GEOLOGY AND OIL GEOCHEMISTRY OF THE EASTERN PART OF THE BALTIC SYNECLISE

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All known petroleum accumulations in the eastern part of the Baltic Syneclise occur in Cambrian, Ordovician and Silurian reservoirs. The most important reservoir rock is Middle Cambrian sandstones in which 35 hydrocarbon accumulations have been discovered. Other reservoirs are located in reef carbonates and other limestones of both Ordovician and Silurian ages. Lower and Middle Cambrian argillaceous deposits and black claystones of the Middle and Upper Ordovician as well as dark-grey and black argillites of Lower and Upper Silurian are considered to have been source rocks. The onset of petroleum generation in the Baltic Syneclise was in the latest Silurian, whereas the main oil-generative phase occurred between the Devonian and the Permian. Oils tested in Precambrian, Cambrian, Ordovician, Silurian and Devonian rocks have moderate API densities (26-44°API). The asphaltene contents are low to moderate, ranging from 0 to 3%. The oils are typically poor in sulphur (0.04% - 0.44%). A saturated hydrocarbon content of 42-78%, with saturate/aromatic ratios in the range 2.2-5.2. Gas chromatograms of oils show that normal alkane distribution are generally unimodal, light-end skewed, smooth, and linearly decreasing or slightly concave-up with a low content of waxy components.

INTRODUCTION

After more than 30 years of petroleum exploration and production, the eastern part of Baltic Syneclise (Lithuania and Kaliningrad district of Russia) remains a very active exploration area, especially in the onshore part. More than 400 deep wells have been drilled and 40 oil pools discovered. At present the major tectonic, structural and lithological factors controlling sedimentation of petroliferous complexes have been investigated and hydrocarbons generation, migration, and entrapment understood. But as new oilfields are discovered, new methods of investigation are used and new concepts developed. This paper attempts to synthesize the available geological data on the oilfields and geochemical data on the major oil source rocks and oils found in the Precambrian, Cambrian, Ordovician, Silurian and Devonian sequences. There is considerable variation in the physical and chemical properties of these hydrocarbons. Acknowledgment of this variation is valuable in the assessment and prediction of new discoveries in connection with future exploration activities.

GEOLOGICAL SETTING

Lithuania and the Kaliningrad district of Russia are situated in the southeastern part of the Baltic Syneclise, which is a large, roughly NE-SW trending depression of the Precambrian East European Craton. The crystalline basement of the Baltic Syneclise is divided into a block-like pattern by faults, and consists of metamorphic and magmatic rocks. The depth to the crystalline basement varies from 500 -1000 metres on the slopes of the Syneclise, to 3000-5000 metres in the axial parts. The sedimentary cover of the Baltic Syneclise is formed by Cenozoic, Mesozoic, Paleozoic, Upper Proterozoic rocks. Such stratigraphical completeness is characteristic to composite sequence of sedimentary cover, mean while sections of separate districts are rather decreased.

Large gaps in the sedimentary column and the presence of angular unconformities allow the subdivision of the succession into the Baikalian, Kaledonian, Hercynian, and Alpian structural complexes (Suveizdis et al., 1979). The spatial and structural development of these four sedimentary packages is widely different; reflecting the fact that deposition in the Baltic Syneclise was strongly influenced by tectonic movements.

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The Cambrian sediments rest unconformably on weathered granitic basement and locally on the Veiviržėnai volcanic sediments. The Lower Cambrian is represented by the Vergale and Rausve regional stages of the regional stratigraphic scheme. They are identical with **Holmia** and **Protolenus** Zones of the Global Stratigraphic Scale (Paškevičius, 1993). The Lower Cambrian is represented by greenish-gray argillites with interbeds of light-gray siltstones, sandstones or quartzy siltstones. The thickness of the deposits varies from 40 m up to 120 m, locally more. The Middle Cambrian Series is represented by the Kybartai and Deimena regional stages of the Stratigraphic Scheme of the East Europian Platform. The Kybartai Regional stage is coresponding to the lower part of **Eccaparadoxides oelandicus** Zone of the Global Stratigraphic Scale. The Deimena Regional Stage is identical to the upper part of **Eccaparadoxides oelandicus** Zone and with the lower part of **Paradoxides paradoxissimus** Zone of the Global Stratigraphic Scale. The typical Trilobites complex of Eccaparadoxides oelandicus determines the age of Kybartai Regional Stage. Deposits of this stage consists of intercalated greenish-grey sandstones, black and dark-grey argillites and grey clayey quartzy siltstones with glauconite. The Deimena regional stage is represented by rhythmic light-grey quartzy sandstones, sandy-clayey siltstones, and argillites. The thickness of the Middle Cambrian Series in the area varies from 20 m in the eastern part of Lithuania up to 120 m and more in the Baltic Sea.

The Ordovician deposits generally rests unconformably on various levels of the Middle Cambrian and consists of clayey and organogenic-detrital limestones with interbeds of dolomites and limestones marls, argillites. The Lower Ordovician is represented by deposits of Arenig Stage and the lower part of Llanvirn Stage, and composed of glauconitic-quartzy dark-green and brown-grey sandstones, argillites, dolomites and limestones. The total thickness of the Lower Ordovician deposits varies from 14 to 80 m. The Middle Ordovician is represented by upper part of Llanvirn, Llandeilo and Caradoc Stages, with deposits consisting of red or light-grey organogenic-detrital limestones and marls. In the upper part, a bed of dark-grey argillites is present, which is equivalent to the bituminous Mossen Formation of Sweden and Norway. The total thickness of this deposit varies from 25 up to 36.5 metres. The Upper Ordovician is represented by Ashgill Stage, with deposits composed of grey clayey limestones, marls, dolomites and greenish-grey and dark stratified argillites, which are equivalent to the bituminous Fjacka Formation of Sweden. The total thickness of the deposits varies from 22 m to 35 metres.

Deposits of both Lower and Upper Silurian age are present and attain thicknesses from 300 to 900 m. The Lower Silurian is represented by deposits of the Llandovery and Wenlock Stages. The Llandovery Stage deposits are composed of grey aphanitic limestones, marls and greenish grey or black and dark-grey stratified argillites with a high content of dispersed organic matter and graptolites. The Wenlock deposits are dark-grey thinly -stratified argillites, and dark-grey clayey marls with interbeds of grey clayey limestones. The total thickness of the Silurian deposits varies from 100 to more than 150 metres. The Upper Silurian deposits is mostly composed of dark-grey carbonaceous clays and argillites with interbeds of marl of the Ludlow Stage as well as greenish-grey carbonaceous clays, argillites with rare interbeds of marls and clayey limestones of Pridoli Stage. A thickness of the Lower Silurian varies from 400 up to 700 and more metres.

The blockly basement structure of the Baltic Syneclise partly governed the development of structures during later tectonic episodes - in the general monoclinic submergence the structures of II and III order: steps, depressions and elevations are distinguished. The main type of local folds is asymmetrical brachia-anticlines broken up by minor faults. Most of the local folds, which are distinguished in the surface of crystalline basement, may be recognized in the deposits of Caledonian structural stage and smooth down or suddenly disappear in overlying rocks. The main period of the formation of the folds was during the Caledonian tectonic phase (Sakalauskas, 1996).

All known petroleum accumulations in the eastern part of the Baltic Syneclise occur in Cambrian, Ordovician or Silurian reservoirs. The most important reservoir rock is Middle Cambrian sandstone. Other reservoirs are located in reef carbonates and other limestones of both Ordovician and Silurian ages. In total, more than 40 hydrocarbon accumulations have been discovered in the Middle Cambrian sandstone of the Baltic Syneclise. Most of them are oil accumulations, but offshore Poland three oil condensate fields are present (Gorecki et al., 1992). In Lithuania commercial oil accumulations are related to the Middle Cambrian sandstones of the Deimena Group, where at present 15 oil pools have been discovered, with total geological resources of 15.9mln. t. oil. Three oilfields have been discovered in Silurian and one in Ordovician deposits (Fig. 1). Test oil production in Lithuania was started in 1990. Currently, commercial oil pro-

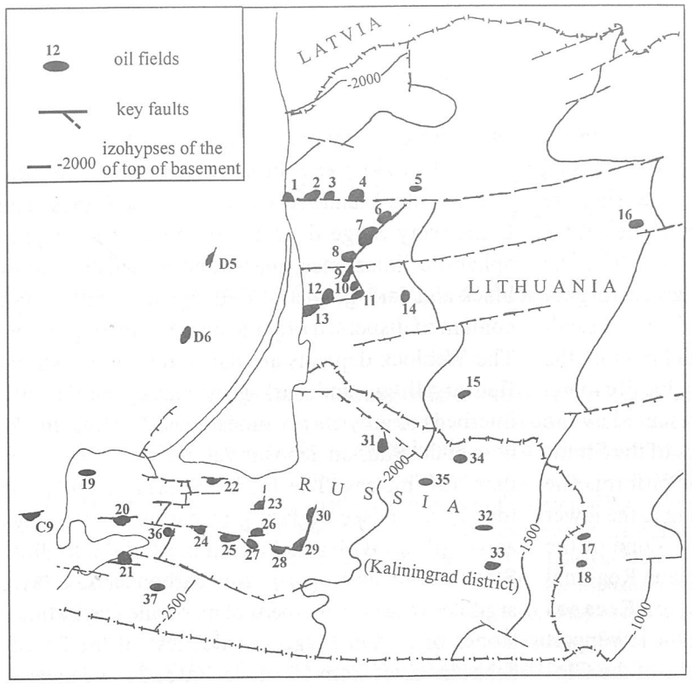

Fig. 1. Sheme showing the oilfields distribution in the Lower Paleozoic reservoirs: *Oilfields*: 1 - Girkaliai; 2 - Genčiai; 3 - Kretinga; 4 - Nausodis; 5 - Plungė; 6 - Ablinga; 7 - Vėžaičiai; 8 - Šiūpariai; 9 - Pietų Šiūpariai; 10 - Degliai; 11 - Pociai; 12 - Vilkyčiai; 13 - Sakučiai; 14 - Šilalė; 15 - Lauksargiai; 16 - Šaukėnai; 17 - Kudirka; 18 - Kybartai; 19 – Yagodnoe; 20 - Veselovskoe; 21 - Ladushkinskoe; 22 – Gaevskoe; 23 – Slavinskoe; 24 - Isakovskoe; 25 – Ushakovskoe; 26 – Deiminskoe; 27 – Malinovskoe; 28 - Zapadno Krasnoborskoe; 29 - Krasnoborskoe; 30 – Severno Krasnoborskoe; 31 – Slavskoe; 32 – Novo Serebrianskoe; 33 – Gusevoe; 34 – Vostochno Gorinskoe; 35 – Novo Iskrinskoe; 36 – Aliochkinskoe; 37 – Chehovskoe.

duction is being carried out in the Genčiai acreage, test production - in the Vėžaičiai, Pietų Šiūpariai, Nausodis, Girkaliai, Kretinga and Vilkyčiai areas. In the Kaliningrad district of Russia 15 commercial oilfields have been discovered, of which nine are currently producing. A few oil-shows have been detected in Devonian deposits.

Based on the stratigraphic, tectonic and lithological factors that were responsible for their formation the oilfields may be classified into structural, combined and reefal (lithological) types, which are further divided into groups and subgroups. The scheme of the trap classification is shown in Fig. 2.

THE MAJOR OIL SOURCE ROCKS

In the southwestern part of the Baltic Syneclise Cambrian to Tremadocian deposits constitute excellent source rocks, being time equivalent to the Alum Shale of Bornholm and Scania. These organic rich shales, however, have been eroded in the eastern part of the Baltic Syneclise. However, where present, the Lower and Middle Cambrian argillaceous deposits are considered to have acted as source rocks together with black claystones of the Middle and Upper Ordovician and dark-grey and black argillites of Lower and Upper Silurian.

In Kaliningrad district and Lithuania dark-grey and black argillites and argillaceous siltstones of the Cambrian deposits are considered to have some potential for generation of liquid hydrocarbons. The total organic carbon (TOC) is variable and ranges from 0.05% up to 2.25%, but as a rule, it is less than 1%, with pyrolysis yields up to 7.35 kg HC/ton rock (Rock-Eval S2, HC - hydrocarbon). Hydrogen indexes are below 450. Values of T_{max} are mainly within the range 433-450°C, indicating a level of thermal maturity corresponding to the early-peak oil generative phase (Espitalie et al., 1985). Catagenetic transformation of the organic matter increases from the northeast towards southwest, from 0.4 up to 0.8% Ro "vitrinite"-like macerals (Buchardt and Lewan, 1990; Kanev et al., 1994). The production indexes are less than 0.2 (except for a local area: well Ramučiai, Klaipėda, Pajūris, where production index is 0.4 on an average).

In the Ordovician complex black, deep-water shales of the Upper Ordovician (Fjäcka and Mossen formations) are considered to be source rocks. The sequence is, however, thin with total thickness of only 5-10 m. Total organic carbon contents (TOC) varies from 0.9 up to 10 %, sometimes reaches 15 %. Pyrolysis yields of hydrocarbons is 22 kg HC/ton rock on an average, but locally it may reach 55-70 kg HC/ton rock, leading to a hydrogen index up to 521. The organic matter in these rocks is a marine type-II with a high liquid hydrocarbon generation potential. In both onshore and offshore parts of Lithuania and Kaliningrad district this source rocks are early mature to mature. The level of thermal maturity increases towards the southwest from 0.4 up to 0.8 % (Ro).

The Silurian succession comprises excellent potential source rocks. These are primarily Lower Silurian (Llandovery) deep-water argillites and marls,

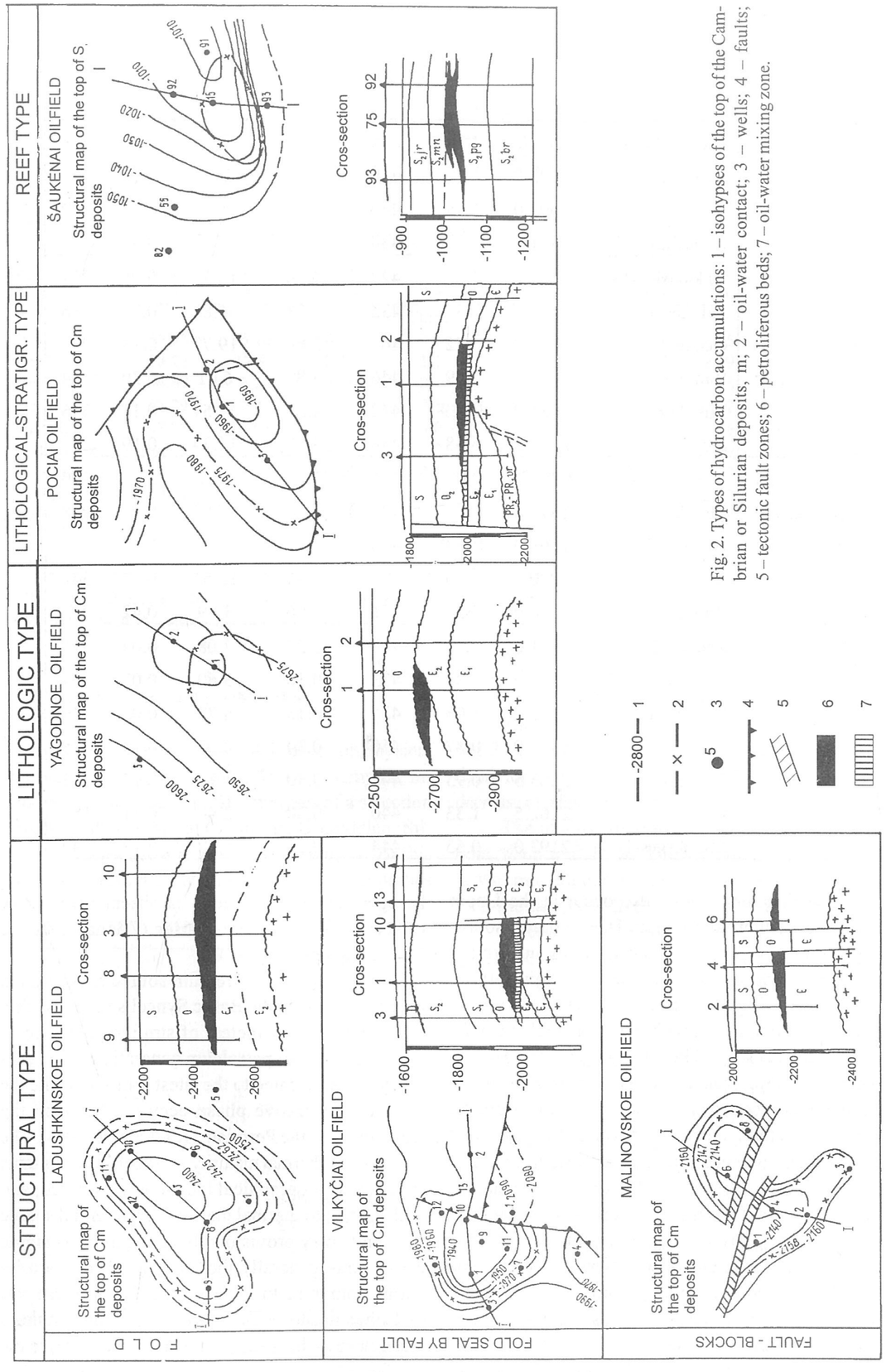

Fig. 2. Types of hydrocarbon accumulations: 1 – isohypses of the top of the Cambrian or Silurian deposits, m; 2 – oil-water contact; 3 – wells; 4 – faults; 5 – tectonic fault zones; 6 – petroliferous beds; 7 – oil-water mixing zone.

Table 1. Selected samples Rock-Eval pyrolysis data

Source rock	Well	Depth, m	TOC, %	Tmax, °C	S1, kg HC/t rock	S2, kg HC/t rock	PI	HI
Upper Silurian	Vilkaviškis-131	789.0	1.27	418	9.24	5.56	0.62	438
	Geniai-1	1583.0	1.21	439	0.35	2.73	0.11	226
	Geniai-1	1601.0	1.14	440	0.30	2.76	0.10	242
	Ramučiai-2	1841,6	0.91	438	0,54	0,80	0,40	88
Lower Silurian	Vilkaviškis-131	1192.0	4.07	429	0.70	13.75	0.05	338
	Paluknė-1	1659.5	7.36	432	1.73	35.82	0.05	486
	Geniai-1	1754.0	6.72	443	2.88	19.77	0.13	294
	Ramučiai-1	2009.1	4,49	446	3,89	6.01	0,39	134
	Mikoliškės-1	2031.0	11.19	442	4.58	37.57	0.11	336
	Klaipėda-1	2040.3	5.58	448	3.69	16.24	0.19	291
Ordovician (Fjäcka & Mossen Fms.)	Vilkaviškis-131	1203.5	0.92	426	5.19	2.67	0.66	290
	Malūkai-1	1813.8	9.45	424	1.24	47.02	0.03	498
	Baubliai-2	1868.0	10.00	448	4.27	52.11	0.08	521
	Rusnė-1	1980.0	4.80	442	2.44	16.51	0.13	344
	Ramučiai-2	2036.0	4.27	451	2.66	3.69	0.42	86
Cambrian	Žemytė-2	1701.0	2.25	439	0.27	7.08	0.04	315
	Paluknė-1	1859.0	1.85	433	0.10	3.60	0.03	194
	Paluknė-1	1862.0	1.08	437	0.13	4.72	0.03	439
	Girkaliai-2	1928.0	0.87	450	0.30	2.07	0.13	238
	Rusnė-1	2063.5	0.95	448	0.30	1.74	0.15	182
	D5-1	2162.5	1.33	440	0.30	2.40	0.11	180
	Mikoliškės-1	2193.0	0.65	444	0.33	1.62	0.17	249

but prolific source rocks also occur in the Upper Silurian (Ludlow) succession. These Silurian source rocks are dark-grey and black argillites and argillaceous marls, which total thicknesses reaching 300 m. TOC generally varies from 0.7 to 11 %, occasionally even up to 16 %, with pyrolysis yields from 7 kg HC/ton rock to 57 kg HC/ton rock. The Hydrogen index varies from 294 to 571. Catagenetic transformation of the organic matter is variable: from 0.4 up to 0.8 % (Ro), increasing towards the southwest as the rocks are becoming deeper buried (table 1).

Considering the Rock-Eval screening data, the kerogen present in immature/early mature samples of Cambrian, Ordovician, and Silurian potential source rocks can be classified as typical marine "Type II". The synthesis of organic matter during the Paleozoic was mostly undertaken by algae and bacteria, and organic-rich Paleozoic deposits can generally be expected to show a comparatively uniform kerogen composition due to the absence or scarcity of terrigenous organic matter (Zdanavičiūtė & Bojesen-Koefoed, 1997).

All potential petroleum source rock units in the eastern part of the Baltic Syneclise occur within a few hundreds of meters of stratigraphic succession. The onset of petroleum generation in the Baltic Syneclise is dated to the latest Silurian, while the main oil-generative phase occurred between the Devonian and the Permian. (Kadūnienė, 1994). The variations in thermal maturity among the various units at different geographical locations are limited, and with respect to thermal maturity all potential source rock units may provisionally be regarded as single entity. Thus, generally, the level of thermal maturity varies from immature-early mature in northern part of Lithuania, to peak mature in on- and offshore areas close to the Kaliningrad district (Russia) to the southwest.

Table 2. Physical and chemical properties of the oils samples

Well	Density, API°	Viscosity, $\mu m^2/sec$	Sulphur, %	Asphaltene, %	Fractions, weight, %			Prist./Phyt.	CPI	Bias
					All.	Arom.	Polars			
Devonian										
Kulikovskoe	30.53	39.62	0.44	2.1	52.6	21.8	25.6	2.21	0.99	2.95
Silurian										
Kudirka-145	26.62	206.84	0.2	1.5	41.8	18.8	39.4	2.07	0.95	6.72
Šaukėnai-1	33.15	54.3	0.17	3.0	62.5	16.7	20.8	2.28	1.03	3.97
Ordovician										
Kybartai-1	33.57	23.76	0.18	7.8	69.6	22.9	7.5	2.3	1.0	4.22
Gusevskoe-6	37.15	18.8	0.23	8.4	63.7	19.8	8.7	2.4	1.0	
Cambrian										
Ablinga-2	36.35	16.76	0.11	0.4	57.8	19.7	22.5	2.35	0.97	5.13
D6-1	38.22	12.9	0.17	1.1	60.1	23.0	16.9	2.29	0.93	5.43
C9-1	44.47	5.5	n/d	0.4	73.0	18.0	9.0	1.88	1.10	16.49
D5-1	42.29	9.4	0.04	0.8	77.8	15.0	7.2	2.52	0.93	4.06
Girkaliai-2	38.77	10.98	0.13	0.0	66.1	21.6	12.3	2.56	1.00	4.00
Lauksargiai-1	34.98	25.64	n/d	1.0	58.4	20.1	21.5	2.39	0.99	3.85
Plungė-1	29.88	164.90	0.19	0.8	49.7	18.3	32.0	2.29	1.02	2.85
Sakučiai-1	40.41	8.0	0.04	0.2	73.7	15.6	10.7	2.40	1.00	3.26
Vėžaičiai-6	42.29	6.38	0.04	0.4	69.8	16.4	13.8	2.36	0.97	3.65
Precambrian										
Girkaliai-2	35.37	8.78	0.25	7.6	62.4	18.5	19.1	2.65	1.00	4.10

CPI – Carbon Preference Index calculated for the n-C_{22-32} range;
Bias – calculated as (sum n-C_{15-22}/sum n-C_{23-30}).

GEOCHEMISTRY OF OILS

The following paragraph is based on physical and chemical data for around 100 oils samples, including 15 biological marker analyses of a selection oils from Precambrian, Cambrian, Ordovician, Silurian and Devonian reservoirs. The purpose of this discussion is to describe the variations in properties and to assess the origin of the oil. Some physical and chemical data from Lithuanian and Kaliningrad district are shown in table below (table 2).

The oils have moderate API densities 26-44 °API. Fig. 3 shows the variations in density (kg/cub. m) with depth for oils in the eastern part of Baltic Syneclise. A decrease of oil density is observed with increasing depth.

The amount of sulfur is low and varies from 0.04 % up to 0.44 %. The asphaltene contents are low to moderate, ranging from 0 to 3 %, except for the sample collected in fractured Precambrian basement and Ordovician reservoirs, there asphaltene content is more than 7 %. A saturated hydrocarbon content of 42-78 %, with saturate/aromatic ratios in the range 2.2-5.2.

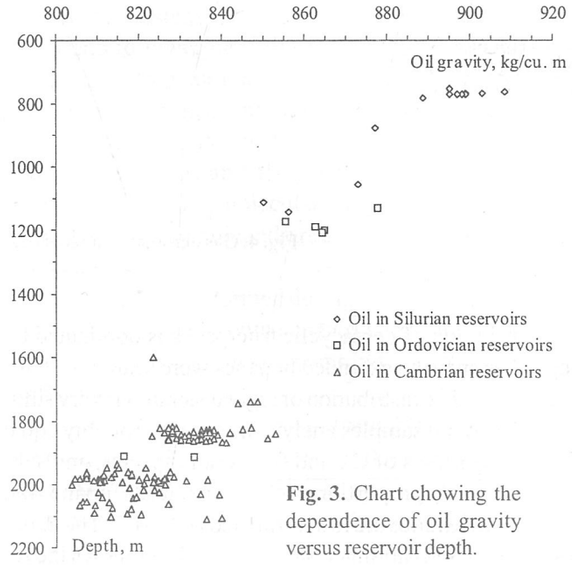

Fig. 3. Chart chowing the dependence of oil gravity versus reservoir depth.

Oils tested in Precambrian, Cambrian, Ordovician, Silurian and Devonian reservoirs show unimodal normal alkane distributions, which are generally light-end skewed, smooth, and show linearly decreasing or slightly concave-up decreasing trends of n-alkane abundance with increaing carbon number (Fig. 4). Data in this plot show a strong normal alkane dominance in the C_{13}-C_{20} molecular weight range with a peak in C_{15} and also show significantly reduced normal alkane abundance above C_{19}. Values of CPI, calculated over the range C_{22-32} are close to unity and pristane/phytane ratios are in range from 2.07 to 2.65.

Biomarker concentrations are very low,

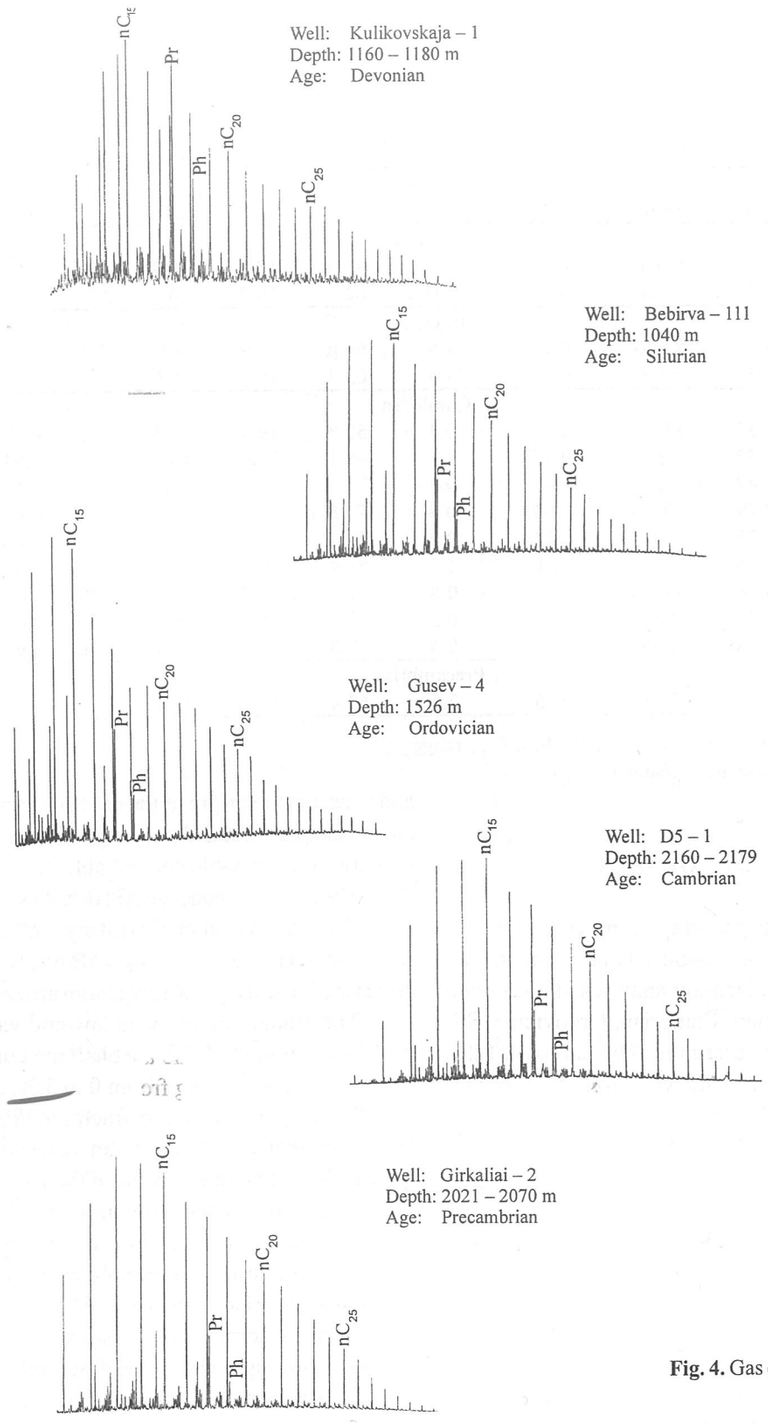

Fig. 4. Gas chromatograms of oils.

and in D5-1 well (Lithuanian offshore), biomarkers were virtually absent, or could not be detected using standard analytical procedures. When biomarkers are present, other general features include high proportions of tricyclic terpanes in the m/z 191 ion trace, forming a homologous series ranging from C_{20} to C_{30} or more (de Grande et al., 1993) were abundant in all oil-samples, irrespective of thermal maturity. The distribution of pentacyclic triterpanes is dominated by hopane, and extended hopanes were scarce.

The distribution of regular steranes is very similar for all samples analyzed, featuring roughly equal proportions of C_{27} and C_{29} sterane species, and subordinate proportions of C_{28} species. Hopane and sterane ratios are low, estimated at 0.3-1.7. The abundance of rearranged steranes roughly follows the regional maturity trends. Overall the compositions are very similar to observed in other Paleozoic oils in the region, e.g. on the Swedish island of Gotland.

Detailed oil-oil correlation studies, particularly using source specific biomarkers such as the relative abundance of C_{27}, C_{28} and C_{29} steranes and the presence of other markers such as 28,30-bisnorhopane and others were carried out by (Zdanavičiūtė and Bojesen-Koefoed, 1997). Features, which could clearly relate oils to particular source rocks were not found. For several reasons correlation of oil samples to possible source rocks is difficult. The organic matter of the source rock is of very similar composition. Furthermore, since all known potential source rocks occur in close stratigraphic proximity, oil accumulations in Lithuania are likely to result from pooling of petroleum generated from several sources. The most important petroleum source rocks are the Lower Silurian shales.

Further correlation study involving stable isotope data and modeling of the hydrocarbon generation could help to identify the source rock and describe the processes of the hydrocarbon accumulations forming.

CONCLUSIONS

Potential source rocks occur in the Lower and Middle Cambrian, the Middle and Upper Ordovician, and Lower and Upper Silurian System. Thermal immature kerogen is identified on the northern and eastern part of the Lithuania. In western Lithuania and Kaliningrad district the Lower Paleozoic source rocks are found in 1700-2000 m depth and are mature for oil generation. Local heating of the magmatic intrusions may be caused abnormally high maturity of the kerogen in wells Ramučiai-1, Klaipėda-1, Rusnė-1.

In the Eastern part of the Baltic Syneclise there is a trend to lower density of oils with increasing depth. Gas chromatograms of selected oils samples from Precambrian, Cambrian, Ordovician, Silurian and Devonian reservoirs show unimodal normal alkane distributions, and also, show n-alkane dominance in the C_{13}-C_{20} molecular weight range with a peak in C_{15} and significantly reduced normal alkane abundance above C_{19}.

Oilfields were formed during a long geological period, and the petroleum accumulations are likely to result from the pooling of contributions from several sources.

The main reservoir rocks are the Middle Cambrian sandstones, where 40 hydrocarbon accumulations have been discovered. The main type of the traps is asymmetrical brachia-anticlines broken up by minor faults. The greatest perspectives for the exploration of the oil fields are connected with the offshore part of the Lithuania and Kaliningrad district.

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