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Exploration of Hydrocarbon Unconventional Accumulations in the Argillaceous Formation of the Autochthonous Miocene Succession in the Carpathian Foredeep

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***Abstract*—**The article shows results of the project which aims at evaluating possibilities of effective development and exploitation of natural gas from argillaceous series of the Autochthonous Miocene in the Carpathian Foredeep. To achieve the objective, the research team develop a world-trend based but unique methodology of processing and interpretation, adjusted to data, local variations and petroleum characteristics of the area. In order to determine the zones in which maximum volumes of hydrocarbons might have been generated and preserved as shale gas reservoirs, as well as to identify the most preferable well sites where largest gas accumulations are anticipated a number of task were accomplished. Evaluation of petrophysical properties and hydrocarbon saturation of the Miocene complex is based on laboratory measurements as well as interpretation of well-logs and archival data. The studies apply mercury porosimetry (MICP), micro CT and nuclear magnetic resonance imaging (using the Rock Core Analyzer). For prospective location (e.g. central part of Carpathian Foredeep – Brzesko-Wojnicz area) reprocessing and reinterpretation of detailed seismic survey data with the use of integrated geophysical investigations has been made. Construction of quantitative, structural and parametric models for selected areas of the Carpathian Foredeep is performed on the basis of integrated, detailed 3D computer models. Modeling are carried on with the Schlumberger's Petrel software. Finally, prospective zones are spatially contoured in a form of regional 3D grid, which will be framework for generation modelling and comprehensive parametric mapping, allowing for spatial identification of the most prospective zones of unconventional gas accumulation in the Carpathian Foredeep. Preliminary results of research works indicate a potentially prospective area for occurrence of unconventional gas accumulations in the Polish part of Carpathian Foredeep.

***Keywords*—**Autochthonous Miocene, Carpathian Foredeep, Poland, shale gas.

I. Introduction

THE Carpathian Foredeep is an exceptional petroleum basin in which biogenic gas is reservoired in a very thick but shallow sediment pile of lithologies varying from mudstones to sandstones. Up to now, gas production has originated from sweet-spot intervals of conventional sandstone reservoirs whereas undetermined gas volume has remained undiscovered in successions of clayey sandstones with mudstones and claystones. Common gas shows and uncommercial inflows from fine clastics prove the presence of gas unconventional accumulations in the basin. However, some features make the Carpathian Foredeep petroleum basin a specific target from the point of view of well stimulation during hydrocarbon production from unconventional reservoirs. Precisely, low consolidation of reservoir rocks requires the innovative stimulation techniques because the "classic", penetrative fracking appears to be useless. Also, the chemical composition of natural gas (usually over 95 vol.% of methane) facilitates its relatively high migration rate throughout the rock formations including the fine clastics.

Another important factor is the intercalation of sandstones, mudstones and claystones, which increases the resultant, effective permeability of the system. The presence of sandy laminae within mudstones (even on microscopic scale) provides an opportunity that such structures can work as conduits for drainage of hydrocarbons from over- and underlaying mudstones and/or claystones layers.

In the Carpathian Foredeep sedimentary sequences, the "classic" source rocks are absent. Instead, gas is generated mainly from the organic matter disseminated in the whole volume of sediments although increased TOC contents are observed in claystones/mudstones. Hence, the important factor appears to be the hydrocarbon sorption capacity for natural gas as well as the effectiveness of gas desorption during exploitation of particular plays. Yet another specific feature of Miocene clastics from the Carpathian Foredeep is the high content of carbonates, which implies the applicability of diluted hydrochloric acid as a possible stimulation agent in unconventional reservoirs. On the contrary, the low-consolidated clayey rocks tend to swell at the presence of water -the factor which must be considered when stimulation technologies are designed and implemented. Finally, an important feature of the whole Foredeep basin is the occurrence of gas in shallow accumulations – from some tens of meters to 1-2 kilometers. Consequently, the low drilling costs provide the economic basis favourable for experiments with various drilling technologies and strategies.

The general aim of the research project was to generate the innovative stimulation techniques of gas production from

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unconventional, low-consolidated reservoirs adjusted to specific features of the Carpathian Foredeep. The strategic task of the studies is the significant increase of gas production from this "classic" petroleum province in Poland. Four principal tasks of the project are specified:

- Evaluation of petrophysical properties and hydrocarbon saturation of the Miocene complex based upon laboratory measurements, interpretation of well-logs and archival data
- Reprocessing and reinterpretation of detailed seismic survey data with the use of integrated geophysical investigations
- Surface geochemical surveys in reference to the analysis of generation processes and regularities of the distribution of hydrocarbon deposits
- Geological and reservoir analysis and hierarchization of optimum zones of occurrence of unconventional gas accumulations on the basis of integrated, detailed 3D computer models

II. Geological Background

The Carpathian Foredeep, filled up with Neogene sediments, extends between the Carpathians and uplands of Central Poland (Fig. 1). It is the youngest unit of the Polish Alpides and its genesis and development were dependent on the development of the Outer Carpathians. The Carpathian Foredeep, genetically connected with the Flysch Carpathians, the youngest geological unit of Poland, is an asymmetric structure filled with Miocene molasse deposits developed as the sequence of shales, mudstones and sandstones, from several hundred to about 3000 meters thick. This complex is determined as so-called Autochthonous Miocene and its sediments originated from erosion of folded Carpathian flysch deposits. The distinct southern boundary of the Carpathian Foredeep is delineated by the margin of the thrust Carpathians, although the Miocene deposits with variable thickness occur also under the Carpathian over thrust [2]-[4]. For this reason, the southern boundary of the area analysed in this study occurs about 15 km to the south of the border of the Carpathian overthrust. Within the Polish state borders, the Carpathian Foredeep stretches latitudinally over more than 300 km, whereas its maximum width does not exceed 100 km. The asymmetry of the Foredeep structure is marked out as well in its transversal (meridional) cross-section where maximum thicknesses of the Miocene deposits are found in the south at the front of the Carpathian overthrust and decrease northwards, as in the longitudinal cross-section where the elevation of its Precambrian-Paleozoic basement, so-called "Cracow Bolt" [5], divides it into unequal parts: the larger Eastern Foredeep and the smaller Western Foredeep. In the eastern part, the basement of the Carpathian Foredeep is formed of erosionally truncated deposits of the West European Platform of different ages: Precambrian and Paleozoic (in the Miechów-Rzeszów area) through Mesozoic (in the Miechów Trough). In the western part, the basement is represented by Mesozoic rock complexes and (principally) Paleozoic (Carboniferous) complexes of the Upper Silesian Trough, which rest over Precambrian metamorphic rocks of the Upper Silesian Block [6]-[8]. The depth to the platform basement of the Carpathian Foredeep ranges from several hundred meters to 3500 m [3].

Fig. 1 Location of research area [1]

III. Evaluation of Petrophysical Properties and Hydrocarbon Saturation of the Miocene Complex Based upon Laboratory Measurements, Interpretation of Well-Logs and Archival Data

The studies on drill-core samples taken from the Miocene complex (Fig. 2) in aiming to the determination of their petrophysical properties which directly control the behaviour of reservoir fluids in the pore/fracture space and influence their migration were carried out. The studies applied mercury porosimetry (MICP), micro CT and nuclear magnetic resonance imaging (using the Rock Core Analyzer). Measurements of petrophysical parameters were supplemented by geochemical methods applied to samples from selected wells, mainly the Rock-Eval pyrolysis aimed to determination of TOC contents. These studies were supported by comprehensive petrographic observations focused on determination of mineral composition, textural features, range of diagenetic alterations and related evolution of pore/fracture space. Petrographic methods include standard microscopic observations of thin sections under the polarizing microscope combined with identification of minerals with the X-ray diffraction (XRD). Textural features were studied under the scanning electron microscope. An important element of the study is the interpretation of lithological and reservoir data as well as the interpretation of geomechanical parameters from well-log profiles in order to identify the potential source-rock horizons (TOC) with various methods (e.g., Passey's method), and the application of interpretation procedures to the identification of intervals saturated with reservoir waters and gas, and the estimation of porosity and permeability of rocks.

Fig. 2 Core material from S-3 well; eastern part of the Carpathian Foredeep

IV. Reprocessing and Reinterpretation of Detailed Seismic Survey Data with the Use of Integrated Geophysical Investigations

The processing includes a set of routinely executed standard or nonstandard procedures for pre-stack time migration and depth migration in azimuthal version, with anisotropy of the geological medium taken into account. Seismic reflections were tied to geology on the basis of synthetic seismograms. Geometrical and frequency seismic attributes were used to identify small-throw faults. To evaluate the thickness of thin beds, the spectral decomposition was applied and its efficiency was tested in the cepstral domain. Example of structural-tectonic interpretation is shown on Fig. 3.

V. Surface Geochemical Surveys in Reference to the Analysis of Generation Processes and Regularities of the Distribution of Hydrocarbon Deposits

Archival modelings of hydrocarbon generation, migration and accumulation are analyzed in close relation to the results of geochemical analyses of natural gases and kerogen, and to geological and geophysical data. The zones of detailed surface geochemical studies were selected basing on the analysis of archival modelings of hydrocarbon generation, migration and accumulation processes. The surface distribution patterns of gas anomalies were determined together with the estimated volume of generated gases and the quantity of recent gaseous hydrocarbons flux to the near-surface zone. These data are used in identification of zones in which the maximum volumes of hydrocarbons might have been generated and then preserved as shale gas deposits.

VI. Geological and Reservoir Analysis and Hierarchization of Optimum Zones of Occurrence of Unconventional Gas Accumulations on the Basis of Integrated, Detailed 3D Computer Models

The research includes the design of database for selected area of the Carpathian Foredeep, which collect maps, bore-hole data (stratigraphy, results of laboratory measurements,

well logs), 3D and 2D seismics (sgy file, geological interpretations, seismic attributes), results of surface and deep geochemical surveys, geomechanical and stress data, ect. The preliminary models are based upon archival data supplied by the industrial partner and are successively updated. The application of seismic reprocessing increases the accuracy of models in terms of structural and tectonic interpretations whereas the application of seismic attributes and seismic inversion improves the resolution of facial and parametric models, particularly in terms of: more accurate estimation of hydrocarbon saturation and spatial distribution of main geomechanical modul, variability of reservoir parameters localization of fractured zones. Finally, prospective zones were spatially contoured in a form of regional 3D grid, allowing for spatial identification of the most prospective zones of unconvencional gas play.

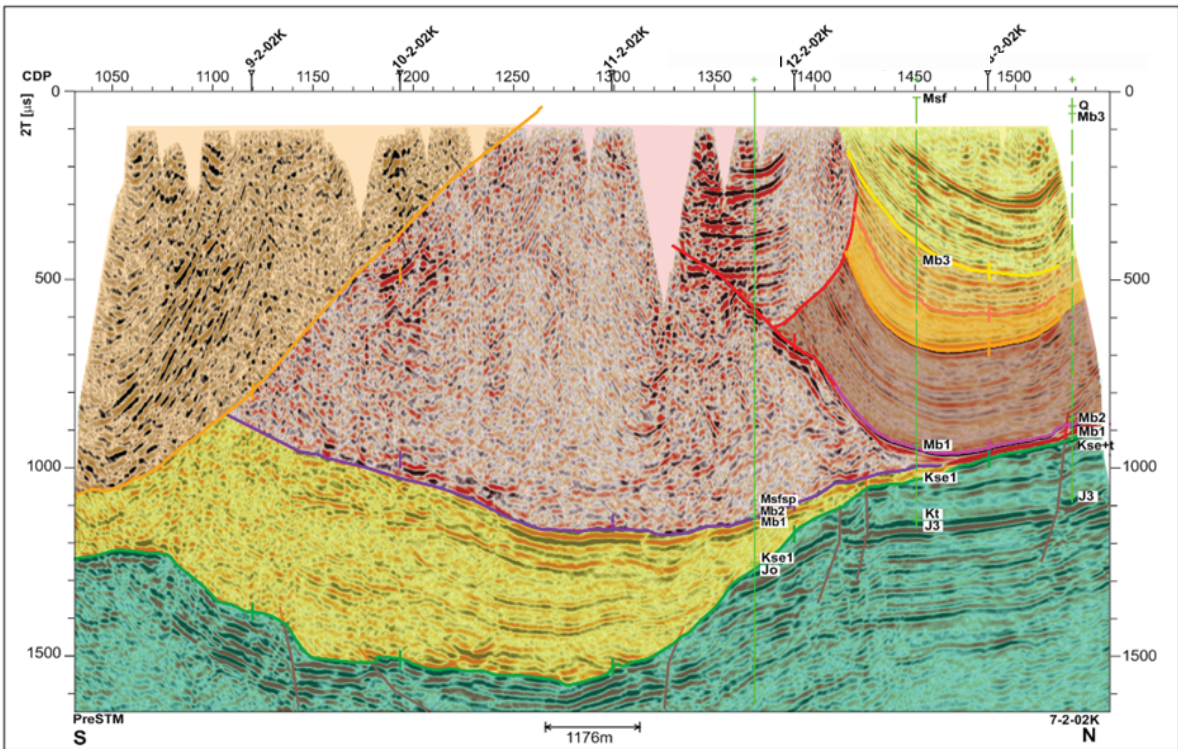

Fig. 3 Example of structural-tectonic interpretation

VII. Results

The results of the research ensure the advance in quantitative evaluation of the variability of lithology, facies, petrophysical parameters, reservoir conditions and geomechanical characterization of gas deposits hosted in mudstone-clayey and sandy mudstone sediments [9]. Geochemical studies of organic matter [10] present in the Miocene deposits of the Carpathian Foredeep involved the most perspective horizons from the point of view of their source rock potential - Upper Badenian and Lower Sarmatian mudstones and claystones. These rocks generally show low organic carbon contents (TOC). The TOC in the 350 samples ranges from about 0 to 3.22 wt%, with an average of only 0.67 wt%. Low contents of organic carbon are usually accompanied by low contents of hydrocarbons (Rock Eval S1 + S2), up to 3.15 mg/g of rock with a median of only 0.69 mg/g of rock. The organic matter deposited in the Miocene sediments is generally immature. In individual samples, from depths greater than 3000 m, Tmax values slightly exceed the limit temperature, pointing to the possibility of entering the Miocene deposits in the initial phase of thermogenic hydrocarbon generation. The results Rock-Eval pyrolysis indicate that the Miocene organic matter is of terrestrial origin, i.e. is gas-prone, which with its low maturity causes that the hydrocarbon potential of discussed deposits can be realized only by the participation of methane bacteria.

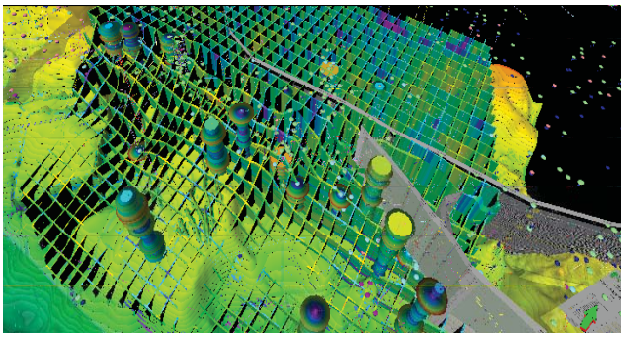

Fig. 4 Example of 3D geomodel

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