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FlexInLog: Flexible, Integrated Well Log Analysis Software, Developed by PRC

- *a keynote lecture* -

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تطوير منهاج تكاملي مرن لتحليل سرود الآبار بمركز بحوث النفط

أبو ريمة علي أبو القاسم وزلطان بارلاي

قام فريق تقييم المكامن بمركز بحوث النفط خلال الفترة 1992–2000ف، بتطوير منهاج علمي لتفسير تسجيلات الآبار بهدف الرفع من مستوى التحليل الكمي لتسجيلات الآبار بقطاع النفط في ليبيا منذ بداية البحث عن النفط عام 1959م.

ففي الآبار القديمة، لا تتوفر إلا تسجيلات جاما، والنيوترون وقياس الجهد الذاتي وهو ما يحد من فاعلية المنهاج ليعطي فقط المسامية ϕ، والحجم الجزئي لحجر الطين وكذلك درجة تشبع صخور المكمن بالماء والزيت.

أما في الآبار المحفورة حديثاً، فتتوفر مجموعة كبيرة من سرود الآبار وتشمل أشعة جاما وتسجيل النيوترون، وتسجيل كثافة الطبقات والتسجيلات الصوتية وقياس قطر ثقب الحفر الأمر الذي يمكّن من استنباط التركيبة الصخرية ويعطي القدرة على تحديد عدد من الخواص البيتروفيزيائية لصخور المكمن بدقة جيدة بعض الشيء حتى في محاكاة المكمن.

ويتميز المنهاج بالمرونة لملاءمته البيتروفزيائية لتسجيلات الآبار القديمة والحديثة على حد السواء وله صفة التكامل وقدرة ربط المعلومات ذات المصادر المختلفة ويمكن معايرته باستخدام العينات اللبية وبيانات إختبار الآبار والسجل التاريخي للإنتاج حيث أن المنهاج يتمتع بصفات بيانية وإحصائية لكونه رياضياً في نطاق التقدير الحسابي.

وتكمن الخاصية الأساسية للمنهاج في تطبيق نماذج صخرية ذات مسامية متعددة (3-5 مكونات) ونماذج درجة تشبع مكونات مسامية مختلفة. وقد تم تقديم مثال تطبيقي فعلي بالبئر V26 بحقل بالحيضان على صخور تكوين القرقاف الرملية التابعة لدهر الحياة القديمة ذات المسامية المتشققة والفجوية. وستشمل المرحلة الثانية من تطوير هذا المنهاج عام 2002 على تطبيقات بعض التقنيات الحديثة المستخدمة في تسجيلات الآبار مثل التسجيلات الصوتية متعددة الصفوف والصور الدقيقة لجدار البئر.

Abstract: *In the recent years, 1992-2000, a scientific well log analysis software has been developed by the Formation Evaluation Group of PRC. The objective was to cope with quantitative well log analysis of the Libyan Oil Sector from the very beginning, 1959.*

In the early wells only gamma ray (GR), neutron and resistivity (plus SP) logs were available, which restrict capabilities of the software to provide only porosity, Φ, shaliness, V_{sh}, and fluid saturations, S_w & S_o.

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In recently drilled wells a rich suite of well logs have been measured: GR, (sometimes SGR), Φ_n, ρ_b, Pe, Δt, Cal; Induction or Laterolog resistivities (SP), and sometimes MSFL. This collection gives an ample chance to derive sophisticated rock composition and determine a large number of petrophysical rock properties at fair accuracy even for reservoir simulation.

The software is flexible since it can suit both old and recent logging conditions; a high integration is involved because all the evaluation techniques are calibrated to core investigations, well test results, and, production history data; the software is statistical & probabilistic since it is mathematically overdetermined.

The basic feature of the software is the application of multiporosity (3 – 5 porosity components) rock models with more efficient fluid saturation models which distinguish between saturations of the different porosity components.

An example of practical application is presented in the Palaeozoic fractured/vuggy Gargaf sandstone of Belhedan oil field (well V26).

A second stage of the FlexInLog software development, will start in 2002, which will involve the application of some novel logging techniques, such as Sonic Array Tool, MicroImages of the wall of borehole, etc.

INTRODUCTION

Oil exploration and production in Libya reached a turning point at the beginning of the 21st century. Production in the old oil fields is declining. Maintaining the present level of production needs the following action:

- Continuation of oil production in mature fields with enhanced and improved oil recovery techniques (EOR, IOR).
- Exploration of new oil/gas fields in the south of the country (Murzuq Basin).

These developments present a new challenge for the formation evaluation activity of Libyan oil producing companies. Their tasks are:

- Re-evaluation of mature oil fields for preparing the application of EOR/IOR;
- Efficient application of the powerful new well logging techniques in new boreholes.

The Petroleum Research Centre (PRC) of Libya and Teknica Ltd., Canada, are prepared to answer the challenge by developing a new formation evaluation software – FlexInLog, the flexible and integrated well log analysis software. Flexibility means that the interpretation is adapted to the availability of well log and other input information. Integration means that formation evaluation is an essential part of the oil development process, utilizing information from geology, well logs, core measurements, well tests and production data. In turn, it provides indispensable results for reservoir simulation and production control.

MAIN GOALS OF FLEXINLOG

Oil exploration including industrial well logging started in Libya in 1959. Oil production started in the early sixties in the Nasser, Amal, Sarir and Gialo fields (among others). In this period well logging implied only

- Gamma ray, GR;
- Neutron;
- Induction resistivity;
- Spontaneous potential, SP.

Output results were simple and lacking any detail; they provided:

- Effective porosity;
- Shale;
- Matrix material (sandstone or carbonate).

The only petrophysical parameters supplied were water and oil saturation.

Later on, new types of well logs were developed and gradually introduced into the routine logging in Libya. The most important are:

- Bulk Density, ρ_b;
- Photoelectric Effect, Pe;
- Sonic Compressional Propagation Time, Δt;
- Spectral Gamma Ray, SGR
- Micro Spherically Focused Resistivity, MSFL.

Existing well logging instruments were also improved. New tool design, improved computerized control and on-line environmental log corrections increased the reliability of neutron and resistivity measurements. Spectral gamma ray is superior to the conventional gamma ray measurement in revealing mineral composition.

Lithological/mineral composition can be evaluated in much more detail. In sandstones, besides sand and clay, silt fraction can also be revealed. In carbonates, density and photoelectric logs enable the distinction between calcite and dolomite. The presence of ferroan minerals is indicated by photoelectric log.

Better lithology interpretation improves the quality of the determination of porosity.

More accurate lithological composition, improved well logs and calibration on core and lab. measurements resulted in a rich set of petrophysical parameters.

Porosity is divided into 3 – 5 parts (the latter in the case of fractured/vuggy rocks). Some of the porosity terms are useful for oil accumulation and production, while others are only water-bearing. Understanding the pore space composition enables more accurate calculation of petrophysical parameters.

Absolute permeability can be calculated if well log data can be integrated with core analysis and well test results. The equivalent pore throat size, r_{pth} is an important result; examining it helps understanding the complicated relationship between porosity and permeability.

In fractured rocks, fracture permeability is the most important factor. If relevant input data are available (*e.g.* good quality micro resistivity), it can be computed quantitatively. In less favourable cases, the fractured intervals can only be qualitatively delineated which are the candidates for perforations.

Fluid saturations namely water saturation, movable oil saturation and residual oil saturation are computed. In multiple porosity systems, each porosity term has a different water saturation level. (They have different pore size and pore throat size structure; lesser pore throat sizes mean greater obstacles for oil accumulation). Water saturation can be divided to irreducible water saturation and movable water saturation in some cases.

A rich set of special petrophysical and reservoir engineering parameters is provided by FlexInLog; if input data are available: good quality of special core analysis measurements are necessary. Calibrating well log analysis formulae on the core analysis results, values of some special petrophysical parameters, can be determined continuously *vs.* depth; these special petrophysical parameters are as follows:

- Wettability of rocks;
- Relative permeabilities for water, oil and gas only in two-phase systems;
- Water cut (at the beginning of production);
- Fractional oil flow.

AREAL PROCESSING OF THE RESERVOIR

Users of formation evaluation results are interested in the hydrocarbon producing potentials of reservoirs and fields. Therefore, parameters of individual wells should be extended to field level which is supported by the FlexInLog system.

Here the total depth interval of the well is divided into zones, namely:

- Lithological zones are determined by lithofacies analysis; for instance, in some Libyan oil fields the reservoir consists of carbonate and sandstone facies;
- Hydraulic zones are separated by barriers of fluid movement, which can be recognized by the FlexInLog.

Zones of the well are characterized by average and cumulative petrophysical properties. These values determine whether a specific zone of the well is producible or not.

The main average and cumulative parameters are:

- Average porosity and equivalent porosity height;

- Average permeability and transmissibility;
- Average oil saturation and equivalent oil column height;
- Average movable oil saturation and equivalent movable oil column height.

Areal maps of average and cumulative reservoir parameters are drawn in FlexInLog by a semi-automatic method which determines also the oil margin of the field.

Evaluation of oil/gas reserves is carried out by modelling the reservoir with triangle-based prisms, and summing up the hydrocarbon volumes of the prisms; this is a new technique provided by FlexInLog.

BASIC CHARACTERS OF THE SOFTWARE

Flexibility, integration and statistical/ probabilistic nature are the basic characters of the software.

Flexibility means that the procedures of formation evaluation are adapted to the completeness of available input information. Simpler methods are applied for the interpretation of only basic logs in older wells. More sophisticated methods are used in recent wells where a complete set of well logs is available. In field studies where older and newer wells are both investigated, the methods applied on the older wells are calibrated on the newer wells where input information is rich and reliable.

Integration means that well log interpretation is carried out not in isolation, but utilizing all available relevant information. In the following we list the most important data sources which should be analyzed for the calibration of well log analysis.

Routine and special core analysis provide data that can't be obtained by any other means. Petrographic investigations reveal not only the mineral content but also the texture of rock samples. Mercury injection describes the pore throat size and pore size distribution which is crucial in determining permeability and saturations. Lab. analysis of reservoir fluids is also necessary, *e.g.* salinity of formation water affects the interpretation of resistivity data.

In core analysis, great care is needed to restore reservoir conditions (temperatures, pressures, wettability, fluid saturations and streaming velocities) during lab. investigations as closely as possible. This principle assures that core data provide a solid base for the calibration of well log interpretation in reservoir conditions. Otherwise, contradictions may occur between results obtained from different types of investigation.

Well tests (PBU, production tests) give evidence about the presence of oil. If formation evaluation follows well logging by several years – as in the case of field studies – studying production history is essential. The volume of oil and the transmissibility estimated by formation evaluation should be in agreement with the actual production data.

The FlexInLog software is statistical and probabilistic. The process of well log measurement and interpretation is burdened with random errors. The FlexInLog system handles this situation by applying mathematically overdetermined systems. Statistical analysis of errors assures that the reliability of interpretation results can be expressed quantitatively (as by incoherence in the case of lithology).

Multivariate statistical methods are included in the FlexInLog system for the analysis of internal connections between input data and interpretation results. Principal component analysis (PCA) of input data is an unbiased tool for checking the results of more sophisticated human-made quantitative methods.

The name of the software: "FlexInLog" refers to the basic two features of flexibility and integration.

PETROPHYSICAL CHARACTERISTICS OF RESERVOIR ROCKS

The basic properties of rocks are determined by the lithology, mineral content, rock texture, grain size distribution, pore and pore throat size distribution and wettability (Fig. 1).

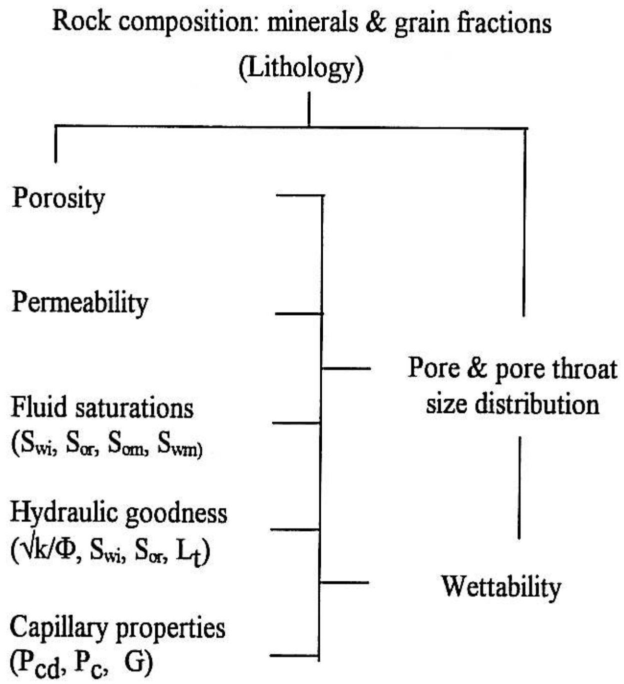

Fig. 1. System-pattern of relations between petrophysical characteristics.

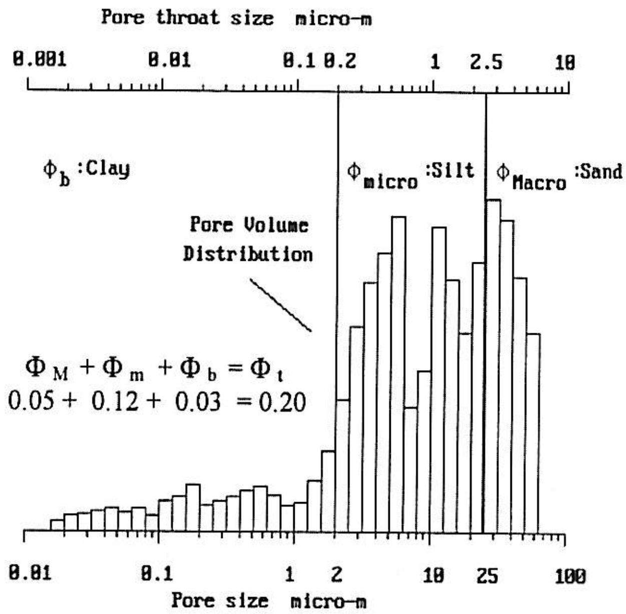

Fig. 2. Triple porosity system in shaly sandstones.

The most important controlling factor of petrophysical parameters is the pore & pore throat size distribution. Pore structure has greater effects on hydraulic properties than the quality of solid rock materials. Therefore, the more information is provided on pore structure, the better is the evaluation of petrophysical parameters.

Presence of reservoir fluids may also alter rock properties. Saturation with oil may also alter wettability: the originally water-wet rocks became oil-wet. Determining wettability of rocks is one of the most difficult tasks – integration of core and log analysis may give the best answer. Knowledge of wettability is crucial in the selection of proper improved oil recovery techniques.

POROSITY COMPOSITION OF SHALY SANDSTONES

In figure 2 a typical example of pore size and pore throat size distribution is shown in a shaly sandstone rock. Accumulation and movement of hydrocarbons are greatly influenced by pore throat sizes. Buoyancy forces push the oil through the pore throats; the smaller the opening, the greater the forces needed.

Well log analysis in itself cannot reveal the pore size distribution *versus* depth; however, in case of an adequate set of input well logs, breaking down total porosity into terms is possible; in shaly sandstones three porosity components can be revealed:

- Macro effective porosity (associated with sand fraction);
- Micro effective porosity (associated with silt fraction);
- Bound water porosity (associated with clay fraction).

POROSITY COMPOSITION OF FRACTURED/VUGGY ROCKS

Composition of porosity is more complex in fractured/vuggy rocks (Fig. 3). Tectonic movements create open fractures in the rocks. These fractures open the way for circulating fluids which in turn dissolve vugs in the rocks. These voids are large enough to accept hydrocarbons during accumulation. Smaller vugs are produced by secondary mineral alterations such as modification of calcite to dolomite. These three porosity components make up the useful (engineering) porosity.

Some other part of porosity has smaller pore throat sizes which prevents hydrocarbons from

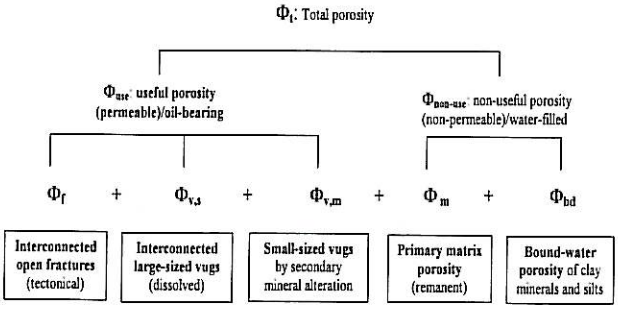

Fig. 3. Composition of the total porosity in fractured/vuggy rocks.

entering it. Primary matrix porosity is what has been left of the original porosity after diagenesis. Bound-water porosity is associated with clay minerals – similar is the porosity associated with micrite which is composed of very fine calcite crystals. These porosity parts do not contribute either to hydrocarbon storage (saturation) or to hydrocarbon movement (permeability), therefore they are called non-useful porosity.

The porosity components of figure 3 are displayed from right to left in order of increasing usefulness for oil production. Fractures are negligible in respect of oil storage but their contribution to permeability is decisive.

EXAMPLE OF FLEXINLOG APPLICATION

The formation evaluation principles of FlexInLog are illustrated by the example of an oil producing well in Belhedan field. The oil is produced from the Gargaf formation, a very old Palaeozoic fractured/vuggy quartzose shaly sandstone. The borehole was drilled in 1992, and a complete suite of well logs was measured, supported by core analysis and well tests. This wide range of input data produced a rich set of output results.

In figure 4 the lithological composition in the upper part of the Gargaf sandstone is shown. Here porosity rarely exceeds 10 %. Quartz is the main constituent; clay and silt are present in 5-20 feet thick intervals; carbonates and ferroan minerals occur in small volumes as accessory components; legend of the solid rock components is presented at the top-right of the figure.

Four components of the fractured/vuggy porosity system – excepting the open fracture porosity – are shown in the middle track:

- Effective porosity is the outcome of the quantitative lithology analysis.
- Matrix porosity is estimated by statistical analysis of effective porosity histograms as an average of the minimum of effective porosities.
- The difference of effective and matrix porosity is the useful porosity, which is divided into large-sized vuggy and small-sized vuggy porosity by application of the sonic Δt log. We utilized the property of the sonic log; that avoids large-sized vugs, so it reflects the sum of matrix and small-sized vuggy porosity.
- Bound water porosity is estimated from the volume fractions of clay, silt and ferroan minerals.

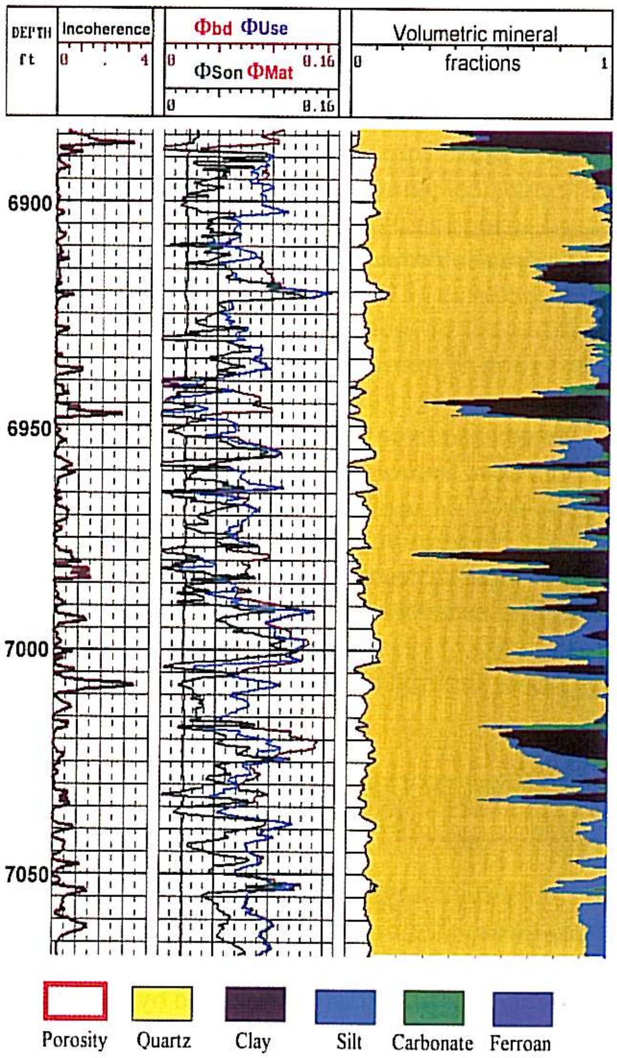

Fig. 4. Lithologic and porosity logs.

FlexInLog applies quantitative statistical lithology/mineral interpretation with a mathematically overdetermined system of equations solved at each depth. It provides – beside the rock composition – measures of reliability of the results. The incoherence is a compound quality indicator – its large values occur where harmony of the input logs is disturbed by measurement errors or other effects; the incoherence is displayed at the lower track.

The lower track of figure 5 shows again the four porosity components; in the middle track the fifth component, open fracture porosity is displayed. A logarithmic scale is applied because the involved quantities are small: the largest fracture porosity in this case is about 0.6 percent.

Fracture porosity was computed in this well from the Micro Spherically Focused Resistivity log (MSFL). Open fractures (filled with mud or mud filtrate) cause a drop in the value of micro resistivity compared to resistivity of fracture-free rock blocks. This method is specific in the FlexInLog system.

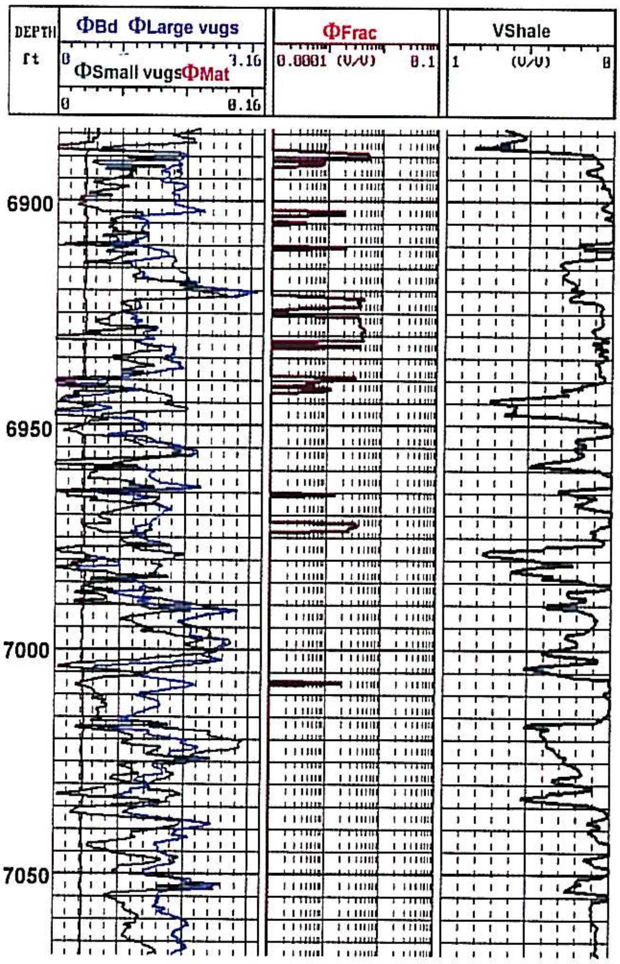

Fig. 5. Fracture porosity log.

In the upper track the volumetric fraction of shale is displayed. Shale is the impermeable part of the rock; the shale is composed of clay, silt, carbonate and ferroan minerals. Presence of shale decreases the value of the rock for fracturing and hydrocarbon production.

In figure 6 those petrophysical parameters are presented which control the oil reserves. In the upper track two quantities are shown which are involved in the computation of water saturation: the deep induction resistivity log is used as an approximation of the true resistivity, R_t; its value is compared to the theoretical resistivity of water-bearing rock, R_0.

The resistivity model of fractured/vuggy rocks, applied in FlexInLog, has been developed by Prof. Z. Barlai; it assumes that the different porosity components form parallel channels of electrical conductances, and they have different water saturation levels.

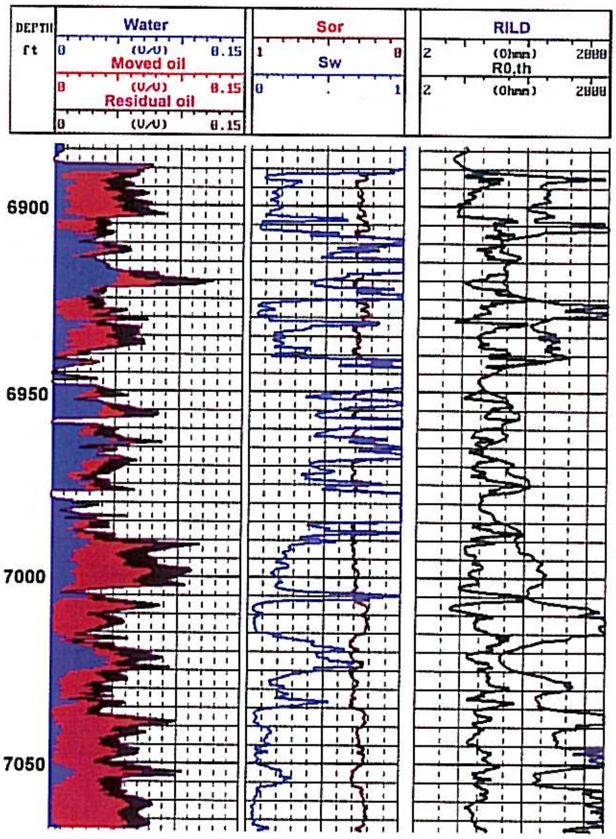

Fig. 6. Fluid volume and saturation logs.

In the middle track the fluid saturations are displayed; water saturation in blue and residual oil saturation in red. Only the porosity components included in the "useful porosity" are filled with oil, so the water and oil saturation values are related to the useful porosity (sum of vuggy and fracture porosity).

In the lower track the useful porosity is shown as filled up with reservoir fluids: water (in blue), movable oil (in light red) and residual oil (in dark red); in this depth interval the water saturation is close to the irreducible level since the oil-water contact (OWC) is at great depth.

In the upper track of figure 7 the total permeability and the block permeability are displayed. Total permeability is the sum of block permeability and fracture permeability. While block permeability is below five millidarcy, the largest values of fracture permeability (and hence total permeability) exceed 20 000 millidarcy i.e. 20 darcy. It is obvious that fractures have the greatest contribution to the total transmissibility.

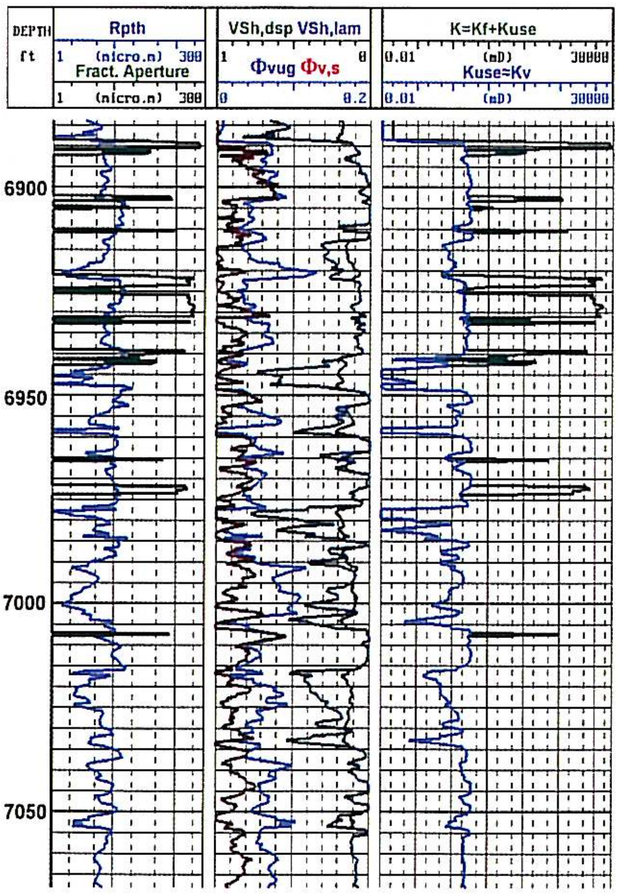

Fig. 7. Permeability and void-size logs.

In the middle track the vuggy porosity divided to large-sized vugs and small-sized vugs is shown together with volume of shale. The shale fraction is separated to laminated shale and disperse shale. Disperse shale has more detrimental effect on the oil producing potential of the rocks. Laminated shale development contain also sandstone laminae with good porosity, permeability and saturation values. FlexInLog applies proper methods for the evaluation of saturations and permeability in the case of laminated shale.

In the lower track equivalent pore throat size (in blue) and fracture aperture (in green) are presented in logarithmic scale. Here again it is apparent that fracture aperture may be 15 times larger than the equivalent pore throat radius (which is a characteristic of vuggy porosity).

The example of the selected well is a good illustration of the novel approach provided by the FlexInLog system. It is important to mention that in this well a rich set of input data were utilized, including core analysis, well tests, production data and Formation Microscanner. All this information was used for the calibration of FlexInLog formation evaluation in an integrated mode.

CONTRIBUTION OF FLEXINLOG TO RESERVOIR SIMULATION

Output results of well log analysis and formation evaluation are utilized in many areas of oil exploration and production. Information provided by FlexInLog is rich and reliable to create a solid base for decision making in reservoir engineering.

Technical and economical decisions about the future production in an oil or gas field are often supported by reservoir simulation. Success of simulation studies depends substantially on the quality of input data. Rock characteristics of the individual wells are provided by formation evaluation.

FlexInLog also applies the "history matching" principle: results of well log analysis should be in agreement with well tests and production results (including production rates and water cut).

During the process of formation evaluation, different sources of information are integrated. Their quality and reliability are evaluated, any contradictions are revealed and possibly resolved. This procedure is beneficial also in the preparation of data for reservoir simulation. Consequently, FlexInLog will improve the quality of reservoir simulations.

THE SECOND PERIOD OF FLEXINLOG DEVELOPMENT

In this stage the software will incorporate the interpretation of those kinds of well logs which are regularly used in Libya. A second phase of development will be started in 2002, in which interpretation of new techniques will be introduced into the software such as:

- Electromagnetic Propagation Tool (EPT);
- Sonic Array Tool (SAT) with full acoustic wave;
- Nuclear Magnetic Resonance (NMR);
- Thermal Decay Time (TDT);
- Geochemical Logging (GL) with energy-selective neutron measurements;
- Borehole wall imaging micro techniques;
- Dual dipmeter tool (SHDT).

SUMMARY

1. The FlexInLog software was developed in a scientific form by PRC in the period 1992-2000; its main goal is to cope with quantitative well log analysis and formation evaluation of Libyan oil/gas wells and reservoirs from the very beginning in 1959 up to now.

2. The basic character of FlexInLog is a flexible and probabilistic integration of well log analysis and all the related disciplines of geosciences into an up-to-date Formation Evaluation.

3. The new way of FlexInLog is to build up the total porosity of the rocks from a number of porosity components, – namely minimum 3 and maximum 5, – by taking into account the pore-throat and pore-size distribution and the fracturing of the rocks.
4. The different porosity components, contributing to the water saturation and to the permeability at different levels, is utilized in FlexInLog with the purpose of recognizing the presence of hydrocarbons even in sophisticated rock developments. Better understanding of reservoir rock behaviour will improve the production control and the quality of reservoir simulations.

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