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https://orcid.org/0000-0002-2169-4991

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Milda Grendaitė

The structure of sedimentary cover of Western Lithuania based on seismic data

DOCTORAL DISSERTATION

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Academic supervisors:

Prof. Dr. Sigitas Radzevičius (Vilnius University, Natural Sciences, Geology – N 005). (1 October 2020 – 30 September 2022).

Prof. Dr. Ulrich Achauer (University of Strasbourg (France), Natural Sciences, Geology – N 005). (1 October 2016 – 30 September 2020).

Academic consultant – Prof. Dr. Elena Kozlovskaya (University of Oulu (Finland), Natural Sciences, Geology – N 005).

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VILNIAUS UNIVERSITETAS
GAMTOS TYRIMŲ CENTRAS

Milda Grendaitė

Vakarų Lietuvos nuosėdinės dangos sandaros ypatumai pagal seisminius duomenis

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Moksliniai vadovai:
prof. dr. Sigitas Radzevičius (Vilniaus universitetas, gamtos mokslai, geologija – N 005). (2020-10-01 – 2022-09-30).
prof. dr. Ulrich Achauer (Strasbūro universitetas, Prancūzija, gamtos mokslai, geologija – N 005). (2016-10-01 – 2020-09-30).
Mokslinė konsultantė – prof. dr. Elena Kozlovskaya (Oulu universitetas, Suomija, gamtos mokslai, geologija – N 005).

ABBREVIATIONS

2D – two-dimensional

3D – three-dimensional

CMP – common mid-point

D1gr – Gargždai Formation, Lochkovian, Lower Devonian

D3st – Stipinai Formation, Frasnian, Upper Devonian

E & P – exploration and production (license)

FFID – record identification number

JV – joint venture

LGT, LGS – Lietuvos Geologijos Tarnyba, Lithuanian Geological Survey

O3 – S1st – Ordovician – Silurian boundary

OPAB – Oljeprospektering aktiebolaget (now Svenska Petroleum), Swedish Oil Exploration Company

P – Permian

Pr – Precambrian crystalline basement

RMS – Root Mean Square

S2 – Upper Silurian

S2db – Dubysa Formation, Ludfordian, Upper Silurian

SEG – Society of Exploration Geophysicists

SEG-D, SEG-Y – file formats for storing geophysical data, open standard developed and maintained by the SEG Technical Standards Committee

SPS – Shell Processing Support format for land 3D surveys, created by Shell Internationale Petroleum, adopted by SEG as the standard format for exchanging geophysical positioning data

TWT – two-way time, two-way travel time

CONTENTS

INTRODUCTION

The Baltic Basin is a sedimentary basin which covers the southwestern part of the East European Craton. It is located in the southern part of the Baltic Sea and in the surrounding countries of Estonia, Latvia, Lithuania, Northern Poland, and a small part of Sweden. Though the basin contains all the geological systems from the Ediacaran to the present, its main sedimentary fill is Palaeozoic. During its long history of development, the Baltic Basin has undergone several stages of development, and its sedimentary fill is divided into the respective stratigraphic intervals. Most of the sediments were deposited during the Cambrian to Silurian – Early Devonian (the Caledonian stratigraphic interval). The present-day structure of this interval largely defines the structure of the Basin as well. The Devonian to Carboniferous deposits (the Hercynian stratigraphic interval) are denoted by the largest thickness in the western parts of Lithuania and Latvia. The Permian to Mesozoic (and Cenozoic) deposits (the Alpine stratigraphic interval) are restricted to the southwestern part of the Baltic Basin. Western Lithuania belongs to the Gdańsk – Kura Depression, which is the deepest part of the basin, where the thickness of the sedimentary strata reaches more than 4 km. The Baltic Basin has proven hydrocarbon resources in this depression.

The geological structure of the Baltic Basin and beneath it was investigated by seismological and seismic methods, including deep seismic sounding experiments, shallow seismic profiling and the exploratory seismic reflection method. Detailed investigations first started in the north-western part of Poland in the 1950's. In Western Lithuania, such investigations have been conducted since the 1960's. Seismic exploration methods, including the single channel seismic reflection method and the 2D common mid-point reflection method, were used. The south-eastern part of the Baltic Sea from Latvia to Germany was also covered with a dense network of exploratory seismic profiles between 1975 and 1990. The western side of the Baltic Sea, specifically, the Swedish offshore, was surveyed as well. A significant amount of three-dimensional (3D) seismic and two-dimensional (2D) seismic data was acquired in Lithuania during the period between 1995 and 2015, which can be characterized as the most active for the hydrocarbon exploration and production industry in Lithuania.

During the recent decades, the seismic data have been continuously acquired in the Baltic Basin. Yet, most of the results still remain unpublished. Results from only a few 3D seismic surveys have been documented, for example, the Silurian reefs in Central Lithuania and the

Lower Palaeozoic of the Opalino Anticline in Pomerania, North-western Poland. Western Lithuania is not an exception, the most recent semi-public structural maps are based on the pre-1995 2D seismic and borehole data. Such maps are sufficient to display the existence of the general trends and large structures. By using all the available recent (1995–2015) seismic data, especially the 3D seismic data, a detailed seismo-geological model of the study area can be built, and the structural understanding of the sedimentary cover of Western Lithuania can be improved. This study presents detailed structural maps for the key seismic reflection horizons, an updated fault trace map, and a few arbitrary composite seismic sections that help illustrate key features of the study area, such as the palaeo-topographic features of the sub-Cambrian peneplain, the Caledonian faults of the Baltic Basin, Permian reefs of the Zechstein Basin. This study is seismic data based; it has a summarizing nature with eleven 3D seismic data sets and nearly 300 2D seismic profiles incorporated into one seismic interpretation. This study is of academic interest as it presents the 3D seismic from the Baltic Basin, which has not been extensively published. This study is unique in the Baltic Basin as it is not single survey based; instead, it describes a rather large area (nearly 60km by 60 km) by using eleven 3D seismic surveys. This study is useful due to the fact that the selected study area includes Gargždai Elevation – a geological structure which contains some of the Lithuanian oil fields in Gargždai and Klaipėda License Areas.

Aim

The aim of this study is to improve the structural understanding of the sedimentary cover near the vicinity of the Gargždai Elevation, which is in Gargždai and Klaipėda License Areas, Western Lithuania, by using the recently acquired and yet unpublished 3D and 2D seismic data.

Tasks

To achieve this aim, the following tasks were formulated.

Seismic data processing: 1) preparation of seven 3D seismic data sets and the respective SPS files for Gargždai License Area; 2) processing of seven merged 3D seismic data sets for Gargždai License Area; 3) additional processing of other seismic data sets for Gargždai, Klaipėda, and, in part, Rietavas License Areas.

Seismic data interpretation: 1) identification of the seismic reflection horizons by the seismic to well tie; 2) horizon interpretation in the seismic sections and the creation of structural maps for the key seismic horizons for the study area; 3) fault interpretation in the seismic sections; 4) seismic attribute calculation; 5) digitization of the historical map representing the main seismic reflection horizon and direct comparison of the horizon surfaces and fault patterns.

Analysis of the selected geological features of the study area within the regional context of the Baltic Basin. Specifically, the investigation is focused on 1) relating the palaeo-topographic shape of the Precambrian crystalline basement to the inselbergs of the sub-Cambrian peneplain, 2) demonstrating the seismic expression and the geological environment of the Permian reefs, and 3) providing a detailed and updated description of the local structures and faults in the study area.

Scientific novelty

For the first time, the recently (1995–2015) acquired 3D and 2D seismic data are included into one seismic interpretation which covers Gargždai, Klaipėda, and, in part, Rietavas License Areas in Western Lithuania. Detailed structural maps for the key seismic horizons are presented within the study area. The network of faults has been considerably updated.

The novelties presented in this study are:

Gargždai Fault is shown to be discontinuous, and it does not terminate at Telšiai Fault.

The Precambrian crystalline basement surface is analyzed in relation to the sub-Cambrian peneplain; an inselberg array is mapped in the southeastern part of the study area.

A structure of the cross-fault type, Agluonėnai, is distinguished in Gargždai Elevation.

The seismic expression of Permian reefs is presented on a carbonate platform near the edge of Zechstein evaporite basin.

Author's contribution

The author personally performed the tasks under supervision by prof. Dr. Sigitas Radzevičius (Vilnius University) and consultation with Dr. Dainius Michelevičius (UAB Geobaltic):

Conceived the topic of the published article *A large array of inselbergs on a continuation of the sub-Cambrian peneplain in the Baltic Basin: evidence from seismic data, Western Lithuania* (with the initial objection from Dr. D. Michelevičius);

Prepared the figures and wrote the texts for all the published articles as well as conference presentations (consultation with prof. Dr. S. Radzevičius and Dr. D. Michelevičius);

Analyzed the selected geological features of the study area within the regional context of the Baltic Basin (consultation with prof. Dr. S. Radzevičius and Dr. D. Michelevičius);

Did all the steps of seismic interpretation: seismic to well tie, horizon and fault interpretation in seismic sections, structural maps for the key seismic horizons, attribute maps, and other derivatives, such as thickness maps, digitized the historical structural map (consultation with Dr. D. Michelevičius);

Did the additional seismic processing for other seismic data for Gargždai, Klaipėda, and, in part, Rietavas License Areas;

Did the seismic processing for the seven merged 3D seismic data from Gargždai License Area (except the near surface static correction by Dr. D. Michelevičius);

Prepared the seven 3D seismic data sets and the respective SPS files for the merge.

Statements presented for the defense

1) In Western Lithuania, there is a large array of inselbergs on a continuation of the sub-Cambrian peneplain.

2) There are Permian reefs on a carbonate platform near the edge of Zechstein evaporites.

3) Gargždai Fault forms a system of faults that do not directly link to Telšiai Fault.

List of publications included into the thesis

Grendaitė, M., Michelevičius, D., Radzevičius, S. 2022. A large array of inselbergs on a continuation of the sub-Cambrian peneplain in the Baltic Basin: evidence from seismic data, Western Lithuania. Geological Quarterly, 66: 2. doi: 10.7306/gq.1633.

Grendaitė, M., Michelevičius, D., Radzevičius, S. 2023. Insights into the structural geology and sedimentary succession of the Baltic Basin, Western Lithuania. Marine and Petroleum Geology, 147: 106009. doi: https://doi.org/10.1016/j.marpetgeo.2022.106009.

List of conference presentations

Grendaitė, M., Michelevičius, D., Radzevičius, S. 2022. Insights into structure of sedimentary succession of Western Lithuania based on interpretation of new seismic data. Open Readings 2022, Vilnius, Lithuania, 15–18 March 2022 [poster presentation].

Radzevičius, S., Grendaitė, M., Michelevičius, D. 2022. Large array of inselbergs and continuation of sub-Cambrian peneplain in the Baltic Basin based on interpretation of seismic data, Western Lithuania. EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-7080, https://doi.org/10.5194/egusphere-egu22-7080, 2022 [poster presentation].

Grendaitė, M., Michelevičius, D., Radzevičius, S. 2020. Sub-kambrinės peneplenos rytinė riba, nustatyta interpretuojant seisminius duomenis (The eastern edge of the sub-Cambrian peneplain based on the interpretation of seismic data). Šeštoji Lietuvos Geologijos krypties doktorantų konferencija, Vilnius, Lithuania, 14 December 2020 [oral presentation].

1. LITERATURE OVERVIEW

1.1. Previous seismic investigations in the Baltic Basin

Seismological and seismic methods, such as deep seismic sounding experiments (EUROBRIDGE Seismic Working Group, 1999), shallow seismic profiling (Flodén, 1980; Tuuling and Flodén, 2009a) and exploratory seismic reflection method (Sopher and Juhlin, 2013) have been used to evaluate the resources and investigate the geological structure of the Baltic Basin. Detailed investigations of the Baltic Basin's sedimentary cover started in the 1950's in north-western Poland (Karnkowski et al., 2010). Such investigations have been conducted since the 1960's in Western Lithuania as well by use of geophysical methods, including the single channel seismic reflection method and the 2D common mid-point reflection method (Ūsaitytė, 2000). From Latvia to Germany, the south-eastern part of the Baltic Sea was surveyed with a dense network of exploratory seismic profiles between 1975 and 1990 (Domźalski et al., 2004; Karnkowski et al., 2010; Ūsaitytė, 2000). The Swedish offshore, the western side of the Baltic Sea, was also similarly explored (Sopher et al., 2016). In Lithuania, the most active time for the hydrocarbon exploration and production industry was between 1995 and 2015, when hundreds of square kilometers of the three-dimensional (3D) seismic and thousands of kilometers of the two-dimensional (2D) seismic data were acquired.

1.1.1. Deep seismic sounding experiments

Deep seismic sounding experiments investigated the structure of the crust and the uppermost mantle down to the depth of 80–90 km in the south-western part of the East European Craton, including the Baltic Basin and the Teisseyre – Tornquist Zone (Grad et al., 2006). BABEL (BABEL Working Group, 1993), a near-vertical deep reflection experiment, was acquired in 1989 in the Baltic Sea along the Swedish coast to investigate the crustal structure. POLONAISE'97 (Guterch et al., 1999), a seismic refraction – wide angle reflection experiment consisted of five profiles and aimed to investigate the upper lithospheric structure across the Teisseyre – Tornquist Zone as well as the structure of the Polish Trough. EUROBRIDGE'94-97 (EUROBRIDGE Seismic Working Group, 1999), a wide angle reflection and refraction profile, was exceptional among this type of experiments in the sense that it did not cross the Teisseyre – Tornquist Zone, but, instead, was acquired across the Baltic Sea, Lithuania and Belarus, as a transect through the Baltic Basin between the Baltic and Ukrainian Shields. Experiments of this type do not aim to investigate the sedimentary cover, but this cover has to be accounted for.

1.1.2. High resolution seismic profiling

The shallow high resolution seismic reflection method is suitable to investigate the shallow part of the subsurface (up to 400 m) due to the use of a high frequency source. High resolution is achieved at the expense of the depth of the investigation. The depth of interpretation is usually even more restricted above the first water bottom multiple (the first 50–300 ms) which depends on the sea bottom depth. Only very limited processing can be applied to such data, especially for the single channel data (Flodén, 1980; Sopher and Juhlin, 2013).

Seismic experiments conducted in the Swedish offshore (the south-western part of the Baltic Basin) were summarized by Sopher and Juhlin (2013), and the exploration and production onshore and on the island of Gotland were summarized by Sivhed et al. (2004).

Continuous high resolution seismic reflection profiling (single channel) was performed during the 1960s–1970s along the Swedish coast from (and around) the islands of Bornholm to Gotland (Flodén, 1980; Wannäs and Flodén, 1994), and during the 1990s–2000s between the islands of Gotland and Saaremaa, a review is given by Tuuling and Flodén (2009a). The acquired seismic data were used for seabed outcrop mapping (Flodén, 1980; Tuuling and Flodén, 2011), seabed relief and bedrock structure mapping which shows that special bedrock forms – clints and cuesta – have formed through the Cenozoic tectonic uplift, the Pleistocene glacial erosion, and the subsequent riverine erosion (Tuuling and Flodén, 2001; 2016; Tuuling, 2017). The seismic data was also used for detailed seismic stratigraphy of the lower part of the Palaeozoic in the northeastern part of the Baltic Basin (Cambrian – Silurian) (Tuuling et al., 1997; Tuuling and Flodén, 2000; 2001; 2009a; 2009b; 2011), and seismic correlation across the Baltic Basin including such important stratigraphic boundaries as the Ordovician – Silurian boundary (Tuuling and Flodén, 2009a, 2011). Ancient erosional surfaces were interpreted (Tuuling and Flodén, 2000), and stratigraphic features, such as the Ordovician carbonate build-ups and Silurian reefs, were mapped (Flodén et al., 2001; Tuuling and Flodén, 2000; 2013).

A summary of the previous geophysical investigations of the Baltic Basin (mainly, the south-eastern part of the Baltic Sea) can be found in a review by Ūsaitytė (2000).

The high-resolution reflection seismic data were also used for the seismic stratigraphy, precise bedrock relief and outcrop mapping of the Upper Silurian – Devonian boundary (Bjerkéus, 2001), Late Silurian (Pridoli) reefs (Bjerkéus and Eriksson, 2001), and the mapping of the Devonian to Cretaceous bedrock surface of the Lithuanian offshore (Gerok, 2015). Though Quaternary deposits are generally thin within the Baltic Sea and become thicker only in the southern part of the Baltic Sea (Gelumbauskaitė, 2009; Mojski et al., 1995; Winterhalter, 1992), the continuous seismo-acoustic profiling was used for not only the bedrock seismic stratigraphy, but also the subdivision of the Quaternary and the Holocene between Gotland, Latvia, and Lithuania and the southern part of the Baltic Sea (Bjerkéus et al., 1994; Gelumbauskaite, 2010; Flodén et al., 1997; Monkevičius and Šliaupa, 2007). Glacial incisions are typical for the southern part of the Baltic Basin (Bjerkéus et al., 1994; Flodén et al., 1997; Gerok et al., 2014; Mojski et al., 1995). They formed near the edge of the continental ice sheet; they are incised into the sedimentary bedrock (usually, softer lithologies) and filled with glacial deposits of various age and genesis. In the more northern parts of the Baltic Basin, the whole surface underwent glacial erosion, forming glacial striations (Tsyrulnikov et al., 2008) and drumlins (Schäfer et al., 2021).

Continuous seismic reflection profiling and multi-channel seismic exploration were used to investigate the geological structure and stratigraphy of the basins around the island of Bornholm, such as Hanö Bay Basin (Vejbæk, 1985; Vejbæk et al., 1994; Wannäs and Flodén, 1994). However, this area belongs to the Teisseyre – Tornquist Zone: it contains significant faulting and features a complicated configuration of sedimentary strata, and many phases of its development can be traced there.

Shallow high resolution seismic experiments are suitable to explore the shallow part of the sedimentary strata, but they do not provide the capacity to investigate a thick sedimentary cover. Experiments of this type are well documented in the Swedish and Estonian offshore, between the islands of Gotland, Saaremaa, and Hiiumaa. Even though there the Lower Palaeozoic strata have been investigated by this method, these areas belong to the slopes of the Baltic Basin, where the lithological composition and facies are different from those prevalent in the deeper parts of the Baltic Basin, including Western Lithuania. Seismic reflection exploration is used to investigate the overall structure of the sedimentary cover of the Baltic Basin and to characterize the hydrocarbon potential of the sedimentary strata.

1.1.3. Seismic reflection exploration

Lithuania onshore

The history of exploration in Western Lithuania can be divided into two parts. The first stage was exploratory, and it lasted until 1991. It was financed and conducted by state owned companies, and the exploration results were documented by internal reports. In 1990, oil production from the middle Cambrian Deimena sandstones began. Respectively, the second stage of exploration in Western Lithuania was aimed to enhance hydrocarbon production. However, the private oil companies which had been granted exploration and production licenses had little interest in making their exploration activities and results public. Therefore, publications are scarce, and often found in non-scientific, popular science journals.

Onshore Lithuania, geophysical exploration started in the 1950s (gravimetric and electric surveys, deep drilling, seismic refraction surveys). Seismic reflection exploration started in the 1960s, and it was aimed at structural mapping. The 2D single fold seismic reflection method was used until the 1970s, and the total length of profiles acquired by this method is 13,000 km. The 2D common mid-point method was introduced in 1975, and it was used until 1990. The total length of profiles acquired by this method in Western Lithuania (oil prospective) is 11,000 km.

Most of the oil containing structures were discovered during this exploratory stage by the use of the 2D seismic reflection method and drilling. Structural mapping, based on the 2D seismic, revealed elevations to be tested by drilling. In Lithuania, drilling was successful, and oil discoveries were made. The first oil discovery was made in 1961 in Kybartai in the Ordovician carbonates; in 1966, Šiūpariai in the Cambrian sandstone (the first discovery in Gargždai Elevation); in 1983 in Kudirka in the Silurian carbonate build-ups (reefs); in 1985 in Genčiai in the Cambrian sandstone (the first discovery near Telšiai Fault). In 1993, 19 accumulations were known in Lithuania. The majority of oil fields are located adjacent to Gargždai Fault and to Telšiai Fault.

The first indication of Gargždai Elevation was observed in the seismic refraction surveys – specifically, the depth of crystalline basement was by 60 m shallower than predicted. The results of the 2D single channel seismic reflection method were good enough to interpret the seismic reference horizon O3 – S1st. It indicated that the basement elevation is expressed in the Lower Palaeozoic sedimentary strata as well. Local elevations of 20–45 m were observed within Gargždai Elevation and tested by drilling. This led to a result – the discovery of the first (in Šiūpariai, in 1966), and, soon, other oil fields (Vilkyčiai 1969, Degliai 1972, Pociai 1976, Sakučiai 1977) within the main elevation. Some negative results were also obtained: Traubai structure yielded the negative result when drilling, Lašai structure was smaller than expected and contained only traces of oil, and Veiviržėnai structure was found not to contain the middle Cambrian sandstone, as the Ordovician directly covers the Precambrian crystalline basement.

In the second stage of exploration, seismic surveying was conducted by private companies within their license areas. During the period of 1995–2015, a large amount of seismic data was acquired in Western Lithuania, including Gargždai, Klaipėda, and Rietavas License Areas (Fig. 1). The 2D common mid-point method was continued to be used; a total of ca. 3,000 km 2D profiles were acquired in Lithuania. The three dimensional (3D) seismic reflection method was introduced in 2000. In total, ca. 1,000 km^2 were acquired in Lithuania.

Most of Gargždai Elevation was surveyed by the 3D seismic method within a short timeframe of several years (2000–2003). Six 3D surveys (ca. 280 km^2) were acquired in 2000–2001: Vilkyčiai, Degliai, Pociai, Lašai, Šiūraičiai, Šiūpariai (Šeštokas, 2001); Kintai in 2002, and Agluonėnai in 2003. Together with the advanced drilling technology, excellent production results were achieved in 2001 (Kirvelis, 2001), which retrospectively stand as the historic peak of hydrocarbon production in Lithuania (LGT pranešimai spaudai, 2021). Since, at this stage, the seismic exploration was aimed to enhance the oil production, mainly, the already discovered structures were surveyed. Since then, only several small oil fields have been discovered in the Cambrian sandstones (Žvirblis et al., 2006).

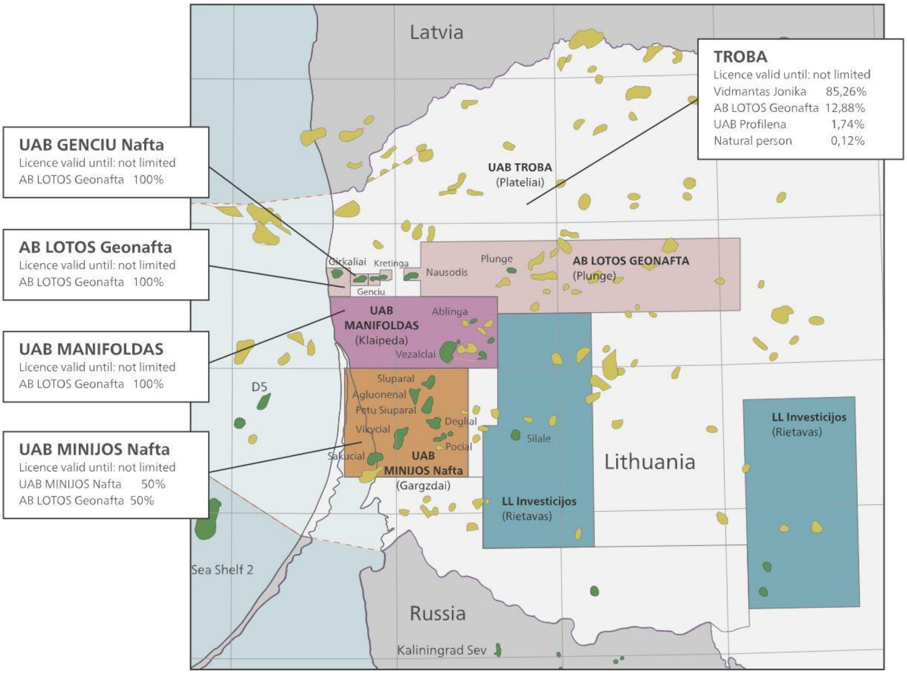


Fig. 1. Exploration and production license areas in Western Lithuania. Oil fields are shown by the green color, other structures are shown in yellow (LOTOS Integrated Annual Report, 2014).

A 3D survey was acquired over Vėžaičiai, which is located in the northern part of Gargždai Elevation and belongs to Klaipėda License Area. To the west, the remaining part of this license area largely covers Kretinga Depression. By virtue of being a depression and having nearly no structures discovered during the first stage of exploration, this part was explored by the 2D common mid-point method. To the east from Vėžaičiai, the acquired 2D seismic profile network is probably the densest in an attempt to reveal a highly complicated structure of that area, but no 3D seismic was acquired. Two 3D surveys, those of Šilalė and Barsukynė, were acquired over Šilalė Elevation. A local structure, Veiviržėnai, also has partial 3D coverage.

Latvia onshore

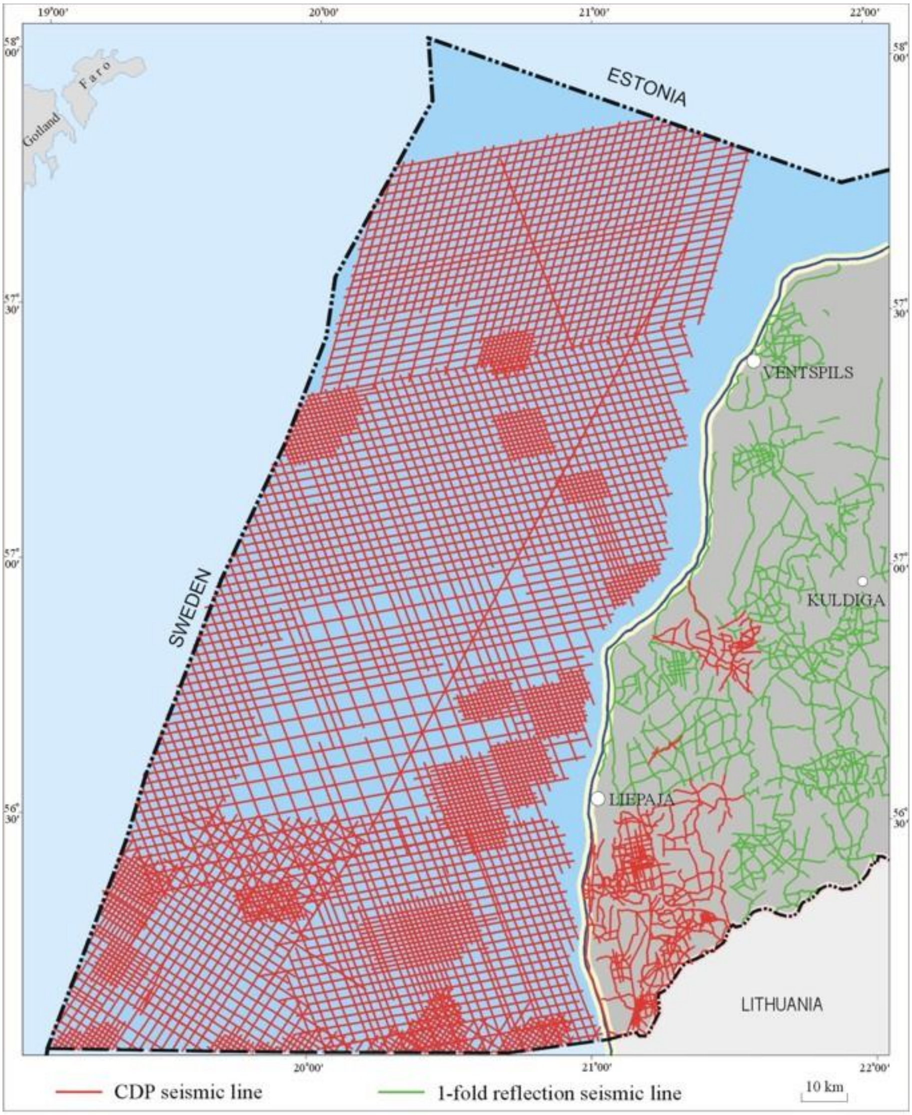
The beginning of seismic exploration in the 1960s in Latvia is similar to that in Lithuania. A comparable total length of the 2D single channel seismic reflection profiles was acquired – ca. 12,000 km. However, only one small accumulation – that of Kuldiga – was discovered in the Cambrian sandstones in 1963 (Kanev et al., 2001), and only traces of oil in the Ordovician limestone. Consequently, after these insignificant discoveries, exploration in Latvia was essentially abandoned in 1971. After the discoveries in Lithuania, some attempts were made again in Latvia – prior to 1993, ca. 1,700 km had been acquired by using the 2D common mid-point method (Fig. 2) (Latvian Environment, Geology and Meteorology Centre, 2010).

Generally, the amount of seismic data ever acquired onshore in Lithuania and Latvia decreases in the direction of the east and northeast. The seismic coverage is irregular, and it exists over the western and, to a lesser extent, central parts of the countries.

Lithuania and Latvia offshore

Offshore Latvia, Lithuania, as well as Kaliningrad Region, the seismic reflection investigation started in the early 1960s. In 1975, the results were summarized in a report (Laskov, 1975). In 1976, Petrobaltic Joint Venture (Petrobaltic Oil and Gas Exploration – Production Company – a group of companies, or a joint company involving the Soviet Union, German Democratic Republic, and Poland; after 1990, Petrobaltic JV became Polish only (Karnkowski et al., 2010), and currently is a part of LOTOS Group) started a comprehensive seismic exploration and deep drilling program in the Southeastern Baltic Sea, including parts of Latvia, Lithuania, Kaliningrad Region, Poland, and Germany (Karnkowski et al., 2010).

The Petrobaltic JV seismic acquisition was carried out in phases from 1976 to 1991. A sparse network of seismic profiles was established, and then subsequently infilled to form a dense and rather uniform network (the separation between profiles was maintained at 4 km by 8 km for regional, and 2 km by 4 km for exploration surveys) (Domźalski et al., 2004). Finally, leads were identified and surveyed with an even denser profile network (less than 1 km) to prepare them for drilling. In the Lithuanian offshore, the total length of 15,000 km was acquired by the common mid-point method. In the Latvian offshore, the total length of 24,000 km (Fig. 2) was acquired by Petrobaltic JV and Minnefteprom (Ministry of the Oil Industry of the USSR) (Latvian Environment, Geology and Meteorology Centre, 2010).



Seismic coverage in the oil prospective area

Fig. 2. Legacy seismic coverage of Latvia (Latvian Environment, Geology and Meteorology Centre, 2010).

A few wells were drilled offshore. In 1982, the first well E7-1 in the Lithuanian offshore (its northern part) reached the Cambrian sandstone and found it to be water-filled. In 1984, E6-1 (one of the largest structures) in the Latvian offshore also reached the Cambrian sandstone water filled with only traces of oil. In 1985, D5-1 in the Lithuanian offshore found oil in the Cambrian sandstones (Zdanaviciute and Lazauskiene, 2004).

In the Latvian offshore, E & P licenses were granted to international companies (Fig. 3). Seismic surveys were acquired over the Latvian part of the structure E24 in 1995 (Dalders – the largest structure in the Baltic Basin), along with the structures E5 and E6 in 2006. A 3D seismic survey was acquired over the structure E23 in 2010, and a well was drilled, yet it did not find hydrocarbons in 2013 (Baltic News Network, 2013; Kanev et al., 2001; Latvian Environment, Geology and Meteorology Centre, 2010).

Regarding the naming of the offshore structures and hydrocarbon fields, letters and numbers are used. The letter indicates the tectonic block (sector) within the Baltic Basin, of which these areas are relevant: A – Slupsk, B – Łeba, C – Gdańsk, D – Curonian, E – Liepāja block.

The Lithuanian offshore has not been licensed and remains less surveyed.

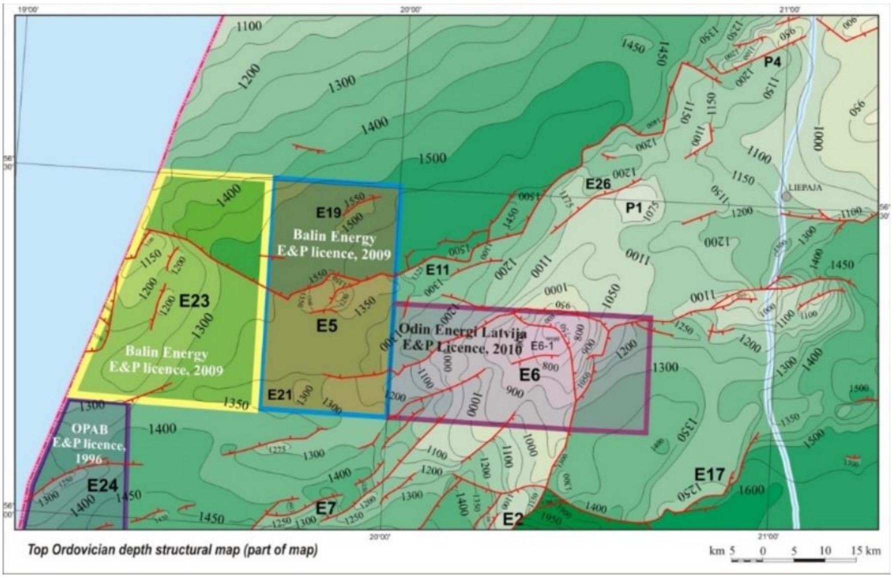


Fig. 3. Exploration and production license areas in the Latvian offshore (Latvian Environment, Geology and Meteorology Centre, 2010).

Kaliningrad Region

Kaliningrad Region offshore was surveyed as a part of the Petrobaltic JV exploration program. In 1983, D6-1 (Kravtsovskoye) in Kaliningrad Region's offshore proved the presence of an oil field in the Cambrian sandstone. After 1990, E & P licenses were acquired by private companies. The development of D-6 began in 1997, and production subsequently started in 2004 (Lukoil fact book, 2013). After the exploration and prospecting in 2015, more oil fields were discovered in the offshore – D29 (Lukoil annual report, 2014), D6 South, D33, D41 (Lukoil fact book, 2015; Verslo žinios, 2018). D2, D9, D18 and D19 failed to find hydrocarbons; D29 was not viable (Verslo žinios, 2018).

Kaliningrad Region onshore also contains oil fields, mostly along Kaliningrad Fault (Zdanaviciute et al., 2012), which have been exploited since 1975.

Poland

In the Polish part of the Baltic Basin, the petroleum exploration onshore started in the 1950s. Several small fields were discovered in the Cambrian sandstones in Northeastern Poland, the Baltic Basin. After Petrobaltic JV was founded in 1975 between the Soviet Union, German Democratic Republic, and Poland, consistent seismic coverage was also acquired in the Polish offshore. As a result, a few more hydrocarbon fields were discovered, again in the Cambrian sandstones (Karnkowski et al., 2010). Legacy seismic survey coverage of Poland’s onshore can be found in Poprawa (2020).

In the Polish offshore, some 33,000 km of the 2D common mid-point seismic reflection profiles were acquired by Petrobaltic JV. Not only oil fields, but also gas – condensate fields were discovered (that is, the fields were drilled, and the presence of hydrocarbons was proven) in the middle Cambrian sandstones. For example, the fields that currently are in production or late preparation for production were discovered in the early 1980s or 1990s (Domźalski et al., 2004). Currently, oil field B3 has been in production since 1992, whereas B8 has been exploited since 2015 (LOTOS press release, 2015). Gas fields B4 and B6 are still in development (LOTOS Integrated annual report, 2014). Seismic data was also continued to be acquired: 3D seismic data was acquired over B16 and B21 in 2013 (Fig. 4) (LOTOS press release, 2013).

For the sake of a full picture, in Northeastern Poland (Western Pomerania, which is beyond the Teisseyre – Tornquist Zone), Carboniferous sandstones, Rotliegend sandstones, and Zechstein Main Dolomite contain hydrocarbons, but these stratigraphic levels are outside the Lower Palaeozoic Baltic Basin (Karnkowski et al., 2010).

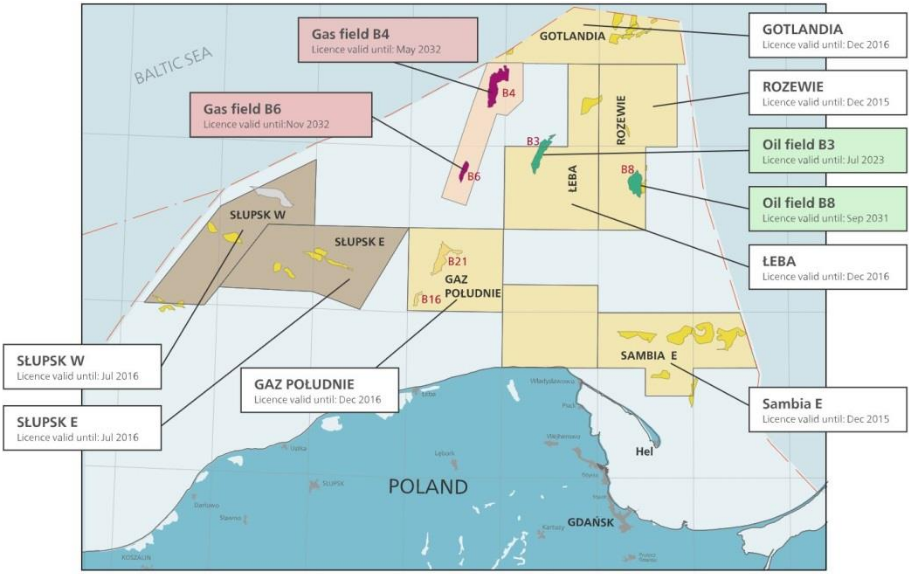


Fig. 4. Exploration and production license areas in Poland's offshore. Oil fields are shown in green, gas fields in red, other structures in yellow (LOTOS Integrated Annual Report, 2014).

Germany

Petrobaltic JV conducted explorations near the island of Rügen (Germany) in the southern part of the Baltic Sea; however, this area belongs to the Teisseyre – Tornquist Zone and is not a part of the Baltic Basin (Erlström et al., 1997).

Sweden

In the Swedish offshore, 2D seismic reflection exploration was carried out in the 1970s and 1980s, and it resulted in the OPAB data set. The acquired seismic data set contains profiles that have a total length of 33,000 km and constitute a rather dense seismic coverage where the separation between profiles is 2–8 km (Erlström et al., 1997). Also, more than a dozen wells was drilled offshore, but they failed to find hydrocarbons. These data have been made available for the academic use, re-processing and re-interpretation only relatively recently (Sopher and Juhlin, 2013).

Indeed, as early as in the first part of the 20th century, oil was being produced in mainland Sweden from the middle Cambrian – lower Ordovician Alum Shale (Andersson et al., 1985). On the island of Gotland, extensive oil exploration started in the 1960s and was focused on Cambrian sandstones, but, in 1974, oil was discovered in the upper Ordovician carbonate build-ups. Between 1974 and 1992, oil was being produced from more than 100 carbonate mounds distributed over the island. Respectively, an extensive seismic exploration took place to locate the mounds, and ca. 2,500 km of seismic profiles were acquired (Sivhed et al., 2004). Together with the seismic reflection data from the Swedish offshore, the seismic data from Gotland have been recently made available for scientific use; however, they might still require vectorization (Sopher, 2017).

This overview of the previous seismic investigations does not aim to present a comprehensive list of all the seismic surveys ever to this date conducted in the Baltic Basin. Such an aim would require access to internal, unpublished, and not scientific reports of all the countries containing part of the Baltic Basin in their territory. However, the examples given in this overview show that (1) the Baltic Basin has been explored by seismic reflection methods since the 1960s, (2) the current coverage is rather dense, especially in the deepest, hydrocarbon-prospective, parts of this basin, and (3) there is no large unexplored part of the Baltic Basin, especially, the Baltic Sea and its southeastern side onshore have a consistent coverage, (4) the numbers (e.g., the total length of the seismic profiles, the profile density) are given as an indication of the amount of the acquired seismic data.

1.2. Structural maps for Lithuania

The information acquired in the course of geophysical exploration was summarized in reports that were complemented with graphical appendices, including structural maps of the key seismic horizons (Laskov et al., 1975; Laškovas, 1996). The map of the Ordovician – Silurian boundary is the most important because it represents the most prominent (the reference) reflecting horizon of the geological section of Western Lithuania (Ūsaitytė, 2000). The lowermost Silurian Stačiūnai Formation has the same lithological composition as the upper part of Ordovician, but it is only a few meters thick in the study area. Therefore, the Ordovician – Silurian boundary is abbreviated to ‘O3 – S1st’, but it is otherwise named the Ordovician – Silurian boundary in the text (Laškovas, 1996). The boundary between Ordovician and Silurian has been questioned and it might be within Stačiūnai Formation (Truuvera et al., 2021).

The first structural map for the seismic horizon representing the Ordovician – Silurian boundary was named the ‘structural map of the top of

Ordovician of the southeastern part of the Baltic Sea' (Laskov et al., 1975). It includes the Lithuanian offshore and the onshore part of Western Lithuania adjacent to the Baltic Sea coastline. In this map, some of the largest structural elements of Western Lithuania are recognizable, for example, a structural high named Gargždai Elevation (also called structure, high, zone of elevations) is one of such features. However, the most complete, and still relevant today, structural map for this horizon was made by Laškovas (1996). It includes the Lithuanian offshore areas and the entire western part of Lithuania. It was compiled from the then-available 2D seismic interpretations and borehole data.

Structural maps for the key seismic horizons, as well as close-ups of interesting and relatively well explored areas, such as Gargždai Elevation, were presented in the in-depth factual-data-based work by Stirpeika (1999; first published in 1980). The most recent tectonic map of Lithuania was presented by Suveizdis (2003). Two suites of structural maps for several stratigraphic levels were summarized by Čyžienė (2003, 2006). These maps, including the top of Ordovician, cover the entire onshore part of Lithuania, but exclude the offshore part. In these maps, the representation of the top of Ordovician in Western Lithuania is essentially the same as in the map of 1996. This shows that, despite the sizable amounts of newly acquired 2D and 3D seismic data, none of this new information was included in the post-2000 maps. Publications considering the interpretation of these new seismic data are scarce (Šeštokas, 2001).

In the Baltic Basin, the seismic data have been continuously acquired during the recent decades, but most of these results remain unpublished. Results of only a few 3D seismic surveys have been published, for example, the Silurian reefs in Central Lithuania (Kaminskas et al., 2015) and the Lower Palaeozoic of Opalino Anticline in Pomerania, Northwestern Poland (Cyz et al., 2018; Konon et al., 2021) have been documented. In the case of Western Lithuania, maps created by using only 2D seismic and borehole data are sufficient to indicate the general trends and display large structures (Brown, 2011). By considering the recent seismic data, and especially the 3D seismic data, it is possible to improve the structural understanding (Šeštokas, 2001). Therefore, this study considers the recently acquired seismic data (1995–2015) with the objective to build a detailed seismo-geological model of the study area. The summarizing nature of the study with eleven 3D seismic data sets will help to improve the knowledge about the structure of the sedimentary cover in the vicinity of Gargždai Elevation in Western Lithuania (Fig. 5). This study presents detailed structural maps for the key seismic horizons, an updated fault trace map, and several arbitrary composite seismic sections illustrating the key features of the study area.

1.3. Geological setting of the Baltic Basin

The Baltic Basin is a sedimentary basin in the southwestern part of the East European Craton which extends over the southern part of the Baltic Sea and the surrounding countries, specifically, Estonia, Latvia, Lithuania, Northern Poland, and a small part of Sweden (Fig. 5). This basin contains sedimentary strata of the geological systems from the Ediacaran to present and has a long history of development. The Precambrian igneous, metamorphic, and sedimentary rocks underlie these strata. The sedimentary fill of the Baltic Basin is mainly composed of the Palaeozoic strata. It is largely and widely comprised of sediments deposited during the Cambrian to Silurian (the Lower Palaeozoic). The Devonian to Carboniferous deposits have the largest thickness in the western parts of Lithuania and Latvia. The Permian to Mesozoic (and the Cenozoic) deposits are restricted to the southwestern part of the Baltic Basin. In the central part of the Baltic Basin, which is located under the southeastern Baltic Sea, Northeastern Poland, and Western Lithuania, the thickness of the sedimentary strata increases towards the Teisseyre – Tornquist Zone and exceeds 4 km (Šliaupa and Hoth, 2011).

The Teisseyre – Tornquist Zone (TTZ) is a major continent scale tectonic structure in Europe which extends from the Black Sea in the southeast to the North Sea in the northwest. It separates the East European Craton (EEC) in the northeast from the other part of Europe in the southwest that exhibits mostly Phanerozoic development. In the northwestern part of the EEC, the crystalline basement – the Baltic Shield – is exposed. The southeastern part of the East European Craton has a sedimentary cover which is called the East European Platform (EEP). The platform cover comprises some Proterozoic and mostly Phanerozoic sedimentary rocks.

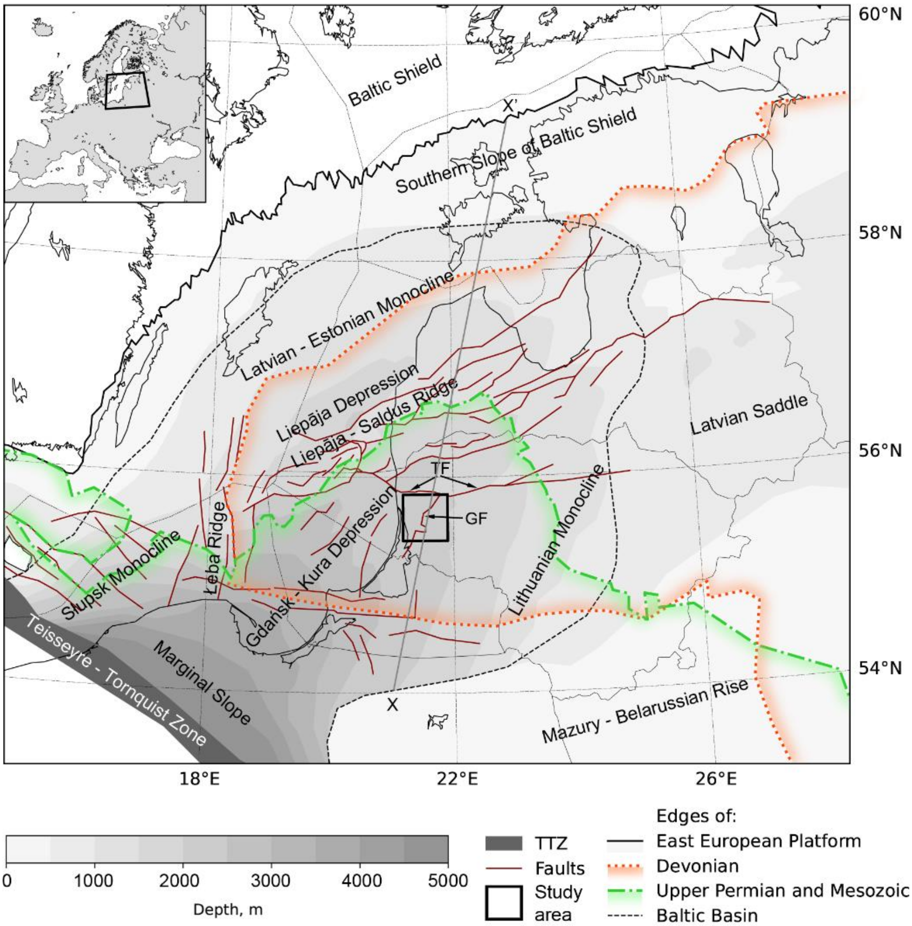


Fig. 5. Schematic map of the structural units of the East European Platform and the Baltic Basin (after Brangulis et al., 1993), as well as the depth of the crystalline basement and major faults (after Brangulis and Kanevs (2002), Čyžienė (2003), Dadlez et al. (2007), Mikołajczak et al. (2019), Papiernik et al. (2019), Sopher and Juhlin (2013), Sopher et al. (2016), Tuuling (2019)). The study area is located in Western Lithuania and indicated with a black rectangle. The faults relevant to this study are labeled: TF – Telšiai Fault, GF – Gargždai Fault. Line XX' marks the location of the regional generalized vertical cross-section of the Baltic Basin. Labels are given to the structural units of the Eastern European Platform and the Baltic Basin as well. The real extent of the relevant stratigraphic limits (edges of the structural complexes) is provided: Palaeozoic platform cover (Caledonian), Devonian (Hercynian) and upper Permian with Mesozoic (Alpine).

In the vicinity of the Baltic Basin, the EEP is divided into several structural units. The Southern Slope of the Baltic Shield is a transition from the Baltic Shield to the Baltic Basin. The Mazury – Belarussian Rise to the southeast from the Baltic Basin is an area where the crystalline basement is shallower and is covered with Mesozoic mainly. The Latvian Saddle is located between two basins (Baltic and Moscow) and two rises (Mazury – Belarus and the Southern Slope of the Baltic Shield). The Baltic Basin is a platform structure by itself, and it is also divided into structural units: depressions (Gdańsk – Kura, Liepāja), slopes (Marginal slope near TTZ), and ridges (Łeba, Liepāja – Saldus). They are related to the present-day structure of the crystalline basement and the Caledonian stratigraphic unit (complex).

The Baltic Basin has gone through several stages of development, namely: the passive continental margin in the Late Ediacaran – Early Cambrian, foreland in the Late Silurian – Early Devonian, intra-cratonic in the Devonian, thermal doming and thermal sag in Carboniferous – Permian and throughout Mesozoic (Šliaupa and Hoth, 2011). The basin fill is divided into stratigraphic units (also called stratigraphic intervals, stratigraphic successions, or simply complexes). They are separated by unconformities and have their own spatial and temporal development. The Caledonian strata were deposited on a passive continental margin and later in a foreland basin, whereas the Hercynian strata were deposited in the intra-cratonic basin whose flanks were later eroded, the Alpine strata were deposited in the thermally sagged and gradually infilled Permian – Mesozoic Polish Basin. There is also the Baikalian stratigraphic unit, but it is mainly distributed outside the Baltic Basin, to its East and North.

1.3.1. Lithostratigraphy

The Baltic Basin covers the southwestern part of the East European Craton and comprises Phanerozoic sedimentary rocks (Fig. 5). The crystalline basement of the southwestern part of the Baltica palaeocontinent formed during the Svecofennian Orogeny between 1.75–1.95 Ga (the Palaeoproterozoic) (Claesson et al., 2001; Motuza et al., 2008; Bogdanova et al., 2015). Mesoproterozoic igneous rocks are encountered in Western Lithuania, Northern Poland, and Western Latvia (Motuza et al., 2006; Dörr et al., 2002). Sedimentary rocks, such as the Jotnian sandstone, are distributed in patches within the Baltic Sea region and are attributed to the

Mesoproterozoic (Lundmark and Lamminen, 2016). In Western Lithuania, they are up to 20 m thick, if present (Stirpeika, 1999).

Western Lithuania belongs to the Gdańsk – Kura Depression (the structural units of the Baltic Basin are listed after Brangulis et al. (1993)), which is the deepest part of the basin and where the sedimentary cover reaches the total thickness of more than 4 km (Fig. 5). The sedimentary fill of the Baltic Basin is traditionally divided into a few stratigraphic intervals which have their own distribution and development in space and time (Stirpeika, 1999). These units or successions are, namely, the Caledonian (lower Cambrian – Lower Devonian), Hercynian (Lower Devonian – lower Carboniferous) and Alpine (upper Permian – Cenozoic) stratigraphic intervals that are separated by major unconformities (Fig. 6). In Western Lithuania, these successions comprise the sedimentary cover which forms a 2.0–2.3 km thick westward thickening package (Poprawa et al., 1999; Poprawa, 2019; Stirpeika, 1999). The oldest of these stratigraphic units is the Caledonian succession. It is the most widespread and the thickest in the Baltic Basin. It suffered intense shortening during the Caledonian Orogeny in the Late Silurian – Early Devonian (Sopher et al., 2016). The Hercynian succession is commonly found in Lithuania and Latvia where its thickness reaches ca. 1 km (Matyja, 2006). The Alpine succession is present in Western Lithuania, and its thickness increases in the direction of the southwest.

The sub-Cambrian peneplain formed in the Baltic Basin region, including Western Lithuania, during the Cryogenian – Neoproterozoic (Lidmar-Bergström et al., 2013; Lidmar-Bergström et al., 2017). The opening of the Tornquist Sea along the southwestern margin of Baltica is related to the onset of sedimentation in a shallow basin during the early Cambrian (Poprawa et al., 2020), which was also accompanied by a global eustatic sea level rise (Nielsen and Schovsbo, 2015).

The Cambrian strata in Western Lithuania are composed of siliciclastic sediments where shales dominate the lower Cambrian, and sandstones dominate the middle Cambrian. The finer lithological division of Cambrian into layers is complicated as the sedimentation of the sandstone and shale was intermittent and varied even on a local scale. The Hawke Bay unconformity separates the shale-dominated lower Cambrian from the sandstone-dominated middle Cambrian (Nielsen and Schovsbo, 2011; Nielsen and Schovsbo, 2015; Nielsen and Ahlberg, 2019). In the study area, the thickness of the Cambrian typically is 125–150 m and increases westward.

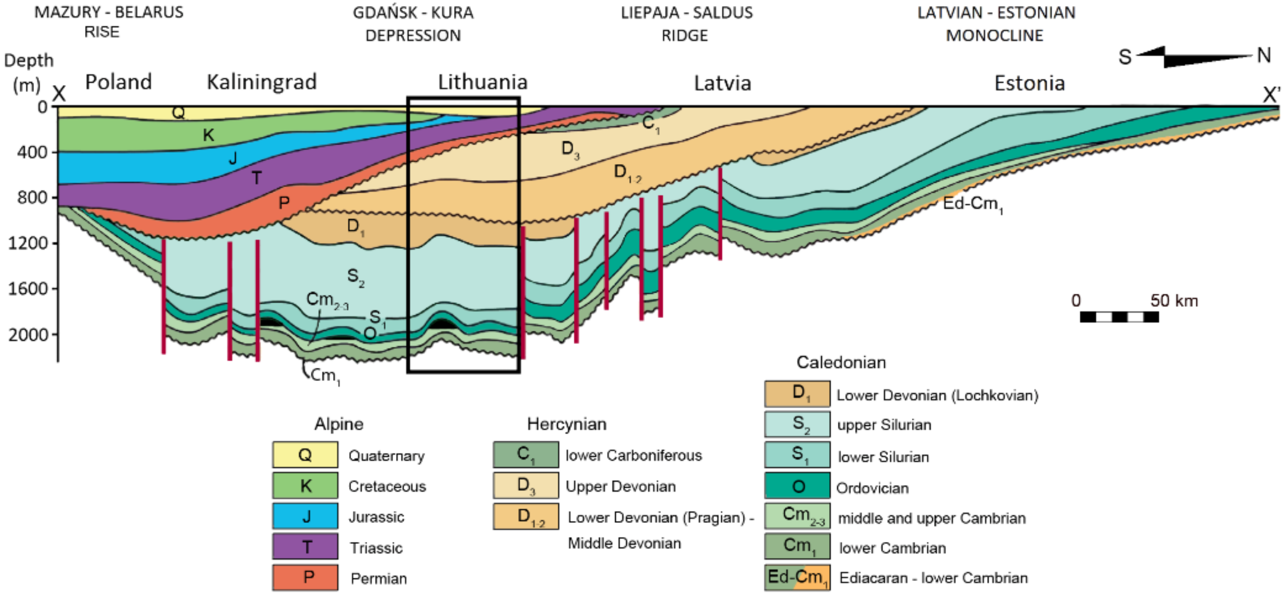


Fig. 6. Regional south-north oriented generalized vertical cross-section of the Baltic Basin (after Dadlez et al., 2007). The position of the study area in Western Lithuania is indicated by the black rectangle. Geological systems are labeled on top of the cross-section, structural units of the Baltic Basin are shown, and countries are labeled above the cross-section. The black-colored anticlines in the middle Cambrian mark the location of oil fields.

It is speculated that the peneplanated Precambrian basement could have been extremely flat with only 20 m variation in height within the Baltic Basin (Lidmar-Bergström, 1995). Consequently, the Cambrian transgression occurred over wide swaths in the Baltic Basin. Thus, the Cambrian deposits are widespread, and their thickness can be expected to vary smoothly. However, local thinning of Cambrian or missing Cambrian is observed in a few dozens of boreholes in Western Lithuania (Stirpeika, 1999). The positive palaeo-topography of the crystalline basement is interpreted to be the cause of the thinning of Cambrian sediments. Associated drape structures formed above these basement highs due to differential compaction of sediments (Šliaupa and Hoth, 2011). Such palaeo-topographic features of the crystalline basement are scarce within the Baltic Basin (Grendaitė et al., 2022).

In Western Lithuania, the Ordovician succession overlies on the Cambrian strata unconformably and comprises various limestones, marlstones, and shales (Jaanusson, 1973; Paškevičius, 1997). Carbonate mounds of the late Ordovician (Katian) are documented by the seismic and drilling data from and around the island of Gotland as well as offshore Latvia (Kanev et al., 2001; Sivhed et al., 2004; Tuuling and Floden, 2000; Tuuling and Floden, 2007). Such carbonate mounds were speculated to be present in Western – Central Lithuania (Geodekyan, 1981), but this suggestion has been disproved. They have not been found in the study area, either. The onset of the Caledonian Orogeny in the late Ordovician led to an uneven pattern of the sedimentation of the Ordovician (Modliński, 1999). The thickness of the Ordovician in the study area is rather stable and ranges between 80 and 100 m.

The Silurian strata in Western Lithuania mainly comprise dark clay and calcareous clay with layers of bentonite, as well as marlstone and limestone. These strata were deposited in a rapidly subsiding foreland basin which formed in relation to the Caledonian Orogeny (Poprawa et al., 1999). In the shallow parts of the Baltic Basin, Silurian reefal structures were formed. Currently, they are among the more interesting features of the Baltic Basin. They are known in Gotland, between Gotland and Saaremaa (Flodén et al., 2001; Tuuling and Flodén, 2011; 2013), and in Latvia and central Lithuania (Kanev et al., 2001; Kaminskas et al., 2015). Silurian reefs have not been discovered in the study area, that is, Western Lithuania, where a deeper marine environment prevailed (Paškevičius, 1997; Levendal et al., 2019). In the study area, the thickness of the Silurian is 600–700 m.

The Devonian and lower Carboniferous strata in Western Lithuania are composed of siliciclastic and carbonate deposits which formed in the shallow sea, lagoon, and delta environments. The Lower and Middle Devonian typically features a varied lithological composition, which is a result of the cyclic sedimentation of sandstone, siltstone and claystone and occasional dolomite. The Upper Devonian is dominated by marlstone, dolomite, and gypsum (Matyja, 2006). Most of the Devonian and all the Carboniferous strata in the Baltic Basin are part of a much wider Devonian cover of the Easter European Platform. In Lithuania and Latvia, they are interpreted as remnants of an intra-cratonic basin (Šliaupa and Hoth, 2011). The thickness of these sedimentary strata is between 800–1100 m thick in the study area.

During the Late Carboniferous – Early Permian, a large scale dextral trans-tensional palaeo-stress field led to the formation of rifts within and near the Tornquist Zone. The rift-related subsidence initiated the formation of the Central European Basin System. The post-rift thermal subsidence accompanied by the load of infilling sediments prolonged the subsidence through the Mesozoic (van Wees et al., 2000). The Permian-aged deposits are present in Western Lithuania because Western Lithuania formed a bay at the edge of this system of basins. The upper Permian in the study area mainly comprises limestones deposited on a carbonate platform setting during the first two depositional cycles of Zechstein Basin (Kadūnas, 2001).

The Triassic and Jurassic strata of Western Lithuania consist of sandstone, siltstone, and claystone as well as marl with oolithic limestone layers. The Cretaceous strata are dominated by chalk. These sedimentary rocks were deposited in lake, deltaic, and shallow marine environments (Paškevičius, 1997). During the Late Cretaceous – Palaeogene, a tectonic inversion related to the Alpine Orogeny occurred in the Teisseyre – Tornquist zone, but its effect is diminished in the Baltic Basin. During Cenozoic, parts of Scandinavia experienced an uplift, which likely caused the removal of the Palaeozoic sediments in southern Scandinavia, thus affecting the eastern side of the Baltic Basin (Lidmar-Bergström et al., 2013). The pre-Quaternary bedrock surface in the Baltic Basin contains glacially incised valleys – palaeo-incisions (Flodén et al., 1997).

1.3.2. Resources

The Baltic Basin has proven hydrocarbon resources where the main reservoirs are the middle Cambrian Deimena sandstones (Fig. 7) (Brangulis et al., 1993; Karnkowski et al., 2010; Zdanavičiūtė et al., 2012). Other reservoir rocks are Ordovician oolithic limestones (Kanev et al., 2001) and carbonate mounds (Sivhed et al., 2004), as well as Silurian reefal and carbonate build-ups (Zdanavičiūtė and Lazauskienė, 2007).

The source rocks are the Lower Palaeozoic organic rich shales, such as the middle Cambrian – lower Ordovician Alum shale (Kosakowski et al., 2016), Ordovician shales of Mossen and Fjacka Formations and the Lower Silurian shales (Zdanavičiūtė and Lazauskienė, 2004). A thick layer of Ordovician and Silurian carbonates and shales seal the Cambrian reservoirs. The subsidence of the Lower Palaeozoic strata, and the formation of the entrapping structures, including Gargždai Elevation, were controlled by the key tectonic event – the Caledonian Orogeny. Consequently, the hydrocarbon generation and migration started in the Late Silurian and continued through the Devonian and Permian (Kanev et al., 2001; Zdanavičiūtė and Lazauskienė, 2004). In Gdańsk – Kura Depression (that is, Lithuania, Kaliningrad Region, and Northwestern Poland), hydrocarbons have been produced from the main reservoir in the Baltic Basin, the middle Cambrian sandstones (Brangulis et al., 1993; Karnkowski et al., 2010; Zdanavičiūtė et al., 2012) that have highly variable reservoir properties (Molenaar et al., 2007). Other reservoirs are of secondary importance; however, in Gotland, oil was produced from the Ordovician carbonate mounds (Sivhed et al., 2004). In Poland, the Carboniferous sandstones, Rotliegend sandstones, and Zechstein carbonates also host hydrocarbons that have been produced (Karnkowski et al., 2010). However, the Permian – Mesozoic sedimentary rocks of the south-western part of the Baltic Basin belong to the Polish Basin (the eastern part of the Southern Permian Basin).

Driven by expectations, intensive work took place ca. 2010 with the objective to evaluate the potential resources of the unconventional hydrocarbons, shale gas, and shale oil (Papiernik et al., 2019; Poprawa, 2020; Šliaupa et al., 2020; Zdanavičiūtė and Lazauskienė, 2009) in the northeastern part of Poland, as well as Kaliningrad Region, and Western Lithuania.

The potential for the geological carbon dioxide (CO_2) storage has been evaluated for the entire Baltic Basin and for several large separate structures by using the average-formula approach or numerical modelling (Shogenov et al., 2016; Shogenova et al., 2009; Sopher et al., 2014; Vernon et al., 2013).

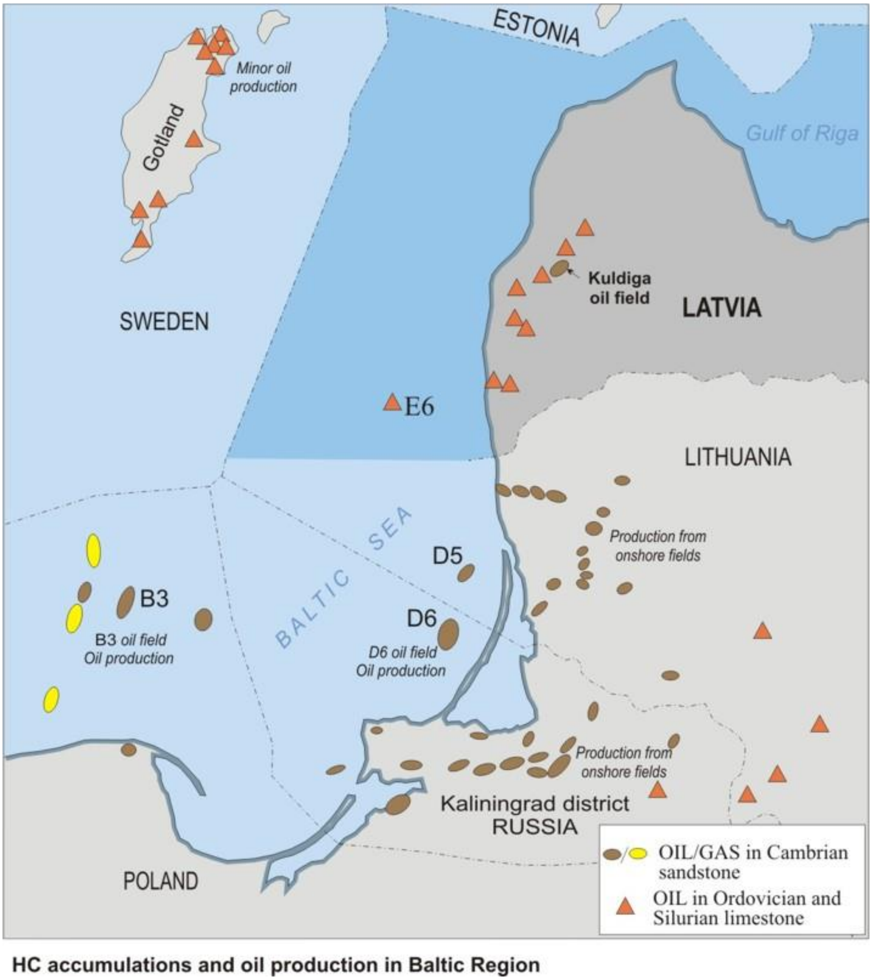


Fig. 7. Hydrocarbon accumulations in the Baltic Basin (Latvian Environment, Geology and Meteorology Centre, 2010).

1.4. Sub-Cambrian peneplain

A peneplain is a surface of sub-continental extent that formed by sub-aerial of fluvial erosion. It has a low relief as its different lithologies are worn down to the same near base level during the last stage of erosion (Philips, 2002). In Scandinavia, three such surfaces have been identified: sub-Cambrian, sub-Cretaceous, and Tertiary (Lidmar-Bergström, 1995; Lidmar-Bergström et al., 2017). In response to prolonged tectonic stability and climate conditions that favored weathering (Phillips, 2002), the sub-

Cambrian peneplain formed in the Baltic Sea region during the Cryogenian – Ediacaran / Cambrian (Lidmar-Bergström, 1995) (Fig. 8). Cryogenian glaciations also contributed to form this flat surface (Keller et al., 2019; Paszkowski et al., 2019); however, glaciations were unable to substantially affect major landforms (Bonow, 2003; Lidmar-Bergström and Olvmo, 2015) and were not the only factor in the formation of the sub-Cambrian peneplain (Lidmar-Bergström, 1995). This peneplain represents the globally traced 'Great Unconformity' which formed during a long period of continental denudation in the Neoproterozoic (Peters and Gaines, 2012), when Baltica was a part of Rodinia (Li et al., 2008; Poprawa et al., 2020).

The peneplain's original surface is thought to have been nearly flat with less than 20 m variation in height (Lidmar-Bergström, 1995). Currently, the surface no longer retains its original flatness, rather, it is found in various settings (most examples are taken from Southern Scandinavia). It is flexed beneath the Caledonian nappes in Western Norway (Gabrielsen et al., 2015). It is found re-exposed in outcrops after the Palaeozoic strata have been removed in Finland, Sweden, and Norway (Lidmar-Bergström, 1995; Gabrielsen et al., 2015). Some of the present-day Sweden's landscape types are derived (re-worked) from the sub-Cambrian peneplain which has been re-exposed during the Mesozoic and Cenozoic (Lidmar-Bergström, 1995; Lidmar-Bergström and Olvmo, 2015; Lidmar-Bergström et al., 2017). The peneplain's surface is recognized in such uplifted areas as the South Swedish Dome (Lidmar-Bergström et al., 2017) and the Hardanger plateau in Southern Norway; the latter is >1000 m above the mean sea level (Jarsve et al., 2014; Japsen et al., 2018) and has not been eroded by recent glaciations (Bonow et al., 2003). Eastwards, the peneplain's surface dips under the sedimentary strata of the Baltic Basin (Lidmar-Bergström, 1993; 1995; Lidmar-Bergström et al., 2013; 2017). The supposed original flatness of the sub-Cambrian peneplain allows using it as the reference surface and helps to interpret the subsequent tectonic events (Lidmar-Bergström et al., 2013; Gabrielsen et al., 2015) and erosional processes (Lidmar-Bergström, 1993, 1995; Lidmar-Bergström et al., 2017).

Even though peneplains are defined as flat surfaces, they contain features called 'inselbergs' – sporadic and isolated rocky hills and clusters of hills that often occur adjacent to plateaus or highlands. They are residual hills that either rise above the peneplain – for example, Jungfrun in Sweden (Lidmar-Bergström, 1993; 1995) – or only the tops of these residual hills are part of a peneplain (residual peneplain), while, at their base, the peneplain has been eroded away (Lidmar-Bergström, 1988; Lidmar-Bergström and Olvmo, 2015; Nenonen et al., 2018). Such inselbergs as Jungfrun do not appear to be common for the sub-Cambrian peneplain, while groups of residual hills occur near the paneplain's erosional edges. In the Baltic Basin, similar isolated sporadic hill-like features of the crystalline basement are reported (Stirpeika, 1999; Modliński et al., 1999; Brangulis and Kanevs, 2002; Sopher et al., 2016; Estonian Land Board, Geological Survey of Estonia, 2020; Ani and Meidla, 2020).

Another characteristic feature of peneplains is saprolite – a weathered bedrock surface (Migoń and Lidmar-Bergström, 2002). It is discussed presently because different authors use their own terminology. The sub-Cambrian peneplain has accumulated only a thin saprolite because sheet-wash and a lack of vegetation prevented the formation of thick saprolite (Lidmar-Bergström, 1993; Lidmar-Bergström et al., 2013). In Sweden, kaolinitic saprolite is associated with the sub-Cambrian peneplain (Lidmar-Bergström et al., 1997). In Estonia, the crystalline basement is found in boreholes at depths of 100–800 m, and the top few tens of meters of this crystalline basement have been affected by weathering (Soesoo et al., 2004). There, this weathered layer is named 'the Baltic palaeosol', and, based on the degree of alteration, it can be divided into three parts (Liivamägi et al., 2014). In Kaliningrad Region (the Russian Federation), the crystalline basement is found in boreholes at depths of 1200–3000 m, and its weathering-affected surface can be divided into the weathering crust and the substrate; the substrate is divided into the upper and lower parts (Meshcherskii et al., 2003). These observations describe saprolite that is a product of deep chemical weathering (Butt et al., 2000). The lowest layer contains only weathering fractures and is the least affected by weathering, the middle layer has retained the original rock structure that can be recognized but has undergone mineral alteration, and the upper layer is a loose unrecognizable material with kaolinitic clay. In Western Lithuania, the crystalline basement is found in boreholes at a depth of ca. 2 km under the platform cover. It is often described as weathered, strongly weathered, or having a weathering crust which is a few meters thick; kaolinitization is also present. The weathering crust of the Lithuanian crystalline basement has not been studied recently (Vasilyev, 1969).

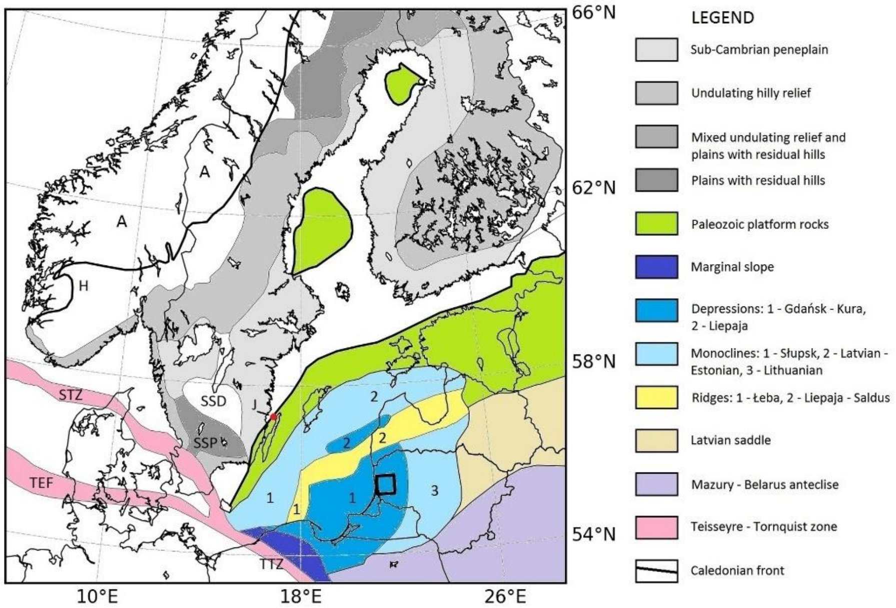


Fig. 8. Location of the study area in Western Lithuania (the black thick rectangle) within both the Baltic Basin and the Baltic Sea region. A) Sub-Cambrian peneplain is exposed in the Baltic Shield between the Caledonian front (edge of the Caledonian allochthon (A)) and edge of the Paleozoic cover rocks (East European Platform). Sub-Cambrian peneplain and relief types related to it are shown in grey. SSD – South Swedish Dome, H – Hardanger plateau, J – Jungfrun. The Baltic Basin and its structural units are shown in blue (monoclines, depressions, slopes) and yellow (ridges); numbers are explained in the legend. Baltic Basin, Latvian Saddle, Mazury – Belarus anteclise (rise) and the Southern Slope of the Baltic Shield beneath the Paleozoic cover) are structural units of the East European Platform. The Teisseyre–Tornquist Zone (TTZ) separates the East European Craton in the northeast from Phanerozoic Europe in the southwest, and it splits into the Sorgenfrei – Teisseyre Zone (STZ) and the Trans-European Fault (TEF). The Mesozoic and Cenozoic sedimentary cover is not shown in order to show the Baltic Basin (after Brangulis et al., 1993; Thybo, 2000; Lidmar-Bergström et al., 2013; Jarsve et at., 2014; Gabrielsen et al., 2015).

A large part of the sub-Cambrian peneplain is not currently exposed – it is overlain by rocks from Ediacaran (Vendian) to Early Ordovician. Hence, the peneplain is called sub-Cambrian as the upper stratigraphic limit of its formation is diachronous within the Baltic Sea region. As a result of the global eustatic sea level rise, large parts of Baltica were subjected to transgression in the early Cambrian (Cocks and Torsvik, 2005), and terrigenous sediments were deposited in the shallow Cambrian Sea (Nielsen and Schovsbo, 2011). The weathering products of the sub-Cambrian peneplain sourced these Cambrian deposits, but the sedimentary provenance is not well studied yet (Konsa and Puura, 1999; Lorentzen et al., 2018). In Scandinavia, the exceptional preservation of the sub-Cambrian peneplain's original surface was possible due to the Paleozoic sedimentary cover which was first removed not earlier than in the Carboniferous or even the Pliocene (Elvhage and Lidmar-Bergström, 1987; Lidmar-Bergström et al., 2017). The Paleozoic sedimentary cover exists today as a part of the Baltic Basin to the southeast from Sweden. Therefore, the original surface of the sub-Cambrian peneplain is supposed to continue eastwards from Sweden under the Baltic Sea and be well-preserved beneath the sedimentary rocks of the Baltic Basin.

In this study, the recently acquired seismic data are analyzed in search of the sub-Cambrian peneplain in Western Lithuania (see Fig. 8).

2. MATERIALS AND METHODS

2.1. Data set

2.1.1. Definition of the study area

Geographically, the selected study area is in Western Lithuania. However, its boundaries are defined by the distribution of the recent seismic data that were acquired in order to develop the E & P license areas. To give an orientation where the boundaries of the study area are located, the extent of the study area can be said to be limited to the North by Telšiai Fault, to the South – the edge of Zechstein evaporite basin, to the West – the coastline of the Baltic Sea and the Curonian Lagoon, whereas no continuous seismic coverage has recently been acquired to the East. The defined area has dimensions of nearly 60 km by 60 km. Due to its hydrocarbon potential, the area has been continuously explored by seismic surveys and deep drilling since 1960s. Currently, in terms of the numbers of seismic surveys and wells, it is one of the best explored parts in Western Lithuania. Gargždai Elevation containing several oil fields is the main geological structural element that is present within the study area.

2.1.2. Data selection

All 3D and 2D data from the study area, mostly acquired during the time interval between 1995 and 2015, were selected and incorporated into a single seismic interpretation (Fig. 9). Eleven 3D seismic surveys were available in the study area, and all of them have been included into the interpretation. In total, they cover ca. 550 square kilometres, which comprises ca. 25% of the study area. Similarly, almost 300 2D seismic profiles from more than 20 individual acquisition projects were included into the interpretation. They cover the remaining part of the study area, their total length is just under 2,000 km, and the profile density is 1–4 km of the profile length per square kilometer. The use of pre-1995 2D seismic profiles was limited to a few occasions when distant surveys had to be related in the interpretation and to fill in the not-surveyed areas. Therefore, the interpretation is mostly, but not exclusively, based on the 1995–2015 seismic data.

The study area mostly coincides with two Western Lithuanian exploration and production license areas: Gargždai License Area and Klaipėda License Area, and also includes parts of Rietavas License Area

(Fig. 1). Gargždai License Area occupies the southern part of the study area and includes a major part of Gargždai Elevation and a minor part of Šilalė Elevation. Klaipėda License Area covers the northern part of the study area. It includes the northern part of Gargždai Elevation, while its western side is a part of Kretinga Depression. Telšiai Elevation is beyond Telšiai Fault, which is to the North and outside the study area (Figs. 5 and 9).

2.2. Seismic data processing

The purpose of seismic signal processing is to convert the seismic data recorded at the field into seismic images representing the subsurface. The exploratory seismic reflection method uses the seismic reflections that originate at rock interfaces to create seismic reflection images. The main processes of seismic data processing are deconvolution, stacking, and migration. Deconvolution aims at enhancing the temporal resolution. Common mid-point stacking decreases the redundancy in the data by reducing the amount of data. Seismic migration aims at enhancing the spatial resolution by moving the reflections towards their correct positions (Yilmaz, 2001).

2.2.1. Merge description

Seven of the 3D seismic surveys available in the study area have an overlap at their margins. These surveys are within Gargždai License Area, and they were acquired between 2000 and 2003 by the seismic crew of Kaliningradgeofizika. These surveys are Kintai, Vilkyčiai, Lašai, Degliai, Šiūraičiai, Šiūpariai, and Agluonėnai. They have similar survey acquisition parameters. First, the surveys were acquired by using the orthogonal 3D land geometry, which is the standard for the 3D seismic acquisition onshore. This acquisition geometry was introduced into the hydrocarbon industry by such large companies as Shell at the advent of 3D land surveys around 1990. It was developed as a theoretically correct way to acquire 3D seismic data, and it is suitable to obtain high quality seismic images. It also happened to be efficient logistically (Vermeer, 2012). The orthogonal geometry consists of the source lines and the receiver lines which intersect at the right angle. These lines have constant spacing, but the source line spacing does not have to be the same as the receiver line spacing. The receiver lines for the most of the separate surveys are orientated in the same direction or rotated at the right angle. A group of three seismic vibrators was used as a seismic source, whereas a group of ten 2.5 m-spaced geophones was used as the recording channel. Other acquisition parameters that are common between surveys area listed in Table 1.

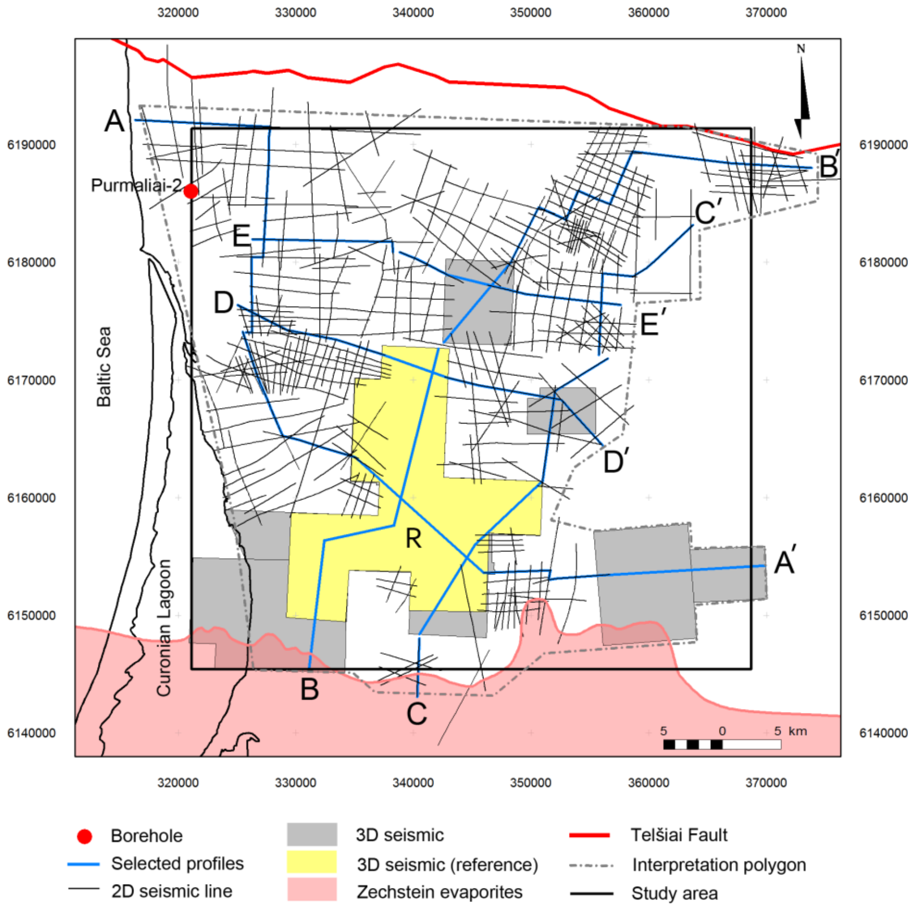


Fig. 9. Position of seismic surveys in the study area. 3D seismic survey coverage is represented by shaded polygons, whilst 2D seismic surveys are delineated by thin gray lines. The location of representative arbitrary seismic lines is shown in blue. The seismic-to-well tie was performed at the borehole Purmaliai-2 which is in the northwestern corner of the study area. The interpretation area is of an irregular shape because it is defined based on the location of seismic surveys. Telšiai Fault is outside the study area. The edge of Zechstein evaporites is partly covered by 3D surveys (Grendaitė et al., 2023).

Table 1. Acquisition parameters of 3D seismic data in Gargždai License Area.

Parameter	**Value**
Geometry type	3D land orthogonal
Source line (SL) separation	300 m (if regular)
Receiver line (RL) separation	200 m (300 m for Degliai)
Source point (SP) interval	50 m
Receiver point (RP) interval	50 m
Sampling interval	2 ms
Source group	3 x VibroSeis
Receiver group	10 geophones spaced by 2.5 meters
Shot template	asymmetric, rectangular (elongated along receiver (IL) line)
Number of active RL per shot (max)	8
Number of active RP per RL (max)	depends on survey, 72–96
IL offset	2 times longer than the largest XL offset
XL offset	400–1200 m
Nominal fold	24

The purpose of merging is to process the seven land 3D seismic data sets as if they were a single data set, that is, to apply the same single solution for static corrections, datum, processing parameters and methods, and to migrate the data sets as a single data set. A single solution for static corrections and a single velocity field can provide a more reliable time-positioning of reflecting horizons. Since these data sets partly overlap, fewer imaging artifacts can be expected at these overlapping parts. Inconsistencies between separate data cubes should be minimized and should not depend on processing as such.

Before the merge, the record identification numbers (FFID), the source and receiver line, and the point numbers were renamed to give them unique identification numbers within the new data set. The numbering of the source positions had to be compliant with the concept of a consistent numbering source and receiver positions within the survey (that is, they had to be given the local survey ‘coordinates’). Hence, they had to be renumbered. The receiver position numbering was mostly correct.

The merge also required preparing the SPS (Shell Processing Support) geometry files respectively – the record identification numbers (FFID), the source and receiver line, and the point numbers were renamed to give them unique identification numbers.

Therefore, due to the overlap and the specific similarity between the seven 3D seismic surveys of Gargždai License Area (Kintai, Vilkyčiai, Lašai, Degliai, Šiūraičiai, Šiūpariai, Agluonėnai), it was possible to merge and process them by using the standard post-stack time processing sequence. The other 3D seismic volumes and all the 2D seismic profiles were processed by applying additional post-stack random noise attenuation.

2.2.2. Static correction

A dataset of static corrections for the near-surface low velocity zone was created and used in re-processing. A few hundred up-hole surveys in shallow wells up to 30 m depth were performed for the determination of the near-surface, weathered zone velocity. The seismic wave travel time from the ground surface to the seismic datum (20 m below the mean sea level) was evaluated from the up-hole records. The average velocity model was created by evaluating the velocity at each up-hole point, and then creating the map of the average velocity distribution. From this model, the final static corrections (to seismic datum -20 m) were calculated by finding the ratio of the distance (from LIDAR surface elevation to seismic datum) map and the average velocity map (Figs. 10 and 11). Then, the static corrections for each source and receiver station were available and used to remove both the local low-velocity environment effect to the sources and receivers and to position the seismic data on a common seismic reference datum. Thus, the merged survey is the data set with a known and reliable seismic reference datum – the reference data set (marked ‘R’ in Fig. 9).

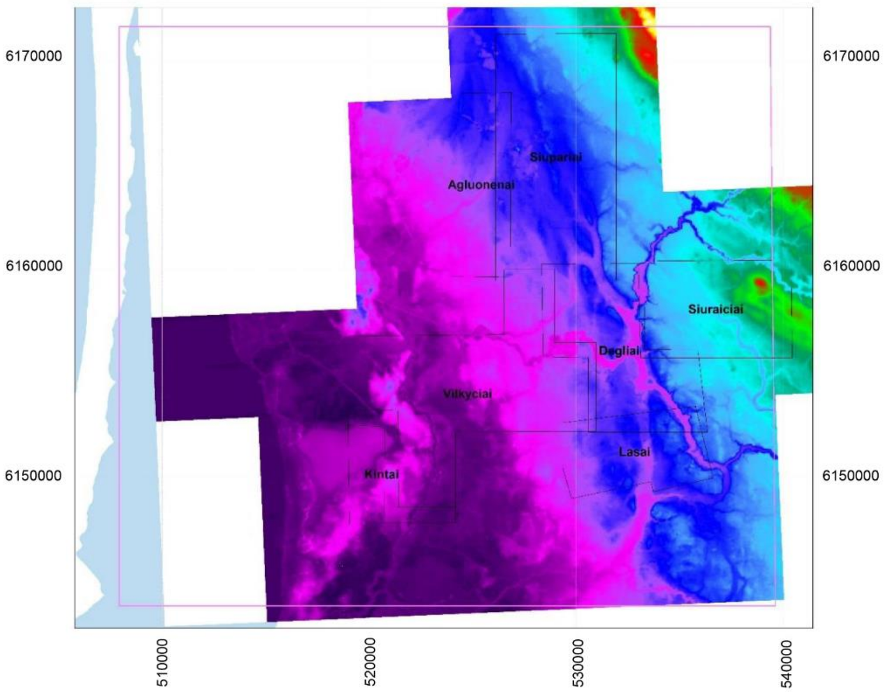


Fig. 10. Surface elevation for part of the study area. It includes most of the area with 3D seismic coverage in Gargždai License Area.

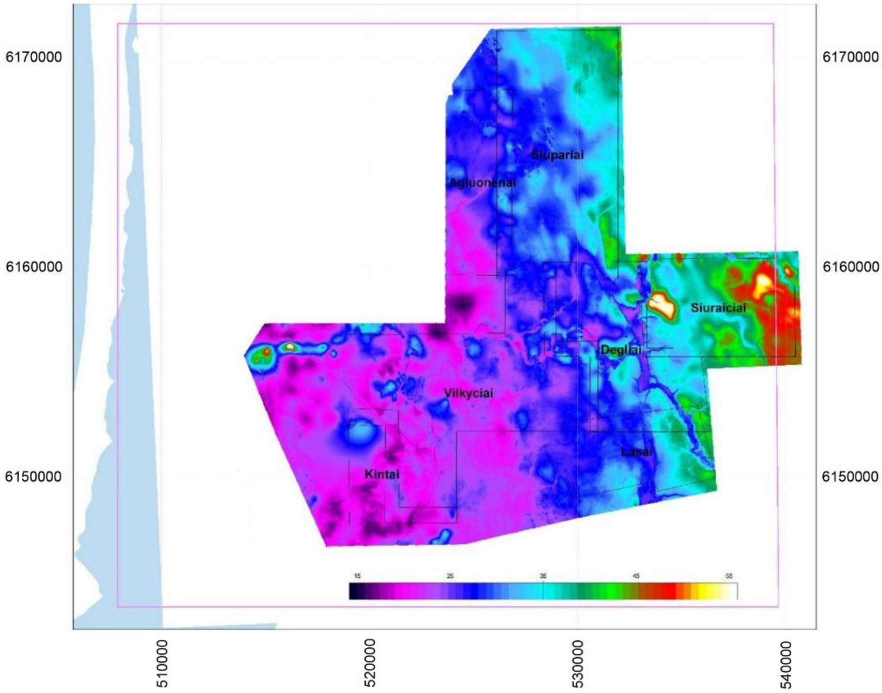


Fig. 11. Near-surface velocity model for part of the study area. It includes most of the area with 3D seismic coverage in Gargždai License Area.

2.2.3. Re-processing sequence

The following is the 3D post-stack time processing sequence that was used to process the seven merged surveys.

1. Reformat from the individual SEGY files;
2. Make geometry databases for individual surveys;
3. Rename the record identification numbers, receiver and shot lines and points in order to prepare the seismic data files to merge, reject parts of Kintai and Vilkyčiai, assign individual geometries;
4. Change these identification numbers in the SPS survey geometry files as well thus making the identifiers unique within the merged data set and consistent within the survey coordinates;
5. Make a common geometry database, bin (grid 25 x 25 m);
6. Merge all the data sets into a single data set, assign common geometry;
7. Edit traces (kill dead traces, attenuate spikes and noise bursts);

8. Calculate trace statistics;
9. Calculate ensemble statistics;
10. Equalize shots and receivers within the full data set;
11. Seismic reference datum calculation (-20 m, replacement velocity 2000 m/s);
12. Apply ‘user’ (external) statics (‘user’ static is calculated for -20 m);
13. Perform ground roll noise attenuation;
14. Perform spherical divergence correction;
15. Conduct air wave attenuation;
16. Perform ground roll noise attenuation 2;
17. Conduct linear noise attenuation;
18. Deconvolution, low velocity filter and band pass filter;
19. Velocity analysis (grid 500 x 500 m);
20. Residual statics analysis and application;
21. Apply the obtained residual statics to the data after the application of the ‘user’ (external) statics and repeat steps 13–20. This ensures that statics are minimized before de-noise, and the velocity field can be obtained more reliably;
22. Trim statics analysis and application;
23. Achieve surface consistent trace balance;
24. Normal moveout, outer mute;
25. CMP de-noise;
26. 3D stack;
27. Trace equalization;
28. Deconvolution after stack;
29. 3D random noise attenuation (3D FXY deconvolution);
30. Migration, 3D post-stack time;
31. Noise attenuation after migration;
32. Time variant band pass filter;
33. SEG-Y output.

2.3. Seismic data interpretation

The seismic interpretation aims at extracting geological information from seismic images. In this study, the so-called structural interpretation was made. Structural interpretation is first of all the interpretation of seismic reflection horizons and faults. It starts with the preview of seismic data. Then, horizons are identified at boreholes, and major faults are determined at seismic sections. This is followed by fault network building, and manual and automatic horizon picking. Faults and horizons are continuously revised as the work progresses. Finally, the time structure of horizons is obtained, and it can be depth-converted. More detailed stratigraphic or reservoir analysis can be started (Brown, 2011).

2.3.1. Seismic to well tie

In Western Lithuania, the lithological section is already well documented by borehole data. In addition, seismic sections are abundant and are denoted by a typical appearance with several reflecting horizons. In order to find out the rock interfaces at which seismic reflections originate, seismic sections in two-way-time must be related to well logs in depth, and both should represent the same geological section. A procedure used to achieve this relation is called the seismic-to-well tie. It provides a synthetic seismic trace which gives a visual relation to the real seismic data. Thus, the relation between stratigraphic and lithological boundaries and the real seismic reflection section can be established.

The synthetic seismic trace is obtained in several steps. First, the acoustic impedance is calculated by using the P-sonic and density logs by the product of the density of the medium and the wave propagation velocity in that medium. Then, the reflection coefficient series is obtained. This series intends to represent the reflecting interfaces and their reflectivity – the reflection coefficients at normal incidence. Finally, the synthetic trace is obtained by convolving the series with an arbitrary source signature, such as the Ricker wavelet that has the frequency bandwidth of the seismic data.

This method requires reliable well logs of the P-sonic and the density that are used to obtain the synthetic trace. The method also requires a good quality seismic section (preferentially, the near angle stack), that has the correct datum, and is the closest possible to the borehole, thus, it represents the same geological section as the borehole. Ideally, both measurements of the seismic wave propagation velocity (P-sonic) and the rock density should be available in a borehole from its top to the bottom. In such a way, the entire geological section is presented by well logs. Unfortunately, in the study area and nearby, the P-sonic log was usually measured only for the intervals of interest (mostly, the Lower Palaeozoic), and almost never for the entire borehole length. The density log was seldom recorded, and this was usually done only for the intervals of interest.

The well Purmaliai-2 in the northwestern corner of the study area was selected for the seismic-to-well tie (Fig. 12). This well fully represents the sedimentary cover of the study area because it reaches the crystalline basement and contains the entire stratigraphic succession. This well has the P-sonic log measured for almost the entire well length and is the only well with this characteristic in the study area and nearby. The synthetic trace at the well Purmaliai-2 was created by using a simplified approach from the P-sonic log only. Despite this, a very good correspondence is observed between the synthetic seismic trace modeled at the borehole and the nearest real seismic section.

2.3.2. Horizon interpretation

After processing, land seismic data usually have an arbitrary seismic reference datum. For our study area, such datums are different for at least each separate processing project (or even each profile = data set), and, on top of that, they are not available. Generally, in such a situation, an interpreted horizon is not at the same time-way-time level in intersecting seismic data sets. Time shifts can be applied for each separate data set to position the interpreted horizon and the data sets themselves on the same seismic reference datum. The finding and application of shifts is called the balancing of the seismic profiles.

In the study area, the reference data set has a reliable seismic reference datum. Other seismic data sets (ten 3D and all the selected 2D) were positioned on the same seismic reference datum by applying individual time shifts. These shifts were obtained during the process of horizon interpretation – a horizon interpreted in different seismic data sets must have the same two-way-time value at the points of the survey intersections and overlaps. In the case of overlapping 3D and 2D surveys, 3D surveys were preferred exclusively. In the case of overlapping inconsistent 2D surveys, preference was given to the most recent surveys. A few ‘old’ 2D profiles had to be used to relate distant surveys and to fill out non-surveyed areas.

2.3.3.Time to depth conversion

Once the horizon has been interpreted in all the seismic data sets, it exists only at the location of these seismic data. The spatial precision of such an interpreted (picked) horizon is the same as the bin size of the seismic data, and its temporal precision is the same as the sampling interval of the seismic data. In the study area, the spatial precision is usually 12.5 m along the 2D seismic profiles and 25 m by 25 m for the 3D seismic volumes. Such a horizon requires gridding on a mesh to make it present over a selected area – the interpretation polygon – which roughly represents the study area. The interpreted horizons were gridded on a 50 m by 50 m mesh. With the objective to obtain structural maps, time horizons were converted to depth horizons (horizons) by using the so-called horizon velocity. A horizon velocity is a model of the average-velocity-to-horizon which can be obtained by interpolating the average-velocity-to-horizon values between wells. This procedure needs at least one well with the depth of the stratigraphic level that corresponds to that seismic horizon. This time-to-depth conversion is simple but suitable for the geological conditions of the study area where the layering is sub-horizontal, and the change in the velocity field is laterally smooth. Carbonate build-ups, such as Ordovician mounds or Silurian reefs, can possibly cause velocity anomalies, but they have not been discovered in the study area. The horizon velocity models are reliable because they are controlled at many boreholes in the study area, with almost 90 boreholes reaching the Precambrian crystalline basement, which is the lowermost seismic horizon.

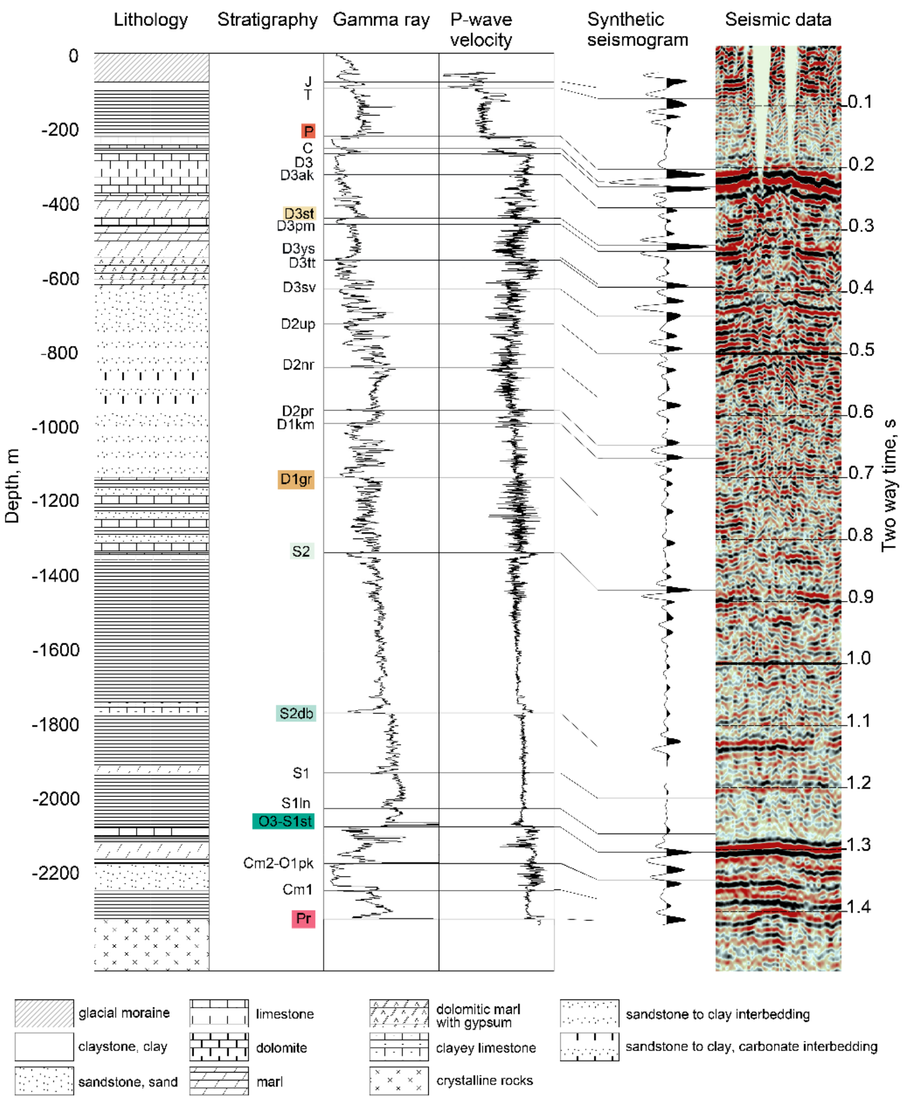


Fig. 12. Seismic-to-well tie for the well Purmaliai-2. In the columns from left to right: generalized geological section with the dominant lithology types, stratigraphic boundaries of importance, well-logs of gamma ray and P-sonic, the synthetic seismic trace, and the corresponding seismic section. The relationship between several seismic reflection horizons and the corresponding stratigraphical and lithological boundaries is shown. Stratigraphical boundaries related to the reflecting horizons are given by symbols in the stratigraphic column. Jurassic (J), Triassic (T), Permian (P), Carboniferous (C), Upper Devonian (D3), Akmenė Formation (D3ak), Stipinai Formation (D3st), Pamūšis Formation (D3pm), Įstra Formation

(D3ys), Tatula Formation (D3tt), Šventoji Formation (D3sv), Upninkai Formation (D2up), Narva Formation (D2nr), Pärnu Formation (D2pr), Ķemeri Formation (D1km), Gargždai Formation (D1gr), Upper Silurian (S2), Dubysa Formation (S2db), Lower Silurian (S1), Lower Silurian, Llandovery (S1ln), upper Ordovician (O3 – S1st), middle Cambrian (Cm2 – O1pk), lower Cambrian (Cm1), Precambrian crystalline basement (Pr). Symbols for the stratigraphical levels related to the high amplitude reflections are highlighted by colors.

2.3.4. Fault interpretation

Faults were interpreted in the 2D seismic profiles and sections of the 3D seismic volumes only where the horizons were obviously discontinuous. A single 2D profile provides only apparent quantitative information about the fault. The true geometric parameters of the fault plane – such as the trend, the dip, and the direction – cannot be inferred from a single profile or section. If a seismic profile is perpendicular to the fault trend, then, the apparent fault parameters are the closest to the true ones. Several profiles are necessary to infer the orientation of the fault plane. This requires care because the same fault must be interpreted in different 2D seismic profiles. When the spacing of the 2D profile network is small, the confidence of tracing the same fault between different profiles increases. It further increases if only one fault is being observed, and if that fault has a consistent amplitude. However, the confidence decreases when several faults are observed, and their amplitude is small or variable, or, relatively, when the distance between profiles is large. Faults can be most confidently interpreted in 3D seismic data because 3D volumes feature dense areal coverage (for example, 25 m by 25 m for the seismic volumes in the study area). Moreover, sections of arbitrary direction can be taken from a 3D seismic volume.

Thickness maps of sedimentary strata might be a useful tool for fault interpretation. A fault is syn-sedimentary if the development of that fault occurred at the same time as the sedimentation. In such a case the pattern of sediment deposition would be affected by the relative uplift and subsidence on the opposite sides of the fault. Thus, the growth strata would accumulate on the faster subsiding block of the fault and point out the presence of a fault. For this method to be effective, the stratigraphic interval should be carefully chosen. It is especially useful when the structure of the sedimentary cover is complicated by several structures within the same area.

2.3.5. Seismic attributes

Seismic attributes are the quantities extracted or calculated from seismic data. They are used to study the structure and the stratigraphy, and to characterize reservoirs. Their purpose is to highlight or display the features in the seismic data that are not visible in seismic sections. The earliest attributes were created by realizing how to represent seismic traces as complex signals (Taner et al., 1979). Time, amplitude, frequency, and attenuation can be used to create attributes. They can be extracted along a horizon or calculated in a window. Attributes are usually derived from the stacked data. Some attributes are only pre-stack (amplitude variation with offset). Time- based attributes provide information about structures. The dip magnitude and azimuth, the roughness, and the shaded relief are time-horizon attributes, while the coherence and the semblance are time-window attributes. Attributes based on the amplitude and the frequency provide information about the stratigraphy and reservoirs. The reflection amplitude and the acoustic impedance are amplitude-horizon attributes. Amplitude-window based attributes are either summed-up values (such as the RMS amplitude), a selected value, or a distribution of values. Frequency-horizon attributes are, for example, instantaneous frequency or spectral decomposition. Obviously, the variety of attributes is huge. Selecting which attributes to use requires knowledge what should be displayed (Brown, 2011).

2.4. Digitization of the map from 1996

Over the course of history, there have been several structural maps made for the seismic horizon associated with the Ordovician – Silurian boundary (O3 – S1st). To date, the map compiled by Laškovas (1996) can still be regarded as the most relevant because of the reasons stated in the introduction. The historical structural map for the seismic horizon associated with the Ordovician – Silurian boundary (O3 – S1st), which was summarized by Laškovas (1996), exists in its original paper form as an appendix of the report from 1996 (Laškovas 1996). Therefore, it had to be scanned into a digital image. The structure of the surface is represented by depth isolines and fault traces, both of which were digitized. Then, these digitized entities were used to create the surface. The study area covers only a part of this digitized structural map, and only this part is presented (Fig. 13A). As it was explained in the introduction, this historic map was compiled from 2D seismic and borehole data. Here, it is presented for comparison to the results of this study (Fig. 13B) because these results (structural maps) are largely based on a more recent, largely 3D, seismic data set.

2.5. Other relevant information

This mostly technical information has been presented here because it might be useful for the reproducibility of the results of this study.

Prior to the merge of seven 3D seismic data sets, their SPS files had to be adjusted/prepared accordingly. Some of these files had to be corrected because they were corrupted, or else they even had to be created anew because they had been lost and were not available anymore. The seismic data were processed using dedicated software for seismic data processing software *Globe Claritas TM*.

The software *LMKR Geographix* provided the geoscientific platform with toolsets to manage geophysical data and perform such complex tasks as, for example, seismic data interpretation. By using this software, the interpretation of horizons, the creation of structural maps, the seismic-to-well tie, and the digitization of the scanned map, were performed.

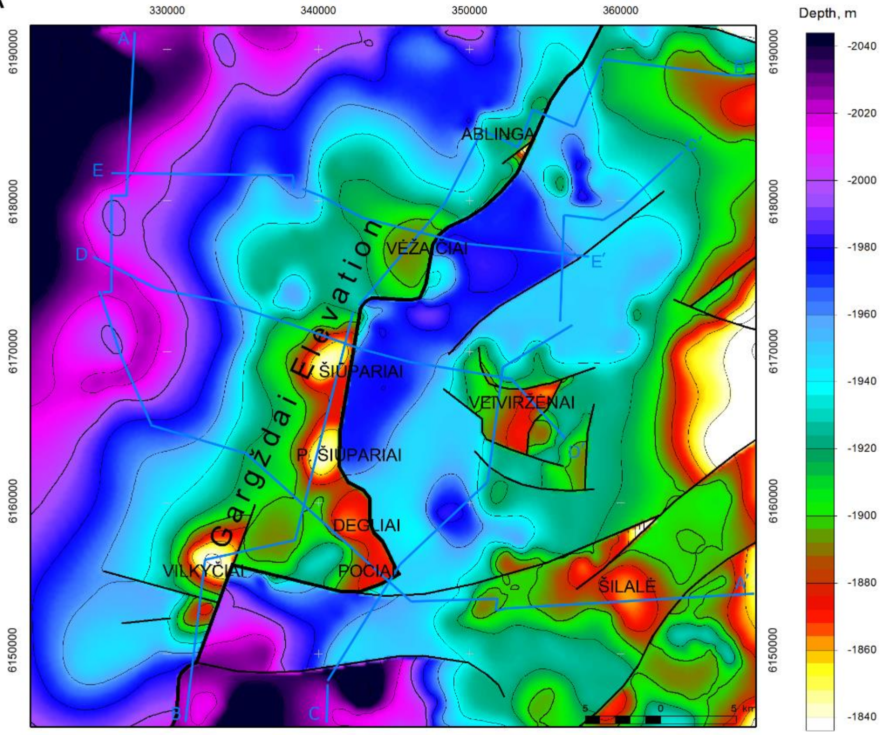
The graphical visualization tools of the *LMKR Geographix* software were employed to present the results in the form of figures. *Matplotlib* (Hunter, 2007), and the graphical data visualization and plotting library for the *Python* programming language was also used for some figures.

The seismic data are presented either in the projected LKS-94 coordinate system, or in the Pulkovo 1942 / Gauss-Krüger zone 4 for older data.

The figures containing maps of the study area are presented in the projected LKS 94 coordinate system. The figures presenting regional maps are given in the WGS84 / UTM 34N coordinate system.

The access to geophysical data, including seismic data, and proprietary software licenses was obtained from UAB *Geobaltic*.

A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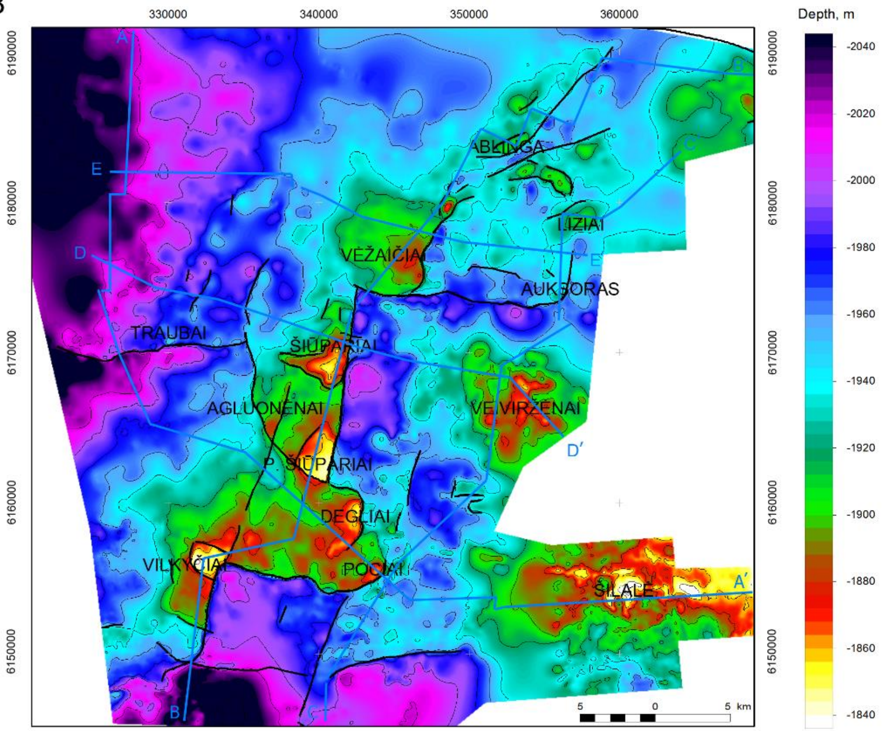
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0
5 km

Fig. 13. (A) Digital representation of the depth map of the top of the Ordovician with fault traces (after Laškovas, 1996). The depth is in meters below the mean sea level. The original map is a compilation of well tops and pre-1995 2D seismic survey interpretations. Gargždai Fault is indicated with a thick black line. This fault limits Gargždai Elevation to the East and South. (B) Depth structure map of the Ordovician – Silurian boundary (O3 – S1st). This map represents the same area and stratigraphical horizon as shown in part (A), but incorporates the recent seismic data. This map displays a higher level of fidelity in terms of the resolved structural features, which has permitted the re-mapping of the fault patterns in the area. The names indicate local structural highs of the Ordovician – Silurian boundary.

3. RESULTS AND DISCUSSION

3.1. Seismic data interpretation

3.1.1. Stratigraphic framework

The P-wave velocity log of the representative borehole Purmaliai-2 (Fig. 12) indicates that, in the study area, the velocity of P-wave propagation is relatively low for the Mesozoic, higher for the Palaeozoic, and high for the Lower Palaeozoic intervals. Carbonate dominated rock type intervals have the highest values of velocity, while clay- and marl-dominated intervals have the lowest values of velocity. Examples of the high velocity intervals are the upper Permian limestone, the Upper Devonian dolomitic marl and dolomite, the Lochkovian siliciclastic-to-dolomite sequence of the Lower Devonian, the Ordovician limestone, the top of the Silurian limestone and the intra-Silurian clayey limestone, as well as the middle Cambrian sandstones, and the crystalline basement rocks. Examples of the lower velocity intervals are the Silurian clays and marls, and also the Middle Devonian siliciclastic sequence.

In both the synthetic seismic trace and the real seismic data, the high amplitude reflections originate at 1) the interface between the Precambrian crystalline basement and the siliciclastic Cambrian, 2) the interface between the limestone-dominated upper Ordovician and the shale-dominated Lower Silurian, 3) ca. 10 m thick clayey limestone layer (Toliai Member) within thick shales belonging to the uppermost part of the Dubysa Formation of the Ludfordian, Upper Silurian (Lapinskas et al., 1985; Radzevičius et al., in press), 4) the interface between the carbonates of the uppermost Silurian and the siliciclastic-to-dolomite sequence of the Lochkovian, Lower Devonian, 5) the interface between the siliciclastic-to-dolomite sequence of the Lochkovian and sandstones of the Pragian in the Lower Devonian, 6) a dolomite layer (Stipinai Fm.) embedded in dolomitic marls in the upper part of the Frasnian, Upper Devonian, and 7) the interface between the carbonates of the upper Permian and the siliciclastic Triassic.

The Upper Devonian geological section also has a notably high reflectivity due to the carbonate content that is in contrast with the seismically transparent Silurian claystones. In the synthetic trace, several higher amplitude reflections are identified as related to the Devonian sandstones: Šventoji Formation of the lowermost Frasnian, the Upper Devonian is overlain by the dolomite and dolomitic marl dominated Upper

Devonian; and the sandstones of Narva Formation and Pärnu Formation, both of which belong to the Eifelian of the Middle Devonian.

3.1.2. Structural maps for key seismic horizons

The seismic reflecting horizons that can be traced regionally within at least part of the Baltic Basin are also observed in the study area. The structural maps were made for these regionally interpretable seismic reflection horizons: the top of the Precambrian, Pr (Fig. 14), the Ordovician – Silurian boundary, O3 – S1st (Fig. 13B), the top of Dubysa Formation in the Upper Silurian S2db (Fig. 15), the top of the Upper Silurian, S2 (Fig. 16), Gargždai Formation of Lochkovian in Lower Devonian, D1gr (Fig. 17), and the top of the upper Permian, P (Fig. 18).

There are several seismic reflection horizons that appear identifiable only in some seismic surveys but are difficult to trace across different seismic data sets. The reflecting horizons that represent Šventoji Formation (D3sv) of the lowermost Frasnian, Upper Devonian, Narva Formation (D2nr), or Pärnu Formation (D2pr) of the Eifelian, Middle Devonian, are such cases. The difficulty of interpretation is caused by the processing quality and the lateral change in the facies.

In addition, several stratigraphic boundaries that are important to this work are not well distinguished in the study area. Both the top of the middle Cambrian and the top of the lower Cambrian are such examples. In such a case, the required structural map can be obtained by using the structural map that is the closest available and subtracting/adding the thickness of the strata between these horizons. This thickness should be obtained from the borehole data. For example, the structural map of the top of the middle Cambrian, Cm2, is obtained from the structural map of the Ordovician – Silurian boundary by subtracting the thickness of the Ordovician strata (Fig. 19).

The thickness of strata between two seismic reflection horizons for the study area can be obtained by subtracting one structural map from another. For example, the thickness between the seismic refection horizons S2 and S2db (part of the Upper Silurian) is evaluated in this way (Fig. 20).

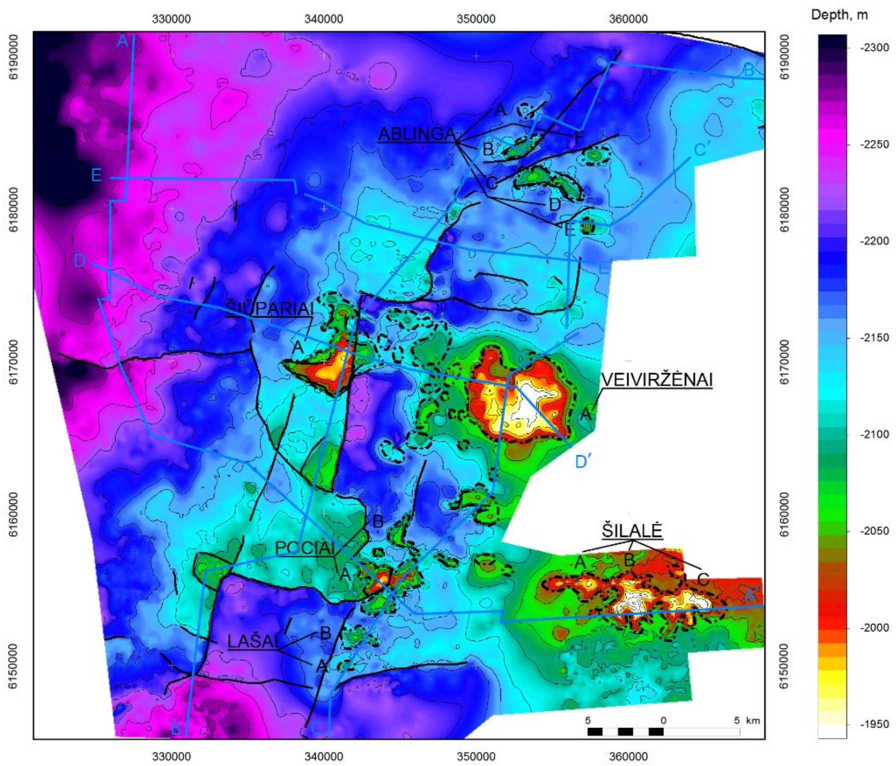

Fig. 14. Depth structure map of the top of the Precambrian (Pr). The horizon represents the unconformity between the crystalline rocks of the Precambrian basement and the lower Cambrian clastic deposits. The areas encircled by the dash-dotted lines represent the local structural highs of the Precambrian basement. Only the largest basement features have been named.

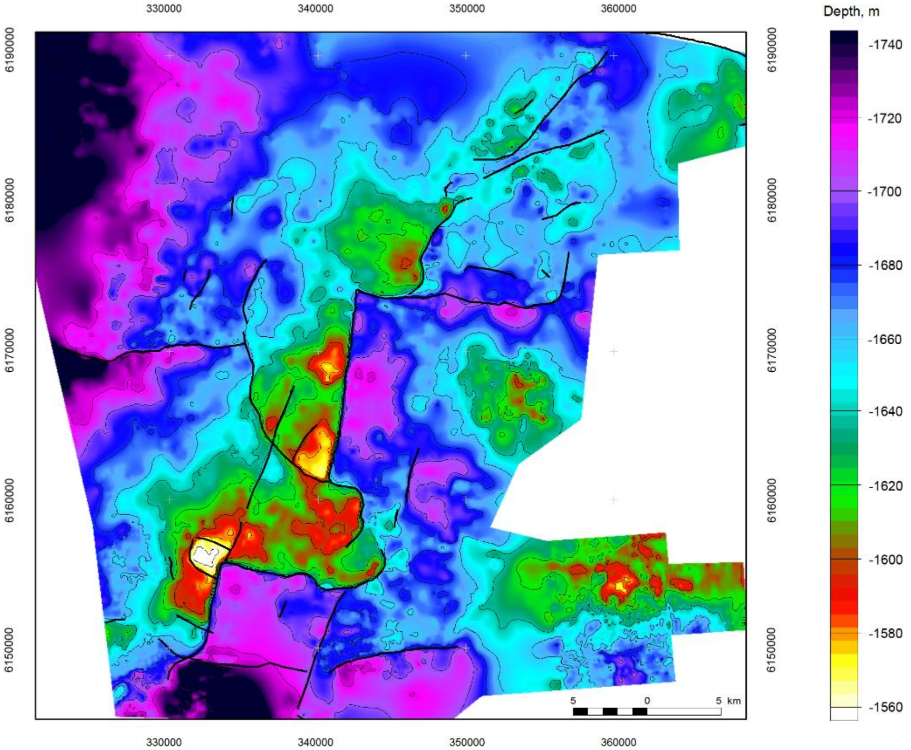

Fig. 15. Depth structure map of the top of Dubysa Formation in the Upper Silurian (S2db). The horizon represents the regional reflector associated with the carbonate layer in the Upper Silurian. It belongs to the Caledonian stratigraphical interval and is affected by the late Caledonian faulting. The overall structure of this horizon is similar to that of the other horizons of the Caledonian stratigraphic interval, and Gargždai Elevation with its local highs is expressed at this stratigraphic level.

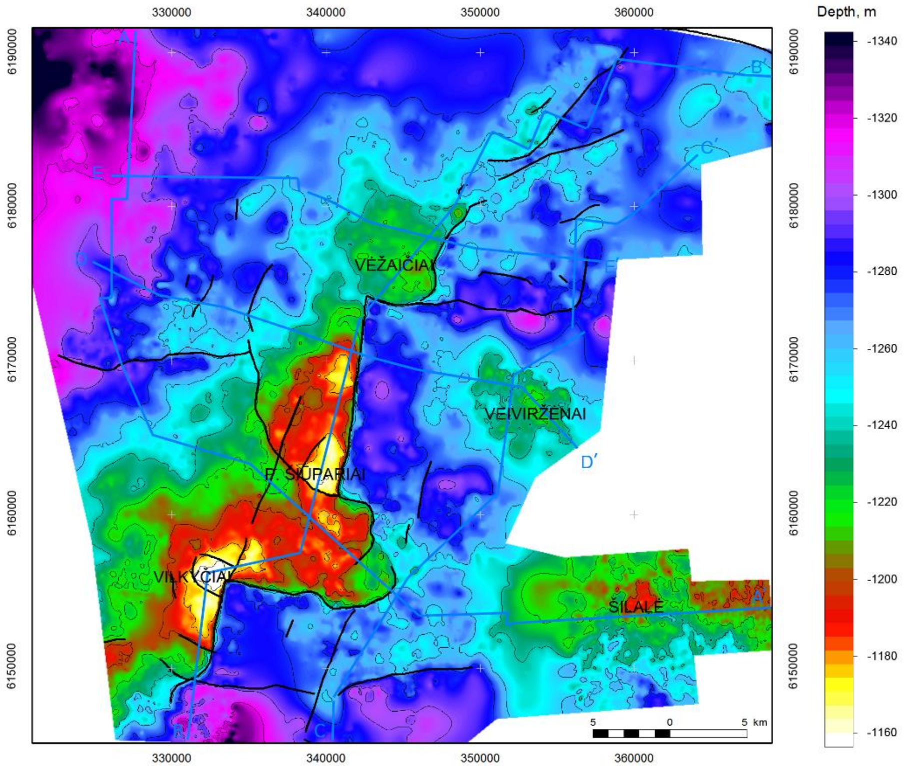

Fig. 16. Depth structure map of the top of the Upper Silurian (S2). The horizon represents the regional reflector associated with the carbonates of the uppermost Silurian. It is the youngest interpretable horizon belonging to the Caledonian stratigraphical interval and is affected by the late Caledonian faulting. The overall structure of this horizon is similar to that of the other horizons of the Caledonian stratigraphic interval, and Gargždai Elevation (with some of its local highs) is still expressed at this stratigraphic level.

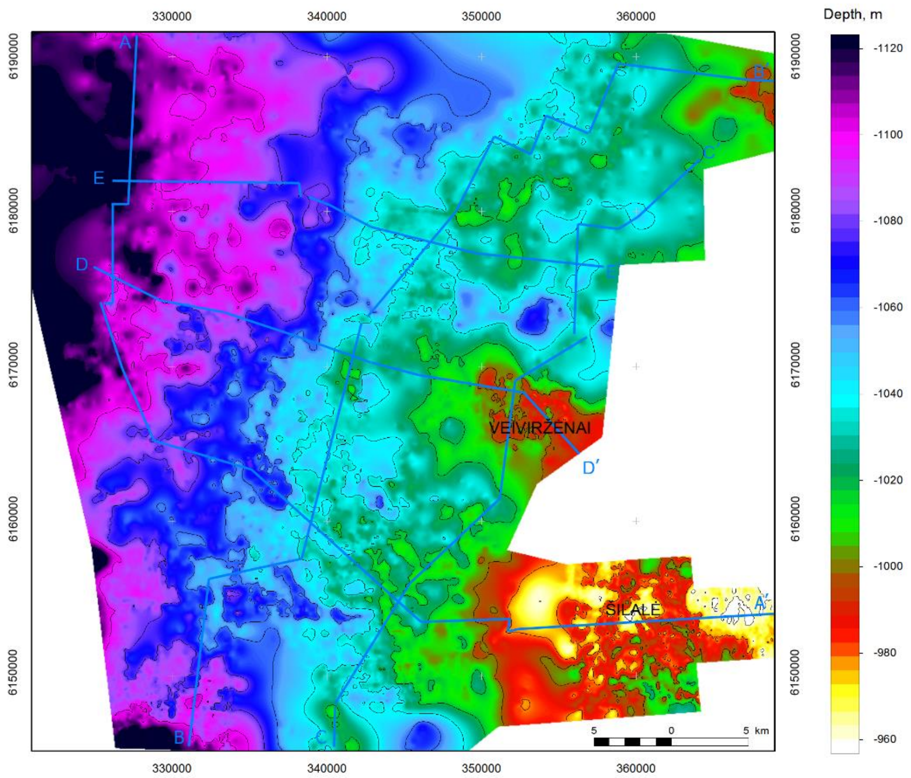

Fig. 17. Depth structure map of the top of Gargždai Formation of the Lochkovian, Lower Devonian (D1gr). The horizon represents the regional intra-Devonian unconformity, which marks the boundary between the Caledonian and Hercynian stratigraphical intervals in the Baltic Basin. The surface of this unconformity is not affected by any imaged or mapped faults in the study area.

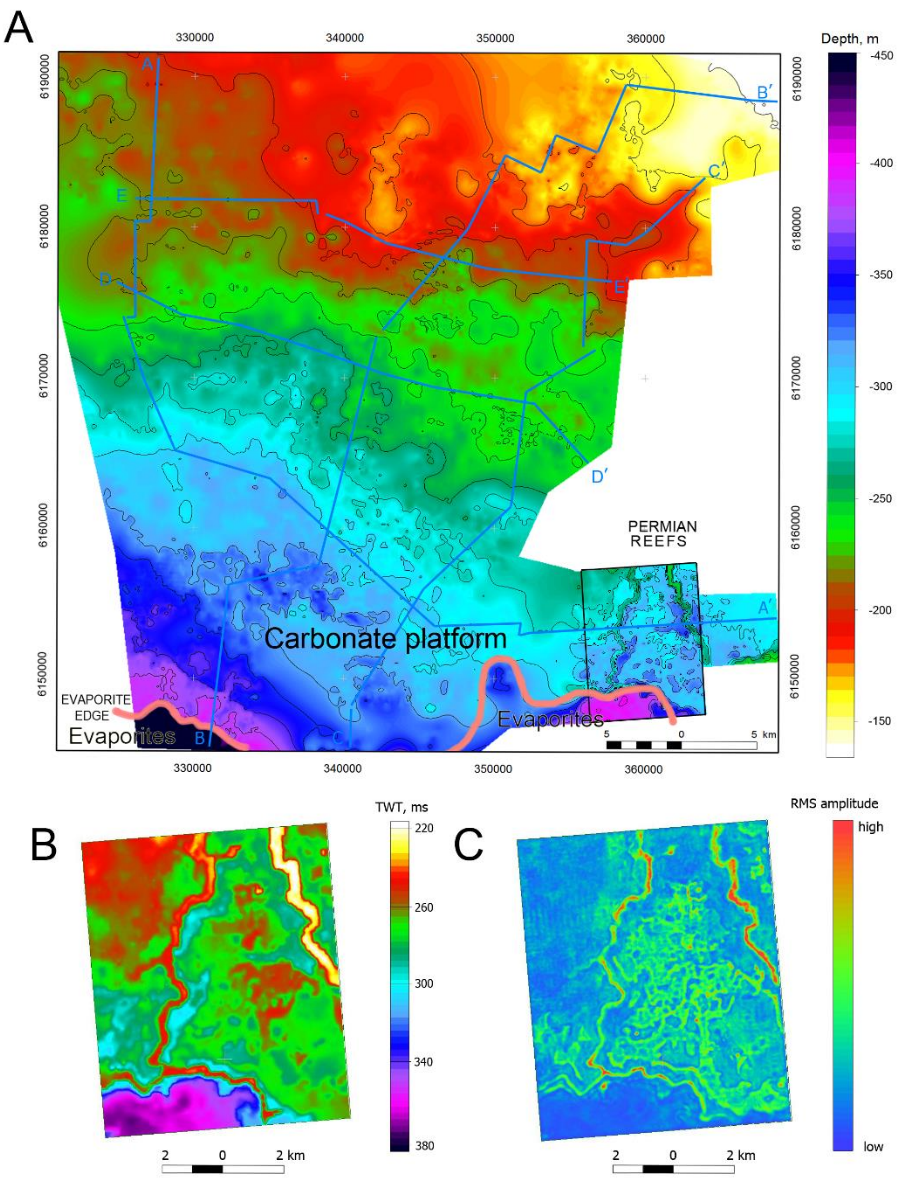

Fig. 18. (A) Depth structure map of the top of the Permian (P). This horizon represents a regional unconformity and marks the boundary between the Hercynian and the Alpine stratigraphical intervals in the Baltic Basin. The interpreted Permian reefs are shown in the south-eastern corner of the map, and their spatial relationship with the edge of Zechstein evaporites is shown (the pink polyline). (B) Time structure map of the interpreted reefs. (C) RMS amplitude map within a 100 ms window above the P horizon. Local topographical features also have a higher RMS amplitude.

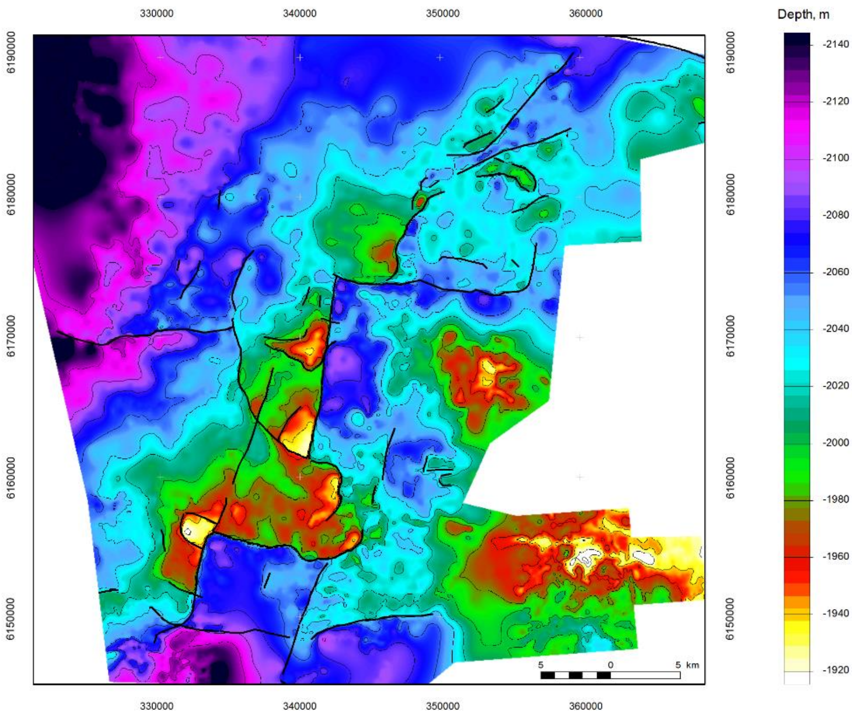

Fig. 19. Depth structure map of the top of the middle Cambrian Deimena sandstone (Cm2) which is the main reservoir in the Baltic Basin. Its overall structure closely resembles that of the other horizons of the Caledonian stratigraphic interval, especially the main seismic reflection horizon, O3 – S1st.

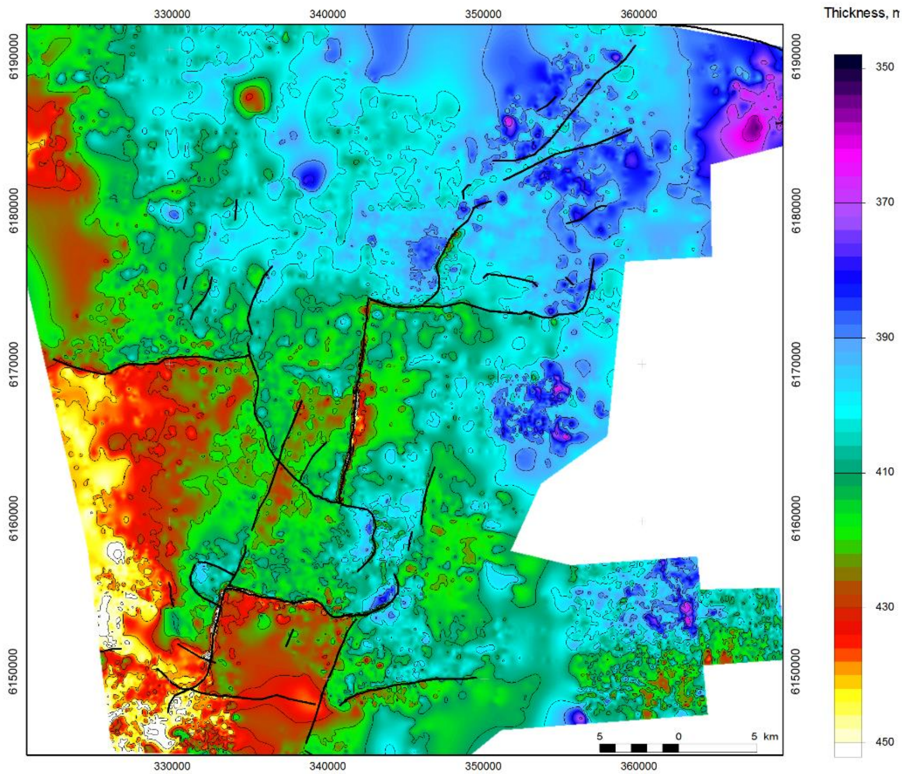

Fig. 20. Thickness of strata between the seismic reflection horizons S2 and S2db.

3.1.3. Seismic section interpretation

In order to illustrate the most important features of the study area and to represent its overall geological structure, several regional seismic profiles were produced. All these profiles are formed as composite seismic sections that are composed of several separate seismic surveys, where continuous profiles are made by joining 2D seismic lines and arbitrary sections of 3D seismic volumes.

Since these profiles cover the entire study area, they inevitably include such interesting features as the structural units – Gargždai Elevation and Gargždai Fault, the Precambrian crystalline basement highs and the related drape structures, the edge of Zechstein evaporites. From the West to the East, four of these composite sections cross the main structural element of the study area, Gargždai Elevation, and the main fault in the study area, Gargždai Fault: AA' (Fig. 21) in the south-central part, DD' (Fig. 24) in the north-central part and EE' (Fig. 25) in the northern part of these structures. In contrast, one of these composite sections, section BB' (Fig. 22), goes along Gargždai Elevation in the direction from the southwest to the northeast and avoids crossing Gargždai Fault. The seismic section CC' (Fig. 23) traverses the drape structures in the southeastern part of the study area.

The seismic reflection horizons interpreted in the sections are those identified as the highest amplitude reflections in the seismic to well tie, namely: Pr, O3 – S1st, S2db, S2, D1gr, D3st, and P.

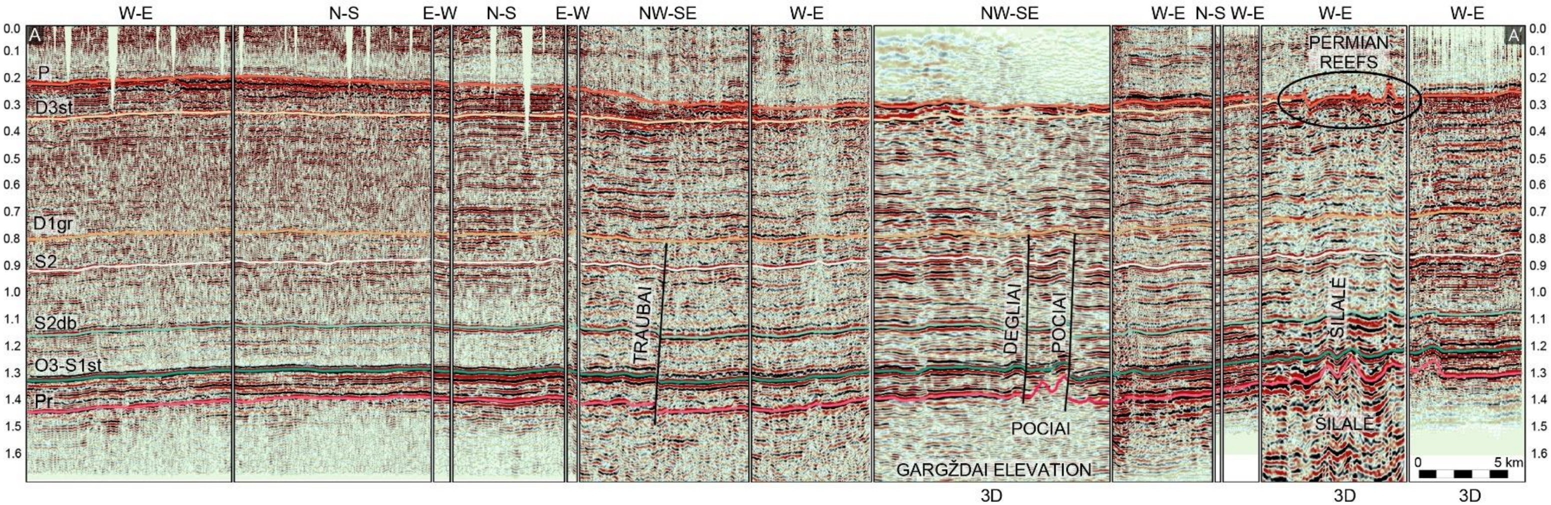

Fig. 21. Interpreted north-west to south-east oriented seismic section AA'. The composite line is a combination of 2D and 3D seismic sections. Labels at the top show the direction of individual seismic sections. Labels at the bottom indicate 3D sections, whereas 2D sections remain unlabeled. The interpreted faults are shown with black lines, but fault dips are apparent due to the horizontal compression. The interpreted seismic horizons are related to the top of Permian (P), Stipinai Formation in the upper part of Frasnian, Upper Devonian (D3st), Gargždai Formation of Lochkovian, Lower Devonian (D1gr), Upper Silurian (S2), Dubysa Formation of Ludfordian, Upper Silurian (S2db), the Ordovician – Silurian boundary (O3 – S1st), Precambrian crystalline basement (Pr). The names of the structural features of the Pr horizon are labeled below the Pr horizon. The names of the structural features of the O3 – S1st horizon are labeled above the O3 – S1st horizon (except for Gargždai Elevation). The section traverses Gargždai Elevation over its south-central part near Degliai and Pociai. The Precambrian crystalline basement is flat in the north-western side, and inselbergs characterize its south-eastern side. The proposed Permian reefs are indicated near the horizon P.

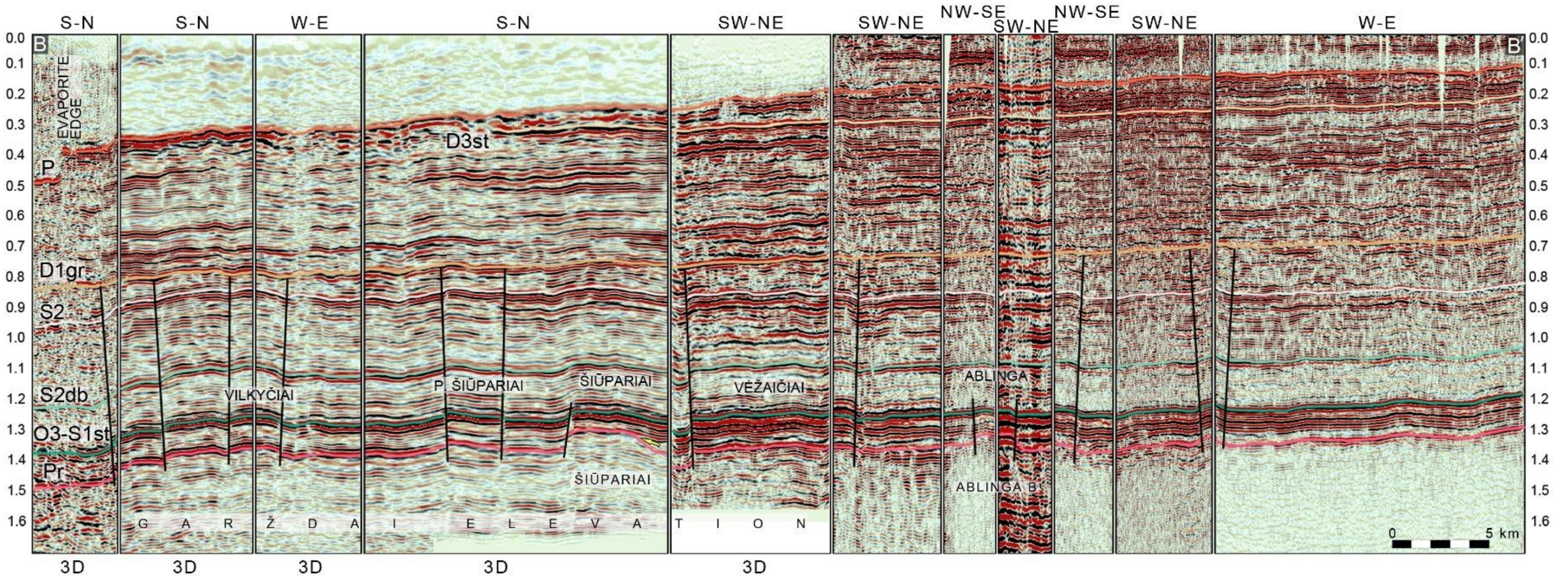

Fig. 22. Interpreted south-west to north-east oriented seismic section BB'. For the description of the interpreted objects, as well as the explanation of the labels and abbreviations, see the caption of Figure 21. The section traverses Gargždai Elevation to its full length from Vilkyčiai in the South – south-west to Vėžaičiai in the North – north-east without crossing the segments of Gargždai Fault. It crosses Šiūpariai, which is one of the largest Precambrian inselbergs in the study area. The edge of Zechstein evaporites is observed in the south-western side of the section.

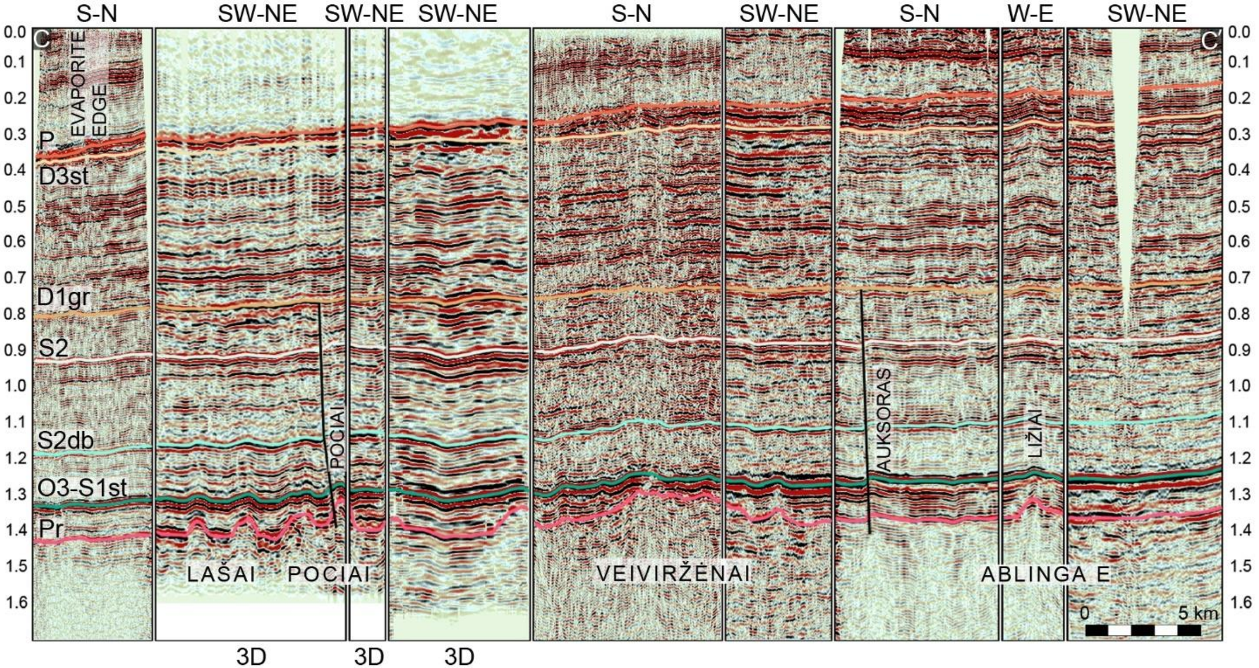

Fig. 23. Interpreted south to north-east oriented seismic section CC'. For the description of the interpreted objects, as well as the explanation of the labels and abbreviations, see the caption of Figure 21. It displays the abundance of Precambrian inselbergs and the associated drape structures, mainly in the south-eastern part of the study area. It crosses Veiviržėnai, which is the largest Precambrian basement feature in the study area. The edge of Zechstein evaporites is observed near the horizon P in the southern side of the section.

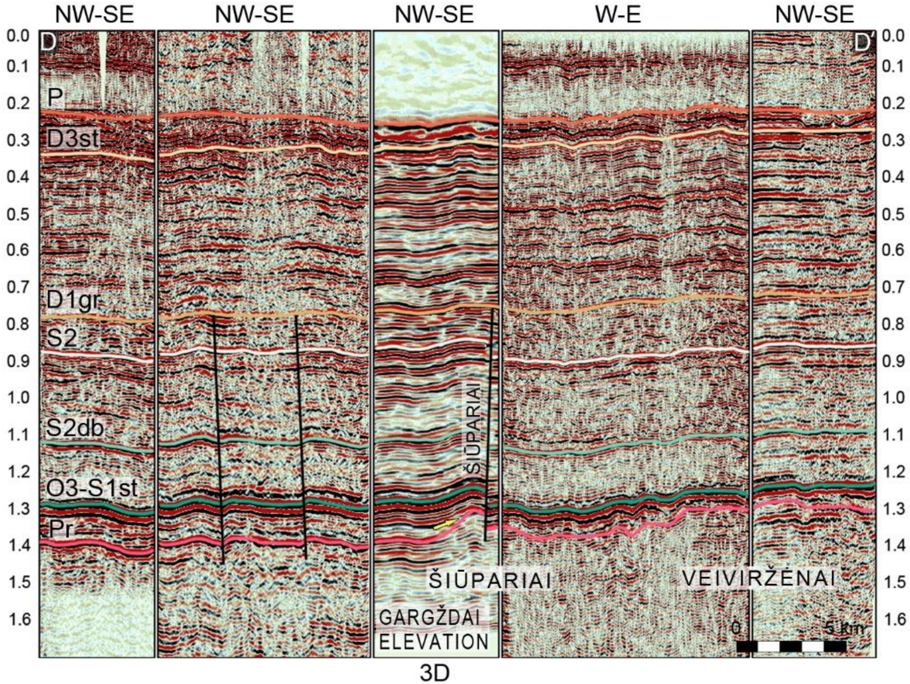

Fig. 24. Interpreted west-to-east oriented seismic section DD'. For the description of the interpreted objects, as well as the explanation of the labels and abbreviations, see the caption of Figure 21. It crosses Gargždai Elevation over its north-central part, which is near Šiūpariai. It also crosses two of the largest Precambrian inselbergs in the study area – Šiūpariai and Veiviržėnai.

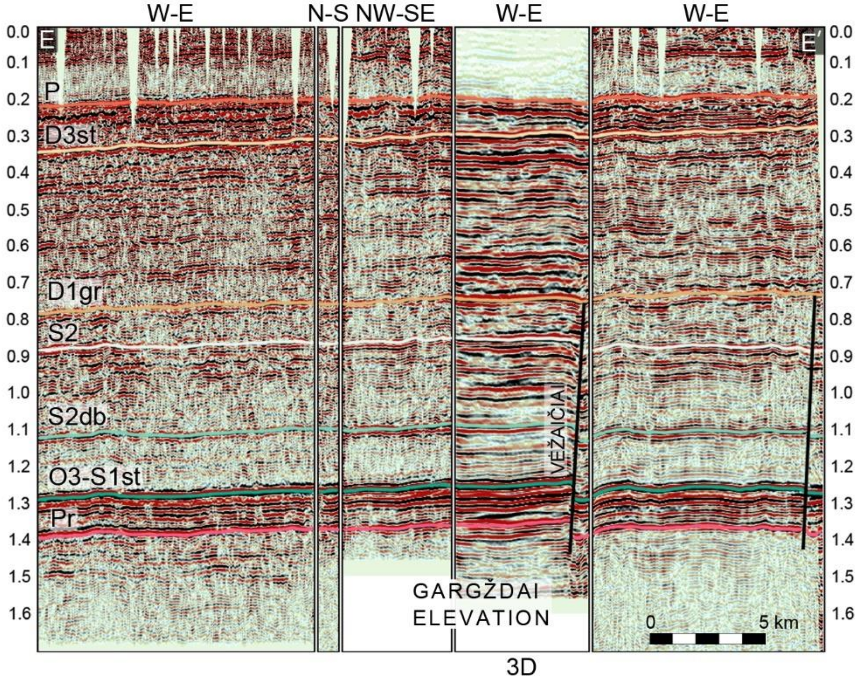

Fig. 25. Interpreted west-to-east oriented seismic section EE'. For the description of the interpreted objects, as well as the explanation of the labels and abbreviations, see the caption of Figure 21. It crosses Gargždai Elevation over its northern part, which is located near Vėžaičiai.

3.1.4. Seismo-geological framework

By virtue of representing the unconformity between the Precambrian crystalline rocks and the Cambrian clastic deposits, the seismic horizon Pr (Fig. 14) is the lower boundary of the Caledonian succession. The seismic horizons O3 – S1st (Fig. 13B), S2db (Fig. 15), and S2 (Fig. 16) are positioned within and belong to the Caledonian succession. The general structure of these horizons is similar. For example, the resemblance is expressed in the overall westward dip, Gargždai Elevation, and the pattern of the main faults (Figs. 13B, 14, 15, and 16). The similarity between the horizons O3 – S1st and Pr indicates that any stratigraphic level in between O3 – S1st and Pr has a similar structure, including the Cambrian stratigraphic levels (such as Cm2), for which, the structural map can be evaluated indirectly (Fig. 19). The Pr horizon has several distinct elevations near Šiūpariai, Veiviržėnai, Šilalė, and Pociai that are discussed separately in Chapter 3.2. The seismic horizon S2db, associated with the intra-Silurian carbonate layer, is also denoted by structural similarity to the main seismic reflection horizon O3 – S1st. The uppermost regionally interpretable horizon that is affected by the late Caledonian faulting and belongs to the Caledonian stratigraphical interval is the seismic horizon S2 (Fig. 16). The horizon D1gr (Fig. 17) represents the regional intra-Devonian unconformity and does not display even the main Caledonian structures, such as the faults or Gargždai Elevation. It is also the upper boundary of the Caledonian succession. Both horizons Pr and D1gr gently dip westward, so the entire Caledonian succession dips westward. The Caledonian interval thickens to the south-west, as it is illustrated by the seismic sections AA' (Fig. 21) and BB' (Fig. 22). The thickening is best observed when the stratigraphic interval between Pr and S2 is considered, because the interval between the horizons S2 and D1gr has been truncated at the horizon D1gr.

The seismic horizons D1gr (Fig. 17) and P (Fig. 18A) represent, respectively, the upper and lower boundaries of the Hercynian stratigraphic interval. The Upper Devonian horizon D3st is nearly parallel to the horizon D1gr. The thickness of the interval between D3st and P increases towards the North. Consequently, the thickness of the entire Hercynian succession increases to the North. This can be observed in the seismic sections AA' (Fig. 21), BB' (Fig. 22), and CC' (Fig. 23), and also by comparing the seismic section DD' (Fig. 24) to EE' (Fig. 25). The horizon D3st becomes difficult to interpret and cannot be distinguished from the horizon P in some southern parts of the study area, as it is shown by the seismic sections AA' (Fig. 21) and BB' (Fig. 22).

The regional unconformity separating the Hercynian and Alpine stratigraphical intervals is represented by the horizon P (Fig. 6, 18A). This is because, in the study area, the top Permian and the bottom Permian reflections cannot be distinguished; thus, the entire Permian strata belong to the Alpine succession, and the top Permian reflection represents the bottom of the Alpine succession. The bottom of the Alpine stratigraphic interval thickens to the south-west, while the top of the Permian dips to the south-west, as illustrated by the seismic sections BB' (Fig. 22) and CC' (Fig. 23).

3.1.5. Comparison of structural maps of the top of Ordovician

The same general features are shared between the previous (after Laškovas (1996) in Fig. 13A) and new (Fig. 13B) structural maps of the Ordovician – Silurian boundary. For example, a regional southwestward tilt of the entire O3 – S1st surface is observed in both maps, as well as the existence of the main structure in the study area – Gargždai Elevation. Gargždai Elevation is a closed elevated area of an elongated shape that is oriented north – north-east to south – south-east. The size of this structure is ca. 30 km in length, 10 km in width, and ca. 100 m in height above its surroundings (Fig. 13A). In the new structural map (Fig. 13B), Gargždai Elevation extends from Vilkyčiai in the south to Vėžaičiai in the north. A gentle gradual dip of sedimentary layers limits this elevation to the West and the North until they plunge beneath the confining depth isoline. To the east and the south, the elevation is abruptly limited by Gargždai Fault.

Gargždai Fault is interpreted as a single fault (as its name suggests), and its trace is typically mapped as a continuous line in the previous map (Fig. 13A). It has a general north-east – south-west strike, and it terminates at another regional east – west striking fault in the North (Telšiai Fault; Figs. 5 and 9). Parts of 'Gargždai Fault' in Fig. 13A can also be recognized in Fig. 13B, but the overall fault pattern is almost completely re-mapped. The first important difference between the maps is the new reverse faults that are mapped near Traubai, Agluonėnai, Ablinga and Auksoras. The second important difference between the maps is that the major faults near Veiviržėnai and Šilalė were not confirmed to exist (Fig. 13B). It is possible, though, that faults of a relatively small vertical throw may exist in the southeastern part of the study area which is dominated by the Precambrian palaeo-topographic features (Fig. 14) and drape structures that make the interpretation of such faults difficult.

As mentioned above, ‘Gargždai Fault’ can be recognized in both maps of the Ordovician – Silurian boundary (Figs. 13). In the map of 1996 (Fig. 13A), this fault is shown as a single continuous fault which also has the largest throw of all the faults in the study area. The trend of this fault has several sharp changes in its direction. The fault also has an obvious link to another regional fault in the north – Telšiai Fault (Figs. 5 and 9). In the new interpretation of faults (Fig. 13B), minor modification is observed at the parts of ‘Gargždai Fault’ that limit Gargždai Elevation near Vėžaičiai, Šiūpariai, and Vilkyčiai. However, no continuity of ‘Gargždai Fault’ is observed between Degliai and Pociai (see also Fig. 21). Moreover, there is no explicit link to Telšiai Fault in the North, that is, ‘Gargždai Fault’ does not terminate at Telšiai Fault in the North, but, instead, its throw diminishes at a distance to the south from Telšiai Fault. According to Žvirblis et al. (2006), ‘Gargždai Fault’ might start to pinch out as far as Antkoptis, which is at a distance to the South from Telšiai Fault. Finally, the acute changes of the fault trend suggest that ‘Gargždai Fault’ might be composed of a system or network of faults rather than a single fault, which might still be collectively known as ‘Gargždai Faults’.

Compared to the map of 1996, the surface of the horizon itself is considerably modified (Fig. 13B). The surface is of a much finer character with smaller scale structural and sedimentary features revealed in greater detail. This allows the identification of features of smaller spatial dimensions. For example, several drape structures of a diameter of 2–3 km are mapped near Ablinga. Agluonėnai structure, located at a 4–5 km distance to the east from Gargždai Fault, is also identified in the new map. This structure is an extension of Gargždai Elevation to the west, but, previously, there was no indication that there is a separate local high (Fig. 13A). The largest drape structures of Šilalė and Veiviržėnai are revealed with enough detail to show that they feature more complicated shapes than merely broad structural highs. The improvement of the fault network and the horizon surface are expected because the structural map (Fig. 13B) is based on the 3D seismic data, a much denser network of 2D seismic profiles, and it covers areas that have not been explored previously by the seismic method (Brown, 2011).

3.1.6. Drape structures and inselbergs

Some of the Precambrian crystalline basement highs, especially the large ones, were known previously. These are the largest highs whose existence was proved by drilling – those of Šilalė, Veiviržėnai, Pociai, Šiūpariai, and Ablinga (Stirpeika, 1999). However, detailed mapping revealed that, in the southeastern part of the study area, the deepest horizon, Pr, has a more complicated structure than the second deepest horizon, O3 – S1st. That is, the Pr horizon exhibits many local highs (Fig. 14).

Unlike previously thought, these highs occur not only as single isolated features, but also as clusters of such features (Ablinga and Pociai – Lašai). There also are many small features in between the large ones of Šiūpariai, Veiviržėnai and Pociai (Fig. 14). These small ones are not given any names yet because they were only partly identified in the 2D seismic profiles. Many more features could be mapped if a full 3D seismic coverage existed for this area. These Precambrian palaeo-topography highs are most likely inselbergs on the sub-Cambrian peneplain, that is, remnants of erosion. As the Baltic Basin developed in the Late Palaeozoic, they were gradually buried under sediments. Otherwise, the sub-Cambrian peneplain does not have many inselbergs; instead, its surface is mostly smooth (Lidmar-Bergström, 1995; Sopher et al., 2016). These observations allow suggesting that, while the crystalline basement was peneplanated in other parts of the study area and in the Baltic Basin, these local highs form an exceptional array of inselbergs in the southeastern part of the study area (Grendaitė et al., 2022). The topic on inselbergs and the associated drape structures is developed in Chapter 3.2. Here, they are shortly introduced, as they are necessary for the subsequent discussion (see the section on the structure types).

3.1.7. Fault types

The dominating faults in the study area are late Caledonian reverse faults which affect the entire Caledonian stratigraphic interval. The major reverse faults are composed of a series of linear segments which display fault-traces extending 10–15 km in length. These segments form an orthogonal network with approximately North – South or East – West strikes (Fig. 13B). The largest throws of ca. 100 m (up to 150 m near Vilkyčiai) typically characterize the segments that belong to ‘Gargždai Fault’ (Fig. 13A). Smaller throws of 10–40 m characterize the remaining reverse faults.

'Gargždai Fault' in sections AA' (Fig. 21), DD' (Fig. 24), and EE' (Fig. 25) serves as the best example of such faults in the study area.

Reflections below the horizon Pr are not observed in the seismic sections. The faulting always involves the Precambrian basement. The vertical displacement of horizons along the major faults (segments of Gargždai Fault) does not show significant variations, as observed at the horizons in the upward direction Pr, O3 – S1st, S2db and S2. The vertical displacement for other faults occurs along the fault surface at the lower horizons Pr and O3 – S1st, but, for the upper horizons of S2db and especially S2, it is distributed along the folded surface thus forming fault-propagation folds (Brandes and Tanner, 2014). The dominant rock type might also have undergone some influence on the distribution of deformation near faults. For the Precambrian crystalline basement rocks, Cambrian sandstones, and Ordovician limestones, the deformation was more brittle. For the shale dominated Silurian succession, the deformation was softer. In the study area, the reverse faults are likely to have formed at the end of the formation of the Caledonian stratigraphic interval (in the Early Devonian) because they always involve the Precambrian basement and terminate at the regional intra-Devonian unconformity (D1gr), and the vertical displacement of the horizons along these faults does not show significant variations. This can be cross-checked in the S2 – S2db thickness map (part of the Upper Silurian), where this thickness shows variations across faults only near Traubai, Vilkyčiai, and Lašai. The faults of the study area represent the late stage of the Caledonian Orogenic event. In the Baltic Basin, the Caledonian Orogeny resulted in compressional folding and faulting (Poprawa et al., 1999), as well as the subsequent uplift and erosion, which is evidenced by the regional intra-Devonian unconformity at the horizon D1gr (Sopher et al., 2016). As a result, the major structures of the Baltic Basin formed (Brangulis et al., 1993), including the heavily faulted, uplifted, and eroded Liepāja – Saldus Ridge (Figs. 5 and 6).

In the seismic sections of the study area, the faults that occur in relation to the Precambrian palaeo-topographic features can also be observed (Figs. 13B and 14). These faults can be characterized by their irregular and curvilinear trends. They also closely follow the boundaries of the Precambrian crystalline basement highs. Consequently, such faults have a trend that rarely exceeds 5 km, as their spatial extent does not exceed the size of the Precambrian palaeo-topographic features. In terms of the vertical throw, it is largest at the level of the seismic horizon Pr, then it diminishes gradually upwards within the Caledonian stratigraphic interval until it virtually disappears or turns into a slope of a drape. They are not typically interpreted at the S2, or even the S2db horizon. Thus, the interpretation of these faults is merely a sharp expression of drape structures when a fault-like structure is observed in the lower stratigraphic level instead of a broad anticline. The original shape of the Precambrian palaeo-topographic features has likely had influence on the formation of such fault-like structures where the shape of the Palaeo-topographic features has been inherited. For example, when a Precambrian palaeo-topographic feature has a high and steep escarpment instead of a gentle slope, and it is coupled with differential compaction, the slope of the related drape structure should also be rather steep. For example, such a fault-like structure can be observed in the seismic section BB’ (Fig. 22) and is related to the Šiūpariai palaeo-topographic feature (Fig. 14).

3.1.8. Structure types: fault related, drape structure related, composite, and cross-fault

Gargždai Elevation hosts hydrocarbon accumulations in its highest parts whose names are given in Fig. 13B. The reservoir is in the middle Cambrian sandstones, sealed by the Ordovician and Silurian shales and carbonates. A structural type can be assigned to these highest parts of the main Gargždai structure.

These local highs that are located next to Gargždai Fault can be termed as fault-related structures (such as Vilkyčiai, Degliai, Vėžaičiai). Some structural highs are surrounded by faults from several sides (such as P. Šiūpariai, Agluonėnai in Fig. 14). The seismic sections BB’ (Fig. 22) and EE’ (Fig. 25) illustrate the fault related structures: section BB’ goes along Gargždai Fault (Vilkyčiai, P. Šiūpariai, Vėžaičiai in the seismic section BB’, Fig. 22), whereas the section EE’ goes across Gargždai Fault (Vėžaičiai in the seismic section BB’, Fig. 22).

Several structural highs are drape structures that formed above the Precambrian crystalline basement highs. They are named as drape related structures (for example, Veiviržėnai, Šilalė). For a structure of this type to occur, an underlying positive palaeo-topographic feature of the Precambrian crystalline basement must be present. Since these Precambrian basement structures were buried under the Lower Palaeozoic sediments, a depositional thinning or even pinch out of the Cambrian strata (or Cambrian and Ordovician together) can be observed against the palaeo-topographic features. After they were completely buried under a thick overburden, broad and gentle anticlines got formed above those features as a result of the differential compaction of the sedimentary strata after the burial. As it can be observed both in the structural maps and the seismic sections, the amplitude of such broad drape anticlines diminishes gradually in the upward direction within the Caledonian stratigraphic unit. Only-drape related structures are observed in the seismic sections AA’ (Šilalė in Fig. 21), CC’ (Lašai, Fig. 23) and DD’ (Veiviržėnai, Fig. 24). Veiviržėnai crystalline basement high is related to the largest drape structure in the study area and is found at the intersection of the seismic sections CC’ (Fig. 23) and DD’ (Fig. 24).

The overlap of the drape structures and the fault-related structures create structural highs of the composite type (such as Pociai, Šiūpariai, Ablinga). The overlap is possible because the location of the Precambrian crystalline basement highs (Fig. 14) is not related to the pattern of the Caledonian faulting (Fig. 13B). One of the structures of composite type, specifically, Pociai, is observed near the intersection of the seismic sections AA’ (Fig. 21) and CC’ (Fig. 23). Another structure of this type, Šiūpariai, is located at the intersection of the seismic sections BB’ (Fig. 22) and DD’ (Fig. 24). Indeed, Šiūpariai structure is covered by the 3D seismic. This structure displays all of the characteristics of a drape structure (see the paragraph above), as illustrated by the seismic sections BB’ (Fig. 22) and DD’ (Fig. 24), and by the structural maps of the horizons Pr (Fig. 14), O3 – S1st (Fig. 13B), S2db (Fig. 15), and S2 (Fig. 16).

These three structure types – fault related, drape structure, and combined – were also recognized by Stirpeika (1999). Structures that are bound by several crossing faults (Agluonėnai) were not previously observed in the study area; however, they were known in other parts of the Baltic Basin (north-western Poland), and are called cross-fault structures (Domźalski et al., 2004).

3.1.9. Features of the top of Permian

Several features observed in the structural map of the top of Permian, P (Fig. 18), and the seismic sections BB’ (Fig. 22) and CC’ (Fig. 23) are related to Zechstein Basin. In the southern part of the study area, there is a sudden increase in the depth of the top of the Permian. The area with a larger depth is beyond the irregular line in Fig. 18. As it can be observed for the seismic horizon P on the southern side of the seismic sections BB’ (Fig. 22) and CC’ (Fig. 23), the two-way time for the seismic horizon P increases in a step-like drop of up to 100 ms. This sudden increase in depth in the structural map is interpreted as the edge of Zechstein evaporites.

In the southeastern part of the study area, a few features can be observed that are characterized by a narrow, elongated shape. They can be observed in the southeastern part of the study area in the structural map (Fig. 18A), as well as in the southeastern side of the seismic section AA' (Fig. 21). The close-up of the area is based on 3D seismic survey (Fig. 18B). In order to be more descriptive, the length of these objects is at least 7–8 km, whereas the width is up to 1 km. They form areas of 50 ms of the palaeo-topographical relief at the seismic horizon P in the seismic section AA' (Fig. 21) in the southeastern part of the study area. These structures are located on a carbonate platform adjacent to the mapped edge of Zechstein evaporite basin (Fig. 18), and they are within the area of Permian reefs, as proposed by Kadūnas (2001). These elevated elongated features are characterized by an observably higher reflection amplitude (Fig. 18C). In the seismic section AA', the velocity pull-up effect can be observed for reflections slightly beneath these structures (Fig. 21). This effect indicates a higher seismic wave propagation velocity for the rocks that form those structures than the rocks that embed them. Therefore, these structures are tentatively interpreted as representing Permian reefs likely composed of high-velocity carbonate rocks which typically have higher interval velocities and are the cause of these velocity pull-ups. Carbonate build-ups of a similar elongated shape on time structure maps were documented by Rafaelsen et al. (2008). Unfortunately, no borehole was drilled through these interpreted reefs, and no borehole data were available to support this interpretation.

Zechstein Basin is known as one of the typical locations of reef development in the Permian. Western Lithuania was a north-eastern bay of the Zechstein Sea in the Late Permian. Significant carbonate platforms developed in the first two sedimentation cycles of Zechstein Basin (Krzywiec et al., 2017). Reefs are confined to these carbonate units and typically occur at the shelf to basin edges (Kuznetsov, 2018). However, on topographic highs, reefs can develop in basinal facies (Peryt et al., 2012; 2020). The carbonate units can be sealed either from the top (the first cycle), or from both sides (the second cycle), when evaporites are present. In such cases, they form entrapping structures for hydrocarbons (Karnkowski, 2007; Karnkowski et al., 2010). The upper Permian carbonate platform in Western Lithuania belongs to the first (Werra) sedimentation cycle of Zechstein Basin. In the study area, this carbonate platform is not covered with a thick layer of evaporites that could form a seal for the proposed reefs that are observed on the edge of this platform adjacent to the edge of evaporites. The Permian strata form a high velocity layer. Seismic images beneath this high velocity layer, including the hydrocarbon containing lower Palaeozoic, can be distorted by the variable thickness of this high velocity. This distortion leads to the interpretation of false (apparent) structures; therefore, it must be accounted for. Good understanding facilitated by the detailed mapping of Permian is needed to avoid interpreting false structures of the Lower Palaeozoic.

3.2. Inselberg array

3.2.1. Thickness of the succession between the O3 – S1st and Pr horizons

The main seismic reflectors (horizons) in our study area, while being also of regional importance, were distinguished by the seismic-to-well tie. To investigate the sub-Cambrian peneplain, which is at the base of the sedimentary cover, only the two lowermost horizons are relevant. These horizons are the top of the Precambrian crystalline basement (Pr) and the Ordovician – Silurian boundary (O3 – S1st). The location of the recent seismic surveys determined the irregular spatial extent of the interpreted horizons, which is confined within an irregular interpretation polygon (Fig. 13B and Fig. 14). Within the context of the development of the Baltic Basin, the study area has a local extent, and the geological structure of the study area can be described as rather simple. In the study area, the Ordovician – Silurian boundary is at 1860–2040 m and the top of the Precambrian crystalline basement is at 1960–2310 m below the mean sea level. These structural maps are comparable – both of them are generally smooth and have an overall tilt to the West. Both horizons are also complicated by the same set of Caledonian faults of a relatively small throw (up to 150 m). The thickness of the strata between horizons also varies smoothly. The Ordovician – Silurian boundary usually mimics the crystalline basement; however, this mimicking is not obvious in the southeastern part of the study area, which suggests that the structure of the horizon Pr is more complicated than that of O3 – S1st.

The two structural surfaces, the Ordovician – Silurian boundary (O3 – S1st, Fig. 13B) and the top of the crystalline basement (Pr, Fig. 14), confine a part of the Lower Palaeozoic – the Cambrian and Ordovician – sedimentary strata. The thickness of these strata can be obtained from the difference in the burial depth of both horizons, that is, by subtracting one surface from another. Based on the distribution of the thickness values (the map of thickness), the study area can be divided into two domains (Fig. 26).

One domain has a greater (200–250 m), rather constant and smoothly varying thickness and occupies the northwestern part of the study area. The other domain has a smaller (50–150 m) and irregular thickness and occupies the southeastern part of the study area.

In the study area, the map of thickness between the horizons O3 – S1st and Pr excludes the general westward tilt of the crystalline basement and the overlying strata. It also effectively removes the displacement of sedimentary rocks that was caused by the faults that occurred in the Late Silurian – Early Devonian in relation to the Caledonian orogeny. The process of the subtraction of one horizon from another can be viewed as the flattening of the upper horizon – the Ordovician – Silurian boundary (O3 – S1st) – because the sedimentary rocks above the Ordovician – Silurian boundary are not accounted as if they have been stripped off. In this way, the surface of the Ordovician – Silurian boundary is reconstructed to the flat surface which existed at the time of deposition at the end of the Ordovician – the beginning of the Silurian. The surface of the top of the Precambrian crystalline basement is also reconstructed to nearly its original topography. This is a valid general approximation because, in the early Paleozoic until the Late Silurian, the Baltic Basin did not experience a rapid subsidence or uplift in the study area. Therefore, the lesser thickness in the southeastern part of the study area indicates both the lack of sedimentary rocks and the positive topography of the Precambrian crystalline basement.

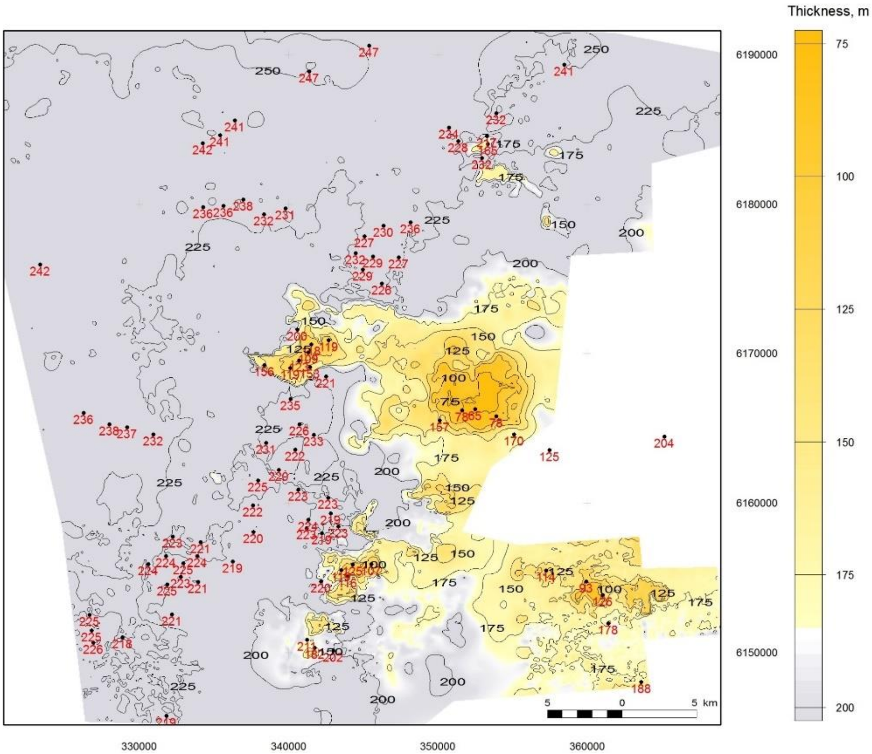

Fig. 26. Thickness of the Cambrian and Ordovician strata taken together, obtained as the difference between the horizons of the top of the Ordovician (Or) and the top of the pre-Cambrian crystalline basement (Pr). The depth is indicated by the color scale (grey – thick, yellow – thin), the contours of equal depth and the depth values on contours. Contours of equal thickness are drawn every 25 m. Black dots mark wells with both top of Or and top of Pr constrained; the numbers below borehole symbols show the actual thickness in those boreholes in meters.

3.2.2. Precambrian palaeo-topography

A possibly sub-continental extent of the sub-Cambrian peneplain is much larger than the extent of the study area. If the sub-Cambrian peneplain had been present across the entire study area, then the expression of its presumably flat surface would allow only a relatively small and smooth variation in the thickness between the horizons O3 – S1st and Pr over a large horizontal distance. However, the distribution of thickness values on the O3

– S1st to Pr thickness map shows at least two domains. Moreover, a sharp change in the O3 – S1st to Pr thickness and its character can be observed in the southeastern part of the study. Hence, the change from one domain to another is also sharp, and it can be interpreted to represent a palaeo-topography transition from a peneplain-like flat to a more hilly terrain. The southeastern part of the study area, which has a rougher palaeo-topography, is at least 30 km wide. Its highest points are 100–150 m above the flat peneplain's surface. Currently, it is not possible to determine the full extent of this area because seismic surveying has not been conducted recently to the East of our study area.

The extent of palaeo-topography features (Fig. 27) was evaluated based on the thickness map (Fig. 26) and seismic sections (Fig. 28). The distribution of the Precambrian crystalline basement palaeo-topography features allows distinguishing several groups of features.

1) Ablinga is a cluster in the northeastern part of the study area that lies outside the main high palaeo-topography area and is comprised of six individual features (A and B – Ablinga, C and D – Žadeikiai, E – Ližiai, F – Mostaičiai).

2) Šiūpariai has one large, distinguished feature, namely, Šiūpariai A, which is of an irregular shape with a diameter of 6–7 km. Probably, it is cut by Gargždai Fault because the thickness of the strata confined O3 – S1st to Pr horizons is reduced on both sides of the fault.

3) Veiviržėnai also has one distinguished feature, specifically, Veiviržėnai A, which also is the largest and roundest feature in our study area with a diameter of at least 7–8 km. It is also the highest feature in the study area. The thickness of the O3 – S1st to Pr sedimentary strata above this feature is the smallest, to that extent that the Cambrian strata are completely missing (Fig. 26).

4) Pociai – Lašai is a cluster of at least four individual features with Pociai A being the largest (~4 km in diameter, with the others being 1–3 km in diameter). Pociai A is of a somewhat complicated shape and appears to be cut by Gargždai Fault.

5) Šilalė is of an irregular and elongated shape, ca. 12 km long and ca. 4 km wide; it is oriented E-W and is comprised of three parts (A, B, and C).

6) The remaining numerous small features between Šiūpariai, Veiviržėnai, Pociai – Lašai and Šilalė are not named and not assigned to any feature group.

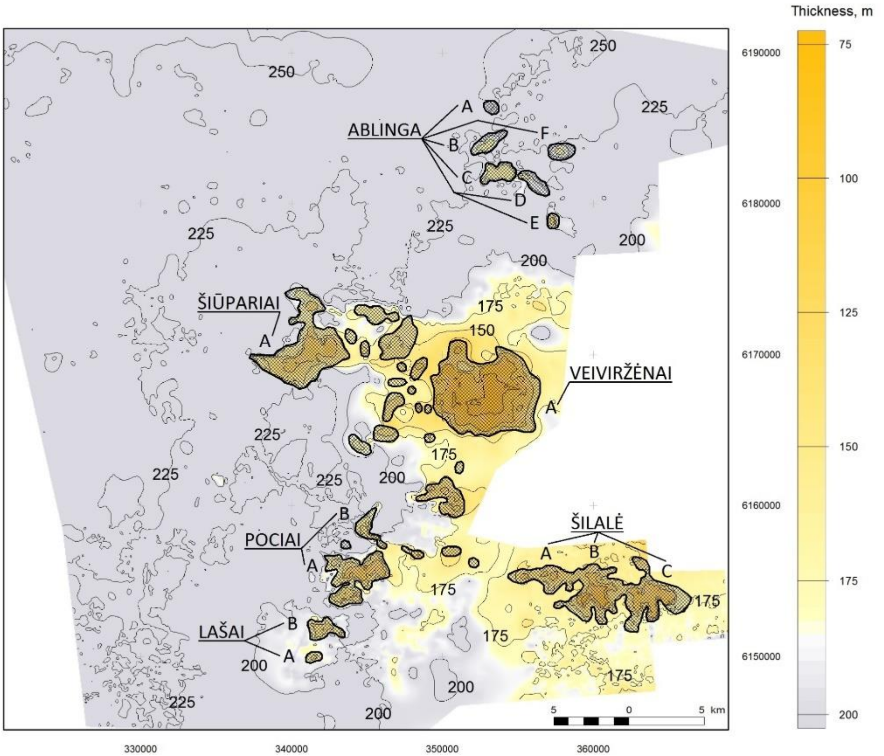

Fig. 27. Full areal extent of the Precambrian crystalline basement topographic features (shaded areas) overlain over the thickness of the Cambrian and Ordovician strata (Fig. 26).

The inferred palaeo-topography of the sub-Cambrian peneplain is approximate because it is based on the present-day thickness between the horizons O3 – S1st and Pr. The unconformities in the lower/middle Cambrian (the Hawke Bay unconformity), and in the upper Cambrian and the upper Ordovician were not accounted for. An unknown amount of compaction was experienced by the sedimentary rocks but not the crystalline rocks, as a thick overburden accumulated in the subsiding basin. Nevertheless, the sedimentary effects on the thickness of the strata limited by the horizons O3 – S1st to Pr, appear to be of a much lesser importance than the effects of the subsequent tectonic events which need to be attenuated, as discussed in the previous chapter. Also, the O3 – S1st to Pr thickness map is only one of the tools to distinguish the Precambrian palaeo-topographic features, the other being the interpretation of the seismic sections themselves.

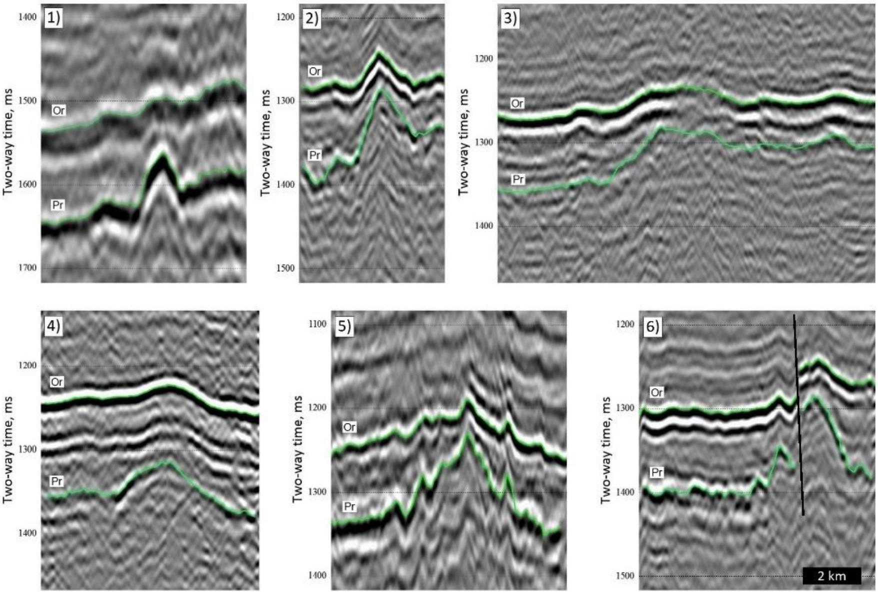

Fig. 28. 2D seismic sections with examples of pre-Cambrian crystalline basement topographic features. Or – top of Ordovician, Pr – top of pre-Cambrian. The length of the black ribbon at the bottom right corner of the last section corresponds to a horizontal distance of 2 km; the same scale applies to all of these sections. Feature name, position and size (see also Fig. 27): 1) unnamed isolated feature in the Lithuanian offshore area (outside our study area), diameter <2 km; 2) Pociai A, N-S section, diameter ~3 km; 3) Veivirženai A, largest feature in the study area, diameter up to 10 km; 4) Ablinga B, diameter ~4 km; 5) Šilalė B, diameter ~5 km; 6) Pociai A, E-W section, diameter >3 km. The diameter is approximate, and it is evaluated from the bases of the topographic features.

3.2.3. Seismic sections of drape structures

The additional complexity of the two surfaces of top of the Precambrian crystalline basement (Pr) and the Ordovician – Silurian boundary (O3 – S1st) can be demonstrated by their respective seismic horizons in the seismic sections (Fig. 28). These sections are taken from the southeastern part of the study area. The top of the Precambrian crystalline basement (Pr) has 'hill'-like features of the basement. The sedimentary cover of the Precambrian basement, as illustrated by the Ordovician – Silurian boundary, drapes the Precambrian features. The draping is a result of the differential compaction of the Ordovician and Cambrian sedimentary rocks. The sedimentary rocks experienced a reduction in their thickness, whereas the Precambrian crystalline rocks did not. This led to the formation of drape structures (also called compaction structures) above the positive palaeo-topography of the crystalline basement.

3.2.4. Context of western Lithuania

In Western Lithuania, several palaeo-topography features of the Precambrian crystalline basement were known previously (Stirpeika, 1999). Some of these are found within our study area: Šiūpariai A, Veiviržėnai A, Pociai A, Šilalė B, and Ablinga B. In this work, many new ones have been mapped with their characteristics outlined in detail – Ablinga cluster, Pociai – Lašai cluster, Šilalė true shape, and many smaller features in between Šiūpariai, Veiviržėnai, Pociai – Lašai and Šilalė (Fig. 27). Moreover, 2D and 3D seismic data have been used to map the shapes and dimensions of these features to a very high precision, both for the features known previously and those mapped in this work for the first time.

The other Precambrian palaeo-topography features in Western Lithuania, and outside our study area, are these: Plungė to the North, Baubliai to the East, Lauksargiai to the South with respect to the study area (Fig. 29). All of these features were confirmed by drilling, that is, a smaller thickness of the O 3 – S1st to Pr succession was observed in boreholes. The thickness is reduced at the expense of the lower part of the Cambrian or even an absent Cambrian, hence the high Precambrian palaeo-topography.

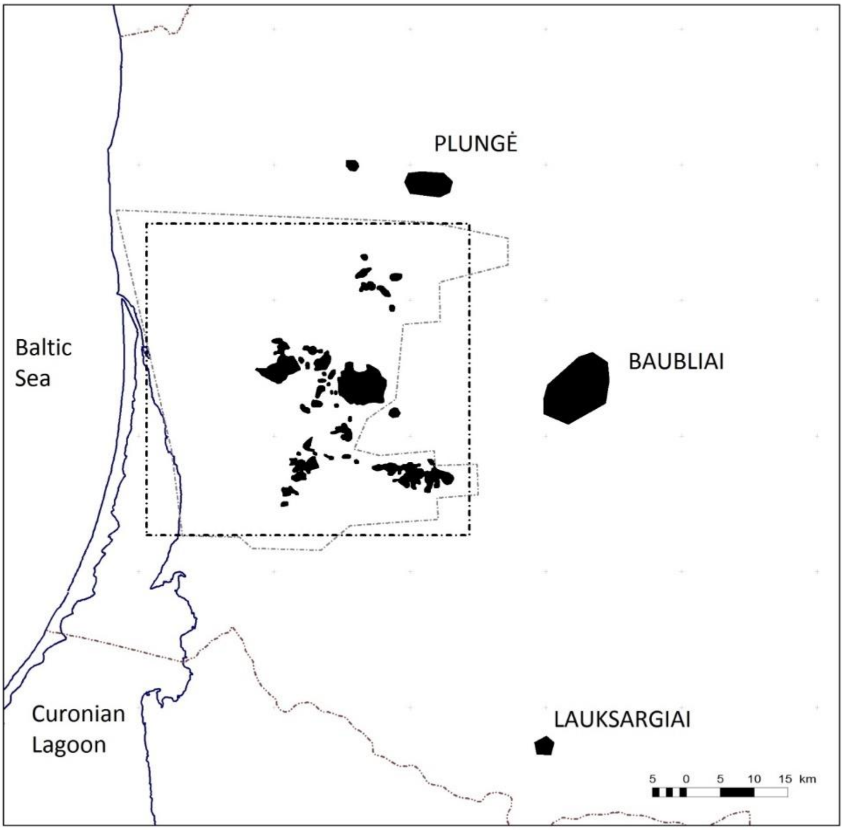

Fig. 29. Precambrian crystalline basement topographic features (black areas) in Western Lithuania, within our study (detailed) area and outside it (sketch). The black rectangle defines our study area, the grey polygon defines the interpretation polygon, and the main palaeo-topographic features are named.

3.2.5. Context of the Baltic Sea region

The palaeo-topography features of the Precambrian crystalline basement are reported in the Baltic Basin outside Western Lithuania; therefore, they are not unique to Western Lithuania (Fig. 30). Presented here is a list of such features that has been compiled from the currently available scientific and other sources.

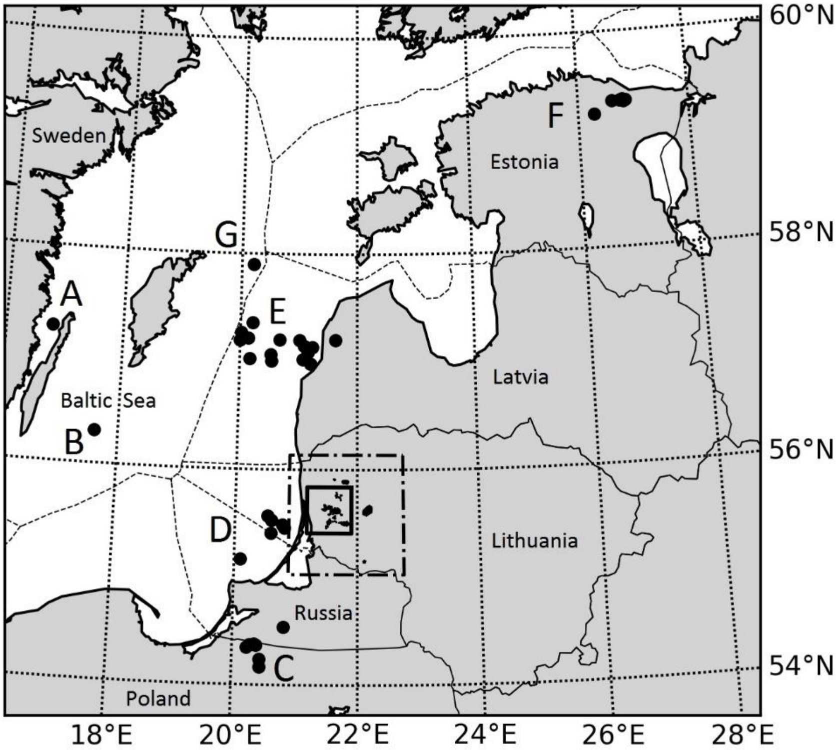

Fig. 30. Pre-Cambrian crystalline basement palaeo-topographic features within the Baltic Sea region. The black solid rectangle defines our study area (Figs. 5 and 9), the black dashed-dotted rectangle defines Western Lithuania as shown in Fig. 29. Black dots show the topographic features at their location, but not their true size (except for our study area and the rest of Lithuania onshore which are shown to their true scale). A – Blå Jungfrun, Sweden, B – the missing lower Cambrian in one well, east of Sweden, C – Zaręby, North Poland, D – unnamed, Lithuania and Kaliningrad Region offshore, E – Piltene, Latvia onshore, and the rest unnamed, Latvia offshore, F – North Estonia, G – rugose topography, northeast of Gotland. See Chapter 3.2.2 for more explanation.

Firstly, off the coast of Sweden there is the Jungfrun inselberg (Fig. 30A). It is an elevation of the crystalline basement that extrudes above the surrounding Lower Palaeozoic, and it is explicitly identified as the inselberg of the sub-Cambrian peneplain. Its top is an island of Blå Jungfrun in the Baltic Sea, and the entire island is protected as a national park (Lidmar-Bergström, 1995; Lidmar-Bergström et al., 2017).

In one of the wells in the offshore of Sweden (B-10), the absence of the lower Cambrian is reported; instead, a likely Mesoproterozoic quartzite is found (Fig. 30B) (Sopher et al., 2016).

In Northern Poland, there is one palaeo-topography feature of an irregular shape and less than 10 km in diameter, and six smaller features of less than 5 km diameter (Fig. 30C) (Stirpeika, 1999; Modliński et al., 1999).

In Kaliningrad Region, one palaeo-topography feature that is directly overlain by the middle (not lower) Cambrian has been reported (Fig. 30C). There, the crystalline basement also has a weathering crust (Meshcherskii et al., 2003). Unfortunately, the knowledge that concerns the Precambrian palaeo-topography features from the onshore of Kaliningrad Region is incomplete due to the unavailability of data.

In the offshore area of Lithuania and Kaliningrad Region, only five palaeo-topography features have been identified so far. They are small and isolated, and none of them has been drilled yet (Fig. 30D) (VO Tekhnoeksport, 1985).

In the offshore of Latvia, there is a sparse group of 15 small palaeo-topography features. They are irregularly distributed in an area spanning over some 100 km by 50 km that is mainly under the Baltic Sea between the island of Gotland and the coast of Latvia (Fig. 30E). Only one of these features, Piltene (Latvia onshore), has been confirmed by drilling (Brangulis and Kanevs, 2002). This fact enhances the expectation that the other 14 features would also be of the same nature.

In Northern Estonia, near the Gulf of Finland, a closely spaced group of six small palaeo-topography features has been reported (Fig. 30F). They have a diameter of 1–3 km, and their height is of less than 100 m. The Cambrian and/or Ediacaran strata overlie these features. Half of them have been confirmed by drilling (Estonian Land Board, Geological Survey of Estonia, 2020; Ani and Meidla, 2020).

The presented overview suggests that a typical palaeo-topographic feature is small, usually 1–3 km in diameter, and rises less than 100 m above the peneplain. As the well data from Western Lithuania and Kaliningrad Region indicate, such features may have a weathering crust that is a result of the chemical weathering of crystalline basement rocks. Therefore, these small palaeo-topographic features of the Precambrian basement can be interpreted as inselbergs rising above the sub-Cambrian peneplain.

The overview also suggests that inselbergs within the Baltic Basin can occur either as isolated features, as very sparse groups of features, or as feature clusters (Figs. 27 and 30).

An isolated inselberg is literary a singleton feature over a large area. The best example for an isolated feature is the Jungfrun inselberg in the Swedish offshore (Fig. 30A).

A sparse group of inselbergs can be characterized by the large distance between features compared to the diameter of the individual ones. The best examples depicting a sparse group of inselbergs are inselberg groups in the Lithuanian and Latvian offshore (Fig. 30D and E).

A cluster of inselbergs can be characterized by the diameter of the individual features being of the same order as the distance between them. The best examples representing a cluster of inselbergs are Zaręby, North Poland (Fig. 30C), a cluster in North Estonia (Fig. 30F), and also Ablinga Group (Fig. 27).

3.2.6. Array of inselbergs

As it has been pointed out, the southeastern part of our study area (with many ‘hills’ of various sizes) is denoted by a different style of palaeo-topography from that in the northern and western parts of our study area (which is a peneplain-like flat). The pattern transition from one palaeo-topographic domain to another is sharp.

In the wider view, the lack of these palaeo-topography features in the western part of our study area is not unique to our study area only. Just to the West of the study area, in the Lithuanian and Kaliningrad Region offshore, only five sparsely distributed features have been identified. There are several reasons to regard this number (five only) as at least a reliable indication (though this number might also be correct). 1) The seismic horizons, representing both the top of the Precambrian crystalline basement and the top of the Ordovician, are regional reflectors clearly identifiable in offshore Lithuania. A misinterpretation of such key horizons is very unlikely (Fig. 12). 2) A dense network of 2D seismic lines was acquired over the entire southeastern part of the Baltic Sea. It constitutes adequate coverage that was indeed able to reveal these small features (VO Tekhnoeksport, 1985). 3) In the Swedish offshore, the crystalline basement beneath the Baltic Basin is typically featureless (Sopher and Juhlin, 2013; Sopher et al., 2016). Hence, the Precambrian crystalline basement in the Baltic Basin between Sweden and the Baltic States has no significant palaeo-topography.

The amount of seismic data ever recorded onshore decreases towards the East and the North. The extent of the study area to the East is limited by the lack of any recent seismic data. One of the consequences is that the extent of the 'hilly' domain that occupies the southeastern part of the study area currently remains unknown. It can be noted that this domain is at least 30 km in diameter, but its full extent to the East cannot be determined from this study. However, Baubliai, another large palaeo-topography feature, is located to the East of our study area (Fig. 29). It is possible that more of these features actually exist between the study area and Baubliai.

Based on the observations that the southeastern part of our study area has a different topographic style, its size is considerable and is expected to be extended to the East, it is also denoted by small individual palaeo-topography features occurring in large numbers which are densely distributed, we propose that the southeastern part of the study area represents part of a large array of inselbergs. Such an array of inselbergs does not comply with the definition of a peneplain on a local scale (Phillips, 2002). On a broader scale, such an array is still a feature of a peneplain because its diameter is of the order of tens of kilometers while peneplains have a sub-continental extent (a few hundred or even thousand of kilometers across). Nevertheless, this array of inselbergs appears to be the largest and densest group, cluster, or array of inselbergs discovered so far within the Baltic Basin.

3.2.7. Origin of the inselberg array

Several aspects can be discussed about the inselbergs, for example, the rock type, erosion, shape, and the pre-existing topography.

The Precambrian palaeo-topographic features are composed of either the original crystalline rocks of the Proterozoic crystalline basement, or the Jotnian sedimentary strata. For example, Jungfrun inselberg is made of crystalline rocks, while borehole B-10 in the Swedish offshore encountered a monadnock made of the Jotnian quartzite (Sopher et al., 2016). In our study area, the Precambrian basement features are mainly composed of Paleoproterozoic crystalline rocks. The Jotnian sedimentary strata (Veiviržėnai Bed) occur around these Precambrian features, and it is an erosional relic, a thin layer of quartz sandstone (Stirpeika, 1999). The positive palaeo-topography features can be explained as remnants of erosion in both cases, but the relation between inselbergs and the Jotnian sediments cannot be stated yet.

Stirpeika (1999) speculated that these features had formed by the late Baikalian stage (Ediacaran – early Cambrian), but the cause of formation was not explained in his work.

Based on the geological map of the crystalline basement of Lithuania in Motuza et al. (2008), the crystalline basement of Western Lithuania is composed of many types of crystalline rocks. Even though different types of rocks might offer relative resistance to erosion, in our study area, these different rock types of the crystalline basement do not relate to the occurrence of inselbergs.

Glacial erosion can shape the landscape by creating linear or elongated landforms of various sizes (Dowdeswell et al., 2016), but the inselberg array in our study area does not exhibit any consistent linear pattern (Fig. 27). Also, the largest inselbergs of this array possess irregular edges. Their central parts have the maximum height (Figs. 26 and 27), and they look as if all sides have been equally affected by erosion.

The entire southeastern part of our study area, with a probable extension to the East, still contained inselbergs at the onset of the Cambrian transgression. This means that, in the early Cambrian, this segment had not reached the final stage of erosion, that is, the total peneplanation. It is possible that it had been subjected to erosion lastly because it had a generally higher topography.

Therefore, the array of inselbergs may be a remnant of erosion located in the area that did not reach the final stage of peneplanation because it had a generally higher topography.

Sopher et al. (2016) observed an apparently similar object in the seismic sections, but made a different proposition. In the seismic sections from the northeast of the island of Gotland (Fig. 30G), the Precambrian basement is overlain by the Cambrian, and it is reported to feature a 'rugose topography'. This unusual topography is interpreted to have formed due to the fluvial erosion which took place near the edge of the Precambrian basin. However, that location is surrounded by the sub-Cambrian peneplain from all sides (Fig. 8), and this proposition of an edge of a basin is uncertain.

Similarly, the study area in Western Lithuania is defined and limited by the position of the recent seismic data. The results are also limited, because the full extent of the inselberg array cannot be determined (Figs. 27 and 29). Although the transition from the peneplain-like northwestern part to the rough terrain in southeastern part of the study is obvious, it cannot be concluded definitively that the edge of the basin has been observed. Rather, based only on the current study, it can be proposed that this large array of inselbergs is a remnant of erosion.

CONCLUSIONS

This study presents the main results of the investigation into the deep geology of the Baltic Basin in the Gdańsk – Kura Depression, Western Lithuania. The study area includes one of the main oil-containing structures in the region, Gargždai Elevation. A collection of the recent 2D and 3D seismic data, mostly acquired in Western Lithuania during the period between 1995 and 2015, was incorporated into a single seismic interpretation. A detailed seismo-geological model of the study area has been built, and it is illustrated by structural maps for the key seismic reflection horizons, an updated fault trace map, and arbitrary composite seismic sections. The summarizing nature of the interpretation results with eleven 3D seismic data sets included provides a detailed structural perspective about the structure of the sedimentary cover near Gargždai Elevation and its surroundings in Western Lithuania.

1. The main fault in the study area, Gargždai Fault surrounding Gargždai Elevation to the East and the South, has been shown to form as a system of reverse faults. Unlike previously interpreted, the fault is discontinuous between the local structures of Degliai and Pociai, as well as between Vėžaičiai and Ablinga. Another difference from the previous interpretation is that Gargždai Fault is not directly linked to the regional Telšiai Fault in the North, but, instead, it terminates a few kilometers to the south of Telšiai Fault. The faults in the study area formed during the Early Devonian in the late stage of the Caledonian Orogeny, which resulted in compressional folding and faulting, as well as in the subsequent uplift and erosion in the Baltic Basin.

2. Gargždai Elevation contains several small-scale structures, called local highs, that are either of a fault-related, drape structure, or of a combined type. Agluonėnai structure, a newly mapped extension of Gargždai Elevation, is located 4–5 km to the west of Gargždai Fault. It is surrounded by reverse faults and is of the cross-fault structure type, which has not been observed in the study area previously.

3. In the southern part of the study area, parts of the northern edge of Zechstein evaporites have been confidently mapped by using the 3D seismic. On the structural map of the top Permian, several small narrow geological structures have been identified in the southeastern part of the study area. They are located on the carbonate platform to the North of the evaporite edge. They have a relatively high reflection amplitude, and they cause velocity pull-ups. Thus, these features are interpreted as Permian carbonate reefs. They contribute to the detailed understanding of the Permian strata,

which is beneficial for the structural mapping of the hydrocarbon hosting Lower Palaeozoic. The length of these interpreted reefs is at least 7–8 km, while the width is up to 1 km. They form areas of ca. 50 ms of the palaeo-topographical relief at the seismic horizon for the top of the Permian.

4. In Western Lithuania, a continuation of the sub-Cambrian peneplain has been identified. From the West to the East in the study area, the palaeo-topography of the Precambrian crystalline basement changes from a peneplain-like flat to relatively high and rough. In addition to the previously known several large separate features, many closely spaced palaeo-topographical features of the Precambrian crystalline basement have been newly mapped in the south-eastern part of the study area. These Precambrian crystalline basement highs are interpreted as inselbergs on the sub-Cambrian peneplain surface.

5. The inselbergs constitute a relatively large and dense array of inselbergs, which is of considerable extent (at least 30 km in diameter), and which is not consistent with a peneplain on a local scale. Compared to other documented inselbergs in the Baltic Basin, this array is unique both by the number of inselbergs in the array and the area it has been shown to occupy, and its full extent can be expected to be even larger. The other known pre-Cambrian/pre-Ediacaran palaeo-topographic features are buried beneath the strata of the Baltic Basin. They occur either as isolated features, as very sparse groups of features, or as feature clusters and can be interpreted as inselbergs. The diameter of separate palaeo-topographic features varies from 1–3 km to ca. 10 km, and their height ranges from 100 to 150 m.

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LIST OF PUBLICATIONS

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CURRICULUM VITAE

Surname, Name: Grendaitė, Milda
Contact details: milda.grendaite@gmail.com; +370 693 05871

Work experience
July 2016 – present. Geophysicist at *Geobaltic* (Lithuania). 3D and 2D land and marine seismic data processing. Software tools for work automation.
September 2014 – May 2016. Processing Geophysicist at *CGG Services* (Norway) AS, SI. 3D marine seismic data processing: parameter testing, production quality control, velocity analysis, client documentation for all project stages. Courses: Geophysicist Processing Introduction (5 weeks).
June 17 – August 12, 2013. Summer job at *AS Norske Shell* (Norway). Target area: Source rock expression in seismic data.
August 2012 – June 2013. Work in projects for the geophysical company *Geobaltic* (Lithuania).
May 2011 – July 2012. Technician at the oil production company *Minijos Nafta* (Lithuania). Digitization, correlation of wireline well logs; a month as a junior well site geologist.

Education
2016 – present. PhD student (Geology) at Vilnius University (Lithuania, Vilnius), Faculty of Chemistry and Geosciences.
2012 – 2014 MA student of Geophysics at the University of Oslo (Norway, Oslo), Faculty of Mathematics and Natural Sciences; 2014: Master of Science in Geosciences.
2009 – 2012 student of Geology at Vilnius University (Lithuania, Vilnius), Faculty of Natural Sciences; 2012: Bachelor in Geology.
2005 – 2009 student of Physics at Vilnius University (Lithuania, Vilnius), Faculty of Physics.
2005 graduated from Vilnius Lyceum.

Languages: English, Lithuanian (mother tongue).

Research internship as part of the PhD studies: ERASMUS+ internship at the University of Oulu, Oulu, Finland, February – July 2017 (6 months).

Vilniaus universiteto leidykla
Saulėtekio al. 9, III rūmai, LT-10222 Vilnius
El. p. info@leidykla.vu.lt, www.leidykla.vu.lt
bookshop.vu.lt, journals.vu.lt
Tiražas 15 egz.