VILNIUS UNIVERSITY

NATURE RESEARCH CENTRE
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PLEISTOCENE DEPOSIT STRUCTURE AND SEDIMENTATION CONDITIONS OF LITHUANIAN MARITIME REGION

Summary of Doctoral Dissertation
Physical sciences, Geology (05 P)

Vilnius, 2015

This dissertation was prepared at the Nature Research Centre, Institute of Geology and Geography in 2008-2013.

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The dissertation will be defended at the Defence Council of Geological Sciences of Vilnius University:

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The official defence of the dissertation is due to be held at the public meeting of the Defence Council at the Nature Research Centre, Institute of Geology and Geography on 15 May 2015, at 3 p.m.
Adress: Akademijos Str. 2, LT-08412, Vilnius, Lithuania.

The summary of dissertation was distributed on 15 May 2015.
The dissertation is available in the libraries of Vilnius University and Nature Research Centre.

VILNIAUS UNIVERSITETAS

GAMTOS TYRIMŲ CENTRAS
GEOLOGIJOS IR GEOGRAFIJOS INSTITUTAS

JURGITA PAŠKAUSKAITĖ

LIETUVOS PAJŪRIO PLEISTOCENO NUOGULŲ SANDARA IR SEDIMENTACIJOS SĄLYGOS

Daktaro disertacijos santrauka
Fiziniai mokslai, geologija (05 P)

Vilnius, 2015

Disertacija rengta 2008-2013 metais Gamtos tyrimų centre, Geologijos ir geografijos institute.

Mokslinis vadovas – prof. dr. Petras Šinkūnas (Vilniaus universitetas, fiziniai mokslai, geologija – 05 P).

Disertacija ginama Vilniaus universiteto Geologijos mokslo krypties taryboje:

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Disertacija bus ginama viešame Geologijos mokslo krypties tarybos posėdyje 2015 m. gegužės 15 d., 15 val. Gamtos tyrimų centro salėje, Akademijos g. 2, LT-08412 Vilnius, Lietuva.

Disertacijos santrauka išsiųsta 2015 m. balandžio 15 d.
Su disertacija galima susipažinti Vilniaus universiteto ir Gamtos tyrimų centro bibliotekose.

INTRODUCTION

PROBLEMATICS

Notwithstanding the numerous attempts to decipher palaeogeographic conditions of the Lithuanian maritime region, many questions on lithology, stratigraphy and sedimentation of the Pleistocene deposits remain unsolved. Many problems of Pleistocene lithology and stratigraphy have been pointed out in the course of latest investigations in the maritime region. An urgent need arose for a synthesis of the available geological information on the maritime Pleistocene sediments, their composition, stratigraphy and sedimentation conditions. The newly obtained data in Lithuania and neighbouring countries allows for a new, state-of-the-art interpretation of the maritime geology in Lithuania taking into consideration the most modern approaches and knowledge.

TOPICS

The maritime region in Lithuania develops faster than other regions because of its unique geography, landscape, economic and recreational importance. A need for mineral and natural resources increases considerably with the growth of economy, industry, related infrastructure (e.g. building engineering etc.) and development of tourism and recreation. The increased exploitation of natural resources leads to the greater number of problems related to the natural deposits protection and their pollution risks (waste utilization etc.). An interest in geological environments and processes also increases. Modern and future geological processes depend very much on processes of the geological past therefore the latter have to be thoroughly studied. The Pleistocene deposits make up the largest part of maritime surface or are buried beneath a thin layer of the Holocene sediments. They are being continuously reworked by human activities, and are of great scientific and practical interest. The expansion and deepening of the Klaipėda port as well as a need for sustainable energy resources require a deep knowledge on the Pleistocene deposits and their formation. Therefore a deep understanding of the Pleistocene sediment composition, geological evolution as well as a good knowledge of the past geological processes are of prime interest for the land management and planning. Moreover, scientists of variable fields are interested and ready to discuss the origin of these deposits, their sedimentation conditions, stratigraphic subdivision and palaeogeographic conditions.

SUBJECT OF THE STUDY

An area, so-called "Lithuanian maritime region" (LMR), was chosen for this study. The study area comprises ca 40 km of land stretching to the east from the Baltic Sea coast: through the Pajūris lowland, and Nemunas delta region towards western slopes of the Žemaičiai (Samogitian) Upland (Basalykas, 1965) (Fig. 1). The study area partly coincides with the term "maritime region" defined by V. Gudelis (Gudelis, 1998) except for its easternmost boundary. Thus, the Lithuanian maritime region comprises the Pajūris lowland with Nemunas delta, Curonian Spit and Curonian Lagoon. The easternmost boundary based on climatic changes approximately coincides with a +40 m counter line which stretches from north to south along the western slopes of the Samogitian Upland including Skuodas, Gargždai, Kretinga, Žemaičių Naumiestis and Pagėgiai towns and crosses Nemunas river near the Vilkiškiai ridge (Rambynas). Whereas boundaries of the study subject, i.e. the sequence of Pleistocene deposits, do not follow modern landscape boundaries, a line along the 21°40′ meridian was chosen for the easternmost boundary in order to make technical things simpler.

The study subject is a sedimentary sequence deposited during the Pleistocene time of the Quaternary period, i.e. ca 730-12 ka (Satkūnas et al., 2007), distributed in the maritime region and composing a thick (from tens to ca 150 m) layered sequence. The deposits overlie the Pre-Quaternary surface dissected by palaeo-incisions (Šliaupa, 2004) and are either covered with a thick Holocene sediment layer or are outcropping at the surface. The sediments were deposited during the distinct Pleistocene climate oscillations. A complex sequence of sediments had been formed that was further complicated by the following recurrent glacier exarations, eroded by ice melt and river waters and other geological processes. That is why is so difficult to study the Pleistocene deposit structure, to subdivide it stratigraphically and to correlate between its separate units. The maritime region is dominated by a Pleistocene tills left after the melting glacier itself, while inter-till sediments deposited by ice melt waters and in lakes are only sporadically distributed. Interglacial sediments are especially rare in the study area. However one of the inter-till layers is present in the study area and will be thoroughly described later.

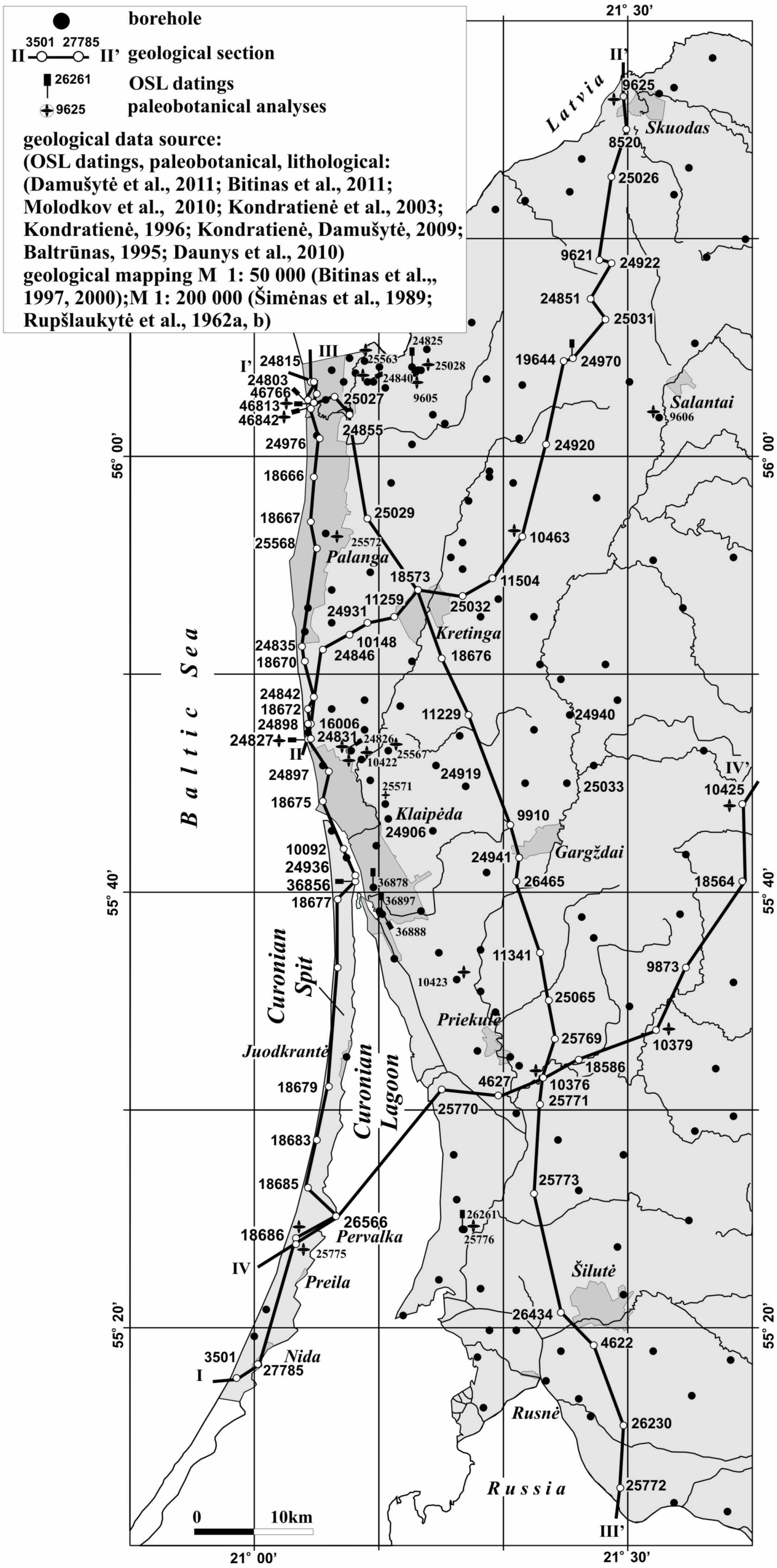

Fig. 1 Map of study area

The presence of this complex allowed the stratigraphic subdivision and correlation of the Pleistocene deposits in the maritime region because the available biostratigraphic and absolute age data was insufficient to obtain proper sediment ages. As the investigation results had shown, the subdivision and correlation of till layers are complicated in the study area. Meantime, the evolution of palaeogeographic conditions in the region is still under the discussion. Even ice advances or retreats are questionable for some time slices. All the above stated problems on stratigraphy and sedimentation conditions in the maritime region were the major cause for the choice of the study subject.

AIM OF STUDY

Aim of the study is to obtain the Pleistocene deposit structure and sedimentation conditions in the Lithuanian maritime region on the basis of the available geological information.

TASKS

- to define and evaluate criteria for the Pleistocene sediments stratigraphy and correlation;
- on the basis of the obtained criteria, to carry on a stratigraphic subdivision and correlation of the Pleistocene sediments in the Lithuanian maritime region;
- to create a digital spatial (3D) model of the structure of the Pleistocene sequence;
- to reveal characteristics of the Pleistocene deposit structure beddding conditions;
- to define sedimentation conditions of the tills and inter-till sediments.

STATEMENTS TO BE DEFENDED

1. The gravel and pebble petrographic composition of the tills in the maritime region is similar, however the mineral composition differs in till sandy parts.
2. The position of the wide-spread Pamarys and other inter-till sediment complexes in the Pleistocene strata allows the till complexes to assign to certain stratigraphic subdivisions.
3. A digital spatial (3D) model based on the geological information serves a base for a control of the consistency of the obtained results on Pleistocene deposit structure composition and stratigraphy.

NOVELTY OF STUDY

A new model of the structure of the maritime Pleistocene deposit was created on the basis of the state-of-the-art results of geological investigations (descriptions of drillcores, results of the plant palaeobotanical, petrographic and mineralogical investigations as well as radiometric age datings). The model reveals the structure, deposition conditions and stratigraphy. New Pleistocene subdivisions were found and a stratigraphic position of some of the deposits was justified. The obtained results are illustrated with cross-sections, sketches of sediment distribution, thicknesses and deposition surfaces. Methods of data canonical ordination were used for a stratigraphic subdivision and correlation of the sediment strata. Sedimentation conditions for the till and inter-till deposits in the Lithuanian maritime region were deciphered.

APPLICABILITY

The digital 3D model of the Pleistocene deposit structure created on the basis of available geological information and computer programmes can be used by a wide variety of specialists (e.g. geologists, ecologists, architects etc.) in different fields (e.g. nature protection, exploration of mineral deposits, groundwater distribution etc.) and helps to solve different problems on sustainable land use, exploitation of energy and mineral resources etc. Such the visual model can provide different specialists with the geological information (cross-sections, sketches of sediment bedding, deposition surfaces, sediment distribution etc.) useful for any analysis of the sedimentary sequence. They can use the model for their own needs and for planning of future investigations. Different sketches (sediment distribution, thicknesses etc.) can be easily extracted from the model. A compiled package of sketches on sedimentation conditions in different times is useful for a reconstruction of palaeogeographic conditions and other scientific and practical purposes.

APPROBATION

The obtained results were published in 2 scientific publications with co-authors in periodical journals and presented in international conference.

CONTENTS

The thesis consists of introduction, review of the previous studies, data and methods, presentation of lithological criteria for stratigraphy and correlation of Pleistocene deposits, as well as the peculiarities of deposit structure, stratigraphy and sedimentation conditions, conclusions. The thesis comprises 109 pages, 44 figures, 5 tables.

ACKNOWLEDGEMENTS

The author is grateful to her supervisor prof. Dr. P. Šinkūnas, head of the Quaternary Research laboratory at the Institute of Geology and Geography Dr. V. Šeirienė and other employees for their help and advices while preparing the thesis. She thanks very much Dr. A. Damušytė for descriptions of the newly obtained drillcore data and Dr. A. Bitinas for valuable geological information and consultations.

1. PREVIOUS INVESTIGATIONS OF PLEISTOCENE DEPOSITS IN LITHUANIAN MARITIME REGION AND PROBLEMS OF THEIR STRATIGRAPHY

The chapter provides an overview of previous geological investigations in order to understand how the knowledge on the Pleistocene deposit structure, sedimentation conditions and palaeogeography have been changing with increasing data and time in the Lithuanian maritime region (LMR). The most important and detailed studies of the Pleistocene deposits are associated with a geological mapping. Despite the fact that the LMR was covered by a complex geological mapping at different scales three times: in 1961-1962, 1989, 1997-2000; and numerous data was obtained during the local explorations, the stratigraphical subdivision, structure and sedimentation history of the Pleistocene deposits is still poorly understood there. An overview of the previous investigations showed that most of the problems on the structure of Pleistocene deposits in the LMR are related to variable age interpretations of the widespread inter-till sediment beds and to the correlation of dominant till layers. This widely distributed inter-till sediment sequence contains organic matter and might serve as an important marker for stratigraphical subdivision of the Pleistocene deposits. However, age interpretations of these inter-till sediments vary widely (Vonsavičius, 1967; Gudelis, 1973; Kondratienė, 1967, 1971, 1996; Kondratienė et al., 2003; Kondratienė, Damušytė, 2009; Bitinas et al., 2013). The results of latest investigations show that these sediments might have been formed during a few sedimentation cycles starting from the Late Saalian and finishing in the Middle Weichselian (Bitinas et al., 2013). So, rather different stratigraphy and interpretation of a structure of the Pleistocene deposits in the LMR were given by different researches. Lithological approaches traditionally used for stratigraphical subdivision and correlation of Pleistocene tills, such as gravel and pebble petrography, results of geochemical or even hornblende grain roundness analyses carried out in this region during geological mappings and other investigations do not give satisfactory results (Bitinas et al., 1999). Based on the lithostratigraphical and palynological data, some authors provide two (Vonsavičius, 1967) or three (Gaigalas, Saladžius, 1974; Bitinas et al., 1997, 2000) major glacial advances in the LMR during the middle Pleistocene attributed to the Dainava (Elster), Žemaitija (Drenthe) and

Medininkai (Warthe) glacial periods. Also either two corresponding to the Marine isotope stage (MIS) 2 (Baltija and Grūda glacial stages) or three corresponding to the MIS 5a-d, 4 (Varduva) and MIS 2 (Baltija and Grūda) (Vonsavičius, 1967) ice sheet advances are thought to have had occurred during the Nemunas (Weichselian) glacial period. The opinion that Lithuania was not covered by ice sheets since the end of Merkinė (Eemian) Interglacial through the Early and Middle Nemunas and was glaciated only in the Late Nemunas (Weichselian) time has predominated for a long time. However the recently published results of geological investigations in the Šventoji harbour and Klaipėda strait showed that probably the part of or even whole Western Lithuania was covered by yet another ice advance during the early Middle Weichselian (MIS 4) glacial period (Molodkov et al., 2010; Damušytė et al., 2011; Bitinas et al., 2011). The idea of till existence in the Middle Nemunas is also supported by the OSL dates of the till complex underlying (113-84 ka) and overlaying (49-44 ka) inter-till sand deposits in the area of Šventoji harbour (Damušytė et al., 2011). Based on the dating results this till complex was attributed to the earliest stage of Nemunas (Weichselian) ice advance during Middle Nemunas time and named as Melnragė sub-formation (Molodkov et al., 2010; Bitinas et al., 2011; Damušytė et al., 2011).

2. DATA AND METHODS

2.1 Data on sediment composition

Results of the geological mapping at a scale of 1:50 000 in the Šilutė and Kretinga areas (Bitinas et al., 1997, 2000) as well as of the offshore and onshore geological and geological-hydrogeological mappings at 1:200 000 scale (Šimėnas et al., 1989; Rupšlaukytė et al., 1962a, 1962b) provided by the Geological Survey of Lithuania (Fig. 1) were used for an analysis of Pleistocene sediments in the Lithuanian maritime region. The obtained data was also supplemented with the palaeobotanical, lithological and geochronological data published by different authors (Bitinas et al., 2013; Bitinas et al., 2011; Damušytė et al., 2011; Molodkov et al., 2010; Kondratienė, Damušytė, 2009; Kondratienė et al., 2003; Kondratienė, 1976, 1962; Vonsavičius et al., 1967).

Data of petrographical analysis of till gravel and pebbles

Results of the 251 petrographical analysis were used for the stratigraphic subdivision and correlation of tills. The largest part was obtained by standard methodics (Gaigalas, 1965, 1979) by M. Melešytė during the geological mapping and scientific research in the maritime region (Bitinas et al., 1997; Šimėnas et al., 1989; Malinauskas et al., 1986; Gaigalas, Saladžius, 1974). She has distinguished the most informative petrographic rock groups such as crystalline rocks, dolomite, Silurian, Ordovician and other (late Palaeozoic and Mesozoic) limestone, sandstone, marl etc. The remaining part was obtained by the same methodics during different studies and taken from publications: V. Baltrūnas (1995, analysed by P. Šinkūnas), and Daunys et al. (2010, analysed by J. Paškauskaitė). Since the results on petrographic compositions were taken from the different sources, diameters of the investigated sediment particles varied considerably: 3-5 mm, 3-7 mm, 5-7 mm, 5-10 mm, and 7-10 mm. Most of the results come from the 5-7 mm and 5-10 mm sized particles. Such discrepancies in sizes of particles from the different sources might have caused some errors in the subdivision and correlation of deposits according the petrograpic analysis. However, as was implied from the obtained results, such discrepancies are small in the particles of similar size (Gaigalas, 1979).

Data of till mineral analysis

The mineral composition of tills from 6 boreholes was analysed by P. Šinkūnas in a 0.1-0.25 mm fraction using the immersion method. Light and heavy minerals were separated by a bromoform liquid. 16 heavy and 6 light minerals were identified and their number was calculated in percentages for the 66 till samples.

Data of palaeobotanical (palynological and diatom) investigations

Results of the palaeobotanical investigations were also used for the Pleistocene sediment stratigraphy. Most of the results were obtained by standard methodics (Grichiuk, 1940; Battarbee, 1986) during the geological mapping (Bitinas et al., 1997, 2000; Šimėnas et al., 1989; Rupšlaukytė et al., 1962a, 1962b). The other part was published (Damušytė et al., 2011; Kondratienė, Damušytė, 2009; Kondratienė et al., 2003; Šeirienė, Kondratienė, 2004; Kondratienė, Šeirienė, 2003; Kondratienė, 1976, 1962, 1996, 1971; Malinauskas et al., 1986; etc.) as the results of local investigations.

2.2 Statistical analysis for the lithological data of tills

A statistical canonical ordination analysis using a computer programme for multivariate statistical analysis CANOCO 4.5 (Ter Braak and Šmilauer, 1998) was applied for the mineralogical and petrographical data in order to obtain the reliable subdivision and correlation of Pleistocene till beds. To summarize the major gradients in mineralogical and petrographical data, a preliminary Detrended Correspondence Analysis (DCA) was performed on the data sets to estimate gradient lengths in standard deviation (SD) units of the first DCA axis and to determine linear or unimodal ordination methods to be used for the data analysis (Ter Braak and Šmilauer, 1998). Since the gradient length was less than two SD, a Principal Component Analysis (PCA) was applied on the data sets. The Principal Component Analysis (PCA) allowed the evaluation of compositional differences between till complexes of different age. Additionally, a Canonical Correspondence Analysis (CCA) for 3 boreholes was used to identify relationships between mineralogical and petrographical compositions of tills.

2.3 Structural analysis of the Pleistocene deposits

A correlation of the 200 drillcore logs (Fig. 1) was carried out in order to obtain structural variations of the Pleistocene sediment beds. Sediment characteristics given in the drillcore descriptions, bedding conditions, results of the palaeobotanical, lithological studies and age datings were evaluated. All the obtained information served a basis for a 3D model of the Pleistocene strata. A 3D model is based on altitudes of bedding surfaces obtained from the stratigraphic correlation of the beds. A structure of the Pleistocene sequence was obtained from the above data by means of computer programmes *Rockwoks* and *Surfer,* and by compiling differently-oriented cross-sections, sketches of bedding surfaces, thicknesses and distribution. The results allowed to improve bed correlation and to compile a final 3D model for the Pleistocene sequence. For visualization, 4 representative cross-sections compiles using *Rockwork*s programme are provided in the thesis because the model itself is digital, compiled by mentioned computer programme. Such cross-sections can be compiled from a model through any drillings in any direction. Final sketches of the distribution of till and inter-till beds of different age, thicknesses and bedding surfaces were created by means of *Surfer* computer programme using a „kriging“ interpolation method.

Reliability of the data

The model is interpretational by its nature but supported by real geological information therefore it can be easily changed with time and advances in science and geological investigations of Pleistocene deposits. Such flexibility and visuality are greater advantages of the created model than its “perfection” because it can be easily supplemented with a new data, corrected, re-interpreted if needed and renovated.

Quality of petrographic and mineralogical analyses is of prime interest because the entire correlation between beds and stratigraphic subdivision often depend on it when other geological information is lacking. Insufficiency of data and its sporadic distribution can also cause a lot of problems. Irregular distributed drillings and different thicknesses of variable tills are responsible for inconsistent information on till and inter-till deposits.

Irregularities arouse because the results of gravel and pebble petrography used in the study were taken from different investigators. In order to evaluate the reliability of the used data a Principal Component Analysis was applied for the results by different authors obtained at different time. The analysis has shown that most of the results by the same author even obtained at different times plot in a diagram centre and are compatible, whereas the results of other authors plot in marginal parts. Such discrepancies can be explained by the fact that different authors have used different methods how to identify rocks.

3. LITHOLOGICAL CRITERIA FOR STRATIGRAPHIC SUBDIVISION AND CORRELATION OF THE PLEISTOCENE DEPOSITS

Stratigraphic subdivision and correlation of the Pleistocene sediment beds and their sedimentation conditions are based on geological criteria defined during variable geological investigations (Čepulytė, 1968; Baltrūnas, 1995; Bitinas, 2011). Such criteria that characterise differently-aged till beds might be their lithology, i.e. their composition (e.g. petrographical, mineral, geochemical and granulometric) and visual-lithological features. Tills might be attributed to distinct glacial-sedimentational cycles according to changes in their lithology (Gaigalas, 1979). Lithological criteria allow for reliable subdivision and correlation of tills even when palaeobotanical and age data is missing.

Petrographic and mineral compositions of till beds were evaluated after statistical treatment of the petrographical and mineral analyses data from the 66 drillings in the Lithuanian maritime region (Fig. 3.1). Finally the till beds were subdivided into complexes according to predominating rock and mineral groups. The 6 lithologic till complexes were distinguished on the basis of statistical analysis, till petrographical and mineral composition as well as visual-lithological features, bedding conditions, palaeobotanical and age data. The complexes have different lithological characteristics. The Pleistocene sediment beds were stratigraphicaly subdivided and correlated according to visual-lithological features characteristic of the distinguished lithological complexes in those onshore drilling cross-sections where no petrographical or mineral investigations were carried out.

Because of peculiarities in till formation (likely because of the same exaration sources, similar glacial flow directions and post-sedimentation processes) resulting in similarities and variability of differently-aged till beds, it was difficult reliably subdivide and correlate some till beds even after the statistical treatment. That is why their attribution to a distinct lithological complex is still questionable and ubiquitous. In some cases the obtained till lithological compositions contradict the logics of sedimentation. Therefore one or another interpretation was chosen based more on the available geological information than on the results of statistical analysis.

3.1 Mineral and petrographical composition of the Pleistocene tills

According to the results of petrographical and mineral investigations, tills of different ages have variable lithological composition (Gaigalas, 1965, 1979; Klimašauskas, 1965, 1967). These compositions depend on the distribution of lithologically distinct crystalline, Palaeozoic or Mesozoic rocks on the Pre-Quaternary surface as well as recurring directions of ice advances. Different lithological compositions and glacial flow directions have influenced petrographic and mineralogical features and some rhythmic cyclicity in the differently-aged lithological complexes (Gaigalas, 1979; Klimašauskas, 1965, 1967; Šinkūnas, 1998). This was confirmed also by a ratio of Mesozoic vs Palaeozoic rocks in the differently-aged tills (Šinkūnas, Jurgaitis, 1998). Thus, variations in petrographic and mineral compositions may serve as major criteria for subdivision and correlation of differently-aged till beds.

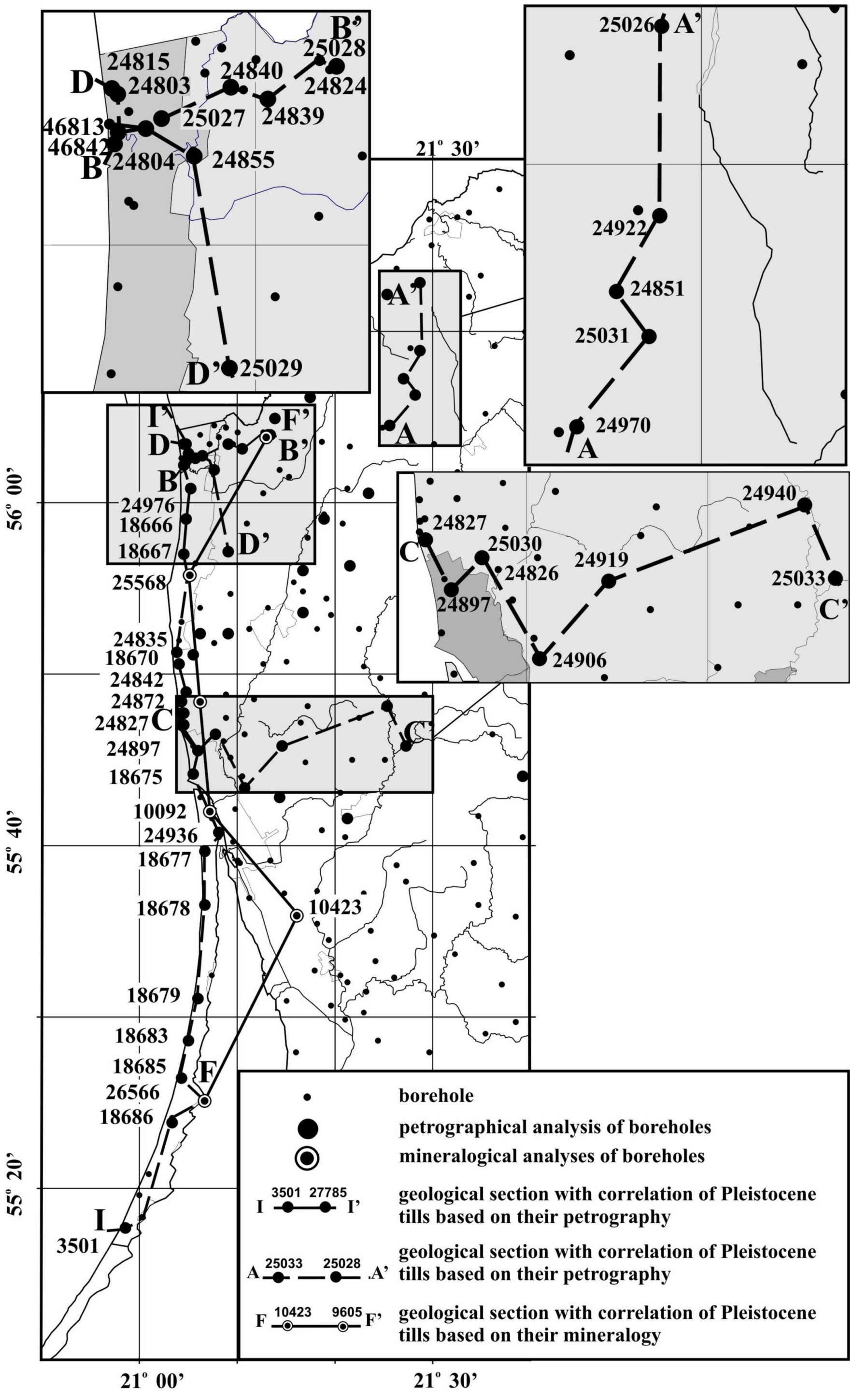

Fig. 3.1 Location of petrographically and mineralogically analysed sections in Lithuanian maritime region with detailed study areas

Mineralogy of till sandy parts

Mineral composition was estimated in the 6 onshore drillings. The results of statistical analysis point toward more prominent differences in mineral composition than in petrographical one in distinct till lithological complexes (Fig. 3.1.1).

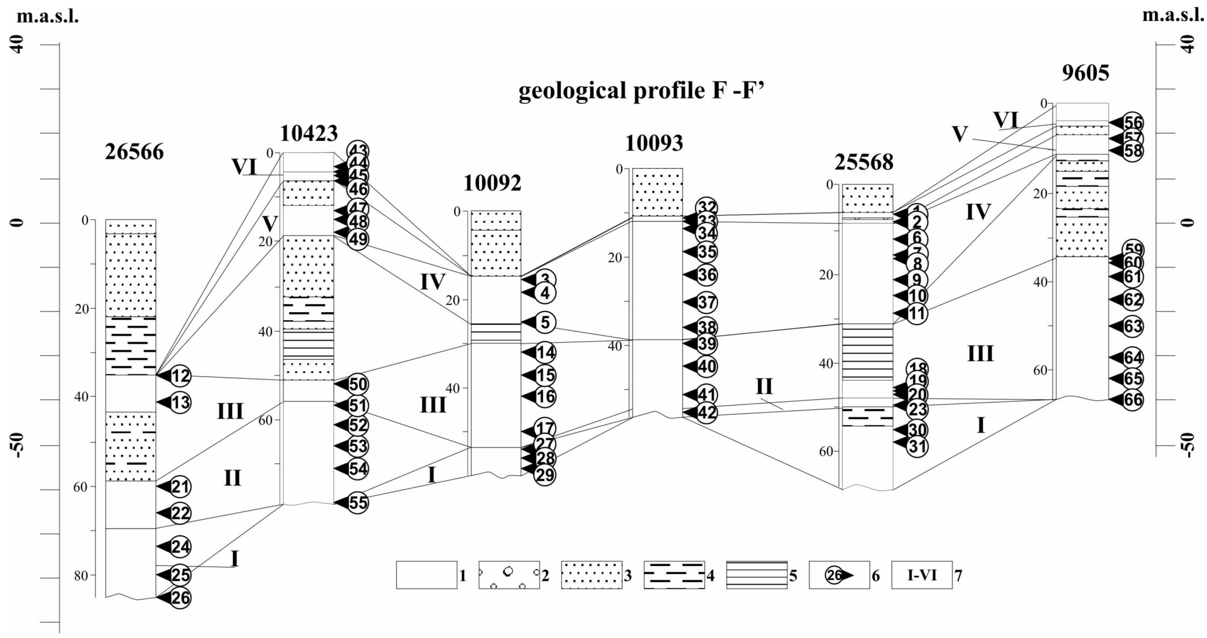

Fig. 3.1.1 Correlation of Pleistocene till complexes based on their mineralogy: 1 – till, 2 – gravel, 3 – sand, 4 – silt, 5 – clay, 6 – sampling point with number, 7 – till complexes (for location see Fig. 3.1)

The values of mean mineral amounts distinguished in the six LMR till complexes did not differ considerably by composition in the different till complexes. Meanwhile the totals of different mineral associations characterize mineralogical differences of the till complexes. A distribution of heavy minerals in the DCA biplot indicates the existence of such associations: 1) pyroxenes-tourmaline-garnet-epidote-amphiboles, 2) rutile-white pyrite, 3) pyrite-disthen, 4) staurolite-apatite-phoshates-zircon-ilmenite and magnetite-leucoxene-iron oxides and hydroxides (Fig. 3.1.2).

The LMR till complexes differ by amounts of the first (Fennoscandian) mineral association which amounts tend to increase in the younger till complexes (Fig. 3.1.1, 3.1.2). The lowest amount of mineral association pyroxenes-tourmaline-garnet-epidote-amphiboles and highest amount of mineral association pyrite-disthen are characteristic of the oldest till (I) complex.

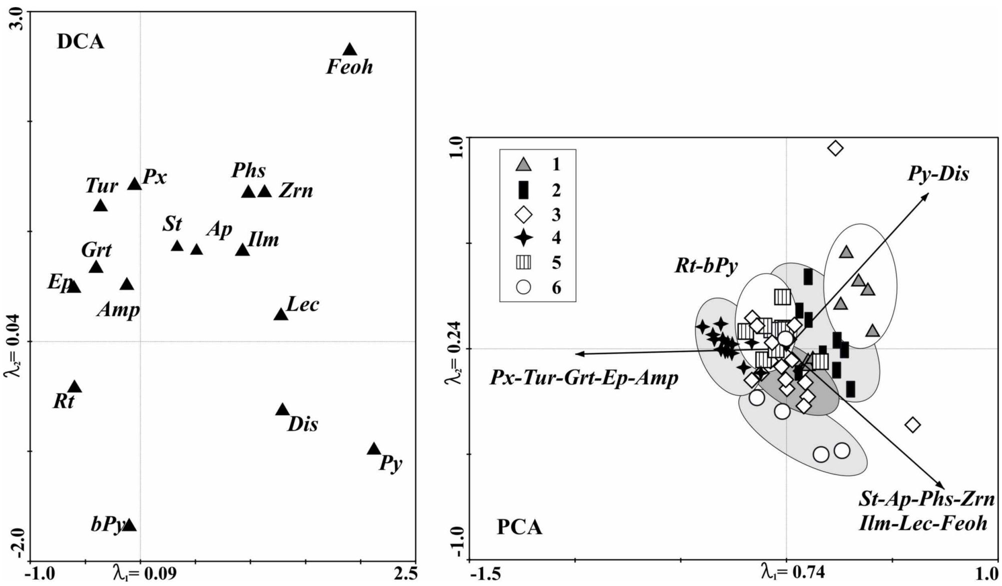

Fig. 3.1.2 Ordination diagrams of Detrended Correspondence Analysis (DCA) illustrating the arrangement of minerals and Principal Component Analysis (PCA) illustrating arrangement of till samples depending on amounts of mineral associations: 1) pyroxenes-tourmaline-garnet-epidote-amphiboles, 2) rutile-white pyrite, 3) pyrite-disthen, 4) staurolite-apatite-phoshates-zircon-ilmenite and magnetite-leucoxene-iron oxides and hydroxides; till complexes: 1 – I, 2 – II, 3 – III, 4 – IV, 5 – V, 6 – VI

The average values of mineral composition of the rest two till complexes (II and III) show the similarity between these lithocomplexes, however, the PCA biplots show that third (III) till complex has higher amount of the pyroxenes-tourmaline-garnet-epidote-amphiboles association minerals than the second (II) one. The greatest differences of mineralogical composition represent the forth (IV) till complex (Fig. 3.1.2). Its samples cluster as a discrete group along the first mineral association gradient showing the highest amounts of these minerals there in the sequence. The two uppermost (V, VI) till lithocomplexes, however, have slightly lower contents of the Fennoscandian minerals, but higher pyrite and disthen. The uppermost till complex (VI) has the highest amount of staurolite-apatite-phoshates-zircon-ilmenite and magnetite-leucoxene-iron oxides and hydroxides mineral association.

Petrography of till gravel and pebbles

Petrographic analyses of till gravel and pebbles from 29 deep, cross-secting the whole Pleistocene and 37 shallow drillings were treated statistically. The means of petrographical amounts in the distinguished six LMR till complexes are similar. The statistical evaluation of petrographic composition revealed that the differently-aged till beds can be better subdivided and correlated in separate cross-sections.

They differ by amounts of Silurian limestone, dolomite and crystalline rocks. Local differences in petrographic composition of the complexes disappear at a larger scale, therefore no prominent petrographical compositional variations were detected in the LMR and no directions of ice advances were obtained from those results.

Tills of the first (I) complex contain slightly bigger amounts of Ordovician and Silurian and other (late Palaeozoic and Mesocoic) limestone, marl and smaller amounts of dolomite compare to overlying till beds of the second (II) complex. The second (II) and third (III) complexes do not differ considerably in petrographic composition. According to the PCA results they differ in amounts of Silurian limestone and dolomite. Till beds of the second (II) complex contain more dolomite, while those of the third (III) complex are richer in Silurian limestone (Fig. 3.1.3). Till compositions of the forth (IV), fifth (V) and sixth (VI) complexes only slightly differ in dolomite, crystalline rock and Silurian limestone contents. An enrichment in dolomite, crystalline rocks and other (late Palaeozoic and Mesocoic) limestone as well as a decrease in Silurian limestone and sandstone is observed when moving up the cross-section.

A comparison of the third (III) and fourth (IV) complexes reveals the similarity in their till petrographical compositions, however the larger part of the forth (IV) complex is projected on vectors of Silurian limestone and sandstone. The forth (IV) complex has the lowest averages of dolomite (slightly more than 10%) and the largest amounts (over 40%) of Silurian limestone.

The Canonical Correspondence Analysis (CCA) has showed, that the glacial moving through crystalline rocks were enriched with quartz, biotite, feldspar, pyroxenes, epidotes, amphiboles and garnet (mostly Fennoscandian minerals) while after the exaration of sedimentary rocks (sandstone, limestone, dolomite and marl) the amount of iron oxides and hydroxides, pyrite, glauconite, leucoxene, zircon and carbonate minerals had increased in tills.

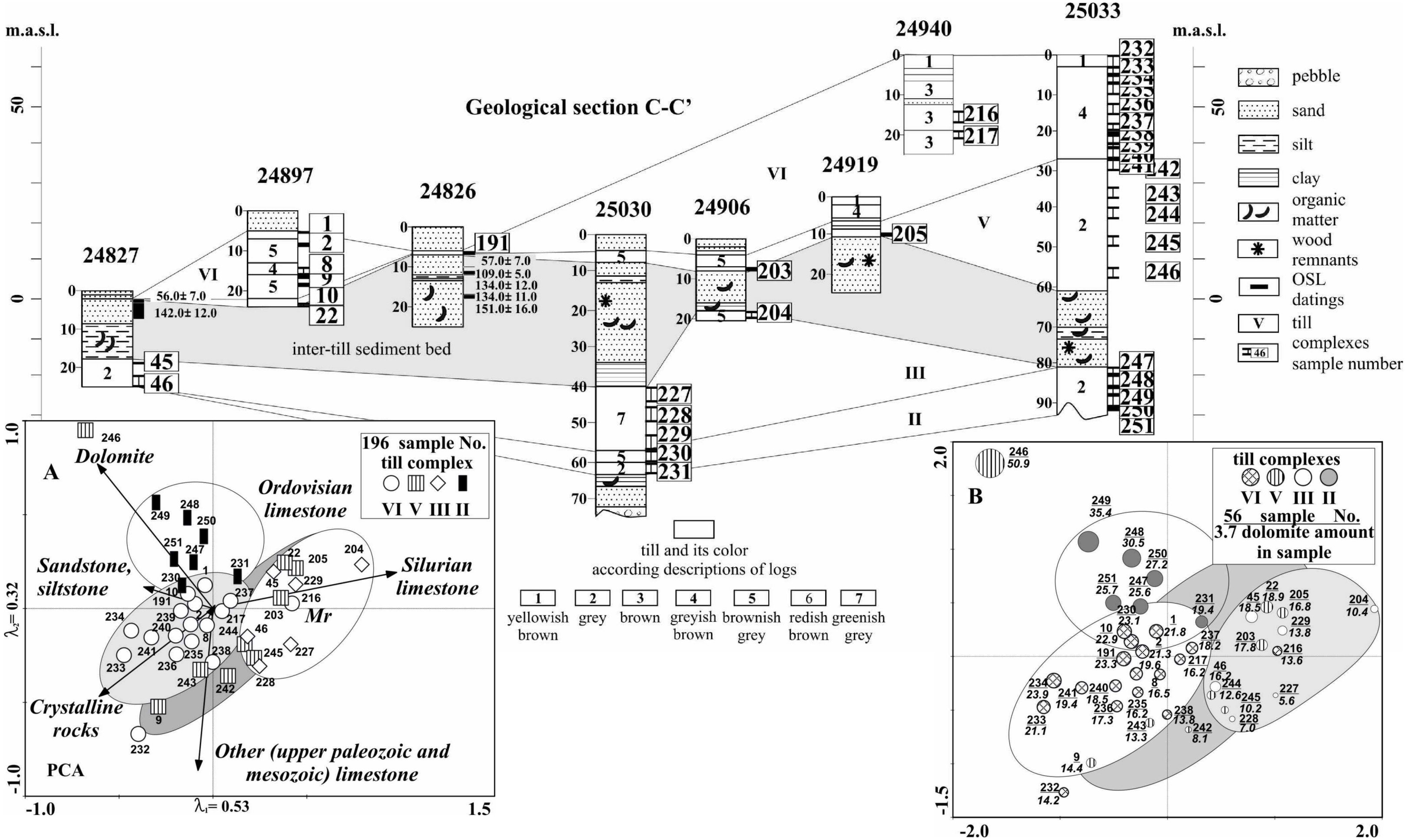

Fig. 3.1.3 Correlation of tills in geological section C-C'; A) Biplot of Principal component analysis (PCA) of till petrographical composition and B) dolomite content in different till complexes (for location see Fig. 3.1)

3.2 Visual-lithological properties of the tills

In the maritime region cross-sections without petrographic and mineral analyses, the Pleistocene sediment beds were subdivided stratigraphicaly also using visual-lithological properties and their bedding conditions. Later, they were correlated with those where petrographical and mineral investigations had been carried out. Some typical visual-lithological properties were distinguished for distinct lithological complexes after the revision of the LMR drillcores. Till colour and other physical properties are most important, that can serve as criteria for a subdivision and correlation of differently-aged tills when other geological information is absent.

However the results of investigations revealed that visual-lithological properties, especially colour, differ within a separate layer in the cross-sections and areas. Therefore a subdivision and correlation of differently-aged till beds in the Lithuanian maritime region based only on visual-lithological properties are rather complicated. They can be used locally as criteria for a stratigraphic subdivision and correlation of the till beds. The limited usage was caused likely by different, often subjective descriptions of the same drillcore as well as similar composition of the Pre-Quaternary rocks and similar geological processes (weathering, erosion etc.).

3.3 Results of the inter-till investigations and their usage for the Pleistocene stratigraphy

The available data on inter-till biostratigraphic and geochronological investigations helped very much for the age and stratigraphic interpretation of the Pleistocene sediment beds as well as of already distinguished lithological complexes. Stratigraphic interpretations of the maritime Pleistocene beds are based on inter-till age data, especially on the dating results for one lithologically well-distiguishable inter-till bed, as well as palaeobotanical investigations and bedding conditions. Bedding conditions of the palynologically studied Butėnai Interglacial were also used as criteria for the stratigraphic subdivision in the study area.

There are only two sediment sections identified as Butėnai (Holsteinian) Interglacial, located in the western slope of the Žemaičiai (Samogitian) Upland, eastern part of the study area. Although these sediments cover an incomplete interglacial as is indicated by a pollen succession, but the composition of pollen complex reflects interglacial conditions and correlates well with pollen from the Butėnai Interglacial sections in Lithuania and neighbouring countries (Kondratienė, 1962; 1996).

Another quite widely spread inter-till sediment sequence of sandy deposits containing organic matter, named as Pamarys sediment complex pretends to serve as an important marker for a subdivision of Pleistocene deposits. According to the OSL datings these sediments were deposited during several sedimentation cycles, starting from Late Saalian and finishing by Middle Weichselian (Bitinas et al., 2013).

Interpretations of location and distribution of the newly distinguished till beds asigned to the Middle Nemunas (Weichselian) Melnragė subsuite used for the Pleistocene model were influenced very much by the OSL dating results for the underlaying and overlying sandy sediments (Damušytė et al., 2011).

Thus, the available results on inter-till geochronology coupled with bedding conditions of the Pamarys complex, its lithology and palaeobotanical investigations contributed very much to the correlation of onshore Pleistocene sediment beds and their subdivision into two major segments, i.e. those of the Upper and Middle Pleistocene. However, an age of Pleistocene beds overlaying and underlying the described inter-till sequence is more a matter of interpretation than a fact without reliable biostratigraphic and geochronoly data even if it is implied from the bedding conditions.

4. PECULIARITIES OF THE PLEISTOCENE DEPOSIT STRUCTURE

A digital spatial (3D) model of the Pleistocene deposits for the LMR was compiled based on the available geological data and results of statistical analysis after the stratigraphical correlation of beds. Complexes of sketches showing a vertical sequence of the Pleistocene sediment beds were obtained from the above model. In the sketches, bed thicknesses, distribution, surfaces of distinct layers are presented layer by layer from the oldest to the youngest sediments. The compiled sketches contributed to the interpretation of the LMR bedding conditions, however attention should be drawn to the fact that the sketches only partly reflect former bed thicknesses, distribution areas and palaeosurfaces because they were affected by later ice advances, ice melt waters and interglacial processes. Moreover that the applied computer programmes limit interpretation possibilities.

The Pleistocene sediment beds are deposited on the uneven, dissected by palaeoincisions Pre-Quaternary surface (Šliaupa, 2004) composed of Triasic, Jurassic, Cretaceous and Upper Permian rocks (Bitinas, 2002) and are covered in places by late glacial and Holocene sediments (Bitinas et al., 2001; Bitinas et al., 1997, 2000). Three accumulation zones were distinguished according to the distribution of Pleistocene sediment bed thicknesses in the study area. The thinnest Pleistocene sediment cover is characteristic of southern (Rusnė, Šilutė surroundings) and northern (to the east from Šventoji, Senoji Įpiltis, Žalgiriai, Kernai, Skuodo regions) parts of the study area where the sediments are up to 40 m thick because of elevations of the Pre-Quaternary surface. Meanwhile in the remaining central (largest) area, the Pleistocene sediments are mostly 60-80 m thick, gradually reaching 140 m in the eastern part. Pleistocene thicknesses increase in the palaeoincisions deeply dissecting Pre-Quaternary rocks and in depressions of the Pre-Quaternary surface where the total bed thickness reaches 100-140 m.

Six Pleistocene till complexes were distinguished in the Lithuanian maritime region. Two of them are distributed only sporadically while the remaining complexes cover the whole region except for a few small areas. Till complexes are interlayered with inter-till beds of different origins, which are sporadically distributed as reasonably thin layers except for a one which is quite thick and widely distributed between the Middle and Upper Pleistocene sediment beds. This inter-till layer separates three till complexes in the upper and three in the lower parts of the Pleistocene sequence.

Gradual sloping south-westwards, toward the Baltic Sea, of the Pre-Quaternary surface might have affected the Pleistocene sediment bed formation and distribution. Such slopping tendency remained during the entire Pleistocene. Consequently, the waters were dammed up in fronts of the retreating ice sheets preventing the formation of glaciofluvial deposits. Proglacial lakes were small except for the one when a widespread inter-till sequence was deposited during its existence in early Late Pleistocene. Recurrent glacial exaration, erosion by ice melt waters and, in places, later abrasion by the Baltic Sea water might have been responsible for the lack of inter-till deposits in the studied sediment sequence.

First (I) till lithocomplex. Till beds of the I-st lithocomplex often overlie the Pre-Quaternary rocks or, in places, very locally, the older ice melt water sediments filling up the palaeoincisions or depressions in the study area. They are distributed only locally. In the western part, near the Baltic Sea coast they fill up the palaeoincisions in pre-Quaternary rocks or cover Pre-Quaternary depressions. Their thickness varies in the area reaching 40 m in some places. The I-st till lithocomplex is covered with inter-till sediments that are mostly related to the palaeoincisions and depressions in the Pre-Quaternary surface. These sediment beds usually overlie till of the I-st lithocomplex and practically cover the same area as the above tills. In places they cover pre-Quaternary rocks and fill up the palaeoincisions and depressions. Their thickness varies from several to 30 m. They might have been formed during the Butėnai Interglacial time according to the results of palynological investigations carried out for this sequence in the two drillings. Top of the sequence is at 20.1 m (drilling 10425) or at –17.9 m (drilling 10379) altitudes, and their thicknesses are 18.8 and 12.8 m accordingly.

Second (II) till lithocomplex. Tills of the II-nd lithocomplex are more widely distributed and cover almost all study area except for small areas, southern part of the Curonian Spit and an area eastwards from the Ventė horn, stretching along the Nemunas valley. Till thicknesses vary from several meters to 50 m being 10-15 m in average and only in the NW part, in the palaeoincision near Būtingė reaching 110 m. As a matter of fact, the inter-till sediments overlying tills of the II-nd lithocomplex are more widely distributed than the underlying inter-till sediments. They occur in depressions as well as on elevations of the surface. The inter-till sediment thickness is small and varies from 0.5 to 33 m in the study area.

Third (III) till lithocomplex. Till beds of the III-rd lithocomplex cover the entire study area except for several small areas where tills were likely removed by later ice advances or eroded by ice melt waters (Fig. 4.1A). Till thickness varies from several to 35 m, while 10-15 m thickness predominates. The compiled sketches of till thicknesses and distribution show that the sedimentation was more powerful in the western part of study area. Glaciofluvial sediments (gravel, pebbles, and variably grained sand) are only present as single patches in surface depressions or on elevations mostly in northern and eastern parts of the study area. Their thicknesses vary from several meters to 20 m, in some incisions in the NW part of area reaching 60 m (Fig. 4.1B). Meantime among the inter-till sediment beds a quite lithologically uniform complex is prominent (Fig. 4.1C). These inter-till sediment beds cover all the western part with the exception of an area to the north from Nemirseta, between Vydmantai-Rūdaičiai-Darbėnai toward Šventoji. They appear again in drilling sections in the northwest, in vicinity of Laukžemė and Šventoji.

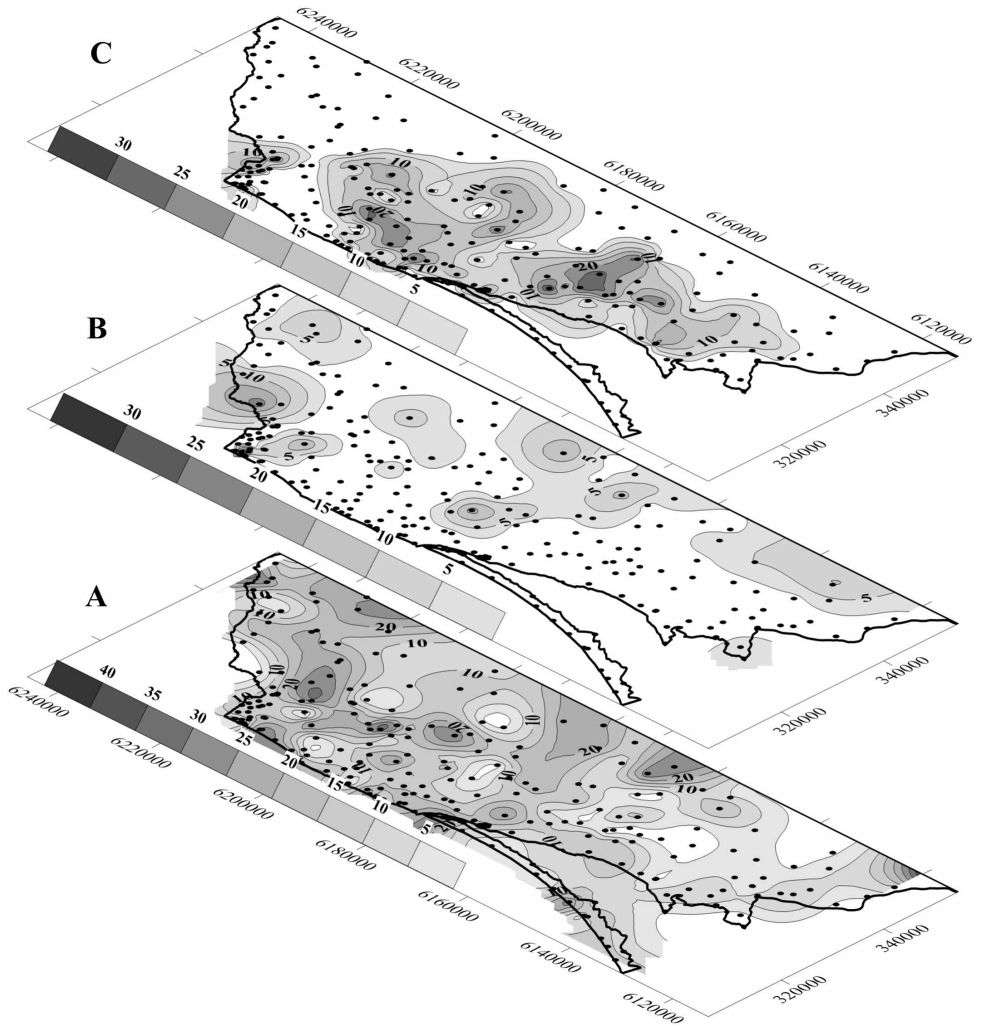

Fig. 4.1 Distribution and thickness of III-rd till complex and inter-till sediments overlaying the till: A – till; B – glaciofluvial deposits; C – lacustrine sediments

Such the sediment distribution indicates that sedimentation occurred in a large basin. At the top of inter-till sediment complex, a very fine-grained (occasionally fine-grained) sand consisting of carbonates, feldspars with prevailing quartz was deposited interlayered with a silt containing organic matter and, in places, with silty sediments with organics material and timber admixture and interlayers of organic sediments. Clay and silt layers often occur deeper in the sequence. The sediment thickness varies from several to 30 m. The thickest beds (20-30 m) were accumulated in the central basin parts and in depressions (Fig. 4.1C).

Fourth (IV) till lithocomplex. Tills of the IV-th lithocomplex are distributed only locally in the study area. They can be found in the western part, in depressions of a narrow stripe stretching along the Baltic Sea coast. Tops of these beds are at the –14-6 m altitude. The thickness varies from several tens of centimetres to almost 27 m. The thickest sequence (26.5 m) is found near Karklininkai in the drilling 10093. Inter-till sediments covering the tills of IV-th lithological complex are only locally distributed in small patches. They are composed of very fine and fine grained sand or silt. This inter-till sequence was dated by the OSL. Such datings in the Šventoji area indicate that a 0.5-1.5 m thick layer of fine-grained yellowish-grey sand consisting of carbonates, feldspar and quartz was deposited in the Middle Nemunas (Weichselian), i.e. at ca 43.7±4.0-48.8±6.2 ka (Damušytė et al., 2011).

Fifth (V) till lithocomplex. Tills of the V-th lithocomplex cover the entire study area except for the Curonian Spit and separate small areas where they had been removed by ice advances, ice melt waters or abraded by the Baltic Sea trangressions. They are the thickest in the central part where a more than 30-60 m thick sequence had accumulated. The 13 m thick beds dominate the study area elsewhere. Glaciofluvial sediments are sporadically distributed mostly in the northern part (to the north from Klaipėda), filling small depressions between elevations where sediment thickness varies from several metres to 26 m. Glaciolacustrine sediments are also sporadic, distributed as small distinct patches in the study area. Their thickness varies from several metres to 52 m.

Sixth (VI) till lithocomplex. Tills of the VI-th lithocomplex cover almost the entire study area except for the Curonian Spit, southern part of the study area (present in some places) and small patches throughout the remaining area. Their thickness varies from 0.5 to 55 m, with one average thickness of 9 m. Meantime, the glaciofluvial sediments overlying the till beds are sporadic and can be found only as small separate areas. Glaciolacustrine sediments (sand and silt) are more frequent and occur mostly in southern part of the study area.

5. STRATIGRAPHIC SUBDIVISION AND CORRELATION OF THE PLEISTOCENE DEPOSITS

Even though the Pleistocene till complexes interlayered with inter-till sediments were distinguished in the Lithuanian maritime region by using visual and lithological criteria, the available sparse palaeobotanical data and sediment age datings were insufficient to provide ages for all till beds and to attribute them to certain stratigraphical subdivisions. A Quaternary stratigraphy chart obtained in 2005 and applied by the Geological Survey of Lithuania for mapping in the Šilutė and Kretinga areas (Satkūnas et al., 2007; Guobytė et al., 2011) was used for the stratigraphical subdivision and identification of Pleistocene sediment beds in the LMR, however the newly obtained results allowed another interpretation of some subdivisions (Table 5.1).

<table>
<tr><th>Division</th><th>Subdivision</th><th>MIS</th><th>Age (ka)</th><th colspan="2">Stratigraphical subdivision of Pleistocene deposits after: Bitinas et al., 2011, 2013, Damušytė et al., 2011, Molodkov et al., 2010</th></tr>
<tr><td rowspan="10">Pleistocene</td><td rowspan="5">Upper</td><td>2</td><td>12–24</td><td colspan="2">Upper Nemunas - nm_3</td></tr>
<tr><td>3</td><td>24–59</td><td rowspan="2">Middle Nemunas - nm_2</td><td>?</td></tr>
<tr><td>4</td><td>59–74</td><td>Melnragė - ml</td></tr>
<tr><td>5a-d</td><td>74–117</td><td>Lower Nemunas - nm_1</td><td rowspan="2">Pamarys - pm</td></tr>
<tr><td>5e</td><td>117–130</td><td>Merkinė - mr</td></tr>
<tr><td rowspan="5">Middle</td><td>6</td><td>130–140–160–198</td><td colspan="2">Medininkai - md</td></tr>
<tr><td>7</td><td>198–252</td><td colspan="2" rowspan="2">Žemaitija - žm</td></tr>
<tr><td>8-10</td><td>252–302</td></tr>
<tr><td>11</td><td>302–428</td><td colspan="2">Butėnai - bt</td></tr>
<tr><td>12</td><td>428–480</td><td colspan="2">Dainava - dn</td></tr>
</table>

Table 5.1 Stratigraphical subdivision of Pleistocene deposits in Lithuanian maritime region

The oldest lithocomplex (I) till patches occur only in depressions of Pre-Quaternary surface or in palaeoincisions. The clear lithological and visual difference of lowest Middle Pleistocene till complex (I) from two overlying (II, III) appears to be formed by separate glaciation with different ice flow direction and greater influence of the local Pre-Quaternary rocks defined by their direct glacial erosion. In eastern part of the LMR, the till of this complex is covered with the Butėnai (Holsteinian) Interglacial sediments in the two sections. It seems that the till complex occurring below these interglacial sediments could be related to the

Dainava (Elster) glaciation (Fig. 5.1). Even though they might be even older, no reliable geological data on their age is available in the study area so far to prove it. The till can be correlated with the Letiža deposits in Latvia and Sanian 2 in Poland. Meanwhile, variable inter-till sediments overlaying the oldest compex (I) till might have been formed by ice melt waters of the Dainava glacier.

The compositional and other lithological differences between two overlaying till complexes (II and III) are negligible. These till complexes usually overlie each other, and only in some places are separated by thin beds of inter-till deposits. On the basis of till lithology, the existence of only one glaciation between the Butėnai (Holsteinian) and Merkinė (Eemian) interglacials in western Lithuania was proposed by V. Vonsavičius (Vonsavičius, 1967). However, in accordance with the Stratigraphical chart for the Quaternary of Lithuania officially assigned for the State geological investigations (Guobytė, Satkūnas, 2011), based on a slightly different visual characteristics and mineralogical, petrographical compositions, these complexes were related to the Žemaitija (Drenthe) and Medininkai (Warthe) glaciations. The lower complex can be attributed to the Žemaitija glaciation because of enrichment in dolomite, pyrite, disthen and rutile while the upper might belong to the Medininkai glaciation because of the larger content of Silurian limestone, garnet, amphiboles, epidote, pyroxenes and tourmaline. Tills of only one advance of the Saalian glaciation are widespread in Latvia. Meantime, the data in Poland indicates even three advances in the Saalian time and can be correlated with tills of the last Odra glaciation and its Wartanian maximum (Marks, 2011). Differently-originated inter-till sediment beds overlying the II-nd lithocomplex might have been formed by the melting and retreating Žemaitija glacier.

Inter-till sediments of the Merkinė Interglacial are absent in the Lithuanian maritime region, however they were palynologically identified further east, ca 50 km from the eastern boundary of the study area, in Gaurė section (Šeirienė, Kondratienė, 2004).

Inter-till sediments often overlying the Medininkai tills, well defined lithologically, occuring almost at the same altitude and widely spread in the western part were assigned to the Pamarys complex as was confirmed stratigrapically by the age dating results.

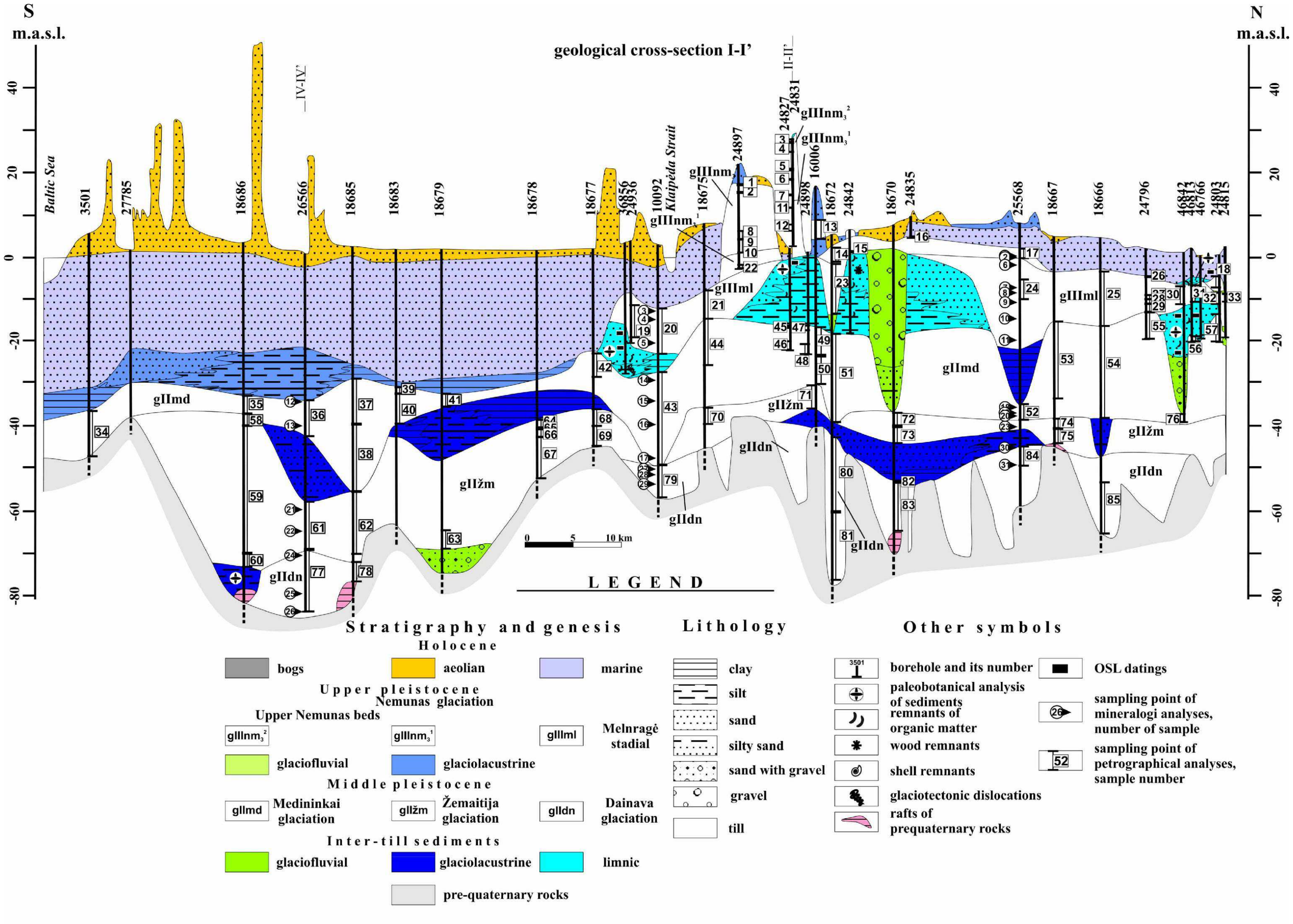

Fig. 5.1 Quaternary deposits section I-I' in Lithuanian maritime region (for location see Fig. 1)

The results of age datings and palynology indicate that those sediments have been formed with breaks in sedimentation but during a long time span starting with the end of Medininkai glaciation and finishing in the Middle Nemunas (Bitinas et al., 2013). Sedimentation in the basin had started at ca 160–140 ka, but stopped by the end of Medininkai glaciation, was resumed at ca 118–119 ka and likely proceeded during the whole early Nemunas (Weichselian) time until the area was covered again with a glacier re-advance (Bitinas et al., 2013).

Three visually distinct till complexes (IV, V and VI) attributed to the upper Pleistocene are characterised by the gradual decrease in pyroxenes-tourmaline-garnet-epidote-amphiboles mineral association and increase in staurolite-apatite-phoshates-zircon-ilmenite and magnetite-leucoxene-iron oxides and hydroxides mineral association as well as dolomite and crystalline rocks from the lowermost till complex upwards. Such compositional characteristics of these till complexes could be explained by the same source of exaration, but a slightly different composition of the underlying Pre-Quaternary rocks. Probably these till complexes were formed during the re-advances of the same ice sheet during the Last Glaciation. The tripartite glacial deposit structure based on compositional, especially mineralogical differences of till complexes well corresponds with the results of recent investigations in the LMR (Molodkov et al., 2010; Bitinas et al., 2011; Damušytė et al., 2011) showing that coastal zone or even whole western Lithuania in Late Pleistocene probably was first affected by an ice sheet advance during the Middle Nemunas (Weichselian) glaciation. It would contradict the opinion on presence of non-glacial palaeoenvironments since the end of Merkinė (Eemian) Interglacial through the Early and Middle Nemunas and that area was covered by glaciers only in the Late Nemunas (Weichselian) time. The idea of Middle Nemunas till occurrence is also supported by the OSL dates of till complex underlying (113-84 ka) and overlaying (49-44 ka) inter-till sandy deposits in the area of Šventoji harbour (Damušytė et al., 2011). Based on the dating results this till complex was attributed to the earliest stage of Nemunas (Weichselian) ice advance during the Middle Nemunas time and named as a Melnragė sub-formation (Molodkov et al., 2010; Bitinas et al., 2011; Damušytė et al., 2011). Thus, according to the age dating, bedding conditions and differences in mineral composition those till beds were found only in a narrow stripe along the Baltic Sea coast. The available lithological data is insufficient to define eastern boundaries of the till distribution. However the three visually distinct till beds overlying the Pamarys inter-till complex in the upper part of Pleistocene sequence might have been formed by three ice advance stages during the Last Glaciation. The lowermost till bed could be assigned to the Middle Nemunas (Weichselian). Another interpretation was suggested by the peculiarities of mineral and petrographical compositions of till beds attributed to the IV lithocomplex. These tills have very distinct mineral composition being enriched in Fennoscandian minerals and Silurian limestone and depleted in dolomite. No tills with such distinct mineral compositions were detected eastwards from the Baltic Sea coast according to the sparse lithological data. In neighbouring Poland, the Melnragė till beds can be correlated with the Swiece till beds occurring in the middle and north of the country (Marks, 2011). No indications of the presence of this glaciation in Latvia were found so far however the scientists assume that the Middle Weichselian glacier might have advanced in Latvia and reached its maritime lowlands (Saks et al., 2012). Sporadically distributed and overlying the IV till complex (Melnragė) sediments compose the Melnragė and Upper Nemunas (Weichselian) inter-till beds. Sandy sediments beds overlying the Melnragė tills were attributed to this complex because of the OSL datings indicating that inter-tills have accumulated in the Middle Nemunas (Weichselian) time. Sedimentary sections belonging to the Middle Nemunas (Weichselian) were found in northwestern Lithuania, near Venta (Satkūnas et al., 2009, 2012), in the western Latvian maritime region, between Ventspils and Pāvilosta towns (Saks et al., 2012), in southwestern Estonia, in the Arumetsa area (Raatas et al., 2010), however an additional data is needed for their correlation (Satkūnas, 2011).

Two mineralogically and visually distinct uppermost till complexes are interpreted to be formed during the Late Nemunas glacial stages, however there are no interstadial sediments found in the area (Bitinas, 2011).

6. SEDIMENTATION CONDITIONS OF PLEISTOCENE SEDIMENTS IN THE LITHUANIAN MARITIME REGION

Sedimentation conditions were reconstructed on the basis of the available geological data and model of Pleistocene deposit structure in the Lithuanian maritime region. It is difficult to reconstruct earlier sedimentation processes than the Dainava glaciation because neither early Middle Pleistocene (Dzūkija glaciation and Turgeliai Interglacial) nor early Pleistocene sediments were found in the study area. They might have been removed by later ice re-advances therefore their sedimentation conditions cannot be reconstructed.

A pre-existing surface has influenced very much Pleistocene sedimentation processes and sediment distribution in the study area. An irregularly-shaped lowland (depression) gradually slopping towards the Baltic Sea had occupied the study area before the Dainava ice advance as was implied from the drillcores. The depression surface was exarated by the advancing Dainava ice and nowadays near the Baltic Sea coast lays at 60-80 m altitude b.s.l. Its surface was dissected by variably-deep valleys, incisions and depressions. The inheritance of surface forms, sediment accumulation mostly in incisions, depressions and troughs of the former surface let us to assume, that the Dainava ice advance and its melt waters did not much modify the pre-exsisting surface. Not being stopped by any obstacle except for Pre-Quaternary depressions and palaeoincisions the Dainava ice advanced most likely from the northwest (Gaigalas, 1979), moved through the study area leaving behind only a thin till bed at basal till plain that was easily removed by later ice re-advances. The northwestern direction of the glacier advance might be a case why these till beds are enriched in lower Palaeozoic (Silurian and Ordovician) limestone, Mesocoic marls and sandstones compare to the overlaying tills. A fragment of a possibly marginal moraine ridge composed of sandy and clayey tills and glaciofluvial sediments (differently-grained sands with gravel and pebbles) was preserved in the eastern part of study area, in the Kartena-Kuliai-Švėkšna surroundings. The basal till plain is covered with sediments deposited by ice melt waters (sand, clay and silt). These sediments were likely deposited in lakes dammed near the ice-sheet margin or, in places; some ice melt waters flowing from the ice sheet transported coarser sediments and deposited them in surface depressions, possibly deltas. During the Butėnai Interglacial, the westwards slopping maritime lowland (depression) containing numerous waterholes dissected by rivers and rivulets and repeatedly affected by different geological processes continued to exist. However the Butėnai Interglacial sediments were found only accumulated in single lakes on the western slopes of the marginal ridges of Dainava glaciers in the eastern part of study area. A conclusion can be drawn that the study area was considerably exarated during the Žemaitija glaciation that was implied from sporadic distribution of the Dainava tills and inter-tills and their occurrence mostly in Pre-Quaternary depressions and palaeoincsions as well as from the fact that the Žemaitija tills were more widely distributed and overlie mostly Pre-Quaternary rock surface. Erosional and denudational processes in late glacial and interglacial conditions have also affected the sporadic distribution of those tills in the study area. Moreover, the Baltic Sea depression which likely started to form in the Butėnai Interglacial time served a natural obstacle for ice advances. Therefore the western margin of the area was exarated more intensively when the moving ice climbed out of it (Bitinas et al., 2000). The newly accumulated till and inter-till deposits have considerably corrected the earlier existing surface. Thus, with the deposition of glacial sediments, the lowland (depression) near the Baltic Sea coast became shallower because it was filled up with lithologically variable sediments. According to the investigations results the Žemaitija glacier has reached Lithuania from the north (Gaigalas, 1979). Only just relatively bigger amounts of dolomite, smaller of sandstone and Mesozoic marl, but very similar of lower Palaeozoic limestone compare to the Dainava tills do not indicate any pronounced differences in glacial ice movement direction or geological composition of the substrate. Most likely the moving glacial ice on its way had assimilated similar Pre-Quaternary rocks and, in turn, accumulated tills of similar composition. Removal of the earlier deposited tills and their assimilation mostl likely had "smoothed" compositional differences. However they differ more in mineral composition: the Dainava tills contain the lowest amounts of Fennoscandian minerals, but the largest of ore minerals, pyrite and zircon.

The retreating Žemaitija glacier left behind ca 15 m thick till layer forming a slightly undulating basal plain. In the eastern part of study area, in vicinity of Kartena-Kuliai-Švėkšna and to the north, as a result of retreating glacier ice and locally margin stabilisation, a marginal ridge emerged exceeding the study area. Thus, a modern Žemaičiai Upland started to form on a top of the previously deposited Dainava marginal ridges and around them. Ice melt waters have accumulated glaciofluvial and glaciolacustrine sediments. Small dammed basins likely have accompanied a retreat of the glacier margin into the Baltic Sea depression.

According to A. Gaigalas, the later Medininkai glacier reached the study area from the northwest (Gaigalas, 1979). Recurrent glacial ice advances of the Dainava and

Medininkai glaciations from the same northwestern direction have affected very much compositional similarities of the tills. However, the obtained study results show that the Žemaitija and Medininkai tills are even more compositionally similar, what might be explained by re-advances of the same glacier. The retreating Medininkai glacier left behind in the study area ca 14 m thick till layer forming an undulating basal till plain. The maritime lowland pre-existed before the Medininkai glaciations was practically filled up by variable sediments. The glacier retreat was followed by the appearance of large dammed lake and lacustrine sedimentation in its area.

During Middle Pleistocene in the eastern part of the study area, a belt of glacial deposits had formed on the western Žemaičiai Upland slopes reaching in places 60 m, which have dammed ice melt waters. In the dammed basin the sediments assigned to the Pamarys complex were deposited. According to the sediment lithological composition implied from drillings the sedimentation is assumed to start there immediately after the westwards retreating glacier had dammed the melt waters. The ice melt waters transported a large amount of clastic material and deposited a 30 m thick sediment sequence. As was implied from the sediment type, firstly were deposited clays (in places varved or laminated) followed by silt, i.e. the sediments characteristic of proglacier basins. Their sedimentation was followed by very fine, rarely fine sand with silt, organics matter and timber admixture. Peat and sapropel present in places indicate that sedimentation conditions had changed for warmer ones and that sediments were deposited mostly in lakes. The remaining basin was probably dammed by the marginal moraine ridges stretching along the modern Baltic Sea coast. Poor variety of spore and pollen spectrum indicates that climatic conditions did not change much either because cold and wet climate or rapid sedimentation (Damušytė et al., 2011).

Distribution of basin lithofacies was defined by different sedimentation processes and composition of the brought material. In general, sedimentation of fine-grained material predominated in the basin. Changes of lithofacies indicate that the brought material is finning inward the basin centre. Along the basin shore, there was a littoral sedimentation zone with predominating sedimentation of relatively coarser material, i.e. sand in the sections. Lithofacies with finely dispersed sediments are characteristic of transitional and deepest basin zones. Meanwhile, the concentration of coarse sediments in places near the basin margins is likely related to water flow discharges leading to the formation of deltaic sediments or is caused by erosional or abrasional processes at basin margins. According to the OSL data, the basin existed quite a long time, however sedimentation was punctuated as implied from the palynological data, what may indicate water level oscillations (Bitinas et al., 1997). However, no signs of erosion evidencing breaks in sedimentation were found in the studied drillcore sections. According to the OSL datings, the sedimentation started at ca 140-160 ka and most likely stopped when the Medininkai glacier had retreated and melted. After the ice dam had disappeared, the basin water likely drained into the Baltic Sea depression.

During the Merkinė Interglacial, probably the region was uplifted because of glacial isostasis; therefore no marine Merkinė (Eemian) sediments are present in the area (Bitinas et al., 2013). In the Merkinė Interglacial time, the maritime plain (depression) continued to exist with its surface slopping towards the west. Sediments should have been deposited in lakes, river valleys and peat bogs, however no sediments of that time were found in the study area therefore it is impossible to reconstruct sedimentation conditions during the Merkinė Interglacial. The IR-OSL datings indicate that sedimentation in the basin resumed ca 118-119 ka and likely continued during the entire early Nemunas (Weichselian) time (Bitinas et al., 2013) until ice of the Melnragė ice advance reached the area in the Middle Nemunas. According to the distribution of Medininkai till deposits and inter-tills and change of their thicknesses, the later Melnragė ice advance (the oldest stage of the Nemunas glaciation) or even later glacial ice advances had no strong erosional power. On the basis of the Melnragė till bedding conditions (limited distribution in the Baltic Sea coast) as well as the results of mineral and petrographical composition a conclusion might be drawn that this glacier had reached only lower parts of the Baltic Sea coast and left behind thin till layers in surface depressions. Prominent differences in till composition, especially mineral, point toward the fact that this glacier had advanced from other direction than the earlier ones. The Melnragė tills from the Olando Kepurė cliff containing minimal amounts of dolomite and maximal of crystalline rocks as was implied from their petrography studies are assumed to have been left behind by a glacier advancing from the north as was obtained from the measurements of pebble long axes (Molodkov et al., 2010). On the other hand, Vonsavičius stated that the Kurzemė or early Nemunas tills of grey, in places bluish colour and enriched in the Baltic Sea bottom and upper Mesozoic rocks were left behind by a glacier moving from the northwest (Vonsavičius, 1984). According to the reconstructions by A. Gaigalas (Gaigalas, 1979), southwards advancing glaciers should have larger amounts of dolomite. The results of petrographic investigations of Swiecie stage tills in northeastern Poland show that a glaciation's centre might have been situated slightly to the west from Finland and Alland Islands (Krzywicki, 2002). Ice melt waters should have deposited sediments when the glacier was retreating however they were found only sporadically, along the Baltic Sea coast. According to the OSL data, lacustrine deposits near Šventoji were formed at ca 44-49 ka, i.e. in the Middle Nemunas. Their sedimentation likely proceeded in the pre-existing basin after the Melnragė glacier had retreated. Many changes in the Lithuanian maritime region happened because of sediment accumulation during oscillations of the retreating Late Nemuno (Weichselian) glaciers. They left behind two lithologically different till layers covered with sediments deposited from ice melt waters. The Late Nemunas glacier which deposited the lower till bed in the study area had formed basal till undulating plain which to the northwest from Veiviržiai towards Padvariai, Darbėnai and Lenkimai is cross-cut by a marginal moraine ridge stretching in northwestern-southeastern direction and in places exceeding 40-60 m. These marginal moraines might indicate a glacier stop near this boundary. Thus, the Žemaičiai Uppland grew and widened with the accumulation of tills in the marginal morainic ridges, therefore the coastal plain has decreased especially in the northern part of the area. At the same time, the sporadically distributed inter-till sediments likely had been removed by the Last Glacial ice advance. According to the till composition (gradual decrease in amphiboles and increase in zircon and epidote) the retreat of glacier was lesser extent than in the Melnragė stage. Gradual increase in Mesozoic limestone and dolomite and decrease in Silurian limestone might have been caused not by another ice movement direction than it was during the Melnragė stage. However, according to the reconsturctions of carried out by A. Gaigalas glacier advance directions, this glacier should have reached Lithuania from the northwest (Gaigalas, 1979). The last ice advances of the Nemunas glaciation had accumulated the uppermost till beds as well as its melt waters had deposited sediments covering the earth surface. Thus, they have composed present day surface in the larger part of the study area. Palaeogeographical conditions of that time were investigated and described during geological mapping in Kretinga and Šilutė areas (Bitinas et al., 1997, 2000).

CONCLUSIONS

1. Visual properties of the Lithuanian maritime region till complexes differ not only vertically in the drilling cross-sections but also laterally in the study area. These facts allow their stratigraphical subdivision but make their correlation quite complicated.
2. Mineral compositions of till sandy parts are more differentiated, and the till complexes vary by amounts of distinct mineral groups: 1) pyroxenes-amphiboles-garnet-tourmaline-epidote, 2) rutile-white pyrite, 3) disthen-pyrite, 4) leuxocene-zircon-staurolite-apatite-phosphates-ilmenite and magnetite-iron oxides and hydroxides.
3. Petrographicial compositions of till gravel and pebbles from distinct glaciations vary considerably in the Lithuanian maritime region; therefore they are more applicable for local stratigraphical subdivision and correlation of till complexes where gravel and pebbles of these complexes vary most in amounts of Silurian limestone, dolomite and crystalline rocks.
4. Six Pleistocene till complexes interlayered with inter-till sediment beds stands out in the Lithuanian maritime region. The thickest, most widely distributed at the same altitude and having similar lithological regularities the Pamarys inter-till complex divides three till complexes in the lower and three in the upper Pleistocene sediment sequences.
5. According to the age datings, the till complexes underlying the Pamarys inter-till complex are attributable to the Middle Pleistocene. The till complexes belong to Dainava, Žemaitija and Medininkai glaciations respectively.
6. The till complexes overlying the Pamarys inter-till beds are attributable to the Nemunas (Weichselian) glaciation. According to the age data for inter-till sediments, the lower one belongs to the early Middle Nemunas, while the upper two to the Late Nemunas.
7. The accumulation of tills have prevailed during the entire Pleistocene in the Lithuanian maritime region with the exception of the Middle and Late Pleistocene limit when a large water basin had formed and lacutrine sediments had accumulated almost in all study area.

8. A digital spatial model of the Pleistocene deposit structure based on geological information and applied statistical methods allowed for the justification of Pleistocene deposit stucture and stratigraphy in the Lithuanian maritime region.

LIETUVOS PAJŪRIO PLEISTOCENO NUOGULŲ SANDARA IR SEDIMENTACIJOS SĄLYGOS

SANTRAUKA

Nepaisant daugybės geologinių tyrimų ir bandymų atkurti Lietuvos pajūrio paleogeografines sąlygas, pleistoceno nuogulų sandara, jų stratigrafija ir sedimentacijos sąlygų raida vis dar kelia nemažai klausimų. Pastarųjų metų tyrimai pajūryje tik dar labiau išryškino čia egzistuojančias pleistoceno nuogulų sandaros ir stratigrafijos problemas ir parodė būtinybę apibendrinti turimą geologinę informaciją apie pajūrio pleistoceno nuogulų savybes, sandarą ir stratigrafiją, bei atlikti nuogulų sedimentacijos sąlygų interpretaciją. Tuo labiau, kad nauji tyrimų duomenys gauti ne tik Lietuvoje, bet ir kaimyninėse šalyse, verčia naujai pažvelgti į turimus geologinius faktus, juos išanalizuoti ir interpretuoti šiuolaikinių mokslinių pažiūrų ir žinių kontekste.

Pleistoceno nuogulos ir nuosėdos, plačiai išplitusios pajūrio regione ir slūgsančios žemės paviršiuje arba po nestora holoceno nuosėdų danga ir tiesiogiai veikiamos žmogaus ūkinės veiklos yra svarbios, tiek praktiniu, tiek ir moksliniu požiūriais. Taip pat ir dabartinis uostų gilinimas ir plėtra, atsinaujinančių energetinių resursų planavimas didina kvartero, o tuo pačiu ir pleistoceno nuogulų sandaros žinojimo ir ištirtumo poreikius. Tokiu būdu pajūrio pleistoceno nuogulų sandaros, geologinės raidos pažinimas, o taip pat čia vykusių geologinių procesų suvokimas yra ypač aktualus, sprendžiant įvairius praktinius klausimus. Tačiau ne ką mažesnį susidomėjimą ir disputus tarp mokslininkų kelia šių nuogulų ir nuosėdų genezės, jų sedimentacijos sąlygų, stratigrafijos klausimai bei paleogeografinių sąlygų atkūrimo galimybė.

Tyrimams pasirinkta teritorija įvardijama – Lietuvos pajūriu, t. y. apsibrėžtas tyrimų plotas apima beveik 40 km pločio sausumos ruožą besitęsiantį į rytus nuo Baltijos jūros kranto, per pajūrio žemumos, Nemuno deltos rajonus, link vakarinių Žemaičių aukštumos (plynaukštės) šlaitų (Basalykas, 1965) (1 pav.).

Tyrimų objektas – nuogulos ir nuosėdos susiklosčiusios kvartero periodo, pleistoceno epochos metu, maždaug tarp 730-12 tūkst. m. (Satkūnas ir kt., 2007) bei plačiai išplitusios pajūryje ir sudarančios gana didelio storio (nuo kelių dešimčių metrų iki beveik 150 m) sluoksniuotą nuogulų storymę.

Šio darbo tikslas – turimos geologinės informacijos pagrindu ištirti Lietuvos pajūrio pleistoceno nuogulų sandarą ir nustatyti jų sedimentacijos sąlygas. Tikslui pasiekti buvo sprendžiami šie uždaviniai: nustatyti ir įvertinti kriterijus pleistoceno nuogulų stratigrafiniam skaidymui ir koreliacijai, atlikti Lietuvos pajūrio pleistoceno nuogulų stratigrafinį suskirstymą ir koreliaciją remiantis nustatytais kriterijais, sudaryti pleistoceno nuogulų storymės sandaros skaitmeninį erdvinį (3D) modelį, nustatyti pleistoceno nuogulų sandaros ir slūgsojimo sąlygų ypatumus, nustatyti moreninių ir tarpmoreninių nuogulų sedimentacijos sąlygas.

Ankstesni Lietuvos pajūrio pleistoceno nuogulų tyrimai Lietuvos pajūryje, parodė, kad dažniausios problemos aiškinantis pleistoceno nuogulų sandarą čia susijusios su vienų plačiai išplitusių tarpmoreninių nuogulų sluoksnių amžiaus interpretavimu bei su moreninių nuogulų skaidymu ir koreliacija, o su tuo susijusi ir visų pleistoceno nuogulų stratigrafijos, jų sandaros ir susidarymo interpretacija.

Pleistoceno nuogulų stratigrafinis skaidymas ir koreliacija atlikta remiantis moreninių nuogulų mineraloginės ir petrografinės sudėties, jų vizualinių-litologinių savybių, tarpmoreninių nuogulų paleobotaninių ir geochronologinių tyrimų rezultatais, bei nuogulų slūgsojimo sąlygomis. Remiantis turimais duomenimis buvo išskirti 6 litologiniai moreninių nuogulų kompleksai pajūryje, charakterizuoti pagal būdingiausius mineralinės, petrografinės sudėties ir vizualinių-litologinių savybių požymius.

Statistinė mineralinės sudėties analizė parodė, kad moreninių nuogulų smėlio mineralinė sudėtis yra labiau diferencijuota nei žvirgždo, gargždo petrografinė. Skirtingi moreniniai litokompleksai skiriasi statistiškai išskirtų mineralų grupių: 1) piroksenų-amfibolų-granatų-turmalino-epidoto, 2) rutilo-balto pirito, 3) disteno-pirito, 4) leukokseno-cirkono-staurolito-apatito-fosfatų-ilmenito ir magnetito-geležies oksidų ir hidroksidų kiekiais atskiruose moreniniuose litokompleksuose.

Pajūryje atskirų apledėjimų moreninių nuogulų žvirgždo ir gargždo petrografinė sudėtis yra labai kaiti, todėl labiau tinka nuogulų kompleksų stratigrafiniam skaidymui ir koreliacijai lokaliai, kur moreninių nuogulų kompleksai petrografiškai labiausiai skiriasi žvirgždą ir gargždą sudarančių silūro klinties, dolomito ir kristalinių uolienų kiekiais.

Gręžinių kerno aprašymų analizė atskleidė vizualinių-litologinių moreninių nuogulų savybių, ypač spalvos nepastovumą sluoksnių viduje tiek vertikaliai pjūvyje, tiek ir plote, todėl įvairiaamžių moreninių nuogulų skaidymas ir koreliacija pajūryje, remiantis tik vizualinėmis savybėmis, yra komplikuotas.

Lietuvos pajūryje išsiskiria šeši pleistoceno moreninių nuogulų kompleksai persisluoksniuojantys su tarpmoreniniais dariniais. Storiausias, panašiame aukštyje labiausiai teritorijoje išplitęs, dėsningos litologinės kaitos markiruojantis Pamario tarpmoreninių nuogulų kompleksas atskiria po tris moreninių nuogulų kompleksus apatinėje ir viršutinėje pleistoceno storymės dalyse.

Remiantis absoliutaus amžiaus datavimo duomenimis, žemiau Pamario tarpmoreninių nuosėdų slūgsantys moreninių nuogulų kompleksai priskirtini viduriniajam pleistocenui. Moreninių nuogulų kompleksai atitinkamai priklauso Dainavos, Žemaitijos ir Medininkų apledėjimams.

Virš Pamario tarpmoreninių nuosėdų slūgsantys trys moreninių nuogulų kompleksai priskirtini Nemuno apledėjimui. Apatinysis iš jų pagal tarpmoreninių nuogulų datavimo duomenis yra priskirtinas viduriniojo Nemuno pradžiai, o du viršutinieji – vėlyvajam Nemunui.

Dėl susidariusių sedimentacijos sąlygų Lietuvos pajūryje viso pleistoceno metu vyravo moreninių nuogulų sedimentacija, išskyrus viduriniojo ir vėlyvojo pleistoceno ribą, kai susidarius didesniam vandens baseinui beveik visame tyrimų plote vyko ežerinių nuosėdų klostymasis.

Geologinės informacijos pagrindu sudarytas erdvinis skaitmeninis pleistoceno nuogulų modelis ir panaudoti statistiniai metodai leido patikslinti Lietuvos pajūrio pleistoceno nuogulų sandarą ir stratigrafiją.

Disertacinį darbą (109 pls.) sudaro: įvadas, ankstesnių tyrimų apžvalga, darbo metodika, tyrimų rezultatai, išvados, literatūtos sąrašas. Jis iliustruotas 44 paveikslais ir 5 lentelėmis.

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