since 1961

Baltica

http://www.geo.lt/geo/index.php?id=71C

BALTICA Volume 23 Number 2 December 2010 : 157-164

Sand accumulation under varying lithohydrodynamic conditions in the coastal area of the north-eastern Baltic Sea

Andres Kask, Tarmo Soomere, Sten Suuroja, Jüri Kask

Kask, A., Soomere, T., Suuroja, S., Kask, J. 2010. Sand accumulation under varying lithohydrodynamic conditions in the coastal area of the north-eastern Baltic Sea. *Baltica, Vol. 23 (2),* 157–164. Vilnius. ISSN 0067-3064.

Abstract A total of over 90 million m^3 of sand have been found on the Estonian shelf in the course of explorations since the 1990s. The present paper aims to summarize the exploration results and to evaluate the occurrence, genesis and formation conditions of sand deposits. Sand exploration has been conducted in three main regions: west of the Island of Hiiumaa, in Tallinn area, the Muuga and Ihasalu bays, and in the south–eastern Gulf of Finland. Sand deposits overlie postglacial clay in deeper areas and glacial till in shallower regions. Deposits, mostly extending down to a depth of 25 m, lie at the foot of bedrock escarpments and on the slopes of positive landforms consisting of glacial deposits. Parameters of mean grain size and sorting were calculated from sieve analysis results of 249 samples. Sand predominantly is formed as a result of the abrading of glacial deposits. The sedimentation area is determined by the hydrodynamic conditions and depth of water. Another source of sand west of the Island of Hiiumaa is the glacio-fluvial sediment, which adds more well-sorted, coarse grained material to the deposit. Sand forms deposits on the slopes of shallows where the equilibrium conditions for the settling of sand particles exist. South and south-east of the Island of Naissaar, the retreating shoreline supplies sand to the deposit and poor sorting indicates rapid sedimentation. Sand is poorly sorted in eastern study areas that reflect rapid sedimentation and short distances between the sand sources and accumulation area. Deposits located near the islands and those located at shoals develop largely step-like terraces and are governed by infrequent strong storms. Comparative analysis of grain size distribution and statistics of different deposits provided new information about sedimentation processes in sand areas.

Keywords *Marine sand deposits, mean grain size, sorting, Estonian shelf, Gulf of Finland, Baltic Sea.*

Andres Kask [andres@altakon.ee] and Tarmo Soomere [tarmo.soomere@cs.ioc.ee], Tallinn University of Technology, Institute of Cybernetics, Akadeemia 21, 12618 Tallinn, Estonia; Jüri Kask [jyri.kask@phys.sea.ee], Tallinn University of Technology, Marine Systems Institute, Akadeemia 21, 12618 Tallinn, Estonia; Sten Suuroja [s.suuroja@egk.ee], Geological Survey of Estonia, Kadaka tee 82, 12618 Tallinn, Estonia; Institute of Ecology and Earth Sciences, University of Tartu.
Manuscript submitted 18 August 2010; accepted 18 November 2010.

INTRODUCTION

Marine sand deposits have been widely investigated worldwide (Almagor *et al.* 2000; Finkl, Hobbs 2009). Several studies were also performed in the Baltic Sea in the recent past (Cato 2004; Harff *et al.* 2004; Kramarska *et al.* 2004; Moskalenko *et al.* 2004; Nielsen *et al.* 2004; Kask *et al.* 2008; Gulbinskas *et al.* 2009). Until the 1990s, only scarce data were available on sand deposits of the Estonian shelf (Lutt, Tammik 1993), however in recent years the information has increased (Suuroja *et al.* 2007; Kask *et al.* 2008). The earliest data about sand deposits were obtained in the framework of geological mapping of the Estonian shelf carried out in 1981–1991. The results of these explorations have been generalized in a series of geological maps (scale 1:200 000).

The use of sand is largely related to building activities. The annual amount of sand used in Estonia was ca 7.5 million m^3 in 1975–1990, ca 0.9 million m^3 in 1990–1995 (Raudsep, Räägel 1993; Räägel 1997) and ca 3 million m^3 in 2006 (Raudsep 2008).The need for sand increased due to construction of new large harbours (e.g. Sillamäe) and extension of the Port of Muuga and Paldiski Harbour. In particular, large amounts of landfill were needed, but its delivery from mainland deposits would have been inexpedient. The possibility to obtain sand from the seafloor deposits initiated active sand exploration in the 1990s. Sand deposits were studied west of Hiiumaa, in Tallinn, Muuga and Ihasalu bays and in south–eastern Gulf of Finland. In these areas a total of over 90 million m^3 of sand has been found during several research works starting from the 1990s.

The current paper aims to summarize the exploration results and to evaluate the occurrence, genesis and formation conditions of sand deposits. Comparative analysis of the grain size distribution and statistics of different deposits provides new information about sedimentation processes in the sand areas. The understanding of the formation mechanisms is important in order to foresee, prevent or mitigate environmental impacts of sand extraction (Boyd *et al.* 2005; ICES 2007) and in prospecting for new deposits.

MATERIAL AND METHODS

Sand explorations have been conducted in three main regions (Fig. 1, Table 1): west of Hiiumaa, in Tallinn, Muuga and Ihasalu bay areas and in south–eastern Gulf of Finland. In 1991–1997, the Geological Survey of Estonia (GSE) gathered data on extensive sand deposits west of Hiiumaa (Fig. 2A). Some sand was required for burying the wreck of MS *Estonia* in 1996. Additional studies were performed in this area in 2006 by GSE and in 2009 by the Institute of Geology at Tallinn University of Technology.

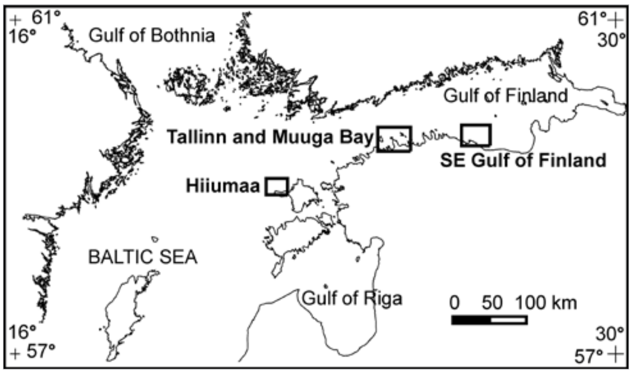

Fig. 1. Location of the study areas. Compiled by S. Suuroja, 2010.

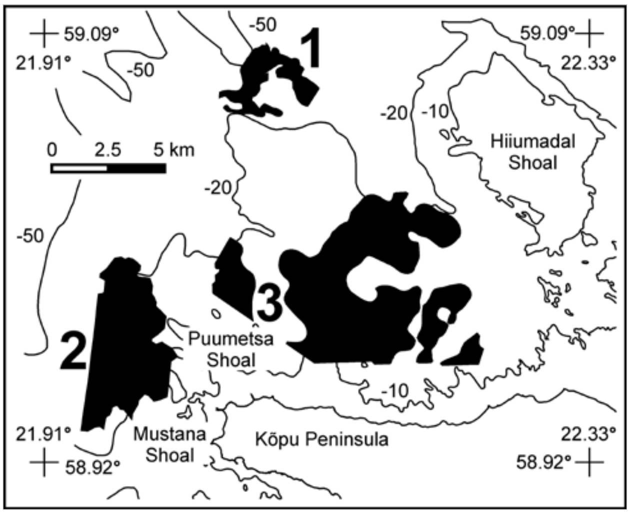

Fig. 2A. Location of the study areas west of Hiiumaa. Compiled by S. Suuroja, 2010.

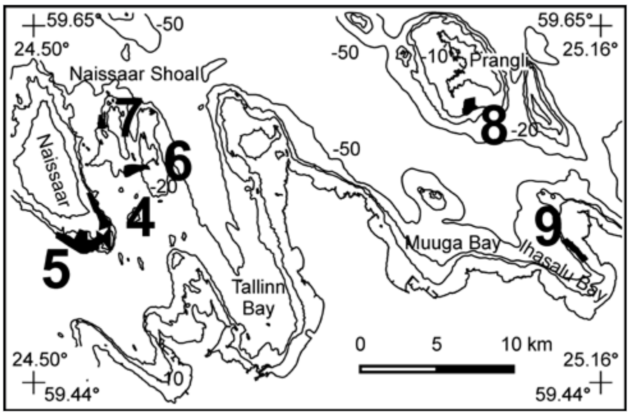

Fig. 2B. Study areas in Tallinn and Ihasalu bays. Compiled by S. Suuroja, 2010.

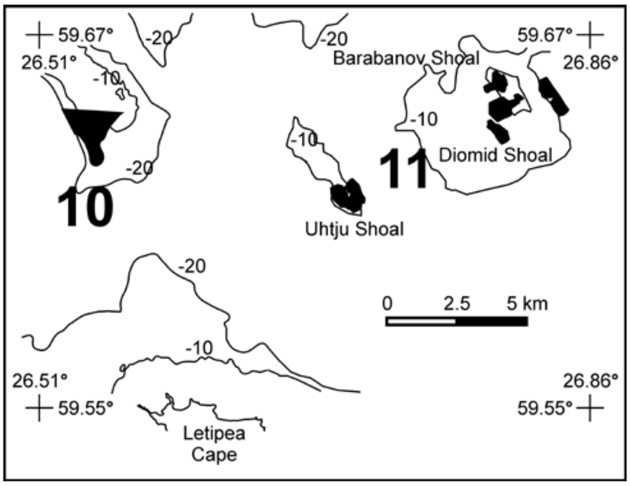

Fig. 2C. Study areas in the SE Gulf of Finland. Compiled by S. Suuroja, 2010.

The geological investigations of sand deposits in the Muuga Bay area south of the Island of Prangli were initiated by *NYBIT,* Ltd in 1992 (Fig. 2B), followed by the *REI,* Ltd in 1994–1995, and by GSE in 2003. East of Muuga Bay, in Ihasalu Bay, the Marine Systems Institute at Tallinn University of Technology (MSI) carried out explorations in 2005 and 2006. In the Tallinn Bay area, the areas south of the Island of Naissaar and shallows east of Naissaar were the first sites prospected for sand by REI, Ltd in 1994. Supplementary studies were conducted by MSI in 2003–2005. In 2007 and 2008, the *ALTAKON*, Ltd and GSE carried out geological and geophysical investigations in the south–eastern Gulf of Finland north of Letipea Cape (Fig. 2C). *ALTAKON*

Table 1. Major parameters of the studied sand deposits.

Area	Location	Water depth (m)	Maximum sand thickness (m)	Area (ha)	Volume (x1000 m^3)
1	South–east of Hiiumadal Shoal	20–30	2.5	477	6 540
2 and 3	Maksimov Shoal and north–east of Koroljov Shoal	10–30	3.9	5 666	64 324
4 and 5	South and south–east of Naissaar	6–40	11.2	417	10 711
6 and 7	Naissaar Shoal	10–25	3.7	68	984
8	South of Prangli	6–20	8	45	867
9	North–eastern part of Ihasalu Bay	6–35	4	107	793
10 and 11	South of Lõuna–Uhtju and Uhtju, Diomid and Barabanov shoals	6–30	3.8	2 441	2 813

explored the shallows of Uhtju, Diomid and Barabanov shoals in 2007, and GSE studied the area south of the Island of Lõuna–Uhtju in 2008.

Over thirty marine geology and geophysics works of sand prospecting have been performed on the Estonian shelf since the 1990s. However, the results are presented as unpublished internal reports, with the exception of sand deposits south of Naissaar and Prangli (Kask *et al.* 2008). The explorations were carried out in three stages: geophysical investigations, drilling and sampling, and grain size analyses. Echo sounding and seismo–acoustic sounding were made to estimate the depth of water, and to determine the boundaries of lithologic units, repectively. Simultaneous application of low–frequency echo sounder (*Pinger* with frequency 24 kHz), seismo–acoustic devices (*Boomer* with operational frequency 1.6 kHz, and *Chirp* with the frequency range 3-9 kHz) and side–scan sonar allow improve the resolution of seismo–acoustic profiles at the site south of Lõuna-Uhtju. At sites in Tallinn and Ihasalu bays and near Uhtju, Barabanov and Diomid shoals the depth of water was surveyed with *Atlas Deso 14* echo sounder (frequency range 33-210 kHz). Seismo–acoustic sounding was carried out with *EdgeTech* sub–bottom profiler 3100P (frequency range 2-15 kHz). *Van Veen* grab sampler and a grip scoop were used for fast identification of the bottom sediment type, prior to drilling. Drilling was mostly performed by the vibratory method. Drilling sites were chosen according to the results of geophysical investigations. Field work was done from the research ships *Junikon*, *Mare* and multifunctional vessel *EVA-316*.

Grain size distribution was determined by sieving sediments into eight fractions from >10 mm to <0.05 mm (sieve aperture sizes 10; 5; 2.5; 1.25; 0.63; 0.315; 0.16; and 0.05 mm). For the present paper, the grain size distribution of 249 samples from the upper 0.5 m layer of sand deposits was analysed. Grain size distribution analysis and calculation of statistics were performed with *GRADISTAT* software (Blott, Pye 2001). For each study area, the results of all existing samples were merged to reveal the average properties of the particular deposit. The mean grain size and sorting were calculated in terms of *phi* units based on the log–normal distributions with *phi* size values (Folk, Ward 1957). The values presented below were extracted from the cumulative percentage curve using a linear interpolation between the adjacent known points on the curve. The mean grain size description follows that presented by Blott and Pye (2001) and sorting is described using the scheme of Folk and Ward (1957).

RESULTS

West of Hiiumaa, the upper portion of sedimentary bedrock is represented by Ordovician argillaceous limestone, in Tallinn and Ihasalu bay area by Cambrian and Ediacarian rocks, and south of Prangli and in the south–eastern Gulf of Finland by Ediacarian rocks. Quaternary deposits such as glacial till and glacio–limnic clay cover the surface of bedrock and fill its depressions.

In general, clay overlies sand in deeper areas and till in shallower ones. Sand deposits are mostly located at the foot of bedrock escarpments and on the slopes of positive landforms consisting of glacial deposits. The thickness of sand is greatest south of Naissaar and Prangli, (maximum 11.2 and 8 m, respectively). West of Hiiumaa and in south–eastern Gulf of Finland the maximum thickness of sand is 4 m. The deposits stretch mostly to a depth of 25 m, those west of Hiiumaa, however, somewhat deeper.

The study areas are governed by largely variable geomorphic and hydrodynamic conditions. Deposits in the northern Baltic Proper have developed in relatively energetic hydrodynamic environment as the predominant south–western and north–western winds frequently excite large waves and strong currents in these locations (Soomere 2003; Soomere *et al.* 2008*a*; Räämet *et al.* 2010). Although the study area 3 is partially sheltered from waves approaching from the south to west, the highest waves in this area are apparently produced by N–NW winds that here are the strongest (albeit not the most frequent; Soomere, Keevallik 2003).

Sand deposits 4–8 lying at the ‘down wave’ side of medium or small islands or shoals (see Fig. 2B). The wind and wave regime in the Gulf of Finland is such that the largest waves approach these islands and shoals either from the west or from the east (Soomere, Keevallik 2003; Soomere *et al.*, 2008*b*; Räämet *et al.* 2010); whereas the proportion of waves approaching from the west or northwest is obviously larger for sites located in the eastern part of the Gulf. Therefore, littoral flow to the south has played a large role in the formation and contemporary development of these deposits. In principle, deposits located near islands and those located at shoals develop under quite different conditions. While there is quite intense sand inflow into sand bodies at islands with rapidly eroding soft coasts such as Naissaar, similar bodies near shallow areas have apparently no sand inflow and usually lose some sand to deeper areas. This difference may become evident both in different grain size and different level of sorting. The evolution of coasts and the nearshore in this area is largely step–like and governed by infrequent strong storms from a specific direction. Such events (that frequently occur in exceptionally high water level conditions) are accompanied by very intense sediment transport processes, which affect a wide range of grains. One should, therefore, expect relatively poorly sorted sedimentary bodies in these locations.

Sand bodies of Ihasalu Bay and south of Prangli are located in semi–sheltered areas. High-energy hydrodynamic conditions are extremely rare at these sites and in many cases sand bodies actually consist of almost immovable material that has deposited long ago. Local hydrodynamic conditions are therefore favourable for the presence of much finer sand (which would have been carried away by waves and currents from other, more open sites).

Mean grain size statistics show that very fine sand forms a substantial part of the sand mass in areas 8 and 9, whereas medium and coarse sand dominates in areas 2 to 7 (Table 2). It is somewhat surprising that sand in area 1 is relatively fine: west of Hiiumaa, west of Hiiumadal Shoal 41% of sediment are medium sand and 35% fine sand. This feature may stem from the larger average water depth at that site as in the neighbouring areas on Maksimov and Koroljov shoals coarse sand prevails in 40% of samples. Much larger grain size (medium to coarse sand, and even a large proportion of very coarse sand in small deposits 10 and 11) predominates also, in all other areas that develop under energetic hydrodynamic conditions. In particular, medium (43% of samples) and coarse or very coarse sand (43% of samples) prevails in the deposits of the south–eastern part of the Gulf of Finland, south of Lõuna–Uhtju. On the contrary, in the most sheltered study site, Ihasalu Bay, very fine sand dominates in 56% of samples and medium sand in 33% of samples. In the samples from south of Prangli, 42% is very fine and 24% fine sand.

The sand properties clearly depend also from the water depth at a particular sampling site. The mean grain size decreases, as expected, with the increase of the water depth. The correlation of depth and mean grain size indicates that sand is finer in deeper parts of the sea. This dependence is most strongly expressed for the sand body in area 1, which is located deeper and in high energy hydrodynamic conditions, because of that is relatively well sorted (Fig. 3A). This correlation is much weaker in more sheltered areas 2 and 3, and also in rapidly developing deposits in Tallinn Bay (Fig. 3B).

Further information about sand properties that may shed some light on the development conditions of the

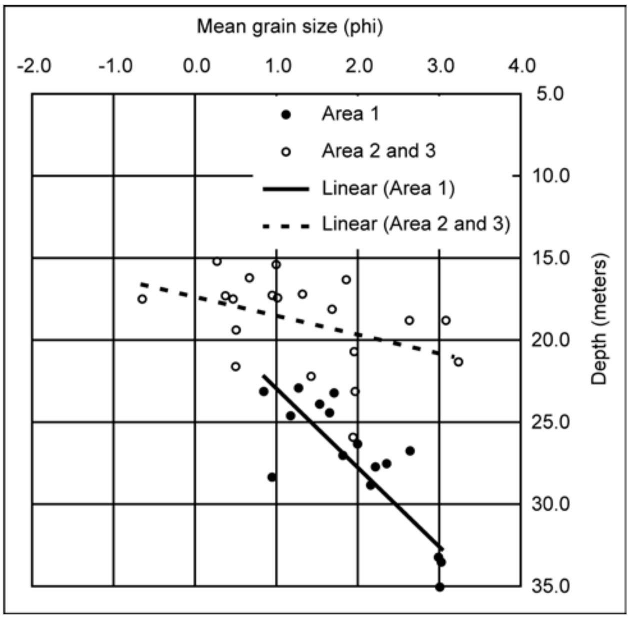

Fig. 3A. Mean grain size to depth correlation with a linear trendline, at sand deposits west of Hiiumaa. Straight lines indicate the relevant linear regression lines. Compiled by A. Kask, 2010.

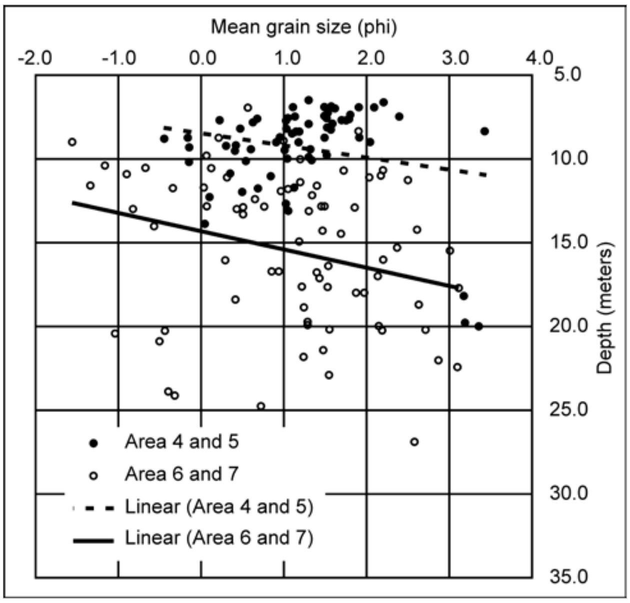

Fig. 3B. Mean grain size to depth correlation with a linear trendline at sand deposits in the Tallinn Bay area. Straight lines indicate the relevant linear regression lines. Compiled by A. Kask, 2010.

Table 2. Mean grain size and sorting of the majority of sand.

Area	Mean grain size of sand (% of samples)	Sorting of sand (% of samples)
1	35% fine and 41% medium	59% moderately and 24% moderately well sorted
2 and 3	40% medium and 40% coarse	65% moderately sorted
4 and 5	55% medium and 26% coarse	74% poorly sorted
6 and 7	37% medium and 25% coarse	71% poorly sorted
8	42% very fine and 24% fine	42% poorly and 33% moderately well sorted
9	56% very fine and 33% medium	56% poorly and 36% moderately well to well sorted
10 and 11	43% medium and 43% coarse and very coarse	64% poorly and 29% moderately sorted

deposit may be extracted from the sorting in different areas. The sand in 59 to 65% of samples is moderately sorted and in 24% of samples, from west of Hiiumadal Shoal, even moderately well sorted. As expected, areas 1–3 located in the most energetic hydrodynamic conditions exhibit much better sorting than most of the other areas (Table 2). Although poorly sorted sand prevails at Ihasalu (56% of samples), a substantial amount of well sorted material is also found at this site. As it is the most sheltered sand body, this feature evidently shows that this deposit has probably been formed long time ago under variable conditions.

All sand bodies around Naissaar are relatively poorly sorted. In the Tallinn Bay area, medium sand prevails in 55% of samples from south and south–east of Naissaar and in 37% of samples from Naissaar Shoal. Tallinn Bay deposits are dominated by poorly sorted sand (71-74% of samples) (Table 2). Sorting is a little better in the south–eastern Gulf of Finland. This feature may be interpreted as indicating a combination of intense sand inflow in the recent past and the development of these sand bodies in similar highly variable hydrodynamic conditions with single extreme events (Soomere *et al.* 2008*b*). Sorting is also relatively good at both sites in the Muuga Bay area (Fig. 3C). Sand is poorly (42% of samples) and moderately well sorted (33% of samples) in the deposit south of Prangli.

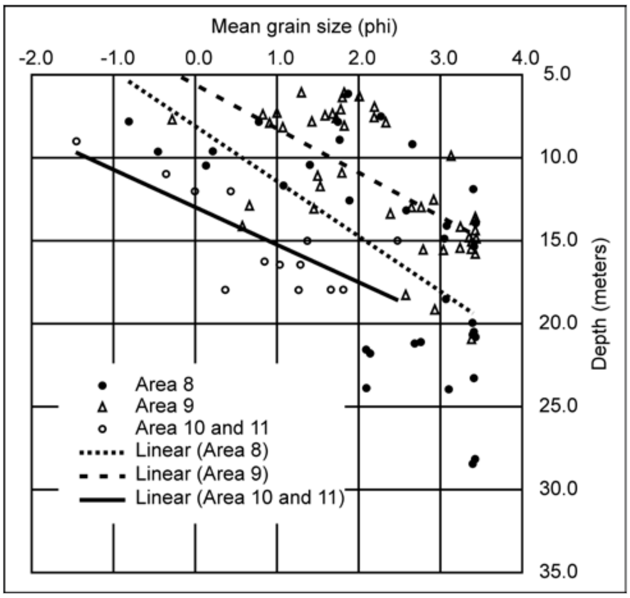

Fig. 3C. Mean grain size to depth correlation with a linear trendline south of Prangli (Area 8), in Ihasalu Bay (Area 9) and in the SE Gulf of Finland (Areas 10 and 11). Compiled by A. Kask, 2010.

DISCUSSION

There are intrinsic uncertainties in the reconstruction of the formation process of marine sediments. Bedding conditions and distribution of Quaternary sediments in the area of sand deposits have been influenced by the geological setting and relief of sedimentary bedrock, continental glaciations, development of water bodies inside the Baltic Sea depression and neotectonic movements (Raukas, Hyvarinen 1992). The sediment bodies have mainly been influenced by the distribution and abrasion of till of the latest glaciations.

The resulting contemporary marine sediments forming sand deposits, therefore, are spread at the foot of bedrock escarpments and on the slopes of positive landforms consisting of glacial deposits. In this sense, the area west of Hiiumaa, where several moraine hillocks, eskers and kames have been identified (Noormets 1994), is favourable for the formation of moderately and well sorted contemporary sand bodies.

The sediment grain size statistics show that the sand properties vary from place to place in different deposits west of Hiiumaa. Sand is coarser and better sorted in the westernmost study area, indicating variable formation conditions. Firstly, the hydrodynamic activity is diverse due to the openness of the region west of Hiiumaa. Secondly, the source of sediment is partly different. The main source material for sand is glacial till. However, west of Hiiumaa, the glacio–fluvial deposits have been found at the foot of steep escarpments and under the glacial till in deeper depressions in sedimentary bedrock (Noormets 1994). Glacio–fluvial sediments add more well–sorted coarse grained material to the sand deposits. Sand has predominantly formed as a result of abrading of glacial deposits. Waves and currents sort the abraded material so that coarser material accumulates closer to the outcrop of parent sediment and finer material is carried farther. The sedimentation area is determined by the hydrodynamic conditions and depth of water. The depth and mean grain size correlation has confirmed that finer sediments accumulate in deeper and coarser ones in shallow areas. Similar processes and grain size pattern are observed in the south–western Baltic Sea (Harff *et al.* 2004). The glacial till in coastal areas and on shallow sills is subject to erosion by currents and waves which rework and redistribute the sand and silt components, while coarser (boulders and gravel) particles remain as lag sediments. Along the transport path to deeper areas, the sediment becomes progressively finer.

The results of seismo–acoustic sounding and vibro–coring show the sand deposits overlie clay in deeper areas and till in shallower ones. Bedding conditions are similar in the Słupsk bank site in Polish EEZ (Kramarska *et al.* 2004) where part of the deposit lie on ice lake clay and part on till.

Several shoals (Naissaar, Kuradimuna, Uhtju, Barabanov) occur in the neighbourhood of sand deposits. Their roofs and slopes are covered with constituents of glacial till: mostly pebbles, cobbles and boulders that withstand wave activity. In the Baltic Sea majority of sand deposits are located in the shoal area (Cato 2004; Kramarska *et al.* 2004; Nielsen *et al.* 2004; Moskalenko *et al.* 2004; Gulbinskas *et al.* 2009). The fine grained part of till is washed out by waves and accumulates in deeper areas. Sand forms deposits on the slopes of shallows where the equilibrium conditions for settling of sand particles exist. Silt and clay particles settle in the deepest parts of the shelf. The bedrock is exposed northwest of Hiiumaa on some shallows because high wave energy shifts the suitable conditions for sediment accumulation to deeper areas. Therefore till and sand is transported to the slopes of shoals and the depressions of the bedrock surface. Owing to the rough hydrodynamic environment, a distinct correlation exists between the depth and mean grain size. Sand is well sorted between different depth zones.

An extensive sand accumulation area, which feeds from the sedimentary material abraded on the shore occurs south of Naissaar and Prangli (Kask *et al.* 2008). Similarly, large amounts of sand have accumulated southwards of other islands in the Gulf of Finland, forming capes, headlands, spits and shoals (Moskalenko *et al.* 2004).

Similar processes take place near the islands of Uhtju. The abrasion on the shores of islands is intensive during extreme storms with high water level and wave energy, as evidenced by the retreating shoreline in several sections on the eastern coast of Naissaar. On the western coast of Island of Rammu in Kolga Bay the escarpment retreats approximately one metre per year (Kask 2002). The sand that is formed as a result of abrasion of the coastal escarpment is carried to the spit reaching south–east of the island.

The amount of material eroded on the shore and carried to the deposition area can be rather large and it accumulates rapidly. During almost sixty years the mines originating from World War II have been covered by sand layer up to 4 m thick in the deposit south of Naissaar (Kask *et al.* 2008). The poor sorting and correlation between the mean grain size and depth reflect the rapid sedimentation south and southeast of Naissaar.

CONCLUSIONS

Sand has predominantly formed as a result of abrading of glacial deposits. Waves and currents sort the abraded material so that coarser material accumulates closer to the outcrop of parent sediment and finer material is carried farther. The sedimentation area is determined by hydrodynamic conditions and depth of water. The depth and mean grain size correlation has confirmed that finer sediments accumulate in deeper and coarser ones in shallow areas. The glacial till in coastal areas and on shallow sills is subject to erosion by currents and waves which rework and redistribute the sand and silt components, while coarser particles (boulders and gravel) remain as lag sediments. Along the transport path to deeper areas, the sediment becomes progressively finer. Silt and clay particles settle in the deepest parts of the shelf. Sand forms deposits on the slopes of shallows where the equilibrium conditions for settling of sand particles exist. Sand deposits overlie clay in deeper areas and till in shallower regions.

Sand is coarser and better sorted in the westernmost study area, indicating variable formation conditions. Firstly, hydrodynamic activity is diverse due to the openness of the region west of Hiiumaa. Secondly, the source of sediment is partly different. The main source material for sand is glacial till. However, west of Hiiumaa, glacio–fluvial deposits have been found at the foot of steep escarpments and under the glacial till in deeper depressions in sedimentary bedrock which add more well sorted coarse grained material to the sand deposits.

At Ihasalu Bay and south of Prangli, local hydrodynamic conditions are favourable for the presence of much finer sand (which would have been carried away by waves and currents from other, more open sites). Sand is poorly sorted in eastern study areas. Poor sorting reflects rapid sedimentation and short distance between the source of the sand and accumulation area. Deposits located near the islands and those located at shoals develop largely step–like and governed by infrequent strong storms.

Acknowledgements

The authors are grateful to Port of Tallinn Ltd., EE Ressursid Ltd. and Veelinna Kinnisvara Ltd. for financing the geological investigations. Professor Petras Šinkūnas (Vilnius) and Dr. Nerijus Blažauskas (Klaipėda) are thanked for valuable reviews of the manuscript. The study was supported by the Estonian Ministry of Education and Research (grant SF0140077s08) and the Estonian Science Foundation (grants ETF7413, JD172 and ETF8049).

References

Almagor, G., Gill, D., Perath, I., 2000. Marine sand resources offshore Israel. *Marine Georesources and Geotechnology 18*, 1–42.

Blott, S.J., Pye, K., 2001. Gradistat: A grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms 26*, 1237–1248.

Boyd, S.E., Limpenny, D.S., Rees, H.L., Cooper, K.M., 2005. The effects of marine sand and gravel extraction on the macrobenthos at a commercial dredging site (results 6 years post-dredging). *ICES Journal of Marine Science 62*, 145–162.

Cato, I., 2004. Marine mineral deposits within the Swedish EEZ. *In* J. Harff, E.M. Emelyanov, M. Schmidt–Thomé, M. Spiridonov (eds), Mineral resources of the Baltic Sea – exploration, exploitation and sustainable development. *Zeitschrift für Angewandte Geologie, Sonderheft 2*, Hannover, 147–158.

Finkl, C.W., Hobbs, C.H., 2009. Mining sand on the continental shelf of the Atlantic and Gulf coasts of the US. *Marine Georesources and Geotechnology 27(3)*, 230–253.

Folk, R.L., Ward, W.C., 1957. Brazos River bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology 27*, 3–26.

Gulbinskas, S., Trimonis, E., Blažauskas, N., Michelevicius, D., 2009. Sandy deposits study offshore Lithuania, SE Baltic Sea. *Baltica 22(1)*, 1–9.

Harff, J., Bobertz, B., Granitzki, K., Lemke, W., Wehner, K., 2004. Sand and gravel deposits in the south–western Baltic sea, their utilization and sustainable development. *In* J. Harff, E.M. Emelyanov, M. Schmidt–Thomé, M. Spiridonov (eds), Mineral resources of the Baltic Sea – exploration, exploitation and sustainable development. *Zeitschrift für Angewandte Geologie, Sonderheft 2*, Hannover, 111–123.

ICES, 2007. Report of the *Working Group on the effects of extraction of marine sediments on the marine ecosystem (WGEXT).* Helsinki, Finland, 17–20 April, ICES CM 2007/MHC 08, 96 pp.

Kask, A., Kask, J., Kornejev, V., Okuntsov, E., 2008. Sedimentation conditions of marine Prangli and Naissaar sand deposits, the Estonian coastal sea. *Baltica, 21(1–2),* 79–84.

Kask, J., 2002. *Naked world: islands in Kolga Bay*. Stockholm Environment Institute, 131 pp. [In Estonian].

Kramarska, R., Maslowska, M, Uscinowicz, S., Zachowicz, J., 2004. Review of marine sand and gravel resources in the Polish exclusive economic zone of the Baltic Sea *In* J. Harff, E.M. Emelyanov, M. Schmidt–Thomé, M. Spiridonov (eds), Mineral resources of the Baltic Sea – exploration, exploitation and sustainable development. *Zeitschrift für Angewandte Geologie, Sonderheft 2*, Hannover, 125–134.

Kubicki, A., Faustino, M., Diesing, M., 2007. Morphological evolution of gravel and sand extraction pits, Tromper Wiek, Baltic Sea. *Estuarine, Coastal and Shelf Science 71*, 647–656.

Lutt, J., Tammik, P., 1993. Mineral resources. *In* J. Lutt, A. Raukas (eds), *Eesti elfi geoloogia [Geology of the Estonian Shelf],* Estonian Geological Society, Estonian Academy of Sciences, Institute of Geology, Geological Survey of Estonia, Tallinn, 138–141. [In Estonian].

Moskalenko, P.E., Zhamoida, V.A., Manuilov, S.F., Spiridonov, M.A., 2004. The geological structure, history of geological development and potential mineral resources of the eastern Gulf of Finland. *In* J. Harff, E.M. Emelyanov, M. Schmidt–Thomé, M. Spiridonov (eds), Mineral resources of the Baltic Sea – exploration, exploitation and sustainable development. *Zeitschrift für Angewandte Geologie, Sonderheft 2*, Hannover, 135–145.

Nielsen, P.E., Bo Jensen, J., Binderup, M., Lomholt, S., Kuijpers, A., 2004. Marine aggregates in the Danish sector of the Baltic Sea: Geological setting, exploitation potential and environmental assessment. *In* J. Harff, E.M. Emelyanov, M. Schmidt–Thomé, M. Spiridonov (eds), Mineral resources of the Baltic Sea – exploration, exploitation and sustainable development. *Zeitschrift für Angewandte Geologie, Sonderheft 2*, Hannover, 87–109.

Noormets, R., 1994. Quaternary deposits in the Baltic Sea west of Estonia: preliminary results of a seismic reflection survey. *Proceedings of the Estonian Academy of Sciences, Geology 43(1)*, 18–31.

Räägel, V., 1997. Sand and gravel. *In* A. Raukas, A. Teedumäe (eds), *Geology and Mineral Resources of Estonia,* Estonian Academy Publishers, Tallinn, 436 pp.

Räämet, A., Soomere, T., 2010. The wave climate and its seasonal variability in the north–eastern Baltic Sea. *Estonian Journal of Earth Sciences 59(1)*, 100–113.

Raudsep, R., 2008. Estonian georesources in the European context. *Estonian Journal of Earth Sciences 57(2)*, 80–86.

Raudsep, R., Räägel, V. (eds), 1993. *Riches of Estonian bowels of the earth.* Geological Survey of Estonia, Tallinn, 34 pp. [In Estonian].

Raukas, A., Hyvärinen, H. (eds), 1992. *Geology of the Gulf of Finland.* Valgus, Tallinn, 422 pp. [In Russian].

Soomere, T., 2003. Anisotropy of wind and wave regimes in the Baltic Proper. *Journal of Sea Research 49(4),* 305–316.

Soomere, T., Keevallik, S., 2003. Directional and extreme wind properties in the Gulf of Finland. *Proceedings of the Estonian Academy of Sciences, Engineering 9(2),* 73–90.

Soomere, T., Behrens, A., Tuomi, L., Nielsen, J.W., 2008*a*. Wave conditions in the Baltic Proper and in the Gulf of

Finland during windstorm Gudrun. *Natural Hazards and Earth System Sciences 8(1),* 37–46.
Soomere, T., Myrberg, K., Leppäranta, M., Nekrasov, V., 2008*b*. Progress in knowledge of the physical oceanography of the Gulf of Finland: a review for 1997–2007. *Oceanologia 50(3)*.
Suuroja, S., Suuroja, K., Talpas, A., 2007. Seafloor geological investigations in Estonian shelf area. *Baltica 20(1-2)*, 53–58.