KLAIPĖDA UNIVERSITY

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GEOLOGICAL STRUCTURE AND SPATIAL DISTRIBUTION OF PALAEO-INCISIONS IN THE SOUTHEASTERN PART OF THE BALTIC SEA AND ADJACENT LAND

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The dissertation is available at the Library of the Klaipėda University.

CONTENTS

1. INTRODUCTION

Importance of the study. This study contributes to the understanding of the geological structure of the greater part of the southeastern Baltic Sea and neighboring land areas. The palaeo-incisions are widespread in this region. The term *palaeo-incision* means a hidden buried valley cutting into the surface of pre-Quaternary sedimentary bedrock. Palaeo-incisions are generally filled in by till and glaciofluvial or glaciolacustrine sediments of the respective glaciations. In general, these structures are exposed within a wide zone. The outer boundary of this zone coincides with the extensions of the Pleistocene ice sheets, i.e. the Netherlands, Denmark, Germany, Poland, Lithuania, Latvia, Estonia, Northwest Russia and Belarus. They are less common in Scandinavia. In some areas, e.g. in Lithuania, Latvia and Denmark, they may be related to river valleys or fracture systems in the pre-glacial bedrock. The terms palaeo-incision, palaeo-tunnel, tunnel valley, buried valley, palaeo channel, etc. are used by scientists in different countries.

Studies of palaeo-incisions contribute to a better understanding of ice sheet dynamics and sedimentation processes during Quaternary glaciations. The distribution of palaeo-incisions is irregular and complicated. Thus, the present-day published schemes and maps of sub-Quaternary surfaces of the southeastern part of the Baltic Sea with palaeo-incisions are solely indicative. Most schemes and maps are based on drill-core data, and therefore they contain very little geophysical information. As the inner structure of palaeo-incisions differs radically from the surrounding deposits or rocks, geophysical methods are apt to contain the most appropriate tools for investigation of their morphology and distribution.

The study area is delimited by the coordinates 55^{o} 20’–56^{o} 20’ N and 19^{o} 00’– 22^{o} 00’E. It is a part of the southeastern part of the Baltic Sea (Lithuanian offshore and adjacent part of Latvian offshore) and neighboring land areas.

Aims and Objectives. The objective of this work is *to study the extension of the network of palaeo-incisions, to analyze their infillings and to detail the geological structure of the southeastern part of the Baltic Sea and adjacent areas on land.* The following tasks are addressed:

1. Re-interpret the previously obtained offshore continuous seismic profiling data applying modern digital post-processing technique;
2. Interpret the infilling of palaeo-incisions offshore applying both seismic and well data;
3. Introduce new methods of geophysical prospecting and post-processing technique for high resolution land investigations of palaeo-incisions and estimate the effectiveness of the used methods;
4. Compile a set of geological maps of the southeastern Baltic Sea and adjacent areas on land: a map of palaeo-incisions in the sub-Quaternary surface and a pre-Quaternary geological map.
5. Compare the newly compiled maps with the results of previous investigations.
6. Overview the geoecological significance of palaeo-incisions in the investigated area.

Novelty of the study. This work presents a detailed analysis of palaeo-incisions applying modern digital technique for interpretation of seismo-acoustic records made in the southeastern part of the Baltic Sea. This resulted in the updating of the previous knowledge and detailing maps of sub-Quaternary relief and pre-Quaternary geology. These maps specify the previously established geological boundaries of different geological periods. The map of distribution of the palaeo-incisions updates the channel system in the southeastern part of the Baltic Sea and neighboring land areas.

The analysis of palaeo-incisions presents new information on their infillings.

The new methodological approach includes 2D shallow seismic profiling and electrical tomography. This combination is used for the first time to locate palaeo-incisions on land in the western Lithuania.

Statements to be defended:

1. Palaeo-incisions are widely distributed in the southeastern part of the Baltic Sea and form three complicated irregular networks, differentiated by their morphology and relative depth.

2. Different infillings of the palaeo-incisions are characterized by an original lithological structure and unique seismic signature. The identified palaeo-incisions have seven types of internal seismic reflectors.

3. The application of modern digital technique for the interpretation of the vintage marine continuous seismic profiling (CSP) data together with the latest additional CSP data makes it possible to improve the knowledge of the geological structure of southeastern part of the Baltic Sea and to compile more detailed maps of the sub-Quaternary relief and the pre-Quaternary geology.

Scientific approval. The early results of this study have been presented in two international and three Baltic Sea regional conferences and seminars:

The 5th scientific-practical conference Marine and Coastal Researches – 2011, Palanga, Lithuania, April 2011;

IEEE/OES Baltic INTERNATIONAL SYMPOSIUM, Klaipėda, Lithuania, May 2012;

The 9th Baltic Sea Science Congress 2013, Klaipėda, Lithuania, August 2012;

The 7th scientific-practical conference Marine and Coastal Researches – 2013, Klaipėda, Lithuania, April 2013;

Scientific-practical conference Sea Science and Technologies – 2014, Klaipėda, Lithuania, April 2014.

The material of this study had been presented in two original publications, published in peer-reviewed (ISI WOS) scientific journals:

Gerok D., Bitinas A., 2013. Geophysical study of palaeo-incisions in the Šventoji–Būtingė coastal area, north-west Lithuania. *Baltica, 26 (2),* 201—210.

Gerok D., Gelumbauskaitė L. Ž., Flodén T., Grigelis A., Bitinas A., 2014. New data on the palaeo-incisions network of the southeastern Baltic Sea. *Baltica, 27 (1)*, 1–14.

Thesis structure. The dissertation includes ten chapters: introduction, review of previous investigations, material and methods, results, discussion, conclusions, references and three appendixes. The material is presented on 114 pages, 39 figures, 11 tables and 3 appendixes. The dissertation refers to 102 literature sources. The dissertation is written in English with an extended summary in Lithuanian.

Acknowledgments. I would like to thank my supervisor Dr. Albertas Bitinas for his support, patience and profound advices. I want to express my deepest gratitude to Professor Algimantas Grigelis and Dr. Živilė Gelumbauskaitė (Nature Research Centre, Institute of Geology and Geography, Sector of Marine Geology and Geodynamics) for having given me the possibility to use archive data of the seismic graphic records collected during joined Lithuanian-Swedish expeditions, consulting with methods and interpretation of marine geophysical-geological data. I would like to thank Professor Tom Flodèn (Stockholm University) for performed marine CSP data, advice in their interpretation, comprehensive consulting and sharing experience with me. Thanks to Professor Grigelis, Dr. Gelumbauskaitė and Professor Flodèn for consulting with methods and interpretation of marine geophysical-geological data. I would like to thank Dr. Saulius Gulbinskas, Dr. Nerijus Blažauskas, Dr. Dainius Michelevičius and Juozas Bičkunas for help in organization of the land field investigations. My thanks to Jaunutis Bitinas and Viktoras Lokutijevskis from Lithuanian Geological Survey for performed data; Dr. Jonas Satkūnas for help during the seismic data digitizing; Dr. Rimantas Šečkus for processing the data of electrical tomography; Dr. Sergej Kanev for performed VSP data of several marine wells; Nikita Dobrotin, Mindaugas Baliukonis and Manvydas Šaltis for help during land field investigations; Mantas Budraitis and Dr. Dainius

Michelevičius for advice in applying the modern software. Thanks to Dr. Nerijus Blažauskas and Dr. Rimantas Šečkus for reviewing the final version of this work. I would like to thank Aloyzas Alius for English grammar revising.

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Abbreviations.

Abbreviation	**Explanation**
2D	Two-dimensional
CDP	Common depth point
CMP	Common mid-point
CSP	Continuous seismic profiling
GPR	Ground penetrating radar
GPS	Global Positioning System
LGS	Lithuanian Geological Survey
MIS	Marine isotope stage
RMS	Root-mean-square
VSP	Vertical seismic profiling

2. REVIEW OF PREVIOUS INVESTIGATIONS

2.1 GEOLOGICAL AND TECTONIC SETTINGS

2.1.1 Tectonic settings

The investigated area is located within the Baltic Syneclise which is a regional depression in the western part of the East European platform. In general, the axial part of the Baltic Syneclise extends in NE–SW direction (Puura *et al*. 1991a). Folded structures and faults with displacement amplitudes up to 170 m were formed in westernmost Lithuania during the Early Ediacaran (Šliaupa, Hoth 2011). The tectonic activity had decreased and the marine transgression had begun during the Late Ediacaran–Cambrian. Then small-scale and sporadically distributed uplifts of the basement were detected in the western Lithuania.

The main stage in the evolution of the Baltic Syneclise took place in the Late Caledonian. Up to four kilometers of deposits had been laid down in the axial part of the Baltic Syneclise at this time. Intensive structural displacement of basement blocks took place in the Carboniferous–Early Permian when the region was subjected to NE–SW horizontal compression. As a result Polish–Lithuanian Syneclise stretching to Tornquist–Teisseyre lineament was formed in the Southern Baltic (Fig. 1; Grigelis 2011). E–W and NE–SW faults dominates here, their amplitudes are from 50 to 200 m, and they dip to the west at angles of 70–80^{o} (in the Telšiai zone) (Šliaupa, Hoth 2011).

The Late Hercynian complex overlays azimuthally the irregular Caledonian surface, often with an angular unconformity (Puura *et al*. 1991a). The complex consists of two structural levels, namely Early Devonian–Carboniferous and Permian. Tectonic processes were reactivated during the Late Devonian–Permian period. The maximum thickness of the Hercynian complex (up to 1000 m) is located in the Baltic Syneclise (Stirpeika 1999). From a tectonic point of view, most structures, both the local and the major ones, were finally formed in the Hercynian orogenesis (Suveizdis 1994b).

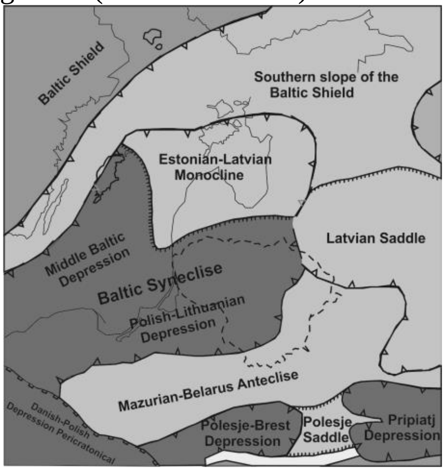


Fig. 1 The tectonic setting of the Baltic region after P. Suveizdis, 2003 (Grigelis, 2011).

The tectonic processes ceased in the Permian and restarted in the Late Cretaceous. Inverse tectonic structures with amplitudes up to 200 m are identified in southern Lithuania and in the Kaliningrad Region of Russia (Šliaupa, Hoth 2011). Modern tectonic processes are mostly connected to postglacial relaxation (Puura *et al*. 1991a; Šliaupa 1981).

2.1.2 Stratigraphy

The investigated area is located in the central part of the Baltic Syneclise of the East European platform, which was consolidated during the Early Proterozoic (Šliaupa, Hoth 2011).

Achaean–Early Proterozoic (AR–PR_1) crystalline basement is located at a depth of c. 2 km in the area of investigation. It consists of gneiss, biotitic granite–gneiss, crystallized shale, amphibolite, quartzite, marble and volcanic rocks (Puura *et al.* 1991b).

After a break in sedimentation, the deposition was re-established **in the Ediacaran (Vendian).** The deposits consist of siltstone, sandstone, clay and conglomerate. The total thickness reaches 200 m (Grigelis 1994a).

The Cambrian (**Cm)** is associated with marine terrigenous rocks: sandstone, siltstone, argillite, clay and gritstone. The maximum thickness ranges from 175 m on land in the western Lithuania to 288 m in the western Latvia. Offshore, the thickness ranges from 176 m in the well D5 (Fig. 2, Appendix 1) to 213 m in the well E7 and 193 m in the well D6 (Aliavdin *et al.* 1991; Appendix 1).

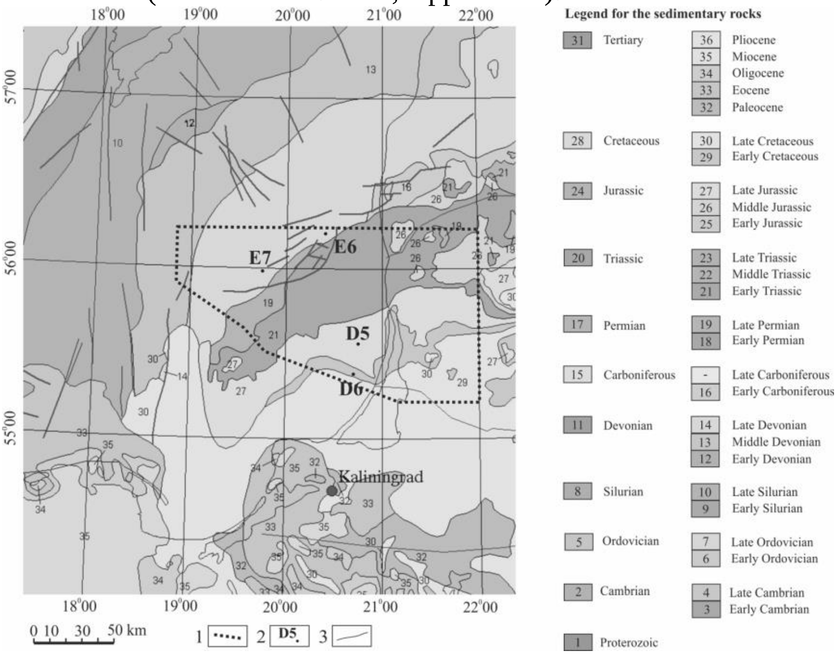


Fig. 2 Bedrock geology of the southeastern Baltic Sea (after Grigelis 2009, modified 2012): 1 – area of investigation; 2 – wells (see Appendix 1); 3 – faults.

Ordovician (O) sedimentary rocks overlay the Cambrian with stratigraphic unconformity. The Ordovician deposits consist of limestone, marlstone and clay. The deposits are between 60–160 m thick in the offshore area and up to 210 m on land (Šliaupa, Hoth 2011). The top of Ordovician is a regional seismic marker.

The sedimentation significantly increased during **the Silurian (S)**. It is composed of argillite, dolomite, gypsum, limestone, carbonate clay and is extremely rich in different fauna. The maximum thickness is from 600 m in the well E7 to 870 m in the well D6 and up to 1000 m in the western Lithuania (Grigelis *et al*. 1991a).

Early Devonian (D_1) deposits are composed of terrigenous rocks (sandstone, siltstone and argillite) with intercalations of dolomite. The thickness is about 150 m in the western Latvia and increases to the south reaching c. 300 m (Grigelis *et al*. 1991b). A sedimentary break occurs at the boundary between the Early and the Middle Devonian.

The Middle Devonian (D_2) is represented by clayey–sandy and sandy sediments, dolomite, marlstone and dolomitic breccia. The maximum thickness varies from 200 m in the well D6 to 270 m in the western Lithuania (Narbutas 1994).

Late Devonian (D_3) deposits are composed of dolomite, sandstone, siltstone and clay. The maximum thickness is presented in the vicinity of Klaipėda, where it reaches up to 250 m (Narbutas 1994). The total thickness of the Devonian rocks ranges from 960 m offshore Latvia to 1100 m near Klaipėda.

Carboniferous (C) rocks are of limited extent. They are developed on land in Latvia and north-western Lithuania, but are absent in the offshore part of the investigated area. They are represented by sandstone and limestone with a thickness of up to 110 m (Šliaupa, Hoth 2011).

Early Permian (P_1) rocks are associated with gritstone and sandstone, about 30 m thick, on land in Lithuania (Grigelis 1994a).

Late Permian (P_2) rocks were deposited after a break in sedimentation. They are absent in the western and northern parts of the investigated area. They are composed of limestone, gypsum, anhydrite and salt (in the southernmost part of the investigated area). The thickness is 107 m in the well D6 and up to 150 m on land (Suveizdis 1994a).

Early Triassic (T_1) rocks are presented across almost the same area as the Late Permian. They are composed of clay, siltstone and sandstone, about 280 m thick in the well D6 and up to 200 m in the western Lithuania (Suveizdis 1994c).

Middle Triassic (T_2) – Early Jurassic (J_1) rocks are absent in the investigated area.

Middle Jurassic (J_2) rocks and sediments overlay the Upper Devonian, Permian and Triassic with a stratigraphic unconformity. They are absent in the northwestern part of the investigated area. **Bathonian** strata are composed of sandstone and clay. Their maximum thickness reaches 50 m. **Callovian** strata are represented by sand, sandstone, limestone and clay, also about 50 m thick (Grigelis *et al*. 1991c; Grigelis 1994b).

Late Jurassic (J_3) rocks and sediments are presented in western Lithuania and in the southern offshore part of Lithuania. Marlstone, clay, siltstone and sometimes limestone of **Oxfordian** age with a maximum thickness of up to 85 m compose the Upper Jurassic in the investigated area (Grigelis *et al*. 1991c).

Late Jurassic (J_3) Kimmeridgian – Early Cretaceous (K_1) strata up to **the Early Albian** are absent in the investigated area.

Early Cretaceous (K_1), Albian, rocks and sediments are developed in the southern–southeastern part of the investigated area. They are represented by sand and siltstone with intercalations of clay and phosphorite concretions. The maximum thickness ranges from 28 m in the offshore area to 100 m on land (Grigelis 1994c).

Late Cretaceous (K_2), Cenomanian–Santonian rocks and sediments are distributed only in the southeastern part of the investigated area. They are composed of sand, sandstone, siltstone, limestone and marlstone. They are about 100-m thick in the offshore area and up to 200 m on land in the western Lithuania (Grigelis 1994b).

Quaternary (Q) deposits cover the entire area of investigations. They are described in detail below (see Chapter 2.1.5).

2.1.3 The seismostratigraphic framework

Table 1. Stratigraphic subdivision and boundaries of the Late Paleozoic and Mesozoic strata in the southeastern Baltic Sea (Flodèn 1980, Grigelis 1999).

STRATIGRAPHY				Environment	Seismic unit
Period	**Epoch**	**Age**	**Formation**		
Cretaceous	Late	Santonian, Coniacian, Turonian	Brasta Formation	Marine	K2
		Cenomanian	Labguva Formation	Shallow marine	K1
	Early	Albian	Jiesia Formation		
Jurassic	Late	Oxfordian	Ažuolija Formation	Marine	J4
	Middle	Callovian	Skinija Formation Paprtinė Formation	Shallow marine	J3 J2
		Bathonian	Skalviai Group (upper part)	Brackish water basin	J1
Triassic	Early		Purmaliai Group	Continental basin	T2 T1
Permian	Late	Zeichstein Werra Cycle	Naujoji Akmenė Formation	Shallow marine	P2 – P3
			Sasnava Formation		P1
			Kalvarija Formation		
Devonian	Late	Frasnian	Gauja Beds to Amula Beds	Shallow marine	D3 – D4

The lithology and internal structure of geological layers are the basics of the seismostratigraphic subdivision. Seismic boundaries are the reflections of the boundaries between geological units. In addition, seismic reflectivity patterns respond to the structure of geological layers. This fact may be also used to locate the boundary between different geological layers. Especially in the cases, when the reflection of the boundary is indistinct and weak.

The exposed sedimentary bedrock of the investigated area ranges from Middle Devonian to Late Cretaceous (Table 1; Fig. 2).

Four seismically contrastive units can be identified into **the Devonian** sedimentary sequence, but only one of these units with mainly marine deposits is presented in the investigated area. The stratigraphic subdivision is based on lithological and biostratigraphical evidence from offshore Latvia. Seismic unit **D3–D4** is subdivided and interpreted as D_3 Frasnian rocks. The Baltic Sea transgressed in the Frasnian age. Clay, marl, limestone and dolomite were deposited (except for short intermissions) in the sea at that time. The D3–D4 unit may be further subdivided into two seismic intervals: a lower interval is characterized by particularly weak seismic reflectivity pattern and an upper one by a more distinct seismic pattern (Fig. 3). Both intervals display irregular bedding with frequent sedimentary breaks. A rather strong and stable reflector separates these two intervals. This reflector forms an important seismic marker within the unit and is traceable across a large area. The maximum thickness of the D3–D4 unit is about 200 m in rather equal proportions between the intervals (Flodén 1980).

A distinctly layered seismic reflectivity pattern is a characteristic for **the Late Permian** offshore (Fig. 4). It is interpreted as the lower part of the Zeichstein Werra cycle with typical seismic signatures (from bottom to top): **P1 unit** consists of dolomite or limestone; **P2 unit** – hard limestone and dolomite with concretions of silica; **P3 unit** – carbonate strata. The P2 unit is affected by palaeokarsts and becomes thicker in the direction of the Lithuanian shoreline (Grigelis

1999). The maximum observed thickness of the Late Permian within investigated area is 107 m in the well D6 (Appendix 1).

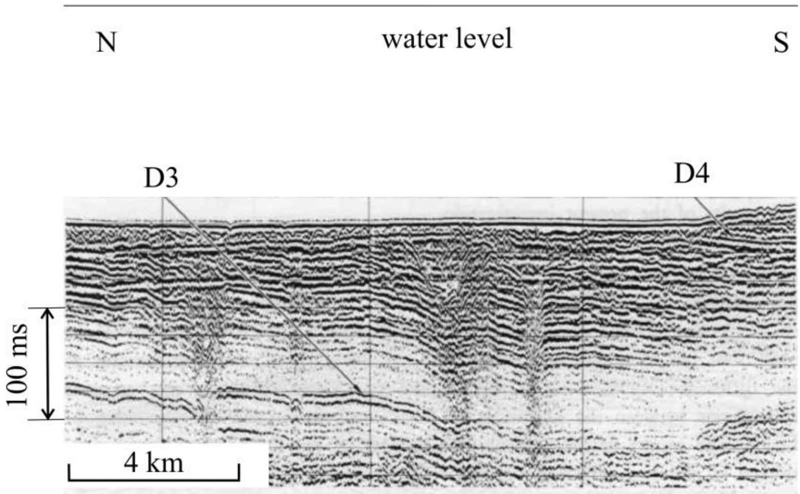


Fig. 3 Example of seismic unit D3–D4 from the area SE of Gotland. D3 — base Gauj (base of Upper Devonian), D4 — base Mur (base of Upper terrigenous Devonian) (after Flodén 1980).

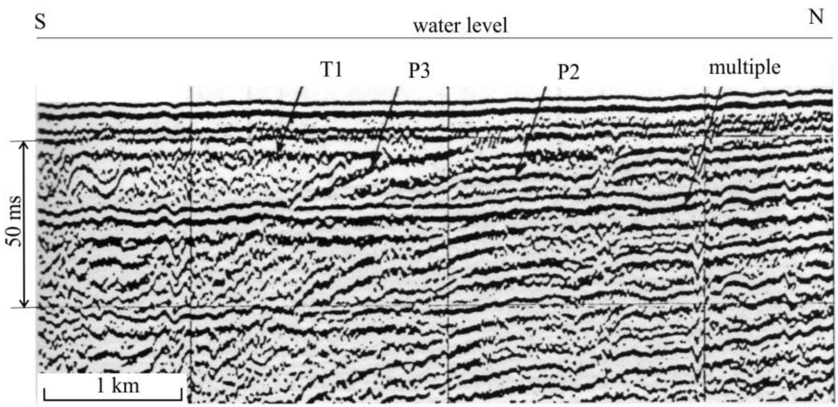


Fig. 4 Examples of seismic units P2, P3 and T1 from the SE Baltic Sea (after Grigelis 1999).

The seismic reflection of **the Early Triassic** is facially separated into two units: T1 and T2. Both units are interpreted as Early Triassic argillite, supposedly equivalent to the Purmaliai Group. **T1 seismic unit** is expressed by a comparatively weak regular seismic reflectivity pattern (Fig. 4). It is presented in the southeastern part of the investigated area. The T1 unit is regarded as lowermost part of the Nemunas Formation. **T2 seismic unit** is interpreted as equivalent to the Early Triassic Palanga Formation. This unit is characterized by a comparatively weak, irregular and typically transparent seismic reflectivity pattern (Fig. 5). The irregularities of the seismic reflectivity pattern are most evident in the northern part of the investigated area. The maximum thickness of the Early Triassic is about 50 m (Grigelis 1999).

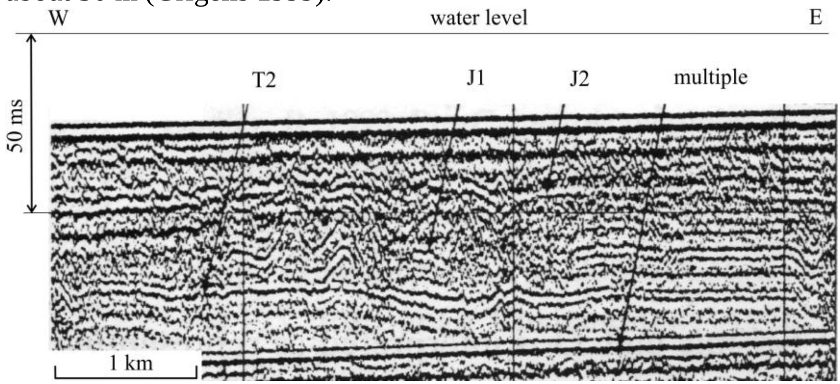


Fig. 5 Examples of seismic units T2, J1 and J2 from the SE Baltic Sea (after Grigelis 1999).

The seismic reflection of **the Middle–Late Jurassic** is subdivided into four seismically derived units. **J1 unit** is associated with terrigenous brackish water deposits equivalent to the upper part of the Middle Jurassic Skalviai Group. It is characterized by an almost transparent seismic reflectivity pattern (Fig. 5; Fig. 6). The maximum thickness is 25 m. **J2 unit** is associated with Early Callovian sandy carbonate deposits and is referred to the Papartinė Formation. It is characterized by a horizontally layered seismic reflectivity pattern with several strong internal reflectors (Fig. 5; Fig. 6). The J2 unit is conformed to the maximum northwestern transgression. The maximum thickness of this seismic unit is 50 m. **J3 unit** is regarded to represent the Skinija Formation of Late Callovian age. It is composed of argillaceous clay and silt. The seismic reflectivity pattern is similar to the J2 unit, but separated from it by a distinct reflector in the eastern part of the offshore area (Fig. 6). The maximum thickness reaches 70 m. **J4 unit** is referred to the Oxfordian argillaceous carbonate deposits equivalent to the Ąžuolija Formation. It is expressed by a distinct layered seismic reflectivity pattern and is distributed in the southern part of the investigated area. The maximum thickness of this unit is up to 75 m.

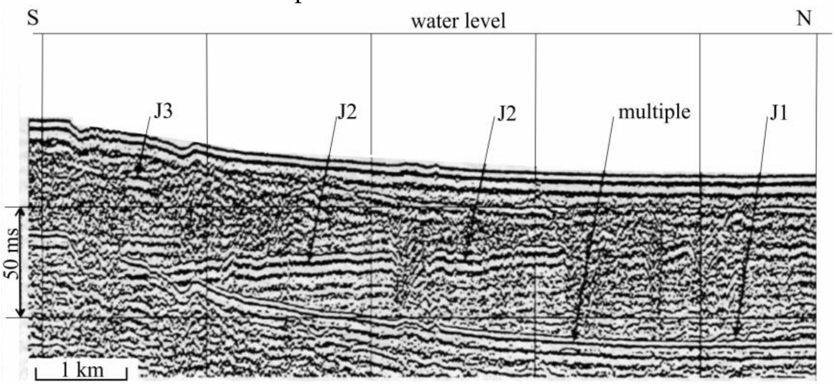


Fig. 6 Examples of seismic units J1, J2 and J3 from the SE Baltic Sea (after Grigelis 1999).

The seismic reflection of **the Cretaceous** is subdivided into two seismically contrastive units. **K1 unit** is characterized by terrigenous quartz–glauconitic deposits of Albian and Cenomanian and regarded to the Jiesia and Labguva Formations. K1 unit may be subdivided into two seismic intervals: a lower interval with a weakly layered seismic reflectivity pattern and an upper interval with a regularly layered seismic pattern. The maximum thickness is about 80 m. **K2 unit** is interpreted as Turonian–Santonian carbonate chalky deposits of the Brasta Formation. It is described by a distinct coherent seismic reflectivity pattern. The maximum thickness of this seismic unit is about 100 m (Grigelis 1999).

2.1.4 The sub–Quaternary surface

The first version of the sub–Quaternary surface map of the south-eastern Baltic Sea with palaeo-incisions was compiled and described in 1995 (Gelumbauskaitė 1996). Later this scheme was updated having applied new data. The topography of the sub–Quaternary morphostructure is characterized by uplifts, depressions and structural terraces (Gelumbauskaitė, Litvin 1986; Gelumbauskaitė 1996; Gelumbauskaitė, Grigelis 1997) (Fig. 7).

The recent sub-Quaternary relief of the southeastern Baltic region was formed during Late Paleogene–Neogene regression and peneplenization. Erosion and denudation processes were active due to uplifting of the area in the end of the Neogene (Gelumbauskaitė 1999).

Late Devonian Klaipėda–Liepaja Uplift namely the structural terraces of the banks (Fig. 7), was formed in the Pļaviņas–Pamūšis time. The Uplift separates the East Gotland Trough from the Gdansk Depression. Its top occurs at an absolute depth from –40 to –60 m. The Curonian Plateau and the Gdansk Depression are located on the peneplain formed in the Late Permian–Cretaceous rocks.

The palaeo-incisions of the Eastern Trough of the Gotland Depression, cut into the structural–denudational surface of the Middle–Late Devonian rocks, were examined in seventy three segments. The absolute depth of these incisions ranges from –207 to –337 m (Gelumbauskaitė, Grigelis 1997).

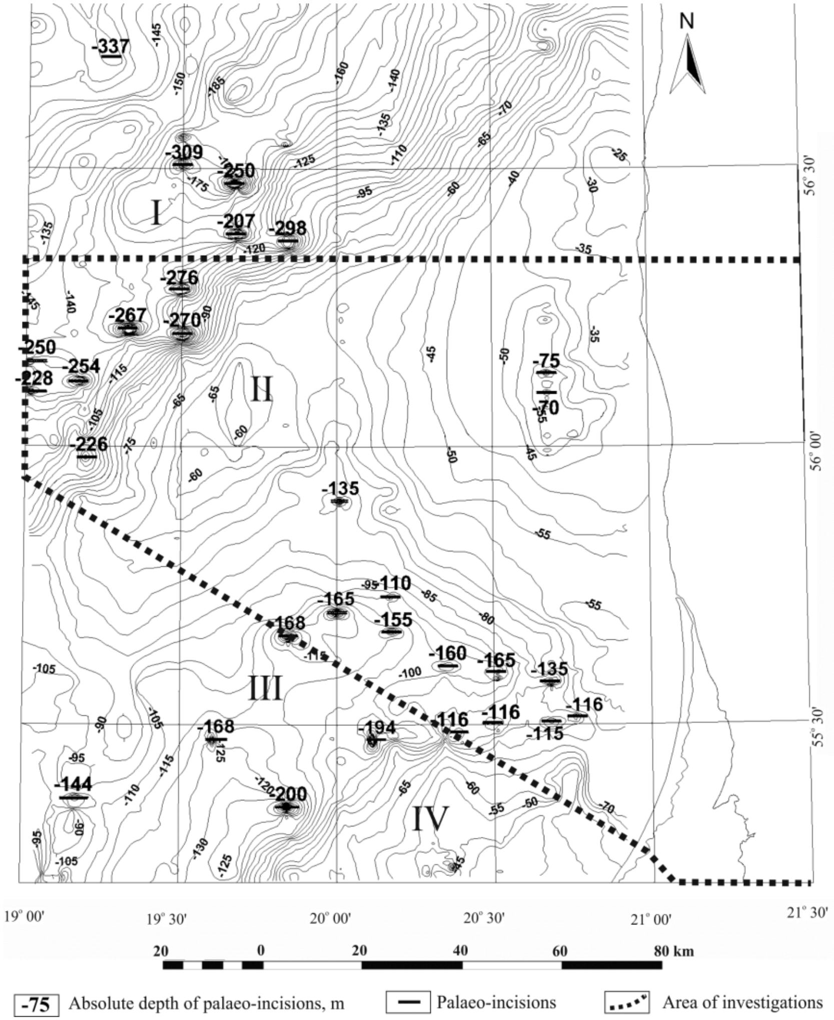


Fig. 7 The sub–Quaternary surface of the southeastern Baltic Sea (after Gelumbauskaitė 1995). Subdivision of morphostructure: I – Eastern Gotland Through; II – Klaipėda-Liepaja Uplift; III – Gdansk Depression; IV – Curonian structural terrace. Segments of the palaeo-incisions are in absolute depth in meters.

Land part of sub–Quaternary surface is formed during the Oligocene/Neogene uplift and denudation. The map has been compiled essentially having applied data from the regular geological mapping supplemented by well data (Šliaupa *et al*. 1994).

The most recent land geological mapping has been performed by the Lithuanian Geological Survey from the Lithuanian coastline and eastwards to 22° E.

2.1.5 Thickness of Quaternary cover

Quaternary cover in the south–eastern Baltic Sea was evaluated by Gelumbauskaitė in 1996. In general, the Quaternary thickness varies from 5 m to 20–25 m on the plateau and reaches 40 m in the depressions. Shoreward in the coastal zone, the thickness of the Quaternary cover increases up to 50–60 m. The lithostratigraphy is based on short drill core data analysis. These cores are drilled through the entire Quaternary depositional complex (data from the marine geological mapping at the scale of 1:500 000/1:200 000 in 1975–1978; engineering geological research of PETROBALTIC in 1989–1990). The depositional Pleistocene–Holocene complex varies from 10 m in the shallow zone to 48 m on the Klaipėda Slope (on E–W Klaipėda traverse) (Majore *et al.* 1997; Gelumbauskaitė 2009).

According to continuous seismic profiling data, three separate till units, clay, and also stratified and unstratified layers of sand and gravel, have been established in the Baltic Proper. It is possible to classify at least three generations of palaeo-incisions (Table 2). These three generations of palaeo-incisions are associated with Elsterian, Saalian, and Weichselian glaciations respectively (Bjerkéus *et al.* 1994). The palaeo-incisions are infilled by till and stratified, or unstratified, glaciofluvial material, and all the palaeo-incisions are covered by sediments of the Weichselian glaciation. Weichselian till is developed in a significant part of the Baltic Sea bottom except particular near shore areas, where it was eroded during different stages of the Baltic Sea formation in Holocene, and where Saalian till outcrop on the seafloor (Repečka *et al*. 1991; Bitinas *et al.* 1999).

Table 2. Chronostratigraphic subdivision of the Pleistocene deposits in the Lithuanian coastal zone and their lithological characteristics*.

Chrono-stratigra-phic stages	**Marine isotope stage**	**Time scale, ka BP**	**Genesis and lithology of sediments**
Holocene	1	11.6	Marine, lagoon, lacustrine, aeolian, alluvial deposits and sediments: sand, mud, gyttja, peat, silt.
Weichselian	2	24	Glacial deposits. Upper till: yellowish brown, soft and slightly weathered. Lower till: brownish grey and greyly brown, contains glacio-dislocated floes of glaciofluvial gravel, sand.
	3	59	Lacustrine sediments: greyish-yellow or greyish-brown fine-grained sand.
	4	74	Glacial deposits: till, grey and greenish-grey, in some places grey-brown, compact. In the environs of the Klaipeda Strait contains a big amount of glacio-dislocated floes of lacustrine sediments with organic.
	5a-d	117	Lacustrine sediments: greyish-yellow fine- and very fine-grained sand.
Saalian complex	6-10	337	Glacial lacustrine sediments: greyish-yellow fine- and very fine-grained sand or silty sand with admixture of finely dispersive organic matter; in some places with interlayers of gyttja or peat. Glacial deposits: compact greyish-brown or grey till.
Elsterian	12	478	Glacial deposits: compact grey and greenish-grey till developed in the depressions of sub-Quaternary relief and palaeo–incisions.

*Chronostratigraphic units and time scale – after Gibbard, Cohen 2008; Guobytė, Satkūnas 2011. Stratigraphic subdivision and lithology – after Bitinas et al. 1999, 2000, 2004, 2011; Molodkov et al. 2010; Damušytė et al. 2011.

Quaternary thickness varies in relatively wide range from 20 m in the southern part of investigated area up to 60–80 m in the northern part. It reaches up to 130–140 m in the palaeo-incisions. Tills prevail in the upper and in lowermost parts of the Quaternary strata. An inter-till complex of sediments is developed in the middle part. Three till layers are established in the lowermost part of the Quaternary strata. They most probably represent Elsterian and Salian glacial sediments (Table 2). A more detailed stratigraphic identification of the oldest Pleistocene tills is complicated, because no section with interglacial sediments, i.e. marine sediments of Holsteinian and Eemian Seas, has been found on the Lithuanian Baltic coast or offshore. According to the results of luminescence dating, the inter–till complex of sediments was formed in a few sedimentary basins during late marine isotope stage (MIS) 6, MIS 5d-5a, and MIS 3 (Molodkov *et al.* 2010; Bitinas *et al.* 2011). Till layers from the uppermost part of geological section represent a few glacial advances of the Weichselian glaciation (occurred during MIS 4 and MIS 2) (Bitinas *et al.* 2011). MIS 4 and MIS 2 strata include a large amount of Pleistocene floes. Both this fact and glaciotectonic deformations are key features of MIS 4 and MIS 2 Weichselian glacial stages.

2.1.6 Geological features of palaeo-incisions

The distribution of palaeo-incisions is irregular and complicated (Sviridov 1984). Thus, the present day published schemes (Gaigalas 1976; Šliaupa, Repečka 1995; Šliaupa 2001) and maps of sub-Quaternary surfaces (Sviridov *et al.* 1976; Šliaupa *et al.* 1994; Šliaupa 2004) on land in the western Lithuania with evidences of palaeo-incisions are not detailed enough to serve as guidelines for investigating palaeo-incisions.

In general, palaeo-incisions appear as buried valleys, most often filled with Quaternary sandy-clayey deposits in various combinations. The shape of these geological structures looks slightly similar to river valleys. Commonly these structures are of U- or V-shape in perpendicular profile, with the angle of slopes reaching 40^{o}–45^{o}. The width of palaeo-incisions varies from a few meters (Piotrowski 1994) to several hundred meters and even up to 5 km according to some estimation (Šliaupa 2004; Smit, Bregman 2012; Atkinson *et al*. 2013). The depth of palaeo-incisions varies from several meters to 300 m. Depth of 300 m in absolute values is reported from the Dutch sector of the North Sea. The width of the structures exceed the depth by about 10 times (Huuse, Lykke–Andersen 2000; Smit, Bregman 2012). The length of palaeo-incisions may reach 100 km (Janszen *et al*. 2012).

Palaeo-incisions are mainly filled in with Pleistocene sediments to their average depth of 80 m. Several different infilling units, i. e. tills, clay, sand and gravel deposits have been classified in the southeastern Baltic Sea in the eastern part of the Baltic Proper (Bjerkéus *et al*. 1994; Flodén *et al*. 1997). The infilling of the palaeo-incisions often indicates two, or sometimes three, depositional events.

The prevailing relative depth of the palaeo-incisions is about 40–70 m in the Lithuanian coastal area; merely a few of them are deeper as e.g. a palaeo-incision reaching an altitude of –147 m in the vicinity of Šventoji. The deepest palaeo-incision in this area has been recorded in a borehole drilled in the Nemunas Delta area; its bottom reached an altitude of –269 m (Šliaupa 2004).

Different opinions have been put forward with regard to the genesis of palaeo-incisions in the sub-Quaternary surface. Numerous studies favor an idea of a complex stepwise periglacial, sub-glacial-glaciofluvial, postglacial-fluvial origin of the palaeo-incisions that were then even further reshaped by the next generation of Pleistocene glaciers (Timofeev *et al*. 1974; Gaigalas 1976; Sviridov *et al*. 1976; Gudelis *et al*. 1977; Blazhchishin *et al*. 1982; Tavast, Raukas 1982; Eberhards, Miidel 1984; Sviridov 1984; Veinberga *et al*. 1986; Rozhdestvensky 1989; Repečka *et al.* 1991; A. Šliaupa *et al*. 1995; Savvaitov *et al*. 1999). Initially it had been noted that the zones with fragments of incisions extended clearly in the NE–SW direction, responding to the distribution of the soft sedimentary rocks of the Triassic, Jurassic and Cretaceous geological systems, respectively (Sviridov 1984, 1991). Later on, an idea was expressed on possible links between glacial-sub-glacial incisions and fossil cryogenic structures in the Mesozoic bedrock of the southeastern Baltic Sea (Monkevičius 1999).

Other authors have put forward a sub-glacial or more precisely a sub-glacial–fluvioglacial hypothesis. It is based on that the palaeo-incisions are the result of glacier-derived water erosion caused by catastrophic releases of huge water masses under the high pressure during ice recession (Kuster, Meyer 1979; Ehlers *et al.* 1984; Wingfield 1989; Bjerkeus *et al*. 1994; Flodén *et al.* 1997; Bitinas 1999; Jurgens 1999; Satkūnas 2000, 2008). This hypothesis is based on the theory of melt-water circulation under continental ice sheet (Boulton, Hidmarsh 1987; Boulton *et al.* 1993; Piotrowski 1994, 1997; Boulton, Caban 1995; Boulton *et al.* 1995). J. Satkūnas (2000) particularly analyzed palaeo-incisions in Lithuania and deduced that lowering of the global ocean-level is not sufficient to explain the intensive entrenching of palaeo-rivers and formation of palaeo-incisions. The palaeo-incisions of some generations had been determined to repeat each other in the same places. This fact is also confirmed by the results of marine seismic profiling in the Baltic Sea (Sviridov 1984; Bjerkeus *et al.* 1994) and in the North Sea (Wingfield 1989).

Used marine data, which originate from seismo-acoustic investigations in the southeastern segment of the Central Baltic Sea, show that the palaeo-incisions are imprinted into the Neogene peneplain surface here. They are weakly expressed as compared to the palaeo-incisions in the subsurface of the Middle Devonian terrigenous rocks along the eastern slope of the Gotland depression (Bjerkéus *et al.* 1994; Gelumbauskaitė, 1996; Flodén *et al.* 1997). Their connection to the fragmented system of late- to post-glacial channels in the Late Quaternary sequence of the study area is not clear yet. Otherwise, geophysical surveys in the central western part of the Baltic Sea, e.g.

in the Hanö Bay, have not revealed any similar structures which strongly indicate that the valleys are truly of a general periglacial origin generated during major standstills of ice sheets (Flodén *et al.* 1997).

Some scientists do not associate palaeo-incision infill with any specific glaciation (Janszen *et al.* 2013). It corresponds with the fact, that various seismic reflectivity patterns of tills confirm the complex and differential infill of palaeo-incisions. Geophysical methods, which have been used during this study, are suitable only for detection of location, morphology and infill of palaeo-incisions, but they do not allow establishing their genesis or accurate age.

2.2 OVERVIEW OF PREVIOUS GEOPHYSICAL ACTIVITY

2.2.1 Marine continuous seismic reflection profiling (CSP)

In the 1970s, the pioneers of shallow seismo-acoustic surveys of the Baltic Proper were investigators of the Stockholm University dealing with the distribution of Paleozoic sedimentary rocks, as well as the researchers from the Atlantic Branch of Kaliningrad Oceanology Institute working in the area where Mesozoic and Cenozoic rocks are abundant. At this time the methods and equipment of continuous seismic profiling (CSP), focused on the upper parts of the pre–Quaternary rocks (0–200 m), were successively developed improving the quality of the seismic records. The research area was covered by a dense network of seismo-acoustic profiles surveying the sub–Quaternary surface relief, structure of the Mesozoic and Cenozoic sedimentary cover, displacements in the upper part of sedimentary cover in the south–eastern Baltic Sea (Sviridov 1976, 1983). At the same time, the geology, tectonics and seismostratigraphy of the Paleozoic bedrock of the Central Baltic had been studied in detail (Flodén 1980). In 1984, the data of the Mesozoic and Cenozoic sedimentary rocks in the south–eastern part of the Central Baltic Sea had been summarized displaying different surface heterogeneities, in particular including local palaeo-incisions (Fig. 8; Sviridov 1984, 1991). For the first time it was noted that distinguished zones of fragmentation extend in the NE–SW direction and correspond to the distribution of the soft sedimentary rocks of the Triassic, Jurassic and Cretaceous geological systems, respectively. Later on, an idea was expressed on possible links of glacial–sub-glacial incisions with fossil cryogenic structures in the Mesozoic bedrock of the southeastern Baltic Sea (Monkevičius 1999).

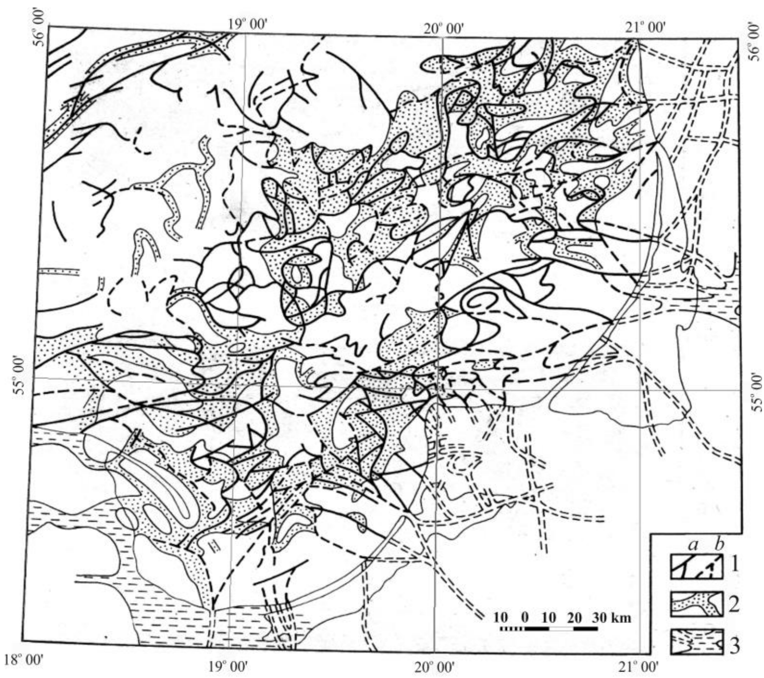


Fig. 8 The distribution of surface heterogeneities in the southeastern Baltic region by continuous seismic profiling and land data. 1 – Local palaeo-incisions: a – without reflection boundaries, b – with reflection boundaries; 2 – zones of fragmentation; 3 – glacial and fluvial palaeo-incisions on land (after Sviridov 1984).

General geological schemes of the pre–Quaternary sedimentary rocks of the Central Baltic Sea had been set in the mid-1960s tracing the boundaries of the geological systems seawards from the East Baltic mainland and from Scandinavia (Gudelis 1970).

Later on, in the last decades of the 20th century, the knowledge of the bedrock geology of the Baltic Proper increased significantly through deep seismic surveys, hydrocarbon prospective drillings and tectonic analyses ranging over an internal structure of entrails. Studies of marine drilling cores applying mainly micropalaeontological methods allowed the exploration of the pre-Quaternary stratigraphic section in the eastern segment of the Baltic Proper (Grigelis 1995).

Moreover, *continuous seismic profiling (CSP)* data, shot during Lithuanian-Swedish marine geological–geophysical expeditions in 1993–1995 (Grigelis *et al*. 1994, 1996), provided a reliable source for detailed investigations of the upper parts of the sub–Quaternary bedrock of the Central Baltic Sea (Fig. 9; Grigelis 1999). An idea was developed about the presence of sub–Permian and sub–Quaternary peneplains in the southeastern Baltic Sea. This facilitated the construction of a modern geological map (Grigelis 1995). The next step was to establish the seismo–stratigraphic units and boundaries of the Late Paleozoic (Permian) and Mesozoic bedrock of the southeastern segment of the Baltic Sea (Grigelis 1999). That supplemented the seismo–stratigraphy of the Paleozoic of the Central Baltic Sea defined in the late 1970s (Flodén 1980).

Several geological maps of the Central Baltic Sea, and of the entire Baltic Sea, have been compiled since 1980 based on more or less relevant geological–geophysical data (see Grigelis *et al*. 1993; Grigelis 2011). A basic geological map of the Central Baltic Sea, the original version at a scale of 1:500 000, had been compiled by A. Grigelis in 1998 (see Fig. 1). Later this map was integrated into the geological map of Northern Europe (Sigmond, Ed. 2002) and in the International geological map of Europe (IGME–5000; Asch, 2005). The most recent version is used in the digital release of the One Geology Europe elaborated in 2011–2012 (Stevenson 2012).

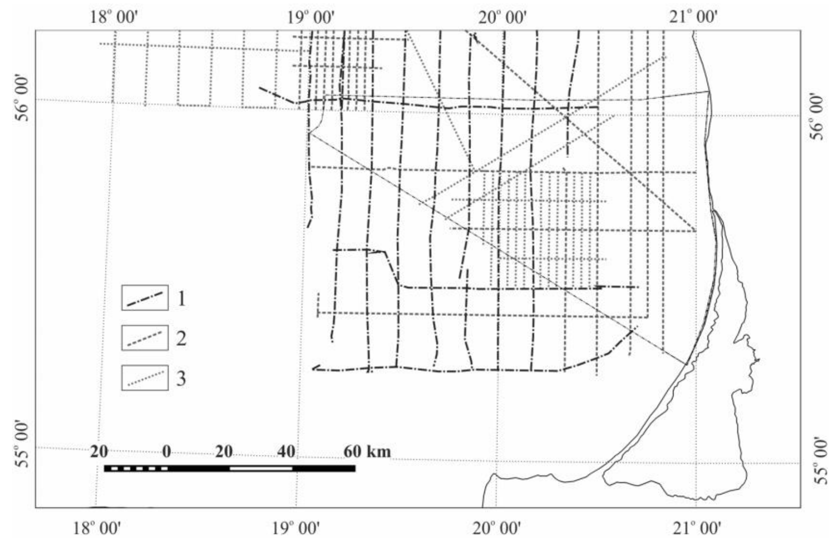


Fig. 9 Location of seismic lines in the southeastern part of the Baltic Sea. Expeditions: 1 – Grigelis et al. 1994; 2 – Grigelis et al. 1996 (1994 expedition); 3 – Grigelis et al. 1996 (1995 expedition).

2.2.2 2D seismic common mid-point (CMP) shooting on land

The western part of Lithuania is covered by a rather dense grid of seismic lines, shot by the common mid-point technique. The objective of these investigations had been Cambrian–Silurian oil and gas perspective sedimentary rocks (Zdanavičiūtė, Sakalauskas 2001). The uppermost part of the sedimentary cover, down to a depth of c. 150 m had not been resolved during these investigations. But in the context of this work that is an area of primary interest.

The geological section of well No. 19623 is used as a key-section for choosing theoretical physical properties of the sedimentary rocks (Table 3).

Table 3. Relative permittivity (ε) and seismic velocity of p-waves (m/s) in well 19623*.

Top of the layer	**Bottom of the layer**	**Age**	**Rock**	**Relative permittivity (ε)**	**[3]Seismic velocity (m/s)**	**[4]Resistivity r, Ω . m**
0	0.5		Peat	[1]11		
0.5	4		Sand	[2]4 – 9		
4	8		Peat	[1]11		
8	11		Sand	[2]4 – 9		
11	16		Till	[2]9 – 25		
16	21		Gravel with sand	[2]4–9		
21	83	Q	Sand	[2]4–9	≤ 1800	30 – 100
83	95		Gravel with sand			
95	104		Till			
104	124		Sandy till			
124	129		Gravel with sand			
129	135		Till			
surrounding bedrock		T1	Clay		2100 – 2300	4 – 15
135	162	P2	Limestone		2000 – 3000	90 – 5000
162	174		Marlstone			
174	190	C1–D3	Sandstone		2400 – 2500	
190	210		Marlstone			
210	240	D3	Dolomite		2450 – 2650	

*(Lithuanian Geological Survey database, http://www.lgt.lt/zemelap/main.php?sesName=lgt1412160593, for location see Fig. 20B). [1] – After Ayalew *et al.* 2007; [2] – after Vladov, Starovoytov 2004; [3] – Vertical Seismic Profiling (VSP) data from well D5; [4] – after Šečkus 2002.

2.2.3 Electrical tomography

The electrical tomography is used during geological, hydrological, ecological and engineering investigations in Lithuania. The object of these investigations is the uppermost part of the sedimentary cover, down to a depth of c. 200 m. It corresponds to an area of primary interest in the context of this work. The electrical tomography is the most commonly used geophysical method for electrical surveys in Lithuania (for example, see Fig. 10, Šečkus 2002).

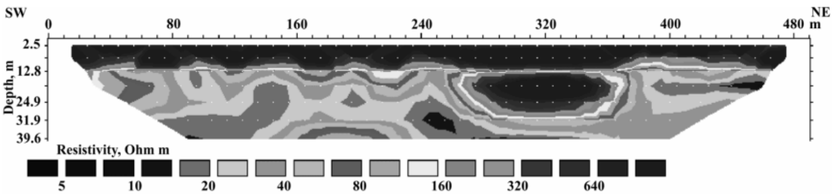


Fig. 10 Line Kleboniškis-1. Inverse model resistivity section (after Šečkus 2002).

The applying of electrical tomography method is described below (see Chapter 3.2.2).

2.2.4 Gravimetric survey

A test gravimetric survey had been performed in the Dovilai area (Klaipėda District) by L. Korabliova in 1996–2000. This survey is part of the integrated geological mapping at the scale of 1:50 000 carried out by the Lithuanian Geological Survey. The objective of the investigation had been the testing of application of gravimetric methods for identification of palaeo-incisions in the particular geological settings that exist in this part of the Lithuanian coastal area. Thus, a palaeo-incision is contoured along the one gravimetric profile in the Dovilai area and confirmed by the section in the well Dovilai-11 (Fig. 11). The geophysical model of the Quaternary thickness and the uppermost part of the pre-Quaternary sedimentary bedrock had been carried out by L. Korabliova (Bitinas 2000). The geological section along the above gravimetric profile and via well Dovilai-11 has been compiled, based on these data.

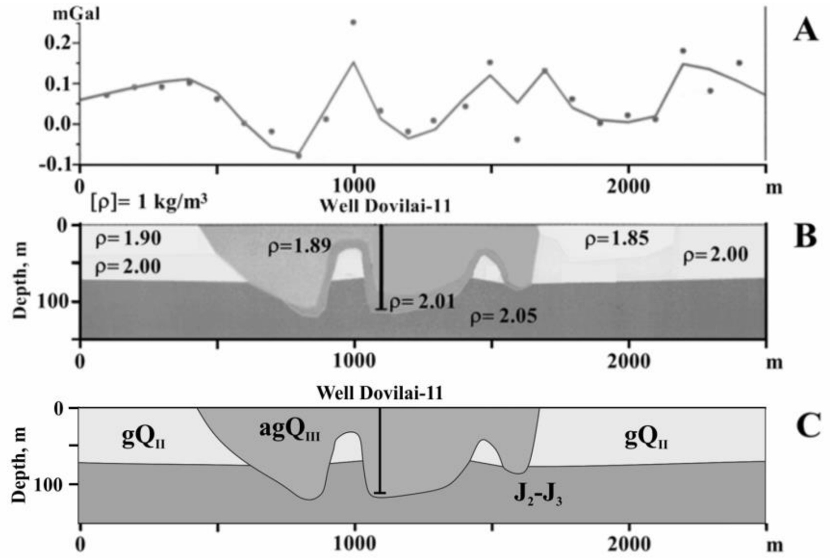


Fig. 11 Results of the gravimetric survey. A: Measured values (dots) and the Bouguer gravity anomaly (polyline). B: The geophysical model; ρ – density. C: Geological interpretation, gQII – glacial deposits of the Middle Pleistocene; agQIII – aqua-glacial deposits of the Last Glaciation inside the palaeo-incisions. Geophysical measurements and model after L. Korabliova.

Based on the results of the gravimetric survey, the following conclusions have been made:

(1) It is possible to locate a palaeo-incision applying gravimetric measurements alone, but there are gravitational anomalies in the area, which are not connected to palaeo-incisions (e.g. at the position 1700 – 2200 m in Fig. 11B). It is impossible to determine the origin of a gravitational anomaly without additional geological or geophysical data. Thus, the location of palaeo-incisions is not fully verified applying the gravimetric survey method alone.

(2) It is almost impossible to determine the depth and locate the slopes of the palaeo-incisions. Nor it is possible to separate the geological layers of enclosing rocks without additional geological or geophysical data.

3. MATERIAL AND METHODS

The Palanga–Šventoji area along the Lithuanian coast has been chosen as a key-area for the detailed experimental investigations (Fig. 12). This area is selected because it contains a number of boreholes, which aided in locating the palaeo-incisions (Bitinas *et al*. 1998). 2D shallow seismic and electrical tomography, has been applied to locate palaeo-incisions on land in the western Lithuania (Table 4).

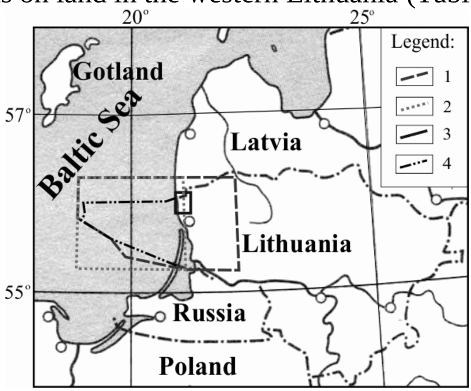


Fig. 12 Areas of investigation. 1 – Area of compiled set of the pre-Quaternary maps; 2 – location of CSP data (see Fig. 14); 3 – the area of geophysical investigations on land (see Fig. 20); 4 – Lithuanian Sea border.

This work also contains a detailed analysis of analogous single–channel continuous seismic profiling data (CSP) in the southeastern part of the Baltic Sea (Fig. 9). The investigated area offshore is located within the Lithuanian economic zone and adjacent areas, where the CSP data are available (Fig. 12). The data have been collected by the Institute of Geology and Geography and also by the Stockholm University.

Table 4. Scope of geophysical investigations

Method	**Continuous seismic profiling**	**2D CMP seismic**	**Electrical tomography**
Location	Offshore	On land	On land
Status	Digitalized and re-interpreted	Newly investigated	Newly investigated
Total length, km	2233.1	6.9	2.6

3.1 CONTINUOUS SEISMIC PROFILING (CSP) FOR MARINE INVESTIGATIONS

The main principle of continuous seismic profiler (CSP) is that, the signal penetrates into the sea floor, where it is reflected at velocity discontinuities (seismic boundaries) in the sediment or bedrock (Fig. 13).

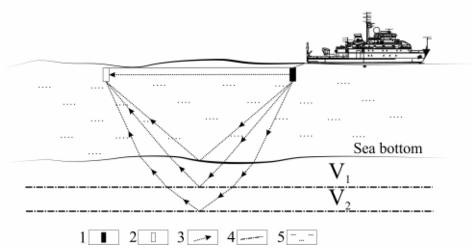


Fig. 13 The seismic profiler: 1—transmitter (seismic source); 2—hydrophone (seismic receiver); 3 – theoretical trace of seismic reflected wave; 4 – seismic boundaries; 5 – water layer; V1 and V2 – geological layers with different seismic velocities.

The reflected signals are recorded by a single channel hydrophone, which is constructed to have its maximum sensitivity perpendicular to the survey line (Flodèn 1980).

The data used in this investigation had been collected during joint geological–geophysical surveys performed by the Lithuanian Institute of Geology and Geography (Department of Baltic Marine Geology) and Stockholm University (Department of Geology and Geochemistry) in 1993–1995 and in 1998–1999 (Grigelis *et al*. 1994, 1996; http://www.eu-seased.net: Seismic and sonar/Euroseismic/ metaformat) (Fig. 14; Appendix 2).

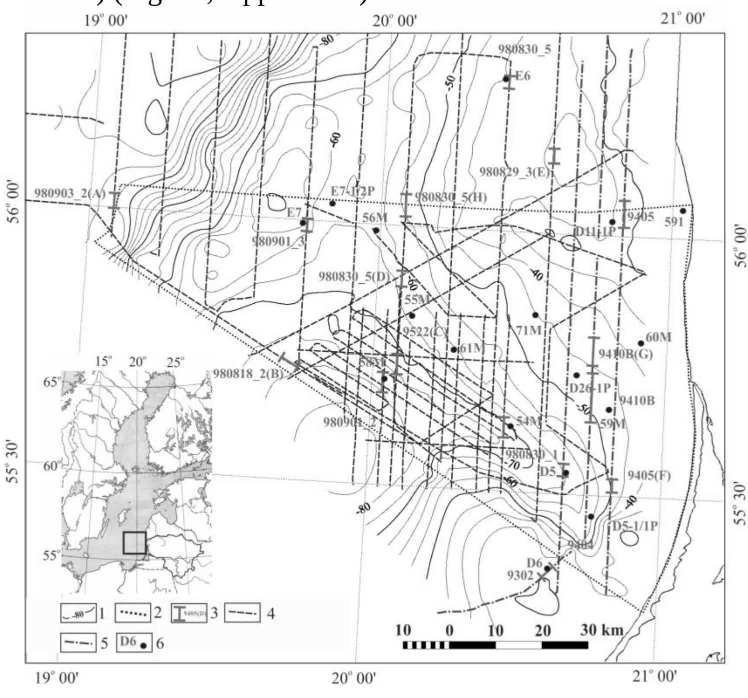


Fig. 14 Location map of CSP lines 2014: 1 – isobaths are drawn at 5 m intervals; 2 – Lithuanian Sea border; 3 – fragments of seismic lines (see Figs. 15 – 19, 30, 32 – 34); 4 – seismic lines interpreted and reinterpreted during this work; 5 – earlier interpreted seismic lines used as basis for general seismic data interpretation; 6 – wells (Appendix 1).

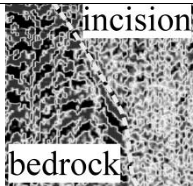
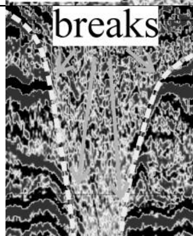
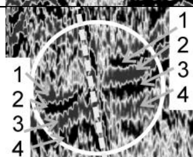
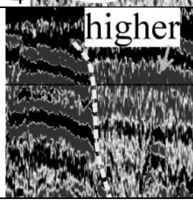
Seismic lines are located every 5 km in the eastern part and every 10 km in the western and northern parts of the investigated area. In the central part of the area the lines are located every 2.5–5 km and a set of NW–SE lines every 2 km. Total length of the 62 seismic lines studied is 2233 km (Appendix 2, Table 4).

A *PAR-600B* air gun, 100–1000 Hz at 14 MPa, was used as seismic source and a hydrophone eel of 20 m length as seismic recorder. The record sweep was 0.5 s, which is sufficient to obtain seismic data down to about 500 m depth (b. s. l.) in the area of investigations. The signal processing was done on site, and both stacked and unstacked records, band pass filtered 200–500 Hz, were displayed on precision graphic recorders. An echo sounder, *FURUNO FE-881 MK-II*, was used to record water depth. A *Raytheon*, and later a *NavTrackXL*, GPS navigator was used for positioning. The obtained accuracy was ± 50 m. A graphical coordinate system based on the *WGS-84* geoid was chosen to fix the position of the seismic lines (see Appendix 2).

The seismic records were used to detect the offshore palaeo-incisions and analyze and describe their infillings. Three offshore wells – 54M, 58M and D11-1P (Fig. 14) – have been drilled into palaeo-incisions. The deposits of the infillings have been analyzed and a correlation between the seismic reflectivity pattern and the type of infilling has been determined. Based on the comparison with the well data, the seismic reflectivity pattern of about one hundred fragments of seismic profiles crossing the palaeo-incisions were analyzed (Appendix 3). The investigated area is 67 km from north to south and 82 km from west to east, 19.5 km^2.

The general features for locating palaeo-incisions are as follows: differences in internal seismic reflectors between the incision and the surrounding bedrock, phase shift, and breaks of distinct seismic events at the boundary of a palaeo-incision, as well as increased amplitudes of the internal seismic reflectors within the incision (Table 5).

Table 5. Criterions for determining slopes of palaeo-incisions according to character of seismic record.

Type of boundary	Criterion	Example
1	Differences in character of internal seismic reflectors between the incision and surrounding bedrock	
2	Breaks of distinct seismic events at boundary of palaeo-incisions	
3	Phase shift of the same seismic reflectors at boundary of palaeo-incisions	
4	Higher amplitudes of the internal seismic reflectors within palaeo-incisions	

The interpretation of seismic lines 9302, 9404, 9405 and 9410 (Bjerkéus *et al.* 1994; Grigelis *et al.* 1994, 1996; Gelumbauskaitė 1995; Flodén *et al.* 1997; Gelumbauskaitė, Grigelis 1997; Gelumbauskaitė 1999, 2000) has been digitalized. Together with well data, it provided the basis for general seismic data interpretation presented in this work (Fig. 15).

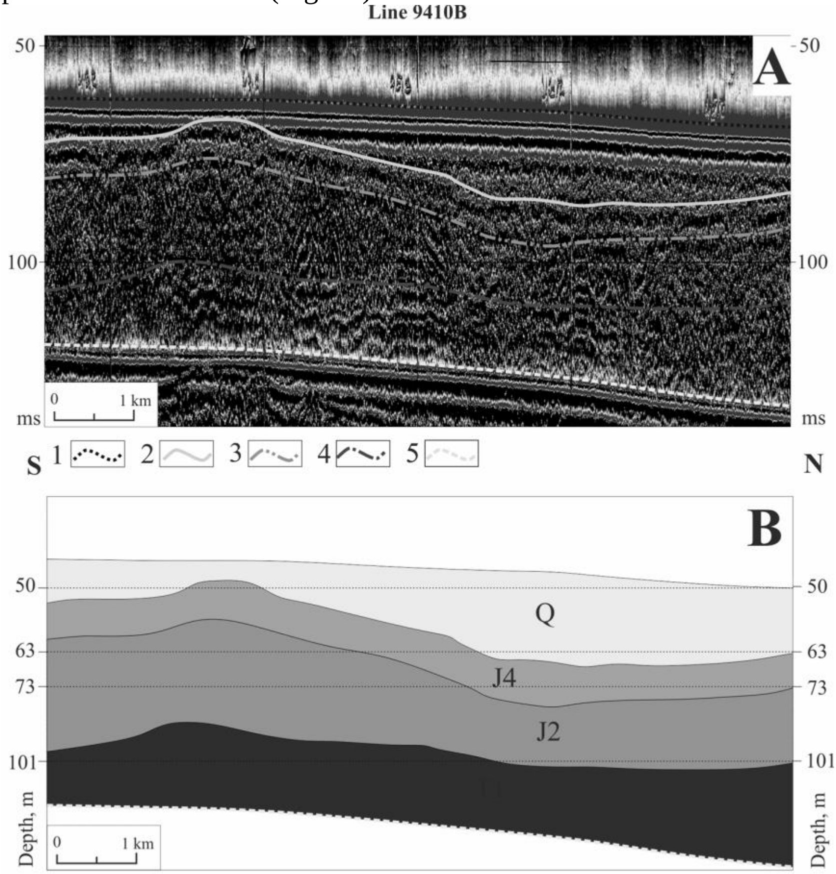


Fig. 15 A: Fragment of seismic line 9410B with interpretation; B: geological section corresponding to A. 1 – seafloor; 2 – top of J4 seismic unit; 3 – top of J2 seismic unit; 4 – inferred top of T1 seismic unit; 5 – multiple reflection from the seafloor (location see Fig. 14).

All the analogous, paper-based seismic records were digitalized. Each seismic record was of a rectangular form with a height of 1 meter and length from 5 to 50 meters. Digital visualization makes it possible to change the scale and the gain of seismic records, to make additional processing of the seismic data, and also to correlate the data of different coordinate systems. Therefore the quality of seismic data interpretation is more precise. Moreover, the time, needed for interpretation and data copying, significantly decrease.

The seismic data have been reinterpreted applying the *Halliburton Geographix* software (identification of geological boundaries was done manually). First the analogous seismic recordings were digitized with *Mathworks Matlab, SegyMat* (free open software) and *IMAGE2SEGY* (Barcelona Institute of Marine Science) to *Seg-Y* file format. Next, all the newly created seismic files were imported to the *Halliburton Geographix* software format. Likewise it was made for the first time (Grigelis 1999), seismic units (Table 1) were interpreted having applied data from the offshore wells D5, D6, E6 and E7 (see Figs. 16 – 19; Appendix 1). The tops of the seismic units J4, J2 and T1 were connected to the well D5 (Fig. 16), the top of units K1, J4, J2 – to the well D6 (Fig. 17). The top of D4–D3 seismic unit was connected to the wells E6 (Fig. 18) and E7 (Fig. 19).

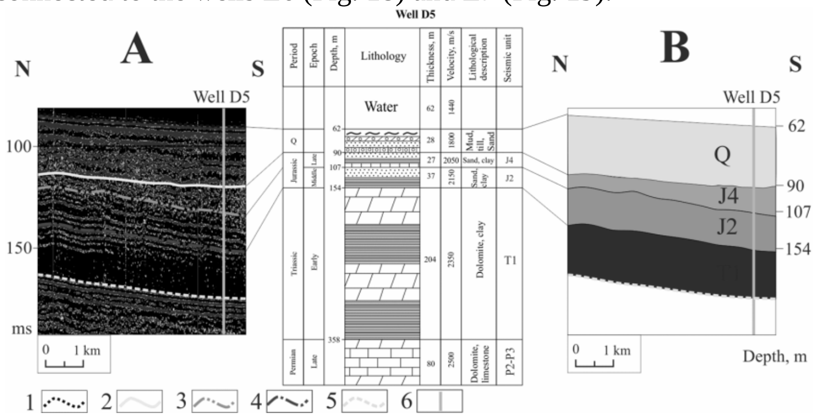


Fig. 16 A: Fragment of seismic line 9404 with interpretation; B: geological section corresponding to A. 1 – seafloor; 2 – top of J4 seismic unit; 3 – top of J2 seismic unit; 4 – top of T1 seismic unit; 5 – multiple reflection from the seafloor; 6 – well (location see Fig. 14).

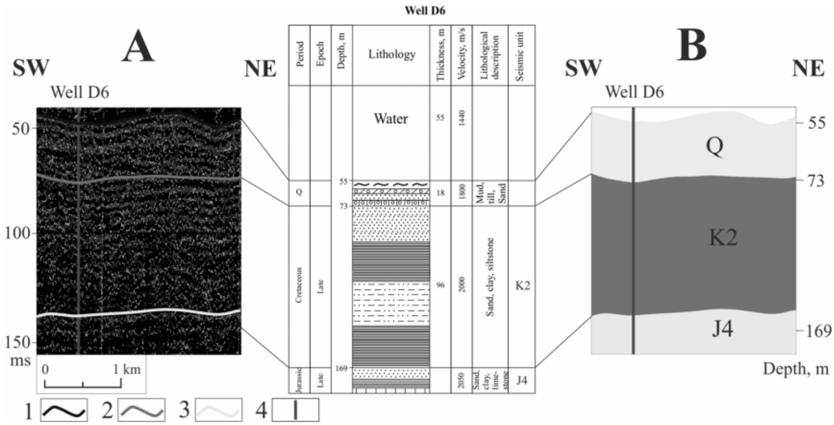


Fig. 17 A: Fragment of seismic line 9302 with interpretation; B: geological section corresponding to A. 1 – seafloor; 2 – top of K2 seismic unit; 3 – top of J4 seismic unit; 4 – well (location see Fig. 14).

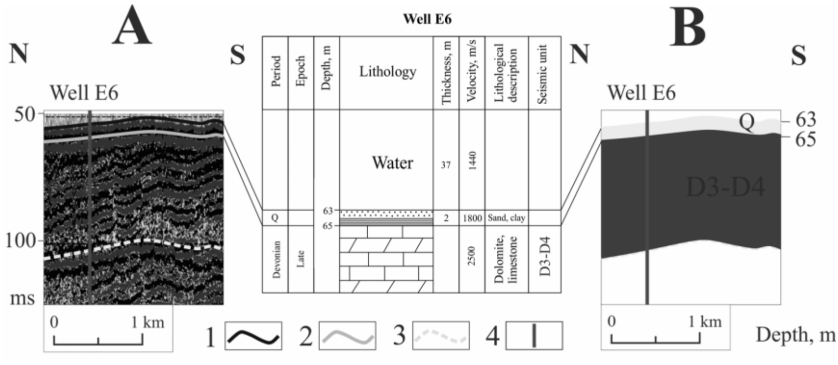


Fig. 18 A: Fragment of seismic line 980830_ with interpretation; B: geological section corresponding to A. 1 – seafloor; 2 – top of D3-D4 seismic unit; 3 – multiple reflection from the seafloor; 4 – well (location see Fig. 14).

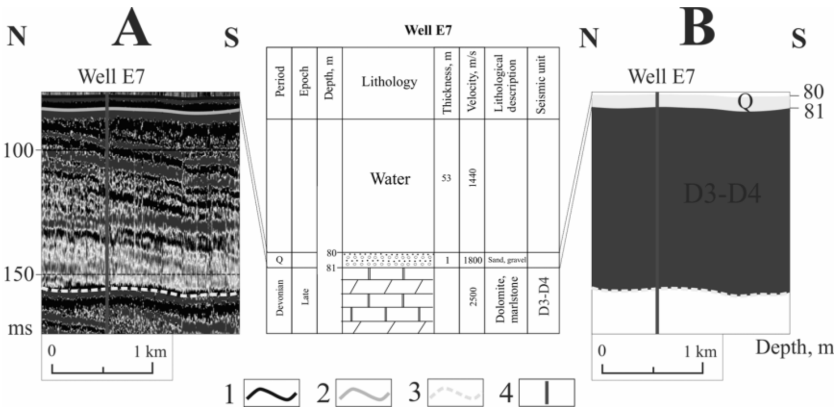


Fig. 19 A: Fragment of seismic line 980901_3 with interpretation; B: geological section corresponding to A. 1 – seafloor; 2 – top of D3-D4 seismic unit; 3 – multiple reflection from the seafloor; 4 – well (location see Fig. 14).

The selection of seismic horizons and their correlation at the intersections of the lines are realized in *Halliburton Geographix* software in the time domain. The seismic boundaries of the bedrock are generally rather distinct and are easily traced along the seismic sections. In places of low reflectivity it is also possible to separate the seismic units by geometric shape, amplitude and the configuration of the seismic reflections. Correlation by time between seismic sections was done having used the seafloor reflection as a seismic marker. The maximum time shift between all the seismic sections is 8 ms.

3.2 GEOPHYSICAL METHODS FOR PALAEO-INCISIONS SURVEY ON LAND

Two-dimensional (2D) common mid-point shooting and electrical tomography, have been deployed in the Palanga–Šventoji coastal area of Lithuania. The methods have been used separately, although combining the interpretation of 2D seismic data with the interpretation of electrical tomography is attempted to describe the palaeo-incisions.

The land part of the geophysical fieldwork has been performed from the summer of 2012 to the spring of 2013. The productivity of the land fieldwork is presented in Table 6.

Table 6. Time consumption of geophysical measurements.

Geophysical method	**Line**	**Length, m**	**Duration, h**	**Total length, m**	**Time consumption, m/man-hour**
2D CMP seismic method	S1201.1	947.5	12.0	6882.5	51
	S1201.2	1747.5	19.0		
	S1202.1	597.5	5.0		
	S1202.2	897.5	9.0		
	S1203	1947.5	18.0		
	S1306	745.0	4.0		
Electrical tomography	ET-1	762.0	14.0	2580.0	28
	ET-4	762.0	12.0		
	ET-5	1056.0	20.0		

3.2.1 The 2D common mid-point (CMP) seismic method

The contrast of seismic velocities (Table 3), theoretical aspects of shallow seismic surveys (Boganik, Gurvich 2006), and advanced employment of 2D deep seismic methods in Lithuania, are the reasons of choosing the 2D CMP seismic method to locate palaeo-incisions on land.

Equipment. The CMP seismic investigations have been performed having used a Wireless Seismic Acquisition System with 100 geophones, namely GS-ONE (manufacturer *OYO Geospace*, open access facility in the Klaipėda University). A Magellan ProMark 3 GPS navigator with accuracy of 0.1 meter is used for the positioning. The main part of the equipment is Geospace Seismic Recorder (GSR). Its basic specifications: built-in GPS, flash memory 16 Gb, about 30 days of continuous recording (depend on environment conditions), <20 µsec of UTC (GPS clock), selectable gain up to 36 dB and recording sample intervals: 0.25, 0.5, 1.0, 2.0, 4.0 ms. Li-On battery BX10 of 9.9 Ah and 16V is used as power supply.

Total length of 6 seismic lines is 6882.5 m (Table 6, Fig. 20).

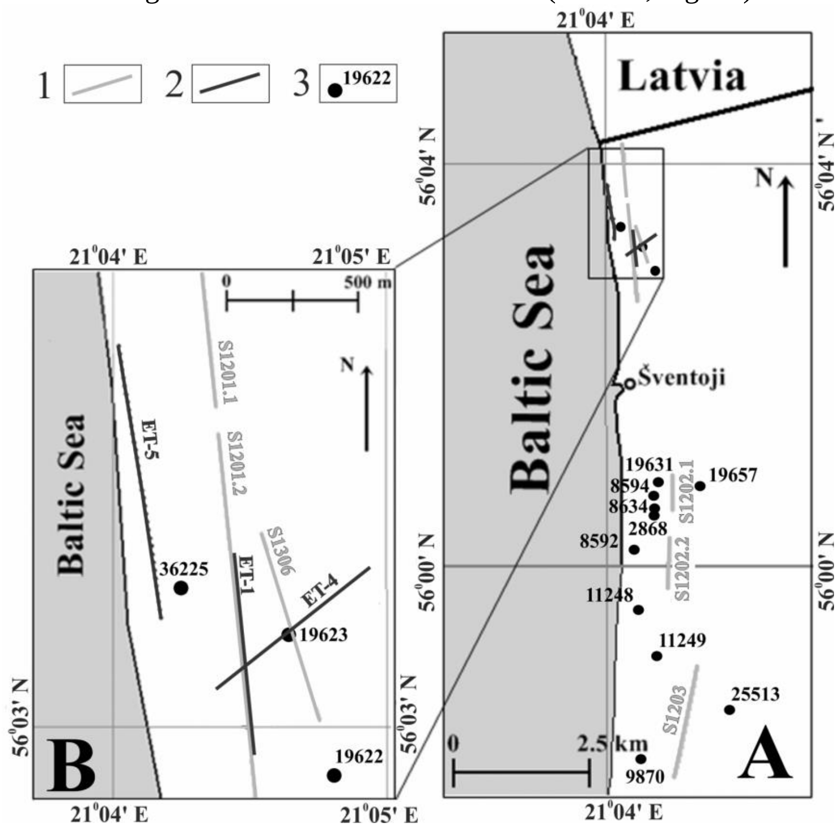


Fig. 20 A: Location of land seismic lines. B: Location of electrical tomography lines. 1 – 2D CMP seismic lines; 2 – lines of electrical tomography; 3 – wells (Appendix 1).

The 2D CMP method has been performed in following steps:

- Calculating theoretical parameters of field survey;
- Field surveying;

- Data processing;
- Analyzing geological information from the wells;
- Interpreting the seismic data.

Calculating theoretical parameters of field survey. During common mid-point (CMP) profiling, it is arranged that a set of seismic traces recorded at different offsets contains reflections from a common depth point (CDP) on the reflector. When *n* traces containing a mixture of coherent in phase signals and random (incoherent) noise are stacking, the quality of signal theoretically is improved by square-root from *n*. This makes it possible to attenuate long-path multiple reflections and also to increase signal/noise ratio. Data are collected along survey lines in 2D surveys (Kearey et al. 2002).

The depth reached with the CMP method is about 1/2–3/2 of the maximum offset (Boganik, Gurvich 2006). Field tests show that the maximum offset, which could be chosen, is 200–300 meters, having used a 5 kg sledge hammer as seismic source in the area of investigations. Therefore, the estimate depth of the method, as deployed in this work, is between 100 and 450 meters.

The following seismic acquisition parameters have been selected: symmetric spread with the maximum offset of 300 m, seismic station spacing 5 m (max 61 channels), seismic source spacing 10 m and seismic source grouping of 16 (seismic source grouping of reference profile is 32 and seismic station spacing is 10 m across the well) (Fig. 21).

Field surveying. The length of the seismic record was 500 ms, the sampling rate 0.5 ms and the frequency range 0-2000 Hz. The synchronization between the seismic source and receivers was provided by a built-in GPS.

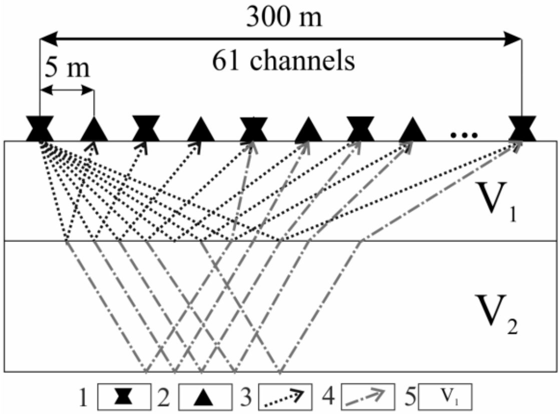


Fig. 21 Reflected ray configuration of CMP investigations. 1 – Seismic station and seismic source; 2 – seismic station; 3 – theoretical direction of reflected ray path in the geological layer with the seismic velocity V1; 4 – theoretical direction of reflected ray path in the geological layer with the seismic velocity V2; 5 – geological layers of different seismic velocity.

The Source Decoder Recorder (SDR) captures the time and precise position of each seismic source, and GSR – of each seismic record with their internal GPS receivers. For synchronization between signal source and record, the sledge hammer is connected to SDR with a twin-wire cable. SDR registers the GPS time of short-circuiting at the moment of the seismic impulse (the hit of sledge hammer).

Data processing. The seismic data processing has been performed having applied *Landmark ProMAX* software with the following procedures: trace editing and killing, summing, true amplitude recovery, air blast attenuation, surface wave noise attenuation, multiple wave attenuation, F-K filtering, predictive deconvolution, band pass filtering (35-40-100-120 Hz), velocity analysis, normal move out correction (NMO), elevation static corrections, autostatics, dip move out correction (DMO) and migration. All the seismic sections are the result of final data processing. The datum of all the seismic lines is 0 m in absolute values.

Analyzing geological information from the wells. The geological information from wells 573, 2868, 8592, 8594, 8634, 9870, 11248, 11249, 19622, 19623, 19631, 19657, 20084, 25027, 25513, 25992 and 25993 (Fig. 20A, B; Appendix 1; Lithuanian Geological Survey database (2014 10 01): http://www.lgt.lt/zemelap/main.php?sesName =lgt1412160593), and the reference seismic line S1306 provide the basis of land seismic data interpretation. The palaeo-incision is detected by the well 19623. The well 19623 is located on seismic line S1306 (Fig. 20B). That is the reason, S1306 is chosen as a reference line. The interpolated data from all the above wells have been used to establish top depth of Quaternary, Triassic, Permian, Carboniferous and Devonian deposits.

Theoretical aspects. Interval seismic velocity is the constant velocity of a single layer or any fixed depth interval:

$v_i = \frac{h_{i+1}-h_i}{t_{i+1}-t_i}$, where h_i – top depth of the geological layer or any fixed depth interval, t_i – corresponding time by seismic or VSP data (Boganik, Gurvich 2006). [1]

In its turn, seismic RMS velocities are calculated from the seismic datum to the depth of interest as follows:

$v_{rms} = \sqrt{\left(\frac{v_1{}^2 t_1 + v_2{}^2 t_2 + \cdots}{t_1 + t_2 + \cdots}\right)}$, where v_i – interval velocity, t_i – time (Boganik, Gurvich 2006). [2]

Interpreting the seismic data. Based on the well data, and the results of earlier investigations, it is presumed, that the palaeo channels cut into Triassic and Permian sedimentary rocks.

The general criterion for locating palaeo-incisions by the seismic record is the differences in seismic reflectivity pattern within the incision in relation to the surrounding bedrock. The secondary criterion is the termination of distinct seismic events at the boundary between a palaeo-incision and the surrounding bedrock, phase shift and also increased amplitude of seismic events within the incision (Table 5, Fig. 22B).

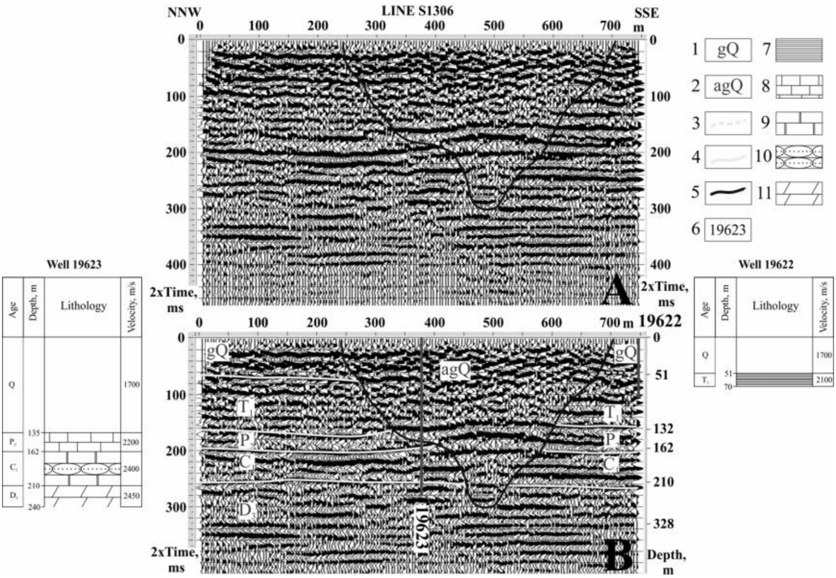


Fig. 22 *Seismic line S1306. A: Interpreted boundaries of the palaeo-incision; B: Interpretation. 1 – glacial deposits; 2 – aqua-glacial deposits; 3 – inferred seismic boundary; 4 – seismic boundary; 5 – palaeo-incision by seismic data; 6 – well (see Table 3); 7 – clay; 8 – limestone; 9 – marlstone; 10 – sandstone; 11 - dolomite.*

Locating and interpreting the seismic boundaries. There are several distinct seismic reflections: at the times 60, 160, 200, 220, 240 and 260 ms. The most distinct seismic reflection is at the 200 ms. It is proposed to be a top of Carboniferous by the data from the well 19623. Then the theoretical top depth of the Carboniferous is calculated, having used the relations of interval (see [1]) and average velocities (from the classic Mechanics) to check the hypothesis: the Quaternary thickness plus the Permian thickness 153+11=164 m. This value approximately equals to the value by the well data (162 m, Fig. 22). The most distinct seismic reflection at the 200 ms is concluded to be the top of Carboniferous. The seismic reflections in the time interval 200–240 ms associate with the internal reflection in the Carboniferous strata (because of its competence by well data). All the other seismic boundaries are associated with the corresponding tops of geological layers from the wells 19622 and 19623 in the same way.

Seismic line S1201.2 is sub parallel to the reference seismic line S1306. The palaeo-incision is also discovered here. It is located between the wells 19623 and 36225, extending up to the well 19622 (Fig. 20B, Appendix 1). The turning ray tomography has been used as an aid in the processing of the seismic data. The feature which reveals the location of a palaeo-incision having used the interval velocity section (as the result of turning ray tomography) is the decreasing velocity in the deepest part of the incision (Fig. 23A).

The RMS velocity sections have been used to reach a better understanding of the geological structures along the sections. Analyzing the velocity section along the profile S1201.2, it is possible to observe some zones of irregular velocities (Fig. 23B). Correlating the sections of interval and RMS velocities, and also seismic sections, all the seismic lines have been interpreted.

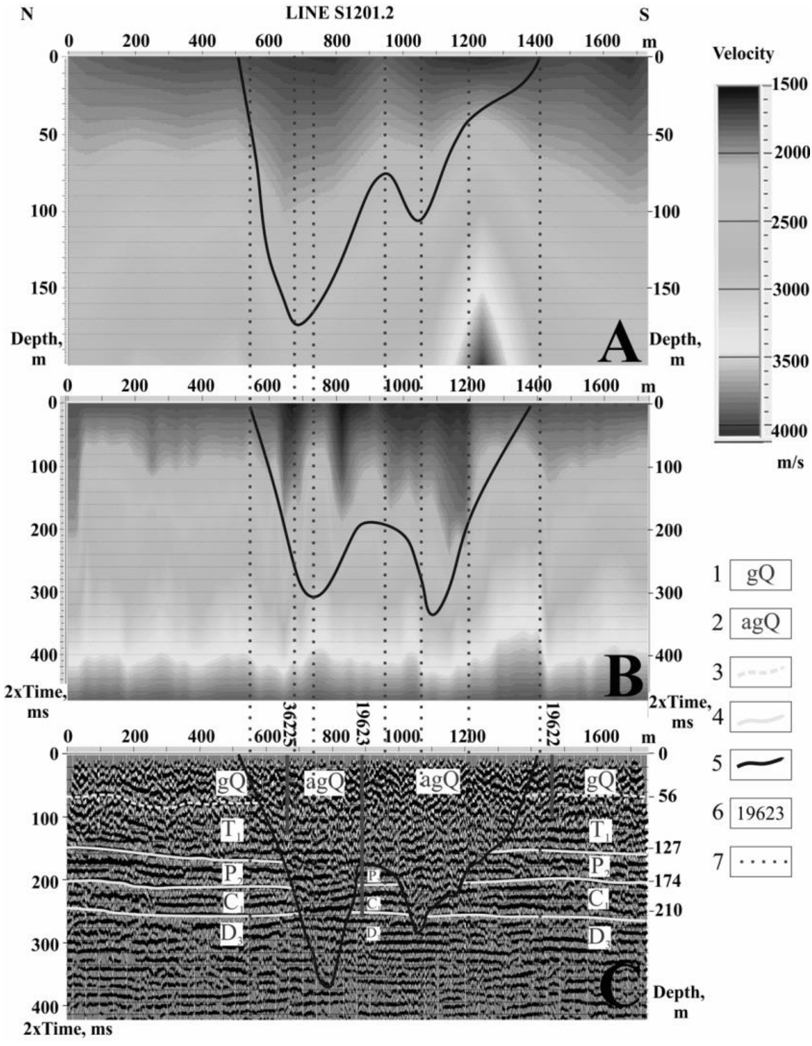


Fig. 23 Seismic line S1201.2. A: Interval velocity section; B: RMS velocity section; C: Interpretation. 1 – Glacial deposits; 2 – aqua-glacial deposits; 3 – inferred seismic boundary; 4 – seismic boundary; 5 – palaeo-incision by seismic data; 6 – wells (Table 3; Appendix 1); 7 – correlation.

3.2.2 Electrical tomography

In general, the electrical tomography combines the vertical electrical sounding and the electrical profiling methods. The electrical tomography method adapts well to the geological setting of Lithuania for exploration of the upper part of sedimentary cover, down to depth of 100–200 m (Šečkus 2002). For this reason the electrical tomography method has been chosen to locate the palaeo-incisions on land in the western Lithuania.

Resistivity methods are the means to study discontinuities in the electrical properties of rocks, and also to detect anomalous electrical conductivity patterns in 3D-bodies (Kearey *et al.* 2002).

A high resistivity contrast (Table 3), and an estimated penetration depth of c. 150 m, has been obtained in the survey area (Fig. 20). The previous positive experiences applying the electrical tomography method in Lithuania is the reason to select this method as one of main survey methods for investigation of palaeo-incisions in Lithuania.

Equipment. "*Allied Tigre-128*" (manufacturer *UAV Survey Inc.*) has been used for the electrical tomography measurements. The field settings used were 1 measurement per 10 seconds and c. 2600 measurements per profile. The acquisition parameters used were: electrode spacing 6 m (128 electrodes at all), electrical field source – 36W with current rate 0.5–50 mA.

Total length of 3 electrical profiles is 2580 m (Fig. 20).

Field Survey. A schematic diagram of the electrical tomography method is presented in Fig. 24. The electric current flows through the commutator to the source (current) electrodes C1 and C2 (*Wenner electrode configuration*). The potential difference between the values at electrode P1 and P2 is recorded along the survey line (the spacing between potential electrodes being fixed). Then the commutator activates another pair of current electrodes with the same spacing between them and potential difference is recorded along the survey line again. After the measurements utilizing all possible (or programmed) C1 and C2 electrodes positions with the same fixed separation are completed, the spacing between the current electrodes

C1 and C2 is increased and the measuring procedure is repeated. The theoretical measurement depth corresponds to half the C1–C2 spacing.

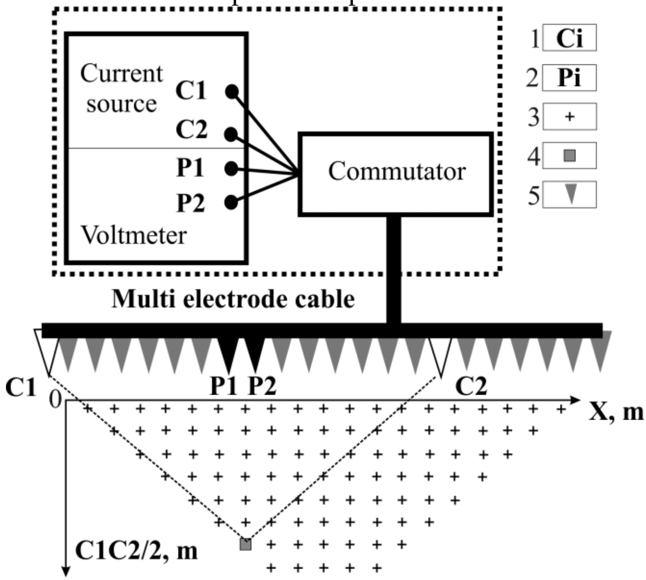


Fig. 24 Schematic diagram of the electrical tomography method. 1 – Current electrodes; 2 – potential electrodes; 3 – projected points of measurements; 4 – point of measurement; 5 – inactive electrodes.

Data processing. Resistivity inversion procedure, having used the *Res2Dinv* software (manufacturer *Geotomo Software SDN BHD*), was performed by Dr. R. Šečkus for all the electrical lines (personal communication).

Data interpretation. Interpretation of electrical tomography data is a rather subjective moment. Precise detection of geological border is possible only when the resistivity of geological layers or depths of geological borders are known (Šečkus 2002). Theoretically (see Table 3), the resistivity of the palaeo-incision infillings should be greater than the resistivity of the surrounding bedrock. This is because the palaeo-incisions are cut into the Triassic clay. This theoretical hypothesis is confirmed in practice by acquisitions of the electrical tomography method across the well 19623 (Table 3). The well is located in the center of the electrical profile ET-4, and is cased with a metallic tube in its upper part (several meters). This may be the reason of the lower resistivity values obtained between 390 and 440 m along the profile ET-4 (Fig. 25). The abrupt changes in resistivity from 160 to 70 Ωm between 576 and 650 m are explained as the slope of the palaeo-incision. The 80–160 Ωm resistivity of the palaeo-incision body is higher than that of the enclosing rocks (70 and less Ωm). Thus, the zone of resistivity 80–160 Ωm between 96 and 582 m of profile ET-1 is also explained as due to the palaeo-incision (Fig. 26).

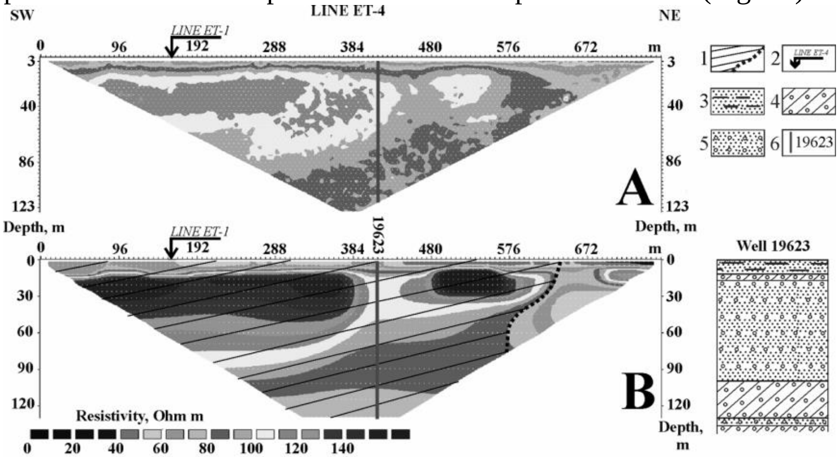


Fig. 25 Electrical tomography line ET-4. A: Measured apparent resistivity section; B: Inverse model resistivity section. 1 – Inferred palaeo-incision; 2 – intersection with the other line; 3 – sand, peat; 4 – till; 5 – sand, gravel; 6 – well (see Table 3).

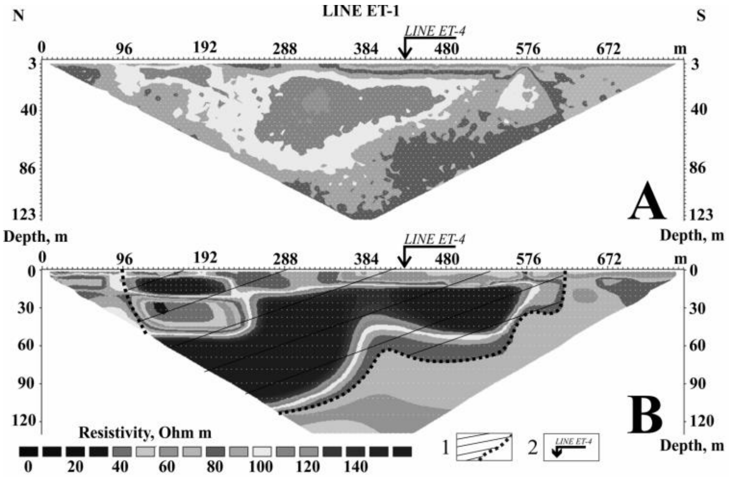


Fig. 26 Electrical tomography line ET-1. A: Measured apparent resistivity section; B: Inverse model resistivity section. 1 – Inferred palaeo-incision; 2 – intersection with the other line.

3.2.3 Integration and interpretation of geophysical data

The combination of the 2D CMP seismic method (positions 460–1222 along profile S1201.2) and electrical tomography (profile ET-1) has been used to obtain the location and details of the palaeo-incision with an enhanced resolution (Fig. 27). First the location of the palaeo-incision was determined by seismic data, and then by electrical tomography data (the principles of interpretation are described above). Next the two results were overlaid and the northern slope of the palaeo-incision, as revealed by electrical data, was added. The main principle of locating palaeo-incisions in seismic recordings is to use the levels in the seismic section, where the seismic reflectivity pattern changes, the phase of the reflection shifts or where it increases in strength (Table 5). These places are considered to reveal the borders between the palaeo-incisions and the surrounding bedrock. In case of electrical tomography the contrast in resistivity properties of rocks within and outside the palaeo-incision is used.

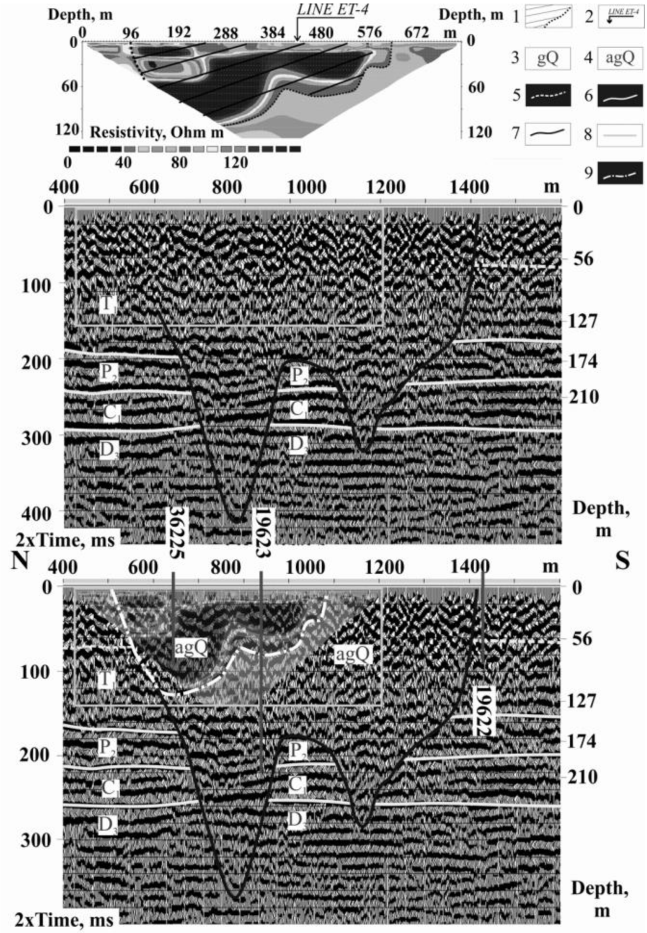


Fig. 27 Combined geophysical interpretation of lines S1201.2 and ET-1: 1 – inferred palaeo-incision by data of electrical tomography; 2 – intersection with the other line; 3 – glacial deposits; 4 – aqua-glacial deposits; 5 – inferred geological boundary; 6 – geological boundary; 7 – palaeo-incision by seismic data; 6 – palaeo-incision by electrical tomography data; 8 – location of electrical tomography line ET-1; 9 – palaeo-incision by combined geophysical interpretation.

3.3 SURVEY OF THE SUB-QUATERNARY RELIEF

New sub-Quaternary relief map has been compiled having used all accessible new data as well as data of previous offshore works (Repečka 1991; Gelumbauskaitė, Grigelis 1997; Gelumbauskaitė 1999), unpublished land data (Bitinas *et al*. 1998, 2004; Bitinas 2000, 2011, 2013; Bitinas *et al*. 2003) and also a schematic sub-Quaternary surface map (Šliaupa *et al.* 1994).

Offshore well data provided the basic information for compiling of the sub-Quaternary surface (Appendix 1). The wells were used as the bench marks, for compiling of the sub-Quaternary surface during the interpretation of seismic data. The relation between seismic data and well data is given in Appendix 1. The seafloor and base of the Quaternary strata were traced in the time domain across the entire offshore part of the investigated area. The next step was to compile the offshore sub-Quaternary surface of the investigated area in the time domain. The obtained surface was then recalculated to the depth domain having used a constant seismic velocity 1800 m/s (personal communication with Professor A. Grigelis and Dr. L.Ž. Gelumbauskaitė).

Finally, the sub-Quaternary relief map of Lithuania (Šliaupa *et al.* 1994), five newly mapped land segments (Bitinas *et al*. 1998, 2004; Bitinas 2000, 2011, 2013; Bitinas *et al*. 2003) and the offshore sub-Quaternary relief map, were imported to the *Global Mapper* software. The last six segments were connected together and attached to the sub-Quaternary relief map (Šliaupa *et al.* 1994) in the entire rectangular area (21^{o} 30′ – 22^{o} 00′ E, 55^{o} 28′ – 55^{o} 42′ N). *Connection* in this case means joining the isolines at the boundaries of neighboring segments. In those cases where isolines of equal depth diverge on the two sides of a boundary, the connection was done by interpolation. The surface of the Quaternary relief was created applying a minimum curvature method and a grid of 100 × 100 m in the Lithuanian LKS-94 coordinate system.

3.4 TECHNIQUE, APPLIED TO COMPOSE THE SCHEME OF PALAEO-INCISIONS

First, all the segments of palaeo-incisions have been discovered in the entire area of investigations offshore (Appendix 3). Next, the relative width and depth of palaeo-incisions have been described. The term *relative width* means in this case the visible width of the palaeo–incision along the seismic line. The angle, differing from 90 degrees, makes the visible width of the palaeo-incision wider.

Discovered segments of palaeo-incisions were connected in the following cases:

- Palaeo-incisions are presented along the neighboring seismic lines. Also it was kept to the rule, that the palaeo-incision could not cross the seismic line without any discovered segment of palaeo-incision along (Fig. 28 B–F).

- The shape, depth, relative width and infilling of the joining segments are similar in general, particularly, when the palaeo-incision is forming during several generations (Fig. 28 A, G).

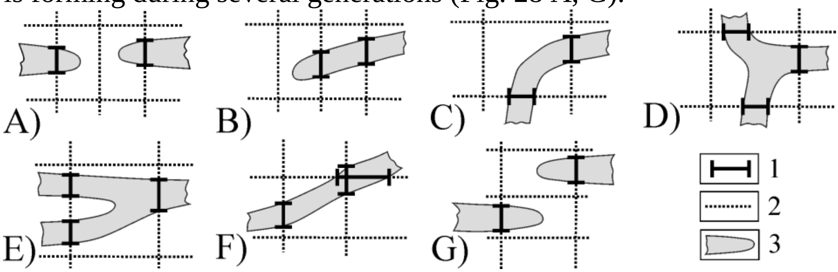


Fig. 28 Main principles of composing the scheme of palaeo-incisions. 1 – Discovered segment of palaeo-incision; 2 – seismic line; 3 – interpreted palaeo-incision.

The orientation of palaeo-incision is known in the cases of at least two connected segments. It corresponds to the direction of joint line from the segment of lower depth to the deeper segment. In the other cases, the orientation of palaeo-incisions is considered to be conformed to the sub-Quaternary relief (Fig. 29). Knowing the orientation, it is possible to determine the true angle between the palaeo-incision and crossing seismic line in order to establish the width of palaeo-incision more precisely. Finally, the true width has been calculated from the relative one and tagged on the CSP data location map.

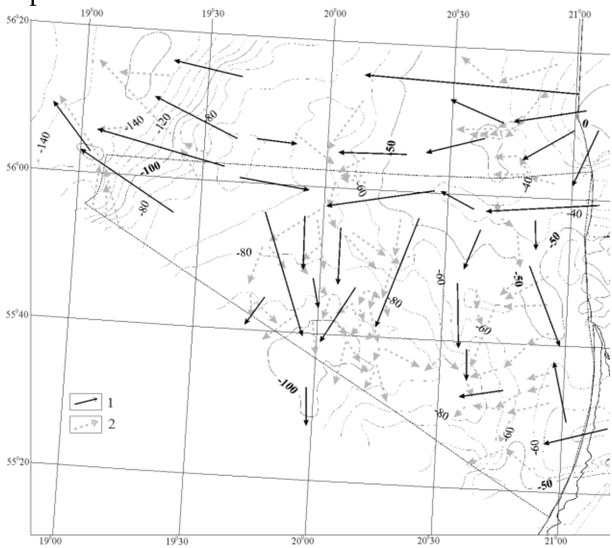


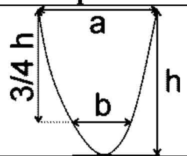
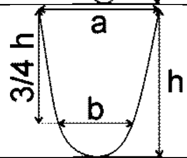
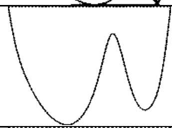
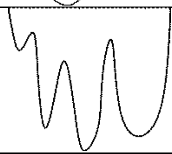
Fig. 29 Downward trend of sub-Quaternary relief(1) and orientation of palaeo-incisions(2): arrows show deepening direction.

The shape of palaeo-incision has been described visually, analyzing their sections. The sections, perpendicular to the orientation of palaeo-incisions, were preferred and were the basis of this analysis. The palaeo channels of simple shape, incisive in the bottom part, were assumed to be of V-shape, while those similar, but smooth in the bottom part were of U-shape. More complex shapes were assumed to be of W- and WW- (the most complicated visually) shapes (Table 7).

Analyzing the sections of palaeo-incisions it has been noticed, that their depth and morphology differ in three certain segments in the southeastern part of the Baltic Sea.

An attempt has been made to determine the palaeo-incisions of several generations (blue in Fig. 30A, C–F).

Table 7. Classification of palaeo-incisions according to their cross-section morphology

Shape	Description	Example
V	Two slopes; a/b≥2	
U	Two slopes; a/b<2	
W	Four slopes	
WW	More than four slopes	

The D3–D4 seismic unit is characterized by a slightly folded stratified seismic reflectivity pattern (Fig. 30A).

The reflection from the P2 seismic unit is very intense, easily recognized and possible to use as a seismic marker (Fig. 30B, C, D). The main feature of the palaeo-incisions in the Triassic area (see Fig. 2), as compared to the Devonian area, is the contrast between seismic reflectivity patterns inside the incisions in relation to the surrounding bedrock areas (Fig. 30E, F, G). The palaeo-incisions often exhibit strong reflections crossing over the reflection multiple of the sea floor in the eastern zone (Fig. 30B). Furthermore, breaks in strong and enduring bedrock reflections often facilitate the identification of palaeo-incisions here (Fig. 30D, F, H).

Land network of palaeo-incisions has been composed having used the data of earlier geological mapping (Bitinas *et al*. 1998, 2004; Bitinas 2000, 2011, 2013; Bitinas *et al*. 2003). Palaeo-incisions were joined on the boundaries of neighboring mapped segments. For those cases where two palaeo-incisions similar by morphology and depth diverge on the two sides of a boundary, the connection was done by interpolation.

Land network of palaeo-incisions were joined to the offshore one hypothetically. The main principle was the direction of the palaeo-incisions.

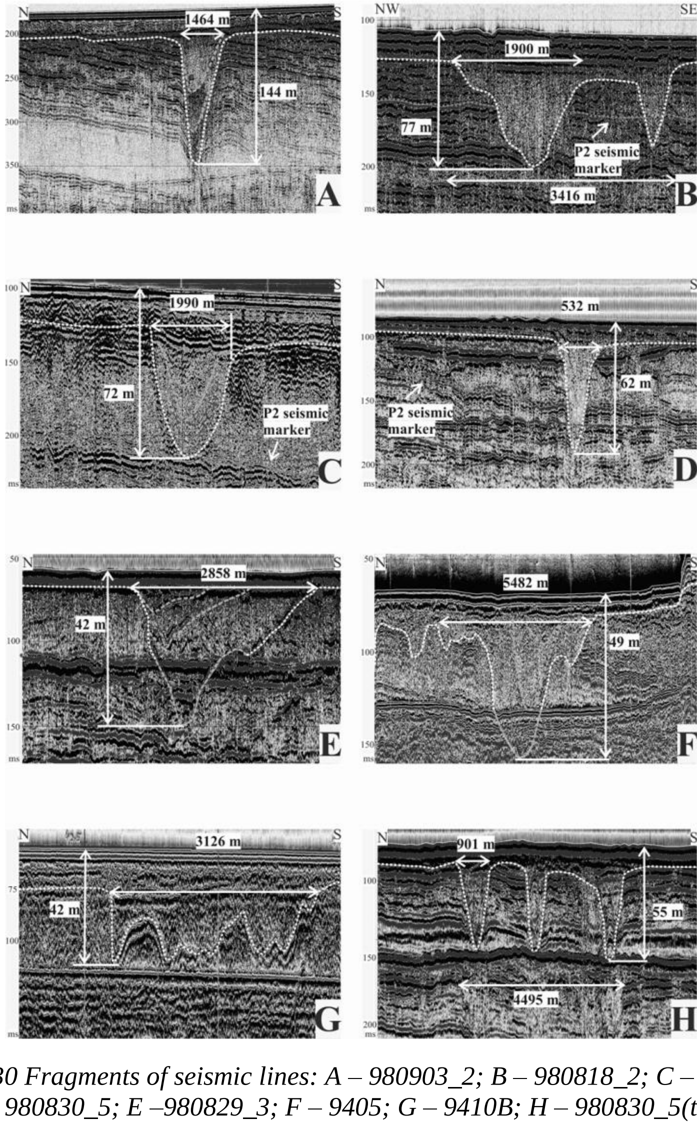


Fig. 30 Fragments of seismic lines: A – 980903_2; B – 980818_2; C – 9522; D – 980830_5; E –980829_3; F – 9405; G – 9410B; H – 980830_5(three palaeo-incisions). Location see Fig. 31. Blue – inferred palaeo-incision, white – palaeo-incision.

3.5 COMPILATION OF THE PRE-QUATERNARY GEOLOGICAL MAP

Combining the seismic interpretations of earlier expeditions (Grigelis *et al*. 1994, 1996) with the last one it became possible to update the pre-Quaternary geological map of the investigated area. This map is based on the map elaborated by Algimantas Grigelis in 1998 as a part of the Geological map of the Northern Europe land and seas areas (Sigmond 2007). It was later modified by Grigelis in 2012 (personal communication). A number of data sets were used for the new interpretation, namely well data (Figs. 16–19; Appendix 1), earlier interpretation of the seismic lines 9302, 9404, 9405 and 9410 (Fig. 15), seismic stratigraphic subdivisions: Late Devonian seismic units D3–D4 (Flodén 1980) and from Late Permian P2 to Late Cretaceous K2 seismic units (Grigelis 1999) (Table 8). The seismic data interpretation starts with the seafloor across the entire investigated area, and is then extended downwards to the deepest seismic boundary in a similar manner. This method has been chosen in order to make a correct tracing of seismic boundaries and conversion to seismic units, particularly in the places of complex seismic reflectivity patterns. Eight surfaces, corresponding to the top of seismic units (including the top of pre-Quaternary surface) were defined, based on seismic data.

The result was exported to *Global Mapper* software. There it was united with the previous geological map of the southeastern segment of the Baltic Sea (Fig. 2; after Grigelis 2009, modified in 2012 (personal communication)) in the area framed by 20^{o} 50′ – 22^{o} 00′ E. Finally, the area framed by 21^{o} 00′ – 22^{o} 00′ E updated having used the newest data of geological mapping (Bitinas *et al*. 1998, 2004; Bitinas 2000, 2011, 2013; Bitinas *et al*. 2003).

Table 8. Values of seismic velocities in lithological-stratigraphic complexes of the Baltic Sea.

Age of complexes	**Layer velocity[1], m/s**	**Interval velocity[2], m/s**	**RMS velocity[2], m/s**	**Chosen velocity, m/s**
Water layer	1438 – 1446	—	—	1440
Quaternary	1700 – 1850	—	—	1800
Paleogene–Neogene	1950	—	—	—
Cretaceous	2000	—	—	2000
Late Jurassic	2100	—	—	2050
Middle Jurassic		—	—	2150
Triassic	2350	4565	1835	2350
Permian	2200 – 5000	3940	2005	2400
Carboniferous	2500	—	—	—
Devonian		3060	2450	2500
Silurian	3000	3365	2745	—
Ordovician	3500	4340	2885	—
Cambrian	2750	4270	2945	—

[1] — Grigelis 1999; [2] — by VSP data from well D5 (location see Fig. 14).

4. RESULTS

4.1 THE SUB-QUATERNARY RELIEF

The scheme of palaeo-incisions have been composed on the background of the pre-Quaternary relief with the number of regional morphostructures determined during the previous investigations (Gelumbauskaitė 1995; Šliaupa 2004), i.e. the Eastern Gotland Through in the northwest (I), the Klaipėda–Liepaja Uplift in the west central part (II), the Gdansk Depression in the southwest (III), the Curonian structural terrace in the southeast (IV), the Telšiai swell in the northeast (V) and Western Žemaitija step in the west (VI) (Fig. 31).

The palaeo-incision network of the investigated area is divided into three parts, namely eastern zone (3 in Fig. 31), central zone (4 in Fig. 31) including northern part of the Gdansk Depression and its Klaipėda Slope, and western zone (5 in Fig. 31) including eastern slope of the Gotland Depression. The names of the zones are chosen according to their geographical location within the investigated area.

Level of the sub-Quaternary surface in the Eastern Gotland Through varies from –150 m to –60 m in the southeastern direction. The palaeo-incisions of the western zone (5 in Fig. 31) cut the sub-Quaternary surface down to –280 m in absolute values. Five fragments of palaeo-incisions are newly discovered in the deepwater zone.

The Klaipėda-Liepaja Uplift separates deepwater and central zones of palaeo-incisions. Palaeo-incisions of the central zone (4 in Fig. 31) cut the sub-Quaternary surface down to –200 m in absolute values. The absolute values of the sub-Quaternary surface vary from –60 m at the Klaipėda–Liepaja Uplift to –100 m in the direction of the Gdansk Depression. Forty-five new fragments of palaeo-incisions were discovered, which include twenty-five in the northern part of the central zone (4 in Fig. 31). This means that the network of palaeo-incisions is wider and more complicated, than it has been presumed earlier.

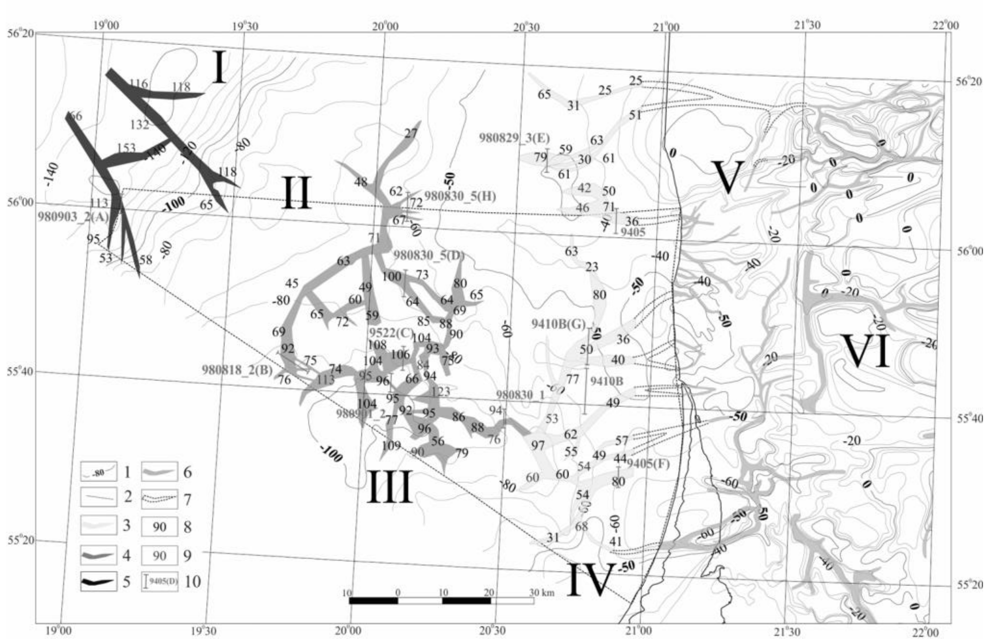


Fig. 31 The map of palaeo-incisions on the sub-Quaternary surface. 1 – contour lines of the sub-Quaternary surface (drawn every 10 m); 2 – Lithuanian Sea border; 3 – eastern zone of palaeo-incisions; 4 – central zone of palaeo-incisions; 5 – western zone of palaeo-incisions; 6 – palaeo-incision on land(Bitinas et al. 1998, 2004; Bitinas 2000, 2011, 2013; Bitinas et al. 2003); 7 – inferred palaeo-incisions; 8 – relative depth of newly discovered palaeo-incisions in meters; 9 – relative depth of confirmed palaeo-incisions in meters; 10 – fragments of seismic lines (Figs. 15 – 19, 32 – 34).

The eastern zone of palaeo-incisions is divided into two separate parts by the 56° N parallel, here referred to as the northern and the southern parts (3 in Fig. 31). The absolute depth of the sub-Quaternary surface varies from –10 m to –60 m and the depth of the palaeo-incisions – from –65 m to –130 m in the northern part of the eastern zone. Two fragments of palaeo-incisions, discovered by other investigators previously, have been confirmed, and fourteen new fragments have been discovered there. The absolute depth of the sub-Quaternary surface is from –40 m to –80 m in the southern part of the eastern zone. In absolute values, the depth decreases from South to North, but it increases again to –80 m at the northwestern slope of the Curonian structural terrace. The depth of palaeo-incisions varies from –60 m to –140 m. Three previously mapped palaeo-incisions have been confirmed, and seventeen new palaeo-incisions have been discovered there. The shape of the seafloor and the sub-Quaternary surface is more different near the coastline as compared to the results of earlier investigation.

The level of the sub-Quaternary surface on land varies from sea level in the northeast and southeast to –60 m in the southwestern direction. The palaeo-incisions prevail near the coastline and in the northwestern land areas.

Generally orientation of palaeo-incisions and downward trend of sub-Quaternary relief are corresponding. As mentioned above, the main directions of deepening are the Telšiai swell – the Eastern Gotland Through, Western Žemaitija step – the Gdansk Depression, the Klaipėda-Liepaja Uplift – the Gdansk Depression and the Klaipėda-Liepaja Uplift – the Eastern Gotland Through (Fig. 29, 31).

To summarize, eighty-two new fragments of palaeo-incisions have been discovered in the offshore part of the investigated area (Fig. 31, Appendix 3). First of all, the new fragments, found during the new investigation, made it possible to reconstruct the network of palaeo-incisions. Secondly, the palaeo-incisions have wider distribution in the offshore part of Lithuania, and also exhibit a more complicated pattern, than previously assumed (Fig. 7). The newly compiled sub-Quaternary surface map generally corresponds to the earlier one. But there are some differences. Maps primarily do not match near the shore and in the central zones. It is due to inclusion of the new mapping data from the coast and denser network of seismic lines, including the more recent seismic data used in this part of the investigated area.

4.2 MORPHOLOGY AND NETWORK OF PALAEO-INCISIONS

The distribution of palaeo-incisions is irregular in the entire area of the investigations. But there are zones, where it is possible to generalize their relative depth, width and shape. This generalization is the principle of dividing the network of palaeo-incisions into three parts, namely the eastern zone, the central zone and the western zone (Fig. 31).

The relative depth of the palaeo-incisions below the bedrock surface ranges from 23 to 153 m. It increases from shore area to the deep-water area.

The width of the palaeo–incisions varies in the interval of 240 – 7220 m. The average width decreases from the eastern zone (2340 m), through the central zone (1460 m) to the western zone (960 m).

The distribution of palaeo–incisions by shape changes from quite a few complicated W- and WW-shapes in the eastern zone to the prevailing of trivial V-shapes in the deepwater zone. No palaeo-incisions penetrated into the sub–Quaternary surface of the Klaipėda–Liepaja Uplift have been identified.

The palaeo–incisions in **the eastern zone** predominantly extend in the ENE to WSW direction (Fig. 29). The visible lengths of the palaeo–incisions are about 20–25 km. Towards the NNE they do simply terminate, whereas towards the SSW they generally merge together (Fig. 31). The palaeo-incisions in this zone are generally rather shallow reaching relative depth of 23–80 m into the bedrock. Their average depth is about 50 m (Fig. 31). W- and WW-shapes are widely distributed accounting for 53% of the analyzed incisions (W-shape 36%, WW-shape 17%). V- and U-shapes comprise the remains: V-shape 28% and U-shape 19% respectively (Appendix 3). Wide palaeo-incisions, with widths of more than 2000 m, occur frequently in this zone. The network of palaeo-incisions in the eastern zone forms several isolated groups of palaeo-incisions. The palaeo-incisions cut Late Permian–Early Triassic strata in the northern part and Early Triassic–Late Jurassic strata in the central–southern part.

The incisions in the northern part of **the central zone** extend from northeast to southwest and from north to south. The distribution of the palaeo-incisions in the southern part is more complicated (Fig. 31). The palaeo-incisions of the central zone (northern part of the Gdansk Depression and its Klaipėda Slope) extend to relative depth of 27–113 m into the bedrock, at an average about 80 m (Fig. 31). Palaeo-incisions of various shapes are presented in this zone. The V-shape dominates to 44%, whereas the U-shape is also widely distributed to 33%. The majority of remaining incisions (23%) demonstrates W-shape in cross-section (Appendix 3). The width of the palaeo-incisions varies widely, from 340 m to 7220 m. The palaeo-incisions form single complicated (shape-wise) system in the central zone. The palaeo-incisions cut Late Permian–Late Jurassic sedimentary strata in this zone.

The palaeo-incisions of **the western zone**, namely the eastern slope of the Gotland Depression, mainly traverse from northwest to southeast. Towards the north and west they continue outside the area of investigations. The length of two main incisions is about 42 km inside the investigated area (Fig. 31). This is the zone with the deepest palaeo-incisions. Their relative depth is in the range of 53–153 m into the bedrock with an average depth of about 100 m (Fig. 31). The V-shape dominates in the cross-sections to 73% in this zone (Appendix 3). The width of the palaeo-incisions is between 300 and 1760 m. This zone is separated from the central zone by the structural high of the Klaipėda-Liepaja Uplift. The palaeo-incisions are of NW–SE orientation. The palaeo-incisions form system, which is close by shape to the river network in this zone. The palaeo-incisions cut Late Devonian strata in this zone.

All the palaeo-incisions cut the Quaternary strata. The Quaternary thickness varies from 1–5 m in the western zone, to 20–40 m in the central zone and reaches up to 50–60 m in the eastern zone.

Table 9. Relationship between shapes and surrounding bedrock of palaeo-incisions.

All the investigated area

	Shape, pcs				
Surrounding bedrock	**U**	**V**	**W**	**WW**	**total**
D_3	4	11	2	–	17
P_2	6	11	13	2	32
T_1	20	28	22	6	76
J_2	19	22	12	5	58
J_3	14	16	6	3	39

Central zone

	Shape, pcs				
Surrounding bedrock	**U**	**V**	**W**	**WW**	**total**
D_3	3	3	–	–	6
P_2	4	7	5	1	19
T_1	15	21	9	1	46
J_2	14	17	8	–	39
J_3	9	11	3	–	23

Eastern zone

	Shape, pcs				
Surrounding bedrock	**U**	**V**	**W**	**WW**	**total**
P_2	2	4	8	1	15
T_1	5	7	13	5	30
J_2	5	5	4	5	19
J_3	5	5	3	3	16

Western zone

	Shape, pcs				
Surrounding bedrock	**U**	**V**	**W**	**WW**	**total**
D_3	1	8	2	–	11

The relationship between shapes and surrounding bedrock of palaeo-incisions is analyzed in this work (see Table 9). The palaeo channels of V-, U- and WW-shape, cut into Late Permian sedimentary rocks, are distributed similarly in percentage correlation within the central and eastern zones. The palaeo channels of W-shape, cut into Late Permian–Early Triassic strata, dominate within the eastern zone to about 50%. The palaeo-incisions of WW–shape cut Early Triassic–Late Jurassic strata and dominate in the eastern zone. The V- and U-shape dominate to 80% among the palaeo-incisions cut into Early Triassic–Late Jurassic strata in the central zone. The palaeo channels of V-, U- and W-shape, cut into Middle–Late Jurassic sedimentary rocks, are distributed similarly in percentage correlation within the central and eastern zones. The palaeo-incisions of W-shape occur rarely in the Late Devonian strata. Only two of them found in the entire area. The majority (65%) of palaeo-incisions cut into these rocks are V-shaped.

The distribution of V- and U-shapes is similar in percentage correlation for Late Permian–Late Jurassic rocks in the central and eastern zones (Table 9). Also the V-shape of palaeo-incisions within Late Devonian strata dominates in the entire area of investigations.

4.3 INFILLING OF PALAEO-INCISIONS OFFSHORE

The infillings of the palaeo-incisions are widely different and complex. The Quaternary section of the southeastern Baltic Sea has been evaluated from 17 vibrocores and short drill cores (see Appendix 1) applying lithological–biostratigraphical and radiometric methods (Majore *et al.* 1997; Gelumbauskaitė 2000, 2009). The penetration into the Quaternary depositional complex in the short drill cores varies from 4 to 10–20 m. Thirteen of the deep wells (Figs. 32–34, Appendix 1) disclose the Quaternary section in full. The relative depth of the palaeo-incisions ranges from approximately 50 in the near shore area to around 100 m in the deepwater area. In the deepwater areas there are generally five different erosional and depositional units found in the incisions, whereas in the near shore shallow areas there are only two or three (Bjerkéus *et al.* 1994). Some of palaeo-incisions contain indications of merely one or two of the above depositional events (Vaher *et al.* 2010; Janszen *et al.* 2013). The infillings generally contain several sediment types, namely glacial, glaciofluvial and glaciolacustrine sandy–clayey deposits, till and gravel as reported from Lithuania (Bitinas *et al.*1999), Estonia (Vaher *et al.* 2010), Sweden (Bjerkéus 1998), and Germany (Janszen *et al.* 2013).

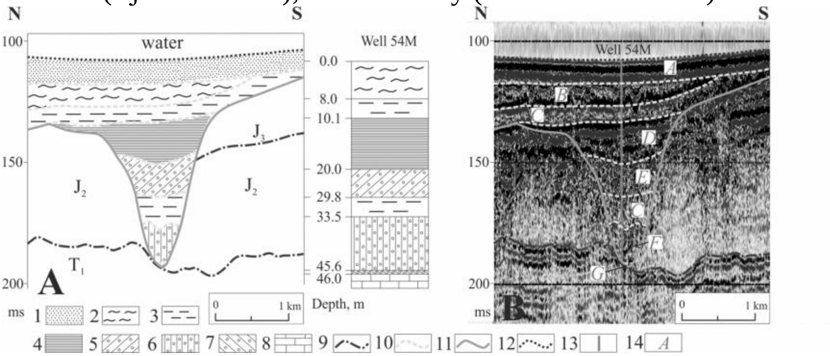


Fig. 32 Fragment of seismic line 980830_1. A: Geological section; B: Interpretation. 1 – sand; 2 – mud; 3 – silt; 4 – clay; 5 – Till-1; 6 – Till-2; 7 – Till-3; 8 – bedrock; 9 – geological boundaries; 10 – geological boundaries within the Quaternary strata; 11 – palaeo-incision; 12 – seafloor; 13 – well (location see Fig. 14); 14 – seismic unit of palaeo-incision infilling.

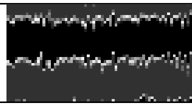
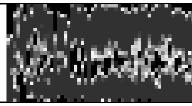
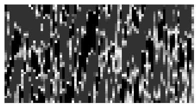
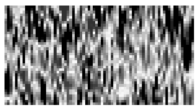
Seven seismic units (*A*–*G*) of palaeo-incision infilling, including three types of tills, namely Till-1, Till-2 and Till-3, are classified based on the well data and internal seismic reflectors in the area of investigation (Table 10, Figs. 32–34).

Unit A. Seismic reflectivity pattern is described by coherent distinct and strong seismic events (Fig. 32, 110–120 ms; Fig. 34, 40–50 ms). This unit is associated with layers of sand and gravel.

Unit B. Seismic reflectivity pattern is characterized by sub-coherent and rather strong seismic events, although weaker compared to *unit A* (Fig. 32, 120–130 ms; Fig. 33, 90–120 ms). This unit is associated with mud.

Unit C. Seismic reflectivity pattern is rather homogeneous with some irregularities (Fig. 32, 130–140 ms and 170–180 ms; Fig. 33, 140–150 ms). This seismic unit is connected to silt.

Table 10. Subdivision of palaeo-incision infilling: seismic units A–G.

Seismic unit	**Description of seismic reflectivity pattern**	**Geological interpretation**	**Typical example**
A	Coherent distinct and strong seismic events	Sand and gravel	
B	Sub-coherent and rather strong seismic events, weaker compared to unit A	Mud	
C	Rather homogeneous seismic events with some irregularities	Silt	
D	Rare, wide and comparatively coherent seismic events	Clay	
E	High-dip incoherent reflections with distinct fragments of seismic events	Till-1	
F	Almost homogenous seismic events with rare amorphous reflections (‘semi-transparent’)	Till-2	
G	Coherent, thin and irregular seismic events with some noise	Till-3	

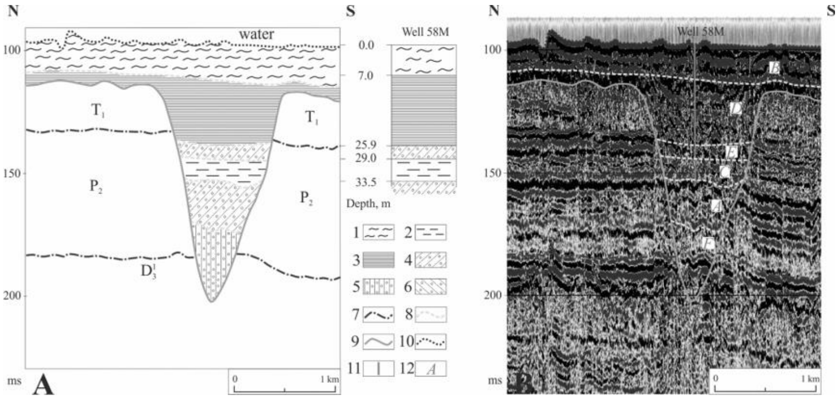


Fig. 33 Fragment of seismic line 980901_2. A: Geological section; B: Interpretation. 1 – Mud; 2 – silt; 3 – clay; 4 – Till-1; 5 – Till-2; 6 – Till-3; 7 – geological boundaries; 8 – geological boundaries within the Quaternary layer; 9 – palaeo-incision; 10 – seafloor; 11 – well (location see Fig. 14); 12 – seismic unit of palaeo-incision infilling.

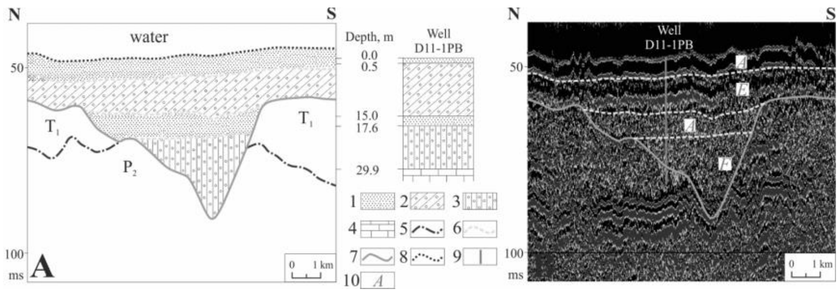


Fig. 34 Fragment of seismic line 9405. A: Geological section; B: Interpretation. 1 – sand; 2 – Till-1; 3 – Till-2; 4 – bedrock; 5 – geological boundaries; 6 – geological boundaries within the Quaternary layer; 7 – palaeo-incision; 8 – seafloor; 9 – well (location see Fig. 14); 10 – seismic unit of palaeo-incision infilling.

Unit D. Seismic reflectivity pattern is marked by rare, wide and comparatively coherent seismic events (Fig. 32, 140—150 ms; Fig. 33, 110—130 ms). It is associated with clay.

Unit E. Seismic reflectivity pattern is described by high-dip incoherent reflections with distinct fragments of seismic events (Fig. 32, 150–170 ms; Fig. 33, 130–140 ms). This unit is associated with Till-1.

Unit F. Seismic reflectivity pattern is almost homogenous, with rare amorphous reflections (“semitransparent”) (Fig. 33, 170–200 ms) or incoherent reflections with small fragments of seismic events (Fig. 34, 70—90 ms). This unit is connected to Till-2.

Unit G. Seismic reflectivity pattern is described by coherent, thin and irregular seismic events with some noise (Fig. 30A, 290–340 ms). This unit is associated with Till-3.

The lowermost three units are separated by erosional surfaces creating strong contrast and, thus, strong seismic events within the palaeo-incision (Fig. 32, 180 ms; Fig. 33, 150 ms; Fig. 34, 50 ms; Fig. 30A, 270 ms and 320 ms). In consequence of this fact, distinct seismic borders within the palaeo-incisions and between different types of seismic reflectivity patterns correspond to erosional surfaces dividing between different types of tills.

Based on the foregoing relationship between seismic reflectivity pattern and type of deposits, about one hundred seismic sections crossing palaeo-incisions have been analyzed (see Appendix 3, Table 11). Seven different types of deposits, described above as units *A–G* have been found in the palaeo-incisions.

Layers of sand and gravel (*unit A*) are absent in the northern part of the central zone (Fig. 31) and truncated across the entire part of the investigated area. The average thickness of *unit A* deposits is about 10 m, minimum is about 4 m and maximum is about 30 m in the western zone. Generally the thickness of these infilling increases from shore area to the western zones (Fig. 31). Clay (*unit D)* disappears in the northwestern direction.

Till-1 (*unit E*) is abundant across the entire area. The thickness of the Till-1 is between 5 and 50 m, with a mean thickness of about 20 m. Till-2 (*unit F*) is locally absent in the central and eastern zones.

Table 11. Statistical data about infilling of the palaeo-incisions.

All the investigated area

	Thickness, m							
Seismic unit	**A**	**A2**	**B**	**C**	**D**	**E**	**F**	**G**
Min	3.6	7.2	2.7	6.3	2.7	5.4	5.4	7.2
Max	29.7	27.0	10.8	21.6	26.1	47.7	46.8	45.9
Average	11.6	12.4	7.4	12.5	12.3	18.9	20.5	21.7

Western zone

	Thickness, m							
Seismic unit	**A**	**A2**	**B**	**C**	**D**	**E**	**F**	**G**
Min	9.9	9.9	—	12.6	7.2	5.4	7.2	16.2
Max	29.7	27.0	—	21.6	20.7	47.7	39.6	45.9
Average	19.3	15.9	—	16.7	12.7	20.1	24.7	32.9

Eastern zone

	Thickness, m							
Seismic unit	**A**	**A2**	**B**	**C**	**D**	**E**	**F**	**G**
Min	3.6	7.2	—	6.3	2.7	7.2	5.4	7.2
Max	16.2	12.6	—	14.4	17.1	42.3	40.5	28.8
Average	8.9	10.4	—	10.7	9.0	19.3	17.9	18.8

Central zone

	Thickness, m							
Seismic unit	**A**	**A2**	**B**	**C**	**D**	**E**	**F**	**G**
Min	6.3	10.8	6.3	7.2	6.3	6.3	9.0	7.2
Max	23.4	15.3	10.8	19.8	26.1	42.3	46.8	36.9
Average	11.2	12.4	8.1	12.1	13.5	18.3	21.1	20.0

The mean thickness of the Till-2 is about 20 m, with its minimum being about 5 m, and maximum about 45 m in the northern part of the central zone. Till-3 (*unit G*) is presented in about 50% of the investigated palaeo-incisions in the eastern zone. They are also locally absent in the central zone. But they are abundant across the entire western zone. The thickness of the Till-3 is between 7 and 45 m, with the mean thickness being about 20 m. The quantity of till deposits increases from the eastern zone to the western zone. The thickness of sediments associated with the *units A–F* increases also in the direction of the southern part of central zone (northern part of Gdansk depression), but *unit B* is found only in the central zone, and *unit C* reaches its maximum thickness in the western zone.

To summarize, based on analysis of internal seismic reflectors, seven types of deposits have been classified in infillings of palaeo-incisions in the entire area of investigations (see Appendix 3).

4.4 THE PRE-QUATERNARY GEOLOGY

In a general way, the investigated area may be divided into four parts according to bedrock outcropping on the sub-Quaternary surface: the northwestern, the northeastern, the southeastern and the southern one. The Late Devonian layered sedimentary rocks crop out on the sub-Quaternary surface in the northwestern part of the investigated area, the Early Triassic–Late Jurassic sedimentary rocks – in the north-eastern part, the Late Permian–Late Jurassic – in the southeastern part and the southern part is covered by Cretaceous sedimentary strata (Fig. 35). The outcrops of the Early Triassic sedimentary rocks "cut" the Middle Jurassic ones along palaeo-incisions in the northeastern part. The central part is raveled by outcrops of the Late Devonian–Middle Jurassic within palaeo-incisions. Examples of the geological sections are presented in Figs. 36–38. A comparison between the new bedrock map and the previous one is presented in Fig. 36.

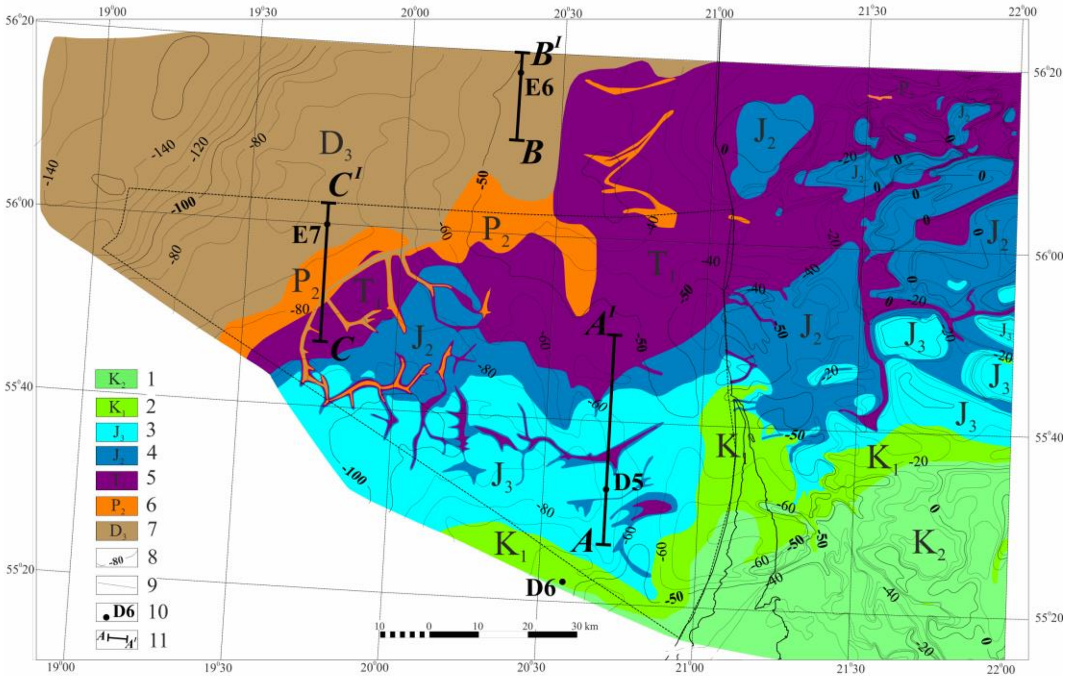


Fig. 35 The pre-Quaternary geological map of the south-eastern Baltic Sea: 1 – Late Cretaceous; 2 – Early Cretaceous; 3 – Late Jurassic; 4 – Middle Jurassic; 5 – Early Triassic; 6 – Late Permian; 7 – Late Devonian (Frasnian); 8 – contour lines of the sub-Quaternary surface (drawn every 10 m); 9 – the Lithuanian Sea border; 10 – wells (see Appendix 1); 11 – geological sections (see Figs. 37 – 39).

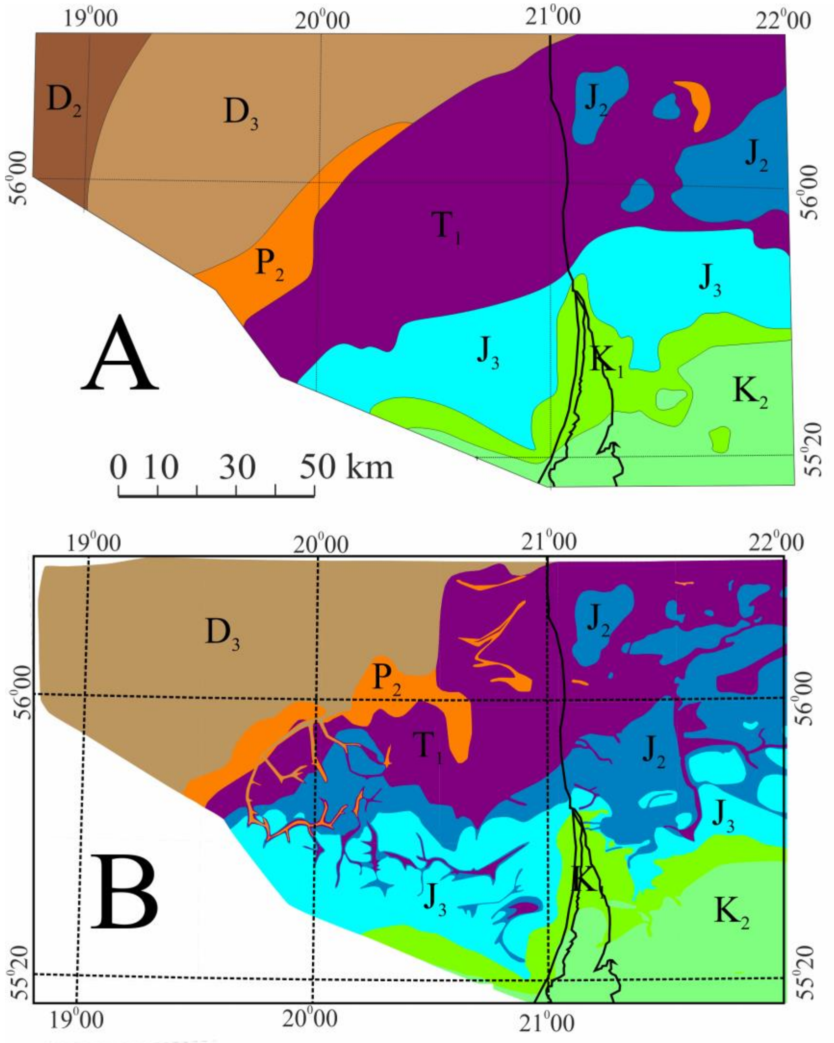


Fig. 36 Comparison of geological maps. A: Bedrock geology of the southeastern Baltic Sea (after Grigelis 2009, modified 2012); B: Bedrock geology of the southeastern Baltic Sea by D. Gerok, 2014.

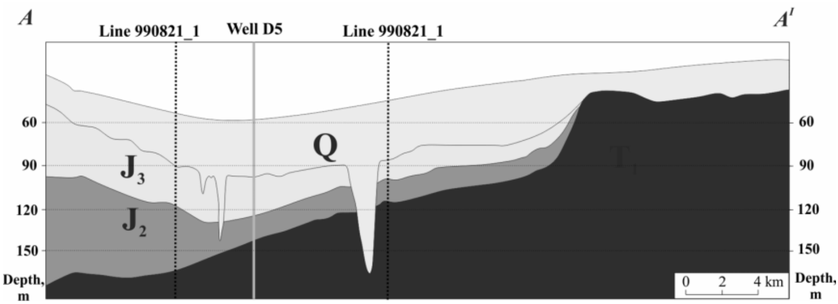


Fig. 37 Geological section. Fragment of seismic line 9404 (for location see Fig. 14).

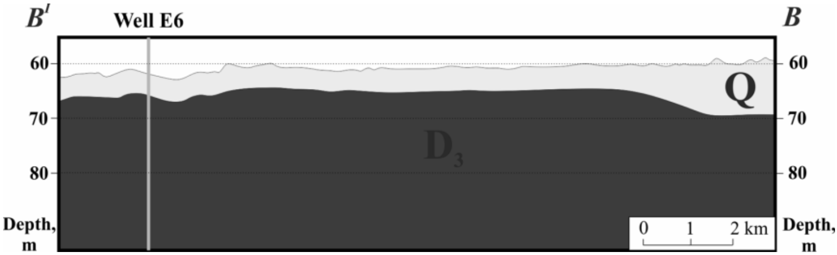


Fig. 38 Geological section. Fragment of seismic line 980830_5 (for location see Fig. 14).

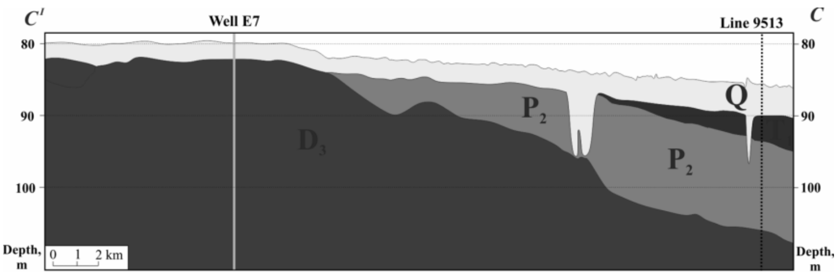


Fig. 39 Geological section. Fragment of seismic line 980901_3 (for location see Fig. 14).

The new investigation reveals that Middle Devonian outcrops are absent on the sub-Quaternary surface in the northwestern part of the investigated area contrary to earlier works (A in Fig. 36). This fact is confirmed by the 1998-1999 seismic data, which are more recent than those used for compiling of the earlier map.

Late Permian sedimentary rocks crop out on the sub-Quaternary surface in the central part of the investigated area and there are some fine details connected to palaeo-incisions in the northeastern part as well. The Late Permian outcrops in the central part of the area coincide in general with the earlier map. New outcrops of Late Permian have been confirmed on the sub-Quaternary surface in the central part of the investigated area.

In general, the Early Triassic outcrops conform to the earlier map, but its northern boundary extends further to the west than presumed previously. Also, the new details associated with palaeo-incisions are added in the northeastern part of the investigated area.

Denser network of seismic lines, including the data of the 1998–1999 expeditions, revealed the presence of Middle Jurassic outcrops in the offshore part of the investigated area for the first time. Moreover, the new geological mapping on land provided the new details of geological boundaries in the northeastern part of the investigated area.

The outcrops of the Late Jurassic sedimentary rocks also conform in general to the earlier map. They are abundant in the larger part of the offshore area and in a small area on land as results of the new investigation there. There are also the new details in the map connected to palaeo-incisions in the southeastern part of the investigated area.

Outcrops of the Cretaceous conform between the maps in the offshore part of the investigated area, but there are some new details connected to palaeo-incisions in the southeastern part on land.

In conclusion, the outcrops of the Early Triassic, the Late Jurassic and the Cretaceous sedimentary rocks coincide in general with the results of the earlier investigation. Outcrops of the Middle Devonian, as known in the older map, are not verified, but new outcrops of the Late Permian and the Middle Jurassic are found in the area of investigation (Fig. 36). Usage of the new geological mapping on land and the seismic data offshore (1998-1999 expeditions) provided the new details of the Late Devonian–Late Cretaceous outcrops (except the Cretaceous offshore). Moreover, the fine details, connected to palaeo-incisions are added to the geological knowledge of the investigated area.

5. DISCUSSION

5.1 INTERPRETATION OF GEOPHYSICAL DATA

The depth penetration of the CMP seismic method proved sufficient to locate even the deepest parts of palaeo-incisions, but it proved difficult to describe in any detail the upper geological boundaries due to the fuzziness of seismic section there. Sometimes turning ray tomography procedures and sections of root-mean-square velocities allowed solving this problem. A seismic source grouping of 32, was used for the reference profile (Fig. 22B), showed a superior result compared with a grouping of 16 (Fig. 23C). Probably it is also necessary to increase the CDP fold having used smaller source spacing for better results in the future. It is only possible to use the shallow seismic method to locate the buried valleys under these conditions. The productivity is about 25 m per man-hour in this case (see Table 6).

Electrical tomography, as it was anticipated, can be used to locate the slopes of palaeo-incisions. It proved impossible to get the full information of the palaeo-incision shape, however. Equipment should be of deeper penetration for better result. Applying this method alone is not sufficient to identify the location of palaeo-incision, i.e. if the profile is located along a palaeo-incision or if the width of the palaeo-incision is greater than the profile. Therefore different electromagnetic methods with deeper penetration should be tested. Usage of the methods with deeper penetration might help to solve this problem.

Gravimetric surveys previously performed in the Lithuanian coastal area, with the above mentioned results for the Dovilai area, show that the method is useful and it could be added as an additional method into the described complex of geophysical methods for prospecting of palaeo-incisions. For example, it could be useful for locating potential palaeo-incisions for future investigations.

The complexity of the CSP data interpretation involves several aspects. The first limiting factor is that only a few deep offshore wells are accessible within the investigated area (see Appendix 1). The second limiting factor is connected to complicated composition of the Quaternary glacial deposits. The next problem is the water depth of the investigated area. Multiple reflections from the seismic boundaries are most often very intense and overprint the reflections of deeper seismic boundaries in the shallow areas. This is the reason, the shallow water part is less investigated in the entire area. It is possible to solve this problem having used multichannel equipment and common deep point (CDP) seismic method in the shallow water.

The deepest parts of palaeo-incisions (3 in Fig. 31) are often deeper than the multiple seismic reflections from the seafloor in the eastern zone. Supposedly, this is the reason why *unit G* is only found in a half of investigated palaeo-incisions there. The seismic reflectivity pattern of this unit might be described in different ways according to the data digitizing quality and the local area. But it seems possible to understand the quantity of palaeo-incision generations by their erosional surfaces, which associate with high contrast and strong seismic events within palaeo-incisions.

The fact that the infilling of palaeo-incisions often has up to three depositional events, might indicate that some channels are successively reopened, possibly even during each glaciation. Thus, due to differences in the infillings, it is presumed, that there are at least three generations of palaeo-incisions formed during three different glaciations. The younger generations cut into the soft sedimentary bedrock or into the infilling of older palaeo-incisions. In general the palaeo channels of older generations are deeper than the younger ones (Bjerkéus *et al.* 1994). An attempt has been made to show this with inferred boundaries within the palaeo-incisions (Fig. 30A, C–F). But because the contrast of seismic reflectivity pattern is rather low, these details are only assumed. More precise research could make the question of several generations clearer.

The dating of the infilling till units could be based on their different contents of rounded hornblende grains. The average contents are: Weichselian (16–25%), Saalian (21–42%) and Elsterian (6–17%) (Majore *et al.* 1997). But this analysis is done for the local region and only several palaeo-incisions have been analyzed. For this reason, this dating had not been used. The information about contents of rounded hornblende grains could make it possible to determine the age of different till units and prove the establishment of several generations within the palaeo-incisions in the entire area of investigations.

In addition, locally it is rather hard to resolve the changes of stratigraphic seismic units, the location of palaeo-incisions or other events such as e.g. gas-saturated rocks, various geological facies and local irregularities in the sediments by the seismic reflections.

The seismic reflections are often weak in the lowest parts of the palaeo-incisions, because their infillings are composed in a complicated way (it finds expression in seismic reflections of infilling). Thus, to determine the depth of a palaeo-incision may become a rather tough issue.

The irregular distribution of the seismic lines (Fig. 14) inadvertently results in different accuracies in the shape and direction of the palaeo-incisions, also in different details of mapped geological boundaries and sub-Quaternary surface within the offshore part of the studied area.

The fragment of Latvian land territory on the sub-Quaternary map contains no new data and it has been compiled having used the data from neighboring areas of Lithuania and Latvia offshore. Thus, it may be regarded as the ‘soft spot’ of this map.

The correlation between the land and offshore palaeo-incision networks is not established due to lack of data in the shallow waters.

The shape of palaeo-incisions is known from seismic sections, which often are not perpendicular to the direction of palaeo-incisions.

But, this factor seems to affect the horizontal scale of the section but not the shape.

The difference in thickness together with the heterogeneities in the Quaternary strata may act as the additional factor, influencing on the shapes of palaeo-incisions and becoming the agent for their irregular distribution in the entire area of investigations.

5.2 GEOECOLOGICAL SIGNIFICANCE OF PALAEO-INCISIONS

Palaeo-incisions are specific geological structures – they cut, as a rule, into different geological layers. The information, obtained about morphology and distribution of the palaeo-incisions in the southeastern Baltic Sea region, shows that often the palaeo-incisions dissect a part or the entire Quaternary thickness as well as the upper part of the pre-Quaternary sedimentary bedrock. Thus, if a palaeo-incision is filled by aqua-glacial sediments with a high permeability, i.e. sand and gravel, it could be associated with a 'hydro-geological window' between different aquifers. The aquifers are usually separated by layers of impermeable deposits or rocks, e.g. till, clay, dolomite, marlstones, etc. Quaternary inter-till sandy horizons, Cretaceous–Jurassic sand and sandstone and Permian limestone are associated with main aquifers of fresh groundwater supply in the area of investigation. Whereas the glacial till and clay separate the Quaternary aquifers, Cretaceous–Jurassic and Triassic clayey deposits (confining beds) separate the pre-Quaternary aquifers (Juodkazis 1979). If one or a few aquifers of groundwater supply are presented in the region of palaeo-incision development, some potential geoecological risks are possible. During the groundwater extraction, when the hydrostatic pressure in the particular aquifers falls, vertical circulation of water between neighboring aquifers might start (or be significantly intensified) via the above 'hydro-geological windows', i.e. palaeo-incisions. Thus, two possible scenarios of geoecological risk are available in this case in the southeastern Baltic Sea region:

- the groundwater from the upper aquifers, including unconfined groundwater, might begin to infiltrate into lower horizons. The unconfined groundwater is not protected from anthropogenic influence and often contains anthropogenic pollution (fertilizers, heavy metals, oil products, etc.). In this case polluted water from unconfined groundwater horizon could infiltrate into the deeper horizons having used for drinking purposes, as a result of this process the drinking water could receive a particular dose of the above pollutants of anthropogenic origin;

- particular aquifers in the pre-Quaternary rock sequence contain not fresh, but salt water – such water is characteristic of the Permian and Jurassic aquifers located in the southernmost part of the investigated area (Juodkazis 1979; Mokrik 2003). During the intensive drinking water extraction, the salt water located in deeper horizons might begin to infiltrate into the upper ones (via palaeo-incisions first of all), reducing the quality of the drinking water.

Another geoecological risk could be related with the distribution of palaeo-incisions in the bottom of the Southeastern Baltic Sea. As it has been established during earlier investigations, the palaeo-incisions are closely connected to zones of tectonic faults (Nechiporenko 1989). Tectonic activity could stimulate destruction of sediments solidity, i.e. to form crushing zones along the tectonic faults where more intensive water circulation might begin (Bitinas 1999, 2011; Satkūnas 2000, 2008). Furthermore, tectonic faults in the pre-Quaternary sedimentary bedrock are zones where groundwater (including salt water) discharges. Several zones are described, where salt or fresh groundwater is discharged at the seafloor of the Southeastern Baltic Sea, and these zones could be connected to tectonic faults and palaeo-incisions (Mokrik 2003). The salt/fresh water discharged from the pre-Quaternary sedimentary bedrock of the Southeastern Baltic Sea is characterized by different chemical compositions in relation to the modern Baltic Sea water. The differences in chemical composition of benthic water (Mokrik 2003) most probably reflect the above tectonic processes. Thus, the differences in chemical composition of near bottom water could potentially affect the development of benthic ecosystems, and this is still not an investigated issue of marine biology and ecology in the southeastern Baltic Sea area. The distribution of palaeo-incisions might act as a potential indicator for the identification of submarine groundwater discharge zones.

The palaeo-incisions cut into the Quaternary strata, produce irregularities in the field of seismic velocities during seismic surveys both on land and offshore. In case the reason is unknown, the irregularities of the seismic velocities in the upper part of geological section might affect the reflections of deeper geological layers, followed by possible incorrect interpretation of deep seismic data during planning the well for oil exploration, for example.

The palaeo-incision infills are different as compared to the enclosing stratal sequences, especially in the cases when the palaeo-incisions are cut into the pre-Quaternary rocks. Their occurrences are of dual importance on land. From a hydro-geological point of view, they are not only ‘hydro-geological windows’, subjected to possible potential geoecological risks, but are at the same time attractive areas for fresh groundwater exploration and pumping. This is especially true when there is a need for major amounts of groundwater for centralized supply of cities or settlements. On the other hand, the palaeo-incisions may be regarded as obstacles, which are dissecting the homogenous sedimentary structures – this fact has a negative significance during the construction of massive buildings or extraction of different mineral resources. Thus, it is possible to argue, that the distribution of the palaeo-incision network in the seafloor of Southeastern Baltic Sea could be a negative factor from an engineering-geological point of view, taking into account that this region is perspective of future marine industry: building oil prospecting and extraction platforms, wind-power plants, etc.

6. CONCLUSIONS

1. Eighty-two fragments of palaeo-incisions have been discovered by the continuous seismic profiling data digital interpretation in the southeastern part of the Baltic Sea. They form three separate networks differentiated by their morphology and depth of the palaeo-incisions.

2. The morphology of the palaeo-incisions changes from the complicated W- and WW-shape forms near the shore to the simple V-shape in the western zone. The average width decreases from the eastern zone (2340 m), through the central zone (1460 m) to the western zone (960 m). The relative depth of palaeo-incisions increases from 23–80 m in the eastern zone, through 27–113 m in the central zone to 53–153 m in the deepwater zone.

3. The newly compiled map of palaeo-incisions on the sub-Quaternary surface primarily differs from the previous one in the eastern and in the central zones: the sub-Quaternary relief have been detailed, and the network of previously unknown fragments of palaeo-incisions have been discovered and compiled.

4. A new version of the pre-Quaternary geological map of the investigated area has been compiled. The outcrops of Late Devonian, Late Permian, Early Triassic, Middle and Late Jurassic, also Cretaceous sedimentary rocks on the sub-Quaternary surface, have been contoured more precisely compared to the previously published maps.

5. Based on the analysis of internal seismic reflectors, seven types of deposits have been differentiated in infillings of palaeo-incisions in the entire area of investigations. The particular type of palaeo-incision infilling was interpreted having used well data: sediments of the different Pleistocene stages – clay, silt, mud, stratified and unstratified layers of sand and gravel and three type of till – have been determined.

6. The integrated geophysical investigation, consisting of 2D CMP seismic method and electrical tomography survey, makes it partly

possible to locate palaeo-incisions and describe their shape and depth on land. To locate and describe the palaeo-incisions effectively, it is necessary to append the gravity method to the integrated geophysical survey, and to test and choose the other electromagnetic method of deeper penetration.

REFERENCES

Ayalew G., Holden N.M., Ward S.M. 2007: Microwave dielectric properties of horticultural peat products. *Mires and Peat, Vol. 2*: Article 03 (http://www.mires-and-peat.net/map02/ map_02_03.htm).

Aliavdin F., Amantov A., Efimov A., Grigelis A., Kovalenko F., Malkov B., Kharin G., Janovskij A., 1991. Cambrian. In: Grigelis A. (ed.), 1991. Geology and geomorphology of the Baltic Sea. Nedra. Leningrad, 93—114. [In Russian].

Asch K. (Ed.), 2006 (2005). *The 1:5 Million International Geological Map of Europe and Adjacent Areas – IGME5000.* Geologische Bundesanstalt, Hannover, 1 map.

Atkinson N., Andriashek L.D., Slattery S.R. 2013. Morphological analysis and evolution of buried tunnel valleys in northeast Alberta, Canada. *Quaternary Science Reviews 65,* 53–72.

Bitinas A., Kadūnas K., Damušytė A., Putys P., Popov M., 1993. Geologinių tyrimų Būtingės naftos terminalo rezervuarų parko statinių ataskaita. *Lietuvos geologijos tarnyba*, *Reg. Nr. 93 – 25*. Vilnius. [Manuscript in the Archive of Lithuanian Geological Survey; in Lithuanian].

Bitinas A. (chief executor) Bitinas J., Damušytė A., Stančikaitė M., Gedžiūnas P., Mašauskaitė R., Mičiudienė V., Bucevičiūtė S., Putys P., Piepolienė V., Kanopienė R., Dansevičienė D., 1998. Kompleksinis geologinis kartografavimas 1:50 000 masteliu Kretingos plote. Kvartero geologija ir geomorfologija. *III tomas, Lietuvos geologijos tarnyba, Inv. Nr.4685, Vilnius,* 119 pp. [Manuscript in the Archive of Lithuanian Geological Survey; in Lithuanian].

Bitinas A., 1999. Some remarks on distribution and genesis of palaeo-incisions in the East Baltic area. *Geological Quarterly 43 (2)*, 183–188.

Bitinas A., Repečka M., Kalnina L., 1999. Correlation of tills from the Southeastern Baltic Sea bottom and nearshore boreholes. *Baltica Special Publications 12,* 5–10.

Bitinas A. (chief executor) *et al.*, 2004. Baltijos jūros krantų geologinis atlasas. *Lietuvos geologijos tarnyba, Inv. Nr. 7297, Vilnius,* 92 pp. [Manuscript in the Archive of Lithuanian Geological Survey; in Lithuanian].

Bitinas A., 2011. Paskutinysis ledynmetis Rytinės Baltijos regione. Klaipėdos universiteto leidykla, 156 pp. [In Lithuanian].

Bitinas A., Damušytė A., Molodkov A., 2011. Geological Structure of the Quaternary Sedimentary Sequence in the Klaipėda Strait, Southeastern Baltic. *In* J. Harff *et al.* (Eds.), The Baltic Sea Basin, Springer-Verlag Berlin Heidelberg, 135–148.

Bitinas J., 2000. II lygio prekvartero geologinis kartografavimas 1:50 000 masteliu Šilutės plote. *Lietuvos geologijos tarnyba, Inv. Nr. 5312, Vilnius,* 193 pp. [Manuscript in the Archive of Lithuanian Geological Survey; in Lithuanian].

Bitinas J. (chief executor), Nasedkin V., Šliaupa A. *et al.* 2003. II lygio prekvartero geologinis kartografavimas 1:50 000 masteliu Ylakių plote (lap. 3114, 3123). *Lietuvos geologijos tarnyba, Inv. Nr. 6205, Vilnius,* 152 pp.

Bitinas J., 2011. Prekvartero geologinis kartografavimas M 1:50 000 Pagėgių plote ataskaita. *Lietuvos geologijos tarnyba, Inv. Nr. 15395, Vilnius,* 96 pp.

Bitinas J. (chief executor), 2013. Erdvinis geologinis kartografavimas M 1:50 000 Platelių-Plungės plote. *Lietuvos geologijos tarnyba, Vilnius,* 55 pp.

Bjerkéus M., Gelumbauskaitė L. Ž., Sturkell E., Flodén T., Grigelis A., 1994. Paleochannels in the east central part of the Baltic Proper. *Baltica 8,* 15–26.

Blazhchishin A. I., Boldyrev V. L., Efimov A. N., Timofeev I. A., 1982. Ancient shorelines and shore formations in the south–eastern part of the Baltica Sea. Baltica 7, 51–64. [In Russian with English summary].

Boganik G.N., Gurvich I.I. 2006. Seismic: Textbook for Universities. Tver, AIS, 744 pp. [In Russian].

Boulton G.S., Hindmarsh C.A. 1987. Sediment deformations beneath glaciers: arheology and geological consequences. *Journal of Geophysical Research 92 (B9),* 9059–9082.

Boulton G.S., Slot T., Blessing K., Glasbergen P., Leijnse T., Gijssel van K. 1993. Deep circulation of groundwater in overpressured subglacial aquifers and its geological consequences. *Quaternary Science Reviews 12,* 739–745.

Boulton G.S., Caban P.E., Gijssel van K. 1995. Groundwater flow beneath ice sheets: part I – large scale patterns. *Quaternary Science Reviews 14,* 545–562.

Boulton G.S., Caban P.E. 1995. Groundwater flow beneath ice sheets: part II – its impact on glacier tectonic structures and moraine formation. *Quaternary Science Reviews 14,* 563–587.

Eberhards G., Miidel A., 1984. Main features of the development of river valleys in the east Baltic. *Proceedings of the Academy of Sciences of the Estonian SSR, Geology 33,* 136–144.

Ehlers J., Meyer K. D., Stephan H. J., 1984. The pre–Weichselian glaciations in north–west Europe. *Quaternary Science Review 3,* 1–40.

Flodén T., 1980. *Seismic stratigraphy and bedrock geology of the Central Baltic.* Stockholm Contributions Geology XXXV, 240 pp.

Flodén T., Bjerkéus M., Sturkell E., Gelumbauskaitė L. Ž., Grigelis A., Endler R., Lemke W., 1997. Distribution and seismic stratigraphy of glacially incised valleys in the southern part of the Baltic. *Sveriges Geologiska Undersökning, Ser. Ca 86,* 43–49. [Proceedings of the Fourth Marine Geological Conference – the Baltic, Uppsala 1995].

Gaigalas A., 1976. The buried palaeo-incisions of the sub–Quaternary rock surface of the south-east Baltic region. Mokslas Publishers, Vilnius, 140 pp. [In Russian with English summary].

Gelumbauskaitė L. Ž., Litvin, V. M., 1986. Bottom geomorphology of the southeastern Baltica Sea. *Geomorfologiya 1,* 55–61. [In Russian with English summary].

Gelumbauskaitė L. Ž., Litvin, V. M., 1990. On development of bottom morphostructure of the Baltica Sea. *Geomorfologiya 2,* 66–71. [In Russian with English summary].

Gelumbauskaitė L. Ž., 1996 (1995). Bottom relief and genesis of the Gotland depression. *Baltica 9,* 65–75.

Gelumbauskaitė L. Ž., Grigelis, A., 1997. Paleogeomorphological reconstruction of the sub–Quaternary surface of the Central Baltic Sea. *Sveriges Geologiska Undersökning, Ser. Ca 86,* 51–56. [Proceedings of the Fourth Marine Geological Conference – the Baltic, Uppsala 1995].

Gelumbauskaitė L. Ž., 1999. Sub–Quaternary surface of the south–eastern Baltic Sea. *Baltica 12,* 15–18. (Proceedings of the Fifth Marine Geological Conference, Special Publication).

Gelumbauskaitė L. Ž., 2000. Late– and Postglacial palaeogeomorphology on the Klaipėda submarine slope, south–eastern Baltic Sea. *Baltica 13,* 36–43.

Gelumbauskaitė L. Ž., 2009. Character of sea level changes in the subsiding southeastern Baltic Sea during Late Quaternary. *Baltica 22 (1),* 23–36.

Gerok D., Bitinas A., 2013. Geophysical study of palaeo-incisions in the Šventoji–Būtingė coastal area, north-west Lithuania. *Baltica, 26 (2)*, 201—210.

Gerok D., Gelumbauskaitė L. Ž., Flodén T., Grigelis A., Bitinas A., 2014. New data on the palaeo-incisions network of the southeastern Baltic Sea. *Baltica, 27 (1),* 1–14.

Gibbard, P., Cohen, K.M., 2008. Global chronostratigraphical correlation tabale for the last 2.7 million years. *Episodes 31*, 243–247.

Grigelis A. (ed.), 1991. Geology and geomorphology of the Baltic Sea. Appendix 2. Nedra, Leningrad, 398—416. [In Russian].

Grigelis A., Efimov A., Kovalenko F., Malkov B., Kharin G., 1991a. Silurian. In: Grigelis A. (ed.), 1991. Geology and geomorphology of the Baltic Sea. Nedra. Leningrad, 141—167. [In Russian].

Grigelis A., Efimov A., Kovalenko F., Malkov B., Kharin G., Janovskij A., 1991b. Devonian. In: Grigelis A. (ed.), 1991. Geology and geomorphology of the Baltic Sea. Nedra. Leningrad, 168—190. [In Russian].

Grigelis A., Efimov A., Kovalenko F., Kharin G., 1991c. Jurassic. In: Grigelis A. (ed.), 1991. Geology and geomorphology of the Baltic Sea. Nedra. Leningrad, 203—210. [In Russian].

Grigelis A., Amantov A. A., Efimov A. N. *et al.*, 1993. *Geological map of the Baltic Sea bottom and adjacent land areas. Scale 1:500 000.* Cartography Enterprise, Sankt-Petersburg / Institute of Geology, Vilnius. 7 sheets.

Grigelis A., 1994a. Palaeozoic. In: Grigelis A., Kadūnas V. (eds.), Geology of Lithuania. Science and encyclopaedia publisher, Vilnius, 34—35. [In Lithuanian].

Grigelis A., 1994b. Jurassic.In: Grigelis A., Kadūnas V. (eds.), Geology of Lithuania. Science and encyclopedia publisher, Vilnius, 139—152. [In Lithuanian].

Grigelis A., 1994c. Cretaceous. In: Grigelis A., Kadūnas V. (eds.), Geology of Lithuania. Science and encyclopedia publisher, Vilnius, 153—166. [In Lithuanian].

Grigelis A., Flodén T. (chief scientists); contributors Bjerkéus M., Gelumbauskaitė L.Ž., Repečka M., Jokšas K., Šimkevičius P. (contributors), 1994. Joint Lithuanian–Swedish marine geological-geophysical expedition: Report of investigations in the Central Baltic / cruise of R/V „Vėjas" No. 6/48, June 17–July 2, 1993, No. 14/56, August 20–September 8, 1994. Department of Baltic Marine Geology, Institute of Geology, Vilnius; Department of Geology and Geochemistry, Stockholm University. Vilnius–Stockholm, Institute of Geology, 1994, 23 pp. [Manuscript in the Archive of Institute of Geology].

Grigelis A., 1995. Mesozoic and Paleogene stratigraphy of the southeastern part of the Baltic Sea. *Prace Państwowego Instytutu Geologicznego* 149, Warszawa, 43–46. (Proceedings of the third Baltic Marine Geological Conference „The Baltic").

Grigelis A. (chief scientist); Gelumbauskaitė L.Ž., Repečka M., Šimkevičius P., Radzevičius R. (contributors), 1996. Gotland Basin Experiment (GOBEX): Final report of investigations in 1994-1996. Science and Studies Foundation of Lithuania. Institute of

Geology.Vilnius, 35 pp. [Manuscript in the Archive of Institute of Geology].

Grigelis A., 1999. Stratigraphic units of Late Paleozoic and Mesozoic bedrock of the Baltic Sea. *Baltica 12,* 19–27. (Proceedings of the Fifth Marine Geological Conference, Special Publication).

Grigelis A., Bitinas J. 2004. Paleogeografinių sąlygų kaitos ypatybės. *Lietuvos žemės gelmių raida ir ištekliai* [Special aspects of changes of palaeogeographical conditions. *The evolution and resources of Lithuanian interior*]. Vilnius, *Litosfera,* 249–251.

Grigelis A., 2011. Research of the bedrock geology of the Central Baltic Sea. *Baltica 24 (1),* 1–12.

Gudelis V., 1961. General features of the sea coast development of the Eastern Baltic mainland in late- and postglacial time. *Proceedings of the Institute of Geology of the estonian Academy of Sciences VIII.* [In Russian with English summary].

Gudelis V., 1970. General features of geology and geomorphology of the seafloor at the central sector of the Baltic Sea. *Baltica 4,* 103–113. [In Russian with English summary].

Gudelis V., Lukoševičius, L., Kleymenova, G. J., Vyshnevskaya, E. M., 1977. Geomorphology and late– and postglacial bottom deposits of the southeastern Baltic. *Baltica 6,* 245–256. [In Russian with English summary].

Guobytė, R., Satkūnas, J., 2011. Pleistocene Glaciations in Lithuania. In J. Ehlers *et al.* (eds) Developments in Quaternary Science. Vol. 15, Elsevier B.V., 231–246.

Huuse M., Lykke–Andersen H. 2000. Over deepened quaternary valleys in the eastern Danish North Sea: morphology and origin. *Quaternary Science Reviews 19,* 1233–1253.

Janszen, A., Spaak, M., Moscariello, A. 2012 (October). Effects of the substratum on the formation of glacial tunnel valleys: an example from the Middle Pleistocene of the southern North Sea Basin. *Boreas. 41*, 629–643.

Juodkazis V., 1979. Pabaltijo hidrogeologijos pagrindai. Vilnius, Mokslas, 144 pp. [In Lithuanian].

Jurgens U., 1999. Burried Quaternary channels in the southern Baltic Sea north of Rügen Island, Germany: distribution and genesis. *Baltica 12*, 43–47. (Proceedings of the Fifth Marine Geological Conference, Special Publication).

Kearey P., Brooks M., Hill I., 2002. An Introduction to Geophysical Exploration. Third Edition. Blackwell science ltd., London, 43—98, 183—199.

Kuster H., Meyer K. D., 1979. Glaziäle Rinnen im mittleren und nordöstlischen Niedersachsen. Eiszeithalter und Gegenwart 29, 135–156.

Majore J., Rinke R., Savvaitov A., Veinbergs I., 1997. Lithostratigraphical identification of tills in the southeastern part of the Baltic Sea by the method of the rounded hornblend grains. *Baltica 10*, 9–12.

Mokrik R., 2003. Baltijos baseino paleohidrogeologija. Neoproterozojus ir fanerozojus. Vilniaus universiteto leidykla, 333 pp. [In Lithuanian].

Molodkov A., Bitinas A., Damušytė A., 2010. IR-OSL studies of till and inter-till deposits from the Lithuanian Maritime Region. *Quaternary Geochronology 5*, 263–268.

Monkevičius A., 1999. Glacial incisions and fossil cryogenic structures in the Mesozoic deposits of the SE Baltic Sea. *GFF 121*, 1–12.

Narbutas V., 1994. Devonian. In: Grigelis A., Kadūnas V. (eds.), Geology of Lithuania. Science and encyclopaedia publisher, Vilnius, 97—119. [In Lithuanian].

Nechiporenko L.A. 1989. Conditions of bedding and tectonic predeterminacy of antropogenic cover in Byelorussia. Minsk: Science and technics, 114 pp. [In Russian]

Piotrowski J.A. 1994. Tunnel valley formation in the northwest Germany – geology, mechanisms of formation and subgacial bed conditions for the Bornhoved tunnel valley. *Sedimentary Geology* 89, 107–141.

Piotrowski J.A. 1997. Subglacial environs – an introduction. *Sedimentary Geology* 111, 1–5.

Puura V.A., Amantov A.V., Sviridov N.I., Kanev S.V., 1991a. Tectonics. In: Grigelis A. (ed.), Geology and geomorphology of the Baltic Sea. Nedra, Leningrad, 257—290. [In Russian].

Puura V., Aliavdin F., Amantov A., Efimov A., Korsakova M., Malkov B., 1991a. Archean and Proterozoic. In: Grigelis A. (ed.), 1991b. Geology and geomorphology of the Baltic Sea. Nedra. Leningrad, 203—212. [In Russian].

Repečka M., 1991. Relief of surface of pre–Quaternary rocks. In A.Grigelis (ed.), *Geology and geomorphology of the Baltic Sea*, Nedra Publishers, St. Petersburg, 229–234. [In Russian].

Repečka M., Rybalko A., Malkov B., Blazhchishin A., Emelyanov E., Efimov A., Isachenko S., Spiridonov M., Juškevičs V., 1991. Quaternary. In A. Grigelis (Ed.), *Geology and geomorfology of the Baltic Sea*, 229–256, Leningrad, Nedra. [In Russian].

Rozhdestvensky D. S., 1989. Buried lower Cenozoic valleys in the southeastern Baltic Sea (according to the 13 data of seismoacoustic profiling). *Bulletin of MOIP, Geological Section*, Vol. 54 (5), 41-45. [In Russian].

Satkūnas J. 2000. Palaeoįrėžių formavimas kontinentinių apledėjimų aplinkoje – Rytų Lietuvos atvejis. [The forming of palaeo-incisions in continental glaciation environment – case of East Lithuania]. *Geologija*, 52–65.

Satkūnas J. 2008. Morphotectonic implication of tunnel valleys in areas with thick Quaternary cover. *Third Conference of MELA; Cartographical Approach of the Morphotectonic of European Lowland Area, May 18–21, Abstracts,* Międzyzdroje, Poland, 42–44.

Savvaitov A., Veinbergs, I., Goldfarb, Yu., 1999. General features of the sub-Quaternary relief of the Baltic Sea in the Latvian Economic Zone. *Baltica 12,* 99–102. (Proceedings of the Fifth Marine Geological Conference, Special Publication).

Sigmond E. M. O. (Ed.), 2007 (2002). *Geology of the land and seas of Northern Europe.* NGU, Special Publication 10, Trondheim, Norway.

Smit F.W.H., Bregman E.P.H. 2012. Buried glacial valleys as drinking water reservoirs. An assessment on function and risks in their role as drinking water reservoirs in the ice-marginal landscape of northern Europe. ENCORE project record

Stirpeika A., 1999. Tectonic evolution of the Baltic syneclise and local structures in the South Baltic region with respect to their petroleum potential. Lithuanian Geological Survey, Vilnius, 50—58.

Stevenson A., 2012. The European marine observation and data network – geological data. *Baltica 25 (1),* 87–90.

Suveizdis P., 1994a. Permian. In: Grigelis A., Kadūnas V. (eds.), Geology of Lithuania. Science and encyclopaedia publisher, Vilnius, 122—131. [In Lithuanian].

Suveizdis P., 1994b. Tectonics. In: Grigelis A., Kadūnas V. (eds.), Geology of Lithuania. Science and encyclopaedia publisher, Vilnius, 213—226. [In Lithuanian].

Suveizdis P., 1994c. Triassic. In: Grigelis A., Kadūnas V. (eds.), Geology of Lithuania. Science and encyclopaedia publisher, Vilnius, 122—131. [In Lithuanian].

Sviridov N. I., Litvin V. M., Gaigalas, A. J., Repečka, M. A., 1976. Relief of the sub-Quaternary surface of the Baltic region. *Sovetskaya Geologiya 5,* 60–69. [In Russian].

Sviridov N. I., Litvin V. M., 1983. Structure of the sedimentary cover of the southeastern areas of the Baltic Sea. *Sovetskaya Geologiya 4,* 86–94. [In Russian].

Sviridov N. I., 1984. The origin of faults in the upper part of sedimentary cover of the Baltic Sea. *Sovietskaya Geologiya 6,* 72–79. [In Russian].

Sviridov N. I., 1991. Seismostratigraphic subdivision of the sedimentary cover. In A. Grigelis (Ed.), Geology and geomorphology of the Baltic Sea, Nedra, Leningrad, 50–66. [In Russian].

Šečkus R. 2002. The main principles of the use of electrical tomography for geological purposes. *Geologija 38,* 49–60.

Šliaupa A. 1981. Neotectonic structure and the plan of hydrographical network in the southern Baltics. *In* B. I. Koshechkin (Ed.), *Investigations of Scandinavian Icecap Evolution in the USSR,* Apatites, 29–35. [In Russian].

Šliaupa A., Repečka M. 1995. The sub-Quaternary relief of the Eastern Baltic Sea and adjacent territory. *Technika Poszukiwań Geologicznych, Geosynoptika i Geotermia 3,* 75–78.

Šliaupa A., Gelumbauskaitė Ž., Straume J., Šliaupa S., 1995. Neotectonic structure of eastern part of the Baltic Sea and adjacent land area. *Technika Poszukiwań Geologicznych, Geosynoptika i Geotermia 3,* 63-65.

Šliaupa A. 2001. Neotectonic structure of Lithuania and adjacent territory. Institute of geology, Vilnius [In Russian].

Šliaupa A. 2004. The surface of pre-Quaternary rocks. *Kn.* V. Baltrūnas (red.), *Lietuvos Žemės gelmių raida ir ištekliai.* Vilnius, Petro ofsetas, 254–258. [In Lithuanian].

Šliaupa S., Čyžienė J., Lazauskienė J., 1994. The 1:200 000 sub-Quaternary relief map of Lithuania. *Lithuanian Geological Survey*. Vilnius. [In Lithuanian].

Šliaupa S., Hoth P., 2011. Geological Evolution and Resources of the Baltic Sea Area from the Precambrian to the quaternary. In: Harff J., Björck S., Hoth P. (eds.), The Baltic Sea Basin. *Central and Eastern European Development Studies (CEEDES) XIII*. Springer—Verlag, Berlin Heidelberg, 13—51.

Tavast E., Raukas A., 1982. Relief of bedrock in Estonia. Tallinn, Valgus, 194 pp. [In Russian with English summary].

Timofeev I., Bergman V., Efimov A., Namestnikov A., Gorban L., 1974. Quaternary deposits of the Baltic Seafloor within the limits of the sector Liepaja–Klaipėda. Problems of Quaternary Geology 7, Zinaatne, Riga, 33–37. [In Russian with English summary].

Veinberga A. F., Veinbergs I. G., Klavinš I. R., 1986. Geomorphology of the bottom in the southeastern part of the Baltic Sea and the features of retreat the Last ice sheet from this region. *Morphogenesis of the relief and palaeogeography of Latvia,* Riga, 130–144. [In Russian with English summary].

Vladov M.L., Starovoytov A.V. 2004. *Introduction to GPR method. Study guide*. Moscow State University, 153 pp. [In Russian].

Wingfield R. T. R., 1989. Glacial incisions indicating Middle and Upper Pleistocene ice limits of Britain. *Terra Nova 1,* 538–548.

Zdanavičiūtė O., Sakalauskas K. (eds.), 2001. Petroleum geology of Lithuania and Southeastern Baltic. Institute of Geology, Vilnius, 8–19.

Data sources:

Lithuanian Geological Survey database (2014 10 01): http://www.lgt.lt/zemelap/main.php?sesName=lgt1412160593

The technical parameters of *The Upgraded Quartzitic Land Gravimeter* (*GNU-KV*) (2014 10 01): http://www.enoutech.com/en/sh_product.asp?cid=46&id=83

EUROSEISMIC project (2014 10 01): http://www.eu-seased.net: Seismic and sonar/Euroseismic/metaformat

Leibniz Institute for Applied Geophysics (2015 02 04) http://www.liag-hannover.de/fileadmin/user_upload/dokumente/Grundwassersysteme/BURVAL/buch/065-076.pdf

APPENDIX 1

The catalog of used wells.

Land wells[1]

Well	East	North	Depth	Geology	Lithology	Top depth, m
573	319326.9	6218493.6	282.5	Q		0
				T1	clay	49
				P2	limestone	136
				C1	marlstone	163.5
				D3	dolomite	208
2868	318192.3	6212189.5	251	Q		0
				T1	clay	57
				P2	limestone	153
				C1	marlstone	178
				D3	dolomite	228
8592	317605.8	6211521.6	185	Q		0
				T1	clay	46
				P2	limestone	153
8594	318221.2	6212391.3	250.5	Q		0
				T1	clay	60
				P2	limestone	150
				C1	dolomite	178

[1] Lithuanian Geological Survey database (2014 10 01): http://www.lgt.lt/zemelap/main.php?sesName=lgt1412160593

				D3	dolomite	232
8634	318201.9	6212280.8	250	Q		0
				T1	clay	58
				P2	limestone	154
				C1	marlstone	176
				D3	dolomite	229
9870	317615.4	6207682.4	258	Q		0
				T1	clay	54
				P2	limestone	178
				C1	dolomite	189
				D3	dolomite	237
11248	317711.5	6210315.6	300	Q		0
				T1	clay, siltstone	46
				P2	limestone	153.5
				C1	marlstone	182
				D3	dolomite	229
11249	317884.6	6209277.7	90	Q		0
				T1	clay	78
19622	318115.4	6216547.6	70	Q		0
				T1	clay	51
19623	317970.3	6217088.3	240	Q		0
				P2	limestone	135
Table 3				C1	marlstone	162
				D3	dolomite	210
19631	318278.9	6212670	270	Q		0
				T1	clay	52
				P2	limestone	141

				C1	marlstone	178
				D3	dolomite, limestone	201
19657	318432.7	6212655.6	275	Q		0
				T1	clay	62
				P2	limestone	143
				C1	marlstone	180
				D3	dolomite, limestone	233
20084	317663.5	6215610.6	233	Q		0
				T1	clay	48
				P2	limestone	132
				C1	marlstone	158
				D3	dolomite	207
25027	319480.8	6216355.4	148	Q		0
				P2	limestone	136
25513	318884.6	6208177.3	254	Q		0
				T1	clay	97
				P2	limestone	171
				C1	dolomite	196
				D3	dolomite	237
25992	319413.5	6217508.6	240	Q		0
				T1	clay	53
				P2	limestone	132
				C1	marlstone	158
				D3	dolomite	213
25993	319403.9	6217326	238	Q		0
				T1	clay	53

				P2	limestone	132
				C1	marlstone	159
				D3	dolomite	213
36225	317567.3	6217282.7	116	Q		0

Deep offshore wells[2]

Well	East	North	Depth	Geology	Lithology	Top depth, m
D5	290425.8	6161089.6	2367	Water		0
Fig. 24; Fig. 16				Q		62
				J3	clay	90
				J2	marlstone	107
				T1	clay, siltstone, sandstone	154
				P2	limestone, dolomite	358
				D3	dolomite, sandstone	438
D6	284277.4	6140296.2	2396	Water		0
Fig. 17				Q		30
				K2	sandstone	48
				J3	clay	144
				J2	marlstone	203
				T1	clay, siltstone, sandstone	239

[2] Grigelis 1991

				P2	limestone, dolomite, anhydrite	519
				D3	dolomite, sandstone	643
E6	277686.4	6245927.2	1095	Water		0
Fig. 18				Q		36.5
				D3	dolomite, sandstone	38
				D2	clay, siltstone, sandstone	145
E7	232694.7	6216139.4	1651	Water		0
Fig. 19				Q		53
				D3	dolomite, sandstone	54
				D2	clay, siltstone, sandstone	214

Shallow offshore wells[3]

Well	East	North	Depth	Geology	Lithology	Top depth, m
591	314176.1	6218052	11	Q		0
54M	277791.2	6171882.5	47	Q		0
Fig. 30				bedrock		46
55M	256823.8	6194568.5	30	Q		0
56M	250952.8	6211893.5	30	Q		0
				bedrock		28

[3] Majore *et al*. 1997; Gelumbauskaitė 2009.

58M	251411.9	6181497.5	74	Q		0
Fig. 32						
59M	299475.7	6175613	25	Q		0
				bedrock		23
60M	305246.5	6183912.5	12	Q		0
				bedrock		11
61M	266471.3	6188127.5	23	Q		0
71M	283508.4	6195324.5	39	Q		0
				bedrock		38
D11-1P	299694.8	6213686	30	Q		0
Fig. 33				bedrock		29
D26-1P	292991.5	6179827.5	15	Q		0
				bedrock		14
D5-1/1P	295974.7	6154181.8	30	Q		0
				bedrock		28
E7-1/2P	240430.8	6218877	2	Q		0
				bedrock		1

APPENDIX 2.

The coordinates of CSP seismic lines.

Line	Start of line		End of line		Length, km
	Lat N	Long E	Lat N	Long E	
9302B	55˚ 15.9’	20˚ 21.0’	55˚ 23.3’	20˚ 42.2’	26.4
9404	56˚ 20.0’	20˚ 40.0’	55˚ 18.5’	20˚ 39.7’	114.2
9405	55˚ 18.7’	20˚ 49.9’	56˚ 21.7’	20˚ 50.1’	116.9
9410A	56˚ 22.9’	20˚ 45.0’	56˚ 00.9’	20˚ 45.1’	40.8
9410B	55˚ 57.3’	20˚ 45.0’	55˚ 24.9’	20˚ 45.0’	60.0
9513	56˚ 09.9’	20˚ 50.5’	55˚ 44.1’	19˚ 35.3’	91.8
9514	55˚ 41.5’	19˚ 43.0’	55˚ 60.0’	20˚ 35.0’	64.2
9515	55˚ 50.0’	20˚ 27.5’	55˚ 30.0’	20˚ 27.5’	37.0
9516	55˚ 30.0’	20˚ 25.0’	55˚ 50.0’	20˚ 25.0’	37.1
9517	55˚ 50.0’	20˚ 22.6’	55˚ 30.0’	20˚ 22.5’	37.2
9518	55˚ 30.1’	20˚ 17.5’	55˚ 50.0’	20˚ 17.5’	37.0
9520	55˚ 30.0’	20˚ 12.5’	55˚ 50.0’	20˚ 12.5’	37.0
9521	55˚ 46.6’	20˚ 07.5’	55˚ 30.0’	20˚ 07.5’	30.8
9522	55˚ 30.0’	20˚ 05.0’	55˚ 50.0’	20˚ 05.0’	37.1
9523	55˚ 50.0’	20˚ 02.5’	55˚ 30.0’	20˚ 02.5’	37.0
9524	55˚ 30.0’	19˚ 57.5’	55˚ 50.0’	19˚ 57.5’	37.1
9525	55˚ 50.0’	19˚ 55.0’	55˚ 37.0’	19˚ 55.0’	24.2
9526A	55˚ 35.0’	19˚ 59.9’	55˚ 35.0’	20˚ 32.5’	34.2
9526B	55˚ 45.0’	20˚ 32.5’	55˚ 45.0’	19˚ 45.0’	49.7
980829_3	56˚ 22.7’	20˚ 35.0’	55˚ 40.0’	20˚ 35.0’	79.3
980829_4	55˚ 40.0’	20˚ 35.0’	55˚ 26.9’	20˚ 34.5’	24.4
980830_1	55˚ 30.4’	20˚ 25.0’	56˚ 05.9’	20˚ 25.0’	65.8

980830_3A	56° 07.8’	20° 25.4’	56° 08.2’	20° 25.0’	0.9
980830_3B	56° 08.9’	20° 25.0’	56° 10.0’	20° 25.0’	2.0
980830_5A	56° 10.3’	20° 25.0’	56° 18.9’	20° 25.0’	15.9
980830_5B	56° 20.0’	20° 21.9’	56° 20.1’	20° 10.2’	12.1
980830_5C	56° 18.2’	20° 05.1’	55° 43.7’	20° 05.0’	64.0
980830_6A	55° 42.0’	20° 04.7’	55° 38.0’	20° 05.0’	7.3
980830_6B	55° 36.7’	20° 06.0’	55° 33.5’	20° 13.8’	10.2
980830_6C	55° 33.8’	20° 15.0’	56° 22.4’	20° 15.0’	90.2
980901_1	56° 21.9’	19° 55.0’	56° 04.7’	19° 54.9’	31.9
980901_2A	56° 04.4’	19° 54.7’	55° 40.5’	19° 55.0’	44.5
980901_2B	55° 40.3’	19° 54.0’	55° 41.7’	19° 49.1’	5.8
980901_3	55° 44.3’	19° 45.0’	56° 19.5’	19° 45.0’	65.3
980901_4A	56° 19.7’	19° 25.0’	55° 49.1’	19° 26.6’	56.8
980901_4B	55° 52.0’	19° 35.0’	56° 19.9’	19° 35.0’	51.8
980901_6	56° 18.7’	19° 15.1’	55° 56.0’	19° 15.0’	42.1
980903_1	55° 57.0’	19° 05.0’	55° 58.7’	19° 05.0’	3.2
980903_2	55° 58.9’	19° 05.0’	56° 17.5’	19° 05.0’	34.5
990818_2	56° 00.0’	18° 49.3’	55° 37.1’	20° 03.2’	88.2
990818_3A	55° 37.1’	20° 03.3’	55° 40.1’	20° 22.6’	21.1
990818_3B	55° 41.4’	20° 23.8’	55° 49.9’	19° 58.6’	30.7
990818_3C	55° 48.8’	19° 56.0’	55° 38.6’	20° 25.4’	36.1
990819_1A	55° 38.0’	20° 27.3’	55° 37.4’	20° 28.8’	1.8
990819_1B	55° 36.0’	20° 29.8’	55° 47.4’	19° 54.3’	42.7
990819_2	55° 46.6’	19° 51.8’	55° 38.9’	20° 15.0’	28.2
990820_1A	55° 37.5’	20° 19.2’	55° 35.7’	20° 24.5’	6.5
990820_1B	55° 34.3’	20° 24.0’	55° 45.8’	19° 49.1’	42.3
990820_1C	55° 44.9’	19° 47.5’	55° 39.8’	20° 03.1’	18.9
990821_1A	55° 39.4’	19° 59.3’	55° 43.9’	19° 44.9’	17.3

990821_1B	55˚ 43.4’	19˚ 44.6’	55˚ 32.1’	20˚ 47.0’	68.9
990821_1C	55˚ 34.1’	20˚ 46.8’	55˚ 37.7’	20˚ 36.9’	12.3
990821_2D	55˚ 37.7’	20˚ 36.9’	55˚ 38.0’	20˚ 36.1’	1.0
990821_3A	55˚ 38.6’	20˚ 36.0’	55˚ 48.2’	20˚ 36.0’	17.8
990821_3B	55˚ 49.3’	20˚ 36.6’	55˚ 55.5’	20˚ 53.6’	21.2
990821_3C	55˚ 56.2’	20˚ 54.1’	55˚ 59.6’	20˚ 12.5’	43.8
990821_3D	56˚ 00.3’	20˚ 09.4’	56˚ 00.1’	20˚ 04.9’	4.7
990821_4A	56˚ 00.0’	20˚ 05.0’	55˚ 50.8’	20˚ 23.5’	25.8
990821_4B	55˚ 50.0’	20˚ 23.4’	55˚ 50.0’	20˚ 17.5’	6.2
990821_4C	55˚ 50.5’	20˚ 14.1’	55˚ 58.7’	19˚ 59.4’	21.5
990822_1	56˚ 00.0’	19˚ 54.0’	56˚ 01.5’	19˚ 45.7’	9.0
990822_2	56˚ 09.7’	19˚ 01.0’	56˚ 10.0’	18˚ 51.9’	9.5
				Total:	**2233.1**

APPENDIX 3.

The coordinates and the shape of palaeo-incisions, also thickness of infilled seismic units.

No.	Enclosing seismostrati-graphic units	The center of palaeo-incision: Lat, N	Long, E	Shape	Thickness of infilled seismic unit, m: A	A2[1]	B	C	D	E	F	G	Infilling, m	
1	D3	56° 14.6’	19° 05.0’	V					10.8	15.3	25.2	42.3	93.6	**Western zone**
2	D3	56° 13.5’	19° 15.1’	V				17.1	14.4	21.6	25.2	29.7	108.0	
3	D3	56° 10.0’	18° 54.1’	V	14.4					7.2	18.0	16.2	55.8	
4	D3	56° 09.1’	19° 15.1’	V	18.9				9.9	16.2	27.0	45.9	117.9	
5	D3	56° 06.4’	19° 05.0’	V	17.1				10.8	47.7	22.5	31.5	129.6	
6	D3	56° 04.0’	19° 25.0’	W				15.3	9.0	9.0	30.6	45.0	108.9	
7	D3	56° 02.4’	19° 25.0’	U				21.6	7.2	10.8	21.6	35.1	96.3	
8	***D3 (Fig. 30A)***	***56° 01.2’***	***19° 05.0’***	***V***	***19.8***	***10.8***			***13.5***	***28.8***	***25.2***	***29.7***	***127.8***	
9	D3	55° 57.9’	19° 03.4’	V	25.2			12.6	18.0	27.0	29.7	30.6	143.1	
10	D3	55° 53.1’	19° 12.3’	W	9.9	27.0				32.4	39.6	22.5	131.4	
11	D3	55° 56.0’	19° 06.4’	V	29.7	9.9			20.7	5.4	7.2		72.9	

[1] – the same as Unit A, but deeper.

Eastern zone

12	P2	56˚ 17.7’	20˚ 50.1’	V	3.6				5.4	7.2	11.7		27.9
13	P2	56˚ 13.6’	20˚ 50.0’	U	6.3				5.4	9.0	12.6		33.3
14	***P2, T1 (Fig. 34)***	***56˚ 02.1’***	***20˚ 50.0’***	***W***	***6.3***					***9.0***	***18.9***		***34.2***
15	P2, T1	56˚ 16.7’	20˚ 45.1’	V					8.1	20.7			31.5
16	P2, T1	56˚ 10.6’	20˚ 45.0’	V	7.2				9.0	22.5	22.5		61.2
17	P2, T1	56˚ 09.7’	20˚ 45.0’	V	9.0				9.0	21.6	18.0		57.6
18	T1, J2	56˚ 05.5’	20˚ 45.0’	WW				10.8	9.0	16.2	18.0	18.0	72.0
19	T1, J2	56˚ 03.5’	20˚ 45.0’	W	12.6			7.2		16.2	16.2	21.6	73.8
20	P2, T1	56˚ 16.4’	20˚ 40.0’	W				13.5		18.9	23.4	9.0	64.8
21	P2, T1	56˚ 08.9’	20˚ 40.0’	W	7.2	7.2		14.4		10.8	11.7	20.7	72.0
22	P2, T1	56˚ 07.6’	20˚ 40.0’	W	7.2			11.7		27.9	12.6	15.3	74.7
23	P2, T1	56˚ 06.8’	20˚ 40.0’	W	5.4			10.8		26.1	11.7	7.2	61.2
24	P2, T1	56˚ 05.2’	20˚ 40.0’	U	9.9			6.3		18.0	13.5	17.1	64.8
25	P2, T1	56˚ 02.6’	20˚ 40.0’	W	7.2	10.8				23.4	6.3		47.7
26	P2, T1	56˚ 17.2’	20˚ 35.0’	W	8.1	11.7			17.1	18.9	7.2	26.1	89.1
27	***P2, T1 (Fig. 30E)***	***56˚ 09.1’***	***20˚ 35.0’***	***W***	***14.4***	***12.6***			***16.2***	***15.3***	***5.4***	***23.4***	***87.3***
28	T1, J2, J3	55˚ 45.7’	20˚ 50.0’	V					2.7	15.3	10.8		28.8
29	T1, J2, J3	55˚ 40.1’	20˚ 50.0’	WW					5.4	12.6	12.6		30.6

30	T1, J2, J3	55˚ 35.9’	20˚ 50.0’	WW					5.4	13.5	14.4		33.3
31	***P2, T1, J2, J3(Fig. 30F)***	***55˚ 31.1’***	***20˚ 50.0’***	***WW***					***7.2***	***12.6***	***21.6***	***27.9***	***69.3***
32	J2, J3	55˚ 23.5’	20˚ 50.0’	WW					5.4	14.4	23.4		43.2
33	***T1 (Fig. 30G)***	***55˚ 47.5’***	***20˚ 45.0’***	***WW***	***6.3***	***9.9***				***11.7***	***11.7***	***18.9***	***58.5***
34	T1, J2, J3	55˚ 37.7’	20˚ 45.0’	U						12.6	21.6	28.8	63.0
35	J2, J3	55˚ 36.7’	20˚ 45.0’	V						30.6			30.6
36	T1, J2, J3	55˚ 31.8’	20˚ 45.0’	V						23.4	25.2		48.6
37	T1, J2, J3	55˚ 26.6’	20˚ 45.0’	W						21.6	32.4		54.0
38	T1, J2, J3	55˚ 36.1’	20˚ 40.0’	W						16.2	40.5		56.7
39	T1, J2, J3	55˚ 31.4’	20˚ 40.1’	U						15.3	18.9		34.2
40	J2, J3	55˚ 30.9’	20˚ 35.1’	U						42.3			42.3
41	T1, J2, J3	55˚ 36.0’	20˚ 35.0’	U	12.6				12.6	16.2	30.6	17.1	89.1
42	T1	55˚ 58.3’	20˚ 41.8’	W	16.2				17.1	22.5	14.4		70.2
43	T1	55˚ 53.5’	20˚ 48.2’	V	12.6					15.3	25.2	11.7	64.8
44	J2, J3	55˚ 30.1’	20˚ 39.5’	V						20.7	22.5		43.2
45	T1, J2, J3	55˚ 35.0’	20˚ 44.3’	U						36.9			36.9
46	T1, J2, J3	55˚ 36.4’	20˚ 40.4’	V						33.3			33.3
47	T1, J2, J3	55˚ 37.0’	20˚ 38.8’	W						25.2			25.2

Central zone

48	P2	55° 52.0’	19° 45.0’	W			6.3			12.6	9.0	7.2	35.1
49	P2, T1	55° 47.9’	19° 45.0’	W						12.6	15.3		27.9
50	T1	55° 45.6’	19° 45.0’	V						6.3	10.8		17.1
51	D3	56° 05.7’	19° 55.0’	V	7.2		8.1		13.5	19.8	9.9	33.3	91.8
52	D3, P2	55° 56.6’	19° 55.0’	U			7.2		14.4	9.9	23.4		54.9
53	P2, T1	55° 50.5’	19° 55.0’	W				7.2	24.3	30.6	29.7		91.8
54	P2, T1	55° 48.7’	19° 55.0’	U				7.2	19.8	33.3	21.6		81.9
55	T1, J2	55° 51.2’	20° 15.0’	U				18.0	11.7	27.0	20.7		77.4
56	T1, J2	55° 49.5’	20° 15.0’	V				15.3	12.6	19.8	21.6		69.3
57	T1, J2	55° 47.5’	20° 15.0’	U				7.2		23.4	23.4	17.1	71.1
58	T1, J2	55° 45.8’	20° 15.0’	W				8.1		18.9	24.3	19.8	71.1
59	T1, J2, J3	55° 37.8’	20° 15.0’	U	9.9				15.3	20.7	31.5	18.0	95.4
60	T1, J2, J3	55° 36.5’	20° 15.0’	V					12.6	18.0	23.4	17.1	71.1
61	T1, J2, J3	55° 40.9’	20° 25.0’	V	6.3				11.7	11.7	20.7	17.1	67.5
62	T1, J2, J3	55° 37.9’	20° 25.0’	V	9.0				12.6	18.9	31.5	18.9	90.9
63	***T1, J2, J3 (Fig. 32)***	***55° 32.7’***	***20° 25.0’***	***V***				***11.7***	***14.4***	***13.5***	***18.0***		***57.6***
64	T1, J2, J3	55° 36.7’	20° 27.5’	U					10.8	16.2	34.2		61.2
65	P2, T1	55° 46.2’	19° 41.7’	V	9.9					9.9	23.4	15.3	58.5

66	P2, T1	55° 49.2’	19° 50.2’	WW	10.8				16.2	14.4	13.5	17.1	72.0
67	P2, T1	55° 52.1’	19° 58.8’	W	11.7					27.9	9.0	16.2	64.8
68	***P2, T1, J2 (Fig. 30D)***	***55° 54.1’***	***20° 04.6’***	***V***	***8.1***					***42.3***	***22.5***	***26.1***	***99.0***
69	P2, T1, J2, J3	55° 42.3’	19° 45.2’	V					13.5	9.9	12.6	18.9	54.9
70	T1, J2	55° 50.2’	20° 07.6’	W	6.3				9.0	13.5	15.3		44.1
71	T1, J2	55° 52.3’	20° 13.5’	U	6.3		10.8			24.3	17.1	12.6	71.1
72	P2, T1	55° 53.7’	20° 17.4’	U	7.2		9.0			22.5	24.3	10.8	73.8
73	T1	55° 51.9’	20° 21.1’	V						23.4	25.2	21.6	70.2
74	P2, T1	55° 53.7’	20° 17.6’	V	7.2		9.0			22.5	24.3	10.8	73.8
75	D3, P2, T1	55° 57.9’	20° 00.9’	V				9.9		14.4	10.8	14.4	49.5
76	T1, J2	55° 54.0’	20° 07.9’	W	19.8	15.3				27.9	21.6	18.0	102.6
77	T1, J2	55° 45.0’	20° 01.6’	U	10.8				9.0	17.1	21.6	33.3	91.8
78	P2, T1, J2	55° 45.0’	20° 06.6’	V	9.9				11.7	14.4	35.1	36.9	108.0
79	T1, J2	55° 45.0’	20° 09.1’	W	9.0				11.7	17.1	44.1	25.2	107.1
80	T1, J2, J3	55° 35.0’	20° 04.8’	V					6.3	8.1	18.9	16.2	49.5
81	J2, J3	55° 35.0’	20° 14.4’	W				17.1		6.3	18.9		42.3
82	J2, J3	55° 35.0’	20° 25.6’	U	11.7					15.3	19.8		46.8
83	J2, J3	55° 35.0’	20° 30.9’	W	9.9					17.1	23.4		50.4
84	T1, J2, J3	55° 41.3’	19° 57.5’	V	11.7				14.4	24.3	18.9	21.6	90.9

85	T1, J2, J3	55˚ 42.5’	19˚ 57.4’	U	12.6				17.1	26.1	18.0	20.7	94.5
86	***T1, J2, J3 (Fig. 33)***	***55˚ 42.4’***	***20˚ 02.5’***	***V***	***12.6***				***11.7***	***33.3***	***18.0***	***18.9***	***94.5***
87	T1, J2, J3	55˚ 37.4’	20˚ 07.5’	W					16.2	11.7	24.3	15.3	67.5
88	T1, J2, J3	55˚ 36.8’	20˚ 12.5’	U					9.9	18.0	19.8	24.3	72.0
89	T1, J2, J3	55˚ 38.2’	20˚ 12.8’	V					11.7	10.8	46.8	20.7	90.0
90	T1, J2, J3	55˚ 42.3’	20˚ 12.5’	U					14.4	17.1	36.0	22.5	90.0
91	T1, J2	55˚ 46.1’	20˚ 12.5’	V	11.7				11.7	10.8	10.8	21.6	66.6
92	T1	55˚ 49.4’	20˚ 12.5’	U	8.1				13.5	9.9	16.2		47.7
93	T1, J2, J3	55˚ 37.3’	20˚ 22.5’	U	19.8	11.7			6.3	16.2	14.4	24.3	92.7
94	P2, T1, J2	55˚ 46.2’	20˚ 09.6’	V	15.3	13.5			10.8	24.3	10.8	22.5	97.2
95	P2, T1, J2	55˚ 48.9’	20˚ 01.4’	W	15.3	12.6			9.0	27.0	11.7	21.6	97.2
96	***D3-J3 (Fig. 30B)***	***55˚ 43.6’***	***19˚ 42.6’***	***V***					***8.1***	***20.7***	***16.2***	***26.1***	***71.1***
97	D3-J3	55˚ 42.4’	19˚ 46.4’	U					14.4	23.4	18.0	22.5	78.3
98	D3-J3	55˚ 41.2’	19˚ 50.1’	U	17.1	10.8			20.7	20.7	37.8	22.5	129.6
99	T1, J2, J3	55˚ 40.6’	19˚ 52.1’	V	23.4	11.7			18.9	9.0	12.6	27.9	103.5
100	T1, J2, J3	55˚ 38.3’	19˚ 59.4’	V	9.0	14.4			26.1	11.7	9.9	27.0	98.1
101	***D3 (Fig. 30H)***	***56˚ 02.4’***	***20˚ 04.9’***	***V***	***10.8***		***6.3***	***11.7***		***14.4***	***14.4***	***7.2***	***64.8***
102	***T1, J2 (Fig. 30C)***	***55˚ 43.9’***	***20˚ 04.9’***	***U***	***9.9***	***9***		***19.8***		***17.1***	***34.2***	***12.6***	***102.6***