Geology and hydrocarbon prospects of the Paleozoic in the Baltic region

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Abstract: Within the East Baltic region the main prospective area for hydrocarbons is the Peribaltic Depression ('Baltic Syneclise'). Four sedimentary successions are developed, separated by major tectonic hiatuses. Total sedimentary thickness ranges from less than 1 km to over 8 km. Hydrocarbon occurrences are limited to the Paleozoic section where rich oil-prone source rocks are found. These contain TOC of 11–23% in the alum shale facies of the Cambrian, with 13% and 16% in the Ordovician and Silurian, respectively. Oil window maturity is reached on burial to 2000 m, with the main kitchen being in the Gdansk–Kura Depression.

Main reservoir development is within Middle Cambrian sandstones, where porosities of 20–30% and permeabilities of a few Darcies are preserved. Fields are combined structural/stratigraphic traps associated with fold noses and fault blocks providing structural closure. Ordovician and Silurian carbonates contain abundant shows, with current limited production from the Swedish island of Gotland. These traps are associated with algal mudmounds draped by organic-rich clays.

Most new prospects have been identified in the offshore Baltic Basin, where 35 wells have been drilled, resulting in the discovery of eight oil and gas fields, one of which is the largest found to date in the Baltic region.

The Baltic Syneclise is the largest tectonic element of the western margin of the East European Craton (Fig. 1). Towards the north, east and southeast the syneclise is bounded by the Baltic Shield slope, the Latvian Saddle and Byelorussian Anteclise, respectively. The exact boundaries of the syneclise are not well defined, but are generally where the crystalline basement is buried to depths greater than 0.5–0.8 km. However, the southwestern margin of the syneclise, that separates it from the epicaledonian Middle European Plate, is very clear and is defined by the Tesseyre–Tornquist zone of large fractures (TT line, Fig. 1).

The platform cover of the syneclise, which may be up to 8 km thick is composed of sedimentary deposits of Vendian to Phanerozoic age (Fig. 2). The section can be subdivided into four structural complexes: the Baikalian, the Caledonian, the Hercynian and the Alpine (Figs 2 and 3).

The Baikalian complex (Vendian–Tommotian stage of Lower Cambrian), which overlies the deeply eroded surface of the crystalline basement, is developed mainly on the eastern margins of the syneclise. The section is composed of terrigenous and volcanic rocks with an overall thickness of up to 300 m (Fig. 3).

The Caledonian complex (Atbadanian stage of the Lower Cambrian to the Dittonian stage of the Lower Devonian) is developed everywhere within the syneclise and it defines the main structural features of the region under discussion. At the base of the section the terrigenous formation of the Lower–Middle Cambrian is found to vary in thickness from approximately 10 to 600 m. The 100–150 m thick sandstone member at the top of the Lower–Middle Cambrian is the main hydrocarbon-bearing reservoir of the Baltic region. An Upper Cambrian interbedded shale/limestone formation with a thickness of up to 20 m overlies the sandstone. It is absent in the eastern part of the syneclise. This formation, in the extreme westernmost part of the region (Gotland Island, Bornholm Island), grades into, and is stratigraphically equivalent to, the Alum shale which may be up to 25 m thick. This section is above the *Eccaradoxides oelandicus* Zone (middle of the Middle Cambrian) and is represented by black shales enriched by organic matter with interbeds of phosphatic conglomerates.

At the base of the Ordovician, the section is composed of interbedded, sporadically distributed sand and shale members and 'Alum' shale of the Tremadocian which may be up to 10 m thick. Another interbedded succession of shales and limestone overlies this package and is present across the whole area. This section is represented by the deposits of three separate facies: the Skone (comparatively deep water black bituminous clays), the Swedish–Latvian (limestones, marls, clays) and the Estonian (mainly shallow shelf carbonate rocks). Reefal build-ups are found in the shallow marine facies. The thickness of this section varies from 70 m to 250 m, but it thins to 40 m in condensed basinal sections near the TT line.

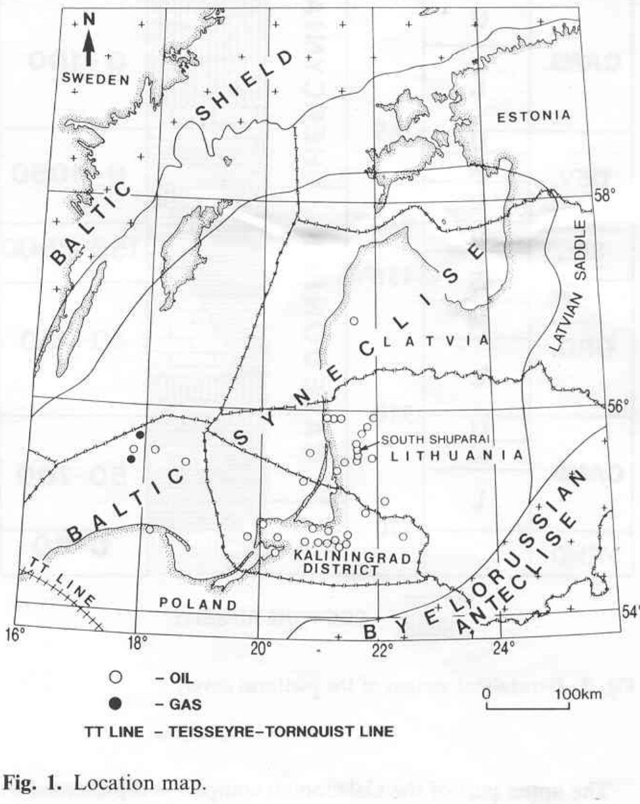

Fig. 1. Location map.

The Silurian deposits are represented by a third limestone and shale succession. The composition of the formations change with increased distance from the platform margin. Shaly deposits with graptolites predominate in the south and southwest. These deposits grade into marls, limestones and

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clays of the open marine basin to the northeast and finally into the shoal carbonate facies in the farthest northeastern part of the area. Barrier reefs are typically found within the shoal carbonate facies. This reefal facies may be found towards the southwest due to the regression that the basin experienced during the Silurian. The thickness of the Silurian deposits changes from tens of metres in the north to 3–4 m in the southeastern part of the syneclise.

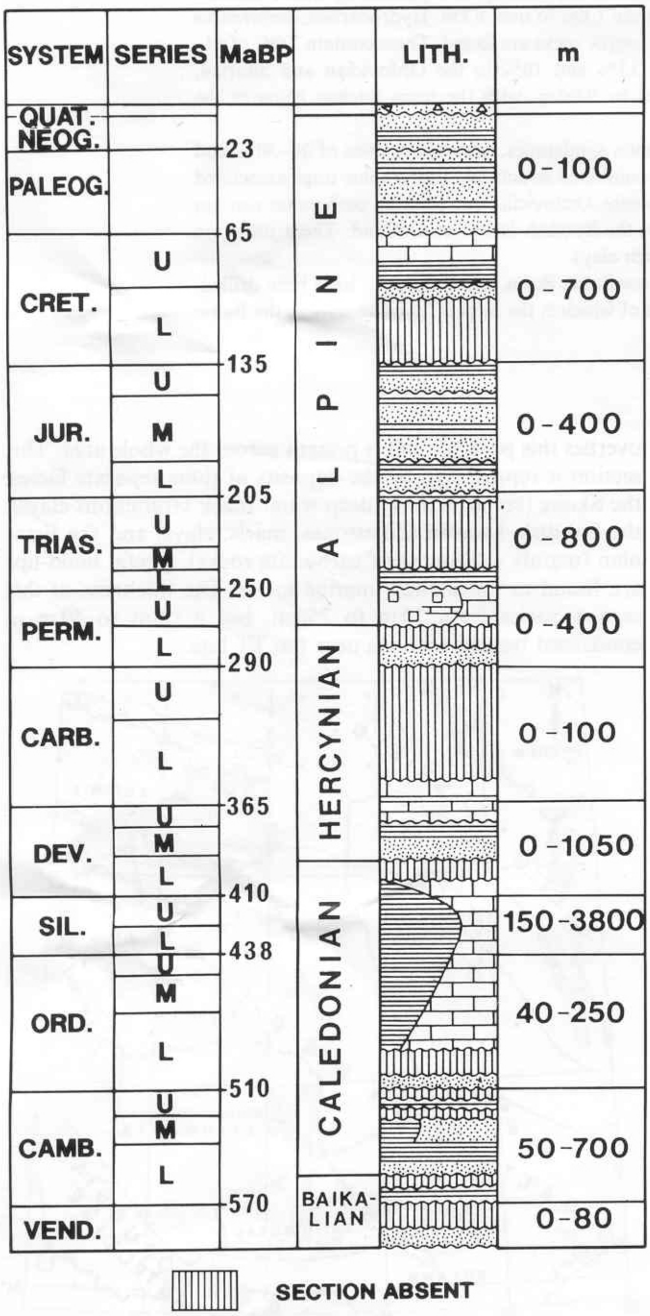

Fig. 2. Generalized section of the platform cover.

The upper part of the Caledonian complex is represented by Lower Devonian (Dittonian) lagoonal-continental deposits with a thickness of up to 200 m. The total thickness of the Caledonian complex changes from hundreds of metres on the margins of the syneclise to 4.5–5 km near the TT line.

The Hercynian complex consists of rocks from the Pragian stage of the Lower Devonian to the Lower Permian. The Devonian and Carboniferous deposits are distributed only in the east of the syneclise. They are represented by terrigenous and carbonate, often gypsum-bearing, formations, with a total thickness up to 800 m. The Lower Permian rocks (red loam) occur as remnant erosional outliers in the southern part of the syneclise. These continental sandstones, conglomerates and siltstones have a thickness of up to 70 m. The total thickness of the Hercynian complex reaches 800 m offshore Lithuania.

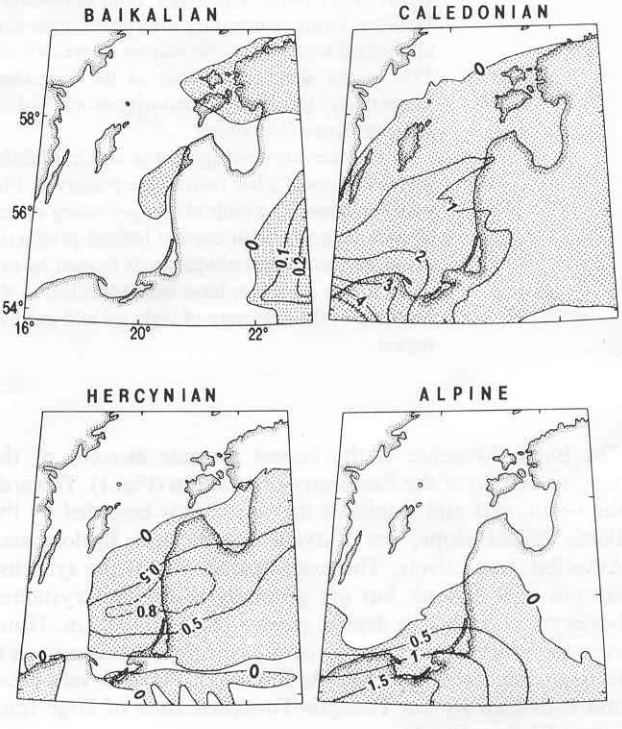

Fig. 3. Distribution of structural complexes (isopachs km).

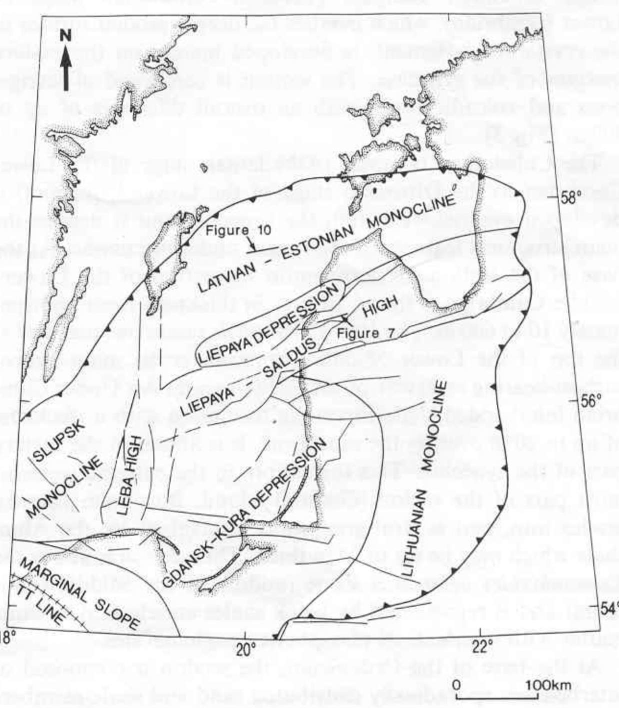

Fig. 4. Main structural elements of the Baltic Syneclise.

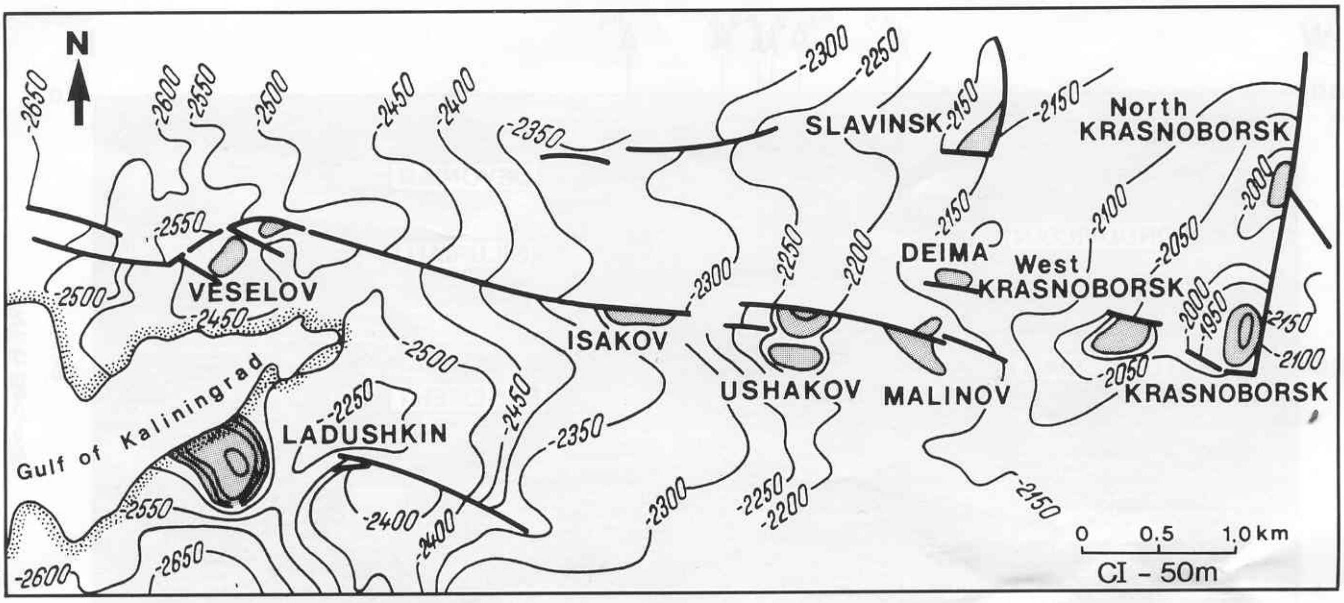

Fig. 5. Oil fields of Kaliningrad zone (onshore).

The Alpine complex includes the Upper Permian carbonate–halogenic deposits and the Mesozoic and Cenozoic terrigenous rocks. The total thickness of the Alpine complex can be up to 1.5 km. This sequence unconformably overlies the Caledonian and Hercynian formations and it is distributed only in the south and southwest of the region under discussion.

The Baltic Syneclise (Figs 1 and 4) represents a marginal platform depression opening towards the southwest to the Danish–Polish trough. The area of the syneclise is about 200 000 km^2, with the long axis being approximately 700 km and the maximum width in the southwest near the TT line being 400–500 km. The basement surface gradually deepens from the northeast to the southwest to depths of 3.5–4 km. Further to the southwest, at the marginal slope, it subsides steeply, where at depths of 7–8 km it plunges under the folded Caledonides. The structural elements of the syneclise are defined by the basement surface and the deposits of the Caledonian structural complex. The central part of the Baltic Syneclise belongs to the Gdansk–Kura Depression where the section reaches thicknesses of 2–4 km. Southwards this depression merges with the Marginal Slope, which is the deepest part of the syneclise. The sedimentary cover in this area increases up to 6–8 km in thickness. To the west and the north, the syneclise is affected by the Leba High and Liepaya–Saldus High, respectively. The edges of the syneclise are represented by monoclines: in the west, the Slupsk; in the north, the Latvian–Estonian; in the east the Lithuanian and Latvian. Northeast of the TT line there is a zone of extensional block faulting known as the Fennoscandian marginal zone which grades into the Margin Slope of the syneclise.

Associated with the larger tectonic elements are found step, nose and trough structures and their associated smaller scale ramparts and the hemi-ramparts.

The highs prospective for hydrocarbons are represented by brachyfolds. Structures with areas up to 10–15 km^2 and amplitudes up to 30–50 m predominate. The largest structures have areas of 50 km^2 and amplitudes of approximately 100 m. The distribution of local highs is irregular. However, it has been noted that more highs are found in association with noses, and fewer with the edges of the monoclines. The brachyfolds, as a rule, are grouped along large faults and involve all horizons of the Caledonian complex. They are oriented parallel to the strike of the main faults and some of them are cut by later and smaller edge break faults (Figs 5, 6 and 7).

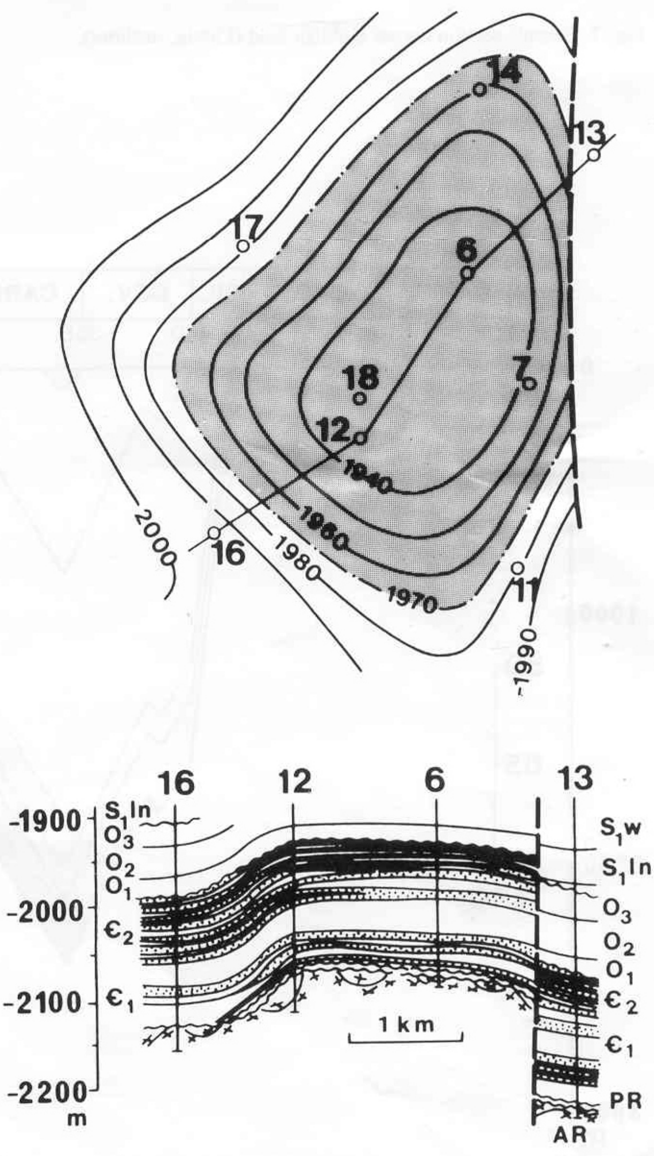

Fig. 6. South Shuparai oil field (Lithuania, onshore).

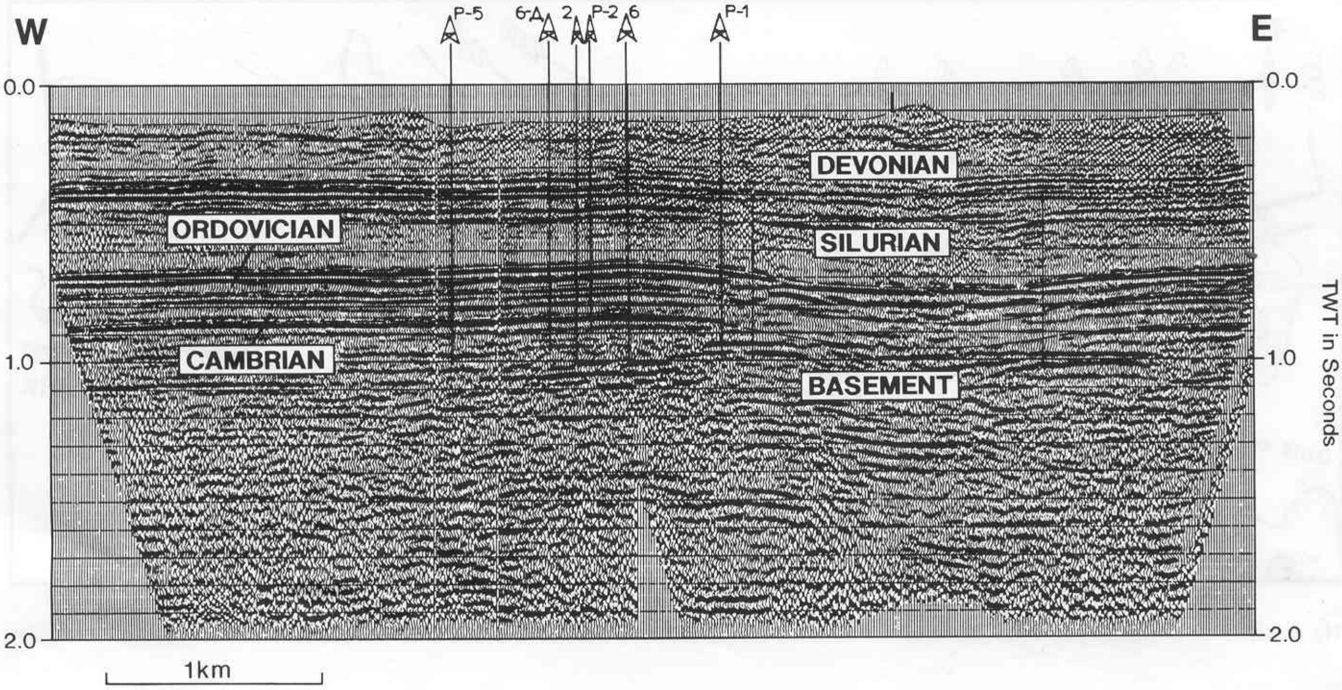

Fig. 7. Seismic section across Kuldiga field (Latvia, onshore).

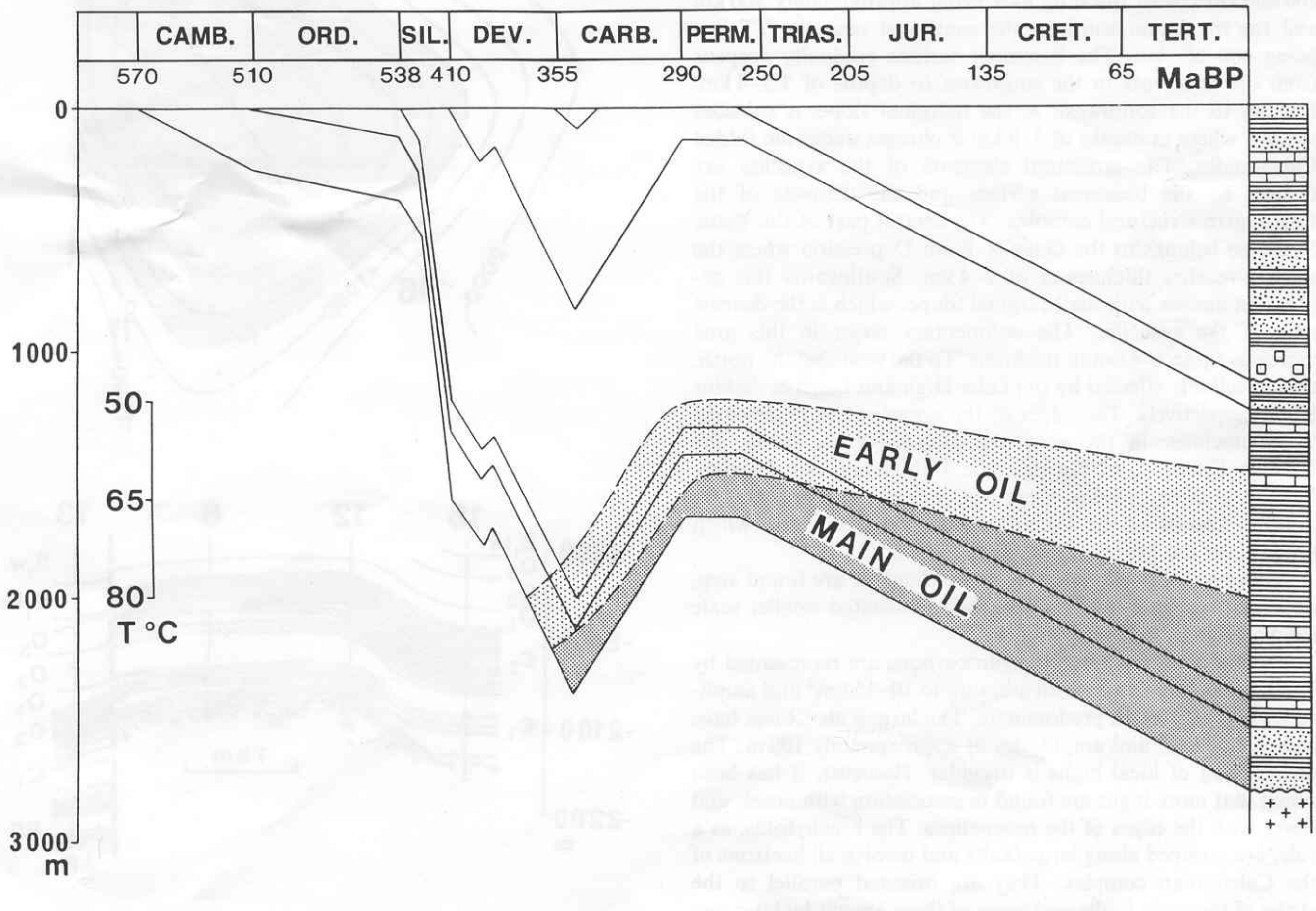

Fig. 8. Subsidence chart for the southern part of the axial zone of the Baltic Syneclise.

The origin of the structural elements is associated mainly with the movements of the basement blocks. The throws of the largest faults reach 200–500 m and the lengths of the fault zones can be up to a few hundred kilometres. The majority of the faults have associated fold structures, but usually most of them do not cut the Hercynian and Alpine complexes.

The petroleum potential of the Baltic Syneclise is associated with the Cambrian, Ordovician and Silurian deposits. The shale and argillaceous carbonate rocks of these ages are the main source rocks.

The organic carbon content (C org) in the Cambrian argillites in the eastern part the area varies from 0.03 to 1.91% (average value being approximately 0.3%). The quantity of dispersed organic matter (DOM) increases in the southern and western directions due to the appearance of a fine detrital marine facies. A C org mean value of 0.53% has been described from the western part of the Kaliningrad enclave (Vosilius 1987), and in Poland, C org mean values between 0.2–0.7% were reported by Calikowski (1984). The Middle–Upper Cambrian Tremadocian Alum shale found in the western marginal part of the syneclise displays a high quantity of DOM with a C org of 11–23%. For aminic DOM of the Cambrian deposits the predominance of colloalginite (algal remains) is typical. DOM of the Cambrian clays (H/C = 1.5–17) may be associated with the Type II kerogen of Tissot and Welte (1978). The degree of the catagenesis of the DOM of the Cambrian deposits varies from the coalification stage of brown coals at the depths of up to 1500 m to fat (Ro = 1.15) at depths of about 3000 m.

The Ordovician carbonate deposits are characterized by the low content of DOM and the C org average value does not exceed 0.2%. In the continuous layers of the comparatively deep-water clays, which have a total thickness of approximately 50 m, the content of C org reaches 12.9%. The initial organic matter is carbohydrate-albumen.

The Silurian black graptolitic clays have a higher content of DOM with C org of up to 16.46%. The conversion of the DOM in the Silurian clays begins to appear at depths of approximately 1.5–1.9 km, when chloroform bitumoid (with a C org of up to 84% and oil fractions up to 50%) increases. At the depth of about 2 km, all indices decrease (Golovanova 1975).

The main oil generation phase (MOGP) in the Lower Paleozoic deposits is determined by the sharp transformation of DOM, which is marked at the depths of about 1.8–2 km. Maturity is reached at about the same depth for all source rocks whether of Silurian, Ordovician, or Cambrian age (Fig. 8).

The oil generation from the Cambrian, Ordovician and Lower Silurian deposits began on the pericratonic platform which subsided in the Late Silurian. At that time, these organic-rich deposits entered into the main zone of oil generation at about the depth of 2 km (MOGP). The further downwarping of the depositional basin promoted progressive catagenesis in the section near the platform margin which lowered the younger Silurian strata into the zone of MOGP and thus successive advancement of the 'oil window' occurred towards the northern boundary of the syneclise. The 'oil window' reached the central part of the Gdansk–Kura Depression during the Early Devonian. In the Early Devonian, after the Caledonian orogeny which uplifted the Paleozoic section of the platform margin on the boundary of the Caledonian fold belt and removed the Upper Silurian deposits by intensive erosion, the depocentre of the downwarping syneclise moved far to the north, and at the Hercynian stage the oil generation process spread to the Gdansk–Kura and Liepaya depressions. Thus, the Gdansk–Kura Depression and Marginal Slope of the Baltic Syneclise are the main kitchens of oil generation and the main zones of oil accumulation are noses and faulted ramparts within the kitchens and the adjacent highs.

The main productive petroleum potential of the Cambrian deposits is associated with the upper part of the Middle Cambrian horizon, which may reach a thickness of 100–150 m. The zone of interest is composed of sandstone layers of 5–35 m thick which are separated by siltstone–clay interbeds. Usually, the oil fields are concentrated in the upper three to five sandstone layers. These sandstones are generally well sorted. The best reservoir properties are noted in the northern part of the Baltic Syneclise where the porosity ranges from 25–30% and the permeability may be several Darcies. From a depth of about 2 km, secondary quartz appears in sandstones and the reservoir properties of the deposits deteriorates and at depths of more than 2.5 km the sandstone porosity rarely exceeds 5–7% (Fig. 9).

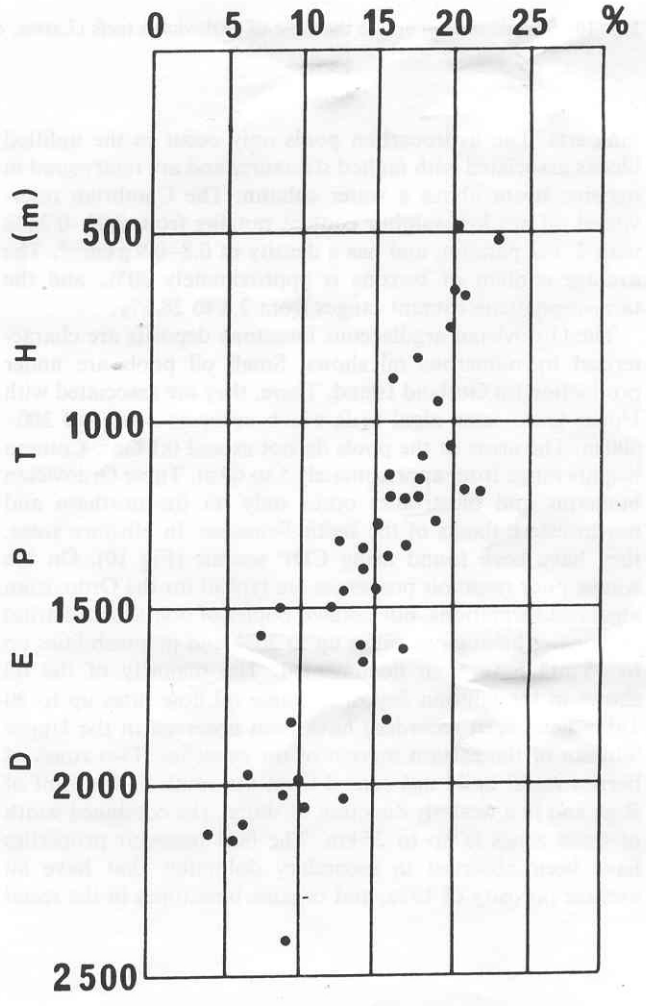

Fig. 9. Chart of Cambrian sandstone porosity versus depth.

The thick Ordovician–Silurian carbonate-clay layers are the seal for the Middle Cambrian oil fields. The Upper Cambrian–Lower Ordovician shale horizon, which is 20 m thick, is the best caprock.

Approximately 35 hydrocarbon accumulations have been discovered in the Middle Cambrian horizon of the Baltic Syneclise. The majority of the accumulations are oil, but offshore Poland three gas pools with condensate were discovered. Nine oil fields of the Kaliningrad district are now under production.

The hydrocarbon fields are associated with local brachyfolds, the majority of which are located on domes near fault

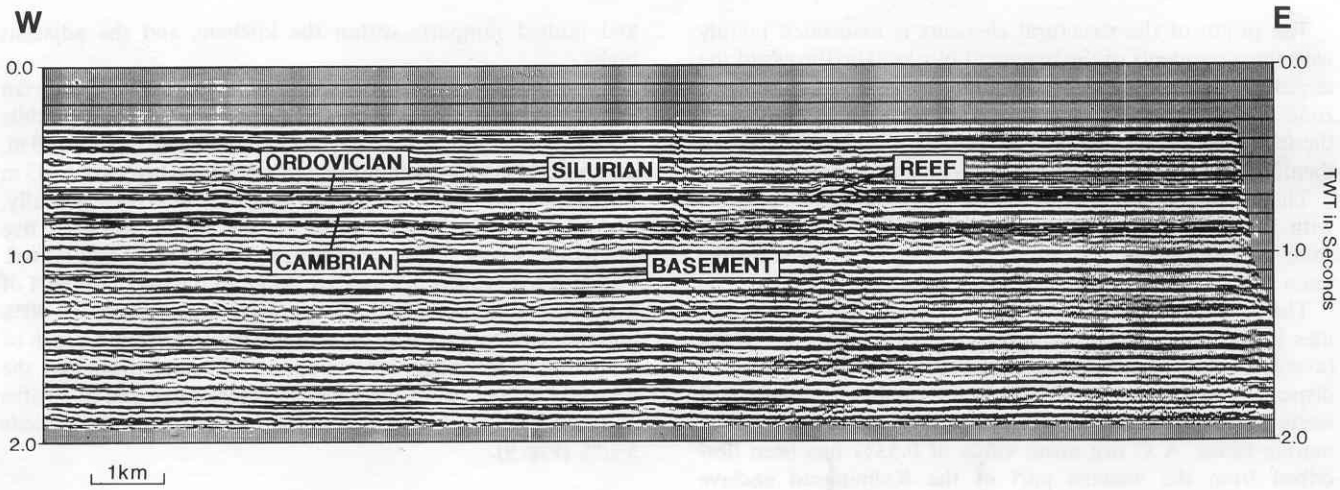

Fig. 10. Seismic section across the zone of Ordovician reefs (Latvia, offshore).

ramparts. The hydrocarbon pools only occur in the uplifted blocks associated with faulted structures and are reservoired in massive strata above a water column. The Cambrian reservoired oil has low sulphur content ranging from 0.03–0.26% with 2–3% paraffin, and has a density of 0.8–0.9 g cm^{-3}. The average content of benzine is approximately 30%, and the tarry-asphaltene content ranges from 2.8 to 28.6%.

The Ordovician argillaceous limestone deposits are characterized by numerous oil shows. Small oil pools are under production on Gotland Island. There, they are associated with Upper Ordovician algal reefs which occur at depths of 300–500 m. The areas of the pools do not exceed 0.1 km^2. Column heights range from approximately 5 to 60 m. These Ordovician bioherms and biostromes occur only on the northern and northwestern flanks of the Baltic Syneclise. In offshore areas, they have been found using CDP seismic (Fig. 10). On the whole, poor reservoir properties are typical for the Ordovician algal reef formations, but isolated bodies of oolitic and detrital carbonates having porosities up to 20% and permeabilities up to 35 mD have been documented. The majority of the oil shows in the Silurian deposits (where oil flow rates up to 30 1/day have been recorded) have been observed in the Upper Silurian of the eastern margin of the syneclise. Two zones of barrier reefal build-ups extend from the south to the Gulf of Riga and in a westerly direction offshore. The combined width of these zones is up to 25 km. The best reservoir properties have been observed in secondary dolomites that have an average porosity of 15%, and organic limestones in the reefal build-ups with porosities up to 15%, and permeabilities up to 450 mD. The thickness of these formations does not exceed 75 m.

Thus, within the Baltic region the commercially exploitable hydrocarbon deposits are represented by fields reservoired in the Cambrian. The prospects of commercially viable hydrocarbons in the Ordovician and Silurian formations are considered to be low. The source rock properties of the Cambrian deposits increase from the margins to the centre of the Baltic Syneclise and the direction of fluid migration flow can be reconstructed for most of the prospective areas. The majority of prospective highs of the Gdansk–Kura Depression and its adjacent areas are situated offshore. In spite of the low density of offshore drilling (not more than 35 stratigraphic and exploratory wells), 8 hydrocarbon fields have been discovered in this area. One of them is the largest found to date in the Baltic region.

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