Comparative Morphological Analysis of the Early Paleozoic Marine Impact Structures Kärdla and Neugrund, Estonia

STEN SUUROJA

TALLINN UNIVERSITY OF TECHNOLOGY
Department of Mining

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Supervisor:
Prof. emer. Dr. Enn Pirrus, Tallinn University of Technology

Opponents:
Prof. Dr. Henning Dypvik, Oslo University, Norway
Acad. Anto Raukas, Tallinn Univetsity

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LIST OF ORIGINAL PUBLICATIONS

PAPER I. 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.

PAPER II. **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.

PAPER III. Kirsimäe, K., **Suuroja, S.,** Kirs, J., Kärki, A., Polikarpus, M., Puura, V. and Suuroja, K. 2002. Hornblende alteration and fluid inclusions in Kärdla impact crater, Estonia - evidence for impact induced hydrothermal activity. *Meteoritics & Planetary Science 37*, 449–457.

PAPER IV. Suuroja, K., Suuroja, S., All T., Floden, T. 2002. Kärdla (Hiiumaa Island, Estonia) – the buried and well-preserved Ordovician marine impact structure. Deep Sea Research II 46:   101–124.

PAPER V. **Suuroja, S.** & Suuroja. K. 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.

PAPER VI. **Suuroja, S.** & Suuroja, K. 2006. Kärdla 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 6*, 121–146.

1. INTRODUCTION

The total area of the Earth is ca 500 million km^2, of that 150 million km^2 is mainland. On the Earth ca 180 (by Earth Impact Database) hypervelocity meteorite impact structures and their fields (Grive 1987, Grive et al. 1995, Grive & Pesonen 1996, French 1998, Earth Impact Database 2006) have been identified, and 3–5 new discoveries are added annually. Compared to the other planets of the Solar System or their natural satellites, this is still a relatively small number because on the Moon alone, which volume (ca 2.2×10^{10} km^3) exceeds that of the Earth about 50 times, millions of impact craters are identified. Over 20 000 of those craters are more than 1 km and 45 more than 300 km in diameter. The scantiness of the impact structures on the Earth is due to the up-to-600-km-thick atmosphere (troposphere, its densest part is up to 15 km thick) and the large (70.8% of the Earth's territory) and thick (77% deeper than 3000 m) hydrosphere. Only the Venus has a thicker and denser atmosphere than the Earth. None of the planets of the Solar System or their satellites has such small quantity of visible impact craters as the Earth. The activity of geological processes, which on the Earth is especially high, has also influenced the number of impact craters on a planet. The average cratering rate of the Earth is one crater per ca 3 million km^2. More than 30 craters are situated in Fennoscandia (Pesonen & Henkel 1992, Pesonen 1996, Abels et al. 2002, Puura & Plado 2005, Earth Impact Database 2006), which has an area of ca 3 million km^2, i.e. one crater per ca 300 000 km^2; this is 10 times as high as the Earth's average cratering rate.

The territory of Estonian mainland is 45 277 km^2, together with the aquatory ca 75 000 km^2, i.e. ca 0.015% of the Earth's area. In Estonia eight impact structures and their fields (Ilumetsa, Kaali, Kärdla, Lasnamäe, Neugrund, Simuna, Tsõõrikmäe and Vaidasoo) have been discovered (Tiirmaa et al. 2006, Suuroja et al. 2007). Six of them (Ilumetsa, Kaali, Lasnamäe, Simuna, Tsõõrikmäe and Vaidasoo) are small (up to 500 m in diameter) and relatively young (formed during the Quaternary), while the remaining two (Kärdla and Neugrund) are considerably larger (rim-to-rim diameter 4 and 9 km, respectively) and older (455 and 535 Ma, respectively). The cratering rate in Estonia is one crater per ca 10 000 km^2, i.e. about 300 times as high as the the Earth's average. Of course, such drastic numbers have some objective geological arguments, among which most decisive is the geological setting of the area: old (Precambrian) but not very deeply eroded platform (up-to-0.5-km- thick layer of sedimentary rocks has been eroded during the post-Devonian period). The rate of geological investigations of an area and the relations between the water and mainland have also affected the result.

Kärdla and Neugrund are two quite similar Early Palaeozoic marine impact structures, which are situated ca 60 km apart from each other in the coastal area of Estonia (Fig. 1). In spite of many similar features (geological setting of the target, presence of ring fault), there are also many differences (e.g. measurements, age, etc). Both structures were discovered in the course of applied geological research (geological mapping carried out at different scales and for different purposes, prospecting for mineral resources and groundwater, drilling of
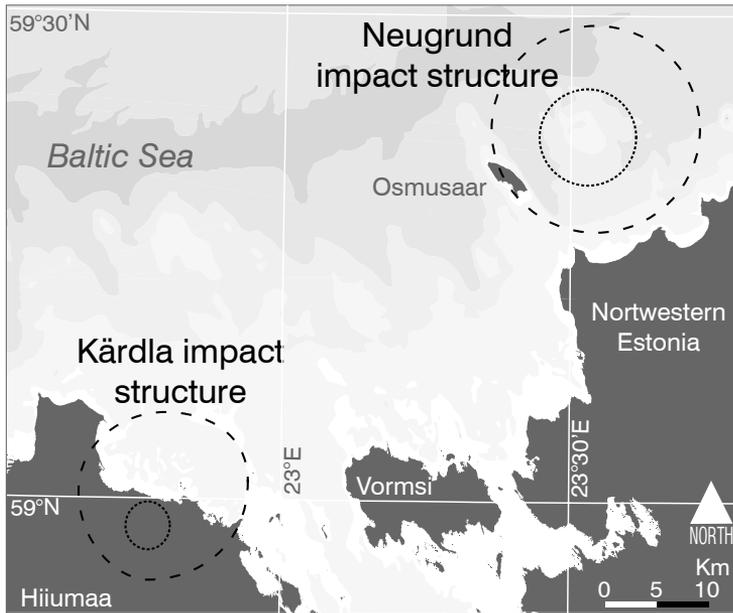
Figure 1. Location of the Kärdla and Neugrund impact structures. The inner crater is marked by dotted lines and the outer crater by a dashed line.

artesian wells: Viiding et al. 1969, Kala & Eltermann 1969, Kala et al. 1971, Suuroja et al. 1974, Kala et al. 1974, Kala et al. 1976, Tassa & Perens 1984, Malkov et al. 1986, Suuroja et al. 1987, Suuroja et al. 1991, Talpas et al. 1993, Suuroja et al. 1994, Suuroja et al. 1997, Suuroja et. 1999b). In some cases the author of the thesis also participated in the investigations (Suuroja et al. 1997, Suuroja et al. 1998, Suuroja et al. 1999; these works as well as the papers he has co-authored (PAPER I – Suuroja & Suuroja, 2002; PAPER II – Suuroja et al. 2002; PAPER III – Suuroja et al. 2002; PAPER IV –Suuroja et al. 2002; PAPER V – Suuroja & Suuroja 2004; PAPER VI – Suuroja & Suuroja 2006; Suuroja & Suuroja 2000, 2003, 2004; Suuroja 1996, 1997; Suuroja et al. 2003; Puura et al. 2000, 2004) are based on the surveying and analytical data, macro- and microscopical study of drill cores obtained during the above applied geological investigations.

The **Kärdla impact crater** (Hiiumaa Island, Estonia; 58º58´N, 22º46´E) was formed in a shallow (ca 100 m) epicontinental sea not far (up to 100 km) from the land and erosion area (Nestor & Einasto 1997) in the present Fennoscandian Shield, which belongs to the ca-1.9-Ga- old Svecofennian Crustal Domain (Gorbatschev and Bogdanova 1993, Puura & Flodén 1997). Presently, it is situated in the NW part of the Russian Platform in the area where the metamorphic rocks of the crystalline basement are covered by a ca 250-m-thick complex of sedimentary rocks (Kala et al. 1971, Suuroja et al. 1991). The structure is completely buried and has been buried during the whole post-impact period (Puura & Suuroja 1992, Ainsaar et al. 2002).

The Kärdla crater has a rim-to-rim diameter of 4 km (the diameter of the crater proper is 3.5 km). It is surrounded by an elliptical ring fault, 12–15 km in diameter. Inside the ring fault the sedimentary target rocks are disturbed (fissured, folded), while outside it they are mostly intact.. According to the classifications of terrestrial impact craters (Melosh 1989), it is a complex impact structure with the central uplift 130–190 m high and up to 700–800 m in diameter (Suuroja et al. 1994, PAPER IV, 2002). The depth of the crater proper is difficult to establish because the boundary between the crater floor and subcrater fracturing zone (Puura & Plado 2005) is quite transitional. The estimate depth of the crater floor ranges from 523 m (PAPER IV, Suuroja et al. 1991, Puura & Suuroja 1992, Suuroja et al. 1994, Suuroja 1996, Suuroja et al. 1999, Suuroja 2001, 2002) to 589 m (Suuroja & Põldvere 2002, Puura et al. 2004).

The time of the impact has been established ca 455 Ma, i.e the Late Ordovician (Caradoc) (Suuroja et al. 1974, Puura & Suuroja 1984, Bauert et al.1987, Puura et al. 1987, Pirrus 1987, Puura & Suuroja 1992, Grahn et al. 1996). This was mostly determined by ordering of the time position of ejecta layer in the well stratified and biostratigraphically well characterized sequence (chitiniozoan zones) of the Ordovician bioclastic limestones.

 The **Neugrund impact structure** (Gulf of Finland, Estonia; 59º20´N, 23º31´E) was formed in a shallow (100–200 m) sea not far (ca 100 km) from the land and erosion area in the present Fennoscandian Shield belonging to ca-1.9-Ga-old Svecofennian Crustal Domain (Gorbatschev and Bogdanova 1993, Mens and Pirrus 1997a,b). Nowadays it is situated at the NW boundary of the Russian Platform where the Precambrian crystalline basement is covered with a less-than-180-m-thick complex of sedimentary rocks (Kala et al.

1971). At the moment of the impact the basement was covered by a ca 120-m-thick layer of Vendian and Early Cambrian clays, siltstones and sandstones (PAPER I, II, V; Suuroja & Suuroja 1999). By preservation level (PL by Dence 1972) the Neugrund impact structure has PL 2 – an impact structure where elements of the primal structure and the ejecta layer have mostly preserved (Puura & Plado 2005). The formed structure was shortly, some million years after the impact, buried under marine deposits. It was newly partially opened after ca 530 millions years when the erosion, which formed also the Baltic Klint, reached the structure (PAPER IV).

The Neugrund impact structure with its rim-to-rim diameter ca 9 km (diameter of the crater proper is ca 5 km) is surrounded by an elliptical ring fault, 20–21 km in diameter. The latter is given as a diameter of the structure. The sedimentary target rocks are disturbed (fissured, folded) inside the ring fault and are mostly intact outside it. By classifications of terrestrial impact craters (Masaitis et al. 1980, Grive 1987, Melosh 1989, Gurov & Gurova 1991, Melosh & Ivanov 1999), it is a complex impact structure with three ring-ridges. The data about the depth and setting of the crater proper are missing because it is filled with post-impact deposits and covered by Ordovician limestones (Meidla et al. 2002, 2003; Suuroja & Suuroja 1999, PAPER I).

The time of the impact (ca 535 million years ago) was proved by determination of the position of the ejecta blanket in the sequence of the pre- and post-impact siliciclastic target rocks (PAPER I, V, Suuroja & Suuroja 1999), end of the Lontova time (Early Cambrian). Some authors (Pirrus 1997, 2000) have contested this conclusion and have proposed that the event occurred 60 Ma earlier, around the time the Osmusaar breccia dykes and bodies were formed.

The purpose of the present investigation is a comparative morphological analysis of the two nearby situated Palaeozoic marine impact structures formed in quite similar conditions. The Kärdla impact structure is situated mostly on mainland and is well investigated by numerous drill holes and geophysical methods. The Neugrund structure is situated on the sea floor and is not accessible for investigations by direct methods, except diving. From these circumstances arises the need for a comparative morphological analysis of the two impact structures. In the course of data analysis and morphological reconstruction of structural elements the features obtained by direct investigations (Kärdla) were used for clearing up the morphology and post-impact development of the other (Neugrund) impact structure, since direct data were absent or insufficient for the latter area.

2. INVESTIGATION METHODS AND TECHNIQUES

The discovery and the subsequent investigation of the Neugrund, and especially the Kärdla impact structure, have been closely connected with applied geological research (geological mapping, prospecting for mineral resources and groundwater, engineering geological investigations, etc.) and, therefore, the used methods and techniques are dependent on the established goals. Laboratory investigations (chemical, mineralogical, lithological, petro-

physical) were carried out mostly at the Laboratory of the Geological Survey of Estonia (Suuroja et al. 1974, Kala et al. 1976, Suuroja et al. 1991, Kivisilla et al. 1999 etc). The special crystal optical investigations (studying of shock-metamorphosed changes in minerals and rocks) and investigations of fluid inclusions in shock-metamorphosed minerals were partially carried out by the author (PAPER III, Suuroja 1996, Suuroja 1997). The complex of marine geological investigations (continuous seismoacoustic profiling, side-scan sonar profiling, divings and sampling of submarine outcrops, video robot observation of seabed) was predominantly carried out during the marine geological mapping (Suuroja et al.1999).

2.1. Investigation of submarine outcrops in the course of skin-diving is a new method used in geological research of the impact structures. At first the skin-diving was used for proving the hypothesis (Suuroja & Saadre 1995) that the erratic boulders consisting of gneiss-breccias, which contain shock-metamorphosed minerals and are widely distributed in western Estonia, were pulled off from the rim walls of the Neugrund impact crater. Afterwards this method was used for studying the sections of sedimentary rocks from filling and covering complexes of the Neugrund impact structure. During 1998–2003, seven marine
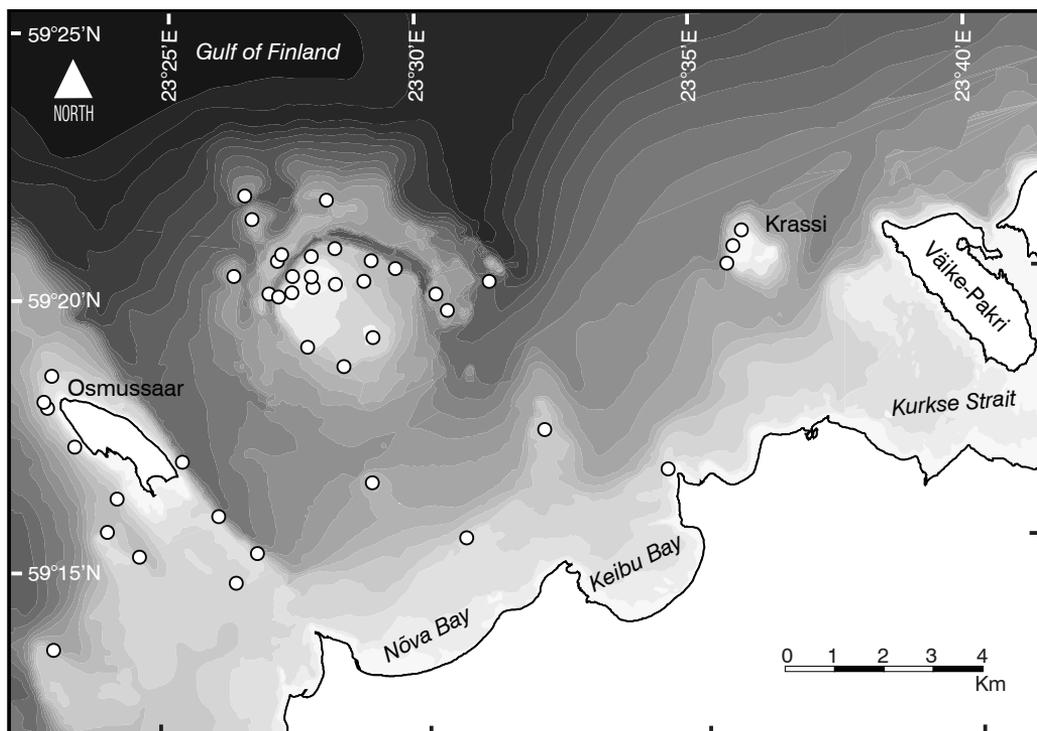
Figure 2. Location of diving sites in 1998–2003.

Figure 3. Submarine sampling.

expeditions with a full duration ca 30 days were carried out in the area of Neugrund structure. During these expeditions scientists dived in 21 different locations (Fig. 2). Samples were collected from 12 locations. The depth of sampling points varied between 2 and 42 m.

The staff of the skin-diving group was maximum three persons: a geologist and two assistants. Besides the usual diving equipment (tanks, regulators, suits, stabilizing jackets, swim fins, masks, digital depth gauges, etc) the divers had at their disposal a specialized suitcase for the collected specimens. It was a 9-box suitcase with a removable transparent plastic cover and a ca 100-m-long lifeline rope. For collecting the samples a ponderous (weight ca 5 kg) hammer furnished with lifeline rope was used. The process of submarine sampling was the following: the above-described diving group dived at a proper place, which was selected by the readings of echosounder (Interphase 200) and where the research vessel had dropped the anchor. On the outcrop at the proper place and depth the geologist collected specimens with a weight between 0.1–3 kg. The assistant fixed the depth of the specimen by a digital depth gauge (accuracy 0.1 m) and wrote the depth on the specimen with waterproof pencil and the same number on the transparent cover of the suitcase above the box where the specimen was placed. The first figures in the number mark the number of the outcrop and the next ones – depth of the sampling site. Simultaneously, the other assistant recorded the outcrop by a videocamera.

During diving, as a rule, the exposure and sometimes the process of sampling was recorded by the Sony camcorder TR 810E-Hi8 accommodated with ikelite underwater systems (Fig. 3).

Sampling of the submarine outcrops unambiguously proved that the erratic boulders of Neugrund-breccia (formely named gneiss-breccia by Öpik 1927, Thamm 1933, Orviku 1935, etc.), which are common in western Estonia, originate from the structures of the Neugrund meteorite crater and were transported to their present location by a glacier (PAPER I, II, V). The recording of the outcrops on videotape allowed decoding the submarine exposures (sections) after diving, whereas the results of sampling were considered as well.

2.2. Seismic reflection profiling (SRP) is one of the methods most widely used in investigating the submarine Neugrund structure. It was the first method, which cleared up the elements of the buried impact structure (Fig. 4). In Kärdla, seismic reflection profiling was used only for observing the limits of the structure (the ring fault).

The principle of marine seismic reflection profiling is accomplished by towing a seismic wave (sound) source that emits acoustic energy in timed intervals behind a research vessel (Kearey et al. 2002). The transmitted acoustic energy is reflected from the boundaries between various mediums of different acoustic impedances (i.e. the water–sediment interface or interface between geologic units). The bulk density of the medium and the velocity of the sound within that medium define acoustic impedance. The reflected acoustic signal is received by a ship-towed hydrophone (or array of hydrophones), which converts the reflected signal to a bipolar analog signal. The analog signal from the hydrophone can be filtered and displayed on a graphic recorder. The analog signal is digitized and logged in digital format. The digital data can then be processed further and plotted on paper or imported to computer mapping programs for interpretation.

The marine seismic reflection profiling in the area of the Neugrund structure was carried out in different years by several research vessels from different countries, including r/v "Marina" (Estonia) 1985, 1989; r/v "Strombus" (Sweden) 1996; r/v "Littorina" and "Humboldt" (Germany) 1996, r/v "Skagerak" (Sweden) 2001) and using somewhat different versions of this method. Altogether on ca 250 km^2 about 500 km of seismic reflection profiles were shot, most of them (300 km) by r/v "Marina" (Fig. 4).

Investigations from r/v "Marina" were carried out using a single channel equipment of Sparker-type working at frequencies 0–450 Hz. A generator with preamplifier supplied with 30 sensors was hauled at a depth of 1.5 m, at a distance of 30 m from the ship. The distance between the base generator and the receiver was 10 m, length of the receiver (hydrophones) 10 m. The profiles were printed on paper. Shot points were fixed by the Decca Navigator system at a time interval ca 10 minutes (Malkov et al. 1986, Talpas et al. 1993).

Investigations from r/v "Strombus" were carried out by single channel seismic equipment using a A PAR-600 air-gun at 12 MP wave generator. A 50 elements hydropfone streamer received and reflected signals, two frequency bands at 100–200 and 250–500 Hz were filtered. Simultaneously, a mud-penetrator sounder at 4 kHz was used to obtain high-resolution profiles of Quaternary deposits (Flodén 1980, 1981; Tuuling 1998; Tuuling et al. 1997). The position was determined by GPS at a time interval of 10 minutes.

A similar investigation equipment was used on r/v "Skagerak" (two types of seismic instruments: the chirp wave generator with recording frequency 4 kHz and the air gun wave
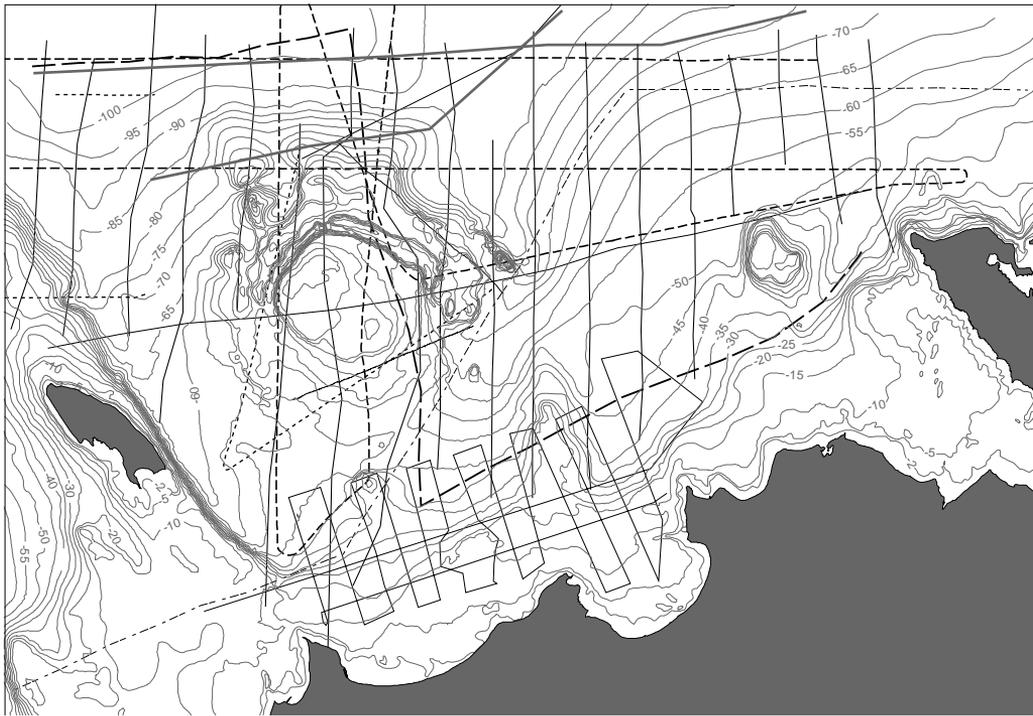
Figure 4. Location of seismic reflection record profiles carried out in 1996–2001 in the area of Neugrund impact structure.

generator with recording frequencies 250–500 Hz). The profiles were recorded both digitally and printed on paper, the recording range was 250–1000 msec (ca 60 cm). In addition to paper, the data were also recorded electronically. The position was determined by GPS.

Investigations from r/v "Littorina" and "Humboldt" were made using a spark wave generator with recording frequencies 1.2–5 kHz. The profiles were printed on paper and the recording range was 1000 msec. The position was determined by DGPS.

The digitalized metadata of all these records are stored in the Euroseimic Database and the diagrams of records – at the Geological Survey of Estonia. The recording diagrams shot from r/v "Strombus" (1996) and "Skagerak" (2001) were interpreted by the author without special programs (Meridata etc). In the interpretation the following seismic velocity values were used (by Flodèn 1981, Tuuling 1998, Tuuling et al. 1997): seawater – 1440 m/s; Quaternary deposits – 1750 m/s; Ordovician limestones – 3500 m/s; Cambrian silt- and sandstones – 2725 m/s; Precambrian crystalline basement rocks – 5500 m/s.

By the SRP method in 1996 for the first time the existence of a crater-like structure in the bedrocks in the surroundings of Neugrund Bank was verified (PAPER I, Suuroja et al. 1997). The first SRP profiles across the crater area were shot already in 1986 (Malkov et al.), but then the bedrock structures of the crater were interpreted as moraine walls (Talpas et al. 1993, Lutt & Raukas 1993). Subsequent investigations by the SRP method revealed all elements of the buried bedrock structures of the crater.

In the case of the Kärdla crater, SRP was used for searching the ring fault at sea. Above
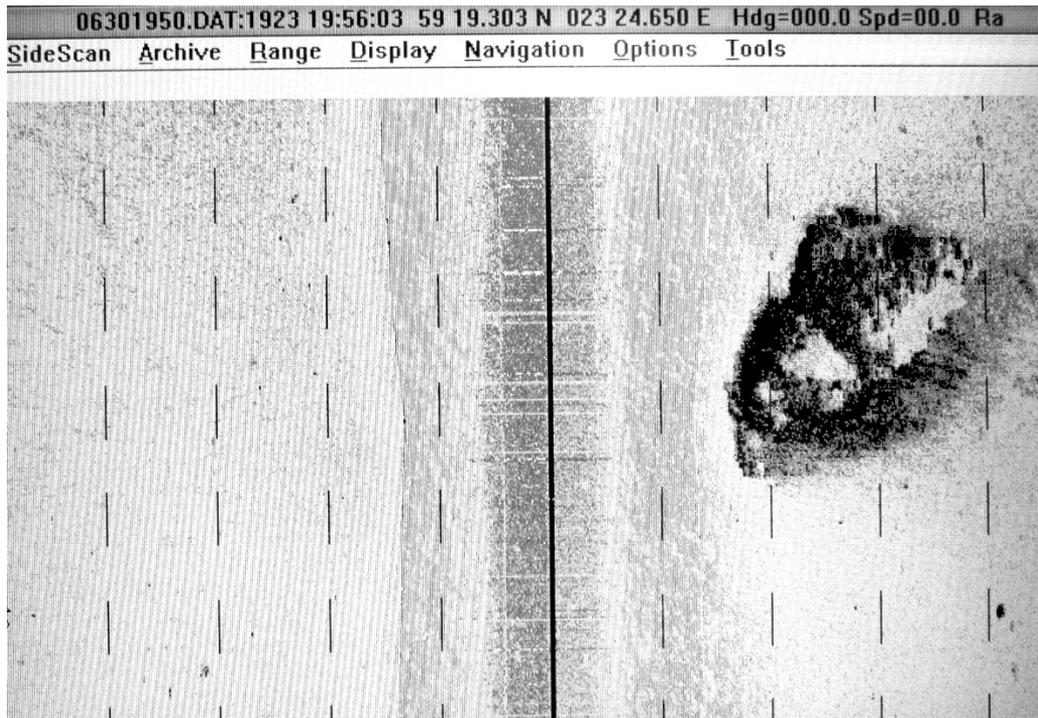
Figure 5. Huge block of mega-breccia on a screen of side-scan sonar. Distance between the dashed lines is 75 m.

the hypothetical ring fault the depth of water was very small (ca 5 m). Since this method can be better applied when the depth of water exceeds 20 m, satisfactory results were not achieved (PAPER IV).

The filtered bands 250–500 Hz were more suitable for revealing deeper buried bedrock layers (surface of crystalline basements rocks), while the filtered band 4 kHz was used for observing the buried bedrock surface under the Quaternary deposits and for revealing the details inside the latter. A disturbing circumstance was the presence of gas-bearing thicker layers of Quaternary deposits (especially varved clays), which could not be penetrated by the wave of higher frequency bands (4 kHz).

2.3. Side-scan sonar (SSS) profiling investigations were carried out only in the area of the Neugrund structure and mostly from r/v "Mare" (altogether ca 120 km) and to a lesser extent from r/v "Marina" and "Littorina". The sea floor topography and its sediment composition were surveyed within a 100–400 m wide area. The intensity of sound received by the side-scan sonar tow vehicle from the sea floor (backscatter) provides information on the general distribution (topography) and characteristics (composition) of the studied rocks and deposits. In the lower left schematic, strong reflections (high backscatter) from boulders, gravel and vertical features facing the sonar transducers are white; weak reflections (low backscatter) from finer sediments (escarpments) or shadows behind positive topographic features are black (Blondel & Murton 1997). Using the SSS profiling method some of ele-

ments of the topography and numerous gigantic erratic blocks and boulders of the Neugrund-breccia were discovered on the sea floor.

The side-scan profiling unit used by r/v "Marina" was the EdgeTech LC-100, consisting of a Digital Control Unit (DCU), a tow-fish and a tow cable (Edge Tech 1996). The DCU communicates with the sonar tow-fish via the tow cable, and is responsible for the generation of the power that operates the tow-fish. The tow-fish houses the components that form and transmit the acoustic pulse, and process the data returned. The tow-fish emits two acoustic pulses from either side of the tow-fish unit. As with most sonar data, the signals are initially amplified and then sent to the DCU via the tow cable. The tow cable itself serves two roles – firstly, as a communications carrier between the tow-fish and the DCU, but also as the means by which the tow-fish is transported through water (Leach et al. 2002).

The SSS profiling method was used mostly for verifying the nature and composition of unevennesses (escarpments, walls, hillocks, blocks, trench etc) encountered on the sea floor and for examining the future diving sites (PAPER I, II). The origin of the mega-blocks and giant erratic boulders discovered in rather deep (more than 50 m) sea within the Osmussaar Deep westward of the Neugrund Bank was established by the SSS profiling. The SSS profiling of the escarpment edging the Neugrund Bank from the north allowed searching better sites (where the blocks did not cover the foot of the escarpment) for diving. The intensity of rebounded beam made possible deciphering the lithological composition of the seabed.

2.4. Survey of seafloor by remote operated vehicle (ROV) camera system
In the areas too deep for diving (more than 40 m) and when sampling was not required, on r/v "Mare" the underwater remotely operated vehicle (ROV) camera system SeaLion was used for investigating the anomalous relief elements and rock types of seafloor. ROV SeaLion is a completely mobile, high performance underwater camera system capable of moving in any direction. With a ROV the investigation team can locate, inspect, and videotape an underwater target without having to enter the water. The SeaLion ROV employs a six-motor propulsion system with four motors for forward/reverse and two motors for vertical and lateral thrust. The SeaLion was designed for those applications where long cable lengths are required or for working in currents up to three MPH. In addition to all the features the SeaLion has two additional horizontal thrusters, and variable lighting from 0 to 400 watts. During the investigations under discussion the additional sensors and driving system of ROV camera system were not applied and it was towed.

ROV SeaLion was used for investigating problematic areas on seafloor in the area of Neugrund structure in poorly accessible surroundings (too deep for long-term divings). With the help of images obtained by ROV camera several submarine geological sections were interpreted, because boundaries of different lithological complexes of sedimentary rocks (limestones, sandstones, argillites, etc) and crystalline rocks are rather well distinguishable. Besides, some structural elements (e.g. bedding, fissures, faulting, folding, glacial stress marks, etc.) of rocks were identified from these images.

2.5. Computer modelling or composing 3D computer images of the Kärdla and Neugrund

impact structures, which demonstrate different stages of development of these structures. PC and programs MapInfo (release 7) and Surfer for Windows (release 8) were used. When the data grid was too sparse or data points were distributed too irregularly for compiling a truthful model, additional data points were derived by interpolating the existing data points (mostly received from the drill core sequences).

The 3D model of contemporary topography of the Kärdla crater was compiled using the data points obtained by digitizing and subsequent transforming of the contours of the topographic map at a scale of 1:25 000 (PAPER IV).

In the case of the Neugrund structure, the database of the Estonian Maritime Administration (PAPER I) comprising ca 15 000 measuring points of seafloor depth carried out by single-beam echosounder bathymetry system was used for this purpose. The NOAA survey vessels were equipped with Odom Echotrac DF3200 MKII echosounders that logged high-frequency (100 kHz) single-beam soundings throughout the sidescan-sonar and multibeam echosounder operations. For the northern part of the area (northwards of the Central Plateau), where similar surveying was not carried out, the Estonian nautical chart at a scale of 1: 50 000 sheet 612 was used as the basis for the database (PAPER V). The chart projection was Mercator and horizontal datum WGS-84 where the depths of seafloor are reduced to Mean-Sea Level Datum.

The 3D model of the bedrock topography of the Kärdla structure was compiled by using mostly a regular net of ca 200 data points of the bedrock topography. Generally, the data obtained from outcrops or drill core sections and by interpolating the existing data if necessary, were used as data points (elevation after BHS 77 (the Normal Baltic Height System) (PAPER IV).

In the case of Neugrund, in the areas where the bedrock cropped out on the sea floor, the depth of water above these outcrops served as data points. In the areas were the bedrock was buried under the Pleistocene and Holocene deposits the data points were obtained by interpreting the diagrams of continuous seismic reflection profiling (PAPER V).

The 3D models of the topography of the crystalline basement were more complicated to compile because the net of real data points (obtained from drill core sections or exposures) were sparse, especially in the case of Kärdla, and were located irregularly. In this case we used a supplementary net of the interpreted data points and due to this (small number of real data points) the topography of the crystalline basement (PAPER V) sometimes seems too regular (circular). The 3 D computer model for the crater proper in the case of Neugrund could not be compiled because of lack of data (PAPER I, V).

3. GEOPHYSICAL CHARACTERISTICS OF THE IMPACT STRUCTURES

The geophysical recordings (gravity, magnetic, seismic, etc.) play a substantial role in clearing up the geological setting of the Kärdla and Neugrund impact structures, which both are buried under the covering rocks (Kärdla) and water (Neugrund). The Kärdla structure has been profoundly investigated by drilling, while the Neugrund structure has been

studied mostly by remote sensing (geophysical) methods. Therefore, the data obtained by geophysical methods are of great importance for revealing the buried structural elements of the Neugrund structure and their comparison.

3.1. Seismic reflection profiling was used mainly for studying the buried structural elements of the Neugrund impact structure. In 1985–2001, in the latter area about 600 km of seismic reflection profiles were carried out from five research vessels (Fig. 4.). The best results in terms of clearing up the morphology of the submarine impact structure produced the investigations that were carried out on board of r/v Strombus (1996) and Skagerak (2001). Since these two expeditions conducted investigations in sufficiently deep water (more than 40 m) the seismoacoustic signals were able to penetrate the more than 50 m deep(thick?) layer of bottom deposits and rocks, and follow the crater structures below them (PAPER I, Fig. 7.). The higher frequency bands of registration (ca 4 kHz) have the better resolution but their depth of penetration was insufficient for advancing the buried structures of the meteorite crater, especially in gas containing deposits (PAPER I, Fig. 6, 7). The ring fault is expressed in seismic reflection profiles mostly as an up to 60 m high escarpment in the crystalline basement rocks but sometimes also disturbances in the sedimentary target rocks inside this limit can be observed (PAPER V, Fig. 6b). In the 4–5-km-wide zone between the ring fault and the rim wall, block-like disturbances occur in both the crystalline basement and sedimentary rocks (PAPER 1, Fig. 7b).

This method could not be applied in shallow (less than 20 m) water either, because the signals reflecting from the nearby seafloor did not allow following the signals originating from the low-lying reflectors. Therefore, we have very little information about the crater proper and don't know whether there is a central uplift or not.

In the case of Kärdla impact structure, the seismic reflection profiling method was used for studying the nature of the ring fault in the sea area. In 1996 one profile was shot across the ring fault (PAPER IV, Fig. 10). As the water depth was small (5–10 m) in the profile area and a wall consisting of Quaternary deposits (pebbles, cobles etc.) runs along the presumable ring fault, the presence of the ring fault was not clearly expressed.

In 2006, in the Kärdla crater area reflection seismic ground investigations were carried out using a 24-channel Summit CU seismometer (Jõeleht et al. 2007). The results of these investigations are in good agreement with the existing drilling data showing also that the rim of the crystalline basement rocks is not morphologically uniform.

3.2. Side-scan sonar (SSS) profiling method was used mostly for studying the deep-lying seafloor in the surroundings of the Neugrund structure. Altogether some 200 km of SSS profiling was carried out from r/v *Mare*, *Littorina* and *Humbolt*. This method of profiling mostly gave a general overview of the exposed structure of the crater (PAPER I, Fig. 11.) and provided less information about the lithologic composition. By using this method, numerous gigantic blocks (up to 500 m in diameter) and erratic boulders (diameter up to 50 m) were discovered on the seafloor (Suuroja 2005, Suuroja 2006). The SSS profiling method was also used for searching the diving sites.

3.3 Gravity surveying is among **the** main investigation methods of geophysical potential fields in the areas of impact structures (Elo et al. 1992, Henkel 1992, Plado et al. 1996, Plado et al. 1999, Abels et al. 2000, Plado 2000, Kearey 2002), especially in Kärdla where O. Gromov carried out ground gravity mapping at a scale of 1:25 000 for surveying the uplifts in the crystalline basement for producing splinters (Barankina & Gromov 1973, Suuroja et al. 1974). Thereupon it appears plainly that the Paluküla uplift (placanticlinal), which was discovered earlier (Viiding et al. 1969), forms only a part of a crater-like structure where the crater deep, ca 3 km in diameter, is surrounded by a rim wall, 4 km in diameter. The Bouger gravity anomaly demonstrated that up to 3 MGgal negative is related to the crater deep and up to 2 mgal positive anomaly to the rim wall (Gromov et al. 1980). The three gullies in the rim wall in the northern, southeastern and southwestern parts of the structure are expressed as up to 1.5 MGal negative anomalies. On the large-scale gravity (residual) anomaly map of Hiiumaa Island, where effects of deep-seated sources have been removed, the crater appears as a wall surrounding the depression against the rather monotonous gravity field of the island (PAPER IV, Fig. 7, 8; Plado et al. 1996). Along the ring-fault, which surrounds the crater elliptically in 6–7.5 km radius, the gravity anomalies do not occur, and therefore there is reason to suppose that the dislocations connected with the ring fault prevail mostly in the sedimentary cover.

In the area of the Neugrund impact structure high-resolution gravity measurements have not been performed, except airborne survey with the sensitivity of 1 MGal and with the distance between profiles 5 km (Ellmann et al. 1999). However, gravity anomalies that might refer to the structures of the meteorite crater were not observed there.

3.4. Magnetic surveys using ground and airborne methods were carried out in the area of the Kärdla structure (Barankina & Gromov 1973, Suuroja et al. 1974, Gromov et al. 1980). The contours of the crater on the ground magnetic map (Gromov et al. 1980) are expressed as a negative anomaly 200–400 nT, especially over the crater depression. On the aeromagnetic map at a scale of 1:50 000 (Metlitckaya & Papko 1992) and on the shaded relief map of the aeromagnetic anomalies (PAPER IV, Fig. 7) the negative anomaly over the crater proper, which is filled with nonmagnetic rocks (breccias, limestones), is clearly visible**.**

On the aeromagnetic map of the Neugrund structure area (Metlitckaya & Papko 1992) and on the shaded relief map of aeromagnetic anomalies of NW Estonia (PAPER I) the morphological elements of the Neugrund impact structure are weakly visible. Only a small negative anomaly over the up to 6 km in a diameter depression in the central part of the structure and a segment of positive anomalies (up to 400 nT) over the 2.5–3 km wide area of the ring ridges are observed. The unsettled and complicated pattern of the magnetic anomalies is due to variable properties of the Svecofennian metamorphic rocks of the Precambrian basement in the area under discussion (PAPER I, Fig. 12; Suuroja et al. 1987, Koistinen et al. 1996, All et al. 1997, Koppelmaa & Kivisilla 2000). The origin of the orientated structures, which intersect the western part of the structure, has remained somewhat incomprehensible. The results of the aeromagnetic survey do not allow drawing conclusions about the composition of the rocks filling the crater.

3.5. The recommendations for further geophysical investigations. In the case of the Kärdla impact structure, the nature of the ring fault is not clearly determined and, therefore, this area needs further geophysical, desirably electrometrical investigation. The latter is the best method for clearing up the fracture zones in limestone complexes. It is also advisable to continue reflection seismic ground investigations on the slopes of the rim wall and in the surroundings of central uplift.

For clearing up real measurements of the Neugrund impact structure detailed profile gravity survey by a marine bottom gravimeter must be carried out in the marine area under discussion; besides, a more detailed (at a scale of 1:25 000) airborne magnetic survey is needed.

4. TOPOGRAPHY OF THE IMPACT STRUCTURES AT DIFFERENT STRUCTURAL LEVELS

The topography of the Kärdla and Neugrund impact structures is described at the level of the Precambrian crystalline basement, at target level, at the level of the bedrock and present topography. Most of the figures have been presented in PAPER IV (Fig. 4a, 4b; 5a, 5b) and PAPER V (Fig. 3 and 4). The primary data for modelling the topography of these impact structures have been obtained from geological reports and explanatory notes to geological maps: Kala et al. 1971, Suuroja et al. 1974, Kala et al. 1976, Tassa & Perens 1984, Suuroja et al. 1991, Suuroja et al. 1994, Suuroja et al. 1997 (Kärdla structure), and Kala et al. 1969, Malkov et al. 1986, Suuroja et al. 1987, Suuroja et al. 1999 (Neugrund structure). The latter contains also some unpublished data obtained through the interpretation of the diagrams acquired in 2001 during the marine expedition led by T. Floden on board of r/v *Skagerak* (Sweden).

4 .1. Topography at the level of the crystalline basement
Both impact structures are better expressed at the level of the Precambrian crystalline basement rocks, because at this level they are relatively little affected by erosion. The Kärdla structure has been well studied by drilling (in the surroundings of the crater the crystalline basement is opened by ca 100 drill holes) and geophysical methods (gravity, magnetometry) providing mostly information on the structure of the crystalline basement. The main source of information about the crystalline basement in the Neugrund area is seismic reflection sounding; the submarine outcrops and the rare drill holes in the surroundings.

Kärdla. At the level of the Precambrian crystalline basement the topography of the impact structure is well expressed, even unduly well (PAPER IV, Fig. 5). The **rim wall** consisting of metamorphic rocks is expressed as a nearly circular ca 50–100 m high and 800–100 m wide uninterrupted wall. On this wall, the segments of Paluküla (length ca 4 km), Tubala (ca 1.5 km) and Kärdla (ca 2 km) rise up to 150, 120 and 100 m, respectively. Between the ridges three ca 100-m-deep gullies are distinguished: Northern, Southern and
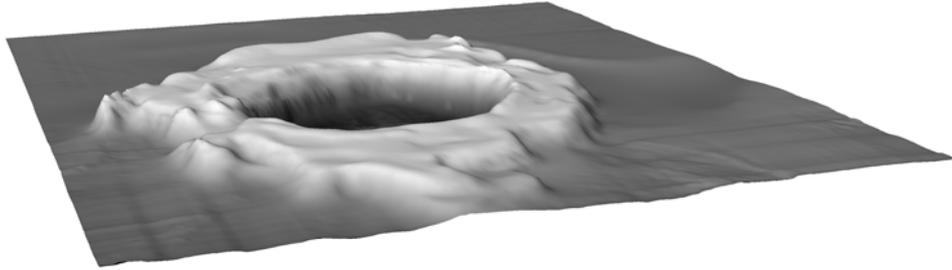
Figure 6. Topography of the Neugrund impact structure at the level of crystalline basement rocks.

Western Gully, which are accordingly 1.2, 3 and 2.5 km wide. The **crater proper** is up to 300 m deep (about 220–520 m u.s.l.) and has a diameter of up to 3.3 km. The **central uplift** is up to 130 m high (about 395–525 m u.s.l.) with a diameter up to 700 m.

Neugrund. At the level of the Precambrian crystalline basement rocks, the topography of the Neugrund impact structure is very complicated, mostly due to the lack of direct data (drill holes). Thus, there are no drill holes opening the crater proper. Similarly, no drill holes have been made within the zone of ring ridges or in the zone of distal disturbances inside the ring fault. The **ring fault,** 20–21 km in diameter, is clearly distinguished by the geophysical methods (seismic reflection profiling) and in the Neugrund case it is considered as the limit of the structure. In the western part of the structure, along the ring fault and outside it, rocks of the crystalline basement are ca 50 m uplifted, while in the eastern part they are 30–40 m subsided (PAPER V; Fig. 6a, 6b). Besides, the origin of the 4–5-km-wide zone between the ring fault and the outer limit of the ring ridges is ambiguous. In the above zone, gigantic (up to 0.5-km-diameter) blocks of strongly deformed Precambrian crystalline metamorphic, and Ediacaran and Lower-Cambrian sedimentary siliclastic rocks are thrust upon each other. This phenomenon is reflected both on the seismic reflection profiles (PAPER I, Fig. 7) and on the side-scan sonar survey diagrams.

In PAPER V (Fig. 8) the rim wall is imaged as the relict of a crystalline rock of a more extensive ca 3-km-wide and ca 200-m-high rim wall – the limit of the inner crater. The space between the huge blocks of the deformed crystalline rocks was filled with substantially weaker siliclastic rocks (Ediacaran and Lower-Cambrian silt-, sandstones and clays), which were lately eroded. Somewhat mysterious is the origin of the ca 80 m deep and up to 400 m wide gully in the eastern part of the rim wall. It cannot be excluded that this is connected with flows of glacial water.

Direct data about the structure of the **crater proper,** which is filled with post-impact Lower-Cambrian siliclastic rocks and covered by Ordovician carbonate and siliclastic rocks, are absent at the level of the crystalline basement rocks. Neither have investigations of the crater proper by remote sensing methods provided any results. The depth of water above the crater proper (Central Plateau) is too small (below 10 m) (PAPER I, Fig. 6, 7) for successful operating with continuous seismic reflection record and the aeromagnetical anomaly map (PAPER I, Fig. 12) does not provide any additional information about the
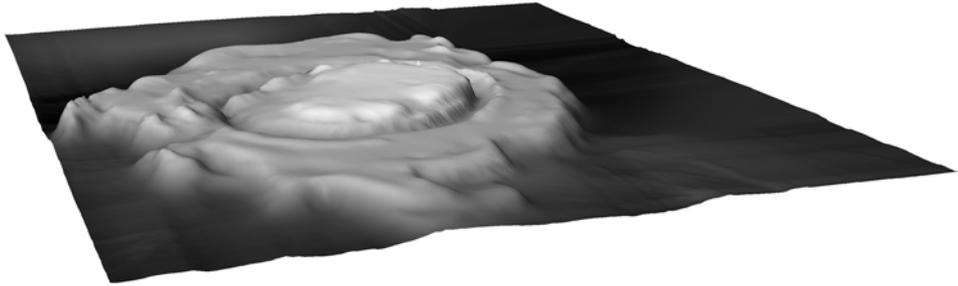
Figure 7. Topography of the Neugrund impact structure at the level of the bedrock.

interior of the crater proper (PAPER I, Fig. 7).

Thus, at the level of the crystalline basement rocks, there is an obvious discrepancy in setting of the impact structures – Kärdla is a complex crater with a central uplift (peak), while Neugrund is a complex crater with a three-ridged rim wall.

4.2. Topography of the structures at the level of the bedrock

Kärdla. The topography of the bedrock surface was restored by using mainly the data obtained from numerous drill holes. In some places (e.g. south-western part of the structure), adjunct data points obtained by interpolating the primary data points (drill hole sections) were also used.

At the level of the bedrock topography the structure is expressed less clearly than at the level of the crystalline basement (PAPER IV, Fig. 5). This is due to the smoothening effect of the crater filling and covering rocks, and the subsequent subsidence of these under the pressure of 300–400-m-thick rock complex, which has been eroded from this place (Kirsimäe 2000) after the Devonian period and by the Pleistocene glaciers.

The structure is expressed in the bedrock as quite monolithic up-to-40-m-high and 0.5–1.0-km- wide semicircular wall. The wall's inner slope is steeper (up to 20°) than the outer one. In Kärdla, eastward of Tubala and in the surroundings of the Nuutri Creek in the bedrock the wall is completely absent. Above the central uplift an about 10 m high elevation is observed in the bedrock. In some respect, the northwest–southeast trend of the bedrock topography is partly due to the Pleistocene glaciation and northwest–southeast movement of the glaciers. The straight-lined structures in the western part of the rim wall are obviously due to the incorrect interpretation of sparse data from this area.

Neugrund. The bedrock topography of the impact structure was restored mostly using the data obtained from seismic reflection records and was controlled by sparsely located drill holes and investigation and sampling of the submarine outcrops carried out in the course of skin-divings.

Above the first and well-shaped ridge of the **rim wall** (PAPER V, Fig. 4) the bedrock is represented by crystalline basement rocks. In the composition of the other (II and III) ring ridges obviously also blocks of sedimentary siliclastic rocks occur. In 1992, in the course of dragging seafloor above the rim wall pieces of the Vendian silt-and sandstones were caught

(Talpas et al. 1993).

Somewhat peculiar is the process of forming the circular **Central Plateau,** ca 5 km in diameter and up to 80 m in height, above the crater proper. The depth of water above the plateau is 1–15 m and there crop out Middle and Upper Ordovician limestones from the Kunda up to the Keila regional stages. The 60–100-m-high circular escarpment edging the plateau exposes (PAPER V – Fig. 7) the filling and covering sedimentary rocks from the Middle Ordovician limestones to the Lower Cambrian sandstones. All these layers, which are lithologically similar to those deposited in facial conditions typical of the surrounding area, have been biostratigraphically characterised (Meidla et al. 2002, 2003). The plateau is an erosional relict of a sedimentary rock complex, which by Overeem et al. (2001) ca 10 million years ago covered the whole structure, and it was shaped by the same erosinal processes which designed the Baltic Klint.

According to E. Pirrus (2002), the crater proper is filled by a large migratory block, or some blocks thrust to the crater proper at the time of the formation of Osmussaar breccia intrusions (Suuroja et al. 2003) in the Middle Ordovician Kunda time ca 475 Ma. Below are presented some arguments contradicting the above statements. The cross-section of the escarpment edging without any visible spatial and time breaks the Central Plateau covers a time span from ca 530 Ma up to 450 Ma, including also the time of the formation of the Osmussaar breccia intrusions ca 475 Ma. The side-scan sonar follows the continuity of the section during ca 12 km and, besides, it was followed by the remote operated vehicle camera system 'SeaLion' and during the numerous skin-divings.

4.3. Nowadays topography of the structures

Kärdla. The model of the nowadays topography of the crater area has been composed on the basis of the Soviet-time topographical maps at a scale of 1:25 000 where the interval of the altitude isolines is 2.5 m. In this model the margins of the structure are expressed poorer than at the level of the bedrock. This is because most structures, which are visible in the bedrock topography, are buried under the Quaternary deposits (till, sand, silt, varved clays). The thickness of the above Q deposits inside the crater proper reaches 24 m, while above the elevated parts of the rim wall it is 0.2–0.5 m (PAPER IV, Puura & Suuroja 1992). The semicircular gentle-sloped wall, which is piled up from the pebble and cobble consisting mostly of limestones, marks the run of the ring fault on the seafloor. The Kakralaid and Paerahu islets are located above this wall. On the mainland the ring fault is sometimes marked by a gentle-sloped low ridge of glaciofluvial deposits (Suuroja et al. 1994, Suuroja 2002). The central uplift is not expressed in nowadays topography and Soovälja lowland at the level of 5–6 m u.s.l. spreads above the central uplift as well as above the remaining part of the crater proper.

Neugrund. The present-day altitude model of the Neugrund impact structure is based on the seafloor topography and has been composed mostly on the basis of the data obtained from the database of Estonian Maritime Administration. A total of ca 10 000 data points of measuring of water depth were used. The altitude model for the northern part of the area (northwards of the ring canyon) was composed on the basis of the data obtained from the Soviet nautical charts at a scale of 1:25 000 published in 1980.

In the contemporary topography, the buried impact structure, which is partially exposed,

is expressed on the seabed similarly to the level of the bedrock, and only the ring canyon and the rim wall (ring ridges) are partially buried under the Quaternary deposits (PAPER V, Fig. 10, 11). Likewise, the belt of distal dislocations between the ring fault and the outer limit of the ring ridges at the level of 30–70 m u.s.l is quite smooth and is covered prevailingly by a 20–40-m- thick layer of Quaternary deposits. Only the megablocks (diameter up to 0.5 km) of brecciated crystalline basement rocks penetrate this layer in the western and southern parts of the structure.

In both Kärdla and Neugrund the traceable structural contours of the impact structures are well observable at the lowermost crystalline basement level, and are less distinct at upper levels (bedrock and present-day topography).

5. COMPARATIVE MORPHOLOGICAL ANALYSIS OF THE KÄRDLA AND NEUGRUND IMPACT STRUCTURES

Kärdla and Neugrund are two quite similar impact structures, which are situated in a rather similar geostructural situation on the eastern coast of the Baltic Sea: Kärdla on the northeastern coast of Hiiumaa Island and Neugrund at the entrance to the Gulf of Finland eastward of Osmussaar Island. At the moment of the impact these impact sites with the Baltica Continent (Donner 1996, Buchan et al. 2000, Torsvik et al. 1992, 2001) and within the Estonian-Lithuanian Confacies Belt (Männil 1966, Mens & Pirrus 1997b, Nestor & Einasto 1997) were situated in the Southern Hemisphere under 35–40 latitudes.

Final versions of computer compiled morphological models of the structures at different structural levels (crystalline basement, bedrock, contemporary) are presented in PAPER IV (Fig. 4, 5) and Fig. 9 (Kärdla); PAPER V (Fig. 3, 4) and Figs. 7, 8 (Neugrund).

Kärdla impact structure is geostructurally situated at the northwestern edge of the Russian Platform and Neugrund – directly at the boundary of the Russian Platform and Fennoscandian Shield (Gorbatschev and Bogdanova 1993, Donner 1996, Puura and Flodén 1997, Uutela 1998). In the present topography it is expressed as a ring-shaped ridge of low (5–20 m high and up to 1 km wide) plane-sloped hillock along the line of Linnumäe, Hausma, Paluküla, Ala, Tubala and Prähla settlements (Fig. 9; Puura et al. 1987, Kleesment et al. 1987, Puura & Suuroja 1992 etc.). The wall is monolithic and clearly expressed in the ca 5-km segment between the villages of Hausma and Ala (Jõeleht et al. 2007).

Neugrund impact structure is in the seafloor topography better expressed and the inner wall of the three-ridged ring-rides consisting of fractured Precambrian metamorphic rocks crops out along a semicircular segment, more than 12 km in length. The other (outer) ring-ridges crop out only fragmentally, and these fragments are represented by huge (up to 0.5 km in a diameter) blocks of fractured Precambrian basement rocks. Above the crater proper with a diameter of 5.5 km, there is the circular Neugrund Bank, ca 5 km in a diameter, which is covered by the Ordovician limestones (PAPER I and V, Meidla et al. 2002). Above the bank the depth of water is 1.5–15 m. The bank is encircled by Ring Canyon, up to 60 m deep and 200–400 m wide (PAPER I and V, Suuroja et al. 1999).

The time interval between these two impacts was quite considerable – ca 80 million years: the Neugrund impact occurred ca 535 Ma (Paper I, Suuroja & Suuroja 1999) and the Kärdla impact ca 455 Ma (PAPER IV, Puura & Suuroja 1992, Grahn et al. 1996). Both structures were formed in a shallow epicontinental sea where sedimentary rocks of the target were covered by a ca 200-m- thick water layer. In the case of the Neugrund impact the thickness of water layer above the solid target rocks has been unanimously estimated at up to 200 m (PAPER I and IV), but in the Kärdla case, at ca 20–50m (Suuroja et al. 1991, Puura & Suuroja 1992, Lindström et al. 1992), ca 50 m (PAPER III, Suuroja 1996) and ca 100 m (PAPER V). As suggested by numerical modelling of impacts into shallow sea (Crawford & Mader 1998, Artemieva 2002, Shuvalov 2002, Shuvalov et al. 2002, Pieracco & Collins 2003), in case of so shallow (less than 100–200 m) water impacts normally do not arise a tsunami, but in the Kärdla case the resurging tsunami was so violent that broke three up to 1.5 km wide gullies in the more than 300 m high rim wall (PAPER IV).

At the moment of impact, in both cases the target consisted of a complex of sedimentary rocks below the water layer. In Kärdla the target was somewhat thicker - about 140 m (PAPER IV etc.), while in Neugrund it was about 120 m thick (PAPER I and V). The target in Kärdla consisted of the following layers (from top downwards): Middle Ordovician limestones (up to 14 m), Early Ordovician sandstones and argillite (up to 8 m), Early Cambrian clay-, silt- and sandstones (up to 120 m) (PAPER IV). In Neugrund the sedimentary cover consisted completely of Lower Cambrian and Ediacaran (Upper Vendian) siliclastic rocks (clay, silt- and sandstones) (PAPER I and V, Suuroja et al. 1999, Mens & Pirrus 1997a, 1997b) and the limestone layer was absent in the target.

The composition of Precambrian basement rocks is also rather similar. In both cases, they are represented by metamorphic and plutonic rocks of 1.8–1.9 Ga Svecofennian orogeny (Koistinen et al. 1994, 1996). The area belongs to the West-Estonian Zone and the basement rocks are represented predominantly by medium- and fine-grained biotite-hornblende and granite gneisses, and amphibolites, which have been migmatized by microcline granites (Suuroja et al. 1991, Koppelmaa et al. 1996, Puura et al. 1997, Koppelmaa & Kivisilla 2000).

The crater proper morphology is characterized only in the case of Kärdla, because there is almost no information on this part of the Neugrund structure. The Kärdla structure is a complex crater with a normal central uplift (PAPER IV). Supposedly, in the Neugrund structure the central uplift is missing inside the crater proper and the three-ridged and up to 3 km wide rim wall surrounding the crater deep is treated as a three-ridged ring-chain (PAPER V).

The rim walls were in both cases during a short time period (some millions years) after the impact slightly eroded and after that buried under the siliclastic (Neugrund – PAPER I and V) or carbonate (Kärdla – PAPER IV, Ainsaar et al. 2002) deposits.

The Neugrund impact structure was predominantly reopened during the Neogene erosion (PAPER I and V, Suuroja 2005 etc.), but the Kärdla structure is still buried. Notwithstanding, on the ridge of the rim wall at Paluküla the Precambrian basement crystalline rocks lie at a depth of only 15–20 m (PAPER IV, Puura & Suuroja 1984 etc.), i.e. closer to

the ground surface than anywhere else on the territory of Estonia.

The zone of distal disturbances (belt between a rim wall and a ring fault where the target rocks are disturbed - ruptured, folded, with block-like shifts) is traceable in both cases (PAPER II, IV and VI). It is expressed especially well in the case of Neugrund strucure where on seismic reflection profiles and side-scan sonar profiling various gigantic (up to 500 m in diameter) blocks of sedimentary and crystalline target rocks are observed (PAPER V etc.).

The ring faults are traceable in both cases: in Kärdla as a semicircular 6–7-km-radius lined structure observed on the aerial photographs (PAPER IV) and in Neugrund as about 10-km-radius semicircular escarpment in the bedrock. In the case of Kärdla, the nature of the ring fault is not unambiguously clear (fracture, escarpment, etc.), but in the case of Neugrund, the ring fault has been determined on the seismic reflection profiles (PAPER I, II etc.) as an up to 60 m high escarpment in the crystalline basement rocks. In both cases, it marks the limit between the target rocks disturbed by the impact, and mostly intact target rocks.

The ejecta layers have preserved in both cases, but only in Kärdla it is well recognizable as a 0.01–4.6-m-thick layer of siliclastic rocks inside the complex of carbonate rocks (PAPER IV etc.). In the case of Kärdla, the ejecta layer is marked as an up-to-2-thick layer of siliclastic rocks (mostly sandstones) within the complex of rather similar siliclastic rocks (mostly silt- and sandstones) and is distinguished only by the findings of shock metamorphosed minerals (quartz grains with PDF-s). In the Kärdla case, the limit of the circular ejecta blanket, about 60 km in diameter, is well followed (PAPER VI), while in the case of Neugrund, the thickness of the ejecta layer is smaller and the farthest point where it is detected with certainty is 14 km from the impact centre (PAPER II etc.).

The uplifted parts of the structures were in both cases shortly (some millions of years) after the impact slightly eroded and then buried under the siliclastic (Neugrund – PAPER I and V) or carbonate (Kärdla – PAPER IV, Ainsaar et al. 2002) deposits.

6. CONCLUSIONS

The Early Palaeozoic impact structures of Kärdla and Neugrund are separated by about 60 km in space and about 80 Ma at a time-scale, nevertheless they have several common morphologic features. The latter are mostly due to the similarity of the composite three-bedded targets: water – sedimentary rocks – crystalline rocks (Puura et al. 1994; Abels et al. 2002; Puura & Plado 2005). One of the principal problems of the morphology of these impact structures is related to real diameters of the structures. This is especially important because the rim-to-rim diameter of a structure serves as a basis for most calculations associated with the dimensions of an impact structure as well as some parameters of the projectile, such as diameter, mass, etc. (Shoemaker 1960, Dence 1972, Pike 1980, Pike 1985, Grive 1987, Melosh 1989, O'Keefe & Ahrens 1993, O'Keefe & Ahrens 1999, Dypvik & Jansa 2003). The problem is not especially complicated and can be easy modelled

when we have under consideration a simple meteorite crater formed in an unvaried target. The situation is much more difficult when under discussion is a complex impact crater or structure (Gault & Sonett 1982, Deutch & Shärer 1994, Poag 1997, Crawford & Mader 1998, Dresler et al. 1999, Melosh & Ivanov 1999, Kenkmann et al. 2000, Kenkmann & von Dalwigk 2000, Dence 2002) formed in a multi-layered target, e.g. the Kärdla and Neugrund impact structures.

In both Kärdla (PAPER III, IV, VI; Puura & Suuroja 1992) and Neugrund (PAPER I, II, V) the rim wall (rim-to-rim diameter 4 and 9 km, respectively) is surrounded by an elliptical ring fault 12–14 and 20–21 km in diameter, correspondingly. In Kärdla the rim wall is clearly developed and with normal (calculated) width (ca 1 km at the level of the target), but in Neugrund the situation is more complicated. Here, the up-to-5-km wide rim consists of three separated rim walls with the rim-to-rim diameters 6.5, 9 and 12 km, respectively, and these are described also as separate ring ridges (PAPER V, Fig. 4). Only the innermost (diameter 6.5 km) of these walls is more or less monolithic and intact; the others are fragmental, whereas the farthest from the centre are most fragmental. Obviously, the gaps between the fragments (hillocks) are of erosional origin, since primarily after the impact in these places the wall consisted of gigantic blocks of rather soft rocks (Ediacaran and Lower-Cambrian clay, silt- and sandstones), which were abraded during a short-term erosion during the post-impact time.

The latest SSS (side-scan sonar) profiling (Suuroja 2005, Suuroja 2006) and interpretation of seismic reflection profiles (PAPER I, Fig. 7) have demonstrated that in the area between the outer wall and the ring fault numerous gigantic blocks (up to 0.5 km in diameter) occur consisting of the same rocks as the rim walls (Neugrund Breccia – crystalline metamorphic rocks brecciated by the impact). Only small (less than 50 m in diameter) and rounded blocks have been derived from the ring ridges and transported there by a glacier, while the largest blocks (more than 50 m in diameter) of irregular shape have been thrust there in the course of the impact and lie at a 50–100 m lower level than the ridges of the rim walls.

In Kärdla the target rocks (particularly Lower-Cambrian clays, silt- and sandstones) in the belt between the rim wall and the ring fault, which is considerably wider than in Neugrund (up to 10 km and ca 8 km, respectively), are also disturbed and in the bottom of the layer contain clasts of crystalline target rocks.

In Kärdla the nature of the ring fault is not completely clear, except that it is supposedly the limit between the area where target rocks are disturbed and the area where these are mostly intact (PAPER II, IV). In the Neugrund structure, the ring fault appears as an up to 60 m high escarpment in the crystalline basement rocks (PAPER V, Fig. 8) and of course is also the limit between disturbed and mostly intact target rocks. It is somewhat incomprehensible why the structure is sort of inclined: its eastern part is uplifted, whereas the western one is subsided.

In the Kärdla case the ratio of the ring fault diameter to the rim wall diameter is about 3.25, while in the Neugrund case it is about 2.3.

In spite of several differences the Kärdla and Neugrund impact structures are in prin-

ciple rather similar. The similarities are mostly due to the similarity of the targets, while differences associate with the parameters (mass, density, approach velocity and angle) of the projectiles. Despite that, the diameters of the Kärdla and Neugrund impact structure are equalized to the diameters of the ring faults or limits of outer crater (Kenkmann and von Dalwigk, 2000; Glamoclija et al. 2007) (15 and 21 km, correspondingly), that is the diameter, which serves as a basis for most calculations of parameters of the impact structures and the projectiles.

The prior can be summed up in eight conclusions:

1. Despite the similarity of targets, the two impact structures have some morphological differences, especially in setting of their rim walls. In the Kärdla structure, the rim wall is a simple monolithic wall around the crater proper, 3.5 m in diameter (PAPER IV), while in the case of Neugrund it is more complicated – the crater proper, 5.5 km in diameter, is surrounded by ca 3-km-wide three-ridged ranges of uplifted megablocks (PAPER V).

2. Kinetic energy of the projectiles (impactors) was different and consequently the formed impact structures, too, belong to different formations of complex impact craters: Kärdla – a complex impact crater with a central uplift (peak), and Neugrund – a complex peak ring crater (PAPER IV and V).

3. A specific feature for both impact structures is the presence of ring faults running outside the rim walls, which has been established by remote sensing methods. In the case of the smaller (Kärdla) structure the ring fault is expressed more weakly, because it does not reach the crystalline basement rocks and is not expressed in the potential (geophysical) fields (PAPER IV). The ring fault surrounding the bigger Neugrund structure is expressed more clearly in the form of up-to-60-m-high escarpments in the crystalline basements rocks, which were obviously caused by vertical movements of the blocks (PAPER V).

4. In the case of the Kärdla impact structure, the ratio of the ring fault diameter to the rim wall diameter is about 3.25, while in the Neugrund case it is about 2.3. This is due to variations in the parameters of the projectiles (impactors) and the targets. Experience obtained through the investigation of impact structures indicates that the ratio of the ring fault diameter of the formed impact structure to the rim wall diameter also depends on the kinetic energy of a projectile, as well as on the composition of the target. Therefore, a diameter of a ring fault cannot be used for calculations without taking into account also the composition of the target.

5. In the Kärdla structure the impact-produced rocks (impact breccias, suevites) in the crater proper have been penetrated by numerous drill holes (PAPER V), while in Neugrund the interior of the crater proper and the impact-produced rocks, which supposedly occur there, have not been opened yet (PAPER I and II). Nevertheless, all types of impact-produced rocks (except limestone-breccias) that are known in Kärdla have been distinguished among the impact-produced rocks of the Neugrund impact structure as well. K-phenomenon (enrichment of impact-produced granitic rocks with potassium and the decreasing content of sodium) is also followed in both cases (PAPER I and V).

6. The investigations of potential (magnetic) field (PAPER II and IV) allow supposing that in both cases in the interior of the crater proper the lenses of melted rocks are absent.

This phenomenon is obviously due to the marine origin of both impact structures.

7. The ejecta and impact-influenced rocks in the surroundings of the Kärdla impact structure are rather well investigated (PAPER VI), but in Neugrund these certainly need additional investigations, especially in connection with the problems relating to the spreading of impact-influenced minerals (quartz with PDF) in Osmussaar breccias and rocks of the Pakri Formation (Middle Ordovician, Kunda Stage) in farther surroundings of the Neugrund structure.

8. For solving several problems connected with the Neugrund structure a drill hole should be made within the Central Plateau. Realization of the drill hole should be promoted by the recently submitted proposal to establish a wind farm composed of 40 windmills within the Neugrund Bank, where the depth of water is 2–15 m. In the course of geological investigations of the base of the future wind farm a drill hole should be established for studying the deeper layers of impact-produced rocks in the interior of the crater proper. The author hopes that these studies, including the comparative morphological investigations of the Kärdla and Neugrund impact structures carried out by him, will promote further investigation of these undoubtedly notable and world's best preserved meteorite craters – Kärdla among buried and Neugrund among marine structures.

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ABSTRACT

Kärdla and Neugrund are two quite similar Early Palaeozoic marine impact structures, which are situated ca 60 km apart in the coastal area of Estonia. Besides many similar features (geological setting of the target, presence of ring fault), there are also several differences (e.g. measurements, age, etc).

The purpose of the present investigation is a comparative morphological analysis of the two adjacent Palaeozoic marine impact structures formed in rather similar conditions. The Kärdla structure is situated mostly on mainland and has been thoroughly investigated by numerous (ca 160) drill holes and mainland geophysical methods, while the Neugrund structure is situated on the sea floor and cannot be investigated by direct methods, except diving. These circumstances raise the need for a comparative morphological analysis of the two impact structures. In the course of data analysis and morphological reconstruction of structural elements the features obtained by direct investigations in Kärdla were used for clearing up the morphology and post-impact development of the Neugrund impact structure, since direct data were absent or insufficient for the latter area.

The discovery and subsequent investigation of the Neugrund, and especially of the Kärdla impact structure, have been closely connected with applied geological research (geological mapping, prospecting for mineral resources and groundwater, engineering geological investigations, etc.) and therefore the methods and techniques used have been dependent on the established goals. The marine geological investigations (continuous seismoacoustic profiling, side-scan sonar profiling, diving and sampling of submarine outcrops, video robot observation of seabed) were predominantly carried out during the marine geological mapping.

The comparative morphological analysis of the impact craters was carried out by computer modelling or composing 3D computer images of the Kärdla and Neugrund impact structures, which depict different structural levels of their development (crystalline basement, sedimentary bedrock, nowadays). Mostly in the result of these investigations the following conclusions were reached. Despite the similarity of targets, the two impact structures have some morphological differences, especially in setting of their rim walls; kinetic energy of the projectiles (impactors) was different and consequently the formed impact structures, too, belong to different formations of complex impact craters: Kärdla is a complex impact crater with a central uplift (peak), and Neugrund – a complex peak ring crater. A specific feature for both impact structures is the presence of ring fault running outside the rim walls, which has been established by remote sensing methods. In the case of the smaller structure (Kärdla) the ring fault is expressed more weakly, because it does not reach the crystalline basement rocks and is not expressed in the potential (geophysical) fields. The ring fault surrounding the bigger structure (Neugrund) is more clearly expressed as up-to-60-m-high escarpments in the crystalline basement rocks, obviously caused by vertical movements of the blocks. The ratio of the ring fault diameter to the rim wall diameter of the Kärdla carter is about 3.25, while that of the Neugrund crater is about 2.3. Such difference is due to variations in the parameters of the projectiles (impactors) and the targets. Experi-

ence obtained through the investigation of impact structures indicates that the ratio of the ring fault diameter of the formed impact structure to its rim wall diameter also depends on the kinetic energy of a projectile, as well as on the composition of the target. Therefore, the diameter of a ring fault cannot be used for calculations without taking into account also the composition of the target. All types of impact-produced rocks (except limestone-breccias) that are known in Kärdla have been distinguished also among the impact-produced rocks of the Neugrund impact structure. K-phenomenon (enrichment of impact-produced granitic rocks with potassium and the decreasing content of sodium) is also followed in both cases. The investigations of potential (magnetic) field allow supposing that in both cases the lenses of melted rocks are absent in the interior of the crater proper. This phenomenon is obviously due to the marine origin of both impact structures. The ejecta and impact-influenced rocks in the surroundings of the Kärdla impact structure are rather well studied, while in Neugrund these certainly need further investigations, especially in connection with the problems related to the spreading of impact-influenced minerals (quartz with PDF) in Osmussaar breccias and rocks of the Pakri Formation (Middle Ordovician, Kunda Stage) in farther surroundings of the Neugrund structure. For solving several problems connected with the Neugrund structure a drill hole should be made on the Central Plateau. Realization of such drill hole could be fostered by the recently submitted proposal to build a wind farm composed of 29 windmills within the Neugrund Bank, where the depth of water is 2–15 m. The comparative morphological investigations of the Kärdla and Neugrund impact structures will promote further investigation of these undoubtedly notable world's best preserved meteorite craters – Kärdla among the buried and Neugrund among the marine structures.

KOKKUVÕTE

VARAPALEOSOILISTE KÄRDLA JA NEUGRUNDI (EESTI) MERELISTE IMPAKT-STUKTUURIDE VÕRDLEV MORFOLOOGILINE ANALÜÜS

Kärdla ja Neugrund on kaks lähedalasuvat meteoriidikraatrit (impakt-struktuuri) Loode-Eestis, mida lahutab 60 km pikkusmõõdus (esimene asub Hiiumaal Kärdla lähistel ja teine Soome lahe väraval Osmussaare lähistel) ja umbes 80 miljonit aastat ajaskaalal (esimene tekkinud umbes 455 mln ja teine 535 mln aasta eest). Vaatamata paljudele sarnasustele (tekketingimused, morfoloogia, vanus, suurus, uuritus jne) on neil ka mitmeid erinevusi ja seda niisamuti tekketingimuste, morfoloogia, vanuse, suuruse, uuritus jne osas.

Kuigi mõlemad meteoriidikraatrid tekkisid rannalähedases (vähem kui sadakond kilqmeetrit rannast ja kulutusalalt)" madalmeres toimunud meteoriidiplahvatuse tagajärjel, oli plahvatusaluse ehitus siiski mõnevõrra erinev – kui Kärdlas kattis umbes 240 m sügavusel lasuvat varaproterosolistest moondekivimitest plahvatusalust lisaks umbes 100 m paksusele veekihile 20 m lubakive ja 120 m liivakivi-aleuriiti-savi, siis Neugrundi puhul oli kat-

tekiht veidi õhem (umbes 200 m) ja lisaks umbes 100 m paksusele veekihile oli selles veel umbes 100 m Vendi-Kambriumi vanusega liivakivi-aleuriiti-savi.

Kui Kärdla puhul võttis anomaalse struktuuri leidmisest (1967) kuni selle meteoriitse päritolu tõestamiseni (1981) aega 14 aastat, siis Neugrundi puhul vaid 3 aastat – 1995. aastal püstitati hüpotees meteoriidikraatri olemasolust Neugrundi madala piirkonnas ja juba 1998. aastal tõestati see lõplikult. Kindlasti kiirendasid Neugrundi meteoriidikraatri olemuse selgitamist ka Kärdla meteoriidikraatri uurimisel omandatud kogemused.

Kui täielikult mattunud Kärdla meteoriidikraatri elemendid on avatud enam kui 150 puurauguga, siis Neugrundi puhul küünivad osaliselt mattunud (ringvall ja sellest kaugemale jäävad struktuurid paljanduvad osaliselt merepõhjas) meteoriidikraatri elementideni vaid üksikud (kuni 5) puuraugud Loode-Eestis ja kraatrisüvik on täielikult avamata.

Kärdla kraatrialal olid peamisteks uurimismeetodiks puurimine, millest suurosa tehti mitmesuguste rakendusgeoloogiliste uuringute (mitut liiki ja eri mõõtkavades geoloogiline kaardistamine, hüdro- ja ehitusgeoloogilised uuringud, maavarade otsingud ja uuringud) ja maapealsed ning puuraukudes läbi viidud geofüüsikalised uuringud (gravimeetria, magnetomeetria, elektromeetria jne). Neugrundi puhul laekus põhiosas teabest paljandite ja neilt pärit rändkivide uurimisest ning merele omaste spetsiifiliste uurimismeetodite kasutamisest (proovimine ja paljandite dokumenteerimine sukeldumiste käigus, merepõhja seismoakustiline pidevprofileerimine, merepõhja vaatlused külgvaate sonari ja robotkaameraga). Kõik need meetodid koos ja eraldi andsid üldiselt hea ülevaate impaktstruktuuride morfoloogiast ja võimaldasid jälgida ka nende arengut sadade miljonite aastate jooksul. Viimast eriti Kärdla meteoriidikraatri puhul, kus lisaks kraatristruktuurile endale õnnestus jälgida ka kraatrist plahvatusega välja paisatud ja pea täielikult säilinud väljapaisatud aluse peenpihustatud materjalist kihi levikut ning sellega aset leidnud muutusi.

Struktuuride arengu paremaks jälgimiseks koostati nende digitaalsed kolmedimensionaalsed struktuurimudelid ja seda kolmel eri struktuursel tasandil: struktuuriala kristalse aluskorra kivimite pealispind, aluspõhja kivimite pealispind ja tänapäevane reljeef. Suuresti nende, aga ka teiste vaatlus ja prooviandmete põhjal tehtud järeldused on summeeritud järgnevas kaheksas kokkuvõtvas punktis:

1. Vaatamata Kärdla ja Neugrundi meteoriidikraatrite plahvatusaluste sarnasusele on tekkinud struktuuridel ka rida erinevusi, seda eriti ringvalli osas. Kui Kärdlal ümbritsed 3,5 kilomeetrise läbimõõduga kraatrisüvikut, mille keskosas on hästi välja kujunenud keskkerge, kuni 1 km laiune lihtne ringvall, siis Neugrundi puhul on asi tunduvalt keerulisem – siin ümbritseb 5,5 kilomeetrise läbimõõduga, ja ilmselt ilma keskkerketa kraatrisüvikut umbes 3 km laiune 3-st ringahelikust koosnev ringvall. Kui sisemine ringahelik on suhteliselt monoliitne, siis välimised kaks koosnevad kristalse aluskorra kivimite tõstetud hiidplokkidest, mis vahelduvad plahvatuseelse aluse settekivimite tugevast deformeeritud plokkidega.

2. Nii nagu meteoriidikraatreid tekitanud meteoorkehade kineetiline energia oli erinev, nii erinevad ka nende poolt tekitatud impaktstruktuurid: Kärdla puhul on tegu keskkerget omava komplekse kraatriga ja Neugrundi puhul – ringahelikega komplekse kraatriga.

3. Mõlema kraatri üheks erakordsemaks omaduseks on selgesti jälgitava ringmurran-

gu olemasolu, kuid ka siin on jälgitavad mõningased erinevused: kui Neugrundi puhul väljendub ringmurrang hästijälgitava murranguga kristalsetes kivimites, siis Kärdla puhul on ringmurrangu olemus täpselt välja selgitamata, kuid ilmselt piirdub see vaid deformatsioonidega plahvatuseelsete settekivimite lasundis.

4. Kui Kärdla puhul on ringmurrangu raadiuse suhe ringvalli raadiusse 3,25 (13 km : 4 km), siis Neugrundi puhul on see suhe väiksem ehk 2,3 (20,5 km : 9 km). Selle erinevus on tingitud ilmselt üheltpoolt erinevustes löögikeha (meteoorkeha) parameetrites ja teisalt plahvatusaluse ehituses.

5. Kädla ja Neugrundi kraatri kristalsete kivimite arvel tekkinud impaktbretšad on nii visuaalselt, mineraalselt kui keemiliselt üksteisele väga sarnased. Seesama K-fenomen (granitoidse kivimi rikastumine kaaliumiga ja naatriumi väljakanne), mis oli jälgitav Kärdla kraatri granitoidse koostisega impatbretšades, on jälgitav ka Neugrundi kraatri sarnastes kivimites.

6. Nii nagu puudub impaktsulami lääts Kärdla kraatris, nii puudub see, otsustades magnetvälja uuringute järgi, ilmselt ka Neugrundi kraatris. Sulamiläätse puudumine on ilmselt omane kõigile selle suurusjärgu (väikestele ja keskmistele) meres tekkinud meteoriidikraatritele.

7. Kui Kärdla väljapaiskematerjali (ejecta) kiht on selgesti äratuntav ja selle levik detailselt kaardistatud, siis Neugrundi puhul, kus väljapaiskematerjali kiht on raskesti äratuntav (liivaka materjali kiht liivalasundis) on see tuvastatav üksnes löögimoonde tunnustega mineraalide (kvartsi) terade leviku järgi. Täiendavat uurimist vajab ka osmussaar-bretšas ja Pakri kihistu (Kesk-Ordoviitsiumi Kunda lade) lubiliivakivis esinevate löögimoonde tunnustega mineraalide (kvartsi) terade päritolu. Ilmselt on tegu siiski neugrund-bretšast ümbersetitatud materjaliga.

8. Neugrundi kraatri siseehituse tundmaõppimiseks oleks vaja puurida selle keskossa (Keskplatoole) puurauk, mis avaks meteoriidiplahvatuse käigus tekkinud kivimite lasundit. Kuna koostamisel on igati tänuväärne projekt, mis näeb ette Neugrundi madala lubjakiviplatoole 40 generaatoriga tuulepargi rajamist. Tuulegeneraatorite aluste uuringute käigus võiks rajada ka eelmainitud uuringupuuraugu. Tuulepargiga kaasnev infrastruktuur võiks soodustada ka meteoriidikraatri uurimist ja selle, kui maailmamere teadaoleva kõige paremini säilinud meteoriidikraatri tutvustamist asjaosahuvilistele.

ORIGINAL PUBLICATIONS

I

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16 Neugrund Structure – the Newly Discovered Submarine Early Cambrian Impact Crater

Kalle Suuroja and Sten Suuroja

Geological Survey of Estonia, Kadaka tee 80/82, EE12618, Tallinn, Estonia.
(s.suuroja@egk.ee)

Abstract. The Neugrund Bank is situated on the southern side of the entrance of the Gulf of Finland (59°20'N; 23°31'E) between Osmussaar and Krass islands. It is a shoal of a very peculiar multi-ring shape. In the coastal and offshore area of North-Western Estonia, numerous erratic boulders, consisting of rocks resembling impact breccias, have been found. The investigations proved that under Neugrund Bank and in its surrounding is located a classic buried and partially newly exposed impact crater. The studies revealed the general morphology of the structure. In the summer of 1998, during three expeditions, the submarine impact structure was investigated in detail by diving and sidescan sonar profiling. As a result, the hypothesis, which had been indirectly indicated by remote sensing, was finally verified.

The Neugrund impact crater formed ca. 540 My ago in a shallow epicontinental sea as the result of the impact of an extraterrestrial body with a diameter of ca. 400 m. As a consequence of the impact a crater with the rim-to-rim diameter of 7 km was formed. The depth of the ca. 5 km-diameter crater has not yet been determined, but is assumed to range over 500 m. At the distance of about 10 km around the crater, the target rocks are strongly disturbed. After the impact the crater deep was filled with clastic deposits and was buried within a rather short time (some millions of years). The sedimentation conditions in the crater differed from those of the surrounding area until the Middle Ordovician. Since then, and up to the Tertiary, the crater remained buried and was partially uncovered during the Neogene.

In the impact-derived rocks (clast-supported mono- and polymict impact breccias), the following evidence for shock metamorphism has been observed: shatter cones, mosaicism of quartz and feldspar, planar fractures and planar deformation features in quartz, kink bands in biotite, diaplectic glass, partial

melting of clasts, occurrence of recrystallized glassy grains, occurrence of thin veins of melt. The impact origin of the Neugrund structure may be considered verified. In the impact-affected Precambrian basement rocks of the Neugrund structure, we observed an enrichment of potassium, and a decrease in the sodium content, similar to the behavior of these elements in some rocks of the Kärdla impact crater.

Introduction

Neugrund Bank is situated on the southern side of the entrance of the Gulf of Finland (59°20' N; 23°31' E) between Osmussaar (Odensholm) and Krass islands. It is a shoal of a very peculiar multi-ring shape (Figs. 1, 2). The integrated large-scale (1:50 000) geological mapping of coastal and offshore area in North-Western Estonia has provided abundant interesting information on this geologically problematic area (Suuroja et al. 1997). In the coastal and offshore area of North-Western and Western Estonia, as well as on Osmussaar, Muhumaa and Saaremaa islands occur more than 600 singular erratic boulders, consisting of brecciated metamorphic rocks (amphibolites, migmatites, and gneisses) of the Precambrian crystalline basement (Figs. 1, 4, 5).

Firstly the gneiss-breccia boulders were described on Osmussaar Island by Öpik (1927), who named the rock type as gneiss-breccia. Somewhat later, Thamm (1933) investigated the mineralogy of these rocks more thoroughly. He tried to identify the origin and source area of these boulders, but without any success. Orviku (1935) and Viiding (1960), too, have described several finds of these boulders in Western Estonia.

In 1984–1988, the Geological Survey of Estonia carried out marine geological mapping of the North-West Estonian shelf at a scale of 1:200 000. The Neugrund structure was interpreted as a glacial formation – moraine wall (Raukas and Hyvärinen 1992; Lutt and Raukas 1993).

During the large-scale (1:50 000) geological mapping, geologists Suuroja and Saadre (1995), who had for several years participated in the investigations of the nearby (ca 60 km SW) Kärdla impact crater (Puura and Suuroja 1992) noted the obvious similarity of the gneissbreccias to the allo- and authigenic impact breccias of the Kärdla impact crater. Microscopic investigations of the fine-grained clast-supported impact breccias (Suuroja et al. 1997) showed that they belong to the low shock metamorphism stage (0–I). The distribution fan of the gneiss-breccia erratic boulders pointed to the sea area eastward of Osmussaar Island, where the submarine Neugrund Bank is located (Figs. 1, 2). Therefore, the hypothesis was

proposed that the peculiar multi-ring-shaped Neugrund Bank and its surrounding could be a buried impact structure, partially exposed as a result of the Quaternary glaciation (Suuroja and Saadre 1995).
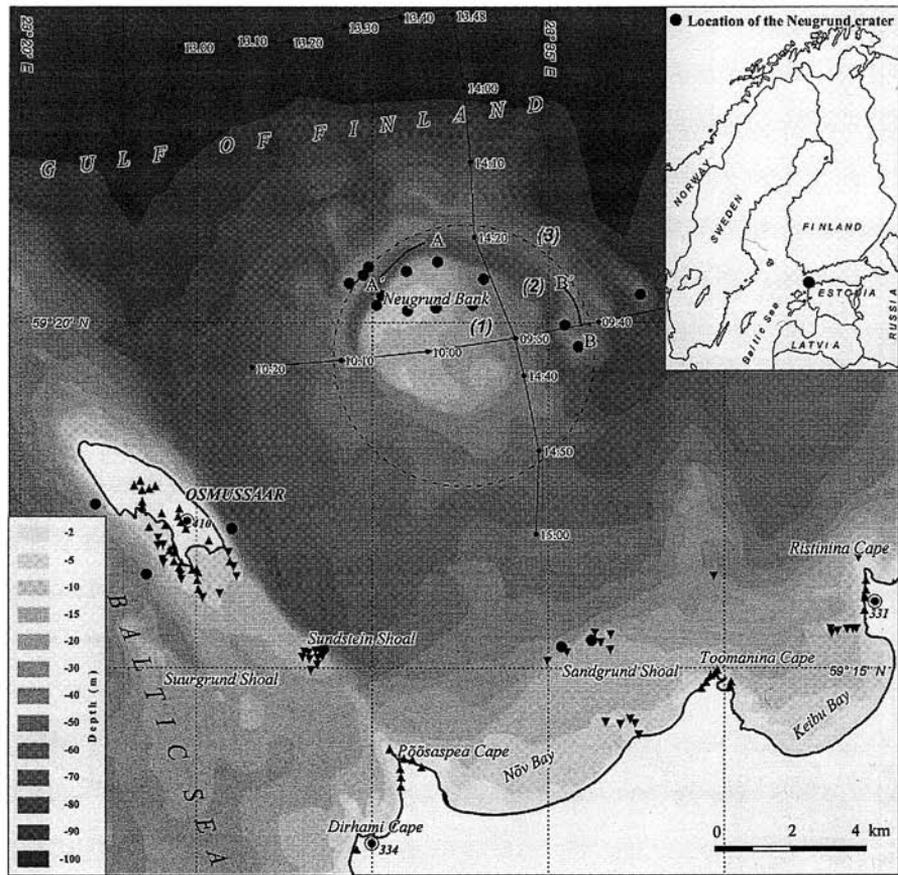
Fig. 1. The location and bathymetric maps of the Neugrund crater area . 1 = central plateau; 2 = circular erosional canyon; 3 = rim-wall. Triangles = erratic boulders made of Neugrund Breccia; dots = diving and sampling sites; dotted line = rim- wall ridge; circles = drill hole and its number; lines with numbers = seismo-acoustic profiles in Fig. 6 and 7.; lines A – A' and B- B' = side-scan sonar profiles.
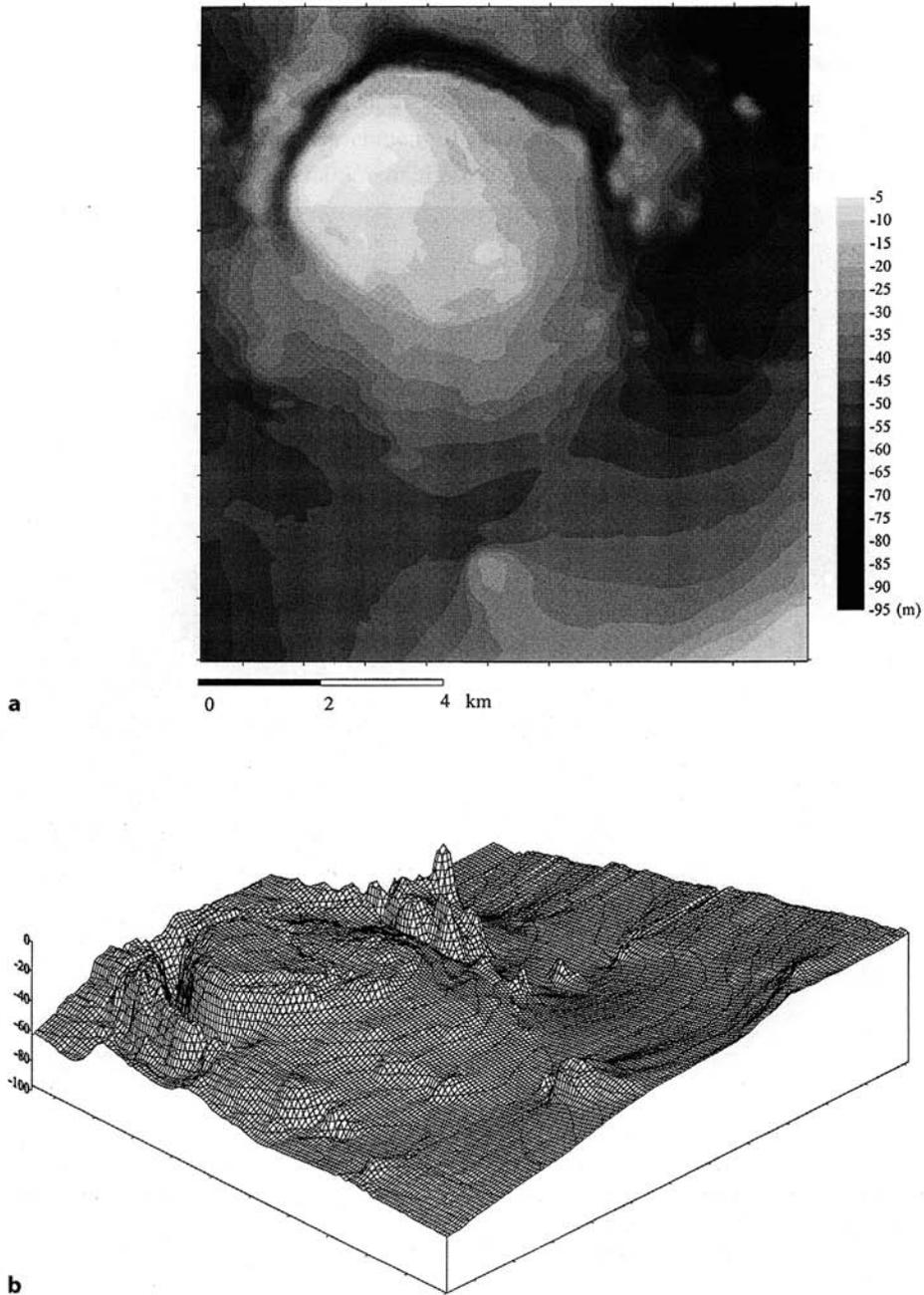
Fig. 2. Sea bottom relief of the Neugrund crater area. (a) bathymetric map (data of the Board of Waterways of Estonia); (b) bar chart of the same area.
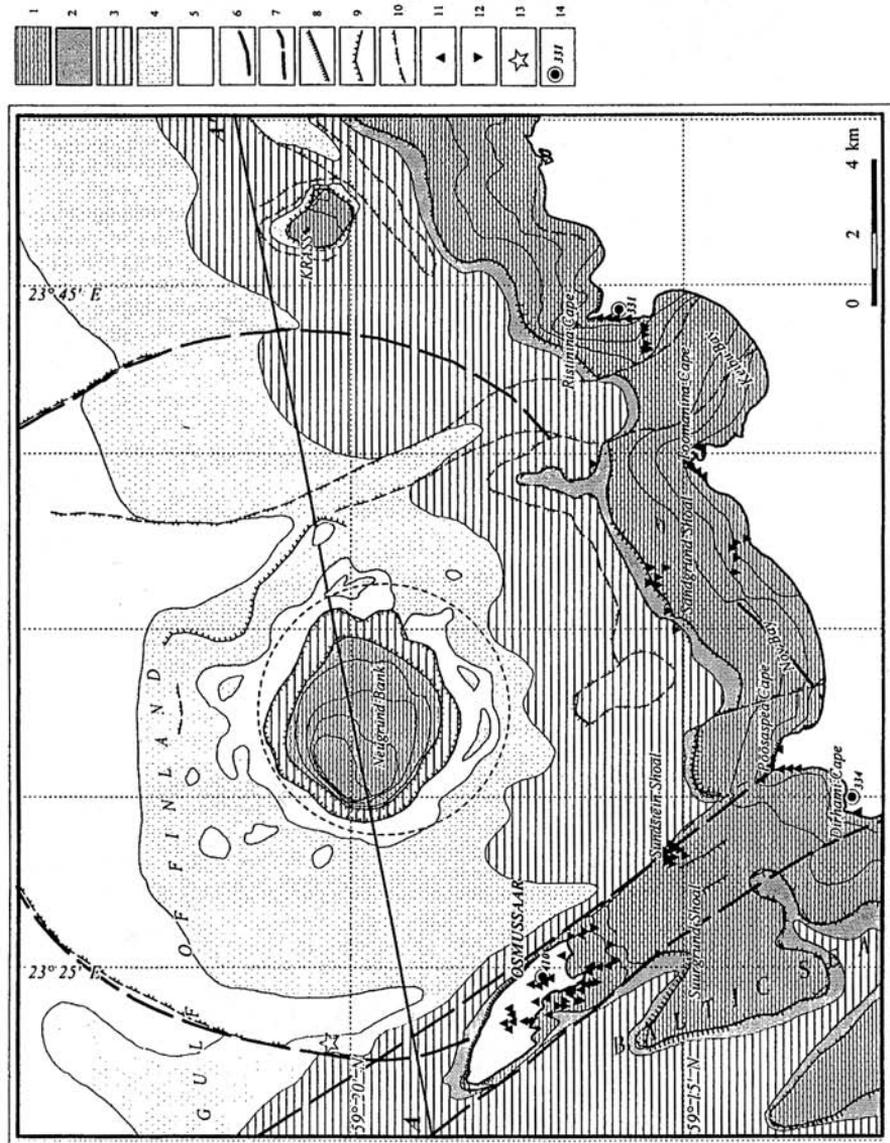
Fig. 3. Bedrock geological map of the Neugrund crater area. 1 = Precambrian basement metamorphic rocks; 2 = pre-impact terrigenous rocks (Vendian and Early Cambrian); 3 = post-impact terrigenous rocks (Early Cambrian); 4 = Early Ordovician terrigenous rocks; 5 = Middle Ordovician limestones; 6 = coastline; 7 = supposed fault; 8 = terrace on land; 9 = terrace on sea bottom; 10 = buried terrace on the sea bottom; 11 = erratic boulders made of Neugrund breccia on land; 12 = same on the sea bottom; 13 = inferred epicentre of the Osmussaar earthquake of 1976. 14 = drill hole and its number (cross-section A – A').

Fig. 4. Some erratic boulders of Neugrund breccia derived by glacial action from Neugrund crater rim-wall or ejected blocks on the North-Western Estonian coast: (a) on Toomanina Cape; (b) on Põõsaspea Cape.

Fig. 5. The impact-affected Precambrian metamorphic rocks (autochthonous impact breccia) from the Neugrund crater area: (a) amphibolite rock; (b) granitoid.

Considering the above-mentioned presumption, in the summer of 1996 Stockholm University and the Geological Survey of Estonia organized a joint expedition on r/v "Strombus", headed by Tom Floden. Neugrund Bank and the surrounding sea bottom were geophysically investigated using continuous seismo-acoustic and magnetometric profiling (Fig. 6; 7). These studies proved that under Neugrund Bank and in its vicinity lies a buried and partially newly exposed impact crater. The general morphology of the structure was revealed as well (Suuroja 1996; Suuroja et al. 1997), but direct verification – by studying samples of impact-derived rocks collected directly from the crater structure – was not obtained.

In the summer of 1998 the submarine impact structure was investigated in detail by diving and sidescan sonar. All reachable structures and rocks at the depth of 2–43 m were investigated, sampled and recorded by video camera. 100 miles sidescan sonar profiling was carried out. As a result, the hypothesis previously indirectly proposed from remote sensing was supported by direct evidence. Macroscopic and geochemical similarity of the rocks provide clear evidence that all so-called gneiss-breccia (or the Neugrund Breccia – as they could be named in the future) erratic boulders in Western and North-Western Estonia are derived from the Neugrund structure (crater) rim-wall and most likely are of impact origin. A lot of information about of the lithology of target rocks and impact and post impact processes has been obtained by investigating the Osmussaar (no. 410, 5 km SW of the crater rim), Ristinina (no. 331, 10 km SE of the crater rim) and Dirhami (no. 334, 10 km S of the crater rim) drill cores (Fig. 1; 3).

Geological and paleogeographical setting of the crater

The Neugrund impact event took place in the Early Cambrian, during the middle of the Lontova age (ca 540 Ma) in shallow epicontinental sea not far from the shoreline of that time (Fig. 8). In the Early Cambrian the impact site on the Baltic Continent was situated on the Southern Hemisphere at latitudes of 30–40° (Torsvik et al. 1996). At that time the Precambrian crystalline basement of the impact site was covered with Vendian (ca 60 m) and Early Cambrian (ca 40 m) terrigeneous rocks (sandstones, siltstones, clays) and water (ca 50 m). Prior to the impact, the sedimentary cover presented a horizontal monocline (Fig. 9a). A hypothetical cross-section of the target rocks has been reconstructed on the basis of some drill cores from the surrounding area (Osmussaar Island, Ristinina Cape, and Dirhami Cape).

The Early Cambrian Lontova age sedimentation in the basin was characterized by relatively smooth changes in facies environment (Mens and Pirrus 1997), considering the gradual decrease of sand content and increase in clay content from the west to the east (Fig. 8). Evidently the changes in facies were mainly due to the changes in the depth of the basin. In the impact site the deposits of the pre-impact Lontova Formation are represented by fine- to coarse-grained weakly lithified quartzose sandstones (ca. 70 %) with interlayer of clayey siltstone. Such association of sediments is typical for a shallow offshore sea, were the water depth may be 50-100 m (Mens and Pirrus 1997). Biostratigraphically the impact event is sufficiently characterized and marks the pre-trilobite Early Cambrian *Platysolenites antiguissimus* biozone of the East-European Platform (Mens et al. 1990). The above-mentioned skeletal fragments have been found in impact-related sedimentary breccias in surrounding area, as well as in the deposits above and below them (Fig. 8).

In the pre-impact section the ca 60-m thick Vendian complex (Fig. 10) consisted mainly of fine- to coarse-grained, weakly lithified and water-saturated sandstones (the Kotlin Stage). Along the base of the Vendian complex there is a 2–10-m thick bed of multicoloured unsorted clayey-sandy-gravelly deposits (mixtite). The clayey matrix of this rock consists mostly of kaolinite, in contrast to the Early Cambrian deposits, where illite is the dominant clay mineral.

The Svecofennian orogenic metamorphic rocks form the Precambrian crystalline basement of the impact site. Information about of the crystalline basement has been obtained by drilling in the surrounding area, investigation of numerous erratic boulders derived from the crater structures (rim-wall and ejected megablocks) and by the direct observing and sampling submarine outcrops.

Amphibolites are the most widely distributed rock type in this area, forming over 50 % of the crystalline basement. They occur mainly as large layer-like bodies containing varying amounts (5–30 %) of migmatite granite veins and lenses. In addition to granites, intercalated quartz-feldspar gneisses and biotite gneisses have been recorded as well.

The amphibolites of the Neugrund crater area are migmatized to a variable degree and are fine- to medium-grained (grain size 1–5 mm), of linear or massive texture and greyish-green or dark-green in colour. Mineralogical composition (vol. %) of amphibolites, which based on microscopic assessment 15 thin sections is the following (Table 1): plagioclase (An 40–50 %) = 40–45 %; amphibole (Hbl) = 50–60 %; quartz = 0–2 %; biotite 1–5 %; pyroxene (clinopyroxene) = 1–5 %; K-feldspar = 0–2 %. Accessory minerals are represented by apatite, orthite and zircon; ore minerals are mainly magnetite, pyrite and ilmenite. According to the chemical composition ($SiO_2 = 48$–50 %, $Na_2O+K_2O = 3$–6.5 wt%), the

amphibolites of the Neugrund crater area correspond to the rocks of the basalt group. The above-mentioned rocks are very similar to the amphibolites of the crystalline basement of the Kärdla impact crater area (Koppelmaa et al. 1996)

The information obtained from the study of erratic boulders and submarine outcrops indicates that biotite gneisses in the basement of the Neugrund crater area are of more restricted distribution than amphibolites, but they form rather large layer-like bodies in the eastern part of the area. Biotite gneisses are relatively homogeneous, but fragmentary-banded reddish-grey medium-grained strongly migmatized rocks. Major minerals are plagioclase (An 30–35 %), quartz, K-feldspar and biotite, the ratios of which may vary to some extent. In places the biotite gneisses contain also some hornblende. Accessory minerals are apatite, magnetite, zircon and orthite. By chemical composition (SiO_2 = 63–68 wt%; Na_2O+K_2O = 5.5–7.5 wt%) the biotite gneisses of the Neugrund crater area correspond to the rocks of the andesite group and some amphibolites, and they greatly resemble analogous rocks of the Kärdla crater area (Koppelmaa et al. 1996). The crystalline basement rocks in this area are weathered below the contact with the Vendian sedimentary rocks (Fig. 10). Evidence of Precambrian (Vendian) weathering has been found up to ten meters below the peneplane surface of the crystalline basement.
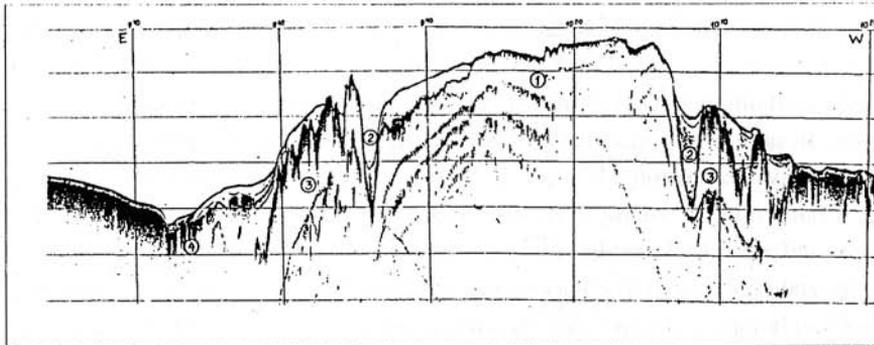
Fig. 6. E–W direction continuous seismo-acoustic profiling record across the Neugrund crater area. Record frequency 4 kHz, space between horizontal lines ca. 18 m in water; space between vertical lines 10 minutes or ca. 2.3 km. 1 = Neugrund Bank or central plateau; 2 = circular erosional canyon; 3 = rim-wall; 4 = surrounding area.
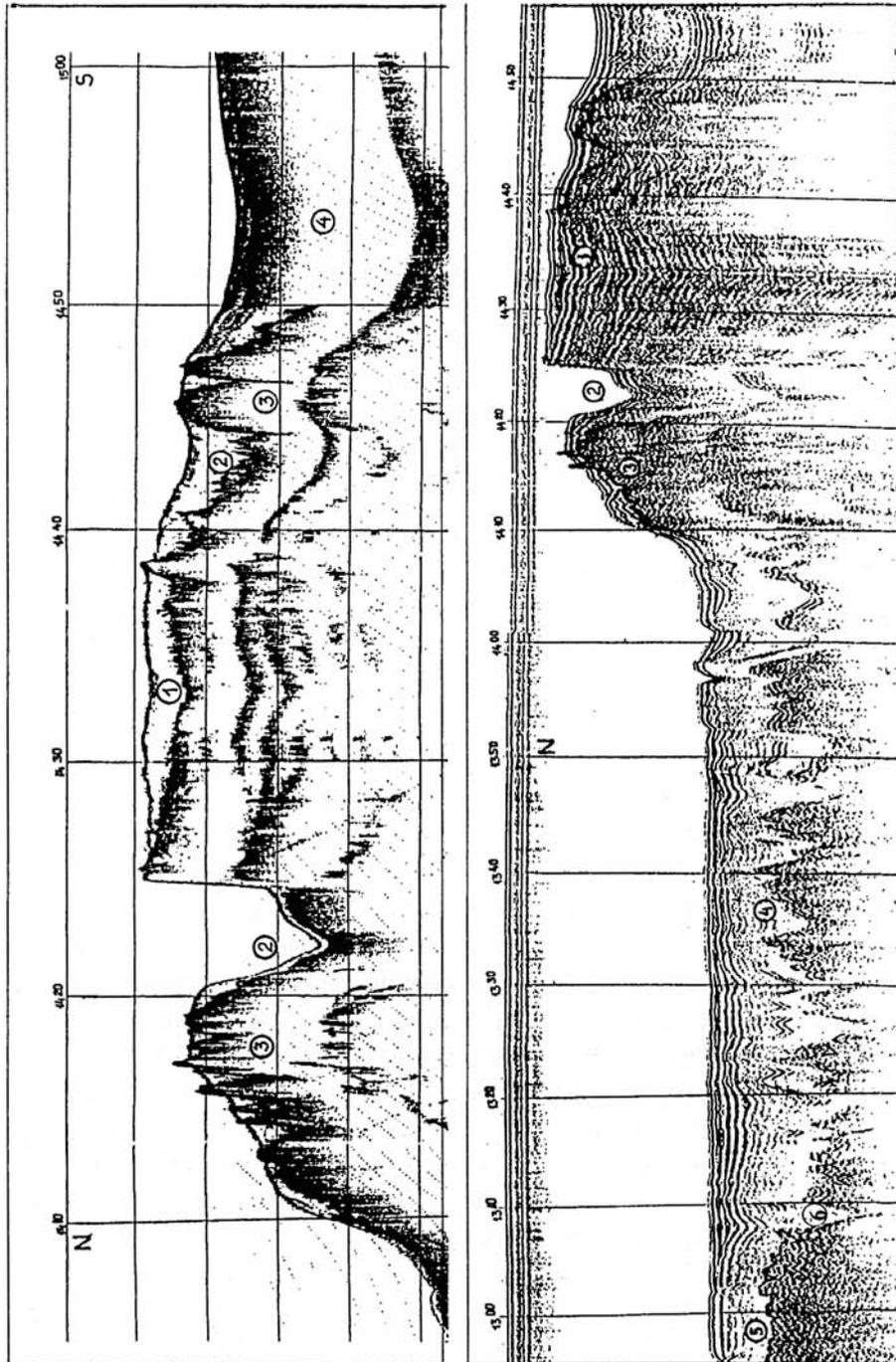
Fig. 7. N–S direction seismo-acoustical record across the Neugrund structure. Space between horizontal lines ca 18 m in water; space between vertical lines 10 minutes or ca. 1.8 km. (a) record frequency 4 kHz. (b) record frequency 250 – 500 Hz. 1 = Neugrund Bank or central plateau; 2 = circular erosional canyon; 3 = rim-wall; 4 = disturbed target rocks in the surrounding area; 5 = undisturbed target rocks; 6 = ring-fault.
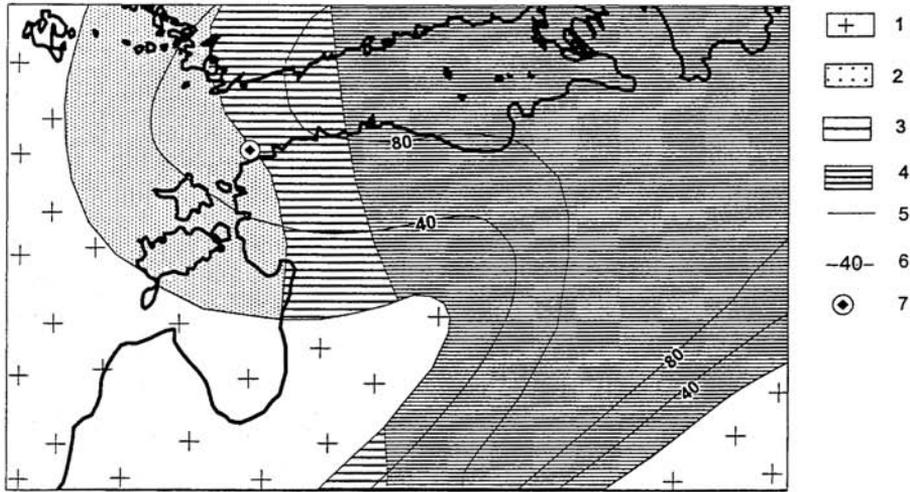
Fig. 8. Lithological sketch-map of the Neugrund crater area during Lontova Age (modified from Mens and Pirrus 1997): 1 = land, represented by igneous and metamorphic rocks; 2 = area of sandstones; 3 = area of ca 50 % argillaceous rocks; 4 = area of >75 % argillaceous rocks; 5 = boundary of facies belt; 6 = isopachs of Lontova Formation; 7 = Neugrund impact site.

Morphology of the crater

By now, the morphology of the crater has been relatively well investigated (Table 2). The major structural features of the submarine impact crater (rim-wall, crater proper, ejecta layer and ring fault) have been distinguished. The best overview of the preserved and exposed crater structure was obtained by diving and sidescan sonar profiling (Fig. 11). The crater rim-wall is made of brecciated crystalline basement metamorphic rocks (authigenic impact breccias) and is exposed on the sea bottom as a 25–50 m high, 100–500 m wide and 9–10 km long semicircular (southern part of the rim is buried under the Quaternary deposits) range of smooth hills resembling *roche moutonnée* features (Fig. 11 b). The external slope of the rim is gently sloping (10–20°), while the inner slope is steeper (30–50°) and in places penetrated by joints sub-parallel to the rim. Along these joints blocks of the rim have slid down towards the crater deep. The rim-wall, together with ejected blocks, has served as the main source of the Neugrund Breccia erratic boulders of Western Estonia. The preserved rim-wall is composed of fragments of up to 120 m high elevation (Fig. 6). The primary height of the structure may have been over

300 m, and total height of the rim-wall together with the talus slope, about 500 m. The rim-wall was partially eroded immediately after the impact by resurge wave and short-time (some millions of years) erosion before burying of the structure. It is as yet unknown, which parts of the rim-wall were eroded shortly after the impact in the Early Cambrian, and which during the Tertiary erosion and the Quaternary glaciation (or Paleocene).

Between the rim-wall and at the crater filling and overlying complexes (central plateau), there is up to 70 m deep and 200–500 m wide circular canyon-like depression (Fig. 2; 6; 7). The external slope of the canyon is the rim-wall and the internal slope the section of the central plateau. The internal slope of the circular canyon, where the filling and overlying complexes of the crater is exposed for ca. 50 m, is remarkably steeper (40–90°). It is especially well expressed in the northern part of the Neugrund structure (Fig. 7), where over a difference of ca. 100 m, a step-like lowering of the limestone plateau from the depth of 2–3 m to the depth of 18–20 m can be observed. A-6–8 m high precipice, exposing Middle and Late Ordovician limestones follows the "steps". The foot of the escarpment is presented by ca. 30–40 m high slope with an angle of 30–40°, where Early Ordovician deposits (glauconitic sandstone, Dictyonema shale, biodetritic sandstone) and Early Cambrian post-impact silt- and sandstones crop out. The exact time of final burial of the crater is unknown, but there is reason to assume that it occurred a short time after the impact at the end of the Early Cambrian. Therefore, the Early Cambrian terrigeneous deposits of the Tiskre and Lükati Formations are considered to belong to the crater filling complex, and Early and Middle Ordovician deposits to the overlying complex.

The relatively flat bottom of the circular canyon (Fig. 11 a) is covered by a 10–20 m thick layer of Holocene (Baltic Ice Lake) varved clay (Fig. 6). In the southern part of the structure the varved clays fill the canyon and the thickness of the layer reaches up to 40 m (Fig. 7). The canyon is obviously of erosional origin and was formed by flowing water at the contact of two rock complexes with very different physical-mechanical properties: the hard and durable complex of the brecciated crystalline basement metamorphic rocks, and friable complex of Cambrian terrigeneous rocks (silt- and sandstones). The time of formation of this erosional structure as well as the primal denudation of the buried crater, is related to the Tertiary (Neogene) and intensive tectonic uplifting of the area (Puura 1991; Puura and Floden 1997; Mozayew 1973) and is directly connected with the formation of the important erosional structure known as the Baltic Clint. During the Pleistocene glaciation the rim-wall, as well as the surrounding area, were additionally eroded by glaciation.
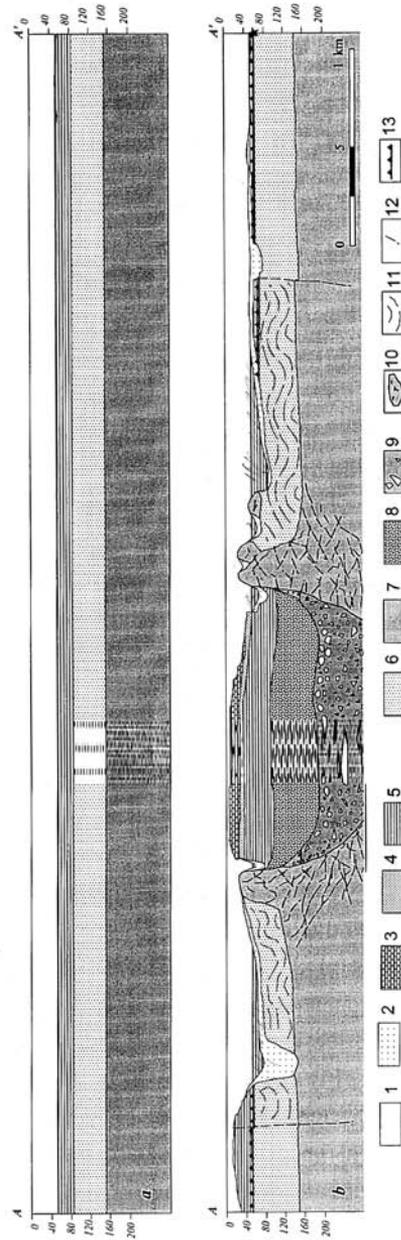
Fig. 9. Cross-section of the Neugrund crater area (for location of the cross-section, see Fig. 3.): (a) reconstruction of the impact target; (b) present configuration. 1 = sea water; 2 = Quaternary deposits; 3 = Middle and Early Ordovician limestones; 4 = Early Ordovician terrigeneous rocks; 5 = post-impact Early Cambrian terrigeneous rocks ; 6 = pre-impact Early Cambrian and Vendian terrigeneous rocks; 7 = metamorphic rocks of the Precambrian basement; 8 = crater filling complex; 9 = inferred impact breccias; 10 = ejected megablocks; 11 = disturbed sedimentary target rocks; 12 = faults; 13 = ejecta layer.

System		Formation		Depth (m)	Descriptions
Ordovician	POST-IMPACT COMPLEX				Quaternary deposits.
					Limestones.
				12,0	Brecciated limestones with sedimentary dikes
				13,0	Glauconitic sandstone.
				18,5	Kerogenenous argillite (Dictyonema shale).
Early Cambrian		Tiskre		33,5	Light-grey thin-bedded coarse-grained siltstone with intebeds of silty clay and pyrite concretsions in the lower part.
		Liikati		40,8	
				47,0	
				62,5	Greenish-gray thin-bedded silty claystone with siltstone interbeds.
		Lontova (post-impact)		65,0	Fine- grained quartzone sandstone.
		IMPACT EVENT		73,6	Greenish - grey claystone. The uppermost 2 m of the rock is reddish - brown. Discontinuity on the base of layer surface.
		Lontova (pre-impact)		84,0	Strongly distrubed layer of greenish-grey silty claystone.
				101,7	Fine- to coarse - grained greenish - grey claystone. The uppermost 2 m of the rock is reedish - brown. Discontinuity on the base of layer surface. The layer is distrubed and tilted 20-30°.
				111,3	Greenish - grey thin-bedded silty clay wit interbeds of quartzone sandstone. The layer is disturbed and tilted 20-30°.
Vendian	TARGET COMPLEX	Kotlin		132,0	Light - grey fine - grained friable quartzone sandstone.
				154,5	Light - grey fine- to coarse-grained friable quartzone sandstone.
				168,0	Greenish - grey mictite.
				170,0	Basal conglomerate.
Paleo-proterozoic				177,3	Weathered rocks of Precambrian crystalline basement.
				193,4	Metamorphic rocks of Precambrian crystalline basement - migmatites. Complex penetrated by cracks and tilted 60 - 80°

Fig. 10. The Osmussaar drill core (nr. 410) lithostratigraphic section. The drill hole is situated 9 km SW from the centre of the impact site.

In the centre of the Neugrund structure is an almost circular central plateau 4.5 km in diameter, the so-called Neugrund Bank. The plateau is covered with Middle Ordovician limestones and it is located directly at the crater (Fig. 1; 9b). Water depth on the Neugrund Bank varies between 1–15 m, increasing from NW to SE. Geomorphologically the central plateau may be considered a submerged erosional relict or a so-called klint island. On the plateau are exposed the Middle Ordovician limestones of the Viivikonna, Uhaku, Väo, Aseri and Pakri

formations. The preliminary results of diving showed that the thickness and composition of limestones of these formations within the crater differ greatly from rocks of above-mentioned formations in the surrounding area. The thickness of the limestone cover on the plateau is approximately 20 m, decreasing from NW to SE. The plateau is from all sides bordering with 6–10 m high escarpment, which is buried under the Quaternary deposits (varved clays) in the south-eastern part of the crater.

Submarine investigation of the canyon section showed that the crater is filled mainly with Early Cambrian and Early Ordovician clastic rocks. Due to the discovery of Early Cambrian and Early Ordovician deposits in the crater, it became necessary to correct the previous assessment (474 Ma) of the age of the crater (Suuroja 1996). The latter was preliminary determined mainly by the evidence of catastrophic seafloor crushing which is widespread in North-Western Estonia and is recorded also in a section of Osmussaar Island. The new age determination is based on the presence of the Early Cambrian deposits in the crater proper and the occurrence of over 20 m thick layer of disturbed and brecciated (impact-influenced) rocks on the top of the Lontova Formation (the Early Cambrian, Lontova age, ca 540 Ma) in drillhole sections located not far from the impact centre (Osmussaar Island – 9 km SW, Ristinina –13 km SE).

Recognition of impact origin of the Neugrund structure

Various criteria have been developed for the recognition and confirmation of impact structures. The characteristics are the evidence of shock metamorphism, crater morphology, geophysical anomalies, and presence of meteorites or geochemical discovery of traces of the meteoritic projectile (Koeberl and Anderson 1996; Melosh 1989).

The morphology of the Neugrund structure is strongly suggestive of an impact origin. The negative magnetic anomaly at the crater deep and positive corresponding to the rim-wall are clearly expressed (Fig. 12). Up to now, gravimetric studies and detail geochemical investigations of impact-influenced rocks have not been carried out in the Neugrund crater area. Data about the existence of a central uplift in the crater are absent, but from experience based on a slight (some meters) uplift of the limestone beds in the central part of the crater (Fig. 6) indicate its possible presence. A ring fault with a diameter ca 20 km as an outer boundary of the structure, which concentrically surrounds the inner crater (Fig. 3), is also typical for impact craters of this type.
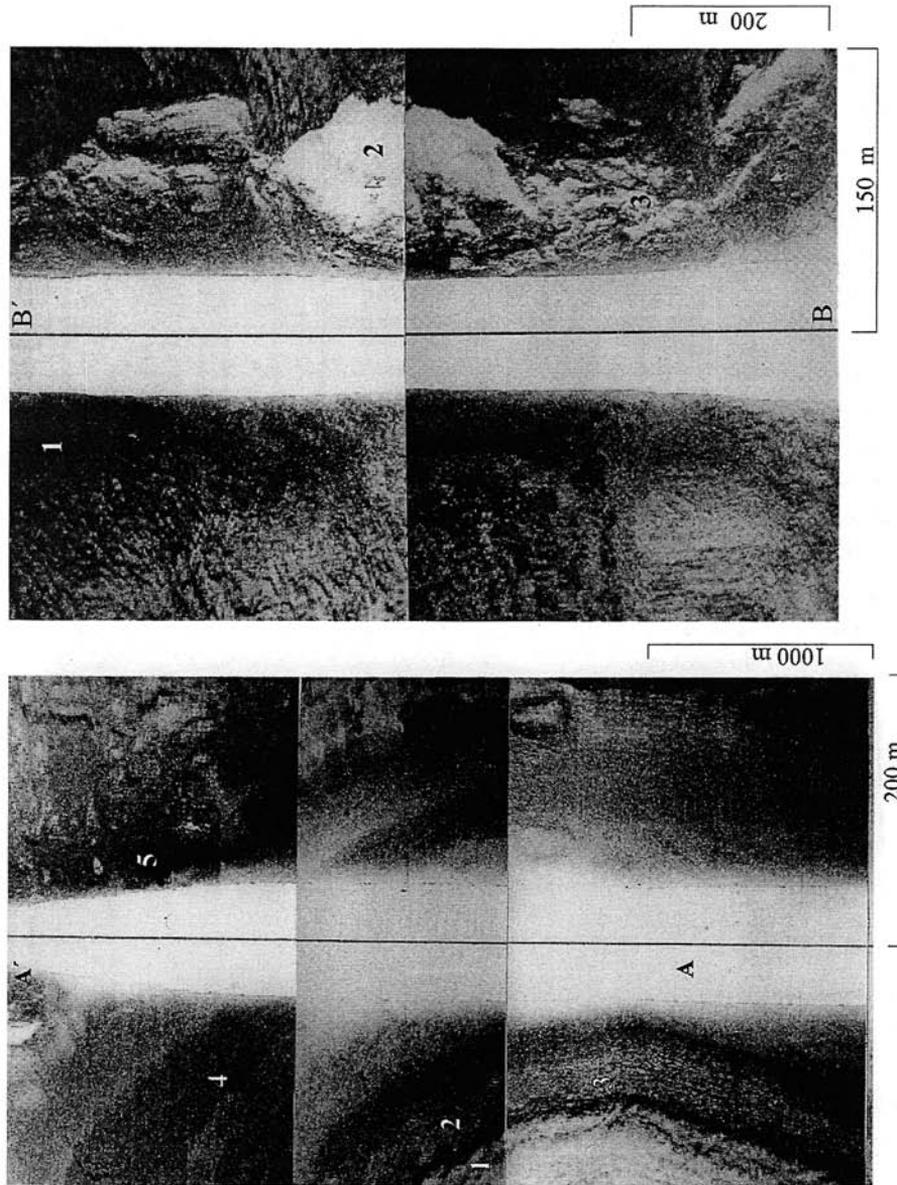
Fig. 11. Sidescan sonar profiles across the circular canyon of the Neugrund structure. A – A' = across the circular erosional canyon in the western part of the structure. 1 = gradually lowered limestone plateau; 2 = ca. 6 m high limestone precipice; 3 = ca. 30 m high escarpment (from top to bottom) glauconitic sandstone, Dictyonema shale, biodentritic sandstone and siltstone; 4 = flat bottom of the canyon covered with varved clay; 5 = rim-wall were cropped out brecciated Precambrian metamorphic rocks. Width of the recording strip 200 m. B – B' = along the rim-wall. 1 = inner slope of the rim-wall; 2 = outcrop of brecciated Precambrian metamorphic rocks; 3 = glacially eroded part of the rim-wall (*roche ·mountaunce* features).
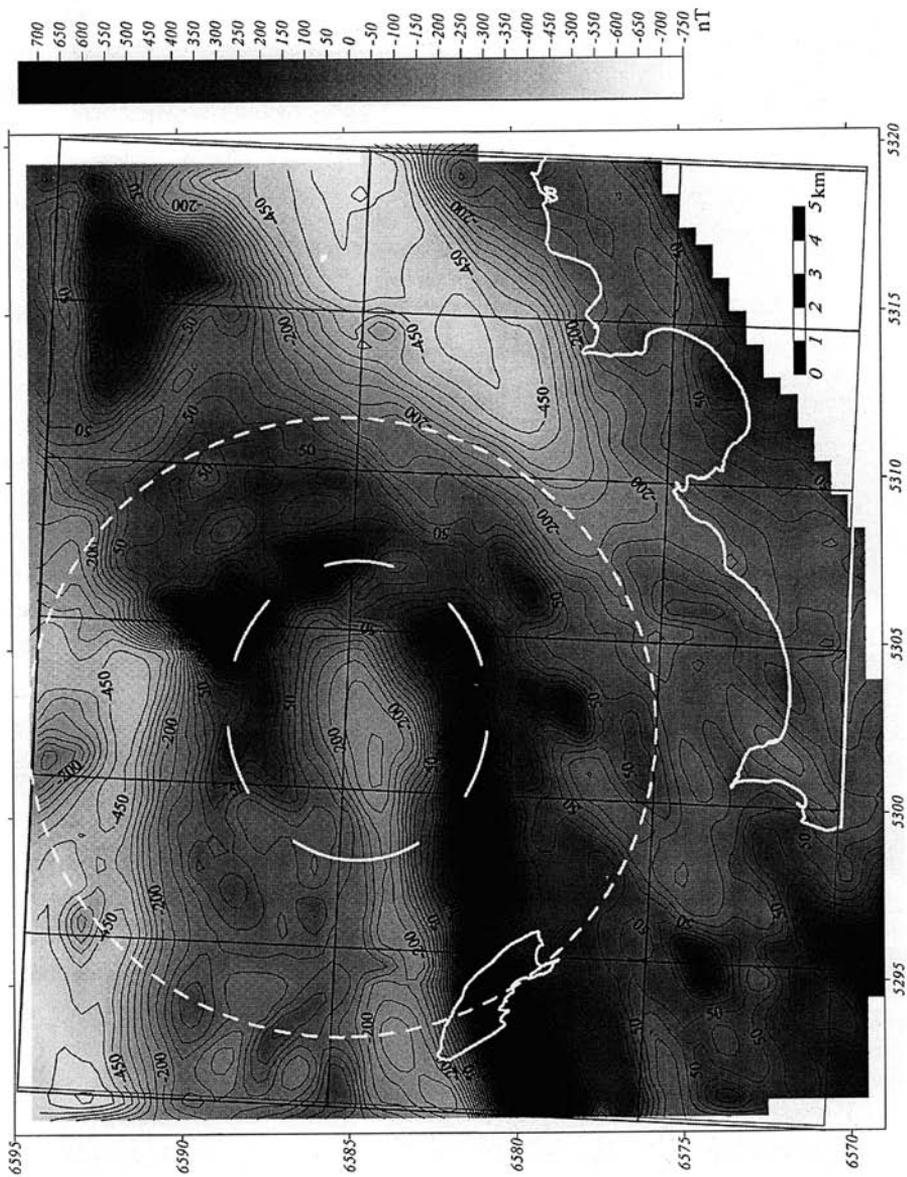
Fig. 12. DGRF-65 aeromagnetic anomaly (total field) map of the Neugrund crater area. The dashed lines denote the ridge of crater rim (inner) and the ring fault (outer). Compiled by Tarmo All (Geological Survey of Estonia).
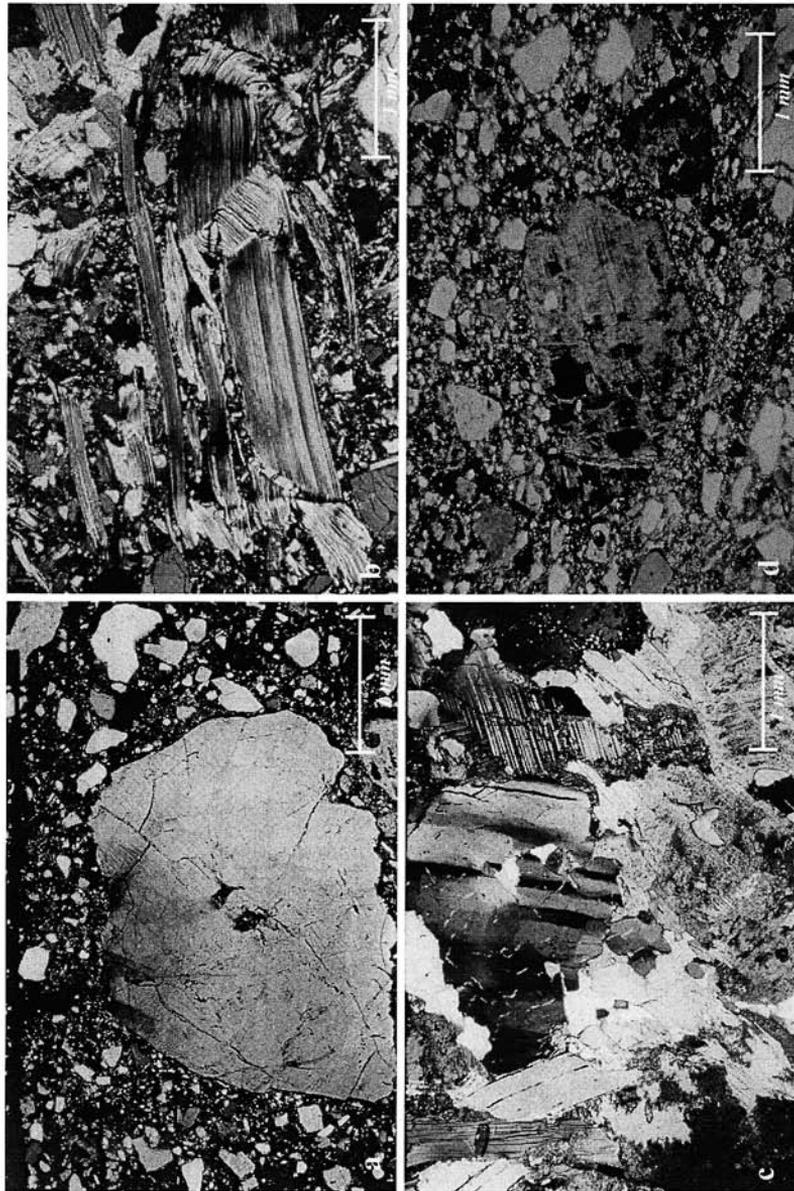
Fig. 13. Photomicrographs of matrix supported polymict impact breccia veins from the Neugrund crater rim-wall and erratic boulders. (a) Two weakly developed sets of nondecorated planar deformation features (PDF) in a quartz clast. Sample from rim-wall. Crossed polarizers (b) Biotite leaves near – horizontal cleavage and well-developed kink bands. Crossed polarizers, sample from matrix supported polymict impact breccia vein in crater rim. (c) Quartz grain with intensive band-like mosaicism.. Sample from erratic boulder. Crossed polarizers (d) Strongly altered and partially melted feldspar (plagioclase) clasts from matrix-supported polymict impact breccia (in the center), sample from ejected megablocks. Crossed polarizers.
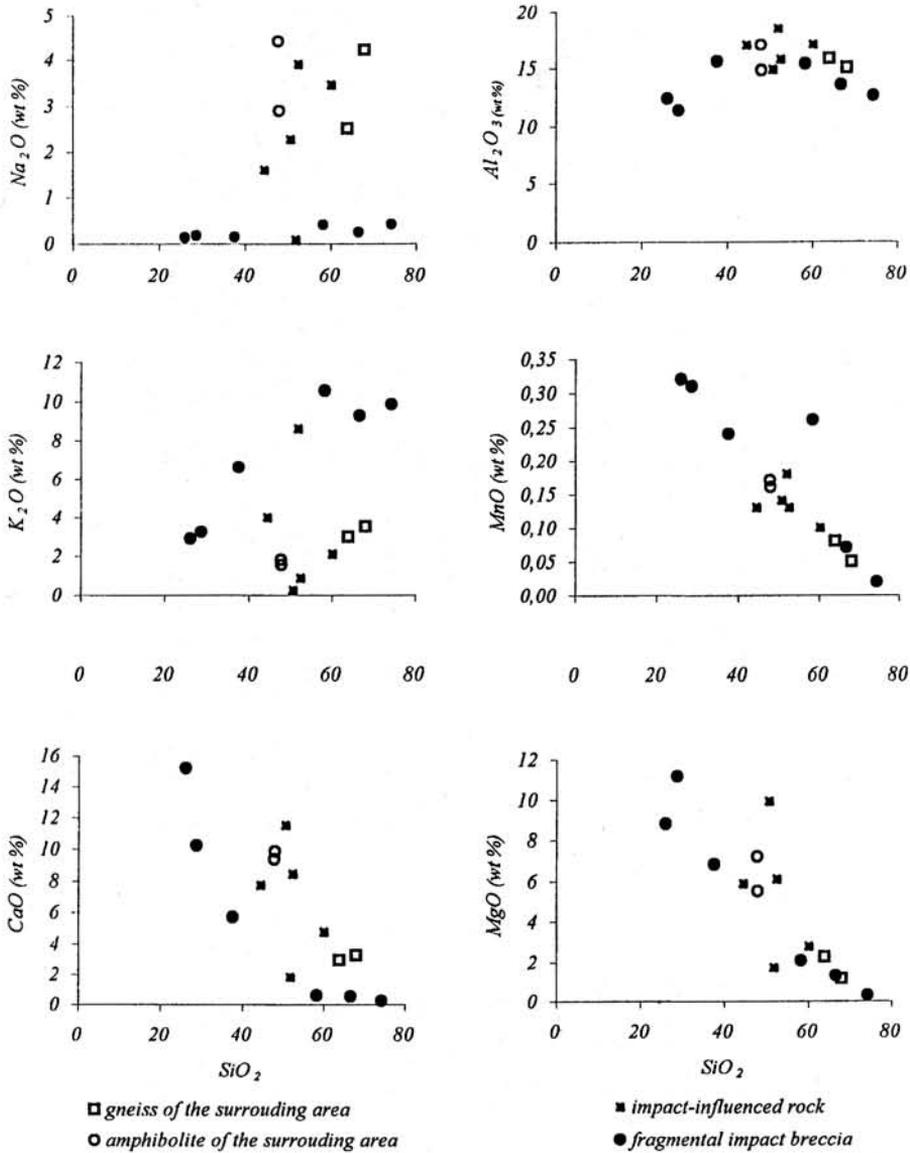
Fig. 14. Harker-diagrams of the variations of silica versus selected major element contents (wt %) in the Precambrian rocks and impact breccias of the Neugrund impact structure.

Table 1. Chemical composition (wt%) of Precambrian target rocks and impact breccias of the Neugrund area.

| | Surrounding area | | | | Crater area | | | | | | | | | | | |
| | gneisses | | Amphibolites | | Impact influenced target rocks | | | | | Matrix supported breccia | | | | | | Melt |
Sample nr.	331246	3342536	3342030	3342336	31	63	8285-2	8285-3	8229-28	18	17	8285-1	3-26	8285-4	8229-29	20
SiO_2	63,92	68,02	47,97	47,84	50,70	60,14	51,88	44,54	52,50	74,28	66,64	26,06	58,30	37,64	28,70	50,90
TiO_2	0,40	0,34	0,95	1,11	0,51	1,22	1,12	0,58	0,70	0,09	0,43	0,45	0,67	1,24	0,50	0,05
Al_2O_3	15,72	14,98	14,74	16,94	14,83	16,99	18,42	16,91	15,71	12,56	13,53	12,36	15,31	15,52	11,36	10,52
Fe_2O_3	5,00	2,05	6,46	5,16	1,90	2,76	-	-	-	1,23	3,68	-	7,33	-	-	-
FeO	1,36	2,01	7,76	6,75	4,89	3,45	-	-	-	<0,20	1,80	-	0,22	-	-	-
$Fe_2O_{3\ total}$	-	-	-	-	7,33	6,59	12,42	12,24	10,43	1,23	5,68	16,32	7,57	13,93	16,55	19,76
MnO	0,08	0,05	0,16	0,17	0,14	0,10	0,18	0,13	0,13	0,02	0,07	0,32	0,26	0,24	0,31	0,14
MgO	2,25	1,15	5,50	7,18	9,91	2,79	1,72	5,86	6,08	0,29	1,28	8,79	2,05	6,81	11,15	4,37
CaO	2,93	3,24	9,85	9,37	11,52	4,74	1,81	7,72	8,44	0,21	0,53	15,2	0,58	5,67	10,25	3,27
Na_2O	2,50	4,21	2,89	4,40	2,26	3,46	0,08	1,59	3,90	0,41	0,24	0,13	0,40	0,14	0,17	0,13
K_2O	3,00	3,53	1,56	1,81	0,26	2,10	8,60	4,00	0,88	9,84	9,26	2,88	10,52	6,59	3,25	1,57
P_2O_5	0,13	0,17	0,16	0,80	0,02	0,35	0,50	0,26	0,15	0,03	0,24	0,24	0,41	0,28	0,25	0,07
S	<0,10	0,05	0,36	0,19	<0,10	<0,10	<0,10	<0,10	0,08	0,10	<0,10	0,10	<0,10	0,10	0,04	0,10
CO_2	-	-	-	-	-	-	-	2,55	-	0,55	0,21	12,54	-	7,00	11,75	-
LOI	2,10	0,49	1,18	1,23	1,44	0,98	3,51	5,85	0,95	1,15	2,31	17,99	2,77	11,33	17,26	6,56
Total	99,39	100,29	99,54	99,95	99,02	99,56	100,34	99,78	100,06	100,22	100,22	100,84	98,95	99,50	99,79	97,44

Table 2. Characteristics of the Neugrund crater

Characteristics	Size
Pre-impact geological succession of the target:	
sea water	ca 50 m
Lower-Cambrian claystones, siltstones and sandstone's	40 m
Vendian sandstones	60 m
Sedimentary rocks cover in all	100 m
Precambrian crystalline basement metamorphic rocks	>3000 m
Lateral dimensions of the impact structure:	
Diameter (rim-to rim) of the crater	7 km
Diameter of the crater on the level of target surface	6 km
Diameter of the ring fault	20 km
Diameter of the area with impact-derived debris (ejecta) layer	>30 km
Diameter of the central uplift	ca 1 km
Diameter of the biggest ejected megablock	ca 500 m
Vertical dimensions:	
Depth of the crater proper below the target surface	>500 m?
Height of the eroded rim above the target surface	ca 120 m
Height of the central peak	ca 100 m?
Thickness of impact-related breccias:	
In the crater	>200 m
Outside the rim (ejecta)	0-100 m
Magnetic anomalies:	
Negative, correspondending to the crater proper	200 nT
Positive, over the crater rim	500 nT
Thickness of the post impact cover:	
Lower and Middle Ordovician limestone in the crater proper	24 m
Lover Ordovician and Lower Cambrian terrigenous rocks in the crater proper	>50 m
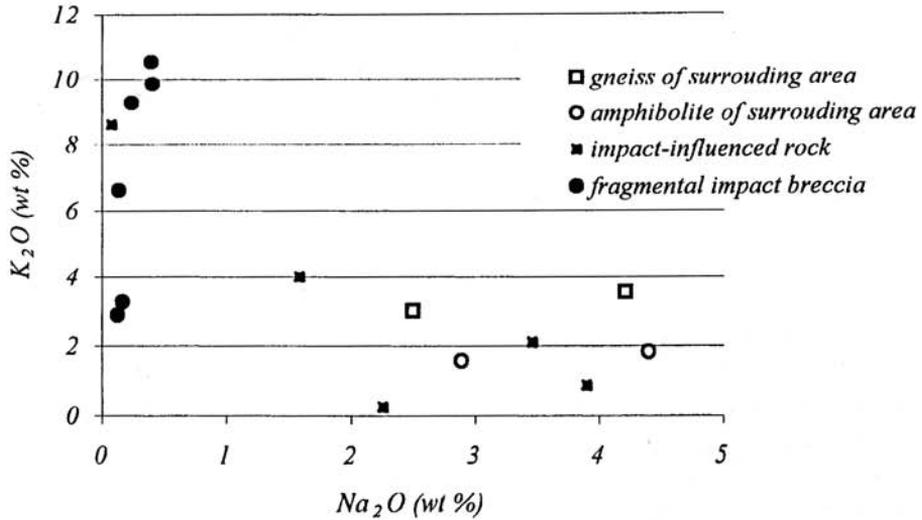
Fig. 15. Na_2O versus K_2O plot of the Precambrian target rocks and impact breccias of the Neugrund impact structure.

In addition to the structure, the major criterion for the recognition and confirmation of an impact structure is the occurrence of shock metamorphic effects (Stöffler 1972; Stöffler 1974; Stöffler and Langenhorst 1996; Grieve et al. 1996). The evidence of shock metamorphism in the impact-derived rocks of the Neugrund crater has been recognized in 20 thin sections of hand specimens collected from clast-supported impact breccias of the rim-wall ejected blocks and erratic boulders. Melt-supported impact breccias, (suevite), as well as massive bodies of clast-supported impact breccias have not been discovered in the Neugrund crater area, probably because the fill, where they possibly could occur, is buried under post-impact sedimentary rocks. All evidence of shock metamorphism is connected with impact breccias formed in metamorphic rocks of the crystalline basement. In the rocks of the Neugrund crater are four types of impact breccias can be distinguished:

1 . breccias forming clear-cut dike-like allochthonous bodies in crystalline basement rocks, with a mineralogical composition that differs from the surrounding (host) rocks. Evidence of low stages of shock metamorphism are common (Fig. 4)

2 .autochthonous breccias in crystalline basement rocks, mineralogical composition similar to host rocks (Fig. 4). The evidence of shock metamorphism is limited to 0 stage (Stöffler 1972).

3. Autochthonous breccias or brecciated rocks of crystalline basement (Fig. 5). The evidence of shock metamorphism absent;

4. Brecciated sedimentary rocks (clays, silt- and sandstones) are observed on in sections of the drill holes no. 331 and 410.

In general, the evidence of shock metamorphism in the Neugrund crater breccias are the following:

1. widespread fracturing of the target rocks (Fig. 5);
2. conical fracture surfaces (shatter cones);
3. mosaic extinction of quartz and feldspar (Fig. 13c);
4. planar fractures (PF) of quartz corresponding to planes (0001) and {1011};
5. rare and weakly developed planar deformation features (PDF) in quartz (Fig. 13a), 2 sets parallel to {1013} and (0001)
6. kink bands in biotite (Fig. 13b);
7. diaplectic glass by quartz and feldspar;
8. rare occurrence of glassy grains, partly recrystallized to chlorite (Fig. 13 d);
9. occurrence of thin (0.5–2 cm) pseudotachylitic veins of melt.

The small number of PDFs in the clast-supported impact breccias of the Neugrund crater can be explained by the limited exposures that are available for sampling and that microscopic investigation has been limited to impact breccias from the rim-wall and ejected blocks. As shown from experience with Kärdla impact crater (Puura and Suuroja 1992) PDFs in the impact breccias of this part of the crater are rare or absent.

As a result of the impact in the impact-derived crystalline basement target rocks of the Neugrund crater, unusual chemical alterations have taken place (Fig. 14; 15), greatly resembling the chemical alterations observed in the Kärdla impact crater (Puura and Suuroja 1992). The K_2O content of the crystalline basement target rocks (amphibolites, biotite gneisses, and migmatite granites) is 1.6–1.8 wt%; 3.0–3.5 wt% and 4–5 wt% respectively, but the impact breccias formed from them contain 8–10.5 wt% of K_2O (Table 1). At the same time, Na_2O content of the same rocks decreased from 3–4.5 wt%; 2.5–4.2 wt% and 2–2.5 wt% respectively to 0.1–0.4 wt% in clast supported impact breccias (Table 1). The decreased sodium content in these rocks can be explained by weathering and hydrothermal alteration of plagioclase during post-impact processes, which has been observed in thin sections. The reason of enrichment of the rocks with potassium and especially its source, however, is difficult to identify. In some cases the enrichment of impact breccias with potassium has been explained by forming new potassium-rich K-feldspars (orthoclase) on account of plagioclase (Puura et al. 1996).

Due to impact (or post-impact) processes the silica content of brecciated amphibolitic rocks has rapidly decreased (Fig. 7). The SiO_2 content of the

unaltered amphibolitic target rocks is 48–52 wt%, but the impact breccias formed from these rocks contain often only 26–28 wt% of SiO_2 (Table 1).

Summary and conclusions

The Neugrund impact crater was discovered began only three years ago in 1996. The present paper provides a preliminary review of these studies. The first samples from the crater structure, verifying the hypothesis of the impact structure locating under the Neugrund Bank and its surrounding area were obtained in 1998. In the course of marine investigations, we used the methods for investigating a submarine impact structure situated in a shallow sea. The continuous seismo-acoustic profiling record, gravimetric and magnetometric mapping, sidescan sonar profiling, as well as diving to study the submarine exposures, are the most suitable methods for investigating such structures. On Neugrund Bank, all the above-cited investigation methods, except gravimetric survey, were used. The data obtained have served as the basis for reconstruction of the morphology of the Neugrund structure. Its major parameters are presented in the tables and figures. The Neugrund impact crater has several common features with other Paleozoic impact structures discovered in Fennoscandia (French et al. 1997; Lindström et al. 1993; Sturkell 1988, Sturkell 1997, Henkel and Pesonen 1992).

In the Neugrund impact structure only the weakly eroded structural uplift of the rim-wall, some ejected megablocks, the upper part of the crater filling and the whole overlying complex are available for direct investigation. This means that although only a small part of the crater is visible, it still provides abundant information on the whole crater. One of the most clearly expressed structural elements of the Neugrund impact structure is the ring-fault with a zone of disturbed target rocks. In the northern part the ring-fault is expressed as up to 60 m high terrace in bedrocks, which is buried under Quaternary deposits. Between the rim-wall and ringfault, the sedimentary target rocks are strongly disturbed. At present, data about the extent of the disturbance down to the rocks of crystalline basement are missing.

The impact origin of the Neugrund structure may be considered verified. In the crater area shock metamorphic effects up to II shock stage or 40 GPa according to the scale of Stöffer and Langenhorst (1994) have been found. PDFs in quartz, the main indicator of an impact origin for crater-like structures, are, in the case of Neugrund, rarely observed. This may be explained by the fact that impact-related rocks, which are the primary hosts of these features (clast- and melt supported impact breccias), are located mainly inner the crater and are not accessible.

Autochthonous impact breccias of crater rim are in most cases low in PDFs (Puura and Suuroja 1992).The problem of the so-called potassium phenomena (elevated K contents and Lower Na contents in the impact breccias compared to in the target rocks), which is expressed in the Kärdla as well in the Neugrund case, stay still unsettled. This phenomena has been found in a variety of impact craters around the world (Ames – Koeberl et al. 1997; Boltysh – Gurov et al. 1986; Brent – Grieve 1978; Ilynets – Gurov et al. 1998; Kärdla – Puura and Suuroja 1992; Newport – Koeberl and Reimold 1995; Rotter Kamm – Reimold 1994 etc.). The mobilization of the alkali elements in a post-impact hydrothermal system (Koeberl et al. 1997) seems to be the most likely explanation for this phenomenon. But a direct connection with the age, composition of target, peculiarities of post-impact history, etc. of the impact crater, and the potassium phenomena has not yet been found. The potassium phenomena seems to be restricted to plagioclase-rich rocks (granitoids, gneisses, amphibolites) and is connected with decomposition of plagioclase and forming of new K-feldspar (Puura et al. 1996) or sericite.

Acknowledgements

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Geology and Magnetic Signatures of the Neugrund Impact Structure, Estonia

Sten Suuroja[1,2], Tarmo All[1,3], Jüri Plado[3,4], and Kalle Suuroja[1]

[1]Geological Survey of Estonia, 12618 Tallinn, Estonia. (s.suuroja@egk.ee; t.all@egk.ee)
[2]Institute of Mining, Tallinn Technical University, Estonia.
[3]Institute of Geology, University of Tartu, 51014 Tartu, Estonia.
[4]Geological Survey of Finland, FIN-02151 Espoo, Finland.

Abstract. The Early Cambrian Neugrund crater, Estonia, has a rim-to-rim diameter of 7 km. In addition to the structural elements common in impact structures (crater cavity, rim wall, crater filling, ring fault), there occurs a specific, up to 70 m deep and 200 - 500 m wide circular canyon between the rim wall and the crater. Theoretically, Neugrund should also have a central uplift, but there is neither geological nor geophysical evidence as yet. The seismic reflection data show that the disturbed strata around the structure are spatially delimited by the ring fault, which has a diameter of about 21 km. The ring fault is interpreted as the outer limit of the impact structure. The true depth of the crater, as well as the distribution of post-impact sediments and impactites within the crater, is still unknown. Magnetic modelling and comparison with other impact structures of the Fennoscandian shield (e.g., Kärdla, Lappajärvi, Lockne) suggest that the maximum depth of the interface between autochthonous and allochthonous breccias is approximately 700 m. A distinct, slightly elongated negative magnetic anomaly about 5 km in diameter marks the crater cavity. This magnetic low is caused mainly by weakly magnetic post-impact sedimentary infill and its screening effect, but possibly also by allochthonous breccias and post-impact oxidation processes. The absence of high-amplitude local anomalies within the minima suggests a lack of highly magnetic melt bodies. The magnetic data show no evidence of a central uplift.

1

Introduction

The Early Cambrian (~540 Ma; Suuroja and Suuroja 2000) Neugrund impact structure (59°20′N; 23°31′E) is located in the Gulf of Finland north-east of Osmussaar Island (see Abels et al., this volume; Fig. 1). The well-preserved
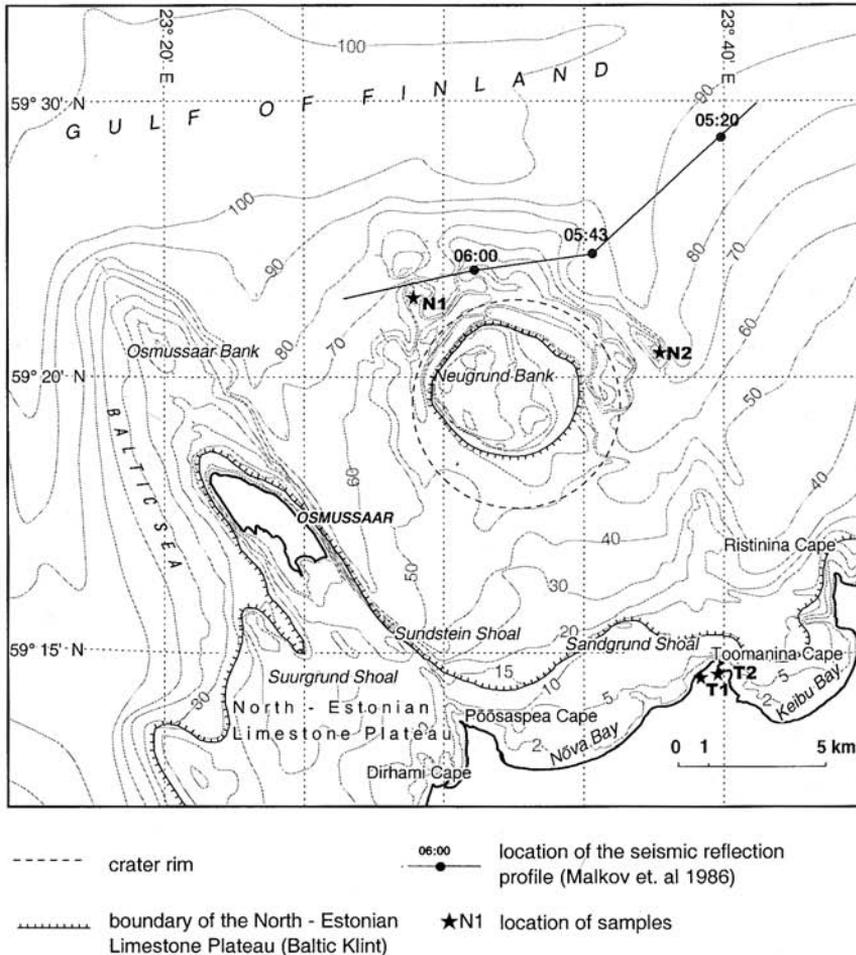
Fig. 1. Bathymetric map of the Neugrund structure area.

circular crater has a rim-to-rim diameter of 7 km and is surrounded by a 21-km-wide area of deformed sedimentary target rocks. The crater cavity is filled with post-impact Cambrian and Ordovician sedimentary rocks. The Ordovician layers consist of hard, erosion-resistant limestone, forming a nearly circular 4.5-km-wide central plateau inside the crater, the Neugrund Bank (Fig. 2). A 200 - 500 m wide and up to 70 m deep semicircular canyon surrounds the central plateau (Suuroja and Suuroja 2000) along the inner side of the crater wall.

The Neugrund impact structure was discovered in the course of integrated geological and geophysical mapping at the NW of Estonia. The first medium-scale geological mapping of the mainland was carried out in 1965 - 1969 (Kala and Eltermann 1969). Deformations in the Vendian and Early Cambrian terrigenous

rocks of a drill core from Osmussaar Island (Fig. 2a) were investigated. The geological mapping of the basement of the onshore area was conducted in 1984 - 1987 (Suuroja et al. 1987). An about 20 m thick layer of brecciated sedimentary rocks was discovered at the top of the Lontova Formation (Early Cambrian) in one core (F-331; Figs. 2a and 3). Simultaneously, marine geological mapping of the
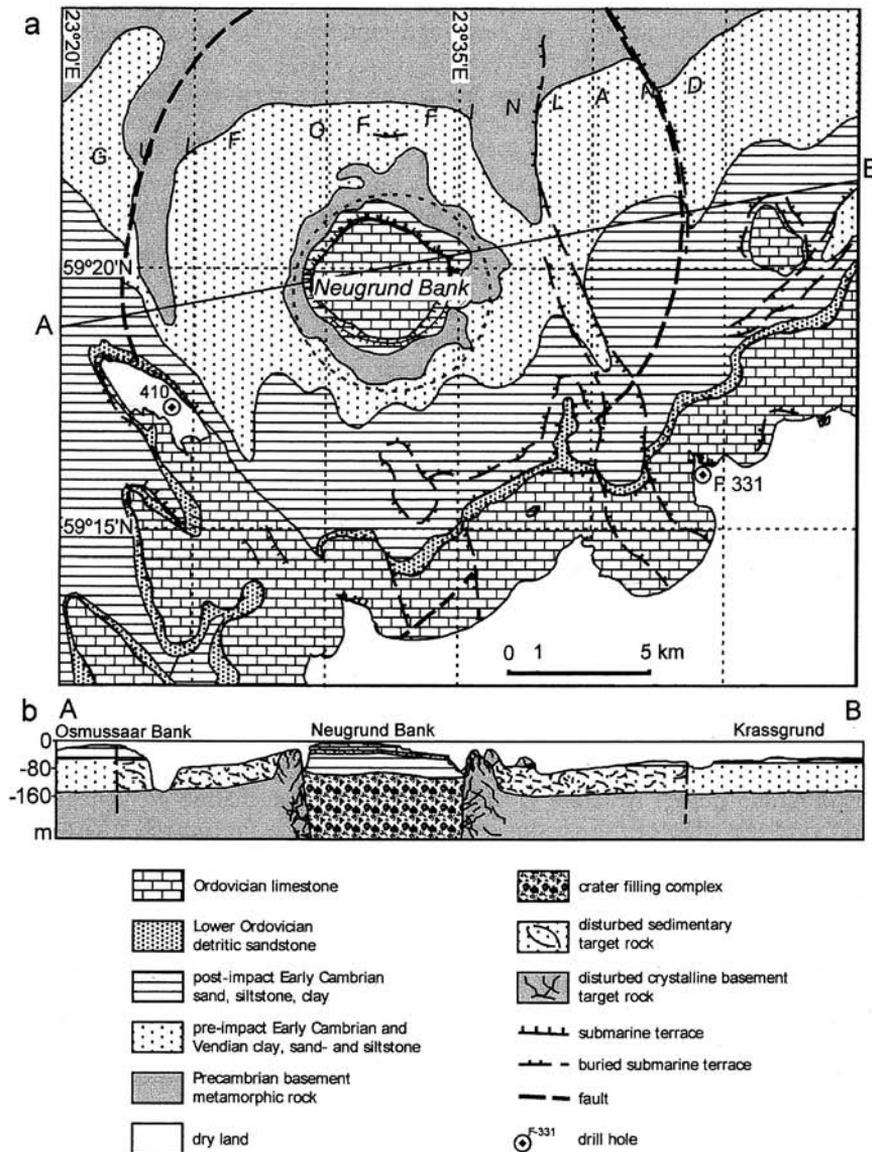
Fig. 2. (a) Generalised bedrock map and (b) cross-section of the Neugrund structure area.

offshore area was carried out (Malkov et al. 1986). An east–west seismic profile north of the Neugrund Bank (Figs. 1 and 4) revealed small hills and short ridges, which were first interpreted as being of glacial origin (moraine walls). During subsequent marine geological mapping across the Neugrund structure, seismoacoustic reflection recording was performed along five N - S profiles and bottom sediments were sampled with a cavity-corer (Talpas et al. 1993). A comprehensive geological study of the Estonian shelf (Lutt and Raukas 1993) gave only slight indication of the Neugrund structure. The interpretations once again relied on the glacial theory.

In the years 1994 - 1995 numerous brecciated erratic boulders were discovered in the course of large-scale (1 : 50 000) geological mapping of the onshore area (including the islands) (Suuroja et al. 1998). Suuroja and Saadre (1995) suggested that these boulders might be associated with an impact structure. This idea prompted seismic reflection and marine magnetic study of the Neugrund Bank and its nearest surroundings in 1996 (Suuroja et al. 1999b). Aeromagnetic mapping of this area had been carried out already earlier (Metlitckaya and Papko 1992), but no traces of the Neugrund impact structure had been recognised. In the course of subsequent marine geological research (Suuroja et al. 1999a), the impact structure was investigated by diving, side-scan sonar and submarine sampling. The discovery of shock metamorphosed rocks provided direct evidence for the hypotheses derived from remote sensing data, and confirmed the impact origin of the Neugrund structure (Suuroja and Suuroja 2000).

The aim of the present paper is to analyse the geological and geophysical characteristics of the Neugrund structure. The physical properties of impact-influenced rocks of the structure and erratic boulders are discussed and a magnetic model composed to describe the subsurface structure of the Neugrund crater.

2
Bedrock Geology

The Neugrund impact structure is well expressed on the marine geological map (Fig. 2a) at the edge of the erosional boundary with the Precambrian basement. The North-Estonian Limestone Plateau, consisting of post-impact Ordovician limestones, is located to the south of the structure. The shallow northern edge of the plateau is partially submerged. The plateau borders on a well-jointed escarpment - the Ordovician cliff of the Baltic Klint (Fig. 1). The submarine cliff is well traceable, as Quaternary deposits only rarely cover it. The isolated and circular submerged cliff-island, about 4.5 km in diameter, the so-called Neugrund Bank, constitutes the central sedimentary infill of the Neugrund crater.

In the northern part of the area, above the rim wall and in the bottoms of buried valleys west and north-east of the structure, the crystalline basement crops out. It is composed of Precambrian (Paleoproterozoic) metamorphic rocks formed by the Svecofennian Orogeny. The data obtained from drill holes (Fig. 2a), five submarine outcrops, and more than 350 erratic boulders derived from the
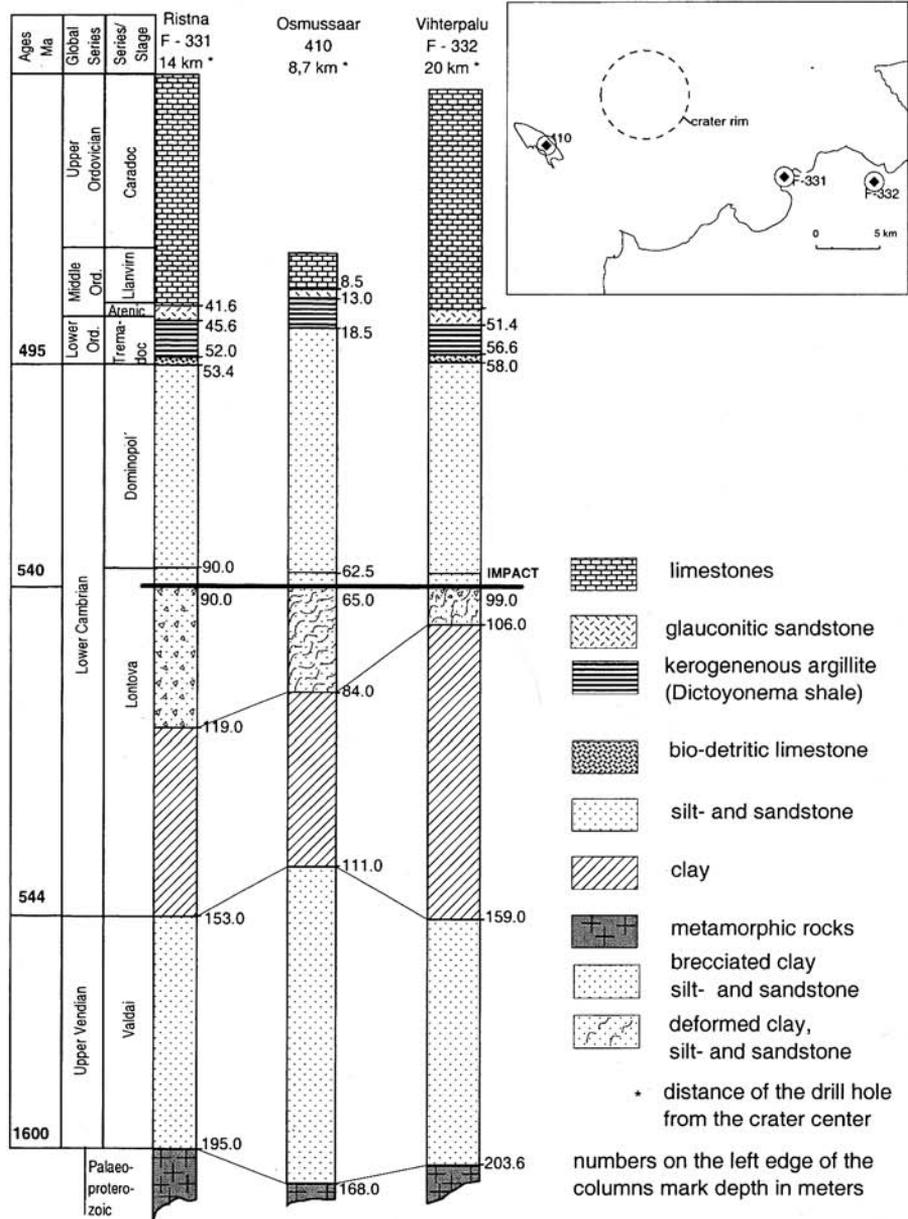
Fig. 3. Stratigraphic columns of the drill cores outside the area of Neugrund structure.

Neugrund impact structure, show that the crystalline basement consists of migmatized gneisses (54 %) and amphibolites (46 %). Brecciated crystalline basement rocks crop out around the Neugrund Bank, on the crater rim wall. Small

outcrops of crystalline basement rocks behind the rim consist in large (up to several hundred metres in diameter) blocks ejected from the crater (Suuroja and Suuroja 2000). The Neugrund crater is filled (from base to top) with: (i) impact deposits of unknown thickness; (ii) post-impact Early Cambrian silt- and sandstones with a thickness of over 40 m; (iii) Ordovician sandstone, shale, and limestone of more than 40 m thickness (Fig. 2).

The ring fault (Fig. 2) is expressed in the bedrock relief by a 10 - 80 m high escarpment. Inside the ring fault the sedimentary cover and the crystalline basement are strongly deformed, but almost intact outside (see Fig. 7b in Suuroja and Suuroja 2000).

3
Quaternary Deposits

A map of Quaternary deposits (Fig. 4a) was compiled through integrated geological mapping of the on- and offshore areas of NW Estonia and combining the results with the bedrock map (Kala and Eltermann 1969; Malkov et al. 1986; Talpas et al. 1993; Suuroja et al. 1998; Suuroja et al. 1999b). The distribution of the Quaternary deposits is clearly influenced by the pre-Quaternary bedrock relief, which reflects the structures of the partially exposed Neugrund impact crater.

The Quaternary deposits of the impact structure area can be roughly divided into the ones distributed to the north or to the south of the submerged Baltic Klint (Figs. 1 and 4). In the areas southward of the Baltic Klint (on the North Estonian Limestone Plateau), where the water depth is less than 15 m, the thickness of the Quaternary deposits is minor (0 - 2 m). The coastal deposits (sand, gravel, pebbles) of the present Baltic Sea (Limnea Sea) are widespread in submerged areas with a very thin (less than 0.5 m) Quaternary cover.

In the northern part of the area, where the water depth generally exceeds 15 m, the sea floor is covered with 1 - 10 m of mud deposited during the post-glacial Limnea Sea stage. Upper Pleistocene, glaciolacustrine varved clays of the Baltic Ice Lake crop out around the rim wall, in especially great thickness of 30 - 60 m in the circular canyon.

Nowadays, the Neugrund Bank appears as an erosional area, partly covered with coarse-grained sediments (cobbles, pebbles, coarse-grained sand). Mud is deposited in most regions with water depths greater than 50 m. The coastal area is mostly non-depositional or erosional, except the areas of clastic sedimentation. However, the sedimentation north of the Neugrund Bank is minimal due to strong seawater currents (Suuroja et al. 1999a).
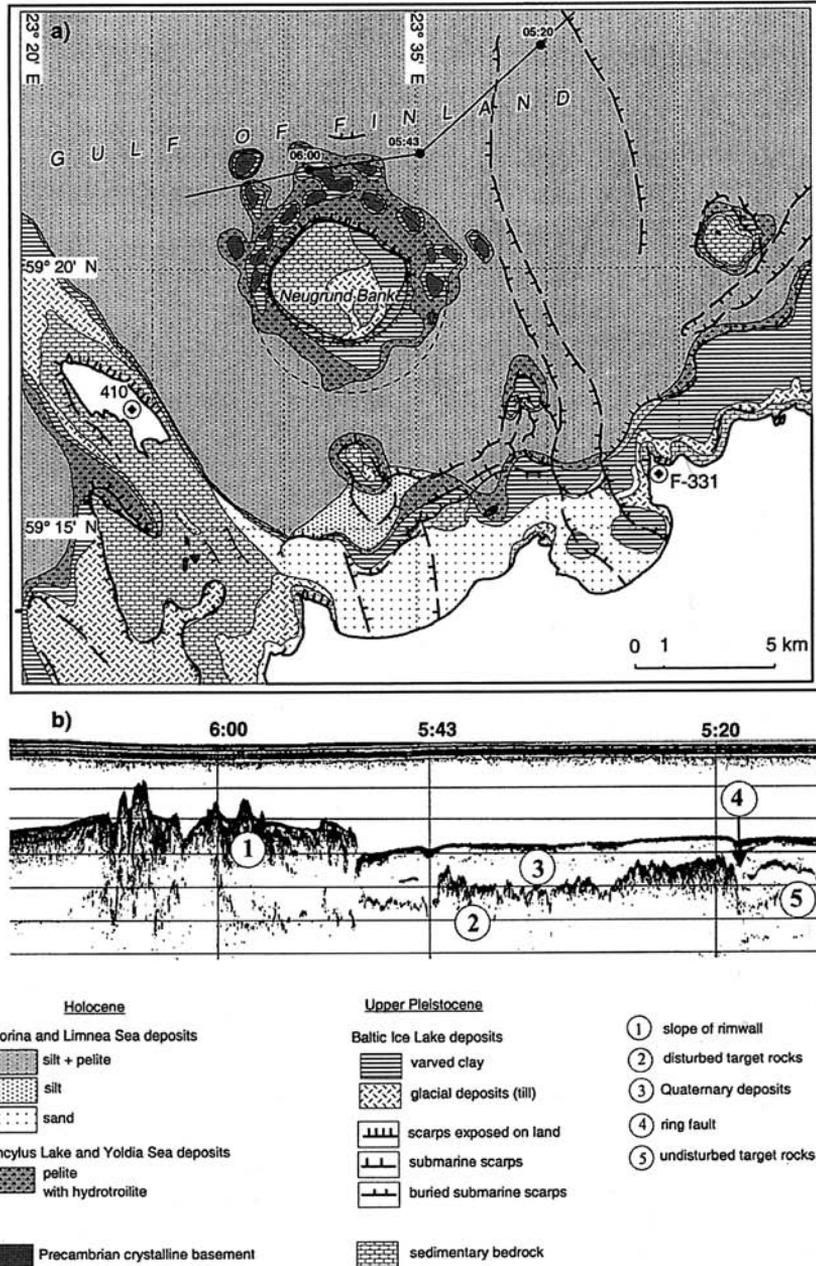
Fig. 4. (a) Quaternary deposits map of the Neugrund area and (b) seismic reflection record across the northern part of the structure. Recording frequency was 0 - 425 Hz; distance between horizontal lines is about 32 m in water (modified after Malkov et al. 1986).

4
Geophysical Signatures

The subsurface of the Neugrund structure has been investigated by seismic and magnetic methods, the morphometry and volume of the crater cavity by magnetic modelling. The latter was supported by petrophysical data of samples collected from the crater rim and erratic boulders derived from it.

4.1
Marine Seismic Investigations

Malkov et al. (1986) recorded the first seismic signatures of the Neugrund structure during a reflection survey of the Estonian side of the Gulf of Finland. One east–west profile studied by them a few kilometres north of the Neugrund Bank is presented in this paper (Figs. 1 and 4b). The profile revealed a rugged morphology directly north of the Neugrund Bank, the sedimentary cover to the north-west, and the Quaternary deposit on an eroded Precambrian surface to the north-east (Fig. 4). The earlier, seismic surveys, carried out in the Baltic Sea (Flodén 1981), revealed the block and fault structure of the Svecofennian basement (Flodén 1980). Malkov et al (1986) interpreted the above-mentioned rugged morphology as small hills and short ridges of glacial origin. The fault observed north-east of time mark 05:20, as all the other faults, were interpreted as the regular block and fault structure of the basement. However, we interpreted these hills and ridges to constitute the outer slope of crater rim. The correlation of fault structures fixed in the others seismograms by Malkov et al. (1986) and by Talpas et al. (1993) suggests the occurrence of a ring fault, 21 km in diameter (Suuroja 1996; Suuroja et al. 1997). The impact origin of the Neugrund crater largely facilitates the interpretation of the structural elements in the seismograms.

A group of researchers from Stockholm University and the Geological Survey of Estonia headed by Tom Flodén performed a geophysical survey of the area in 1996. The new seismic and magnetic data allowed them to refine the outline of the crater and the structural patterns beyond the crater rim (Suuroja and Suuroja 1999b, 2000).

4.2
Magnetic Studies

The Geological Survey of Byelorussia conducted an aeromagnetic survey of northern and western Estonia and the surrounding shelf in 1988 - 1992 (Metlitckaya and Papko 1992), with the aim of outlining the general structural and tectonic pattern of the Precambrian basement. The terrain clearance of the survey was 300 m on the sea. The east-west profiles proceeded at 0.5 km intervals. Total field readings were taken approximately every 50 m. The accuracy of the survey was ± 3 nT.

The magnetic data of the Neugrund crater and its surroundings were analysed. The aeromagnetic map (Fig. 5) shows that the regional magnetic field around the
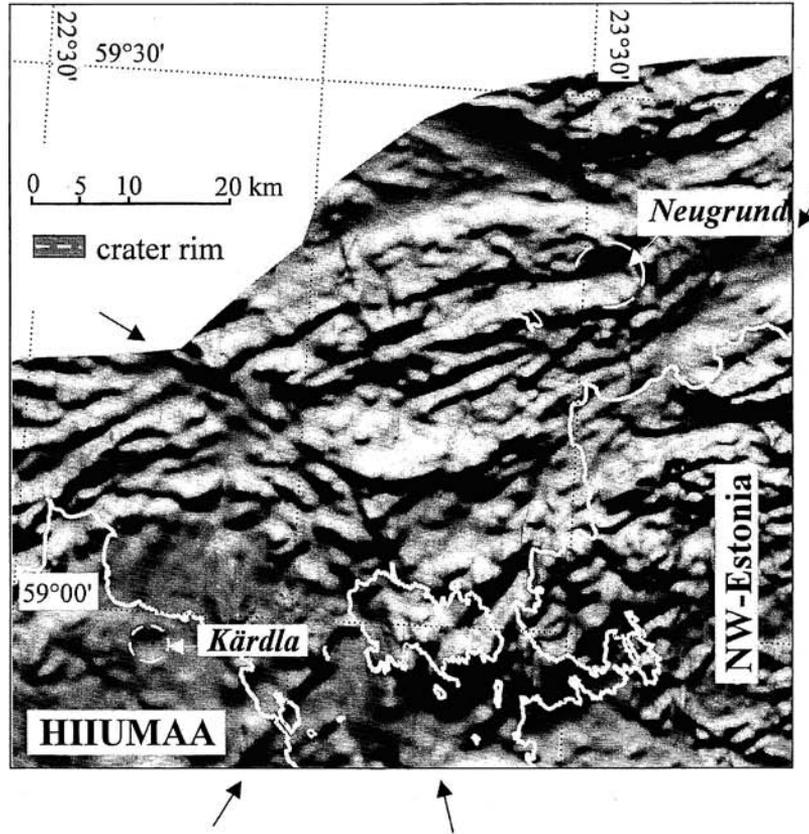
Fig. 5. Shaded relief map of aeromagnetic anomalies of NW Estonia, illuminated from north-west. Arrows indicate linear magnetic anomaly belts due to regional shear zones.

Neugrund impact structure has a complicated pattern due to variable magnetic properties of the Svecofennian metamorphic belt (Puura and Vaher 1983; Koistinen et al. 1996; Korhonen et al. 1999). The regional north-east and north-west trending faults and shear zones (Koistinen et al. 1996; Koppelmaa and Kivisilla 2000) are revealed as distinct linear magnetic anomaly belts (Fig. 5). The structure is located over a positive NEE-trending linear magnetic anomaly, but not influenced by regional shear zones. The central part is superposed on the western limit of magnetic minimum. The map of aeromagnetic anomalies (Fig. 6) demonstrates the presence of an arc of positive anomalies (up to 400 nT), which corresponds to the northern, eastern and south-eastern parts of the crater rim. The amplitudes of the anomalies are equal to those in the surroundings. Therefore, the impact-related anomalies are fairly similar to the regional field, and were not recognized as caused by an impact event in the early 1990s. However, the rim wall of the Neugrund structure produces a local bow-shaped positive anomaly pattern bordering the minimum related to the crater cavity in the east. This anomaly
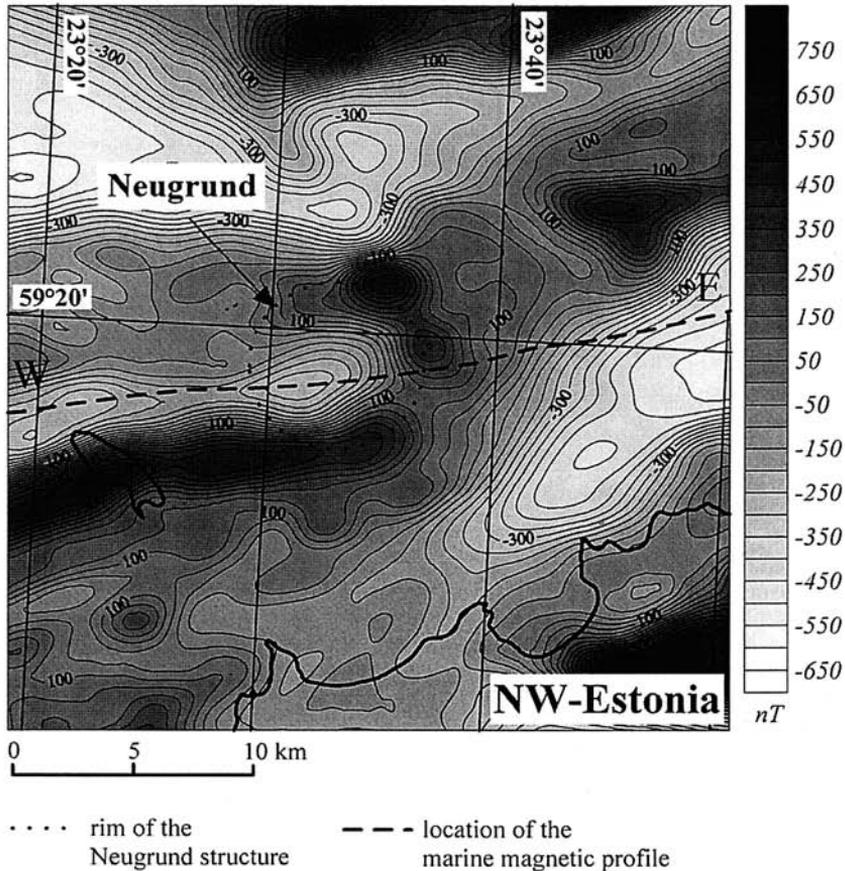
Fig. 6. Aeromagnetic anomalies map of the Neugrund structure area.

pattern can be followed mainly as a secondary structure within the prevailing linear anomaly pattern typical of the surrounding metamorphic Svecofennian rocks (Suuroja et al. 1987). Figure 5 shows the existence of a similar, but weakly expressed, anomaly pattern to the west of the structure. Altogether, these positive features form a circular anomaly pattern around the magnetic minimum.

To interpret the magnetic anomalies the forward modelling technique was used, where we calculated a magnetic response curve along the west-east magnetic profile (Fig. 6). The data were obtained during the marine study in 1996 and are first published in the present paper. By changing the shapes of polygonal prisms (for impact breccias and crater fill) and polygons (for regional bodies), we tried to match the model curve to fit the observed data by trial-and-error techniques.

For modelling the structure, we made the following assumptions, based on results of seismic and geological mappings: (i) the pre-impact deposits and the lowermost part of post-impact deposits in the surrounding area are preserved; (ii)

impactites within the crater proper are preserved; (iii) the post-impact Cambrian and Ordovician rocks fill the crater cavity and (iv) the crest of the rim is partly exposed on the sea floor.

To remove the long-wavelength magnetic anomalies responding to deeper sources and unrelated to the subsurface impact structure, the data were filtered with a low-pass filter with a radius of 8 km. This transformation provided a residual magnetic anomaly curve describing the anomalies produced by the near-surface sources. For the modelling, physical properties of the impact-influenced crystalline rocks (Table 1) and data from the basement of western Estonia (Table 2; Puura and Vaher 1983) were used. The petrophysical measurements were performed at the Geological Survey of Finland with instruments and techniques described in Puranen and Sulkanen (1985). Due to the absence of oriented samples no orientation of the natural remanent magnetisation (NRM) was obtained. Declination of 326° and inclination of 60° were used to specify the direction of remanence in the target units of the magnetic model. This direction corresponds to the Early Svecofennian (1.88 Ga; Pesonen et al. 1989), i.e., to the age of the crust in this particular area. The rocks from the rim wall show relatively low susceptibilities (Table 1), probably due to weathering and increased oxidation along impact-produced fractures. Also, the NRM intensity yields Koenigsberger ratios generally below 2. However, according to Puranen (1989), the mean magnetic susceptibility of the Svecofennian metavolcanic belt in SE Finland is higher ($8,450 \times 10^{-6}$ SI). The same is valid for the crystalline rocks in western

Table 1. Physical properties of the crystalline rocks from the Neugrund impact structure and surroundings

Sample	Rock type	Loc.	ρ_w (kgm^{-3})	Φ (%)	χ (10^{-6} SI)	NRM (mAm^{-1})	Q
10a	Amphibolite	N1	2729	7.4	760	25	0.9
13	Amphibolite	N1	3199	0.6	12180	310	0.6
63	Brecciated amphibolite	N2	2773	0.4	740	210	7.1
66	Brecciated amphibolite	N1	2631	4.8	3290	50	0.3
10b	Migmatite granite	N1	2644	2.0	230	20	1.8
26	Migmatite	N1	2463	4.5	250	20	1.5
18	Brecciated granitoid	N1	2498	3.5	1180	15	0.4
19	Weathered biotite-gneiss	N1	2605	3.4	305	25	2.0
23	Biotite gneiss	N1	2649	3.4	520	110	5.1
3-21	Biotite gneiss	N1	2644	6.5	700	50	1.7
47	Biotite gneiss	N1	2625	1.9	250	10	1.3
T-5	Brecciated amphibolite	T1	2661	7.0	740	10	0.3
7	Brecciated amphibolite with veins of calcite	T2	2706	7.9	790	10	0.3

Loc., Location (see Fig. 1); ρ_w, density of water-saturated samples; Φ, porosity; χ, magnetic susceptibility; *NRM*, intensity of natural remanent magnetization; *Q*, Koenigsberger ratio

Table 2. Physical properties of the unshocked target rocks in western Estonia (data from Puura and Vaher 1983).

Petrology	ρ_w (kgm^{-3})	χ (mean) (10^{-6} SI)	χ (range) (10^{-6} SI)	Q
Migmatized metamorphic rocks	2760	3775	10-111,500	1.13
Metamorphic rocks	2800	4875	10-67,500	1.23
Amphibolite	2850	4000	10-62,800	1.32
Biotite-gneiss	2630	9100	65-67,500	0.8

ρ_w, density of water-saturated samples; χ, magnetic susceptibility; Q, Koenigsberger ratio

Estonia (Table 2), but the maximum values recorded there reach $110,000 \times 10^{-6}$ SI (Puura and Vaher 1983). Therefore, to model the short-wavelength anomalies surrounding the Neugrund structure, we used susceptibility values between $10,000 \times 10^{-6}$ and $90,000 \times 10^{-6}$ SI. According to the results of petrophysical measurements of different rock types in the Neugrund structure area (Table 1), the Q-value was set to 1.5. Also the density and porosity of impact-influenced rocks were measured, but no specific trends due to the impact were recorded. The porosity seemed to be slightly higher in intensively brecciated rocks (Table 1), but the weathering could also be the cause of this effect.

We assumed that the impact did not alter the magnetic properties of target rocks beyond the crater rim. The main source of the magnetic minimum is located inside the crater due to practically nonmagnetic sedimentary rocks and weakly magnetic allochthonous impact breccias. The model following these assumptions depicts a 700-m-deep crater cavity, filled with sedimentary rocks down to the 270 m depth, and, from 270 to 700 m, with breccias (Fig. 7). To ensure a better fit of the observed and calculated curves it was necessary to add some highly magnetic blocks simulating the variation in magnetic properties of the metamorphic belt outside the crater area. The relative elevation of the magnetic field in the central part of the crater, as well as the sharp narrow positive peaks (up to 150 nT) on both sides of the crater, reflect the geometry of the structure. In the case of the homogeneous surrounding, the raised walls will produce a 3-km-wide positive anomaly with amplitude of up to 40 nT (Fig. 7a). However, in the real field (Fig. 7b) this anomaly can be recognised only in the western part of the crater. On the eastern side anomalies from highly magnetic target rocks overprint the rim anomaly.

The central uplift of the Neugrund structure is not evident in the magnetic field. However, we added this feature into the model according to the size criteria for terrestrial impact structures (e.g., Grieve and Pesonen 1996). The diameter of the central uplift (1.5 km) was estimated from the equation of Pike (1985). The Söderfjärden impact structure, western Finland, similar to Neugrund in age and diameter (see Abels et al., this volume), reveals a 287-m-high central uplift with a diameter of ~1.2 km. (Abels et al. 1998). Based on these, and data of few other similar-sized structures (Crooked Creek, Ragozinka, Serpent Mound), we assume
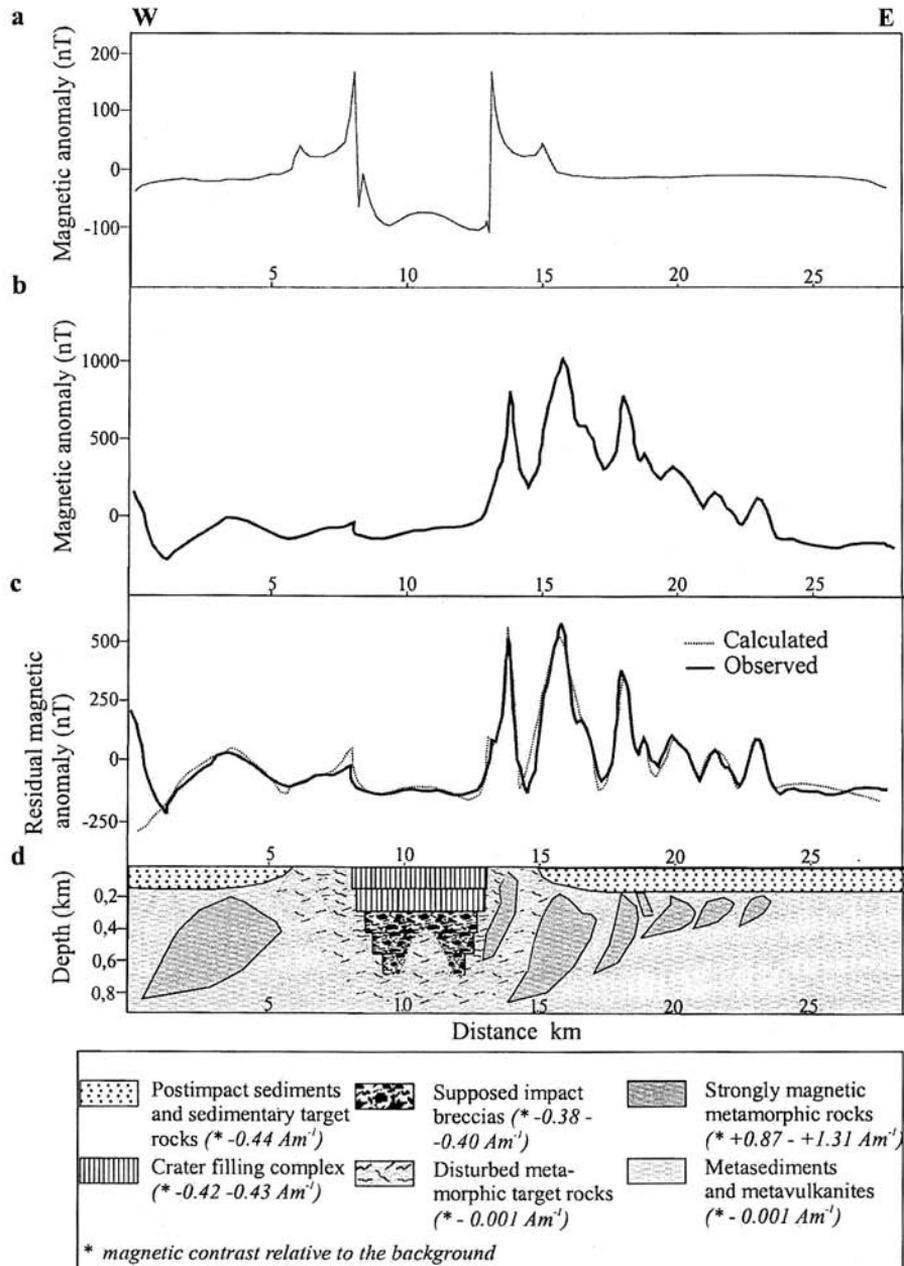
Fig. 7. Magnetic model of the Neugrund structure; (a) theoretical effect of the weakly magnetic complex of crater filling rocks and rim wall. Homogeneous background producing the level field of 0 nT; (b) observed magnetic anomaly curve (marine survey); (c) residual anomaly, and (d) calculated magnetic effect of model.

that the uplift in Neugrund is ~300 m high. This value was used in the model (Fig. 7d) as well.

5
Discussion and Conclusions

The Neugrund structure formed during Early Cambrian Lontova times of ~540 Ma (Suuroja and Suuroja 2000; Torsvik et al. 1992), in a shallow epicontinental sea as a result of the impact of an extraterrestrial body of about 400 m in diameter and possibly of iron meteorite composition (Suuroja and Suuroja 2000). The true depth of the structure, and composition of the lowermost part of crater fill, are unknown. After the impact the crater was submerged, filled with siliciclastic deposits, and buried. The structure remained buried until the Paleo- or Neogene, when it was partially exposed by water and glacier erosion.

The geological maps reveal the outlines of structural elements (crater, rim wall, ejected blocks, ring fault) of this partially buried structure. On the bedrock geological map (Fig. 2) the structure is expressed as an extraordinary circular pattern of outcrops. Deformed and uplifted crystalline basement rocks represent the rim wall. A circular plateau of the Ordovician limestones, the Neugrund Bank, overlies the crater. Small hillock-like outcrops of the crystalline basement rocks on the sea floor around the crater rim, some hundred metres in diameter, probably represent ejected megablocks. The tens of metres high escarpments in the target rocks follow the ring fault. The boundary of the North Estonian Limestone Plateau follows the southern part of the ring fault to a certain extent.

The Quaternary deposits (Fig. 4a) above the rim wall and crater proper are largely eroded. About 10 - 40 m of glaciolacustrine (varved) clays fill the 200 - 400 m wide and up to 80 - 100 m deep circular canyon between the Neugrund Bank and the crystalline rim wall. The canyon is of erosional origin and formed during pre-Quaternary times. The deeper (over 50 m) sea floor around the crater is covered with mud of the present Baltic Sea (Limnea Sea).

Magnetic lows can be often seen in impact structures, like the Lake Saint Martin crater (Grieve and Pesonen 1992), the complex Lake Lappajärvi crater (Elo et al. 1992), Kärdla and Tvären, which are very similar to Neugrund in other aspects as well (Puura and Suuroja 1992; Ormö and Blomqvist 1996), Lockne (Sturkell and Ormö 1997), Mien (Henkel 1983), Söderfjärden (Abels et al. 1998), and Dellen (Henkel 1992). The magnetic minimum is, however, most obvious where the structure is developed in highly magnetic crystalline bedrock.

The Kärdla impact crater (4 km in diameter), partly exposed in Precambrian target rocks, is located ~60 km to the south-west from Neugrund, in northern Hiiumaa, and has a distinct circular aeromagnetic minimum (Fig. 5) of -150 nT. Inland magnetic measurements have revealed a circular minimum with an amplitude of −200 nT, surrounded by a narrow maximum with an amplitude of +100 nT (Suuroja et al. 1974). Models by Plado et al. (1996) show that the magnetic contrast between the non- or weakly magnetic crater fill and unshocked

target rocks plays a leading role in producing the magnetic low. The rim wall, where the Precambrian crystalline basement is uplifted up to 200 m above its regional level, is the cause of the circular pattern of the positive anomalies. We can see almost analogous effects in the potential fields of the Neugrund and Kärdla structures due to the comparable sizes, more or less similar impact conditions and target lithologies. Here the magnetic modelling suggests an approximate crater depth of 700 m. The negative magnetic anomaly is mostly due to weakly magnetic crater fill. The post-impact oxidation of magnetite to hematite (Henkel 1992) in parautochthonous breccias could also contribute to this minimum.

The central area of the magnetic low of larger craters often contains high-amplitude, short-wavelength anomalies. These are suggested (e.g., Pilkington and Grieve 1992) them to be caused by near-surface impact-melt bodies with strong remanence, and by bodies of unaltered magnetic target rocks within the brecciated region. Most of the marine-targeted Fennoscandian impact structures do not consist of coherent impact melt bodies; in agreement with study by Kieffer and Simonds (1980). Lack of short-wavelength high-amplitude magnetic anomalies observed in several melt bearing structures (e.g., Dellen, Henkel 1992; Söderfjärden, Abels et al. 1998), suggests that Neugrund does not host any coherent highly magnetic melt body. However, if any melt is present, it does not cause specific anomalies due to low magnetisation, as observed, e.g., in Lappajärvi (Elo et al. 1992).

Many terrestrial impact craters show a decrease in density of impact-related rocks relative to the target (e.g., Lappajärvi, Elo et al. 1992; Clearwater West, Plante et al. 1990). The density of Neugrund rocks is variable, but shows also a decrease with respect to the target rocks (see Table 1). However, there should exist a significant gravity contrast between the metamorphic rocks and the infill of structure (e.g., Plado et al. 1996). Thus, a composite geophysical model basing on the gravity and magnetic data should prove more realistic. Unfortunately no gravity data for the Neugrund area are currently available. According to the estimates of Pilkington and Grieve (1992), one can be expect a Bouguer anomaly of 6 - 7 mGal.

The Neugrund impact structure was discovered during integrated geological mapping. Despite the structure's age, most of the morphological elements are well preserved. The structure is easily recognisable on geological and geophysical maps.

Acknowledgements

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III

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Hornblende alteration and fluid inclusions in Kärdla impact crater, Estonia: Evidence for impact-induced hydrothermal activity

KALLE KIRSIMÄE[1,2]*, STEN SUUROJA[3], JUHO KIRS[1], AULIS KÄRKI[4], MAILE POLIKARPUS[1], VÄINO PUURA[1] AND KALLE SUUROJA[3]

[1]Institute of Geology, University of Tartu, Vanemuise 46, 51014 Tartu, Estonia
[2]Institute of Geography, University of Tartu, Vanemuise 46, 51014 Tartu, Estonia
[3]Geological Survey of Estonia, Kadaka tee 80/82, 12618 Tallinn, Estonia
[4]Department of Geosciences, University of Oulu, P.O. Box 333, FIN-90571 Oulu, Finland
*Correspondence author's e-mail address: arps@ut.ee

Abstract–The well-preserved Kärdla impact crater, on Hiiumaa Island, Estonia, is a 4 km diameter structure formed in a shallow Ordovician sea ~455 Ma ago into a target composed of thin (~150 m) unconsolidated sedimentary layer above a crystalline basement composed of migmatite granites, amphibolites and gneisses. The fractured and crushed amphibolites in the crater area are strongly altered and replaced with secondary chloritic minerals. The most intensive chloritization is found in permeable breccias and heavily shattered basement around and above the central uplift. Alteration is believed to have resulted from convective flow of hydrothermal fluids through the central areas of the crater. Chloritic mineral associations suggest formation temperatures of 100–300 °C, in agreement with the most frequent quartz fluid inclusion homogenization temperatures of 150–300 °C in allochthonous breccia. The rather low salinity of fluids in Kärdla crater (<13 wt% NaCl$_{eq}$) suggests that the hydrothermal system was recharged either by infiltration of meteoric waters from the crater rim walls raised above sea level after the impact, or by invasion of sea water through the disturbed sedimentary cover and fractured crystalline basement. The well-developed hydrothermal system in Kärdla crater shows that the thermal history of the shock-heated and uplifted rocks in the central crater area, rather than cooling of impact melt or suevite sheets, controlled the distribution and intensity of the impact-induced hydrothermal processes.

INTRODUCTION

Most impact cratering studies have focused on the processes of crater formation; consequently, far less is known about the post-impact crater evolution. Post-impact hydrothermal alteration of crater rocks is a common impact-related phenomenon, which can provide insight into crater formation and development. Formation of hydrothermal systems in impact craters results from the large amount of kinetic energy released to the target. Propagation of supersonic shock wave into the target and projectile causes extraordinarily high pressures and temperatures reaching, respectively, >100 GPa and >3000 °C in large-scale impacts (Melosh, 1989). Adiabatic decompression of projectile and target rocks compressed above ~45 GPa during shock wave passage may lead to their melting and vaporization (Stöffler, 1972). Strong differential temperatures in the crater basement due to the post-shock residual heat remaining in rocks after decompression creates a hydrothermal circulation system if water is present at the crater

site or it can be also fed by fluids formed during degassing of impact melt in large craters such as Ries (Newsom *et al.*, 1986).

Impact-induced hydrothermal activity, although poorly studied, is known in many terrestrial craters (*e.g.*, Allen *et al.*, 1982; Newsom *et al.*, 1986; Komor *et al.*, 1988; Koeberl *et al.*, 1989; Masaitis and Naumov, 1993; Boer *et al.*, 1996; McCarville and Crossey, 1996; Sturkell *et al.*, 1998; Naumov, 1999; Gibson and Reimold, 2000) and implied for extraterrestrial craters as well (Allen *et al.*, 1982; Newsom *et al.*, 1996). Except for the Lockne (Sturkell *et al.*, 1998) and Roter Kamm craters (Koeberl *et al.*, 1989; Reimold *et al.*, 1997), impact-induced hydrothermal activity is accompanied by a cooling of the impact melt bodies or suevites. Signs for an occurrence of an impact melt sheet and/or suevite have not been found in the Kärdla. Moreover, the coptogenic fragmental breccias that constitute the crater filling allochthonous deposits contain <1 vol% melted material (Puura *et al.*, 2000). We present data on the alteration of hornblende in amphibolitic target rocks and of secondary fluid inclusions in impact

breccias, both of which indicate a short-lived, yet well-developed, hydrothermal system formed in the brecciated and heated crater basement after impact.

LOCATION AND GEOLOGICAL SETTING

The Kärdla impact crater is located on the island of Hiiumaa, 25 km off the northwestern coast of Estonia. The crater is 4 km in diameter and ~540 m deep with a central uplift exceeding 100 m high (Fig. 1). The Kärdla crater formed in a shallow (<100 m deep) epicontinental Ordovician sea ~455 Ma ago into a target composed of a 150 m thick early Paleozoic siliciclastic and carbonate sedimentary sequence covering a crystalline basement (Puura and Suuroja, 1992). Although the diameter of the Kärdla crater is the same as the transition diameter between simple and complex, the presence of an uplift suggests a structurally complex impact crater. Plado *et al.* (1996) has suggested that the presence of seawater on top of the target facilitated the formation of the central uplift.

The Paleoproterozoic crystalline basement, representing a 1.7–2.0 Ga old Svecofenninan crustal segment (Gorbatchev and Bogdanova, 1992), is composed of regionally metamorphosed amphibolite-facies migmatitic granites and quartz-feldspar gneisses with amphibolites, biotite gneisses and biotite-amphibole gneisses. Amphibolitic rocks constitute up to 30% of all rock types.

The well-preserved crater depression is filled with autochthonous and allochthonous coptogenic fragmental breccias (including slumped and fallback fragmental breccias) covered by resurge conglomerates, conglomeratic turbidites and sands that were eroded from uplifted crater walls prior to burial by carbonate sediments (Puura and Suuroja, 1992). Carbonates also comprise the upper part of the crater depression filling (Fig. 1). Autochthonous breccias are composed of cataclastic crystalline basement rocks which are fractured to different degrees. Fracturing decreases gradually with depth and extends to ~1 km beneath the original surface. The porosity of the shock-affected rocks decreases from ~18% in impact
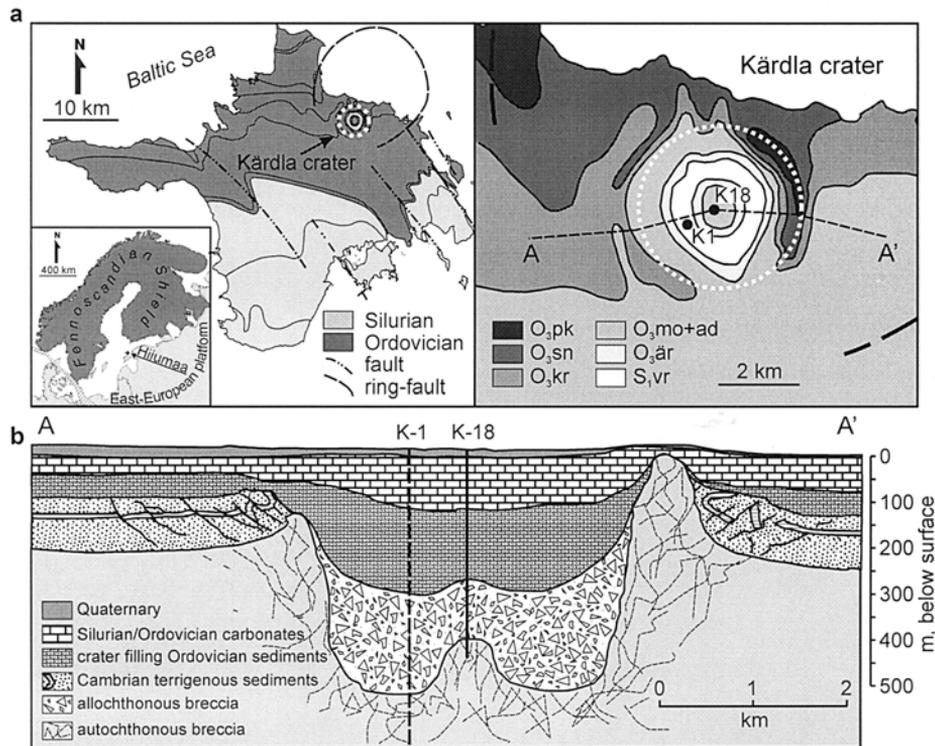
FIG. 1. Simplified geological map of Hiiumaa Island and of Kärdla crater area (a), and cross-section of the crater in a west-east direction with the location of the drill cores studied (b). Legend: O_3pk = Upper Ordovician Paekna Formation, O_3sn = Saunja Formation, O_3kr = Kõrgesaare Formation, O_3mo+ad = Moe and Adila Formation, $O_3är$ = Ärina Formation, S_1vr = Lower Silurian Varbola Formation. White dashed line shows location of Kärdla crater.

breccias to ≤5% in the fractured basement at a depth of 815 m (Plado *et al.*, 1996). Allochthonous fragmental breccias of different generations consist of a polymict mixture of crystalline and sedimentary rock fragments. Amphibolitic rocks occur within autochthonous breccias as fractured and displaced blocks. The amphibolitic rock fragments in allochthonous breccias occur as clasts of various sizes in the fine-grained breccia matrix. In the crater area the fractured and crushed amphibolites are strongly altered, being often totally replaced by secondary mineral phases.

MATERIAL AND METHODS

A total of 18 samples of altered amphibolite inclusions from the allochthonous fragmental breccia sequence and crushed amphibolite rocks from the autochthonous breccias, and 12 fluid inclusion samples from the upper part of autochthonous fragmental breccias in the crater depression were taken from drill-cores K-1 and K-18 (Figs. 1 and 2). Drill-core K-1 penetrates the whole section of the allochthonous and autochthonous breccias inside the crater up to 815 m depth below ground surface. Drill-core K-18 opens section of the allochthonous breccias in central part of the crater and reaches the slightly brecciated crystalline rocks of central peak (depths 399–432 m).

Minerals in the original host rock and their alteration products were studied by x-ray diffractometry (XRD), optical microscopy, scanning electron microscopic (SEM) back-scattered electron images and semiquantitative energy dispersive spectrometer analysis (EDS).
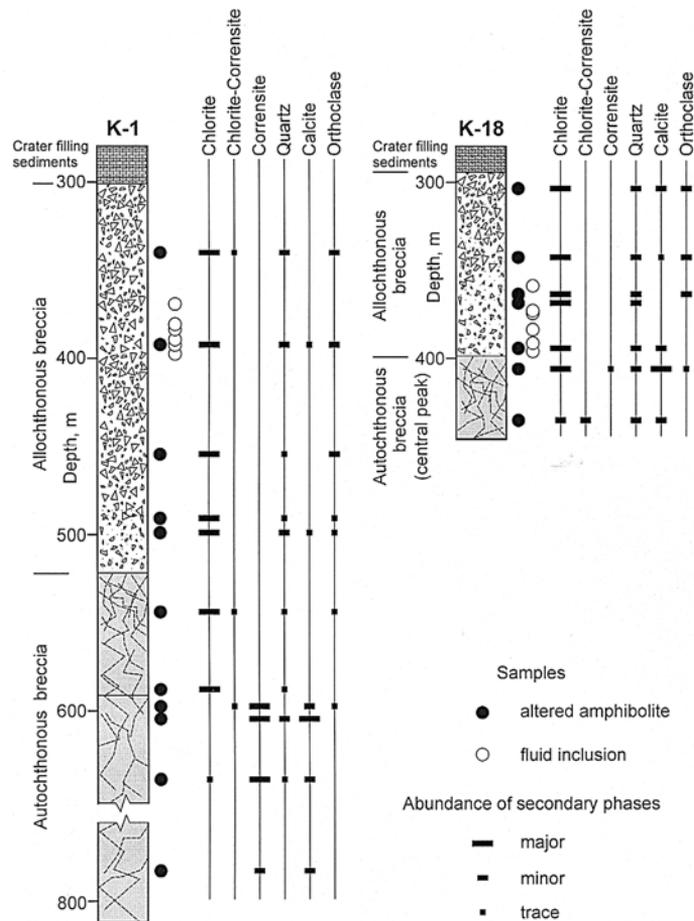
Fig. 2. Schematic lithological profiles of the drill-cores K-1 and K-18 with the location of samples and distribution of the secondary mineral abundances.

For XRD analysis, the whole-rock powder and oriented <2 μm clay fractions were used. Oriented clay fractions were analysed in the air-dried state and after treatment with ethylene glycol (EG). Diffraction patterns were recorded using a DRON 3M diffractometer, with Ni-filtered CuKα radiation, and step scanning at 0.02° 2θ steps for 3 and 5 s for oriented preparations and random powders, respectively.

SEM studies were performed with a JEOL 6300 SEM equipped with Oxford ISIS EDS at the Oulu University, Finland. Digital x-ray images of Ca, K, Na, Mg and Mn were collected and also qualitative line analyses over zones of different compositions were collected and examined.

Microthermometry on fluid inclusions in quartz was measured in thin sections by standard techniques of heating and freezing (Roedder, 1984) using a modified MKS-2 heating-cooling stage at the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences, St. Petersburg.

RESULTS

Hornblende Petrography

The hornblende abundance in autochthonous breccias varies between 5 and 60 vol%. The amphibolites have a massive and
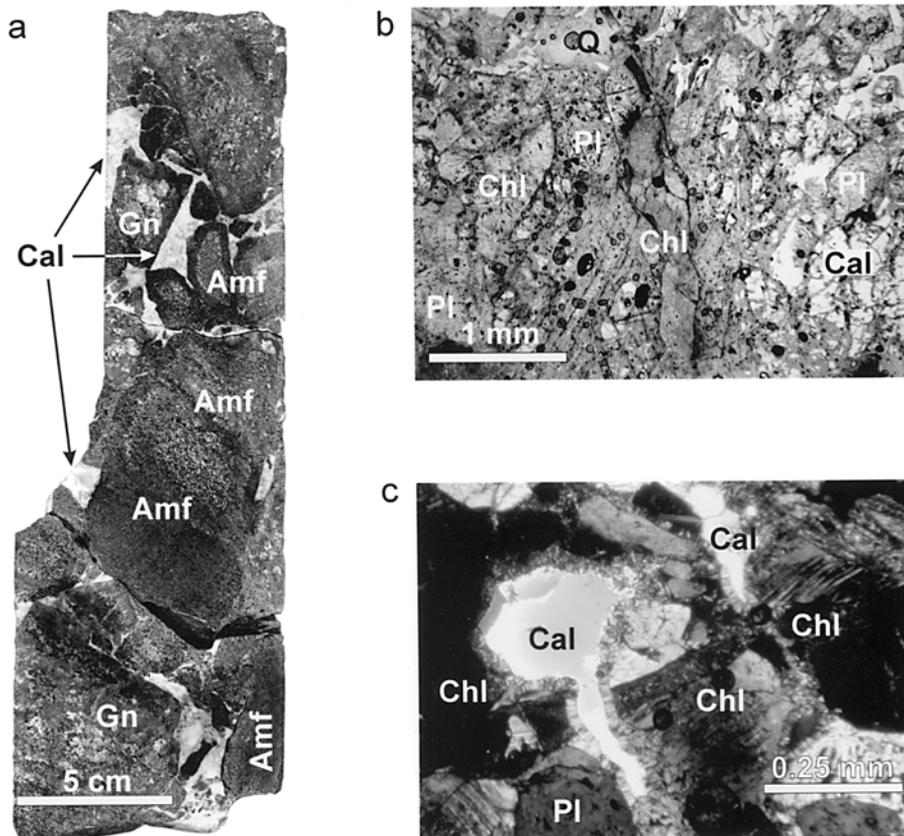
FIG. 3. Polished rock sample and photomicrocraphs of altered amphibolites at Kärdla. (a) Crushed amphibolite and gneiss clasts with calcite lined fractures and cavities. Note the alteration fronts inside the clasts. Drill-core K-18, depth 301 m; (b) altered amphibole replaced by chlorite and secondary calcite and quartz with plagioclase relics replaced mainly by K-feldspar. Amphibole crystals are completely altered to chlorite, but original elongated prismatic outlines of hornblende crystals are still observable. Plane polarized light. Drill-core K-18, depth 398.4 m; (c) radially oriented chlorite crystallites growing into a pore space filled by secondary calcite. Crossed polars. Drill-core K-18, depth 398.4 m. Amf = amphibolite, Gn = gneiss, Cal = calcite, Chl = chlorite, Pl = altered plagioclase, Q = quartz.

locally linear fabric with unevenly spaced fractures filled with secondary calcite aggregates. Green hornblende consists of isometric or elongated prismatic grains between 0.5 and 2 mm in length. Optical mineralogic analysis suggests a hastingsitic composition of the hornblende. Planar deformation features (PDFs) are missing, but mineral grains are usually fractured and crushed into smaller pieces. Generally, the hornblende grains are replaced with chlorite aggregate, but linear fabric of elongated hornblende crystals is still observable (Fig. 3).

Allochthonous fragmental breccias contain only ~5 vol% of hornblende. Hornblende grains are severely crushed and predominately replaced by a fine-grained submicroscopic mass of secondary chlorite, quartz, Fe-oxides and calcite. Cavities and fractures between amphibolite clasts are filled with calcite (rarely dolomite), quartz, K-feldspar and minor sulphides (mainly pyrite) and goethite (Fig 3).

Scanning Electron Microscopy

SEM and SEM-EDS examination shows that hornblende has been replaced by fine-grained Fe-Mg rich silicate (chlorite, corrensite) and silica (quartz) (Fig. 4). Areas composed only of silica (quartz) consist of irregular patches with angular edges in a fine-grained chlorite crystallite matrix, indicating authigenic quartz precipitation in the form of individual crystals and/or secondary overgrowths. The Al-, Mg- and Fe-rich fine-grained mass of submicron crystallites which fill most of the former hornblende area is interpreted to be chlorite and/or corrensite. High-magnification SEM images of the chloritic masses in allochthonous breccia matrix show the typical euhedral platy clay mineral morphology of chlorite crystallites.

X-Ray Diffraction

Examples of the whole-rock powder XRD patterns of amphibolites are shown in Fig. 5 and the distribution of the secondary phases in the drill cores in Fig. 2. The major alteration products of hornblende in amphibolite rock fragments were identified as trioctahedral chlorite, mixed-layered chlorite-smectite (corrensite) and corrensite-chlorite type phases. The samples also contain quartz, K-feldspar and albite, calcite, Fe-oxyhydrates, relic biotite and traces of hornblende (Figs. 2 and 5). Amphibolitic clasts within fall-back breccias have been completely replaced by chlorite and/or mixed-layered chlorite-corrensite phases, secondary quartz, K-feldspar, calcite, and rarely dolomite. In the fractured basement rocks and autochthonous breccias, the hornblende has been replaced by trioctahedral chlorite and chlorite-corrensite type interstratified phases. The maximum alteration of hornblende occurs in alteration haloes surrounding the calcite-filled veins in the upper part of the crater floor and central peak. Macroscopically unaltered and weakly altered amphibole in this section is significantly altered to mixed-layered chlorite-smectite (corrensite) type phase. Chlorites are Ib(β97°) polytypes characterized by a single
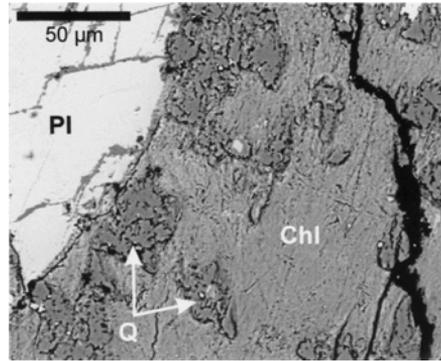
FIG. 4. SEM photomicrograph of altered hornblende grain in contact with unaltered plagioclase in autochthonous breccia in drill-core K-1, depth 603.4 m. Chl = chlorite and/or corrensite, Pl = plagioclase, Q = quartz.
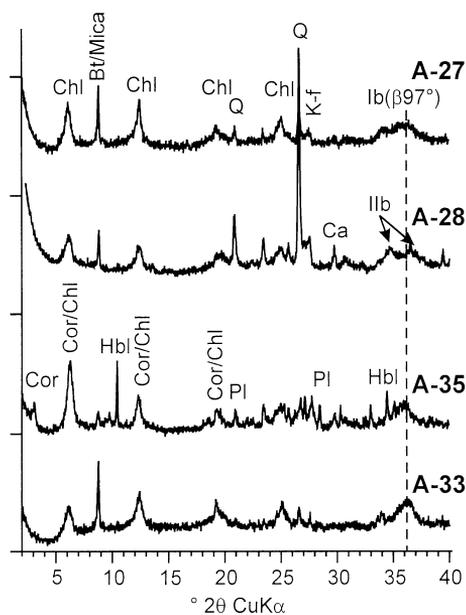
FIG. 5. Representative XRD patterns of the amphibolite whole-rock unoriented powder preparations. Samples A-27 and A-28 represent amphibolitic fragments in allochthonous breccia at depths 496 and 500 m of drill-core K-1, respectively, whereas A-33 and A-35 are from amphibolite fragments in autochthonous breccia at depths 588 and 597 m, respectively. Chl = chlorite, Cor-Chl = chlorite-corrensite, Cor = corrensite, Bt/Mica = biotite and/or K-mica, Hbl = hornblende, Q = quartz, Pl = plagioclase, K-f = K-feldspar, Ca = calcite. Ib(β97˚), IIb = characteristic lines of the chlorite polytypes.
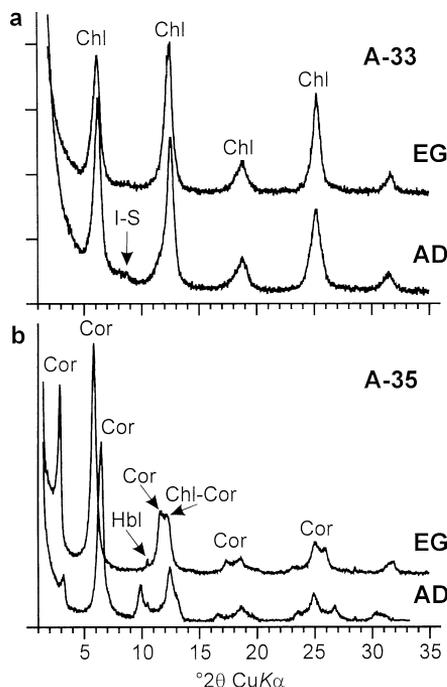
FIG. 6. Representative XRD patterns of the <2 μm fraction in air dry (AD) and in ethylene glycol (EG) solvated state. (a) Sample A-33 from drill-core K-1, depth 588 m. (b) Sample A-35 from drill-core K-1, depth 597 m. Chl = chlorite, I-S = illite-smectite, Cor = corrensite, Chl-Cor = chlorite-corrensite.

strong, but broad peak at 2.47 Å (Fig. 5). Only 1 sample out of 18 revealed a IIb polytype together with the dominant Ib(β97°) type. The Ib(β90°, 97°) polytype chlorites are usually Fe-rich compared to IIb type metamorphic chlorites (Curtis *et al.*, 1985).

The clay fractions (<2 μm) contain mixed-layered chlorite (corrensite and corrensite-chlorite) and discrete Fe-rich chlorite minerals (Fig. 6). The presence of a 50:50 chlorite-smectite (corrensite) mixed-layer phase is confirmed by superstructure d(001) spacing expansion from 29 Å in air-dried state to 31.1 Å in EG saturated state (Fig. 6b). Heating of the corrensite-rich sample at 500 °C for 1 h caused the spacing to collapse to 24 Å. The slight Fe-rich chlorite peak shift towards higher d-spacings and a peak broadening after EG solvation (Fig. 6a) probably reflects the presence of chlorite-corrensite type phase in chlorite rich samples. The XRD patterns of samples from the autochthonous breccia sequence show the presence of a mixed-layer illite-smectite, which also either have a hydrothermal origin or, most probably, reflect highly illitic illite-smectite, the most abundant clay mineral in the Lower Cambrian clayey sediments (Kirsimäe *et al.*, 1999), which formed the thickest part (~100 m) of the sedimentary target at the impact event.

Fluid Inclusions

Fluid inclusions (Fig. 7) were measured in fractured single-crystal quartz and granitic rock fragments in allochthonous fragmental breccias. The size of the fluid inclusions typically vary from 2 to 10 μm, rarely up to 20–30 μm. The inclusions are most frequent in quartz grains without any visible shock features and in quartz where the fluid inclusion trails crosscut the PDFs. In rare cases grains of yellowish-grey quartz were identified with up to four sets of decorated PDFs with gaseous single-phase fluid inclusions along PDF planes. The composition of the fluid inclusions is predominantly aqueous (NaCl-H_2O), but rare H_2O-CO_2 (NaCl-H_2O-CO_2) or CO_2 composition fluids were also found.

These fluid inclusions were most probably formed by impact-generated hydrothermal solutions. High temperatures (>400 °C)—which are much higher than the decrepitation temperatures of fluid inclusions—and particularly high pressures (>10 GPa) during PDF formation in quartz (Grieve *et al.*, 1996) exclude the survival of primary fluid inclusions. In addition, the fluid inclusion trails, which crosscut the planar elements, show that they postdate the impact event. This confirms that the entrapped fluids are impact related. Similar conclusion based on the relationship between fluid inclusion trails and PDF systems have been drawn by Komor *et al.* (1988), Koeberl *et al.* (1989) and Boer *et al.* (1996) for the Siljan, Roter Kamm and Manson impact craters, respectively.

The results of homogenization temperature (T_h) measurements of the quartz fluid inclusions encompass a wide range from 110 to 440 °C, with the maximum peak between 150 and 300 °C (Fig. 8). This temperature range is similar to the T_h values obtained for fluid inclusions in quartz found in Siljan (Komor *et al.*, 1988), Roter Kamm (Koeberl *et al.*, 1989) and in the Manson impact structures (Boer *et al.*, 1996). Trapping temperatures (T_t) are estimated assuming that pressures during entrapment were due to the overburden of
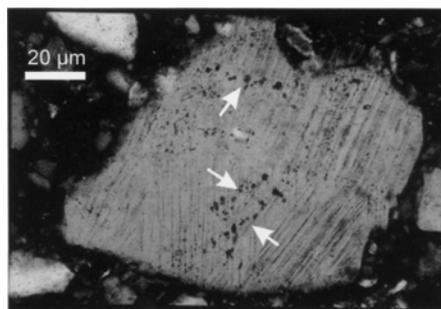
FIG. 7. Photomicrograph (crossed polars) of fluid inclusions in a quartz grain with three sets of PDFs in allochthonous breccia. K-1 drill-core, depth 383 m. Arrows indicate fluid inclusion trails crosscutting PDFs.
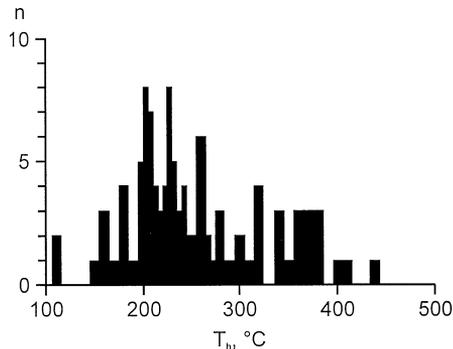
FIG. 8. Histogram of the aqueous (H_2O-NaCl) quartz fluid-inclusion homogenisation temperatures (T_h) in allochthonous breccia unit in Kärdla crater.

porous and unconsolidated fall-back and resurge breccias and hence, nearly equal to the hydrostatic pressure. Consequently, the pressure corrections are negligible and minimum T_t values are about 230–350 °C for the most common inclusions with most frequent T_h. The final ice melting temperatures of inclusions range from –9.1 to –0.3 °C with a maximum at –3 °C, which reflect fluid salinities between 13 and 0.8 wt% $NaCl_{eq}$, with most samples ≤5wt% $NaCl_{eq}$ (Bodnar, 1993). The aqueous fluid inclusions are NaCl dominated, although the melting behaviour of some inclusions suggests a few $CaCl_2$ ($CaCl_2$-NaCl-H_2O) inclusions.

DISCUSSION AND CONCLUSIONS

The formation of secondary clay minerals and particularly of Fe-smectite (saponite), corrensite and chlorite in impact-hosted hydrothermal systems is described in Allen *et al.* (1982), Phinney *et al.* (1978), Komor *et al.* (1988), McCarville and Crossey (1996), and Naumov (1999). Chloritization of mafic minerals (hornblende, pyroxene) begins with the formation of saponite type smectite, which in progressive hydrothermal alteration transforms to corrensite (Reynolds, 1988). Corrensite, however, can form directly under hydrothermal conditions at temperatures between ~100 and 200 °C (Inoue and Utada, 1991), whereas the upper limit of corrensite thermal stability lies at 220–225 °C (Tómasson and Kristmannsdóttir, 1972). The next stage in corrensite-to-chlorite conversion is the growth of chlorite layers in corrensite to form discrete chlorite domains in a corrensite matrix (Beaufort *et al.*, 1997). Hayes (1970) concluded from studies of sedimentary chlorites that the natural polytype progression with increasing temperature is Ib_d – Ib(β97°) – Ib(β90°) – IIb(β97°) with the temperature for the Ib–IIb transition to be about 150–200 °C. Thus, the prevalence of the Ib(β97°) polytype and the rarity of the IIb polytype in the Kärdla samples would suggest fluid temperatures of ≤200 °C. However, Walker (1993) showed

that the Ib polytypes can be stable up to 300 °C and IIb polytype may possibly form at temperatures as low as 50 °C. Nevertheless, Inoue (1995) states that trioctahedral Fe-chlorite appears ubiquitously in the higher-grade alteration zones where the temperature exceeded 200 °C in alkaline or neutral solutions and at ~300 °C chlorite starts to react with illite and/or K-feldspar to form biotite. Therefore we propose that maximum temperatures of 200–300 °C were reached during hydrothermal alteration (widespread Fe-chlorite formation) of the amphibolite rocks in the upper part of the autochthonous breccias and in amphibolitic clasts including in the allochthonous breccias in the central crater area. Chloritization intensity decreases with decreasing fracturing downward into the crater floor, where chlorite occurs only in immediate proximity to the fracture planes and corrensite prevails within macroscopically unaltered amphibolite blocks, indicating maximum temperatures below 200 °C.

The temperature range estimated from the alteration assemblage is in good agreement with the most frequent quartz fluid inclusion homogenization temperatures (150–300 °C) in the allochthonous breccia. The temperature range of fluid inclusion homogenization (110 to 440 °C) probably reflects the temperature evolution in the central part of the hydrothermal system developed in the Kärdla crater. The highest fluid-inclusion trapping temperatures were about 400–500 °C directly after the crater formation. However, the absence of the high-temperature hydrothermal mineral assemblages (*e.g.*, garnet-actinolite-epidote) suggests that the initial high-temperature stage (>300 °C) was too short for alteration to achieve equilibrium phases. The most intense fluid-inclusion entrapment and the hydrothermal alteration occurred at lower temperatures (100–300 °C) resulting in the chloritization of amphibole. Precipitation of calcite (rarely dolomite) in veins and cavities reflects probably the final stages of the cooling, when the temperature reached ambient conditions.

The most frequent PDF orientations in quartz are along the $\{10\bar{1}3\}$ and $\{10\bar{1}2\}$ planes (our unpublished data), pointing a shock stage Ib (Grieve *et al.*, 1996) for the rocks at Kärdla crater. This corresponds to a shock pressure range of 20–35 GPa and post-shock temperatures of about 170–300 °C (Grieve *et al.*, 1996), which well agrees with the temperatures suggested by secondary minerals and fluid inclusion data. In the central part of the crater depression, however, the high-temperature (>300 °C) fluid inclusions suggest higher initial post-shock temperatures. Also, the localization of the most intensive chloritization in fall-back and resurge breccias around and above the shattered rocks of the central uplift indicates that the hydrothermal fluids were driven by convective passage and discharge through the most heated central peak area of the crater (Fig. 9). However, the approximate stratigraphic uplift of the central peak in Kärdla crater is ≤1 km, which would have added a maximum of only 35–40 °C assuming a geothermal gradient of 25–30 °C km^{-1} and average surface temperature of 10 °C. Therefore, the shear heating during formation of the central
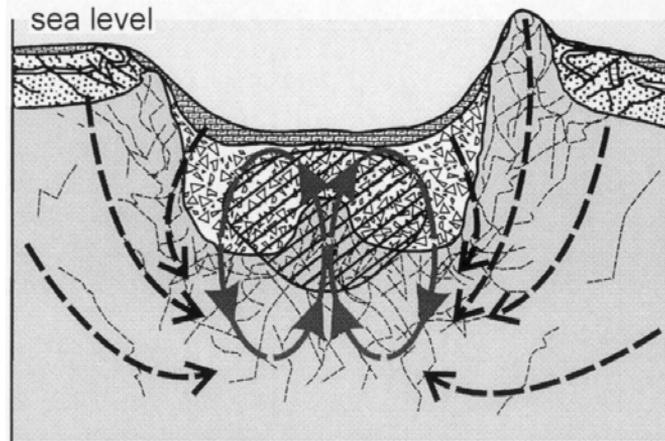
FIG. 9. Schematic reconstruction of the short-lived impact-induced hydrothermal system at Kärdla crater. Striped area shows the zone with the maximum alteration. Dashed arrows indicate water infiltration pathways and solid arrows show probable location of the post-impact hydrothermal system.

uplift and the rapid unloading of the target basement likely provided an additional thermal impulse into this area, which initiated the hydrothermal fluids movement (Masaitis and Naumov, 1993; Crossey *et al.*, 1994). A similar post-impact hydrothermal system within a central uplift was described in the ~80 km diameter Puchezh–Katunki impact crater (Naumov, 1999) and in the 35 km diameter Manson crater (Boer *et al.*, 1996). Although scale and the amounts of energy released in these impacts are considerably different, both exhibit similar post-impact hydrothermal alteration patterns. Therefore, it is reasonable to expect the same spatially limited hydrothermal processes in all other terrestrial and, presumably, in extraterrestrial complex impact craters, providing that water is present.

The low salinity of fluid inclusions is usually interpreted as indicative of hydrothermal circulation feed by meteoric waters, whereas high salinity solutions are thought to be related to the fluid release during silicate rock melting (*e.g.*, Koeberl *et al.*, 1989). The rather low salinity of fluids in Kärdla crater (<13 wt% of NaCl$_{eq}$, most ≤5 wt% NaCl$_{eq}$) suggests that the hydrothermal system was recharged either by infiltration of meteoric waters from the crater rim walls raised above sea level after the impact, or by infiltration of seawater (3.0–3.5 wt% NaCl$_{eq}$) through the disturbed sedimentary cover and fractured crystalline basement (Fig. 9).

The maintenance time of such hydrothermal systems may be few hundred years to several tens of thousand years for small- to large-size craters (Onorato *et al.*, 1978; McCarville and Crossey, 1996; Newsom *et al.*, 1996) and up to 2 Ma for the largest terrestrial craters (Ivanov and Deutsch, 1999). The hydrothermal system in Kärdla crater could last for several hundreds of years, given its moderate size, high water/rock

ratios, absence of distinctive impact melt sheet and involvement of both conductive and convective cooling mechanisms.

In conclusion, we propose that the formation of fluid inclusions and the hornblende degradation proceeded by corrensite-to-chlorite transformation in Kärdla impact crater is related to the development of a local, probably short-lived, hydrothermal system in the crater depression immediately after the crater formation in a shallow (<100 m) seabed. Temperatures of the hydrothermal waters recorded by fluid inclusions and mineral associations range from 100 to 300 °C. The fluid inclusion data suggest the initial temperatures of the hydrothermal fluids were up to about 100–200 °C higher, but the temperature decline to ~300 °C was probably rapid, and the high-temperature hydrothermal mineral assemblage was not formed. The hydrothermal system was possibly driven by thermal convection of low salinity (≤5 wt% NaCl$_{eq}$) meteoric or sea water through the crater central peak area. The high-temperature conditions, extensive fluid exchange and, consequently, the high-rate pervasive hydrothermal alteration processes existed probably for only a relatively short time of several hundred years. Although the well-developed hydrothermal system in Kärdla crater is unrelated to the cooling of impact melt or suevite bodies, it shows similarity with hydrothermal systems in large, impact-melt rich craters. The thermal history of the shock heated and uplifted rocks in the central crater area, rather than of melt or suevite sheets, controls the distribution and intensity of these impact-induced hydrothermal processes.

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IV

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Kärdla (Hiiumaa Island, Estonia)—the buried and well-preserved Ordovician marine impact structure

Kalle Suuroja*, Sten Suuroja, Tarmo All, Tom Floden

Geological Survey of Estonia, Kadaka tee 82, EE-12618 Tallinn, Estonia

Abstract

The Kärdla marine impact structure (Estonia, 58°58′N, 22°46′E) was formed at 455 Ma (Upper Ordovician), in a shallow epicontinental sea some tens of kilometres from the land and erosion area. The iron-rich projectile about 200 m in diameter approached from the west at an angle of 30–45°. The impactor penetrated about 50-m-thick water layer and the sedimentary cover and exploded in the uppermost part of the crystalline basement. A complex crater, 4 km wide and about 500 m deep, with a central uplift rising 130 m from the crater floor, was formed. The highest point of the rimwall is 110 m above the target level. The rimwall is cut by at least two resurge-excavated gullies. The variable height of the rimwall obviously results from the obliqueness of the impact. Outside the crater an elliptical area was revealed, 12–15 km in diameter, with deformed sedimentary rocks below the target level. The elliptical shape of this area may also be due to the oblique impact. Because the crater and its surroundings were buried directly after the impact, the whole complex of impact-related sediments is preserved there. They are recovered by 160 wells, six of which penetrate the entire complex of impact breccias inside the crater. © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

The Kärdla meteorite crater is one of the six impact structures discovered in Estonia (Fig. 1). Four of them (Kaali, Ilumetsa, Tsõõrikmäe and Simuna) are small (up to 110 m in diameter) and relatively young (formed after Pleistocene glaciation), while the remaining two (Kärdla and Neugrund) are considerably larger (accordingly 4 and 7 km in diameter) and older (accordingly 455 and 530 Ma).

The Kärdla impact structure (58°58′N and 22°46′E), with rim-to-rim diameter of 4 km, is located on Hiiumaa Island (Moonsund Archipe-

lago), eastward of the town of Kärdla. It was formed in the Upper Ordovician about 455 Ma (Grahn et al., 1996) ago, in a shallow marine environment in a stable carbonate-covered epicontinental sea (Nestor and Einasto, 1997). Sedimentation resumed immediately after the impact and the structure was buried in a few million years (Ainsaar et al., 2002). The crater is one of the best-preserved impact structures of this kind.

Its history of discovery can be divided into four periods: (1) pre-historical (1840−1967); (2) discovery of the basement uplift (1967−1972); (3) determination of the crater (1972−1980); and (4) identification of the impact structure (since 1980). The pre-historical period began with the discovery of dislocations in the bedrock near the village of Paluküla (Eichwald, 1840) 160 years ago (Fig. 2).

*Corresponding author. Fax: +37-6720091.

E-mail address: k.suuroja@egk.ee (K. Suuroja).

Fig. 1. Location of the Kärdla impact structure and 10 other impact structures in the surrounding area.

During the second period, the crystalline basement uplift was found near Paluküla (Viiding et al., 1969). Detailed gravimetric and magnetometric mapping was performed in the third period, and the material obtained from numerous drill holes permitted the identification of the structure as a crater (Suuroja et al., 1974). The occurrence of breccias in the crater was interpreted as an evidence of cryptovolcanic explosion. The impact origin of the crater was established by the discovery of quartz with planar deformation features (PDF) (Masaitis et al., 1980).

In the course of the deep geological mapping on the island (Suuroja et al., 1991), 30 on average 300-m deep wells were drilled and geophysical mapping was carried out. These investigations provided data on the distribution of ejecta in the crater surroundings. Inside the crater, the 815 m deep

Fig. 2. The Kärdla impact crater area on the orthophoto. White dashed line—the position of the ridge of the buried rimwall. Black dots—drill holes. Important drill holes are marked with numbers. A–A′ cross-section line is shown in Fig. 9. B—B′ western part of the section line is shown in Fig. 6.

well Soovälja (K-1) was drilled (Fig. 2). On the outer slope of the rimwall, on the contact of the Cambrian sandstones disturbed by the impact and post-impact limestones, perspective lead and zinc ore mineralisation was discovered. Around the crater hydrocarbons of migratory origin occur. The Kärdla crater and its surroundings are penetrated by 160 drill holes, making it one of the best studied impact structures of this size.

To obtain geological information from the outer crater area marine geophysical investigations were carried out in June 1996 in co-operation with the Geological Survey of Estonia (Tallinn) and the Department of Geology and Geochemistry of Stockholm University (Sweden). On board the

research vessel "Strombus", seismic reflection profiling crossing the presumptive ringfault zone was performed at two sites in Kärdla Bay (Fig. 3). More than 20-km-long profile was shot in this area using single-channel seismic reflection equipment (Floden, 1981). The recorder frequency bands were 250–500 and 4 kHz. The results of these studies are presented in this paper for the first time. (Table 1)

For studying the chemical alteration evoked by the impact, in the course of several mapping projects (Suuroja et al., 1974, 1991 etc.) from drill cores of host rocks (granitoids and amphibolites) and impact breccias, 96 samples were taken and analyzed by wet chemical analyses of major

Fig. 3. The Kärdla impact structure on the satellite images. White dashed lines—the positions of the ridge of the buried rimwall and the ringfault. White dots—the seismic reflection profile shown in Fig. 10.

Table 1
Some characteristics of the Kärdla impact structure

Characteristic	Size
Pre-impact geological succession of the target	
Sea water	∼50 m
Sedimentary rocks above the crystalline basement	142 m
Ordovician limestones	14 m
Ordovician sandstones and argillites	8 m
Weakly cemented Cambrian sandstones, siltstones, clays	120 m
Metamorphic rocks of the Precambrian crystalline basement	>3000 m
Crater	
Diameter of the rimwall	4 km
Diameter of the the ringfault	12–15 km
Diameter of the crater at the level of the target surface	3.5 km
Diameter of the central uplift	∼800 m
Diameter of the area with a continuous ejecta layer	∼60 km
Vertical dimensions	
Depth of the crater below the target surface	410 m
Depth of brecciaas below the target surface	∼1 km
Maximum height of the preserved rim above the target surface	110 m
Minimum height of the structural uplift of the rim	100 m
Maximum height of the structural uplift of the rim	240 m
Height of the central uplift (min)	130 m
Thickness of the impact-related complexes	
Continuous ejecta layer in the surrounding	0.01–14 m
Post-resurge turbidites	23–28 m
Resurge deposits in the crater proper	8–30 m
Fallback breccias	2–14 m
Slumped breccias above the central uplift	42 m
Slumped breccias above the ring depression	140 m
Allogenic suevite	44–52 m
Authigenic breccias in the crater	>800 m
Thickness of some complexes of post-impact sediments (rocks)	
Quaternary deposits inside the crater	18–24 m
Quaternary deposits above the elevated parts of the rim	0.2–2 m
Vormsi Stage (Kõrgessaar Formation) inside the crater	14 m
Vormsi Stage (Kõrgessaar Formation) in the surrounding	10–12 m
Nabala Stage (Paekna and Saunja formations) inside the crater	27 m
Nabala Stage (Paekna and Saunja formations) in the surrounding	18–22 m
Räe Formation (cryptocrystalline limestones) inside the crater	30 m
Rägavere Formation (cryptocrystalline limestones) above the rim	9.5 m
Rägavere Formation (cryptocrystalline limestones) in the surrounding	22–24 m
Tatruse, Jõhvi, Keila and Hirmuse formations inside the crater	53 m
Tatruse, Jõhvi, Keila and Hirmuse formations in the surrounding	22 m
Idavere Stage (Paluküla Formation) inside the crater	115 m
Idavere Stage (Paluküla Formation) in the surrounding	0.05–0.45 m

elements. Comparable information from host rocks was obtained on modal mineralogical composition (Kivisilla et al., 1999). The results of 54 more presentable analyses are given in Tables 2, 3 and 4. The primary mass of a sample for the chemical analysis was 100–200 g and the whole

Table 2
Chemical (wt%) and modal mineralogical (vol%) composition of granitoids (5–12) of the Kärdla impact structure area and its surroundings

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Drill hole	F175	K-1	F379	F380	F374	F375	F376	F352	F353	F353	F353	F359	F359	F361	F361	F361	F362	F375	F361
Sample	0696	8150	1602	1840	2087	2830	0552	2614	2662	2760	2820	2850	3025	3126	3408	3458	2770	2830	3465
SiO_2	75.40	72.52	73.70	72.80	73.34	73.14	74.66	72.20	76.54	76.58	77.84	70.98	71.30	73.66	73.46	73.72	79.84	73.14	73.00
TiO_2	0.21	0.38	0.36	0.22	0.22	0.21	0.48	0.25	0.14	0.13	0.04	0.50	0.50	0.50	0.46	0.40	0.19	0.21	0.50
Al_2O_3	10.93	12.56	12.71	13.08	1.93	2.80	9.67	13.38	11.85	11.31	12.66	13.78	13.38	12.41	12.63	13.15	9.06	12.80	13.06
Fe_2O_3	0.92	1.15	1.47	1.50	1.99	1.52	2.89	1.48	1.12	1.01	1.64	1.99	2.51	1.05	1.56	1.27	1.25	1.52	1.27
FeO	0.70	1.47	1.04	2.08	0.90	0.72	1.15	1.26	0.86	1.65	1.36	2.05	1.54	1.58	1.40	1.47	0.50	0.72	1.47
MnO	0.03	0.01	0.03	0.03	0.02	0.02	0.04	0.03	0.03	0.06	0.06	0.03	0.04	0.04	0.04	0.05	0.01	0.02	0.05
MgO	0.56	0.60	0.76	0.69	0.74	0.35	0.80	0.82	0.28	0.25	0.09	0.78	0.73	0.34	0.31	0.36	0.46	0.35	0.36
CaO	1.11	0.19	1.30	1.94	0.54	1.06	1.27	2.21	1.20	1.20	0.76	2.23	2.23	1.48	1.48	1.49	0.25	1.06	1.49
Na_2O	1.18	1.11	2.30	2.48	0.60	1.95	0.93	2.50	2.00	2.82	2.00	3.18	3.12	2.83	2.52	2.46	1.90	1.95	2.46
K_2O	7.12	9.00	5.22	4.42	7.83	7.22	6.43	4.20	4.90	5.02	2.53	4.09	4.00	4.94	4.94	5.13	4.42	7.22	5.13
P_2O_5	0.03	0.03	0.06	0.13	0.11	0.08	0.12	0.07	0.08	0.08	0.06	0.14	0.14	0.05	0.04	0.04	0.04	0.08	0.04
S	0.16	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	0.1	0.1	0.1	0.14	<0.2	<0.1	<0.0	<0.1	<0.1	<0.1	0.03	<0.1
LOI	1.11	0.91	0.42	0.60	1.35	0.73	1.65	0.75	0.18	0.37	0.20	0.76	0.65	0.50	0.28	0.59	0.99	0.73	0.23
Total	99.46	99.93	99.37	99.97	99.57	99.80	100.21	99.15	99.28	100.58	99.38	100.51	100.14	99.38	99.12	99.16	98.91	99.83	99.06
H_2O	0.13	0.22	0.18	0.17	0.26	0.22	0.31												
Q	33.0	38.0	31.0	9.3	35.0	31.0	40.5	34.9	38.8	33.5	51.0	29.1	31.8	29.8	30.7	30.4	46.0	35.0	30.4
Pl	21.9	13.0	21.0	26.0	9.5	22.5	14.5	25.1	22.4	25.3	22.0	35.0	34.2	25.4	24.5	26.6	14.3	20.0	25.9
An.%	26	25	27																
Ksp	41.6	43.0	38.7	4.0	43.0	42.5	35.0	37.6	32.0	31.8	22.0	28.4	23.1	37.5	38.5	36.5	36.0	42.0	37.0
Hbl	0.2		–			2.6	2.8	–		–				1.6	5.4	2.7	2.2	1.6	2.3
Bt	1.3	4.5	6.4	6.7	9.0	4.0	9.0	2.2	4.7	7.0	3.0	4.6	4.8	2.8	2.6	3.2	3.6	3.0	2.8
Ap	0.2	+	+	+	+	+	+	+	+	+	+	0.1	+	+					
Zrc	–	–	+	+	+	+	+	+	+	+	+			+	+	+		+	+
Orth	–	–	0.3	0.3	+	–	–		+			0.2	+	0.2	0.3	+			0.4
Opaq.	1.8	1.5	2.6	1.1	0.7	+	1.0	0.2	2.7	1.8		1.0	0.7	1.6	1.2	1.7	0.1	+	1.3

1–4—quartz-feldspar gneiss; 5—syenogranite (migmatite); 6—granite (migmatite); 7—syenogranite; 8—granite (migmatite); 9 and 10—quarts-feldspar gneiss; 11—granite; 12 and 13—granite gneiss; 14 and 15—granite (migmatite); 16—granite; 17 and 18—granite (migmatite); 19—granite.
Number of the sample marks its depth in dm.

Table 3
Chemical (wt%) and modal mineralogical (vol%) composition of amphibolites of the Kärdla impact structure area and its surroundings

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Drill hole	C8	F170	F175	F241	415	F380	413	K18	F373	F373	F378	F352	F352	F353	F359
Sample	80370	1700587	1750555	2411000	4151088	3801944	4130423	184040	3736018	3737660	3782213	3522305	3522516	3532620	3592970
SiO_2	48.06	48.14	47.78	48.66	50.58	49.82	46.72	46.38	44.60	45.40	46.00	49.35	48.59	50.72	50.30
TiO_2	0.66	1.10	0.88	0.70	1.22	0.52	1.34	0.60	0.46	0.49	1.09	0.44	0.79	1.56	1.35
Al_2O_3	15.11	12.82	14.86	14.47	13.89	15.72	14.70	15.76	15.68	15.48	16.93	15.90	16.62	13.77	13.31
Fe_2O_3	3.96	6.78	3.07	3.41	3.24	2.99	3.45	2.91	4.53	4.34	5.16	3.16	2.64	3.63	5.80
Feo	8.48	8.41	8.40	9.20	8.40	7.11	8.76	8.76	8.76	7.71	8.26	5.61	9.12	11.10	10.56
MnO	0.18	0.15	0.14	0.19	0.08	0.08	0.08	0.11	0.12	0.15	0.17	0.15	0.21	0.20	0.21
MgO	7.28	7.25	7.69	7.90	6.66	9.74	9.28	8.56	10.18	9.31	7.67	7.70	5.90	4.07	3.43
CaO	8.92	10.73	10.53	10.01	9.34	9.92	9.12	8.55	7.22	9.17	9.30	10.99	11.20	8.15	8.70
Na_2O	2.29	1.80	2.21	2.45	2.80	2.04	2.90	2.45	2.29	3.55	1.89	3.72	3.00	2.65	2.83
K_2O	1.83	1.57	0.96	0.70	1.30	0.81	2.15	1.83	2.00	1.61	1.59	0.85	1.00	1.25	1.61
P_2O_5	0.10	0.58	0.14	0.07		0.11		0.10	0.14	0.06	0.16	0.09	0.15	0.30	0.28
S	0.07		0.25	0.16	0.16	0.21	0.18	0.10	<0.10	<0.10	<0.10	0.10	<0.1	<0.16	<0.1
LOI	2.28	0.78	2.43	1.72	1.59	1.75	1.22	3.28	3.38	2.70	2.14	0.97	1.25	0.61	1.70
Total	99.22	100.11	99.34	99.64	99.26	100.82	99.90	99.39	99.36	99.97	100.36	98.93	100.46	99.17	100.08
H_2O	0.22	0.26	0.20	0.17	0.20	0.39	0.32		0.88	0.34	0.47				
Q	–	2.6	–	–	1.0	–	–		1.1	–	–	+	0.1	0.5	5.5
Pl	44.3	35.0	34.0	38.7	46.2	38.5	37.2		38.0	39.2	42.5	55	51.6	46.5	29.5
An%	47	50	58	47	40	44	39		33	41	47				
Ksp	–	–	–		–	–	–		0.5	0.2	–				1.2
Hbl	52.2	59.3	61.0	59.4	49.2	56.3	58.2		53.6	53.7	42.5	43	47.6	40.5	56.1
Py	–	–	4.0	–	–	–	–		–	–	9.0	2.0	0.5		
Bt	2.8	2.6	0.4	1.3	3.4	4.5	4.5		5.6	5.7	5.6	+	0.1	6.3	7.1
Ap	0.1	0.3	0.1	0.1	+	0.2	+		+	+	0.2		0.1	0.3	0.3
Tit	–	–	–	–	–	–	0.1		–	–	–				
Opaq.	0.6	0.2	0.5	0.5	0.2	0.5	+		1.2	1.2	0.2	+	+	1.4	0.3

1, 2, 5–15—amphibolite; 3, 4, 11—pyroxene amphibolite. The last four digits in the number of the sample marks the depth in dm.

Table 4
Chemical composition (wt%) of impact breccias and weathered crystalline basement rocks of the Kärdla impact structure area

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	
Rock type[a]	IMP	IMP	IMP	IMP	GRIMP	IMP	IMP	IMP	IMP	IMP	GRIMP	GRIMP	IMPW	IMPW	IMPAMF	IMPAMF	GRHIW	GRHIW	GRHIW	
Drill hole	K-1	K-1	K-1	K-1	K-1	K-18	K-18	K-18	K-18	K-18	K-18	K-18	K-1	K-1	K-18	K-1	F-364	F-365	F-375	K-5
Sample	13610	15570	15820	15950	13720	183616	183670	183801	183863	183950	183090	184160	15778	17005	183995	15985	3642930	3652977	3752780	50550
SiO_2	71.69	63.55	69.96	69.64	72.26	79.95	72.34	72.18	70.96	63.42	62.96	70.42	82.78	84.77	59.77	60.70	68.26	58.66	70.70	82.32
Al_2O_3	11.63	15.51	11.68	12.29	12.54	8.15	12.83	11.56	10.46	14.07	15.25	13.05	7.38	6.35	13.05	12.80	15.51	21.19	15.77	2.07
Fe_2O_3	1.04	2.41	2.24	0.95	0.89	0.41	0.80	1.36	1.73	2.38	2.49	1.04	0.32	0.64	2.34	2.46	1.70	2.21	2.04	0.85
TiO_2	0.28	0.39	0.37	0.33	0.23	0.07	0.31	0.37	0.42	0.50	0.55	0.02	0.09	0.09	0.39	0.39	0.42	0.16	0.13	0.13
MnO	0.03	0.05	0.02	0.03	0.01	0.02	0.03	0.02	0.03	0.03	0.04	0.01	0.01	0.01	0.03	0.04	0.00	0.01	0.01	0.06
CaO	0.33	0.41	0.36	0.43	0.33	0.78	0.79	0.91	0.85	1.04	0.33	0.33	0.22	0.33	0.89	0.41	1.23	0.21	0.18	6.33
MgO	1.26	2.01	2.50	1.98	0.90	0.89	1.29	2.05	1.96	3.52	1.75	0.94	0.52	0.54	6.03	6.60	0.20	0.56	0.23	0.23
S_{total}	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	0.13	<0.10	0.12
P_2O_5	0.10	0.11	0.08	0.08	0.08	0.05	0.06	0.07	0.08	0.12	0.07	0.06	0.03	0.05	0.14	0.12	0.03	0.11	0.02	0.03
FeO	2.30	2.87	2.26	3.74	2.01	1.65	1.69	1.94	1.98	3.29	3.23	1.80	1.15	0.65	4.81	4.99				0.00
Na_2O	0.19	0.04	0.16	0.13	0.13	0.06	0.65	0.50	0.45	0.60	0.18	0.32	0.09	0.07	0.18	0.36	0.05	0.04	0.09	0.03
K_2O	8.50	10.17	7.59	8.60	11.17	5.90	8.58	8.18	8.50	8.00	11.17	11.17	5.80	5.60	7.10	6.25	8.34	13.86	8.00	1.34
L.O.I.	1.38	2.33	1.95	1.82	0.86	1.17	1.72	1.23	1.82	2.47	1.79	0.85	0.41	0.36	4.09	3.91	3.46	2.45	2.61	5.88
Fe_2O_{3total}	3.60	5.60			3.12	2.24					6.08	3.04	1.60	1.36	7.68	8.00	1.70	2.21	2.04	0.85
CO_2		0.27			0.27	0.60					0.35	0.19	0.19	0.19	0.44	0.19	1.15	0.11	0.09	5.18

[a] IMP—suevite; GRIMP—suevite by granitoids; IMPW—weathered suevite; IMPAMF—suevite by amphibolites; GRHIW—weathered granitoids from the crater surrounding area; SEJ—sandy ejecta.

The last four digits in the number of the sample mark the depth in dm, other digits show the drill hole number.

rock was analyzed. An account of modal mineralogical composition was carried out from the thin sections. The analyses were done at the Laboratory of the Geological Survey of Estonia.

2. General geology and morphology of the crater

The Kärdla marine impact crater was buried partially shortly after the event and, completely, a few millions years later. Therefore, the structures and rocks are well preserved, yet not directly available for investigation. The influence of the buried structures on the topography of the bedrock (Fig. 4) and basement (Fig. 5) is obvious. The present relief, however, is less affected. The horseshoe-shaped, 15−20 m high and 3−4 km long hillock with bedrock substance along the line through Paluküla and Ala villages reflects the buried and more uplifted part of the buried rim. Two smaller, 10−15-m-high hillocks between Tubala and Kärdla are caused by the structural uplifts of the rimwall. Two lowlands between Kärdla and Paluküla, and Ala and Tubala, are interpreted as gullies (Figs. 2, 4 and 5). Inside the rimwall, about 6 m a.s.l., lies a cultivated lowland 3 km in diameter (Soovälja). On the satellite image (Fig. 3), we have marked an ellipse 12–15 km in diameter, which marks the ringfault, interpreted as the outer boundary of dislocations in the target rocks caused by the impact. In the topography, this boundary is expressed as a low glacifluvial ridge. The ringfault is especially well expressed in the northeastern sea area (Fig. 3) where it is marked by a 5–10-m-high terrace in the bedrock and in a submarine beach ridge. Two islets, Kakralaid and Paerahu, lie directly above this structure.

The contours of the buried crater are only barely visible in the present relief due to the cover of Quaternary glacial, marine and lacustrine deposits. The Quaternary cover inside the crater reaches 23 m in thickness, while on the rim, it is only 0.2−2 m thick.

The morphology of the buried crater after the removal of the Quaternary deposits is shown in Fig. 4. Up to 40 m high and about 1 km wide circular rimwall becomes visible. In the southern part of the rimwall, it is intersected by about 10 m deep and some 100 m wide gully. In the crater centre a central uplift is present. The bedrock surface inside the crater is 5−10 m lower than in the surrounding area.

The Pleistocene glaciation has been the main agent forming the bedrock topography of the Kärdla impact site. The pressure of continental glaciers and the accompanying compaction of underlying terrigeneous bedrock brought out the outlines of the buried rimwall. At the same time, the areas above the rimwall were intensely eroded by continental glaciers. About 60 m of the sedimentary cover was removed from the rimwall. However, it is still unclear as to which part of this erosion happened and before which of the Pleistocene glaciations. Also, the exact time of the subsidence of limestone beds covering the structure (Fig. 6) is not yet unambiguously constrained. Taking the bottom of the Ordovician cryptocrystalline limestones (Saunja Formation) in the surrounding area as reference level, the limestone beds above the rimwall seem to be uplifted by up to 60 m, whereas inside the crater they have sunk down by about 60 m. As a result of these movements, the limestone beds on the slopes of the rimwall are tilted by up to 30°. A sedimentary origin of this tilt is excluded, as the lime mud cannot have been deposited on a highly tilted sea bed. Tectonic movements of the small blocks in the rimwall are also hard to imagine. In the area surrounding the crater, the thickness of impact breccias and terrigeneous rocks is about 130 m and the reference level, i.e. bottom of the Saunja Formation, is approximately at −40 m (Fig. 7). Above the rimwall at Paluküla where the impact breccias and terrigeneous rocks are missing, the reference level is at +21 m or about 60 m higher than in the surrounding area. Inside the crater the complex of impact breccias and terrigeneous rocks is about 260 m thick and the reference level is at −100 m or about 60 m lower than in the surrounding area. Thus, the elevation of the reference level varies by 120 m within the section.

The participation of up to 400-m-thick layer of the post-impact Silurian and Devonian deposits cover cannot be totally excluded, but obviously the pressure of the 2−3-km-thick continental glacier
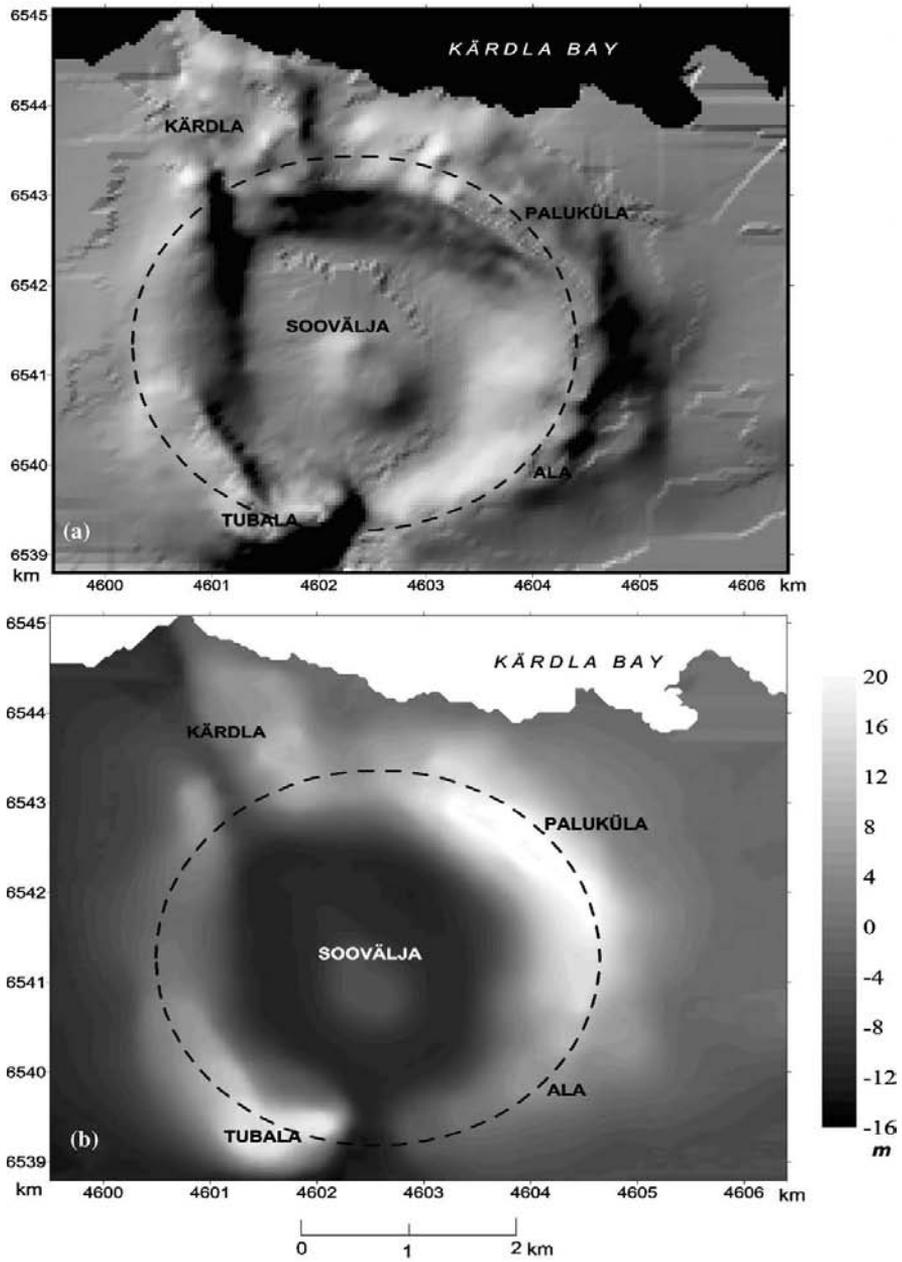
Fig. 4. Bedrock topography of the Kärdla crater area: (a) in isolines; (b) shaded relief. Dashed line—the position of the buried rim.
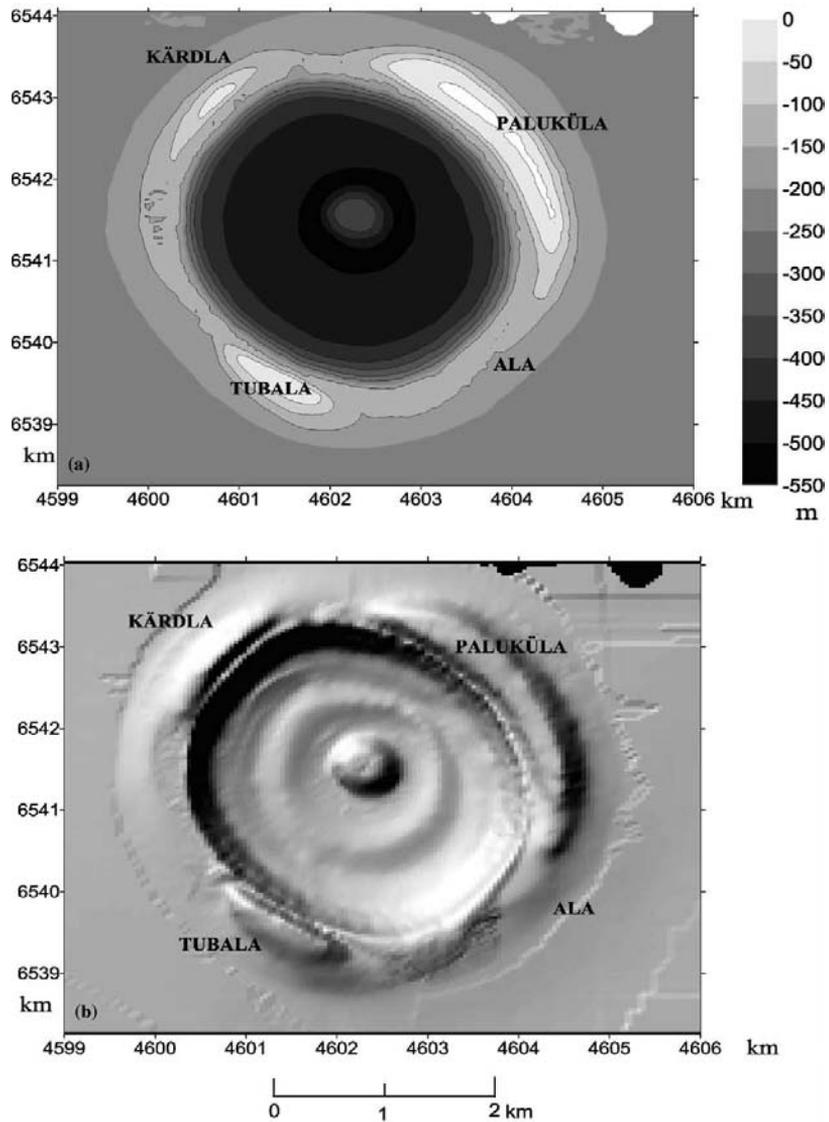
Fig. 5. Basement relief of the Kärdla crater area: (a) in isolines; and (b) shaded relief.

was of greater importance. The pre-compaction porosity of the terrigeneous deposits may have been 30−50%, while their present porosity in the crater area is 15–30%. The subsidence of the crater floor must be taken into account as well. As a result of these processes, the thickness of terrigeneous rocks may have decreased by 30%.
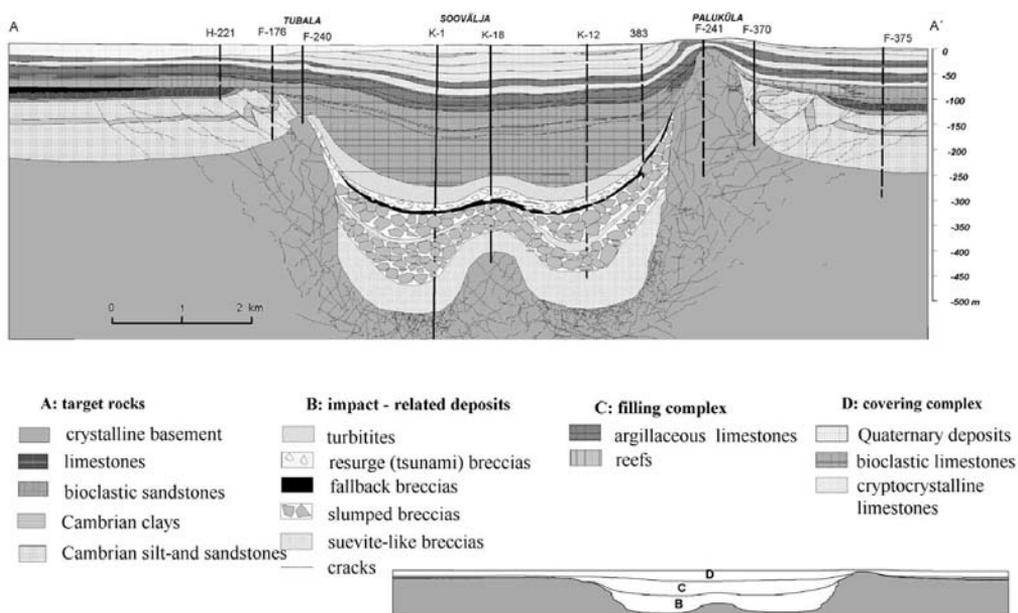
Fig. 6. West–east cross-section A–A′ of the Kärdla crater on the line of drill holes F-240 and F-370. For location of the cross-section see Fig. 2.
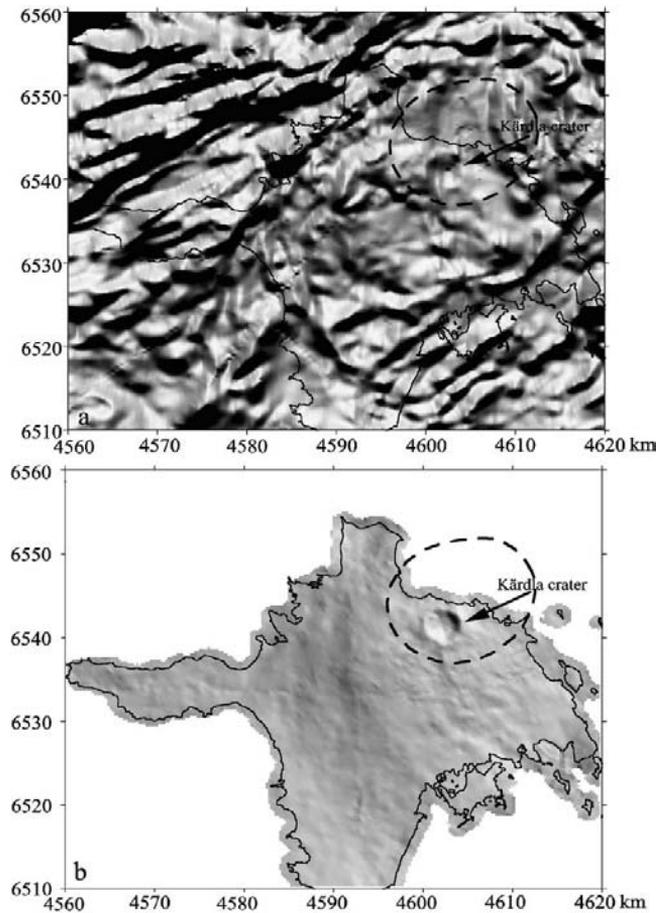
Fig. 7. Potential fields of the Hiiumaa Island: (a) shaded relief of the aeromagnetic field; (b) shaded relief of the gravity (Bouguer) field. Black dashed line—the position of the ringfault.

The buried structure appears quite clearly on gravity, ground and aeromagnetic maps (Figs. 8, 9 and 10). Data for these maps have been recorded at a scale of 1:50 000 (All et al., 1997; Gromov et al., 1980; Suuroja et al., 1991). The maps show negative anomalies over the crater depression that is filled with low-density (average 2.4 g/cm^3) and practically non-magnetic sedimentary rocks. Positive anomalies correspond to the rimwall consisting of magnetic crystalline rocks of higher density (average 2.7 g/cm^3). On the aeromagnetic map (Fig. 8a), the crater structure is weakly expressed. On the gravity (Bouguer) map, the crater appears as a pronounced wall against the background of the rather monotonous gravity field of Hiiumaa Island (Fig. 8b). On the large-scale gravity (residual) anomaly map (Fig. 7), where effects of deep-seated sources have been removed, height differences within the rimwall, as well as the lower areas in its northern and southern parts are clearly visible. As anomalies along the ringfault (Fig. 3) do not occur, we assume that the dislocations
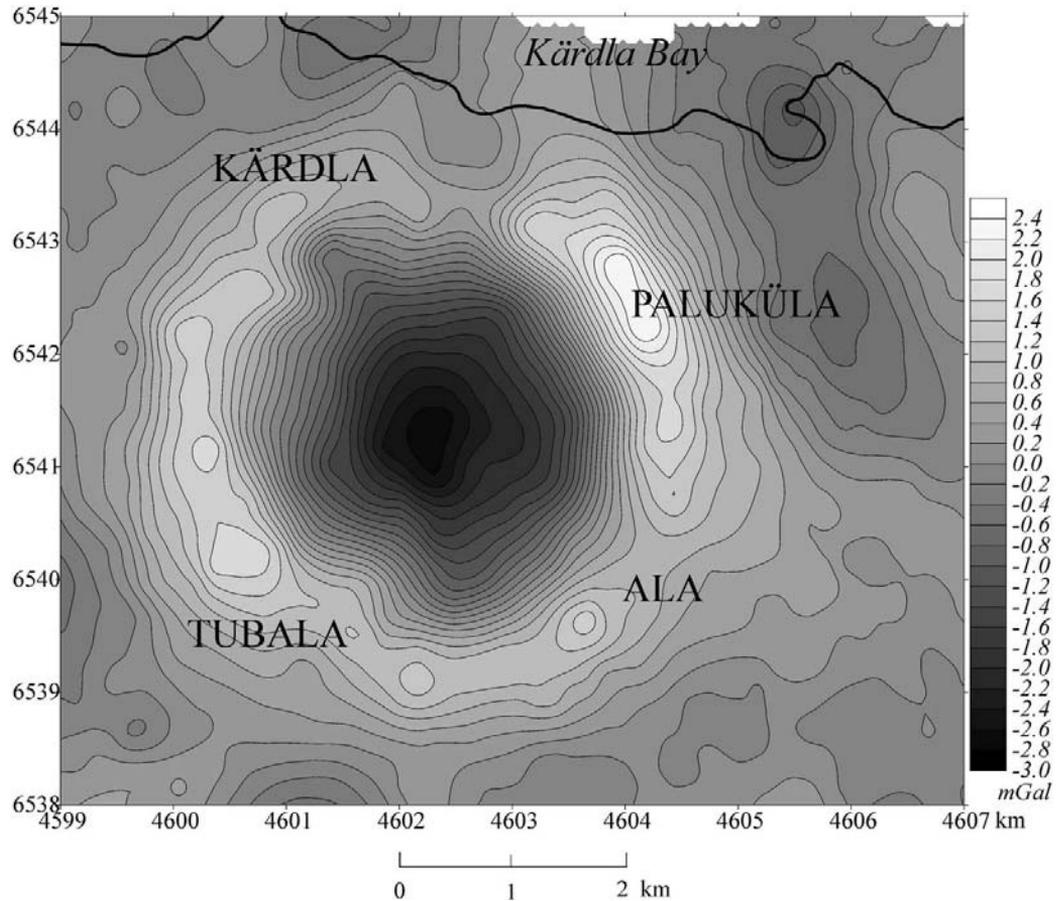
Fig. 8. Residual gravity (Bouguer) anomalies of the Kärdla crater area. Average radius 2 km.

between the rimwall and the ringfault are only present in the sedimentary cover, but do not reach the crystalline basement.

3. The age of the crater and ejecta

The age of the Kärdla impact event is biostratigraphically precisely established (Puura and Suuroja, 1992; Grahn et al., 1996). The impact occurred in the lowermost Caradoc, Upper Ordovician, corresponding to the lowermost part of the Idavere Regional Stage, which according to global stratigraphic charts (Cowie and Bassett, 1989) established a crater age of about 455 Ma. Outside the crater, the impact event is marked in the sequence of limestones by a 0.01–0.5-m-thick ejecta layer consisting of silt- to gravel-sized debris of target rocks (Fig. 7). In the lower part of the layer and closer to the impact centre, coarser clasts also occur. The continuous ejecta layer is distributed within a distance of ca. 30 km from the impact centre. As an admixture to limestones, ejected fine-grained material from Kärdla occurs even farther away. Away from the impact site the grain size of the ejecta decreases, together with a
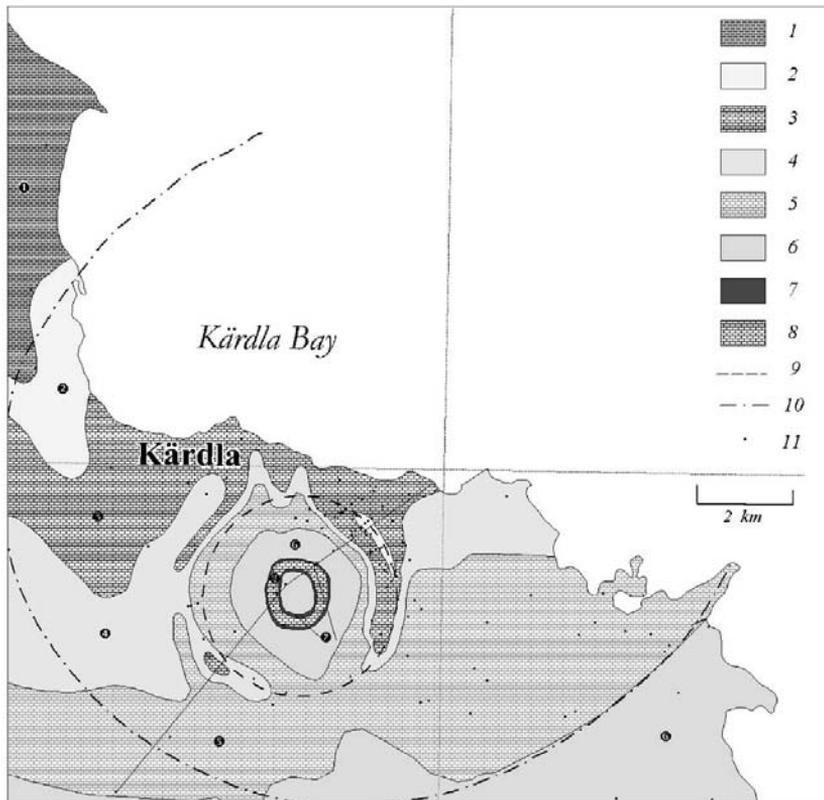
Fig. 9. Schematic bedrock geological map of the Kärdla impact structure area. (1) O_3rg (Rägavere Formation—cryptocrystalline limestone); (2) O_3pk (Paekna Formation—argillaceous limestone); (3) O_3sn (Saunja Formation—cryptocrystalline limestone); (4) O_3kr (Kõrgessaare Formation—limestone); (5) O_3mo (Moe Formation—microcrystalline limestone); (6) O_3ad (Adila Formation—argillaceous limestone); (7) O_3är (ärina Formation—bioherms and bioclastic limestone); (8) S_1vr (Varbola Formation—argillaceous and bioclastic limestones); (9) ridge of the rimwall; (10) ringfault; and (11) drill hole.

decrease in the thickness of the layer. The grain size of the ejecta layer decreases from bottom to top. In the immediate vicinity (up to 5 km) of the impact site coarse clasts (blocks, cobbles, pebbles) are founded. On the outer slope ca. 1 km from the rimwall, a block of brecciated crystalline rocks about 40 m in diameter, was discovered. In the ejecta layer at least two separate beds can be distinguished. The lower, thinner bed consists of angular clasts (silt to pebbles) from the target rocks. The material of disintegrated Cambrian terrigeneous rocks (silt and sandstones) prevails,

but angular debris of basement metamorphics and limestones is recorded as well. Numerous clasts display evidence of shock metamorphism (planar fractures (PF) and PDFs in quartz and feldspar). This layer contains ballistically ejected material. In this 0.01–14-m-thick bed, lying at a depth of 40 m in the northern part of Hiiumaa Island and up to 190 m in its southernmost part, the carbon-rich spherules and microparticles of the projectile (Puura et al., 2000a,b) are found. The upper, thicker part of the ejecta layer consists mainly of the silt and sand fractions of disintegrated
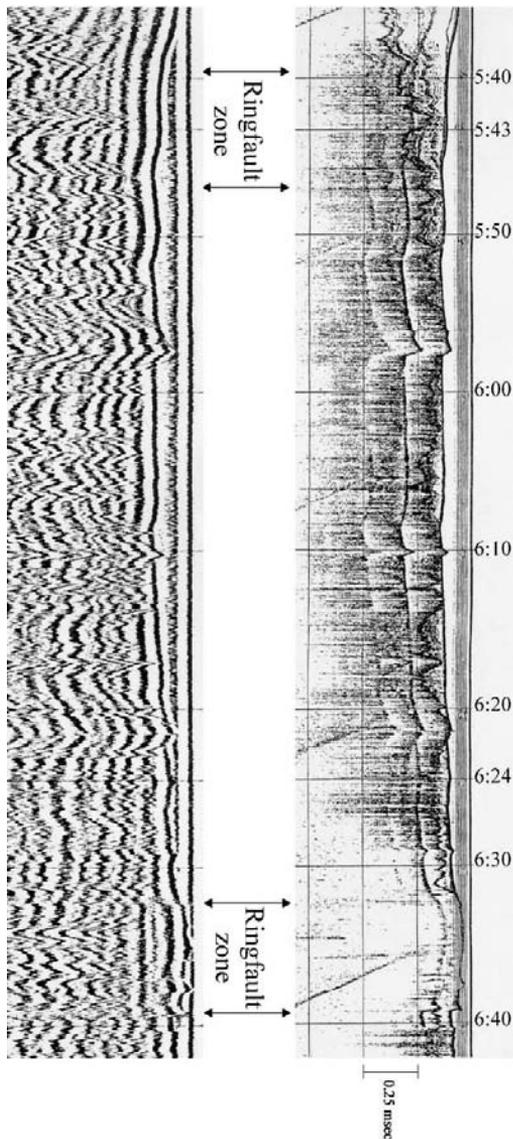
Fig. 10. Seismic reflection profile across the sea area of the Kärdla impact structure: (a) record frequency 250–500 Hz; (b) record frequency 4 kHz. Location of the profile is shown in Fig. 2. Interval between horizontal lines 0.25 ms or 19 m in water.

Cambrian siliciclastic rocks. These were deposited from mud-saturated water somewhat later than the lower part of the layer. Redeposited material from the rimwall and dislocated Cambrian sandstone blocks occur here, especially in the sections closest to the rim. The quartz grains with PF and PDFs are found.

The southward dip of 2–4 m km of the ejecta layer in the bedrock section is related to long-term regional tectonic movements in post-impact time. Original deposition of the ejecta layer, except the nearest surroundings of the crater took place on the very smooth sea floor approximately at a constant depth (about 50 m). The resurge wave did not affect the sea bed and bottom deposits farther than 10 km off the crater rim.

4. Geological setting of the impact structure

The Kärdla impact event took place in an epicontinental sea. Target stratigraphy is well determined from geological mapping and drilling. From top, the target consisted of: (1) sea water; (2) < 0.5 m layer of non-lithified carbonate mud on top of 14 m lithified Ordovician limestones; (3) 8 m of Lower Ordovician and 120 m of Lower Cambrian friable and water-saturated siliciclastic rocks (clays 20 vol%, argillites 1 vol%, siltstones 30 vol% and sandstones 49 vol%); (4) basement consisting of Palaeoproterozoic migmatized metamorphic rocks.

(1) Estimates for the water depth at Kärdla vary from 20 m (Puura and Suuroja, 1992; Ormö and Lindström, 2000) and 50−100 m (Lindström et al., 1992) up to 100 m (Suuroja, 1996). At the time of the impact event the Kärdla target area was situated at the northern margin of an epicontinental sea within the Estonian−Lithuanian Confacies Belt (Männil, 1966). The pre-impact Kukruse regression that resulted in the deposition of algal oil shale (kukersite), was followed by a new transgressive eustatic macrocycle during which bioclastic argillaceous–calcareous mud deposited (Nestor and Einasto, 1997). The depth of the sea at the impact site was evidently greater than that at Kukruse time. However, as the sedimentation depth of the bioclastic argillac-

eous–calcareous mud, varied from some tens of metres up to 200 m and more, we cannot get a conclusive answer to the problem of the water depth. The texture of the pre-impact limestones (seminodular with argillaceous films) at the impact site indicates that these were formed deeper than the zone of tempestites. As the sublittoral environment of the Kärdla site had only a minimal depositional slope, the level of tempestites may have been 30–50 m. The high and well-developed rimwall, however, seems to refer to very shallow water (Ormö and Lindström, 2000). In our calculations the water depth of 50 m was considered.

(2) Up to 14-m-thick section of target limestones consisted of thin to thick-bedded hard bioclastic limestones. Their chemical and physical–mechanical characteristics are rather close to each other: content of CaO—42–50%; MgO—2–4%; insoluble residue—6–30%; volume weight—2.5–2.6 T/m^3; water absorption—1–3%; compressive strength—50–170 MPa (Suuroja, 1996).

(3) In the 120-m-thick section of the Vendian, Lower Cambrian and Lower Ordovician siliciclastic rocks, the following units have been distinguished (from the top): Dictyonema Shale—1 m; weakly cemented quartzose bioclastic sandstone—6 m; interbedded clay- and siltstones with interlayers of fine-grained quartzose sandstones—4–6 m; fine-grained weakly cemented quartzose sandstones—10–12 m; fine-grained weakly cemented quartzose sandstones with thin interbeds of silty claystone in the lower part—18–20 m); silty claystone (70%) with minor interbeds of quartzose silt- and sandstones (30%)—12–14 m; fine-grained quartz-feldspar weakly cemented sandstones and siltstones with thin clay interbeds—28–32 m; fine-grained weakly cemented quartzose silty sandstones dominate in the upper part 35–42 m. In the eastern part of the impact structure 2–6 m thick layer of weakly cemented Vendian quartzose sandstones with a thin (<1 m) basal conglomerate occurs.

(4) The Palaeoproterozoic basement in the target area consists of Svecofennian metamorphic rocks (Gorbatchev and Bogdanova, 1992) that are widely distributed in the whole northeastern part of Hiiumaa Island: metabasites (amphibolites, biotite-amphibole and biotite gneisses) and granitoids (migmatite granites and granitic gneisses). Less frequent are garnet-bearing mica gneisses and quartzites which have been observed only as clasts in the allogenic impact breccias. The whole basement complex is migmatised, granitised and strongly folded. The topmost 5–10 m of the basement was subjected to the Vendian weathering. The exact thickness of the metamorphic complex is unknown, but according to geophysical data it is probably 10 km or more.

Amphibolites are a widely distributed (32 vol%) type of crystalline rocks in the Kärdla crater area (Suuroja et al.,1991; Kivisilla et al., 1999). The content of amphibolites is higher (about 50 vol%) in the surroundings of Paluküla and lower (8%) inside the crater and surroundings of Tubala. The chemical and mineralogical composition of amphibolites of the Kärdla crater area is presented in Table 2. Plagioclase (andesine An 37 to labrador An 53) is rather saussuritised or sericittised. In deeper parts of the weathering crust hornblende as well as plagioclase in amphibolites are in places partly decomposed (replaced by chlorite-carbonate aggregate and impregnated by Fe hydroxides). These alterations might be connected with the weak influence of the impact.

Granitoids are the most widely distributed metamorphic rock type of the Kärdla area (58 vol%). In the chemical composition (Table 3) these granitoids mainly resemble potassium-rich syenogranites (Debon and Le Fort, 1982; Niin, 1997). According to the mineralogical composition (Table 3), the majority of the granitic rocks should belong to normal granites. The apparent incongruence between the mineralogical and chemical aspects of the granitoids is due to very intense changes of plagioclase. Plagioclase has often been subjected to complete sericitisation and pelitisation, effected by outwashing of Na (together with Ca) and replacement by potassium. This feature is common to all target granitoids of the Kärdla crater area, weakening with increasing distance from the impact site. K-feldspar is normally represented by cross-hatched microcline. The plagioclase is albite to andensine, predominantly acid oligoclase. Plagioclase is mostly strongly altered (sericitised and pelitised).

5. Course of the impact

Three main stages can be distinguished in the formation of impact structures (Melosh, 1989): contact and compression, excavation and modification. In marine impacts the resurge stage ought to be added.

Like in other cases, the data about the size and composition of the Kärdla projectile are few and circumstantial. The composition of spherules and microparticles of the projectile found in the ejecta layer and allogenic impact breccias inside and outside the crater (Puura et al., 2000a, b) indicates that the projectile might have been iron-rich. The different heights of the uplifted rimwall, the location of the resurge gullies as well as the asymmetric distribution of the ejecta layer, and ringfault, indicate an oblique impact. The projectile obviously approached from the northeast at an angle of $30-45°$.

As usual, the size and mass of the projectile are difficult to determine. Based on the rim-to-rim diameter of the crater (Gault, 1974; O'Keefe and Ahrens, 1977; Melosh, 1989), the projectile diameter at Kärdla has been taken as equal to 200 m. The penetration depth of a projectile in target is greater for an impact in a water than on hard rock due to lower density of water. The penetration depth in water would be minimum 1.65 times greater than into granitic rock target (Ormö and Lindström, 2000). In the Kärdla case, the situation for the described calculations is more complicated—the impact was oblique and the target complex consisted of four rather different layers. We estimate, based on the amount of the crystalline material in the allogenic clast- and matrix-supported impact breccias ($>95\,\text{vol}\%$), that the projectile exploded in the upper part of the complex of crystalline rocks (at the depth of about 300 m).

The presence of water in the target influenced the morphology of the formed crater as well as the amount of the vapour and melt formed during cratering. A coherent melt lens is missing at Kärdla as in most marine impact craters with the target covered by sedimentary rocks Ames (Carpenter and Carlson, 1997); Chesapeak Bay (Poag, 1997); Flynn Creek (Roddy et al., 1977); Granby

(Ormö and Lindström, 2000); Kaluga (Masaitis, 1999); Kamensk (Movshovich and Milyavsky, 1990); Lockne (Lindström et al., 1996); Mjolnir (Dypvik et al., 1996); Neugrund (Suuroja and Suuroja, 2000); Tvären (Lindström et al., 1994). Dispersed and strongly altered impact melt occurs in Kärdla crater only in the suevites of the crater floor; the melt content very rarely exceeds 20%. Following Grive, 1987, in the Kärdla the melt volume might be $1-2\,\text{vol}\%$ of the totally excavated material. This material (water excluded) had in the Kärdla case a volume of about $3 \times 10^9\,\text{m}^3$, but the volume of observed impact melt is considerably smaller than the calculated one. The steam from the pore water and the CO_2 from the carbonates expanded explosively, and thereby dispersing widely the molten silicates (Kieffer and Simonds, 1980). In this way, suevites and matrix-supported impact breccias with a very low impact melt content were generated.

The rise of the structural uplift of the rimwall and formation of the outer $2-8$-km-wide elliptical zone of dislocations (so-called "outer crater") are obviously also directly connected with the events of excavation stage (Fig. 2). The centre of the elliptical outer crater is displaced by ca. 5 km towards the northeast. The structural uplift of the rimwall, fixed well on the relief of the crystalline basement, is of varying height (50–240 m, Fig. 6). The northern and southern resurge gullies have broken through just at the sites where the uplift of the rimwall is the lowest. In these places, the resurging water partly removed the strewed rimwall, but the core of the rimwall (structural uplift) remained intact. The formation of the gullies in the course of post-impact regional tectonic movements is excluded. A possible explanation could be that the formation of the gullies was favoured by the oblique impact, but structural irregularities of the crystalline rocks should be considered as well.

In the highest part of the rimwall (surroundings of Paluküla) a well-developed overlap, where huge blocks (a few tens of metres in diameter) of basement are tipped over the Cambrian terrigeneous rocks, is preserved. The rimwall consists of the uplifted and fractured crystalline rocks. The drill hole F–241, situated on the rimwall at Paluküla (Figs. 3 and 9), penetrates 248 m (up to

−224 m u.s.l., which is about 25 m below the regular basement level in this place) into fractured crystalline basement rocks without passing through them.

Interesting is the 2−8 km wide zone between the rimwall and ringfault (Figs. 2 and 9), where the sedimentary cover, except limestones, is strongly disturbed—brecciated, fractured, folded, and highly dislocated blocks occur. With increasing distance from the rimwall, the extent of dislocations decreases till the ringfault. On the outer slope of the rimwall, in an about 1 km wide circular zone, a 14-m-thick limestone layer has been completely removed by the subsurface rarefaction wave (Fig. 11). This could not have been due to resurging water, because in some places (e.g., drill hole F–176) disturbed Cambrian terrigeneous rocks of the target are covered by suevite breccias of the ejecta layer. Farther away from this zone, up to the ringfault, the upper beds of the limestone cover are strongly brecciated and contain small clasts of crystalline basement rocks. The extent of this dislocation, also, decreases with the distance from the rim. According to the drilling and geophysical data, the basement there is not brecciated.

The diameter of the transient cavity of the Kärdla crater may have been about 3 km and its depth more than 500 m. The collapse of the inner slopes of the transient gravity released a slump as a result of which in the crater a 40−140 m thick layer of the breccias was formed. Breccias consist of more than 90 vol% of strongly deformed blocks, several tens of metres in diameter, and smaller clasts of the Cambrian siliciclastics. Within the slumps, even smaller blocks of crystalline rocks as well as lenses and clasts of suevite breccias of the crater floor occur, while clasts or blocks of the upper part of the target (limestones) are absent. The layer of breccias and slumps is thinner (up to 40 m) over the central uplift and thicker (ca. 140 m) above the ring depression, which obviously signals that the formation of the central uplift started before the transient cavity had reached its final volume. The existence of a central uplift is proved by drill holes K-1, K-18, K-12 (Fig. 3) as well as by structural characteristics—above the central uplift, the limestone beds covering the crater are elevated

by 5–8 m. The dimensions of the central uplift (diameter ca. 800 m, height ca. 130 m), which were rather difficult to determine due to scarcity of data, nearly correspond to calculated dimensions (Grive et al., 1981; Grive, 1987; Melosh, 1989).

In the Kärdla case the resurge stage, during which mud- and debris-loaded water started to surge back into the crater deep, can be attributed to the modification stage only conditionally because a considerable time break separates it from the other events of the latter stage. Taking into account that the sea floor erosion extends for more than 7 km from the impact centre (Fig. 11), it can be supposed that the water was removed at least to this distance. Approximately from this distance the material ejected, released by the rarefaction wave, and slopes of the uplifted rimwall and non-lithified sea floor were removed by the resurging wave. The removal and tsunami-like collapse (resurge) of the debris-saturated water mass (mudflow) into the crater took at least a few minutes. During that time, inside and in the surroundings of the crater the ejected material was deposited. Thus, in the crater deep the 8–30-m-thick layer of the resurge breccias overlies the 2–14-m-thick layer of fallback breccias (Fig. 9) formed. The fallback breccias consist mainly of shock-influenced clasts of crystalline basement rocks. The resurge breccias consist of clasts and blocks from all the target rocks recovered during the excavation stage, prevailingly (ca. 80%) of the clasts from the topmost part of the target, but some clasts of the suevite-like breccias of the crater floor have been found as well. The content of limestone clasts and blocks in the resurge breccias is up to 40%, while in the ca. 140 m thick target section of sedimentary rocks these makes up only 10%.

6. Discussion

The 455 Ma well-preserved buried Kärdla marine impact structure has been thoroughly studied by drilling (160 wells) and geophysical methods. The stratified target consisting of four layers with different properties (water, Ordovician hard limestones, weakly cemented Cambrian silt- and

◇ - Amphibolites from the surrounding (target rocks)
+ - Granitoids from the surrouding (target rocks)
✳ - Suevite breccias
□ - Weathered crust of the crystalline rocks of the surrounding
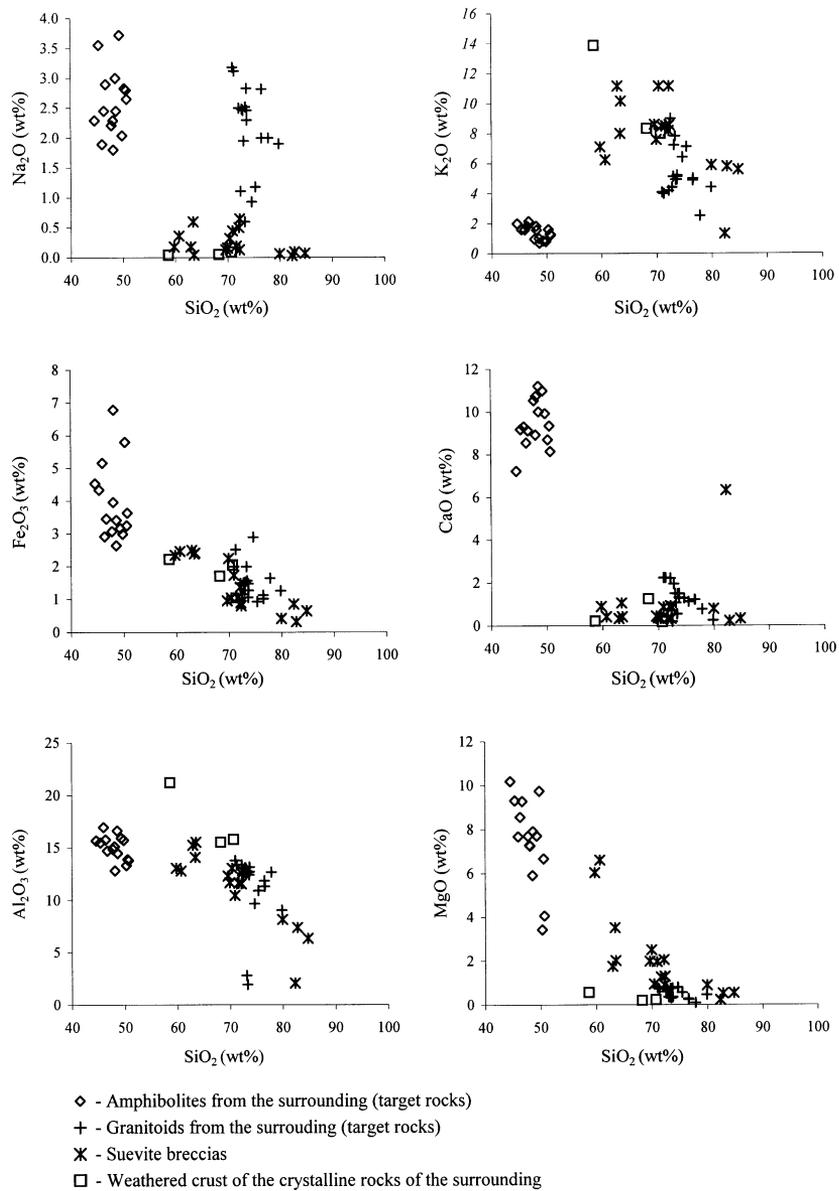
Fig. 11. Harker-diagram variations in silica versus contents of selected major elements (Na_2O, F_2O_3, Al_2O_3, K_2O, CaO, MgO) in target rocks (amphibolites and granitoids), suevite breccias, and the weathered crust of granitoids from the surrounding.

sandstones, Paleoproterozoic crystalline rocks) allows us to constrain impact-related material transport. The height of the structural uplift of the rimwall varies from 50 to 240 m, while the computed height is 160 m. The primal rimwall might have been even higher because a small part of the rim is eroded. Flattening of the rimwall is a common characteristic for marine impact craters (Ormö and Lindström, 2000), but at Kärdla the situation is rather the opposite. The disproportion in the height of the rimwall may result from the oblique impact in a shallow sea.

Exciting problems are connected with dislocations in the area between the rimwall and the ringfault. These dislocations involve only the sedimentary cover and do not reach the basement. The situation is similar in about 535 Ma old Neugrund impact structure (Suuroja and Suuroja, 2000), where the crater, 7 km in rim-to-rim diameter, is surrounded by a ringfault of about 21 km in diameter. At Kärdla, these values are 4 km and 12–15 km, respectively. The ratio of the diameter of the crater to the area surrounded by ringfault is in both cases 1:3. A similar regularity has also been observed in some other impact craters formed in the sea and having sedimentary rocks in the target (Lockne—Lindström et al., 1996; Kaluga—Masaitis, 1999; Mjolnir—Dypvik et al., 1996; Chesapeake Bay—Poag, 1997). It is evident that in the Kärdla case the lateral influence of the shock wave evoked by the impact on the crystalline basement rocks extends farther than that supposed earlier, when this area was limited to the ringfault or 6–7 km from the impact centre (Puura and Suuroja, 1992). The absence of the primal fluid inclusions in minerals (mainly quartz) of the crystalline rocks indicates that these were weakly influenced by the shock wave. Within this area the crystalline basement rocks are to a certain degree fractured and slightly secondary altered. In the Kärdla case this area reaches up to 15 km from the impact centre. This value coincides relatively well with the data observed in some other impact structures (Gardnos—Andersen and Burke, 1996; Manson—Boer et al., 1996; Siljan Ring—Komor et al., 1988; Ries—Newsom et al., 1987; Lockne—Sturkell, 1998). According to Plado et al. (1996), in the Kärdla crater the influence of the impact could reach about 800 m below the crater floor.

In the Kärdla impact breccias the following shock features have been observed: enhanced fracturing of target rocks; shatter cones in sandstones and crystalline rocks; disappearance of primal fluid inclusions; mosaicsism of quartz and feldspar; PF and PDF in quartz, plagioclase and microcline; kink bands in biotite; partial to complete isotropisation of quartz, plagioclase and K-feldspar; diaplectic glass from quartz, plagioclase and K-feldspar; partial or complete melting of granitoids; and occurrence of recrystallied and strongly altered impact melt.

In quartz grains, up to five sets of PDFs of different crystallographic orientations (parallel to $\{1\,0\,1\,3\}$, $\{1\,0\,1\,2\}$, $\{0\,0\,0\,1\}$, $\{0\,0\,1\,1\}$, $\{0\,0\,2\,2\}$) have been observed, indicating a shock pressure of 10–14 GPa (Suuroja, 1999). The presence of melt, however, indicates the pressure of 30–40 GPa (Masaitis et al., 1980; Stöffler and Grieve, 1994; Stöffler and Langenhorst, 1994; Grive et al., 1996). The co-occurrence in a specimen of grains, bearing traces of very different shock stages, is characteristic of the impactites of Kärdla crater as well as others. It is still not clear, whether this is as a result of extensive mixing of shock-influenced rocks or is connected to the peculiarities of shock wave.

The shocked crystalline rocks and impact breccias at Kärdla exhibit an enrichment in potassium and decrease in sodium and calcium. This phenomenon also occurs on other impact craters with similar target lithologies: Ames (Carpenter and Carlson, 1997); Bosumtwi (Koeberl et al., 1994); Boltysh (Masaitis et al., 1980; Gurov et al., 1986); Brent (Grive, 1978); Gardnos (French et al., 1997); Ilynets (Gurov et al., 1998); Jänisjärvi (Masaitis et al., 1980); Kaluga (Masaitis et al., 1980); Lappajärvi (Lehtinen, 1976); Neugrund (Suuroja and Suuroja, 2000); Newport (Koeberl and Reimold, 1995); Saltpan (Koeberl et al., 1994).

At Kärdla, the average K_2O content of amphibolites and granitoids is 1.5 and 4 wt%, respectively (3.5 wt% is average for crystalline rocks of this area). In the suevite breccias, however, the average is 9 wt%. In contrast, Na_2O average content is 2.5 wt% in amphibolites, and 2 wt% in

granitoids (2.2 wt% average for crystalline basement of this area), yet only 0.2 wt% in the suevite breccias.

The average CaO content of amphibolites and granitoids is 9 and 1 wt%, respectively, or 4% for the whole complex of the crystalline rocks. In the suevite breccias the average is 0.5 wt%. Briefly, in the result of the impact in crystalline rocks considerable chemical alteration has been taken place—depletion of Na and Ca and enrichment with K (Puura and Suuroja, 1992; Puura et al., 1996, 2000a, b). Changes in the contents of other major elements (Si, Al, Fe, Mg) are not so clearly expressed. Mineralogically all these alterations can be explained mostly by post-impact decomposition of plagioclase and hornblende. The enrichment of impact breccias with K is associated with the replacement of plagioclase by illite and orthoclase. The enrichment with K is everywhere in good correlation with the decomposition degree of plagioclase. Chemically similar alterations are observed in the weathered granitic rocks (weathering crust) of the surrounding area. The only difference is that in the weathered granitic rocks plagioclase has been replaced mainly with illite or sericite, but in the impact breccias, especially in the suevite breccias, the final product of the replacement often is the K-rich orthoclase. These quite widespread phenomena have been tentatively explained in various ways: by mobilisation of the alkali elements in the post-impact hydrothermal system (Koeberl, 1997; McCarville and Crossey, 1996), by vaporisation processes (Gurov et al., 1998) and by chemical interaction between impact fluids and hard rocks within the fireball (Puura et al., 1996) or impact cloud (Puura et al., 2000a, b).

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The Neugrund Marine Impact Structure (Gulf of Finland, Estonia)

Sten Suuroja[1,2] and Kalle Suuroja[1]

[1]Geological Survey of Estonia, Kadaka tee 82, Tallinn 12168, Estonia.
[2]Department of Mining, Tallinn Technical University, Kopli 82, Tallinn, Estonia.
(s.suuroja@egk.ee)

Abstract. The Early Cambrian (approximately 535 Ma) Neugrund marine impact structure is located on the southern side of the entrance to the Gulf of Finland, immediately eastward of Osmussaar Island, Estonia. The origin of the structure was noted already in 1995 - 1998, but data obtained during the expeditions of 2000 and 2001 have shed new light on its morphology. The impact structure is about 20 km in diameter and spatially delimited by a ring fault between dislocated rocks and mostly intact target rocks. The structure has a central depression (crater deep or crater proper) 5.5 km in diameter, surrounded by a 50 - 100 m high and anomalously wide (2.5 - 3 km) 3-ridge shaped rim wall. The crater deep is filled with post-impact Early Cambrian and Early Ordovician siliciclastic rocks and covered with Middle and Late Ordovician calcareous rocks. The slight (some metres) uplift of limestone beds in the centre of the crater suggests that a central uplift also exists. The Ordovician erosion-resistant limestone forms a circular Central Plateau (Neugrund Bank) above the crater proper about 4.5 km in diameter. The plateau is surrounded by a 200 - 500 m wide and 20 - 70 m deep canyon (Ring Canyon). A 3 - 5 km wide circular depression where the crystalline target rocks are dislocated lies outside the rim wall. Sedimentary target rocks are eroded in the northern part of the structure. Outside the ring fault (outer boundary of the structure), sedimentary target rocks are dislocated within about 10 km, obviously due to the Neugrund impact. The 1 - 2 m thick ejecta layer consists of sandstones with abundant shock-metamorphosed quartz grains with well-developed planar deformation features (PDFs). Erratics consisting of Neugrund Breccia, derived by glacial action from the exposed parts of the impact structure, spread in an area of more than 10 000 km^2.

1
Introduction

The approximately 535 Ma (the age of the structure was determined by using the reconstructions of Torsvik et al. 1992; Tucker and McKerrow 1995 and the International Stratigraphic Chart by IUGS 2000) Early Cambrian Neugrund impact structure (59° 20′ N and 23° 32′ E) is located on the southern side of the entrance to the Gulf of Finland (Figs. 1, 2) about 7 km NE of Osmussaar Island. The structure is about 20 km in diameter and is spatially delimited by a ring fault (Figs. 1, 5). The ring fault runs across Osmussaar Island and serves as a boundary between dislocated target rocks and mostly intact target rocks. It is not visible in recent relief but (Figs. 2, 3, 4) is quite well recognisable in seismic reflection profiles (Fig. 6).
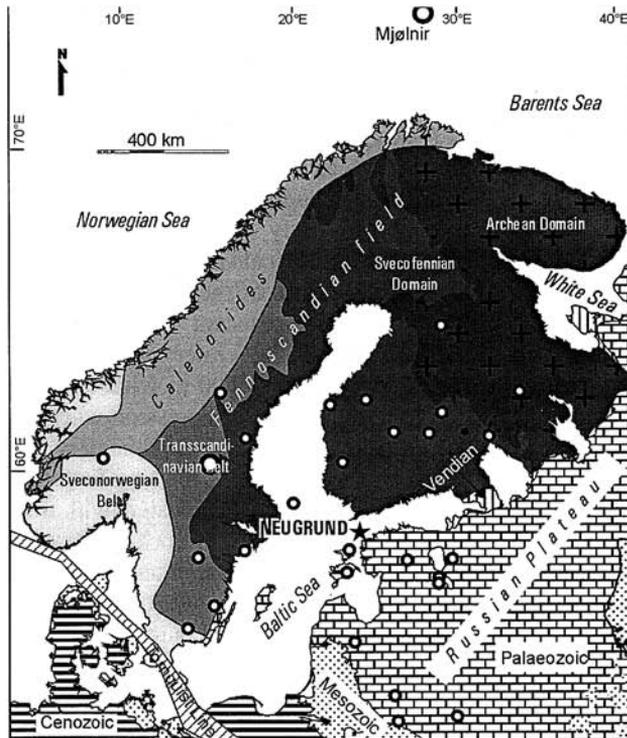
Fig. 1. Location of the Neugrund and other impact structures in the East European Platform. Black star – Neugrund impact structure; rings with a white core – other impact structures.

The impact structure has a central depression 5.5 km in diameter, surrounded by a 50 - 100 m high and 2.5 - 3 km wide 3-ridged rim wall (Fig. 4). A central uplift probably exists in the central depression, which is filled with the post-impact Early Cambrian siliciclastic rocks and covered by Middle and Late Ordovician limestones. There is no firm evidence yet, but slight (some metres) uplift of the infilling limestone in the central part of the crater proper supports this suggestion. The erosion-resistant Ordovician limestone forms a nearly 4.5 km wide circular Central Plateau (Neugrund Bank) over the central depression, which is surrounded by a 200 - 500 m wide and 20 - 70 m deep canyon, the so-called Ring Canyon (Figs. 7,8).
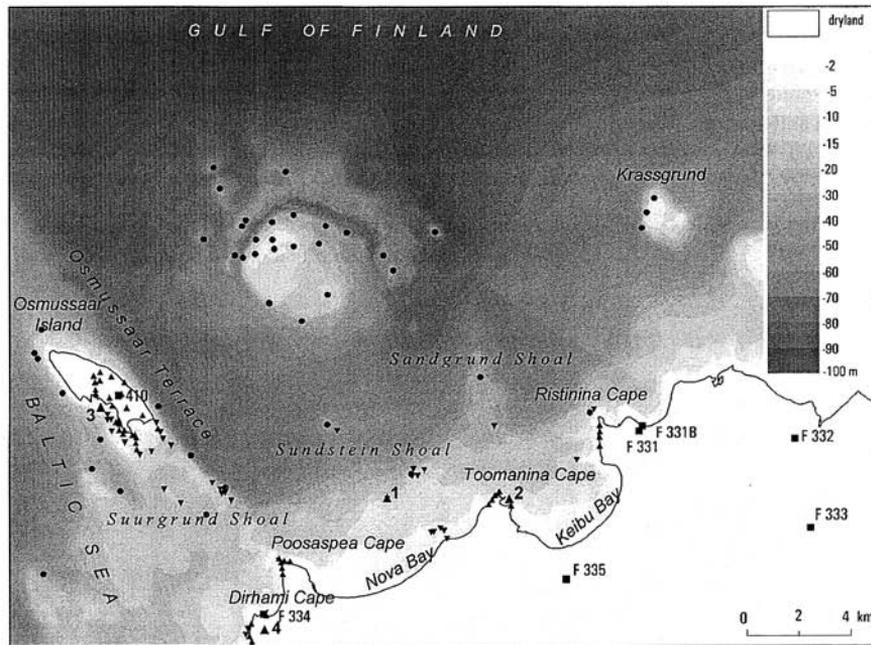
Fig. 2. Bathymetric map of the Neugrund impact structure area. Triangles: small – single, small to big erratic boulders made of Neugrund Breccia; big – gigantic erratic boulders made of Neugrund Breccia (1 = Toodrikivi, ca. 1200 m^3; 2 = Nõva Suurkivi, ca. 400 m^3; 3 = Skarvan, ca.400 m^3; 4 = remnants of Twins of Osmussaar. White marks land. Circles = drill hole and its number. Dots = diving and sampling sites.

The crystalline target rocks are strongly dislocated outside the rim wall in a 3 - 5 km wide circular area. These rocks are eroded, especially in the northern part, up to 10 km outside the impact structure. Beyond the ring fault, the sedimentary target rocks (Early Cambrian clay- and sandstones) are, in places, disturbed within 2 - 30 m of the upper part of the section, most likely due to the Neugrund impact event. Above the disturbed strata, a 1–2 m thick layer of post-impact silt- and sandstones occurs over thousands of square kilometres in Northwest Estonia. These sandstones contain abundant shock-metamorphosed quartz grains with well-developed planar deformation features (PDFs) and evidently represent the ejecta layer of the Neugrund impact.

The discovery of the Neugrund impact structure was based on the information obtained in the course of integrated geological and geophysical mapping at the NW Estonian coast in 1983–1999. The results of these investigations are presented in numerous reports (Malkov et al. 1986; Suuroja et al. 1987; Suuroja et al. 1998; Suuroja et al. 1999; Talpas et al. 1993) and papers (Suuroja et al. 2001b). The existence of an impact structure in this area was first suggested in 1995 (Suuroja and Saadre 1995). In 1996, this hypothesis was confirmed by seismic reflection profiling and in 1998 by direct submarine observations. The shock-metamorphic features in the brecciated crystalline rocks were studied some time later

(Suuroja and Suuroja 2000).
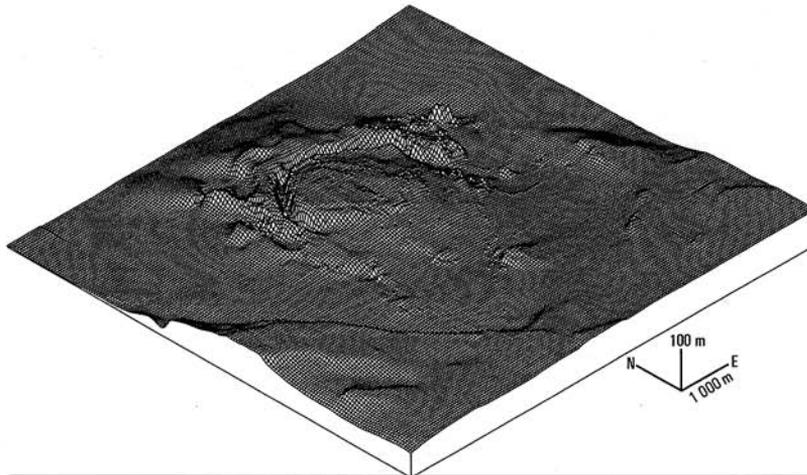
Fig. 3. 3D diagram of the topography of the Neugrund structure area.
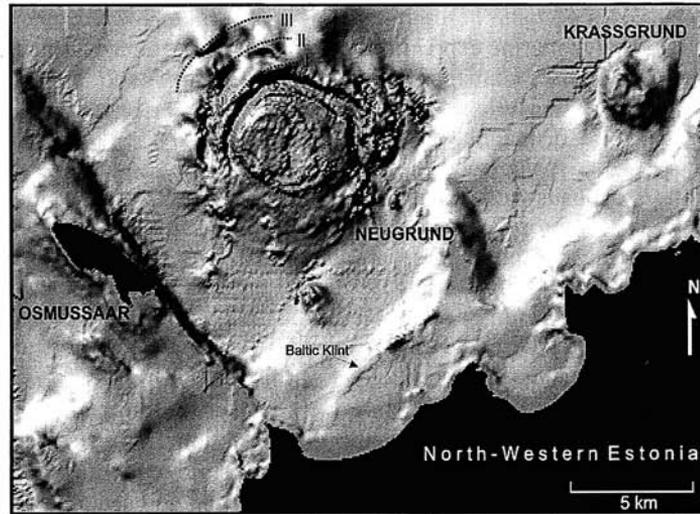
Fig. 4. Shaded relief of the Neugrund impact structure area. Ridges of several parts of the rim wall are marked by Roman numbers. Land is in black.
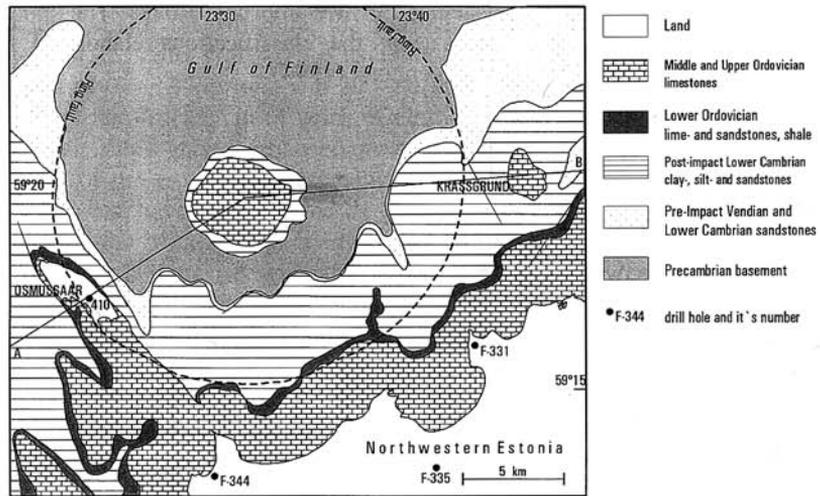
Fig. 5. Schematic bedrock geological map of the sea floor of the Neugrund impact structure area.

It was also established that the Neugrund and nearby Kärdla Palaeozoic marine impact structures had many similar features (Suuroja et al. 2001).

In 2000 and 2001 five marine expeditions to the Neugrund impact structure and its surroundings were carried out (four on board the r/v "Mare" and one on board the r/v "Skagerak"). The following methods were used: seismic reflection profiling – about 300 km; magnetometric profiling – about 200 km; observing submarine outcrops by a video robot; side scan sonar profiling – about 100 km; sampling of bottom deposits with gravity corer and scarp – at 52 sites; sampling of submarine bedrock outcrops during divings – 54 samples. Unpublished interpretations of some reflection profiles (about 120 km) have been provided earlier (Malkov et al. 1986; Talpas et al. 1993), and they are used also here (Figs. 6, 7, 8).

Based on the results of these and earlier expeditions, as well as mineralogical analyses, some concepts about the morphology of this old, but well-preserved and partially exposed submarine impact structure were revised. Additionally, the area of the distribution of erratics derived by the glacial action from the Neugrund impact structure was studied. In all, 1020 erratic boulders over 1 m in diameter, consisting of Neugrund Breccia, were observed over a land and sea area of some hundred square kilometres (Fig. 10).

The present paper gives a more detailed characterization of the morphology of the Neugrund impact structure (central depression, rim wall, circular depression, zone of farther dislocations, distal ejecta). The classification and nomenclature of shock-metamorphic rocks follows that proposed by Stöffler and Grieve (1996) to the IUGS Subcommission on the Systematic of Metamorphic Rocks. The shock-metamorphic stages were determined using the classifications elaborated by Grieve et al. (1996) and Stöffler and Langenhorst (1994).

2
The Rim Wall

The well-exposed rim wall is the best-preserved and most studied part of the Neugrund impact structure (Figs. 4,7,8). In the present relief of the sea floor there are 3 circular ridges of glacier-eroded 30 - 60 m high hillocks, where brecciated Precambrian metamorphic rocks crop out (Figs. 5,8,13). The preserved but strongly eroded rim wall is 60–120 m high and 2.5 - 3 km wide. The initial height of the rim wall might be 2 or 3 times higher. In the southern part of the structure the rim wall is more eroded and mostly buried under Quaternary (Pleistocene) deposits. The northern part of the impact structure, as well as the rim wall, was generally uplifted at post-impact time and the entire structure area has an incline of 3 m per km to the S or SW.

Nine hillocks were investigated in the rim wall area at depths of 16 - 34 m and sampled directly by diving (Figs. 2,13). The entire area, where the rim wall cropped out, was investigated by side-scan sonar, and seismic reflection profiling (Fig. 6). These investigations showed that the rim wall consisted of brecciated

Precambrian (Palaeoproterozoic) metamorphic rocks (amphibolites, migmatite granites, gneisses), penetrated by veins and bodies of clast- and matrix supported impact breccias containing shock-metamorphosed quartz with PDFs (Fig. 9d) and signs of partial melting.

The depressions between the hillocks or different parts of the rim wall are mostly buried under Quaternary (Pleistocene) glaciolacustrine deposits – varved clays. As suggested earlier (Suuroja and Suuroja 2000), the deformed Early Cambrian and Late Vendian siliciclastic pre-impact target rocks were not found in these depressions.

A more detailed characterisation of different parts (ridges) of the rim wall is given below.

1) The first, or so-called Inner Wall is 400–800 m wide at the base, 30 - 100 m high and has a rim-to-rim diameter of 6.5 km (Figs. 4,8) This is the best preserved and undisturbed part of the rim wall consisting of slightly brecciated Precambrian metamorphic target rocks penetrated by veins of clast- and matrix supported impact breccias, containing shock-metamorphosed quartz with PDFs. In the southern part of the structure, the inner wall is lower (30 - 60 m) and buried under Quaternary (Pleistocene) glaciolacustrine (varved) clays. In the south-eastern part of the structure, an approximately 0.5 km wide and 100 m deep gully cuts through the Inner Wall, as well as the other two walls (Figs 2, 4).

2) The second, or so-called Middle Wall is 0.5 - 1 km wide, 20 - 50 m high and has a rim-to-rim diameter of 9 km (Fig. 4). It has a common base with the Inner Wall but is separated from the latter by a 0.3 - 1 km wide irregular (largest in the western and narrowest in the eastern parts of the rim wall) depression. In the southern part of the structure, the Middle Wall as well is buried under varved clays. The Middle Wall is not as monolithic and intact as the Inner Wall. It consists of 0.5 - 2 km long and 20 - 80 m high hillocks of brecciated crystalline (metamorphic) rocks, cut of veins of clast- and matrix supported impact breccias containing shock-metamorphosed quartz with PDFs.

Most of the erratic boulders consisting of Neugrund Breccia, found so far in West Estonia, have been derived by glacial activity from this part of the rim wall. Generally, the Middle Wall is lower and more fragmentary than the Inner Wall. The reasons for this irregularity are not known; these can be primary (have contained soft siliciclastic rocks) or secondary (higher rate of erosion).

3). The third, or so-called Outer Wall, with a rim-to-rim diameter of about 12 km, consists of 1 - 1.5 km wide and 40 - 100 m high hillocks, which are separated from the Middle Wall by a 50 - 80 m deep and 1 - 1.5 km wide depression (Fig. 4). This part of the rim wall is most strongly eroded and deeply buried under the Quaternary deposits (varved clays). Thus, its remnants are observable only at four sites in the northern part of the structure. This allows us to suppose that the Outer Wall was primarily more monolithic and the irregularities appeared due to the prevalence of soft pre-impact siliciclastic rocks (silt- and sandstones) in the part of
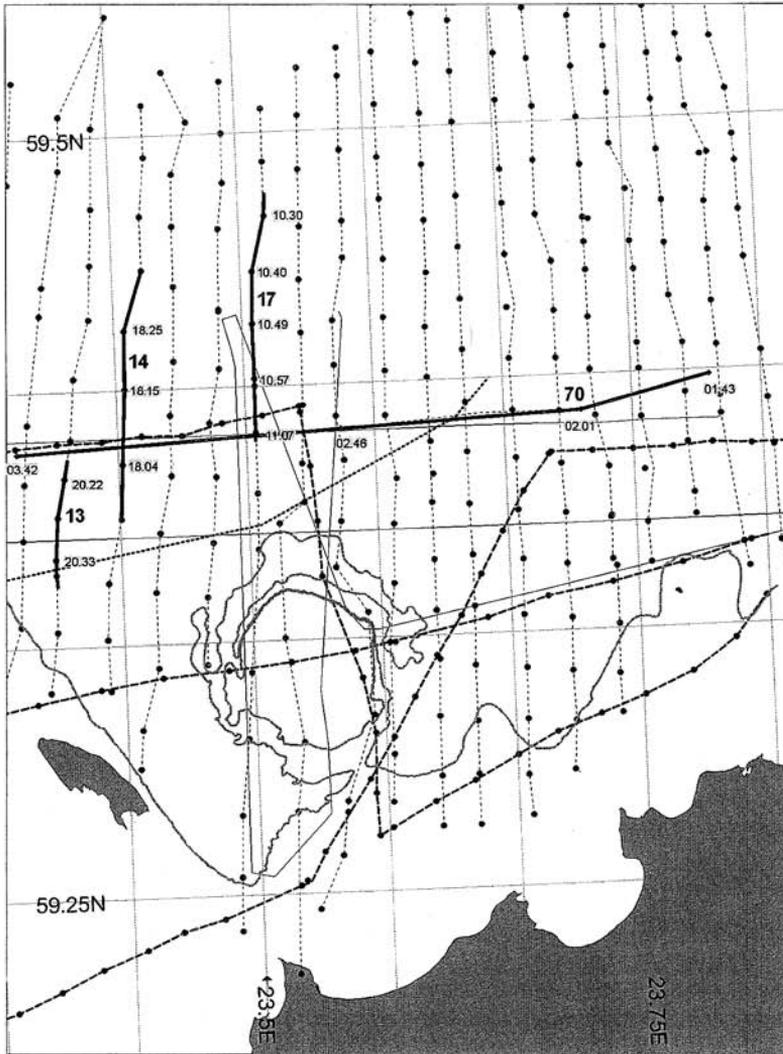
Fig. 6a. Location of the seismic reflection profiles on the Neugrund impact structure area. Bold lines are profiles given in Fig. 6 b.
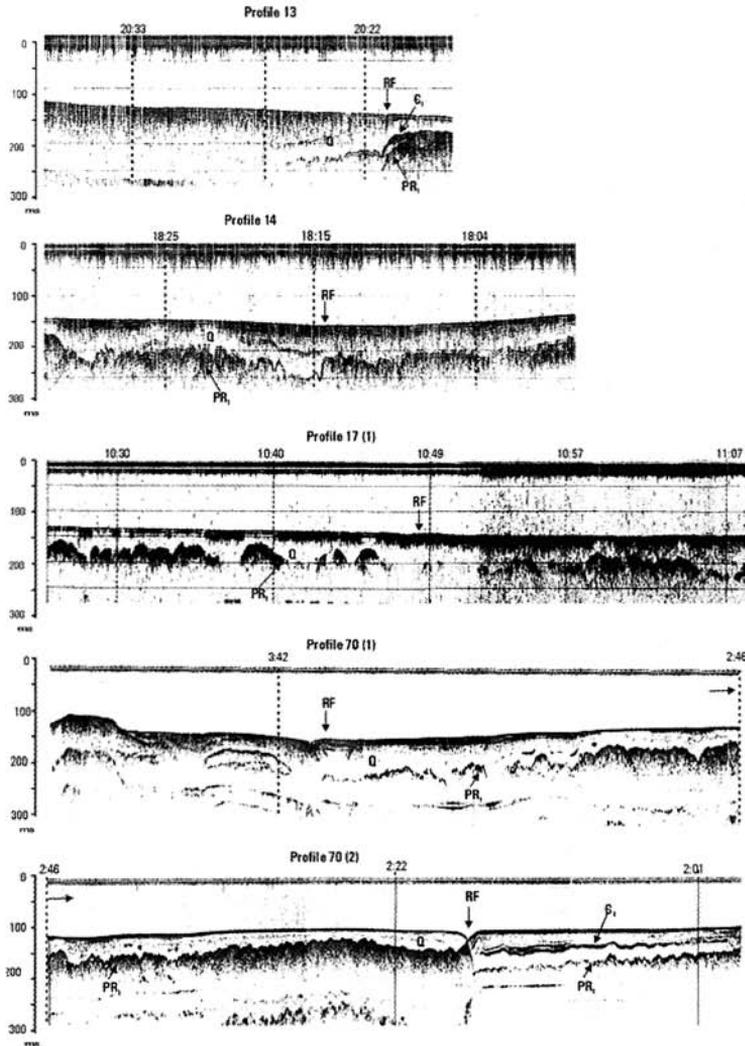
Fig. 6b. Fragments of the seismic reflection profiles crossing the Neugrund impact structure. Profiles were carried out by the r/v "Marina": profiles 13, 14, 20 - Talpas et al. (1993); profile 70 – Malkov et al. (1986). Space between horizontal lines 50 mm/sec or ca 36 m in water; space between vertical lines 220–260 m per minute. Record frequency 400–800 Hz. Q – Quaternary deposits; C_1 – pre-impact Early Cambrian; PR_1 – Precambrian (Palaeoproterozoic) basement; RF – ring fault.

the rim wall that later became eroded. The outcrops of the Outer Wall were sampled only at two points. The rocks are similar to those of the Inner and Middle walls – brecciated Precambrian metamorphic rocks with veins of clast- and matrix supported impact breccias containing shock-metamorphosed quartz, with PDFs.
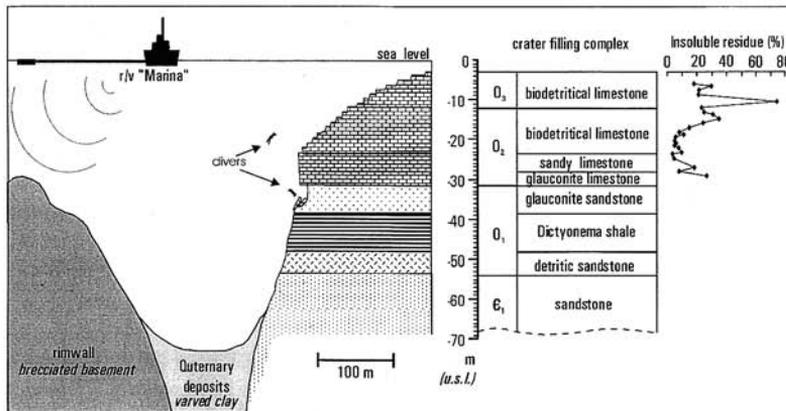
Fig. 7. The cross-section of the Ring Canyon. Vertical exaggeration is five times.
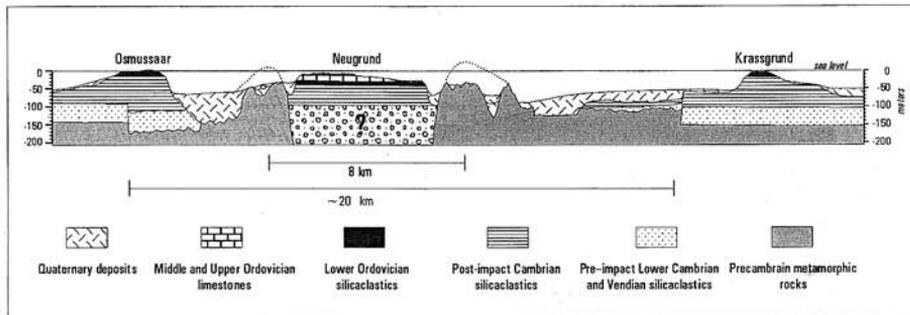
Fig. 8. West – east cross-section of the Neugrund impact structure.

3
The Circular Depression and Ring Fault

The target rocks, both sedimentary (siliciclastic) and crystalline, are dislocated in a 3 - 5 km wide circular area around the rim wall, called the circular depression. The bedrock relief of this area is strongly jointed due to uneven displacement (sinking) of huge (hundreds of metres in diameter) blocks of crystalline rocks during the impact. In the recent sea floor relief, these buried irregularities are not particularly expressed, but are well visible in seismic reflection profiles (Fig. 6). The dislocated bedrock is everywhere in this area buried under a 10 - 50 m thick layer of the Quaternary (Pleistocene) glacio-lacustrine deposits – varved clays, and in the southern part of the area also under the post-impact deposits. The crystalline target rocks lie at a depth of 160 - 180 m in the western part of the depression and at a depth of 100–130 m in its eastern part. The eastern part of the structure is uplifted by up to 60 m in relation to the western part (Fig. 8). The regional slope of the Precambrian basement in this region is 2–3 m per km south- or south-eastward (Suuroja et al. 1999).

The ring fault has been treated as the boundary between the disturbed rocks and mostly intact target rocks, but this does not mean that deformations do not occur farther away, especially in the sedimentary target rocks. In the recent bedrock topography, the ring fault is expressed as a 10 - 60 m high terrace, mostly buried under the Quaternary deposits and, therefore, not observable everywhere. In the southern part of the structure, the ring fault is also buried under the post-impact Lower Cambrian siliciclastic deposits. The crystalline basement in the north-western part of the structure, outside the ring fault, is uplifted by up to 50 m, but in the eastern part of the structure has sunk some 20 - 40 m. In the seismic reflection profiles, the ring fault in the crystalline basement is well observed only in the northern part of the structure and was identified in 15 profiles at 24 sites. The best results were obtained in areas where the thickness of the covering sedimentary rocks and Quaternary deposits is least (0 - 30 m) and depth of water is greater (30 - 110 m). In the southern part of the structure, the ring fault is not observable in seismic reflection profiles, due to shallow water (10 - 20 m) and a thicker (60 - 80 m) sedimentary rock cover.

4
The Zone of Distal Deformations

The metamorphic rocks of the Precambrian basement are disturbed within the area delimited by the ring fault, while the pre-impact sedimentary siliciclastic rocks are sporadically dislocated farther away, at radial distances of up to more than 20 km from the impact centre. In the section of drill hole F-332 (Vihterpalu), 20 km to
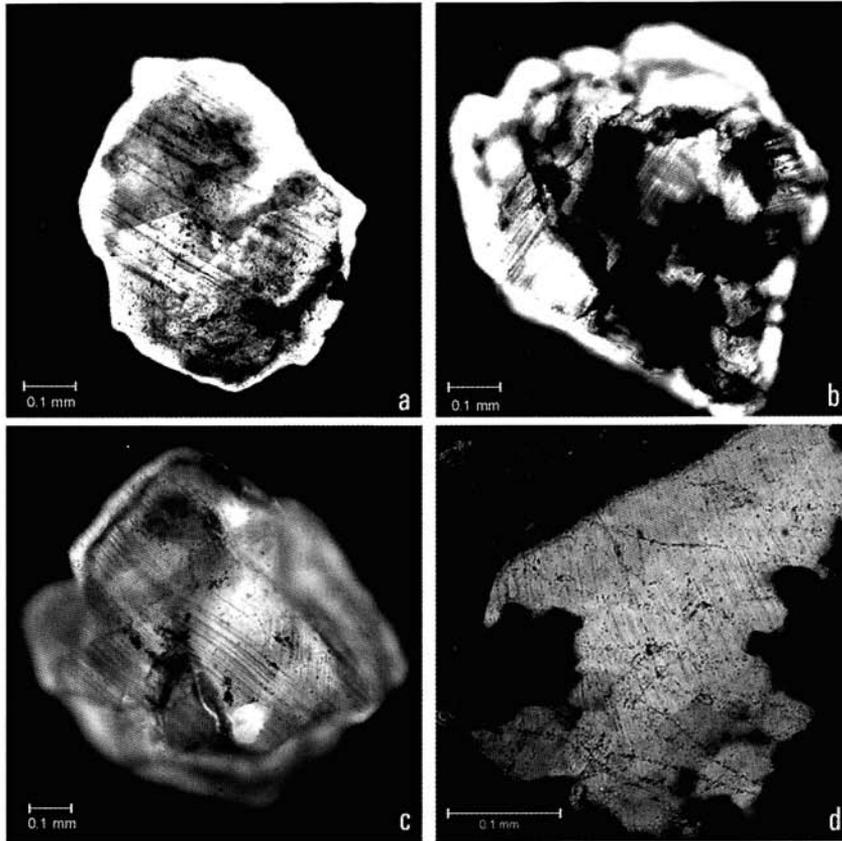
Fig. 9. Shock-metamorphosed quartz grains with multiple PDFs from the impact-related rocks of the Neugrund impact structure: a) Subrounded quartz grain with 1 set of decorated PDFs, separated from the brecciated target rocks (Early Cambrian clay- and sandstones) at a distance of 15 km from the impact centre. Sample 331-100 from drill hole F-331, at a depth of 100.0 m. In immersion liquid, cross-polarised light. b) Subrounded quartz grain with 3 sets of decorated PDFs, separated from the brecciated target rocks (Early Cambrian clay-and sandstones) at a distance of 15 km from the impact centre. Sample 331-40 (drill hole F-331 at a depth of 94.0 m). In immersion liquid, cross-polarised light. c) Subrounded quartz grain with 2 sets of decorated PDFs, separated from the distal ejecta at a distance of 15 km from the impact centre. Sample 331-08 (drill hole F-331 at a depth of 90.8 m). In immersion liquid, cross-polarised light. d) Quartz grain with 3 sets of slightly decorated PDFs. Sample N99-A1 from a vein of matrix supported impact breccia from the brecciated crystalline basement rocks of the rim wall at a depth of 24.2 m. Thin-section, cross-polarised light.

the south-east of the impact centre, the Early Cambrian pre-impact silt- and claystones of the Lontova Formation at depths of 100 - 110 m are slightly brecciated. Similar deformations at the same stratigraphical level are observed in the section of drill hole F-335, 22 km south of the impact centre. In the area of Ristna Cape, 3 km south-east of the ring fault or 12 km from the impact centre (Fig. 2), the pre-impact clay- and siltstones of the Lontova Formation are brecciated in the sections of drill holes F-331 and F-331A at depths of 92 -120 m. This breccia contains angular clasts of Vendian sandstones (5 - 20 cm in diameter) and Precambrian metamorphic rocks (0.5 - 5 cm in diameter).

Sandy fractions (0.063 - 0.5 mm) derived from this breccia matrix contain quartz grains (on average about 4% of total quartz) with well-developed PDFs (Fig. 9a, 9b). Up to four sets of PDFs with a frequency of 200 - 400 lamellas per 1 mm can be observed. The PDFs are most numerous (up to 8% of total quartz) in the 0.5 - 0.25 mm fraction and among subrounded grains (up to 5%). Planar deformation features are observed also in grains of apatite (up to 20% of the total apatite) and plagioclase.

The brecciated layer is absent in the section of drill hole F-331B, 200 m north-east of drill hole F-331 and closer to the impact centre. The corresponding rocks are only slightly crushed for some metres below the ejecta layer. Consequently, this breccia layer is not spread evenly. These deformations are connected with the Neugrund impact event. The crystalline basement in this area appears to be intact, but how should one explain the presence of the angular clasts of metamorphic rocks, undoubtedly derived from the crystalline basement of this area, more than 60 m higher, above the intact sedimentary rocks?

5
Distal Ejecta

The distal ejecta of the Neugrund impact event are not as well recognizable as those of the nearby Kärdla impact event (Fig. 10), where the sandy layer of impact-related deposits lies between limestone beds over thousands of square kilometres around the crater (Suuroja et al. 2000). Nevertheless, we have a reason to believe that the 1 - 2 m thick basal layer of the Early Cambrian siliciclastic deposits (silt- and sandstones of the Sõru Formation) may be the distal ejecta of the Neugrund impact event. This relation does not apply to the entire Sõru Formation, because the thickness of the Sõru Formation (1 - 2 m at a distance of 10 -20 km from the impact centre) increases farther away from the impact centre. In Hiiumaa Island, 80 km west of the Neugrund impact centre, the thickness of this layer is up to 20 m. In core sections of drill holes closest to the impact centre (F331and F331A- Ristna, distance between the drill holes is only 5 m, F332-Vihterpalu, 410-Osmussaar) the 1 - 2 m thick Sõru Formation, consisting of fine-grained microbedded quartzose sandstone and above-lying deformed pre-impact Early Cambrian claystones, contains abundant shock-metamorphosed minerals, especially quartz grains with well-developed PDFs.
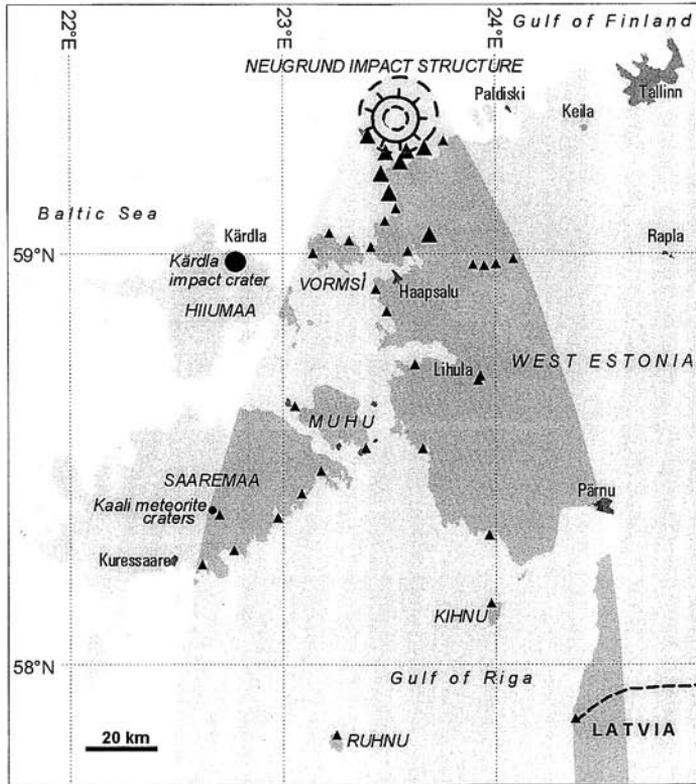
Fig. 10. Distribution of erratic boulders derived by glacial action from the exposed structures of the Neugrund Impact Structure. Large black triangles = numerous Neugrund Breccia boulders; small black triangles – rare Neugrund Breccia boulders.

For example, in drill core F331 at a depth of 90.8 m, 13 km to the south-east of the impact centre, up to 8 % of total quartz in the fraction 0.5 - 0.25 mm is represented by subrounded and rounded grains with PDFs. Here, up to 4 sets of PDFs with a frequency of 200 - 400 lamellas per 1 mm are also observed (Fig. 9c). Among fine fractions (0.063 - 0.25 mm) and subangular and well-rounded grains the shock-metamorphosed quartz grains are far less numerous (ca. 1 vol%) or may be completely absent just like amongst angular grains. The shape and fractional composition of the quartz grains with PDFs indicate that these are derived from the Early Cambrian or Vendian pre-impact siliciclastic target rocks and not from the crystalline basement of the target.
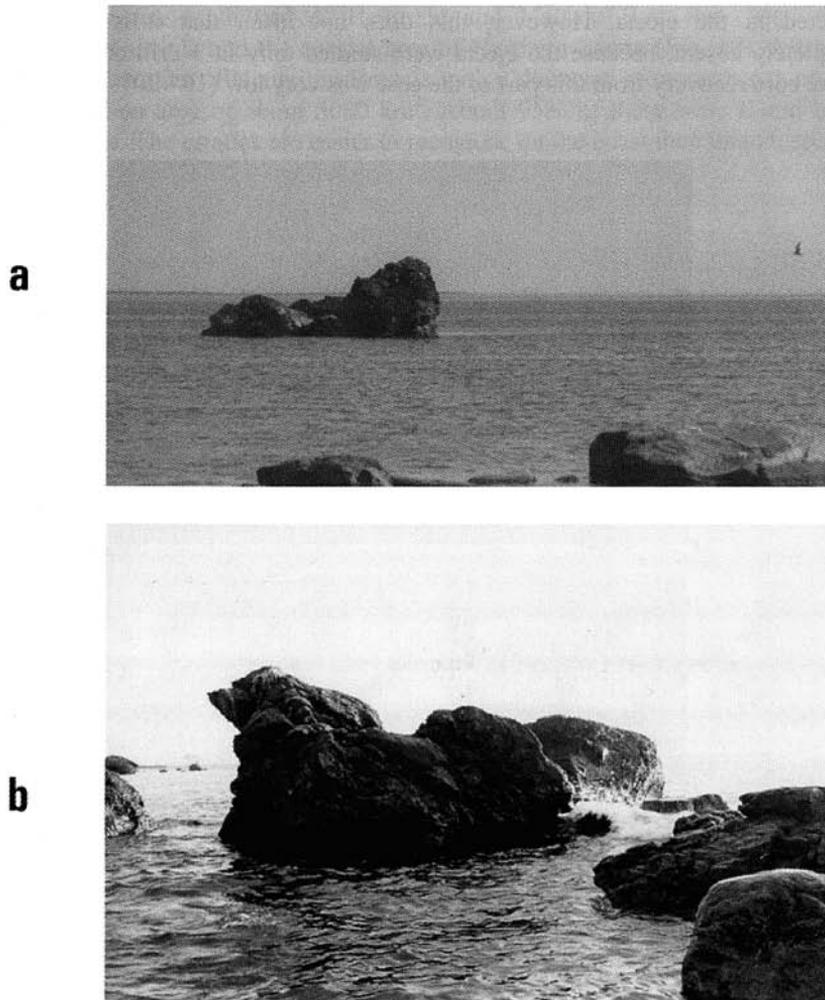
Fig. 11. Some erratic boulders of Neugrund Breccia derived by glacial action from the impact structure: a) "Skarvan" (ca 400 m^3) - on the west coast of Osmussaar Island; b) Nõva Suurkivi (ca 400 m^3) – on Põõsaspea Cape.

Farther from the impact centre, the distal ejecta form only a minor part of the Sõru Formation. The ejecta layer in the Neugrund case is deposited in water and consists mostly of pulverized pre-impact siliciclastic deposits, which at the time of the impact formed the about 100 m thick topmost part of the target (Suuroja et al.

2001b). As yet, no material derived from the crystalline target rocks has been detected in the ejecta. However, this does not mean that it is necessarily completely absent, because the ejecta were studied only in 3 drill core sections, where core recovery from this part of the core was very low (10 - 20%).
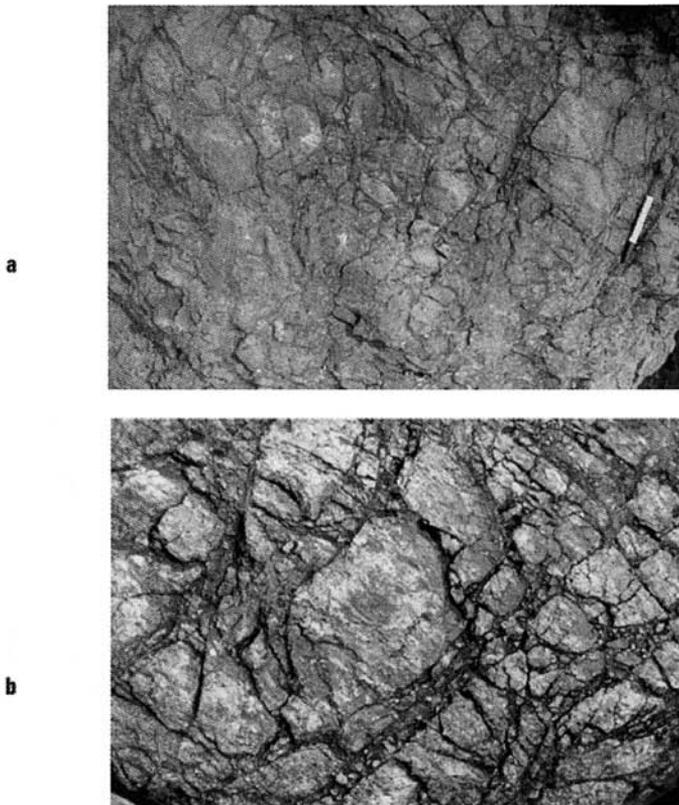
Fig. 12. Samples of the Neugrund Breccia from the erratic boulders of Toomanina Cape: a) brecciated granitoid; b) brecciated biotite gneiss. Pencil (13 cm) for scale in both a and b.

6
Distribution of Erratics of Neugrund Breccia

The distribution of erratics of Neugrund Breccia, derived from Pleistocene glacial action from the exposed areas of the impact structure, was studied in the course of the expeditions of 2000 and 2001. The following new sites were discovered: the shallow sea westward of Osmussaar Island, the coast between Cape Dirhami and

Riguldi village, Vormsi Island, surrounding of Rohuküla Harbour, Muhu Island, the coastal area southward of Haapsalu and Matsalu Bay, the coast of the Tõstamaa Peninsula and the coastal area of Northern Latvia (Fig. 10). A total of about 1000 erratics of Neugrund Breccia with a diameter of more than 1 m were observed in an area of about 5000 km^2. About 95% of these were found in the coastal areas. The erratics are easier to recognise on the coast than inland, so these numbers do not reflect the real pattern of distribution.

Fig. 13. Continental glacier eroded Inner Wall of the Neugrund impact structure, at a depth of 25 m.

The size of the erratics varied from small cobbles (smaller ones are not recognisable) to large boulders (diameter more than 10 m). Toodrikivi, the biggest erratic boulder (about 1200 m^3) in the Quaternary glaciation area of Eastern Europe (Fig. 2, 11), lying on the submarine Sandgrund Bank 5 km south of the rim wall, consists of Neugrund Breccia, as do gigantic boulders Skarvan (initial volume about 400 m^3) on the west coast of Osmussaar Island (Fig.12) and Nõva Suurkivi (about 400 m^3) on the coast of Toomanina Cape (Fig. 11). A total of 2120 erratic boulders, more than 1 m in diameter, were observed in a 6 km long and about 300-m-wide coastal zone between Cape Dirhami and Riguldi village. About 10% of these (210) were of Neugrund Breccia. Eleven boulders were larger than 5 m in a diameter.

By the composition of the clasts the following types of Neugrund Breccia erratic boulders were differentiated: amphibolitic (45 vol%); gneissic (25 vol%); granitoidic (18 vol%), migmatitic (12 vol%).

The distribution area of these erratics was limited by the Neugrund Breccia occurrences on Ruhnu Island and the coast of North Latvia, respectively 150 and 180 km from the impact structure. The north–south stretched shape of the area obviously indicates the movement direction of the last continental glacier sheet (Fig. 10).

7
Discussion

As a result of marine geological and geophysical investigations carried out in the Neugrund impact structure and the surrounding area in 2000 and 2001, the interpretation of the morphology and measurements of the structure has changed. Calculations of the impact energy and definitions of immeasurable parameters are almost always based on the rim-to-rim diameter of a structure (Dence 1973; Deutsch and Schärer 1994; French 1998; Grieve 1987; Melosh 1989; Melosh and Ivanov 1999; O'Keefe and Ahrens 1997; O'Keefe and Ahrens 1999; Pike 1985; Poag 1997; Tsikalas et al. 1998). The rim-to-rim diameter of the Neugrund structure is not easy to determine, because it has an extremely wide (up to 3 km) 3-ridged rim wall and a 20 - 21 km wide outer rim or ring fault outside it. Moreover, dislocations in the pre-impact sedimentary cover, obviously connected with the Neugrund impact event, can be detected outside the outer rim up to a distance of 20 km from the impact centre. The ring fault (limit of the outer wall) separates the area where crystalline target rocks are dislocated from the area where these are mostly intact.

What is the real rim-to-rim diameter of the Neugrund impact structure that could be used in all calculations: the 6.5 km wide ridge of the inner and best-preserved part of the rim wall (Inner Wall), the 9 km wide ridge of the Middle Wall, or the ring fault 20 km in diameter? In the cases where the inner rim is absent or not preserved, the diameter of the outer rim has been treated as the rim-to-rim diameter of an impact structure (Abels et al. 2000; Dypvik et al. 1996; Gibson and Reimold 2000; Kenkman et al. 2000; Koeberl and Anderson 1996; Lindström et al. 1996; Lilljequist 2000; Ormö and Lindström 2000). When there exists a well-developed rim wall and problems arise with the outer rim, the diameter of the former has been taken as the rim-to-rim diameter of a structure (Puura and Suuroja 1992; Suuroja et al. 2001b).

Also, the very wide distal distribution of the shock-metamorphosed material (mainly quartz grains with PDFs) and in deposits of different age is problematic in the case of the Neugrund structure. The size and roundness (subrounded and rounded grains dominate) of quartz grains bearing shock-metamorphic features indicate that these grains are derived mostly from Late Vendian and Early Cambrian siliciclastic deposits, which at the time of the impact formed an

approximately 100 m thick layer. It is difficult to explain how shock-metamorphosed quartz got into the breccia-like deposits, or so-called sediment intrusions (Suuroja et al. 2002) of Osmussaar Island. These intrusions are about 60 Ma older than the Neugrund structure and the island is located on the outer boundary of the Neugrund impact structure. As other impact structures of the same age are absent in the nearest surroundings (Pesonen 1996; Pesonen and Henkel 1992; Ormö and Lindström 2000), the only probable explanation is that the shock-metamorphosed matter of these intrusions has been derived from the submarine outcrops of the Neugrund impact structure. This statement is not correct either, since the geological section of the crater proper shows that before penetration of sediment intrusions all structures of the crater must have been buried and siliciclastic deposits bearing shock-metamorphic matter were not accessible.

Acknowledgements

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VI

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Kärdla Impact (Hiiumaa Island, Estonia) – Ejecta Blanket and Environmental Disturbances

Sten Suuroja[1;2] and Kalle Suuroja[1]

[1]Geological Survey of Estonia, Kadaka tee 82, Tallinn 12168, Estonia.
[2]Department of Mining, Tallinn Technical University, Kopli 82, Tallinn, Estonia. (s.suuroja@egk.ee)

Abstract. The Kärdla impact occurred ca 455 Ma (Upper-Ordovician, Caradoc) in a shallow (ca 100 m) epicontinental sea not far (ca 100 km) from the erosion area on the Baltic Shield (Grahn et al 1996). The explosion of the meteorite ca 200 m in diameter generated a complex crater 4 km wide and more than 500 m deep on the sea bed. The crater is surrounded by elliptical ring fault, up to 15 km in diameter, within which the sedimentary target rocks are strongly deformed. The ejected matter was spread almost concentrically around the crater, within a 50-km radius, on ca 5500 km^2. The ejected matter is found also farther away as an admixture in limestones. Most of the ejecta blanket was covered by limy mud immediately after the impact. The crater was buried somewhat later; therefore the ejecta blanket is well preserved, except the rim wall area. Rate of accumulation of deposits and its facial composition in the crater deep, rim wall area and surroundings was different during some millions of years.

The ejecta blanket lies in a succession of Upper-Ordovician carbonate rocks as a 0.01–3.5 m thick southward inclined (from 40 m u.s.l. in the island's northernmost point up to 190 m u.s.l. in the southernmost point) bed of silty and sandy limestones or limy silt- and sandstones. On the sea bed about 10 km northward of the island the ejecta blanket is cut by the erosion escarpment (Baltic Klint). The distal ejecta layer consists mostly of silt- to gravel-sized debris of the target rocks (mostly Cambrian siliciclastic and Paleoproterozoic metamorphic rocks). In the lower part of the bed and closer to the impact centre coarser clasts occur. Farther from the impact site, the thickness of the ejecta layer, as well as the size of the grains decreases. The size of the ejected matter decreases also from the bottom towards the top of the layer. The ejected matter contains up to 1% shock metamorphosed quartz grains with PDF-s. The Kärdla impact was too small to cause substantial and

long-term global environmental changes and catastrophic shifts in the bio-sphere. Its long-term effect was restricted mostly to changes in sea bed relief and related facial changes, as well as the changes in the biotic communities of pelagic organisms caused by the latter

1
Introduction

The Kärdla meteorite crater (Hiiumaa Island, Moonsund Archipelago, Estonia; $58^o58´$N, $22^o46´$E) (Fig. 1.) was formed in the Upper Ordovician (Salvador 1994; Remane 2001; Remane et al 1996), earliest Caradoc time (ca 455 Ma) in a shallow epicontinental sea not far (ca 100 km) from the erosion area in the Baltic Shield (Puura and Suuroja 1992; Plado et al 1996; Suuroja 2001; Suuroja et al 2001; Suuroja 2002). The time of the impact was obtained by several authors (Suuroja et al 1991; Lindström et al 1992; Grahn et al 1996) and it was proved by determination of the position of the ejecta layer in the sequence of the pre- and post-impact sedimentary rocks.

Fig. 1. Location of the Kärdla impact structure.

Between 1968 and 1994 more than 150 drill holes for different purposes were drilled in the area of Kärdla impact structure (geological and hydro-geological mapping (Kala et al 1971; Suuroja et al 1991; Suuroja et al 1994), exploration of mineral resources (Kala et al 1976) and other applied geological activities), and 42 of these penetrate the ejecta blanket. To study the ejecta layer, 25 cores from these drill holes were studied in more detail (Fig. 2). The drill core in the interval of the ejecta blanket was bisected us-ing a diamond saw, photographed and described in detail macro- and mi-croscopically (in thin sections). Special attention was paid to structural changes, changes in fauna and traces of their activity. Altogether 36 sam-ples from 10 drill cores (F-340, F-343, F-345, F-355, F-362, F-364, F-366, F-369, F-372 and K-31) were analytically investigated (grain-size distribu-tion and grain shape, and mineralogical analysis).
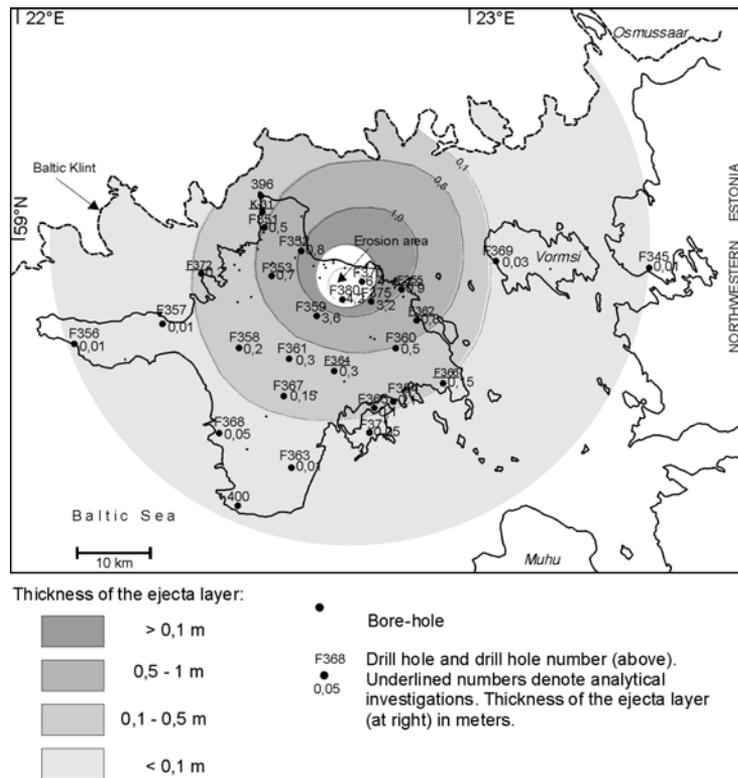
Fig. 2. Distribution of the ejecta blanket.

All of them were studied for shock-metamorphosed minerals (quartz grains with PDF-s - planar deformation features) and the latter were identified in 22 samples from the above-mentioned drill cores. Insoluble residue and size, shape and mineralogical content of the grains were analyzed in the samples. The insoluble residue was produced by long-term (ca 7 days) solution of the crushed rocks in 5% hydrochloric acid (HCl) at room temperature. Grains were divided into four size groups: clay (less than 1/256 mm); silt (1/256– 1/16 mm); sand (1/16–1 mm); granules (1–4 mm). By shape the grains were angular, subangular, subrounded, rounded and well rounded. The 1000 quartz grains from the insoluble residue from the size group "sand" (1/16–1 mm) were picked up under a binocular and examined for PDF-s in immersion liquid under polarised light by identifying the crystallographic orientations of the planes. The most distributed orientations were {10$\underline{1}$3}, {10$\underline{1}$2} and {10$\underline{1}$1}. All these analyses were carried out in the Laboratory of the Geological Survey of Estonia.

2
Geological Settings of the Blanket

The ejecta blanket of the Kärdla impact in the sequence of the Ordovician carbonate rocks (limestones) is marked by a sandy layer 0.01–3.5 m thick (Fig. 5, 8, 9, 10). Soon after the impact the ejecta blanket was buried under marine deposits (biodetrital limy mud) and is therefore mostly well preserved. On the top of the rim wall and outer slopes of the crater in a short time (some thousands years) after the impact the ejected matter was eroded. On the outer slope of the rim wall and in its closest surroundings, the brecciated target rocks are covered by up to 6 m thick bed of sandstones. This bed is not connected with the ejecta blanket, but formed as a result of the erosion of the ejecta on rim wall.

Table 1. Some characteristics of the ejecta blanket of the Kärdla impact.

Core	Thickness of the ejecta layer (cm)	Depth of the bottom of ejecta layer (m a.s.l)	Distance from crater centre (km)	Core	Thickness of the ejecta layer (cm)	Depth of the bottom of ejecta layer (m a.s.l)	Distance from crater centre (km)
F345	10	-88	42	F363	10	-162	26
F351	50	-54	13	F364	30	-141	12
F352	80	-76	7	F365	10	-149	18
F353	70	-92	9	F366	15	-145	20
F354	10	139	18	F367	15	-148	17
F355	90	-101	8	F368	50	-152	27
F356	10	-97	38	F369	30	-101	22
F357	10	-85	25	F370	640	-81	3
F358	20	-118	16	F371	50	-145	21
F359	360	-108	5	F372	20	-67	19
F360	50	-130	12	F375	320	-106	5
F361	10	-128	12	F380	420	-163	3
F362	80	-116	12				
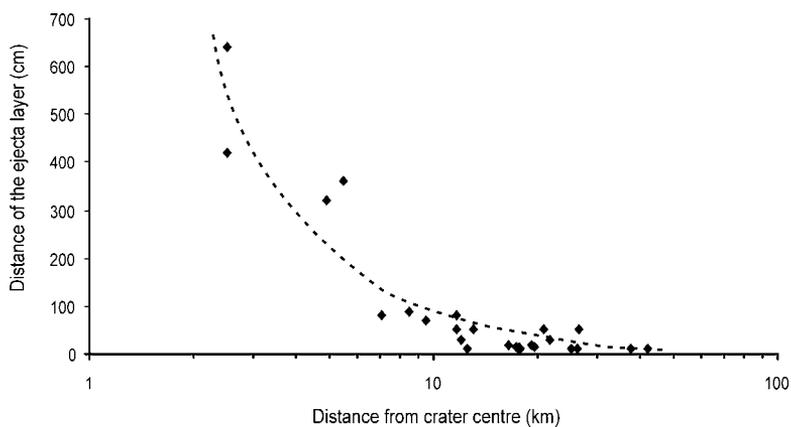
Fig. 3. Thickness of the ejecta layer *versus* distance from the impact centre.

The ejecta connected with the Kärdla impact was distributed almost concentrically around the crater in more than 50-km radius (Fig. 2; Table 1). As an admixture in limestones the ejected silt and sand grains from the Kärdla are found farther away, too. The core section of drill hole F-340 is the farthest site (55 km to NEE from the impact centre) where the shock matter (quartz grains with PDF-s) ejected from the Kärdla impact site has been found. The ejecta blanket like a bed with the distinct boundaries is spread in more than 40-km radius around the crater (42 km N-S and 38 km W-E direction; see Fig. 2). Farther the ejecta blanket may exist as rare quartz grains in limestone, but samples were not taken from the sections where the layer of ejected material was not observed with a naked eye. The distal ejecta contains clay-size matter as well, but it cannot be recognised which part of this originates from the pre-impact target rocks and which is produced in the course of the impact. The present-day distribution of the ejecta blanket is restricted by the erosion escarpment of the Baltic Klint (Tammekann 1940) on a sea bed 10–12 km northward of the island. Northward of this line the ejecta blanket was eroded in pre-Pleistocene time (Neogene?).Investigations of the surface upon which the ejecta blanket is deposited are of special interest (Fig. 3). In the area around the crater, in ca 4-km radius the ejecta layer as well as the part of the rim wall and crushed by the subsurface release target rocks have been removed by tsunami-like resurging waves or short-term post-impact erosion. As a result of subsurface release caused by reflection of a rarefaction wave (Melosh 1989; Dence 2002), in the crater's surroundings (up to ca 5 km from the impact centre) up to 30 m of the subsurface layers of the target sedimentary rocks were crushed and partially or entirely removed (Fig. 5). It is difficult to establish which part of the removed rocks were displaced by the releasing of subsurface layers and which by resurging tsunami or erosion, because afterwards all of them have been eroded. Farther from the crater the share of removed and crushed target rocks decreases up to wedging out at a distance of about 6 km.

Due to long-term post-impact regional tectonic movements in this region (Puura and Floden 1997) the ejecta blanket inside the sequence of the Upper-Ordovician carbonate rocks has acquired gentle (ca 3.5 m per kilometre) southward dip. As a result of these movements the ejecta blanket presently lies in the succession of the Upper Ordovician carbonate rocks (mostly limestones) at a depth of 40 m u.s.l. in northern part of the island (drill hole 396 Tahkuna), and at a depth of 190 m u.s.l. southern part (drill hole 400 Sõru) (Fig. 2.). Farther south and deeper the run of the ejecta layer cannot be followed because in this area the drill holes are missing and content of the ejected matter in the limestones is limited, too. East- and

westward of the centre of the Kärdla impact crater the ejecta blanket lies at a depth of 100–110 m u.s.l. (Fig. 4.).

In some places, especially westward of the impact site, in the areas where the ejecta blanket is 10–50 cm thick (drill holes F-351, F-352, F-358, F-366, F-367, F-368, F-372 in Fig. 2 and Fig. 3) it is impregnated with natural bitumens (Suuroja et al 1991; Kattai et al. 1994).
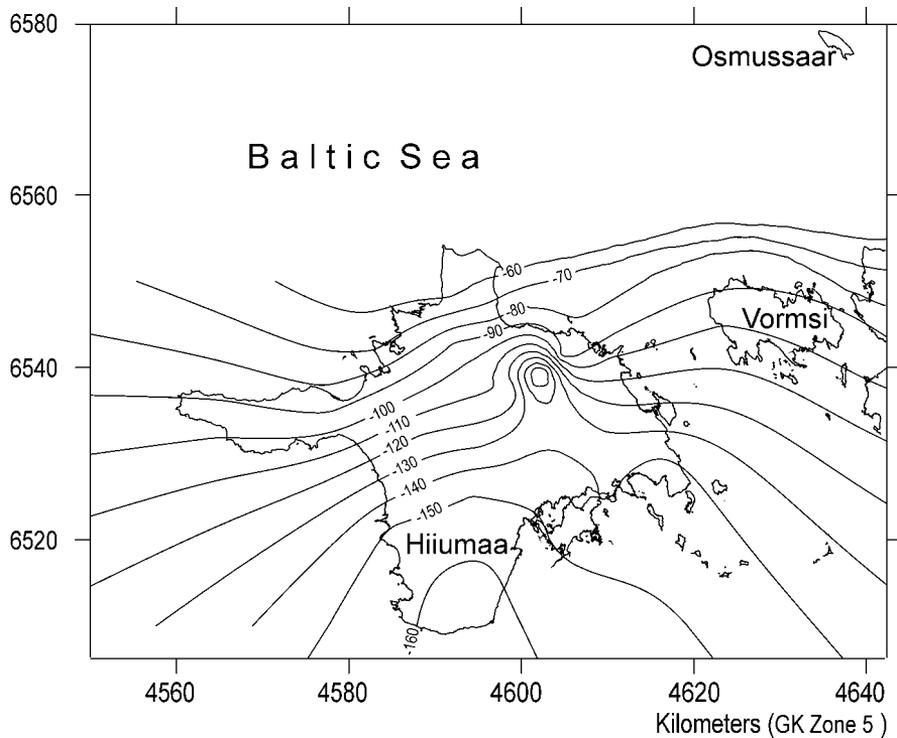
Fig. 4. The isolines of the ejecta blanket. Distance between isolines 10 m.
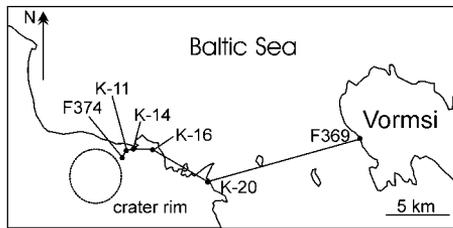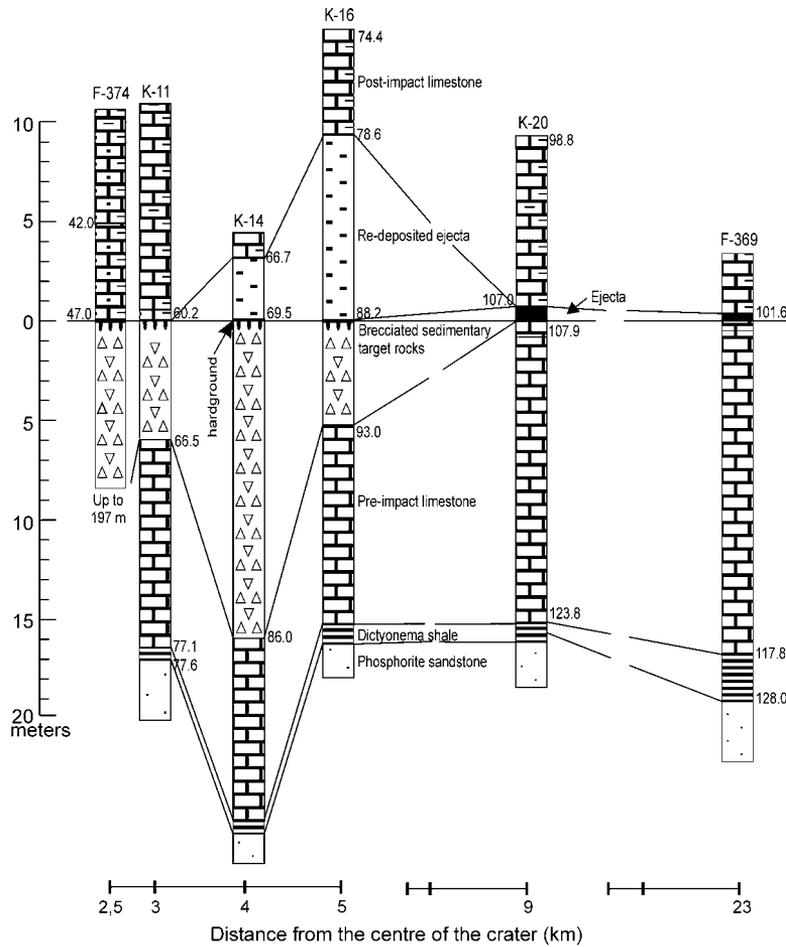
Fig. 5. W-E cross-section (drill holes F-374; K-11; K-14; K-16; K-20; F-369) of the impact-related rocks of the surroundings of the Kärdla crater.

Fig. 6. The post-impact surface of erosion in the surroundings of the Kärdla crater.

3
Composite of the Ejecta Blanket

The ejecta blanket consists mostly of silt- to gravel-size debris of the target rocks. In its lower part and closer to the impact centre coarser clasts (pebbles, cobbles, and blocks) occur, too. The clasts consist of the sedimentary (limestones, sandstones, siltstones, clays) and crystalline (gneisses, granitoids, amphibolites, migmatites) target rocks. In the proximal and coarse ejecta mainly clasts of the target rocks (sedimentary and metamorphic) occur, while in the distal and finer ejecta clasts of the minerals or grains of the disintegrated siliciclastic rocks (Cambrian silt- and sandstones) prevail.

Farther from the impact centre thickness of the ejecta layer (Fig. 3.) as well as the grain size of the ejected matter decrease. Within a section, the grain size of the ejecta decreases from the base to the top of the layer. In the surroundings of the impact centre (6–8 km from the centre) coarse clasts (blocks, cobbles and pebbles) are found. On the outer slope of the rim wall, at a distance of ca 1 km from the ridge (drill hole K5) a huge (ca 40 m in diameter) block of brecciated metamorphic target rocks (granite, gneisses) was discovered (Fig. 6).

At a distance of 6–12 km from the impact centre at least two separate beds of siliciclastic rocks with sharp contacts (Fig.9) are observed – coarser (below) and finer (above). Closer to the impact centre the ejecta layer has been partly or entirely removed, and farther away the contacts between different layers are smoother or transitional (Fig. 10).

The character of the lower contact of the ejecta layer mainly depends on the distance from the impact centre. Closer to the crater (5–8 km) the layer of crushed sedimentary target rocks are strongly eroded by the tsunami (Fig. 9), but at a distance of 8–16 km from the crater the pre-impact sea bed (unlithified carbonate mud at the time of the impact) weakly eroded by the tsunami. Farther than 20–25 km from the impact centre noticeable traces of the sea bed erosion are absent and the contact is clear and it becomes transitional at a distance of more than 30 km (Fig. 9).

At the upper boundary of the ejecta layer in this area (where it is not eroded) noticeable diversities are observed. At a distance of 5–15 km (Fig. 8, 9) the boundary is transitional rather than sharp, but at a distance of 15–30 km on the top of the layer often an impregnated (pyrite and/or phosphate) or non-impregnated wavy discontinuity surface occurs (Fig. 10). The boundary between separate parts of the ejecta layer (lower – coarse and upper – finer) is quite sharp, but less than 10 km from the centre (Fig.

7, 8) it becomes more transitional (Fig.9, 10). Two separate layers can be distinguished up to a distance of 30 km from the impact centre.

The lower, coarser bed of the ejecta layer consists of angular clasts (cobble, pebble, granules, sand) derived from the target rocks by the explosion, and they are cemented by the fine-grained (silt and clay) matrix (20–40%).
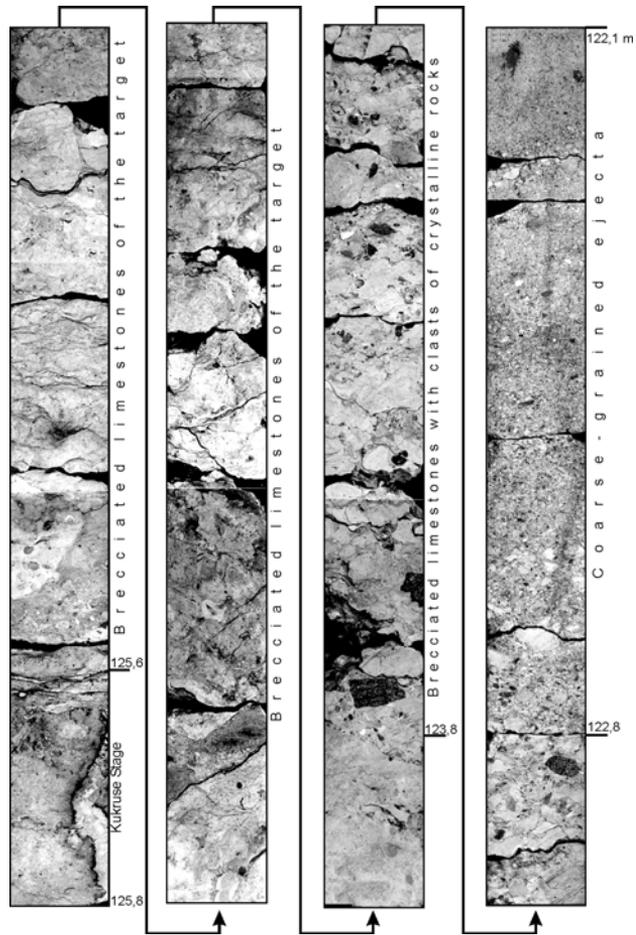
Fig. 7. Photo-log of drill core F-359 (5 km SW of the impact centre). The brecciated target limestones and the ejecta layer. 125.8-125.6 m – almost intact pre-impact Upper-Ordovician limestone of the Kukruse Stage with a hardground on the top; 125.6-123.8 m – brecciated by a subsurface release limestones of the target; 123.8-122.8 m – brecciated target limestones, containing clasts of crystalline rocks; 122.8-122.1 m – coarse-grained ejecta.
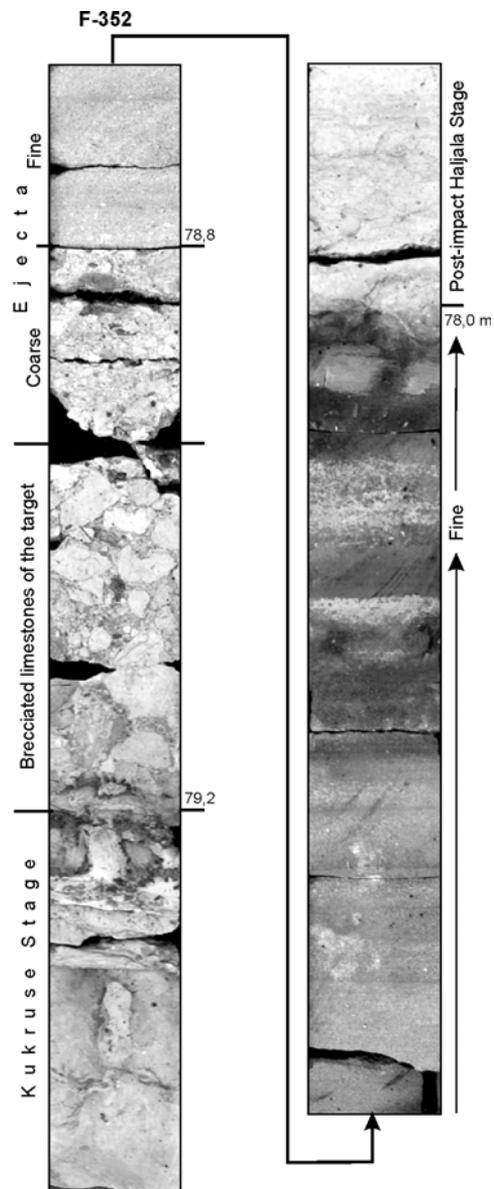
Fig. 8. Photo-log of drill core F-352 (6 km WSW from the impact centre). Dark grey – ejecta impregnated with hydrocarbons.
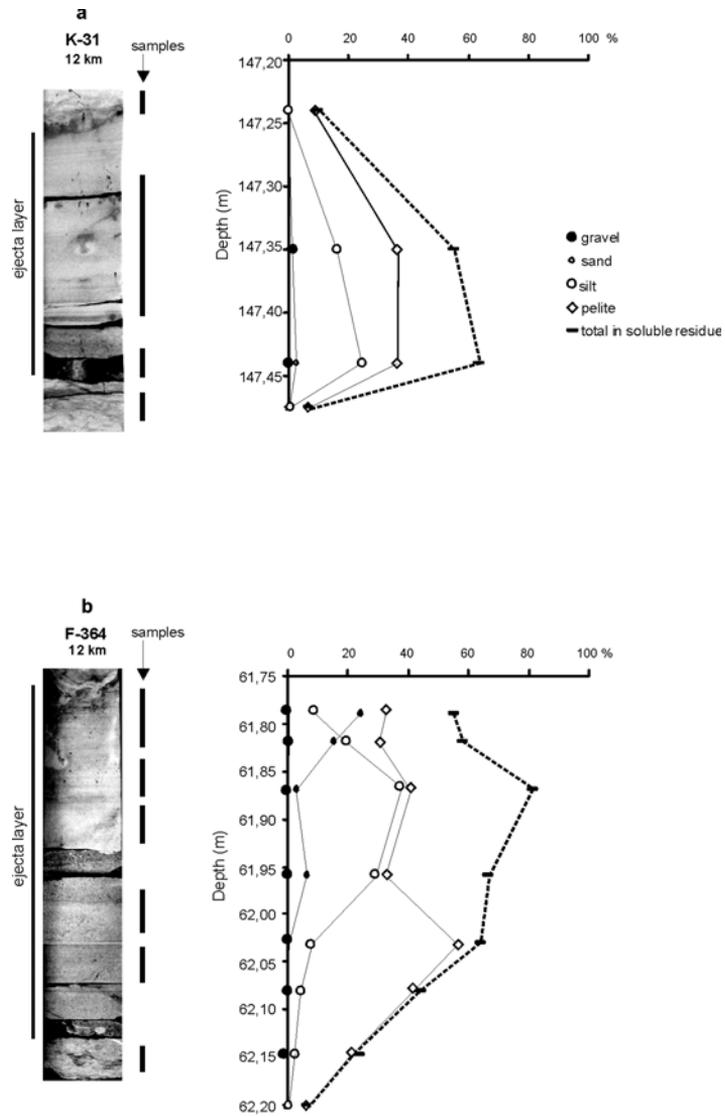
Fig. 9. Photo-logs of the ejecta layer from drill cores: a) F-361 (12 km SSW of impact centre); b) F-360 (12 km SE of impact centre); c) F-372 (18 km W of impact centre).
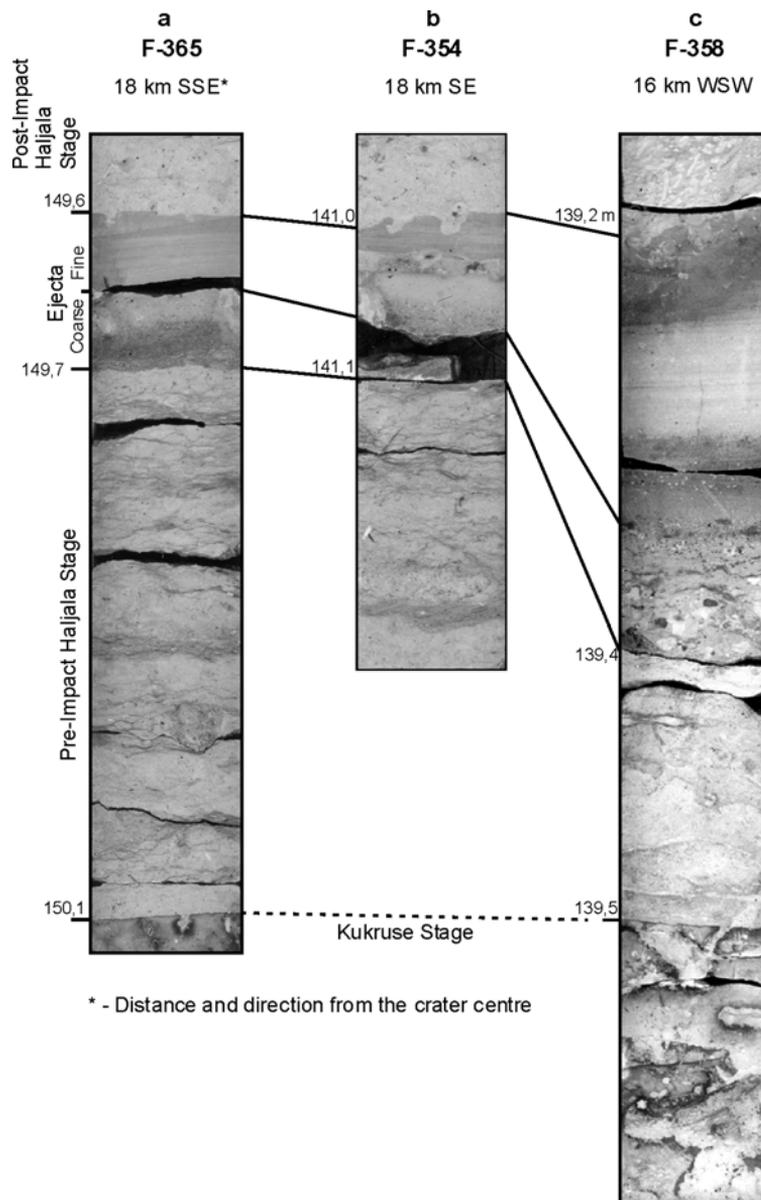
Fig. 10. Photo-logs of the ejecta layer from drill cores: a) F-365 (18 km SSE of impact centre); b) F-354 (18 km SE of impact centre); c) F-358 (16 km WSW of impact centre).

In the matrix disintegrated Cambrian siliciclastic rocks (clay, silt- and sandstones) prevail but fine angular debris of crystalline basement metamorphic rocks and limestones is observed as well. From this part of the ejecta layer only two grain-size distribution and mineralogical analyses have been made, both from the drill core F-359 (5 km SW of the impact centre) from a depth of 122.6 and 122.4 m. The content of insoluble residue is 74 and 83% respectively; from this, granules form 18 and 11%, sand – 46 and 48%, silt – 6 and 10%, and clay – 30 and 21%. The share of coarse material decreases with increasing depth, while total content of the insoluble residue, conversely, increases. The coarser fraction (granules) in these samples consists mainly of angular clasts of different target rocks (crystalline 75–62%; siliciclastic 16–12%; limestones 9–12%). With increasing depth the content of insoluble residue decreases and the size of clasts increases. On the grounds of the evidence of two analyses is difficult to judge on mineralogical changes of the coarse part of the ejecta layer, but it seems that with increase of the depth the content of the rocks derived from crystalline basement decreases.

Numerous shock metamorphosed (quartz grains with PF-s (planar fractures) and PDF-s clasts and disintegrated grains of Cambrian silt- and sandstones (up to 1% of the analysed grains of 1–1/16-mm fraction) are encountered in the ejecta layer. By shape the grains are mainly (80%) rounded or well rounded. The upper (fine-grained) part of the ejecta layer consists mainly of clay, silt and sand fractions of the disintegrated Cambrian siliciclastic rocks. Coarser clasts (pebbles, granules) of crystalline and sedimentary target rocks are very rare (Fig. 11 and 12). Farther away from the impact centre, the absolute thickness of this part of the ejecta layer decreases but its relative importance increases. The total content of insoluble residue is higher (60–80%) in the middle part of the layer and decreases downwards and upwards. The upper part of the ejecta layer differs occasionally from the pre- and post impact limestones, mostly by the content of insoluble residue and by the fractional composition: in the pre- and post-impact limestones the content of insoluble residue is 5–15% and it consists of more than 95% of clay, while in the ejecta layer the content of insoluble residue is 40–80%, and the content of the clay decreases to 40–60%. The content of carbonate (calcite) in the surrounding limestones is mostly more than 90%, while in the ejecta layer it decreases to 20–40%. Farther away from the impact centre the content of calcite in the layer increases and content and grain size of insoluble residue decrease. The mineral composition of the silt and sand fractions of insoluble residue in the layer becomes simpler farther from the impact centre, and in a vertical direction – from the top to base. In the upper part of the layer and far from the impact centre the insoluble residue consists mostly (ca 90%) of quartz.

The quartz grains with shock metamorphic features (PF-s and PDF-s) are abundant and the analysed fraction (1–1/8 mm) contains approximately 1% of them. In these, 6 different directions of lamella (3 per grain) are observed. According to some authors (Stöffler et al 1975; Masitis et al 1980; Stöffler and Langenhorst 1994; Stöffler and Grieve 1996) that may indicate a shock pressure of about 10 GPa or same as in the case of suevites from the Kärdla crater (Suuroja et al 2002). The shocked quartz grains are mostly (95%) rounded or sub-rounded; angular and well-rounded grains are very rare.

* - Distance and direction from the crater centre
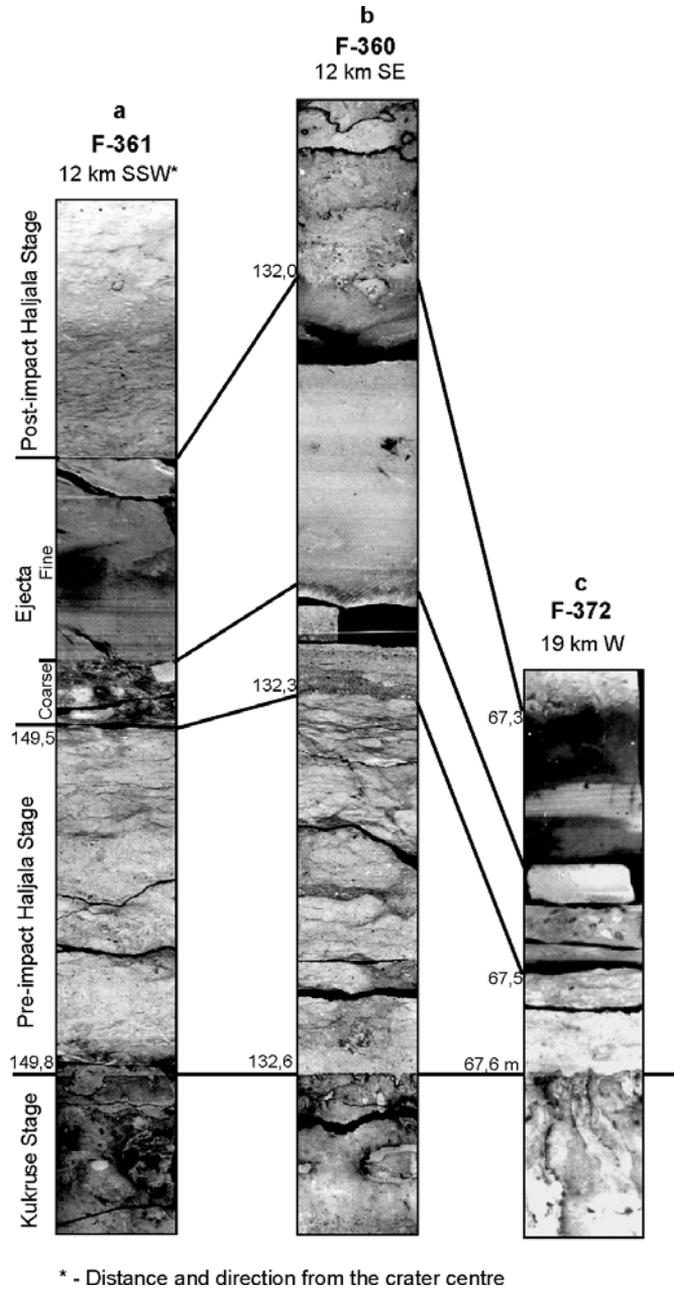
Fig. 11. Photo-logs of the ejecta layer and grain size and content of insoluble residue: a) drill core K-31; b) drill core F-364.
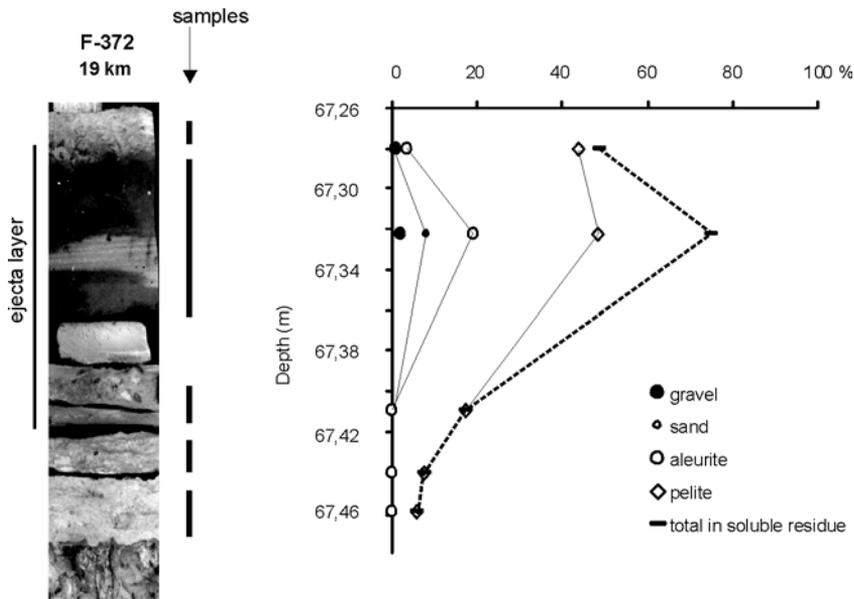
Fig. 12. Photo-logs, grain size and content of insoluble residue: a) drill core F-372; b) drill core F-355.

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 (Fig. 8 and 9). The substance of this sharp boundary is not clear yet, but it seems possible that deposition of the upper layer is connected with re-deposition of the primary ejecta. This presumption is supported by the observation that the upper part of the ejecta layer has sometimes fine-bedded textures. In the quartz of the ejected matter five sets (maximum 3 orientations per grain) of PDF-s of different crystallographic orientation are distinguished (Suuroja et al 2001).

Ejecta deposition, except the nearest surroundings of the crater, took place on smooth sea bed at approximately constant depth (ca 100 m). The tsunami caused by the impact did not affect the sea bed and bottom deposits farther than 10 km off the impact centre.

4
Discussion

Kärdla impact took place 455 Ma ago (Puura and Suuroja 1992; Suuroja et al 1994; Grahn et al 1996) in shallow epicontinental sea (ca 100 m deep) where at that time, i.e. in the Upper Ordovician (Cowie and Basett 1989; Webby 1998) bioclastic debris-rich limy mud deposited (Männil 1966; Jaanusson 1995; Nestor and Einasto 1997). In the described sea, 700–800 km from the Kärdla impact site, at approximately the same time one small-scale (Tvären) and one medium-scale (Lockne) meteorite impact took place (Lindström et al 1992; Lindström et al 1996; Ormö and Lindström 2000; Sturkell et al 2000; Abels et al 2000; Abels et al 2003). Considering the distance and size of these meteorite impact structures it can be assumed that these were too small and the distance from the Kärdla impact site was too great to influence the deposition in the latter region.

By calculations the impactor ca 200 m in diameter penetrated more than 100 m thick water layer and ca 140 m thick sedimentary cover and exploded in the uppermost part of the crystalline basement. The explosion which had a power of about 600 MT, removed more than 2×10^9 m^3 of crushed crystalline and sedimentary target rocks from the crater deep. In the result of this, a complex crater 4 km wide and more than 500 m deep, having a central uplift 130 m high and 600–700 m in diameter, was formed (Suuroja 2001). Due to the marine environment most impact-related deposits, among these the ejecta blanket, were buried and therefore are still preserved in an area of thousands of square kilometres around the crater. The ejecta blanket was eroded by short-term post-impact erosion from the rim wall and its outer slopes around the crater within ca 4 km radius (Fig. 2.).

Earlier optimistic suggestion (Põlma 1982; Hints 1997) that quartz sand in the bioclastic limestone of the Kisuvere Member (corresponding to the level of the post-impact limestones of the Haljala Stage) distributed more than 200 km east of the Kärdla crater in eastern Estonia, is in some way connected with the Kärdla impact, is not proved. Firstly, the sand from the Kisuvere Member does not contain shock metamorphosed quartz grains with PDF-s, and secondly, the interval of the distribution of sand (up to 1 m) is too thick for such short-time and violent event as an impact. Also, the distance to the erosion area on the Baltic Shield, from where the silici-clastic matter was transported to the Kisuvere Member, was more than two times shorter than distance to the Kärdla impact site.

One possible site from which the shock metamorphosed quartz grains might have been transported to the Upper-Ordovician carbonate deposits of

western Estonia could be the shock metamorphosed rocks of the Neugrund meteorite crater. The latter formed in the Early Cambrian (535 Ma) time and is relatively close (60 km NE) to the Kärdla impact site (Suuroja and Suuroja 2000; Suuroja et al 2002). However, even closer to the Kärdla impact site (55 km NE of Osmussaar Island) cropped out the so-called Osmussaar breccia veins (Middle Ordovician, ca 475 Ma) which too, contain shock metamorphosed matter (quartz grains with PDF-s). The shock metamorphosed matter in the Osmussaar breccias as well as spatially and temporally closely related with them sandstones and sandy limestones of the Pakri Formation (Middle Ordovician, Kunda Regional Stage) are supposed to originate from the Neugrund impact structure area (Suuroja et al 2003). Presence of the shock metamorphosed material of Neugrund origin in the limestones corresponding to age of the Kärdla impact is excluded, because the area of Neugrund impact structure and its surroundings, including the ejecta blanket, were at that time already buried under the cover of carbonate deposits.

   It is difficult to calculate the initial volume and thickness (Fig. 3) of the ejecta blanket of the Kärdla impact because the impact took place in water, shortly after that the structure was eroded to a 6–8-km radius and finally it was buried. The calculations become even more complex considering that in the surroundings of the crater it is difficult to distinguish between the material formed in the result of subsurface release of sedimentary target rocks, in the result of resurging tsunami, in the result of deposition of the ejecta, and re-deposited matter from the eroded rim wall and the ejecta layer.

   During a crater formation and excavation stage about 90% of all material excavated from a crater is deposited as a proximal ejecta (McGetchin 1973; Oberbeck 1975; Melosh 1989; Koeberl and Martinez-Ruiz 2003; Dence 2002) at a distance equal to 3–4 radii of the crater. In the case of the Kärdla impact this distance may have been equal to 6–8 km and this is what we observed (Fig. 3). In Kärdla the proximal ejecta layer was strongly eroded by the resurge wave and post-impact erosion and therefore it has only partially preserved. In addition, closer to the rim wall it is difficult to differentiate between the primal proximal ejecta, re-deposited ejecta and the material carried to the deposits from the strewing wall.

   The origin of the up to 16 m thick bed of brecciated limestones lying at a distance of 3–6 km from the impact centre, on the top of the mostly intact (about 5 m from the 15 m thick layer of the limestones have been removed) complex of the target rocks, has been remained ambiguous (drill core K-14; Fig. 5). In the area where the upper part of this layer contains clasts of the crystalline rocks it is treated as a proximal ejecta layer. The

lower part of this layer has formed in consequence of subsurface release as a result of reflection of a rarefaction wave.

The natural bitumens locally distributed in the sandy ejecta layer (Kattai et al 1994; Suuroja et al 1994; Suuroja 2002) are not authigenic and probably are of migratory origin. They are distributed at other stratigraphical levels and in other rock types (limestones) as well. There was a regional W-E or NW-SE direction flow of hydrocarbons which brought them not only to the island of Hiiumaa and to the surroundings of Kärdla crater, but also to some other sites on the eastern coast of the Baltic. The version of NW-SE migration is supported by the so-called "shade" of the Kärdla crater – a 15 km long oval area around the Kärdla crater where occurrences of natural bitumens (impregnation, liquid oil, asphalt) are missing. However, abundant occurrences of the natural bitumens are found on NW slope of the Kärdla crater. The exact time of migration of the hydrocarbons has not been identified but it must have been in the post-Silurian time because the natural bitumens impregnate the whole sequence of the Silurian limestones in this region (Suuroja et al 1991).

The asymmetrical features (different height of the rim wall, elliptical shape of the ring fault) of the Kärdla structure (Suuroja et al 2001), which according to the some authors (O´Keefe and Ahrens 1977; Deutsch and Langenhorst 1994; Artemeieva 2002; Shuvalov 2003) imply an oblique impact, are not observed in the distribution of the ejecta blanket around the Kärdla crater.

The Kärdla impact was too small to cause substantial and long-term environmental changes (Ainsaar et al 2002) and catastrophic shifts in the biosphere. However, the anomalous structure generated by the meteorite explosion (the highly uplifted rim wall and the deeply sunken crater proper) on the sea bed caused short-time anomalies in the sedimentation and changes in the biotic communities of pelagic organisms. For example, at the time (Upper Ordovician, Haljala time) when the ridge of the rim wall rose above the sea level and was eroded, graptolite-containing mud deposited in the about 300 m deep crater proper (Kala et al 1971). Some millions of years later (Upper Ordovician, Oandu time) when around the rim wall's outer slopes one of Europe's earliest reef-like build-ups (the complex of skeletal grainstones consisting only of the fragments of shafts of the cystoids) formed, fossil-rich marls containing only the cup plates of these cystoids accumulated in the crater deep. Differences in the facies composition between the crater deep, rim wall area and surroundings of the crater lasted for about ten million years, up to middle of the Rakvere time (Caradoc, Upper Ordovician).

The ejecta blanket of the Kärdla impact event as well as many other small- and medium-scale impact events (Deutch and Shärer 1994; Koeberl

and Anderson 1996; Masaitis 1999; Gilmour and Koeberl 2000; Koeberl 2001; Koeberl and Mac Leod 2002; Masaitis 2002; Gurov et al 2002; Gurov et al 2003; King and Petruny 2003; Valter and Plotnikova 2003 etc) have been a good, but unfortunately of only local importance, time-marker in a biomorphic matter rich sequence of the marine deposits.

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CURRICULUM VITAE (CV)

Name: Sten Suuroja
Date of birth: 27.06.1972
Citizenship: Estonian

Contact: Institute of Mining, Tallinn University of Technology, Ehitajate tee 5,
               Tallinn, Estonia, E-mail: s.suuroja@egk.ee

Education: Tartu University, Bachelor in 1994
               Tartu University, MSc. in 1997

Research and professional experiences:
               From 1994 up to now geologist in Geological Survey of Estonia

Scientific work:
               Impact geology, marine geology

Academic degree:
               MSc (in geology-mineralogy), 1996, Tartu University

ELULOOKIRJELDUS (CV)

Nimi: Sten Suuroja
Sünniaeg: 27.06.1972
Kodakondsus: Eesti
Kontakt: Telefon: 6720090
               E-mail: s.suuroja@egk.ee

Haridus: Tallinna 3. Keskkool
               Tartu Ülikool, geoloogia eriala 1990 – 1994
               Tartu Ülikool, Geoloogia Instituut, magistriõpe
               Tallinna Tehnikaülikool, Mäeinstituut, doktoriõpe
Teenistuskäik: Alates 1994 Eesti Geoloogiakeskus
Teaduskraad: Magister

Teadustöö põhisuunad: Meteoriitika, meregeoloogia