The prospects for petroleum exploration in the eastern sector of Southern Baltic as revealed by sea bottom geochemical survey correlated with seismic data

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Abstract. In the Polish offshore Łeba (B) tectonic block in the southeastern part of the Baltic Sea the oil and gas fields are accumulated in Middle Cambrian quartzose sandstone, often fractured and diagenetically sealed at depth by advanced silification developed in reservoir around the petroleum deposit. Petroleum traps are mainly of structure-tectonic type, i.e., anticlines closed with strike-slip faults. At least four gas-condensate and four oil deposits of total reserves more than 10 Gm^3 gas and 30 Mt oil were discovered by the "Petrobaltic" Co. in the Polish Baltic sector.

The subsurface petroleum deposits in the Cambrian reservoir are the source of secondary vertical hydrocarbon migration to the surface which produces surface microseepages and hydrocarbon anomalies. Geochemical survey of the sea bottom sediments and waters run along seismic profiles was completed in 1999–2002 within a joint project of "Petrobaltic" Co. Gdańsk and the Fossil Fuels Dept., AGH University of Science and Technology, Kraków, approved by the Ministry of Environmental Protection, Natural Resources and Forestry.

It was found that seafloor hydrocarbon anomalies are closely related to subsurface geologic structure and location of petroleum deposits. Particularly the faults as principal venues for vertical hydrocarbon migration are reflected in high-magnitude seafloor anomalies. Above petroleum field there occurs a "halo" effect of high-magnitude anomalies contouring the deposit with damping related to productive zone situated inbetween. Thus, the section of sea bottom anomalies over a petroleum deposit resembles the shape of a volcanic caldera.

Positive subsurface structures manifest themselves as neotectonic features in the sea-floor morphology and as petrological variations of the bottom sediments. Along the contours of petroleum field, the sea-floor seeps of gas and submarine springs of subsurface water occur. These are seismically recognizable as gas chimneys, geysers, craters and effusive cones. The sea-floor geysers and springs disturb thermal and density stratification of sea water column. The submarine geochemical studies strictly correlated with seismic profiles may contribute greatly to offshore petroleum exploration and marine environmental protection.

Key words: *petroleum exploration, Baltic offshore, bottom sea geochemical survey, surface hydrocarbon anomalies*

Petroleum exploration in the Polish economic zone of the Baltic Sea (totally 26,700 square kilometres) has been run since 1975 by the Joint Petroleum Exploration Organization (established by the East Germany, Poland and the Soviet Union) transformed in 1990 into the state-owned company "Petrobaltic", and again in 2003 into the joint stock company "Petrobaltic" S.A. Up to date, the company completed regional hydromagnetic and gravimetric surveys as well as seismic surveys, first regional (4x8 and 2x4 km grid), then exploratory (2x4 and 2x2 km grid), and finally, after location of potential structures, detailed survey at 1x1 km grid, in order to localize the wildcat wells.

By 1997, offshore seismic lines of total length of 33,000 kilometres were shot. These data led to the identification of several dozens of structural and structure-tectonic traps out of which 14 were selected as potential accumulations and drilled with 25 wells of cumulative length of 60,000 metres (Domżalski & Mazurek, 1997).

The principal aim for Petrobaltic was to explore the offshore Łeba (B) — (Figs 1, 2), Kuronian (D) and Gdańsk (C) tectonic blocks for which the company has been granted the exploration and petroleum production concessions. In the offshore part of the Łeba Elevation, four gas-condensate deposits (B4/1991, B6/1982, B16/1985, B21/1996) and three oil deposits (B3/1981, B8/1983, B24/1996) were discovered of the total reserves reaching 10 Gm^3 of gas and about 30 Mt of oil. In the onshore part of the Łeba Elevation first, small oil deposit Żarnowiec was discovered in 1970 at the depth of 2,750 metres. Next onshore discoveries were also small oil deposits: Dębki (1971, depth 2,700 metres), Żarnowiec West (1987) and Białogard East (1990) (Fig. 2).

Oil and gas deposits are accumulated in the Middle Cambrian quartzsose sandstones of the thickness varying from 120 m in the nearshore zone to 60 m in the northern zone extending several tens of kilometres offshore. Gas is methane-dominated (70–90 vol.%) and contains higher gaseous hydrocarbons (6–25 vol.%), nitrogen (<5 vol.%), carbon dioxide (up to 2 vol.%) and traces of helium and argonium. Condensate concentrations are variable–from 100 g/m^3 in high-methane gas to over 250 g/m^3 in other gases. Oil from the Baltic deposits is light, low in sulphur and asphaltenes but rich in the gasoline fraction. Some oils reveal features intermediate between gasolines and the lightest oils, which enables them to be classified as hydrocarbon condensates.

Most of the discovered deposits and structures relate to the regional system of fault zones. Gas-condensate deposits trend along the "Łeba Arch" — the 80-kilometre-long anticlinal belt adjacent to the Łeba (Smołdzino) Fault, which forms the western boundary of the Łeba Block (B). Along the Łeba (Smołdzino) fault, the rock formations are thrown at 200–350 metres to the west, i.e., towards the Słupsk Block (A). This particular meridional fault provides closure to the gas-condensate deposits accumulated on its eastern, upthrown wall: B16 and B21 (at 1,700 metres depth) and B6 (at 1,410 metres depth) as well as to the oil deposit B34 (at 1,410 metres depth).

The prospective reserves of natural gas in the Baltic Polish offshore sector are estimated to be of about 100 Gm^3 and the prognostic oil reserves amount several hundred millions of metric tonnes.

The offshore part of the Łeba Block (B) covers an area of some 7,000 square kilometres, which corresponds to almost 4% of the entire Baltic Syneclise. The Syneclise is a vast, marginal depression of the East European Platform

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developed as a foredeep at the front of meridional range of Pomeranian Caledonides (Pożaryski & Nawrocki, 2000; Dadlez, 1993, 1995; Witkowski, 1989a, b). The main exploration target is petroliferous Middle Cambrian sandstone (Cm_2 = *Paradoxides paradoxissimus* zone, also known as Deymenas Formation in the so-called Latvian, Lithuanian and Russian "Pribaltica" (Lendzion, 1988). In this particular formation tens of oil deposits were discovered both offshore and onshore Latvia (Kuldiga–Lipava), in western Lithuania (Klaipeda) and in Kaliningrad = Königsberg = Królewiec District (Russia) (Geodekian et al., 1976; Suvejzdis et al., 1979, Afanasev et al., 1977; Gudelis & Jemelyanov, 1982; Depowski et al., 1979; Witkowski, 1993; Górecki & Strzetelski, 1984).

The petroleum source rocks for Cambrian reservoirs were presumably Middle and Upper Cambrian (Cm_{2+3}), Ordovician (Or) and Lower Silurian (S_1) dark claystones (Witkowski, 1988; Jarmołowicz-Szulc, 2001; Karnkowski, 2003). The principal hydrocarbon migration and accumulation phase might have taken place during the final stage of Caledonian movements, i.e., in the Late Silurian–Early Devonian (Siegenian = Erian phase). Subsequent Variscan deformations and uplifts caused restructuring and partial or complete destruction of the previously formed petroleum deposits (Geodekian et al., 1976; Strzelski, 1979; Górecki et al., 1979; Witkowski, 1993; Karnkowski, 2003).

Reservoir properties of the Cm_2 sandstones are mostly controlled by their secondary silicification and fracturing related to the depth of burial (critical depth of pressure-solution silification is 2,200–2,500 m) as well as to the thickness and facies development (Strzetelski, 1977a, 1979). Some deposits are accumulated in structural-lithologic traps sealed diagenetically due to advanced quartzitization of the sandstones (Sikorska, 1998; Jarmołowicz-Szulc, 2001). However, the decisive entrapment factor were structural-tectonic deformation events. The main venues of secondary, vertical water and hydrocarbon migration are mostly the micro- and macrofractures in the fault-confined zones and along limbs of the folds (Strzetelski, 1977a, b, c, 1979).

Generally, all the petroleum traps in the Cm_2 sandstones are fault-related anticlines or cross-fault structures genetically related to parallel or mostly meridional faults. Most part of the oldest (Baikalian) faults were rejuvenated at the end of Caledonian tectonic epoch and during the Variscan vertical movements (Balashov et al., 1972; Modlinski, 1976; Stolarczyk, 1979).

At present the Łeba Elevation forms the northwestern limb of the Gdańsk-Kuronian (Modlinski, 1976; Górecki et al., 1979) central depression of the southern part of Baltic Syneclise (Fig. 1). The top surface of the Cambrian formation is identified seismically by the Or reflector and dips towards the south and southeast to the depths 2,500–2,900 m along the Baltic Sea coast, then to 3,500–3,800 along the Słupsk–Lębork–Kartuzy line and finally to 4,000–4,500 m along the axis of the Gdańsk Depression. The latter rises to northeast, to about 3,000 m depth at the Hel Peninsula (Fig. 1).

Faults interpreted from the seismic data (Piaśnica, Smołdzino, Łeba–Sambia, Żarnowiec–Dębki, Karwia–Jastrzębia Góra, Rozewie, Kuźnica) are of strike-slip character, as revealed by their echelon pattern, alternating position of fault drag structures, slightly curved strike and changing throw.

It is highly probable that similarly as the meridional Smołdzino (Łeba) Fault turns into latitudinal Białogóra dislocation, the meridional Kuźnica (Władysławowo) Fault at its southern end (Jastarnia segment) turns to WSW, across the Puck Bay towards Wejherowo (Fig. 1).

These turns and the transcurrent character of dislocations suggest a dextral rotation of the entire Łeba Block with the corresponding rotation of the axis of the Baltic Syneclise by 45^o as early as during the Palaeozoic, which was suggested in earlier publications. According to Strzetelski (1979) and Górecki et al. (1979), the axis of the syneclise changed its direction from almost meridional (SSW–NNE) in the Cambrian to SW–NE and finally to WSW–ENE recently. The centre of this rotation was located close to the western edge of the old East-European Platform, which suggests that the rotational movement was strictly related to the formation of Pomeranian Caledonides and transcurrent movements along the T-T (Teisseyre-Tornquist) fault zone (Brochwicz-Lewiński et al., 1981; Dadlez, 1993, 1995; Pożaryski & Nawrocki, 2000). The Łeba Uplift, initially located by the axis or in the southeastern limb of the syneclise, was finally moved to its northwestern limb, which was crucial for hydrocarbons migration directions and their accumulation in fault-related anticlines. It is obvious that the faults provided the principal routes of post-entrapment, vertical migration of hydrocarbons (mostly gaseous) which has been reflected by surface (submarine) geochemical anomalies observed nowadays.

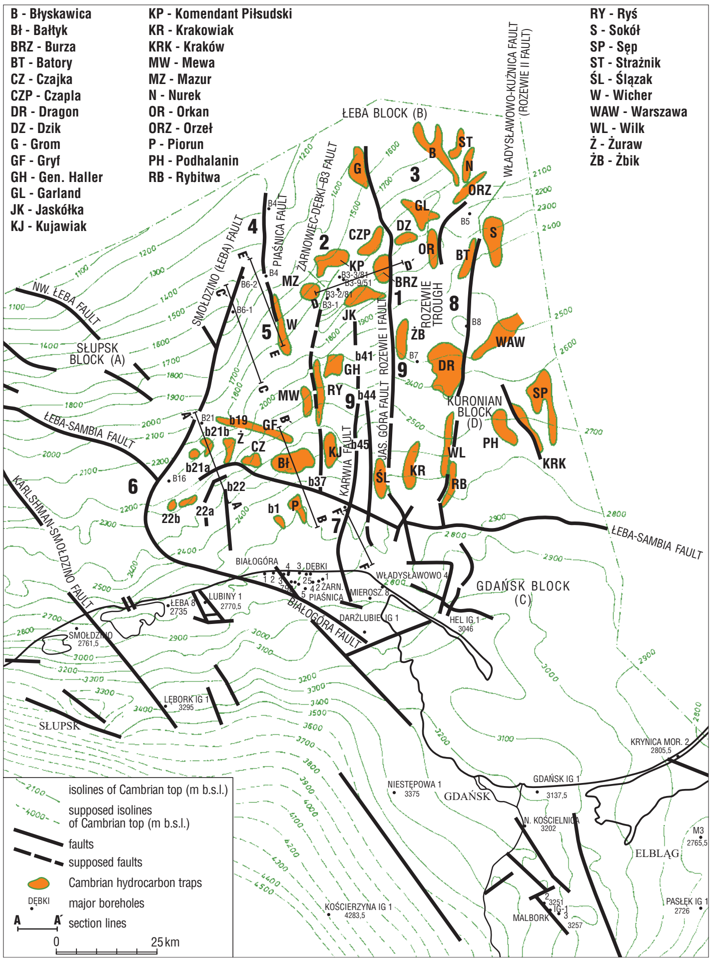

Fig. 1. Structure contour map of the Cambrian sediments and petroleum prospective zones as inferred from sea bottom geochemical studies correlated with subsurface geology from seismic profiles. Perspective zones were given the names of former warships of the Polish Navy

Onshore surface geochemical survey has been run since 1991 by the research team of the Department of Fossil Fuels, AGH University of Science and Technology in Kraków, headed by one of us (W.G.). The survey confirmed the applicability of the surface free-gas method for hydrocarbon exploration in the Polish Lowlands and the Carpathian Foredeep, and demonstrated the close relation between the pattern of surface hydrocarbon anomalies and the subsurface position of petroleum deposits in the Fore-Sudetic area and the Lublin Graben, as well as in the Pomerania (Polish Baltic coast) (Górecki et al., 1995a, b; Strzetelski, 1996, Strzetelski et al., 1996). In 1996, the Department of Fossil Fuels completed and interpreted seven geochemical profiles run along the coast in the onshore part of the Łeba Elevation and along the Hel Peninsula.

In 1997, one of us (K.S.) has initiated the research project aimed at the examination of the Recent sea bottom sediments in the Southern Baltic, approved by the Ministry of Environment Protection, Natural Resources and Forestry. The project included geochemical survey of marine sediments and adjacent coastal zone extending from the Gdańsk Bay to the Odra River estuary. In the years 1999–2002, the geochemical survey of the sea floor was completed only in the area of the Łeba Offshore Block (B). A few reconaissance profiles were made also towards the Kuronian Offshore Block (D) and Gdańsk Block (C).

The project relied upon the occurrence of a close linkage between the results of geochemical survey of the sea floor and the seismic subsurface structure data. Therefore, the offshore geochemical traverses were positioned exactly along the already completed seismic lines. Such positioning required precise navigation of the research vessel along the planned, optimized course.

The working group from the "Petrobaltic" Company reprocessed over 1,000 kilometres of seismic sections and compared them with the results of geochemical survey.

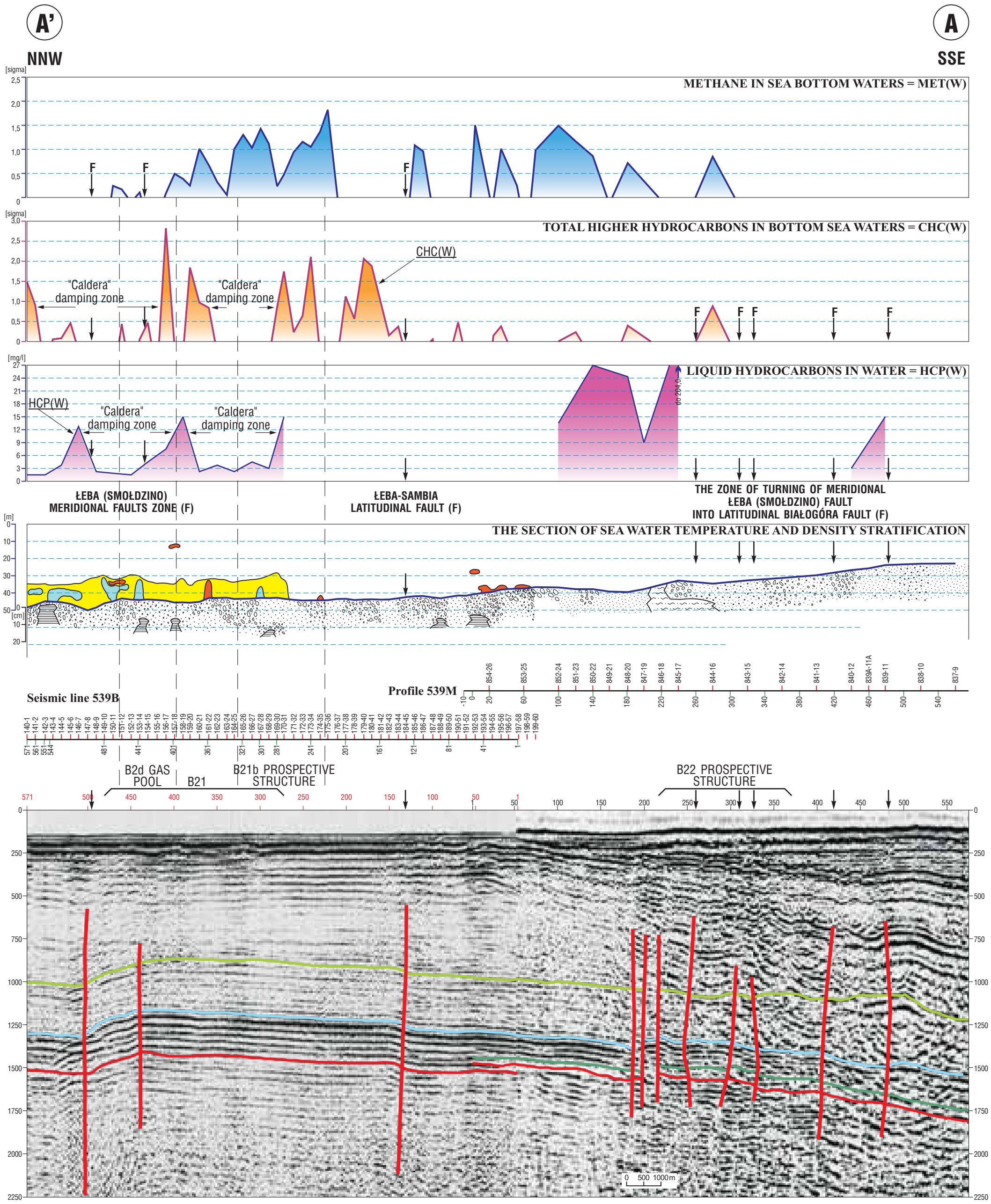

Fig. 2. Offshore geochemical-seismic profile A-A' (NNW–SSE) running from B21 gas-condensate deposit accumulated on hanging wall of the Smołdzino (Łeba) meridional fault to the tectonic crossing of the Smołdzino (Łeba) and the latitudinal Łeba–Sambia and Białogóra Fault

This enabled a direct correlation of sea-floor geochemical anomalies with geological setting of the area. First, the regularities in anomalies distribution over known petroleum deposits were considered. Then, the established regularities were applied to the recognition of further prospective petroleum structures.

Geochemical samples were collected from the research vessel with the probe equipped with the bathymeter and the instruments recording the physical parameters of sea water. The "Ocean-0.25" probe ensured the sampling of sediments column of undisturbed structure along with the sea-bottom water. Air-tight water and sediment samples were degassified and gas was analysed for hydrocarbon concentrations. Moreover, liquid hydrocarbons were extracted from water and sediment samples, and their concentrations and fraction composition were analysed (Tkachenko, 2001).

Totally, 2,600 sediment/bottom water samples and 1,500 surface water samples (from the so-called "microzone") were degassified. The structure of the sea water column was analysed at 3,000 measurement sites. Moreover, at 1,200 sites the liquid hydrocarbon contents were analysed in water — HCP (W) and in sediments — HCP (OS). Finally, the interpretation included changes in concentration of liquid and gaseous hydrocarbons in the sea-floor sediments and bottom waters, as well as measurements of thermal properties and density of sea water column (Tkachenko, 2001). For the purposes of the project, the following patent was applied: "Method of recognition and identification of anomalies of migrating gaseous and

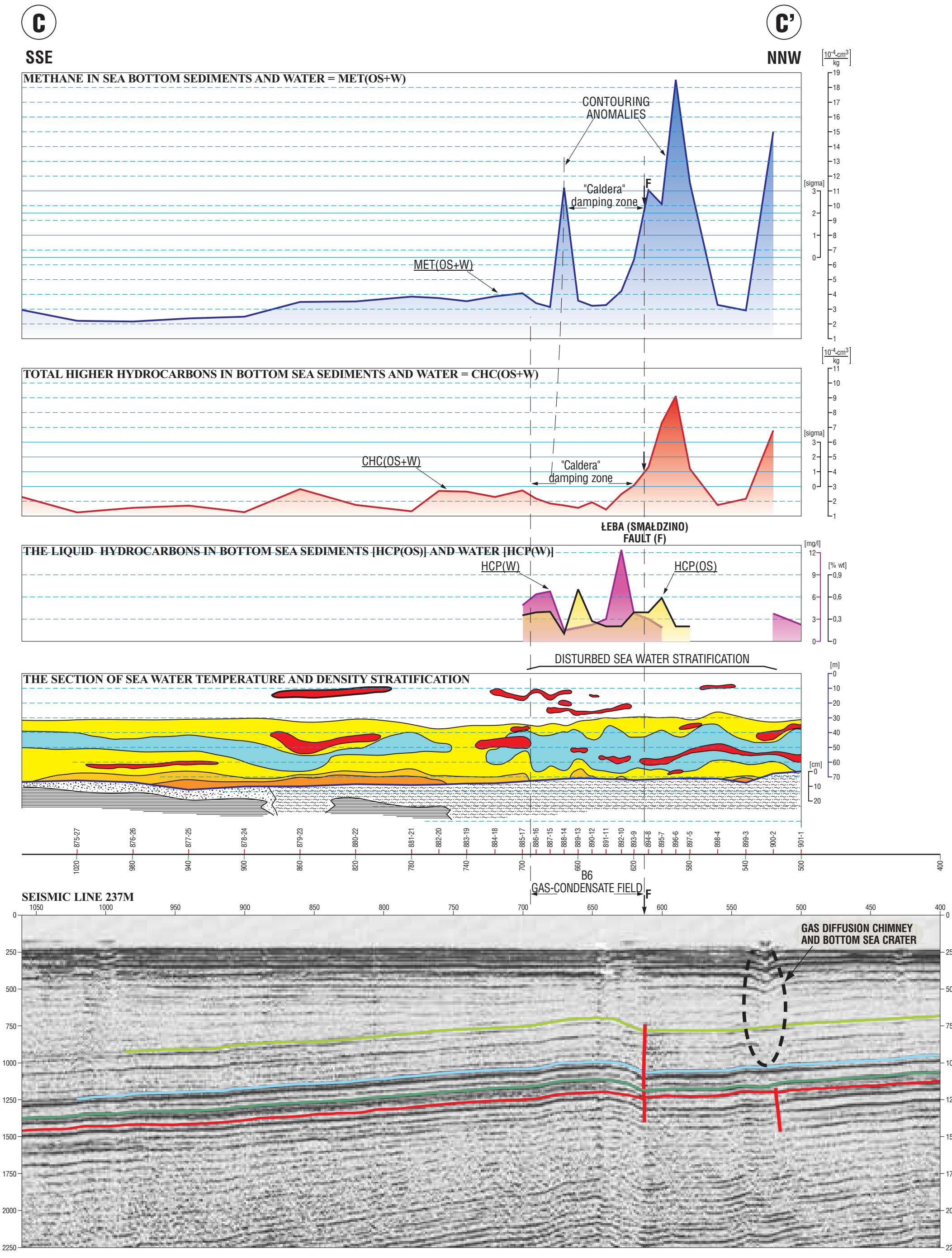

Fig. 3. Offshore geochemical-seismic profile C-C' (SSE–NWW) showing on its northern ending the location of B6 gas-condensate deposit accumulated on the hanging wall of the meridional Smołdzino (Łeba) Fault

liquid hydrocarbons over the sea bottom as indicators of petroleum deposits accumulation and natural contamination of marine environment (patent No. P346204 Szamałek et al., 2001).

Even the preliminary results indicated that liquid and gaseous hydrocarbon anomalies are mostly of deep origin and correlate well with subsurface petroleum structures, thus, providing a credible petroleum exploration indicator. The faults are disclosed mostly by increased methane concentrations, whereas both the offshore and onshore petroleum structures are indicated by high, anomalous haloes which contour the oil and gas deposits.

Over 2,700 samples of gases collected from sea-floor sediments were analysed at the laboratory of the Department of Fossil Fuels, AGH University of Science and Technology in Kraków, namely for methane and higher gaseous hydrocarbons: alkanes (ethane, propane, i-n butane, i-n pentane) and alkenes (ethylene, propylene, 1-butene). N-hexane was so rare that its analyses were cancelled.

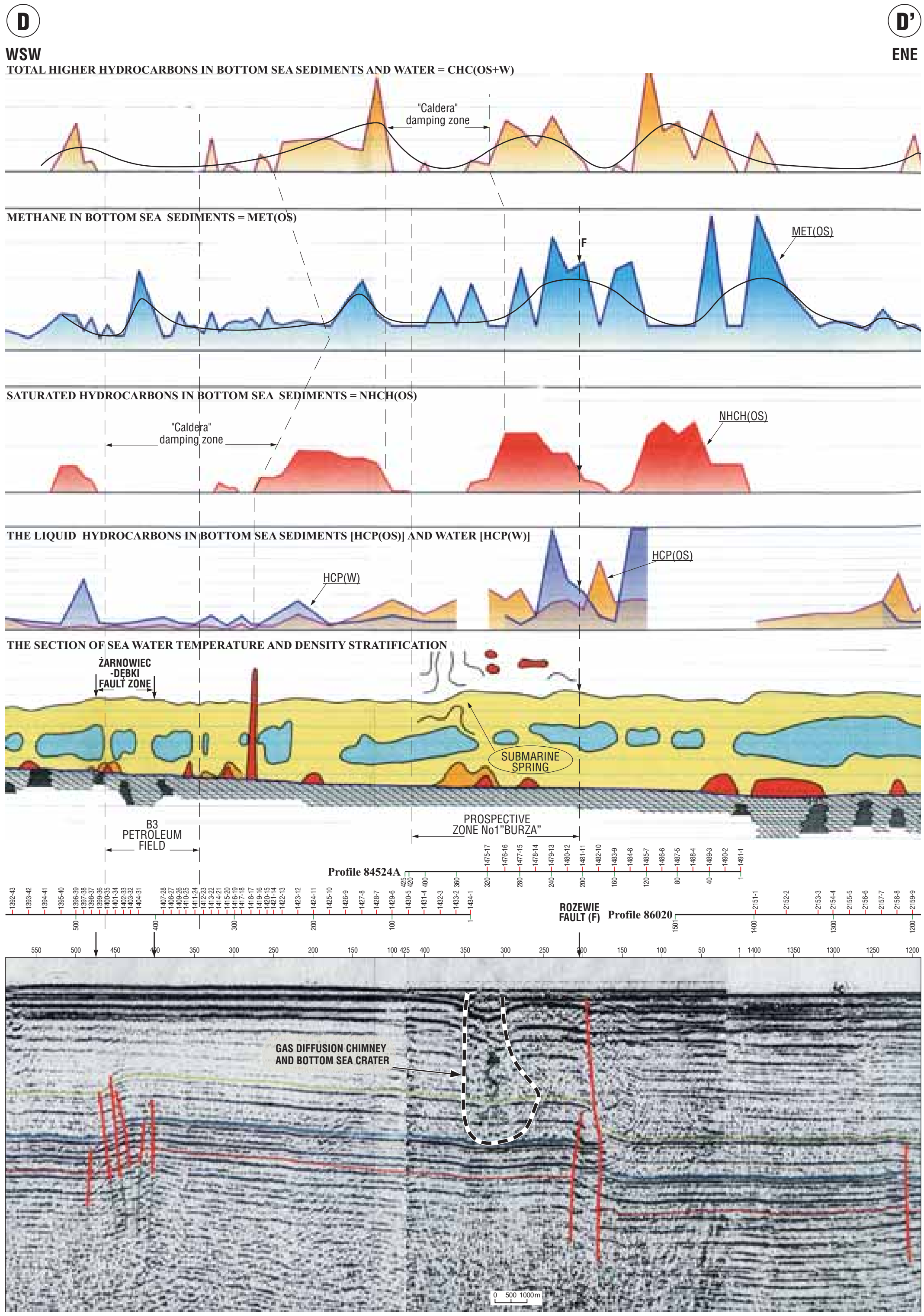

Fig. 4. Offshore geochemical-seismic profile D-D' (WSW–ENE) showing the location of B3 oilfield accumulated in a fault-confined anticline on the northern extension of the Żarnowiec–Dębki Fault zone (western ending of the profile) and the prospective zone "Burza" on the hanging wall of the meridional Rozewie Fault

Totally, 28,000 single component analysis were completed with the use of GC 8160 Fission Instruments chromatograph and flame-ionisation selection. Accuracy of analyses was 0.005 ppm. Obtained chromatographs were subject to computer processing and interpretation using WINNER Spectra Physics software. Results including methane, total higher alkanes and total alkenes concentrations were processed statistically and normalized to geochemical background level determined with an original method developed at the Department of Fossil Fuels, AGH University of Science and Technology in Kraków (Dzieniewicz & Mościcki, 1983; Dzieniewicz & Sechman, 2001).

Methane was detected in all analysed samples and reached magnitudes as high as 22,710 ppm. Methane anomalies were found in 1/3 of all samples. Anomalous concentrations of total higher gaseous alkanes up to 104 ppm and those of total alkenes up to 11 ppm were indicated in 45% of all samples.

Statistical distributions of methane, total alkanes, i-butane and i-pentane concentrations point to the contribution of several sources of hydrocarbon emanations. This may result from diversified mechanisms of vertical hydrocarbon migration (diffusion, effusion, filtration, microfracture flow of gas bubbles) from petroleum deposits of various composition (oil, gas condensate) or from the sea-floor biochemical processes and sea-floor contamination. However, the statistical approach applied enables to distinguish the effects of recent biochemical processes and sea-floor contamination from the anomalies that really originate from the deep sources, i.e., petroleum deposits or source rocks. Nevertheless, statistical distribution analysis of gaseous hydrocarbon concentrations in bottom sediments clearly indicates the deep origin of most of the anomalies observed. Moreover, the character of some anomalies advocates for the occurrence of oil deposits in the subsurface.

Correlation of surface geochemical anomalies with the seismic data included the comparison of the seismic sections, the structural map of the Cambrian top surface (or seismic reflector, Fig. 1) and the results of geochemical survey (Figs 2–4) which presented the changes in concentrations of:

❏ methane (MET) in bottom sediments MET (OS) and bottom waters MET (W),

❏ total higher gaseous hydrocarbons (CHC) in bottom sediments CHC (OS) and bottom waters CHC (W),

❏ total saturated hydrocarbons (NHC) in bottom sediments NHC (OS) and bottom waters NHC (W), and in waters with the application of smoothing procedure ("Heming filter") NHCH (W),

❏ total liquid hydrocarbons (HCP) in bottom sediments HCP (OS) and bottom waters HCP (W).

The clayey bottom sediments reveal high sorption capacity, thus entrapping a significant part of migrating hydrocarbons. Particularly, the content of liquid hydrocarbons in unconsolidated black clays covering the sea floor at depths below 90 metres is a perfect indicator of deep-sourced anomalies. Of course, the black, deep-sea clays with characteristic, greenish hue contain high amounts of decaying organic matter, hydrogen sulphide and biogenic methane.

Lithology of bottom sediments is closely related to the morphology of sea floor and wave-base. In the central part of Baltic Sea the zones shallower than 60–70 metres are eroded by storm waves of wavelength over 100 metres. Morphological sea-floor heights of neotectonic origin are covered with sand/gravel sediments in which gas sampling was useless. In such areas gas samples were taken from bottom waters (up to 30 centimetres over the sea floor). The deep structures, e.g., B4 and B5, are manifested by neotectonic morphological heights and sandy sea-floor sediments. Also the faults reaching the sea-floor surface are marked with neotectonic forms: scarps and breaks.

The patterns of faults and subsurface petroleum structures are undoubtedly reflected by general changes in hydrocarbon concentrations in sediments and bottom waters. From the point of view of petroleum exploration the most important are zones in which anomalies of various components overlap. Additional shows confirming the zones of increased vertical hydrocarbon migration are sea-floor springs of subsurface waters, floor gas seepages and related disturbances in water column stratification. Studies on the structure of sea-water column enabled the location of intensive hydrogeothermal fluxes over the sea-floor groundwater springs. Such flows, in turn, correspond in most cases to increased concentrations of liquid and gaseous hydrocarbons in sediments and bottom waters. Flows of warm, highly mineralized groundwaters disturb and break through the layers of cold sea water thus causing the thermal inversion.

Directly over the petroleum deposits the zones of suppressed hydrocarbon anomalies are visible. These are contoured by high-magnitude anomalies, which in a section resembles as a whole the shape of a volcanic caldera.

An example of such a "caldera" is the seismic-geochemical traverse A-A' (NNW–SSE) (Fig. 2) running obliquely to the B21 gas-condensate deposit which is accumulated in fault-confined anticline of an amplitude 10–35 metres located at 1,700 metres depth on the eastern, upthrown wall of the Smołdzino (Łeba) Fault. Over the deposit the relative suppression of liquid hydrocarbon HCP (W) and total higher gaseous hydrocarbon CHC (W) anomalies is observed ("caldera effect"). The caldera effect is visible further to SSE (Fig. 2) where the traverse crosses the B21b petroleum prospective zone (Fig. 1), which forms the structural nose plunging to the south. Therefore, the pattern of anomalies shows the additional petroleum prospects confined with that secondary structure thus proving the B21 structure to be more extended and diversified. Here appears the problem of possible petroleum prospects of seismically poorly reflected structural terraces and noses that occur in the central parts of tectonic blocks, apart from readily visible framing faults which directly close and seal the already discovered tectonic traps.

More to the north, along the same fault-related Łeba anticlinal trend, the seismic-geochemical traverse C-C` (SSE–NNW) was run (Fig. 3). The traverse is running obliquely to the fault-confined anticline of an amplitude 45 metres which reservoirs the B6 gas-condensate deposit at the depth of 1,450 metres. The zone of damped concentrations of methane (MET), higher gaseous hydrocarbons (CHC) and liquid hydrocarbons (HCP) is visible both in sea-floor sediments (OS) and the bottom waters (W). The "caldera" shape of surface anomalies determined by "methane shadow" is 1.4 km wide and its position corresponds to the location of the B6 gas-condensate deposit. From the NW the contouring anomalies, MET (OS+W), CHC (OS+W) and HCP (W), are particularly high as they occur over the Smołdzino (Łeba) Fault, which provides the trap closure. It should be noted that over the faults which do not disturb the Silurian strata, gas diffusion chimneys and sea bottom effusion craters are also visible. The B6 anticline is also indicated by the present morphology of sea-floor height and sandy character of Recent bottom deposits, which resulted from a neotectonic uplift and erosion of Recent sediments over the crest of the structure.

Over the crest part of the B6 structure, as well as over its eastern limb and southern pericline the sea-floor springs of warm, mineralized waters were found together with adequate thermal inversion of the sea water column. Disturbances and thermal/density inversions of sea waters correlate with geochemical anomalies and their intensity reaches its maximum values over the contour of petroleum field (Fig. 4).

About 25 kilometres ENE from the B6 structure the seismic/geochemical profile D-D` (WSW–ENE) was run (Fig. 4). The traverse cuts the fault-related B3 structure (amplitude: 50 metres, depth: 1,280 metres) closed by the offshore extension of the Żarnowiec–Dębki fault zone (Fig. 1). The traverse revealed a wide (about 5 kilometres) zone of relative decrease in methane MET (OS), higher gaseous hydrocarbons CHC (OS), saturated hydrocarbons NHCH (OS) and liquid hydrocarbons HCP (W) anomalies, bordered from both sides by contouring, high-magnitude anomalies. The zone clearly corresponds to the position of the B3 oil field. Over the Żarnowiec–Dębki fault zone, the methane anomaly MET (OS) was found. Moreover, close to the contour of this petroleum deposit, the submarine springs of warm, mineralised waters were discovered. These also produce the temperature inversion, thickness variations and disruptions of cold sea water transitional layer with its warped top surface (Tkachenko, 2001).

It is to be mentioned that the "caldera" of low-magnitude concentrations of liquid hydrocarbons over the B3 oil deposit which has been in operation for 12 years (since 1991) demonstrates its environmentally friendly exploration and production run by the "Petrobaltic".

Basing upon the results of the above geochemical project "Geochemical indicators of hydrocarbons occurrence based upon the analysis of southern Baltic Sea, Polish Offshore Łeba Block (B)", run in the years 1999–2002 by the "Petrobaltic", nine prospective areas were selected for further petroleum exploration (Fig. 1). These areas were enumerated according to the rising exploration risk, considering the geochemical and hydrochemical indicators along with expected entrapment capability of a given recognized geological structure.

Further analysis of the pattern of specific sea-floor anomalies, geological structure and tectonics allowed to select 30 smaller zones and sites prospective for hydrocarbon exploration (Fig. 1). These localities were given the names of former warships of the Polish Navy, which on week days helps and closely cooperates with the "Petrobaltic".

The selected prospective zones embrace not only the most promising fault-related elevations occurring along the upthrown walls of longitudinal and meridional faults, but also alternating, drag anticlines on downthrown walls, as well as structural terraces and noses located upon central part of tectonic blocks.

Correlation of the results of geochemical and seismic survey, and the location of petroleum deposits already discovered in the Cm_2 sandstones in the offshore part of the Łeba Elevation allow to conclude the following:

1. The pattern of relative variations in hydrocarbon concentrations in sea-floor sediments and bottom waters is generally closely related to the subsurface geological structure of the area. Hence, the sea-floor geochemical anomalies are mostly of deep origin and, consequently, the regularities in their distribution can be applied to petroleum exploration, thus following the results of seismic survey.

2. The principal venues for vertical hydrocarbon migration from reservoir rocks to the sea-floor are faults and accompanying fracture zones manifested by sea bottom anomalies (mostly methane) occurring directly over the faults or aside the fault-plane, commonly with two peaks separated with a mute point over the fault, which suggests the sealing character of the fault fracture itself.

3. Directly over or aside the faults the zones of seismically recognizable diffusion chimneys (gas clouds) and effusive sea-floor craters and cones appear, marking the gas seepages and warm subsurface waters submarine springs disturbing the thermal and density stratification of sea water.

4. Methane and total higher gaseous hydrocarbons anomalies correlate mostly with tectonic zones and limbs of structures. Methane anomalies appear also over the crests of hydrocarbon traps. Both the methane and the higher gaseous hydrocarbons concentrations in the "microlayer" of surface sea water correspond solely to the strike of faults. The total higher gaseous hydrocarbons concentrations in sea water increase down the limbs and over local crestal heights of structures. Above the petroleum deposits the overall increase of liquid hydrocarbons concentrations in sediments and sea bottom waters is visible. Such anomalies rise up over the limbs of structures and over cross-cutting faults. It is inferred that such anomalies are the most adequate indicators of vertical hydrocarbon migration from the depth.

5. The petroleum accumulation zones in the subsurface are reflected by a general increase in hydrocarbon concentrations in the sea bottom zone. On the other hand, the haloes of anomalies over petroleum-bearing structural traps commonly occur. As a consequence, the zones of petroleum accumulation are reflected as relative decreases in anomalous hydrocarbon concentration values contoured by "haloes" or "calderas" of high-magnitude anomalies (Figs 2–4). Such a pattern results presumably from most effective sealing provided by caprocks directly over crest of the deposit and a contrastingly intensive fracturing and fissuring on more deformed limbs and periclines of the structure, as well as along the fault zones closing the trap.

6. Faults and positive deep structures manifest themselves as neotectonic features in the sea-floor morphology, i.e., as scarps and uplifts together with an increased content of sandy coarse grain fraction in Recent sediments. The contours of petroleum deposits are accompanied by sea-floor gas seeps and subsurface water submarine springs manifested by geisers, craters and effusive cones, as well as by thermal and density disturbances of stratification of the sea water column.

7. Submarine geochemical and seismic identification of barren and petroliferous traps requires the relevant, detailed studies including the recommended geochemical survey of the sea-floor in the area of structures localized and contoured with seismic data. If such survey confirms the occurrence of possible petroleum accumulation in a given structure, geochemical data may provide an important contribution to the location of a wildcat well and may even enable the contouring of a future petroleum field.

Considering the above conclusion coming from the regional studies completed in the years 1999–2001 in the area of the offshore Łeba Block (Tkachenko, 2001), the detailed geochemical survey was run within the B5 structure that had been seismically contoured on the western upthrown wall of the northern extension of Kuźnica (Władysławowo) Fault (Fig. 1). The survey covered the area of 150 km^2 applying 1x1 kilometre grid of submarine geochemical profiles. The concentric halo pattern was found of contouring methane and higher gaseous hydrocarbons anomalies sampled from bottom sediments and waters with the characteristic damping zone over the top of petroliferous structure. The distribution of submarine hydrocarbon anomalies led to the prediction about the occurrence of an oil deposit with a possible gas cap since the lack of saturated hydrocarbons among higher gaseous hydrocarbons, typical of free gas deposits was observed there (Tkachenko, 2001).

The offshore B5-1/01 well (sea depth 88 metres) drilled from a marine platform located about 45 km east from the already producing B3 oil deposit and about 100 kilometres from Gdańsk was started in July of 2001. The consecutive lithologies included: Quaternary (thickness 8 metres), Devonian dolomites, claystones and mudstones (thickness 494 metres), Silurian claystones (thickness 1,243 metres), Ordovician marls and marly limestones (thickness 90 metres), Middle Cambrian (Cm_2, thickness 171 metres) and Lower Cambrian (Cm_1, thickness 136 metres) sandstones, mudstones and claystones as well as Eocambrian (Upper Ediacaran), sandstones and conglomerates (thickness 5 metres). At 2,236 metres depth, the drilling encountered the Precambrian crystalline basement (granitic gneisses). The top part of Cm_2 sandstones of porosity 7.5–13.5% accumulates light oil at depth 1,951–1,990 m (Domżalski et al., 2002).

This discovery was simultaneously the first successful application of the sea-floor geochemical survey as correlated with seismic data for petroleum exploration purposes. The results obtained provide a decisive argument for extension of such combined surveying into the adjacent, Gdańsk (C) and Kuronian (D) offshore blocks to the east and into the Słupsk offshore block (A) in the west with the links to surface geochemical onshore survey of coastal area.

The sea-floor geochemical studies revealed an important ecological aspect. It appeared that geogenic (i.e., natural) hydrocarbons constitute an important contribution to the pollution of marine environment, presumably comparable to the anthropogenic pollutants. The solution of these problems is the aim of a new research project "Geochemical studies on sediments of the southern Baltic Sea aiming to the analysis of geogenic pollution and petroleum exploration", planned for the years 2004–2007 as a joint research of the Polish Geological Institute, Department of Fossil Fuels, the AGH University of Science and Technology in Kraków and the "Petrobaltic" Company Gdańsk.

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