Master’s Thesis in Geology

Origin of the Conglomerates from the Southern Coast of Osmussaar

Siim Sepp

Supervisors: Kalle Kirsimäe
Juho Kirs

Head of Department:

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Northwestern part of Estonia is a geologically interesting and still somewhat enigmatic region which has drawn the attention of many generations of researchers. Perhaps the most noteworthy is the fact that two large complex impact structures (Kärdla and Neugrund Craters) are located in this relatively small area. Both of them are buried and partly (Kärdla) or wholly (Neugrund) in the Baltic Sea which is the reason for their relatively recent discovery in late 20th century. Neugrund structure is dated by stratigraphic means to the Early Cambrian (535 Ma) (Suuroja and Suuroja, 2010) and Kärdla event is dated to the Late Ordovician (455 Ma) (Suuroja et al., 2002a). The study of the latter has benefited greatly from the drilling program in the Soviet era. 160 boreholes were drilled which makes Kärdla Crater one of the best studied impact structures in the region (Suuroja et al., 2002a).

Kärdla and Neugrund are large complex craters, but Estonia hosts several other confirmed, smaller, and considerably younger impact structures. The Kaali crater field in Saaremaa was confirmed to be of impact origin by Ivan Reinwaldt in 1938 (Veski et al., 2002). The Kaali crater is definitely the best known among the Holocene craters of Estonia and it was the first confirmed impact crater in Europe. The cratering rate in Estonia is the highest worldwide (Suuroja, 2008).

The discovery of the Neugrund structure finally gave an adequate geological explanation to the question regarding the origin of the gneiss-breccias, as they were called by Armin Öpik (Öpik, 1927). These rocks, called Neugrund breccias now, are firmly linked to the Neugrund impact structure, representing the brecciated basement material carried away from the impact site by glacier (Suuroja and Suuroja, 2010).

Not only interesting because of it’s craters, the region around the Osmussaar Island is known to be the most seismically active part of generally aseismic Estonia. The earthquake with a magnitude of 4.7-4.8 that took place near Osmussaar in October 25, 1976 is the most powerful instrumentally recorded earthquake in Estonia (Nikonov, 2002).

Moreover, the Osmussaar Island has given the name to the Osmussaar Breccia, which is a brecciated bedrock layer of sandy limestone of Ordovician Kunda Age, which is penetrated by numerous limy sandstone ejections. The breccia beds are thickest at Osmussaar Island (Suuroja et al., 2003). These rocks were also first described by Öpik (1927) who interpreted the brecciation to be the result of an earthquake. This hypothesis may still hold but
discoveries made recently, especially the find of extraterrestrial chromite grains and planar deformations in quartz grains, suggest that this formation may be the result of a large impact event (Alwmark et al., 2010).

Another particular feature of the geological section in northwestern Estonia is the Pakri Formation of Ordovician Kunda Stage, a bedrock layer in northwestern Estonia that consists mostly of sandy limestone and limy sandstone (Meidla, 1997c). The formation of this clastic lime-rich layer of sedimentary rocks is one of the still unanswered geological questions of the northwestern Estonia – whereas the relations between the Pakri Formation and the Osmussaar breccia are not entirely clear, but for the most part it seems that the clastic dikes of the Osmussaar Breccia are filled with material from the Pakri Formation and penetrate the limestones of the Volkhov Stage directly beneath the Formation (Suuroja et al., 1999).

Another curious feature of northwestern Estonia is the quartz arenitic coarse-grained sandstone and conglomerate pebbles and boulders with strong dolomitic cement called Tahkuna erratics. They are found in several places along the coastline of Hiiumaa and are also still waiting for a satisfying explanation. They have been interpreted to originate from the same Pakri Formation (Pöldsaar, 2007). However, the conglomerates have a dolomitic cement while the Pakri Formation is known to be predominantly calcitic and it is unclear to what extent these rocks are related.

Recently, in addition to quartz sandstone erratics mentioned above, several conglomerate pebbles were found at the southern coast of Osmussaar Island. These conglomerates are mixtures of sedimentary and crystalline rock pieces and coarse grained quartz grains. There is no equivalent sedimentary beds known for such conglomerates in geological section of northwestern Estonia. Unusual character of the Pakri Formation as such, different types of conglomerates with an unknown origin, and extraterrestrial chromite grains in Osmussaar Breccia, which can not be associated with any known impact structure, might be somehow connected. One of the most important goals of the current thesis is to find out if there is a link between these unusual rocks.

In order to establish such a link, several hypothesis were proposed and tested. The main aims of the current thesis were following:

1. Study the petrographic and compositional similarities and differences of the conglomerates from Tahkuna, Dirhami, and Osmussaar.
2. Test the hypothesis that conglomerates from these locations originate from the same sedimentary layer.

3. Investigate what might be the source regions of the material these conglomerates are made of.

4. Propose a hypothesis explaining the formation of the conglomerates.
2. GEOLOGICAL SETTING

2.1 OSMUSSAAR

Osmussaar is a small island (4.7 km²) seven kilometers from the northwestern extremity of Estonian mainland. The geographical coordinates of the island (center of the island) are 59° 17’ N 23° 23’ E. Osmussaar is a low-lying island that rose out of the sea (due to neotectonic adjustment after the last glacial epoch) about 2000…3000 years ago (Suuroja et al., 1999).

Osmussaar is elongated in the NW-SE direction. At the northeastern coastline the westernmost section of the Baltic Klint in Estonia is exposed. The Klint is the only outcrop of bedrock in the island despite the fact that loose sediments from the Quaternary form only a thin veneer (0…2 m) on top of the upper part of the bedrock which is composed of limestone of the Väo, Kõrgekallas, and Viivikonna Formations (Suuroja et al., 1999). These formations are part of the Darriwilian and Sandbian (Sandbian) Stages of the Ordovician Period (Meidla et al., 2008; Nõlvak et al., 2006).

Drillhole with an original number 410 (668 according to the new system of the Geological Survey of Estonia) was drilled in the southern central part of the island in 1970 (Appendix VI). The borehole is 193 meters deep and penetrates into the crystalline basement. The basement was reached at a depth of 170 meters below the surface, which is 4.70 meters above the mean sea level (http://www.egk.ee/osa-kondade-teenused/andmebaasid/puursudamik/04.05.2012).

On top of the highly folded and migmatized metamorphic rocks of the Fennoscandian complex (from the Paleoproterozoic) is an unfolded and normally bedded but not necessarily undisturbed sedimentary sequence which is mostly composed of sandstones and claystones from the late Ediacaran (59 m), early Cambrian (92 m), and early Ordovician (Suuroja et al., 1999). Description of the drillcore is shown in the Appendix VI.

2.2 THE NEUGRUND CRATER

The Neugrund Crater is a marine impact structure located less than 10 kilometers east of Osmussaar (59° 20’ N 23° 31’ E). The crater is partly buried; its interior is filled with a sedimentary sequence but the inner rim or the crater, which is composed of crystalline rocks, is exposed on the seabed (Suuroja and Suuroja, 1999).
The Neugrund impact structure was formed 535 Ma in a shallow epicontinental sea as a result of an impact with an asteroid about 1 km in diameter. The Neugrund is a complex crater about 20 km in diameter although the existence of the central uplift is not proven. The width of the inner crater rim composed of shattered crystalline rocks is 7 kilometers (Suuroja and Suuroja, 2010).

There is a sedimentary plateau (with a diameter of 4.5 km) inside the crater inner rim which is separated from the rim by a circular canyon about 70 meters deep and 200-500 meters wide (Suuroja et al., 2002b). The circular canyon is of erosional origin and was probably sculptured by Neogene glaciers flowing along the contact between rocks of very different characteristics – hard metamorphic rocks of the inner rim and soft terrigenous rocks of the central plateau (Suuroja and Suuroja, 1999).

The rimwall is composed of brecciated metamorphic rocks, predominantly migmatized gneiss and amphibolite (Suuroja et al., 2002b). The exposed rimwall is 25-50 meters high and 100-500 meters wide smooth glacially eroded circular hill. The primary height of the structural elevation may have been over 300 meters. It is not known which parts of the rim were eroded shortly after the explosion in the Early Cambrian and which ones during the glaciations of the Neogene (Suuroja and Suuroja, 1999).

The crater started to get buried soon after the explosion – the lower layers of central plateau are composed of rocks that formed in the Early Cambrian. However, it is not exactly known when the crater got completely buried (Suuroja and Suuroja, 1999). The structure remained buried until the Palaeo- or Neogene, when it was partially exposed by water and glacial erosion (Suuroja et al., 2002b).

The upper surface of the central plateau is in some places only 1 meter below the mean sea level. The upper part of the central plateau is composed of limestone just as the upper part of the bedrock of Osmussaar Island. Most of the central plateau is composed of terrigenous rocks: fine-grained quartz sandstone (Tiskre Formation, about 10 meters in thickness), obolus sandstone (sandstone with phosphatic brachiopod fragments) from the Kallavere Formation (about 5 m), graptolite argillite (Türisalu Formation, 5 m), glauconitic sandstone (Leetse Formation, about 5 m), and limestones (about 20 m) on top of them (Suuroja and Suuroja, 2010).
2.3 THE OSMUSSAAR BRECCIA

The Osmussaar Breccia is a mixture of fragmented and slightly displaced limestone which is penetrated by clastic dikes of strongly cemented lime-rich sandstone up to 2-3 meters in thickness. The rocks below and above the brecciated layer are undisturbed. The Osmussaar Breccia occurs in beds of local bedrock, it is thickest at Osmussaar Island (1-1.5 meters) and covers an area of approximately 5000 km². The breccia is found in outcrops on Osmussaar Island, Väike and Suur Pakri islands, and Pakri Peninsula (Suuroja et al., 2003). The extent of the Osmussaar Breccia is shown on the map in Appendix V.

According to an ostracod study conducted by Tinn (Tinn et al., 2010), the brecciated layer belongs stratigraphically to the Volkhov and Kunda Regional Stages (Middle Ordovician). The conodont study by Mellgren (Mellgren et al.) confirms this by stating that the succession of thin-bedded limestone found directly above the Osmussaar Breccia mainly represents the Kunda Regional Stage.

Several hypotheses explaining the brecciation have been proposed: catastrophic earthquake, tectonic movements, and an impact event. Historically, the earthquake hypothesis seems to have gained the most attention. Armin Öpik proposed the idea in 1927 (Öpik, 1927). Since then, the same conclusion has been reached by several authors.

The earthquake with a magnitude of 4.7-4.8 that took place near the Island of Osmussaar in October 25, 1976 is the most powerful instrumentally recorded earthquake in Estonia (Nikonov, 2002) and definitely gave additional support to the now well established notion that northwestern part of Estonia is the most seismically active region in Estonia. This may be due to the fact that neotectonic uplift there is highest in Estonia and the region is underlain by a deep-seated Åland-Paldiski-Pskov fault (Miidel and Vaher, 1997).

However, the Osmussaar Breccia contains large amount of extraterrestrial angular chromite grains (more than 13 grains per kilogram) which strongly suggests that the brecciation was impact triggered (Alwmark et al., 2010). Impact hypothesis gains further strength from the fact that sandstone ejections contain quartz grains with planar deformation features (PDF) – a common indicator of ultra-high pressure conditions associated with impacts (Suuroja et al., 2003).

It would be tempting to associate the Osmussaar Breccia with the Neugrund impact event. However, the formation times of approximately 466 Ma (Alwmark et al., 2010) and 535 Ma
(Suuroja and Suuroja, 2010) respectively eliminate the possibility that the Neugrund impact event was directly responsible for the formation of the Osmussaar Breccia.

The angularity of chromite grains studied by Alwmark (Alwmark et al., 2010) in contrast to the many co-existing rounded terrestrial chrome spinels, implies that the extraterrestrial grains have not been transported or reworked to any large extent. This strongly indicates that the brecciation is a result of a contemporary impactor, either as a direct consequence of the impact or as a result of an earthquake triggered by the impact. Hence, the chromite grains most likely do not originate from the Neugrund structure nearby. None of the chromite grains extracted from the Neugrund material exhibited a composition indicating an extraterrestrial origin (Alwmark et al., 2010). The impact hypothesis also concurs well with the probable timing of the breakup of the L chondrite parent body $470 \pm 6$ Ma and an associated Middle Ordovician meteorite shower that followed shortly afterwards (Korochantseva et al., 2007).

2.4 THE PAKRI FORMATION

The Pakri Formation spreads as a roughly SW-NE trending layer of unusually sandy limestone (in relation to other Estonian limestones which mostly do not contain sand) and limy sandstone formation of the bedrock in the northwestern part of Estonia, being thickest at the Hiiumaa Island (4.5 meters) (Meidla, 1997c). In addition to impure sandstone and limestone, the formation also consists conglomerate (in the basal parts) which may contain phosphatic nodules. The formation is vertically inhomogenous, there are several muddy (marly) layers between coarser sediments (Põldsaar, 2009).

The Osmussaar Breccia is closely tied to the Pakri Formation. The clastic dikes that penetrate the Volkhov Stage limestone beneath the Pakri Formation (the Kunda Stage) are most likely filled with a material from above i.e. the Pakri Formation if the Pakri Formation and Breccia are not even coeval (personal communications with Kalle Kirsimäe). The rocks of these stages are separated by an unconformity. The hiatus could have lasted perhaps a million years which was long enough for the lithification of the Volkhov Stage limestones (personal communications with Leho Ainsaar) which was needed for the brecciation (brittle deformations) to take place. Coeval rocks of the Baltic paleobasin are almost exclusively composed of normal limestones which are in stark contrast to the sandy Pakri Formation (Põldsaar, 2009).
2.5 CONGLOMERATES

The Northwestern part of Estonian coastline hosts rocks with an unknown origin in several locations. Conglomerate pebbles and boulders with a dolomitic cement from the Cape Tahkuna (*Tahkuna neem*) on the Island of Hiiumaa have been studied before (Põldsaar, 2007; Põldsaar and Ainsaar, 2011, 2012). The conclusion of the aforementioned studies is that these rocks formed a distinctive uniform nearshore paleoenvironment of Kunda (Darriwilian) age. The authors suggest that the source formation of the studied rocks probably witnessed an impact event or impact triggered earthquake near the Osmussaar Island during the Middle Ordovician meteorite shower (Põldsaar and Ainsaar, 2011).

Such rocks are not confined to the northern tip of Hiiumaa. Conglomerates which until now have not been studied are found on the northwestern tip of the Estonian mainland (Cape Dirhami and Cape Põõsaspea). It is not known whether these pebbles are related to the sandstone-conglomerate pebbles in Hiiumaa, neither is the source location of these rocks known.

In addition to that, there are conglomerates on the southern coast of Osmussaar which contain large amount of sedimentary (mainly phosphatic nodules) and crystalline rock fragments. These rocks have no known analogues elsewhere, although they could be related to the conglomerates of Dirhami and Tahkuna because they also have a dolomitic cement. The question of cement is of great interest because the rocks of the Kunda regional stage are predominantly calcitic (personal communications with Leho Ainsaar).
3. MATERIAL AND METHODS

3.1 METHODS

Mineral composition of the samples was measured by means of X-ray diffraction (XRD) method on Bruker D8 ADVANCE diffractometer. Quantitative mineral composition of the samples was interpreted and modelled using Rietveld algorithm based codes Siroquant 3.0 (Taylor, 1991) and freeware Brass 2.0 (the latter was used for qualitative interpretation only). Samples were powdered by hand using agate mortar and unoriented preparations were made for mineral analysis.

The chemical composition of the samples was measured by means of X-ray fluorescence spectrometry (XRF) on Rigaku Primus II XRF spectrometer using SQX quantification model. Prior to the analysis, samples were powdered using planetary mill in two subsequent steps using different ball diameters.

For petrographic studies coherent sample pieces were embedded into low viscosity epoxy resin and double polished petrographic thin-sections (0.03 mm in thickness) on glass were prepared.

Scanning electron microscopy (SEM) study was performed using Zeiss EVO MA15 electron microscope equipped with Oxford X-MAX energy dispersive detector system (EDS) and AZTEC software for element analysis. Polished thin-sections were coated with carbon for scanning electron microscope analysis in high vacuum mode or were analysed uncoated in low vacuum mode. Photos of the samples were taken with Canon EOS 450D with macro lenses Tamron AF 60mm f/2 and Canon MP-E 65mm 1-5x.

3.2 STUDIED MATERIAL

The material studied was collected separately by several people (Siim Sepp, Kalle Kirsimäe, Kairi Põldsaar) from different locations (Cape Dirhami, Cape Takhuna, Osmussaar, etc.) The list of samples and their collecting locations are given in Appendix I.

Geological material used in this study consists of two conglomerate pebbles with phosphatic nodules from the southern coast of Osmussaar, seven quartz conglomerate pebbles from the Cape Dirhami, one quartz conglomerate pebble from Cape Põõsaspea, two quartz conglomerate pebbles from the Cape Takhuna, one quartz conglomerate from Reigi (Hiiumaa), and two samples of Osmussaar Breccia clastic dikes. Thirteen thin sections were
made, seven of them by other students as a laboratory assignment for the sedimentary petrology course. X-ray diffraction (XRD) analyses were made of all fifteen samples. X-ray fluorescence (XRF) analyses were made of seven samples. One thin section that turned out to be the most versatile (O2) was repeatedly and thoroughly investigated by SEM-EDS. One rock sample (O1) was also studied with SEM-EDS. The composition of microcline clasts of the sample O2 was compared to the composition of K-feldspar from the Lumparn Crater. The compositions were determined by SEM-EDS. Mineralogical composition of the cementing material of the drillcore 356 from Hiiumaa was determined by means of XRD analysis.

3.3 PETROGRAPHY

**Conglomerates from the Osmussaar (O1 & O2)**

Two conglomerate pebbles from southern coast of Osmussaar are lithologically versatile mixtures of well-rounded phosphatic nodules, angular quartz, microcline, almandine, and zircon grains (qualitative assessment of roundness is based on comparison with the roundness chart authored by Powers (Powers, 1953) with diagenetic pyrite, glauconite, and dolomitic cement (Figure 2). Thin section images of sample O2 are shown in figures 4, 6, Appendix VII, and Appendix IX.

The abundance of pyrite probably suggests that the sedimentary layer these rocks are made of contained originally appreciable amount of organic matter. Decay of organic matter caused the environment to become reducing which favors the formation of pyrite and glauconite (Deer *et al.*, 1996). Glauconite, however, may be allogenic as well.

Phosphatic nodules range in size from less than a millimeter to well over one centimeter. They exhibit no concentric layering or other obvious internal structures. The composition of nodules is variable. They may be composed of almost pure fluorapatite (note high fluorine content of Osmussaar samples (Appendix IV)) to a mixture of fluorapatite and angular quartz grains of variable grain size (Elemental map in Appendix X). Pyrite is also a common component as small disseminated grains. The nodules also contain barite, clay, and zircon among other minerals of lesser importance (determined by means of SEM-EDS).
The conglomerates studied contain abundant phosphatic (chemical composition by means of EDS analysis is shown in Appendix VIII) brachiopod shells (Figure 1 and Appendix VII), which probably represent the species *Ungula ingrica* (personal communications with Ivar Puura).

All of it is cemented together by a carbonate cement with a composition of ankeritic dolomite.

![Samples O2 (left) and O1 (right) from the southern coast of Osmussaar. O1 looks darker because it was covered with carbon for the study conducted by means of scanning electron microscope.](image)

**Sandstones and Conglomerates from Other Locations**

Coarse-grained sandstones and conglomerates from Cape Dirhami, Cape Põõsaspea (both from Estonian mainland), Cape Tahkuna, and Reigi (both from Hiiumaa Island) are composed of almost pure subrounded quartz grains and dolomitic cement (Appendix XI and XIII). One almandine grain was found in sample D3. Sample H-17 from Tahkuna contains pyrite (H-17 was examined only visually and is therefore not listed in the tables in the Appendix). Neither brachiopod shells nor phosphatic nodules were found. No significant difference in chemistry, mineralogy or petrography was detected between the samples from different locations.

**Sandstone from Clastic Dikes**

Sandstone from the clastic dikes (Appendix XII) of Osmussaar Breccia is composed of subangular moderately well-sorted (assessed only visually, no granulometric study has been made) quartz and microcline grains and calcitic cement. Small amount of pyrite, muscovite, and kaolinite were also detected by XRD analysis (Appendix III).
4. SOME TERMINOLOGICAL ISSUES

4.1 DIKES, VEINS, INTRUSIONS, OR CRACKS?

The clastic dikes inside the Osmussaar Breccia have been named by different authors in a different manner. Öpik (1927) called them 'earthquake cracks'. Orviku (1960) preferred the term 'sedimentary vein'. Puura and Tuuling (1988) introduced the term 'clastic dike'. Suuroja (Suuroja et al., 1999) decided to put forward yet another term, 'sedimentary intrusion'.

To simplify matters, in this study only one of these terms is used. 'Earthquake crack' does not seem to be correct because we do not know for sure whether the cracks are indeed caused by an earthquake. Sedimentary vein also raises doubts because the term 'vein' is in structural geology usually associated with any fracture that contains mineralized material (Jackson, 1997). These veins, however, are predominantly filled with allogenic quartz grains. 'Sedimentary intrusion' seems to be a misnomer because sedimentary intrusions are injections on a relatively large scale (forcing upward of salt, clay, gypsum, etc.) (Jackson, 1997). These 'intrusions' are neither large in scale nor forcing upward, because the beds directly below the brecciated layers are lithologically distinct glauconitic sandstones. The cracks above, however, contain no glauconite grains (Suuroja et al., 2003). 'Clastic dike' is described as a body cutting through the bedding of preexisting rocks in a manner similar to igneous dikes and it is not of any importance whether the clastic material comes from below as a forcible injection or falls into the cracks because of gravity (Jackson, 1997). Hence, the term 'clastic dike' is used in the current study as the most appropriate and least pretentious.

4.2 CONGLOMERATE OR GRAVELLITE?

I am using the term 'conglomerate' despite the fact that 'gravellite' seems to be more popular term in the studies conducted so far (Põldsaar and Ainsaar, 2011, 2012). The rationale behind this is rather straightforward – the term 'gravellite' seems to be a not accepted geological term in the English language. It is not included in the „Glossary of Geology“ (Jackson, 1997), neither is it mentioned in the Encyclopaedia Britannica (http://www.britannica.com/30.04.2012), nor in the Encyclopedia of Sediments and Sedimentary Rocks (Middleton, 2003), nor in the McGraw-Hill Encyclopedia of Science and Technology (McGraw-Hill, 2007), nor in the 5-volume set of Encyclopedia of Geology (Selley et al., 2004). Merriam-
Webster online dictionary also does not recognize the existence of the term 'gravellite' (http://www.merriam-webster.com/ 30.04.2012).

Conglomerate is a coarse-grained clastic sedimentary rock, composed of rounded or subangular fragments larger than 2 mm in diameter (Jackson, 1997). According to this definition, the rocks included in the current study are either coarse-grained sandstones or conglomerates.

Some of the conglomerates (from Osmussaar) described in the current study could possibly also be described as breccias because most of the clasts apart from well-rounded phosphatic nodules are rather angular. However, I decided to avoid naming them that way because it would potentially create lots of confusion, as the term 'Osmussaar Breccia’ is already in existence in a different manner and used in the current study as well. In addition to that, those grains that are angular are mostly smaller than 2 mm and are therefore smaller than the grains which define whether it is a breccia or conglomerate. The grains that are clearly larger than 2 mm are mostly well-rounded. Hence, the term conglomerate is probably appropriate.

4.3 OBOLUS OR UNGULA?

I am aware of the question whether the term 'Obolus sandstone’ is appropriate because brachiopods that form large part of the rock are not Obolus fragments at all (Puura and Holmer, 1993). However, there seems to be no other more appropriate name and this question does not influence the conclusions of the current study. Hence, the traditional 'Obolus sandstone’ is used.

4.4 THE TERM 'TSUNAMIITE’

The term 'tsunamiite’ is relatively new and used infrequently but it is nevertheless established itself as a valid geological term. In 1989 the term 'tsunamite’ (note that there are only one 'I’ in the word) was used by Yamazaki in 1989 (Shiki and Yamazaki, 2008) to describe tsunami-worked sediments in an upper bathyal. The spelling with one 'I’ was considered to be erraneous by professor Ales Smith from England. According to his recommendation, the term was revised as 'tsunamiite’ in Shiki and Yamazaki (Shiki and Yamazaki, 1996).

There is an older term 'tsunami deposit’ which is sometimes interpreted to be synonymous with 'tsunamiite’. In fact, there is a considerable overlap in the meanings of these terms but 'tsunamiite’ is considered to have a wider meaning encompassing also subaqueous marine sediments, while 'tsunami deposit’ is used only for subaerial sediments (Shiki and Yamazaki, 2008).
The problem is even more pronounced in the Estonian language. It would be comfortable to spell it 'tsunamiiit'. However, that would most likely be just as erroneous as the version with one 'i' seems to be in English. I asked an advice in this question from The Institute of the Estonian Language (Eesti Keele Instituut). There is a precedent – the word 'šiiit' is written with triple-I. However, the reluctance to accept the versions 'tsunamiiit' or 'tsunami-iit' was clearly evident. Hence, if the need arises to use the term in the Estonian language, the version with double-I should be preferred.
5. RESULTS AND DISCUSSION

The conglomerates from Osmussaar contain large amount of angular microcline clasts. According to Appendix II and Figure 3 these microclines are compositionally identical to the microcline of the wall of the Neugrund Crater and clearly distinct from the K-feldspar of the Lumparn impact structure in Åland.

Therefore, it would be tempting to associate the conglomerates with the ejecta layer of the Neugrund impact event. However, the conglomerates also contain numerous phosphatic nodules which most likely originate from the Kallavere Formation which is known to contain nodules with a very similar appearance (compare figures 4 and 5). The conglomerates also contain numerous fragments of phosphatic brachiopods (Appendix VII), probably lingulate *Ungula ingrica*, which form a layer of obolus sandstone in the Kallavere Formation. The base of the Kallavere Formation (Late Cambrian according to Pirrus *et al.*, 2006) formed almost 50 million years after the Neugrund Impact event (Early Cambrian) which excludes the possibility that Osmussaar conglomerates are derived from the ejecta layer.

However, the fact remains that the conglomerates contain abundant geological material (microcline, almandine) which is obviously derived from the crystalline basement. The crystalline basement in northwestern Estonia was at the probable formation time of the conglomerates (which had to be later than
the formation time of the Kallavere Formation) covered with more than 100 meters (Appendix VI) of sedimentary rocks. Hence, it is most likely safe to exclude the local basement, apart from the Neugrund Crater wall and/or ejecta, as the source material of microcline and almandine.

According to the geological map of the basement rocks (Koistinen, 1996), it seems that the general character of the basement rocks is not significantly different (Figure 10) at the site of the Neugrund Crater and a few kilometers north and westward where the possible shoreline according to Nestor and Einasto (1997) was located at the Early Ordovician (Volkhov Stage). Therefore, these crystals may represent a nearshore facies of terrigenous detrital sediments. However, the angularity of the grains (Figure 6) suggests that the material has not been transported or reworked to any large extent. Hence, it is doubtful that the material comes from the paleoshoreline of the Early Ordovician. Thus, the hypothesis that angular almandine and microcline grains are somehow extracted from the Neugrund crater walls (or some other prominent outcrop of the basement rocks) seems to be the most parsimonious explanation.
One characteristic feature of the Osmussaar conglomerates is their rich heavy mineral content. These conglomerates have visually abnormally high heavy mineral concentration (Figure 7 and Appendix IX) when compared to the conglomerates of Cape Dirhami and Cape Tahkuna which are composed of almost pure quartz with dolomitic cement (Appendix XI and XIII). The most abundant heavy mineral by far is pink almandine. X-ray diffraction indicates also the presence of dravite (brown Mg-tourmaline), but thin section and SEM-EDS analyses failed to confirm this finding. The presence of tourmaline in such a high concentration (0.5-1%) is unlikely because the local basement is composed of high-grade metamorphic rocks: metamorphosed intermediate or mafic igneous rocks (amphibolite) and metamorphosed sedimentary rocks (migmatite) (Koistinen, 1996). These rocks generally do not contain tourmaline (Deer et al., 1996). Indeed, the local rocks are not known to be rich in tourmaline, let alone in that high concentrations. There are considerable amount of green grains (Figure 8) which were found to be quartz. Green color is possibly caused by chlorite inclusions (personal communications with Juho Kirs). The conglomerates also contain zircon (not detected by XRD but several grains were found with SEM-EDS) and pyrite (0.2-1.5%). Large amount of pyrite is most likely diagenetic (formed after the deposition of the material the conglomerates are made of), particularly the pyrite masses with highly irregular outline that have formed between the pre-
existing grains. Few grains of titanium oxide (possibly anatase), cassiterite, galenite, and iron oxides were found as well with SEM-EDS.

Iron-rich garnet (almandine) is moderately stable in the weathering environment (Pettijohn et al., 1973). Hence, it is not possible to say, based on garnet study alone, whether the material is local (the Neugrund Crater, for example), or a disintegration product of more distant metamorphic rocks. In the current case, heavy minerals may not be very useful in determining the provenance of the material but their high concentration clearly indicates that some sort of mechanism had to be involved that preferentially sorted out heavy minerals i.e., carried away lighter grains.

Heavy minerals may become concentrated naturally by hydrodynamic sorting, usually in shallow marine or fluvial depositional settings. Such deposits, if they contain economically valuable minerals, are frequently exploited commercially. Gold, cassiterite, ilmenite, monazite, magnetite, zircon, and rutile are among the minerals that are often extracted from placer deposits (Morton, 2007). Natural heavy mineral concentrates form in two principal sedimentary environments: marine deposits (heavy minerals concentrated by sea waves) or fluvial deposits (concentrated by running water) (Guilbert and Park, 2007). The conglomerates contain broken bits of marine fossils (lingulate brachiopods) which excludes the possibility that these rocks are former fluvial sediments.

Most marine heavy mineral deposits form as a storm deposit. High-energy run-up storm waves carry all sorts of material on the beach but are able to pick up only the lighter component when they recede. Therefore, a layer enriched in heavy minerals is left behind and will be buried in the future by subsequent storm deposits (Guilbert and Park, 2007). Such a mechanism is thought to be involved in the formation of most marine placers. However, placers like that are commonly at least moderately well-sorted, which is not the case with very poorly sorted Osmussaar conglomerates. The driving force behind the conglomerates had to be energetic – it was capable of picking up grains with a highly variable pick-up speed and it did not sort the grains according to their size. However, it somehow enabled the heavy minerals to be concentrated. There is a geological phenomenon which is theoretically capable of doing all of it – a tsunami.

The study of tsunami deposits is a relatively new branch of sedimentology. First investigations of tsunamiites (a general term for all tsunami deposits (Shiki and Yamazaki, 2008)) were undertaken in 1960 (Nanayama, 2008) after the Valdivia earthquake related to the subduction zone along the coast of Chile. This was the most powerful earthquake ever
recorded with a magnitude 9.5 on the moment magnitude scale (M$_w$) (Wen et al., 2011). The earthquake created tsunami waves which devastated even the coastal areas of Japan thousands of kilometers away from Chile (Shiki and Tachibana, 2008). Significant progress has been made in the study of tsunamiites after the Indian Ocean Tsunami in 2004 (Shiki et al., 2008a) which was caused by the Sumatra-Andaman Earthquake with a magnitude of M$_w$ 9.2 (Waldhauser et al., 2012) and killed 227,898 people (http://earthquake.usgs.gov/earthquakes/equinthenews/2004/us2004slav/#summary 09.05.2012).

It must be noted that the investigation of possible tsunamiites is a complicated task because there are no obvious criteria which distinguish tsunamiites from sediments generated by other events (Sugawara et al., 2008). Tsunami can transport any material available, from clay to huge boulders. Tsunamiites are not necessarily composed of coarse-grained sediments (Shiki et al., 2008b). Therefore, tsunami deposited sand is often difficult if not impossible to distinguish from sand deposited by ordinary sea waves. However, if the rocks being studied are coarse-grained, contain heavy minerals, fossil fragments, and clasts most likely ripped up from the seabed, the list of possible trigger mechanisms narrows down considerably.

The most important characteristic of tsunami waves is a very long period and wavelength. The period of storm waves is generally several seconds in small bays, and maximally 10-20 seconds on open coasts. The wavelength of tsunami waves could be up to 100 km and the period between ten minutes and one hour. This is more than 100 times more than those of wind-induced waves (Fujiwara, 2008). Hence, tsunamis generally leave a distinct fingerprint which is a collection of sedimentary structures and bedforms. The most important characteristics of tsunamiites are: (1) an alteration of sediments deposited by high- and low-energy currents, (2) repeated reversals of current directions, (3) a fining of sediments in upward and landward

![Figure 9. A rock sample from Tahkuna displaying an alteration of conglomeratic (top and bottom) layers with sandstone layers (middle) which is characteristic to tsunamiites.](image-url)
directions (Fujiwara, 2008). These characteristics are a direct consequence of an extremely long wavelength of tsunami waves. High-energy waves leave behind coarse-grained sediments, while there is plenty of time between consecutive waves for the sea to calm which allows the fine-grained material to start falling out of the suspension to form mud drapes between coarser material (Shiki et al., 2008b). In Figure 9, sandstone from Tahkuna is shown which displays alternating bands of coarse- and medium-grained sandstone. These coarse layers may represent tsunami waves and associated high-energy water flow while the finer material settled when sea was calmer between the waves. However, in order to be reasonably sure whether it was indeed a tsunami that deposited the material these pebbles are made of, more than just a few pieces of sandstone and conglomerate are needed.

Tsunamiites somewhat similar to the Osmussaar conglomerates are reported from Nicaragua. These tsunamiites formed after the tsunami of 1992: "Proximal deposits on the beach ridge are typically 5- to 10-cm thick and composed of very coarse sand with pebbles and shell debris. The body of the deposit, over most of the profiles, comprises 1-5 cm of coarse to fine sand, fining landward. Some deposits exhibit flat to low-angle heavy mineral lamination“ (Higman and Bourgeois, 2008). Heavy minerals, according to the study of the Nicaraguan tsunami, tend to occur together with coarse-grained sediments and rip-up clasts (Fujiwara and Kamataki, 2008) which typically represent the basal part of tsunami deposit where the shear stress is the greatest (Shiki et al., 2008b). This results in many clasts ripped up from the sea bottom.

So, are the phosphatic nodules in the Osmussaar conglomerates rip-up clasts? Bottom erosion is the most violent when the wave breaks (Shiki et al., 2008b). Hence, possibly the waves started to break where the phosphatic nodules cropped out on the seabed which explains their abundance in these pebbles? These questions are of course very difficult to answer, especially when considering the scarcity and unknown original location of the studied geological material. In order to positively confirm whether these rocks are indeed tsunamiites, investigation of a complete tsunamiite profile is needed. There is only one possible and promising candidate of a tsunamiite in the northwestern part of Estonia – the Pakri Formation.

Pakri Formation is up to 4.5 meters thick but mostly significantly thinner and composed of yellowish gray calcareous sandstone, sometimes with conglomerate beds (Meidla, 1997c). Põltsaar in her masters thesis (Põltsaar, 2009) divides the sequence into five intervals. The interval A in the bottom of the sequence is notable for containing lots of coarse-grained quartz sand. The layer may contain phosphatic nodules. Orviku (1960) also describes the lower part
of the Pakri Formation as a phosphatic basal conglomerate. The five intervals may represent the units of a typical tsunami deposit, each having alternate flow direction, run-up or backwash. They can also represent consecutive run-up waves. What seems to suggest that this hypothesis is worth a closer inspection is the fact that these intervals are sometimes separated by muddy intervals which may represent the mud drapes deposited in a calm water between two consecutive tsunami waves. Hence, there is a possibility that the whole of the Pakri Formation is a tsunamiite and therefore deposited in a very short timeframe. In that case, the conglomerates on the southern coast of Osmussaar may originate from the basal parts of the Pakri Formation and were deposited in a high-energy conditions of a run-up tsunami wave.

The hypothesis of tsunami-created Pakri Formation faces several challenges, some of which are not currently apparent. Since no field work has been conducted with this possibility in mind, the hypothesis is in most part a mere theoretical speculation based on literature and geologic reasoning.

So far, I only offered a possible explanation regarding the Osmussaar conglomerates. What about the conglomerates of Dirhami and Tahkuna? It seems plausible to assume that they originate from the same sedimentary layer as they are also coarse-grained and have a dolomitic cement while the bedrock in the region has no other serious candidate other than the Pakri Formation as a source of such a material. However, there are obvious differences in the composition. The conglomerates from Dirhami and Tahkuna are composed of almost pure quartz and dolomite. Hence, they seem to represent a different (more typical) basal coarse-grained part of a tsunamiite. These differences are most likely the direct consequence of differences in the lithology of the source. A tsunami can transport only the material available (Shiki et al., 2008b). So, the question should be asked in a different manner: why are some of the conglomerates (from Osmussaar) having so unusual composition while most conglomerates from this region are much simpler? In order to answer this question we have to remember that the Osmussaar conglomerates contain lots of angular microcline clasts which have to originate from the basement. So, the Osmussaar conglomerates originate from a distinct lithological section of the tsunamiite which derived much of its material from the basement rocks. Does it mean that these rocks represent the northern part of tsunamiite where the crystalline rocks of the Fennoscandian Shield cropped out? There exists a possibility that this material is extracted from the Neugrund crater walls. However, according to current understanding the Neugrund impact structure was already buried at that time. The oldest sedimentary rocks found inside the crater formed already in the Early Cambrian (Suuroja and
Suuroja, 1999). If the possible tsunami scraped the material off the rim of the Neugrund Crater, the extent of the Osmussaar conglomerates must be relatively restricted and there should be no analogous rocks on the coast of Hiiumaa, for example, because the Neugrund Crater is far away. One could argue that the Kärdda Crater is very near to Tahkuna just as the Neugrund Crater is close to Osmussaar, but this argument is not valid because the Kärdda Crater (455 Ma) (Puurua and Suuroja, 1992) formed after the possible tsunami event (466 Ma) (Alwmark et al., 2010) if tsunami is coeval with the formation of the Osmussaar Breccia.

If there was a tsunami, it had to be triggered by something. What could it be? There are four mechanisms that are known to be capable of tsunami generation: earthquakes, submarine landslides, volcanic eruptions, and impact events. Earthquakes are by far the most important triggering mechanisms of tsunamis (Sugawara et al., 2008). The Osmussaar Breccia is thought to be a result of a large submarine earthquake (Suuroja et al., 2003). However, the occurrence of a tsunami-generating earthquake in the paleogeographical conditions prevalent in the studied area in the Early Ordovician is somewhat problematic.

The area of northwestern Estonia in the Early Ordovician was a shallow epicontinental shelf sea (Nestor and Einasto, 1997). Nearest Ordovician subduction zones were in the Tornquist Sea bordering the Avalonia microcontinent but these activated in the Caradoc, more than five million years later (Torsvik and Rehnström, 2003). The modern earthquakes responsible for the tsunami generation are almost always associated with subduction zones (Sugawara et al., 2008). These subduction zone related earthquakes, if they are going to cause a tsunami, have a shallow focus and the associated movements of fault blocks at the bottom of the sea is measured in meters (Sugawara et al., 2008). It is unlikely that earthquakes that powerful took place beneath the shallow Ordovician shelf sea. Equally unlikely is the hypothesis that the tsunami was caused by a large submarine slump. The sea in the Early Ordovician bordering the Baltica at the time of the possible tsunami event was characterized by slow sedimentation (Nestor and Einasto, 1997) and the seafloor in the interior of the gulf bordered by the Baltica was far away (http://www.scotese.com/newpage1.htm 09.05.2012) from the continental margin where slumps of considerable size (turbidity currents) take place. The Ordovician system in Estonia is known to contain several bentonite layers which could suggest that maybe a large volcanic eruption was involved and triggered the tsunami. However, the bentonite layers of Keila and Haljala regional stages (Hints, 1997; Hints and Meidla, 1997) are considerably younger (from the Caradoc as well) and possibly also associated with the closure of the Tornquist Sea and the Iapetus Oceans (Fortey et al., 1995).
Accordingly, an impact event remains the only mechanism that can not be ruled out yet. How likely is it that the tsunami was triggered by an impact event? According to today’s terms not very likely. However, the timing of the possible tsunami and impact event concurs well with the breakup of the L chondrite parent body 470 ± 6 Ma (Korochantseva et al., 2007) and an associated Middle Ordovician meteorite shower when the influx of meteorites increased by up to two orders of magnitude (Schmitz et al., 2001). The Osmussaar Breccia is known to contain large amount of extraterrestrial chromite grains (more than 13 grains per kilogram) (Alwmark et al., 2010) and the sandstone clastic dikes contain quartz grains with planar deformation features (Suuroja et al., 2003). All of it together means that an impact event associated with the formation of the Osmussaar Breccia is not only possible, but even likely to have taken place.

Which direction did the hypothetical tsunami waves come from? The paleoshoreline at the time of the Volkhov Age was located north- and northwestward from the location of today’s Osmussaar Island (Nestor and Einasto, 1997) (Appendix V). The shoreline was most likely shifted more to the south by the time of the possible tsunami because, according to Männil, Kunda Age represented a prominent sea level fall in the Baltic paleobasin (Männil, 1966, cit. Suuroja et al., 2003). Hence, it would be logical to assume that the tsunami waves came from the southerly direction. However, this part of the shelf sea was shallow and gently dipping, dominated by slow carbonate sedimentation without high water energy (Jaanusson, 1973). Hence, there was no sand available for the tsunami to form the layer we know today as the Pakri Formation. The only direction left where the tsunami could have originated seems to be south-west. Tsunami waves from this direction could have brought lots of sandy material because there was Gotland-Gotska Sandön tectonic uplift area which probably reached from Gotland to near Hiiumaa (Jaanusson, 1973).

What seems to give further credit to the idea is the fact that the Pakri Formation is the thickest in Hiiumaa and gets thinner in the northeastern (landward?) direction. An interesting aspect of the conglomerates of Osmussaar is the complete absence of the clasts from the Türisalu Formation which form a thick layer (5.5 m) in the Osmussaar drillcore (Appendix VI) between the thin (0.2 m) Kallavere Formation (which is the source material of the Obolus fragments and phosphatic nodules) and the Pakri Formation. Hence, the material had to be scraped from the seafloor where the Türisalu and few other formations are missing. There are drillcores from Hiiumaa where the rocks of the Pakri Formation lay directly on top of the Kallavere Formation (Heinsalu and Viira, 1997a, b; Meidla, 1997a, b, d). Therefore, this
strongly suggests that the studied conglomerates originate from more westerly position in relation to their current location.

Another important aspect supporting the tsunami hypothesis is the fact that pebbles similar to the material found in northwestern Estonia are also found in Sweden and sometimes even in Germany and Denmark (Buchholz, 2011) as a glacial debris. These rocks, known as Jentzschi conglomerates, are interpreted to correspond stratigraphically to the Pakri Formation (Schallreuter and Hinz-Schallreuter, 2007). It could potentially give further credit to the tsunami hypothesis because tsunami deposits are known to spread over extensive areas but do not necessarily need to form a continuous deposit (Sugawara et al., 2008).

What about the possible link between microclines of the Neugrund crater rim and the Osmussaar conglomerates? Although the material is chemically identical (Appendix II) it is very difficult to explain where is the phosphatic material of the conglomerates coming from. The Kallavere Formation is covered with ten meters of sediments, so it seems rather unlikely that this material originates from or near the Neugrund crater wall. Another aspect that makes it hard to believe that the Neugrund Crater indeed is the source area of the microclines is the undisturbed nature of the sedimentary rocks inside the crater. The sedimentary plateau inside the crater, as known today, shows no obvious traces of tsunami influence (personal communications with Sten Suuroja). Consequently, the question regarding the origin of microcline clasts inside the Osmussaar conglomerates is not solved yet. It seems plausible to assume that these rocks originate from more northerly part of a tsunami deposit and got carried to the Osmussaar as a glacial debris. In order to prove that, more samples of basement rocks from the vicinity should be studied in the future.

Figure 10. An excerpt from the Map of the Precambrian basement of the Gulf of Finland and surrounding area (Koistinen 1996). General character of the basement rocks is comparable around Hiiumaa and Osmussaar Islands. Green – mafic and intermediate metavolcanic rocks (amphibolite); blue – mica schist and mica gneiss (migmatite).
If the hypothetical tsunami was caused by an impact event, then there has to be an impact structure somewhere. Although extensive geophysical surveys have been carried out in the Central Baltic Sea (Tuuling and Flodén, 2001), no crater has been found. There could be many explanations: (1) there is no crater because even if the tsunami hypothesis holds, the tsunami could be still generated by an earthquake despite the fact that strong earthquakes, according to our current knowledge, were not very probable in the area at that time; (2) crater may be buried deep beneath sediments. Hence, we do not recognize it from the geophysical profiles; (3) the impact structure existed originally but has been eroded in time and therefore does not exist anymore.

One of the most controversial aspects that did not fit well into the picture described above is the fact that all the studied conglomerates have a dolomitic cement. This is in stark contrast to the predominantly calcitic rocks of the Pakri Formation. However, this controversy was solved in the course of this study. The drillcore 356 (Figure 11) from western part of Hiiumaa where the Pakri Formation is directly on top of the Kallavere Formation was found to be dolomitic. In order to prove that, basal part of the Pakri Formation (3 cm up from the contact between the Kallavere and the Pakri Formations) was tested by means of X-ray diffraction. It is not yet known how extensive the dolomitization is. This has to be determined by studies conducted in the future. Still, the finding is most important when considering the hypothesis proposed in the current thesis. Now it is possible to say with fairly high degree of certainty that basal parts of the Pakri Formation may indeed be the source location of the conglomerate pebbles because it is at least partly dolomitic just as the rock samples found on the coast.

Figure 11. Drillcore 356 (section 3.385...3.43 meters deep) from Hiiumaa where the Kallavere (lower) and Pakri Formations (upper) are in contact. The approximate boundary between them is annotated. The Kallavere Formation contains lots of black phosphatic brachiopod shells.
6. CONCLUSIONS

The aim of this study was to investigate the possible origin and formation mechanisms of the conglomerates found on the southern coast of Osmussaar. It must be said that the results are preliminary and somewhat inconclusive. A hypothesis about the origin of the rocks was proposed but the confirmation remains an objective of future studies. As is often the case, this study gave rise to more questions than it answered. Finding solutions to these problems might lead to new possible discoveries which could have much more far-reaching consequences than the origin of a few pebbles in Osmussaar.

The conglomerates from Cape Dirhami and Cape Tahkuna are similar in appearance and composition. Hence, they probably originate from the same formation. The conglomerates from Osmussaar are compositionally more versatile than the conglomerates of Dirhami and Tahkuna. The combination of phosphatic rip-up clasts, high heavy mineral concentration, quartz gravel, and angular microcline clasts suggest that these rocks were formed by moving water with a high energy. It is possible that these conglomerates once formed the basal part of a tsunamiite. These conglomerates too, just like the pebbles from Tahkuna and Dirhami, have a dolomitic cement which suggests that they might originate from the same formation but with a lithologically different source material.

In addition to the conglomerates, the Pakri Formation as a whole was also found to have certain features which often characterise tsunami deposits. The most important of them is the presence of mud drapes between successive coarser-grained material which may represent the calm water phase between higher energy phases of a tsunami waves. The basal part of the Pakri Formation is coarse-grained conglomerate which is common feature of a tsunamiite and in the current case could be the source region of the conglomerates studied.

The hypothetical tsunami possibly came from southwest because this is the only direction where enough clastic material was probably available (apart from the landmass in north which obviously could not have been the starting point of tsunami) to form the Pakri Formation. Also, the drillcore from Hiiumaa suggest that the conglomerates we find today in Osmussaar probably originate from more westerly location where the Pakri Formation is laying directly on top of the Kallavere Formation. Another important aspect strengthening the hypothesis that the tsunami originated from southwest is the discovery of dolomitic cement holding together the rocks of the Pakri Formation of the drillcore 356 (only the basal part of the section is...
tested). This is a very important finding because it solves the controversy over dolomitic vs. calcitic cement of conglomerate pebbles and the Pakri Formation respectively. Now it can be said with much more certainty that these pebbles indeed most likely originate from the Pakri Formation. How extensive is the dolomitization is currently unknown.

The composition of microclines in the Osmussaar conglomerate suggest that the source material comes from the local basement. The composition is identical to the microcline of the Neugrund Crater. However, the Neugrund is believed to have been a buried structure at the time.

In addition to that, it is hard to explain the existance of phosphatic material in the conglomerates because the bedrock layer from which these particles originate (the Kallavere Formation) is covered by ten meters of bedrock around the Osmussaar Island. Hence, the source material could originate from other area where basement rocks were exposed. The material is angular, so it most likely does not come from the paleoshoreline.

The most important finding of this thesis is the possibility that the northwestern part of Estonia may have witnessed a tsunami in the Early Ordovician. Future field work and studies should bear this in mind to enhance the possibility of finding new evidence for or against the hypothesis. Another important contribution is the discovery of dolomitic cement in the Pakri Formation which effectively solves one of the most puzzling aspects of the conglomerate pebbles found on the coast – the question of their origin.
Osmussaare lõunaranniku konglomeraatide tekkeviis ja päritolu


Käesoleva töö eesmärgiks oli võrrelda Tahkuna, Dirhami ja Osmussaare kivimeid, et teha kindlaks, kas tegemist on tõenäoliselt samast setekihist pärineva materjaliga või mitte. Lisaks oli eemärkiks püstitada hüpoteees, mis seletaks eelkõige Osmussaare veeriste tekkeviisi. Osmussaare materjal on antud uurimuse kontekstis kõige olulisem, sest sealt leitud kivimite erakordselt suur litoloogilis-mineraloogiline mitmekesisus pakub tekkeviisi väljaselgitamiseks kõige paremaid võimalusi.

Osmussaare veeristele on iseloomulik suur raskete mineraalide sisaldus, fosfaatsete konkretsioonide esinemine, halb sorteeritus, käsijalgsete fragmentide, savi ning orgaanika sisaldus, mis viitab kõige tõenäolisemalt sellele, et antud kivim on pärit tsunamilainest väljasettinud materjalist. Ka ülejäänud materjal, Dirhami ja Takhuna veerised, on seletatavad tsunami-hüpoteesi abil. Kõigil juhtudel seob setteosakesid üheks kivimiks dolomiitne tsement. Dirhami ja Takhuna kivimid on keemilis-mineraloogiliselt väga sarnased (peamiselt kvartsiterad dolomiidiga), mistõttu võiks eeldada, et tegemist on ühest ulatuslikust setekihist pärit materjaliga, mis on randa kantud liistiku jää poolt. Kuigi Osmussaare veerised on litoloogiliselt mitmekesisemad, on nende põhiolus käsijalga fused venusteel ja oluliselt tõenäoline, et Osmussaare konglomeraadid on pärit litoloogiliselt heterogeemsemast lähtepiirkonnast.

Kuna Osmussaare kivimid sisaldavad fosfaatsete konkretsioonide ning käsijalgsete kodade fragmente, mis väga suure tõenäosusega pärinevad Kallavere kihistust, võiks eeldada, et hüpeteetiline tsunami on nad lahti kraapinud merepõhjast, kus nimetatud kihistu paljandus. Osmussaare piirgonnas vahetult Kallavere kihistu kohal puuduvas kivimkihid, kust sellise ilmeka kivimid võiksid pärineda. Tegelikult on terves Loode-Eesti aluspõhjas ülevalpool Kallavere kihistut olemas vaid üks tõsiseltvõetav kandidaat – Pakri kihistu. Pakri kihistu ja
Kallavere kihistu puutuvad üksteisega vahetult kokku vaid Hiiumaa piirkonna aluspõhjas, kus ajaliselt nende vahel moodustunud kivismikhid (graptoliitargilliit, glaukonitiiliivakivi) puuduvad. Sellest lähtudes võib eeldada, et oletatav tsunami pidi pärinema umbes edela suunast, liikudes Hiiumaalt Osmussaare poole ning setitades materjali randa ja rannalähedasse merre, mis asus tänase Soome lahes, kusjuures maismiga asus põhja ning meri lõuna suunas. Täiendavalt lisab kirjeldatud hüpoteesile kaalu asjaolu, et Hiiumaa puuraugus 356, kus Pakri kihistu lasub vahetult Kallavere kihistul, on Pakri kihistu liivakivi tsement dolomiitne. Siiani oli arvatud, et terve Pakri kihistu on kaltsiitse tsemendiga. Seega on käesoleva töö üheks olulisemaks leiaks asjaolu, et see pole vähemalt Hiiumaa piirkonnas tõsi. Kui suure ulatusega on Pakri kihistu kivismite dolomiidistumine, on tulevaste uuringute teema, mis kahtlemata on väga oluline ka käesolevas töös püstitatud tsunami-hüpoteesi paikapidavuse kontrollimisel.

Käesoleva töö kolm kõige olulisemat järeldust on:

1. Pakri kihistu alumine osa on vähemalt osaliselt dolomiitse tsemendiga
2. Tahkuna, Osmussaare ja Dirhami konglomeraadid on tõenäoliselt pärit Pakri kihistu basaalset kihist
3. Materjal, millest konglomeraadid koosnevad, on tõenäoliselt tsunamitekkeline. Sama kehtib arvatavasti ka kogu Pakri kihistu kohta.
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## 10. APPENDIX

### 10.1 TABLES

**Appendix I. The samples studied.**

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<td>O</td>
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<td>Kairi Põltsaar</td>
<td>Tahkuna</td>
<td>Siim Sepp</td>
<td>–</td>
<td>O</td>
</tr>
<tr>
<td>T2</td>
<td>Kairi Põltsaar</td>
<td>Tahkuna</td>
<td>–</td>
<td>–</td>
<td>O</td>
</tr>
<tr>
<td>R1</td>
<td>Kairi Põltsaar</td>
<td>Reigi</td>
<td>Siim Sepp</td>
<td>–</td>
<td>O</td>
</tr>
<tr>
<td>O1</td>
<td>Kalle Kirsimäe</td>
<td>Osmussaar (S coast)</td>
<td>Hanna Raig</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>O2</td>
<td>Kalle Kirsimäe</td>
<td>Osmussaar (S coast)</td>
<td>Kristiina Ojamäe</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>OCD1</td>
<td>Kalle Kirsimäe</td>
<td>Osmussaar (NE coast)</td>
<td>Mare Laan</td>
<td>O</td>
<td>O</td>
</tr>
<tr>
<td>OCD2</td>
<td>Kalle Kirsimäe</td>
<td>Osmussaar (NE coast)</td>
<td>Rudolf Välja</td>
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(O) analysis conducted, (–) analysis not conducted.

**Appendix II. Chemical analysis of K-feldspar grains by means of energy dispersive spectrometry from three samples.**

<table>
<thead>
<tr>
<th>Sample</th>
<th>O</th>
<th>Si</th>
<th>K</th>
<th>Al</th>
<th>Na</th>
<th>Ba</th>
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</tr>
<tr>
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<td>9.7</td>
<td>0.9</td>
<td>0.5</td>
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<td>10.1</td>
<td>9.4</td>
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<td>13.8</td>
<td>10.3</td>
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<td>Osmussaar 6</td>
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Appendix III. Mineralogical composition of the samples studied by means of XRD analysis.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Quartz</th>
<th>Dolomite</th>
<th>Kaolinite</th>
<th>Microcline</th>
<th>Calcite</th>
<th>Pyrite</th>
<th>Muscovite</th>
<th>Almandine</th>
<th>Apatite</th>
<th>Dravite</th>
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<tbody>
<tr>
<td>D1</td>
<td>O①</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>–</td>
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<td>–</td>
<td>–</td>
</tr>
<tr>
<td>D2</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>D3</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
<td>D4</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>D5</td>
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<td>O</td>
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<tr>
<td>D6</td>
<td>69.1</td>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
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</tr>
<tr>
<td>D7</td>
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<td>0.7</td>
<td>7.6</td>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<td>68.8</td>
<td>21.4</td>
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<td>8.7</td>
<td>0.1</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>T1</td>
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<td>–</td>
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</tr>
<tr>
<td>T2</td>
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<td>–</td>
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<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>R1</td>
<td>O</td>
<td>O</td>
<td>–</td>
<td>–</td>
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<td>–</td>
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<td>–</td>
<td>–</td>
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<tr>
<td>O1</td>
<td>44.0</td>
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<td>0.2</td>
<td>1.3</td>
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<tr>
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<td>23.0</td>
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<tr>
<td>OCD1</td>
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<td>7.4</td>
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<td>1.1</td>
<td>–</td>
<td>–</td>
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</tbody>
</table>

1 - XRD analysis exists for every sample listed but numerical values are given for these samples that have been analysed by Topas and Siroquant software in addition to freeware Brass which was used for qualitative analysis only. (O) mineral was found, (–) mineral was not found.

Appendix IV. Concentration of chemical elements in seven samples by means of X-Ray fluorescence analysis.

<table>
<thead>
<tr>
<th></th>
<th>D6</th>
<th>D7</th>
<th>P1</th>
<th>O2</th>
<th>O1</th>
<th>OCD1</th>
<th>OCD2</th>
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<td>Na2O</td>
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<td>0.03</td>
<td>0.04</td>
<td>0.18</td>
<td>0.17</td>
<td>0.04</td>
<td>0.05</td>
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<tr>
<td>MgO</td>
<td>3.37</td>
<td>3.52</td>
<td>3.26</td>
<td>3.02</td>
<td>2.39</td>
<td>0.09</td>
<td>0.06</td>
</tr>
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<td>Al2O3</td>
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<td>0.51</td>
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<td>4.46</td>
<td>4.20</td>
<td>0.42</td>
<td>0.21</td>
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<tr>
<td>SiO2</td>
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<td>60.05</td>
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<td>0.13</td>
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<td>0.03</td>
<td>0.09</td>
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<tr>
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<td>0.17</td>
<td>0.06</td>
<td>0.05</td>
<td>0.02</td>
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</tr>
<tr>
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<td>0.04</td>
<td>0.14</td>
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<td>CaO</td>
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<td>0.06</td>
<td>0.05</td>
<td>0.03</td>
<td>0.03</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>MnO</td>
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<td>Fe2O3</td>
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<td>15.12</td>
<td>17.21</td>
<td>23.77</td>
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</table>
Appendix V. Map of northwestern Estonia with annotated collecting locations of the samples studied.
Appendix VI. Drillhole 410 in Osmussaar showing the sedimentary sequence of Osmussaar on top of the metamorphosed basement from the Paleoproterozoic.

Appendix VII. Fragment of a phosphatic lingulate brachiopod shell. Photos of thin section O2 taken in plane polarized light (left) and in crossed polars (right).
Appendix VIII. Image of the lingulate brachiopod shell taken with scanning electron microscope (the width of the view is 1.3 mm). Chemical composition of the shell is determined by means of Energy-dispersive X-ray spectrometry.

Appendix IX. Thin section O2 in plane polarized light (left) and crossed polars (right). In the middle are triangular garnet (extinct in crossed polars) and zircon beneath it (colorful in crossed polars). Dark mineral in plane polarized light is pyrite. Blocky crystals (with straight edges) are microcline grains. White grain in crossed polars is quartz. Cement surrounding the grains is composed of ankeritic dolomite.
Appendix X. Element map of the interior of a phosphatic nodule from the thin section O2. Angular grains are mostly composed of quartz (they are bright in Si (silicon) and O (oxygen)). Groundmass is phosphatic (bright in P (phosphorous) and Ca (calcium)).
Appendix XI. Samples D1...D5 from Cape Dirhami are almost monomineralic coarse-grained sandstones and conglomerates with dolomitic cement.

Appendix XII. Limy sandstone (OCD1) from the clastic dikes of Osmussaar.
Appendix XIII. Rock samples from Cape Põõsaspea (P1), Cape Tahkuna (T1), and Reigi (R1).