OPEN HOLE WIRELINE LOGGING

Self Learning Module

This document is part of a self learning programme designed for new petroleum engineers with limited experience of logging operations. Experienced engineers not directly involved with logging operations but who would like to learn more about the subject may also find the module useful.

The module contains an example of the Brent sands from the Northern North Sea and a step by step guide for how to approach the planning, supervision, interpretation and reporting of a logging job. The document is intended to double as a quick reference guide for wellsite or office based staff who have followed the Wireline Logging self learning programme.

CONTENTS

1. PLANNING A LOGGING JOB

Introduction

Electric logs represent a major source of data to geoscientists and engineers investigating subsurface rock formations. Logging tools are used to look for reservoir quality rock, hydrocarbons and source rocks in exploration wells, support volumetric estimates and geological modelling during field appraisal and development, and provide a means of monitoring the distribution of remaining hydrocarbons during production life time.

A large investment is made by oil and gas companies in acquiring open hole log data, logging activities can represent between 5% and 15% of total well costs. It is important therefore to ensure that the cost of acquisition can be justified by the value of information generated and that thereafter the information is effectively managed. To this end a number of questions need to be asked before commencing logging operations, these include:

1. What is the objective of the data acquisition?
2. What type of logging programme is appropriate?
3. How must the data acquisition be managed?
4. In what form should the data be presented?

To answer such questions it is necessary to assess the consequence of prevailing geophysical uncertainty, be aware of both the principles of measurement and operational limitations of the logging tools available, and understand how the logging results will be used.

This document is intended to provide the reader with guidelines for planning a logging job, witnessing logging operations and the basic evaluation skills needed to address some of the more common North Sea data gathering objectives. It is also designed to serve as a handy wellsite reference for open hole logging activities. Further details of both tool theory and evaluation techniques can be found in the Western Atlas Wireline Log Analysis manual or the Schlumberger Log Interpretation Principles / Applications manual, both of which are widely available within most petroleum engineering offices.

Logging objectives and programmes

Wells can be broadly divided into two groups in terms of how logging operations should be prioritised; information wells and development wells. Exploration and appraisal wells are drilled for information and failure to acquire log data will compromise well objectives. Development wells are drilled primarily as production or injection conduits and whilst information gathering is an important secondary objective it should normally remain subordinate to well integrity considerations.

In practical terms this means that logging operations will be curtailed in development wells when hole conditions begin to deteriorate. This need not rule out further data acquisition as logging through casing options still exist.
In exploration wells where existing information is very limited logging programmes will be rather extensive. Typical objectives might include:

- detection of shallow hydrocarbons (rig safety issue)
- assessment of mechanical rock properties (for well design)
- hole volume and shape estimates
- stratigraphy and lithology identification
- supporting information for structural interpretations
- identification of depositional environments
- assessment of source rock potential
- measurement of acoustic properties (for time/depth relationships)
- samples for lithology, hydrocarbon identification and rock dating
- identification of potential reservoir intervals
- location of hydrocarbon bearing reservoirs
- reservoir quality and capacity assessment
- estimation of reservoir deliverability
- determination of pressure regime

The acquisition of data to fulfill all of the objectives above would require an extensive logging programme containing the tools such as those listed below (many of which can be run in combination). Each logging contractor has their own version of the these tools and in most cases equipment is identified by three letter abbreviations. Examples of the two main contractors Schlumberger and Western Atlas are shown overleaf.

Tool Types	Schlum.	W. Atlas
Induction and/or Resistivity devices	DIL/DLL	DIFL/DLL
Micro resistivity	MSFL	ML
Litho-density and Neutron porosity	LDT/CNL	CDL/CNL
Acoustic	LSS	ACL
Caliper	CAL	CAL
Natural gamma	GR	GR
Spontaneous potential	SP	SP
Dipmeter (not covered in this document)	SHDT	HRDIP
Pressure testing devices	RFT	FMT
Rock and fluid sampling devices	CST	SWC

This sort of logging programme could be achieved in 4 or 5 runs over each open hole section, and examples of how this would appear on a well programme are shown below:

Western Atlas	Schlumberger
DIFL/ACL/CDL/CNL/GR/CAL	DIL/LSS/LDT/CNL/GR
DLL/ML/GR/SP	DLL/MSFL/GR/SP
HRDIP	SHDT
FMT (+ samples)	RFT (+ samples)
SWC (3 runs)	CST (2 runs)

NOTE: Details of these tools and applications can be found in the next section.

In appraisal and development wells many of the information objectives listed earlier may no longer apply and logging programmes will be reduced accordingly. In North Sea development wells where the reservoir is well understood logging programmes will typically reduce to 2 runs; a combined tool string to assess reservoir thickness, porosity and hydrocarbon saturation, and a second run to acquire pressure (and connectivity) information. Logging in intervals other than the reservoir may be dropped completely.

2. WITNESSING OPERATIONS

In this section the principles of measurement, limitations and operational considerations of the most common open hole logging tools are described. To highlight the treatment of typical local issues, reference is made in each case to a log example from the Brent Sands in the North Sea.

The individual log examples are presented together on the next page in a panel format similar to that which could be supplied to you on the wellsite by a logging engineer (though the scale is rather compressed compared to reality). Pressure measurements are also included along side the logs.

Using these logs and the information supplied in the rest of this section make an evaluation with the following objectives:

- Identify all potential reservoir intervals

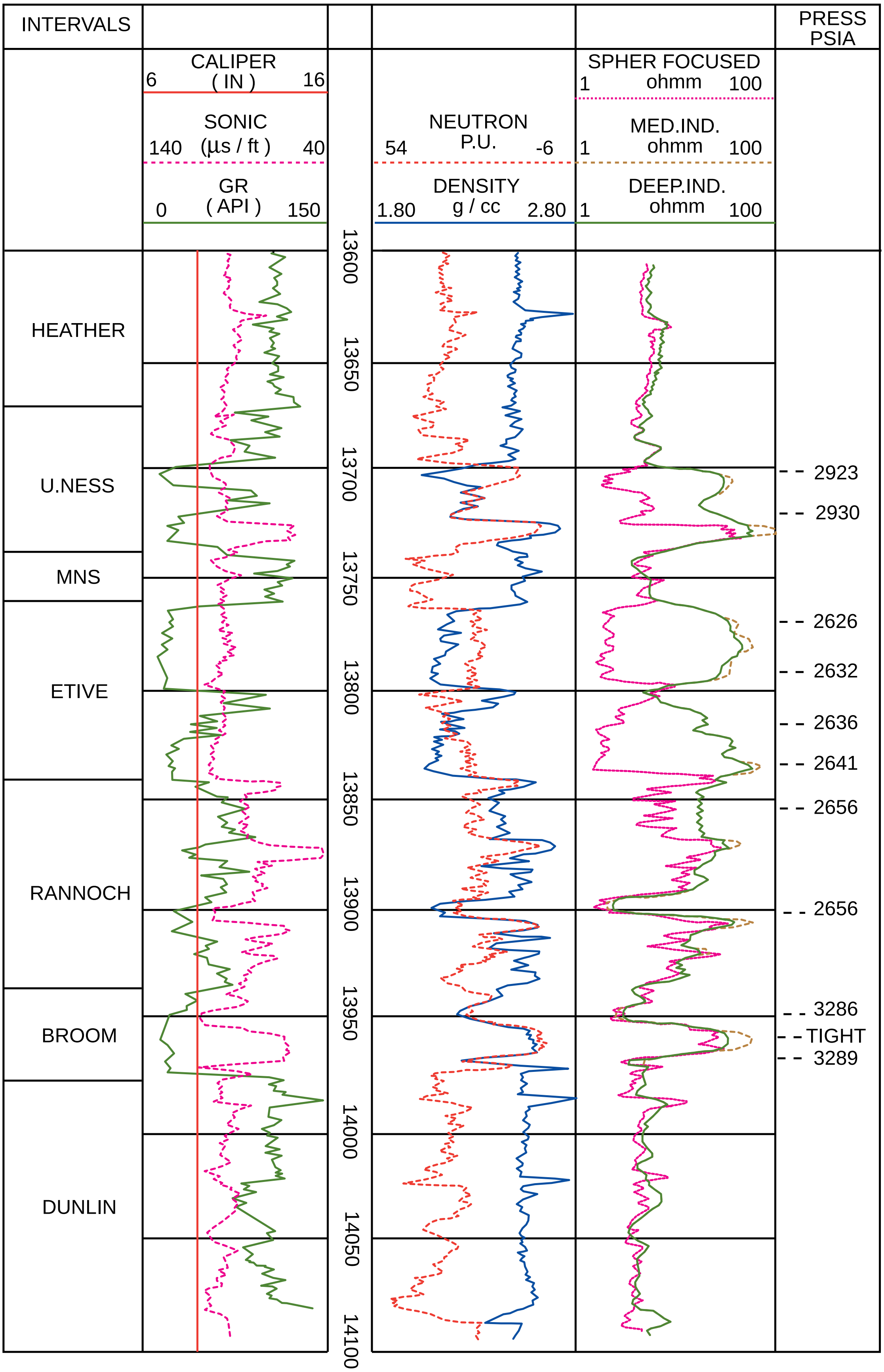
and for each reservoir interval

- Determine the fluid type
- Calculate the average porosity
- Calculate the average hydrocarbon saturation

- Lastly explain the pressure profile over the sequence

NOTE: *The results are presented in the next section but you will get more value out of the example if you try it first without referring to the solution.*

Well : NNS-08


INTERVALS
CALIPER (IN) 6 16
SONIC (µs / ft) 140 40
GR (API) 0 150
NEUTRON P.U. 54 -6
DENSITY g / cc 1.80 2.80
SPHER FOCUSED ohmm 1 100
MED.IND. ohmm 1 100
DEEP.IND. ohmm 1 100
PRESS PSIA
HEATHER
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MNS
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2656
3286
TIGHT
3289

Suggested procedure:

1. Read through the remainder of this section a find out how to process each log. Each log from the composite panel (previous page) is described seperately.

2. Working on the log panel use a combination of lithology and permeability indicators to identify the potential reservoir intervals.

   [Tip: The sequence is predominantly sand and shale though a significant amount of calcite is present as discrete layers and dispersed within sand and shale layers].

3. Use the Density/Neutron and resitivity logs to identify fluid type and distribution

4. Calculate the average porosities from the density log (read the log values from the results panel once you have identified the reservoir intervals and fluid distribution)

5. Use the Archie equation (described in the next section) to calculate the average hydrocarbon saturation using the porosities calculated in step 4 above and the resistivity log (read the log values from the results panel).

6. Plot the pressure readings against depth and interpret the resultant pressure profile.

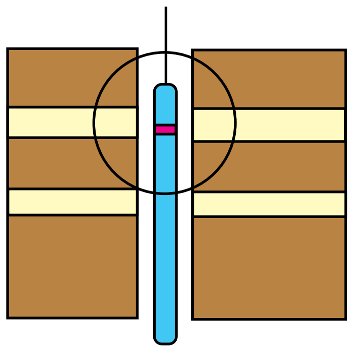
NOTE: *Although the well is highly deviated the well drops off to ca. 30deg. before penetrating the reservoir. The top pressure was taken at 13702 ft.ahbdf. (=7934ft.ss).*

THE GAMMA RAY LOG

Typical applications

- Determination of reservoir thickness
- Lithology indicator
- Correlation between wells
- Estimation of shale volume

Principle of measurement


Gamma Ray Tool

The GR log is a recording of the count rate of at gamma emissions from rock formations adjacent to the borehole. The gamma emissions result from the decay of naturally occurring radioactive isotopes such as potassium, uranium and thorium, contained in the formation rock matrix. The standard GR tool records total radioactivity, whereas Spectral GR tools record the Gamma Ray Tool gamma ray spectrum and isolate the contribution from each of the three radioactive isotopes.

Interpretation

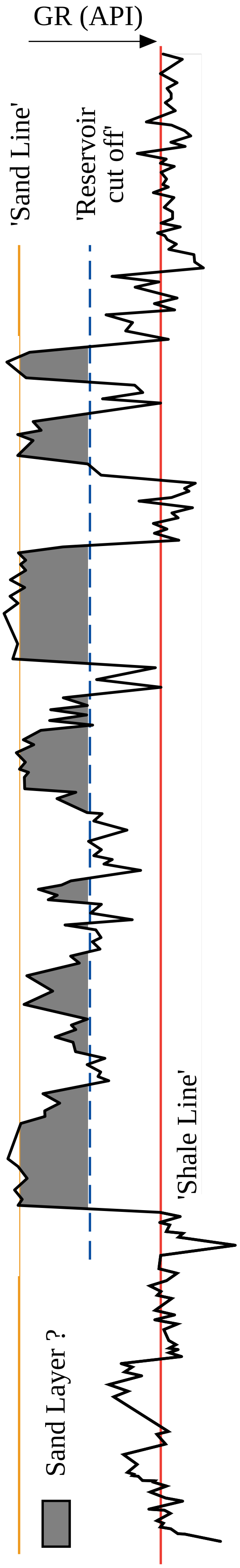
The table below shows typical GR levels (in API units) for a number of common minerals and formation materials. The radioactivity levels are largely a result of potassium content.

Rock Type	GR Reading	Rock Type	GR Reading
Sandstone	10 -20	Limestone	5 - 10
Dolomite	10 - 20	Shale	80 - 140
Halite	0	Sylvite(KCl)	500
Coal	0	Mica	100- 170

Shales exhibit relatively high GR count rates due to the presence of potassium ions in the lattice structure of the clay minerals. The most common reservoir rock minerals (quartz, calcite and dolomite) in a pure state do not contain radioactive isotopes and yield low GR readings. The shale content of reservoir rock can be estimated by linear interpolation between the GR log readings across clean rocks (the sand line) and shales (the shale line), such that:

$$V_{sh} \leq \frac{GR_{\log} - GR_{sd}}{GR_{sh} - GR_{sd}}$$

Permeability generally has a negative correlation with shale content and a GR cut off is often used to define the limit of effective permeability (ref. log panel). It is thus possible to distinguish permeable reservoir rock from impermeable shale. For quick look evaluations a GR cut off of 50% shale volume is often used to discriminate reservoir quality rock.



This approach works well in pure sand-shale sequences, however where coal, evaporites or tight carbonates are present low GR readings do not necessarily imply reservoir rock. Minerals like mica and feldspar are radioactive and give rise to relatively high GR readings, though their presence in a sand need not destroy reservoir properties. For reliable reservoir thickness determination, it is wise to cross check for indications of reservoir quality with other logs.

Logging operations

A scintillation detector registers incoming gamma rays that are generated in a statistical process of radioactive decay. To get a reliable measurement readings have to be accumulated over a certain time interval, typically two seconds. As a result count rates are also accumulated over specific depth intervals and represent the average GR signal for the layers within those intervals. The logging speed therefore influences the vertical resolution of a tool, and to minimise this effect the tool speed has to be limited to 1800ft/hr under which the log has a resolution of ca 3ft. The effects of statistical averaging and tool speed smear out boundaries between layers with different radiation intensities, though layer boundaries can still be inferred from inflection points on the GR log. Providing recommended logging speeds are observed repeat runs should overlay closely.

Tool calibration

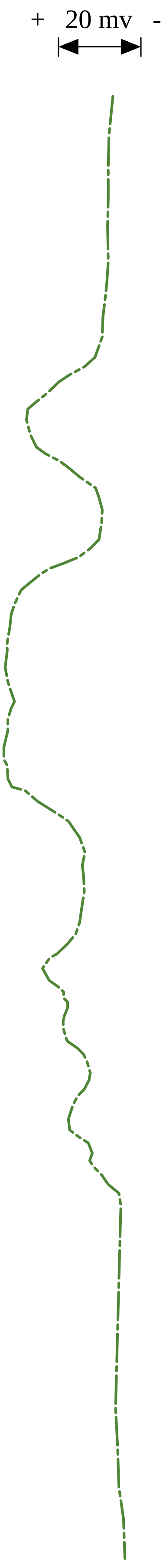
The calibration standard for the GR is the API test pit in Houston, Texas. The difference in radioactivity opposite the intervals of low and high radioactive concrete is defined as 200 API units. At the wellsite, prior to running the tool, the GR is checked and adjusted using a GR jig; a clamp on arm which locates a small GR source of known strength at a fixed distance from the tool.

Influence of borehole environment

Tool count rates reduce with increasing borehole size or mud weight as the GR detector is shielded from the formation signal. Casing has an even larger influence which accounts for the marked reduction in GR signal when a tool enters a casing shoe. If a hole is filled with potassium rich fluids e.g. KCL mud, there will be an overall shift to higher radiation levels and there may be a reduction in dynamic range. These effects can often be ignored for qualitative interpretation, but borehole corrections have to be made before GR readings in different hole sizes can be compared in absolute terms.

Example

The Brent Reservoir sequence shown opposite is predominantly a sand shale series but contains a number of calcite layers (or 'doggers') and a radioactive sand. A sand count based solely on a GR cut off would therefore be inaccurate and must be supplemented by other logs such as formation density or sonic transit time. Many attempts have been made to sample calcite layers mistaken for clean sands. Coal is often present in Brent Reservoirs and can be mistaken for sand based on the GR alone, though can be distinguished by its low density.

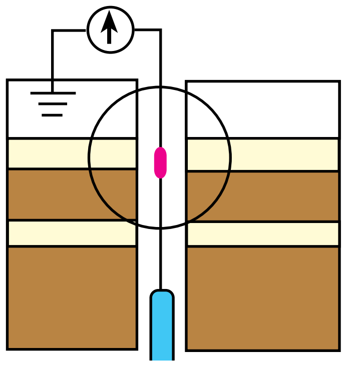


SPONTANEOUS POTENTIAL LOG

Typical applications

- Determination of reservoir thickness
- Permeability indicator
- Estimation of formation water resistivity

Principle of measurement



Spontaneous Potential

The Spontaneous Potential (SP) log records the difference between the electrical potential of a movable electrode in the borehole and the electrical potential of a fixed surface electrode. Variations in borehole potential result from electric currents flowing in the mud caused mainly by electrochemical effects. If a salinity contrast exists between mud filtrate and formation water a liquid junction Spontaneous Potential is created as Na and Cl ions with different mobilities move towards an equilibrium state. Shales act as a semi-permeable membrane allowing the passage of Na ions whilst repelling Cl ions, creating a membrane potential.

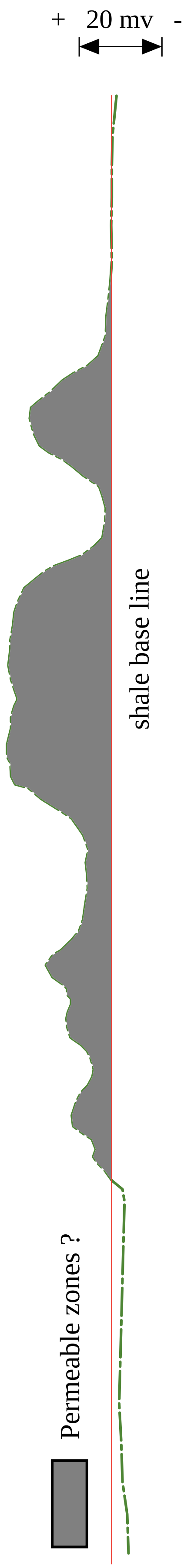
Interpretation

The SP deflection over a reservoir interval is established by measuring the deflection from the shale base line at that depth. The shale base line is not constant along the borehole, usually there is a gradual drift with depth.

SP deflections will only occur opposite permeable zones. This property makes the SP useful as a reservoir thickness log though the resolution is poor. The SP deflection will also react to variations in shale content in the reservoir, and can therefore be used to recognise rock characteristics and correlate these from well to well. Both applications work particularly well in sand-shale sequences, provided there is sufficient salinity contrast between mud filtrate and formation water. Note that permeable zones does not need to be fully water bearing to show a SP deflection. In a hydrocarbon bearing zone there is still a sufficient amount of formation water present to allow the SP to develop.

The direction and magnitude of an SP deflection opposite clean permeable zones gives information about formation water salinity. If the formation water is more saline than the mud filtrate, the SP will show a negative deflection. If the formation water is fresher than the mud filtrate, the SP deflection will be positive. If both salinities are similar, no deflection will be observed.

Variations in formation water salinity with depth can be detected by a difference in SP deflection opposite clean zones. This is important information, as it is indicative of hydraulic isolation between reservoir intervals.



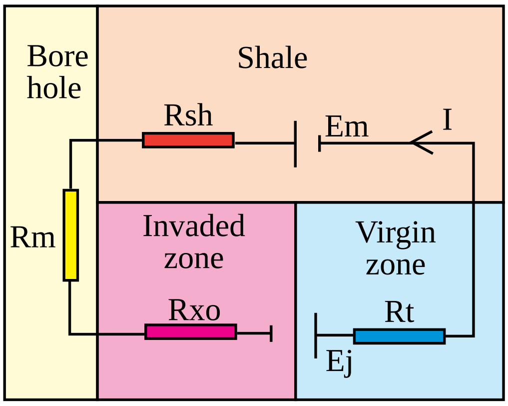
Logging operations

The log is made by measuring the variation in (rather than the absolute) potential versus depth. Over a typical survey interval these deflections can generally be captured on a scale of 0-100 mV. The measurement relies on a good fixed reference potential at surface and small stray voltages picked up by the reference electrode (the SP "fish") make the measurement meaningless. Isolating stray voltages can be a particular problem on offshore rigs. On land the reference electrode is buried or clamped to a suitable grounding point, offshore it is hung in the sea or lowered to the seabed. Log readings in casing are meaningless.

Tool calibration

No calibration is required for the SP electrodes, though electrical continuity and isolation checks are normally performed on the circuit prior to logging.

Influence of borehole environment



The circuit shown in the adjacent figure shows current flow through the borehole, shale and reservoir. The resistivities of these zones have an impact on the potential difference measured in the borehole. If the mud resistivity (Rm) is very low, there will be a short-circuiting effect in the mud and the potential difference between points opposite shale and reservoir layers will be suppressed. The SP deflection will also be low if shale, formation and invaded zone restivities (Rsh, Rt and/or Rxo) are high.

A strong SP deflection requires the following conditions:

- Large salinity contrast between mud(filtrate) and formation water
- Clean reservoir next to pure shale
- High mud resistivity Rm (but Rm < infinity)
- Low shale resistivity Rsh or formation resistivity Rt.

Note: *Oil based mud renders the SP useless*

Example

In many North Sea Brent reservoirs the salinity contrast between seawater muds and formation water is low, consequently the SP development is poor. The example opposite has been artificially enhanced to demonstrate its use. The example suggests that permeable zones exist but that reservoir quality deteriorates with depth. The positive deflection from the shale base line indicates formation water is more saline than the mud filtrate. Poor bed definition is characteristic and is a consequence of the potential gradients within the borehole.

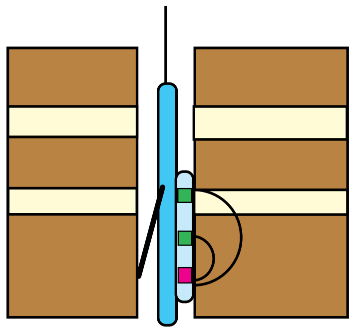
FORMATION DENSITY LOG

Typical applications

- Porosity determination
- Lithology indicator

Principle of measurement

A focused radioactive source carried in the density tool emits gamma rays of medium energy into the formation. As gamma rays travel through the formation they collide with electrons and are scattered, losing energy in the process, until captured. Detectors mounted in the tool count the number of gamma rays at a fixed distance from the source. The gamma ray count rate is inversely proportional to the electron density of the formation which can be related to the bulk density.


Formation Density Tool

Modern density tools also monitor the scattered gamma rays in the low energy region. The gamma ray count rate at low energies is determined by the capture cross section of the formation and can be used to discriminate between different lithologies.

Interpretation

The density log reading (ρ_b) is interpreted in terms of porosity (Φ) of the formation using the following expression:

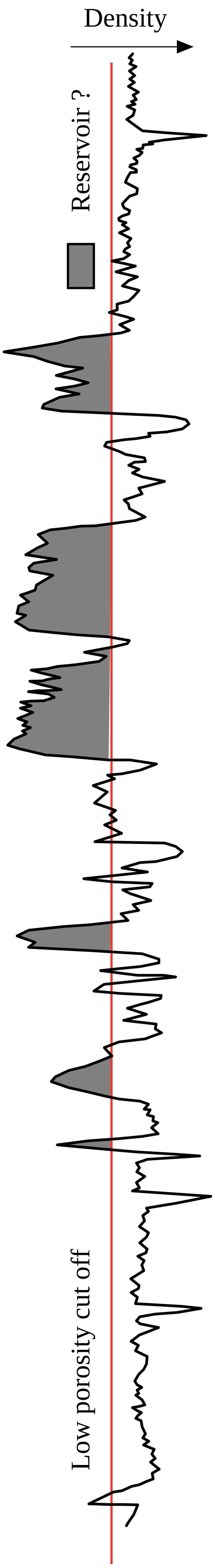
$$\Phi = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_{fl}}$$

Interpretation requires knowledge of the density of the matrix material (ρ_{ma}) and of the pore fluid density (ρ_{fl}) The table below lists the densities (in g/cc) of a number of common formation minerals and fluids, as they are seen by the tool.

Matrix	Density	Pore Fluid	Density
Quartz	2.65	Fresh water	1.00
Calcite	2.71	Salt water (200 g/l)	1.13
Dolomite	2.87	F.Water+30% oil	0.9-0.94
Rock salt	2.03	F.Water+30% gas	0.73-0.78

Shales often have matrix density similar to quartz so the porosity expression above can be used in shaley sands without knowledge of the relative volumes of shale and sand.

As density tools investigate formation within ca. 6 inches of the borehole wall the pore fluid (in reservoir intervals) is predominantly invading mud filtrate. Mud filtrate density is dependent on its salinity which can be determined from resistivity measurements made on a surface sample.



In a hydrocarbon bearing zone, the fluid in the invaded zone will be a mixture of mud filtrate, residual hydrocarbons and connate water. For quicklook evaluation it is often acceptable to assume a fluid density of 1 g/cc however care must be taken over gas bearing intervals if filtrate invasion is limited as effective fluid density will be much lower. In mixed lithologies such as calcite cemented or mica rich sands the matrix density must be modified to reflect the mixture if accurate porosities are required.

Logging operations

Considerations regarding measurement statistics and logging speed are similar to those discussed for the GR tool, however owing to the higher radiation intensities, restrictions are not so severe. At a typical logging speed of 1800 ft/hr, the resolution of the tool is 2-3 ft. Repeat log sections should overlay closely though there will be some statistical variation between runs. Occasionally if the pad is oriented in another direction on the repeat differences may be more apparent, though this is not common.

Tool calibration

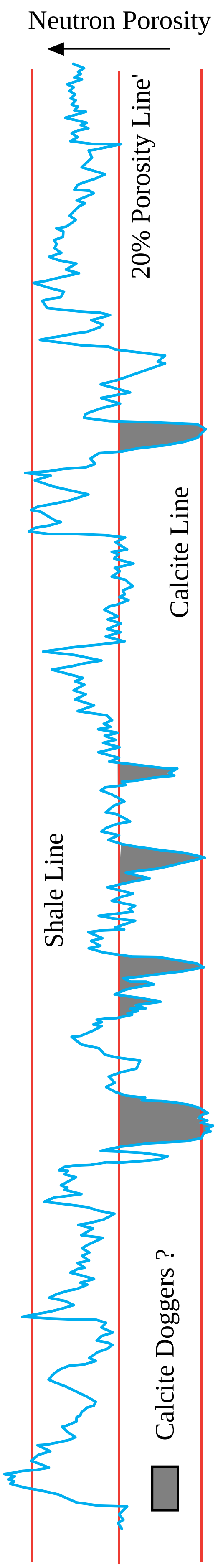
The primary calibration standards for the density log are fresh water filled blocks of limestone. At the contractors field base, the calibration is regularly checked and adjusted using large blocks of aluminium (high density reference) and sulphur (low density reference). A small internal source is used to regulate the detector electronics and to check the tool response at the well site prior to and after the logging job.

Influence of borehole environment

The presence of a mudcake can seriously affect formation density measurement so the tool is constructed with the source and detectors mounted on a skid which, when pushed against the borehole wall, ploughs through the mudcake. The remaining mudcake influence is corrected by comparing count rates at a short and long spacing detector. The correction applied to the density measurement is also displayed as a separate curve on the log. If this correction exceeds 0.05 g/cc, it is considered less reliable and confidence attached to the log reading at that point is reduced. This situation commonly occurs when the hole is rugose or washed out so that low density mud is present between the tool and the formation. High density barites laden mudcake can also significantly effect the density reading in the opposite sense. The density correction curve therefore serves as a quality check on the density measurement.

Example

A ‘low porosity’ cut off is sometimes applied to the density curve to discriminate productive from non productive zones. The cut off is usually based on core derived porosity / permeability relationships. In the example a cut off is set at 2.42 g/cc (equivalent to ca. 12% porosity) below which the reservoir ceases to be productive. In this environment where reservoir discrimination using the GR is affected by radioactive sands and tight calcite layers the density cut-off is a more effective quick look tool.

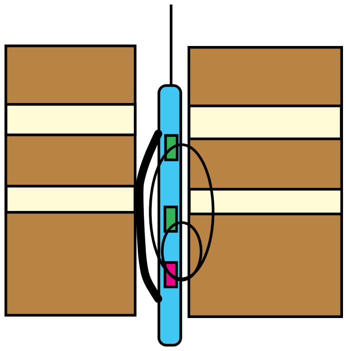


NEUTRON LOGGING

Typical applications

- porosity determination
- lithology and gas indicator

Principle of measurement


Neutron Porosity Tool

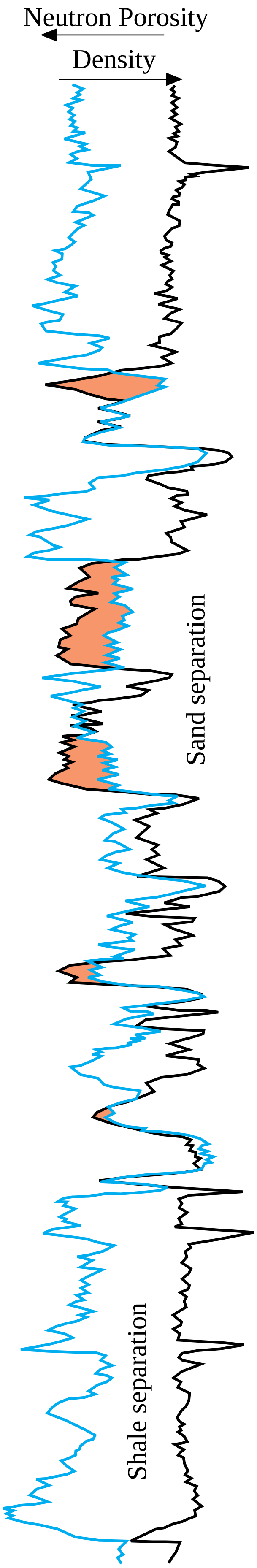
A neutron source emits fast, high energy neutrons into the formation and monitors the population of neutrons at some distance from the source which have been slowed down to thermal energy levels during passage through the formation. The neutrons are slowed down primarily through collision with hydrogen atoms (which have almost the same mass as a neutron) and are captured. The remaining thermal neutron population (sampled by the tool) can be related to the amount of hydrogen in the formation. Hydrogen is mainly present as water (or hydrocarbon) in the pore spaces, so the neutron population can be interpreted in terms of the formation porosity.

Interpretation

The log porosity output is based on a simple limestone / fresh water model and is scaled in limestone porosity units. Accurate porosity values can only be read from the log over fresh water bearing limestone intervals. For any other rock type or pore fluid corrections have to be applied, though for clean oil or water filled sandstone reservoirs the corrections will be small and the log can be used as a rough estimate of porosity. Lithology and pore fluid corrections are described in the logging contractor chartbooks. Gas and shale have particularly marked effects on the log reading. Gas filled formation has a low hydrogen population (relative to water and oil) which the tool records as low apparent porosity. High apparent porosities are recorded in shale due to the presence of hydrogen in OH groups and clay bound water within the shale matrix. Great care must therefore be taken if the neutron log is used independently.

Neutron and density logs are generally displayed together on compatible scales such that increasing porosity leads to a leftward shift of the log curves. The 'zero' neutron porosity point is made to coincide with the 2.70 g/cc density point (the limestone matrix density) and if the scale were extrapolated to 100% porosity it would be seen to coincide with 1.0 g/cc (the density of fresh water).

On this type of scale the separation of neutron and density curves is a useful shale indicator as the neutron tool reads a high apparent porosity in shale compared to the low porosity density reading. This is in contrast with the gas effect (low apparent neutron porosity and low density reading, i.e. high apparent density porosity), which can be seen clearly in clean, gas bearing sands. In shaley, gas bearing sands the two effects (gas and shale) counteract, and one has take care when making an interpretation.



Logging operations

Two detectors are used to sample the population of thermal neutrons at a short and long spacing away from the source. The tool is pushed against the formation by a bow spring to minimise the influence of the borehole on the tool reading. The resolution of the neutron tool is similar to that of the density tool, ie. 2-3 ft., and as the measurement is statistical the logging speed is normally limited 1800 ft/hr. Depth of investigation of the tool is some 6" to 8", somewhat greater than that the density tool. The presence of gas is therefore usually more obvious on the neutron than on the density log. Because it is less directional than the density tool repeat log sections should over lay well (allowing for statistical variation) even when the tool orientation changes between passes.

Tool calibration

The primary calibration standard for the neutron tool is a pit containing blocks of fresh water filled limestone of known porosity. At the contractors field base, the calibration is regularly checked and adjusted against the ratio of near and far detector count rates in a standard fresh water filled tanks. Wellsite calibration checks made before and after surveys are carried out with a portable jig containing a small neutron source.

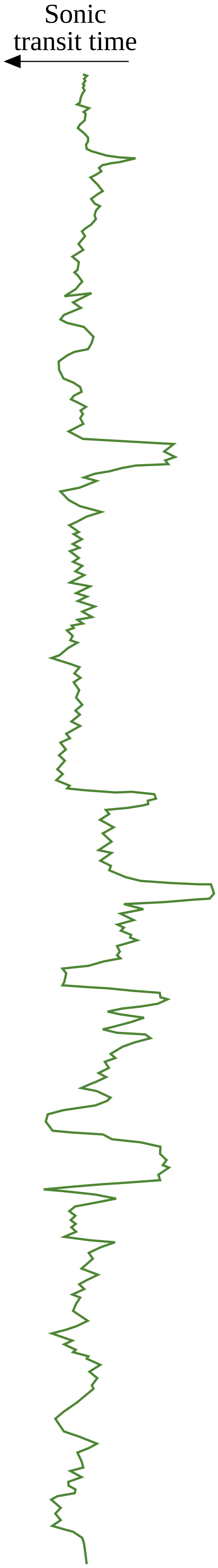
Influence of borehole environment

Although neutron tool is designed to be run against the formation like the density tool, the source and detectors are not mounted in a skid. As a result the tool is rather more vulnerable to high frequency borehole rugosity and will record high apparent porosities when contact with the formation is poor and a mud filled space is created between tool and borehole wall.

Example

In this sequence the neutron can be used quite effectively as a stand alone lithology indicator by defining a shale, sand and calcite lines. The thicker calcite doggers stand out particularly well though the thin doggers are better resolved on the density log. The sand line in this case defines clean sand of similar porosity and is less effective where sand porosity variation is not a function of shale content. The relative position of the neutron curve between the sand and shale line gives a qualitative measurement of shaliness.

Where the curves are shown together lithology determination becomes easier as the logs separate in shale and overlay in calcite layers (the doggers). The small sand separation is characteristic of clean sand intervals and is a result of the limestone scale used as a standard.



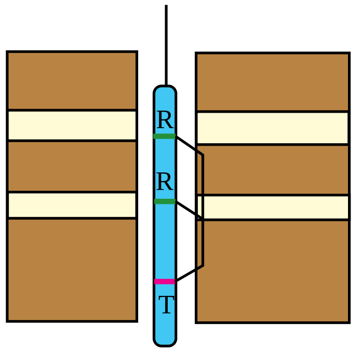
SONIC LOG

Typical applications

- Porosity determination
- Lithology indicator
- Seismic velocity calibration

Principle of measurement

A sonic log is a recording against depth of the travel time of high frequency acoustic pulses through formation close to the borehole. This is done by measuring the pulse arrival time at two receivers spaced at different distances from an acoustic transmitter. By subtracting the transit time to the near receiver from that of the far receiver the acoustic velocity of the formation is defined over the interval between the receivers



Sonic Tool

Interpretation

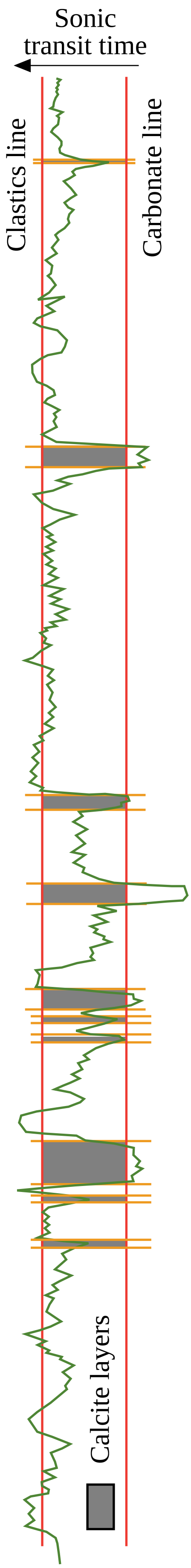
The formation travel time measurement Δt can be interpreted in terms of the porosity of the formation according to the Wyllie or Time Average equation, such that:

$$\Phi = \frac{\Delta t_{\log} - \Delta t_{ma}}{\Delta t_{fl} - \Delta t_{ma}}$$

This model assumes that the formation is made up of a homogenous mix of a rock matrix and pore fluid and that transit time is related to the proportion of each. Matrix and fluid travel times represent 0% and 100% porosity respectively and values between these extremes can be interpolated assuming a linear relationship, providing the acoustic properties of each medium is known. Travel times for some of the more common formation minerals and fluids are shown in the table below:

Material	**Travel Time** (μ *sec/ft)*
Sandstone matrix	51 - 55.5 (Quartz:56)
Limestone matrix	43.5 - 48 (Calcite:49)
Dolomite matrix	38.5-43.5 (Dolomite:44)
Fresh water/salt water	218 / 189
Oil	238
Casing	57

For salt water mud systems a fluid travel time Δt=189 μ sec/ft can be used which assumes the formation investigated is entirely flushed with mud filtrate. This approach works well in consolidated water or oil bearing reservoirs, but is not suitable in uncompacted formations where the time average relationship breaks down. In unconsolidated formations poor grain contacts increase transit times and corrections (compaction factors) must be applied to porosity calculations.



In the Brent sands a cut off of ca. 100 µ sec/ft is sometimes used to identify reservoir intervals which may be prone to sand production. Whilst useful as a sand production flag these cut offs are not very reliable.

The sonic tool can sometimes be used to detect secondary porosity by comparing sonic and density derived porosities. Travel times in vuggy formations are not normally influenced by the vugs providing the vug population is limited. Therefore the sonic log responds to primary porosity only. The density log makes a bulk measurement of the formation and thus responds to total porosity, a difference may indicate the presence of secondary porosity (fractures or vugs).

By integrating travel time over a section of hole the total time taken for a sound wave to travel over this section is obtained This information calibrated with checkshot data can be used for interpreting seismic velocity times in terms of depth. The integrated travel time (ITT) is displayed on the log in the form of small marker pips at the edge of the track at intervals of 1 msec.

Logging operations

There are many varieties of sonic tools available with different transmitter and receiver arrays, to compensated for borehole shape and tool position within the borehole. Transit time data is usually acquired with either a regular or long spaced sonic tool (or other tools run in these modes). Long spacing tools are employed to try and investigate the formation beyond the drilling damaged zone, but acoustic signals attenuate over distance so there are limits beyond which a signal cannot be distinguished from background noise.

Tool calibration

Acoustic transit time is measured very accurately using quartz clocks and the tools need no calibration, only electronic checks. The tool response can be tested downhole by recording the Δt in casing, which should be 57 µ sec/ft.

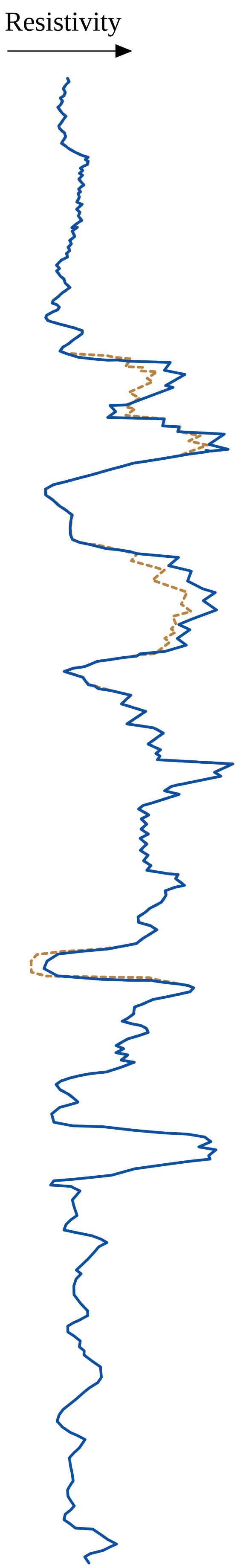
Influence of borehole environment

In very large (or washed out) holes the first compressional arrival may be through the mud, effectively short circuiting the formation arrival. In such cases the log will record a constant value, the mud transit time. In some cases the problem can be resolved by using a longer spacing or by eccentering the tool close to the borehole wall.

In gas bearing formations acoustic travel times increase and the first arrival amplitude can fall below detection level. If the tool triggers on a later arrival the transit time recorded is much longer, a phenomena described as cycle skipping.

Example

In the Brent sequence shown the sonic cannot be used to discriminate sand from shale. However the tight (high velocity) calcite layers stand out very clearly and the tool resolution is good. The intermediate Δt values probably represent poor reservoir intervals such as calcite cemented sands.



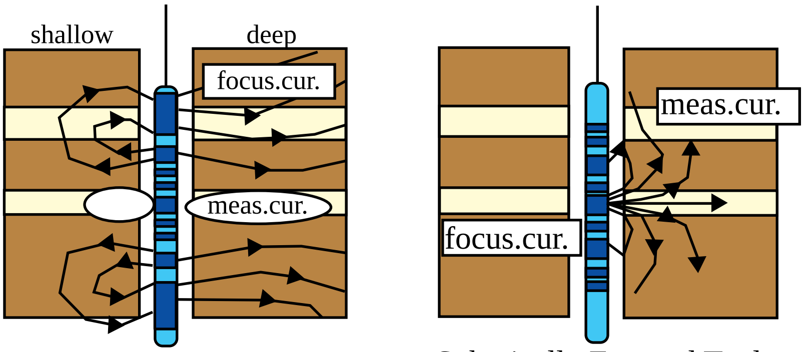
LATEROLOGS AND SPHERICALLY FOCUSED LOGS

Typical applications

- Hydrocarbon saturation determination
- Permeability indicators

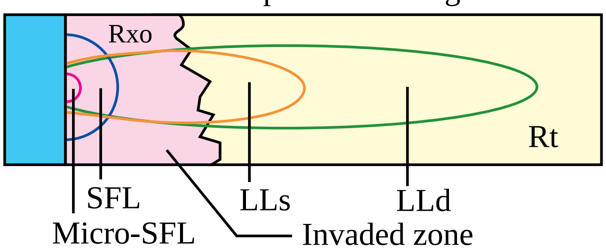
Principle of measurement

Formation resistivity logs are now made predominantly with tools that use arrangements of electrodes to focus measuring currents into a specific volume of investigation. Laterolog tools use focusing (or bucking) currents to force a measuring current into a planar disc shape and monitor the potential drop between an electrode on the tool and a distant electrode (which in electrical terms must be effectively at infinity). The potential drop varies as the measure current and the formation resistivity change, therefore the resistivity can be determined.

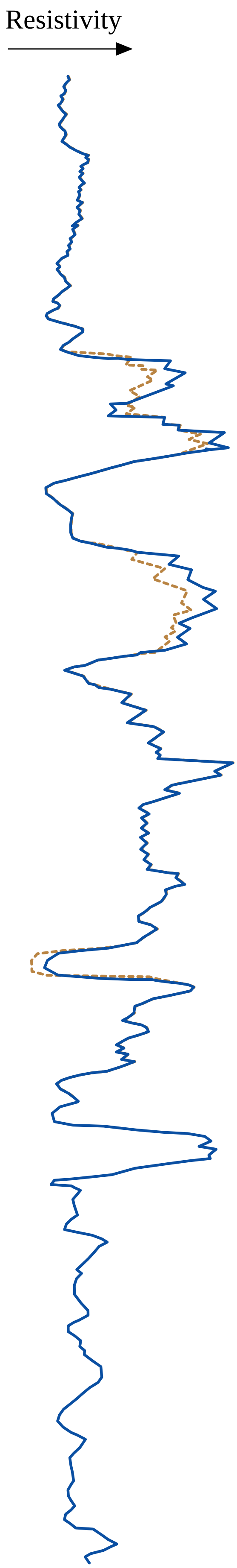


Dual Laterolog Tool   Spherically Focused Tool

Spherically focused tools employ focusing and measuring currents to establish spherical equi-potential shells in the formation around the tool. A focusing current effectively plugs off the borehole and forces the measure current into the formation. A constant potential difference is maintained between two equi-potential shells at fixed distances from the current electrode by adjusting the current in response to changing formation resistivity. For investigating formation very close to the borehole, pad mounted versions of the laterolog tool and spherically focused tool are used in which electrode spacing is much closer.



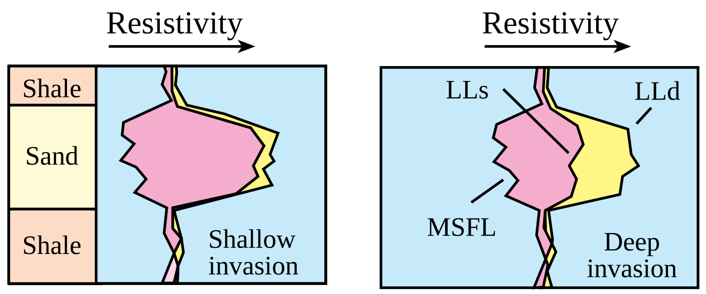
The tools described investigate the formation to different depths from which it is possible to determine the true resistivity (Rt) of the virgin formation by extracting the mud cake and flushed zone resistivities (Rmc and Rxo respectively) from the deepest reading device.



Interpretation

The calculate of hydrocarbon saturation (Sh) for which Rt is required is described in a later section entitled “Quicklook Evaluation”. In thick formation layers perpendicular to the borehole, Rt can be determined accurately by entering the appropriate (tornado) chart with resistivity measurements from three depths of investigation. A typical combination of tools yielding this information would be the deep and shallow laterologs (LLd and LLs) and microspherically focused log (MSFL).

A great deal of qualitative information however can be extracted from resistivity logs without using charts. Separation of resistivity logs from tools with different depths of investigation is indicative of permeability as it implies that pore fluids close to the borehole have been displaced by invading mud filtrate. The position of the LLs curve relative to the LLd curve indicates how much the latter is affected by invasion and consequently whether the LLd can be used as a quick estimate of Rt



RLLd ca. Rt   RLLd ≠ Rt

Across non permeable intervals such as shales the resistivity curves should nearly overlay. Lack of separation does not rule out permeability however, as if mud filtrate and formation water salinities are the same the resistivity tools will not differentiate between the invaded and non invaded zones.

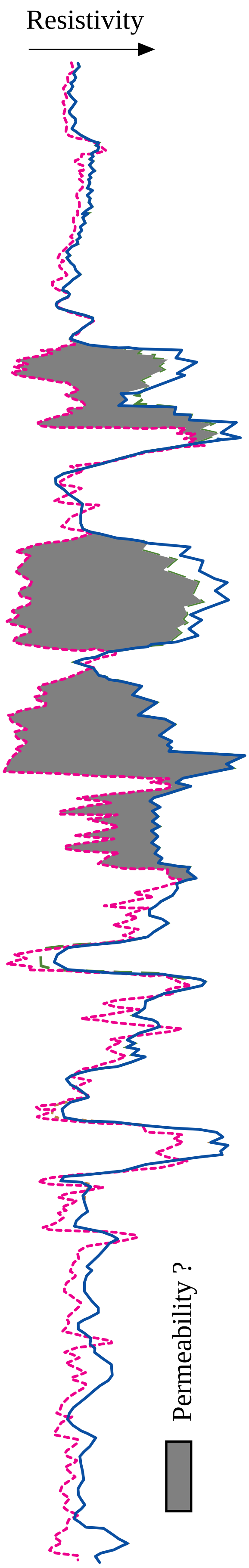
The MSFL tool measures resistivity in the invaded zone (Rxo) which can be used to determine the residual hydrocarbon saturation near the well bore, and thus give an indication about the amount of movable hydrocarbons. In water bearing intervals the invaded zone can be assumed to be completely flushed with mud filtrate and the formation water resistivity (Rw) can be estimated using the ‘ratio method’ where:

$$R_w / R_t = R_{mf} / R_{xo}$$

[Mud filtrate resistivity Rmf is measured on a surface mud sample]

Logging operations

The dual laterolog tools are most effective in low resistivity mud and high resistivity formation, i.e. where the formation resistivity represents the largest contribution to the signal. The resolution of the tool is about 3-5ft; the depth of investigation about 3ft for the LLs and 9-12ft for the LLd. A surface electrode is used with the LLd as a current return and must be properly earthed to



guarantee a good signal. The LLS uses the cable as a current return electrode, but to avoid direct earthing to the cable armour the tool is run below a long rubber insulated extension called a bridle. As the measurements depend on electrical continuity the tools will not function in oil based muds.

Pad mounted tools such as the Microspherically Focused Log (MSFL) or Microlaterolog (MLL) have a much higher resolution and very shallow depth of investigation both in the order of inches. Logging speeds of up to 3600ft/hr are normal for all the resistivity tools though if a borehole is very rough the pad devices may require lower speeds to maintain log quality. Single or two way caliper devices are normally an integral part of the pad tools.

Tool calibration

Current emitting devices such as the Dual Laterolog, SFL and MSFL or MLL, are calibrated electronically before and after logging surveys in the well is made. This can be done while the tool is down hole by using precision resistors in the tool, no shop calibration is required. The tools can also be function tested on surface using a set of clamps and cables to route current through a resistors of known value.

Influence of borehole environment

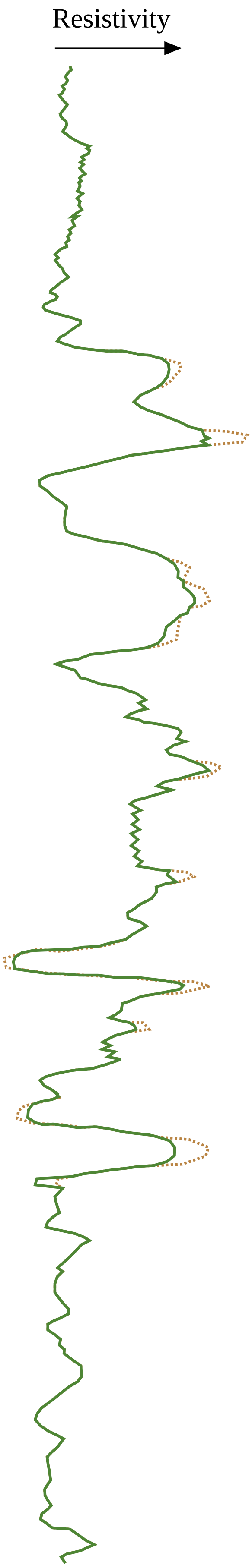
The tools are designed so that borehole effects are minimised for an 8.5" hole. The effect of different borehole sizes can be corrected using charts, though providing hole conditions are good and mud resistivity is low these corrections can be ignored in a quick-look evaluation.

Where thin resistive layers are sandwiched between thick low resistivity beds it becomes difficult to maintain the shape of the measure current and resistivity will be underestimated. However if bed thickness remains greater than the tool resolution the effects are small.

Pad tools are vulnerable to rugose hole and wash outs. In very big holes the pad may lose contact with the formation and give a flat mud resistivity reading. In very sticky holes the pads can become balled up with mudcake or shale and readings become meaningless.

Example

Permeable layers can be identified easily from separation of the deep and very shallow curves, and this information should be used to qualify the sand count based on the GR log. The tracking of the LLd and LLs implies that invasion is very shallow so the LLd should be a reasonable approximation of Rt. The peaky nature of the log suggests that not all the thin resistive layers are fully resolved.



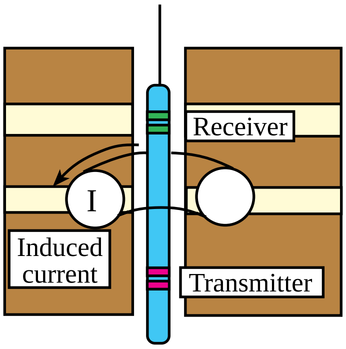
INDUCTION LOG

Typical applications

- Hydrocarbon saturation determination
- Permeability indicator

Principle of measurement

Induction tools employ coils through which is passed a high frequency alternating current to set up an alternating magnetic field in the formation. The magnetic field induces current flow in the formation surrounding the tool which is proportional to the formation conductivity. These currents in turn create a magnetic field which sets up a voltage in a receiver coil. An arrangement of coils is used to suppress borehole and shoulder bed contributions to the signal, and to eliminate direct coupling between transmitter and receiver coils.



Induction Tool

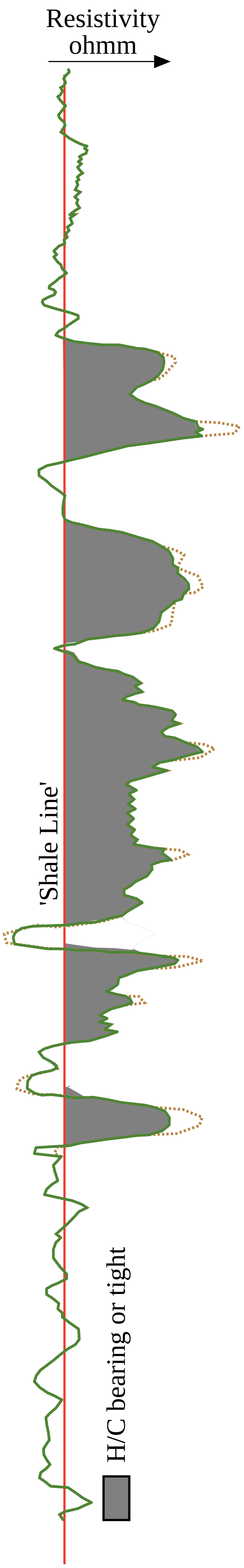
Interpretation

Determination of Rt from induction logs, as a parameter in the hydrocarbon saturation calculation, is almost identical to the description contained in the 'interpretation' section of the Laterolog module. For a quicklook evaluation the induction deep (ILd) and induction medium (ILm) logs can be used to establish Rt in a similar fashion as the LLd and LLs (though different correction charts are used when working in more detail). In wells drilled with saline mud an SFL (built into the induction tool) often provides a shallow reading though care must be taken as the SFL tools investigate deeper into the formation than the MSFL described in the previous module. The SFL tools have a depth of investigation in the order of 18ins so may be influenced by the non invaded formation.

Induction tools work best in low resistivity formations and in wells drilled with high resistivity muds (or non conductive mediums such as air). In this situation the major contribution to the induction signal comes from the formation under investigation as the strength of the induced current is a function of formation conductivity.

Logging operations

The induction tool is designed for an 8.5" hole though can be run successfully in much larger hole sizes in which logging is usually performed with a 1.5" stand off from the borehole wall. The induction is the only tool capable of resistivity measurement in holes drilled with oil based muds. The housing of the induction tool is constructed from glass fibre, to prevent the formation of induced currents in the tool body, and as a result must be handled with care to prevent damage.



A logging speed of 3600ft/hr is typical as though structurally weak, the tool is not very vulnerable to speed related data acquisition problems.

Tool resolution is in the order of 6ft. Depth of investigation is 4-6ft for the Medium Induction log (ILm) and about 10ft for the Deep Induction log (ILd).

Tool Calibration

Induction devices are calibrated at the contractor’s field base, using a zero conductivity environment for the ‘zero’ calibration, and a test loop representing a conductivity of 500 mmho (= 2 ohmm) for the ‘plus’ calibration. At the well site the ‘plus’ calibration is checked electrically using an internal precision resistor, and the calibration drift during the survey is assessed by performing the same calibration after the survey. The zero calibration cannot be checked at the well site as there is no practical zero conductivity environment available.

Influence of borehole environment

The choice of measuring Rt with the Laterolog or Induction is influenced mainly by the salinity of the mud and the contrast between the mud and the formation resistivity. As a rule of thumb in intervals where porosity is greater than 13% the induction is preferred when the ratio of Rmf/Rw>2.

In large holes, high salinity muds and across thin formation beds the induction log will generally require significant correction. Borehole effects are negligible in non conductive oil based muds or gas filled holes.

Example

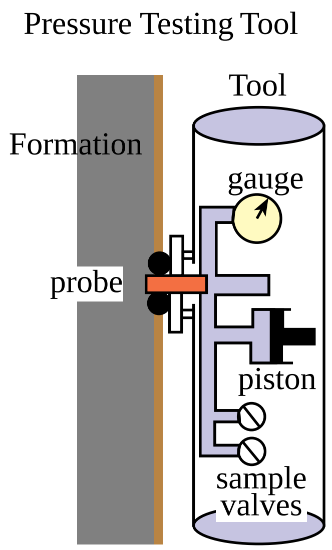
The deep and medium induction curves exhibit no separation in the shale intervals as expected, but also little in the reservoir intervals suggesting very low invasion. The separation observed over high resistivity peaks is mainly due to differences in tool resolution rather than permeability (the shallow induction reading has a higher resolution so the reading is less influenced by adjacent layers). Potential oil bearing reservoir intervals can be identified by flagging resistivity curves on the high side of the shale line. Tight zones (in this case calcite layers) will also be captured by this cut off and must be identified using logs such as the sonic or density.

FORMATION PRESSURE TESTER

Typical applications

- Formation pressure measurement
- Fluid definition and distribution (from gradients)
- Depletion profiling
- Formation fluid sampling

Principle of measurement

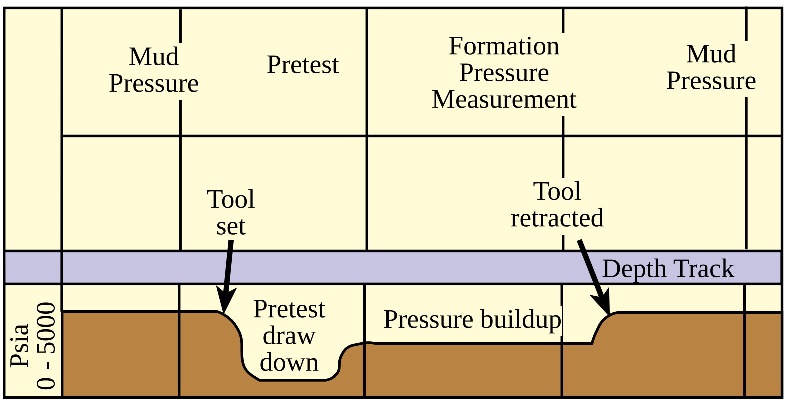


The main component of the formation tester is an accurate pressure gauge which is attached via a flowline to a probe. The tool is positioned opposite a zone of interest and mechanical rams extended to lock the tool against the borehole wall and isolate the flowline from the mud column by forcing a rubber doughnut surrounding the flowline entry port into the mudcake. Once the tool is located a probe is extended through the doughnut to the formation putting the formation and pressure gauge in communication. The probe includes a filter to reduce the risk of formation debris plugging the flowline.

Permeability near the probe can be estimated by drawing down at a fixed rate a small piston (or pistons) connected to the flowline. The magnitude of the resulting pressure drop gives an indication of the deliverability of the formation. Once the pretest chamber under the piston is full the pressure in the flowline builds up quickly to the formation pressure. Sample chambers can be attached to the tool and sample valves opened to route the formation fluids to the chambers if a sample is required.

After recording formation pressure the tool can be retracted and positioned at a different depth. In principle there is no limit to the amount of pressure tests that can be performed in a single run though in practise wear and tear limit the life of the doughnut seal.

One pressure measurement cycle is shown below as it would appear on the log. As the tool is stationary the recording is made against time rather than depth and the left hand boundary line of track one is normally broken periodically, the distance between two gaps represent one minute.

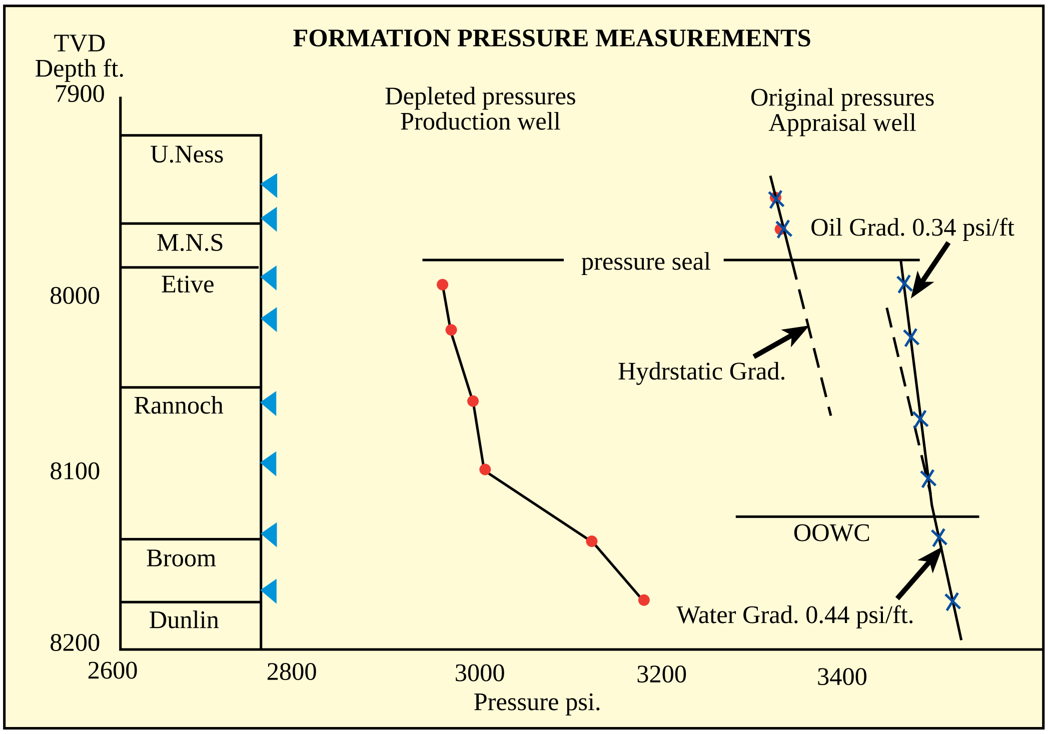


Pressure vs Time - Typical Log Presentation

Some tools have two pretest chambers drawn down at different rates but the principle is much the same as for one. If a sample is required the sampling valves are opened after the formation pressure measurement and a sampling pressure record would also be output on the log for each sample chamber.

Interpretation

Interpretation is generally performed by constructing a pressure/depth plot to establish pressure distribution and fluid gradients. Pressures must be plotted vs. true vertical depth. The intersection of oil and water gradients identify the Free Water Level which in zones of good permeability will almost coincide with the oil/water contact. Absolute pressures can be compared to the hydrostatic gradient as shown below and in non producing areas will establish whether the interval is overpressured. When original pressures are known and pressures have been reduced as a result of production the degree of pressure depletion can be established in subsequent development wells. The depletion profile also gives useful information regarding reservoir quality and connectivity.



Logging Operations

Depth correlation is achieved by running a GR tool with the pressure tester. Once correlation has been established the surface depth measurement wheels are used to position the tool over short intervals. Gauge stability can be monitored by observing the mud pressure reading before and after each formation pressure measurement, a difference of more than 2 psi would imply gauge instability. The after survey mud pressures should also plot on a straight line if the gauge is not drifting with depth. A complete pressure test cycle should take about 3 minutes during which time the tool is stationary.

Pressure test depths are usually selected on the GR-Density-Neutron combination, together with resistivity logs. A good test site should have a low shale content, good permeability and be in an on-gauge hole section. Tests for gradient definition should be evenly spread over the interval. This obviously very much depends on the circumstances. A rule of thumb figure is one pressure test 5-10 metres. This is far enough apart to ensure meaningful pressure gradient determination where original pressures exist.

Pressure tests may be unsuccessful for various reasons which can include, packer seal failure, flowline or probe blockages, poor isolation of the mud column or the formation may just be too tight. If the zone under investigation has a very low permeability the pressure recorded by the tool will drop sharply upon opening of the pretest chambers and may not build up again, or only very slowly. In very low permeability environments formation layers may become 'supercharged' by mud filtrate invasion and pressure points will plot on the high side of the normal pressure gradient line. Supercharging can be identified by bleeding off the pressure into a sample chamber, if the pressure does not build up to the original level once the flow line is closed then supercharging is implied and the pressure should be regarded as unreliable.

A fluid sample may be taken after a pretest has confirmed good permeability. Most tools can carry at least two sampling chambers. Standard sizes are 1 and 2.75 US gallons, but 6 and 12 gallon chambers are also available. Each chamber can be filled at a different depth, or both at the same depth termed 'segregated sampling'. In this case the largest sampling chamber is filled first to clean up the formation of mud filtrate. The smaller chamber is then filled with a less contaminated sample of formation fluid. As the tool is stationary for longer periods during sampling the risk of differential sticking increases significantly.

Sample chambers may be sealed and sent to the laboratory for PVT analysis or opened at the wellsite and the contents measured and sampled at atmospheric conditions. Typically gas is bled off through a gas meter and liquids stored in bottles both of which may be supplied by the client.

Tool (gauge) calibration

Two types of pressure gauges are widely available, strain gauges and quartz gauges. The standard is a strain gauge calibrated at the contractors field base for pressure and temperature effects. Accuracy and resolution vary with strain gauge quality but an absolute accuracy of 10 psi and resolution of 1 psi should be expected. Quartz gauges have a much higher accuracy, up to 1 psi assuming the temperature is known within 1 deg C, and a resolution of 0.1 psi. Quartz gauges require a longer temperature stabilization time. Strain gauge zero is usually 1 atmosphere whereas quartz gauge readings are absolute pressures.

Example

The example shown on the previous page shows pressure plots in a Brent reservoir sequence from both an appraisal well and a development well. The Mid Ness Shale (MNS) is acting as a regional pressure seal below which the formations are overpressured. The development well exhibits pressure depletion in the lower Brent reservoir but not in the upper reservoir which is water bearing and has not been produced.

References

RFT: Essential of pressure test interpretation - Schlumberger
Formation Multi-Tester interpretation manual - Atlas Wireline