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and Palaeogeography
of the Baltic Sea

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BALTICA An International Yearbook on Geology,
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of the Baltic Sea
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PROGRAMME * Seven volumes of the BALTICA Yearbook have already been published during 1963-1982. The idea to issue the renewed BALTICA initiated again from July, 1993.

BALTICA provides a forum for original papers of international interests in the various fields of the Baltic Sea geology. Palaeogeography, palaeoceanology and environmental geology (ecogeology) are the core topics of the yearbook. It accepts papers on Archean-Proterozoic basement, pre-Quaternary and Quaternary geology, including tectonics, neotectonics and geomorphology, especially topics related to the development of the Baltic area. BALTICA focuses on modern techniques and methodology in a scientific publication. This yearbook intends to cover and provide information within a wide range of interests for Earth scientists.

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BALTICA INFORMATION

Some Retrospective Thoughts About the "Baltica"

Everything in the universe has its own distinctive history. The publication - serial BALTICA, now held by the reader, also has its own history, too. It was born in Vilnius, Lithuania, in 1963, published by the Department of Geography, the Lithuanian Academy of Sciences. In 1982 the last volume of the BALTICA appeared, as a failing eyesight of its editor have made the prolongation difficult.

The idea to create a special journal for the Baltic Sea research was proposed by the author, when in 1961 at the 6th INQUA Congress in Warsaw he was elected the Vice-president of "Subcommission on Shorelines of NW Europe". His original concept was to issue a serial of international character devoted to the Baltic Sea and its coasts. In 1962 the future editor informed all colleagues around the Baltic Sea about the new initiative and from all of them he received a cordial approval. But, notwithstanding all possible efforts it was impossible to set up an international editorial board. Therefore, only the editor alone remained in the "field of battle".

The new journal was entitled BALTICA. On title-pages of the journal it was indicated that this publication dealt with the problems of Quaternary geology and paleogeography, coastal morphology and dynamics, marine geology and neotectonics in the Baltic Sea area. The editor intended in the future to widen the thematic scale of BALTICA and include environmental and geoecological problems. Thus, the journal was of geological-geographical character. The articles were published in English, Russian, German and French with summaries in Lithuanian.

The out-of-date polygraphic technology, quality of paper, absence of linguistic editors, etc., could not assure the better habitus of the journal BALTICA.

Seven volumes of BALTICA saw the daylight with about 160 articles (ca. 2,000 pages) on various geographical and geological problems of the Baltic Sea and its coasts. Many outstanding scientists from Finland, Sweden, Denmark, Germany, Poland, Russia, Canada and other countries were contributors of this journal. We would like to mention some of them: E. Seibold, E.H. De Geer, St. Florin, Joh.F. Gellert, J. Donner, Th. Hurtig, H. Kliewe, K. Orviku, O. Grano, A. Dreimanis, K.K. Markov, N.N. Sokolov, R. Knaps, P. Rosa, H. Krog, etc. Every volume contained also the articles written by Lithuanian scientists.

It was a great pleasure for the editor to hear and read in foreign press positive references and compliments as well as to receive constructive proposals. I thank all of them very, very much once again.

Thus, over more then 30 years have passed since the appearance of the first volume of BALTICA. Unfortunately, after the 7th volume (1982) a "hiatus" of more than 10 years intruded into the BALTICA's biography.

At the given moment, due to the requests of numerous scientific organizations and individuals from various countries to revive the BALTICA I give this journal over to a new editor. He is my colleague and scientific collaborator of many years, a well-known geologist Dr.hab. Algimantas Grigelis who has a rich experience in managing scientific and editorial work. I hope that the steering-wheel of BALTICA will be at good hands, and the journal will not swerve from its main course.

Passing over the rudder to the new editor of BALTICA I sincerely wish him, the editorial board as well as all future contributors a great many of new scientific achievements in the vast field of the Baltic Sea research. Besides, the development of complex investigations on the international basis and the representation of received results in this journal would be one of the most desirable aims.

Simultaneously with the expansion of our knowledge about the Baltic Sea and its coasts, we must always bear in our mind the problems concerning the protection of the environment and the effective use of natural resources.

Thus, "navigare necesse est"!

Prof. Dr. hab. Vytautas Gudelis
Academician,
Lithuanian Academy of Sciences
Vilnius, 20th May 1994

Yoldia Stage - the Least Clear Interval in the Baltic Sea History

Anto Raukas

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The Yoldia stage has never been properly defined stratigraphically and until now the correlation of its shorelines is confused. Any precise subdivision of the bottom sediments from the Yoldia Sea on the basis of faunal evidence and diatom flora is difficult due to very poor or mixed fauna and flora assemblages. According to recent diatom studies in the Kalmarsund area (Håkansson in Svensson 1989), there was only a short (100-150 years) influx of salt water during the middle part of the Yoldia stage, which did not reach the open Baltic and the Gulf of Finland.

INTRODUCTION

The Preboreal Yoldia Sea belongs to the interval of an open connection between the Baltic and the Atlantic via the basin of Lake Vänern and the strait of Närke in Central Sweden. The beginning of the Yoldia stage is related to the drop of the Baltic Ice Lake at Billingen about 10,200 B.P. (Nilsson 1968); however, the absence of a clear correlation between calendar, ^{14}C and varve years makes its dating uncertain.

The classical Yoldia stage nowadays is divided into three substages, with brackish water in its mid-stage (Svensson 1989, 1991). The rapid Yoldia regression was followed by the Ancylus transgression. Reconstruction of ecological conditions of the Yoldia Sea is difficult. What is more, except for the territory of Estonia and Finland, the Yoldian marine deposits in the supramarine coastal area are absent elsewhere in the Eastern Baltic (Latvia, Lithuania, St. Petersburg and Kaliningrad area), and all Yoldian shorelines can be traced below the modern sea level, hampering their investigation.

The extent and age of the Yoldia Sea in the Eastern Baltic area have been identified on the basis of emerged and submerged shoreline fragments, lithological investigations of coastal and offshore sediments, pollen and diatom studies and radiocarbon determinations. Earlier authors (Kessel 1961 a.o.) have identified up to six raised beaches at a number of altitudes in Estonia. These beaches consist of morphologically unclear scarps and bluffs, shore terraces, boulder fields and low sand or shingle bars. The number of Yoldia shorelines has been drastically decreasing through the years and until now clear key levels are absent.

All radiocarbon dates in this paper are given as conventional noncorrected radiocarbon ages B.P. With the ESR method we have dated a series of mollusc shells from classical Ancylus sites close to the Yoldian ones. The ages obtained vary between 11,000 and 9,330 B.P. (Hütt et al. 1985; Molodkov & Raukas 1989). Of course, no far-reaching conclusions can yet be drawn from these results, and therefore, further investigations are needed to determine the age limits of the Yoldia Sea. Rather unclear is the beginning of the Ancylus transgression marking the end of the Yoldia stage. This event in the western part of the Baltic Sea is now dated at about 9,500-9,600 B.P. (Svensson 1989), however, we have not obtained enough dates to support this age in the eastern part of the sea.

As is known, the name of the Yoldia Sea is derived from the marine bivalve *Portlandia (Yoldia) arctica*, whose dwarf shells have been found in varved clays in the Stockholm area. As the Yoldia Sea had very low salinity this species did not spread far into the Baltic proper and therefore it cannot serve as an index fossil for the basin. Therefore the name of this interval of the Baltic Sea history should be changed. Besides, the bivalve itself has been renamed from *Yoldia* to *Portlandia*.

In this paper we shall discuss only the problems related to the Preboreal Yoldia Sea. Until now several investigators (Blaszischin 982; Pieczka 1992 a.o.) assume that the saline oceanic waters penetrated into the Baltic Sea in lateglacial time when the Karelian Ice Sea (Hyyppä 1943) or the Lateglacial Yoldia Sea (Sauramo 1958) was supposed to have existed there. In recent Russian publications, compiled on the basis of complex studies, the penetration of saline oceanic waters from the White Sea into the Baltic is denied (Kvasov 1975, 1979). Instead of contributing to the input of saline waters into the Baltic basin, the existing channels might have served as paths along which the surplus fresh water escaped from the basin (Gudelis 1976). The lateglacial history of the Baltic Sea in the eastern portion of the Baltic was recently summarized by Donner and Raukas (1989).

HISTORICAL BACKGROUND

Research into the deposits, topography and shoreline displacement of the Preboreal Yoldia Sea in the Eastern Baltic area goes back to the beginning of the century, but until now this is the least clear interval in the Baltic Sea history. It has never been properly defined stratigraphically and its shorelines are hypothetical.

G. De Geer (1896) called the whole pre-Ancylus stage the "Lateglacial Ice-Sea", although actually it was a freshwater basin. Schmidt (1894) differentiated three stages in the history of the Baltic Sea: 1) the late-glacial fresh-water stage where subfossil molluscs are absent; 2) fresh-water stage with Ancylus mollusc shells, and 3) marine stage with brackish-water mollusc shells. To our mind this scheme is valid for the Baltic until now.

In the St. Petersburg area the early history of the Baltic Sea was studied in detail by Yakovlev (1926) and Markov (1931). It was believed that during the Older Dryas there existed the I-st Baltic Ice Lake with its level at an altitude of 36-38 m in the St. Petersburg area. In the Allerød a deep regression took place during which saline waters penetrated into the Baltic depression, and the I-st Yoldia Sea was formed. It was supposed that in the Younger Dryas a new transgression took place and the II-nd Baltic Ice Lake came into being with its level at an altitude of 28 m near St. Petersburg. Later Kvasov (1975, 1979) demonstrated that the whole early history of the Baltic Sea here was a history of large fresh-water ice-dammed lakes.

Contradictory interpretations are available on Preboreal sediments and shorelines in the St. Petersburg area. In the city of St. Petersburg and its vicinity the Yoldia Sea deposits with mixed diatom flora have been found at depths of -16 to -8 m (Znamenskaya & Cheremisinova 1974), and near Vyborg within the interval -3.2 to +8 m (Vishnevskaya & Kleimenova 1970 a.o.). The waters of the Yoldia Sea didn't reach the depression of Lake Ladoga. According to Znamenskaya and Cheremisinova (1974), the maximum of the Yoldia regression in the St. Petersburg area was - 10 m, according to Kvasov (1979) up to -35 m. In the most recent publications the Russian authors maintain that the Yoldian sediments in this region are characterized by poor ecologically mixed diatom assemblages (Dzhinoridze 1992), the Yoldia Sea itself was considerably desalinated and its final stage, the Echeneis phase, was characterized by somewhat higher salinity (Kleimenova & Vishnevskaya 1992). In the earlier publications the same authors (e.g. Vishnevskaya & Kleimenova 1974) mentioned the considerable salinity of the Preboreal Yoldia Sea with high content of brackish water diatoms (80%) in Yoldian sediments.

Estonian and Finnish geologists (Kessel et al. 1988) are of the opinion that the brackish-water Echeneis stage between the Yoldia and Ancylus stages should be dropped, because the recent investigations of bottom sediments of the Baltic indicate that the ecological conditions prevailing in the basin were rather close to fresh-water environments, and, thus, it may be concluded that during Echeneis stage any extensive inflow from the ocean into the Baltic Sea could not have existed.

Preboreal Yoldia Sea beaches in West and North Estonia were described by Laasi (1940, Öpik & Laasi 1937), who pointed out their close altitudes to the Ancylus levels. For a long time the Estonian Yoldian shorelines were mechanically correlated with corresponding shorelines in Finland, and therefore all mistakes which had been made on the northern coast of the Gulf of Finland were repeated on the southern coast. In the fifties and early sixties Kessel (1990, 1961a, 1961b) differentiated six Yoldia levels (Y_I - Y_{VI}) which according to her were traceable throughout the coastal region in Estonia at altitudes up to 50-60 m a.s.l.(Kessel 1961a,b), near Tallinn at an altitude of 40-47 m (Kessel 1961a). She was of the opinion that Yoldia beaches lower than +20 m in NE and SW Estonia were eroded during the Ancylus transgression (Kessel 1961a). However in another paper from the same year (Kessel 1961b) she mentioned Yoldia beaches at the coast of Pärnu Bay at an altitude of +17 m. In 1963 she described Yoldia beaches here even at an altitude of +19 to +13 m (Kessel 1963). Afterwards she came to the conclusion that most of her Yoldia levels belonged to the stage of the Baltic Ice Lake, and the Yoldia level in North Estonia is traceable only a bit higher than the Ancylus level (Kessel 1966). In several regions she described the lagoons and coastal lakes of the Yoldia Sea with mixed and rather poor diatom flora (Kessel & Punning 1969). Brackish-water diatoms in Sõjamäe and Tondi lagoons include the species now registered in the lakes of the present Kola Peninsula and Lapland (Kessel 1987).

In Latvia the preboreal sediments of the Baltic, which may belong to the Yoldia Stage, have been found in several places some ten metres below sea level (Veinbergs 1979; Veinbergs & Stelle 1981). In Lithuania (Gudelis 1979), Kaliningrad area (Blazcischin 1981) and Poland (Litvin & Rebains 1981) the lowermost zone (40-72 m below present sea level) of the submarine shore formations, however, without corresponding stratigraphical data, has been correlated with the Yoldia Stage. This conclusion is based on the assumption that in the southern and southeastern Baltic the oldest shorelines lie at the greatest depths, and the Preboreal is characterized by the lowest position of the water level in the Baltic basin throughout the whole Postglacial period.

YOLDIA SHORELINES

West and North Estonia may serve as a key region for the study of Yoldia shorelines in the Eastern Baltic. Coastal formations of the Yoldia Sea, higher than the maximum level of the Ancylus Lake, could have been formed only in NW Estonia and near Tallinn at an absolute elevation between 55 (Kõpu Peninsula on the island of Hiiumaa) and 30 m (region of Tallinn). In other areas the Yoldian deposits are buried beneath younger sediments (Fig. 1) and are not immediately traceable.

As we have already mentioned, Kessel erroneously differentiated in the supramarine area of Estonia six (Kessel 1961a,b) Yoldia shorelines, some of which are now considered as lateglacial levels. In terms of shore displacement, the Yoldia Sea in Estonia (as in Finland) was regressive due to the rapid crustal uplift. The highest Yoldia shoreline (Y_I) inside Salpausselkä is between 25 and 30 m below the youngest Baltic Ice Lake level (B_{III}). By extrapolation we obtain 85-90 m a.s.l. for its altitude on the coast near Helsinki (Donner 1982). In Estonia, in the region of Pärnu, the regression after the Billingen outflow was also about 25-30 m (Talviste 1988). Unfortunately, the lowest point reached by the Yoldia regression cannot be precisely determined. In southern Finland it is estimated at about 55 m a.s.l. (Eronen & Haila 1982), which means that the total Yoldia regression on the Finnish coast near Helsinki was somewhat between 30 and 40 m. In NW Estonia it was supposed to have been about 50-55 m (Kessel & Raukas 1979). However, the latter conclusion was based on the assumption that several hundred years after the Billingen outflow, ca. 9,700-9,500 years ago (Kessel & Raukas 1981), there was a short transgressive phase (Y_I) which changed smoothly into a new regression, during which the water level near Tallinn and Piirsalu dropped at least 10 metres.

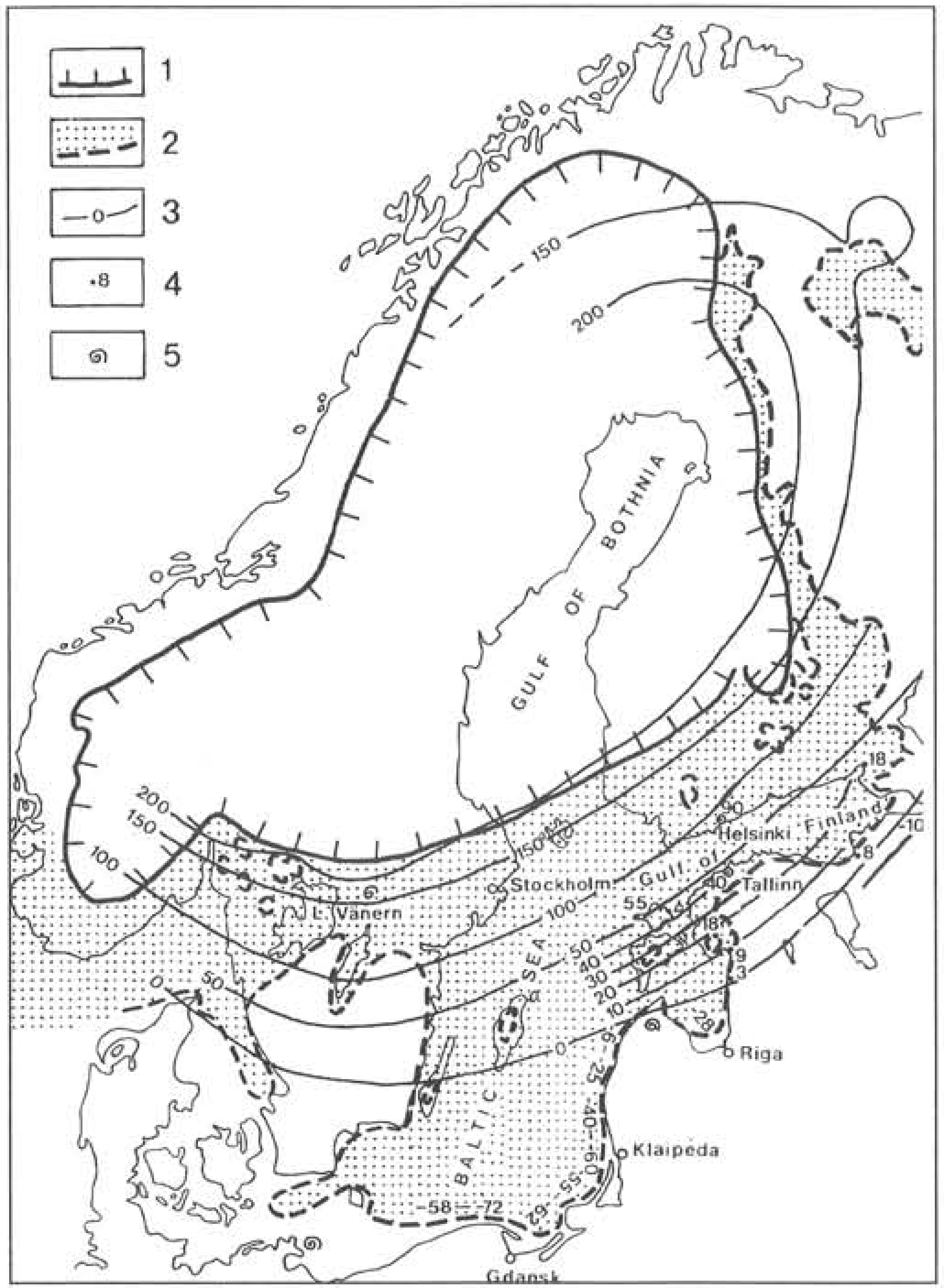

Fig. 1. Distribution of the Yoldia Sea. 1 - ice margin; 2 - dry land; 3 - isolines; 4 - altitudes of Yoldian deposits and landforms; 5 - best-known sites with *Portlandia (Yoldia) arctica* shells.

According to Kessel and Raukas (1981), the altitudes of the level Y_I are 54.8 m at Kõpu, 40 m in Tallinn, 9 m near Pärnu and 3 m at Piiskopi-Lemmeoja. According to Kessel and Punning (1969), the transgressive coastal forms of the Yoldia Sea (Y_{II}) in North Estonia are located about 10 m higher than Yoldia level Y_I and several metres higher than the maximum level of the Ancylus Lake in the same area (near Tallinn at a height of 40 m).

It means, that Kessel has changed her opinion about the highest level of the Yoldia Sea several times. In her earliest papers the highest level was Y_I (Kessel 1960, 1961a,b), then Y_{II} (Kessel & Punning 1969) and afterwards once again Y_I (Kessel & Raukas 1981).

Yoldian (?) coastal formations above the Ancylus level (35 m) have been found in several places around Tallinn, e.g. at Pärnamäe (42-46 m), Vääo (37.8 m), Jõelähtme (38 m), Sõjamäe and Tondi (40 m). However, we have no ground for maintaining that these are transgressive formations and even it is not clear whether these are Yoldian beach deposits or not. We can probably differentiate in western and northern Estonia only one Yoldia level which is about 20 m lower than YI level in the southern Finland (Hyvärinen et al. 1992, Fig. 114). For this reason, direct correlation of Estonian and Finnish Yoldian shorelines is impossible. This kind of correlation was attempted as early as the 1930s. For instance, Tammekann (1936) mentioned that the level of the river delta, which discharged into the Yoldia Sea at Kroodi, was at an elevation of about 30 m. Considering the tectonic uplift of the area, this level can be correlated with the fifth phase of the Preboreal Yoldia Sea on the island of Suursaari (Sauramo 1958). Sauramo (1958) himself reached the conclusion that the maximum level of the Echeneis Sea at Kroodi was about 37 m, and the level of the Ancylus Lake was about 4 m lower. But such correlations without stratigraphic studies are unreliable.

Preboreal Yoldian deposits near the Latvian coast at Ventspils are about 5 m, at the mouth of the Venta River 6-25 m, at the mouth of the Daugava River 20-28.5 m and in the area of Papesciems about 50 m below the present sea level (Veinbergs 1979; Veinbergs & Stelle 1981).

The shoreline of the Yoldia Sea near the Lithuanian coast is 40-50 km to the west of the recent shore, at a depth of approximately - 45—60 m (Gudelis 1979). NW of the Sambian Peninsula in the Kaliningrad area, on the banks of Kuršių-Sambian plateau, three series of submerged cliffs and terrace remnants of the Yoldia Sea have been found at depths of -58.5 - -63.5 m, the clearest of which is situated at a depth of -60 - -62 m (Blazcischin 1981). According to Litvin and Rebains (1981) Yoldian terraces in the Southern Baltic west of Klaipėda and north of Gdansk lie at depths of 58-72 m below the present sea level (Fig. 1).

LITHOSTRATIGRAPHY

The bottom deposits of the Baltic Sea may be subdivided into different sediment units (varved clays, sulphide clays etc.), as suggested by Ignatius et al. (1981). However, these lithostratigraphical units are difficult to relate to any geochronological or biostratigraphical scale (Hyvärinen et al. 1992). According to Ignatius et al. (1981), the uppermost varved clays and the lower transition clays were deposited offshore during the Yoldian Stage. Åker et al. (1988) studied three sediment cores from the northern part of the Gulf of Finland and found it difficult to draw a litho- and biostratigraphic borderline between the Yoldia and Ancylus sediments.

Lutt (1992) distinguished seven more or less distinct lithological units in the Gulf of Finland, but he could not differentiate Yoldian beds. Rennel (1991) correlated in the sections thin silt layers with the "Billingen event", and she included all grey or multicoloured sediments between those layers and "hydrotroilite clay" in the Yoldia Stage. The characteristic grey colour appears in the sediments several centimetres above silt layers and according to the pollen evidence marks the Younger Dryas and Preboreal boundary.

Spiridonov et al. (1988) distinguished three rhythmites in the Gulf of Finland: glacial (I), glacioaqueous (II) and above those brownish-grey soft pelites (III). The latter accumulated in the early Holocene, i.e. in Preboreal and Boreal times. In fact, there is a sharp contact at the base and the top of the units, but no clear lithostratigraphic boundary between the Preboreal and Boreal beds. The microfossils do not offer sufficient criteria for the precise location of the boundary either. The change to a diatom flora indicating brackish and fresh water conditions does not correlate with the changes in the sediment type. According to Dzhinoridze (1986), the lower part of the sequence is dominated by freshwater and fresh-brackish water diatoms, such as *Melosira islandica subsp. helvetica*; there are also single representatives of brackish-water diatom flora. In the overlying Boreal layers there is only a fresh-water diatom assemblage, which is characteristic of the Ancylus Stage. But, as was mentioned by Spiridonov et al. (1988), marine diatoms which Dzhinoridze used as the criteria in distinguishing the Yoldian evolutionary stage were probably redeposited from the Eemian deposits.

In the varved clay series from southern Finland, Sauramo (1923) identified a horizon marking a change from "diatactic to summictic" clays. According to the traditional interpretation, diatactic varves were deposited in fresh water and summictic varves in saline water. This horizon has therefore been taken to mark the inflow of saline water in the Finland area after the opening of the Billingen channel. The varve date of this event is about 300 years after the drainage of the Baltic Ice Lake, and it would thus be about a hundred years younger than the corresponding event in the Stockholm area (Hyvärinen & Eronen 1979). Later authors (Niemelä 1971) have pointed out that the change in the varve types need not always reflect a salinity change but may be determined by other factors, such as the distance from the ice margin and depth of water.

On the raised beaches of northern and western Estonia the Yoldia (?) beach ridges, spits and bars consist of nonrounded shingle carbonate material from the local limestones. They do not contain mollusc shells and their age is unclear. In some places (Iru, Kroodi a.o.) twofold coarse-grained shingle barrier spits of great thickness (7-8 m) of sediments can be found (Raukas et al. 1965). Clasts in lower beds are better rounded and sometimes cemented. Such cemented carbonate conglomerates require subaerial conditions, meaning that prior to the transgression they must have been on dry land. Earlier we believed (Kessel & Raukas 1967) that the lower beds at an altitude of 30-32 m belonged to the Yoldia or Echeneis stage, and the upper beds to the Ancylus transgression. However, as the lower beds do not contain mollusc shells and below them we have not found older organic (lagoonal, lacustrine or paludial) deposits, it is not excluded that these can even be glaciofluvial sediments. Therefore, they cannot be used in solving problems related to the evolution of the Yoldia Sea.

The Preboreal lagoonal sediments of the Yoldia Sea which lie below contemporary sea level near the Latvian and Lithuanian coasts are represented by sandy clays and silts, and contain substantial proportion of marine diatoms, also sometimes plant remains and mollusc shell fragments (Veinbergs 1979) which may be indicative of the inflow of foreign matter and redeposition of sediments.

BIOSTRATIGRAPHY

Differentiation of Preboreal near- and offshore deposits and coastal sediments in the area under consideration is quite easy. The boundary between the Younger Dryas forest-tundra and tundra vegetation and Preboreal moderately warm and dry climate forest vegetation is sharp. Tundra and xerophilous species are reduced or disappear and on the present day soils sparse birch woods have become established. During the maximum of birch (in Estonia ca. 9,350 yr B.P.), the content of birch pollen (mainly *Betula* sect. *Albae*) reached 80%, and in some lakes even 90%. The content of *Betula nana* among the birches is less than 10%. The content of spruce was several percent and pine about 20% (Kajak et al. 1976). The accumulation of sapropel and lacustrine lime started in lakes.

The upper boundary of the Preboreal is transitional. In the first half of the Boreal pine and birch forests expanded, but in the second half of the Boreal (7,800-8,100 yr B.P.) the composition of forests changed considerably: they became differentiated depending upon the soil and other physical and geographical conditions (Kabailienė & Raukas 1987).

Establishing Preboreal sediments without additional ecological data will not help much in studying the distribution of the Yoldia Sea. The malacofauna in the Yoldian coastal deposits in the Eastern Baltic area is unknown. At the same time Lateglacial and early Postglacial sediments tend to be poor in diatoms, and often contain redeposited and/or in-washed taxa. Therefore, clear boundaries cannot usually be drawn between the Baltic Ice Lake and Yoldia deposits (Hyvärinen et al. 1992). The correlation of coastal sediments with Baltic offshore sediments is still in many respects unsettled, as they do not form continuous sequences.

The lagoons and coastal lakes of the Yoldia time were formed in several parts of the area (Kessel 1987), e.g. in the Pärnu region in SW Estonia at an absolute height of 9-11 m. According to ^{14}C datings they were formed in the birch pollen zone about 9,700-9,500 years ago (Kessel & Punning 1969). The content of birch pollen in northern Estonian Yoldian lagoonal deposits, situated at an absolute height of 40-42 m, reaches 85%.

ECOLOGICAL CONDITIONS

The hydrology and salinity of the Yoldia Sea have been subject to much discussion. A detailed account of the ecological conditions in the area of the Baltic-Atlantic straits in western and Central Sweden was provided by Freden (1988). Recent diatom studies in the Kalmarsund area (Håkansson in Svensson 1989) suggest that there was only a brief (100-150 years) influx of salt water during the middle part of the Yoldia stage, which did not reach the open Baltic and the Gulf of Finland (Hyvärinen et al. 1992). According to Abelmann (1992), during the Yoldia stage brackish-marine conditions occurred only in the northwestern part of the Baltic Sea (Karlsö Basin), linked to a limited marine ingression which crossed the southern part of Sweden. According to Gudelis (1979) there were only fresh-water basins of various sizes near the Lithuanian coast in the Preboreal.

Due to the limited connection with the ocean, and abundant meltwater supplied from the nearby ice sheet, the salinity of the Yoldia Sea was low, and the brackish-water malacofauna, including rare dwarf forms of *Portlandia (Yoldia) arctica*, were preserved in a rather small western part of the Baltic. The single specimens of *P. arctica* found in tills and marine deposits in the Southern Baltic (Kliewe & Janke 1978) and in Latvia have probably been redeposited from the Eemian sediments. These are known to occur in the coastal zone of Latvia in tills younger than the Eemian marine deposits (Dreimanis 1970). For example, on the left bank of the Daugava River *P. arctica* has been found in five tills of the last ice age and even in the gravel and varved clay between two of the tills. All together Dreimanis has found shells or fragments of *P. arctica* of more than 23 sites in Latvia. In most cases shells were found in typical tills, and in all cases they were abraded to various degree. Never they were found in Latvia in marine sediments *in situ*.

The Yoldian offshore sediments in the area under consideration are typically barren of diatoms, or may contain a very sparse flora consisting mainly of *Melosira islandica*, which is the dominant species in the richer floras of the Ancylus stage upwards (Hyvärinen et al. 1992). This means that the Yoldian offshore diatom assemblages are mainly fresh.

In some littoral sediments along the Finnish coast varying amounts of brackish, epiphytic and benthic diatoms have been found in sediments underlying the Ancylus strata (e.g. Eronen & Haila 1982; Ristaniemi & Glückert 1987). *Nitzschia navicularis, Diploneis smithii* and *Mastogloia* spp. are frequent components of these floras. In many cases, however, the proportion of brackish-water diatoms is quite small and the floras are dominated by the same oligohalobous taxa as the subsequent Ancylus floras (Hyvärinen et al. 1992). In such cases the occurrence of brackish taxa might be due to redeposition, particularly as the diatom density is often low (Eronen 1974). On the other hand, at some sites horizons containing relatively rich brackish assemblages have been found underlying Ancylus strata; for instance, in the core from Laihalampi, near Helsinki (Eronen & Haila, 1982). And, what is most surprising, occasionally, e.g. in the St. Petersburg area, brackish-water or even marine diatoms have also been found in the overlying Boreal deposits of the Ancylus Lake (Znamenskaya & Cheremisinova 1974).

In the littoral zone of Estonia, e.g. in the Pirita core in Tallinn, brackish-water marine diatoms (*Nitzschia navicularis, N. punctata, Epithemia turgida, Grammatophora oceanica* a.o.) have been found together with typical fresh-water diatoms (*Opephora martyi, Diploneis domblittensis, Cymbella sinuata, Amphora ovalis, Cyrosigma attenuatum* a.o.) not only in the Yoldian deposits (at a depth of 12.90-14.15 m), but also in the Younger Dryas sediments (at a depth of 14.15-16.10 m) of the Baltic Ice Lake (Kessel & Punning 1969). Mixed brackish-water (*Coscinodiscus divisus, Mastogloia smithii, Actinoptychus undulatus* a.o.) and fresh-water diatomaceous complexes (*Opephora martyi, Rhopalodia gibba* a.o.), with a prevalence of the latter (55%), have also been found in Preboreal Yoldian sediments in the Pudisoo core from the Hara Peninsula (Kessel & Punning 1969).

In the Tallinn core brackish-water diatoms (*Nitzschia navicularis, Campylodiscus echeneis, Grammatophora oceanica, Coscinodiscus sp.* a.o.) are prevailing. Rather similar is the diatom content in the Harku core, where the taxa have been registered by Pork (Kessel & Pork 1971). In the lower part of Yoldian sediments *Diploneis smithii f. smithii* and *f. rhombica* prevail (35%), *Nitzchia navicularis* being subdominant. Epiphytic (51%) species are not so abundant as in the upper part of the Yoldian sediments (84%). Oligohalobous species (*Cymbella prostrata, Epithemia turgida*) prevail. Typical fresh water diatoms (*Gyrosigma attenuatum, Cymbella lacustris, C. sinuata*) together with brackish water forms (*Nitzschia navicularis*) occur. Diatom analyses from the Tondi and Sõjamäe mires show a slightly brackish shallow-water environment rich in mineral salts (Lepland et al. 1993).

In the light of the above we should also take a critical look at the sections near the Latvian coast: for example, in the Ventspils lagoon where the Yoldian sandy-clayey sediments occur at a depth of 15 m below sea level and contain up to 48% of marine diatoms (Veinbergs 1979; Veinbergs & Stelle 1981). The complex of saline-water forms comprises *Mastogloia smithii* Thw. + var. *amphucephta* Grun., *Diploneis smithii* (Breb) Cl. + var. *rombica* Mer., *Nitzschia punctata* (W. Sm.) Grun., *Campylodiscus echeneis* Ehr. At the mouth of the Daugava River, at depths of 20-28.5 m below sea level, the content of marine diatoms (*Cocconeis placentula, Diploneis smithii, Cymatoplaera elliptica*) even amounts to 56%. The occurrence of such marine diatomaceous taxa together with fresh-water forms is probably due to redeposition.

M.Kabailienė concluded (1981) that out of all depressions in the central and southern Baltic only the Gotland depression has a somewhat higher amount of brackish-water species. In the Gdansk and Gotland depressions fresh water taxa are clearly prevailing.

ON THE EVOLUTION OF THE YOLDIA SEA

We cannot solve the most topical problems of the Yoldia Sea in the Eastern Baltic, because the events of opening and closing of the connection between the Baltic and Atlantic in Central Sweden were not directly reflected in ecological conditions on the opposite side of the sea which was under the influence of the rapidly melting ice. The Billingen outflow seems to be marked in the sediment sequences (Rennel 1989), but the end of the Yoldia stage is transitional and not traceable. According to the present common concept, the Yoldia Sea was cut off from the ocean about 9500 years ago when the thresholds of the Närke Strait, connecting the Yoldia Basin with the ocean, rose above sea level as a result of glacioisostatic uplift. If the final drainage of the Baltic Ice Lake is estimated at 10,300 B.P. (Svensson 1989), then the total duration of the Yoldia Sea should have been about 800 years. In earlier studies in Finland and adjoining areas a much longer Yoldia stage was postulated (Sauramo 1958); it included the transitional Echeneis stage, which temporally belongs to the Ancylus stage (Kessel et al. 1988). However, there is also an alternative possibility that the strata, which Thomasson (1927) referred to the Echeneis stage, are probably older and actually belong to the saline phase of the Yoldia stage (Svensson 1989).

The ingression of salt water into the Baltic was originally thought to have followed immediately after the drainage of the Baltic Ice Lake (De Geer 1940), but later studies proved that it was delayed by about 200 years and began ca 260 varve years after the drainage or 10,429 varve years before 1950 (Strömberg 1986).

After the Billingen outflow in southeastern Sweden a rapid (ca. 3m/100 years) regression of about 17 m occurred (Svensson 1991), in Lithuania it was ca. 18-20 m (Gudelis 1993). Near Pärnu in Estonia the regression was about 25-30 m (Talviste 1988). W. Ramsay (1927) estimated the drainage in Finland at 28 m at the time when the ice was inside Salpausselkä II (SS II). According to Sauramo (1958), the first drainage of the Baltic Ice Lake down to sea level was during the formation of SS I (B_{I}—g), the second drainage to the level of Yoldia Sea immediately after the formation of SS II (B_{III}—Y_{1}), and the final drainage, again to the level of the Yoldia Sea, after the formation of SS III (B_{IV}—Y_{1}), the first drainage being about 25 m and the two latter ones about 27-28 m. In the Baltic States such complicated lake/sea level fluctuations are unknown (Donner & Raukas 1989).

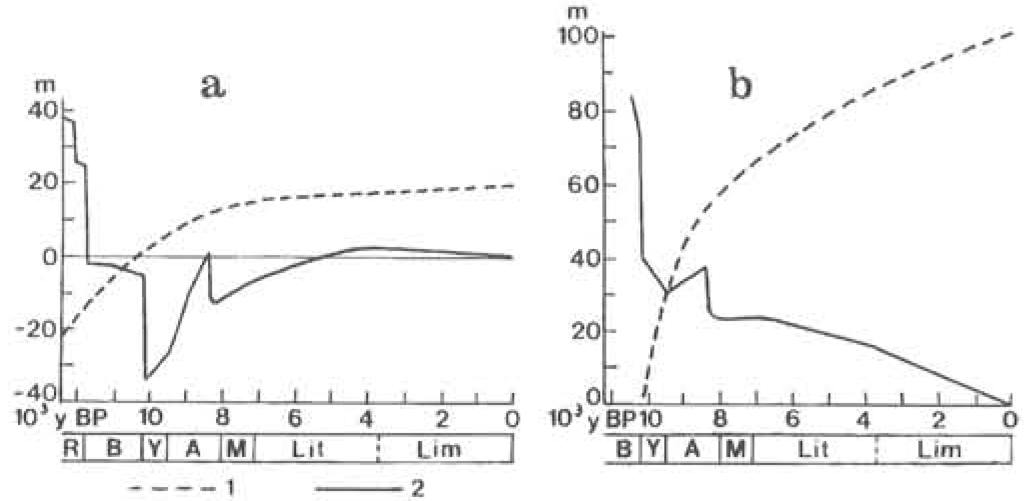

Fig. 2. The Baltic Sea levels depending on the intensity of the neotectonic uplift after D. Kvasov (1979): a - in areas that underwent inconsiderable uplift (St. Petersburg); b - in areas where uplift was more considerable (Tallinn). 1 - the variation of the absolute altitude of the shorelines as a result of isostatic uplift; 2 - the altitude of the Baltic Sea level in relation to its shores.

As the local isostatic uplift in the northern part of the territory under consideration was much faster than the eustatic sea-level rise, and the southern part of the area was subject to sinking, then the whole Yoldia stage in the Eastern Baltic was regressive. The rate of regression during the stage decreased to the south and east with the decreasing isostatic uplift. It should be pointed out that in the stratotype area in NW Estonia the velocity of the neotectonic uplift during Preboreal time was about 3 cm per year (Kessel & Miidel 1973), and therefore it would be difficult to expect the Yoldia Sea transgressions in wide areas. Some evidence of transgression in the second half of the Yoldia stage due to the rise of ocean level in Preboreal (Fairbanks 1989) could exist only in sinking territories (e.g. the Southern Baltic) and in areas of zero land uplift, e.g. in SW Estonia near the Latvian border and in the eastern part of the Gulf of Finland. Regression was deeper, older and clearer in areas that underwent inconsiderable uplift (Fig. 2).

The Yoldia Sea regression was followed by the Ancylus transgression which continued until the water level reached the thresholds in the area of slower land uplift in the region of the Danish Straits. The culmination of the Ancylus transgression, depending on the velocity of the neotectonic uplift, differed with the areas of the Baltic (Kessel & Raukas 1988). If the transgression started at about 9,600 B.P., the water level rose rapidly south and southeast of the discharge area and it did not reach the regions with intensive land uplift in the area of the Bothnian Gulf. In the regions of moderate uplift (N and NW Estonia) regressive coastal formations of the Yoldia Sea and transgressive formations of the Ancylus Lake lie close to each other, and from an absolute height of about 30 m in the contemporary topography all Yoldian shorelines and sediments can be traced only below the Ancylus ones. In Estonia, Yoldian beach ridges have never been found at altitudes below 35 m (Kessel & Raukas 1969).

CONCLUSIONS

In the Eastern Baltic area the fresh-water Yoldia Sea basin was regressive in origin. Its shorelines are in most cases below the contemporary sea level and in the area of more intensive neotectonic uplift (N and NW Estonia) only fragmentary beach ridges can be traced, which most likely belong to one Yoldia level. There is neither morphological nor stratigraphical evidence in support of the existence of several Yoldian shorelines. On the regressive coast of the Yoldia Sea a number of lagoons and coastal lakes formed in the first half of the Preboreal. In all likelihood, their formation continued in the second half of the Preboreal and beginning of Boreal, before they were flooded by the waters of the Ancylus transgression and buried under the Ancylus sediments. In the northern portion of the Eastern Baltic the Ancylus transgression culminated near the PB/B boundary and has been dated at about 9,000 years B.P. (Haila & Raukas 1992).

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Paleochannels in the East Central Part of the Baltic Proper

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Seismic reflection profiling in the eastern part of central Baltic Proper has revealed a system of buried glacial paleochannels incised in Devonian terrestrial bedrock. A system of late glacial to recent submarine valleys, imprinted in the present seafloor morphology, may in part have inherited structural features from the paleochannel system although it seems mainly to extend along present boundaries of water masses, i.e. it trends along boundaries between erosional and depositional seabed.

The paleochannel system includes at least three generations of subglacially eroded valleys, provisionally attributed to the Elsterian, Saalean and the Weichselian glaciations, respectively. The eldest paleochannels are substantially deeper and wider than the younger generations, which is consistent with the conditions on land. Although essentially independent of previous morphology and structure, the paleochannels partly trend along tectonic faults, and presumably also partly along the preglacial drainage system.

The paleochannels are restricted to the easily eroded uppermost Middle Devonian to lowermost Upper Devonian terrestrial sandstones (Šventoji, Burtnieki and Arukula Horizons). The Elsterian paleochannels generally extend through the sandstone unit to the top of the Middle Devonian limestone (Narva Horizon). The paleochannels are typically infilled by till followed by stratified or unstratified glaciofluvial material. Younger paleochannels are occasionally incised into the infillings of older structures. A remarkably even thickness of Weichselian till is deposited on top of a generally flat erosional surface cut partly in bedrock and partly in older glacial/interglacial beds.

INTRODUCTION

Seismic reflection profiling performed during a joint Lithuanian-Swedish expedition, cruise 6/48 of R/V VĖJAS, revealed a system of buried subglacial paleochannels. The seismic profiles also contain new data on the younger, late glacial to postglacial, valley system imprinted on the seafloor south of the Gotland Basin.

The expedition to the east central part of the Baltic Proper was undertaken during the period June 17 to July 2, 1993. Seismic reflection profiling was carried out in the economic zones of Lithuania, Latvia and partly of Sweden (Fig. 1). The cruise was organized by the Lithuanian Institute of Geology, Vilnius, and the Department of Geology and Geochemistry, Stockholm University. Scientists from the Lithuanian Oil Company, Gargždai, the Department of Geology of Latvia, Riga, the Institute of Geography, Vilnius, the Branch of Marine Geology of the Polish Geological Institute, Sopot, the Baltic Sea Research Institute, Warnemünde, and the Institute of Geology, Tallinn, took part in the expedition.

The expedition aimed to investigate in detail the structure and stratigraphy of the upper parts of the Mesozoic and Paleozoic sedimentary bedrock, as well as to collect new data on the glacial and postglacial development of the area. The investigated area included the Fårö and Gotland Depressions, the northern part of the Gdansk Depression, as well as the Klaipėda-Ventspils Plateau, and the northern part of the Kuršių-Sambian Plateau.

This paper is focused on the systems of paleochannels, incised during different glacial phases in the southeastern slope of the Gotland Depression. Some of the channels cut deep into the sedimentary bedrock and are completely filled with Quaternary deposits, whereas others are still visible in the seafloor morphology.

PREVIOUS INVESTIGATIONS

Sviridov et al. (1976), dealing with the pre-Quaternary relief of the Baltic region, was first to mention the presence of glacial grooves in the bedrock on the slopes of the Gotland Basin. The buried channel system on the southeastern slope of the Gotland Depression was again observed by Flodén (1980), and although the paleochannels were used by him to obtain velocity estimates for the Devonian sedimentary bedrock, he never discussed their extension or development.

Gaigalas (ed. 1976), Sviridov & Litvin (1983) and other authors working with the pre-Quaternary relief

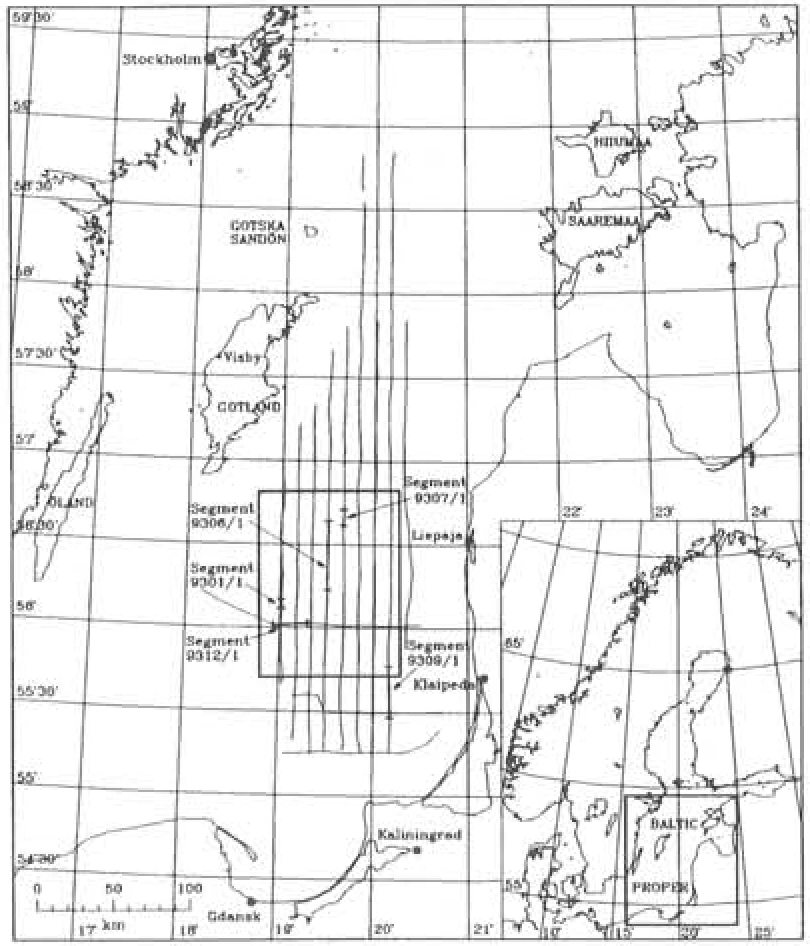

Fig. 1. The Central part of the Baltic Proper with the track lines and location of the three seismic segments described in the text. The present area of investigation is marked by a rectangle.

of the E Baltic region describe onshore and offshore paleochannels in the SE Baltic area. The offshore paleochannels are described as 50-180 m deep and 0.2-10 km wide. They are interpreted as polygenetic due to fluvial, glaciofluvial or glacial groove erosion. Onshore, deeply eroded fluvial paleochannels, reformed by Quaternary glaciers, are described from the western Lithuania and the Kaliningrad District. The base of these onshore channels, which are very characteristic of the region, is located 30-80 m below the present sea level. The lower part of the channels are filled with sediments containing alluvial sands and clays, 12-15 m thick. The upper part of the channels are frequently filled with Early Pleistocene tills, 60-100 m thick.

An extensional amount of geological-geophysical data, including results of deep marine drillings, were analyzed by Grigelis et al. (1991) in the monograph "Geology and Geomorphology of the Baltic Sea". In connection with this work, some general information concerning channel structures in the Baltic Proper was presented by Repečka et al. (1993), and also included by Gelumbauskaitė et al. (1993) on the Map of the Quaternary geology of the Baltic Sea, and on the Geomorphological Map of the Baltic Sea.

MATERIALS AND METHODS

The material used in the present paper was mainly collected during the cruise 6/48 onboard the Lithuanian R/V VĖJAS in the summer of 1993. Some material collected and processed by Flodén (1980) has also been incorporated into the work.

During the 1993 cruise a RAYTHEON GPS navigator was used for the positioning. A PC-computer was attached to the navigator and longitude/latitude positions in WGS-84 were stored as computer data files. The accuracy obtained for the positioning was better than +/- 50 m. A total of 2630 km of continuous echosounding and seismic reflection profiling was performed. The present N-S survey lines in the eastern part of the central Baltic Proper have a spacing of approx. 10' of latitude degree, i.e. ca 11 km (Fig. 1).

Water depth and bottom topography was recorded by a SKIPPPER 607 echosounder at a depth range of 0-250 m. Due to the temporary installation of the echosounder, and the requirement of the seismic profiling to have a ship speed of more than 6 knots, the recordings were of a general low quality.

To obtain information on the sub-bottom structure, an analogue single-channel seismic reflection equipment, based on a PAR-600B airgun, was used. The reflected signals were received by a hydrophone eel containing 100 hydrophone elements housed in a 20 m hose. The signals were filtered on site and two 250-500 Hz records were displayed on precision graphic recorders, one of them was stacked four times before recording. The graphical display time interval was 0.5 s.

DESCRIPTION OF THE CHANNEL SYSTEMS

This paper deals with two morphologically different sets of paleochannels, namely those which are completely infilled and those which are imprinted on the seafloor. The former channels are the oldest, ranging in age, most probably, from the Elsterian to the Weich-

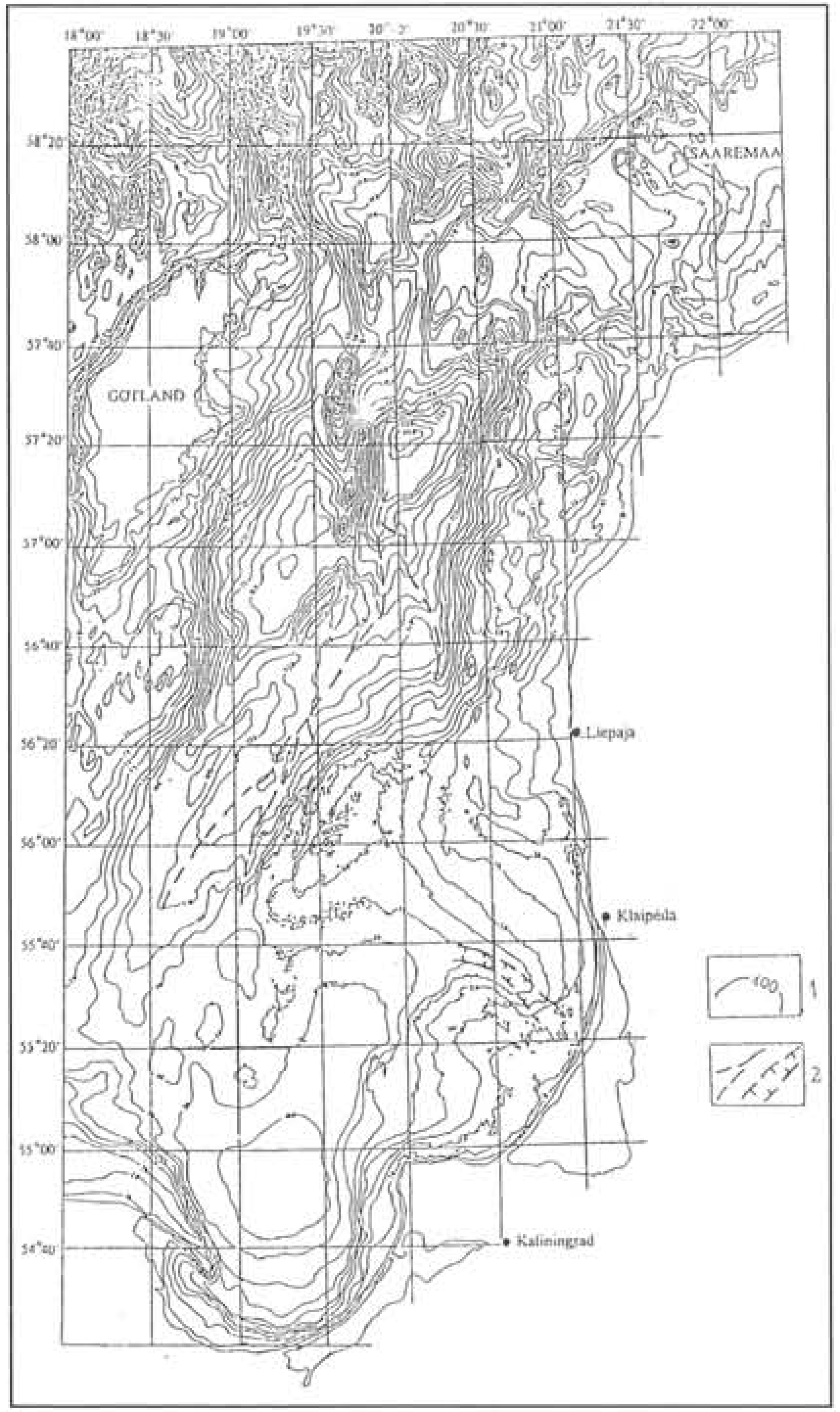

Fig. 2. Bathymetric map of SE Central Baltic Proper. 1 - isobathes in metres; 2 - location of late glacial to recent paleochannels (see enlargement, Fig. 8).

selian, whereas the latter are Weichselian to Recent. Some of the latter channels have inherited their channel morphology from older structures.

Geology and geomorphology

The presently investigated area is located along the generally northward dipping seafloor which forms the southern boundary of the Gotland Basin (Fig. 2). The upper parts of the slope, which is located at depths of 110-180 m, contain frequent paleochannels (Fig. 3). The bedrock surface in this part has a Lower to Middle Devonian peneplainized cuestian relief sculptured mainly in terrestrial sandstones. The Devonian stratal sequence dips gently towards the SE, thereby increasing in thickness in this direction. The bedrock is overlain by a rather thin (less than 20 m) Quaternary cover, mainly composed of till. This gives the seabed a rather rugged appearance along this elevation in contrast to the deeper parts of the Gotland Depression where clays form the sea bed (Fig. 2,4).

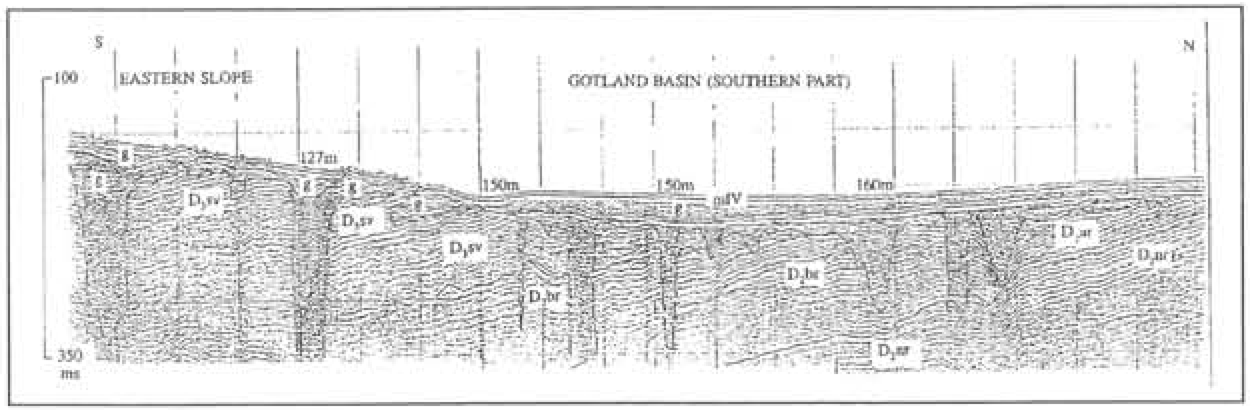

Fig. 3. Seismic recording along profile 9306, with tentative interpretation. Quaternary deposits: **mIV** - post-glacial deposits, **g** - glacial deposits; Devonian sedimentary bedrock: **D_3sv** - Šventoji Horizon, **D_2br** - Burtnieki Horizon, **D_2ar** - Arakula Horizon, **D_2nr** - Narva Horizon.

The Devonian stratal sequence of this area consists of continental as well as marine deposits (Fig. 5). The terrigenous sediments are of the Old Red Sandstone type, namely sandstone, siltstone and clay. The dominating terrestrial sequence, which ranges from the Middle Devonian Arukula Horizon to the Upper Devonian Šventoji Horizon, (Fig. 6) bears signs of numerous erosional events, signified by major discontinuity surfaces.

The terrigenous Šventoji Horizon is overlain by the marine Plavinas to Pamūšis Horizon (Fig. 5). These formations, which consist of limestones and dolomites, form the southeasternmost limit of the Gotland Basin by a system of clints which rise approximately 50 m above the seafloor.

The paleovalleys in the East Central Baltic Proper are mainly confined to the uppermost Middle Devonian and the lowermost Upper Devonian terrigenous sequence, the Arukula, Burtnieki and Sventoji Horizons. One valley was, however, found in the marine Plavinas to Pamūšis Horizons. The paleovalleys generally extend down to the strongly reflecting surface which represents the top of the marine limestones of the Narva Horizon (Fig. 5).

The northern and northwestern slopes of the Gotland Basin are sculptured in Silurian limestone which forms the upper surfaces of an extensive succession of barrier reefs of Wenlockian-Ludlowian age.

The eastern boundary of the Gotland Basin is formed in Upper Silurian rocks, namely the about 20 m high Pridolian Ohesaare Cliff. The bedrock is located at depths of 200-240 m and the Quaternary thickness reaches 50 m. No channels have been observed in the northern and eastern areas.

The extensive Gotland Depression, of which the Gotland Basin forms the deepest northern part, is separated by an escarpment from the Klaipėda-Ventspils Plateau (Fig. 4). It seems as if a watershed has existed between the Gotland Depression and the Nemunas catchment area on the Klaipėda-Ventspils Plateau. The bedrock of the Plateau is composed of Upper Devonian beds of plicative morphostructures, almost without Quaternary cover.

The base of the Gdansk Depression descends southwards from the Klaipėda-Ventspils Plateau (Fig. 2,4). On the easternmost slope of the Depression, there is a well-expressed arm, 6 km wide and 26 km long, of the Nemunas River paleovalley (Fig. 2). This is a fluvial-glaciofluvial channel levelled by later agents of marine abrasional-accumulative processes. The buried network of the Nemunas catchment area can be observed below the 70 m depth. Here the ancient valleys are incised in the Mesozoic, i.e. Triassic-Jurassic deposits (Fig. 7).

Previous investigators (Gaigalas et al. 1976; Sviridov 1984; Grigelis et al. 1991) have noted that the paleochannels in the Central and Southeast Baltic Proper have characteristic V-shapes. The depths and widths of the channels range from 50 to 180 m respectively from 0.2 to 10 km. Their variations in depth and width may indicate multiple deepening. Moreover, some of their imprints in the recent topography indicate that the last deepening took place during the Late Weichselian (see Fig. 8).

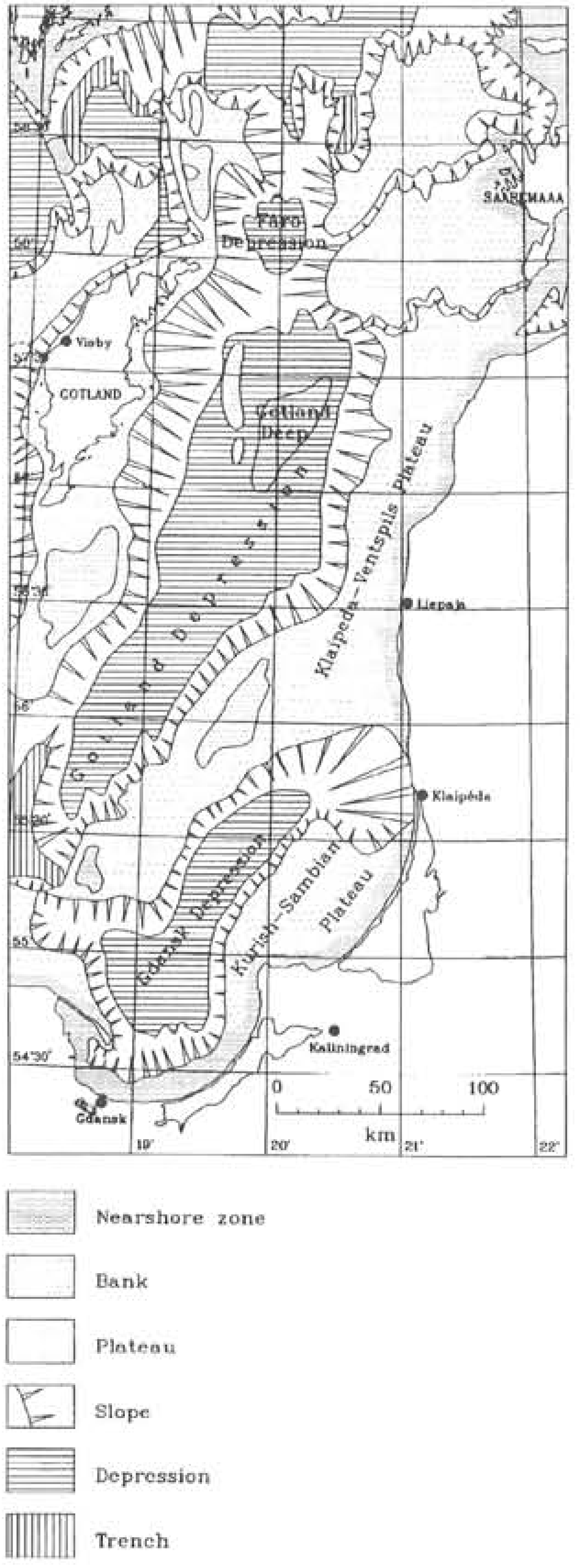

Fig. 4. Morphological map of the SE Central Baltic Proper.

The glacial paleochannel system

Morphology. The glacial paleochannels are all basically of the same morphology, although they may appear different in the seismic records. The differences in their seismic appearance depends simply on the angle of crossing. Those channels which are cut perpendicularly are V-formed and rather narrow, generally about 1 km wide. Those channels which are cut at an angle, are recorded as rather wide structures with flat bottoms, not conforming with the dip of the bedrock. The walls of the channels are generally steep and smooth, those with V-formed appearance have almost vertical walls. The upper parts of the walls bend smoothly outwards. All channels of this type have during, or soon after, their formation been completely filled with Quaternary deposits (Figs. 9-11).

Infilling. The internal bedding in the channels varies. In general, they reveal 3 different erosional and depositional events. Each event left a sediment cycle containing a till at the bottom followed by fluvial stratified or unstratified sediments. The bottom till layer is in some places substituted by a cycle containing both unstratified and stratified sediments. The fluvial sediments differ in their relative disposition when comparing the channels. In some, the bottom till is covered by stratified sediments and in others by unstratified material. The infilling sequences are covered by Weichselian till, resting on a generally flat erosional surface.

The channels are of at least three generations. This is concluded from the fact that younger generations of channels are occasionally cut into the infillings of older channels whereby forming a geologic succession. The channels of the oldest generation are unique regarding their great depths as compared to those of younger generations.

Along segment 9301/1 (Fig. 9) the first generation channel is filled by till I and unstratified sand and gravel. A second generation channel, much smaller and narrower, is incised in the unstratified sediment of the infilled channel. This second generation channel is infilled by till II. Channels of the second generation are also found along the flanks of the original channel. The third generation channels are even narrower and smaller than the second generation, and they have generally been cut into the bedrock on the flanks of the first generation channels. Along segment 9301 a third generation channel cuts through till II and into the bedrock. It is filled with stratified sand and gravel.

The infillings of the channels reveal that they belong to different glacial phases, most probably different glaciations. Thus, the first generation channels are filled with deposits from a first glacial phase, a till at the bottom followed by glaciofluvial material. The second generation channels which are cut into the first generation are mainly filled with a till sequence from a second glacial phase. The third order channels are incised in the older glacial deposits and are filled with glaciofluvial stratified or unstratified sand and gravel.

As just mentioned, the channel infillings can be sub-

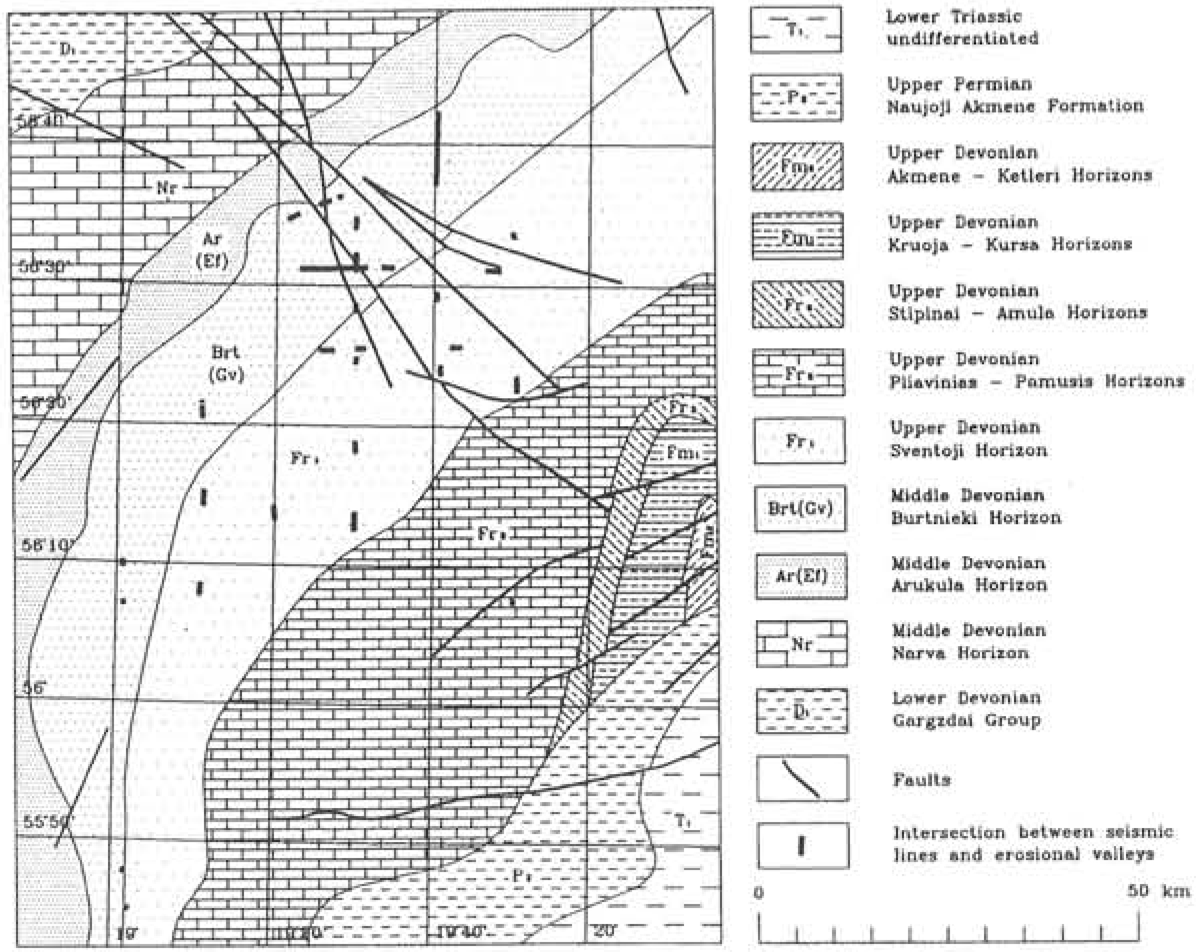

Fig. 5. Sedimentary bedrock of the investigated area. For location see Fig. 1. On top of the marine Gargždai Group and Narva Horizon follows the terrestrial sandstones of Arukula, Burtnieki and Šventoji Horizons. Upwards follows Upper Devonian marine units.

divided in a number of successive lithologic units, and the seismic structure of these units aids their identification. Thus, tills are distinctive seismic units of chaotic internal structure, multilayered sediments are clearly seen and so are in many cases sand units with weak or absent internal beddings. A further refinement of the infilling strata is possible by comparisons with onland and offshore drilling data.

From the seismic data, three generations of tills have been separated, namely till units I, II and III where till unit I is the eldest. Each till sequence is clearly separated from older and younger stratal units by erosional surfaces. Till units I and II are of varying thicknesses, but in general about 30 m. The tills I and II are everywhere clearly separated from till III which seems to form a Late Weichselian bottom moraine resting on the bedrock or ontop of the already infilled paleochannels. Till III is sometimes overlain by clays but constitutes the sea floor along bedrock elevations. It has a generally uniform thickness of around 10 m over large areas.

The seismic records further indicate the presence of stratified and unstratified sand and gravel deposits along the paleochannels. Two glaciofluvial sequences, separated from each other by tills or erosional surfaces, are commonly found. These may be interlayered with one another, in which case the unstratified sequence contains lenses and layers of stratified material.

Comparison with drillings onland and offshore supplies further data on the channel infillings. According to drilling data, two types of infillings are characteristic of the incisions: those with internal laminated structure and those without it. In the first case, these are alluvial deposits, tills and glaciofluvial repetitive structures telling about a multiphase filling process and an extended life of the incisions. In the second case, these are infillings of till and glaciofluvial sediments without internal laminated structure. At the bottom of these latter incisions, the alluvial cover is usually thin or often even absent. The next higher layer contains one or two tills, which are covered with a third till, thus, burying them entirely. The latter type of incisions is most characteristic of the southern part of the Gotland Basin.

The late- to post-glacial channel system

Morphology. The late- to post-glacial channels exposed in the seafloor are rather shallow with only a slightly negative curvated form (Fig. 8). They commonly occur at the boundary between areas of accumulational and erosional seabed.

System	Series	Stage	Formation
TRIASSIC	Lower	Bunt-sandstein	Nida
			Deime
			Sarkuva
			Taurage
			Palanga
			Nemunas
PERMIAN	Upper	Zechstein	Mamonovo
			Galindai
			Aistmares
			Zalgiriai
			Prieglius
			Naujoji Akmene
			Sasnava
			Kalvarija
	Lower	Rotlie-gendes	Perloja
CARBONI-FEROUS	Lower	Tour-naisian	Klykoliai

System	Series	Stage	Formation
DEVONIAN	Upper	Famen-nian	Ketleri
			Zagare
			Svete
			Muri
			Akmene
			Kursa
			Joniskis
			Siauliai
			Kruoja
		Frasnian	Amula
			Stipinai
			Pamusis
			Katlesi
			Daugava
			Dubnik
			Plavinas
			Sventoji
	Middle	Givetian	Burtnieki
		Eifelian	Arukula
			Narva
			Parnu
	Lower	Emsian	Rezekne
			Kemeri
		Lochko-vian	Stoniskiai
			Tilze

Fig. 6. Stratigrapy of the SE Central Baltic Proper.

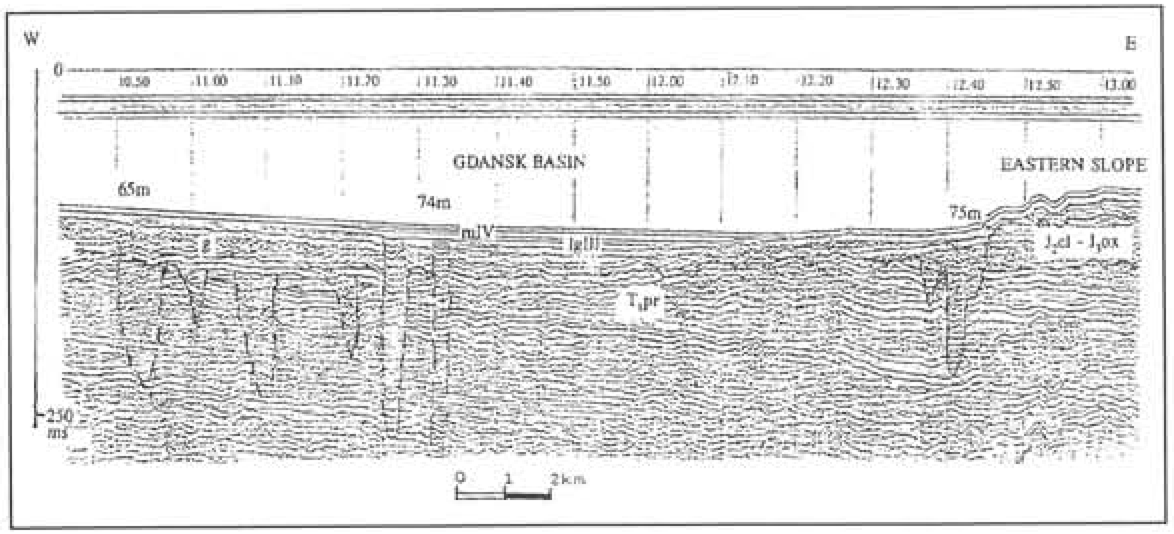

Fig. 7. Seismic recording along profile 9309, with tentative interpretation. Quaternary deposits: **mIV** - post-glacial deposits, **g** - glacial deposits; Sedimentary bedrock: **J_2cl-J_3ox** - Jurassic, Callovian to Oxfordian stages, **T_1pr** - Triassic

As mentioned above, many of the eastern Baltic paleochannels are entirely buried below glacial and probably also interglacial deposits and they have no morphological relief in the present seafloor. The exception is a system of valleys, which has the general outline of an ancient river network, starting at the southernmost end of the Gotland Basin and extending along its eastern side, close to the steep eastern slope (Fig. 2). The topographical map shows that the valleys of this system trend NE-SW and the longitudinal seismic profiles cross them at oblique angles. Thus their images in the seismic profiles is distorted. The valleys are some 4 km wide in the southernmost end of the Gotland Basin (Fig. 2). Towards the NE they

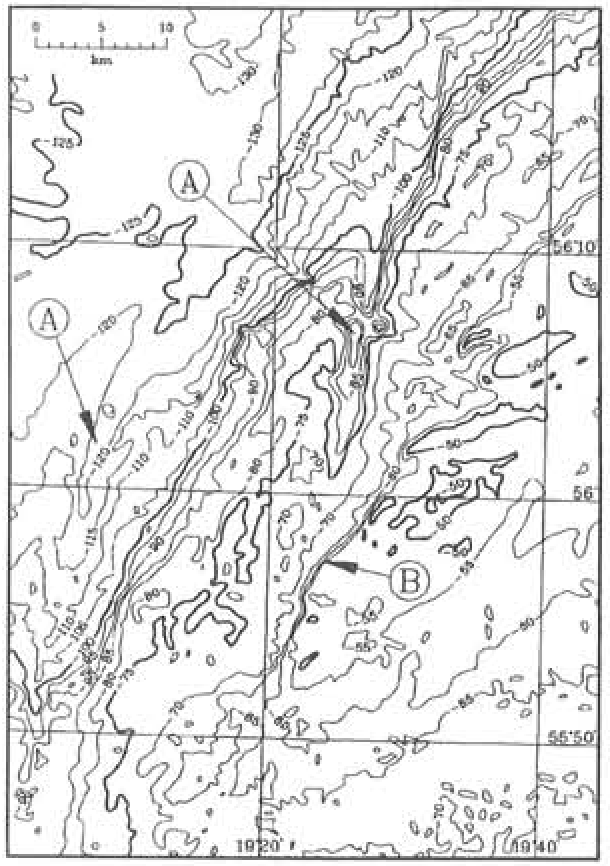

Fig. 8. Sea floor topography of the investigated area. **A** - drowned valleys, possibly of the Weichselian deglaciation phase; **B** - scarp at the western slope of the Klaipėda Bank, possibly of Yoldia age.

merge into one artery at the southern end of the Gotland Basin which widens to 5 km (segment 9307/1, Fig. 10).

Infilling. Sedimentation in the Baltic in general changes from place to place, but also from time to time. Therefore, the late glacial and postglacial sedimentary sequences are rarely complete and continuous. Channel systems in the seafloor is a common feature in the Baltic Sea. They may occasionally be formed by postglacial water current erosion, but most often they result from non-deposition of postglacial sediments. Both types and combinations between them presumably occur along the channels of the Gotland Basin.

Profile segment descriptions

Segment 9301/1 (Fig. 9): Three generations of paleochannels are found along this segment of the seismic profile line 9301 (see location in Fig. 1). The eldest paleochannels are around 120 m deep and roughly 1 km wide. The bottom deposits consists of till I which seems to have an erosional upper surface. On top of the till follows unstratified sand and gravel that probably originally entirely infilled the channels. This sequence was later subjected to erosion, which levelled the surface and cut new channels into the bedrock and into the original channels. On this surface till II was deposited. A new erosional phase followed the deposition of till II, forming third generation channels cutting through till II. This third generation of channels were infilled with stratified sand and gravel. The last glacial period in the area only levelled off the surface and till III was deposited as this ice withdrew.

Segment 9307/1 (Fig. 10): Two generations of paleochannels are present along this segment of profile line 9307. The eldest is around 4.5 km wide, and about 60 m deep (see location in Fig. 1). The width of the channel is presumably greatly exaggerated due to the angle of crossing, however. The basal infilling of the channel consists of till I, which is unevenly distributed within the channel and also found in small thicknesses on the sides of the channel. Possibly, till I has originally completely filled the channel and has later been partially removed by fluvial erosion. On top of till I follows a stratified sand and gravel accumulation. This accumulation is draped over the bottom till and also over the sides of the structure. Its upper surface has an erosional appearance. On top of the stratified accumulation follows a thick sequence of unstratified sand and gravel which completes the infilling of the channel. A second generation channel, infilled with till II is cut into the unstratified accumulation just mentioned. As described for the segment 9301/1, the last glacial phase in the area merely levelled the channel infilling and deposited till III as a rather even layer across channels and bedrock alike.

Segment 9312/1 (Fig. 11): Two, and possibly three, generations of infilled paleochannels and one modern channel in the seafloor are present along this segment of profile line 9312. The eldest channel is very narrow, about 300 m wide and 50 m deep (see location in Fig. 1). It is located adjacent to a tectonic fault which trends NW-SE through the investigated area. The walls of the channel are very steep, almost vertical, and very smooth. The paleochannel is infilled by an unstratified sand and gravel deposit, which seems to have an erosional upper surface. A stratified sandy unit follows on the western flank of the channel. On the levelled upper surface of these two units follows an even cover of till III. A minor second generation channel is cut into till III and into the upper part of the underlying older channel. This younger, narrow, channel is infilled with unstratified sand and gravel. The youngest till unit in the area, till III, is exposed on the seafloor eastwards from the paleochannel area whereas glacial and postglacial clays extend westwards. The boundary between the generally depositional and the generally erosional seafloor along the eastern boundary of the Gotland Depression is followed by a shallow postglacial channel formed in the clay and obviously kept open by bottom currents. A subjacent negative form due to a slight reduction in the thickness of till III suggests that the location of this modern channel is inherited from an older Late Glacial channel system along the eastern limit of the Gotland Depression.

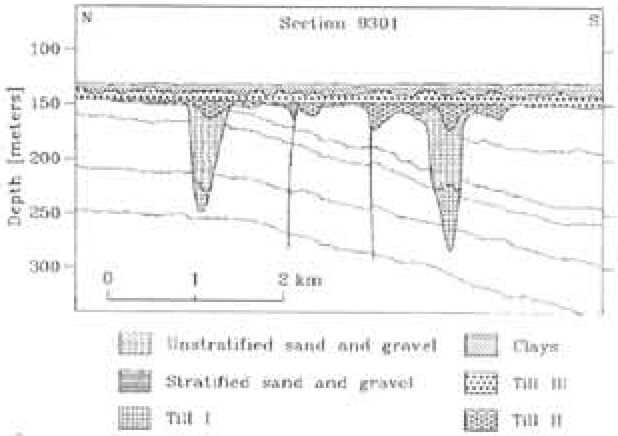

Fig. 9. Geological section based on seismic segment 9301/1 (Fig. 1). The section is located at the outcrop area of Burtnieki and Šventoji Horizons in the southern part of the investigated area.

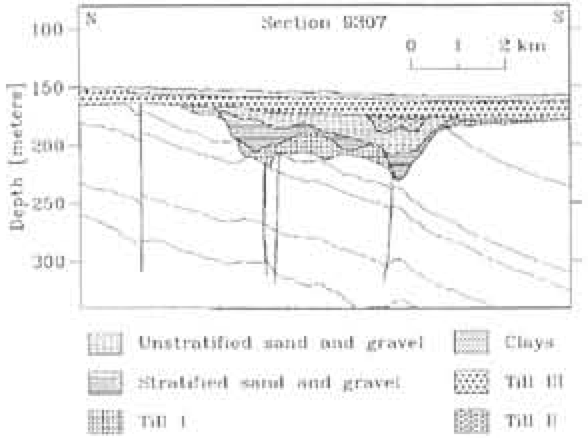

Fig. 10. Geological section based on seismic segment 9307/1 (Fig. 1). The section is located at the outcrop of the Burtnieki Horizon in the northern part of the investigated area.

Extension of the channel systems

The seismic profiles indicate that the paleochannels in general are rather short, they seem to appear and disappear rather suddenly although the present basenet of seismic profiles is not sufficient for a full interpretation (Fig. 5). In a general way, the paleochannels extend NE-SW along the southeastern slope of the Gotland Depression rather than in the dip direction. The present network of seismic profile lines is, however, not sufficient to outline the extensions of the individual paleochannels.

The northern boundary of the channel system area conforms with a change from Upper Silurian to Lower Devonian marine limestones and marls in the north to more easily eroded Middle to Upper Devonian (Arukula-Šventoji Horizons) terrigenous sandstones and siltstones in the south (Fig. 5). The SE boundary of the channel area is controlled by the bedrock, too. It is located along the boundary to Upper Devonian (Plavinas Horizon/L. Frasnian) marine limestones (Fig. 5). The channels are thus restricted to the outcrop of the thick terrigenous sandstone complex at the boundary of Middle-Upper Devonian.

It is furthermore clear that the depths of the paleochannels are restricted by the bedrock composition. The paleochannels nowhere reach further down into the bedrock than to the Narva Horizon in the Middle Devonian. The subjacent harder rocks have evidently resisted channel erosion (Fig. 5).

Tectonic pattern

The NW-SE Proterozoic Västervik-Klaipėda Tectonic Zone (Flodén 1980) extends through the investigated area outlining a system of younger faults in the same general direction through the Paleozoic sequence. In the present area normal faulting is the most common tectonic feature, with displacements generally in the order of a few metres and only exceptionally up to 50 m. The individual faults are of short extensions and generally seem to have resulted from bending along the ancient basement zone. A superimposed NE-SW tectonic system shows some indications of strike-slip movements.

The paleochannels discussed in this paper seem in a general way not to be dependent on the tectonic pattern, but a denser network of seismic lines is needed to decide this. Nevertheless, some few of these channels seem to follow existing tectonic faults for at least parts of their extensions. The only undisputable example in the present seismic profiles is presented along segment 9312/1 (Fig. 11), although the present material does not permit a detailed mapping of this paleochannel. Although the paleochannels appear to be independent of the tectonic pattern, they may coincide with tectonic faults as far as their general trends coincide. For comparison, the Lithuanian onshore channels are not controlled by the tectonic pattern and in this context they may be compared with the channels off shore.

DISCUSSION

Glacially generated systems of channels are common features along the outer margins of major glaciated areas. In northern Europe they occur along the fringe of the glaciated area: in the North Sea (Long & Stoker 1986; Wingfield 1989), in England (Woodland 1970), in Denmark (Hansen 1971; Berthelsen 1972) in northern Germany (Ehlers & Linke 1989; Eissmann 1967), in the east Baltic region (Eberhards & Miidel 1984; Gaigalas 1976, 1989) and in the southern Baltic Proper along a general line from the Arkona Basin through the Hanö Bay to the east Baltic coast, thus connecting with the previously described onland areas.

Channel forming processes

The channels generally cut very deep into the sedimentary bedrock. The average depth in the present area is about 80 m, which is generally similar to those in the land areas around the Baltic. Essentially deeper channels are reported from the North Sea, however. The deep channels start abruptly and terminate equally abruptly, leaving no possibility for normal water drainage. Therefore they cannot have developed as river valleys.

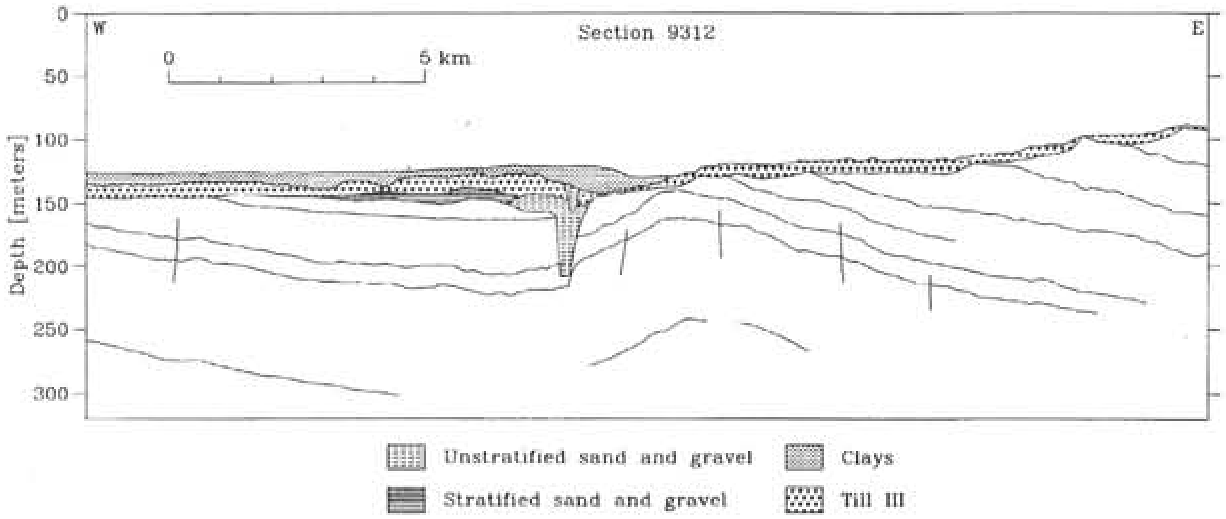

Fig. 11. Geological section based on seismic segment 9312/1 (Fig. 1) located in the central part of the investigated area at the outcrop of the Burtnieki Horizon.

Despite this, modern rivers in the Baltic countries are known to extend along paleovalleys although the excavation capabilities of the rivers never reach down to their basal levels. Likewise, paleovalleys in general are independent of bedrock structure and relief, but despite this they occasionally occur along tectonic faults for shorter or longer distances. Although we have no indications from the present offshore area, it is quite likely that they have also occasionally been cut along ancient preglacial river beds. A conspicuous feature is further, that despite extensive drillings in the Baltic countries there are no reports of preglacial river sediments in the basal part of the channel infillings.

It is further of interest to note that the present paleovalleys are confined to the area of soft terrestrial Devonian sandstone, indicating that erosional resistance is an important factor for their development. This is again quite opposite to the formation of river valleys, which in time will excavate into any rock material.

As to the question how the paleochannels actually were formed there are several opinions. In the Scandinavian region, the "tunnel valleys" of Jutland in Denmark were first described by Ussing (1907, 1913), who concluded that they were formed by excavation of the ice itself in combination with subglacial meltwater streams. The Jutland buried channels have later been descibed in more detail by e.g. Milthers (1948), Sorgenfrei & Berthelsen (1954) and Jessen (1963). Although the classical theory of "tunnel valley" formation proposed by Ussing has been sharply criticised (Hansen 1971; Berthelsen 1972; Andersen 1973), the formation and infilling of channels by high-velocity water discharges in subglacial tunnels near the glacial margin has attained wide acceptance (Wright 1973).

The meltwater required for catastrophic discharges through the frozen foot of a glacier may be of different origins. Bjørnsson (1976) reported on superglacial ice lakes in Iceland. He states that in some cases an ice lake is formed in sink holes on the glacier surface. The hole is tray shaped and collects meltwater from the ice surface. This meltwater is drained englacially through a hole or a crack at the bottom. The process may be rather rapid as the water flows to the base of the glacier under a very high pressure. The water will thus subsequently erode the subglacial surface.

The other process involving meltwater is erosion along subglacial tunnels advocated by several authors (Ehlers & Wingfield 1991; Liedke 1981; Woodland 1968). There is generally water present at the interface between the ice and the bedrock. Wright (1973) discussed the hydrodynamics of the subglacial waters below the Weichselian Superior ice lobe, Minnesota, demonstrating that geothermal flux and frictional heat are sufficient agents for slow subglacial melting although the foot of the glacier remains frozen. The Superior ice lobe covered an area of 80,000 km^2, producing channels of an average 10 m depth and 300 m width. The conditions were essentially more favourable in the Baltic area, where the Baltic Sea alone within its present limits covers an area of 419,000 km^2. The water accumulated during perhaps long periods below the ice occasionally forced its way through the foot of the glacier gathering debris along its way and thereby increasing its erosive power. As the water pressure was reduced the subglacial stream changed from erosional to depositional leaving its load on the bottom of the channel, but also at the margin of the ice.

An interesting approach to the morphology of the ice marginal zone is put forward by Hay et al. (1993). Due to the great load of the ice on the bedrock a wedge or bulge forms at the periphery of the ice. Subareal water may then break through the bulge along streams or rivers. As the ice load is removed the bulge drops and the valleys drop accordingly. The result is channels cut into the bedrock, later filled and buried by Quaternary deposits. It may be argued that the size of the bulge would greatly exceed the lengths of the channels, which in our case is no more than 5-15 km. Also the basal infill of the channels would be clastic sediments rather than till. We should not exclude the possibility of different channel forming agents along the ice margins, however, and some of the minor channels of the third generation in our area are entirely filled by stratified sediments (Fig. 9).

It is probable that parts of the channel system imprinted in the present seafloor morphology of the investigated area has a late glacial history as river valleys. Presently they occur as shallow trenches along boundaries between areas of erosion and deposition. The trench along the base of the eastern slope of the Gotland Depression is representative (Fig. 8). It evidently marks the boundary between a water mass moving along the slope of the Depression and an inactive water mass within the Depression. This does not explain all trench-like features in the area and these will be subject to further investigations.

Age of the channels

The channels of the presently investigated area form a time sequence in which three generations of paleochannels are separated by extensive till units. The Late Glacial to Recent channel system needs no further comments in this respect. The present investigation is purely a seismic study and no drillings have been performed. Therefore the age of the paleochannels can only be discussed from comparisons with other areas.

In Lithuania, and offshore Lithuania, deposits are known from three major glaciations, namely Elsterian, Saalean and Weichselian (Grigelis, ed. 1991). The deepest paleochannels onland belong to the Elsterian glaciation, whereas increasingly smaller channels are attributed to the Saalean respectively the Weichselian glaciations (Gaigalas, ed. 1976). In Northwest Germany a similar system of deep paleochannels was cut into the substratum during the Elsterian glaciation, which incidently is regarded as the first glaciation in NW Europe (Ehlers et al. 1984). No comparative Saalean or Weichselian paleochannels are described from the German area.

Although we lack drill-core evidence from the area in concern, it is reasonable to point out the similarities with the adjacent land data, placing the three generations of channels in the Elsterian, Saalean respectively the Weichselian glaciations. The evidences concerning the Elsterian age of the deep paleovalleys of the first generation are convincing, whereas the two younger systems require further verification.

CONCLUSIONS

The basic network of single channel seismic reflection profiles shot along N-S lines between Gotland and the E Baltic coast has revealed new information on the geological framework and on the Paleozoic to Quaternary stratigraphic successions of the area. Among the geological structures revealed in the area are the glacial deep channels discussed in this paper. Although much details remain to be studied in the course of our joint investigations in the area, and even though the present network of profiles does not permit any detailed mapping of the individual paleochannels, we are able to draw some general conclusions about the newly found paleovalley system.

(1) Two genetically different valley systems are present in the area SE of the Gotland Depression, namely a system of subglacially incised and fully infilled paleochannels and a system of late- to post-glacial valleys imprinted in the present seafloor relief.

(2) The paleovalley system includes at least three generations of valleys, provisionally attributed to the Elsterian, Saalean and the Weichselian glaciations, in congruence with the onland conditions in the SE and SW parts of the Baltic.

(3) The eldest (Elsterian) paleovalleys are larger and deeper than those of later glaciations by a factor of magnitude, which is consistent with the conditions on land.

(4) The paleovalleys are confined to the uppermost Middle Devonian and the lowermost Upper Devonian terrestrial sandstones, i.e. to an easily eroded stratal unit. The eldest paleovalleys generally extend through the sandstone unit to the top of the Middle Devonian limestone (Narva Horizon).

(5) The paleovalleys are typically infilled by till followed by stratified or unstratified glaciofluvial material. Younger paleovalleys are occasionally incised into the infillings of older structures.

(6) The paleochannels and their infillings offer a key to the acoustic signature of the successive till units, whereby mapping the extensions of pre-Weichselian deposits in the SE Baltic Proper becomes prospective.

(7) The late- to post-glacial channel system inside and on the slope of the Gotland Depression is largely due to actions of water masses up to the present day. Their inheritance of older morphological features is still unclear.

(8) A remarkably even thickness of Weichselian till is deposited on top of a generally flat erosional surface cut partly in bedrock and partly in older glacial/interglacial beds. The erosional power of the Weichselian ice seems to have been much less than that of previous glaciations. The base Weichselian forms a good seismic marker surface in the area E and SE of Gotland.

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Seabed Investigations of Upper Proterozoic to Lower Palaeozoic Erratics in the Åland Sea, Sweden, by the SPERESAT Technique

Per Söderberg and Stefan E. Hagenfeldt

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The newly developed seabed sampler, named SPERESAT, has been used for investigations of sedimentary bedrock erratics in the Åland Sea. The technique permits extensive sampling underneath clay beds to a greater extent than with dredging. The samples obtained yielded various types of sedimentary bedrock, e. g. sandstone, shale, and limestone. They are compared with on-shore samples. The Unit 1 of the informal Söderarm formation, being of Middle Riphean age, is exposed in the western parts of the Åland Sea along the fault zone towards the Stockholm archipelago area. Unit 2, representing the upper part of the same formation, being of Late Riphean to Vendian age, is present in the southern Åland Sea. Shale, also included in the unit 2, occurs sporadically as erratics. Lower Cambrian sandstone, forming the lower part of unit 3, is widely distributed as erratics, though not very frequent. The Ordovician limestone, forming the upper part of unit 3, follows the on-shore distribution with the bulk of limestone erratics comprising the Upper Ordovician Baltic limestone in the eastern part of the Åland Sea, and Lower and Middle Ordovician limestone erratics being more abundant in the western part.

INTRODUCTION

This article deals with the background, instrument performance and results of seabed sampling in the Åland Sea area. It is the result of the development of, and fieldwork with, a special bottom sampler concept - SPERESAT (SPEcial REmote SAmpling Technique; Fig. 1). SPERESAT is one in a series of new seabed and subbottom samplers currently being developed by one of the authors (Söderberg 1988). The SPERESAT technique has been tested during several field trials. The sampler was modified successively as a response to field experiences. The present prototype model samples the seabed and brings up representative amounts of bedrock boulders from the glacial drift at the sampling station. This is possible despite some metres of covering clays. The sampler has been found to work very well down to a water depth of at least 90 m (Appendix).

Investigations with the aim to map the sedimentary bedrock sequence have been performed by Veltheim (1962, 1969) in the Bothnian Bay, the Bothnian Sea, and the northern part of the Åland Sea. These investigations were made with grab samplers. The results indicated a close relationship between the distribution of erratics assemblages and *in situ* occurrences of sedimentary bedrock. Later, a comparison was possible through the access of drill cores (Veltheim 1969, Thorslund 1979, Tjernvik & Johansson 1980, Löfgren 1985, Hagenfeldt 1989). In comparing the grab sampler technique with SPERESAT, it was obvious that the SPERESAT tecnique makes it possible to penetrate deeper into the bottom than with grab samplers. This circumstance allows a more complete view of the composition of the erratics from the sampling sites.

Strömberg (1971) investigated the varve-chronology on the land areas surrounding the Åland Sea basin. He included observations of glacial striae in order to make a model for the deglaciation of the area. He concluded that the ice retreat was roughly from SSE towards NNW. Söderberg (1982), using high resolution marine seismics, found marginal morains indicating the ice retreat to be slightly more in the direction towards NW in the Åland Sea Basin.

Flodén (1973) and later Söderberg (1993) errected a model for the development of the Åland Sea Basin and the subsea distribution of sedimentary bedrock. They based their maps on shallow seismic profiling and seismic refraction measurements. The seismic stratigraphic subdivision by Söderberg (1993) concerned 3 separate units. Following Söderberg (1993) these units are also used herein (Figs 2 and 3).

Investigations on the distribution of erratic boulders were performed by Hagenfeldt & Söderberg (1985) and Hagenfeldt (1993). These investigations comprised on-shore sites in the Stockholm Archipelago and along the coastal area around the Åland Sea.

The main subject of this project was to identify seismically indicated remnants of Upper Proterozoic and Lower Palaeozoic *in situ* occurrences underneath the unconsolidated sediments in the Åland Sea. The sampling stations were chosen with regard to the general direction of the last glacial ice movement.

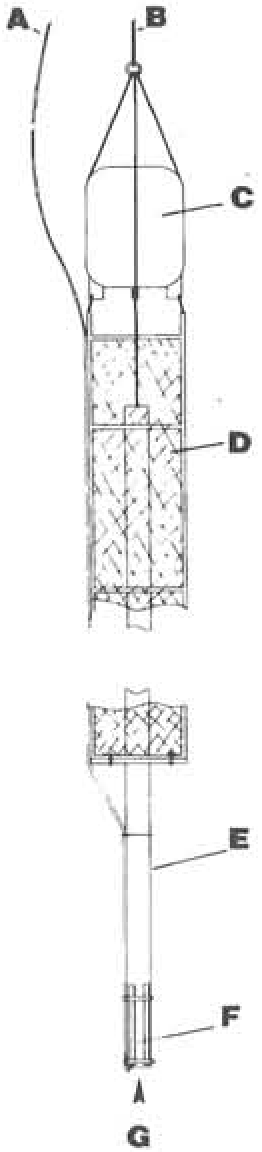

Fig. 1. The SPERESAT-sampler - A. Supply-hose for compressed air. - B. Lowering and lifting wire. - C. Air tank for vertical support. - D. Wire netting. - E. PVC pipe 6 m in length. - F. Air injector inside the pipe. - G. Water and sediment inlet. For further details see text. From Söderberg (1993).

MATERIAL AND METHODS

The prototype sampler consists of a 6 m long PVC pipe with a wire-netting case in its upper part (Fig. 1). Compressed air is injected through the pipe and a connecting hose from compressors onboard the surface ship. The expanding air will pull water and bottom sediments through the pipe into the netting case. The netting case will in its turn allow for clay and mud to pass through, but will catch rock specimens. A minimum size of rock specimens is determined by the meshes in the netting case. After retrieval the rock specimens are extracted for closer examination and laboratory analyses. The SPERESAT technique has been found to work well even at water depth of at least 90 m (Appendix). Further modifications are needed to increase the versatility of the sampler.

The investigated area comprises the southern and western parts of the Åland Sea (Fig. 4). During field work with R/V Strombus in 1988 and 1990, a total of 34 stations were sampled. These were chosen with regard to the general direction of the glacial ice movement which was roughly north-south. Four sampling stations yielded no erratics, viz. nr. 2, 3, 20, and 27 (Appendix), due to the presence of a too thick clay cover. Ferro-manganese nodules were abundant in the clay at these stations.

The lithologies encountered are the same as those met with in the Stockholm Archipelago to the south of the Åland Sea. Hence, for a description of the lithologies the reader is referred to Hagenfeldt & Söderberg (1985) and Hagenfeldt (1993). A tentative stratigraphic column is presented in Fig. 3.

The frequencies of the obtained erratics were calculated from the total number of rock specimens at every sampling station (Appendix). The material totals 1,631 rock specimens. Sampling sites with 30 or more erratics were treated statistically. These sampling stations, i.e. 13 out of 34, are marked by an asterisk in Appendix I. Sites with fewer erratics are considered only to demonstrate whether or not discrete lithologies are present. Comparison is made with current on-shore investigations (Hagenfeldt 1993) in an attemt to suggest *in situ* occurrences from the general trend in the obtained material (see Figs. 6 - 12).

GENERAL GEOLOGY

The Åland Sea is located in a Proterozoic basin which is filled by sedimentary bedrock spanning from the Middle Riphean to Early Palaeozoic (Flodén 1973; Söderberg 1982; Flodén & Söderberg 1984; Hagenfeldt & Söderberg 1985; Hagenfeldt 1993; Söderberg 1993). The lithologic sequence, as indicated by erratics, consists mainly of sandstone, shale, and limestone (Hagenfeldt & Söderberg 1985; Hagenfeldt 1993).

Sedimentary bedrock. The basal part of the stratigraphic column in the Åland Sea has been assigned to the Upper Proterozoic informal Söderarm formation (Hagenfeldt 1993; Fig. 3). This formation is further subdivided into two units, of which unit 1 comprises Middle Riphean (Jotnian) sandstone, and unit 2 Upper Riphean to Vendian sandstone and shale. Unit 3 consists of Lower Cambrian, comprising siltstone and sandstone, and Ordovician limestones. The Lower Ordovician is represented by Orthoceratite limestone, comprising the Latorp to Kunda Stages (Hagenfeldt 1993). The composition of the Middle Ordovician is uncertain, but the Segerstad and probably the Dalby Limestones is present (Hagenfeldt 1993). The Upper Ordovician consists of the Baltic limestone, comprising the Rakvere to Pirgu Stages (Hagenfeldt 1993).

Seismic investigations in the Åland Sea performed by Söderberg (1993) indicate the thickness of the sedimentary rock sequence to be approximately 1600 m. The sedimentary sequence is affected by tectonic displacements and to some extent traversed by several dolerite intrusions (Söderberg 1993).

Quaternary beds. In general terms the entire sea floor of the Åland Sea consists of clays. Both glacial and postglacial clays cover the underlying tills and bedrock (Söderberg 1982; 1993). Over large areas the cover is up to several tens of metres thick. The maximum thickness of the clay is found in the bathymetrically deepest parts of the basin where it reaches approximately 130 m (Söderberg 1993). On the shoal along the Swedish coast the clays are thinner. In the sampled area the clay measures only a few metres. In minor areas the clay is absent or almost absent and the underlying till is exposed (Fig. 5).

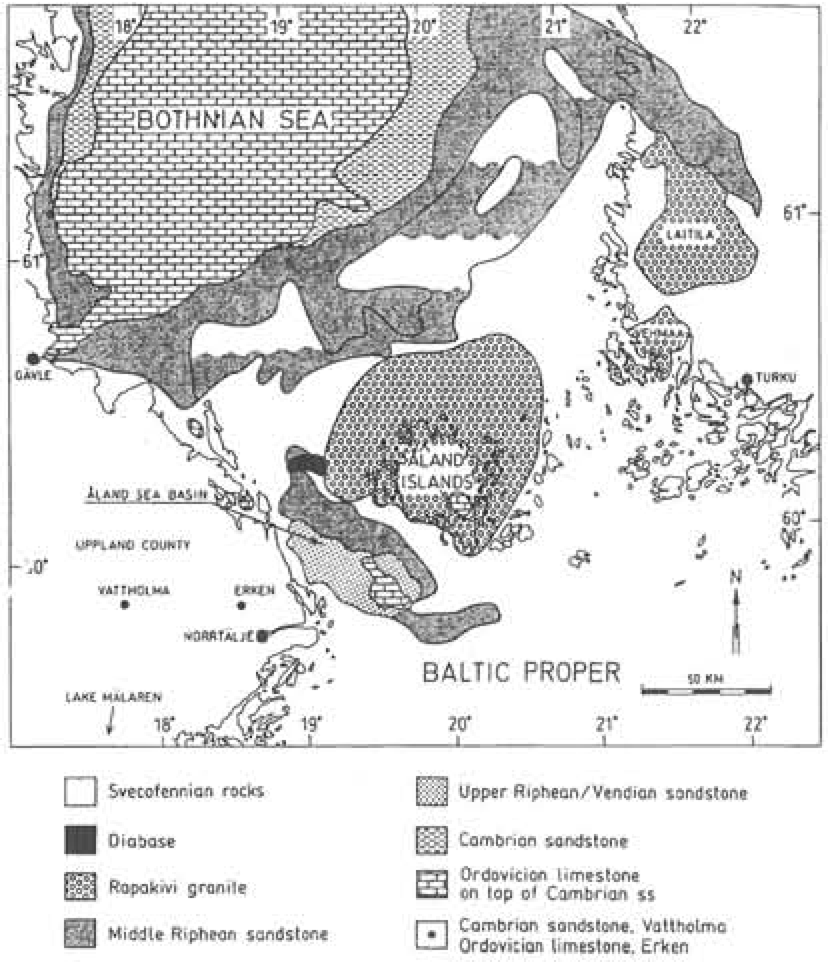

Fig. 2. The distribution of sedimentary bedrock on the sea floor of the Åland Sea. After Söderberg (1993).

Bathymetry. The bathymetry of the Åland Sea Basin is dominated by the deep trench just west off the Åland Islands (Söderberg 1993; Fig. 6). Here water depths extend down to 280 m. The western part of the Åland Sea Basin forms a shallow area. Off shore along the Swedish coast the boundary between the crystalline basement and the sedimentary sequence forms a shelf structure which is deepened by stepwise greater water depth.

RESULTS OF THE FIELD TESTS

Sedimentary bedrock. Sandstone erratics from unit 1 of the Söderarm formation (Fig. 3), are scattered in the material (Fig. 7). The frequency varies between 0 and 32 % (Appendix). These sandstone erratics seem to be abundant off the coast of Väddö and north of the Söderarm Archipelago. To the east of the Söderarm Archipelago the frequency diminishes.

The sandstone erratics from unit 2 of the Söderarm formation are the most widespread and abundant among the investigated samples (Fig. 8). Frequencies between 3 and 52 % are noted (Appendix). The most abundant frequencies were found at sampling stations north of the Söderarm Archipelago. The frequency diminishes to the east, as is also the case for unit 1.

The shale erratics from unit 2 of the Söderarm formation occur at only two sampling stations (Fig. 9). The frequency at those stations is only about 1 % (Appendix).

The Lower Cambrian siltstone and sandstone erratics of the lower part of unit 3 are evenly distributed between the sampling stations (Fig. 10). The frequency is moderate, ranging between 0 and 6 %.

The reddish limestone erratics of the Orthoceratite limestone show scattered occurrences (Fig. 11) with a frequency from 0 to 2 % (Appendix). No clear trend is obvious from the material obtained, but the frequency seems to diminishes to the east.

The erratics of greyish limestone from the Middle Ordovician also occur as scattered occurrences (Fig. 12). The frequency varies between 0 and 3 % (Appendix). The present material does not permit any evaluation of trends regarding the Orthoceratite limestone. However, the greyish limestones seem to be absent in the east.

The top of the sedimentary sequence is represented by erratics of the Baltic limestone. Contrary to the reddish Orthoceratite and the greyish Middle Ordovician limestone, erratics of the Baltic limestone seem to increase in frequency to the east. Also, erratics of the Baltic limestone are present as scattered occurrences throughout the

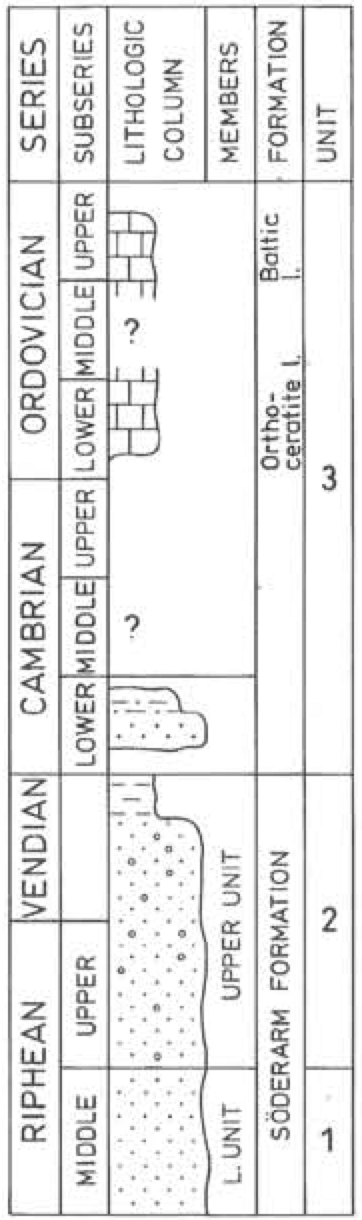

Fig. 3. Tentative stratigraphic column of the sedimentary bedrock sequence in the Åland Sea, as well as in parts of the Stockholm archipelago. Question marks show uncertainties in the reconstructed sequence. Modified after Hagenfeldt (1993).

material (Fig. 13). The frequency ranges between 0 and 8 % (Appendix), with the highest frequences to the east.

DISCUSSION

SPERESAT allows sampling of rock specimens underneath clayey beds of several metres in thickness. This is an improvement over the grab sampling technique, which only permits sampling approximately one metre below the sea floor. Erratics present in postglacial and glacial clay, though not abundant, may contribute to the samples of erratics at the sites. However, the bulk of the material obtained by the SPERESAT technique is here considered to be sampled in moraine beds.

Comparison with on-shore investigations. The maximum frequencies of sandstone erratics from unit 1 of the Söderarm formation are concentrated to the north of the Söderarm Archipelago, as well as off shore the coast of Väddö (Fig. 7). Comparing with the Stockholm Archipelago area and southern Väddö, the frequency diminishes to the south and east. On shore, Uppland unit 1 is absent in our material, though reported by Frödin (1956). The possible exposed *in situ* occurrence of Unit 1, as shown by on-shore investigations in the archipelago area (Hagenfeldt & Söderberg 1985, Hagenfeldt 1993), seems to be at the very border of the Åland Sea Basin and, possibly in its central part.

Erratics from unit 2 of the Söderarm formation are found only in the Åland Sea and the Stockholm Archipelago area (Fig. 8). They are absent in surrounding areas, such as on shore Uppland and the Åland Islands. However, unit 2 is supposed to be present as far as the northern part of the Åland Sea. Investigations with grab sampler made by Veltheim (1962) yielded sandstone erratics, similar to those from unit 2, corroborating the above assumption. Maximum frequencies of erratics from unit 2 are noted north of the Söderarm Archipelago area. The *in situ* occurrence of unit 2 is believed to be located in the Åland Sea. Within that area unit 2 is probably more extensively exposed underneath the sea floor, than is unit 1.

At the present sub-bottom sampling stations, scattered shale erratics from unit 2 of the Söderarm formation give another pattern than on-shore occurrences in the Stockholm Archipelago area (Hagenfeldt & Söderberg 1985, Hagenfeldt 1993). The shale erratics tend to have a narrower distribution in the Stockholm Archipelago (Fig. 9). Maximum frequencies are found near the fault zone between the archipelago and the Åland Sea Basin. In addition, shale erratics have only been found in the northern parts of the Åland Islands (Hagenfeldt 1993). These data suggest that *in situ* occurrences of the shale are resticted to parts of the Åland Sea basin, and possibly also to parts of the Bothnian Sea.

Siltstone and sandstone erratics from the Lower Cambrian part of unit 3 are widely distributed in the sub-bottom samples and on shore in the Stockholm Archipelago area (Fig. 10). On the Uppland mainland and on the Åland Islands, scattered occurrences of Lower Cambrian sandstones are documented (Wiman 1903, 1918, Hagenfeldt & Söderberg 1985, 1993; Hausen 1964; Hagenfeldt 1993). The frequencies are moderate all over the investigated area, generally not exceeding 5 %. *In situ* occurrence of the Lower Cambrian siltstone and sandstone is indicated in the Åland Sea, if the indications from the erratics can be trusted.

Ordovician limestone erratics (unit 3) clearly corroborates the results of on-shore investigations (Hagenfeldt & Söderberg 1985, Hagenfeldt 1993). The Lower Ordovician Orthoceratite limestone (Fig. 11), as well as the Middle Ordovician limestone type (Fig. 12), occur scattered mainly in the western part of the Åland Sea. The eastern part is dominated by the Upper Ordovician Baltic limestone (Fig. 13). In combination with seismic investigations by Söderberg (1982: fig. 26; 1993) and on-shore investigations by Hagenfeldt (1993), this distribution pattern suggests the presence of limestone in sheltered positions in parts of the Åland Sea. The almost complete absence of limestone erratics just north of the Söderarm skerries is remarkable, because abundant finds of limestone erratics have been noted in the archipelago (Hagenfeldt 1993). The explanation of this pattern could be the presence of *in situ* occurrences very near, or inside the mentioned archipelago area.

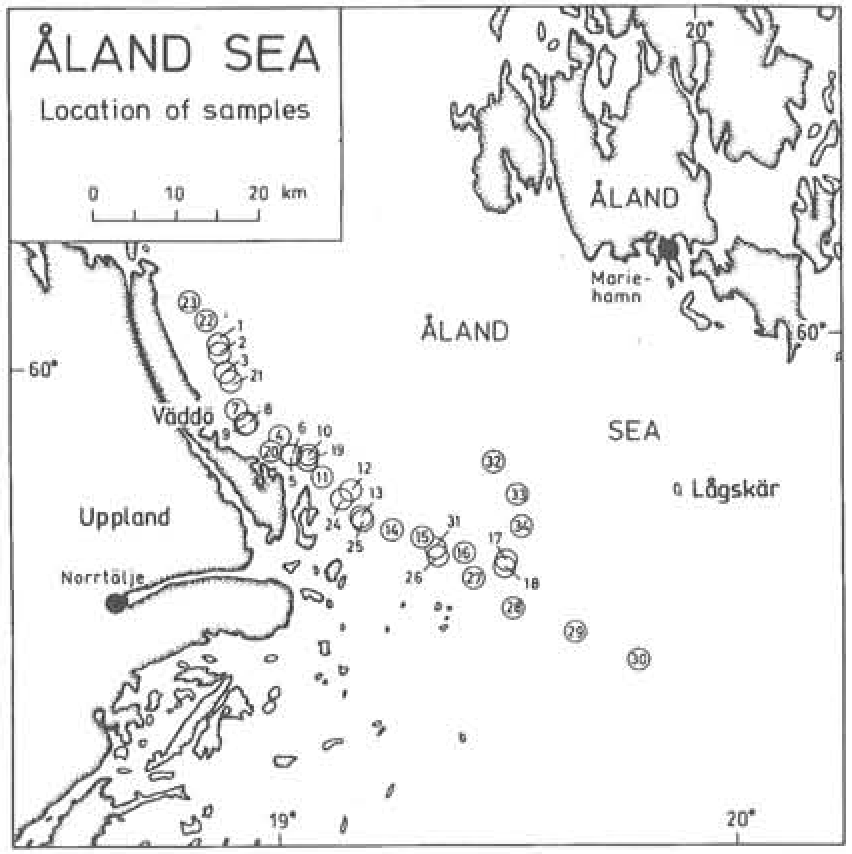

Fig. 4. Location of sampling stations in the Åland Sea Basin. The numbers of the sites correspond to those given in Appendix I.

Comparison with offshore investigations. The present sampling by SPERESAT and the on-shore observations indicates the presence of the seismic units suggested by Söderberg (1993). The seismically indicated distribution of unit 1 and 2 (Fig. 2) makes up the main part of the Åland Sea Basin. The distribution pattern of the erratics reflects this circumstance well. Both the on-shore and the off-shore finds of unit 1 and 2 show an even distribution over the area. This is what can be expected close to an *in situ* occurrence.

The distribution pattern of erratics of unit 3 is more unclear and questionable. The general distribution pattern of unit 3 shows a slight tendency for enhanced values towards the east. This is specially true for the frequency of the Upper Ordovician Baltic limestone erratics in the outermost Stockholm Archipelago area. To the north of this area seismic signatures and velocities indicate the *in situ* presence of the Baltic limestone in the main Åland Sea Basin (Fig. 2; Söderberg 1993).

The enhanced frequency of Lower Ordovician Ortoceratite limestone in the southern part of the Väddö island may originate from the small outcrop situated towards the north, as indicated by Söderberg (1993).

The even onshore distribution of of Lower Cambrian erratics in the area is also confirmed by sampling with SPERESAT. This may depend on small Cambrian outcrops, which were not possible for Söderberg (1993) to interpret from the seismic profiles. These outcrops are thought to be exposed around the margins of the covering Ordovician strata in the central part of the Åland Sea Basin. It may also depend on small occurrences at several localities spread in the Åland Sea Basin.

RESULTS

(1) In sampling clayey bottom sediments for erratics it is necessary to reach down through the clay to reach the interesting till with boulders. It is obvious that SPERESAT with its relative deeper penetration is better than conventional grab-samplers. The latter only penetrate the uppermost metre or so.

(2) Sandstone erratics from unit 1 of the Söderarm formation (Middle Riphean/Jotnian) seem to occur mainly in connection with the fault zone between the Stockholm Archipelago area and the Åland Sea basin. It is believed that unit 1 is exposed in this area. However it could not be ruled out that unit 1 is also exposed in the central parts of the Åland Sea basin.

(3) Erratics from unit 2 of the Söderarm formation (Upper Riphean/Vendian) are frequent in connection with the fault zone separating the Stockholm Archipelago area from the Åland Sea basin. Based on the distribution of the erratics, unit 2 is thought to crop out in the central part of the Åland Sea Basin as well as along the fault zone.

(4) Shale erratics from unit 2 of the Söderarm formation (Upper Riphean/Vendian) are scattered. The shale is thought to be locally exposed near the fault zone between the Åland Sea and the mentioned archipelago

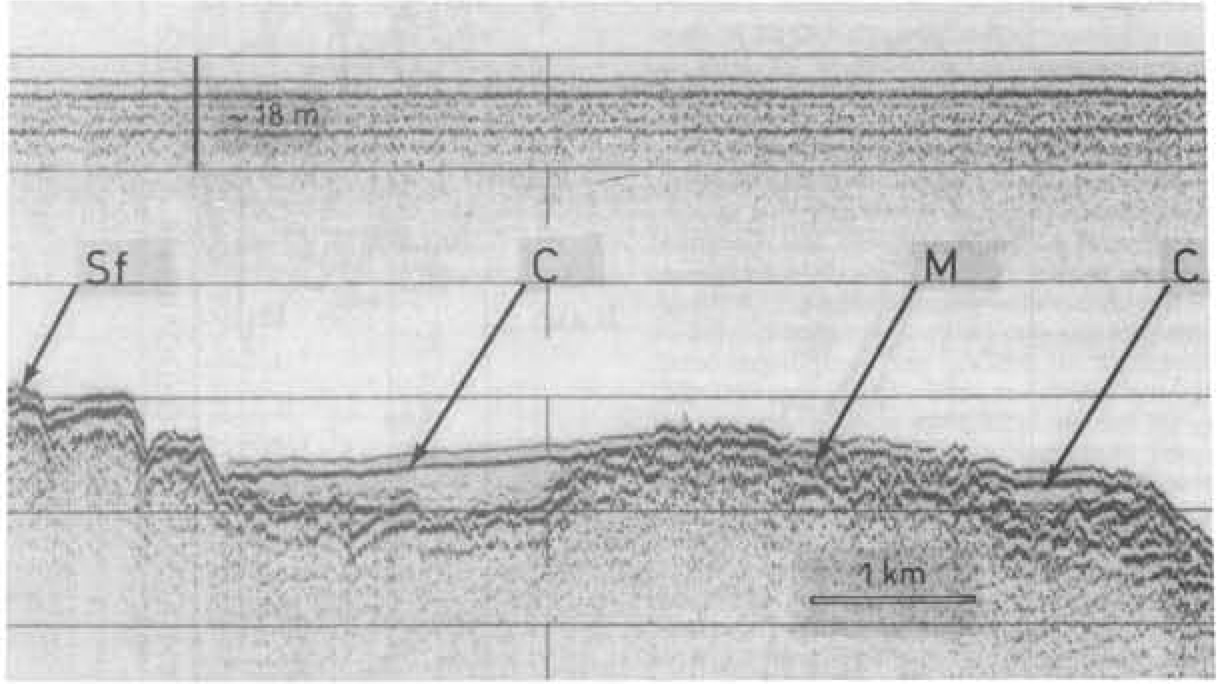

Fig. 5. High resolution seismic profile of the Quaternary beds on the sea-floor in the Åland Sea. A typical SPERESAT sampling site. Abbreviations as follows: Sf - seafloor, C - clay, M - moraine. After Söderberg (1993).

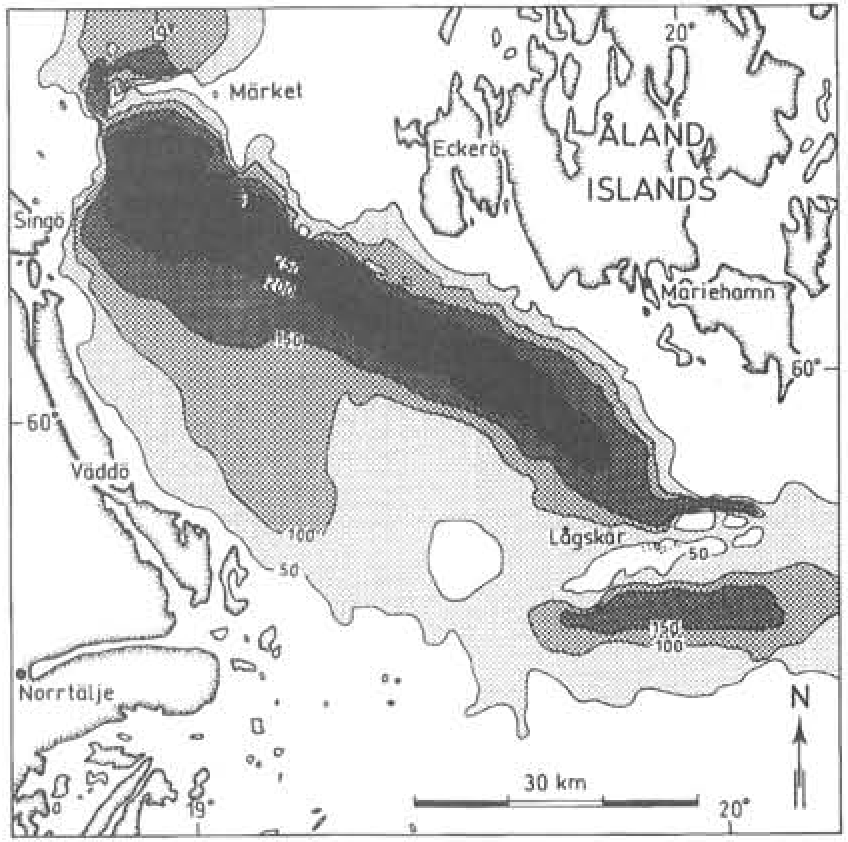

Fig. 6. Bathymetric map of the Åland Sea. After Söderberg (1993).

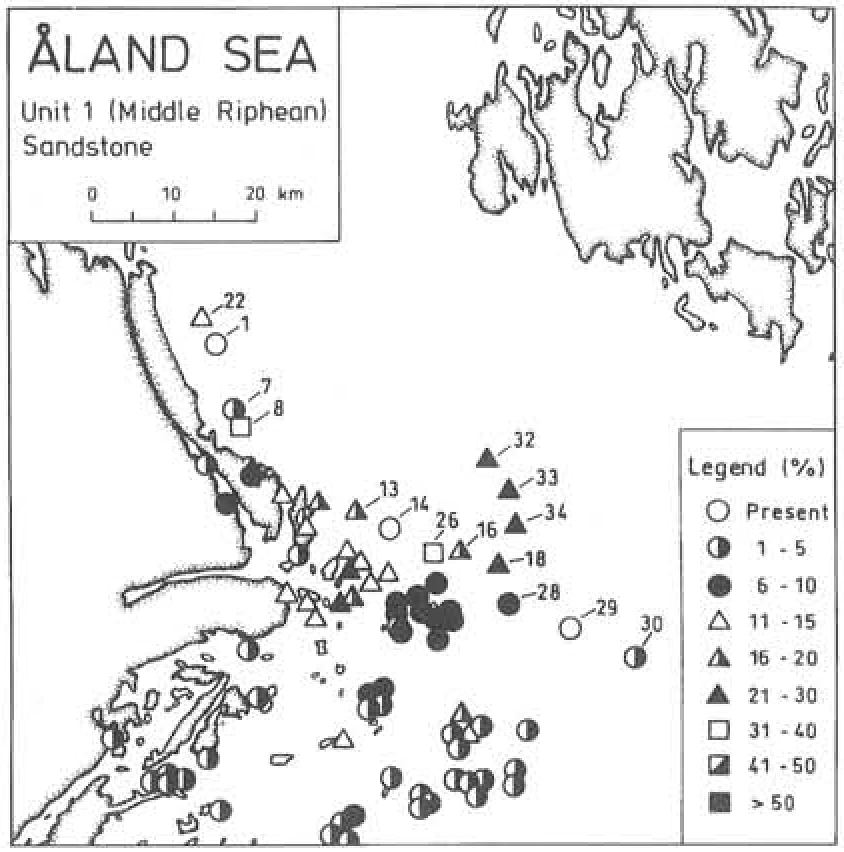

Fig. 7. Frequencies of sandstone erratics from unit 1 of the Söderarm formation, attributed to the Middle Riphean (Jotnian). The numbers of the SPERESAT-sites correspond to those given in the Appendix.

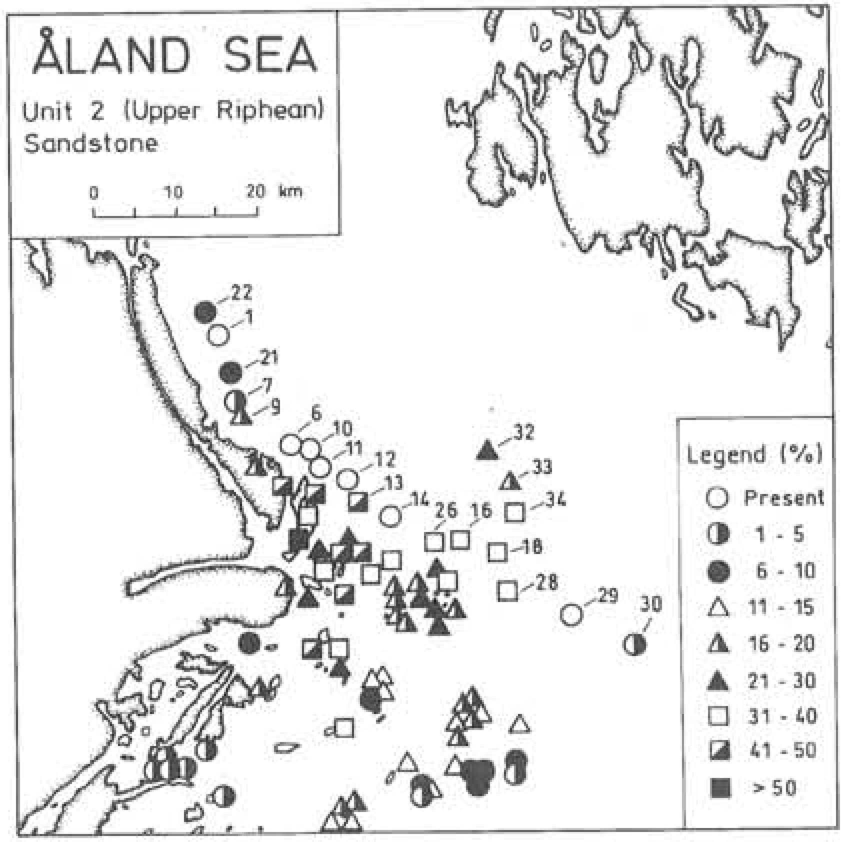

Fig. 8. Frequencies of sandstone erratics from unit 2 of the Söderarm formation (Upper Riphean/Vendian).

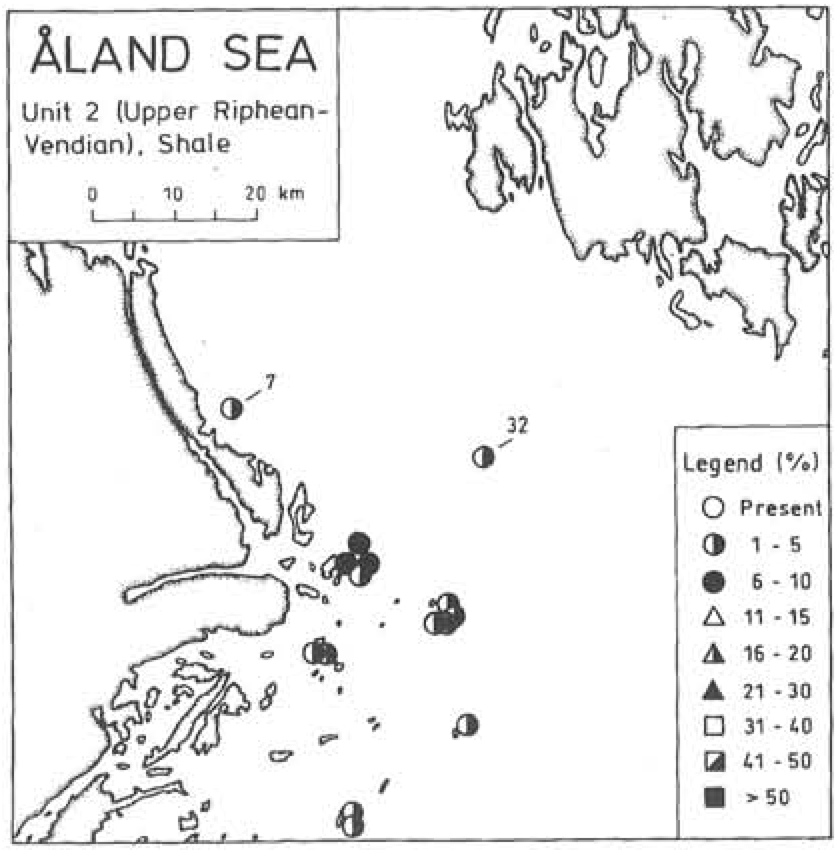

Fig. 9. Frequencies of shale erratics from unit 2 of the Söderarm formation (Upper Riphean/Vendian).

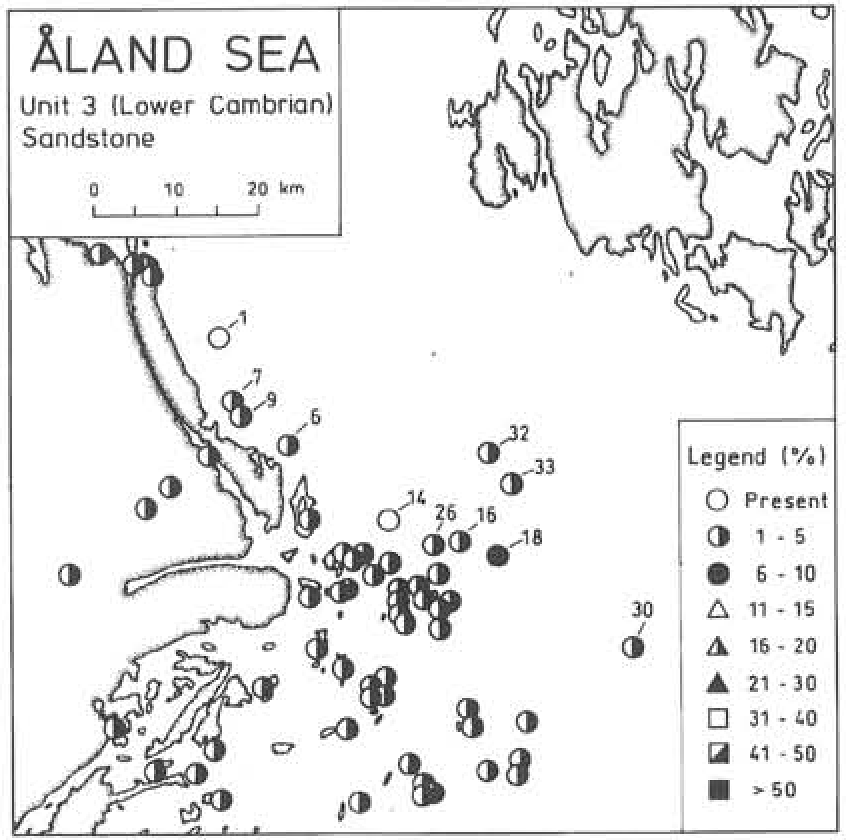

Fig. 10. Frequencies of siltstone and sandstones from the Lower Cambrian part of unit 3.

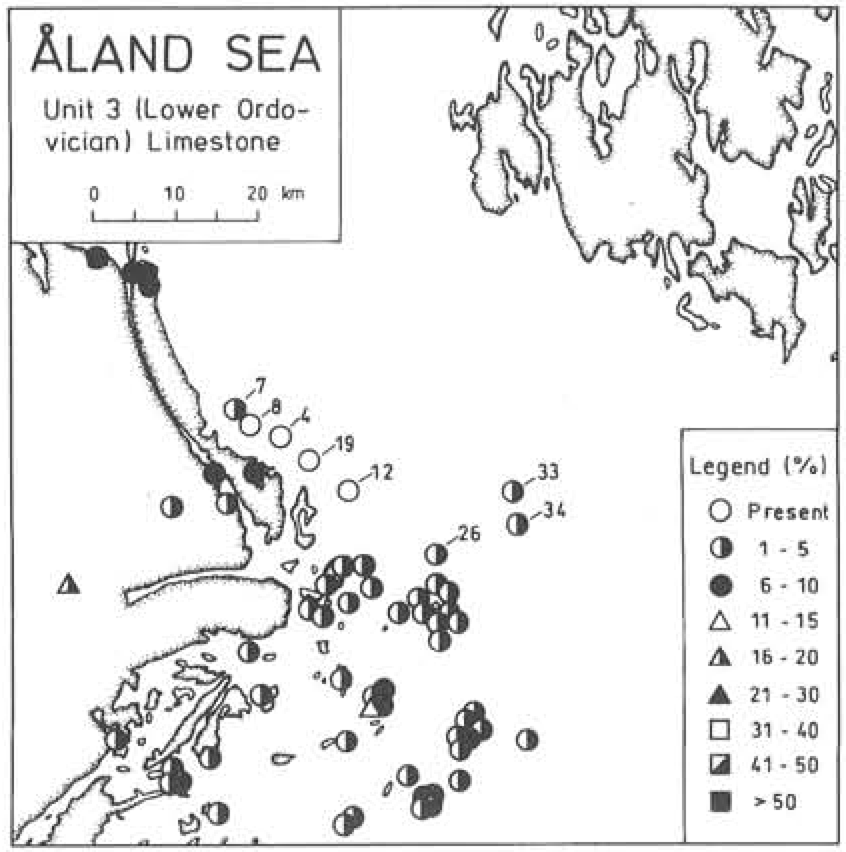

Fig. 11. Frequencies of reddish limestone erratics of the Lower Ordovician Orthoceratite limestone of unit 3.

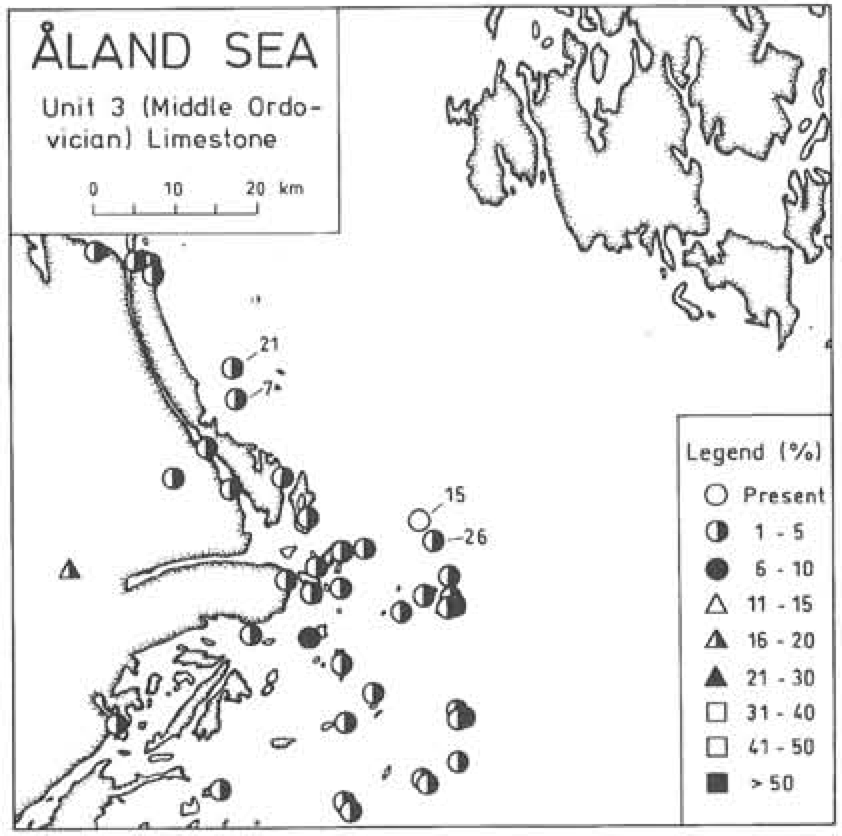

Fig. 12. Frequencies of Middle Ordovician greyish limestone erratics of unit 3.

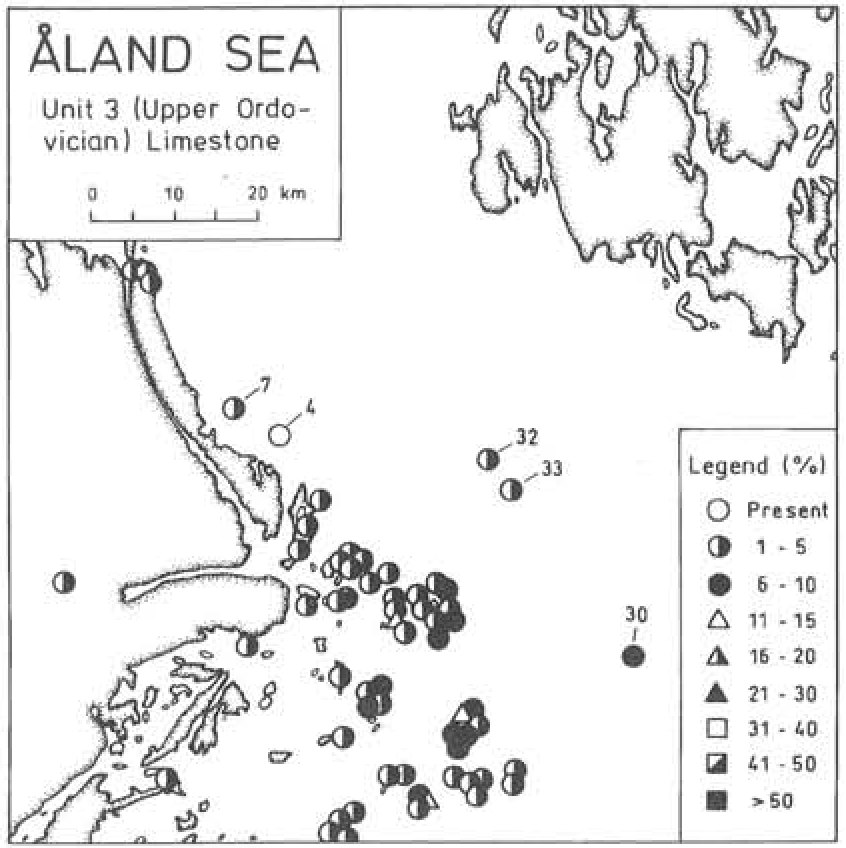

Fig. 13. Frequencies of whitish limestone erratics from the Upper Ordovician Baltic limestone of unit 3.

area. However, the shale is also thought to crop out in positions more to the north, such as in the Bothnian Sea.

(5) Erratics from the Lower Cambrian of unit 3 are evenly distributed all over the investigated sea bottom in the Åland Sea. This pattern is similar to the distribution in the Stockholm Archipelago. However, increased frequencies on shore at the coast of Björkö indicate the off-shore outcrops of Lower Cambrian in the area.

(6) The distribution of Ordovician limestone erratics of unit 3 is similar to the on-shore pattern, obtained in the Stockholm Archipelago. Hence, in the eastern part of the Åland Sea the bulk of the erratics is made up of the Upper Ordovician Baltic limestone, while Lower and Middle Ordovician types dominate in the west. In the central part a drastic decrease of limestone erratics is noticed north of the Söderarn Archipelago.

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APPENDIX Frequencies of erratic specimens collected with the aid of SPERESAT.

Column **1**: geographic position with coordinates presented in the Swedish Gauss Coordinate System (Rikets Nät, 2,5 degrees W, 1938), **2**: % of crystalline bedrock, **3**: % of sandstones from unit 1 of the Söderarm formation, **4**: % of sandstones and conglomerates from unit 2 of the Söderarm formation, **5**: % of shales from unit 2 of the Söderarm formation, **6**: % of siltstone and sandstone from the Lower Cambrian of unit 3, **7**: % of reddish limestones from the Orthoceratite limestone (Lower Ordovician) of unit 3, **8**: % of greyish limestones from the Middle Ordovician of unit 3, probably comprising the Segerstad to Dalby limestones, **9**: % of whitish limestone from the Baltic limestone (Upper Ordovician) of unit 3, **10**: total number of counted rock specimens. **11**. The water depth at the sampling stations.

The sampling stations that yielded enough specimens to be statistically treated are marked by an asterix (*).

SPERESAT - 1988

	1	2	3	4	5	6	7	8	9	10	11
1.	1671150 6665200	49	13	34	0	4	0	0	0	23	83
2.	1673600 6662675	0	0	0	0	0	0	0	0	0	89
3.	1674550 6660800	0	0	0	0	0	0	0	0	0	80
4.	1675075 6659475	64	9	0	0	0	18	0	9	11	96
5.	1675375 6657700	57	0	43	0	0	0	0	0	7	44
6.	1675600 6655425	0	0	100	0	0	0	0	0	3	47
7.*	1676250 6653325	88	1	3	1	1	2	3	1	361	34
8.	1678075 6651350	66	0	0	0	0	33	0	0	3	65
9.*	1678075 6650975	46	32	20	0	2	0	0	0	41	44
10.	1679950 6650250	83	0	17	0	0	0	0	0	12	58
11.	1681800 6650225	75	0	25	0	0	0	0	0	8	66
12.	1683775 6649000	33	0	33	0	0	33	0	0	3	82
13.*	1683600 6648025	27	16	52	0	5	0	0	0	231	25
14.	1683000 6647925	33	24	29	0	14	0	0	0	21	58
15.	1685375 6647400	50	0	0	0	0	0	50	0	2	54
16.*	1687075 6644600	41	19	39	0	1	0	0	0	128	43
17.	1688300 6643100	100	0	0	0	0	0	0	0	4	60
18.*	1690275 6643325	32	22	40	0	6	0	0	0	89	38

SPERESAT - 1990

	1	2	3	4	5	6	7	8	9	10	11
19.	1692125 6641675	67	0	20	0	0	13	0	0	15	73
20.	1691700 6640700	0	0	0	0	0	0	0	0	0	50
21.*	1691675 6639875	90	0	7	0	0	0	3	0	30	74
22.*	1692025 6639075	80	11	9	0	0	0	0	0	35	70
23.	1695425 6638325	100	0	0	0	0	0	0	0	14	49
24.	1699300 6636975	0	0	0	0	0	0	0	0	0	84
25.	1701100 6634850	40	50	10	0	0	0	0	0	10	25
26.*	1703925 6635350	32	32	32	0	2	1	1	0	203	12
27.	1706075 6632875	0	0	0	0	0	0	0	0	0	45
28.*	1709975 6629750	58	7	35	0	0	0	0	0	31	70
29.	1717250 6626000	62	10	28	0	0	0	0	0	21	38
30.*	1725300 6622850	81	5	3	0	3	0	0	8	63	15
31.	1709850 6638500	0	0	0	0	0	0	0	0	0	63
32.*	1710725 6642350	42	24	25	1	4	0	0	4	79	44
33.*	1708075 6646300	56	21	17	0	2	2	0	2	42	39
34.*	1705725 6648325	42	23	34	0	0	1	0	0	141	40

Polen Complexes of Late- and Post- Glacial Sediments in the Gulf of Riga

Vilnis Stelle, Irina Yakubovska and Alexander Savvaitov

16 pollen complexes are determined and characterized for Late Glacial and Post Glacial sediments in the Gulf of Riga on the basis of palynological investigations of more than twenty sections. The pollen complexes are compared with pollen zones: Al_1, Al_2, Al_3, Dr_3, Pb_1, Pb_2, Bo_1, Bo_2, At_1, At_2, At_3, Sb_1, Sb_2, Sa_1, Sa_2, Sa_3.

Stelle, V., Yakubovska, I., & Savvaitov, A. 1994. Pollen complexes of Late- and Post-Glacial sediments in the Gulf of Riga. *Baltica, Vol. 8*, pp. 38-42. Vilnius. ISBN 9986-615-01-1

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INTRODUCTION

The palynological investigations of bottom sediments in the Gulf of Riga began in the 1950s. (Stelle et al. 1976). Investigations became systematic in the 1970s. The biostratigraphical investigations near the West Estonian Archipelago appear at this time as well (Kessel & Pork 1976).

The Quaternary deposits in the Gulf of Riga are spread usually in all the places. The brown and greyish-brown moraine of Last (Weichselian) Glaciation lies on the surface of Devonian rocks as a rule. The Eemian Interglacial deposits are also known (Kalnina 1993). The brown and greyish-brown varved clay of the Baltic Glacial Lake lies above the Weichselian moraine. These sediments are covered by greyish-brown, brown rarely thin bedded clay of the Yoldia Sea and of the Ancylus Lake. The greenish-grey, grey, black mud, aleurite and sand of the Litorina Sea and the Postlitorina Sea form the upper part of the geological section of the Quaternary deposits.

More than 20 geological sections, which were investigated with the pollen method, are known in the Gulf of Riga at present (Fig. 1).

The palynological analytical materials reflect the changes of vegetation, which have occurred during the Late- and Post-Glacial time within surrounding land (Danilans & Stelle 1971). Parts of spores and pollen have been transported by sea currents from the coastal regions of the South Baltic. Moreover, spores-pollen spectra have the natural feature of formation connected with hydrodynamic processes in the large water basin.

DESCRIPTION OF POLLEN COMPLEXES

The following spores-pollen complexes, changing one by one, are observed in the common cross-section of the Late- and the Post-Glacial sediments:

I pollen complex. Characterized by a high content of tree pollen, among which *Pinus* takes first place. *Betula, Betula nana* and in small quantities *Alnus* are present among the pollen of trees from other components. The pollen of *Artemisia* and *Chenopodium* dominate among the pollen of herbs. Spores are observed in small quantities. There are *Sphagnales, Bryales* and *Polypodium*. This pollen complex belongs to the pollen zone Al_1 and has the age of the Early Allerød time.

II pollen complex. It differs with some higher quantity of the pollen of herbs from the previous complex, but the quantity of tree pollen in the total composition predominates. The amounts of pollen of *Betula* and *Betula nana* in the composition of complex are increased. *Sphagnales, Bryales, Polypodium* occur among the spores. The periglacial flora - *Dryas, Hippophae, Ephedra, Selaginella selaginoides*, is presented. The pollen complex belongs to the pollen zone Al_2 and has the age of the Middle Allerød.

III pollen complex. The quantity of tree pollen in composition of this complex, in contrast to previous complex, has increased to the account of pollen of *Pinus* and *Betula nana*. The amount of pollen of herbs has decreased. Pollen and spores of periglacial flora - *Dryas. Selaginella selaginoides* still occur in the composition of the complex. This pollen complex corresponds to the pollen zone AL_3 and has the age of the Late Allerød.

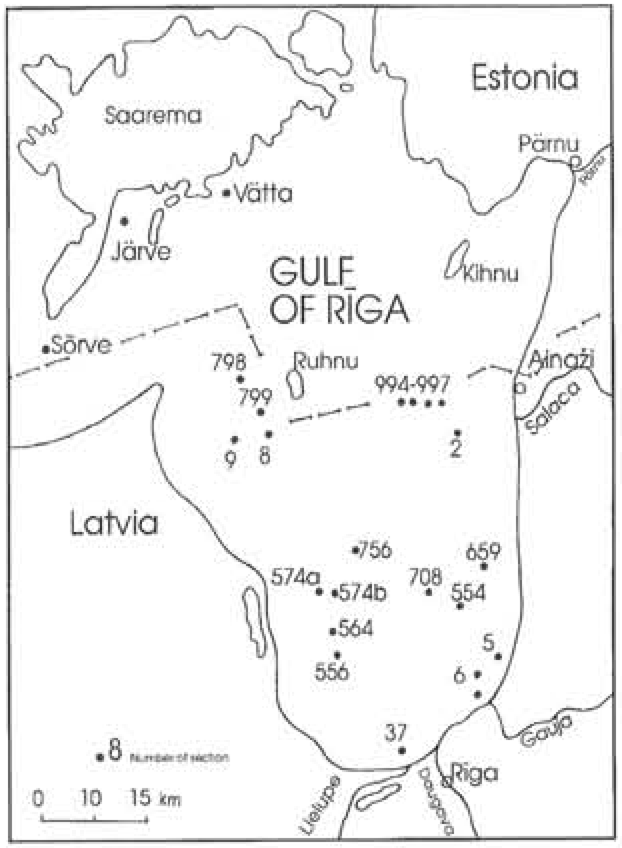


Fig. 1. A scheme showing location of palynologically investigated sections

IV pollen complex. Main feature of the complex is the increase in her pollen, especially the pollen of *Artemisia*. The pollen of *Pinus* is prevailed over by the quantity of pollen of *Betula* by a small amount. The pollen of *Betula nana* occur in high quantities. The pollen of *Picea, Alnus, Salix* occur in minimal quantities. The content of spores and the pollen of periglacial flora - *Ephedra, Hippophae, Lycopodium, Dryas, Selaginella selaginoides* is higher. *Bryales* and *Sphagnales* are most often among the spores. This pollen complex belongs to the pollen zone Dr_3 and has the age of the Younger Dryas time.

V pollen complex. The pollen of herbs decreased in a total composition of this complex. The pollen of tree increased to the account of the pollen of *Pinus*. The pollen of *Betula* and *Betula nana* occur in small quantities. The pollen of *Alnus* is present always. The pollen of *Picea, Quercetum mixtum (Ulmus, Tilia)* and *Corylus* are observed sporadically. The quantity of *Artemisia* and *Chenopodium* has decreased among the spores, however these components can dominate in the composition of herbs. The amount of *Polypodium* has increased among the spores. The periglacial flora - *Dryas, Ephedra, Hippophae* is present. This pollen complex compares with pollen zone Pb_1 and has the age of the Early Preboreal.

VI pollen complex. The quantities of the *Betula* and *Betula nana* pollen have increased. The pollen of *Pinus* dominates in the spectrum of this complex. The pollen of *Alnus, Corylus, Salix* are also present. The pollen of *Picea* and *Quercetum mixtum* occur in minimal quantities. The herbs of *Artemisia, Chenopodium, Poacea, Cyperacea* increase in the pollen complex. *Polypodium, Bryales* and *Sphagnales* are present among the spores. The spores and the pollen of periglacial plants - *Ephedra, Hippophae, Dryas, Selaginella selaginoides* are observed. The pollen complex belongs to the pollen zone Pb_2 and has the age of the Late Preboreal.

The pollen complex is subdivided into two subcomplexes. Lower subcomplex is characterized by maximum content of the pollen of *Betula* and upper subcomplex is characterized by a maximum content of the pollen of *Pinus*.

VII pollen complex. This is characterized by an absolute predominance of the pollen of *Pinus* over *Betula*. The pollen of *Alnus, Picea, Corylus* and *Quercetum mixtum* are marked among the tree pollen. The pollen of herbs occur in small amounts. There are *Cyperacea, Poacea, Varya* and *Artemisia*. The spores present mainly are *Bryales* and *Polypodium*. This pollen complex belongs to the pollen zone BO_1 and has the age of the Early Boreal time.

VIII pollen complex. The content of the pollen of *Pinus* is lower. The pollen of *Alnus, Betula, Picea, Quercetum mixtum (Ulmus, Tilia, Quercus)* and *Corylus* occur in larger amounts than in the complex. Here is only a slight presence of her pollen. The spores *Polypodium* prevail in the composition of spores. The pollen complex corresponds to the pollen zone Bo_2 and has the age of the Late Boreal.

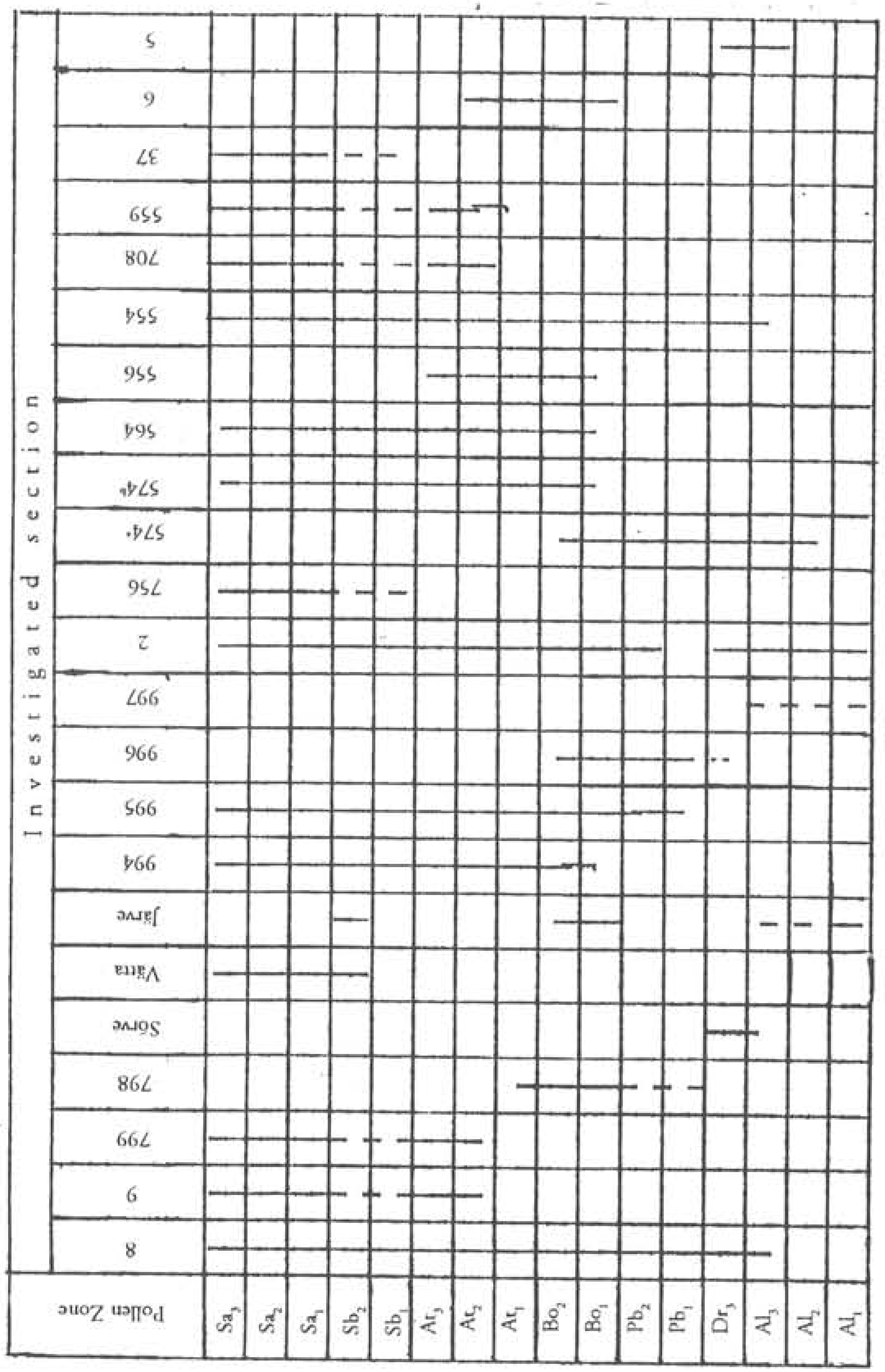
IX pollen complex. This is characterized by a continual decrease in pollen of *Pinus*. The amount of *Betula* and *Alnus* is increasing. The content of the pollen of *Ulmus, Quercus, Tilia, Corylus* is also increasing. The pollen of *Carpinus* are present sporadically. The pollen complex correspond to the pollen zone At_1 and has the age of the Early Atlantic.

X pollen complex. The amount of the pollen of *Betula* and *Alnus* is slightly increased. The contents of the pollen of *Quercetum mixtum* are decreasing. The pollen of *Tilia* dominate among the pollen of *Quercetum mixtum*. The pollen of *Fagus* appear in the complex. The pollen complex is compared with the pollen zone At_2 and has the age of the Middle Atlantic.

XI pollen complex. The quantity of the pollen of *Quercetum* mixtum is increased mainly to the account of pollen of *Quercus* and *Ulmus*. The content of the pollen of *Pinus* and *Corylus* has also increased. The pollen of *Carpinus* and *Fagus* are observed in the composition of spectra. The pollen of *Picea* are present in smaller amounts than in the previous complex. The pollen complex belongs to the pollen zone At_3 and has the age of the Late Atlantic.

XII pollen complex. This differs by a decrease in quantities of the *Quercetum mixtum (Ulmus, Tilia)* and *Corylus* pollen. The amount of the pollen of *Picea, Pinus, Betula, Alnus* is greater. The pollen of *Carpinus* and *Fagus* are present. This pollen complex correlates with the pollen zone Sb_1 and has the age of the Early Subboreal.

Table 1. Correlation of pollen zones



Note: the broken lines are corresponding to the pollen zones, determination of which is difficult.

Table 2. **Palynostratigraphical scheme of the Late-Glacial and the Post-Glacial sediment in the Gulf of Riga**

Stage	Chronozone	Pollen Zone	Typical features of the spores-pollen composition			Stage of Baltic Sea	Sediments: Deep-water part	Sediments: Coastal slope and coastal zone
Post Glacial	Subatlantic	Sa$_3$	Maximum *Pinus*	Increased contents of the herb plants of *Poacea, Cyperacea, Artemisia*		Postlitorina Sea	Mud, clayey mud, black, grey	Aleurite, sand, grey, light grey
		Sa$_2$	*Betula, Alnus, Pinus, Picea*					
		Sa$_1$	*Pinus, Betula, Alnus, decrease of Quercetum mixtum*					
	Subboreal	Sb$_2$	*Pinus, Alnus, Betula, Quercetum mixtum,* sporadically *Carpinus, Fagus*	Beginning of the increase in herbs				
		Sb$_1$	*Pinus, Picea, Alnus, Betula, Quercus, Ulmus, Tilia, Carpinus, Fagus*					
Post Glacial	Atlantic	At$_3$	*Quercus, Ulmus, Tilia, Carpinus, Fagus, Corylus*			Litorina Sea	Mud, clayey mud, greenish-grey, grey	Aleurite, sand, light grey
		At$_2$	*Quercetum mixtum, Betula, Alnus, Carpinus,* sporadically *Fagus*					
		At$_1$	*Ulmus, Tilia, Quercus, Carpinus, Corylus, Alnus, Betula, Pinus*					
	Boreal	Bo$_2$	*Pinus, Betula, Alnus, Picea, Ulmus, Tilia, Quercus, Corylus*			Ancylus Lake	Clay, light brown, grey, brownish-grey	Aleurite, sand, light grey
		Bo$_1$	Maximum *Pinus*			Yoldia Sea	Clay, light brown, brown, brownish-grey, sometimes thin-bedded	Aleurite, sand, light grey
	Preboreal	Pb$_2$	Maximum *Betula, Betula nana*	Decrease in quantity of herbs. Presence of periglacial flora				
		Pb$_1$	*Pinus, Betula, Alnus*					
Late Glacial	Younger Dryas	Dr$_3$	*Pinus, Betula, Betula* shrub species, *Salix*	Maximum of herbs	Periglacial plants: *Ephedra, Hippophae rhamnoides, Dryas, Selaginella selaginoides, Lycopodium alpinum, L.apressum, L. pungens, Botrychium boreale*	Baltic Glacial Lake	Clay, light brown, greyish-brown, thin-bedded, sometimes non-bedded, in down part varve-bedded	Clay, aleurite, clayey aleurite, clayey sand, grey, light grey
	Allerød	Al$_3$	*Pinus, Betula, Betula nana*	Increased content of herbs				
		Al$_2$	*Betula, Betula nana, Pinus*					
		Al$_1$	*Pinus*					

XIII pollen complex. The pollen of *Pinus* is characterized by a slightly higher quantity than in the previous complex. The amounts of pollen of *Quercetum mixtum* have increased.The content of *Pinus* has also increased, but the amounts of pollen of *Alnus* and *Betula* have decreased. The pollen of *Carpinus* and *Fagus* are present constantly. This pollen complex belongs to pollen zone Sb$_2$ and has the age of the Late Subboreal.

XIV pollen complex. This complex differs because of an increase in pollen of conifers and *Quercetum mixtum*. The pollen of *Betula, Alnus* are present in smaller amounts than previously. The pollen of *Carpinus* and *Fagus* are observed sporadically. The role of herb pollen - *Poacea, Cyperacea, Artemisia, Varya* has increased. The pollen complex corresponds to the pollen zone Sa$_1$ and has the age of the Early Subatlantic time.

XV pollen complex. The quantities of *Betula* and *Alnus* pollen are increased, but *Pinus* has decreased. The pollen of *Quercetum mixtum* and *Carpinus* occur in small quantities. Separate grains of *Fagus* pollen are observed. This pollen complex belongs to the pollen zone Sa_2 and has the age of the Middle Subatlantic.

XVI pollen complex. This characterizes the upper part of the bottom sediments. The pollen complex differs by a maximum of *Pinus* pollen. The amount of herb pollen has increased. The pollen complex corresponds to the pollen zone Sa_3 and has the age of the Late Subatlantic.

CONCLUSIONS

The general correlation of pollen zones is illustrated in Table 1. The section of st. 8, 2, 554 is most important and at present has the basic overview of the palynostratigraphy of the bottom sediments in the Gulf of Riga. However, the separate pollen zones in vertical sections are not fully expressed always, and can even be absent sometimes. It is closely connected with the changing processes of the sedimentation in the basin. The conditions during sedimentation are reflected in the composition of spores and pollen of the Preboreal and mainly Subboreal sediments. The composition of the pollen zones of the Preboreal and Subboreal sediments are formed during transitional periods of the development of the Gulf of Riga - at the beginning of the development of the Yoldia Sea and during transition from the Litorina Sea to the Postlitorina Sea.

The described pollen complexes and their vertical succession have been used as a basis for the palynostratigraphical scheme of the Late-Glacial and the Post-Glacial sediments in the Gulf of Riga (Stelle at al. 1992). The scheme is illustrated in Table 2. The palynostratigraphical scheme reflects the period beginning from the Allerød time.

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Distribution of Metals in Bottom Sediments of the East Baltic Sea and the Kuršių Marios Lagoon

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Concentrations of Fe, Mn, Co, Zn, Cu, Cd, Hg, Pb, Cr and regularities of their distribution were investigated in the surface layer of bottom sediments (0-3 cm) and cores (up to 2.5 m deep) in the lower course of the Nemunas River, the Kuršių Marios Lagoon and East Baltic Sea. The obtained results revealed that the type of sediment mainly controls the distribution of Cu, Fe, Zn, Pb and Hg. Especially high values of correlation coefficients were observed between C_{org} and Cr, C_{org} and Zn, C_{org} and Cu.
In the area of the port of Klaipėda the natural background level of heavy metals in surface layer of bottom sediments is exceeded by 1.2 to 11.0 times. Maps are given of the distribution of Zn and Pb concentrations in the surface layer of bottom sediments of the East Baltic.

INTRODUCTION

Metals get into bottom sediments from natural sources and sources related to human economic and domestic activity (contamination). The commonly known transport ways are : throught the atmosphere, water and living organisms. Less investigated routes of metals into recent sediments are: ground water discharge and fluid flows related to sediment diagenesis.

Of crucial importance to quantitative and qualitative distribution of metals in bottom sediments are lithological and mineralogical composition of deposits, ways of input and geochemical processes taking place in the near-bottom water layer and the sediments.

As a result of the rapid development of industry, transport and rural economy the natural flux of metals in sediments was supplemented during the last decades with the anthropogenic pollution.

Concentrations of metals and their distribution in various types of bottom sediments in the East Baltic Sea are described in many publications (Brzezinska et al. 1984, Blashtchishin et al. 1982, Emelyanov 1976, Emelyanov 1987). There are data on metal contents and peculiarities of their accumulation in bottom sediments of the lower course of Nemunas River and Curonian Lagoon (Pustelnikov et al. 1983) and on the pollution load of recent sediments in the eastern part of the Baltic sea (Lukashin 1986).

It is helpful to know the rates of sedimentation in investigation areas. It was established by Kuptsov et al. (1984) that the mean rate of sedimentation in the approaches of Klaipėda port reaches 1.1 mm per year, in the Gdansk Basin - 0.6 mm, and in the Gotland Basin - 0.5 mm. Our investigations showed that in the aquatory of Klaipėda port the rates of sedimentation are considerably higher and range from several to some centimetres per year.

The knowledge of trace element distribution in bottom sediments of Nemunas River, Kuršių Marios Lagoon and East Baltic is considered insufficient because the previous investigations were not so detail, the different analysis schemes and instruments were used. In some study areas there was a lack of quantitative data on selective distribution of trace metals in sediments. Our investigations were aimed at determining trace metal distribution involving chemical fractionation of deep-sea, near-shore and estuarine sedimentation systems. More detail regard was made to heavily industrialized Klaipėda port area.

The aim of this paper was to investigate the content of metals in recent sediments of the lower course of Nemunas River, Kuršių Marios Lagoon and East Baltic Sea and to estimate the degree of their pollution with heavy metals.

METHODS AND MATERIAL

Bottom sediment samples for metal analysis were collected in 1983-1993. A total of 245 sediment samples were collected in the lower course of Nemunas River, the northern part of the Kuršių Marios Lagoon, the Klaipėda port and in the East Baltic Sea areas (Fig.1). Surficial bottom sediments were taken with a box grab, sediment cores obtained with gravity corer equipped with a inert liner (up to 2.5m in length and 6.0 cm in diameter). The collected samples were described, the lamination was examined, redox potential (Eh) and content of C_{org} determined, and grain size analysis made * .

The redox potential of the sediment was measured immediately after sampling with a platinum electrodes which were inserted in each sampling interval of core to a depth of 3 cm (for 2 hours). Samples were taken from the middle of the grab and sediment core in or

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* Grain size analysis of bottom sediments was done by S.Gulbinskas and C_{org} by R.Stakėnienė.

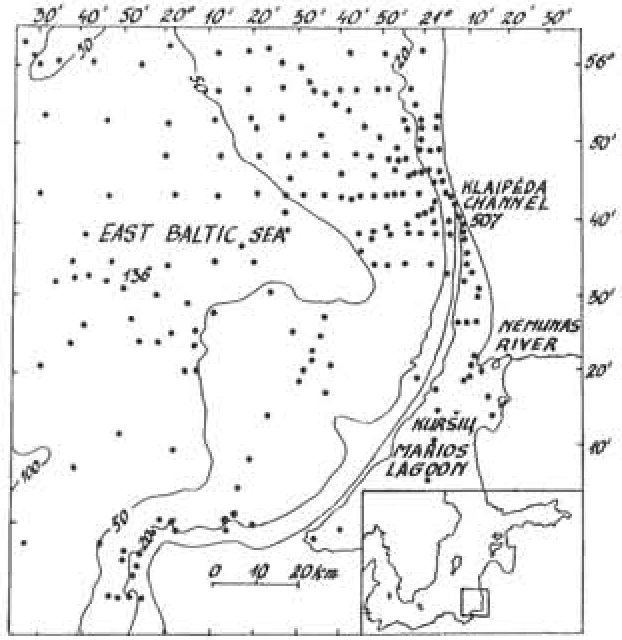

Fig. 1. Sampling stations.

der to avoid contamination. All samples were stored at 4°C in plastic containers before analysis in the laboratory.

Dried at 25-30°C and heated to 500°C sediment samples for Fe, Mn, Co, Zn, Cu, Cd, Pb, and Cr analysis were heated in closed tephlon crucibles with concentrated $HF/HClO_4$ and HNO_3 acid mixture at 120°C for 1 to 3 hours. After cooling, the acids were evaporated and the final solutions were stored in 6 % mixture of nitric and perchloric acids taken in equal volumes (Brzezinska et. al. 1984). The blanks and standard reference materials were prepared in the some way. The accuracy of the results was assessed using the sediment standarts from Russian Institute of Oceanology. The obtained concentrates were analyzed for the total content of metal by atomic-absorption spectrophotometers (AAS) "Perkin Elmer Model 503" and "Saturn 3P" (air/acetylene flame). Mercury analysis was performed using the flameless AAS (cold vapour) technique (Morozov, 1981). The estimated error for determination was 5-21 %.

The total organic carbon (C_{org}) was determined after burning samples to CO_2 by heating to 900°C and applying automatic titration method (device AN-7529, Russia).

RESULTS

Concentrations of Fe, Mn, Co, Zn, Cu, Cd, Hg, Pb, Cr, and regularities of their distribution were established in sample cores (up to 2.5 m deep) and surface layer of bottom sediments (0-3 cm) in lower course of Nemunas, Kuršių Marios Lagoon and East Baltic (Table 1).

A statistical assesment of the obtained results was made with the aid of 3d version of the programme "STATGRAPHICS". Correlation coefficients (r) were computed for determination of interdependence among the concentrations of metals and relationship between different elements and the type of sediments (Table 2). The data obtained in various sedimentation areas were unified into one standardized matrix (189 samples).

DISCUSSION

The obtained results showed in all investigated sedimentation regions that the highest values of metal concentrations can be observed in water-rich clayey sediments, the lowest in coarse-sandy sediments. Such distribution is preconditioned by the content of fine particles (<0.001 mm) in sediments and the linking of most metals with clay minerals. Thus, near shore, where coarse deposits predominate, the metal contents in bottom sediments are lowest and increase in the open sea reaching maximum in the area of deep sea depressions. In bays and embayments this regularity frequently does not work, because clayey-silty sediments accumulate at small depths close to the shore. It was determined (Parks 1975) that particles of thin fractions are characterized by good sorptive capacity because static electric charges on the surface of such fractions attract metal ions from solutions. We fixed that amount of trace elements in bottom sediments directly depends on the quantity and quality of suspended particles and metal concentration in the water column. Under quiet hydrodynamic conditions fine suspended terrigenic and biogenic particles together with trace elements, settle on the bottom. Analysis of sediment fractions and content of metals in them revealed that the smaller the median (Md) diametre of sediments, i.e. the finer the sediments, the higher the content of metals in them shown scematically on (Fig. 2).

According to the increase of concentrations from sandy (> 0.1 mm) to aleurite (0.1-0.01 mm) deposits, metals can be divided into two groups. One group includes Cu, Cr, Hg, Zn and Pb, the other group includes Fe, Mn, Co, and Cd.

Suppose that the average concentration of a metal in sand equals 1, then, in mud it is higher by 1.2 to 3.5 times, depending on the type of metal. The greatest differences between concentrations are characteristic of Hg, Zn and Pb (by 2.4-3.5 times higher than in sand), the smallest ones of Co, Cd and Mn (by 1.2-2.1 times higher than in sand) (Table 1).

The content of organic matter is another very important parameter influencing the concentration of metals in sediments (Hallberg 1991, Volkov 1980, Romankevitch 1977). It is usually expressed as Corg (organic carbon). The results of our investigations shows that the content of C_{org} in the sediments of the considered Sea areas ranges from 0.2 to 5.0% with the average equal to 2.1% of the dry weight of sediments. Similar results have been earlier obtained by Blashtchishin et al. (1982) and Emelyanov et al. (1987). The content of C_{org}, as well as metals, in sediments depends on the content of the clay particles. The finer the deposits the higher the content of C_{org}. A direct dependence between Corg and the content of metals in sediments can be observed (Fig. 2).

Table 1. **Mean concentration of metals in the surface layer (0-3 cm) of bottom sediments in the lower course of Nemunas River, Kuršių Marios Lagoon and the Baltic Sea.**

Sedimentation area	Predominating sediments	Sample number	Concentration, mg/kg, dry weight								
			Fe	Mn	Co	Zn	Cu	Cd	Hg	Pb	Cr
The lower course of Nemunas River	sand	28	4800	230	0.40	25.81	4.59	0.96	-	15.07	13.64
	aleurite	8	6000	240	0.90	36.78	19.37	0.78	-	18.00	14.30
	mud	7	7000	510	1.90	63.60	7.70	1.49	-	21.30	35.86
The northern part of the Kuršių Marios Lagoon (without Klaipėda port)	sand	15	6800	350	4.70	28.40	15.40	0.60	0.08	13.80	35.70
The Miškas Bay (Klaipėda port)	sand	6	31500	290	3.60	139.80	29.40	0.35	0.41	15.46	74.40
	aleurite	6	34000	300	4.45	171.30	26.40	1.19	0.80	17.43	87.5
	mud	10	40100	750	6.36	287.00	757.26	1.76	1.38	25.50	119.0
	till	10	22000	470	3.46	75.40	23.50	0.09	0.06	7.20	39.00
Klaipėda channel	sand	9	8300	150	12.75	25.10	8.50	2.04	0.13	9.10	44.60
	mud	6	13400	230	13.65	39.16	11.75	2.73	0.21	12.91	57.45
	till	4	11900	270	21.40	52.25	15.50	3.50	0.10	15.60	57.25
The nearshore of the Baltic Sea	sand	40	7100	700	13.80	14.75	8.90	2.92	0.07	11.12	41.40
The deep water part of the Baltic Sea (Gdansk and Gotland basins)	aleurite	25	11200	200	2.40	20.81	3.64	1.30	0.08	20.78	35.16
	mud	17	32000	800	17.80	139.70	31.76	1.35	0.09	52.40	73.30
Mean value in sedimentary rocks (Perelman 1975)			33000	670	20.00	80.00	57.00	0.30	0.40	20.00	100.00

Table 2. **Coefficients of correlation of chemical elements in the bottom sediments of the East Baltic (189 samples).**

Components	X	C	Fe	Mn	Cu	Zn	Co	Cd	Hg	Pb	Cr	Type of sediment
C_{org}	2. 10, %	0.90	0.62	0.56	0.71	0.77	0.33	0.20	0.65	0.59	0.78	0.58
Fe	2. 80, %	0.40	-	0.40	0.61	0.68	0.22	0.25	0.38	0.61	0.58	0.69
Mn	0. 04, %	0.01	-	-	0.41	0.50	0.03	0.17	0.27	0.36	0.40	0.22
Cu	30. 5, 10^{-4}%	7.60	-	-	-	0.80	0.28	0.10	0.50	0.70	0.57	0.71
Zn	87. 3, 10^{-4}%	34.40	-	-	-	-	0.24	0.26	0.71	0.73	0.78	0.68
Co	8. 2, 10^{-4}%	4.00	-	-	-	-	-	0.30	0.30	0.19	0.14	0.51
Cd	1. 7, 10^{-4}%	1.10	-	-	-	-	-	-	0.20	0.18	0.25	0.13
Hg	0. 25, 10^{-4}%	0.10	-	-	-	-	-	-	-	0.50	0.61	0.61
Pb	21. 6, 10^{-4}%	15.70	-	-	-	-	-	-	-	-	0.54	0.65
Cr	58. 4, 10^{-4}%	20.30	-	-	-	-	-	-	-	-	-	0.41

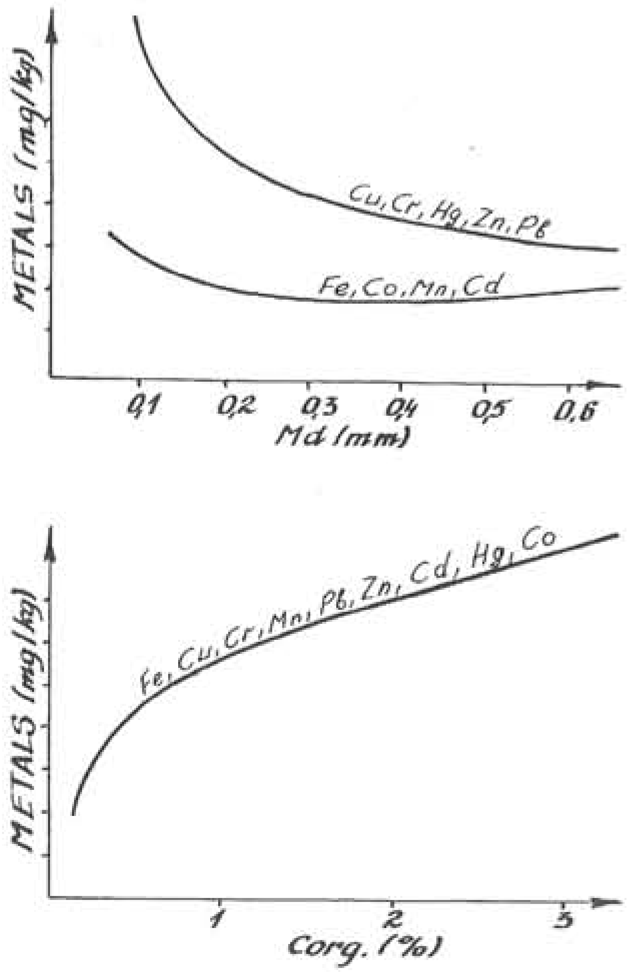

Fig. 2. Dependence of metal concentration on organic matter (C_{org}) and median diameter (Md) mm in bottom sediments from the Klaipėda polygon.

The obtained values of correlation coefficients (r) indicate that there is a direct co-variation between the content of metals in sediments and their granulometric composition (Table 2). The finer the sediments, the higher the content of metals in it. Sediment type mainly predetermines the distribution of Cu (r = 0.71), Fe (0.69), Zn (0.68), Pb (0.65) and Hg (0.61). Its impact on Cd (r = 0.13) and Mn (0.22) concentrations is the least. Grain size makes the greatest influence on the content of Pb, Cu, Hg and C_{org}. Especially high values of correlation coefficient are between C_{org} and Cr (r = 0.78) (influence of pollution in Klaipėda region), C_{org} and Zn (r = 0.77), C_{org} and Cu (r = 0.71). The metals are also strongly related among themselves. It is especially true about heavy metals. Close direct co-variation among heavy metals suggests their common source and mechanism of distribution in sediments.

The data obtained also suggests that the distribution of metals in the surface layer of sediments of the investigated areas is conditioned by mechanical differentiation of sedimentary matter which depends on the conditions of sedimentation and degree of pollution of the area (Table 1). This is also indicated by the observation that the same lithological types of bottom sediments in different areas contain different amounts of metals, but the general tendency of increased values in finer fractions remains. In the nearshore of the Baltic sea, in the northern part of the Kuršių Marios Lagoon and some sections of the lower course of Nemunas River, the content of metals in sediments is comparatively low. This is explained by the predominance of sand fraction. In the zones of local pollution near towns, industrial regions and river mouth it is possible to observe the increased values of heavy metals (Pb, Hg, Zn, Cu, Cd, Cr). Such a situation can be observed in the Nemunas River down the town of Kaunas, Tilžė, the mouth of Dubysa River, and at the town of Klaipėda.

The highest concentration values of heavy metals in all granulometric types of sediments were found in the sediments of Klaipėda port (Table 1). Most polluted sediments were observed in the Miškas Bay, an area of cellulose and cardboard factory; the Danė River mouth and in the harbour basins. Comparison of sand and silt from the central part of the Baltic sea and Miškas Bay revealed that in the sand of the latter there is more Zn by a factor 9.5, Hg 5.8, Fe 4.4, Mn 4.1, Cu 3.3, Cr 1.8, Pb 1.4 and in the mud - Cu by 23.7, Hg 15.3, Mn 9.4, Zn 2.0, Cr 1.6, Cd 1.3 times. Especially highly polluted is the surface layer of bottom sediments. If compared with deeper horizons it has considerably more Cd, Hg, Pb, Zn, Cu and other metals though the lithological composition of bottom sediments is almost similar (except till) (Fig. 3).

Similar situation can be also observed in the open sea with the only exception that the differences of cocentrations in the surface and deeper layers are not so distinct there (Fig.4). This is related to changes of physical-chemical conditions in the surface layer of bottom sediments occuring due to sediment diagenesis and, what is most important, to anthropogenic pollution which has especially increased during the post-war period and is distinctly visible in the vertical section of metals distribution in sample cores. Anthropogenic pollution can be distinguished from natural background according to the associations of specific, technogenic element peculiarities of their migration and accumulation.

Accurate evaluation of pollution of sediments is problematic as the background level is unknown and the notion "background concentration of an element" is conditional in itself. It is impossible to find such an area in the sea which would be free of any anthropogenic impact, therefore, the absolute estimation of pollution is impossible. In every respect the evaluation of pollution with metals is relative. This can be done by comparing the investigated region with the "ecologically clean" one, i.e. less polluted, or the concentration of metals in recent sediments with the concentration in deeper layers of the same type.

The amount of metals settled in bottom sediments as a result of human economic activity is approximately revealed by the coefficient of pollution (K). It is calculated by dividing the concentration of a metal in the surface (0-3 cm) layer of bottom sediments by its concentration in deeper horizons (usually below 1 m).

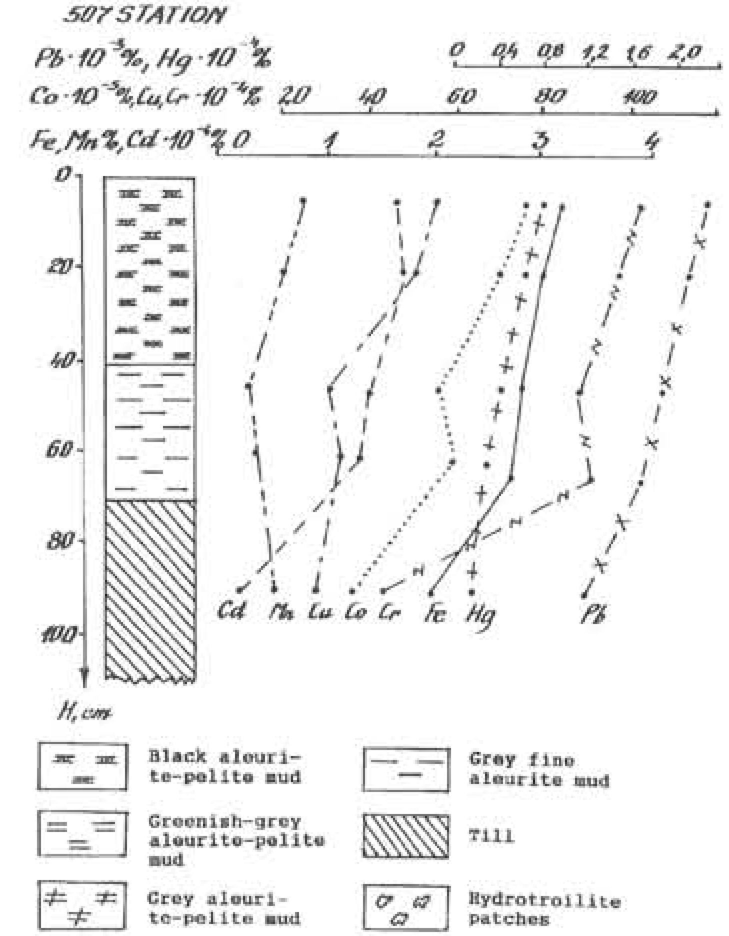

Fig. 3. Distribution of metal concentrations in a core from the aquatory of Klaipėda port (station 507) see Fig 1.

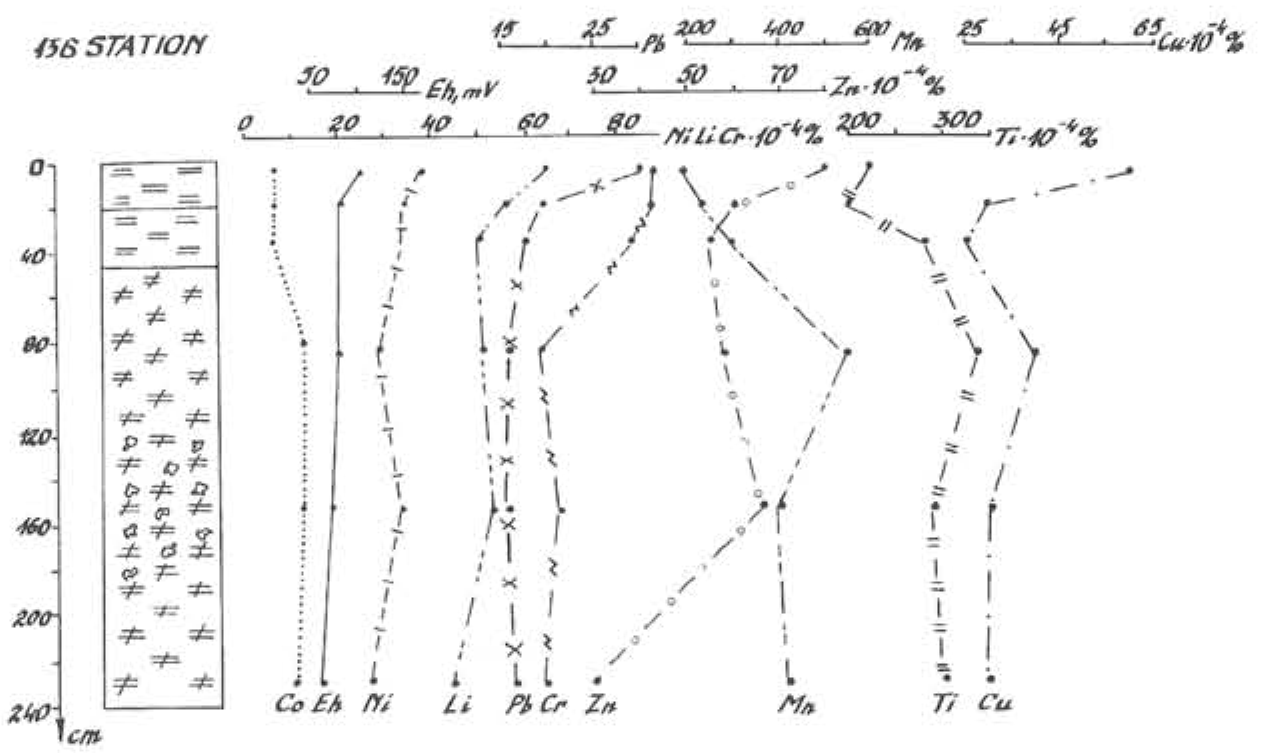

Fig. 4. Distribution of metal concentrations in a core from the south-east part of the Baltic Sea (station 136). Legend in Fig. 3, position in Fig 1.

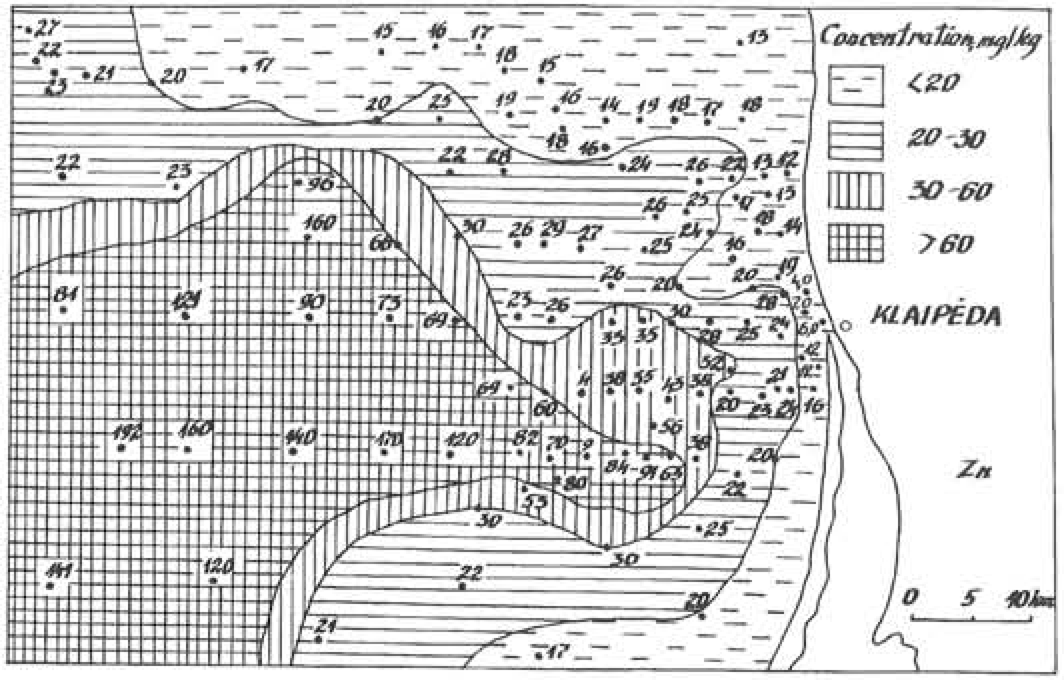

Fig. 5. Distribution of Zn concentrations in the surface (0-3 cm) layer of bottom sediments in the Baltic Sea off Klaipėda, mg/kg.

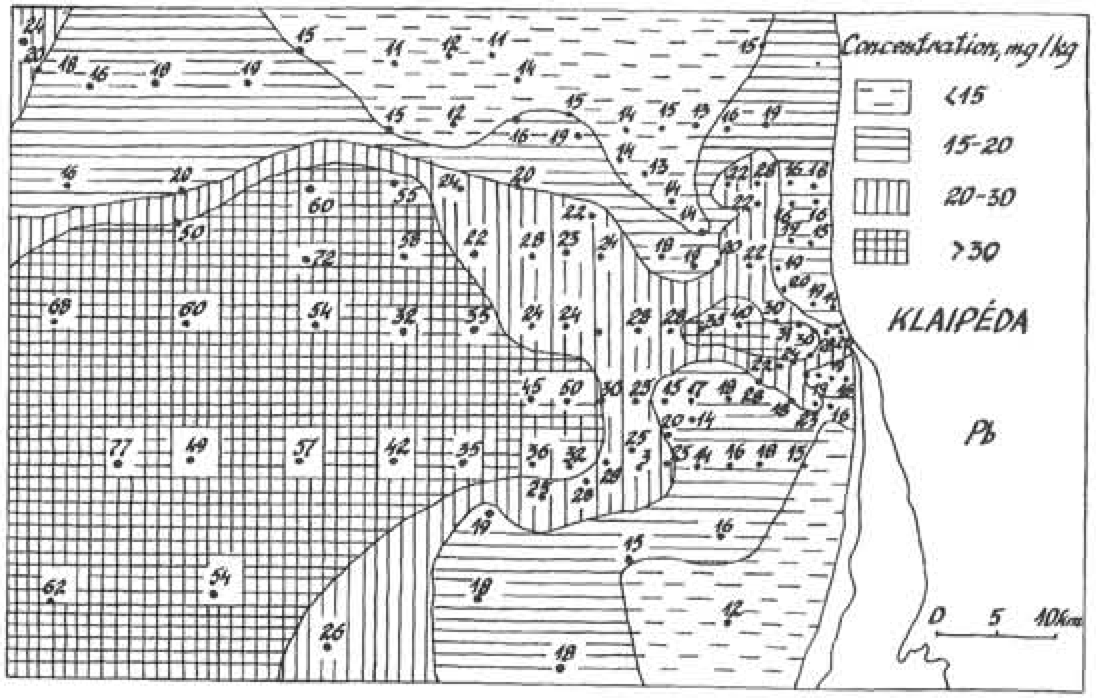

Fig. 6. Distribution of Pb concentrations in the surface (0-3 cm) layer of bottom sediments in the Baltic Sea off Klaipėda, mg/kg.

Table 3. **Average increase of the concentration of metals in recent sediments as a result of human economic activity (K)**

Sedimentation area	Hg	Cd	Zn	Pb	Cu	Cr	Fe	Mn
Klaipėda port (9 cores)	11.4	7.3	3.4	2.6	2.1	2.1	1.8	1.2
The eastern slope of the Baltic Sea (5 cores)	2.2	2.4	2.7	1.4	1.9	1.2	1.4	1.3
Gdansk basin (9 cores)	2.7	1.9	3.0	1.7	2.0	1.5	1.2	0.9

The lower parts of sample cores contain older formations, which in comparison with recent sediments are less polluted with metals (especially heavy metals). There is an assumption that the amount of metals in the lower part of sample cores is predetermined only by natural factors because at the time when old sediments accumulated there was no pollution and no redistribution.

For calculations of the coefficient of pollution in the Klaipėda port, eastern slope of the Baltic sea and Gdansk depression several sample cores were selected in each area. The results are represented in Table 3. The surface layer of bottom sediments is most highly polluted in the aquatory of Klaipėda port. The natural background is there exceeded by 1.2-11.0 times. In the deep water zone (Gdansk basin) the pollution of sediments is also considerable. The natural background is there exceeded by 1.2-3.0 times.

It is evident, that the surface layer of bottom sediments in all aquatories is enriched with heavy metals especially Hg, Cd, Zn, Cu and Pb. Comparison of recent sediments with older ones reveals a slight increase of Fe and Mn, but we can even observe a decrease of Mn contents in the Gdansk basin.

It is interesting to compare mean concentrations of metals in the surface layer of bottom sediments of the investigated regions with mean values in sedimentary rocks (Perelman 1975) (Table 1). The mean value of heavy metal concentrations in the Miškas Bay (Klaipėda port) in all granulometric types of sediments exceeds the mean value in sedimentary rocks by a factor 8.6 for Mn, 4.9 for Cd, 3.2 for Zn, 3.0 for Hg, 1.1 for Pb . The Gdansk and Gotland basins are also enriched with technogenic metals (Cd, Zn, and Pb) if only in smaller amounts. The mean value of Cd exceeds the one in sedimentary rocks by 4.5, Pb 2.6, Zn 1.7 times.

Fig. 5 and 6 represent the distribution of Zn and Pb concentrations in the surface layer of bottom sediments in the East Baltic off Klaipėda. There is a distinct relation of the mentioned elements with fine grain fractions because the areas of maximum concentrations are situated in the deep water sector of the investigation site (Nemunas old valley and Gdansk depression). Part of transported sediments getting into the sea through the Klaipėda channel apparently settle in the nearshore zone. The mentioned zone is characterized by increased concentrations of Zn and Pb in sediments. As 55% and 10% of the Zn get through the geochemical mixing zone of saline and fresh water (Kuršių Marios Lagoon - Baltic sea) as a constituent of suspensions (investigated by the author) it is not difficult to explain their observed distribution in the surface layer of bottom sediments. According to the concentration of Pb in sediments we can easily reconstruct the areas of transportation and discharge of sediment flow from the Kuršių Marios Lagoon (Fig. 6).

The distribution of metals in the bottom sediment cores is a complicated question. Over the general background (increased concentration values of elements in the upper part of sample cores) described above, hardly explainable fluctuations of metals can be observed. Even in the sediments of the same type the concentration of an element may fluctuate within a wide range. It was noticed that most metals are characterized by increased concentrations in layers rich in organic matter and hydrotroilite. Presumably, it could be explained by diferences in physical-chemical conditions of the environment in the past and present, as well as the intensity of the processes of diagenesis in sediments.

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Shallow Gas Traps and Gas Migration Models in Crystalline Bedrock Areas Offshore Sweden

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Numerous shallow gas traps have been geophysically recorded within the glacial and postglacial deposits of Swedish offshore areas of crystalline bedrock and those of sedimentary bedrock. This paper deals with gas traps and gas migration models in the crystalline bedrock areas. Gas accumulations of biogenic origin in the postglacial sediments occur commonly in delimited basins within the Swedish coastal areas and usually form horizontally extensive thin sheets of gas vacuoles, acoustically blanking out reflections from subjacent layers. They are normally found in positions of formation and are rarely associated with pockmarks or bubblemarks. In the offshore crystalline bedrock areas, gas accumulations attributed to migrating thermogenic gas are commonly related to ancient, but recurrently regenerated, tectonic lineaments. The gas traps are often mushroom-shaped and found within overlying glacial and postglacial clays. They are normally associated with degassing structures in the seabed, represented acoustically by either very small pockmarks (termed bubblemarks in this paper) or by mottled seafloor. The sizes of the bubblemarks and their rates of regeneration are highly dependent on the properties of the seafloor sediment. The gas migration pattern depends on crystalline bedrock morphology, till distribution and sediment thicknesses. It appears to be possible to predict the kind of evidence of gas migration which should be expected in any particular area.

INTRODUCTION

Circular depressions in the seabed, termed pockmarks, have been reported from shelf areas around the world, mainly areas of basal sedimentary bedrock, where the presence of petroleum-associated gas is expected. Known occurrences up to the present time are discussed by Hovland and Judd (1988). Pockmarks are normally developed in soft bottom sediments and are usually interpreted as outlet vents for gas or fluid. The clayey sediments often show disturbances - gas turbation - in the vicinity of these structures. Gas traps in the sediment, related to occurrences of pockmarks, are also a common feature.

In the sea areas around Sweden pockmarks of various sizes and origins have been reported by several authors. Whiticar and Werner (1981) describe pockmarks associated with the Mesozoic sedimentary bedrock area in the southern Baltic Proper. Flodén and Söderberg (1988) found degassing structures and gas traps in the sediments overlying the crystalline bedrock of the northern Baltic Proper and within the Stockholm Archipelago.

Those pockmarks and associated trap structures which overlie crystalline bedrock areas are of a special interest to the authors; petroleum associated gas is clearly not present. Nevertheless, most structures offshore Sweden have been shown to be created by gas, as documented by visual gas seepages, gas eruptions and by analyses of absorbed gas in the sediment (Söderberg & Flodén 1989). Locally within the archipelagos, explosive gas eruptions with outbursts as high as 10-15 metres have been reported by the local population.

The sizes of pockmarks within the crystalline bedrock areas studied by the authors appear to depend on the composition of the overlying sediment. Those formed in postglacial clay and mud typically range from some 20-40 cm in diameter in soft muds, up to about 1.5 m in diameter in more consolidated clays. Because of their small sizes, these are referred to as "bubblemarks" in this paper. Some distinctly larger pockmarks in late glacial varved clay have also been found. These are up to 40 metres in diameter, 2-3 metres deep, and exhibit distinctly flat bottoms.

The main gas source within the areas of crystalline bedrock is probably biogenic, with the gas produced in the postglacial sediment. In addition, thermogenic gas has been shown to rise to the seafloor from low levels in the Earth's crust, creating extensive fields of bubblemarks along major tectonic lineaments (Söderberg & Flodén 1991, 1992). The locations of the bubblemarks in relation to the lineaments is dependent on bedrock morphology, the distribution of till and on sediment thicknesses, and several different mechanisms of gas migration can be distinguished.

METHODS

In this study, gas traps and degassing structures have been investigated geophysically by means of low frequency echosounding using a so-called "mud penetrator" at 4 kHz, by shallow seismic reflection profiling at 450-900 Hz and by side scan sonar mapping at 500 kHz using a dual frequency EG & G model 260 image correcting side scan sonar. Further information on the structures was obtained by scuba diving. A sampling and gas analysis programme for some of the structures in the Stockholm Archipelago was performed in order to determine the composition and origin of the gas released through the bubblemarks (Söderberg & Flodén 1989).

Gas traps and their interpretation in sediments overlyng Swedish crystalline bedrock

The crystalline bedrock areas investigated, along the Swedish west and east coasts, belong to the Fennoscandian Shield. In Åbyfjorden Bay, on the west coast, the bedrock consists of Bohus Granites (890 Ma). In the Stockholm Archipelago, on the east coast, the bedrock consists of Svecofennian metasedimentary gneisses and granites (1800-1900 Ma). In neither of these areas have any extensive in situ occurrences of a basal sedimentary bedrock been found.

Seabed structures and subsurface gas traps indicating the presence of migrating gas, i.e. pockmarks and bubblemarks, mottled seafloor, gas-turbated sediments, dense gas vacuole accumulations etc. occur along several reactivated Precambrian tectonic lineaments in the areas investigated (Fig. 1a).

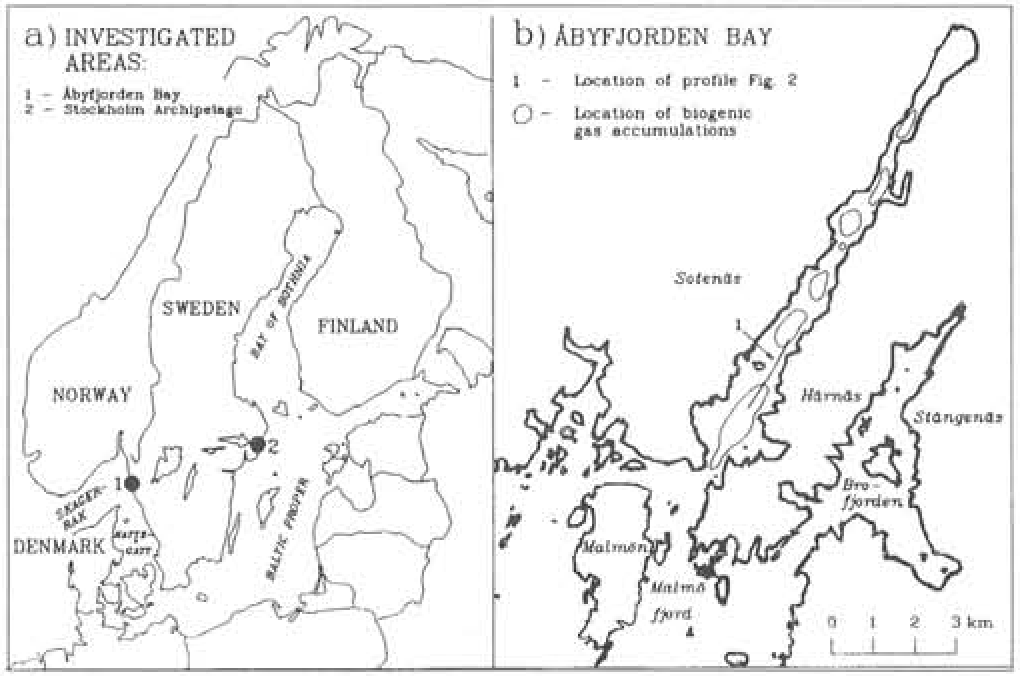

Fig. 1. a) General location of study areas. b) Åbyfjorden Bay.

Gas traps on the Swedish west coast

Åbyfjorden Bay is one of several well-developed fjords eroded along NE-SW striking deep fractures on the Swedish west coast. The sediments of the area typically consist of late glacial varved clay and postglacial clays and muds, only locally resting on some metres of till.

An investigation of Åbyfjorden Bay using mud penetrator sounding and shallow seismic reflection profiling revealed an abundance of gas-related sediment structures in all five fjord sub-basins. The extension of recently forming gas sheets is shown in Fig. 1b. The mud penetrator recordings show that, in addition to these sheets of recent biogas, gas from the bedrock fracture rises through the bottom sediments. This is evidenced by the occurrences of gas- turbation structures in the late glacial varved clay.

The profile (Fig. 2) demonstrates a transition from largely gas free sediments to gas charged sediments (A). Strong gas-turbation and gas remnants occur in the late glacial varved clays (B) and in the postglacial (C) sediments. One level (D) stands out as a "bright spot" due to accumulating gas. In general, it seems that when sufficient gas pressure has built up below a sediment surface, the gas breaks through the surface and migrates to a stratigraphically higher level where a new accumulation may occur.

No bubblemarks were recorded in Åbyfjorden Bay, but this may merely be due to the fact that the vertical sounding methods used in Åbyfjorden were not capable of resolving bubblemarks in the extremely soft bottom sediments. In comparison, bubblemarks located by side scan sonar in similar soft bottoms in the Stockholm Archipelago were found to be very small, normally not more than 20-30 cm in diameter.

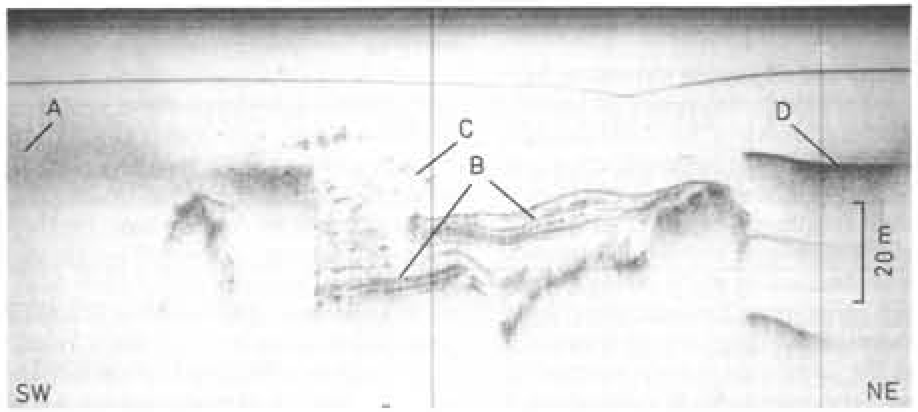

Fig. 2. Gas-trap structures in Åbyfjorden Bay (b in Fig. 1). A - gas-charged sediments, B - gas turbated glacial varved clay, C - gas turbated postglacial sediments with gas remnants, D - gas accumulation below structural surface causing "bright spot" image. Mud penetrator recording at 4 kHz.

Gas migration model for Åbyfjorden Bay. The records obtained during the present study reveal a large number of places where gas vacuole accumulations are trapped, or have previously been trapped, below successively higher stratigraphic surfaces. In addition, the records show gasfree areas where gas-turbated glacial and postglacial sediments reveal the locations of previous gas accumulations. These gas traps are located towards the central part of the fjord, directly above the tectonic lineament along which the fjord has developed. This vertical gas migration seems to be typical of areas where glacial and postglacial clays rest directly on the bedrock (see Fig. 3, section 1).

From these sediment structures it can be concluded that gas more or less continuously rises from deep sources in the bedrock along the fjord fracture. Future sampling of the gas vacuole accumulations using a newly developed gas-sediment sampler (Söderberg 1988) should be able to confirm this.

Gas traps in the Stockholm Archipelago

The crystalline bedrock of the Stockholm Archipelago is traversed by deep-seated tectonic lineaments trending mainly NE-SW, NW-SE and E-W. The NE-SW and NW-SE lineaments are assumed to have been initiated during the culmination of the Svecofennian orogeny at about 1850 Ma. Lineaments trending E-W are younger. Although forces during later orogenic phases have led to the development of new lineaments, they have mainly reactivated and opened older ones. Sediments in the Archipelago typically consist of glacial and postglacial clayey deposits resting on a few metres of basal moraine.

In the Stockholm region, the investigations were concentrated on three major tectonic lineaments, namely the Vaxholm-Söderarm- Lågskär lineament (V-S-L in Fig. 4), the Strömma lineament (S) and the Södertälje-Landsort lineament (S-L).

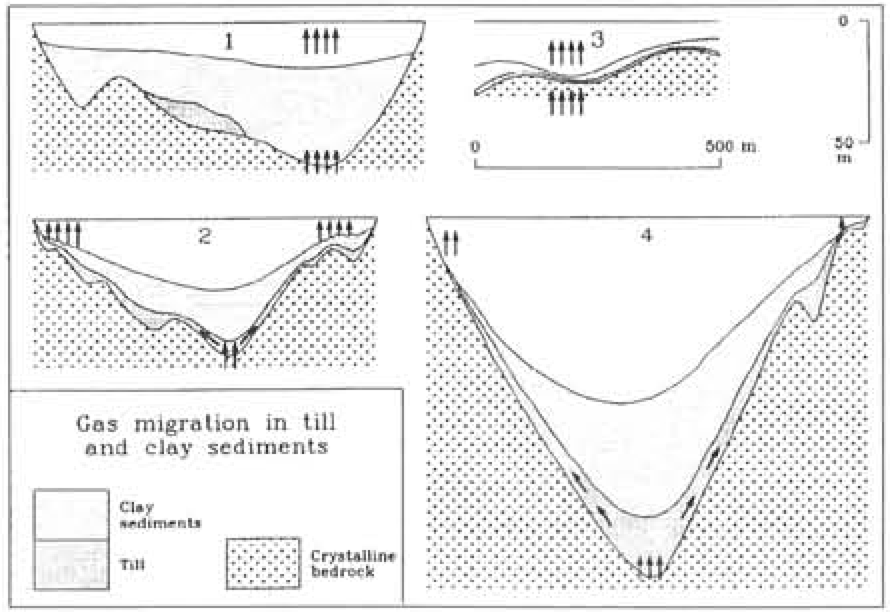

Fig. 3. Migration models of thermogenic gas along tectonic faults in crystalline bedrock areas. Sections are drawn to scale from shallow seismic recordings. 1 - in areas where the basal till is patchy or absent, the gas is observed to rise vertically through the sediment. 2 - in areas of a continuous basal till cover, the gas is observed to migrate sideways to nearshore outflow areas. The outflow areas are scarred by bubblemarks. 3 - in areas of thin clay cover, the gas rises vertically to the seafloor. The outflow areas form mottled seafloor. 4 - In areas where the basal till is exposed alongshore, no bubble marks occur despite surface observations.

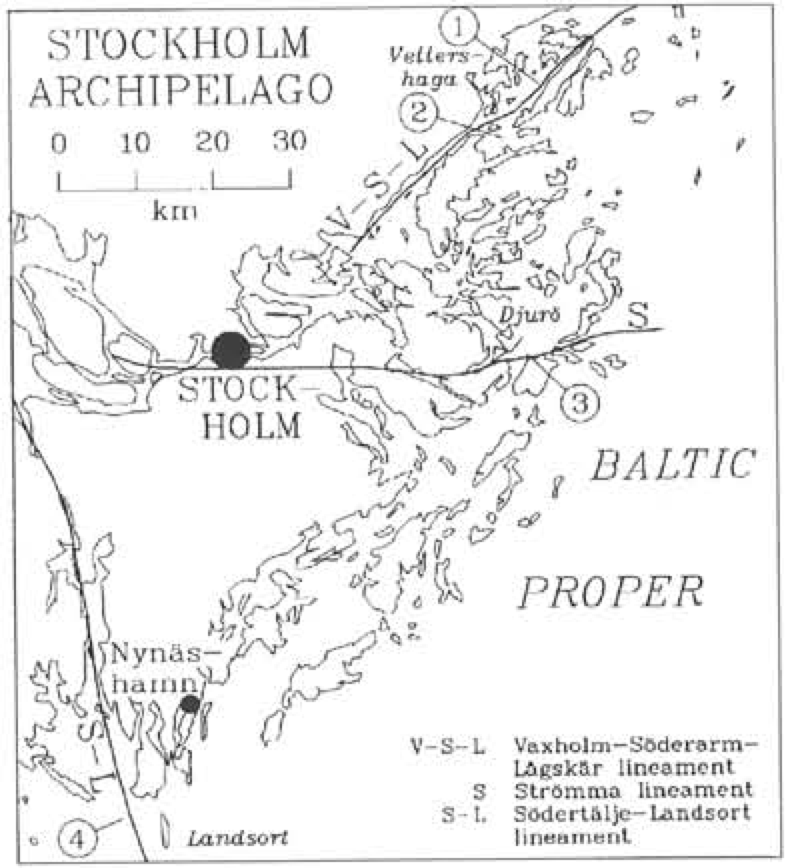

Fig. 4. Stockholm Archipelago. Encircled numbers denote locations mentioned in the text.

Bubblemarks. Whereas bubblemarks in the bottom sediments are common along many of the major tectonic faults of the Stockholm Archipelago, they are rare elsewhere. The bubblemarks normally group along the strings of islands on both sides of the submarine faults, at water depths of 6-16 m. Bubblemarks are not found along the deep central parts of the faults. Nor are any gas- turbation structures found there. We explain the nearshore occurrences of the bubblemarks as due to a sideways migration of gas within the bottom moraine to the shallow nearshore areas where the cover of glacial and postglacial clay sediments is small (see Fig. 3, section 2). The bubblemarked areas (Fig. 5, loc. 1 in Fig. 4) normally extend a few hundred metres lengthwise along the islands, whereas their widths are dependant on the slope of the seabed. A width of 25-50 m is normal.

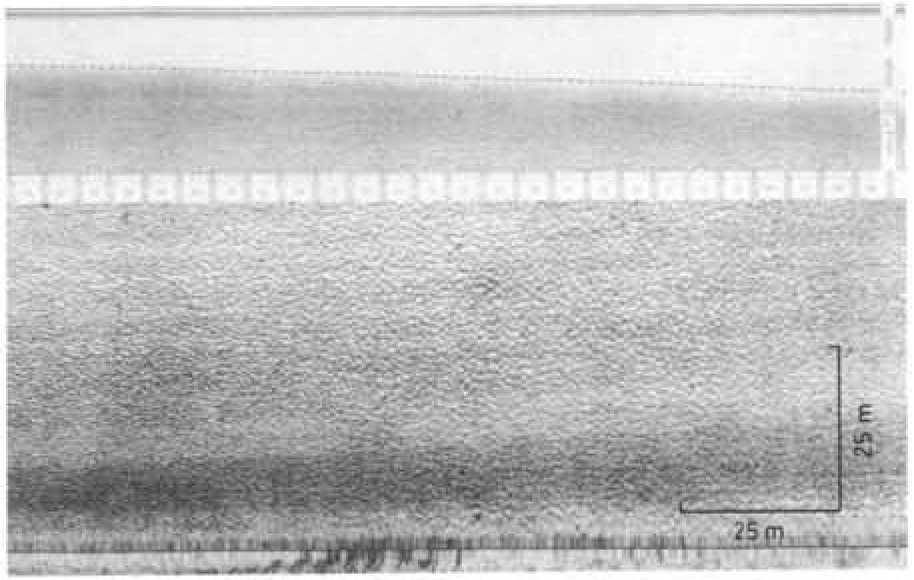

Fig. 5. Side scan sonar recording at 500 kHz. An example of bubblemarks in postglacial sediments along the Vaxholm-Söderarm-Lågskär lineament (loc. 1 in Fig. 4). The bubblemarks occur alongshore at water depths of 6-16 m.

Sediment and gas analyses indicate that the gas seepages mentioned above include a significant contribution of thermogenic gas (Söderberg & Flodén 1989, 1991). This fact, together with the locations of the seepages along major lineaments, leads to the conclusion that the structures are formed by gas which rises to the surface from deep levels in the crystalline bedrock. Evidence of large fields of bubblemarks in the vicinity of an earthquake area in the northern part of the Stockholm Archipelago (Söderberg & Flodén 1989, 1991) further supports the concept of gas from deep sources in the bedrock as the principal feeder for these structures.

Mottled seabed. Patches of high reflectivity on side scan sonar recordings have been reported from the Norwegian North Sea, where they are associated with shallow seabed depressions (Hovland 1984).

Areas of "mottled seabed" occur in side scan sonar recordings from the Stockholm Archipelago, too. In the Archipelago the patches of mottled seabed are often associated with areas of muddy sediment along narrow straits. The structures are normally elongated and extend for several hundreds of metres, lying directly above bedrock fractures. A typical side scan sonar profile is presented in Fig. 6. The location of this particular side scan sonar profile (loc. 2 in Fig. 4) is along a narrow NE- SW lineament which parallels the Vaxholm-Söderarm-Lågskär main lineament (V-S-L in Fig. 4). Section 3 in Fig. 3, which is based on a seismic reflection profile along the same line as the sonar recording (Fig. 6), shows that the area of mottled seabed conforms with an area of unusually thin sediment cover. Further to the northeast along this particular lineament, the thickness of the sediment cover increases and the mottled seabed is replaced by an area with bubblemarks offset shorewards from the central fracture.

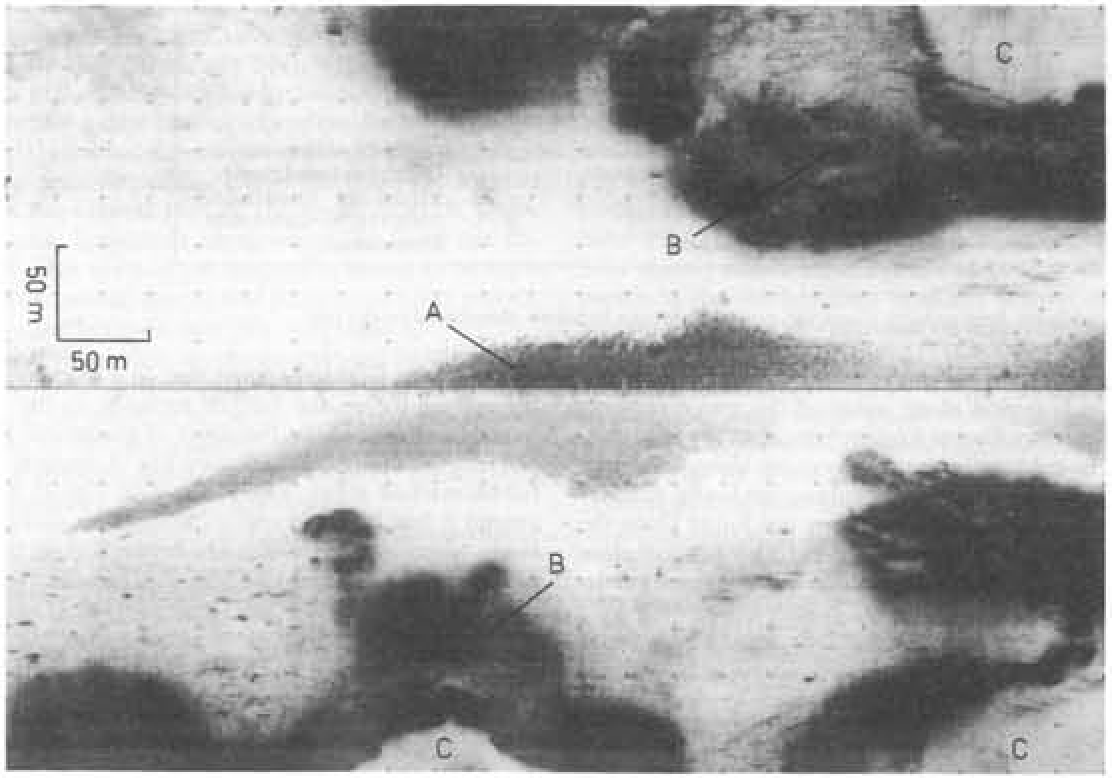

Fig. 6. Side scan sonar recording at 500 kHz. An example of mottled seabed (A) in muddy sediments (loc 2 in Fig. 4). Till and bedrock (B) is exposed on the submarine slopes between small islands (C). The sediments are thin and areas of mottled seafloor occur at several places along the centre of this lineament.

The areas of mottled seabed are interpreted as visual evidence of gas seepages along those parts of the tectonic lineaments where the sediment cover is thin and where therefore no horizontal migration occurs (see Fig. 3, section 3). The thin sediments hold no accumulations of gas; so gas seepage seems to be almost constant. According to our diver observations, the mottled seabeds are actually areas of extremely small bubblemarks, i.e. bubblemarks on a scale which cannot be resolved, even using a 500 kHz side scan sonar.

Featureless seepages. Along parts of the investigated lineaments gas seepages occur despite the fact that no gas traps are seen in the seabed. These seepages are known to exist from reports of gas outflow at the water surface. One area of featureless seepages is located along the Strömma lineament at Djurö (loc. 3 in Fig. 4) (Söderberg & Flodén 1992). Numerous reports of gas seepages at Djurö have been verified by analyses of absorbed gas in clay samples. There is a strong correlation between the extension of the Strömma lineament and the amount of thermogenic gas absorbed in the clay.

The absence of gas traps and seafloor structures at Djurö may be explained by the local seabed geology (see Fig. 3, section 4). The bedrock is exposed or covered only by a thin basal moraine down to depths of 35-45 m. Below this level, outwards thickening layers of glacial and postglacial clays occur. The gas leaving the bedrock fracture migrates sideways within the bottom moraine and is released alongshore where the bottom moraine is exposed in the seabed, thus no bubblemarks or other acoustically visible gas traps are created.

DISCUSSION AND SUMMARY

The gas which occurs in the offshore sediments overlying the Baltic Shield is of a mixed biogenic and thermogenic origin (Söderberg & Flodén 1989, 1991). The biogenic gas, mainly methane, is in general autochtonous and occurs as extensive acoustic masks of gas vacuoles located near the surface of the postglacial sediments. The thermogenic gas is allochtonous, rising to the surface along ancient tectonic lineaments in the Shield. The thermogenic gas, normally mixed with biogenic gas when it reaches the seafloor, is responsible for the large variety of gas associated sediment structures presented above.

The chemical composition and the thermogenic signature of the gas absorbed in the offshore sediments, as well as its restricted occurrences along major tectonic lineaments, lead to the conclusion that gas commonly seeps from deep levels in the crystalline bedrock of the Baltic Shield.

Biogenic gas. It is assumed here that the biogenic gas produced in the upper parts of postglacial and recent sediments normally escapes vertically to the seabed, but that the flow is far too small to leave any detectable deformation of the seafloor. This does however need further investigation.

Thermogenic gas. A major difference between the gas traps found in Åbyfjorden Bay and those found in the Stockholm Archipelago is that, in the former area, the gas rises vertically through the thick central parts of the sediment pile, whereas in the Stockholm region the gas normally migrates sideways to outlet vents nearshore where the clays are thin or absent. The various locations of the gas structures described above suggest at least four different models of gas migration (Fig. 3).

In Åbyfjorden, the cover of bottom moraine is irregular. Over large parts of the fjord bottom, glacial clay rests directly on the bedrock (section 1 in Fig. 3). Under these conditions, gas from the bedrock fracture rises almost vertically through the sediment, lending the varved glacial clay a gas-turbated appearance. Possibly, gas migrates along the boundary between bedrock and sediment too, but so far this has not been investigated.

In the Stockholm region, the cover of bottom moraine is more complete. Thermogenic gas normally migrates sideways within the moraine to outlet areas alongshore, where the clay is thin or absent (sections 2 and 4 in Fig. 3).

Along the main tectonic lineaments these outlet areas are normally located nearshore to the string of islands bordering the lineaments. In some areas, as along the Vaxholm-Söderarm-Lågskär lineament at Vettershaga (Söderberg & Flodén 1991), the outlet vents are developed as bubblemarks which occur extensively near the islands at water depths between 6 and 16 m. The clays in the outlet areas are usually only some few metres thick (section 2 in Fig. 3). In other areas, as along the Strömma lineament at Djurö (loc. 3 in Fig. 4), no seabed gas trap structures have developed at all due to the absence of clay sediments on the steep slopes nearshore (section 4 in Fig. 3).

Along those parts of the tectonic lineaments where the clay cover is very thin (section 3 in Fig. 3), gas leaks directly through the sediment, acoustically marking the location of the bedrock fracture in the seafloor (see Fig. 6).

In summary, bubblemark distribution can be explained by the local geology and it is now possible to predict the kind of evidence of gas migration which should be expected in any particular area. By using a combination of acoustic surveying together with analyses on absorbed gas in samples taken in profiles along and perpendicular to fault lines it is possible to recognize and locate the active parts of the tectonic lineaments in crystalline bedrock areas and to distinguish them from those parts which are now sealed.

Size and time aspects of pockmarks and bubblemarks. Not only the locations but also the general size and recycling time of the bubblemarks in the crystalline bedrock area follows a general pattern. In areas of very loose postglacial sediments, clay and gyttja, bubblemarks are normally rather small, ranging from some 20-30 cm up to 60-70 cm in diameter (see Fig. 5). Recycling time is very short. In a matter of a few months time a bubblemarked area may change from having a limited number of 60-70 cm bubblemarks to having a large number of 20-30 cm bubblemarks. Larger bubblemarks are associated with increased gas flow of short duration. A limited number of large bubblemarks is what is normally found as the immediate result of major gas eruptions.

In areas of relatively stiff postglacial clay, bubblemarks are usually somewhat larger, ranging from 60-70 cm to 150-200 cm in diameter. Recycling time is longer. Normally, no significant changes within an area were evident during the time span of the current program.

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Lithogenetic Features of the Quaternary Section in the Liepaja Region of the Baltic Sea

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Early, Middle and Late Pleistocene tills, Middle Pleistocene intertill marine clay and Late Pleistocene intratill glaciolacustrine varved clay were investigated in a boring section (40.3 m) situated ca. 18 nautical miles NW of Liepaja, at a water depth of about 55 m. Different detailed core examinations revealed the lithogenetical peculiarities of five units. Palaeogeographic depositional conditions and secondary deposit transformations are characterized. The differences between the tills depended on the glacier size and the environments of their alimentation, transition and ablation areas.

INTRODUCTION

Seismic data show reduced, rather simple Quaternary sequences in the SE Baltic. Complete ones are present only in few regions. The Ventspils palaeodepression (Goldfarb et al. 1991) is the largest one. However, the Quaternary cover is penetrated only by few boreholes and only one of them is thoroughly studied. The latter one is the borehole 37 penetrating sufficiently representative part of the Quaternary, including three palaeoglacial deposit complexes. According to available seismic data the lower complex is the oldest one in the region. The borehole 37 cores were investigated according to geotechnical standards; further specimens were studied by palynologic, micropalaeonthologic, lithostratigraphic and lithogenetic methods. This article presents the results of the lithogenetic study. Macroscopic and microscopic examinations, specimen and thin section photography, clay-mineral identification by x-ray diffractometry.

DESCRIPTION OF THE SECTION

Borehole No. 37 was drilled in 1988 from the r/v "Kimberlite" at a distance of ca. 18 nautical miles NW from Liepaja, at a water depth of 55 m. Following deposits (depth in meters below the sea-bottom) were penetrated:

1. (0 - 8.1 m) brown-grey, with brownish-yellow iron-stained spots and zones, soft and tight loam including gravel, pebbles, rubbles (ca. 10-20%), scattered boulders. The loam is mainly massive, but locally bedded. A varved clay interbed is present at the loam bed top (0.2-0.7 m depth interval) and black clay lenses 2-4 cm thick are recorded near its base.

2. (8.1 - 24.4 m) grey and greenish-grey, stiff and hard sandy loam with incorporated gravel and cobbles (ca. 10 - 15%), mainly enriched in local bands. There are a few gravel-sand, sandy-silt and loam interbeds 5 to 20 cm thick in the 16.5 - 21 m interval.

3. (24.4 - 28.6 m) brownish-grey, stiff clay with low silt contents (ca. 15 - 20%). The bed is locally thinbedded, subsequently disturbed.

4. (28.6 - 30.8 m) dark-grey, stiff, homogenous loam with preserved platy-edged sets of parting.

5. (30.8 - 36.4 m) dark-grey, hard loam with irregularly distributed gravel, pebbles, thin sand lenses (1 - 5 mm thick).

6. (36.4 - 40.3 m) grey, hard sandy loam with gravel, cobbles; clayey sand and calcareous clay sand interbeds (2 - 5 cm thick).

Lithostratigraphic investigations (Ulst & Majore 1964, Springis et al. 1964, Kuten & Klagish 1989, Goldfarb et al. 1991) allowed to assign preliminarily the beds Nos 1 and 2 to the Upper- and Middle-Pleistocene glacial deposit complexes, and the beds Nos 4, 5 and 6 to the Lower-Pleistocene one, which is not completely penetrated. The bed No. 3 containing no certain organic remains is supposed to be a result of the Middle-Pleistocene either marine or lacustrine deposition. Recent marine sediments are absent in the core. Glacial deposits are exposed at the Sea floor.

THE LATE PLEISTOCENE GLACIAL DEPOSITS

They consist of two related types of sediments: till, and glaciolacustrine varved clay. The till consists mainly of pelite (37 - 41% of the bulk till), silt (30 - 35%), sand (20 - 25%), gravel and pebbles (3 - 20%). Each frac-

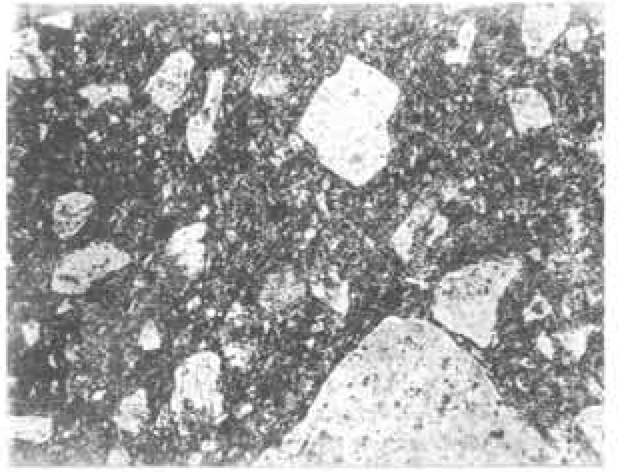

Fig. 1. Fragments of decomposed granites are enclosed in the Upper Pleistocene till clayey matrix. The cleavage sets are displayed by the orientation of the rectangular quartz grain outlines and the inherent regularly arranged fluid microinclusions.

Sampling depth in the borehole No. 37 (SD) 4.1 m, magn. 125 X. Figs 1, 2, 3, 5, 7 and 9 are microphotographs of thin sections made in polarized transmitted light using parallel (Figs 1, 2, 3 and 5) or crossed nicols (Figs 7 and 9).

tion is characterized by different morphologic peculiarities.

The psephitic fraction contains predominantly multisized fragments of Palaeozoic rocks (limestone, dolomite, siderite, siltstone, argillite, shell fragments) as well as Rapakivi type granitoides, migmatites, decomposed pegmatites, rare diorites and detrital material of the rocks mentioned: quartz and feldspar fragments of rectangular shape, often with slightly rounded corners. The habit of the clastic feldspar is determined by cleavage, whereas the quartz grain shape depends on the inherited fracture and microcleavage sets, usually traced by minute fluide inclusions (Figs 1 and 2; Matsuo & Sawa 1975).

The sand component, medium- and fine-grained, amounts to 15-20%. It consists chiefly of quartz with admixture of slightly altered and fairly fresh feldspars, carbonates, and heavy minerals (dark colored hornblends, biotites, epidote, ilmenite, accessories; Fig. 3). There are monocrystalline grains completely liberated from multimineral aggregates, mostly isometric but having different degree of roundness (Figs 1, 2 and 3). Obviously, the well-rounded ones endured many cycles of resedimentation. The correlation between the main feldspar groups varies in the vertical section. At the till base alkaline ones prevail diminishing progressively upward. This suggests that during the Late Pleistocene the till composition was modified as a result of the erosion of different rocks along the glacier route including local weathering crust residues (Afanasyev 1977, Gaigalas 1974, Kurshs 1992).

The silty fraction (25 - 30%) generally consists of the same minerals as the sandy one, but the definite increase of the less resistant and crushable phases as carbonates, feldspars is noticed. This results in essential contents of broken grains and sharp-edged fine debris (Fig. 2).

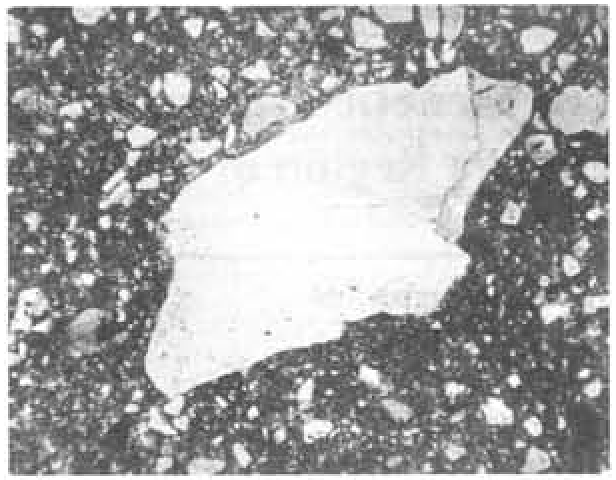

Fig. 2. The gravel-size quartz grain is incorporated in the Upper Pleistocene till sandy loam matrix. The inherent cracks in the grain are traced by minute fluidal inclusions determining the conchoidal fracture and specific shape of the cryoclastic. SD 6.4 m, magn. 50 X .

The pelitic fraction contains clay minerals, carbonates, quartz detritus, feldspars, dark colored minerals. The clay minerals consist of hydromicas mainly of the illite type (72%), kaolinite originated from hydromicas (6 - 15%), chlorite (8 - 18%), montmorillonite (0 - 10%). The maximum of the kaolinite contents is observed at the till base, whereas the one of chlorite is recorded at the till top, where montmorillonite is absolutely absent.

The typical texture of the upper till is massive, intact (Figs 1, 2 and 3). An undisturbed matrix with marks of fluidal fabric contains turbulent orientated elongated fine particles and irregular disposed psephitic fragments (Figs 2 and 3).

The glaciolacustrine interbed consists of dark colored winter laminae of 1 - 3 mm thickness and light 4 - 10 mm summer ones (Fig. 4). The composition of calcareous clay winter laminae does not differ essentially from that of the pelitic till fraction, except for some additional amount of chemically precipitated carbonates. The summer laminae consist of sandy silt, with gravel inclusions. The sand grain shape is isometric, moderately rounded, represented by detrital forms of quartz, carbonates, fairly fresh or somewhat altered feldspars, rare glauconite spherules and accessory minerals. The silty size particles are slightly rounded, but finer clastic material is angular or sharp-edged. Adsorbed Fe-hydroxides seem to provide brownish color to the winter laminae and slight brownish-grey shades to the summer ones.

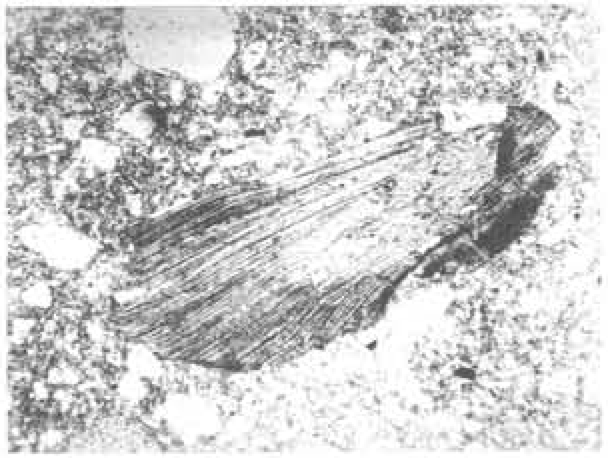

Fig. 3. Upper Pleistocene till. The gravel-size plate of the detrital, partly altered biotite is incorporated in a clay-silt matrix; dark, exfoliated outer part of the plate is more decomposed. SD 1.9 m, magn. 63 X .

Fig. 4. Upper Pleistocene glaciolacustrine varved clay. Clay (dark) and sandy-silt (light) with gravel-size grains laminae are alternating. SD 0.1 m, magn. 3 X .

Figs 4, 6 and 8 are the photographs of the core specimens fresh fracture.

THE MIDDLE PLEISTOCENE GLACIAL DEPOSITS

They are represented by rather monotonous mainly massive tills differing from the upper ones by a higher sand content, specific features of the clay mineral assemblage and another composition of the erratic material. The till differs essentially from all other units of the section by all main physical and mechanical parameters (Table 1).

There are diorites, gabbros, amphibolites, gneisses, granites, migmatites , pegmatites, carbonate rocks among the relatively small (10 - 15%) psephitic fraction. The prevailing sand fraction (45 - 65%) contains a lot of comparatively well-rounded grains (Fig. 5) with a high amount of hornblende, pyroxene, epidote, biotite. In the light part of the fraction carbonates, quartz and feldspars, predominantly plagioclases are common. Sometimes alteration traces with clay developed along joints and cracks on feldspar grains are observed. Carbonate debris is present mainly in the form of finest silt-sized particles, intimately intermixed with the clayey matrix (Fig. 5).

The pelitic fraction consists of highly calcareous clay containing tightly intermixed carbonates, less quartz, feldspars and other fine dispersed clastic material. The montmorillonite and illite clay mineral assemblage is completed by kaolinite (related to the illite) and less chlorite. X-ray analyses show the increase of the swelling phases to 26% of the clay mineral bulk, while hydromicas, in general, of illite type decrease to 55% in average. More complex relations between the clay phases are observed both at the till bottom and the top: i.e. a significant increase of kaolinite and chlorite. The first is suggested to be due to various supergenetic alteration processes. The content of the latter may be modified as a result of excavation and redeposition of the underlying clay material, with uniform fine ferrous carbonate and chlorite incorporated in lower part of the till (22.0 - 22.4 m depth interval).

Fig. 5. Semidecomposed gravel-size feldspar-quarts fragment in a very fine grained clayey-carbonatic matrix (with disseminated sandy and silty particles) of the Middle Pleistocene till. SD 9.65 m, magn. 14.3 X .

Sandy and gravel interlayers observed in the base of the unit are similar, in grain composition and morphology to the till described.

THE MIDDLE PLEISTOCENE INTERTILL CLAY

The characteristic features of the clay bed are as follows: a homogeneous macro-texture, a high degree of material sorting and dispersion, and high plasticity. At the same time it varies insignificantly from the underlying till by the bulk density and liquidity index (Table 1). The pelitic fraction comes up to ca. 80% of the total clay bulk. It contains a smaller amount of carbonate clastic compared with the upper and lower clay and loams. Hydromicas of the illite type (75%) with an associated minor amount of kaolinite (up to 18%), chlorite (ca. 10%) and sometimes some montmorillonite form the clay mineral assemblage.

Several subsequently formed clay bed generations are recognized in thin sections. The first one is represented by chemically precipitated fine-dispersed ferrous carbonate stringers with silt-sized quartz inclusions. They associate with the clay laminae, where clay particles are subparallel to the top-base plane and arranged in a face-to-face way.

Those primary peculiarities of the clay fabric and the clay mineral assemblage are observed mainly at the bed and the top of the clay stratum. They resemble

Table 1. **Some physical, mechanical and mineralogical parameters of the deposits penetrated by the borehole No. 37 in the Baltic Sea.**

Deposits	Bulk density (G/ccm)	Void ratio	Natural water contents (%)	Plasticity index (%)	Liquidity index	Contents of the fraction < 0.005 mm grain size	Contents of the clay minerals within the pelitic fraction (%):			
							hydromica	kaolinite	chlorite	montmorillonite
Upper Pleistocene glaciolacustrine varved clay *	1.82-1.87	0.98-1.01	35-40	16-20	(+0.85)- (+0.95)	?	69	17	8	11
Upper Pleistocene till	2.07-2.12	0.51-0.60	17-22	9-12	(+0.2)- (+0.7)	36.72-40.87	68-75	6-15	8-18	0-10
Middle Pleistocene till	2.28-2.32	0.27-0.31	10-12	4-7	(-0.6)- (+0.2)	10-30 **	53-62	13-20	7-13	11-26
Middle Pleistocene intertill clay	1.95-2.02	0.68-0.90	26-30	21-24	(0.0)- (+0.2)	68.04-80.52	61-75	12-16	7-16	0-10
Lower Pleistocene till	2.00-2.18	0.41-0.62	16-24	11-15	(-0.2)- (+0.2)	27.78-39.61	55-56	12-15	8-10	22-22

* The parameters of this unit refer to the neighbouring borehole No. 38

** Microscopic data

those of the Holocene marine mud of the Baltic Sea studied by the authors in the Gotland Deep, about 32 miles NW of the borehole No. 37.

The primary clay texture was many times deformed and here and there disrupted. There are distinctly visible sets of brecciation: fissures, cracks and joints (Fig. 6) cemented with aggradated illite. There are also recorded secondary cementation marks of the squeezed clay and significant recreation of the clay particles, as well as microfolding, microfaults (Fig. 7). Obviously, the deformation took place in a frozen state and the sediment was consolidated and rigid enough to break, while the cementation started in a thawed state. The upper part of the clay stratum was enriched by thin bands of minute siderite (0.003 - 0.004 mm diameter), but was markedly eroded.

The high content of the clay fraction gives rise to the highest clay plasticity in the section and a rather high void ratio. At the same time the natural consolidation degree is responsible for an increase in the bulk density and a decrease of the liquidity index (Table 1).

THE EARLY PLEISTOCENE GLACIAL DEPOSITS

The distinct features of the sediments are bedding and marks of subsequent disruption. Typical till beds of calcareous loam, with dolomite and various magmatic rocks cobbles, are interbedded with calcareous clay sands, mainly in the lower part of the unit. In the loam fresh core fractures platy-edge cleavage resulted in the multiangular texture (Fig. 8). The loam fragments are slickensided, separated one from another by surfaces of planar discontinuities: fissures, joints, filled with clay, calcite and colloidal substance. The till matrix differs from that of the overlaying tills by a much more expressed top-base plane orientation of the clay particles. There are relic patterns of random spacing, though the clay flakes still expose a tendency to surround the quartz grains and to produce edge-to-edge fabric arrangements (Fig. 9).

Quartzites and minor clastic particles of decomposed granites (altered feldspar and quartz grains, often with limonite patches and coatings on their surface) prevail in the rather scarce erratic psephite group.

The sandy fraction of the loam beds is oligomictic, composed mainly of quartz and, in lower quantities, of slightly altered feldspars, carbonates and detrital hydromicas. Plagioclases prevail among the feldspars. There are predominantly rounded coarse grains, particularly consisting of quartz and carbonate. Fine grains are mainly angular.

The sandy fraction of the calcareous clay sand interbeds is approximately similar to that of the loam, but there are some differences. It is polymictic, and alkaline feldspars occur in the same quantity as the plagioclases. The grain morphology is nearly the same as mentioned above.

Fig. 6. Middle Pleistocene intertill clay: note the disturbed primary bedded texture. SD 25.6 m, magn. 2.5 X .

Fig. 8. The rounded pebble is enclosed in the Lower Pleistocene till loam; platy-edged cleavage sets are visible. SD 30.9 m, magn. 2,5 X.

Fig. 7. Middle Pleistocene intertill clay: the disturbed clay contains lenses and clusters of fine quartz debris (white). The clay fragments retain elements of the closely packed slaty fabric: i.e. grey clay aggregates with undulated extinction. SD 24.9 m, magn. 50 X , crossed nicols.

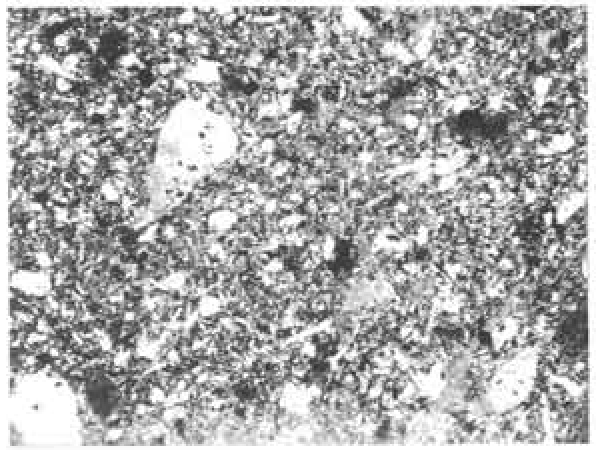

Fig. 9. The Lower Pleistocene till matrix shows elements of the preferred fabric orientation, though it preserves the relic patterns of the random spacing, too. SD 40.0 m, magn. 160X, crossed nicols.

The clay minerals of the loam are represented by a montmorillonite-illite assemblage, similar to that of the Middle Pleistocene till: i.e. illite (55% on the average), montmorillonite (22%), kaolinite (14%) and chlorite (9%).

It is very likely that the Lower Pleistocene complex contains both glacial and marine-glacial deposits.

DISCUSSION AND CONCLUSIONS

The obtained data prove that the three tills are rather similar. They are characterized by typical lithological, textural, physical, mechanical and other common features verifying their glacial origin. At the same time, significant differences between the tills have been found. The common and special till features are similar to those of the East European Platform tills described previously by many authors.

It is worth to mention the usual high clastic carbonate content in the till gravel, sand and clay fractions (Springis et al. 1964, Gaigalas 1974, Kuten & Klagish 1989). Traces of glacier overloading, dynamic influences and the signs of frosty weathering are observed in the till matrix, as well as in the spacing of various size fragments, grains, flakes, affecting each other (Moskwitin 1936, Osipov & Sokolov 1975).

The most abundant erratic psephite material is observed in the Upper Pleistocene till, while the most various one including a lot of crystalline rock types is found in the Middle Pleistocene till contains scarce and petrographically rather monotonous rock fragments which appear to be most stable under supergenous conditions (Vitovskaya & Nikitina 1986).

The Middle Pleistocene till is distinguished by the abundance of sand characterized by well-rounded sand grains and the highest contents of dark-colored heavy minerals. The Middle Pleistocene and especially the Lower Pleistocene tills contain sand interbeds. Their composition and grain appearance are close or identical to that of the sand within the loam and sandy loam. This fact indicates their close origin.

Two persistent clay mineral assemblages are observed in the studied section. The first one, consisting mainly of illite, is presented both in the Upper Pleistocene till and in the varved clay, as well as in the Middle Pleistocene intertill clay. The other montmorillonite-illite assemblage was found in the Middle Pleistocene and Lower Pleistocene tills. Kaolinite and chlorite are present in diverse quantities in all the units of the section.

The Upper Pleistocene till including the varved clay interbed displays a well-preserved primary texture. It is characterized by the highest liquidity index and a high void ratio. Characteristic features of the Middle Pleistocene till are as follows: a considerable homogeneity, the highest bulk density and hardness, the lowest plasticity and liquidity indexes (Table 1). The lower laying strata are essentially destroyed. The bedded Lower Pleistocene till stands out againstathe other tills by a comparatively low bulk density and high plasticity. Many of the gained data affirm previous results obtained for three tills in the Kurzeme seaside region (Springis et al. 1964).

There are two water basin originated clay strata in the studied section. The younger one, within the Upper Pleistocene till, has got the typical texture patterns of glaciolacustrine sedimentation and characteristic inclusions of coarse clastic grains delivered from floating ice. The older one, between the Middle Pleistocene and Lower Pleistocene tills, differs from the mentioned above by a considerably higher material sorting degree and much more homogenous primary texture.

* * *

The above mentioned features of three tills and of the clay strata may be caused by particular geological conditions, palaeogeographic environments and glacier spreading during diverse epochs of the Quaternary period.

The Early Pleistocene glacier delivered a residual material from the upper zones of the Prequaternary weathering crust developed in the SE part of the Scandinavian Shield, as well as material of Silurian and Devonian rocks (including the old red formation) widely spread in the recent Baltic Sea area (Gaigalas 1974, Afanasyev 1977, Nemtsova 1986, Kurshs 1992). It is supposed that during the Early Pleistocene glaciation the boundary between the palaeoglacier and the sea was near the site of the borehole No. 37. This resulted in the bedded structure of the lower till including the facial varieties of the glacio-marine type.

The Middle Pleistocene intertill clay stratum was formed during several stages. The sedimentation and lithification processes resulted in a rather homogenous primary composition and structure, and a simple texture with slightly pronounced very thin bedding. These features, as well as their similarity with the Holocene sediments of the Gotland Deep in the Baltic Sea, confirm the assumption that the clay stratum is deposited in a deep water basin, apparently in a marine one. The following advance of the great Middle Pleistocene glacier and the subsequent significant overloading had caused the clay fissuring and even brecciating, obviously in a frozen state. That means, that the sea bottom was drained dry before the Middle Pleistocene glaciation. During the next interglacial epoch recreation and cementation of the clay in a thawed state took place.

The Middle Pleistocene glacier abraded many diverse rock and mineral sources: both weathered and fresh Precambrian rocks in the alimentation area (Gaigalas 1974), obviously uplifted after the previous glaciation, as well as Palaeozoic and Quaternary (marine, alluvial, loess, glacial) deposits along the glacier path. Therefore, there is such a variety of erratic material in the middle till. Its compaction and homogeneous structure may be explained by the position of the borehole 37 site with regard to the central lateral part of the widespread palaeoglacier. That thick glacier essentially disturbed both the underlying intertill clay and the lower till.

The Late Pleistocene glacier abraded mainly the slightly weathered and fresh solid rocks of Fenno-Scandia, as well as predominantly glacial Quaternary deposits of the recent Baltic Sea area (Springis et al. 1964, Gaigalas 1974). That is why the upper till contains abundant, but less diverse erratic material and semimonomineral (hydromicaous) clay matrix, analogous to that of the Valday tills of European Russia (Springis et al. 1964, Nemtsova 1986) and the Wisconsin tills in Illinois, USA (Willman et al. 1963).

At the end of the Late Pleistocene there was an oscillating edge of the glacier, close to the studied site, and the glaciolacustrine interbed deposited inside the upper part of the upper till. During the Holocene the upper till was probably partly washed out by erosional processes on the sea bottom.

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Shipboard Determination of Deposition Rates of Recent Sediments Based on Chernobyl Derived Cesium-137

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The increased level of Cesium-137 in the Baltic Sea sediments following the Chernobyl nuclear power plant accident of 1986 forms a clear marker that can be used for evaluating present day rates of sedimentation. A shipboard gamma-spectrometer, designed for bulk analysis of the radioactivity of marine sediments, was used in the experiment to determine the depth of deposition of increasing Cs-137 activity. Using other dating methods, the onset of the increased level was found to coincide with the 1986 Chernobyl fallout.

INTRODUCTION

The Chernobyl nuclear power plant accident in 1986 and the increased fallout of radionuclides in the Baltic Sea area caused an increase in the level of Cs-137 and Cs-134. This was well recorded in the terrestrial and marine environment including the muddy sediments of the Baltic Sea. The anomalous increase forms a marker that has been buried to increasing depths in the sediment, equivalent to the rate of sedimentation, i.e. the time since the accident. This marker has been successfully used to confirm the inferred present day rate of sedimentation. Measureable levels of Cesium-137 have been observed even in the most watery layers of some of the sedimentation basins chosen for environmental radionuclide monitoring of the Baltic Sea. In 1992, 6 years after the fallout, a clear stratigraphic marker of Cs-137 was found above the gradually vanishing 1963 peak in several sediment core samples (Ikäheimonen et. al 1988).

In sampling sediments from completely new sites this marker can be used as an aid to date sediments. The rates of deposition in active sedimentary basins have normally been determined by tedious and expensive methods involving the use of e.g. Pb-210 and Cs-137 and related nuclides in land-based laboratories. Besides being time-consuming, the results are often available later than most of the other parameters used in various sedimentological research. The idea of having an on-board preliminary dating method in which the Cs-137 peak of the Chernobyl accident could be determined, preferably during ongoing sampling, would drastically increase the reliability of both choice of sampling site and the sediment sampling itself. This article introduces a suggestion for a new quick on-board method for the determination of the 1986 layer in a sediment core.

MEANS AND METHODS

The Marine Ecogeological Patrol (MEP) cruise in August 1992 on board the Russian r/v Professor Multanovsky was a multidisciplinary endeavor incorporating various geological and geophysical research activities. The available equipment included a shipboard gamma-spectrometer, which was used for routine bulk analysis of the radioactivity of sea-floor sediments collected with a grab sampler. The idea was aroused to try to measure the gamma-spectrum of carefully sliced, one centimeter thick sections of sediment taken with a second generation Niemistö-corer ("Gemini" with a 80 mm diameter core liner) to check whether the Chernobyl event could be detected at specific levels in the sediments.

Sectioned samples from two stations in the eastern Gulf of Finland were chosen for analysis using the transportable, low-background, shipboard gamma-spectrometer, type "UMKA", built at the Radiochemical Laboratory of the Krylov Institute in St.Petersburg. The chosen stations (No. 1 and No. 2) represent areas with a assumed high rate of sediment deposition.

No. 1	Nar-4	59 33'.44	27 47'.20	depth 38 m
No. 2		60 11'.18	28 53'.52	depth 29 m

The gamma-spectrometer system consisted of:

- detector of gamma-radiation based on a scintillation crystal of NaI(Tl) 63 x 63 mm in size, with the following characteristics:
  - sensitivity 4x10-3 (1/Bq.s) (Cs-137);
  - background level 15(1/s);
  - lower limit of detectable activity - 5 (Bq);
  - energy range - 0.1-3 (Mev);
  - energy resolution - 11% along gamma-line for Cs-137;
- housing with lead shielding;
- 1024-channel pulse analyzer;
- PC-based software for analysis and display of results.

SHIPBOARD PROCEDURES

The gamma-spectrum of each 1 cm thick slice of sediment taken with the Gemini corer and deposited in a flat plastic dish, was measured with the shipboard analyzer for 103 to 104 seconds. The actual spectrums (Fig. 1) were calibrated using a predefined program and a set of standards to establish the background level. The gamma-peaks present in the spectrum were calculated on the basis of the area of each photo peak. In the present study the radionuclides Cs-134 and Cs-137 were given special attention. The total activity and the specific activity of the sediment samples were evaluated in Bq/kg, based on the volume and dry weight of the sample (Fig 2).

To establish the reliability of the shipboard method, the same subsamples were analyzed for gamma-activity (Table 1) at the Radioactivity Protection Laboratory, Helsinki. The ages of the samples were determined by the well-established lead-210 method at the Reactor Laboratory, Espoo.

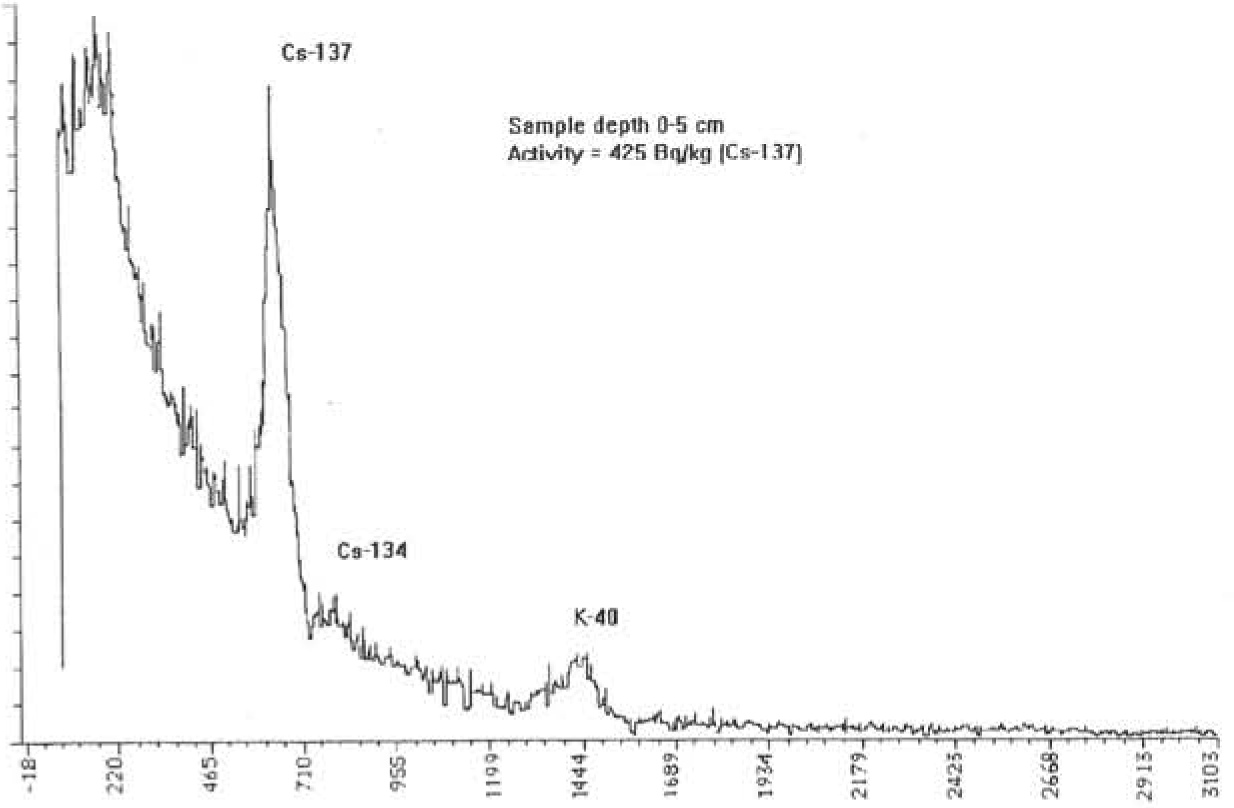

Fig. 1. An example of a gamma-spectrum of a recent sediment sample from the Gulf of Finland produced with the gamma-spectrometer developed at the Krylov Institute, St.Petersburg. Note the strong Cs-137 and the vague Cs-134 peak. The activity is calculated for dry matter although the measurement itself was made on wet material.

RESULTS

During the 1992 r/v Multanovsky cruise in the Gulf of Finland, a large number of sediment samples were taken from active sedimentary basins. They were found to have a specific Cs-137 activity of 25 to 500 Bq/kg . Since most of the measurements were made on grab samples, the results were indicative of the average specific activity of sea-floor sediments.The results indicated that the uppermost few to 10 centimeters of sedi-

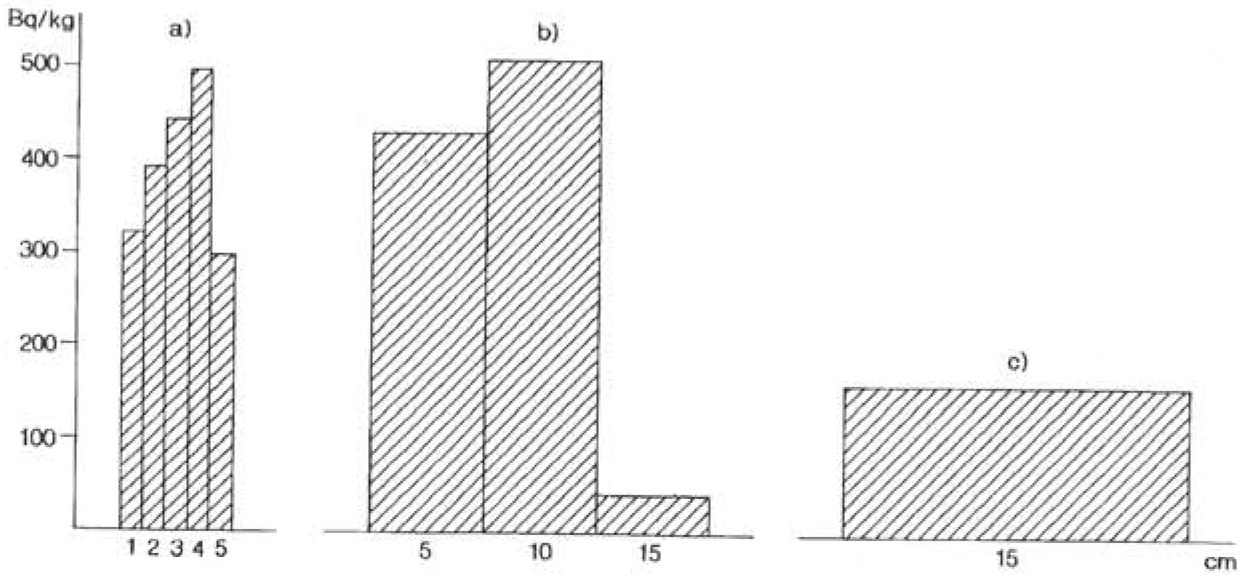

Fig. 2. The vertical distribution of Cs-137 in three sediment samples from two stations in the Gulf of Finland. The activity is given in Bq/kg of dry matter. The horizontal axis denotes the thickness and depth of sample from station No. 1 / Nar-4 (a) and station No. 2 taken with a corer (b) and a grab (c).

ments in recent Baltic Sea depositionary basins contain measurable concentrations of Cs-137. The ratio of Cs-137 to Cs-134 in the photo peaks clearly indicate that the main source of the contamination can be attributed to the Chernobyl accident.

The use of the Niemistö-gravity corer and the special slicing procedure made it possible to separately measure 1 centimeter thick sections of the sediment core. The abrupt increase in Cs-137 activity from a low, pre-Chernobyl level, to a definite anomalous peak at a stratigraphic level that was dated by the Pb-210 method and found to coincide with the Chernobyl event of 1986. Fig. 2 gives the results of the two cores used in this preliminary study.

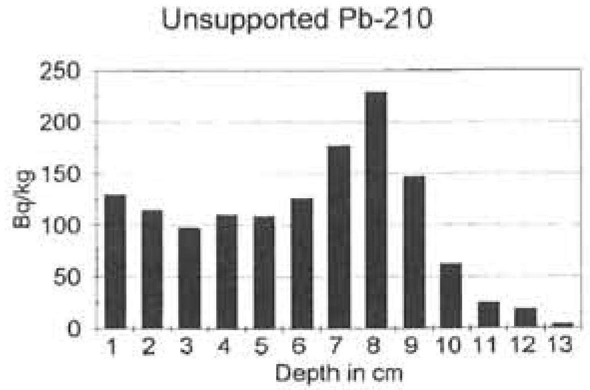

Fig. 3. Activity of lead 210 (Bq/kg dry matter) in the upper 13 centimeters of sediment core from station No. 1 Nar-4. The distinct decrease in Pb-210 activity above 7-8 centimeters and a rather uniform distribution within the upper 6 centimeters could be indicative of a rather well-mixed sediment layer either due to bioturbation or simply exhibiting a storm layer.

DISCUSSION

The Nar-4 sediment samples in Fig.2 and Table 1 show a moderate Cs-137 activity. This is in good agreement with the lower Pb-210 activities shown for the upper part of the core in Fig. 3. These observations can be explained by dilution of the sediments with older, less active sediments. This becomes obvious when comparing the K-40 and Cs-137 activities in the two cores (Nar-4 and XV-1). The higher potassium activity in Nar-4 is due to a higher concentration of potassium rich minerals (micas, feldspars, etc.) being typical of older late-glacial clayey and silty sediments.

The results from station XV-1 (Table 1) clearly show that the Chernobyl accident and the flux of radioactive cesium occurred when the material, now located 4 to 6 centimeters below the sea bed, was being deposited. The fact that high cesium concentrations are found at levels higher up along the core (maximum at 2-4 cm), can be explained as a result of formerly deposited modern material being slowly transported from shallower areas into the sediment basin where station XV-1 is located.

Thus, a closer scrutiny of the distribution of e.g. Cs-137 within the sediment column can be indicative of the nature of the depositionary environment. An uniform distribution of concentrations throughout the upper sediment layer could indicate unstable depositionary conditions, while a definite maximum at a specific level followed by a clear decrease in activity would mark more stable conditions. A steep decrease would indicate that large amounts of older, uncontaminated material is being deposited, while a gradual decrease would indicate substantial lateral transport of recent material.

Table 1. **Two sediment cores from the Gulf of Finland measured at the Radioactivity Protection Laboratory, Helsinki**

Station	Depth in core (cm)	K-40 Bq/kg (+/- %)	Cs-134 Bq/kg (+/- %)	Cs-137 Bq/kg (+/- %)
Nar 4/13.07.1992	0 - 2	1100 (5)	21 (5)	340 (3)
59°33'44"	2 - 5	1130 (5)	38 (5)	550 (3)
27°47'20"	100 - 105	1130 (5)	<1	<1
XV-1 06.07.1992	0 - 2	740 (7)	140 (2)	1640 (3)
60°14'10" 27°15'17"	2 - 4	780 (7)	270 (2)	3090 (3)
	4 - 6	800 (7)	190 (2)	2320 (3)
	6 - 8	740 (7)	17 (8)	280 (3)
	8 - 10	770 (5)	5.4 (20)	160 (4)
	10 - 15	830 (7)	3.0 (20)	120 (6)
	15 - 20	790(5)	2.3 (25)	96 (4)

CONCLUSIONS

Our preliminary results show that the increased level of Cs-137 activity following the Chernobyl accident is well preserved in the sediment strata of active sedimentary basins. The maximum Cs-137 peak found at the depth of 4-5 cm (Fig. 2) coincides with the Chernobyl event established with other dating methods. The fact that the decline of the activity in overlying deposits is very gradual can be explained by redepositionary processes and delayed river runoff. Although the fallout was originally unevenly distributed in the marine area, mixing and transportation of the particulate matter by wave action and currents caused cesium to be deposited on various sea bottoms. Due to resuspension by waves and currents, contaminated material is still being transported to active sedimentary basins. Strong bioturbation by benthic animals (Mesidotea entomon and Monoporeia affinis) can be a further explanation to the rather high levels of Cs-137 activity found in the uppermost sediments and not only co-incident with the Chernobyl-event. It should be noted that the strongest Cs-137 peak coincided with the Pb-210 date of 1986.

It is obvious that the transportable gamma-spectrometer developed at the Krylov Institute, St.Petersburg, can be successfully used on board to determine the Cs-137 maximum peak directly from thin slices of recent sediments. Despite the rather short half-life of the radionuclide, the level of radioactive fallout in Baltic Sea sediments, following the 1986 Chernobyl accident, seems to have been sufficient to make Cs-137 a reliable sediment stratigraphic marker. Furthermore, the vertical postdepositional migration of the element seems to be negligible. The vague peak of the short-lived Cs-134, still found in the samples, confirms that the observed anomaly was caused by Chernobyl. Due to lateral transportation and redeposition, seafloor sediments deposited on top of the 1986 deposit still contain high concentrations of cesium-137. However, below the Chernobyl horizon the level of this radionuclide decreases rapidly to the very low level that prevailed before the accident indicating that the downward diffusion of the radionuclide is negligible.

Thus, gamma-spectrometric measurements can be successfully used to preliminarily determine the rate of deposition of recent sediments in active basins of the Gulf of Finland. Besides being quick a further advantage of the method is the fact that the samples are unaffected by the measuring procedure and can thus be used for other analytical purposes.

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BALTICA INFORMATION

LARGE SCALE GEOLOGICAL MAPPING IN THE COASTAL PART OF THE BALTIC SEA

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The Geological Survey of Lithuania started to carry out a complex geological mapping (1:50 000) in the coastal part of the Baltic sea (Kretinga project, 1993-1997). The area of investigations is a 25-28 kilometre wide belt from the state border with the Republic of Latvia in the north to Klaipėda in the south. This region is very sensitive ecologically, therefore mapping covers a wide complex of different investigations and is closely connected with geological mapping of the Baltic sea on the same scale. The objectives of the Kretinga project are as follows:

* drilling through the whole Quaternary thickness and the upper part of pre-Quaternary (Cretaceous, Jurassic, Triassic) deposits;

* geophysical, hydrogeological and geotechnical field studies;

* sampling and laboratory analysis for stratigraphical, genetical and geochemical evaluations, etc.

As a result of these investigations, a series of special maps will be compiled:

* geological and hydrogeological maps of Quaternary and pre-Quaternary deposits;

* geomorphological, tectonic, geotechnical and geochemical maps;

* a map of mineral resources;

* and a set of environmental geology maps.

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