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Open-Hole Well Logging: Technological Innovations Driving Precision in Subsurface Evaluation

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Abstract: Measurement from open-hole well logging has been a significant variability in the oil and gas business as it offers mud logging and measurement while drilling in conventional and wireline logs. Measurement is the base in formation evaluation, proving to be crucial information in applications from simple assessment of individual drilling wells to more general reservoir characterization. Improvements that the open-hole well-logging technology has experienced over time have overruled the challenges related to the accuracy or the efficiency demanded by the requirements of precise and reliable reservoir evaluation. Some of the significant technological progress resulted in better capabilities for measuring the key properties of a reservoir and, thereby, offering scopes for even better decisions about exploration and production. It depicts several examples of such development that describe their real-world application in a holistic view of the modern technological landscape. This paper also reveals ideas about what trends are surfacing and shaping open-hole wells, logging into a future that will see them become a constant process within the industry of continuous change and innovation in methods used to evaluate the subsurface.

Keywords: Open Hole Logging; Wire Line Logging; Porosity and Permeability; Numerous Technology; Shale Volume; Logging Tools; Resistivity Logs; Lithology Logs; Water Saturation; Environmental Parameters.

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1. Introduction

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Therefore, the paper requires an integrated approach combining data from a broad spectrum of sources, including 3D seismic imaging, vertical seismic profiling, mud logging, coring, measurement-while-drilling, logging-while-drilling, wireline logging, pressure tests, and fluid sampling. These individual data sets offer comprehensive information on subsurface geology, reservoir characteristics, and fluid properties- all elements important for optimizing exploration and production activities [1]. Scientific petroleum reservoir evaluation inherently requires multidisciplinary information that encompasses geophysics, petrophysics, and reservoir engineering insights [2]. Though oil and gas experts often specialize in disciplines like seismic interpretation, log analysis, or core analysis, effective reservoir evaluation requires specialists to collate data into a workable reservoir model [3].

This area has played a crucial role through R&D activity in driving the development of the subject, and studies are aimed at the characteristics of reservoir rocks and fluids and their link to observable properties [4]. Such oil and gas companies invest a lot in research and development activities to study how porosity and permeability, among others, affect the performance of reservoirs, especially under the recent technological changes [5]. For example, new seismic systems would be able to image more minutely intricate structures by geological structures, which many industrial applications have only recently confirmed [6]. In contrast, logging tools provide detailed measurements at high resolutions for measurements in porosity, permeability, and fluid saturation [7]. Similarly, core samples would present direct information on lithology and mineralogy for direct comparison with indirect measurements from other techniques [8].

In like manner, the relationship between properties of rock and fluid and their measurable attributes remains at the core of continuous research - although efforts in modelling used in the industry [9] show. Here, there is the presentation of relations of porosity with permeability and fluid flow characteristics [10], relations between rock compositions and seismic velocity [11], and the relation of pressure and temperature conditions to the alteration behavior of fluids [12]. These would give insights that may enrich the interpretation of an existing dataset. Still, they could also develop a predictive model to predict reservoir performance for various production scenarios [13].

Interdisciplinary approaches accelerate studies of reservoir evaluation. One example was the collaboration between academia, technology providers, and oil and gas companies [14]. Other advanced developments, such as machine learning and artificial intelligence, are increasingly finding workflow applications to analyze big data sets and recognize patterns that the old methods would miss [15]. The virtual models of reservoirs- a digital twin- simulate their behavior in real-time and are increasingly applied, revolutionizing the industry's ability to make data-driven decisions [16]. Integrated with modern innovative efforts, petroleum reservoir evaluations would continue to evolve to develop something sustainable and meet the requirements of the global energy sector.

Wireline well logging operations are an important activity during the exploration and production phases in the petroleum industry. It takes specific measurements of borehole and formation properties at any required depth. It thus helps petroleum professionals like geologists, geochemists, and geophysicists collect key data about subsurface formations. However, these experts are generally much more interested in the relationship of measurements to the reservoir's physical and chemical properties than in the logging tools' intricate function. They aim to find petroleum-bearing reservoirs. To do this, full knowledge of subsurface sedimentary formations is needed. Logs are one of the most important means of obtaining detailed information about such formations. Other research proves that wireline well logs are an excellent tool for describing and characterizing reservoirs [17]. The method has widely been used by various researchers to deliver data that defines or infers key formation properties like porosity. Porosity is the property of a formation that determines its ability to hold fluids [18].

Logging applications have been studied extensively in the volume measurement of shale, which is a must for the effects of reservoir quality [19]. Lithology identification is very significant, and it forms a most important constituent of the interpretations of wireline log reports provided by experts [20]. Fluid saturation levels, deciding the percentages of water oil or gas in the formation, were also evaluated using advanced logging techniques. As shown by the examples of several works, these techniques help make sound decisions about reservoir appraisal and development [21]. These techniques help petroleum professionals maximize the extraction of hydrocarbon while improving the efficiency of the operation, as it is supported by studies that reflect the real-life implementations of well logging [22]. Therefore, wireline well logging is essential to know and manage subsurface resources.

The critical parameters of reservoir characterization and management include permeability estimation, prediction of water cut, over-pressure zone determination, and residual oil calculation [23]. Log analysis, most importantly, is used to describe the properties of the formation, especially for an individual. Usually, log data and core samples are compared to define a reservoir's properties [24]. This synergism allows an integrated view of the subsurface environment. If cores are unavailable, then log data usually supplements core analysis; comparisons with logs of other wells provide critical information. It becomes a strong adjunct in geology when a set of logs is obtained from several wells in some particular geological area and ceases to be an adjunct only to individual analyses of wells [25]. This information will help the geologists describe the geology and stratigraphy locally, the depositional environment, and reservoir geometry under present geological conditions to delineate the reservoir better and enhance the understanding of the complex geological systems. Increases the probability of making hydrocarbon exploration and production in the right direction.

2. Literature Survey

Wireline logging is a very important process in the petroleum industry; electric instruments are used constantly to measure the properties of subsurface formations. It remains among those tools that aid informed decision-making regarding drilling and production operations. It's the process in which the specialized tools or equipment are lowered into the borehole to measure down-hole formation attributes. This is referred to as well logging and is used in identifying oil and gas intervals and quantifying the properties of reservoir rocks. The attributes measured include lithology, geologic structure, porosity, fluid saturation, and the extent of drilling fluid invasion. Sensors applied in wireline logging can detect electric, electromagnetic, acoustic, neutron, and gamma-ray signals, among others, transmitted into the geological formation. These signals, character, and strength, modified by the properties of the rock and borehole conditions around it, are captured and analyzed to establish the characteristics of the formation, which are very important for hydrocarbon production [3].

Caliper logs are normally used with other tools to determine the size and profile of the borehole. Imaging tools help determine fractures and faults, giving more information about reservoir characterization [4]. Downhole imaging tools can detect fractures and high-permeability thief zones that may impact fluid flow [5]. The information obtained from wireline logging is crucial in establishing how a well will be completed to maximize production and plan future wells effectively to develop and manage the reservoirs [6]. Wireline logging is further classified into open holes or cased holes. Open-hole logging is performed in a newly drilled borehole, and rock composition and hydrocarbon saturation properties are measured there [7]. After setting the casing, cased-hole logging is made to evaluate the integrity of the casing and detect possible damage that may have occurred [8]. These techniques provide accurate decisions about well completion and production [9].

The process of wireline logging has a rich history, dating back to its introduction by the Schlumberger brothers in the early twentieth century [10]. Initially developed to detect metal ore deposits, the technique was later adapted for the oil and gas industry [11]. In 1927, resistivity logging was first employed in Alsace, France, marking a significant milestone in the field [12]. Shortly after, an SP log was developed to determine permeable zones with hydrocarbons [13]. Then, in 1939, the gamma-ray log was developed by Well Surveys, Inc. The Gamma-ray log measures natural radioactivity to identify shale beds and can be run in cased holes [14]. By the late 1940s, the induction log was developed to work in non-conductive, oil-based mud environments, significantly expanding wireline logging capabilities [15].

Every logging tool has a technical purpose. As an illustration, resistivity logs measure electrical resistivity fluids in a formation. The resistor tool takes advantage of the property that water conducts electricity considerably better than oil and gas [16]. Resistivity tools use two electrodes to form the circuit, which depends on the current amount of conductivity fluid in question formation [17]. High resistivity values usually indicate the presence of oil zones [18]. The most common resistivity tools are dual lateral logs, micro-spherically focused logs, and dual induction logs that provide fluid type and saturation information [19]. Among the oldest tools is the SP log, which measures the potential difference from the borehole to the surface to identify the most permeable formations [20]. Density logs measure the bulk density of formations based on gamma-ray counts that are affected by Compton scattering and photoelectric absorption. It is one of the crucial information to be used in determining the porosity of rocks.

Acoustic logs measure the travel time of sound waves in the rock for characterization, including porosity, lithology, and texture [22]. These logs emit sound waves, record their travel time from transmitter to receiver, and give detailed information on the properties of the rocks. The gamma-ray log identifies shale beds because it detects natural radioactivity, distinguishing it from the sandstone layers composed of non-radioactive quartz particles [22]. Caliper logs are fitted with arms that press against the borehole wall to provide a detailed profile of the shape and diameter of the borehole. An acoustic technique known as spectral noise logging is used to evaluate the integrity of the well and the production or injection intervals based on the noise caused by the fluid flow within the subsurface.

The second main tool is the diameter log, which characterizes the reservoir by finding the orientation of geological beds, faults, and fractures through imaging techniques. A significant milestone in the industry was marked by the appearance of Measurement While Drilling technology in the 1970s. MWD tools attached to the drill string give real-time information on formation properties, including rock porosity, density, fluid pressure, and borehole trajectory. Mud pulse telemetry sends this data to the surface by transmitting pressure pulses in the mud column. MWD, or logging while drilling, is a key feature of horizontal drilling and gives immediate information regarding the location and direction of lateral sections.

The Tucker Wireline unit is one great example; contributions of the different tools explain how successful wireline logging works. The logging suite consisted of a complement of open-hole logs for comparison. The Dual Laterolog, Phased Induction, BHC Sonic porosity, and density porosity tools were included. The Dual Laterolog tool measures deep and shallow resistivity, which is important to understanding formation properties. Shallow resistivity measurements reflect effects from flushed, invaded, and transition zones. The virgin zone almost solely influences deep resistivity measurements. A sufficient contrast of resistivity values between mud and formation is required. On one run, the tools ran by Tucker managed to pick up good deep resistivity in the Tensleep formations. Logging had a few problems along the way: a bridge at 4,400 feet, which kept getting past that. Re-entry was possible again, though, and another triple-combo string ran to a depth of 5,947 feet; it is good data.

Today, wireline logging is an integral part of the oil and gas industry's tool for complete information regarding subsurface formations to steer decisions toward efficient development and management of reservoirs. The integration of advanced technology, such as MWD and real-time data transmission, has significantly enhanced the accuracy and efficiency of the logging operation to ensure the capability of the industry to handle the challenges of modern hydrocarbon exploration and production.

3. Methodology

It involves gathering, processing, analyzing, and inferring subsurface geological and petrophysical data from a reservoir using open-hole wireline logging. The method begins by running those wireline logging tools across the uncased boreholes of that system, from where the details about the formation properties start coming forth, beginning from some real-time. Some major logging tools used in deciding lithology include gamma-ray logs. Resistivity logs may be applied in fluid characterization. Tools that apply neutron and density are used in estimating porosity. Sonic logs help measure mechanical properties and formation evaluation. Gamma-ray logs help in identifying between shale and non-shale. Resistivity logs measure formation resistivity. It can determine the electrical conductivity. Therefore, the log can identify zones bearing hydrocarbons. Neutron and density logs can measure porosity, the response of a zone to hydrogen content, and bulk density.

These measurements are calibrated using the core samples wherever possible, making them more precise. Sonic logs measure the formation's acoustic travel times and assist with evaluating porosity and mechanical strength. This data can then be complemented with information from some highly developed NMR logs, which provide data associated with the very detailed pore structure and the mobility of fluids. Data is acquired at different depths and intervals to obtain a holistic concept of the heterogeneity of the reservoir. This entails environmental corrections to account for the impacts of the borehole and fluid effects such that the measurements may become reliable. Integrating data acquired is also very important; cross-plots and statistical analysis are conducted to correlate various log responses, for instance, to ensure interpretation and validation. This will complement the evaluation of log signatures, mud logs, and cuttings analysis for a comprehensive understanding of the reservoirs.

This means that the heart of hydrocarbon exploration and production is based on the interpretation of petrophysical data. Raw log data are transformed into valuable reservoir parameters with the help of advanced software and modeling techniques. Such parameters include porosity, permeability, saturation, and lithofacies distribution, giving crucial insights into subsurface formations and their physical and chemical properties. The interpretation process considers data sources from wireline logs to core samples and seismic data to achieve a general understanding of the reservoir. It is applied to identify productive zones, estimate reserves, and optimize completions of wells that impact productivity and efficiency in such exploration and production operations. Advanced software technologies made the transformation of complicated data sets into high-resolution images of multidimensional reservoirs possible. Such images capture spatial heterogeneity and variability of properties in both rock and fluid- a couple of factors critical to cutting down uncertainty regarding the characterization of a reservoir.

Such information will be necessary for geoscientists and engineers to interpret critically when they seek better decisions regarding the specific placement of wells and optimum production or when they must select the optimum technique for enhanced recovery. Rapid and definitive interpretation ensures that important decisions are taken based on reliable information by minimizing uncertainties within the subsurface and associated risks. Petrophysical data interpretation is essential at every stage of the reservoir's lifecycle, from initial exploration to field development and production. In field development, it guides decisions on drilling and completion designs, while in production, it informs strategies for maintaining or enhancing reservoir performance. For example, knowledge of lithofacies distribution helps predict fluid flow behaviour in the reservoir, which is vital in designing efficient extraction methods. Similarly, reliable permeability and porosity values are vital if the reservoir's behavior is simulated under various production schemes to optimize recoveries at a minimal cost.

Dynamic models that can be built based on petrophysical interpretations describe the change in fluid flow behavior and pressure buildup over time. Such a nature of dynamic reservoir models is crucial for production planning in a sustainable manner, especially for the design of the secondary and tertiary recovery schemes of water injection as well as gas injection. The characteristic behavior of this kind of reservoir allows an operator to optimize recovery in a responsible, economical, and environmentally friendly way.

Mastery of petrophysical properties from their interpretation has enabled data to be an energy expression whose landscape is characterized by efficiency and sustainability. This data characterizes the reservoir with high-resolution resolution and entails actionable insight to help decide on data in the context of hydrocarbon exploration and production. Many improved recovery techniques, such as the identification of productive zones and placement optimization, fall into a success story about energy projects. Also, a diversified set of datasets and the newest technological applications of the latest petrophysical interpretation help operators realize maximum potential by providing the lowest risks and operating uncertainty on a given reservoir.

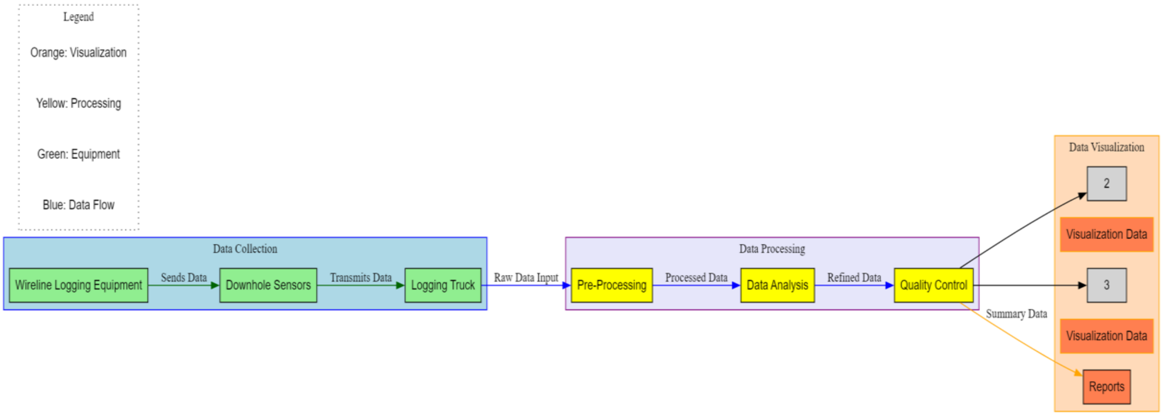


Figure 1: Reservoir characterization framework using open-hole wireline logging data

Figure 1 shows the processes and elements of the reservoir analysis workflow. It is divided into three major groups: Data Collection, Data Processing, and Data Visualization, with different functions. The Data Collection group includes components such as Wireline Logging Equipment, Downhole Sensors, and Logging Trucks that interact to collect and transmit raw subsurface data. Downhole Sensors collect the data, and then the wireline logging equipment sends it to the Logging Truck for transfer into the processing stage. The data processing cluster contains three stages of operation: pre-processing, data analysis, and QC; these are three steps where the raw data undergoes cleaning and refining and becomes validated for its accuracy and usability. Pre-processing feeds the cleaned data into Data Analysis, which recognizes patterns and insights before QC finalizes the processed data for interpretation. The Data Visualization group packages the curated data into workable formats: 2D plots, 3D Reservoir Models, and reports that help various stakeholders make educated decisions. Connections refer to the flow between these groups and to distinguish the roles: blue equipment contains the encoded flowing data for processing, which is yellow-green; for visualization, orange-an accompanying legend solidifies the idea of the meaning intended with those colours. This diagram offers a coherent layered view of technical and analytical processes involved in reservoir characterization and seamlessly integrates field equipment, computational workflows, and visualization tools.

4. Results

Open-hole wireline logging analysis provided a detailed account of the geological and petrophysical properties of the reservoir. Thus, a full characterization of the formation was accomplished. Gamma-ray logs adequately delineated the lithological boundaries, such as shale-rich intervals and cleaner sand zones, which may represent potential hydrocarbon reservoirs. Resistivity logs picked up areas with a high resistivity level, such as hydrocarbon-bearing formations. This was also proved through models of petrophysical to be an area of relatively low water saturation levels. Neutron and density logs helped pick areas with high porosity levels; this was then confirmed using cross plots to define the types of fluids and the nature of lithology. Sonic log data improved the understanding of mechanical properties and trends in porosity by verifying travel time variations and reiterating the reservoir heterogeneity. The NMR data integration clarified pore-size distribution and fluid mobility aspects concerning both producible and bound fluids present in the intervals.

This was an important productive area with favorable porosity and saturation of hydrocarbons; it corresponded to the depth of primary target formations. All environmental corrections and calibration through core data ensured accurate interpretation results. Advanced interpretation techniques, such as multi-log cross plots, were also used to verify the consistency of trends between lithology, porosity, and fluid saturation across the reservoir. Variations in log responses were related to variations in depositional environments and, hence, lateral and vertical heterogeneity within the formation. High-resolution reservoir models made out of wireline data indicated zones of optimum reservoir quality, assisting strategic decisions regarding where to place wells and a completion design. In general terms, the integration of open-hole wireline logging presented a solid framework relative to the appraisal of possible reserves in a reservoir, translating into effective exploration and production strategies for hydrocarbon resources.

Calibration of calliper logs is a process that will ensure the right measurement of the borehole dimension, especially at the top of the well, where the diameter of the casing is known. This has to be corrected because different callipers could read differently; this is mainly because of the caliper's design and the hole's cross-section. Logging is a better data acquisition technique to access subsurface properties throughout. The process involves formation measurements recorded as continuous acquisitions obtained by lowering electrical instruments down to the borehole and extracting the data captured about variables such as lithology, porosity, and resistivity. Recorded information is called a log, which is very detailed and encompasses all aspects of the formation, so geoscientists with high accuracy can interpret it.

Well-logging services, including ONGC, are a part of the exploration and production process that offers a complete range of data acquisition, processing, and interpretation services. These services help operators to define, reduce, and manage risks in the exploration and development of hydrocarbons. Some of the examples are open holes, cased holes, and production logs tailored towards specific operational requirements. The main three suits under the Open Hole logging heads include:

Suit 1: This suit includes Rt, GR, SP, and Caliper Logs.
Suit 2: That comprises Sonic, Neutron, Density and GR Logs
Suit 3: This comprises R.F.T. Side Wall Samplers and the Dip Meters.

All the suits provide crucial information about the lithology, porosity, and resistivity of the formations within the borehole. Lithology logs- Gamma Ray SP logs for defining the lithology of the formation are very useful. These indicate zones of interest and are basic to define any productive interval in the well log. Porosity logs: Neutron, Formation Density, Sonic to measure pore volume in the rock, which is considered a deciding factor for assessing the possible storage of hydrocarbon in the reservoir. Resistivity logs: conventional, focused, Induction, and micro resistivity to measure the capacity of the formation to resist current flow and indirectly to interpret the fluid content and saturation level in the pores of the rock. These logs are combined to provide a multidimensional characterization of the reservoir, aiding in decision-making for well placement, completion, and production strategies. The borehole and formation properties are measured during wireline logging operations at precisely recorded depths. Measurements from logging tools occur under pseudo-dynamic circumstances; that is, the borehole fluid remains stationary during measurement. Logging tools normally run up the hole and pick measurements on their way. Sometimes, the tool may stop at one point or fall when entering or exiting formation fluids. This flexibility in the operations assures varied subsurface conditions are captured and recorded appropriately.

The log should itself hold all data acquired in the well and present the data in a form easily interpreted and compared. Other parts of the log include the log header, tool configuration, calibration data, and operating conditions. The log header will carry general information about the well and job, including the company name, well name, tools used, logged interval, and mud record. The tool configuration will indicate the tools used, their serial numbers, and the sensors. Calibration is the step to ensure that the tools behave correctly within known environmental conditions. Operating conditions involve any deviation from standard procedures. These details will only be reliable and consistent in the log data if proper documentation is done.

Data acquired from logging not only permits the initial characterization of the reservoir but also forms the basis of advanced modeling and simulation. Only by having accurate logs can geoscientists create detailed reservoir models, simulate fluid flow, predict how the reservoir might perform under different production scenarios, optimize hydrocarbon recovery, and reduce uncertainties that minimize operations risks. Logs are critical in exploration, production operation planning, and implementation since they ensure complete, reliable data for informed decision-making. Logging ensures that data is well acquired, processed, and interpreted for successful and sustainable reservoir management (Figure 2).

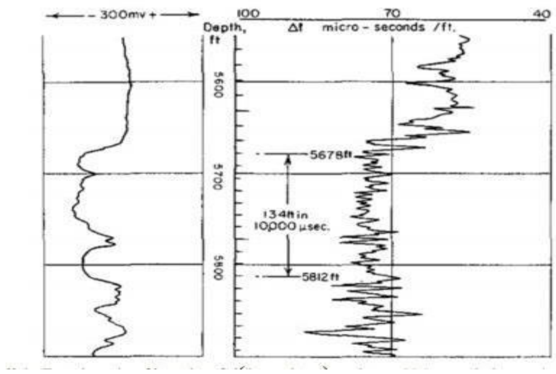


Figure 2: Porosity Resistivity Log

The major content of a log is a complete record of the required data versus depth throughout the entire well, presented in client-defined colour codes and scales, usually 1/500 and 1/200. The record indicates subsurface conditions and is, hence, very crucial for interpreting properties in formations. Remarks regarding logs include disclaimers and other notes aiding in the process of interpretation. Calibration records prove that all checks for accuracy and reliability are conducted for the operational functions before running the tools into the hole and after pulling out. For example, testing under known conditions tests that they read within acceptable tolerances. Technical logging accounts for how the tools are performed during the logging process. The tool records voltage and current measurements to check the status of its operations. Green colour means good electrical function, while red means it has an issue. The log's tail end is where all the collected data will be presented in graphical form for a comprehensive and standard record review. For this study, with focus, these logs are GR, SP, Neutron, Formation Density logs, Sonic, Focused Induction, Micro Resistivity, and Caliper. These logs traditionally interact with the materials in pores and have chemical make-ups of the rock matrices; therefore, intrinsic chemical classification does seem good for interpretation. Logs record these drilling and completion events, and header information will probably be derived directly from the logging crew's measurements or observations conducted at the surface.

Such is essential when it comes to formation evaluation, given that these details complement log response interpretation and best measuring practices. SP and GR logs are part of lithology logs that register natural phenomena under in-situ conditions. The SP log acts as a permeability indicator with a sensitivity towards identifying the presence of permeable beds through negative SP excursions when the mud salinity increases to more saline than that of the connate formation water. It also allows for bed boundary recognition, formation correlations, Rw detection, or the resistivity of the formation water. The GR log is a shale indicator that measures gamma-ray emissions from the formation scaled in API units to estimate shale volume, Vsh. SP and GR logs differentiate shale from reservoir rocks, correlate formations, evaluate shale content, and analyze minerals. SP and GR logs define bed boundaries, identify lithology, and distinguish porous and permeable rocks, such as sandstone and dolomite, from non-permeable clays and shales.

Some examples of porosity logs indicating the rock's porosity include density, neutron, and sonic logs. It is the most significant criterion in the reservoir evaluation. Formation bulk density is calculated by this log using gamma-ray scattering, which varies directly with the number of electrons in the formation. In addition to calculating porosity and hydrocarbon-bearing zones, it determines formation density. A neutron log measures deceleration neutrons caused by collisions with nuclei hydrogen, which aids in porosity and type determinations of fluid within the formation. It may be considered an effective tool, especially in gas-bearing zone identification and estimating a liquid-filled pore volume. The environment also impacts neutronic logs, such as borehole fluids, salinities, and temperature changes. It also determines the speeds of velocities corresponding to traveling sounds within the borehole and connects porosity determination with the changes in the lithologies and fractures of rock material. Sonic logs integrate the seismic data and travel time estimations and identify the cement behind the casing. The well-known Wyllie Time-Average Equation is widely applied for porosity determination from sonic log measurements once the required lithology-dependent parameters are included (Figure 3).

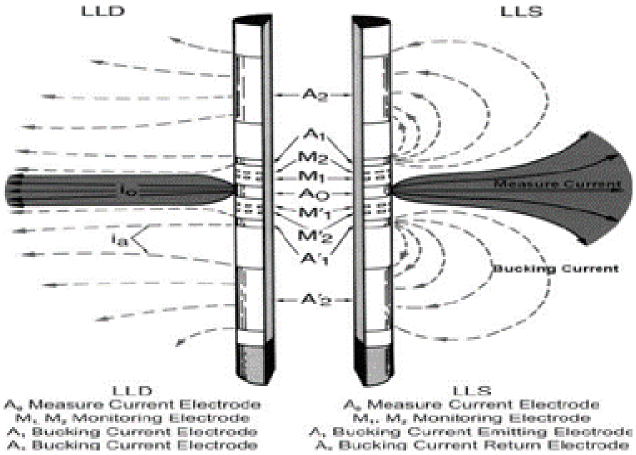


Figure 3: Dual Latero Log Electrode

Formation resistivity is controlled by various factors such as pore geometry, fluid type, and total saturation. Resistivity logs measuring potential or apparent resistivity variation include Normal, Lateral, and Dual Laterolog (DLL) for formation property assessment. LLS and LLD measurements are available in DLL tools. From such measurements, the true formation resistivity can be obtained. These measurements are useful in determining porosity, hydrocarbon existence, and fluid saturation in the zone of interest. Deep-resistivity logs are effective in hydrocarbon-bearing zones, but shallow resistance measurements add information when the formation is analyzed.

Logs collectively offer a detailed subsurface characterization, helping identify productive zones, estimate reserves, and optimize hydrocarbon exploration and production strategies. They give important data about lithology, porosity, and resistivity that aid in making better decisions and enhance the accuracy of reservoir models. Logs form a basis for advanced modeling and simulation that help operators optimize recovery by managing uncertainties and reducing operational risks. The value of accuracy and reliability of logging data is known for achieving sustainable and efficient resource extraction with environmental and economic feasibility. With continuous improvements in technology and methodology, logs remain the only indispensable tools to unlock the subsurface reservoir's potential.

Uses: Estimation of true resistivity Identification of diameter of invasion

The spontaneous potential is calculated using the equation:

$$SP = -K \cdot \log\left(\frac{R_m}{R_w}\right) \quad (1)$$

SP: Spontaneous potential (in millivolts)
K: Constant depending on temperature, salinity, and formation properties
R_m: Mud resistivity (ohm-m)
R_w: Formation water resistivity (ohm-m)

Gamma-ray index is computed to estimate shale volume:

$$I_{GR} = \frac{GR - GR_{\min}}{GR_{\max} - GR_{\min}} \quad (2)$$

Where:

I_{GR}: Gamma ray index
GR: Measured gamma ray value
$GR_{\min}$: Minimum gamma ray value (clean sand baseline)
$GR_{\max}$: Maximum gamma ray value (shale baseline)

Shale volume (V_{sh}) can be calculated using:

$$V_{sh} = 0.083 \cdot (2^{37 I_{GR}} - 1) \quad (3)$$

Permeable beds can be identified using the resistivity and SP logs. Zones where SPReject0 and resistivity show high values typically indicate permeability and hydrocarbon presence. Abrupt changes in log responses identify bed boundaries.

ΔGR: Sudden changes in gamma-ray values indicate boundaries. Resistivity logs often show sharp contrasts at lithological interfaces. Determining R_w (Formation Water Resistivity) as:

$$R_w = \frac{R_t}{\Phi^m \cdot S_w^n} \quad (4)$$

R_t: True resistivity (from resistivity log)
Φ: Porosity (from neutron/density logs)
S_w: Water saturation
m: Cementation exponent (typically 2 for clean formations)
n: Saturation exponent (typically 2)

From gamma ray logs, higher I_GR values indicate the staleness or shaliness of the formation. A qualitative comparison helps in inferring depositional environments. Porosity (Φ) can be estimated from density and neutron logs as:

$$\Phi = \frac{\rho_m - \rho_b}{\rho_m - \rho_f} \quad (5)$$

Where:

ρ_m: Matrix density
ρ_b: Bulk density
ρ_f: Fluid density

The acoustic velocity (V_p) and integrated travel time (t_{int}) are calculated as:

$$V_p = \frac{1}{\Delta t} \quad (6)$$

$$t_{int} = \int_0^d \frac{1}{V_p} dz \quad (7)$$

Δt: Sonic travel time (from sonic logs)
d: Depth interval

Cement bond quality is evaluated using amplitude and attenuation as:

$$A = A_0 \cdot e^{-\alpha x} \quad (8)$$

Where:

A: Attenuated amplitude
A_0: initial amplitude
cx: Attenuation coefficient (related to cement bond quality)
x: Distance travelled

The Microlaterolog measures the resistivity of the flushed zone (Rxo) and provides information about permeable beds since they are also sensitive to mud cake presence. Its response varies with the ratio Rxo/Rmc since the inflow of currents into the mud cake is restricted. Under low or moderate invasion conditions, the depth of investigation of 3–5 inches enables this tool to measure the invaded zone. However, MLL has very low sensitivity when the thickness of the mud cake is more than 3/8 inches due to the unavailability of proper readings. It is used extensively in defining permeable beds and collecting resistivity data for the flushed zone. Micro Spherical Focused Log measures the resistivity of the flushed zone, but with highly accurate electrode spacing, the equipotential surface is spherical. This log has been proven to be highly effective in low invasion conditions and thick mud cake scenarios where near-true Rxo values are achieved. Reservoir interpretation and characterization involved setting parameters including Rw, that is, the formation water resistivity, Φeff, or the effective porosity; Vsh, the shale volume; and Sw, the saturation by water. The amalgamation of the scientific experience in systematic rules makes the reservoir's geological framework and composition valid during interpretation. Pre-selected before interpretation, shale resistivity, maximum resistivity values, formation water resistivity values, and neutron-density porosity values are all control parameters, which consist of gamma-ray minimum and maximum counts. When characterizing the reservoir, these will put log data in a known framework for better accuracy.

Rw is the resistivity of undiluted formation water by invasion and is required for saturation calculations. It may be from the following lists: water catalogs, SP curves, resistivity-porosity cross-plots, etc. Static SP in clean water-bearing formations will provide Rw from equation SSP = -K log Rmf / Rw, and K varies by temperature. Hence, Rw estimation will consider formation temperature, temperature gradients, and resistivity at depth. Rmf and Rwe can be found from graphs and calculated values and then used to calculate the actual formation water resistivity. Archie's experiments proved that the clean formation resistivity was proportional directly to the brine-saturated rock resistivity, and the proportionality constant was known as the formation resistivity factor, F. That was an empirical correlation related to the formation factor to porosity and an insight into the properties of the reservoir rocks. These resistivity-based techniques, together with advanced logging tools such as MLL and MSFL, enable the additional detailed characterization of a reservoir by identifying the zone of permeability, determination of water resistivity, and computation of porosity and saturation. This detailed interpretation would enable proper decision-making during hydrocarbon exploration and production (Figure 4).

$$F = R0 / RW \quad (9)$$

$F = a / \Phi^{m}$
Where m = Cementation Exponent u = Achies's constant

The most widely used Archie's relation between F and Φ for sands is

The mathematical equation in the provided image can be written as:

$$F = \frac{\sigma 0}{\sigma_{eff}} = \frac{\rho_{eff}}{\rho_0} = \frac{1}{\varphi \beta} \qquad (10)$$

Where:

$\sigma_0(\rho_0)$: Pore solution conductivity (or resistivity)
$\sigma_{eff}(\rho_{eff})$: bulk conductivity (or resistivity)
φ: Porosity
β: Pore connectivity factor. The mathematical equations in the provided image can be written as:

$$F = \frac{0.62}{\Phi^{2.15}} \qquad (11)$$

$$F = \frac{0.82}{\Phi^2} \qquad (12)$$

Where:

F: Formation factor

Φ: Porosity

From Archie's equation, we can derive an expression for water saturation as a function of the ratio of these up-curves. Saturation in terms of porosity:

$$S_w = \frac{\Phi_w}{\Phi_{tota1}} \qquad (13)$$

Where:

S_w: Water saturation
Φ_w: Water-filled porosit}
Φ_{tota1}: Total porosity. Saturation of Water in Terms of Resistivity:

$$S_w^2 = F \cdot \frac{R_w}{R_t} \qquad (14)$$

Where:

$$F = \frac{R_o}{R_w} \qquad (15)$$

Where:

R_o: Resistivity of a water-saturated formation
R_w: Resistivity of formation water. Water saturation can also be expressed as:

$$S_w = F \cdot R_w \qquad (16)$$

Alternative Form of Water Saturation:

$$S_w = [\frac{R_{xo} \cdot R_w}{R_t R_{mf}}]^{\frac{5}{8}} \qquad (17)$$

Where:

R_{xo}: Resistivity of flushed zone

R_{mf}: Resistivity of mud filtrate. Water Saturation Based on Archi′s Law is:

$$S_w^n = a \cdot \frac{R_w}{\Phi^m \cdot R_t} \quad (18)$$

Where:

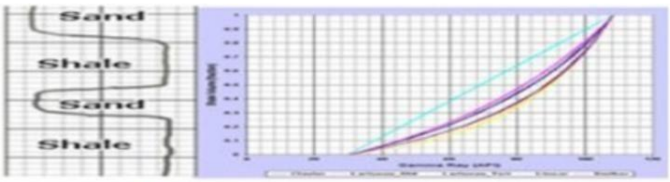
S_w: Water saturation
n: Saturation exponent (typically 2)
a: Tortuosity factor (typically 0.81-1)
Φ: Porosity
m: Cementation exponent (typically 2 for clean formations)
The mathematical equation for Shale-Connected Water Saturation car

$$S_w = \left(\frac{V_{sh} \cdot R_{sh} + (1 - V_{sh}) \cdot R_w}{R_t}\right)^1 \quad (19)$$

Where:

S_w: Water saturation
V_{sh}: Shale volume (from gamma-ray or other methods)
R_{sh}: Resistivity of the shale
R_w: Formation water resistivity
R_t: True resistivity of the formation
n: Saturation exponent (Archie's law parameter, typically 2)

Several formulae for shale volume calculations are shown below (Figure 4).



- Larionov (1969) for Tertiary rocks : $V_{sh} = 0.083(2^{3.7 I_{GR}} - 1)$
- Steiber (1970) : $V_{sh} = \frac{I_{GR}}{3 - 2 \times I_{GR}}$
- Clavier (1971) : $V_{sh} = 1.7 - \left[(3.38 - (I_{GR} + 0.7)^2\right]^{\frac{1}{2}}$
- Larionov (1969) for older rock : $V_{sh} = 0.33 \times (2^{2 I_{GR}} - 1)$

Figure 4: Shale Volume

5. Discussions

The characterization process of the reservoir shows that the mud filtrate invades the formation in the near-wellbore zone during drilling operations; it is very dominating in the interpretation of wireline logging data. Infiltration occurs because, with pressure, drilling mud infiltrates the formation and pushes out the original fluids in the near-wellbore zone. This impacts the formation's resistivity and other petrophysical properties in proximity to the borehole; hence, the logging response changes. This is a greater effect in shaly formations, where gamma ray and resistivity log responses may differ regarding how far the mud filtrate has invaded the formation. These are clay-bound water in the shales, which offers another degree of complexity that interacts with the mud filtrate, thus the varying resistivity and porosity. All these must be emphasized in understanding how the invasion profile impacts record log data for formation evaluation and hydrocarbon saturation estimation. The complexity of measurement involves logging tools to calculate the properties at different depths of investigation, including both the invaded and the uninvaded zone of the formation. In shallow resistivity, there's a general measurement of resistivity in the invaded zone using mud filtrate.

In contrast, in deep resistivity, it targets the uninvaded zone with its fluids free from damage. This is important because it shows the depth of invasion and the contrast of formation fluids with the mud filtrate. Therefore, this makes the identification of hydrocarbon-bearing zones and the estimation of water saturation much more precise. It also makes it easier to estimate the formation water resistivity and fluid saturation, which are vital in appraising the potential productivity of the reservoir. Shale volumes must be interpreted carefully, reflecting the interaction of shale and mud filtrate. These shale volumes and resistivity and density logs acquired from gamma-ray logs are used to account for clay-bound water in the shaly zones. Differentiate very well between intervals of productive and non-productive of the reservoir. In addition, assessing such structures' porosity and saturation will necessitate data generated from a number of logs, such as density, neutron, and nuclear magnetic resonance.

In such interaction, on account of the relationship set forth by Archie's Law, even in some cases of the modified model scenarios for shaly formation, one reaches the appropriate evaluation of hydrocarbon and water saturation in a more precise approach to evaluate hydrocarbon in the reservoir. These analyses lead to findings that suggest the variation in resistivity is closely related to saturation volume and the formations' porosity. Greater resistivity represents zones saturated with hydrocarbons due to having lower water saturation; the resistance will be smaller if saturated since resistivity reduces with rising saturation. This also allows for the correlation of porosity with saturation and can also estimate the producible hydrocarbons. It also helps one understand the ability of the reservoir to become productive. These have been critical to reservoir management and decision-making, ensuring that completions and production strategies are optimized to maximize recovery. Therefore, integrating resistivity, porosity, and saturation data with an understanding of mud filtrate invasion provides a robust framework for reservoir characterization and evaluation.

6. Conclusion

Resistivity of water ($R_{w)}$, the volume of shale ($V_{sh)}$ effective porosity (Φeff), and water saturation (S_w) are the crucial parameters evaluated for water-bearing and hydrocarbon-bearing formations based on sample data obtained from well-logging operations. All the above parameters are extracted based on careful analysis of log data processed through Geoframe software, available at workstations at Well Logging Services. This software enables combining and interpreting many log responses to generate an integrated view of the reservoir. All reservoir parameters, like gas-oil contact, oil-water contact, and gas-shale contact, are detected and recorded in parameter logs wherever these appear. The contacts can provide valuable insight into fluid distributions within the reservoir and how these might change with depth. The characterization of clean sand, shaly sand, and fluid contacts—oil, gas, and water—is done by correlating log responses with depth, unfolding the reservoir's geological and fluid dynamics. Clean sands characteristically have unique resistivity, porosity, and saturation profiles, distinguishing them from shaly sands affected by clay-bound water and showing mixed log responses. The hydrocarbon-bearing zones have high resistivity and low water saturation, while the water-bearing formations have comparatively lower resistivity values. Their depth markers are essential for delineating reservoir boundaries and, thus, understanding their vertical and lateral heterogeneity. This makes for an integrated approach where the reservoir is evaluated with great precision, allowing the accurate evaluation of hydrocarbon volumes and, with that, the development of strategies to meet optimal production.

6.1. Limitations

Some of the study's limitations directly impact the accuracy and reliability of the results. The log quality greatly depends on the borehole conditions. Significant factors that distort the log measurement include washouts, rugosity, and mud invasion. Models and assumptions of the petrophysical type are indispensable for interpreting the log data. Some of the data might not express heterogeneity and complexity in the properties of reservoir rock and fluids, so it cannot be understood completely. It is also liked with some disadvantages of the tools linked with the depth of investigation and resolution. It might not be able to acquire some finer scale variations or some features at deeper parts of the reservoir. This shall also involve some environmental parameters, such as fluid content in the borehole and temperature and pressure influence factors, which may add uncertainty to the measurement. A wireline logging measurement happens through indirect measurement, thus giving its accuracy solely depending upon the quality of calibration carried along with integration with other sub-surface data. For instance, dealing with a complex type of lithology, say shaly sands or carbonates, becomes inconvenient and even rather complicated. The kinds of rock from that of the fluid in multiple forms require greater interpretation techniques. Therefore, despite being an extremely powerful tool, these shortcomings make proper data acquisition, processing, and interpretation imperative to characterize reservoirs accurately.

6.2. Future Scope

Using more technologically advanced inputs in machine learning and artificial intelligence improves the appraisal of the reservoir accurately with effectiveness based on "Characterization of Reservoir by Open Hole-Wireline Logging." With society's demands for more sustainable energy escalating, data relating to multi-physics wireline logging, petrophysical, geomechanical, and geochemical data might be used to ensure better modeling of a decision-making system in a reservoir. For more complex reservoirs, such as deep-water environments and unconventional shale formations, high-resolution imaging tools and real-time data analytics will be coupled with advanced sensor technologies. The open-hole wireline logging data will be combined with the subsurface datasets, which are seismic and production data, to give a comprehensive view of the reservoir dynamics. This would ensure optimum hydrocarbon recovery, minimize risks during exploration, and provide for a more responsible resource extraction with environmental sensitivity. More importantly, as this energy transition continues, methods and insights gained through reservoir characterization will also be applicable for carbon capture and storage projects and geothermal energy exploration, further increasing its scope and impact on open-hole wireline logging within the energy industry.

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