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ROCK TYPE-BASED CHARACTERIZATION AND PETROPHYSICAL ANALYSIS OF THE SILURIAN ACACUS SANDSTONES, GHADAMES BASIN, TUNISIA

Charakterystyka litologiczna oraz analiza petrofizyczna sylurskich piaskowców Acacus w basenie Ghadames w Tunezji

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Treść: Przedmiotem badań były sylurskie piaskowce Acacus o zróżnicowanych własnościach petrofizycznych, wynikających ze zmiennych warunków sedymentacji. Zmienne zailenie oraz wysoko zmineralizowana woda złożowa spowodowały zaniżenie oporności piaskowców. Dodatkowo, obecność minerałów bogatych w żelazo spowodowała, że standardowa interpretacja profilowań geofizyki otworowej w celu wyznaczenia porowatości była nieefektywna. Wykonano podział piaskowców na 5 typów litologiczno-strukturalnych, oparty na cechach rozpoznanych w wyniku badań laboratoryjnych na próbkach piaskowców. Porowatość i przepuszczalność dla wydzielonych typów piaskowców okazały się znacznie lepiej skorelowane w porównaniu do całej grupy danych. Podział zastosowano podczas interpretacji profilowań geofizyki otworowej.

Słowa kluczowe: porowatość, przepuszczalność, piaskowce Acacus, Tunezja

Key words: porosity, permeability, Acacus sandstones, Tunisia

INTRODUCTION

Pioneer Natural Resources Tunisia LTD and partners have conducted an intensive exploration and appraisal program over the past six years targeted on Silurian Acacus sandstones in the Ghadames Basin of southern Tunisia (Fig. 1). The complex sedimentological character of the formation results in widely varying petrophysical properties that have complicated the play development. Lithology effects (extensive microporous chlorite clay coats on grain surfaces, thin bedding) and highly saline formation water suppress resistivity log response. The presence of abundant iron-rich minerals (Fe-chlorite and siderite) makes conventional porosity evaluation both more time-consuming and unreliable. Evaluation of permeability-flowing thickness kH and flow potential by standard evaluation techniques (e.g. by regression) is impossible due to a large dispersion of porosity-permeability (up to four orders of magnitude variation in permeability for a given porosity (Fig. 2, 3). A very large dispersion of mercury-injection capillary pressure curve data further reveals large variability in pore structure (Fig. 4).

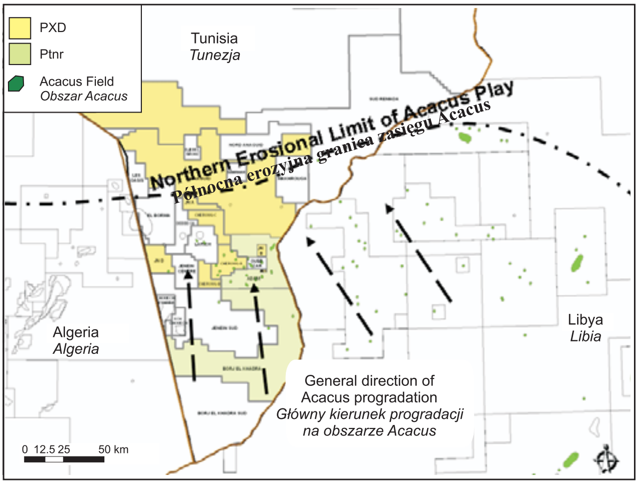

Fig. 1. The Acacus play

Fig. 1. Położenie rejonu badań

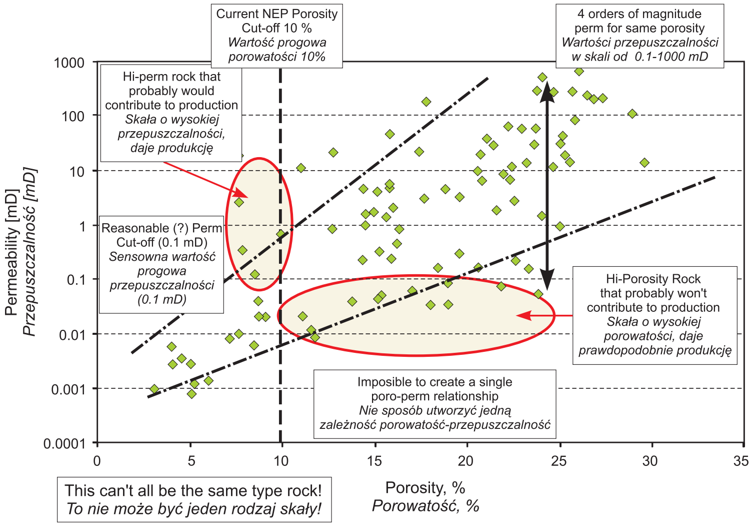

Fig. 2. Porosity and Permeability

Fig. 2. Wykres porowatość–przepuszczalność

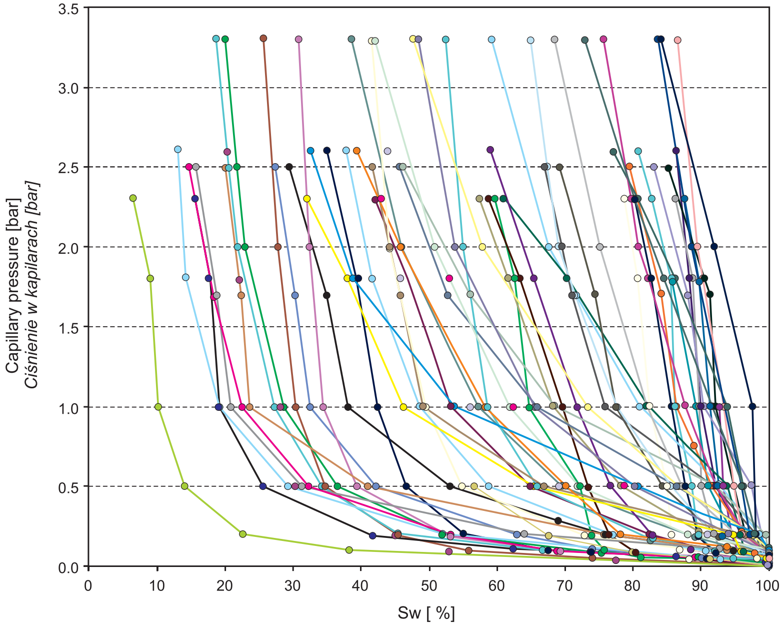

Fig. 3. Capillary pressure curves

Fig. 3. Krzywe kumulacyjne ciśnienia w kapilarach

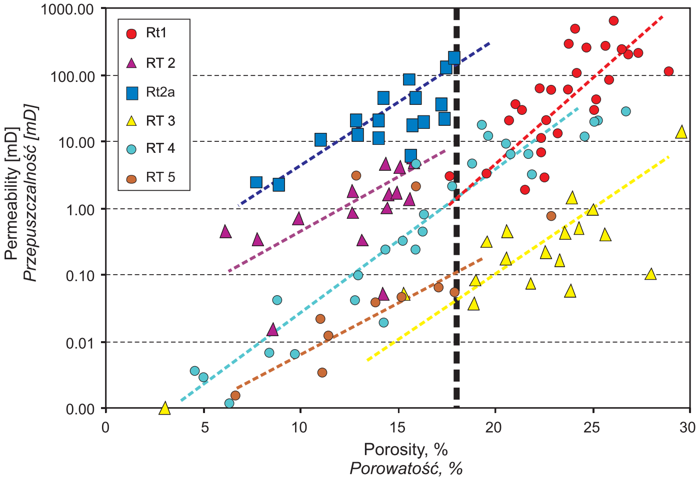

Fig. 4. Porosity – Permeability relationships based on Rock Types: RT1 – Chlorite-lined/cemented, RT2 – Qtz cemented, RT2a – Qtz cemented, enhanced K, RT3 – Clorite plugged, RT4 – Compacted grains, RT5 – Siderite cemented

Fig. 4. Zależność porowatość – przepuszczalność dla różnych typów skał: RT1 – spoiwo chlorytowe, obwódki, RT2 – spoiwo krzemionkowe, RT3 – spoiwo krzemionkowe, wzrost K, RT3 – spoiwo chlorytowe zatykające pory, RT4 – ziarna upakowane, RT5 – spoiwo syderytowe

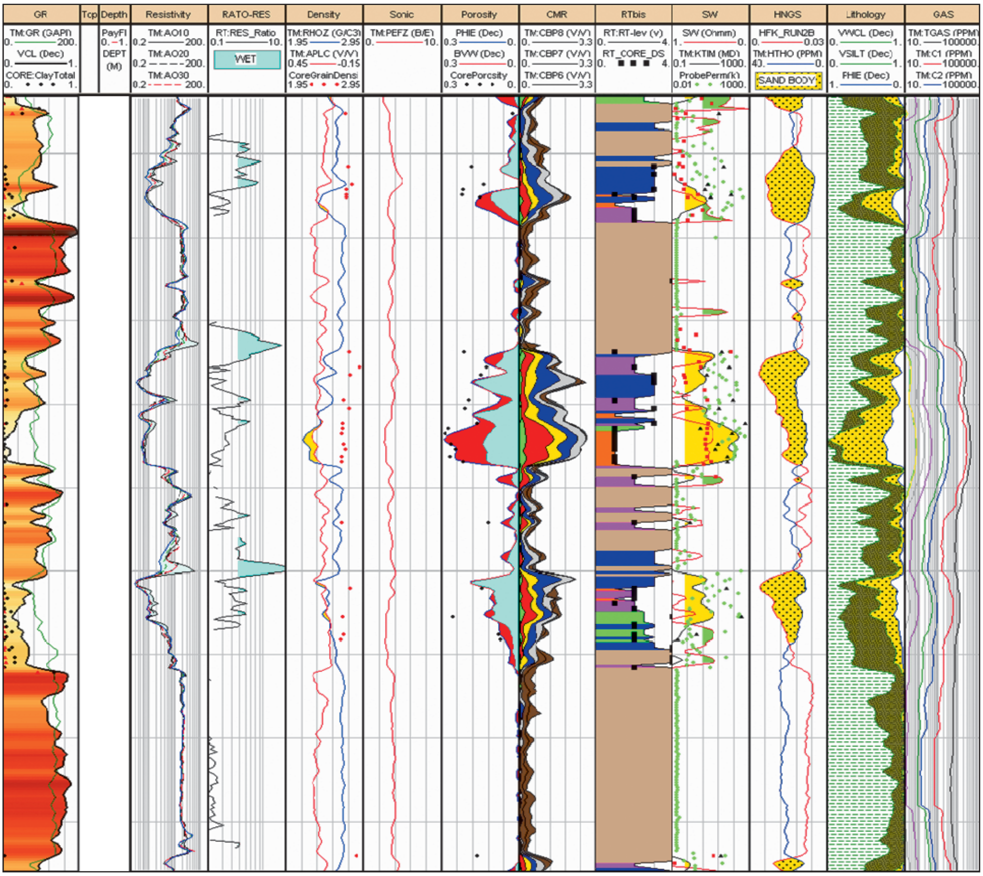

Fig. 5. Rock type display, TM GR – Total Gamma Ray (U + Th + K) from Spectral Gamma Ray logging tool, VCL – Calculated volume of clay, Core Clay Total – Volume of clay from X-ray diffraction, Dept – Depth, AO10-AO30 – One-foot resolution calculated resistivities from the Array Induction logging tool, RT:Res_Ratio – Ratio of AO10/AO90 resistivity, TM RHOZ – bulk density from the Lithodensity logging tool, TM APLC – Neutron limestone-calibrated porosity from the APS neutron logging tool, CoreGrainDensi – matrix density from conventional core analysis, TM PEFZ – photoelectric absorption index, PHE – calculated effective porosity, BVW – calculated total bulk volume of water, CorePorosity – Total porosity from conventional core analysis measured at net reservoir stress, TM CBP8-CBP6-NMR results – CBP1-CBP8 Amplitude of CMR bins 1–8 from CMR logging tool. Note that there are 8 curves but you can see only the headers for the last 3 bins, 6–8. The log display shows 6 bins, from bin 1+2 (shaded brown, to bin 7, shaded green) because in general we do not have any long-T2 amplitudes for bin 8 (small pore sizes), RT RT-lev – Calculated Rock Type. The scale reflects the RT: 1 is RT1 (shaded orange), 2 is RT2 (shaded pink), 2.5 is RT2a (shaded green), 3 is RT3 (shaded blue) and 4 are RTs 4–6, non-reservoir rock, RT_Core_DS-Rock Type from thin section core description. The scale of the position of the points for the RT is the same as for the calculated RTs, SW – Calculated total water saturation, TM KTM – permeability calculated from CMR data according to the Coates-Timur model, ProbePerm – Permeability from conventional core analysis measured at net reservoir stress (mD). Green points are for horizontal permeability, green points are for vertical permeability and black triangles are for permeability calculated from MDT tests, HFK – _Run28 – Potassium curve

Conventional log analysis methods yield anomalous porosity, water saturation and permeability profiles. Apparent water above oil in rock layers with hydraulic continuity is not uncommon. It is quite difficult to distinguish oil from water-bearing intervals and evaluate pay. An extensive program of wireline-based pressure and fluid analysis (MDT and DFA) was required in order to identify permeable zones and fluid composition (water versus oil). Due to multiple potential pay zones, such testing proves expensive, accounting for approximately 50% of the total formation evaluation costs. Calculations of hydrocarbons in place, potential reserves and reservoir performance suffer from a high degree of uncertainty.

DATA COLLECTION AND INTERPRETATION

An extensive coring program (more than 200 rotary sidewall core samples and 282 m of continuous full-size core) was undertaken with the aim of better defining rock properties, tailoring and optimizing logging programs, and developing a rock-based formation evaluation methodology to deal specifically with problems posed by complex lithology and pore geometry characteristics. Petrographic, routine and special core analysis data sets were developed for on all core samples. Integration of these data with open hole log data was undertaken by a multidisciplinary team.

The initial step in development of a more robust formation evaluation model involved the compositional, diagenetic and pore level characterization of Acacus sandstones. These studies revealed extensive diagenetic alteration of reservoir rocks causing considerable variation in rock pore structures and, in turn, the large dispersion of the petrophysical properties. Petrographic, X-ray diffraction, SEM and pore imaging studies identified the nature and distribution of chlorite as by far the most important control on reservoir quality. Chlorite occurs as depositional clay coatings on grain surfaces, as fecal pellets, ooids and as detrital matrix.

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from Spectral Gamma Ray (%), measured in logging run 2B, HTHO – Thorium curve from Spectral Gamma Ray, same logging run, SAND BODY – Shading between K and Th curves to indicate possible sand or sand-rich body, VWCL – Calculated volume of wet clay (decimal fraction), shaded dashed green, VSLT – Calculated volume of silt, shaded brown; unseen header, missing: Calculated volume of sand, shaded yellow with black dots, PHE – Calculated effective porosity, shaded white , TM:TGAS – Total gas from wellsite chromatography, TM:C1, TM:C2 – Light (C1) to heavier (C2) gas fractions from wellsite chromatography. Note that the headers for C3 and C4 (ppm) are unseen

Fig. 5. Prezentacja wyników badań, TM GR – spektrometryczne profilowanie gamma w jednostkach API(U +Th+K), VCL – obliczona objętość iłów, CCT – objętość iłów na podstawie badań dyfrakcyjnych promieni X, Depth – głębokość, AO10-AO30 – oporność obliczona z pionową rozdzielczością równą 1 stopie na podstawie pomiaru Array Induction, RT:Res_Ratio – stosunek oporności AO10/AO90, TM RHOZ – gęstość objętościowa na podstawie pomiaru sondą Lithodensity, TM APLC – porowatość neutronowa w jednostkach porowatości wapienia, pomiar sondą APS neutron, CoreGrainDensi – gęstość szkieletowa ze standardowych badań na rdzeniu, TM PEFZ – indeks absorpcji fotoelektrycznej, PHE – obliczona porowatość efektywna, BVW – obliczona całkowita objętość wody, CorePorosity – porowatość ogólna z badań na rdzeniu przy zachowaniu ciśnienia złożowego, TM CBP8-CBP6 – wyniki pomiarów magnetycznego rezonansu jądrowego, CBP1-CBP8SW – współczynnik nasycenia wodą, TM KTM – przepuszczalność, ProbePerm – przepuszczalność na podstawie testu otworowego, SAND BODY – piaskowiec, VWCL – objętość iłów, VSLT – objętość piaskowca, PHE – porowatość

Thus, much of the clay in these rocks was originally detrital in origin, altered and enriched with respect to iron by colloidal iron flocculated at river mouths (forming berthierene/chamosite) and subsequently recrystallized to Fe-chlorite during burial.

Where chlorite is present as thin coatings on grain surfaces, compaction and quartz overgrowth cementation were inhibited and intergranular porosity preserved.

Where detrital chlorite and chlorite pellets/ooids were abundant, intergranular porosity was largely filled due to compaction and partitioned into micropores.

Where chlorite grain coatings are patchy or absent, quartz overgrowth cementation dramatically reduced porosity and permeability.

Five discrete petrophysical Rock Types were identified based on pore geometry variations:

Type 1 – Rocks with well-developed chlorite rim cement and high porosity–permeability.

Type 2 – Rocks lacking chlorite rims and cemented by quartz overgrowths. Much reduced storage volume and permeability relative to Type 1 sandstones.

Type 2a – Silica cemented sandstones with storage volume augmented by scattered secondary dissolution macropores. Enhanced storage volume and permeability compared to Type 2.

Type 3 – Intergranular pores filled by chlorite grain rims, chlorite matrix and pseudomatrix of compacted chlorite ooids and pellets. Porosity largely restricted to microporosity. Low storage volume and low permeability.

Type 4 – Intergranular pores filled by compaction and silica cement. Low porosity – permeability.

Type 5 – Sandstones with pores lined by chlorite and filled by siderite cement. Low porosity – permeability.

Productive Acacus zones consist predominantly of Type 1 and 2a rocks. Type 2 and 3 rocks contribute to storage but have much reduced permeability and flow potential. Each rock type is characterized by a unique porosity–permeability relationship and has unique capillary pressure and electrical properties. Figure 4 displays the refinement of porosity–permeability data by petrophysical Rock Type.

Petrophysical studies were undertaken to integrate the petrography and laboratory measurements with wireline data. The aim was to translate reliably the pore structures identified by the geological analysis into parameters that could be derived from well log data, providing thus a set of electrofacies-based Rock Types.

The basis for Rock Type identification from well logs is provided by accurate attribution of bin distributions from the NMR log (CMR), reflecting accurately the pore space structure. The resulting petrophysical analysis routine is capable of distinguishing Type 1, 2, 2a and 3 (potential reservoir rocks) with 80+% accuracy (Fig. 5). By varying “m” and “n” (1.7–2) as a function of Rock Type, more reliable fluid saturation profiles and much better agreements with DFA and production results were obtained. Rock Types 4 and 5 are identified by default but are not characterized further since they are of limited interest. A refined lithology model based on dry weights from the ECS tool allows for a more accurate assessment of VCLC.

CONCLUSION

Integration of geological and petrophysical data, starting at the pore scale and discriminating discrete petrophysical Rock Types with unique petrophysical properties yields a much more robust characterization of the reservoir than can be obtained by conventional evaluation techniques. The integrated approach should reduce logging costs by enhancing the ability to identify rock types capable of storing and producing fluids and through the generation of more accurate fluid saturation profiles. Distinction of Rock Types permits more coherent interpretation of porosity-permeability, capillary pressure and electrical properties data measured in the lab. Applying these data in log analysis allows for better saturation and net pay calculations. Finally, the integration of rock types with depositional environments ultimately leads to better and more meaningful reservoir mapping which can be used to better locate future wells.

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