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Geology and lithology of the early
palaeozoic marine impact structures
Kärdla and Neugrund (Estonia)



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LIST OF ORIGINAL PUBLICATIONS

This thesis summarizes and synthesizes the following seven papers, four of which (I, III, IV and VII) concern of the Kärddla meteorite crater, two (II and VI) concern of the Neugrund meteorite crater and one (V) concerns of the Osmussaar event which is supposedly connected with Neugrund impact event. These papers are referred to in the text by Roman numerals I–VII.

- I** Puura, V. & Suuroja, K. 1992. Ordovician impact crater at Kärddla, Hiiumaa Island, Estonia. In: L. J. Pesonen & H. Henkel (eds). Terrestrial impact craters and craterform structures with a special focus on Fennoscandia. *Tectonophysics* 216: 143–156.
- II** Suuroja K. & Suuroja S., 2000. Neugrund Structure – the newly discovered submarine early Cambrian impact crater. In: I. Gilmour & C. Koeberl (eds) *Impacts and the Early Earth*. Springer-Verlag, Berlin–Heidelberg. *Lecture Notes in Earth Sciences* 91: 389–416.
- III** Suuroja, K., 2002. Natural resources of the Kärddla Impact Structure, Hiiumaa Island, Estonia. In: J. Plado & L. Pesonen (eds). *Impacts in Precambrian Shields*. Springer-Verlag, Berlin, Heidelberg. *Impact Studies*: 295–306.
- IV** Suuroja, K., Suuroja, S., All T. & Flodén, T. 2002. Kärddla (Hiiumaa Island, Estonia) – the buried and well-preserved Ordovician marine impact structure. *Deep Sea Research II* 46: 1121–1144.
- V** Suuroja, K., Kirsimäe, K., Ainsaar, L., Kohv, M., Mahaney, W.C. & Suuroja, S. 2003. The Osmussaar Breccia in Northwestern Estonia – Evidence of a 475 Ma Earthquake or an Impact? In: C. Koeberl, F. Martinez-Ruiz (eds.) *Impact Markers in the Stratigraphic Record*. Springer-Verlag, Berlin–Heidelberg. *Impact Studies*: 333–347.
- VI** Suuroja, K. & Suuroja. 2004. The Neugrund Marine Impact Structure (Gulf of Finland, Estonia). In: H. Dypvik, M. Burchell, P. Claeys (eds.) *Cratering in Marine Environments and on Ice*. Springer-Verlag, Berlin–Heidelberg. *Impact Studies*: 75–95.
- VII** Suuroja, S. & Suuroja, K. 2006. Kärddla Impact (Hiiumaa Island, Estonia) – Ejecta Blanket and Environmental Disturbances. In: C. Cockell, I. Gilmour, C. Koeberl (eds.). *Biological Processes Associated with Impact Events*. Springer-Verlag, Berlin, Heidelberg, New York, *Impact Studies*, 309–333.

AUTHOR'S CONTRIBUTION IN PAPERS:

Publication I: The author's contribution involves most of the field works and data collecting, interpretation of results and writing of the manuscript (about 50%).

Publication II: The author is responsible for half of the field works and data collecting, interpretation of results and writing manuscript.

Publication III: The author's contribution involves field works and data collecting, interpretation of results and writing of manuscript (about 50%).

Publication IV: The author is responsible for half of the field works and data collecting, interpretation of results and writing manuscript.

Publication V: The author is responsible for half of the field works and data collecting, interpretation of results and writing manuscript.

Publication VI: The author is responsible for half of the field works and data collecting, interpretation of results and writing manuscript.

Publication VII: The author is responsible for half of the field works and data collecting, interpretation of results and writing manuscript.

Related publications not included in this thesis are collected in the references.

ABSTRACT

The present doctoral thesis is dedicated to two marine complex meteorite structures in Estonia – Kärđla and Neugrund. These subsurface structures have been observed, distinguished and studied during the last 40 years. Here, geological conditions are favourable for survival and research of early Palaeozoic craters, and the two craters belong to this age group. The observed cratering rate in Estonia is the highest worldwide.

In Estonia are two large and old complex impact structures – Kärđla (Hiiumaa Island) and Neugrund (southwestern Gulf of Finland). Both these structures are buried under the post-impacts deposits. Rim-to-rim diameter of the mostly mainland Kärđla crater is 4 km and of submarine Neugrund – 9 km, their age is about 455 (Middle Ordovician) and 535 Ma (Early Cambrian), respectively. The landforms at these crater sites are not directly and easily recognizable as crater features. Due to subsurface setting of the structures different drilling and geophysical techniques were used. On the other hand, the near-surface, shallow position of the structures was favourable for such studies. Good survival of Kärđla and Neugrund structures makes them extraordinarily promising subjects for crater studies, and on the other hand – for search of unique regional geological and paleoenvironmental signatures possibly trapped in crater structures.

However, due to the present physical geographic positions of the Kärđla (on land) and Neugrund (at sea) craters, the methods and techniques available and used for their studies are different. The current stage of their studies also is very different.

The primary detailed research information on these structures is given in a number of reports on applied geological activities: geological mapping, prospecting for mineral resources and groundwater, which are also included in the list of referred works.

The results of the studies are published in a series of original papers (PAPERS I–VII). Geology and lithology as well as formation and development history of Kärđla and Neugrund impact structures are the main topics of these. Observations, methods and techniques, which finally led to discovery and description of these impact structures, are as well shortly presented.

Within the long list of c. 200 known craters the buried Kärđla and Neugrund craters belong to the few old, Early Palaeozoic structures weakly eroded and therefore with perfectly survived interior and almost perfectly survived external structural elements. Among the 26 impact structures (larger than 1 km in diameter) in Fennoscandia and Baltic region there are only 2–4 more structures, which have preserved almost as completely as Kärđla and Neugrund. The Kärđla structure is one of the best-studied structures in the region as well as worldwide.

KEY WORDS: meteorite, Kärđla meteorite crater, Neugrund meteorite crater, Osmussaar event, impact structure, marine impact structure, earthquake, shock metamorphism, impact breccia, Ordovician, Cambrian, mineral resources.

I. INTRODUCTION

This doctoral thesis is dedicated to two marine complex meteorite structures in Estonia – Kärđla and Neugrund that are the largest and oldest in the area. These subsurface structures have been discovered and thoroughly studied during the last 40 years. In Estonia, the geological conditions are favourable for survival and research of early Palaeozoic craters, and the present two craters belong to this age group. At the other six known and hypothetical impact sites in Estonia the craters are small and young, Holocene in age, formed on land after the Pleistocene continental glaciations. The recognition of so many small craters is probably due to the almost perfect survival of the natural landscape during the Holocene, in combination with a high level of geological mapping and special search of craters in Estonia. About seventy years ago the Kaali crater field on Saaremaa Island became (Reinwald 1937) the first firmly verified meteorite impact site in Europe. Subsequent search for and research of meteorite impact structures has been a substantial aspect of geological studies in Estonia and presently, seven impact sites – craters and crater fields – has reached 7. The observed cratering rate in Estonia is the highest worldwide.

Kärđla (Hiiumaa Island, 58°58'N, 22°46'E) and Neugrund (southwestern Gulf of Finland, 59°20'N, 23°31'E) structures are buried under post-impact deposits and do not outcrop to land/sea surface. Furthermore, the Neugrund crater is located below sea level. The rim-to-rim diameter of the mostly inland Kärđla crater is 4 km and of submarine Neugrund – 9 km. The age of the craters is about 455 (Middle Ordovician) and 535 Ma (Early Cambrian), respectively. Both structures are well preserved, which makes them extraordinarily promising subjects for crater studies, and furthermore for the search of unique regional geological and paleoenvironmental signatures that might be trapped in crater structures.

Due to subsurface setting of the structures different drilling and geophysical techniques were used. On the other hand, the near-surface, shallow position of the structures was favourable for such studies. However, due to the present physical geographic positions of the Kärđla (on land) and Neugrund (at sea) craters, the methods and techniques used for their studies are different. The current stage of their studies is also different.

The author of this dissertation has taken part in discovery and investigation of Kärđla and Neugrund structures since 1970-ies. The primary detailed research information on two structures is given in a number of reports on applied geological activities: geological mapping, prospecting for mineral resources and groundwater, which are also included in the list of referred works (see: Suuroja et al. 1974; Kala et al. 1974; Kala et al. 1976; Suuroja et al. 1981; Tassa & Perens 1984; Suuroja et al. 1987; Suuroja et al. 1991; Suuroja et al. 1994; Suuroja et al. 1997; Suuroja et al. 1998; Suuroja et al. 1999b). The current research has been completed in the course of regional studies and survey of mineral resources carried out by the Geological Survey of Estonia (EGK). The author

was responsible for the geological mapping and other applied research in NW Estonia. After the discovery of craters, respective research projects were launched at the Geological Survey of Estonia, but also at the Institute of Geology at the Tallinn University of Technology (then at the Estonian Academy of Sciences) and the Institute of Geology of University of Tartu.

The main scientific results on this research in the Kärđla and Neugrund impact sites and their surroundings are published in a series of original papers (see List of original publications). The geology, lithology, formation and development history of the two impact structures are discussed. Observations, methods and techniques, which finally led to discovery and description of buried and submarine impact craters are shortly described.

There is a shortage of detailed, systematic descriptions of craters, which are well preserved from subsequent erosion or other structural destruction in the world literature. Within the long list of 172 known (mainly terrestrial) craters, the buried Kärđla and Neugrund structures belong to the few old, Early Palaeozoic impact craters that are weakly eroded and therefore very well preserved interior and external structural elements. Among the 26 impact structures, larger than 1 km in diameter, in Fennoscandia and the Baltic region (Abels et al. 2002) there are only 2–4 more structures, which are preserved almost as well these two (Puura & Plado 2005). The Kärđla structure is one of the best-studied structures in the region and worldwide (PAPER IV).

The selected publications, listed above, contain information on the geological setting of the craters, the structure of the pre-impact target and the structure of the craters. Furthermore they contain data on the lithologies of the impact-deformed target rocks, the allochthonous impact-produced deposits, the post-impact filling and the covering deposits. The publications also contain data on the stratigraphic position of impacts, the lithological units, i.e. detailed impact stratigraphies, lithologies and related mineral resources. The impact and post-impact processes of their formation and their present structures are shortly described.

2. OBSERVATIONS, METHODS AND TECHNIQUES OF DISCOVERY AND STUDIES OF METEORITE CRATERS

2.1. Meteorite craters worldwide and in Estonia

Most of the known 172 recognized hypervelocity meteorite impact sites on Earth are located onland (c. 150 million km²) (Grieve 1987; Grieve et al. 1995; Grieve & Pesonen 1996; Gilmour & Koeberl 2000; Earth Impact Database (<http://www.unb.passc/Impact>). Yearly 3–5 new discoveries are added into the global crater record. Compared with other rocky planets or their natural satellites in the solar system this is a relatively small number. On the Moon, alone, there are identified more than 20 000 meteorite craters. The thick atmosphere and the large hydrosphere that covers 70.8% of the Earth surface, as well as the activity of geological processes has resulted in the low number of recognized impact structures on Earth.

Due to the active geological processes on Earth, even in the case of survival, most of the impact structures are soon heavily destroyed or hidden below sedimentary suites or water. Therefore, the recognition of impact structures requires some enthusiasm in observations and the application of special investigations. Presently, the average cratering rate on Earth is around 1 per c. 3 million km². In Fennoscandia, within an area of 3 million km² onland and offshore, about 60 proved and possible impact structures were discussed in 1991 (Henkel 1992; Pesonen & Henkel 1992). Due to the many specific field and laboratory studies, the number of identified craters in Fennoscandia reached 30 in 2005 (Abels et al. 2002; Puura & Plado 2005). Thus, cratering rate in Scandinavia reached 1 per c. 100 000 km².

The Estonian mainland is 45 277 km² and the aquatory is c. 75 000 km² which amounts to ca 0.015% of Earth. In 1970, the local list comprised four impact sites, including two crater fields (Kaali and Ilumetsa), two single craters (Tsõõrikmäe, Simuna) and two traces of meteorite impact (Lasnamäe, Vaidasoo). Thus, the cratering rate in Estonia is 1 per c. 10 000 km², which is about 300 times higher than on the Earth in average, and about 10 times more than in Fennoscandia. However, six of the structures in this list (Kaali, Ilumetsa, Tsõõrikmäe, Simuna, Vaidasoo and Lasnamäe) are small (less than 1 km in diameter) and less than 1 million years old. The lack of small (less than 1 km in diameter) and young craters in the cratering record of other countries is not easy to explain. Two explanations may be valid: a) adverse conditions of preservation of impact structures, b) insufficient search for small meteorite structures.

Although E. Öpik (1916) was one of initiators of the physical theory of meteor phenomena (impact theory), he was unsuccessful in discovering any craters in his homeland (Öpik 1916, 1936, 1958). Since 1922, when J. Kalkun suggested that the crater-shaped Lake Kaali on Saaremaa Island was of a

meteorite impact origin (Kalkun 1922), the geologists in Estonia have paid a lot of attention to possible impact sites. Starting a new cycle of field studies in 1927, I. Reinwald could already in 1937 prove the meteorite origin of the Kaali crater field. He found meteorite iron in a satellite crater (Reinwald 1937, 1938). Afterwards, many new small and two larger complex craters were found in Estonia (Tiirmaa 1997; Suuroja & Suuroja 2004; Tiirmaa et al. 2006).

The main types of impact structures on the Earth are (a) bowl-shaped simple craters (up to 3–4 km in diameter), (b) complex craters – bowl-shaped craters with central uplift (from 3–4 to 10–20 km in diameter) and (c) large multiring basins (with diameters to some 300 km). The Kärđla structure (4 km in diameter) is a typical complex bowl-shaped crater with central uplift. In the setting of the Neugrund structure (20 km in diameter) distinct features of multiring kind occur.

2.2. The Kärđla crater

Throughout the history of geological studies in the northeastern part of the Hiiumaa Island, many unexpected, unusual and unexplained signatures were revealed, which were understood only after the discovery of the Kärđla meteorite crater. Bedrock dislocations, namely tilted bed of limestone, along the slopes of the Paluküla Hill were described already in the 19th century (Eichwald 1840; Ozersky 1844; Schrenk 1854; Schmidt 1858). The dislocations were later identified as the buried rim wall of the Kärđla crater. Later, data on the occurrence of asphalt (Winkler 1922; Scupin, 1927) and galena (Palmre 1961) at Paluküla were published. In 1966, drilling of an artesian well on the Paluküla Hill was stopped, because rocks of the Precambrian crystalline basement were unexpectedly met at the depth of 16 m, instead of anticipated c. 230 m. The revealed uplift of crystalline basement rocks was additionally drilled and interpreted as a placanticlinal (Viiding et al. 1969). A nearby structural depression, which was revealed in course of drilling for geological mapping, was first explained as a tectonic graben, and the impact breccias penetrated in drill hole 412 were interpreted as late Precambrian tillites (Kala et al. 1971). The depression was later found to be the central uplift of the crater proper. During search for uplifts of granitic rocks, suitable for producing high quality splinter, detailed geophysical mapping by means of gravimetry and magnetometry) was carried out (Barankina & Gromov 1973). Tens of prospecting wells were drilled in the area (Suuroja et al. 1974). As a result, the crater structure was revealed (Puura 1974) and a hypothesis of its crypto-volcanic origin of it was put forward (Suuroja et al. 1974). During subsequent prospecting (Kala et al. 1974, 1976) the hypothetical crater floor was reached at the depth of c. 500 m (drill hole K-12).

The thin sections of matrix-supported breccias from drill core K-12 were studied in late 1970-s in the laboratory VSEGEI, St. Peterburg (then Leningrad) and PDF-s (*planar deformations features*) were found in quartz and kink bands

in biotite. Using these data Masaitis et al. (1980) distinguished and published the impact origin of the crater.

The discovery of the Kärđla crater caused initiated a number of large projects focused on detailed geological mapping and deep drillings within the structure and in its surroundings (Suuroja et al. 1981, 1991, 1994, 1997). Prospecting for mineral resources also supported the geological investigations. In the course of prospecting for mineral water (Tassa & Perens 1984), the well K-18 in the central part of the Kärđla crater depression was drilled and more than 130 m high central uplift (peak) was discovered (PAPER I; Puura & Suuroja 1984, 1992). For the geological mapping, the deepest (815.2 m) well in Estonia, Soovälja K-1, was drilled within the annular depression of the crater. The core represents the most complete sequence of the main lithologies of the crater infill and, starting from the depth of 523 m, of the impact-dislocated sub-crater basement (Fig. 1). A large number of the cores were drilled in the crater interior. Among them 6 wells reached the sub-crater basement. Along the crater rim wall, 46 wells reached the impact breccias and the crystalline basement rocks. In the crater exteriors, 64 wells reached the distal ejecta blanket or dislocated pre-impact target rocks. The total number of drill holes giving original information on the crater structure and covering deposits reached 162.

Numerous drillings, geophysical and other materials became considerable source for scientific research. In 2005, the total number of published research papers on the Kärđla structure reached around 50. Since 1973, the author of the present thesis has concentrated on the mapping and investigation of the geology, formation and development of the Kärđla structure. Geophysical-maps, core logs, structural sketches and subsurface geological maps at different structural levels, cross sections summarizing the existing materials served as basis for selecting new drilling sites. The core studies, which were mainly carried out by the author, have included observations and descriptions of core samples and interpretation of geophysical logging data. Large numbers of samples were collected and sent to laboratories for petrographic, lithological, mineralogical and geochemical analysis. The results are presented and used in the published papers. Initially, the main parameters and main features of the crater were presented in the early papers (PAPER I; Puura & Suuroja 1984, 1992). Subsequently, the main results were presented in papers III–IV. Apart from in the present thesis, crater data has been presented in many additional papers by the author, his co-authors and researchers involved into the study of the drilling cores and other materials. In 1996, in co-operation between the Stockholm University and the Geological Survey of Estonia, seabed off from the northeastern margin of Kärđla crater was studied from board of the research vessel “Strombus”. Continuous seismic reflection profiling proved the existence of the presumed ring fault around the crater in Kärđla Bay (PAPER IV; Suuroja et al. 2002).

2.3. The Neugrund crater

Also the Neugrund structure was discovered due to attention paid to indirect phenomena. In the course of geological mapping of northwestern Estonia (Kala et al. 1969) disturbances in the sequence of Ediacaran (Vendian) and Early Cambrian clays and sandstones were observed in drill core 410 on Osmussaar Island. At the time there was no explanation to these structures. Again, almost two decades later, in the course of deep geological mapping of North-western Estonia, in the drill cores (F-331, F-331A, F-332, F-335) intervals of brecciated clay- and sandstones of the upper part of the Early Cambrian subsequences were observed (Suuroja et al. 1987).

Much earlier, in the same coastal area of North-western Estonia, A. Öpik observed, and N. Thamm described, large erratic boulders of an odd gneiss-breccia along the seashore (Öpik 1927, Thamm 1933). Also K. Orviku and H. Viiding described these erratic boulders, but nobody could explain their origin (Orviku 1935, Viiding 1955). Revisiting the area in the course of the geological mapping K. Suuroja and T. Saadre noted that these gneiss-breccias are macroscopically very similar to clast-supported impact breccias from the Kärđla crater (Suuroja & Saadre 1995; Suuroja et al. 1998). They suggested that the specific gneiss breccias of North-western Estonia are impact-produced breccias possibly drifted by glacier. A specific pattern in the seabed, namely the nearby Neugrund Bank in southwestern part of the Gulf of Finland, was proposed as the possible impact structure. Previously, in the course of marine geological investigations (Malkov et al. 1986; Lutt & Raukas 1993; Talpas et al. 1993), a ring-shaped wall around the Neugrund Bank was observed, but it was interpreted as a glacial moraine wall.

In co-operation with the Geology Department at the Stockholm University, and using their equipment and methods, the seabed in the surroundings of the Neugrund Bank was studied by seismic reflection profiling from the Stockholm University research vessel *Strombus* in 1996 (see method descriptions in Flodén 1980, 1981). As the result of these investigations, a 9-km diameter crater-like structure, surrounded by 4–5 km wide zone of dislocations, was discovered (Suuroja 1996b). Shock metamorphic minerals (quartz grains with PDF-s) from the erratic blocks of gneiss-breccias were found and the impact origin looked more probable (Suuroja et al. 1997). In 1998, a diving geologist took samples from submarine outcrops along the rim wall composed of Precambrian metamorphic rocks. Samples similar to the breccias from the erratic boulders yielded quartz grains with PDF-s and other signs of shock metamorphism. The impact origin of the Neugrund structure was proved (PAPERS II, V, VI; Suuroja & Suuroja 1999, 2000; Suuroja et al. 1999b, 2003).

In the period 1998–2003, 7 marine expeditions were carried out on the Neugrund impact structure area. The vessel *Mare* of the Estonian Maritime Museum was used. Captain Vello Mäss directed the marine and submarine investigations, including diving. The total number of diving sites was 21,

located at depths between 2–42 m. At 12 sites the divers succeeded in collecting samples, 0.1–3 kg in size, of impact-produced as well as covering rocks. With few expeditions, the diving's were recorded by a camcorder accommodated with ikelite underwater systems. Additionally, the submarine outcrops were observed by a camera system SeaLion mounted on a remote operated vehicle (ROV) and side-scan sonar (SSS) profiling.

Apart from sampling, the diving geologists made descriptions of each sampling site. An assistant diver using a digital depth gauge measured the depth of each sample. The depth, with accuracy 0.1 m, was noted on each sample using a waterproof pencil. Concomitantly, another assistant diver recorded the outcrop and sampling site to videotape. The sampling sites are located within the crater infill, which is exposed on the central plateau of the shoal. Additionally, exposures of impact influenced Precambrian basement metamorphic rocks were observed and sampled on the ring ridges.

3. GEOLOGICAL SETTING AND AGE OF THE CRATERS

3.1. Geological setting

3.1.1. Regional setting. The Kärđla and Neugrund craters formed in areas with similar regional geological setting. Meteor bodies hit the seabed in the large Early Palaeozoic Baltic epicontinental basin, which was formed in Ediacara time (latest Neoproterozoic) on the East European Craton that covered the present Russian Platform and also large parts of the neighbouring Fennoscandian Shield. At the Neugrund site, the target consisted of an about 100 m thick sequence of Lower Cambrian and Upper Vendian (Ediacaran) soft silts and sands (PAPERS II and VI). At Kärđla of about 200 m thick weakly lithified Vendian (Ediacarian), Cambrian and Lower Ordovician clays, silts and sands, and up to 15 m thick Ordovician carbonate rocks (PAPER I and IV). At both sites, Precambrian crystalline migmatized metamorphic rocks underlie the sedimentary deposits. Consequently, the allochthonous impact breccias are composed of a more or less perfect mix of sedimentary and crystalline rocks. Also, at both sites, the craters extended through the sediments and into the topmost part of the crystalline basement. The basement rocks belong to c. 1.9 Ga old Svecofennian Crustal Domain (Gorbatshev & Bogdanova 1993; Puura & Flodén 1997). In the area of the Kärđla and Neugrund crater the Svecofennian crust is around 47 km thick (Puura & Flodén 2000). The crystalline rocks found in the polymict breccias, and in the huge allochthonous brecciated rock blocks near the main crater structures, are similar to basement rocks drilled in surroundings of both crater sites. At the Kärđla site, the impact breccias are composed of three main lithological types – 1) carbonate rocks, 2) siliclastic to clayey sedimentary rocks, and 3) a variety of crystalline rocks. At the Neugrund site, mainly crystalline rock – derived clastic breccias are found now. Mixed sedimentary siliclastic and crystalline-derived breccias, as well as possible melt rocks are expected to be present in the crater deep.

Both crater structures formed into sea were soon (probably in few millions of years) buried under the sediments. The Kärđla crater has remained buried since that for 455 million years. Presently only some 20 m of covering deposits has preserved above the crater rim wall's highest point. The Neugrund crater was buried for c. 535 Ma. It was re-exposed only recently, due to glacial erosion in the Pleistocene.

3.1.2. The Kärđla crater. The structure of the target at the Kärđla site is well documented by large number (c. 250) of drill holes penetrating into the crater structures (Viiding et al. 1969; Barankina & Gromov 1973; Kala et al. 1971, 1974, 1976; Tassa & Perens 1984; Suuroja et al. 1974, 1981, 1987, 1991, 1993, 1997).

The Kärddla impact hit into a shallow epicontinental sea where at that time bioclastic limy mud were deposited (PAPER I; Männil 1966; Nestor & Einasto 1997; Ainsaar et al. 2002). The depth of the sea is estimated to have been between 20 m (PAPER I), c. 50 m (PAPER IV), 50–100 m (Lindström et al. 1992, Ormö & Lindström 2000) and less than 100 m (Suuroja 1996a; Puura et al. 2004). The criteria for the estimation of sea depth at the impact site come from the pre-impact sedimentation facies signatures and from the post-impact erosion and sedimentation processes in the diversified seabed topography.

The depth of deposition of bioclastic argillaceous-calcareous limy muds may vary from the some tens of meters (i.e. below level of the storm waves in epicontinental seas) down to more than 200 m (Männil 1966; Nestor & Einasto 1997; Ainsaar et al. 2002). Numerical modelling of the meteorite impact into shallow sea is demonstrated by Shuvalov (2002), Shuvalov et al. (2002) and Pierazzo & Collins (2003). In the case of a rather shallow sea (less than 100 m), the tsunami waves initiated by the impact cannot be very strong. However, based on the observations of the allochthonous breccias at the Kärddla site we conclude that the influence of tsunami waves was quite strong (PAPER I and IV), which indicates a considerably deeper sea during the impact than was previously suggested.

At present, the thickness of pre-impact sedimentary bedrocks that covers the Precambrian crystalline basement in the area is c. 140 m (PAPERS I and IV). Middle Ordovician limestones form the uppermost 14 m of this complex. The next subjacent 8 m are made up of Lower Ordovician weakly lithified sandstones (glauconite sandstone and *Obolus* or detritic sandstone) and kerogenic argillite or *Dictyonema* shale.

Below the Ordovician unit follows an about 120 m thick complex of weakly or moderately lithified Lower Cambrian sandstones, siltstones and clays. In of the latter unit, the following formations are distinguished (from top to bottom): c. 10 m Irbe Formation – clay and siltstones; c. 20 m Soela Formation – fine-grained quartz sandstone; c. 20 m Tiskre Formation – fine grained quartzose sandstone; c. 10 m Lükati Formation – clay with interbeds of quartzose sandstones; c. 15 m Sõru Formation – mostly siltstones; c. 50 m Voosi Formation – sandstones, siltstones and clays. In the eastern part of the crater site, a several meters thick layer of Upper Vendian (Ediacaran) silt-sandstones and conglomerates is present in the lowermost part of the sedimentary cover (Suuroja et al. 1991; Suuroja et al. 1994). At the time of the impact, the sandy and silty sequence was less consolidated and therefore much thicker than presently.

The Precambrian crystalline basement (PAPER III; Suuroja et al. 1991; Koppelmaa et al. 1996; Koistinen et al. 1996; Kivisilla et al. 1999; Puura et al. 2004) is composed mainly of Svecofennian metamorphic rocks in which migmatite granites and granitoid gneisses prevail. The microcline-plagioclase granites and amphibolites formed in the strongly folded and migmatized complexe veins and more massive bodies. The topmost part of the crystalline

basement (5–25 m) is weathered and rocks are enriched with secondary minerals illite and kaolinite.

3.1.3. The Neugrund crater. The structure of the target at the Neugrund impact site is best documented by the nearest drill hole on Osmussaar Island, which penetrates all rocks of the pre-impact target (PAPER II; Kala et al. 1969). The Osmussaar well is located 10 km to the west of the structure center. Six wells were drilled in the mainland of NW Estonia some 13–25 km southward of the impact structure.

The Neugrund impact took place in a shallow offshore sea where, at the time, fine- and middle grained quartz sand with interlayer of clayey silt was deposited (PAPER II; Mens & Pirrus 1997a). The depth of the sea is estimated to have been 50–100 m (PAPER II). Biostratigraphically, the impact-related ejecta layer occurs in a succession (PAPER II) that belongs to the pre-trilobite Early Cambrian *Platysolenites antiquissimus* biozone of the East-European Craton (Mens & Pirrus 1997b).

At the moment of the impact, c. 150 m of unconsolidated siliciclastic sediments covered the Precambrian crystalline basement. Presently the compacted 100 m thick pre-impact succession is composed of Lower Cambrian sandstones, siltstones and clays of the Lontova Formation (c. 40 m) and on top of a complex of weakly lithified quartzose sandstones (c. 60 m) of Upper Vendian (Ediacara) age (PAPER II).

In the Precambrian crystalline basement (PAPER II; Suuroja et al. 1987; Koppelmaa et al. 1996) Svecofennian metamorphic rocks migmatite granites and granitoid gneisses dominate. In this strongly folded and migmatized complex microcline-plagioclase granites and amphibolites form veins and also more massive bodies. On the top of the 5–10 m thick, slightly weathered uppermost part of the crystalline basement, there rests a c. 7 m thick illite-rich weathered crust.

3.2. The age of the craters

The ages of Kärddla and Neugrund impact events were determined by means of biostratigraphic dating of their distal ejecta in the marine sedimentary record of the Ordovician and Cambrian.

3.2.1. The Kärddla crater. The earliest estimate on the age of the crater was based on (micro-) biostratigraphy of the lowermost post-impact sedimentary deposits in the crater interior. An extraordinarily thick and complete sequence of the Idavere Regional Substage, Caradoc, was established (Kala et al. 1971). Stratigraphic position of the ejecta layer was established by Suuroja et al. (1974) as the lowermost part of the Idavere Regional Substage, Caradoc Stage, Upper Ordovician. E. Pirrus (1987) studied dislocations on the north-eastern

slope of the rim-wall and dated the crater as post-Cambrian. Bauert et al. (1987) suggested the age of the impact using biostratigraphical dating of the distal ejecta layer in the chitinizoan zone of the continuous sequence of the Ordovician carbonate sediments at a distance of 12 km from the crater centre (PAPER I). Detailed studies of the ejecta blanket, and the stratigraphic position of its underlying and covering deposits, proved that the best conditions for the biostratigraphic dating of the event are at a distance of 10–20 km from the crater centre, where the thickness of the ejecta layer decreases to 10–20 cm (Suuroja & Suuroja 2006). Using chitiniozoa microstratigraphy, J. Nõlvak determined the precise level of the impact-related deposits (ejecta) in the Männamaa core (well F-367) 17 km southeast of the crater centre (Grahn et al. 1996). It was a level above the occurrence of *Cyathochitina* cf. *reticulifera* and below the appearance of “*Eremochitina*” *dalbyensis* (Laufeld), which corresponds to the lowermost *Diplocraptus multidentis* graptolite zone. It belongs to the Idavere Regional Substage, Caradoc Stage, Upper Ordovician, and in the International Stratigraphic Chart (Gradstein et al. 2004) the determined level corresponds to the absolute age of c. 455 Ma.

3.2.2. The Neugrund crater. During the early studies, different indirect criteria were used estimate of the age of the Neugrund impact. Suuroja et al. (1997) suggested, that the impact could be connected to c. 475 Ma old Osmussaar breccia (breccia-like sandstone) dykes that crop out on Osmussaar and Suur-Pakri islands and are also met on North-western Estonian mainland in some drill holes. Later, the sedimentary deposits filling the crater proper in the submarine section along northern slope of the Neugrund Bank, were studied and the sandstone of the Tiskre Formation – found in the lowest part of the crater filling suggested at least c. 530 Ma in age (PAPER II).

Finally, the probably real age of the Neugrund impact was estimated from the discovered ejecta layer within the undisturbed Lower Cambrian clays. The ejecta layer was laid down upon the c. 535 Ma old siliciclastic rocks, namely clays and sandstones of the Lontova Formation, Lower Cambrian (PAPER II, VI). The c. 2 m thick ejecta deposits have been studied in detail only in one drill core section at a distance of 13 km from the impact centre (PAPER VI). Biostratigraphically the deposits reflecting the impact event (PAPER II) belong to the pre-trilobite Early Cambrian *Platysolenites antiquissimus* biozone of the East-European Craton (Mens et al. 1990).

4. STRUCTURE, IMPACT STRATIGRAPHY AND LITHOLOGIES OF THE CRATERS

4.1. Similarities and preservation of the two impact structures

In the local structure and stratigraphy of the sedimentary cover of North-western Estonia, the Early Palaeozoic impact stratigraphic units represent unique portions in addition to the normal field regional stratigraphy. The schematic stratigraphic table of the Early Palaeozoic sequence of North-western Estonia is based on the chitinozoan zones distinguished by Nõlvak and Grahn (1993). Stratigraphic positions of Kärđla and Neugrund impact events are given in PAPER V, fig. 3.

Both structures formed in the two-layered target composed of sedimentary cover and crystalline basement. The impact-produced structures and morphologies of the seabed survived due to the continuous Palaeozoic sedimentation. The impact-produced negative landforms were partly filled with impact-produced mixed crystalline and sedimentary rock debris and, in Neugrund, possibly also with suevitic rocks. The upper parts of craters are filled with post-impact marine deposits with specific facies signatures. The thickness of the post-impact Early to Mid-Palaeozoic (Ordovician – Devonian) deposits in Estonia reached up to 800 m. Below the level of the target surface, the structures have preserved in full primary completeness. The supra-target part of the structures was somewhat eroded by resurging tsunami waves and subsequent shallow marine erosion. Possibly, the peaks of the rims rose above the sea level and were to some degree eroded in sub-aerial or shallow submarine conditions.

During the late Palaeozoic, through early Cenozoic, the structures were subjected to the lithostatic stress from 500–800 m thick post-impact Early to Mid-Palaeozoic deposits. Also, during the Pleistocene, the region recurrently suffered from the loading of some 2–3 km thick continental glaciers.

Under the load of the Palaeozoic deposits and the Pleistocene glaciers, the impact-produced and post-impact deposits were subjected to compaction and diagenetic alternations.

Structural elements composed of crystalline blocks of the basement, namely fragmented crystalline segments of rim walls and central uplifts, compacted less than highly porous fine-grained impact breccias and soft post-impact sediments. Therefore, if to compare with the surrounding structure of the sedimentary cover, the successions of layered post-impact deposits above the crystalline uplifts lie in remarkably uplifted positions, whereas in impact-induced depressions, in lowered positions. In both Kärđla and Neugrund structures the immediate post-impact deposits have nearly completely preserved in the central depression.

The Kärđla and Neugrund impact structures have survived almost intact because the post-impact erosion never reached the target level: the structures formed at sea and soon they were buried due to continuous deposition. The latest Cenozoic regional erosion, which formed the depression of the Baltic Sea and Gulf of Finland (Puura & Flodén 1997), fortunately stopped just before reaching the top of the rim wall (Kärđla) or only slightly destroyed the topmost parts of the rim ridges (Neugrund).

In some aspects, the main structural units are dissimilar. First, signatures of complexity in their nature of craters differ. The central crater proper is proved at both sites. However, the central uplift is found at Kärđla and only supposed at Neugrund. Distinct main annular rims composed of uplifted blocks of crystalline basement are distinguished at both craters. However, multiring signatures are pronounced weakly at Kärđla and rather strongly – at Neugrund. Interior allochthonous breccia suites are well preserved at Kärđla, and most probably they exist also at Neugrund. The outermost feature of both structures is – a ring fault at 13–15 and 20 km from the crater centre, respectively. The ejecta layer is distinguished around both craters. At both craters, a more or less specific succession of post-impact sedimentary deposits, differing in facies patterns and with greater thickness of lowermost post-impact layers, fills the central depression.

According to the 8-stage classification by Dence (1972), both structures under description belong to the preservation level 2, namely “Ejecta partly preserved” (Puura & Plado 2004). The classification extends from well survived as stage 1 to completely destroy as stage 8. Symptomatic signatures are: ejecta partly preserved, topmost portions of the rim wall eroded, crater infill and covering deposits survived all over the structure (Kärđla) or eroded from the highest portions of the rim wall (Neugrund).

4.2. Kärđla – the structure and stratigraphic position of the impact-induced suites

The Kärđla structure is a 4 km wide complex impact crater (Fig. 1) that main subsurface morphology is still nearly bowl-shaped, because the central uplift is considerably small. In general, the concentric structural elements are almost regular, except the height of the rim wall, which is substantially variable, and a slightly quadrangle pattern of the annular crater rim (PAPER IV, Fig. 5). The data on the size and composition of its structural elements are summarized in Table 1.

Table 1. Main characteristics of the A) target of the Kärddla impact, B) Kärddla impact structure, and C) impact lithologies of the Kärddla structure.

Characteristic	Size
A. The target	
Present altitude of the impact-related unconformity surface in the sedimentary record (+ above the present sea level, - below the present sea level):	
Present altitude of the impact-related unconformity surface in the sedimentary record (+ above the present sea level, - below the present sea level):	-70 to – -90 m
In the crater interior	down to -295 m
On top of the rim wall	up to +10 m
Seawater at the moment of impact	Up to 100 (200) m
Pre-impact sedimentary rock cover, total thickness	c. 140 m
<i>(thickness of sedimentary target units at present - after post-impact compaction*)</i> , including (from the top):	
Middle Ordovician limestones	14 m
Lower Ordovician silt- and sandstones and argillite	8 m
Lower Cambrian silt- and sandstones and clays	c. 120 m
Upper Vendian (Ediacaran) silt- and sandstones	0–5 m
*) thickness of the non-compacted sand, silt and clay deposits of the Ordovician to Vendian age at the moment of the impact in the Ordovician was substantially more	
Crystalline basement	(c. 47 km – Moho depth)
Weathered rocks of the crystalline basement, thickness	10–20 m
Fresh rocks of the 1.9–1.8 Ma Svecofennian orogenic complex: Granite-migmatites, granite gneisses, amphibole-biotite and biotite-amphibole gneisses, amphibolites, alumogneisses, quartzite	c. 47 km
B. The subsurface Kärddla impact structure	
Present altitude of the impact-related unconformity surface (+ above the present sea level, - below the present sea level)	
– in the sedimentary record of NE Hiiumaa Island, surroundings of the crater	-70–90 m
– in the crater interior	down to -295 m
– on top of the rim wall	Up to +10 m
The buried complex crater; bowl-shaped with central uplift:	
rim-to-rim diameter	4 km
Top of the par-autochthonous crater floor:	
under the target level	443 m
under the present sea level	518 m
under the present earth surface	523 m

Characteristic	Size
Central uplift:	
height above crater floor	more than 130 m
altitude below the present sea level	395 m
altitude below target level	315 m
estimated diameter	c. 700 m
Height/elevation of the crystalline rim wall	
above (+) or below (-) the target level (tl), and above (+) or below (-) sea level (sl) in segments:	
Kärdla Segment	tl + 50 m, -30 m
Paluküla Segment	tl + 90 m, sl +10 m
Tubala Segment	tl + 63 m, sl -22 m
Northern Gully	tl -30 m, sl -110 m
Southern Gully	tl -80 m, sl -73 m
Western Gully	tl -63 m, sl - m
	240 m
Maximum height of the structural uplift of the basement in the rim wall	
The distal ring fault (outer crater boundary) - diameter	12–15 km
<i>Altitude of the bottom of the ejecta layer below sea level:</i>	
Northern Hiiumaa (DH 396)	-40 m
Central Hiiumaa (DH F360)	-130 m
Southern Hiiumaa (DH 400)	-190 m

C. Impact lithologies of the Kärdla structure	
Allochthonous impact breccia suite in the crater annular mold - thickness (including from top):	Max 323 m
Sedimentary slump and resurge breccias (with rare PDF-quartz grains), thickness	max 40 m
Sedimentary polymict breccias (with rare PDF-quartz grains), thickness	Max 106 m
Granitoid polymict breccias (with abundant PDF-quartz grains), thickness	max 75 m
Par-autochthonous breccias: brecciated crystalline basement rocks	max 67 m
Subcrater basement:	
Fractured and brecciated crystalline basement target rocks with veins of impact breccia, rarely with impact metamorphic features, thickness	more than 226 m
Ejecta layer – partially survived in the crater exterior, thickness	Max 6,4 m
Thickness of the ejecta blanket at a distance from the crater center (No of drill hole):	
3 km NE (DH - F370)	6.4 m
5 km E (DH - F375)	3.2 m
7 km NW (DH - F352)	0.8 m
9 km W (DH - F353)	0.7 m
12 km SE (DH - F360)	0.5 m

Characteristic	Size
13 km NW (DH – F351)	0.5 m
16 km SW (DH – F358)	0.2 m
18 km S (DH - F354)	0.1 m
25 km W (DH - F357)	0.1 m
42 km E (DH - F345)	0.01 m

D. Covering sedimentary deposits	
In thickness	15–300 m
In the crater interior	c. 300 m
In the gullies of the rim wall	77–157 m
On top of the rim ridges	15–157 m
In the surroundings of the rim wall:	
Northwest 7 km (F352)	78 m
East 8 km (F355)	107 m
South 12 km (F364)	147 m
West 9 km (F353)	101 m

Deformed subcrater basement. Beneath and aside the crater proper, a half-sphere of impact-dislocated rocks occurs. Drillings at Kärö and its surroundings, revealed certain parameters of the deformed rock suite.

Beneath the crater, the depth of penetration of the impact-induced deformation into the target and width of the deformation zone around the crater center has been estimated (PAPERS I, IV and VII). Puura et al. (2004, fig. 3) estimated the maximal possible extension of the transient cavity before the modification stage as deep as ca 900 m below the target surface. Due to late-impact structural modification processes, the crater floor uplifted to the level of ca 400 m below the target level. Studies of the core K-1 by Suuroja et al. (1991, 1993), Suuroja (1996) and Suuroja & Pöldvere (2002) revealed that fracturing and local brecciation of the crystalline basement rocks as well as increased porosity (Plado et al. 1996; Plado 2000) that reaches at least 300 m below the present crater floor. This is down to more than 1200 m below the target surface at the stage of the transient cavity. PDF-s in quartz and other impact metamorphic features in minerals are not found in these fractured rocks of the subcrater.

Ontop of the most obviously dislocated, but still autochthonous subcrater basement a more dislocated unit rests, namely a **par-autochthonous breccia or bottom-breccia**. This latter unit is composed of crystalline rocks only (Suuroja 1996a, fig. 16) as described in core K-1 at a depth of ca 523–589 m. In PAPERS I, IV the level 589 m was considered to be the top of the subcrater basement. In the papers by Suuroja & Pöldvere (2002) and Puura et al (2004) the level of crater floor was interpreted to be 522.8 m and the par-autochthonous breccia unit was included into the sub-crater basement. Only heavily fractured and brecciated, basement-derived crystalline rocks are present as rock chips and blocks in this unit. Kink-banded biotite is found here, whereas PDF-s

in quartz and feldspars are rare (PAPERS IV and VI) or absent (Puura et al. 2004). Thus the level of impact metamorphism differs from that of the autochthonous subcrater basement as well as from the allochthonous breccias.

Puura et al. (2004) estimated the apparent volume of the sedimentary and crystalline rocks excavated during the impact as following in km³: Volume of the present crater below the target surface – 2.3; volume of excavated rocks – 3.5, including sedimentary cover – 2.3 and crystalline basement – 1.2. The results of these calculations were approximated to the nearest 0.1 km³. Presently the volume of the within-crater allochthonous breccias equals to 0.5 km³, including sediment-dominated 0.3 km³ and crystalline 0.2 km³.

The central uplift in the centre of the Kärddla crater is rather small, at least 130-m-high and about 700 m in diameter. These parameters are deduced from the data from wells K-1, K-18 and K-12 (Fig. 1) and from a assumption of regular internal symmetry of the crater (PAPERS I and IV). The basement rocks in the central uplift are deformed as intensely as in the subcrater basement in well K-1 (Suuroja 1996b, 2001; Suuroja & Pöldvere 2002; Puura et al. 2004). A. Jöeleht (personal communication 2007) concluded, relying upon the results of seismic reflection investigations that the pike of the central uplift is located some hundred meters east of the wall and that it may therefore be somewhat higher.

The rim wall. The present rim-to-rim diameter of the Kärddla crater is 4 km. The width of the crystalline crater rim wall on the level of the target surface is about 1 km. The present height of the rim wall varies considerably (Fig. 1, Table 1; PAPER IV, fig. 5). The highest points of the crystalline sectors of the rim wall are presently 50–80 m above the target level. However, the lowest segments of the present rim wall are below the target level by 25–50 m. The structural uplift of the rim can be distinguished from the uplifted level of the crystalline basement that is pronounced in the Bouguer anomaly field and found in drillings (Paper IV, figs. 5, 6, 8). Jöeleht et al. (2007) supposed, on the basis of results of seismic reflection investigations, that variations in the rim morphology could be attributed either to oblique impact or differences in the properties of the crystalline target.

The data on the present structure of the rim wall suggest that the original rim wall was higher by at least some tens of meters. The post-impact erosion of the ejecta blanket and topmost portions of the solid wall substantially lowered its height. We suppose that the presently well-pronounced gullies between the high crystalline segments of the rim wall were formed due to the strong erosion during the stage of slumping and resurge tsunami wave processes. The breakthrough into the crater interior of tsunami waves saturated with rock debris up to block size and finally deepened (eroded) the lowest primarily sedimentary sections of the annular rim.

The uplifted target. An annular zone of slightly uplifted basement and dislocated and uplifted sedimentary cover occurs outside the rim wall (PAPER III, figs. 2, 3; PAPER IV, fig. 6). Subsequently to the slumping- and tsunami-

induced erosion, from the top of the rim wall and described external annular zone, the ejecta blanket and topmost part of the disturbed target rocks were truncated due to the marine shoreline and submarine erosion before the burial under the Late Ordovician carbonate deposits (see below). The annular area of erosion of the rim wall, and nearby external zone, is located at a distance from 2 to 4–5 km from the crater centre (PAPER I, fig. 8; PAPER IV, fig. 3; Puura et al. 2004, fig. 2).

The distal part of the crystalline rim wall is locally thrust on top of deformed sedimentary rocks (PAPER I, fig. 7; Suuroja et al. 1991). In this uplifted zone, the dominantly Cambrian sandstones and clayey rocks are in dislocated positions, inclined, bended and crosscut by faults. Locally near the rim wall, crystalline blocks up to 40 m size rest within and above the surface of the sedimentary rocks as occasionally revealed by drilling (PAPER I, fig. 7).

A zone that dislocation and uplift is generally of lower amplitude surrounds this remarkably dislocated area. Here, the ejecta blanket has survived from erosion. However, despite the survival of the main stratigraphic sequence and general hypsometric position of the latest Cambrian and pre-impact Ordovician deposits, the uppermost part of the Lower to Middle Ordovician carbonate rocks is strongly fractured and brecciated (wells K-11, K-15, K-19). This sequence is separated from the overlying proper ejecta blanket by a discontinuity surface (PAPER VI, fig. 7). The outer boundary of this weakly dislocated area is probably marked by the elliptic ring fault with a diameter from 12 to 15 km (PAPER IV, fig. 3).

The allochthonous impact breccia. The impact breccia in the interior of the crater is subdivided into units and subunits, which differ in fragment size and origin of dominant compounds from either crystalline basement or sedimentary target. In the horizontal direction, the composition of these units may vary substantially. However, as deduced from drill cores K-1 and K-12 I (Fig. 1) in the deepest part of the crater, namely the annular mold that surrounds the central uplift, a double succession of the main types of breccias occurs (PAPER IV, fig. 6; Suuroja 1996; Suuroja & Pöldvere 2002; Puura et al. 2004; Versh et al. 2006). Here, on the top of the par-autochthonous breccia, the fine-grained breccia dominantly composed of less than 100-mm clasts of dominantly basement-derived crystalline rocks rests (K-1, depth 471–523 m), which is overlain by a subunit of dominantly more than 100 mm blocks of mainly sandstones (K-1, depth 380–471 m). The upper surface of this two-fold unit is almost on the level of the top of the central uplift. A similar pair of subunits covers both the annular depression and central uplift: (1) the deposits composed of dominantly less than 100 mm blocks clasts mainly from basement crystalline rocks (K-1 depth 350–380 m, K-18 depth 356–400 m) and (2) overlying subunit composed of dominantly more than 100 mm boulders of mainly sedimentary rocks (sandstones) (K-1 depth c. 314–356 m, K-18 depth 315–356 m).

In both subunits of crystalline-derived breccias, impact-metamorphic minerals – quartz and rarely also K-feldspar with PDF-s are systematically found (PAPER IV; Puura et al. 2004). The sedimentary-derived rounded quartz grains with PDF-s are most common. The PDF systems found indicate shock pressures 10–35 GPa. The sedimentary-derived units are composed mainly of weakly deformed blocks, in which shock-metamorphosed minerals are not found. However, in the fine-clastic rocks, the filling space between large clasts contains abundant PDF-s in quartz.

On top of the thick units just described, there rests a resurge breccia unit, which is composed of mixture of fine material (silt, sand) up to boulders. In this breccia, fragments of either sedimentary (K-1, 300–314 m) or crystalline (K-18, 293–315 m) rocks dominate. In core K-18, the breccia suite is similar to the sequences described above. However, it is more differentiated in respect of the ratio of sedimentary or crystalline composition (Preeden 2004). In this unit, PDF-s in quartz is occasionally found.

Near the rim wall, the interior allochthonous breccia suite thins out and is in a hypsometrically higher position. Its top is at the level of c. –245 m in well 383 and at –100 m in K-17). In general, the morphology of the top surface of the allochthonous breccia suite forms a regular round depression, in the centre of which a small structural elevation, c. 7 m high, well K-18, marks the location of the central uplift.

The Ejecta blanket. Ejecta deposits have survived at the distance of 3–4 km and further from the crater centre. The 1–1.5 km wide annular zone around the rim wall is the most uplifted annular zone of the target. The ejecta blanket here has been eroded before the burial under the subsequent sedimentary cover. Due to this erosion, the ejecta blanket is spatially separated from main allochthonous breccia suite of the crater interior (PAPER VI, fig. 6; Suuroja et al. 1994; Puura et al. 2004).

The largest known thickness of the survived ejecta blanket 6.4 m was drilled at a distance of 3 km from the crater centre in well K-370 (PAPER VI, fig. 2 and table 1). Further out from the centre, the thickness of the ejecta blanket regularly decreases down to about 1 cm at a distance of 42 km from the crater center in well F-345 (PAPER VI, fig. 2, table 1).

The ejecta blanket is composed of a complex of proper ejecta lithologies and post-impact redeposited material. The last is derived, first, from the ejecta, and second, from the sub-ejecta sedimentary and crystalline rim rocks reached by erosion before the covering sedimentation started. Therefore, the bottom beds of the ejecta blanket are probably synchronous to the impact, whereas the topmost parts of it are metachronous. The age of the last depends on the changes of sedimentation and erosion areas during the impact-related interregnum in the deposition. Near the crater, real impact breccias occur in the lower part of the ejecta blanket, whereas in the upper part and further from the crater redeposited fine clastic but carbonate-cemented varieties occur (see below).

Table 2. Position and thickness (in m) of the preimpact (target), impact-induced and post-impact deposits in the stratigraphic record of NE Hiiumaa area (PAPER IV). Below, the absence of the target, impact-induced and post-impact covering stratigraphic units is marked as following, respectively: *impact destruction* of the target units, *not deposited* in the impact process, *eroded I* in the late impact and early post-impact process, *break* as the non-deposition during the latest impact and early post-impact deposition process before the final burial of the elevated parts of the structure, *eroded II* corresponds to the erosion of the cover during the Cenozoic, especially during the Pleistocene. See also PAPER IV, fig. 5 and 6.

	Formations (indices)	Crater interior, m	Top of the rim wall in Paluküla, m	Rim wall in northern, gully, m	Rim wall in southern, m	Surrounding area, 4 km north from the center, m	Surrounding area, 10 km south from the center, m
	Ärina (O ₃ är)	1 +	Eroded II	Eroded II	Eroded II	Eroded II	7
	Adila (O ₃ ad)	17	Eroded II	Eroded II	Eroded II	Eroded II	13
	Moe (O ₃ mo)	24	Eroded II	Eroded II	15+	Eroded II	22
	Kõrgekallas (O ₃ kr)	14	Eroded II	Eroded II	10	Eroded II	18
	Saunja (O ₃ sn)	17	Eroded II	14	12	6	4
	Paekna (O ₃ pk)	12	10	10	10	9	10
	Rägavere (O ₃ rg)	30	22	22	28	22	21
	Hirmuse (O ₃ hr)	4	Break	3	2	2	2
	Vasalemma (O ₃ vs)	–	Break	7	4	–	–
	Keila (O ₃ kl)	36	Break	23	31	22	18
	Jõhvi (O ₃ jh)	4	Break	Break	2	1	1
	Idavere (O ₃ id) = O ₃ vsv-tt	12	Break	Break	10	4	7
<i>Impact induced units</i>	Paluküla (O ₃ pl)	112	Break or eroded I	24	29	Not deposited	Not deposited
	Ejecta	–	Eroded I	Eroded I	Eroded I	0,8	0,3
	Kärdla (O ₃ kr) = internal breccias	288	Not deposited	14	7	0,4	Not deposited
	Pihla-Toila (O ₃ ph-O ₂ tl) = limestones of the target	Impact destruction	Impact destruction	Impact destruction	Impact destruction	14	14
	Kallavere-Voosi (O ₁ kl-Ca ₁ vs) = siliciclastics rocks of the target	Impact destruction	Impact destruction	68	Impact destruction	126	123

The early post-impact topography of the seabottom at Kärđla was diversified, especially if to compare with the surrounding almost perfectly levelled and smooth region. Some segments of the rim wall, with uplifted crystalline core, were elevated more than 200 m above the seafloor in Paluküla and about 50 m in Tubala (Fig. 1). The original topography of the rim wall was composed of sedimentary rocks remains unknown because of immediate post-impact erosion. Outwards from the Paluküla Ridge, an area of uplifted (25 m or more) target rocks is about 2–3 km wide. The topography of the rim wall and the annular area surrounding it was probably higher than presently also due to the lost of ejecta cover that was possibly some or first tens of meters thick. The bottom of the depression corresponding to the crater proper after the end of the deposition of impact breccias is now c. 200 m below the target surface. However, immediately after the crater formation the floor of the central depression was somewhat higher as far as the crater filling deposits had larger porosity and larger (possibly, about 10%) volume.

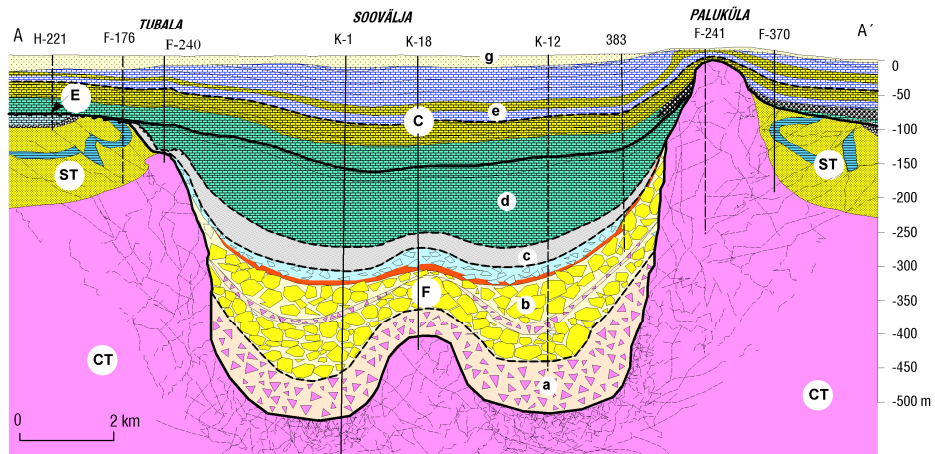


Fig. 1. Kärđla crater – lithostratigraphy and lithology of impact-produced and post-impact deposits and complexes. **CT** – crystalline target rocks, **ST** – sedimentary target rocks. **F** – filling complex: a – Kärđla Formation, Member of Impact Breccias; b – Kärđla Formation, Member of Sedimentary Breccias; c – Paluküla Formation, Member of Turbitites; d – Paluküla Formation, Member of Carbonate Rocks. **C** – Covering complex: l – limestones; r – reef limestones; q – Quaternary deposits. **E** – ejecta layer. **S** – structural level used in structural calculations.

The crater infill and the post-impact stratigraphies. Within the crater, on top of the allochthonous breccia suite namely the Kärđla Formation (Table 3, O₃kr) a continuous marine deposition formed the sedimentary suites of Paluküla (O₃pl) and Idavere (O₃id = O₃ vsv-tt) formations, which are in age synchronous to the stratigraphic units outside of the crater. However, within the crater, these

units are rich in clastic and clayey material derived from the ejecta and surrounding wall under erosion, and their thickness is remarkably larger. The differences in lithologies and thicknesses of the infill units gradually decrease upwards, corresponding to the burial of the crater structure, filling and shallowing of the crater depression, and narrowing of the erosion area. Above the uplifted zones of the rim, and the nearby uplifted exterior zone, a considerable break in deposition occurred. During this break, erosion dominated and eroded material from ejecta and re-exposed deformed sedimentary and crystalline rock sources influenced sedimentation in the central depression and in the surroundings of the crater (Suuroja et al. 1994; Ainsaar et al. 2002).

4.3. Kärddla – detailed lithology, lithostratigraphy and origin of impact-produced deposits

The lithostratigraphy of the impact-produced rocks at Kärddla was studied in 4 core sections (K-1, K-12, K-18 and 412) in the crater interior and 56 sections from the crater exterior.

The impact-induced lithologies accumulated in the crater interior are different from those of the crater exterior. However, the specific deposits accumulated during the impact and early post-impact processes in both areas are divided into the Kärddla Formation of impact breccias and the Paluküla formation of layered post-impact marine sedimentary deposits (Table 2). Both these formations belong to the Middle Ordovician Epoch Caradoc Age Haljala Regional Stage (Idavere Substage) and yield the specific information on the sedimentary processes during the late stages and after the impact-induced processes. Stratotypical for both these formations is the core section of the drill hole K-1, which was drilled in the annular mold of the crater, at the depth of 189.5–588.5 m (thickness 399 m) (Suuroja et al. 1991, 1994; Pöldvere & Suuroja 2002). These deposits are dissimilar in composition to the coeval Tatruse Formation, distributed in the surroundings of the crater and corresponding to the lower part of the regional Idavere Substage. Their lithologies are entirely different – the Tatruse Formation is composed of the biotrititic limestone that is characteristic for the entire northwestern Estonian area.

The ***Kärddla Formation*** (PAPER IV; Suuroja et al. 1994) was deposited during the impact. It consists of different allochthonous layers from large blocks to fine-grained suevite-like breccia suites in the crater and ejecta breccia layers in the crater exterior.

The ***Paluküla Formation*** (PAPER IV; Suuroja et al. 1994) consists of specific early post-impact marine gravellites, sandstones, clays, marlstones and limestones, all containing debris produced due to the erosion of the ejecta blanket and the rim.

The Kärddla Formation is present in the stratotypical core section K-1 at the depth of 301.0–588.5 m (thickness 221.8 m). It is divided into a lower member of impact breccias and an upper member of sedimentary breccias.

The lower **Member of Impact Breccias** formed during the first stages of the impact, namely the stages of compression and excavation (Shoemaker 1960, Melosh 1989). Usually, mainly matrix and clast supported impact breccias and suevites represent this kind of formation (Stöffler & Grieve 1996) whereas in some craters massive impact melt bodies occur (Dence 1972). However, no melt bodies are encountered in the Kärddla crater. The main source rocks of the impact breccias are Precambrian basement rocks. These crystalline rocks form the bulk of breccias in the crater interior. In the crater exterior they occur only rarely in the composition of the ejecta layer (PAPERS IV and VII). In the stratotypical section (drill core K-1 at 471.0–588.5 m) the Member of Impact Breccias reaches its peak thickness, 117.5 m. The lowermost part of it (588.5–522.8 m) has a somewhat dualistic position. This 65.7 m thick sub-member has also been referred to as a “par-autochthonous” breccia. It contains large blocks, up to some meters in diameter, of brecciated metamorphic rocks of the Precambrian basement. Thus, this submember is very similar to the brecciated sub-crater basement in general. However, veins and irregular bodies of fine clasts (including rounded quartz grains from the sedimentary cover) and matrix-supported impact breccias are usually distinguished here. The boundaries between clasts and matrix are transitional as is transition of the lower boundary of the crater floor (Suuroja & Pöldvere 2002, Puura et al. 2004). All the signatures as a unit formed during a huge compression and subdued mixing are characteristic of this sub-member.

The upper **Member of Sedimentary Breccias** was formed during the stages of modification and resurge (PAPER IV, Suuroja 1996). It consists mainly of huge blocks, up to tens of meters in diameter, and minor clasts of the sedimentary target rocks. These are distinguished in the crater proper and outside of it and are named “sedimentary polymict breccias” (Puura et al. 2004) or “slump of sedimentary rocks and resurge breccias” (PAPER I; Suuroja 1996). In the stratotypical section (471.0–301.0 m in drill core K-1) the upper member is the thickest (170.0 m). In the section 326.0–471.0 m (145 m) the sequence of slump breccias consists mainly of deformed blocks of the Cambrian siliciclastic rocks (silt- and sandstones). Inside this layer at 356.5–368.5 m (12.0 m) and at 380–395 m (15 m) thicker layers of more fine-grained, matrix- and clast-supported impact breccias occur. A similar layer is observed also in the core section K-12. These layers are similar to the main suevite-like impact breccia layers at 522.8–471.0 in core K-1 and at 400.0–356.0 in core K-1 and K-18 just above of the central uplift. Obviously, these layers formed due to slumping of impact breccias and suevites ejected during the excavation stage.

In the surroundings of the crater, i.e. 1–1.5 km outside the rim ridge and within an up to 5 km wide annular belt, there is up to 16 m thick (drill core K-14) odd layer of brecciated pre-impact limestones resting on top of the target

sedimentary rocks which are mainly limestone (Suuroja et al. 1994; Suuroja et al. 1999). In between the limestone blocks and clasts, minor (up to 10 cm) clasts of Precambrian metamorphic and Cambrian siliciclastic rocks are encountered within the layer. Obviously, the processes of subsurface release after the passing compression and rarefaction waves are responsible for the observed mixing of local carbonate target and ejected basement debris (PAPER IV). In a way, one can see some analogy in the origin of parautochthonous breccias of the crater bottom and this odd breccia layer.

The Paluküla Formation contains marine deposits formed during early post-impact times (PAPER IV; Suuroja et al. 1994; Suuroja 1996). The deposits contain a major or minor admixture of impact-produced debris and of the matter eroded from the elevated structures of the crater. Stratotype for the formation is the interval 301.2–189.4 m (thickness 111.8 m) in core section K-1.

The Member of Turbitites of the formation consists of conglomerates, gravellites, sand- and siltstones, and clays distinguished mainly in the crater proper. These rocks were deposited from debris- and mud-saturated waters, mudflows, after the arrival of the resurging tsunami (Suuroja et al. 1994). The stratotypical section, drill core K-1 interval 301.2–279.8 m (21.4 m), contains from the bottom: 300.0–301.2 m (1.2 m) – massive unsorted sandy gravelite, 296.0–300.0 m (4.0 m) – thick-bedded fine- to medium-grained sandstone, and 279.8–296.0 m (16.2 m) – massive light grey siltstone. The member has its largest thickness (28 m) in the core section K-12. In the crater interior more coarse-grained deposits, namely unsorted sandstone, gravelite and fine conglomerate, has accumulated close to the rim wall. In the crater exterior this member – the ejecta layer – is thin (0.1–6.0 m).

The Member of Carbonate Rocks contains an extraordinarily thick complex of Ordovician carbonate deposits, marls and limestones. In drill core K-1 the member is present at 279.8–189.4 m (90.4 m). The member was deposited during considerably short time, less than 1 million years, at the beginning of the Haljala Regional Stage (Idavere Substage). During this period the crater depression underwent comparatively quick subsidence of the crater floor due to compaction of the underlying impact breccias. In the surroundings of the crater, in normal marine conditions during that time, there accumulated only a c. 0.5 m thick layer of biotrititic limestone (Nestor & Einasto 1997). Furthermore, during that time the rim wall, consisting mostly of brecciated Precambrian metamorphic rocks, was not buried completely yet. Thus, the rim wall served as a provenance area for debris from the silt up to gravel to be deposited in both crater interior and exterior. In places siliciclastic material formed thin (up to 20 cm) layers of terrigenous rocks.

The buried ejecta layer in the surroundings of the Kärđla crater consists mostly of silt- to gravel-size debris of the target rocks, sedimentary (limestones, sandstones, siltstones, clays) as well as crystalline rocks (gneisses, migmatites, granitoids, amphibolites). In the lower part of the ejecta layer and closer to the impact centre coarser matter (pebbles, cobbles, and blocks) occurs more

frequently. Among the coarse fragments both sedimentary and crystalline rocks occur, although the finer fragments (silt and sand) are mostly made up of disintegrated siliciclastic rocks derived from the Lower Cambrian to Lower Ordovician silt- and sandstones. Further away from the impact centre, both the thickness of the ejecta layer and grain size of the ejected matter decrease. Grain size decreases from bottom to top of the layer, too (PAPER VII).

In the ejecta layer at a distance of 6–12 km from the impact centre, at least two separate beds with sharp contacts are observed, namely coarser bed in lower part and finer bed in the upper part. Closer to the impact centre the ejecta layer has been partly or entirely removed, and further away the contacts between different layers are smoother or transitional. Thus, the base of the ejecta layer depends on the distance from the impact centre (PAPER VII).

In those areas where the ejecta layer has been eroded, noticeable diversities occur. The boundary between the lower coarser and the upper finer beds of the ejecta layer is quite sharp. At distances less than 10 km from the centre it becomes more transitional. The two separate beds are recognizable up to a distance of 30 km from the impact centre. The lower, coarser bed consists mostly of angular clasts (cobbles, pebbles, granules, sand) of the impact origin.

The content of coarse fractions decreases upwards in the ejecta layer, whereas the total content of insoluble residue, conversely, increases. The coarser fraction (granules) in these samples is mainly angular and consists of different target rocks. With increasing depth the content of clasts derived from the crystalline basement decreases as well.

The upper fine-grained part (fraction 1–1/16 mm) of the ejecta layer consists mainly of disintegrated Cambrian silt- and sandstone. The shape of grains are mainly (80%) rounded or well rounded. Coarse fragments (granules) of crystalline and sedimentary target rocks are very rare. Further away from the impact centre, the thickness of this part of the ejecta layer decreases. The total content of insoluble residue is higher (60–80%) in the middle part of the layer. The upper part of the ejecta layer differs from the pre- and post impact limestones, mostly by the content of insoluble residue. Farther away from the impact centre the content of insoluble residue and its average grain size in the ejecta layer decrease. Also, away from the impact centre the mineral composition of the silt and sand fractions becomes simpler and quartz prevails. The upper (finer) part of the ejecta layer, which precipitated from the debris-saturated water somewhat later, is separated from the lower (coarse) bed by a quite distinct boundary. The origin of this boundary is not clear yet, but possibly the upper part of the layer is connected with re-deposition of the primary ejecta. Observations show that the upper part of the ejecta layer has sometimes fine-bedded texture. The deposition of the ejecta, except for the nearest surroundings of the crater, namely the outer slope of the rim wall, took place on practically smooth seabed at almost constant depth (c. 100 m). The tsunami caused by the impact did not affect the seabed and bottom deposits further than 10 km from the impact centre (PAPER I, VII; Suuroja et al. 1991 etc.).

4.4. Neugrund – the structure

In Neugrund the impact-related deposits in the crater proper do not crop out and neither are they penetrated by drilling. The sedimentary rocks of the filling complex everywhere cover them. The identification of this impact structure was achieved due to the study of erratic boulders derived from the rim ridges and scattered in surroundings by the Pleistocene glaciers. Diving geologists provided the main data about the structural features, rim ridges and covering deposits when visiting the submarine outcrops.

The information needed for identification of Neugrund as an impact structure was collected during the investigations of blocks of the specific erratic Neugrund breccias, and of the submarine ring-ridges of the crater (PAPERS V and VI). Injections of melt, suevites, and matrix- and clast-supported impact breccias were studied. The Neugrund-breccia is identical to the gneiss-breccia described in older literature (Õpik 1927; Thamm 1933; Orviku 1935; Viiding 1955). The gneiss-breccia boulders are impact influenced metamorphic rocks of the crystalline target in the Neugrund impact structure area. Therefore we proposed the name Neugrund-breccia (PAPER II).

We have no direct data regarding the existence of massive impact melt and breccia rock bodies in the crater interior. However, the studies of the Neugrund clast- and matrix-supported impact breccias from the Neugrund rim ridges revealed, that they are very similar to the impact breccias of the Kärddla impact crater area. Three main lithological types of clast-supported impact breccias are distinguished considering which types of crystalline rocks they are formed of: 1) granitoids, 2) gneisses, 3) migmatites or 4) amphibolites. Macroscopic similarity of the clast-supported impact breccias of Kärddla and Neugrund impact structures led to the discovery of the Neugrund impact structure (PAPER II; Suuroja & Saadre 1995; Suuroja et al. 1997).

Compared to Kärddla, the Neugrund impact structure is larger, older and much more complex. Following the classifications of terrestrial impact craters (Dence 1972; Masaitis et al. 1980; Grieve 1987; Melosh 1989; Grieve et al. 1995; Grieve & Pesonen 1996; French 1998, Melosh & Ivanov 1999; Abels et al. 2002), Neugrund is a complex impact structure with three ring-ridges. The diameter of the crater proper is c. 5 km and the diameter of the whole structure is about 20 km.

The characteristics of the crater are (PAPER VI, table 3, fig. 8):

- 3-ridged rim,
- Inner crater, with 9-km rim-to-rim diameter,
- Outer crater, about 20-km in diameter.

In our early publications (PAPER II, fig. 9) the above-mentioned 3-ridged area was treated as a dislocated interior of the structure, surrounded by an elliptical ring fault 20–21 km in diameter. Outside the ring fault as the outer limit of the outer crater, the target rocks are almost intact. However, in the far surroundings of the Neugrund structure (wells F-331 and F-334, correspondingly 14 km and

20 km from the impact centre) in the sedimentary cover specific structural and lithological features are found (Suuroja et al. 2002). Thus, in the sedimentary cover mixed and brecciated target rocks containing shock-metamorphosed minerals with PDF-s occur. These are attributed to the Neugrund impact (PAPER VI, fig. 3; Suuroja 2006).

Table 3. The main characteristics of the Neugrund impact structure.

Characteristic	Size
Target:	
Seawater depth	100–200 m
Sedimentary target, thickness	c. 120 m
Stratigraphic units of the pre-impact sedimentary rocks:	
Lower Cambrian silt- and sandstones and clays, thickness	c. 60 m
Upper Vendian (Ediacarian) silt- and sandstones, thickness	c. 60 m
Crystalline basement – thickness of the Earth crust	c. 47 km – (Moho depth)
Weathered rocks of the crystalline basement, thickness	5–20 m
Fresh rocks of the 1.9–1.8 Ma Svecofennian orogenic complex:	(c. 47 km)
Granite-migmatites, granite, biotite-, amphibole-biotite and biotite-amphibole gneisses, amphibolites	
Crater rim ridges and ring fault:	
Crater proper, diameter	5 km
Number of ring-ridges	3
Width of the zone of the ring-ridges	up to 5 km
Rim-to-rim diameter of the inner crater	c. 9 km
Maximum height of the structural uplift of the crystalline rim walls	c. 110 m
Diameter of the ring fault (limit of the outer crater)	20–21 km
Width of the zone between the ring ridges and the ring fault	2.5–3 km

In Table 3, the subsurface structures are deduced from geophysical data and seabed topography (Suuroja 2007). Data on the seabed topography is relevant for the structural studies, because the Pleistocene glacial erosion has selectively truncated the uppermost parts of the impact structure, revealing the presence of hard rock basement walls. The drilling sites located on land, namely on the Osmussaar Island and in the mainland in NW Estonia, penetrate the covering sedimentary complex, the distal ejecta layer and the target rocks (PAPER II; Suuroja et al. 1987). The divers' geological observations of the seabed and the sampling support the information.

Specimens and samples for the investigation of the impact-influenced rocks have been collected from two structural and stratigraphic units of the Neugrund crater: the topmost part of the crystalline rim wall, and the uppermost part of the post-impact sedimentary infill of the crater. Diving geologists described and sampled the rocks of these units.

The Neugrund-breccia is composed mainly of crystalline rocks. Very rarely the presence of sedimentary material has been observed in available Neugrund

impactites. Occasionally, rounded quartz in sand-bearing inclusions are present in the Neugrund breccia matrix. This is similar to the breccia matrix veins in the crystalline breccias of the Kärđla rim wall.

4.5. Neugrund – lithologies of the ejecta

Data from the ongoing research of the Neugrund ejecta layer and distal deformations of the target complexes have been only partially published (PAPER VI). The ejecta layer is studied in five core sections: F-331, F-331A, F-331B (Ristna Cape, 14 km SE from the centre); 410 (Osmussaar, 9 km SW from the centre); and F-332 (Vihterpalu, 20 km SE from the centre). In a specimen collected from the F-331 section at the depth of 90.8 m, the sandy fraction (0.5–0.25 mm) of quartzose sandstone contains up to 8% of shocked quartz grains. In these grains were observed up to 5 sets of PDFs with different orientations, and in a single grain up to 3 sets of PDFs occurs. In average, the frequency of lamellae was 200–400 per 1 mm. Among finer fractions (0.063–0.25 mm) and subangular and well-rounded grains the share of shock-metamorphic matter was up to 1%, and zero amongst angular grains. The shape and fractional composition of the PDF-quartz grains indicate that they are mostly derived from the pre-impact siliciclastic target rocks (sandstones) and only a small part (angular grains) comes from the crystalline basement rocks.

In core sections F-331, F-331A, F-331B – Ristna Cape, 410 – Osmussaar, F-332 – Vihterpalu, F-332, F-334, F-335 the sedimentary target rocks are disturbed – brecciated, fractured, with inclined bedding, folded. In drill cores F-331 and F-331B from Ristna Cape (3 km south-eastward of the ring fault and 14 km from the impact center) these deformations are very peculiar. In core section F-331, at a depth of 92–120 m, the pre-impact clay- and siltstones of the Lower Cambrian Lontova Formation are brecciated and contains angular clasts (5–20 cm in diameter) of Ediacaran (Vendian) sandstones and rocks of the crystalline basement (0.5–5 cm in diameter). The latter are very similar to the granitoids, gneisses, migmatites and amphibolites distributed in the crystalline basement of this area. This suggests that some basement-derived material of distal ejecta was mixed with the strongly deformed sub-autochthonous sedimentary target material. The silt and sand fractions (0.063–0.5 mm) of this breccia matrix contain shock-metamorphosed quartz grains (on average about 4% of total quartz) with well-developed PDFs.

In core sections, the sedimentary siliciclastic target rocks are found sporadically brecciated and dislocated at distances of more than 20 km from the impact centre (Suuroja and Suuroja 2004). In the section of the drill hole F-332 (Vihterpalu, depth of 100–110 m), which is located 20 km to the southeast from the impact centre, the pre-impact silt- and claystones of the Lontova Formation are slightly brecciated. Similar deformations at the same stratigraphical level are observed in drill hole F-335 (22 km south of the impact centre).

5. DISTRIBUTION OF SHOCK METAMORPHIC MINERALS IN THE IMPACT RELATED AND POSTIMPACT DEPOSITS

5.1. The Kärddla crater

Data on the distribution of shock metamorphosed minerals in the impact-induced stratigraphies and structures serves for the characterization of distribution of shock pressure in craters of the same size group and target composition in marine environments.

In Kärddla crater the shock metamorphosed minerals, among which quartz is the best recognizable, are widely spread in the crater interior – in suevite-like breccias, clasts- and matrix-supported impact breccias, as well as in the ejecta, and additionally also in the siliciclastic debris in post-impact deposits derived from impact breccias. A widespread impact metamorphic feature of the shock metamorphism is kink-banded biotite, which marks the lower pressure zone in the sub-crater basement and in the rim wall. In the crater interior, quartz grains with PDFs are often found in the core K-1 in up to 52 m thick bed (471–523 m) of clasts- and matrix-supported impact breccias and suevites (PAPER III; Suuroja 1997) or granitoid polymict breccias (Puura et al. 2004). These breccias originate mostly from the Precambrian crystalline basement rocks of the target and they lie immediately on the crater floor. However, the majority of PDF-quartz grains are rounded, and originate from the Cambrian sandstones suggesting mixing of the basement and sedimentary material during the impact deposition. The boundary between the thick layer of impact breccias and the more intact crater floor is transitional and this interval (523–589 m in the core K-1) is treated as layer of par-autochthonous (Puura et al. 2004) or autochthonous impact breccias (Puura et al. 2000). Kink-banded biotite, but not PDF-quartz, is found in huge blocks of metamorphic rocks. In the dikes/veins of fine-grained impact breccias in the par-autochthonous breccias as well as in the crystalline rim wall PDF-s in quartz grains are very rare. In the core K-1, a more than 130 m thick layer (340–471 m) of sedimentary polymict breccias (Puura et al. 2004) mainly consists of large blocks of Cambrian siliclastic rocks of the target. They obviously are of slump origin. In large slump blocks no quartz grains with PDF were found, whereas in lenses containing bombs of suevite-type breccia and matrix supported impact breccias (up to 24 m thick layer at 356–380 m in core K-1) rare PDF-s are found. It is not excluded that shock-metamorphosed minerals might occur also in weakly lithified mixtolite-like filling between the huge and smaller blocks, but as a rule, this kind of material is lost in the course of drilling.

In the resurge breccias (up to 40 m thick layer at 300–340 m in drill core K-1), shocked quartz is found mainly in bombs of suevite-like breccias and matrix

supported impact breccias, which were ejected by the impact and then carried back by the resurging tsunami. The blocks and clasts of sedimentary and metamorphic rocks do not contain shocked minerals, but rare rounded (originated from disintegrated Cambrian siliciclastic rocks) quartz grains with PDF-s are encountered in the mixtolite-like filling between the blocks. The rounded quartz grains originate from disintegrated Cambrian siliciclastic rocks.

PDF-quartz grains are abundant in the early post-impact clastic deposits that range from siltstones up to gravellites. This kind of layers formed in the crater interior and presently they are located at depth less than 300 m. Core K-1: depth 290–301 m (21 m); K-12 (270–298 m (28 m); K-18 (268–291 m (23 m). The layers are known as the Turbitite Member of the Paluküla Formation (See Ch 4.3.). The Turbitite Member was deposited immediately after the impact from the resurged mud- and debris-saturated water. In three studied thin sections from core K-18, fraction 1–1/8 mm, the share of PDF-quartz was about 1%. Up to 5 different crystallographic orientations of PDF systems (maximum 3 per grain) were observed there. According to Stöffler & Langenhorst (1994) and Stöffler & Grieve (1996) these features refer to a shock pressure of about 10 GPa (Suuroja et al. 2002). The shocked quartz grains are mostly (95%) rounded or well-rounded, angular and sub-angular forms are rare.

In the crater interior, on top of the above Turbitite Member, up to 90 m thick beds of carbonate rocks occur. These marlstones and limestones belong to the carbonate rocks of the Paluküla Formation. They further contain siliciclastics eroded from the rim wall and the ejecta blanket. The siliciclastics contain rare quartz grains with PDF-s, i.e. in 2 samples from core K-18 a few quartz grains with PDF-s were found.

In the ejecta layer further than 5 km from the impact center, the insoluble matter contains quartz grains of the fraction 1–1/8 mm. About 1% of the grains contain PDF-s. In these grains 5 sets (maximum of 3 orientations per grain) of PDF-s of different crystallographic orientation are distinguished (PAPER IV). 95% from the grains are rounded or well rounded, suggesting the source from shocked Cambrian sandstones, and only rare angular grains are derived from the Precambrian metamorphic rocks of the target.

5.2. The Neugrund crater

In the Neugrund case the shock-metamorphosed minerals, namely quartz grains with PDF-s are found in several different settings. A – In the clast- and matrix supported impact breccias and suevite veins in the Neugrund-breccias. These probably originate from the topmost part of the crater rim wall. B – In the re-deposited ejected matter (core F-331 90.0–94.0 m). C – In the distal deformed sedimentary target rocks (core F-331A 92.0–192.0 m). D – In the re-deposited post-impact rocks. Samples were collected from Osmussaar-breccia veins at outcrops on Osmussaar Island (PAPER VI). In summary, quartz grains with

PDFs were found in 5 core sections, in 3 samples taken from the submarine outcrops, in 5 erratic boulders of Neugrund-breccia, and in 2 samples from Osmussaar-breccia veins and from sandy limestone of Pakri Formations on Osmussaar Island (PAPERS II and VI; Suuroja & Suuroja 2006).

In the Neugrund-breccia quartz grains with PDF-s are found mainly in the veins and lenses of clast- and matrix-supported impact breccias and suevites, and rarely in huge clasts of impact influenced (brecciated or partially melted) crystalline basement target rocks. The PDF-quartz is often found in breccias and suevites, which are formed from granitic rocks. Maximum 3 sets of PDF-s in quartz with different crystallographic orientations are found ($\{1013\}$, $\{1012\}$ and $\{1011\}$), which frequently are decorated. The content of quartz grains with PDFs rarely exceeds 1% of total quartz and frequency of lamellae is 200–400 per 1 mm (PAPER VI).

The shocked minerals in the ejecta layer, composed of fine-grained micro-bedded quartzose sandstone, were studied in the core section F-331 at a depth of 90.8 m (Suuroja and Suuroja 2004). The coarse sandy fraction (1/2–1/4 mm) contains quartz grains with PDFs up to 8 %. Up to 5 sets of PDFs with different orientations were observed, $\{1013\}$, $\{1012\}$ and $\{1011\}$ prevail. In a single grain with up to 3 sets of PDF-s were found (Suuroja et al. 2003). The frequency of the lamellae, which are frequently decorated with fluid inclusions (Kirsimäe et al. 2002), is 200–400 per 1 mm. In finer fractions (1/16–1/4 mm) sub-angular and well-rounded grains PDF-s bearing grains contain up to 1% and angular grains contain no PDF-quartz grains. The shape and size of quartz grains with PDF-s indicate that mainly the impact sedimentary target rocks (Cambrian and Vendian silt- and sandstones) and only a small part (angular grains) from the Precambrian metamorphic rocks have been the source of grains with shock metamorphic signatures (PAPER VI).

The ejecta layer was searched for PDF-s in 2 samples from the zone of distal deformations – in core sections F-331 and F-331B (distance from the crater centre 14 km south-eastward and 3 km from the ring fault). Here, below the ejecta layer sedimentary target rocks (silt- and claystones of the Lontova Formations (F-331, 29 m at depth 90.0–119.0 m, F-331B, 25 m at 90.0–115.0 m) are brecciated and contain angular clasts (5–20 cm in diameter) of the Vendian sandstones and Precambrian metamorphic rocks (0.5–5 cm in diameter) characteristic of this area (Suuroja et al. 1987, Suuroja et al. 1998). Silty- and sandy fractions (1/16–1/2 mm) derived from this breccia matrix contain quartz grains with well-developed PDF-s about 4% (from total quartz). Up to 4 sets of PDF-s with a frequency of 200–400 lamellae per 1 mm occur here. In a single grain up to 3 sets of PDFs with different optical orientations occurs (PAPER VI). The PDF-s are most numerous (up to 8% of total quartz) in the fraction of 1/2–1/4 mm and among sub-rounded grains (up to 5%). PDFs are observed also in grains of apatite (up to 20% of total apatite) and plagioclase (single grains). The clasts derived from the Precambrian metamorphic rocks do not, as a rule, contain PDF-quartz.

In the veins and lenses of the Osmussaar-breccia, which is a breccia-like limy sandstone) (Orviku 1960; Puura & Tuuling 1988) on the Osmussaar and Suur-Pakri ilands, PDF-s bearing quartz grains were found. The origin of these specific rock bodies is not understood as yet. Recently they are interpreted as evidence of a c. 475 Ma (Middle Ordovician) catastrophic earthquake or series of earthquakes (PAPER V; Kirsimäe et al. 2001). Single mineralogical analyses from samples of the sandy limestone of the Pakri Formation (Middle Ordovician, Kunda Regional Stage) and Osmussaar-breccia injections, searching for PDFs bearing quartz grains were carried out. Both these contain quartz grains with PDFs. The character of the PDF-s in both cases is quite similar. There is generally only 1 set of lamellae per grain. The prevailing plains are {1013} or angles between c-axis c. 21°, {1012} or c. 32° and {1011} or c. 52°. But content of shocked quartz in the sandy limestone of Pakri Formation is more rare. The PDF-s bearing quartz in these rocks is supposed to be carried from the nearby-situated Neugrund impact structure area (the uplifted rim ridges), which at that time (c. 475 Ma – Middle Ordovician, beginning of Kunda time, see PAPER V) was exposed to erosion.

6. DISCUSSION AND CONCLUSIONS

1. The Neugrund (age c. 535 Ma, diameter 9 km) and Kärddla (c. 455 Ma, 4 km) craters belong to a numerous group of Early Paleozoic craters concentrated in a limited Baltic Sea area of 100 000 km². Apart from Neugrund and Kärddla, the group include Suvasvesi North (560–530 Ma, 4 km; Pesonen 1996, Pesonen et al. 1996 etc), Söderfjärden (540–520 Ma, 6.6 km; Lehtovaara 1992, Laurén et al. 1996), Granby (c. 410 Ma, 3 km; Henkel & Pesonen 1992), Lockne (455 Ma, 8 km; Flodén et al. 1986, Lindström et al. 1992, 1994, 1996; Ormö and Lindström 2000) and one small crater namely Tvären (457 Ma, 1 km (Floden et al. 1986, Lindström et al. 1994). This is one of the largest concentrations of impact structures of the 550–450 Ma age group. Recently it has been speculated (Schmitz et al. 2003; Alwmark & Schmitz 2006; Schmitz & Alwmark 2006; Schmitz & Häggeström 2006; Trieloff et al. 2006) that these and dozens of others Early Paleozoic craters on Earth might be a result of collapse of a big (>100 km in diameter) L-chondritic chromite rich asteroid. The latest geochemical research by Heintz Huber revealed that the Kärddla meteorite most probably was of chondritic composition (Puura et al 2004), and the earlier supposition of its iron composition (Suuroja 1996a) is hardly reliable. The Kärddla meteorite fits with the hypothesis by Schmitz et al. (2003). Data on the composition of other projectiles of the above-mentioned impacts, except Gardnos that is supposedly chondritic (Dons & Naterstad 1995), is not available.

2. Geological conditions during Cambrian and Ordovician were similar across the entire circum-Baltic area. A considerably thin sedimentary blanket, merely a few hundreds meters thick, covered the Precambrian crystalline basement. Impacts truncated both sedimentary cover and the crystalline basement. Consequently, the impact-produced lithologies contain both sedimentary and crystalline rocks. E. Gurov et al. (1998) pointed out that the vertical transport of rock debris in the impact process is focussed on the transfer of rock debris from higher to deeper levels. At Kärddla and Neugrund, 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, and post-impact history.

2a. Within the impact-deformed sub-crater basement at Kärddla, deep under the basement floor (down to more than 70 m) rounded quartz grains mixed with fine non-rounded crystalline rock debris have been found in impact-produced clastic dikes. Most probably, they have been deposited by intrusions of impact plume-produced glowing suspension. In the interclust cement of the parautochthonous crystalline bottom-breccia layer (well K-1, 528–589 m), rounded grains derived from Cambrian sandstones are abundant. Similar clastic dikes are found within the central uplift composed of Precambrian crystalline rocks and in the crystalline rim of the Kärddla structure. At Neugrund, in the samples from the submarine crystalline rim wall and erratic blocks of Neugrund breccias Vendian to Cambrian

sand-derived quartz grains have been found in inter-clast cement as well. In the exterior of the Kärddla crater, within the in-situ broken and mixed target limestone layer, above referred as “limestone breccias”, rock debris originating from e.g. crystalline basement, the Dictyonema shale and disintegrated Cambrian to Ordovician sandstones are abundant.

2b. The rim walls of both Kärddla and Neugrund structures are composed of impact-tectonically uplifted blocks of the crystalline basement rocks and deformed layered sedimentary deposits.

At the 4-km wide Kärddla crater only one crystalline-composed rim wall is present. Its height is variable, from maximal 250 m above the primary position to only 50 m in gullies. The outer wing of the crystalline rim is at least locally overthrusting the Vendian and Cambrian sedimentary strata. The last are most intensely deformed in the near-rim zone, containing also isolated large blocks of crystalline rocks (PAPER I, fig. 8). The target structure in a 4-km wide external zone next to the Paluküla segment of the rim wall is uplifted some tenth meters, and sedimentary rocks are deformed there. The outer limit of the gradually weakening stage of target deformation is fixed by the Kärddla ring fault (12–15 km in diameter). Quite similar to Kärddla is the Brent crater in Canada, Ontario (3.8 km in diameter, c. 400 Ma; Dence 1964). Despite that the diameters the craters are similar and both these are buried, Brent is a simple crater and has not visible ring fault. Somewhat similar to Kärddla is also the Steinheim crater 3.8 km in diameter, c. 15 Ma (Ivanov & Stöffler; Earth Impact Database-Google), it has a well-expressed central uplift but no visible ring fault.

At the c. 9 km rim-to-rim diameter Neugrund crater, the zone of deformed and mixed crystalline and sedimentary rocks starts at the internal rim wall that is up to 5 km in diameter, as documented and sampled by diving geologists. According to seismic profiling data, the external 4 km wide zone located c. 10 km from the centre of the crater, is composed of concentrically arcade shifted blocks of the basement and deformed sedimentary deposits. The ring fault encircling that zone, with a diameter of c. 20 km, is considered as the outer limit of the structure. We have found the Neugrund structure to be quite similar to the 24 km wide Ries crater in Germany (Engelhardt 1967; Earth Impact Database-Google) with its large concentric “megablock zone”. In the Ries case, all outcrops are concentrated to the outer limit of the structure, whereas in Neugrund the submarine outcrops are connected with the internal 3-ridged rim wall.

2c. In the crater interior, the main impact breccia units have different compositions due to the variability of the source materials, the degree of their breaking or just disintegration of soft sediments, and the presence of high-temperature impact influence.

In the interior of the Kärddla 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. Within it there is always a

portion of Cambrian-type rounded quartz present. Randomly, also mm- to cm-size fragments of Dictyonema 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 formed under hydrothermal conditions. This breccia is similar to the suevite breccias found in young craters. Thus, we have also called it also suevite (PAPER IV). 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 (Kirsimägi 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 that case possibly in a secondary position due to the modification stage slump, resurge and other processes.

The middle and upper breccias of the crater interior are mainly dominantly composed of blocks of sedimentary rocks, namely claystones, sandstones and limestones. The blocks may have huge dimensions, up to tens of meters. Intervals dominated of claystones respectively of sandstones or of limestones have been found. 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 tsunami processes. Principally, mixing of materials during the impact process is overwhelming. 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 the Cambrian sand.

In the Neugrund structure, the breccias of the crater interior have not been available for research so far.

2d. The external breccias, namely the ejecta layers, have survived at some distance from the rim wall at Kärddla crater. Occasionally the layer has been drilled at distance from the Neugrund structure center, too. The Kärddla ejecta is composed of debris of both crystalline and sedimentary rocks. Fragments of crystalline rocks are found as far as c. 20 km from the crater centre, and chips of sedimentary rocks, namely limestones, Dictyonema 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.

In the surroundings of the Neugrund structure, where the determination of the ejecta layer is more difficult, crystalline clasts in the ejecta have been found at 15 km from the centre, and sedimentary clasts at 20 km.

2e. The loose mineral material produced by impacts in environments favourable for erosion and removal presented an extra input into the source material of sedimentation processes. At Kärđla, sandy to clayey material of ejecta, and rim wall material of local heights in the seabottom, became a source for the formation of the marly infill that constitutes Member of Turbitites of the Paluküla Formation. The unique Kisuvere Member of sandy limestones in the Tatruse Formation is almost synchronous to the Kärđla impact and is also proposed to be connected to the Kärđla source (Põlma 1982). In this case, however, no proof in the form of PDF-quartz has been found so far.

In the surroundings of the Neugrund structure, a surprisingly large number of post-impact geological processes may be explained by influences from the Neugrund impact and Neugrund structure. The PDF-containing quartz grains (see below) found in breccias and sandy deposits from clastic dikes and lenses of Kunda age (c. 475 Ma) on Osmussaar and Pakri Islands, and drill cores of NW Estonia are presently interpreted as a product of erosion of the Neugrund crater area (PAPER VI). This scattering fan has formed c. 60 Ma after the impact.

Much later, in the Pleistocene, the Neugrund crater became a source area for the formation of a fan of erratic glacial boulders, presently abundant on the islands and mainland of western Estonia (PAPER II). Neugrund breccias of specific dominantly crystalline composition, identical in composition to the submarine Neugrund crater inner rim walls, contain PDF-quartz in both cases. The latter is an evidence of a secondary, far post-impact, sedimentary scattering fan.

2f. 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 named circum-Baltic area, the other 550–450 Ma craters are much more deeply eroded, or tectonically deformed (Lockne). In the Lockne case, horizontal movements of rock megablocks have been traced more than 10 km from the impact center (Sturkell et al. 2000). The good survival of the structures and drillcore studies are in favour for the detailed studies of material transportations at Kärđla and Neugrund.

3. Distribution of PDF-quartz and the pressure of shock metamorphism in different structural/lithologic units. In the Kärđla case the PDF-quartz is widely spread in the more monolithic bodies of suevite-like breccias, and in the clasts- and matrix-supported crystalline-derived impact breccias, in the crater proper and outside of it. The Kärđla PDF-quartz confirms shock pressures in excess of 10–14 GPa (PAPER II) or 10–20 GPa (Puura et al. 2004). PDF-quartz occurs

also, but rarely, in the post-impact siliciclastic and carbonate rocks, namely silt- and sandstones, limestones and marls, containing quartz grains. Generally, in brecciated sub-crater and rim ridge crystalline rocks PDF-quartz is not found. In crystalline blocks and chips of allochthonous breccias, PDF/quartz is present, but considerably rare. However, it is common in rounded quartz grains of clast- and matrix- supported impact breccias. In the sedimentary polymict breccias in the crater deep, which consist mainly of brecciated Cambrian siliciclastic rocks and obviously are of slump origin, PDF-quartz is rare and is connected with lenses and bombs of suevite-like and clast- and matrix-supported impact breccias encountered in this layer. Also the weakly lithified mixtolite-like filling between blocks of sandstones sporadically contains PDF-quartz. In the resurgence breccias PDF-quartz occurs mainly in the ejected bombs of suevite-type and clast- and matrix-supported impact breccias, which were carried back by the resurging tsunamis. The sedimentary blocks do not contain PDF-quartz, but it is rarely encountered in the mixtolite-like filling between blocks.

In the Neugrund case interior of the crater deep is buried yet under post-impact deposits and therefore the most strongly shock-metamorphosed rocks are not opened there. Suevites, clast- and matrix-supported impact breccias that contain PDF-quartz originate from rocks of the rim wall, from the distal deformed sedimentary target rocks, from the ejecta layer or from the re-deposited impact-metamorphic materials as the Osmussaar-breccias. On the islands of Osmussaar and Suur-Pakri PDF-quartz is found in the veins and bodies of breccia-like limy sandstone (Osmussaar-breccia) (PAPERS II, V, VI; Kirsimäe et al. 2001; Suuroja & Suuroja 2006). We suppose that these veins and bodies eroded from the nearby-situated Neugrund impact structure at c. 475 Ma.

The observed findings of PDF-quartz in autochthonous and allochthonous positions reveal information on the level of impact deformation and impact metamorphism in the target. In the Kärđla crater, PDF-quartz has not been found in the par-autochthonous sub-crater basement and not in the crater rim rocks. In the par-autochthonous breccias, at depths of 528–589 m in core K-1, kink-banded biotite suggests an impact pressure of about 1–10 GPa. The fact that impact pressures above 10 GPa reached the uppermost basement is documented by PDF-s in quartz from the crystalline rock fragments in the dominantly crystalline-derived breccias in core K-1, K-18 and cores of ejecta outside the rim. Consequently, the strongly impact-metamorphosed part of the basement was ejected in the impact process.

The other fact is that a large amount of Cambrian and Ordovician quartz sand grains have stored the planar deformation features. Rounded PDF-quartz grains derived from Cambrian and other levels have been found only in allochthonous positions. This PDF-quartz has been mixed with un-metamorphosed rock chips of the basement and rounded quartz grains without PDF-s. The mixture was intruded in the form of suspension into the fracture systems of the subcrater basement and uplifted blocks of the rim. The solid material was deposited and during the post-impact processes moderately cemented. The

rounded PDF-quartz grains have been found also in the inter-block or -clast cement of allochthonous breccia of the crater interior and in the external ejecta layer. This suggests an overwhelming role of the mixing process, in which the probably everywhere dispersed disintegrated quartz grains of the impact cloud and the turbulently moving rock debris and blocks participated. In the early to late post-impact processes of redeposition that continued during some million years. The PDF-quartz grains continued their migrations carrying the extraordinary information on the impact event at 455 Ma. The furthest quartz grains have been found in the ejecta layer at 20 km from the Kärddla crater center (further on it was not searched for), and the latest position of PDF-quartz in covering deposits belongs to the Paluküla Formation, Haljala Regional stage, or ca 1 Ma after the impact.

In the Neugrund case, the PDF-quartz has been found in the samples of the submarine crystalline rim wall, and in similar rocks as erratic blocks along the seashore of North-western Estonia. Consequently, in this case, the PDF-deformed quartz has formed in the crystalline basement, which was impact-tectonically transported to form the rim wall.

A huge mass of PDF-quartz was formed from Vendian and Cambrian sand- and siltstones found in the ejecta layer 15 km south of the crater centre, and in redeposited setting as an abundant admixture in the Osmussaar breccias and sandstone dikes on Pakri Islands.

At larger impact structures, impact metamorphism of higher than 10 GPa pressure reaches the subcrater basement (French, 1998). This is the case for the 9-km-diameter Neugrund crater. At the 4-km Kärddla crater there is view about the impact pressure reaching more than 10 GPa in present subcrater basement.

4. The search for, and discovery of, new buried impact sites in geologically perfectly studied regions are possible using geophysical, remote sensing, and deep drilling techniques. As shown above, in the Kärddla case the challenge started with clearing up the nature of an uplifted block of crystalline basement rocks (PAPER I, Viiding et al. 1969; Puura 1974; Suuroja et al. 1974). In the Neugrund case, the search started with the establishment of the origin of specific gneiss-breccia erratics (PAPER II; Öpik 1927; Thamm 1933; Suuroja & Saadre 1995), and of odd annular depressions on seabed encircling the shallow Neugrund Bank (PAPER II, Suuroja & Saadre 1995 etc). In both cases the discovery of the impact structures was connected with geological mapping (Kala et al. 1971; Suuroja et al. 1981, 1987, 1991, 1994, 1997, 1998, 1999; Kala et al. 1971). Drillings at Kärddla were mostly carried out in the course of prospecting of mineral resources (PAPER III, Suuroja et al. 1974; Kala et al. 1976; Tassa & Perens 1984).

As a whole, in areas with very stable platform sedimentary structure, every kind irregular and odd structural and lithological occurrences, namely stratigraphic “instabilities”, geophysical anomalies, and, of course, findings of impact

metamorphic minerals should be treated as suspect phenomena when keeping in mind search for new craters.

5. Extraordinary stratigraphic and lithological phenomena always accompanying meteorite structures in stratified geological environments attract attention of researchers for at least two reasons.

5a. Distal ejecta layers in well-stratified sedimentary sequences give good opportunities for dating of craters. The method worked well in both Kärddla and Neugrund cases. In the surroundings of the Kärddla impact crater, the ejected matter (sandy layer in limestone sequence) is well traceable within c. 50-km radius (PAPER I and VII). In the case of Neugrund, where the ejecta is represented mostly by sandy layer in a sequence of silt- and sandstones, it is not so well traceable and is therefore exactly determined only due to the occurrence of PDF-quartz (PAPER II and VI).

5b. Within and in the surroundings of meteorite craters specific sedimentary environments occur. Often the proper craters have formed traps for early to late post-impact sedimentary accumulation, with uninterrupted course of deposition. In the Kärddla crater, the record of volcanic ash interbeds (K-bentonites) in the Vasavere Formation (Haljala Stage) is much more complete than in the surrounding shallow shelf area of repeatedly interrupted low-rate sedimentation (Suuroja et al. 1991, 1994; Suuroja & Pöldvere 2002). In the shallow zones of the basin outside the rim ridges and uplifted target areas, local erosion and bioherm-type deposition areas occurred (PAPERS IV, 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 lithostratigraphic units for geological mapping – Kärddla and Paluküla Formations and a number of members (Suuroja et al. 1994; Suuroja & Pöldvere 2002).

In the case of the Neugrund crater, only a distal ejecta layer with characteristic lithological changes has been found. We expect that many surprising stratigraphic, paleoenvironmental and lithological patterns will be met when coring a drill hole into the Neugrund crater.

Results of stratigraphic and lithological studies and stratigraphy-based dating of small- and medium-size impact structures have enriched the regular geological investigations of many areas.

6. The size, internal structure and morphology of a crater may carry information about the projectile size, composition and trajectory.

Both Kärddla and Neugrund craters have well developed ring faults as the outer limits their impact-deformed areas. Similar features have been observed at some other impact structures: Boltysh – 24 km in diameter, c. 65 Ma (Gurov et al. 1986, 2003); Ries – 24 km in diameter, c. 15 Ma (Engelhardt 1967); Mjølner – 40 km in diameter, c. 412 Ma (Dypvik 2006).

The dimensions of the Neugrund and Kärddla impact structures have been under some discussion. For similar complex structures as Kärddla and Neugrund (Gault & Sonett 1982; Sonett et al. 1991; Elo et al. 1992; Dons & Naterstad 1995; Poag 1997), the diameter of the structure has been defined as the ring fault or by the limit of the outer crater (Kenkmann et al. 2000; Wagner et al. 2002; Dypvik & Jansa 2003; Glamolcija et al. 2007), thus separating strongly disturbed target rocks from mostly intact target rocks. Following this practice, the diameter of the Neugrund structure is c. 20 km and of Kärddla – 12–15 km. The classical or so-called rim-to-rim diameter of the Neugrund is c. 9 km, and it is measured a centre of 2.5–3 km wide zone of ring-ridges. The rim-to-rim diameter of the Kärddla crater is 4 km. The diameter of the crater proper at Kärddla is 3 km, at Neugrund 5 km. In the surface topography, the crater proper at Kärddla is marked by a low and flat wetland locally encircled by elevated rim wall. In the Neugrund case it is a shallow (1–15 m) sea on a round sedimentary (hard limestone) plateau (5 km in diameter) with an arcuate erosional deep marking the boundary with the inner rim ridge.

Shoemaker (1960), O'Keefe & Ahrens (1993), Deutsch & Shärer (1994), Artemeieva (2002), Pierazzo & Melosh (2000) and Shuvalov (2002) concluded that asymmetrical elements of a structure, namely height and width of a rim wall, elliptical shape of a ringfault etc., refer to oblique impacts. These features are revealed remarkably well in the Kärddla case, where the asymmetrical ring fault and asymmetry in ring ridge height could be explained by an oblique impact (PAPER IV; Suuroja & Suuroja 2006; Jõelett 2007). Unfortunately, the proximal ejecta blanket is completely truncated by erosion, whereas its distal part is distributed more or less concentrically. The observed asymmetries, however, suggest that the Kärddla projectile of probably chondritic composition and c. 0.5 km in diameter approached from southwest (without corrections to plate drift and rotation) under a quite small angle, probably less than 30°.

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REFERENCES

- Abels, A., Zumsprekel, H. & Bischoff, L. 2000. Basic remote sensing signatures of large deeply eroded impact structures. *Lecture Notes in Earth Sciences* 91,309–326.
- Abels, A., Plado, J., Pesonen, L. & Lehtinen, M. 2002. The impact cratering record of Fennoscandia – A close look at the database. In: J. Plado & L. Pesonen (eds.). Impacts in Precambrian Shields. Springer Verlag, Berlin Heidelberg, *Impact Studies*, 1–58.
- Ainsaar, L. & Semidor, M. 1999. Long-term effect of the Kärđla impact crater (Hiiumaa Island, Estonia) on the Middle Ordovician carbonate sedimentation. In: R. Gersonde & A. Deutch (eds). Oceanic impacts: mechanisms and environmental perturbations. *Reports on Polar Research* 343, 13–16.
- Ainsaar, L., Suuroja, K. & Semidor, M. 2002. Long-term effects of the Kärđla impact. Pergamon. *Deep-Sea Research II* 49, 1145–1155.
- Alwmark, C. & Schmitz, B. 2006. Extraterrestrial Chromite in the Ordovician Lockne Impact Structure, Central Sweden. Proceedings of 69th Annual Meeting of the Meteoritical Society, held August 6–11, 2006 in Zurich, Switzerland, *Meteoritics & Planetary Science* 41, 5056 p.
- Artemieva, N. 2002. Tektite Origin in Oblique Impacts: Numerical Modelling of the Initial Stage. In: J. Plado & L. Pesonen (eds.) Impacts in Precambrian Shields. *Impact Studies*, Springer-Verlag Heidelberg, 257–276.
- Barankina, I. & Gromov, O. 1973. Report of preliminary results of prospecting of the uplifts of granitic rocks in Paluküla (Estonian SSR, Hiiumaa Island) (in Russian). Geological Survey of Estonian SSR, Tallinn.
- Bauert, H., Männil, R. & Suuroja, K. 1987. The age of the Kärđla crater (in Russian). In: P. Suveidis (ed.). Local structures in Belarus and Baltic Region. Thesis of the meteoritic conference. Geological Research Institute, Vilnius, Lithuanian SSR, pp 48–49.
- Claeys, P. 1995. When the sky fell on our heads: Identification and interpretation of impact products in the sedimentary record. *Reviews of Geophysics* Vol. 33. Supplement to US National report to International Union of Geodesy and Geophysics, 1991–1994.
- Crawford, D. A. & Mader, C. 1998. Modelling asteroid impact and tsunami. *Science of Tsunami Hazard* 6, 21–30.
- Dence, M. R., 1964. A comparative structural and petrographic study of probable Canadian meteorite craters. *Meteoritics* 2, 249–270.
- Dence, M. 1972. The nature and significance of terrestrial impact structures. 24th International Geological Congress, Section 15, 77–89.
- Dence, M. 2002. Re-examining Structural Data from Impact Craters on the Canadian Shield in the Light of Theoretical Models. In: J. Plado & L. Pesonen (eds.) Impacts in Precambrian Shields., Springer-Verlag, Berlin-Heidelberg, *Impact Studies*, 59–79.
- Deutch, A. & Shärer, U. 1994. Dating terrestrials impact events. *Meteoritics* 29, 301–322.
- Donner, J. 1996. The Fennoscandian Shield within Fennoscandia. *Bulletin of the Geological Society of Finland* 68, Part I, 99–103.
- Dons, J. & Naterstad, J. 1995. The Gardnos impact structure, Norway. *Meteoritics* 27, 200–215.

- Dressler, B., Sharpton, V. & Copeland, P. 1999. Slate Islands, Lake Superior: a mid-size complex impact structure. In: B. Dressler & V. Sharpton, V. (eds.) *Geological Society of America. Special Paper*, 109–124.
- Dubar, G. & Levin, A. 1971. Injectional clastic dykes in the northern Baltic region (in Russian). *Proceedings of the Estonian Academy of Sciences. Chemistry. Geology* 20, 239–242.
- Dypvik, H. & Jansa, L. F. 2003. Sedimentary signatures and processes during marine bolide impacts: a review. *Sedimentary Geology* 161, 309–337.
- Dypvik, H., Smelror, M., Sandbankken, O. & Kalleson, E. 2006. Traces of the marine Mjølner impact event. *Palaeogeography, Palaeoclimatology, Palaeocology* 241, 621–636.
- Eichwald, E. 1840. Kurze Anzeige einer geognostischen Untersuchung Estlands und einiger Inseln der Ostsee. Die Urwelt Russlands, Heft 1. St.-Petersburg, 1–24.
- Elo, S., Jokinen, T. & Sininen, H. 1992. Geophysical investigations of the Lake Lappajärvi impact structure, western Finland. *Tectonophysics* 216, 99–109.
- Engelhardt, W. 1967. Diaplectic glasses in the breccia at the Nördlichen Ries as evidence of shock wave metamorphism. *Contributions to Mineralogy and Petrology* 15, 93–102.
- Flodén, T. 1980. Seismic stratigraphy and bedrock geology of the central Baltic. *Stockholm Contributions in Geology* 35, 1–240.
- Flodén, T. 1981. Current geophysical methods and data processing techniques for marine geological research in Sweden. *Stockholm Contributions in Geology* 37/5, 49–66.
- Flodén, T., Tunander, P. & Wickman, F. E. 1986. The Tvären Bay structure, an astrobleme in southeastern Sweden. *GFF* 108, 225–234.
- French, B. M. 1998. Traces of Catastrophe. A Handbook of Shock-Metamorphic Effects in Terrestrial Meteorite Impact Structures. LPI Contribution No 954, Lunar and Planetary Institute, Houston, 120 pp.
- Gailius, R., Motuza, G., Kala, E., Puura, V. & Suuroja, K. 1987. Thesis of the meteoritic conference. Vilnius (in Russian). In: The local structures of Belarus and Baltic area, 86–88.
- Gault, D.E. & Sonett, C.P. 1982. Laboratory simulation of pelagic asteroidal impact: Atmospheric injection, bethic topography and the surface wave radiation field. In: L. Silver & P. Schultz (eds). *Geological Implications of Large Asteroids and Comets on the Earth. Geological Society of America. Special Paper* 190, 69–92.
- Glamoclija, M., Schieber, J. & Reimold, W. 2007. Microbial signatures from impact-induced hydrothermal settings of the Ries Crater, Germany; a preliminary SEM study. *Lunar and Planetary Science* 38, A 1989.
- Gorbatshev, R. & Bogdanova, S. 1993. Frontiers in the Baltic Shield. *Precambrian Research* 64, 3–22.
- Gradstein, F. M., Ogg, J. G., Smith, A. G., Bleeker, W. & Lourens, L. J. 2004. A new Geologic Time Scale, with special reference to Precambrian and Neogene. *Episodes* 27/2, 83–100.
- Grahn, Y., Nõlvak, J. & Paris, F. 1996. Precise chitinozoan dating of Ordovician impact events in Baltoscandia. *Journal of Micropaleontology* 15, 21–25.
- Grive, R.F. 1987. Terrestrial impact structures. *Annual Reviews of the Earth and Planetary Sciences* 15, 245–270.

- Grive, R.F., Langenhorst, F. & Stöffler, D. 1996. Shock metamorphism of quartz in nature and experiment: II. Significance in geoscience. *Meteoritics & Planetary Science* 31, 6–35.
- Grive, R. A. F., James, R., Smit, J. & Therriault, A. 1995. The record of terrestrial impact cratering. *Geological Society of America Today* 5(10), 193–196.
- Grive, R. A. & Pesonen, L. 1996. Terrestrial impact craters: Their spatial and temporal distribution and impacting bodies. *Earth, Moon, and Planets* 72, 357–376.
- Gurov, E. P., Gurova, E. P. & Kolesov G. M. 1986. Impactite composition of the Boltysch astrobleme (in Russian). *Meteoritika* 45, 150–155.
- Gurov, E. P. & Gurova, E. P. 1991. Geological structure and rock composition of impact structures (in Russian). Naukovka Dumka, Kiev, Ukraine, 160 pp.
- Gurov, E. P., Gurova, E. P. & Sokur, T. M. 2002. Geology and Petrography of the Zapadnaya Impact Crater in the Ukrainian Shield. In: J. Plado & L. Pesonen, L. (eds.) *Impacts in Precambrian Shields*. Springer-Verlag. Berlin – Heidelberg. *Impact Studies*, 117–171.
- Gurov, E. P., Koeberl, C. & Reimold, W. U. 1998. Petrography and geochemistry of target rocks and impactites from Ilynets Crater, Ukraine. *Meteoritics & Planetary Science* 33, 1317–1333.
- Gurov, E. P., Kelley, S. P. & Koeberl, C. 2003. Ejecta of the Boltysch Impact Crater in the Ukrainian Shield. In: C. Koeberl & F. Martiney-Ruiz (eds). *Impact Markers in the Stratigraphic Record*, Springer-Verlag, Berlin Heidelberg, *Impact Studies*, 179–202.
- Haack, H. 1996. Meteorite, asteroidal, and theoretical constraints on the 500-Ma disruption of the L chondrite parent body. *Icarus* 119, 182.
- Henkel, H. 1992. Geophysical aspects of meteorite impact craters in eroded shield environment, with special emphasis on electric resistivity. *Tectonophysics* 216, 63–89.
- Henkel, H. & Pesonen, L., J. 1992. Impact craters and craterform structures in Fennoscandia. *Tectonophysics* 216, 31–40.
- Hints, L. 1997. Haljala Stage. In: Raukas, A. and Teedumäe, A. (eds.). *Geology and mineral resources of Estonia*. Estonian Academy Publishers, Tallinn, 73–74.
- Huff, W., Bergström, S., Kolata, D. & Kirsimäe, K. 2002. K-bentonite mineralogy and geochemistry. In: Pöldvere, A. (ed.). *Estonian geological sections. Soovälja (K-1) drill core*. Tallinn. Geological Survey of Estonia. Bulletin 4, 12–17.
- Ivanov, B. A. & Stöffler, D. 2005. The Steinheim Impact Crater, Germany: Modelling of a Complex Crater with Central Uplift. *Lunar and Planetary Sciences* 36.
- Juhlin, C. & Pedersen, L. 1993. Further constraints on the Siljan impact crater from seismic reflection studies. *GFF* 115, 151–158.
- Jõeleht, A., Kirsimäe, K., Plado, J., Verš, E. & Ivanov, B. 2005. Cooling of the Kärkla impact crater: II. The mineral parasequence observations. *Meteoritics & Planetary Sciences* 40, 21–33.
- Jõeleht, A., Plado, J., Tuuling, I., Gaškov, M., Rooni, K. & Tsyroulnikov, A. 2007. Rim morphology of the Kärkla crater based on reflection seismic. *Lunar and Planetary Science* 38, A 1615.
- Kala, E. & Eltermann, G. 1969. Report of the integrated geological mapping of Western Estonia (sheet O-35-XII) at a scale of 1:200 000 (in Russian). Geological Survey of Estonian SSR, Tallinn.
- Kala, E., Kajak, K., Kajak, H. & Elterman, G. 1971. The integrated geological-hydrogeological mapping of Hiiumaa Island (sheet O-34-XI) at a scale of 1:200 000

- (in Russian). Map with explanatory note. Geological Survey of Estonian SSR, Keila, EGF..
- Kala, E., Suuroja, K. & Petersell, V. 1974. Report of the prospecting granitic rocks of Paluküla (in Russian). Geological Survey of Estonian SSR. Tallinn. EGF 3295.
- Kala, E., Suuroja, K. & Tassa, V. 1976. Report of the prospecting granitic rocks of Paluküla (in Russian). Geological Survey of Estonian SSR. Tallinn. EGF 3423.
- Kala, E., Puura, V. & Suuroja, K. 1984. Main features of the Kärđla buried crater (in Russian). *Proceedings of the Academy of Sciences of the Estonian SSR. Geology* 33, 1–7.
- Kalkun, J. 1922. Üldine geoloogia. Tallinn, 124 lk.
- Kattai, V., Klubov, B., Bagdasarjan, L. & Suuroja, K. 1990 a. New data of the bitumen-bearing lower Paleozoic of Hiiumaa Island (in Russian). *Proceedings Estonian Science Academy. Geology* 41, 73–80.
- Kattai, V., Klubov, B., Kala, E. & Suuroja, K. 1990 b. Natural bitumen outcrops on Hiiumaa Island (in Russian). *Oil Shale* 7, 10–18.
- Kattai, V., Lokk, U. & Suuroja, K. 1994. The distribution of natural bitumens in Estonia. *Bulletin of the Geological Survey of Estonia* 4/1, 12–16.
- Kenkmann, T., Ivanov, B. A. & Stöffler, D. 2000. Interpretation of ancient impact structures: Low-angle faults and related geological features of crater basements. *Lecture Notes in Earth Sciences* 91, 279–307.
- Kenkmann, T., Patzschke, M., Thoma, K., Schäfer, F., Wünnemann, K., Deutsch, A. & MEMIN-team. 2007. Deformation of sandstone in meso-scale hypervelocity cratering experiments. *Lunar and Planetary Science* 38, A 1615.
- King, D. T., Nearthery, T. L. & Petruny, L. W. 2003. Role of water in the formation of the Late Cretaceous Wetumpka impact structure, inner Gulf Coastal Plain of Alabama, USA. *Meteoritics & Planetary Science* 41, 1625–1631.
- King, D. T., Ormö, J., Petruny, L. W. & Nearthery, T. L. 2006. Structure-filling sediments of the Wetumpka marine-target impact crater (Alabama, USA). In: H. Dypvik, M. Burchell, P. Claeys (eds.) *Cratering in Marine Environments and on Ice*. Springer-Verlag. Berlin-Heidelberg. *Impact Studies*, 97–113.
- King, D. T., Nearthery, T. L., Petruny, L. W., Koeberl, C. & Hames, W. E. 2002. Shallow-marine impact origin of the Wetumpka structure (Alabama, USA). *Earth and Planetary Sciences* 202, 541–549.
- Kipper, A. 1937. aasta 1. juuni meteoriidist. *Eesti Loodus* 4, 150–155.
- Kirsimäe, K., Ainsaar, L., Suuroja, K., Suuroja, S. & Mahaney, W. C. 2001. The Osmussaar breccia in northwestern Estonia – evidence of a ca 475 Ma earthquake or an impact? In: F. Martinez-Ruiz, M. Ortega-Huertas & I. Palamo (eds.). 6th ESF IMPACT Workshop “Impact Markers in the Stratigraphic Record”, Granada, Spain, 67–68.
- Kirsimäe, K., Suuroja, S., Kirs, J., Kärki, A., Polikarpus, M., Puura, V. & Suuroja, K. 2002. Hornblende alteration and fluid inclusions in Kärđla impact crater, Estonia – evidence for impact-induced hydrothermal activity. *Meteoritics & Planetary Science* 37, 449–457.
- Kivisilla, J., Niin, M. & Koppelmaa, H. 1999. Catalogue of chemical analyses of major elements in the rocks of the crystalline basement of Estonia. Tallinn: Geological Survey of Estonia, 94 pp.
- Klesment, A.-L., Pirrus, E., Suuroja, K. & Tiirmaa, R. 1987. Geology of the north-eastern slope of the mound of the Kärđla buried crater (in Russian with English

- summary). *Proceedings of the Academy of Sciences of the Estonian SSR. Geology* 36, 131-139.
- Koeberl, C. 2001. The sedimentary record of the impact events. In: Peucker-Ehrenbrink B, Schmitz B (eds.). *Accretion of Extraterrestrial Matter throughout Earth's History*. Kluwer Academic/Plenum Publishers, 333–378.
- Koeberl, C. & Anderson, R. A. 1996. Manson and company: Impact structures in the United States. *Geological Society of America Special Paper* 302, 1–29.
- Koeberl, C. & Martinez-Ruiz, F. 2000. The stratigraphic record of impact events: A short overview. In: C. Koeberl & F. Martinez-Ruiz (eds.). *Impact Markers in the Stratigraphic Record*, Springer, Berlin-Heidelberg, *Impact Studies*, 1–40.
- Koppelmaa, H., Niin, M. & Kivisilla, J. 1996. About the petrography and mineralogy of the crystalline basement rocks in the Kärđla crater area, Hiiumaa Island, Estonia. *Bulletin of the Geological Survey of Estonia* 6, 4–25.
- Koppelmaa, H. & Kivisilla, J. 1999. Geological map of the crystalline basement of North-western Estonia. 4 maps and explanation to the maps. Geological Survey of Estonia, Tallinn, 30 p.
- Koistinen, T. (ed.) 1994. Precambrian basement of the Gulf of Finland and surrounding area. 1 : 1 000 000. Geological Survey of Finland, Espoo.
- Koistinen, T., Klein, V., Koppelmaa, H., Korsman, K., Lahtinen, R., Nironen, M., Puura, V., Salykova, T., Tikhomirov, S. & Yankovskiy, A. 1996. Paleoproterozoic Svecofennian orogenic belt in the surroundings of the Gulf of Finland. *Special Paper* 21, 21–57.
- Koivisto, M. & Korhonen, J.V. 1997. Lappajärvi impact crater rocks and minerals in Quaternary sediments. In: Autio, S. (ed.) Geological Survey of Finland, Current Research 1995–1996. *Special Paper* 23, 79–88.
- Korja, A., Korja, T., Luosto, U. & Heikkinen, P. 1993. Seismic and geoelectric evidence for collisional and extensional events in the Fennoscandian Shield – implications for Precambrian crustal evolution. *Tectonophysics* 219, 129–152.
- Larsson, K. 1975. Clastic dykes from the Burgsvik Beds of Gotland. *Geologiska Föreningens I Stockholm Förhandlingar* 97, 243–252.
- Laurén, L., Lehtovaara, J. & Boström, R. 1978. On the geology of the circular depression at Söderfjärden, western Finland. *Geological Survey of Finland. Bulletin* 297, 5–38.
- Lehtinen, M. 1976. Lake Lappajärvi, a meteorite impact site on western Finland. *Bulletin of Geological Survey of Finland* 282, 1-92.
- Lehtovaara, J. 1982. Stratigraphical sections through Lower Cambrian at Söderfjärden, Vaasa, western Finland. *Bulletin of the Geological Society of Finland* 54, 36–43.
- Lindström, M., Flodén, T., Grahn, Y. & Kathol, B. 1994. Post impact deposits in Tvärn, a marine Middle Ordovician crater south of Stockholm, Sweden. *Geological Magazine* 131, 91–103.
- Lindström, M., Floden, T., Puura, V. & Suuroja, K. 1992. The Kärđla, Tvären and Lockne craters – possible evidences of an Ordovician asteroid swarm. *Proceedings of the Estonian Academy of Sciences, Geology* 41, 45–53.
- Lindström, M., Sturkell, E.F.F., Törnberg, R., Ormø, J. 1996. The marine impact crater at Lockne, central Sweden. *Geologiske Föreningen Förhandlingar* 118, 193–206.
- Lutt, J. & Raukas, A. (eds.). 1993. *Geology of the Estonian Shelf* (in Estonian with English summary). Academy of Sciences of Estonia, Tallinn, 192 pp.
- Malkov, B., Kiipli, T., Rennel, G., Tammik, P. & Dulin, E. 1986. The regional geological-geophysical investigation of the Baltic Sea shelf area Estonian SSR at a

- scale of 1: 200 000 (in Russian). Report of Investigation. Geological Survey of Estonian SSR, Tallinn, 199 pp.
- Masaitis, V.L. 1999. Impact structures of northern Eurasia: The territories of Russia and adjacent countries. *Meteoritics & Planetary Science* 34, 691–711.
- Masaitis, V.L. 2002. The middle Devonian Kaluga impact crater (Russia): New interpretation of the marine setting. *Deep-Sea Research*. Part 2/ 6, 1157–1169.
- Masaitis, V. L., Danilin, A. N., Maschak, M. S., Raykhlin, A. I., Selivanovskaya, T. V. & Shadenkov, E. 1980. Geology of Astroblemes (in Russian). Nedra Press, Leningrad, 231 pp.
- McGetchin, T. R., Settle, M. & Head, J. W. 1973. Radial thickness variation in impact crater ejecta: Implications for lunar basin deposits. *Earth and Planetary Science Letters* 20, 226–236.
- Meidla, T., Suuroja, S., Ainsaar, L. & Suuroja, K. 2002. Stratigraphy of the sediments in the Neugrund impact structure infilling. In: J. Satkunas & J. Lazauskiene (eds.). Basin Stratigraphy - Modern Methods and Problems. The Fifth Baltic Stratigraphical Conference, Sept. 22-27, 2002, Vilnius, Lithuania. Extended Abstracts, 121–124.
- Meidla, T., Suuroja, S., Ainsaar, L. & Suuroja, K. 2003. Age and formation of the Neugrund Impact Structure infilling. In V. Puura & J. Plado (eds.). The Baltic Sea Region: Formation and Deformation of the Crust. Seminar in Tartu, Estonia, March 4, 2003. Programme and Abstracts, Tartu, 30–32.
- Melosh, H. J. 1989. Impact cratering. A geologic process. Oxford University Press 11, 245 pp.
- Melosh, H. J. & Ivanov, B. A. 1999. Impact crater collapse. *Annual Review of Earth and Planetary Sciences* 27, 385–425
- Mens, K. & Pirrus, E. 1997a. Formation of the territory: Vendian–Tremadoc clastogenic sedimentation basins. In: A. Raukas & A. Teedumäe (eds). Geology and mineral resources of Estonia. Estonian Academy Publishers, Tallinn, 184–191.
- Mens, K. & Pirrus, E. 1997b. Sedimentary cover: Vendian. Cambrian. In: A. Raukas & A. Teedumäe (eds). Geology and mineral resources of Estonia. Estonian Academy Publishers, Tallinn, 35–51.
- Motuza, G. 1994. Impact craters in Lithuania [abs.]. In: Törnberg, R. (ed.) 2nd International ESF workshop: The Identification and Characterization of Impacts, Lockne, Sweden.
- Männil, R. 1966. Evolution of the Baltic basin during the Ordovician (in Russian with English summary). Valgus, Tallinn, 248 pp.
- Nestor, H. & Einasto, R. 1997. Ordovician and Silurian sedimentation basin. In: A. Raukas & A. Teedumäe (eds.) Geology and mineral resources of Estonia. Estonian Academy Publishers, Tallinn, 192–204.
- Nõlvak, J. 2002. Distribution of chitinozoas. In: Põldvere, A. (ed.). Estonian geological sections. Soovälja (K-1) drill core. Tallinn. *Geological Survey of Estonia. Bulletin* 4, 10–12.
- Nõlvak, J. & Grahn, Y. 1993. Ordovician chitinozoan from Baltoscandia. *Reviews of Palaeobotany and Palynology* 79, 245–269.
- Oberbeck, V. R. 1975. The role of ballistic erosion and sedimentation in lunar stratigraphy. *Reviews of Geophysics and Space Physics* 13, 337–362.
- O'Keefe, J. D. & Ahrens, T. J. 1993. Planetary cratering mechanics. *Journal Geophysics Research* 98, 17001–17028.
- O'Keefe, J. D. & Ahrens, T. J. 1999. Complex craters: relationship of stratigraphy and rings to impact conditions. *Journal Geophysics Research* 104, 27 091–27 104.

- Ormø, J. & Lindstrøm, M. 2000. When cosmic impact strikes the seabed. *Geological Magazine* 137, 67–80.
- Ormø, J., Sturkell, E., Lindstrøm, M. & Lepinette, A. 2007. Resurge dynamic at the Lockne and Tvären marine target impact craters analysed with sedimentological and numerical methods. *Lunar and Planetary Science* 38, A 1540.
- Orviku, K. 1935. Gneiss-breccia as a rock of the big erratic boulders. *Eesti Loodus* 4, 98–99.
- Orviku, K. 1940. Lithologie der Tallinna-Serie (Ordovizium, Estland) I. Acta et Commet. Univ. Tartuensis. A XXXVI/1, 216 pp.
- Orviku, K., 1960. Litostratigraphy of the Toila and Kunda Formations in Estonia (in Russian). *Studies of the Institute Geology of the Estonian Academy of Sciences* V, 45–85.
- Oversky, L. 1844. Geognostischer Umries des Nord-Westlichen Ehtland. Verhandl. d. Russ.- Kaiserl. Mineral. Ges. zu St.-Peterburg.
- Overeem, I., Weltje, G., Bishop-Kay, C. & Kroonenberg, S. 2001. The late Cenozoic Eridanos delta system in the Southern North Sea Basin: a climate signal in sediment supply? *Basin Research* 13, 293–312.
- Palmre, H. 1961. Polümetallide esinemisest ja uurimisest Eesti NSV-s. *Eesti Loodus* 6, 359–361.
- Papunen, H. 1969. Possible impact metamorphic textures in the erratics of the lake Sääksjärvi area in southwestern Finland. *Bulletin of the Geological Society of Finland* 41, 151–155.
- Pesonen, L.J. 1996. The impact cratering record of Fennoscandia. *Earth, Moon, Planets* 72, 377–393.
- Pesonen, L.J. & Henkel. 1992. Terrestrial impact craters and craterform structures, with a special focus on Fennoscandia. *Tectonophysics* 216, 1–234.
- Pesonen, L.J., Lehtinen, M., Deutsch, A., Elo, S. & Lukkarinen, H. 1996. New geophysical results of the Suvasvesi N impact structure, Finland [abs.]. *Lunar and Planetary Sciences* 27, 1021–1022.
- Pierazzo, E. & Collins, G. 2003. A brief introduction to hydrocode modeling of impact cratering. In: Dypvik, H., Burchell, M., Claeys, P. (eds.) Cratering in Marine Environments and on Ice. Springer-Verlag. Berlin-Heidelberg. *Impact Studies*, 323–340.
- Pierazzo, E. & Melosh, H.J. 2000. Hydrocode modelling of oblique impacts: The fate of the projectile. *Meteoritics and Planetary Science* 35, 117–130.
- Pike, R. 1985. Some morphologic systematic of complex impact structures. *Meteoritics* 20, 49–68.
- Pipping, F. & Lentinen, M. 1992. Geology, stratigraphy and structure of the Lappajärvi meteorite crater, western Finland: preliminary results of deep drilling. *Tectonophysics* 216, 91–97.
- Pirrus, E. 1987. Paluküla struktuuri vanusest. *Geoloogiline kogumik* 3, 83–87.
- Pirrus, E. 1995. The ratio of depression and mound volumes: a promising criterion for the identification of small meteorite craters Proceedings of the Estonian Academy of Science. *Geology* 44 (3), 188–196. *Eesti Geoloogia Seltsi Bülletään* 2/96, 42–45.
- Pirrus, E. 1997. Suured rändrahnud akvatooriumigeoloogia uurimisel. *Eesti Geoloogia Seltsi Bülletään* 2/96, 42–45.
- Pirrus, E. 2002. Neugrundi impatstruktuuri vanusest Loode-Eesti Kambriumi läbilõigete analüüsi alusel. *Eesti Geoloogia Seltsi bülletään* 6/02, 54–64.

- Pirrus, E. & Tiirmaa, R. 1984. Tsõõrikmägi – ka meteoriidikraater. *Eesti Loodus* 9, 566–571.
- Pirrus, E. & Tiirmaa, 1991. Kas Virumaa boliid jõudis Maale? *Eesti Loodus* 4, 210–214.
- Plado, J. 2000. Gravity and magnetic signatures of meteorite impact structures. *Dissertationes Geologicae Universitatis Tartuensis* 10.
- Plado, J., Jõelegt, A. & Shoegenova, A. 2002. Physical properties. In: Põldvere, A. (ed.). Estonian geological sections. Soovälja (K-1) drill core. Tallinn. *Geological Survey of Estonia. Bulletin* 4, 21–24.
- Plado, J., Pesonen, L.J., Elo, S., Puura, V. & Suuroja, K. 1996. Geophysical research of the Kärddla impact structure, Hiiumaa Island, Estonia. *Meteoritics & Planetary Science* 31, 289–298.
- Plado, J., Pesonen, L. J. & Puura, V. 1999. Effects of erosion on gravity and magnetic signatures of complex impact structures: Geophysical modelling and applications. In: B. Dressler & V. L. Sharpton (eds.) Large Meteorite Impacts and Planetary Evolution II. *Geophysical Society of America. Special Paper* 339, 229–240.
- Poag, C.W. 1997. Structural outer rim of Chesapeake Bay impact crater: Seismic and bore hole evidence. *Meteoritics & Planetary Science* 31, 218–226
- Preeden, U. 2004. Impaktbretša peenfraktsiooni lõimis Kärddla, Neugrundi, Ävike ja Lumparni kraatrites. MSc thesis. University of Tartu, 75 p.
- Puura, V. 1974. The structure of the southern slope of Baltic Shield (in Russian). PhD thesis. Institute of Geology Academy of Science Estonian SSR, 1–28 pp.
- Puura, V., Amantov, A., Tikhomirov, S. & Laitakari I. 1996. Latest events affecting the Precambrian basement, Gulf of Finland, and surroundings areas, edited by Koistinen T. *Special Paper* 21. Helsinki: Geological Survey of Finland. 115–215 pp.
- Puura, V. & Flodén, T. 2000. The Baltic Sea drainage basin – a model of a Cenozoic morphostructure reflecting the early Precambrian crustal pattern. In I. Cato & F. Klinberg (eds.): Proceedings of the Fourth Marine Geological Conference “The Baltic,” Uppsala 1995, *Sveriges Geologiska Undersökning, Research Papers* 86, 131–137.
- Puura, V., Huber, H., Kirs, J., Kärki, A., Suuroja, K., Kirsimäe, K., Kivisilla, J., Kleesment, A., Konsa, M., Preeden, U., Suuroja, S & Koeberl, C. 2004. Geology, petrography, shock petrography, and geochemistry of impactites and target rocks from the Kärddla crater, Estonia. *Meteoritics & Planetary Science* 39/3, 425–451.
- Puura, V., Kala, E. & Suuroja, K., 1987. The structure of the Kärddla astrobleme (in Russian). *Meteoritika* 48, 150–161.
- Puura, V., Kirsimäe, K., Kivisilla, J., Plado, J., Puura, I. & Suuroja, K. 1996. Geochemical anomalies of terrestrial compounds in nonmelted impactites at Kärddla, Estonia. *Meteoritics & Planetary Science* 31, A112–A113.
- Puura, V., Kärki, A., Kirs, J., Kirsimäe, K., Kleesment, A., Konsa, M., Niin, M., Plado J., Suuroja, K. & Suuroja, S., 2000a. Impact-induced replacement of plagioclase by K-feldspar in granitoids and amphibolites at the Kärddla crater, Estonia. In: I. Gil-mour & C. Koeberl (eds). *Impacts and the early Earth*: Springer-Verlag. pp. 415–445.
- Puura, V., Kärki, A., Kirs, J., Kirsimäe, K., Konsa, M. & Suuroja, K. 2000b. Alteration of crater silicate rocks: Examples of similar environments from Kärddla and Manson structures (abstract). In: *Catastrophic events and mass extinctions: Impacts and beyond*. LPI Contribution 1053. Houston: Lunar and Planetary Institute. pp. 172–173.

- Puura, V., Kärki, A., Konsa, M., Floden, T., Pihlaja, P. & Suuroja, K. 2001. Estolites – Magnetic Metalliferous Particles from Suevites of Estonia, Fennoscandia, and Africa. *Meteoritics & Planetary Science* 36, A 169.
- Puura, V., Laitakari, I. & Amantov, A. 1999. Latest events affecting the Precambrian basement, Gulf of Finland and surroundings areas. In: T. Koistinen (ed.). Explanation to the Map of Precambrian basement of the Gulf of Finland and surroundings area 1 : 1 million. *Geological Survey of Finland. Special Paper* 21, 155–126.
- Puura, V., Lindström M., Flodén, T., Pipping, F., Motuza, G., Lehtinen, M., Suuroja, K. & Murnieks, A. 1994. Structure and stratigraphy of meteorite craters in Fennoscandia and the Baltic region: A first outlook. *Proceedings of Estonian Academy of Sciences. Geology* 43, 93–108.
- Puura, V. & Plado, J. 2005. Settings of meteorite impact structures in the Svecofennian Crustal Domain. In: C. Koeberl & H. Henkel, H. (eds.). *Impact Tectonics*. Springer-Verlag Berlin-Heidelberg, 211–245.
- Puura, V. & Suuroja, K. 1984. Kärjala kraater – maapõue varjunud uunikum. *Eesti Loodus* 8, 553–565.
- Puura, V. & Suuroja, K. 1992. Ordovician impact crater at Kärjala, Hiiumaa Island, Estonia. *Tectonophysics* 216, 143–156.
- Puura, V. & Tuuling, I. 1988. Geology of the Early Ordovician clastic dikes of Osmusaar Island (in Russian). *Proceedings of the Estonian Academy of Sciences. Geology* 37/1, 1–9.
- Pöldvere, A. (ed.). 2002. Estonian Geological Sections. Soovälja (K-1) drill core. *Geological Survey of Estonia. Bulletin* 4, 61 pp.
- Pöldvere, A. & Suuroja, K. 2002. Core description and terminology. In: Soovälja (K-1) drill core. Pöldvere, A. (ed.). Tallinn: *Geological Survey of Estonia. Bulletin* 4, 4–6.
- Põlma, L. 1982. Comparable lithology of the Ordovician carbonate rocks of the North and Central Baltic (In Russian). Valgus, Tallinn, 152 pp.
- Ramussen, K. L., Aaby, B. & Gwozdz, R. 2000. The age of the Kaalijärv meteorite craters. *Meteoritic & Planetary Science* 35, 1067–1071.
- Raukas, A. 1986. Deglaciation of the Gulf of Finland and adjoining areas. *Bulletin Geological Survey of Finland* 58/2, 21–33.
- Raukas, A. & Teedumäe, A. 1997. Geology and mineral resources of Estonia. Estonian Academy Publishers, Tallinn.
- Raukas, A. 2000. Investigation of impact spherules – a new promising method for the correlation of Quaternary. *International* 68–71, 241–252.
- Raukas, A., Tiirmaa, R., Kaup, E. & Kimmel, K. 2001. The age of the Ilumetsa meteorite craters in Southeast Estonia. *Meteoritics & Planetary Science* 35, 1507–1514.
- Reinwaldt, I. 1933. Kaalijärv – meteoriidikraatrite väli Saaremaal (in Estonian). *Loodusuurijate Seltsi Aruanded* 39, 183–202.
- Reinwaldt, I. 1937. Kaali järve meteoriidikraatrite väli. *Loodusvaatleja* 4, 97–102.
- Reinwaldt, I. 1938. The finding of meteorite iron in Estonian craters. A long search richly rewarded. *The Sky Magazine of Cosmic News* 2 (6–7), 28–29.
- Rõõmusoks, A. 1983. Eesti aluspõhja geoloogia. Valgus, Tallinn. 224 pp.
- Rõõmusoks, A. 1970. The stratigraphy of the Viru and Harju series (Ordovician) in North-Estonia (in Russian). Valgus, Tallinn.
- Saarse, L., Rajamäe, R., Heinsalu, A. & Vassiljev, J. 1991. The biostratigraphy of sediments deposited in the Lake Kaali meteorite impact structure, Saaremaa Island, Estonia. *Bulletin of Geological Society of Finland* 63, 129–139.

- Schmidt, F. 1858. Untersuchungen über die Silurische Formation von Ehstland, Nord-Livland und Oesel. Archiv f.d. Naturkunde Liv-, Ehst- und Kurlands, Ser. I, Bd. 2. Dorpat.
- Schmitz, B. & Alwmark, C. 2006. The Lockne Crater, disruption of the chondrite parent body and the great Ordovician biodiversification event. In: Lockne 2006. Abstract Volume and Program. Impact Craters as Indicators for Planetary Environmental Evolution and Astrobiology. Östersund (Sweden), June 8–14, 2006. 15–16.
- Schmitz, B., Häggström, T. & Tassinari, M. 2003. Sediment-dispersed extraterrestrial chromite traces a major asteroid disruption event. *Science* 300, 961–964.
- Schmitz, B. & Häggström, T. 2006. Extraterrestrial chromite in Middle Ordovician marine limestone at Kinnekule, southern Sweden – traces of a major asteroid breakup event. *Meteoritics & Planetary Science* 41, 455–466.
- Schrenk, A. 1854. Übersicht des oberen silurischen Schichtensystems Liv- und Ehstlands, vornehmlich ihrer Insel gruppe. Archiv f.d. Naturkunde Liv-, Ehst- und Kurlands, ser.I, Bd. 1. Dorpat.
- Scupin H. 1927. Beiträge zur Geologie der ostbaltischen Länder. 1. Vordevonische Spuren des “Alten Roten Nordlands” im Ostbatikum. Zentralbl. Für Min. Geol. u. Pal., Jahrg. 1927.
- Shoemaker, E., M. 1960. Penetration mechanics of high velocity meteorites, illustrated Meteor Crater, Arizona. In: Rept. of the Sci. Conf. 11th, 2099–2128.
- Shuvalov, V. 2002. Numerical Modelling of Impacts into Shallow Sea. In: J. Plado & L. Pesonen (eds.). Impacts in Precambrian Shields. Springer Verlag. *Impact Studies*, 323–336.
- Shuvalov, V., Dypvik, H. & Tsikalas, F. 2002. Numerical simulations of the Mjølner marine impact crater. *Journal of Geophysics Research* 107, 1–1A2.
- Sonett, C. P., Pearce, S. J. & Gault, D. E. 1991. The oceanic impact of the large objects. *Advances in Space Research* 11, 77–86.
- Spencer, L. J. 1938. The Kaali järv meteorite from the Estonian craters. *Mineralogical Magazine* 161, 75–80.
- Sturcell, E. F. 1998. Resurge morphology of the marine Lockne impact crater. Jämtland, Central Sweden. *Geological Magazine* 135, 121–127.
- Sturcell, E. F. F. & Ormö, J. 1997. Impact-related clastic injections in the marine Ordovician Lockne impact structure, Central Sweden. *Sedimentology* 44, 793–804.
- Sturcell, E. F. F., Ormö, J., Nölvak, J. & Wallin, Å. 2000. Distant ejecta from the Lockne marine-target impact crater, Sweden. *Meteoritics & Planetary Science* 35, 929–936.
- Stöffler, D., Gault, D. E., Wedekin, J. & Polkovski, G. 1975. Experimental hyper-velocity impact into quartz sand: Distribution and shock metamorphism of ejecta. *Journal of Geophysical Research* 80, 4062–4077.
- Stöffler, D. & Grieve, R. A. 1996. Classification and nomenclature of impact metamorphic rocks: a proposal to the IUGS Subcommittee on the Systematic of Metamorphic Rocks. *Lunar and Planetary Sciences* 25, 1347–1348.
- Stöffler, D. & Langenhorst, F. 1994. Shock metamorphism of quartz in nature and experiment: I. Basic observation and theory. *Meteoritics* 29, 155–181.
- Stöffler, D., Artemieva, N. A. & Pierazzo, E. 2002. Modeling the Ries-Steinheim impact event and the formation of the moldavite strewn field. *Meteoritics and Planetary Science* 37 No 12, 1893 p.
- Suuroja, K. 1996a. Formation and development of the Kärddla impact structure. M.Sc. Thesis (In Estonian), Institute of Geology, University of Tartu, 57 pp.

- Suuroja, K. 1996b. The geological mapping as a source of geological discoveries. Geological mapping in Baltic States. *Newsletter* 2, 19–22.
- Suuroja, K. 1996c. Neugrund – võti Soome lahe lõunaosa geoloogia juurde. Eesti Geoloogia Selts. Soome lahe probleemid (konverentsi teesid).
- Suuroja, K. 1998. Neugrundi meteoriidikraater. *Loodus*, November, 16–20.
- Suuroja, K. 2001. Kärddla Meteorite Crater. Geological Survey of Estonia, Tallinn, 34 pp.
- Suuroja, K. 2002. Natural Resources of the Kärddla Impact Structure, Hiiumaa Island, Estonia. In: Plado J, Pesonen, L (eds.) Impacts in Precambrian Shields, Springer Verlag, Berlin-Heidelberg, *Impact Studies*, 294–306.
- Suuroja, K. 2006. Baltic Klint in North-Estonia as a symbol of Estonian nature. Geotrail, Tallinn, 226 pp.
- Suuroja, K. & Põldvere, A. 2002. Description of the Soovälja (K-1) core. In: Põldvere, A. (ed.) Soovälja (K-1) drill core. Appendix 1. Geological Survey of Estonia, Tallinn. 30–46.
- Suuroja, K., Gromov, O., Kala, E., Gromova, G., Petersell, V. & Puura, V. 1974. Report of search of crystalline basement uplifts Notheastern Island of Hiiumaa and assessment for production of quality granitic splinters (in Russia). Geological Survey of Estonia, Keila.
- Suuroja, K., Kadastik, E., Ploom, K. & Saadre, T. 1998. Geological mapping of Northwestern Estonia at a scale of 1:50 000/1:25 000. Explanatory note. Geological Survey of Estonia, Tallinn, EGF 5920.
- Suuroja, K., Kirsimäe, K., Ainsaar, L., Kohv, M., Mahaney, W. & Suuroja, S. 2003. The Osmussaar Breccia in Northwestern Estonia – Evidence of a ca 475 Ma earthquake or an impact? In: Koeberl, C., Martinez-Ruiz, F. (eds.) Impact Markers in the Stratigraphic Record. Springer-Verlag. Berlin-Heidelberg. *Impact Studies*, 333–347.
- Suuroja, K., Koppelmaa, H., Kivisilla, J. & Niin, M. 1987. The deep geological mapping of the Nõva-Haapsalu area at a scale of 1:200 000 (in Russian). Three maps with explanatory note. Geological Survey of Estonian SSR, Tallinn.
- Suuroja, K., Koppelmaa, H., Niin, M. & Kivisilla, J., 1991. Geological mapping of the crystalline basement in Island of Hiiumaa (in Russian). Two maps (crystalline basement, bedrock) at a scale of 1:200 000 and the explanatory note. Geological Survey of Estonia, Tallinn, 291 pp.
- Suuroja, K., Mardim, T., Kadastik, E. & Elterman, G. 1994. Report of the integrated geological mapping of Island of Hiiumaa (in Estonian). Maps and explanatory note. Geological Survey of Estonia, Tallinn, EGF 4696.
- Suuroja, K., Mardim, T., Kadastik, E. & Suuroja, S. 1997. Report of the geological mapping of Island of Hiiumaa at a scale of 1:10 000. Maps and explanatory note. Geological Survey of Estonia, Tallinn, EGF 5820.
- Suuroja, K., Mardla, A. & Puura, V. 1981. Geological and structural maps of Western Estonia at a scale of 1:200 000 (in Russian). Maps and explanatory note. Geological Survey of Estonian SSR, Tallinn, EGF.
- Suuroja, K., Puura, V., Kirs, J., Niin, M. & Põldvere, A. 2002. Geological setting of the Kärddla area. In: Põldvere, A. Soovälja (K-1) drill core. Tallinn: Geological Survey of Estonia. pp. 6–10.
- Suuroja, K., Puura, V. & Suuroja, S. 1999. Kärddla crater (Hiiumaa Island, Estonia) – the result of an impact in a shallow epicontinental sea. In: R. Gersonde and A. Deutch (eds.). Oceanic impacts: mechanisms and environmental perturbations. *Reports on Polar Research* 343, 89–91.

- Suuroja, K., & Pöldvere, A. 2002. Description of the Soovälja (K-1) core. In: Pöldvere, A. (ed.). Estonian geological sections. Soovälja (K-1) drill core. Tallinn. *Geological Survey of Estonia. Bulletin* 4, 30–46.
- Suuroja, K. & Saadre, T. 1995. The gneiss-breccia erratic boulders from northwestern Estonia as witnesses of an unknown impact structure. *Bulletin of Geological Survey of Estonia* 5/1, 26–28.
- Suuroja, K., Saadre, T. & Kask, J. 1999 a. Geology of Osmussaar Island. *Estonian Maritima* 4, 39–63.
- Suuroja, K., Suuroja, S. & Puurmann, T. 1997. Neugrund structure an impact crater (in Estonian with English summary). *Bulletin of Estonian Geological Society* 2/96, 32–41.
- Suuroja, K., Suuroja, S. & Talpas, A. 1999 b. The marine geological investigations of the Neugrund structure area. Maps with explanatory note (in Estonian). Geological Survey of Estonia, Tallinn, 180 pp.
- Suuroja, K. & Suuroja, S. 1999. Neugrund structure – a submarine meteorite crater at the entrance to the Gulf of Finland. *Esonian Maritima* 4, 161–189.
- Suuroja, K. & Suuroja, S. 2000. Neugrund Structure – the newly discovered submarine early Cambrian impact crater. In: I. Gilmour & C. Koeberl (eds.) *Impacts and the Early Earth* Springer-Verlag, Berlin-Heidelberg. *Lecture Notes in Earth Sciences* 91, 389–416.
- Suuroja, K. & Suuroja, S. 2002. Kärddla and Neugrund – two similar nearby Early Palaeozoic marine impact structures in the Estonia. In: *Impact Tectonism*. 8th Workshop of the European Science Foundation Program IMPACT, Mora, Sweden, May 31–June 3, 2002. Abstracts, p 59.
- Suuroja, K. & Suuroja, S. 2003. The ejecta blanket of the Neugrund (Gulf of Finland, Estonia) impact crater. In: ESF-IMPACT Workshop “Biological Processes Associated with Impact Events”, King’s College, University of Cambridge, UK, March 29 - April 1, 2003. Abstracts and Workshop Schedule, Cambridge, 54–56.
- Suuroja, K. & Suuroja S. 2004b. Tähearmid Eesti maapinnas. In: Nestor, H., Raukas, A., Veskimäe, R. (eds). *Maa universumis*, Tallinn, 156–167.
- Suuroja, K., Suuroja, S., All, T. & Floden, T. 2002. Kärddla (Hiiumaa Island, Estonia) – the buried and well-preserved Ordovician marine impact structure. Elsevier Pergamon. *Deep-Sea Research II* 49, 1121–1144.
- Suuroja, S. 1997. Shock effects in impact breccias of the Kärddla crater. In: Raukas, A. (ed.) *Impact and Extraterrestrial Spherules: New Tools for Global Correlation*. International Symposium. IGCP Project 384. Excursion guide and abstracts. Institute of Geology, Tallinn, 54–55.
- Suuroja, S. 2007. Comparative morphological analyse of the early Paleozoic marine impact structures Kärddla and Neugrund, Estonia. PhD Thesis. Tallinn University of Technology.
- Suuroja, S., All, T., Plado, J. & Suuroja, K. 2002. Geology and Magnetic Signatures of the Neugrund Impact Structure, Estonia. In: J. Plado & L. Pesonen, L. (eds.) *Impacts in Precambrian Shields*. Springer-Verlag. *Impact Studies*, 277–294.
- Suuroja, S., Suuroja, K. & Kestlane, Ü. 2003. Neugrund-bretša – suurepärase juhtkivim. In: Pirrus, E. (ed.). *Eluta loodusmälestiste uurimine ja kaitse*. Teaduste Akadeemia Kirjastus, Tartu-Tallinn, 89–99.
- Suuroja, S. & Suuroja, K. 2004a. The Neugrund Marine Impact Structure (Gulf of Finland, Estonia). In: H. Dypvik, M. Burchell, P. Claeys (eds.) *Cratering in Marine*

- Environments and on Ice. Springer-Verlag. Berlin-Heidelberg. *Impact Studies*, 75–95.
- Suuroja, S. & Suuroja, K. 2006. Kärđla Impact (Hiiumaa Island, Estonia) – Ejecta Blanket and Environmental Disturbances. In: C. Cockell & C. Koeberl (eds.). Biological Processes Associated with Impact Events. Springer-Verlag, Berlin, Heidelberg, New York, *Impact Studies*, 121–146.
- Zhukov, F., Petersell, V. & Fomin, Y. 1987. Appearances of the Paleozoic vulcanite in Estonia (in Russian). *Proceedings of Academy of Sciences of Estonia. Geology* 36, 6–13.
- Talpas, A., Väling, P., Kask, J., Mardla, A. & Sakson, M. 1993. The geological mapping of the shelf area of the Baltic Sea at a scale of 1:200 000. Report of Investigations (in Russian). Geological Survey of Estonia, Tallinn, 152 pp.
- Tammekann, A. 1940. The Baltic Glint. I. Morphography of the Glint. Publicationes Instituti Universitatis Tartuensis. Geographici 24, 104 pp.
- Tassa, V. & Perens, H. 1984. Report of the search mineral water for the resort in Island of Hiiumaa (in Russian). Geological Survey of Estonian SSR, Tallinn.
- Terasmaa, J. 2006. Vaidasoo meteoriidikraatrist (in Estonian). *Eesti Loodus* 1, 50–51.
- Thamm, N. 1933. Über eine Gneisbrekzie im Glazialgeschiebe der Insel Osmussaar (Odensholm). *TÜ Geoloogia Instituudi Toimetised* 34, 1–14.
- Therriault, A. & Lindström, M. 1995. Planar deformation features in quartz grains from the resurge deposit of the Lockne structure, Sweden. *Meteoritics* 30, 700–703.
- Tiirmaa, R. 1997. Meteorite craters. In: Raukas, A., Teedumäe, A. (eds.). Geology and Mineral Resources of Estonia. Estonian Academy Publishers, Tallinn, 378–382.
- Tiirmaa, R. 2002. Meteoriidid ja meteoriidikraatrid. TTÜ Geoloogia Instituut, Tallinn, 108 lk.
- Tiirmaa, R., Puura, V., Soesoo, A. & Suuroja, S. 2006. Meteorite craters of Estonia. GeoGuide Baltoscandia. Tallinn. 32 pp.
- Torsvik, T.H., Van der Voo, R., Meert J.G., Mosar, J. & Walderhaug, H.J. 2001. Reconstruction of the continents around the North Atlantic at about the 60th parallel. *Earth and Planetary Science Letter* 187, 55–69.
- Trieloff, M., Korochantseva, E. V., Buikin, A. I., Schwarz, W. H., Hopp, J., Lorentz, C. A. & Jessberger, E. K. 2006. L chondrite asteroid breakup tied to Ordovician meteorite shower by multiple isochron 40Ar-39Ar dating. In: First International Conference on Impact Cratering in the Solar System ESTEC, Noordwijk, The Netherlands, 08-12 May, 2006.
- Tsikalas, F., Faleide, J.I., Eldholm, O. & Dypvik, H. 2002. Seismic Correlation of the Mjølner Impact Crater to Shallow Boreholles. In: J. Plado & L. Pesonen (eds.) Impacts in Precambrian Shields. *Impact Studies*, 307–321.
- Tucker, R.D. & McKerrow, W.S. 1995. Early Paleozoic chronology: a review in light of new U-Pb zircon ages from Newfoundland and Britain. *Canadian Journal of Earth Sciences* 32/4, 368–379.
- Tuuling, I. & Flodén, T. 2001. The structure and relief of the bedrock sequence in the Gotland – Hiiumaa area, northern Baltic Sea. *Geol. Fören. Fördhandl.* 193, 35–49.
- Uutela, A. 1998. Extent of the northern Baltic during the Early Paleozoic area – New evidence from Ostrobothnia, western Finland. *Bulletin of the Geological Survey of Finland* 70, 51–68.
- Wagner, R., Reimold, W. U. & Brandt, D. 2002. Bosumtwi impact crater, Ghana: A remote sensing investigations. In: J. Plado & L. Pesonen (eds.) Impacts in Precambrian Shields. Springer-Verlag. *Impact Studies*, 189–210.

- Ward, S. & Asphaug, E. 2000. Asteroid impact tsunami: a probabilistic hazard assessment. *Icarus* 145, 64–78.
- Webby, B. D. 1998. Steps toward a global standard for Ordovician stratigraphy. *Newsletter on Stratigraphy* 36, 1–33.
- Versh, E. 2002. Parasequence of an impact-induced hydrothermal system at Kärđla impact crater, Estonia. Tartu, 57 pp.
- Versh, E., Kirsimäe, K., Jõelet, A. & Plado, J. 2005. Cooling of the Kärđla impact crater: I. The mineral parasequence observations. *Meteoritics & Planetary Sciences* 40, 3–19.
- Viiding, H. 1955. Eesti NSV rändrahnude petrograafiast. Loodusuurijate Seltsi aastaaruanne 1955, 377–389.
- Viiding, H., Kala, E. & Pobul, E. 1969. Paluküla mõistatus laheneb. *Eesti Loodus* 8, 464–474.
- Winkler, H. 1922. Eesti geoloogia. Tallinn.
- Winterhalter, B. 1982. The bedrock geology of Lumparn Bay. Åland. *Geological Survey of Finland, Bulletin* 317, 115–130.
- von Dalwigk, I. & Ormø, J. 2001. Formation of resurge gullies at impacts at sea: The Lockne crater, Sweden. *Meteoritics and Planetary Science* 36, 359–369.
- Õpik, A. 1927. Die Inseln Odensholm und Maps and explanatory note. Rogö. Ein Beitrag zur Geologie von NW-Estland. *Acta et Comm. Univ. Tartuensis. A XII/2*, 1–69.
- Õpik, E., 1916. Note about the meteoritic theory of the lunar circles (in Russian with French summary). *Bulletin de la Société Russe des Amies de l'Etude de l'Univers* 3 (21), 1925–1934.
- Õpik, E. 1936. Researches on the physical theory of meteor phenomena. Tartu, 24 pp.
- Õpik, E. 1958. Meteor impact on solid surface. *Irish Astronomer* 5, 14–33.

SUMMARY IN ESTONIAN

Eesti varapaleosoiliste mereliste impaktstruktuuride Kärdla ja Neugrundi geoloogiast ja litholoogiast

I. Sissejuhatus

Maal, mille pindala on umbes 510 mln km², on tänaseks avastatud ligi 200 meteoriidiplahvatusel tekkinud struktuuri ehk umbes üks struktuuriüksus 3 mln km² kohta. Samas on Eestis, mille pindala koos territoriaalmerega on umbes 75 000 km², avastatud seni 8 meteoriitseks peetavat struktuuri ehk umbes üks struktuur 10 000 km² kohta. See on ligi 300 korda rohkem kui Maal keskmiselt. Võrreldes üsnagi sarnase geoloogilise ehituse ja uurituse tasemega Skandinaaviaga on Eestis pindalaühiku kohta meteoriitsete struktuure ikkagi enam kui 10 korda rohkem. Kuid vaid kolm neist kaheksast (Neugrund, Kärdla ja Kaali) on kindlakstehtud (st neist on leitud meteoriitset ainet või meteoriidiplahvatusetele viitavaid muutusi mineraalides) ja ülejäänud (Ilumetsa, Tsõõrikmäe, Simuna, Vaidasoo, Lasnamäe) on arvatud meteoriiditekkelisteks struktuursetel kaalutlustel. Ülaltoodud arv 300 on muidugi mõtlemapanev, kuid seejuures tuleb arvestada ka mitmeid, seda suhet oluliselt mõjutavaid tegureid (maa ja vee jaotust Maal, paikkonna maakoore ehitust ja vanust ning selle geoloogilise uurituse taset jne).

Eestis Saaremaal Kaalis asub Euroopa esimene ja maailma seitsmes (Arizona, Odessa, Haviland, Henbury, Wabar, Campo del Cielo järel) kindlakstehtud meteoriidkraater. Ka Kärdla ja Neugrundi meteoriidkraatrid on erakordsed maailmas. Hiiumaal Kärdla linna külje all asuv Kärdla meteoriidkraater on maailma üks paremini säilinud ja uuritud mattunud meteoriidkraatritest. Soome lahe suudmealal Eesti territoriaalmeres asuv ürgvana (u 535 mln aastat) Neugrundi meteoriidkraater on maailmamere kõige paremini säilinud ja kergemini ligipääsetav meteoriidkraater. Kõike eelöeldut võiks kokku võtta ühe väljendiga – Eesti fenomen.

Dissertatsiooni teema valikul oli määravaks see, et dissertant on olnud pikka aega (üle 35 aasta) tegev Kärdla ja Neugrundi meteoriidkraatri uurimisega ning olnud osaline nende avastamisel. Dissertant on publitseeritud mitmeid meteoriidkraatrite teemalisi artikleid nii teaduslikes kui populaarteaduslikes ajakirjades ja avaldanud ka selleteemalisi populaarteaduslike raamatuid.

2. Mattunud meteoriidikraatrite otsimise meetoditest ja tehnikast

Nii Kärkla kui Neugrundi meteoriidikraatri avastamisel ja uurimisel on olulist osa etendanud rakendusgeoloogilised uuringud, st geoloogiline kaardistamine, hüdrogeoloogilised uuringud ja maavarade otsingud ning uuringud. Sellest tulenevalt on uurimismetoodika suuresti lähtunud geoloogilisele kaardistamisele ja maavarade otsingutele-uuringutele omastest uuringumeetoditest.

Kärkla kraatristruktuuri, õigemini küll aluskorrakerke, avastamine oli juhuslikku laadi (Viiding jt 1969) kuigi esimesed vihjed mingile sellele piirkonnale mitteomasele geoloogilisele struktuurile tehti juba 19. saj. keskpaiku (Eichwald 1840 jt). Eraldiseisvatest kergetest sai kraater eeskätt geofüüsikaliste (gravimeetriliste) uuringute tulemusel (Suuroja jt 1974). Kraatri meteoriitne päritolu leidis lõplikku tõestamist 1980.-te algul (Masaitis jt 1980). Kraatri järgneval uurimisel lähtuti eeskätt rakendusgeoloogilistest eesmärkidest (geoloogiline kaardistamine, maavarade otsingud, hüdrogeoloogilised uuringud jne) ja sellest tulenevalt oli suur ka puurtööde maht: kraatrilal on puuritud 162 puurauku, millest tõstetud u 22 km puursüdamikku. Kraatri kohta on avaldatud ka ligi poolsada teaduslikku publikatsiooni ja suurosa neist rahvusvaheliselt eelretsenseeritavates teadusajakirjades.

Neugrundi kraatri avastamisel oli samuti oluline osa geoloogilisel kaardistamisel, kuid eelkõige ikkagi kraatrit uurinud geoloogide poolt Kärkla meteoriidikraatri uurimisel omandatud vahetutel kogemustel. Hüpootees Neugrundi meteoriidikraatri olemasolust Neugrundi madala piirkonnas püstitati 1995. aastal (Suuroja & Saadre), meteoriidikraatritele sobiliku struktuuri olemasolu leidis kinnitamist 1997. aastal (Suuroja jt 1997) ja selle meteoriitne päritolu tõestati lõplikult 1998. aastal (Suuroja & Suuroja 1999). Neugrundi meteoriidikraatri kui merelise struktuuri uurimisel lähtuti eelkõige merepõhja geoloogilise kaardistamise meetodikast, mille juures oluline osa on merepõhja seisnilisel sondeerimisel ja vaatlustel külgsuuna sonariga. Kuna kraatri mitmed olulised struktuurid (ringvallid, deformatsioonidevöönd ja väljaprepareerinud hiidpankad jne) avanevad merepõhjas, siis neid vaadeldi ka videorobotiga ja filmiti ning prooviti sukeldumiste käigus.

3. Kraatrite geoloogiline keskkond ja tekkeae

Kärkla meteoriidiplahvatus toimus umbes 455 mln aasta eest 100–200 m sügavuses epikontinentaalses meres, kohas kus kristalne aluskord oli kaetud enam kui 140 meetrise paksuse settekivimite (liivakivid, savid, lubjakivid jne) lasundiga. Plahvatusel tekkis ringvalli harjalt mõõdetuna 4 kilomeetrise läbimõõduga ja rohkem kui 250 m kõrguse ringvalliga ümbritsetud enam kui 0,5 km sügavune ja enam kui 130 m kõrguse ning kuni 800 meetrise läbimõõduga keskkerkega kompleksne kraater. Meteoriidikraatrit ümbritseb ellipsikujuliselt

ringmurrang läbimõõduga 12–15 km. Ringmurrangu ja ringvalli vahelises vööndis on plahvatusaluse kivimid tugevasti rikunud ja väljaspool seda enamasti rikkumata.

Neugrundi meteoriidiplahvatus toimus umbes 535 mln aasta eest umbes sama, et 100–200 m, sügavuses madalmeres. Kristalne aluskorra kivimid olid siin kaetud lisaks veele veel settekivimite vähemalt 120 m paksuse lasundiga. Erinevalt Kärddlast puudusid siinses settekivimite läbilõikes lubjakivid. Plahvatuse tagajärjel tekkis umbes 9 kilomeetrise (mõõdetuna 3-kordse ja kuni 3 km laiuse ringvalli harjalt) läbimõõduga kompleksne kraater. Kraatri keskel on kuni 5,5 kilomeetrise läbimõõduga kraatrisüvik, mille sügavus ei ole teada, sest see on kaetud umbes 5 kilomeetrise läbimõõduga kattedekivimitest ringikujulise erosioonilise jäänukiga – lubjakivikatteline Neugrundi madalik. Meteoriidikraatrit ümbritseb kontsentriselt umbes 20–21 km läbimõõduga ringmurrang. Seespool ringmurrangut on plahvatusaluse kivimid tugevasti rikunud ja väljaspool seda enamasti rikkumata. Neugrundi meteoriidikraatrile lähim (u 10 km tsentrist) puurauk asub Osmussaarel, st otse ringmurrangu joonel, ja lisaks sellele on meteoriidiplahvatusest mõjustatud aluse kivimeid avatud veel viie Loode-Eesti rannikualal rajatud puurauguga. Paremini uuritud on neist puuraugu F-331 läbilõige, mille puursüdamikus on uuritud nii kraatrist plahvatusega välja paisatud kivimeid (*ejecta*) kui ka omapäraseid Kambriumi savide-liivakivide baasil moodustunud plahvatusbretšasid. Nii ühed kui teised neist sisaldavad šokimoonde tunnustega kvartsi nn PDF-kvartsi teri.

4. Kraatrite struktuuridest, impakt-stratigraafiast ja -litoloogiast

Kärddla kraatri puhul on suurosa meteoriidiplahvatusel tekkinud kivimid (süeviidid, auto- ja allotigeensed impaktbretšad, väljapaiskekivimid, sööstu- ja tsunambretšad jne) nii kraatris kui ka väljaspool seda on avatud ligi sadakonna puurauguga. Meteoriidiplahvatusest mõjustatud kivimid nende poolt avatud läbilõigetel on jagatud kuuluvaks Kärddla ja Paluküla kihistusse.

Kärddla kihistu (Ülem-Ordoviitsium, Haljala lade) ühendab vahetult meteoriidiplahvatuse käigus tekkinud kivimeid. Kihistu stratotüübiks on Soovälja puuraugu (K-1) läbilõige süg. 301–589 m (288 m). Kihistus eristuvad omakorda kuni 118 m paksune impaktbretšade kihistik ja kuni 170 m paksune settekivimibretšade kihistik.

Paluküla kihistu stratotüübiks on Soovälja puuraugu (K-1) läbilõige süg. 189–301 m (112 m). Kihistu ühendab kraatrisüvikus ja kraatrit ümbritseval alal plahvatusjärgsel ajal tekkinud settekivimeid (enamasti lubjakive), mis sisaldavad kraatri kulutusprodukte. Kihistus eristuvad omakorda turbitiitide kihistik ja karbonaatkivimite kihistik. Turbitiitide kihistik (p.a. K-1, süg. 280–301 m (21 m) koosneb vahetult plahvatusejärgsel ajal kraatristruktuuridelt pärit purdsetetest (konglomeraadist kuni savini). Karbonaatkivimite kihistiku (p.a. K-1, süg. 189–280 m (91 m) moodustavad umbes 1 mln aasta kestel pärast

meteoriidiplahvatust kraatrisüvikus ja kraatri lähiümbruses settinud karbonaat-kivimid, mid sisaldavad kristalsetest kivimitest kraatristruktuuride (enamasti ringvalli) kulutusprodukte.

Väljapaiskekiht (ing *ejecta*) ehk plahvatusena meteoriidikraatrist välja paisatud aluskivimite purd on Kärkla kraatri puhul hästi säilinud ja uuritud. 1–260 cm paksuse liivaka kihina lubjakivilasundis leviv on hästi jälgitav kraatri keskmest enam kui 30 km raadiuses ja üksikute teradena on seda tuvastatud kuni 50 km kaugusel. Väljapaiskekiht koosneb valdavalt aleuriidi ja liiva fraktsioonis kvartsi teradest, millisest kuni 1% on löögimoonde tunnustega (planaarsete elementidega, ing *PDF* ehk *Planar Deformation Features*). Selles purrus eristuvad üheltpoolt nurgelised (põhiliselt plahvatusel purustatud kristalsete kivimite killud) ja teisalt, ümardunud terad (põhiliselt plahvatusel pihustatud Kambriumi liivakivid). Nii ühtede kui teiste suurus väheneb kaugene misega plahvatustsentrilt.

Neugrundi meteoriidikraatrit ümbritsevast ringmurrangust seespool ei ole meteoriidiplahvatusel tekkinud kivimeid avavaid puurauke ja meteoriidiplahvatusel tekkinud kivimite olemasolust ringvallidel ja deformatsioonide võõndis annavad tunnistust sealt liustiku poolt lahti kistud ja kaugemale lõuna poole kantud neugrund-bretšast rändkivid. Neugrund-bretšade seas eristatakse vastavalt neid moodustavate kristalsete kivimite koostisele: graniitseid, gneiss-migmatiitseid ja amfiboliitseid bretšasi.

Väljapaiskekiht on Neugrundi puhul esindatud enamasti liivakas-aleuriitsete kivimite kihiga Alam-Kambriumi ladestiku Sõru kihistus. Väljapaiskekiht on raskesti jälgitav ja eristatav üksnes löögimoonde tunnustega kvartsi (PTF-kvartsi) leidudega. Neid on otsitud ja leitud üksnes puuraugu F-331 (Ristna) südamikust, kus väljapaiskekiht on esindatud Sõru kihistiku ülaosas liivakivi umbes 4 m paksus kihiga.

5. Löögimoonde tunnustega mineraalide levik meteoriidiplahvatusetekkelistes kivimites

Kärkla meteoriidikraatri puhul on leitud PTF- kvartsi nii meteoriidiplahvatusena käigus tekkinud kivimeist (Kärkla kihistu süeviigid ja impaktbretšad) kui ka viimaste erosiooniprodukte sisaldavatest Paluküla kihistu kivimitest. PDF-kvartsi on neis kuni 5 eri orientatsiooniga, kusjuures ühes teras on olnud jälgitav kuni 3 erinevat orientatsiooni. Lamellide tihedus on 100–400 tk 1 mm kohta. Toodud näitajad viitavad 10–14 GPa rõhule löögimoondel.

Neugrundi meteoriidikraatri puhul on PDF-kvartsi leitud neugrund-bretšades olevatest süeviidi ja impaktbretša soontest. Üldiselt on siinne PDF-kvartsi terad näitajate poolest üsnagi sarnased Kärkla kraatri omadele.

PUBLICATIONES

Puura, V. & **Suuroja, K.** 1992.
Ordovician impact crater at Kärđla, Hiiumaa Island, Estonia.
In: L. J. Pesonen & H. Henkel (eds). Terrestrial impact craters and
craterform structures with a special focus on Fennoscandia.
Tectonophysics 216: 143–156.

Suuroja K. & Suuroja S., 2000.
Neugrund Structure – the newly discovered submarine early Cambrian impact crater. In: I. Gilmour & C. Koeberl (eds) *Impacts and the Early Earth*. Springer-Verlag, Berlin–Heidelberg. *Lecture Notes in Earth Sciences 91*: 389–416.

Suuroja, K., 2002.
Natural resources of the Kärđla Impact Structure, Hiiumaa Island, Estonia.
In: J. Plado & L. Pesonen (eds). Impacts in Precambrian Shields.
Springer-Verlag, Berlin, Heidelberg. *Impact Studies*: 295–306.

Suuroja, K., Suuroja, S., All T. & Flodén, T. 2002.
Kärdla (Hiiumaa Island, Estonia) – the buried and well-preserved Ordovician
marine impact structure. *Deep Sea Research II* 46: 1121–1144.

Suuroja, K., Kirsimäe, K., Ainsaar, L., Kohv, M., Mahaney, W.C. & Suuroja, S.
2003. The Osmussaar Breccia in Northwestern Estonia – Evidence of a 475 Ma
Earthquake or an Impact? In: C. Koeberl, F. Martinez-Ruiz (eds.)
Impact Markers in the Stratigraphic Record. Springer-Verlag, Berlin–Heidelberg.
Impact Studies: 333–347.

Suuroja, K. & Suuroja. 2004.
The Neugrund Marine Impact Structure (Gulf of Finland, Estonia).
In: H. Dypvik, M. Burchell, P. Claeys (eds.)
Cratering in Marine Environments and on Ice.
Springer-Verlag, Berlin–Heidelberg. *Impact Studies*: 75–95.

Suuroja, S. & **Suuroja, K.** 2006.
Kärdla Impact (Hiiumaa Island, Estonia) – Ejecta Blanket and Environmental
Disturbances. In: C. Cockell, I. Gilmour, C. Koeberl (eds.). Biological Processes
Associated with Impact Events. Springer-Verlag, Berlin, Heidelberg, New York,
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Professional employment:

1969–present: Geological Survey of Estonia (until 2001 – Geological Survey of Estonian SSR) – geologist, senior geologist, head of division of geological mapping.

The main fields of research:

- Geological mapping of bedrock in Estonia;
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- Structural geological investigations;
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- Coastal processes;
- Baltic Klint;
- Erratic boulders;
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Published books:

Suuroja, K., 1988. Viimane marsruut (Novels). Eesti Raamat, Tallinn.
Suuroja, K., 2001. Kärkla meteorite crater. EGK Kirjastus, Tallinn.
Suuroja, K. & Saadre, T. 2003. Estonian waterfalls. Kirjastus ILO, Tallinn.
Suuroja, K., 2004. Kiviaabits – Eesti kivimid (Estonian rocks). GeoTrail. Tallinn.
Suuroja, K., 2004. Põhja-Eesti pangad (Cliffs of Northern-Estonia). Kirjastus ILO. Tallinn.
Suuroja, K., 2005. Põhja-Eesti klint (North-Estonian Klint) . EGK Kirjastus. Tallinn.
Suuroja, K. & Suuroja, M., 2005. Eesti 101 loodusimet (101 natural monuments of Estonia). GeoTrail. Tallinn.

- Suuroja, K., 2006. Põhja-Eesti klint Eesti looduse sümbolina (North-Estonian Klint as a symbol of Estonian nature). Keskkonnaministeerium, GeoTrail. Tallinn.
- Suuroja, K., 2006. North-Estonian Klint as a symbol of Estonian nature. Keskkonna-ministeerium, GeoTrail, Tallinn.
- Suuroja, K. & Suuroja, M., 2006. Eesti 100 tähelepanuväärset rändrahnu (100 notable erratic boulders of Estonia). GeoTrail, Tallinn.
- Suuroja, K. 2007. Kiviaabits – Eesti mineraalid (Minerals of Estonia). GeoTrail. Tallinn.
- Suuroja, K. 2008. Balti klint – loodus ja ajalugu (Baltic Klint – nature and history). GeoTrail. Tallinn.

List of selected Publications:

- Puura, V. & Suuroja, K. 1992.* Ordovician impact crater at Kärđla, Hiiumaa Island, Estonia. In: L.J. Pesonen and H. Henkel (Editors). Terrestrial impact craters and craterform structures with a special focus on Fennoscandia. *Tectonophysics* 216, 143-156.
- Suuroja, K. & Saadre, T. 1995.* The gneiss-breccia erratic boulders from northwestern Estonia as witnesses of an unknown impact structure. *Bulletin of Geological Survey of Estonia* 5/1, 26–28.
- Suuroja, K. & Suuroja, S. 1999.* Neugrund structure - a submarine meteorite crater at the entrance to the Gulf of Finland. *Estonian Maritima* 4, 161–189.
- Suuroja, K. & Suuroja, S. 2000.* Neugrund Structure – the newly discovered submarine early Cambrian impact crater. In: Gilmour I, Koeberl C (eds) *Impacts and the Early Earth*. Springer Verlag, Berlin-Heidelberg. *Lecture Notes in Earth Sciences* 91, 389-416.
- Suuroja, K., Kirsimäe, K., Ainsaar, L., Kohv, M., Mahaney, W., Suuroja, S. 2000.* The Osmussaar Breccia in Northwestern Estonia – Evidence of a ca 475 Ma Earthquake or an Impact? In: Koeberl, C., Martinez-Ruiz, F. (eds.) *Impact Markers in the Stratigraphic Record*. Springer Verlag. Berlin-Heidelberg. *Impact Studies*, 333–347.
- Suuroja, K., Suuroja, S., All, T., Floden, T. 2002.* Kärđla (Hiiumaa Island, Estonia) – the buried and well-preserved Ordovician marine impact structure. Elsevier Pergamon. *Deep Sea Research*. Part II 982, 101-124.
- Suuroja, S., All, T., Plado, J., Suuroja, K. 2002.* Geology and Magnetic Signatures of the Neugrund Impact Structure, Estonia. In: Plado, J., Pesonen, L. (eds.) *Impacts in Precambrian Shields*. Springer Verlag. *Impact Studies*, 277–294.
- Ainsaar, L., Suuroja, K., Semidor, M. 2002.* Long-term effects of the Kärđla impact. Pergamon. *Deep-Sea Research* II 49, 1145–1155.
- Suuroja, K. 2002.* Natural Resources of the Kardla impact structure (Hiiumaa Island, Estonia). Springer Verlag. Berlin – Heidelberg. *Impact Studies*, 294–306.

- Suuroja, K. & Suuroja, S. 2004.* The Neugrund Marine Impact Structure (Gulf of Finland, Estonia). In: Dypvik, H., Burchell, M., Claeys, P. (eds.) Cratering in Marine Environments and on Ice. Springer Verlag. Berlin-Heidelberg. *Impact Studies*: 75–95.
- Suuroja, S. & Suuroja, K. 2006.* Kärđla Impact (Hiiumaa Island, Estonia) – Ejecta Blanket and Environmental Disturbances. In: Cockell, C., Gilmour, I., Koeberl, C. (eds.). Biological Processes Associated with Impact Events. Springer-Verlag, Berlin-Heidenberg, New York, *Impact Studies*, 121–146.

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- Balti klint
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Ilmunud raamatud:

Suuroja, K., 1988. Viimane marsruut (novellikogu). Eesti Raamat, Tallinn.
Suuroja, K., 2001. Kärkla meteoriidikraater. EGK Kirjastus, Tallinn.
Suuroja, K., 2001. Kärkla meteorite crater. EGK Kirjastus, Tallinn.
Suuroja, K., Saadre, T. 2003. Eesti joad. Kirjastus ILO, Tallinn.
Suuroja, K., Saadre, T. 2003. Estonian waterfalls. Kirjastus ILO, Tallinn.
Suuroja, K., 2004. Kiviaabits – Eesti kivimid. GeoTrail . Tallinn.
Suuroja, K., 2004. Põhja-Eesti pangad. Kirjastus ILO. Tallinn.
Suuroja, K., 2005. Põhja-Eesti klint. EGK Kirjastus. Tallinn.
Suuroja, K. ja Suuroja, M., 2005. Eesti 101 loodusimet. GeoTrail. Tallinn.
Suuroja, K., 2006. Põhja-Eesti klint Eesti looduse sümbolina. Keskkonnaministeerium, GeoTrail. Tallinn.

- Suuroja, K., 2006. North-Estonian Klint as a symbol of Estonian nature. Keskkonna-ministeerium, GeoTrail, Tallinn.
- Suuroja, K. ja Suuroja, M., 2006. Eesti 100 tähelepanuväärset rändrahnu. GeoTrail, Tallinn.
- Suuroja, K. 2007. Kiviaabits – Eesti mineraalid. GeoTrail. Tallinn.
- Suuroja, K. 2008. Balti klint – loodus ja ajalugu. GeoTrail. Tallinn.

Olulisemad teadusartiklid:

- Puura, V. & Suuroja, K. 1992.* Ordovician impact crater at Kärddla, Hiiumaa Island, Estonia. In: L.J. Pesonen and H. Henkel (Editors). Terrestrial impact craters and craterform structures with a special focus on Fennoscandia. *Tectonophysics* 216,143–156.
- Suuroja, K. & Saadre, T. 1995.* The gneiss-breccia erratic boulders from north-western Estonia as witnesses of an unknown impact structure. *Bulletin of Geological Survey of Estonia* 5/1, 26–28.
- Suuroja, K. & Suuroja, S. 1999.* Neugrund structure – a submarine meteorite crater at the entrance to the Gulf of Finland. *Estonian Maritima* 4, 161–189.
- Suuroja, K. & Suuroja, S. 2000.* Neugrund Structure – the newly discovered submarine early Cambrian impact crater. In: Gilmour I, Koeberl C (eds) *Impacts and the Early Earth*. Springer Verlag, Berliin-Heidelberg. *Lecture Notes in Earth Sciences* 91, 389–416.
- Suuroja, K., Kirsimäe, K., Ainsaar, L., Kohv, M., Mahaney, W., Suuroja, S. 2000.* The Osmussaar Breccia in Northwestern Estonia – Evidence of a ca 475 Ma Earthquake or an Impact? In: Koeberl, C., Martinez-Ruiz, F. (eds.) *Impact Markers in the Stratigraphic Record*. Springer Verlag. Berlin-Heidelberg. *Impact Studies*, 333–347.
- Suuroja, K., Suuroja, S., All, T., Floden, T. 2002.* Kärddla (Hiiumaa Island, Estonia) – the buried and well-preserved Ordovician marine impact structure. Elsevier Pergamon. *Deep Sea Research*. Part II 49, 101–124.
- Suuroja, S., All, T., Plado, J., Suuroja, K. 2002.* Geology and Magnetic Signatures of the Neugrund Impact Structure, Estonia. In: Plado, J., Pesonen, L. (eds.) *Impacts in Precambrian Shields*. Springer Verlag. *Impact Studies*, 277–294.
- Ainsaar, L., Suuroja, K., Semidor, M. 2002.* Long-term effects of the Kärddla impact. Pergamon. *Deep Sea Research* II 49, 1145–1155.
- Suuroja, K. 2002.* Natural Resources of the Kärddla impact structure (Hiiumaa Island, Estonia). Springer Verlag. Berlin-Heidelberg. *Impact Studies*: 294–306.
- Suuroja, K. & Suuroja, S. 2004.* The Neugrund Marine Impact Structure (Gulf of Finland, Estonia). In: Dypvik, H., Burchell, M., Claeys, P. (eds.) *Cratering in Marine Environments and on Ice*. Springer Verlag. Berlin-Heidelberg. *Impact Studies*, 75–95.
- Suuroja, S., Suuroja, K. 2006.* Kärddla Impact (Hiiumaa Island, Estonia) – Ejecta Blanket and Environmental Disturbances. In: Cockell, C., Gilmour, I.,

Koeberl, C. (eds.). Biological Processes Associated with Impact Events. Springer-Verlag, Berlin-Heidelberg, New York, *Impact Studies*, 121–146.

Muud:

Lisaks tosin novelli mitmetes ajakirjades ning poolsada teaduslikku ja populaar-teaduslikku artiklit ajakirjades ja kogumikes. Kirjutanud neli, Eesti Raadios ette kantud kuuldemängu. Dokfilmi “Kaali saladus” kaas-stsenarist. Esinenud arvukate loengutega Eesti loodust puudutavatel teemadel ja juhendanud loodustemaatilisi matku.

DISSERTATIONES GEOLOGICAE UNIVERSITATIS TARTUENSIS

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