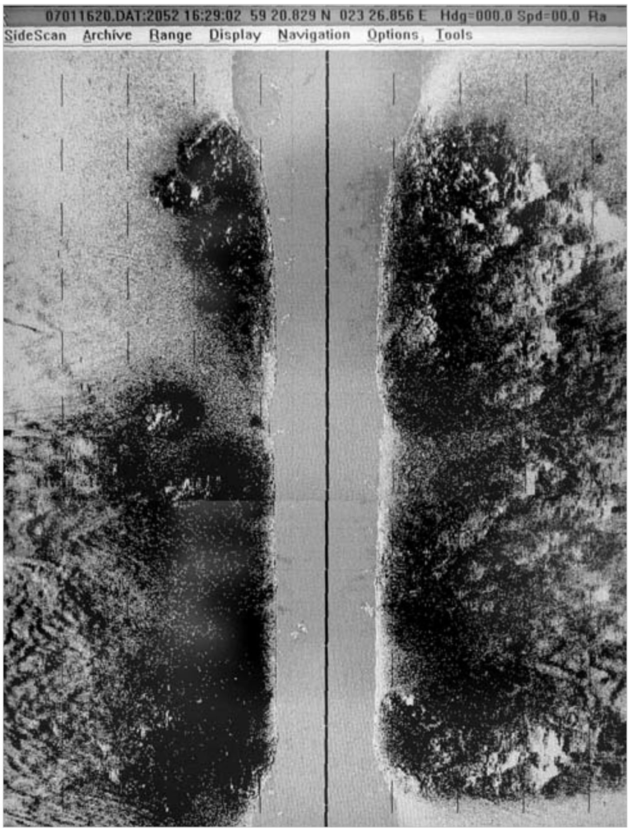

Fig. 8. Image of megablock of brecciated crystalline rocks on the screen of the side–scan sonar. Photo by K. Suuroja, 2005.

Survey of the seafloor by remote operated vehicle (ROV) camera of SeaLion system was made for investigation of the anomalous relief elements and rock types of the seafloor at sites being too deep for ordinary diving (over 40 m) or at areas where the sampling was not required. Images obtained by ROV camera helped to interpret several submarine geological sections, where boundaries of different complexes of the sedimentary rocks (limestone, sandstones, argillite, etc.) and crystalline rocks are rather well distinguishable. Therefore, some structural elements (e.g. bedding, fissures, and faulting, folding, glacial stress marks) of rocks were identified using these images.

MORPHOLOGY OF THE NEUGRUND IMPACT STRUCTURE

The morphological units of the Neugrund impact structure, which during about 535 Ma were buried under post–impact deposits, has been only partially revealed in the course of the Pleistocene erosion. As a result of the latter, some units now have reverse appearance—usually above the crater proper occurs depression, but presently over there spreads the Central Plateau (see Fig. 1).

The Central Plateau (Neugrund Bank) is limestone–covered circular shallow about 5.5 km in diameter above the crater proper. Water depth above the plateau is 1–15 m, increasing from northwest to southeast. Its specific circular shape has been inherited by the ring–shaped Rim Wall (especially the Inner Ridge), which consists of hard Precambrian crystalline rocks resistant to erosion. The Central Plateau is a relict island of the limestone plateau of the Baltic Klint which covered the crater area during the pre–Pleistocene time. The thickness of Upper–Middle Ordovician limestone covering the plateau is 20–30 m, increasing southwards. It is unknown how far the limits of the Limestone Plateau reached in the pre–Quaternary time, but according to some hypotheses a 60–80 m tick layer of bedrock was removed from here during the Quaternary period (Mozhajev 1973).

In the wall of the about 50 m high precipice, edging the plateau from the north, the Early Palaeozoic sedimentary rocks crop out (from the top; Fig. 9): 1) Middle Ordovician grey limestone of about 20 m thick; 2) green weakly lithified Late Ordovician (Hunneberg Regional Stage, Leetse Fm.) glauconitic sandstone – about 5 m; 3) brown Dictyonema Shale (Pakerort Regional Stage, Türisalu Fm.) – about 6 m; 4) yellowish grey Obolus sandstone (phosphorite) with thin interlayers of Dictyonema Shale (Pakerort Regional Stage, Kallavere Fm.) – about 5 m. At the foot of the somewhat sloping escarpment a thick complex of about 10 m fine–grained whitish quartzose sandstone and coarse-grained siltstone with seams of pellitic siltstones (Lower Cambrian, Tiskre Fm.)

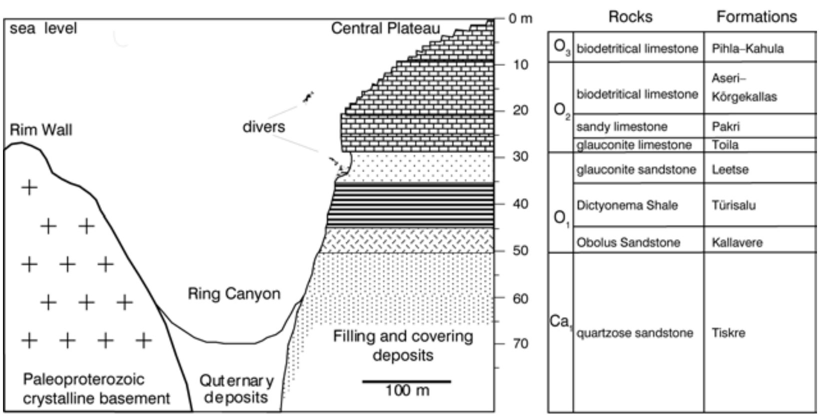

Fig. 9. Geological cross–section of the Ring Canyon.

crops out. The geological sequence beneath the above mentioned succession is unknown, since the foot of the escarpment and bottom of the Ring Canyon are buried under the Quaternary deposits (mud and varied clays). No data are known about the existence of a possible central peak (uplift) beneath the Central Plateau. SRP method could not be applied effectively for this purpose because the water column at the plateau area is too shallow (2–5 m). Even E. Pirrus (2002) supposed that the Central Plateau is composed of the mega–blocks of the pre–impact sedimentary target rocks.

The Ring Canyon is 200–400 m wide and 30–60 m deep valley that surrounds the Central Plateau northward for about 12 km (Fig. 9). The canyon floor is covered by a 30–40 m thick layer of Quaternary deposits (mud, varied clays). Southward of the structure the ring canyon is mostly buried under the Quaternary deposits and therefore is weakly expressed in the seafloor relief. The internal slope of the canyon, where sedimentary rocks of the covering complex (limestone, sandstones, shale) crop out, is steep (45–90°) than the external one (less than 30°). SSS records show that the sedimentary rocks, especially limestone, on the internal slope of the canyon carry the signs of erosion by running water, indicating the Late Pleistocene sub–glacial fluvial activity. The circular shape of the canyon reflects the circular Rim Wall, which consists of Precambrian metamorphic rocks of variable erosion resistance. The external canyon wall is 10–20 m lower than the internal one, along the Central Plateau.

The Rim Wall (Inner Wall) and its composition as well as the real dimensions of the structure, have been under discussion since the Neugrund impact structure was discovered. The Circular Canyon is surrounded by the Rim Wall, about 8 km in diameter, which is 100–150 m high and more than 2 km wide at its base (see Fig. 9). Formerly this structure was defined as the inner and middle part (Inner and Middle Wall) of the up to 3 km wide three–ridged Rim Wall (Suuroja, Suuroja 2004). At present, the detailed interpretation of the continuous seismic reflection and side scan sonar profiles, shot out in 2003–2006, proved that the afore mentioned two walls have common roots (base) of impact–influenced Precambrian crystalline rocks, and it is treated as the two ridged Rim Wall or Inner Wall.

The very fragmental is a third ridge of the Rim Wall, which formerly was treated as about 10 km diameter Outer Wall. At present it is related to a staff of **the Inner Ridge**, which has a rim–to–rim diameter of 6.5 km. It is 400–800 m wide at the base and 80–100 m high. The inner slope of the wall is steeper (30°–50°) than the outer slope (10°–20°). The tops of the ridges of the Inner Wall are 15–50 m b.s.l. In northern part of the structure the Inner Wall is of ca. 10 km long, semicircular, 25–50 m high and 100–500 m wide structure, expressed as the continuous range of the glacier–eroded smooth mounds of impact–influenced crystalline rocks resembling *roche mountonnée* (mutton–head) features. In the southern part of the structure the Inner Ridge is mostly buried under the Quaternary deposits.

The Outer Ridge is about 7 km rim–to–rim in diameter; 20–50 m high and 0.5–1 km wide at the base (see Fig. 9). Here elongated mega–blocks (diameter up to 0.5 km) of impact–influenced Palaeoproterozoic crystalline rocks alternate with disturbed (fractured, folded) blocks of pre–impact Early Cambrian sedimentary rocks (clays, silt– and sandstones). From the Inner Ridge it is separated by up to 100 m deep and 0.3–0.5 km wide irregular moat. In the south–eastern part of the structure, where both ridges as if merge, they are cut through by about 0.5 km wide and up to 100 m deep gully. The latter was obviously eroded by flowing water under the glacier sheet in the Pleistocene.

The Terrace (Outer Crater or Zone of Dislocations) is about 4 km wide circular belt of disturbed by the impact sedimentary and crystalline target rocks surrounding the Inner Crater. Earlier, the about 1 km wide inner zone of the Terrace, where mega–blocks (up to 0.5 km diameter) of brecciate by the impact Paleoproterozoic crystalline basement rocks fragmentally cropped out in the seabed (see Fig. 8), was treated as the outer ridge of the three–ridged Rim Wall (Suuroja, Suuroja 2004). Further interpretations of the seismic reflection profiles carried out in the record frequency span of 250–500 Hz and subsequent study of the side–scan sonar profiling diagrams proved that single uplifted mega–blocks do not form unitary wall and they do not have the roots characteristic for a wall.

The Ring Fault is about 20 km diameter circular fault, which separates the area where target rocks, sedimentary and crystalline, are strongly disturbed by the impact from the area where these are mostly intact. The Ring Fault is not expressed in the seafloor relief, but it is clearly visible on the surface of crystalline rocks, where it is marked by the up to 80 m high escarpment descending gently (below 20°) towards the centre (see Fig. 9). The escarpment is higher (up to 100 m) in the western part of the structure, and lower (up to 20 m) in the eastern part.

The Distal Disturbances are located outside the Ring Fault where the sedimentary target rocks are sporadically disturbed by the impact. For example, in the drill core F-332 (Vihterpalu), which is situated about 20 km to the south–east of the impact centre, the Early Cambrian silt– and claystones of the Lontova Fm. are brecciate at depths of 100–110 m. Similar deformations at the same stratigraphical level are observed in the section of drill core F-335 (Keibu), which is situated 22 km off the impact centre. In the sections of drill holes F-331 and F-331B (5 meters northward from the first), which are situated near the Ristna Cape or 14 km south–east from the impact centre or 3 km from the Ring Fault, at the depths of 90–119 m (F-331; 29 m), and at 90.0–115.0 m (F-331B; 25 m) the pre–impact clay– and siltstones of the Lontova Fm. are disturbed (brecciate and folded) and contain angular clasts of Ediacaran sand– and siltstones (5–20 cm in diameter), also Paleoproterozoic metamorphic rocks (1–10 cm in diameter). Furthermore, well–developed PDFs in quartz grains (on average about 4%) are observed in the sand fraction (0.063–0.5 mm), derived from this breccias matrix (Suuroja, Suuroja 2004). PDFs are here observed also in grains of apatite (up to 20% of the total apatite) and plagioclase. The substance of afore mentioned disturbances remains somewhat unaccountable, because in the core section of well F-331A, which is situated about 200 m north–eastward of wells F-331 and F-331B, and accordingly is closer to the impact centre; at the same stratigraphical level the sequence of pre–impact sedimentary target rocks is undisturbed.

DISCUSSION

The dimensions of the Neugrund impact structure has been discussed since it was discovered. Initially, the 7 km rim–to–rim diameter of the structure was measured (Suuroja, Suuroja 2000). Later, three–ridged 9 km rim–to–rim diameter of the inner crater was distinguished, and the outer crater about 20 km in diameter was outlined by the ring fault (Suuroja, Suuroja 2004, Suuroja 2008 a, 2000 b).

At present 176 impact structures in the Earth Impact Database appear and fourteen complex impact craters are comparable to the Neugrund impact structure (Table 3). They display an inner crater surrounded by a multi–ridged rim wall and an outer boundary is marked usually by a ring fault. From these fourteens eight are mixed, four of sedimentary and only two of pure crystalline targets. The diameters of these structures are 10–40 km, while the diameter of the inner ring reaches 3–15 km. The relationship between the outer structure diameter and the diameter of the inner ring (crater) is 3:1 in the Neugrund case, close to the average of the other, 3, ranging from 1 to 4.

In particular, scientific interesting problems of the Neugrund impact event are connected with the eject layer, formation and distribution, and the occurrences of shocked quartz grains in the Osmussaar Breccias sedimentary dykes. The latter were supposedly formed about 60 Ma after the impact (Middle Ordovician, Kunda time) as a result of erosion of the impact produced deposits of the Neugrund structure, which at that time were cropped out within limits of the extensive Gotland–Hiiumaa uplift zone (Suuroja *et al.* 2003; Suuroja 2008). The surrounded shape and fractional composition of the PDF–quartz grains indicates that they are mostly derived from the pre–impact Vendian and Lower Cambrian siliciclastic target rocks, mostly from sandstones, and only a small portion, what is presented by angular grains, comes from the basement crystalline rocks.

The Neugrund impact event was first estimated to be happened about 475 Ma ago, as the Osmussaar Breccias (breccias–like limy sandstone dykes and bodies which are densifications of the catastrophic earthquakes occurred at that time; Suuroja *et al.* 2003). The latter, frequently cropping out on Osmussaar and Suur–Pakri islands, are present in cores of north–

Table 3. Neugrund and other similar complex impact structures of the world.

Nr	Name of the structure (location)	Composition of target	Diameter of structure, km	Diameter of inner ring, km	Age, Ma	References
1.	**Neugrund** (Estonia)	Mixed	20	7	535	Suuroja, Suuroja 2004
2.	**Kärdla** (Estonia)	Mixed	12–14	4	455	Puura, Suuroja 1992
3.	**Ries Nördlingen** (Germany)	Mixed	24	8	14.5	Englehardt *et al.* 1995
4.	**Gooses Bluff** (Australia, Northern Territory)	Sedimentary	22	6	14.5	Milton et al. 1996
5.	**Lawn Hill** (Australia, Queensland)	Mixed	18	8	515	Shoemaker, Shoemaker 1996
6.	**Shoemaker** (Teague) (Western Australia)	Mixed	30	15	1630	Shoemaker, Shoemaker 1996
7.	**Cleawater West** (Canada, Quebec)	Crystalline	32	12	290	Simonds *et al.* 1978
8.	**Mistastin** (Canada)	Crystalline	28	8	35	Robertson, Grieve 1975
9.	**Upheavel Dome** (U.S.A., Utah)	Sedimentary	10	3	170	Kenkmann *et al.* 2005
10.	**Oasis** (Libya)	Sedimentary	18	5	120	Koeberl *et al.* 1994
11.	**Aorounga** (Chad)	Sedimentary	13	5	515	Koeberl *et al.* 1995
12.	**Araguainha** (Brasil)	Mixed	40	13	245	Crosta 2004
13.	**Serra da Gangalha** (Brasil)	Mixed	12	3	300	Romano, Crosta 2004
14.	**Vargeao Dome** (Brasil)	Mixed	12	4	70	Crosta 2004

western Estonia (Suuroja *et al.*1997). In addition, small single erratic boulders of the Osmussaar Breccias have been found sporadically in some places in the coastal north–western Estonia and Muhu Island. In 1998, the northern slope of the Neugrund Bank, crater filling and cover were studied by diving. Sedimentary rocks which were noticeably (up to 60 Ma) older than at that time supposed age of the crater (Suuroja, Suuroja 2000) were found. Among these sedimentary rocks the about 475 Ma old glauconitic sandstone of Leetse Fm. (Early Ordovician, Hunneberg Regional Stage), Dictyonema Shale of Türisalu Fm. (Early Ordovician, Pakerort Regional Stage), Obolus sandstone of Kallavere Fm. (Early Ordovician, Pakerort Regional Stage) were found. Below this 40 m succession, the Early Cambrian quartzose sand– and siltstones of Tiskre Fm. were found. Based on these data it was concluded that the structure is older than the latest Tiskre Fm. and, consequently, is of more than 530 Ma old.

Accordingly the age of the impact event should be thoroughly discussed. The eject layer of the Neugrund impact is spread over the disturbed sequence of the Lower Cambrian clays, and probably limits an impact age. The eject layer, consisting mainly of sandy matter, was also deposited among the very similar siliciclastic rocks, i.e. Lower Cambrian clays and silt– and sandstones of the Lontova Fm. It can be distinguished by the impact influenced minerals, e.g. shock–metamorphosed quartz grains with PDFs. The eject deposits have been studied in detail (mineral composition, PDFs in quartz grains) only in one drill core section F-331 (Ristna) at a distance of 14 km from the impact centre. In a two meters thick layer, up to 8% of quartz grains were shock–metamorphosed (Suuroja, Suuroja 2004; Suuroja 2008). In terms of biostratigraphy this eject layer belongs to the pre–trilobite Early Cambrian *Platysolenites antiquissimus* biozone of the East–European Craton, or to the Fortunian age of the Cambrian Terreneuvian epoch (International Stratigraphic Chart 2009) ranging about 535 Ma.

The Neugrund impact structure was hypothetically formed by impacting of an asteroid about 1 km diameter, which supposedly belongs to swarm of chondritic meteor bodies revolved close to Earth's orbit about 600–450 Ma (Schmitz *et al.* 2003, 2006).

CONCLUSIONS

The Neugrund impact crater was formed as the result of impacting of the asteroid about 1 km in diameter about 535 Ma ago in a shallow sea of about 100 m deep in the impact site. The impacting projectile (asteroid/comet?) supposedly belonged to a large swarm of chondritic meteoroid bodies that revolved close to Earth's orbit 600–450 Ma (Haack 1996). The impact has produced a complex crater of about 20 km in diameter, with a central uplift surrounded by 7 km diameter the rim wall (see Table 3).

The inner crater is surrounded by 4–5 km wide zone of dislocations, where sedimentary and crystalline target rocks are disturbed in the course of the low–angle slipping of gigantic blocks (up to 0.5 km in diameter) of target rocks towards the centre of the structure. The disturbances of sedimentary target rocks are observed farther of the ring fault (up to 15 km of the impact centre).

The impact structures with a rim wall surrounding the inner crater and a ring fault surrounding the outer crater have the ratio of the diameter of the structure (ring fault) to the diameter of inner crater roughly 3:1. In case of the Neugrund the above ratio is 20:7 (2.9) and it generally responds to the accepted concepts (Turtle *et al.* 2005). Morphologically, the most similar to the Neugrund impact structure are Ries Nördlingen (Germany), Gosses Bluff (Australia) and Oasis (Libya). The ratio of the diameter of the structure to the diameter of the inner crater of these impact structures is 3 (24:8), 3.7 (22:6), and 3.5 (18:5) accordingly.

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