A comparative analysis of two Early Palaeozoic marine impact structures in Estonia, Baltic Sea: Neugrund and Kärdla

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Abstract

Kärdla and Neugrund are two Early Palaeozoic offshore impact structures located some 50 km apart along the Estonian coast of the Baltic Sea. They share many similarities but differing features are also found. The Kärdla impact structure is located at the NE coast of Hiiumaa Island (58°58'N, 22°46'E). The inner crater has a 4 km rim-to-rim diameter and a c. 130 m high central uplift, surrounded by a ring fault, c. 12 km in diameter. The well-preserved buried inner crater is outlined in the landscape by a circular ridge of uplifted bedrock. The perimeter of the outer crater is outlined on the seafloor by a semicircular ridge of narrow shoals. The variable height of the rim wall (50–240 m above the crystalline basement level) and the asymmetric location of the inner crater is obviously a result of an oblique impact in a layered target and partial collapse of the rim wall. Shortly after the impact in a shallow epicontinental sea during Late Ordovician time (c. 455 My), calcareous biodetritic muds were deposited and the crater was buried. The Neugrund impact structure is located in the seabed at the entrance of the Gulf of Finland (59°20'N, 23°31'E). The inner crater has a 7 km rim-to-rim diameter and the outer limit of the structure passes through the Osmussaar Island to the southwest of the impact centre. The crater was buried in a shallow epicontinental sea with siliciclastic deposition shortly after the impact at Early Cambrian time, c. 535 My. It was partially re-exposed by erosion during Pliocene. The target had a three-layered composition: Precambrian metamorphic rocks covered by Ediacaran and Early Cambrian siliciclastic rocks (c. 150 m) and water (c. 100 m). The structure has been studied with seismoacoustic and sidescan sonar profiling, and by diving and sampling of submarine outcrops. Several hundred samples of impact breccias have been collected and investigated from erratic boulders distributed by glacial action in the west Estonian mainland, islands and sea floor.

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Editorial handling: Joonas Virtasalo

1. Introduction

In the Earth Impact Database (www.paasc.net), 183 hypervelocity impact structures are listed. Only ten of these (Bedout, Eltanin, Ewing, Lumparn, Mjölnir, Montagnais, Neugrund, Shiva, Silverpit, Tvären) are located completely on sea floor, and five (Charlevoix, Chesapeake Bay, Chicxulub, Kara, Kärdla) partially (www.paasc.net). In the Baltic Sea region, four similar structures have been found, Lumparn, Tvären, Kärdla and Neugrund. Two of them, Kärdla and Neugrund are located in Estonia.

The Kärdla meteorite impact structure, with its centre at 58°58'N, 22°46'E, is located mostly on the NE coast of Hiiumaa Island in western Estonia, but partly in the Kärdla Bay to the northeast of the island (Fig. 1). The Kärdla impact structure was buried shortly after the impact. Therefore its structures and its complex of impact-generated

deposits, including the ejecta layer, are mostly preserved today. The structure area is penetrated by numerous (162) drill holes. Thus, Kärdla is not only one of the best-preserved impact structures in the world, but also one of the best studied (Fig. 2; Fig. 3).

The Neugrund meteorite impact structure is located in the southern part of the entrance to the Gulf of Finland at 59°20'N, 23°31'E. The centre of the structure is some 10 km to the northeast of the Osmussaar Island (Fig. 1). Thus, Osmussaar is located at the outer boundary of the impact structure. Osmussaar, in Swedish *Odensholm* has a prominent position in Nordic mythology. According to the legends the chief god of the Vikings, Oden (Odin in old Norse), was buried on the island (Eichwald, 1840). Before World War II, there was an erratic boulder on the island named *Odens Stein* and by legends this was the burial site of Odin.
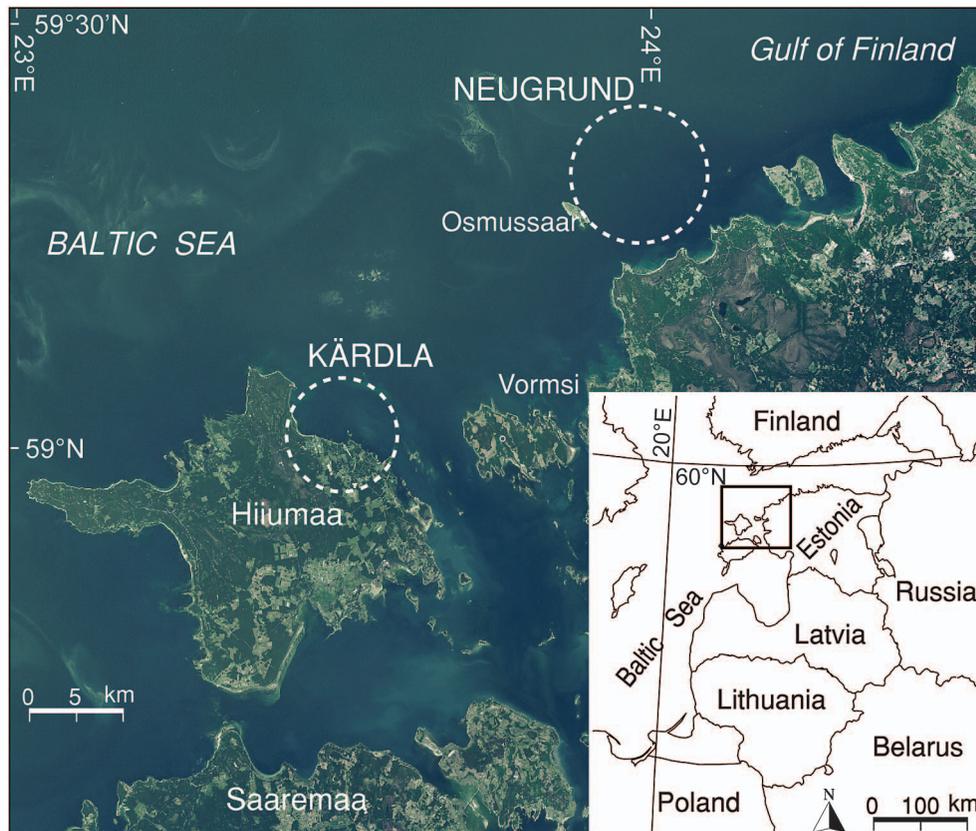
Fig.1. The Kärdla and Neugrund impact structures indicated in a satellite image. The white dashed lines mark the outer limits of the structures.
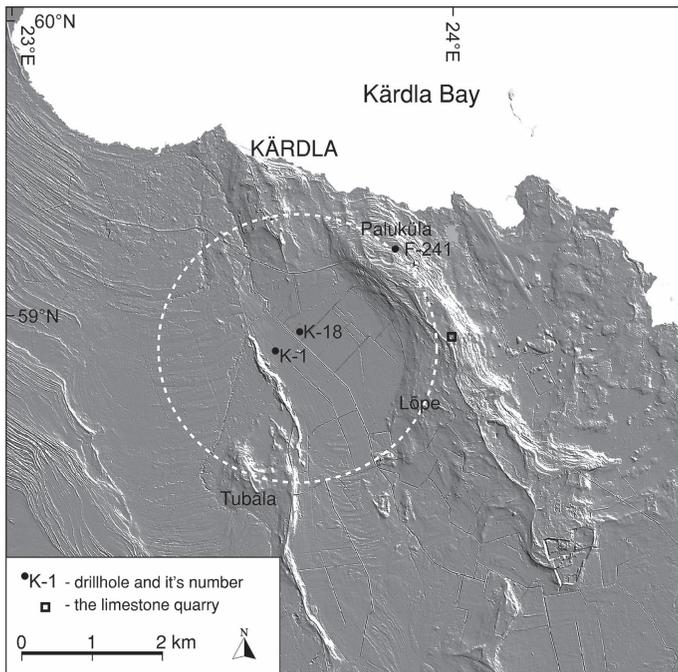
Fig.2. A LIDAR relief of the buried Kärdla meteorite crater. The white dashed line indicates the position of the ridge of the buried rim wall.
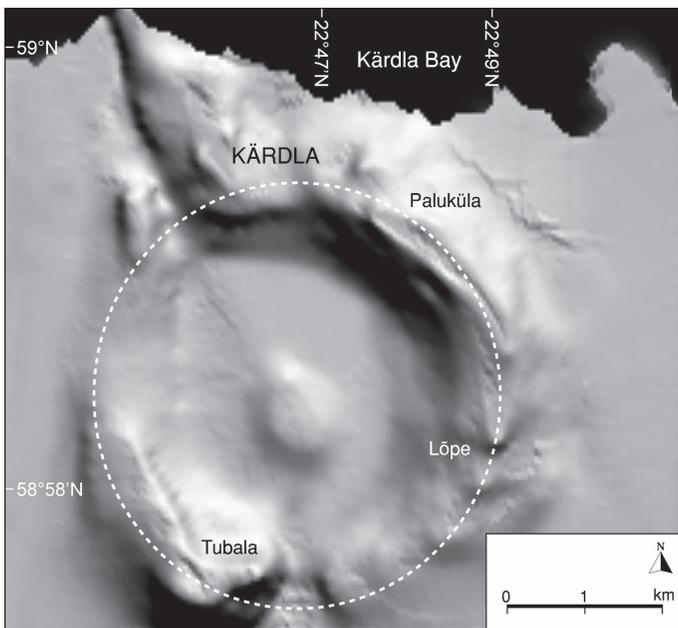
Fig.3. Shaded sedimentary bedrock relief of the central part of the Kärdla meteorite crater area. The dashed line indicates the position of the ridge of the buried rim wall.

The Neugrund structure is the best-preserved offshore impact structure in the world. Moreover, it is the only one whose main morphological units are visible and easily accessible (Fig. 4). The geological section of the target area is well documented by data obtained mainly from the drill hole on the Osmussaar Island.

The distance between the Kärdla and Neugrund impact structures is c. 50 km. The time interval between the two impact events is about eighty million years, them having occurred 455 My and 535 My, respectively. The impact origin of the two structures was established by K. Suuroja et al. (1981) and K. Suuroja (1996), respectively. Experience obtained during the study of the Kärdla impact structure, namely the impact influenced rocks in the core sequences, were the guides leading to the discovery of the Neugrund impact structure.

2. Methods and materials

2.1 The Kärdla impact stucture

Tilted beds of Ordovician limestones (not a common feature in Paleozoic in Estonia) in the Paluküla Quarry on the Hiiumaa Island were described already in the 19th century (Eichwald, 1840; Schrenk, 1854; Schmidt, 1858). Later, data on the occurrence of asphalt (Winkler, 1922; Scupin, 1927) and galena (Palmre, 1961) were published. In 1966, drilling of a well on the Paluküla Hill was stopped as Precambrian metamorphic rocks were unexpectedly met at a depth of 16 m, instead of anticipated c. 230 m. The revealed uplift of crystalline basement rocks was interpreted as a placanticlinal structure (Viiding et al., 1969). A nearby
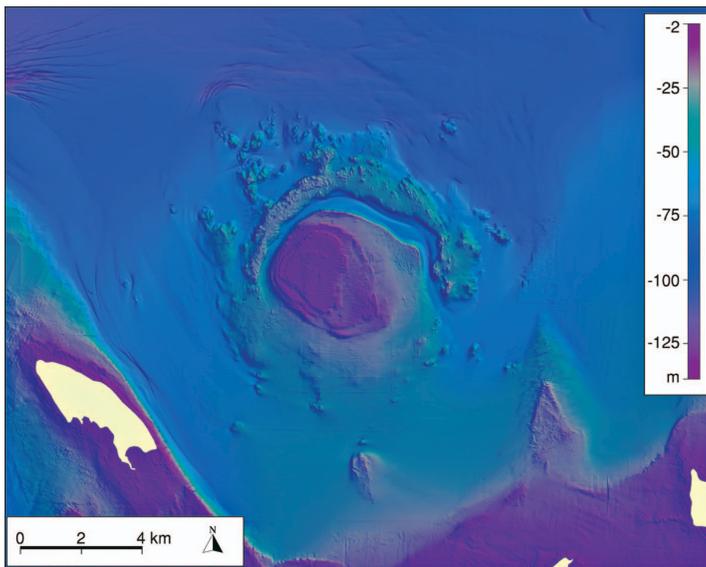
Fig. 4. The shaded relief image of seabed at the Neugrund impact structure area.

structural depression was first explained as a graben. The impact breccias that penetrated in the crater proper were interpreted as Precambrian tillites. Continued exploration of the area included detailed geophysical mapping by means of gravimetry and magnetometry and drillings of tens of wells (Puura & Suuroja, 1984). As a result, the crater structure was revealed and a hypothesis of a crypto-volcanic origin was put forward (Puura, 1974; Suuroja et al., 1974).

Impact breccias, shocked quartz and other features of shock metamorphism were found in thin sections in the late 1970's (Suuroja et al., 1981). The impact origin of the structure was recognized using these data. Subsequently, numerous wells were drilled in the course of several geological mapping and prospecting projects in the crater area (Suuroja et al., 1991, 1994). While prospecting for mineral water, the well K-18 revealed that the central uplift reached massive crystalline basement rock from depth c. 400 m at the end of well to 443 m (Puura & Suuroja, 1992). An important feature of geophysical modelling is the lack of an observable geophysical signature of the central uplift (Plado et al., 1996). It can be ruled out that this would be a huge (more than 200 m in diameter) crystalline fragment (megablock), such as found in the

Chesapeake Bay drilling at Eyreville (Gohn et al., 2008). In the Kärdla case massive crystalline rocks represent the central uplift and are covered by more than 100 m uplifted (similar to uplifting rate of the central uplift) c. 50 m thick sequence of impact-related deposits (suevite-like breccias) (Suuroja & Suuroja 2002). The deepest (815.2 m) well in Estonia, Soovälja K-1, was drilled within the annular crater depression (Suuroja & Põldvere, 2002). The well reached the crater floor at the depth of 523 m, but continued through autochthonous impact-influenced (fractured, with a thin lens of breccias) crystalline basement metamorphic rocks to the bottom of the well. A total of 162 drill holes were drilled, revealing new information on the crater structure, deposits and ejecta layer. Among them, 46 wells reached the impact breccias and the crystalline basement rocks, 64 wells reached the distal ejecta blanket or dislocated pre-impact target rocks, six wells reached the sub-crater basement inside of the crater proper (Puura et al., 2004; Suuroja and Suuroja, 2004).Continuous seismic reflection profiling along the northeastern margin of the Kärdla structure in the Kärdla Bay was made in 1996. It established the existence of the previously assumed ring fault (Suuroja et al., 2002). Along the outer slope of the crater wall, a sulphide ore with concentrations of galena and sphalerite was observed at the contact between the impact-influenced Early Cambrian sandstone and the covering Ordovician limestones (Suuroja et al., 1991; Suuroja, 2002). The c. 5 m thick ore body distinguished in the northeastern slope of the Paluküla Hill at a depth of c. 40 m contained up to 10 % of zinc, and up to 2 % of lead. Solid black asphaltite was found in the fractures and pores of the Ordovician limestones in the crater, as well as brownish blotches impregnated with liquid oil in argillaceous carbonate rocks. The latter are connected with a hydrocarbons inflow captured by the impact structures at Late Ordovician time (Kattai et al., 1990; Suuroja, 2001).

2.2 The Neugrund impact structure

Early in the 20th century, Öpik (1927) and Thamm (1933) described a breccia-like rock, a gneiss-breccia, from large erratic boulders found in the coastal area of NW Estonia and Osmussaar Island. Later the gneiss-breccia boulders were described by Orviku (1935) and Viiding (1955), but the origin of the boulders was not discussed. In the course of geological mapping in NW Estonia, the upper part of the Early Cambrian sequence was found to contain intervals of brecciated clay- and sandstone (Kala & Eltermann, 1969; Suuroja et al., 1987). It was later noted (Suuroja & Saadre, 1995) that the gneiss-breccias are macroscopically very similar to the clast-supported impact breccias found in the drill core sections of the Kärdla meteorite crater. They suggested that the erratic boulders of gneiss-breccia were supposedly glacially transported from an impact structure located in the Neugrund Bank area. The surroundings of the Neugrund Bank were investigated in Estonian-Swedish marine geological co-operation for the first time in 1996 by seismic reflection profiling and sediment soundings (Fig. 5). The seismic data was recorded in the frequency band of 250–500 Hz, and the sediment sounder data at 4 kHz. The profiling revealed a crater-like structure with a c. 7 km rim-to-rim diameter. Suuroja (1996) presumed the impact to have occurred in the Early Paleozoic (c. 475 My). Somewhat later, quartz grains with PDFs (planar deformation features) were found in the gneiss-breccias, which made the impact origin of the structure even more probable (Suuroja et al., 1997). In 1998, samples were collected by scuba divers from the submarine outcrops of brecciated Precambrian metamorphic rocks, and quartz grains with PDFs were found. Herewith, the impact origin of the Neugrund structure was proved (Suuroja & Suuroja, 1999, 2000).

During fifteen years in 1998–2012, the Neugrund impact structure area was the subject of sixteen marine expeditions, using seven separate research vessels (Mare, Marina and Salme from Estonia, Strombus and Skagerak from Sweden, Humboldt and Littorina from Germany). R/V Mare of the Estonian Maritime Museum has participated in nine expeditions and all scuba diving has been done from this ship. The total number of diving sites is 25. Submarine sequences of bedrock were documented and sampled along the edge of the central plateau at the depth 2–46 m during scuba diving. Impact influenced Precambrian metamorphic rocks were
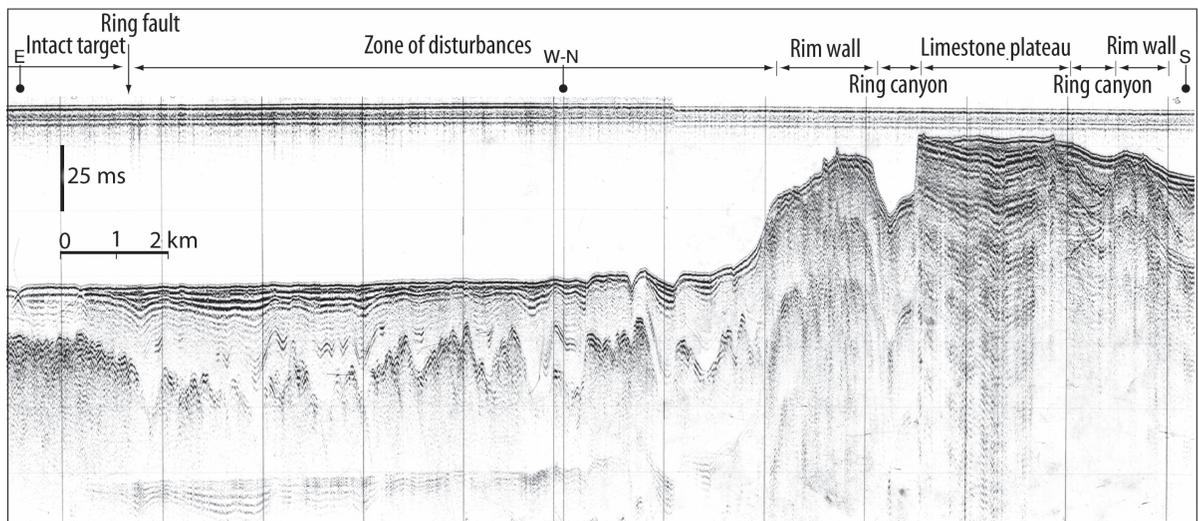
Fig. 5. N-S direction seismic reflection profiling record across the Neugrund structure carried out in 1996 on board of the R/V Strombus. Space between vertical lines 10 minutes or c. 1.8 km. The recorded signals are filtered frequency band 250–500 Hz using a single channel Air-gun system.
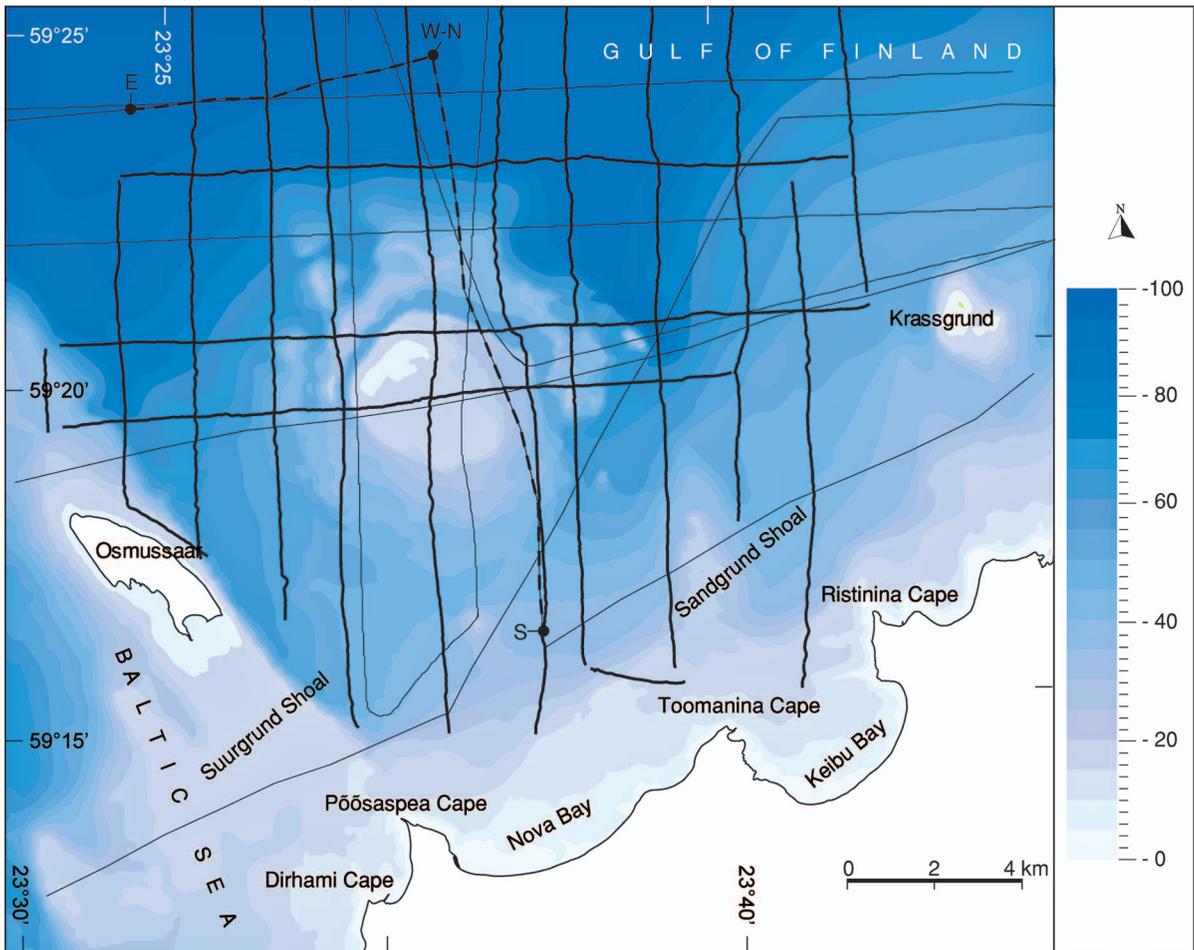
Fig. 6. Seabed relief of the Neugrund meteorite crater area. The thinner lines indicate the location of seismic reflection profiles shot in 1996–2004. The thick lines indicate the location of seismic (PAR) reflection profiles shot in 2010.

likewise documented and collected along the rim wall and the zone of dislocations at the depth of 16–34 m (Fig. 7).

As a rule, the exposures were recorded by a Sony camcorder accommodated with ikelite underwater systems during diving. Additionally, submarine outcrops were observed using a remote operated vehicle (ROV) camera system SeaLion and side-scan sonar. The diving sites include: 1) the limestone sequence of the central plateau and the crater infill from the precipice, 2) the impact influenced Precambrian metamorphic rocks of the rim wall, 3) impact influenced Precambrian meta-
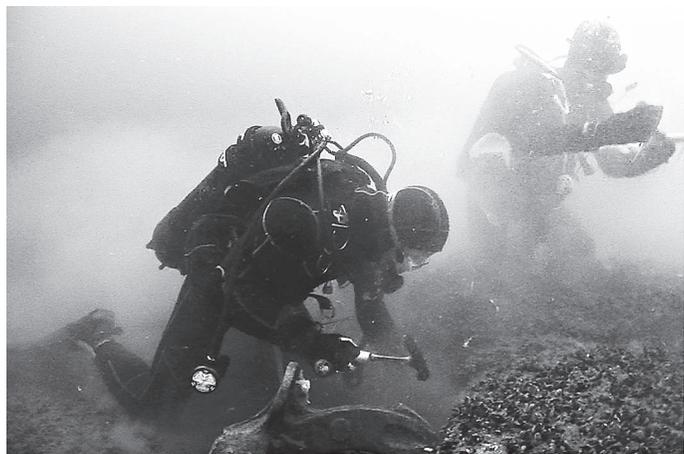
Fig. 7. Geologist scuba diver sampling a submarine outcrop of Pre-cambrian metamorphic rocks.

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morphic rocks of erratics located inside the zone of dislocations, 4) submarine outcrops of post-impact sedimentary rocks in surroundings of the crater.

Seismic reflection profiling is the most extensively applied method for the investigation of the structure, in total approximately 1000 km of profiles were shot. Most of them (c. 400 km) were shot in 2010 (Fig. 6). A grid of 20 profiles with average lengths of 20 km were shot across the structure during this expedition. The profiling was performed using a single-channel Airgun system, PAR–600 at 12 MPa. The recorded signals were frequency filtered 250–500 Hz in order to penetrate the sedimentary bedrock to the basement with high resolution. The Chirp spread spectrum (CSS) technique was simultaneously used to obtain high-resolution records of the Quaternary deposits. The Edge Tech low-frequency (0.5–12 kHz) sub-bottom profiler was used.

3. Geological setting

At Kärdla, as well as at Neugrund, the meteorite hit the seabed at sites with rather similar regional geological setting, the Early Palaeozoic Baltic epicontinental basin on the East European Craton. The basin extended across the present Russian Platform and also covered large parts of the neighbouring Fennoscandian Shield. At both sites, Precambrian migmatized metamorphic rocks underlie the sedimentary (mainly siliciaclastic) rocks. Consequently, the allochthonous impact breccias are composed of a mix of sedimentary and metamorphic rocks. Also, at both sites, the crater extended through the sediments and into the topmost part of the crystalline basement rocks. The basement rocks belong to the c. 1.9 Gy old Paleoproterozoic Orosirian Period of the Svecofennian Crustal Domain (Kirs et al., 2009). In both areas the Svecofennian crust is about 45 km thick (Puura & Flodén, 2000). The metamorphic rocks are found in the polymict breccias, and in huge allochthonous brecciated boulders near the main crater structures. They are similar to the crystalline basement rocks drilled in the surroundings of both crater sites. Both crater structures, that formed in the sea basin, were

soon (probably within a few million years) buried under sediments.

In Kärdla, the meteorite struck in a shallow epicontinental sea where at that time bioclastic limy muds were deposited (Fig. 8). According to different authors various water depths at the impact site have been proposed: 20 m (Puura & Suuroja, 1992), c. 50 m (Suuroja et al., 2002), 50–100 m (Lindström et al., 1992), c. 100 m (Suuroja & Suuroja, 2006), more than 100 m (Suuroja, 2008).
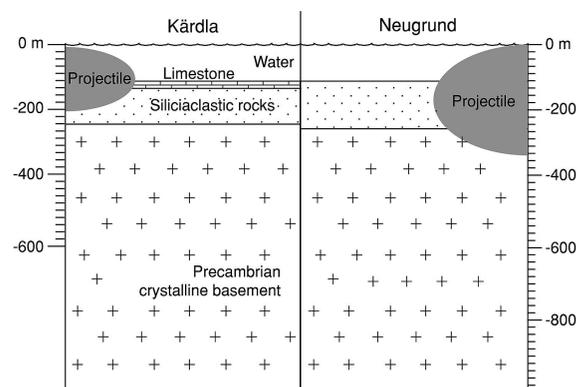
Fig. 8. Setting of the targets and projectiles of the Kärdla and Neugrund meteorite impacts.

Shuvalov (2002) demonstrated by numerical modelling of impacts in shallow sea areas that if the water depth is less than 100 m, the resurge initiated by the impact cannot be strong. However, based on the quantity of the resurge breccias in the Kärdla crater, it was relatively strong. Probably, ample quantity of resurge breccias is associated with the collapse prior to the entry of the resurge (Sturkell et al., 2013).

The criteria for estimation of sea depth at impact sites emit from the pre-impact sedimentation facies signatures. Ainsaar et al. (2002) proposed that the water depth in a crater area, where bioclastic argillaceous-calcareous limy mud are deposited, may vary from some tens of meters (i.e. below level of the storm waves in epicontinental seas) down to more than 200 m.

At present, the thickness of the pre-impact sedimentary bedrock in the area is c. 140 m. Middle
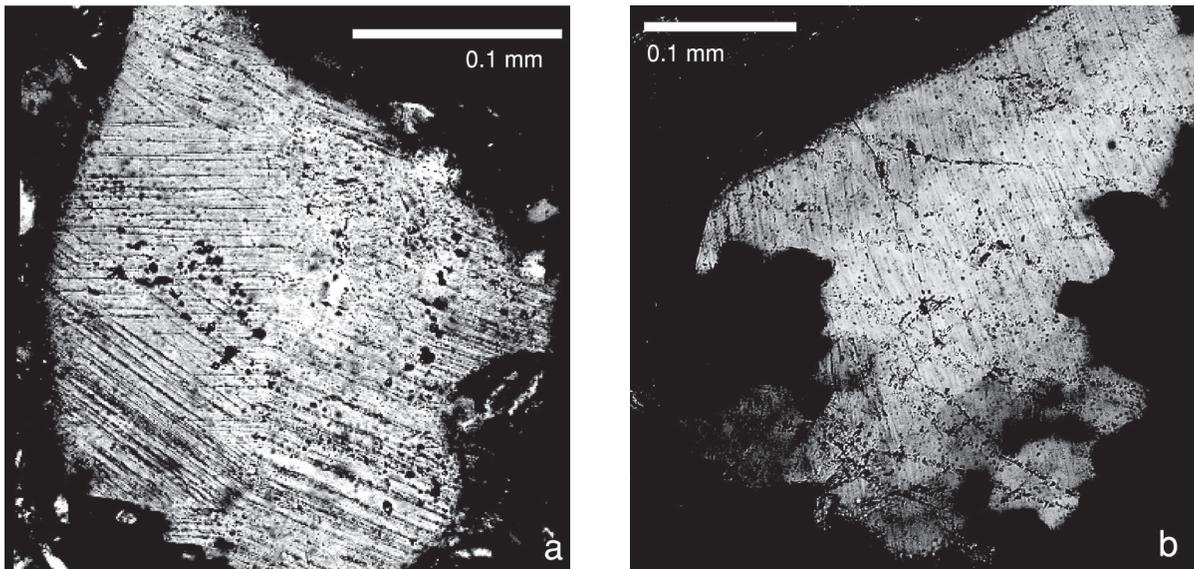
Fig. 9. Shock-metamorphosed quartz grains (PDF-quartz) with multiple PDFs from the impact related rocks of the Kärdla and Neurund impact structures. (a) Quartz grain with 3 sets of slightly decorated PDFs. Sample from a matrix supported impact breccia of Kärdla crater. Thin-section, cross-polarised light. (b) Quartz grain with 3 sets of slightly decorated PDFs. Sample from a vein of matrix supported impact breccia from the brecciated crystalline basement rocks of the Neugrund crater. Thin-section, cross-polarised light.

Ordovician limestones form the uppermost 14 m of this complex. The next subjacent 8 m are composed of Lower Ordovician weakly lithified sandstones (glauconite sandstone and Obolus or detritic sandstone) and alum (*graptolite*) shale. The Ordovician unit is underlain by an about 120 m thick complex of weakly lithified Lower Cambrian sandstones, siltstones and clays. At the time of the impact, the sandy and silty sequence was less consolidated and therefore much thicker than at present. The topmost part of the crystalline basement (5–25 m) is weathered and rocks are enriched with the secondary minerals illite and kaolinite. At the Kärdla site, the polymict impact breccias are composed of three main lithological types: 1) carbonate rocks, 2) siliciclastic to clayey sedimentary rocks, and 3) a variety of crystalline rocks. At the Neugrund site, mainly crystalline rock-derived clastic breccias are found now. Magnetic modelling (Suuroja et al., 2002) indicates that impact breccias are expected to be present in the crater deep (Fig. 10; Fig. 11).

In the Neugrund case the cross-section of the target is best documented by the nearest well that is located on the Osmussaar Island and penetrates all rocks of the pre-impact target (Suuroja and Suuroja, 2000). A c. 150 m thick layer of unconsolidated fine-grained siliciclastic sediments covered the Precambrian crystalline basement at the time of the impact. Presently the compacted c. 100 m thick pre-impact succession is composed of Early Cambrian sandstones, siltstones and clays of the Lontova Formation (c. 40 m) on top of a complex of weakly lithified quartzose sandstones (c. 60 m) of the Neoproterozoic Ediacaran Period.

The depth of the sea, where the blue clay with interlayers of silt and fine- to middle grained quartz sand was deposited, is estimated to have been 50–100 m (Suuroja & Suuroja, 1999).

4. Age of the structures

The ages of the Kärdla and Neugrund impact structures are determined by biostratigraphic dating of the distal ejecta layers inside of marine sedimentary record of the Upper Ordovician and Lower Cambrian sequence, respectively. In Kärdla, where the ejecta layer is represented by a sandy
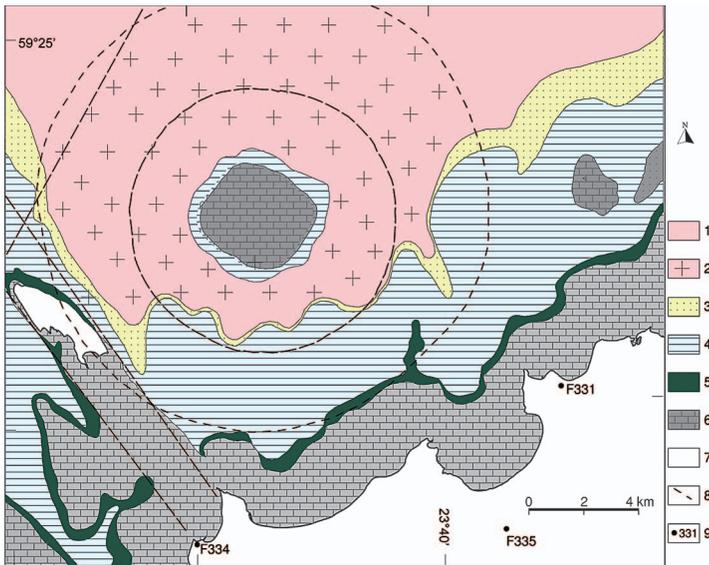
Fig. 10. Schematic bedrock geological map of the Neugrund impact structure area. Legend: 1 – Precambrian (Orosirian) metamorphic rocks; 2 – impact disturbed Precambrian metamorphic rocks; 3 – pre-impact (Ediacaran and Lower Cambrian) siliciclastics (clay-, silt- and sandstones); 4 – post-impact Lower Cambrian siliciclastics (clay-, silt- and sandstones); 5 – Lower Ordovician siliciclastics (sandstones and alum shale); 6 – Ordovician limestones; 7 – Land; 8 – Fault; 9 – Drill hole and it's number.
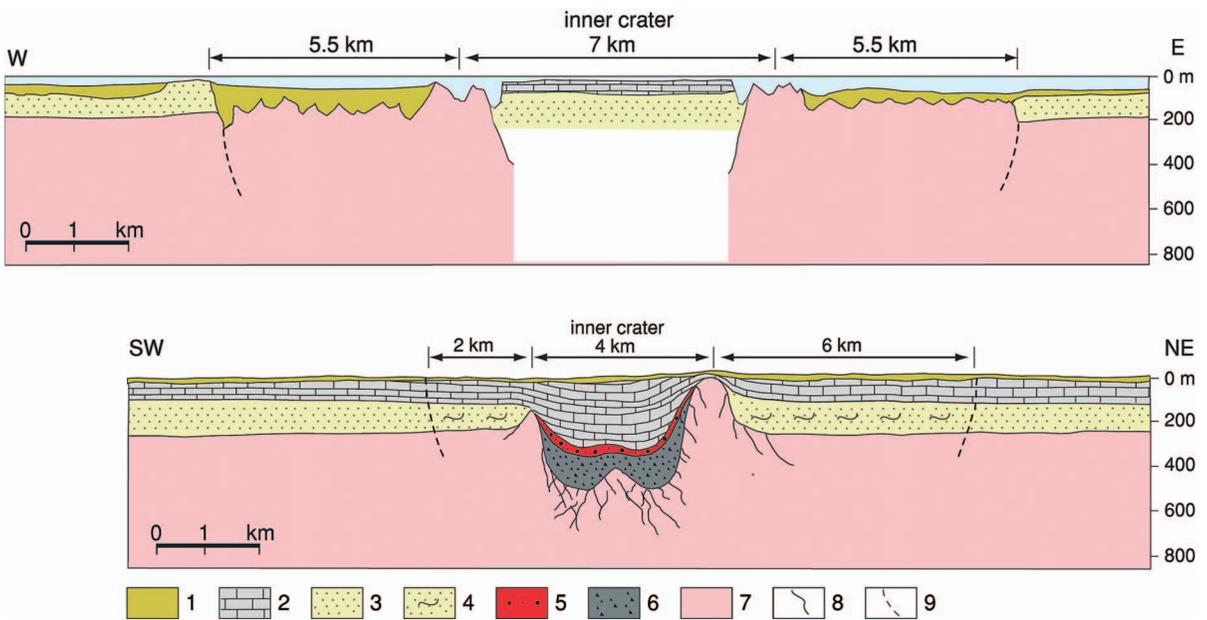
Fig. 11. Comparative schematic west-east gross-sections of the Kärdla (lower) and the Neugrund (upper) impact structures. Legend: 1 – Quaternary deposits; 2 – Ordovician limestones; 3 – Ediacaran and Lower Cambrian siliciclastics (clay-, silt- and sandstones); 4 – Disturbed Ediacaran and Lower Cambrian siliciclastics; 5 – Crater filling siliciclastics; 6 – Impact-related deposits (impactites); 7 – Precambrian (Orosirian) metamorphic rocks; 8 – Fractures; 9 – Supposed ring fault.

interval in the limestone sequence, it is well defined. In Neugrund, where the distal ejecta are represented by a sandy layer inside of a sequence of Early Cambrian sandstones, it is more difficult and possible only by the findings of quartz grains with PDFs (Suuroja & Suuroja 2004) (Fig 9). Small crystalline fragments are very rare.

The age of the Kärdla impact was established using the stratigraphic position of the sandy ejecta layer inside the limestone sequence. The estimated level of the ejecta layer was the lowermost part of the Idavere time, Caradoc Age, Upper Ordovician

Epoch (Suuroja et al., 1974). Bauert et al. (1987) suggested the same age of the impact using biostratigraphical dating of the distal ejecta layer in the chitinizoan zonality of the continuous sequence of the Ordovician carbonate sediments. Grahn et al. (1996) determined the precise level of the ejecta to be above the occurrence of *Cyathochitina* cf. *Reticulifera*, but below the appearance of *"Eremochitina" dalbyensis* (Laufeld). This level corresponds to the lowermost *Diplograptus multidens* graptolite zone. The determined level corresponds to the absolute age of about 455 My (Upper Ordovician, Katian Age) in the International Stratigraphic Chart.

The Neugrund impact event was initially suggested (Suuroja, 1996; Suuroja et al., 1997) to be connected to the about 475 My old so called Osmussaar-breccia, which consists of breccia-like sandstone dykes that crop out on the Osmussaar and Suur-Pakri islands. Dykes are also present in some drill holes on the NW Estonian mainland inside of a c. 1 m thick Middle Ordovician limestone sequence. The oldest rock sampled from the in-filling deposits of the crater proper was collected from a water depth of 46 m. The sample consists of Early Cambrian sandstone of the Tiskre Formation and is at least about 530 My old (Suuroja & Suuroja, 2000). Probably the real age of the crater is better estimated by the ejecta layer above of the blue clays of Lontova Formation (Early Cambrian Terreneuvian Epoch). The c. 2 m thick ejecta layer has been studied at a distance of 13 km from the impact centre (Suuroja & Suuroja, 2004). Biostratigraphically the deposits reflecting the impact event belong to the pre-trilobite Early Cambrian *Platysolenites antiquissimus* biozone of the East-European Craton.

5. Morphology of the structures

Kärdla and Neugrund complex impact structures have principally quite similar morphology. The inner craters (diameter 4 and 7 km, respectively) are surrounded by about three times larger (diameter 12 and 18 km, respectively) outer structure, or rather, zones of disturbances. In the case of the Neugrund structure, the inner crater and the outer structure bounded by the ring fault are positioned more or less symmetrically, whereas in Kärdla the centre of the inner crater is offset about 2 km to the north-east. The rim walls of both the Kärdla and Neugrund craters is composed of brecciated and impact-tectonically uplifted blocks (structural uplift) of crystalline basement rocks.

The Kärdla and Neugrund impact structures are rather similar to the Ries Nördlingen (Germany) and Gosses Bluff (Australia, Northern Territory) impact structures. The Ries impact structure, which is about 14,5 My old and has an outer diameter of c. 24 km and a c. 8 km wide inner crater (Engelhardt et al., 1995). The some 142 My old Gosses Bluff crater has c. 6 km wide inner crater and a total diameter of c. 22 km (Milton et al., 1996). The outer zone, which in Kärdla and Neugrund is interpreted as a zone of dislocations, is in Ries known as a zone of megablocks. In both cases the zones are characterized by the occurrence of deformed megablocks of crystalline and sedimentary target rocks. In Ries, all outcrops are concentrated to the outer limit of the structure, whereas in Neugrund the submarine outcrops are connected with the internal rim wall (Table 1).

The Kärdla concentric impact structure is about 12 km in diameter and has an inner crater rim-to-rim diameter of about 4 km. The outer limit of the structure, as marked on the seafloor by a semicircular ridge of narrow shoals, and on land by a semicircular ridge of glaciofluvial hillocks. The preserved rim wall of Precambrian metamorphic rocks has been uplifted 50-250 m higher than the crystalline basement in surroundings. It is higher in the northeastern segment of the rim (the so called Paluküla segment). The rim is marked in relief by bedrock uplift along a line of villages, Kärdla, Paluküla, Lõpe, Ala and Tubala (Figs. 2 & 3). The rim wall is about 1 km wide. The well F241 (Fig. 2), drilled on the topmost part of the rim wall on the Paluküla Hill, penetrated a complex of Pre-cambrian metamorphic rocks, which are fractured and at times cut by the dykes of impact breccias, within c. 240 meters. Only above of the gullies the rim wall is up to 200 m lower. The outer wing of

Table 1. Kärdla and Neugrund complex impact structures and other similar structures in the world.

Nr	Name of the structure (location)	Country	Composition of target	Diameter of structure km	Diameter of inner crater, km	Ratio of diameters of the structures crater	Age, My	References
1	Kärdla	Estonia	Mixed	12	4	3	455	Puura & Suuroja, 1992
2	Neugrund	Estonia	Mixed	18	7	2.6	535	Suuroja & Suuroja, 2004
3	Ries Nördlingen	Germany	Mixed	24	8	3.0	14.5	Englehardt et al., 1995
4	Gooses Bluff	Australia	Sedimentary	22	6	3.6	142	Milton et al., 1996
5	Mjölnir(Barents Sea)	Norway	Mixed	40	16	2.5	142	Dypvik et al., 2006
6	Lawn Hill	Australia	Mixed	18	8	2.2	515	Shoemaker & Shoemaker, 1996
7	Shoemaker (Teague Ring)	Australia	Crystalline	30	12	2.5	570	Shoemaker & Shoemaker, 1996
8	Clearwater West	Canada	Crystalline	32	12	2.7	290	Simonds et al., 1978
9	Mistastin	Canada	Crystalline	28	8	3.5	35	Robertson & Grieve, 1975
10	Upheavel Dome	USA	Sedimentary	10	3	3.3	170	Kenkmann et al., 2005
11	Oasis	Libya	Sedimentary	18	5	3.6	120	Koeberl, 1994
12	Aorounga	Chad	Sedimentary	13	5	2.6	515	Koeberl, 1994
13	Araguainha	Brasil	Mixed	40	13	3.1	245	Crosta, 2004
14	Serra da Gangalha	Brasil	Mixed	12	3	4.0	300	Romano & Crosta 2004
15	Vargeao Dome	Brasil	Mixed	12	4	3.0	70	Crosta, 2004.

the crystalline rim is at least locally overthrusting the disturbed Early Cambrian clay- and sandstone strata (Puura & Suuroja, 1992). These strata are most intensely deformed in the near-rim zone, containing isolated large blocks of crystalline rocks. The zone of dislocations, also named the outer crater, is 2–6 km wide. The sedimentary targets rocks within this zone, especially the Cambrian siliciclastic rocks, are deformed, i.e. fractured and folded. Occasional blocks of crystalline basement rocks occur there as well, especially close to the rim wall. The limit of the target deformation is bounded by the ring fault. The asymmetric location of the inner (nested) crater and the ring fault, as well the variable height of the rim wall, may be the result of an oblique impact in a layered target and possible slumping of sections of the wall (Sturkell et al., 2013).

The Kärdla crater has a central uplift that is at least 130 m high and about 800 m in diameter. Jõeleht argues (personal communication) that on the basis of data obtained in seismic reflection investigation the central uplift must be somewhat higher and that its centre is located a couple of

hundreds meters northeastward from the well K-18 that was formally suggested to be the centre of the structure.

The Neugrund impact structure forms a prominent shoal area on the seafloor, the Neugrund Bank. The some 5 km wide bank area that covers the crater proper consists of limestone at the surface. The about 7 km wide rim wall of the inner (nested) crater surrounds it. The rim wall forms a semi-circular ridge of *roche moutonnées* (or sheepbacks). The outer limit of the structure has a diameter of about 18 km. As there are no exposures, and as the water is too shallow for the seismic profiling method to reach deep enough, presence of a central uplift inside of the crater, which a crater of the size of Neugrund should have, has not been proven yet. Deformed sedimentary target rocks (Ediacaran and Early Cambrian siliciclastics) and huge (up to 0,5 km diameter) blocks of deformed crystalline basement rocks occur within the outer part of the structure. These crystalline blocks are mapped with seismic reflection and side scan sonar profiling, and also sampled and documented by diving geologists. The ring fault encircling the outer crater is

considered as the outer limit of the structure. In the western and northwestern parts of the structure it is expressed as an up to 80 m high escarpment in crystalline target rocks. In the eastern and southern parts of the crater the limit is not so clear. It is expressed there by a fault zone or by an up to 20 m high escarpment in crystalline target rocks. The preserved rim wall, which crops out in the northern segment but is partially buried in the southern segment, consists of crystalline basement rocks. It is about 1 km wide and approximately 150 m high.

6. The geophysical fields of the structures

The Kärdla impact structure appears clearly on gravity, ground maps and aeromagnetic maps. Data for these maps have been recorded at a scale of 1:50 000 (Suuroja et al., 1991; Plado et al., 1996, 1999). The maps show negative anomalies over the crater depression that is filled with low-density (average 2.4 g/cm³) and practically non-magnetic sedimentary rocks. Positive anomalies correspond to the rim wall consisting of magnetic crystalline rocks of higher density (average 2.7 g/cm³). On the gravity (Bouguer) map, the crater appears as a pronounced wall against the background of the rather monotonous gravity field of the Hiiumaa Island. On the large-scale gravity (residual) anomaly map, where effects of deep-seated sources have been removed, height differences within the rim wall, as well as the lower areas in its northern and southern parts are clearly visible. As visible anomalies along the ring fault do not occur, we assume that the mass dislocations between the rim wall and the ring fault are mostly present in the sedimentary cover, but do not reach substantially the crystalline basement.

The Neugrund impact structure does not appear clearly on the aeromagnetic maps. Gravity maps for that area have not been compiled and therefore size of gravity anomaly evoked by the impact is not revealed. On the other hand, the Neugrund structure is well investigated by seismic reflection and magnetic methods, the volume of the crater proper by magnetic modelling (Suuroja et al., 2002). The latter was supported by petrophysical data of

samples collected from the crater rim and erratic boulders derived from the structure area.

7. The projectiles

The Neugrund and Kärdla impact structures belong obviously to a group of a number of Early Paleozoic meteorite craters limited to the Baltic Sea and its surroundings of about 1 000 000 km² (Puura & Plado, 2005). Apart from Neugrund and Kärdla, the group includes: Suvasvesi North (560–530 My, diameter (D) 4 km; Pesonen, 1996); Söderfjärden (540–520 My, D 6.6 km; Lehtovaara, 1992), Granby (c. 410 My, D 2 km; Alwmark, 2009); Lockne (458 My, D 7.5 km; Lindström et al., 1996) and a small crater Tvären (457 My, D 2 km (Lindström et al., 1994). This is one of the largest concentrations of impact structures of the 550–450 My age group. It has recently been speculated (e.g. Schmitz & Alwmark, 2006; Schmitz & Häggeström, 2006) that these and dozens (Korochantseva et al., 2007) of other Early Paleozoic craters on Earth might be a result of collapse of a huge (more than 100 km in diameter) L-chondritic chromite-rich asteroid. The latest geochemical research (Puura et al., 2004) revealed that the Kärdla meteorite most probably was of chondritic composition. According to the geochemical composition of the impact breccias (Suuroja and Suuroja, 2000) the Neugrund impact structure is similar to Kärdla. Melosh (1989) argues that the diameter of a crater should be approximately 20 times larger than diameter of a projectile. According to Ormö et al. (2013), this scaling is made for craters in a homogenous target not a concentric impact structures formed in a layered target where weaker sediments rocks covered a hard crystalline basement rocks. Therefore, the diameters of the Kärdla and Neugrund craters should be c. 4 and c. 7 km and the diameters of the projectiles c. 200 m and c. 350 m, respectively.

8. The ejecta layers

The ejecta layers have survived at some distance from the rim wall in the Kärdla and Neugrund impacts. In Kärdla, where the sandy bed presents the ejecta

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layer in the limestone sequence, it is easily recognizable, but in Neugrund, where we have the sandy layer in the sandy sequence, it is distinguished only by the findings of PDF-quartz.

In Kärdla, the ejecta layer is composed of debris of both crystalline (metamorphic) and sedimentary (siliciclastic and carbonate) rocks. Fragments of crystalline rocks are found as far as c. 20 km from the crater centre, and chips of sedimentary rocks, limestones, alum shale and Cambrian clays, at 15 km. In the ejecta composition, there is always a portion of fine-grained sandy, silty and clayey material derived from disintegrated Cambrian and Ordovician sedimentary rocks. From the distance of 20 km and up to as far as 40 km, the impact-related siliciclastic layer cemented by carbonates is composed only of sandy to clayey material. The ejected matter contains PDF-quartz (Suuroja and Suuroja, 2006).

In Neugrund, where the ejecta layer it is presented mostly by the sandy bed in the sandy succession, determination is more difficult and established only by means of findings of PDF-quartz. At first the ejecta layer was distinguished in the c. 2 m thick quartzose sandstone layer in Early Cambrian siliciclastic deposits (silt- and sandstones of the Sõru Formation) in the core section of F331 (Ristna, Fig. 10), which is located about 15 km from the impact centre to south-east (Suuroja & Suuroja, 2006).

9. The PDF-quartz

The findings of PDF-quartz were one of the important evidences in proving of the meteoritic origin of the Kärdla (Suuroja et al., 1981) and Neugrund (Suuroja et al. 1997) impact structures (Fig. 9). PDF-quartz is widespread in Kärdla in suevite-like and clast and matrix-supported impact breccias, which are distinguished in the crater proper. PDF-quartz occurs also, but rarely, in the post-impact siliciclastic and quartz grains containing carbonate rocks. Generally, quartz with PDFs is not found in brecciated sub-crater and rim wall. Quartz with PDFs is considerably rare in blocks of crystalline basement rocks and allochthonous breccias. However, it is common in rounded quartz grains of

clast and matrix-supported impact breccias. Quartz with PDFs is rare in the sedimentary polymict breccias in the crater deep, which consist mainly of brecciated Cambrian siliciclastic rocks, and is connected with lenses and bombs of suevite-like and clast and matrix-supported impact breccias. In the resurge breccias quartz with PDFs occurs mainly in the ejected suevite clasts and clast and matrix-supported impact breccias, which were carried back by the resurging wave. The sedimentary rock blocks do not contain PDF-quartz, but it is rarely encountered in the mixtolite-like filling between blocks. In quartz grains, up to five sets of PDFs of different crystallo-graphic orientations have been observed. These confirm shock pressures in excess of 10–14 GPa (Suuroja et al., 2002) or 10–20 GPa (Puura et al., 2004).

In Neugrund, the interior of the crater deep is still buried under post-impact deposits and therefore the most strongly shock-metamorphosed rocks are not accessible there. Suevites, clast and matrix-supported impact breccias that contain quartz with PDFs originate from rocks of the rim wall, from the distal deformed sedimentary target rocks, from the ejecta layer or from the redeposited impact-metamorphic materials as the Osmussaar breccias. Quartz with PDFs on the islands of Osmussaar and Suur-Pakri is found in the veins and bodies of breccia-like limy sandstone (Osmussaar breccia) (Suuroja et al., 2003). We suppose that quartz grains with PDFs of these veins and bodies are eroded from the nearby Neugrund impact structure. PDF-quartz has been found in samples of the submarine crystalline rim wall, and in similar rocks as erratic blocks along the seashore of NW Estonia. Consequently, in this case, the quartz with PDFs has formed in the crystalline basement, which was impact-tectonically transported to form the rim wall.

In quartz grains, up to five sets of PDF-s with different orientations were observed. In a single grain with up to three sets of PDFs were found. The frequency of the lamellae is 200–400 per 1 mm and these are frequently decorated with fluid inclusions (Kirsimäe et al., 2002; Suuroja, 2007). The shape and size of the quartz grains with PDFs indicate

that mainly the impact sedimentary target rocks (Cambrian and Ediacaran silt- and sandstones) have been the source of grains with shock metamorphic signatures and only a small part (angular grains) from the Precambrian metamorphic rocks have contributed.

10. Discussion and conclusions

The geological conditions during Cambrian and Ordovician were similar across most part of Baltoscandian platform. A thin sedimentary blanket, merely a few hundred meters thick, under the shallow (less than 200 m) epicontinental sea, covered the Precambrian crystalline basement (Männil, 1966; Mens & Pirrus, 1997). The comparatively large meteorites passed through the water layer and the sedimentary cover and finally exploded in the topmost of the Precambrian crystalline basement.

In Kärdla, we have observed and documented variable degrees of breaking and disintegration of rock bodies, and a variety of their vertical and horizontal transfers during the impact (Puura & Suuroja, 1984; Puura et al., 1987), and post-impact history (Kleesment et al., 1987; Ainsaar et al., 2002). In the exterior of the crater, within the in-situ broken and mixed target limestone layer, above referred as "limestone breccias", rock debris is abundant, originating from crystalline basement, the alum shale and Cambrian to Ordovician sand, silt and claystones (Suuroja, 2008).

The ring-shaped inner rim of both the Kärdla and Neugrund impact structures, are composed of particularly brecciated and impact-tectonically uplifted blocks (structural uplift) of the Precambrian metamorphic rocks. The Kärdla crater has only one about 1 km wide quite circular and monolithic crystalline-composed rim wall. Its height is variable, from maximal 250 m above the primary position (the Paluküla segment on the northeastern part of the rim) to only 50 m in gullies. The outer wing of the crystalline rim is at least locally overthrusting the Lower Cambrian sandstone strata (Suuroja et al., 1991; Puura and Suuroja, 1992). The latter are most intensely deformed in the near-rim zone,

containing also isolated large blocks of crystalline rocks. The target structure in a 4-km wide external zone next to the Paluküla segment of the rim wall is uplifted some tenths meters, and sedimentary rocks are deformed there. The outer limit of the gradually weakening stage of target deformation is fixed by the ring fault of the Kärdla structure (some 12 km in diameter). At the Neugrund crater, the zone of deformed and a mixed crystalline and sedimentary rock starts at 4 km from the centre. According to seismic reflection profiling data and scuba diving results, the external c. 6 km wide zone of dislocations is composed of blocks of the deformed crystalline and sedimentary rocks. The sedimentary blocks are mostly eroded, crystalline are preserved. The ring fault encircling that zone, with a diameter of c. 18 km, is considered as the outer limit of the structure.

In the crater interior, the main impact breccia units have different compositions due to the variety of the source materials. In the Kärdla crater, the lowermost moderately cemented impact breccia unit, here referred to as "clast-supported impact breccias", is composed of dominantly fine-grained debris of crystalline rocks. There is always a portion of Cambrian-type rounded quartz present within it. Randomly, also mm to cm-size fragments of alum shale are found. In the cement of the breccias, there occurs a large portion of K-feldspar, clay minerals, smectite and in places also chlorite-corrensite. The breccia is, at least partially, hydrothermally altered (Kirsimäe et al., 2002). This breccia is similar to the suevite breccias found in young craters. Thus, we have also called it suevite (Suuroja et al., 2002). However, we cannot confirm the presence of genuine impact melt particles in it. The present mineral association is composed of smectites, chlorites and K-feldspar (Kirsimäe et al., 2002), in which quartz and part of the K-feldspar are the clastic components. recrystallized minerals originate from plagioclase, hornblende, biotite and clay minerals. The latter is derived from Cambrian rocks. Possibly there is a share on unidentified melt particles, too. This kind of breccia is also met at higher levels of the crater infill. In those cases, possibly in a secondary position due to the modification stage slump, resurge and other processes,

which are followed in the Chesapeak Bay (Gohn et al., 2008), Lockne (Sturkrll et al., 2013) and other impact sites . The middle and upper breccias of the crater interior are mainly dominantly composed of blocks of sedimentary rocks, claystones, sandstones and limestones. The blocks may have huge dimensions, up to tens of meters. Occasionally, in drill sections, a large portion of crystalline blocks may be mixed to the sedimentary dominance. Randomly, also fragments of suevite-like breccias are present. The veins of fine-grained sedimentary-derived cement between the blocks may be of different thickness, often, however, almost negligible.

As a whole, the large masses of sedimentary breccias are composed of primary layered material behaving as a compact substance. They have not been disintegrated into clay or sandy mass, or platy limestone fragments. Therefore we interpret the large volume of dominantly sedimentary-derived block breccias as a product of near-horizontal far-and-back replacements during the cratering, slumping and resurge processes. Principally, mixing of materials during the impact process is over-whelming. However, masses originated from certain positions may occasionally dominate here and there in the crater interior. The most homogenous breccia layer is the lowermost crystalline-derived suevitic breccia, with a small but still always observable admixture of Cambrian sand.

As a result, spatial replacement tracks of materials from their primary positions into different breccias or other clastic units in crater interiors and exteriors can be and have been traced. In the circum-Baltic area, the other 550–450 My craters are much more deeply eroded, or tectonically deformed (Lockne). In the Lockne case, horizontal movements of rock megablocks have been traced up to 100 m from the impact center (Sturkell et al., 2000; Ormö & Lindström, 2000). In Neugrund the, glacial erratic derived from the structure are budged more than 170 km to southward up to Ruhnu Island (Suuroja, 2008a).

The search for, and discovery of, new buried impact sites in geologically well-studied regions is possible using geophysical, remote sensing, and deep drilling techniques. In Neugrund, the search started with the establishment of the origin of specific gneiss-breccia erratics and of annular depressions on seabed encircling the Neugrund Bank (Suuroja and Saadre, 1995; Suuroja, 1996). In both cases, the discovery of the impact structures was connected with geological mapping (Kala & Elterman, 1969; Kala et al., 1971; Suuroja et al., 1981, 1987, 1991, 1994, 1997, 1998, 1999). Drillings at Kärdla were mostly carried out in the course of prospecting of mineral resources (e.g. Suuroja et al., 1974; Suuroja, 2002). As a whole, in areas with very stable platform sedimentary structure, all kinds of irregular and odd structural or lithological occurrences: stratigraphic "instabilities", geophysical anomalies, and, of course, findings of shock metamorphic minerals (PDF-quartz) should be treated as suspect phenomena when search for new craters.

Extraordinary stratigraphic and lithological phenomena accompanying impact structures in stratified geological environments attract the attention of researchers for at least two reasons. Distal ejecta layers in well-stratified sedimentary sequences give good opportunities for dating the age of craters. The method worked well in both Kärdla and Neugrund. In the surroundings of the Kärdla impact structure, the ejected matter (sandy layer in limestone sequence) is well traceable within a c. 50-km radius (Suuroja & Suuroja, 2006). In Neugrund, the ejecta are represented mostly by a sandy layer in a sequence of silt- and sandstones. Thus it is not as well traceable and is therefore exactly determined only due to the occurrence of PDF-quartz (Suuroja & Suuroja, 2000). Often a crater deep have formed traps for early to late post-impact sedimentary accumulation, with uninterrupted course of deposition. In the Kärdla crater, the record of volcanic ash interbeds (K-bentonites) within Ordovician limestone is much more complete than in the surrounding shallow shelf area of repeatedly interrupted low-rate sedimentation. In the shallow zones of the basin outside the rim ridges and uplifted target areas, local erosion and bioherm-type deposition areas occurred (Suuroja & Suuroja, 2002; Ainsaar et al., 2003). Eroded material from the ejecta blanket and rim wall influenced the post-impact sedimentation in the wider surroundings of the

crater. The specific lithological suites are distinguished as local litostragraphic units: Kärdla and Paluküla Formations and a number of members (Suuroja et al., 1994; Suuroja, 2008a). In Neugrund, only a distal ejecta layer with PDF-quartz grains has been found. We expect that many surprising stratigraphic, palaeoenvironmental and lithological patterns will be met when coring a drill hole into the Neugrund crater proper.

The size, internal structure and morphology of a crater may carry information about the projectile size, composition and trajectory. Both Kärdla and Neugrund impact structures have ring faults as the outer limits of their impact-deformed areas. Similar features have been observed at some other impact structures: Gosses Bluff, 22 km in diameter (Milton et al., 1996); Boltysh, 24 km in diameter (Gurov et al., 1998, 2003); Ries Nördlinger, 24 km in diameter (Engelhardt et al., 1996); Mjølnir, c. 40 km in diameter (Dypvik et al., 2006). The dimensions of the Neugrund and Kärdla impact structures have been under some discussion. For similar complex impact structures as Kärdla and Neugrund, the diameter of the structure has been defined as the ring fault or by the limit of the structure, thus separating strongly disturbed target rocks from mostly intact target rocks. Following this practice, the diameter of the Neugrund impact structure is c. 18 km and the one of Kärdla c.12 km, whilte the rim-to-rim diameter of the craters being 7 and 4 km, respectively. Pierazzo & Melosh (2000) and Shuvalov (2002) concluded that asymmetrical elements of a structure, height and width of a rim wall, elliptical shape of a ring fault etc., refer to oblique impacts. These features are revealed remarkably well in the Kärdla case, where the asymmetrically located ring fault and asymmetry in rim wall height could be explained by an oblique impact (Suuroja & Suuroja, 2006; Jõeleht et al., 2007) in a layered target (Sturkell et al., 2013). Chemical evidence suggests that the Kärdla projectile was probably of chondritic composition.

The asteroid c. 0.5 km in diameter approached from southwest (without corrections to plate drift and rotation) under a quite low angle, probably less than 30º. For the complex impact structures such kind of asymmetry in location of an outer and inner crater is quite rare. Exclusively, similar elements of asymmetry are traceable in about 570 My old Shoemaker (or Teague) Ring in Western Australia (Shoemaker & Shoemaker, 1996). The centre of the 30 km in diameter complex impact structure is budged about 8 km to westward concerning of the centre of the inner crater.

Acknowledgements

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