

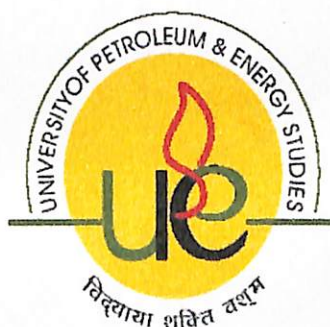
MWD AND LWD INTERPRETATION

By

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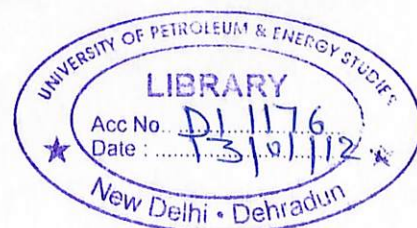
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MWD AND LWD INTERPRETATION

A thesis submitted in partial fulfillment of the requirements for the Degree of

Bachelor of Technology

(Applied Petroleum Engineering, Upstream)

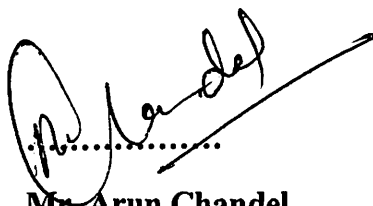
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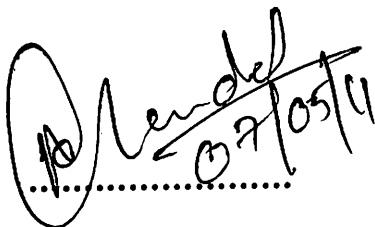
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May, 2011

CERTIFICATE

This is to certify that Rishabh Uniyal, Saurabh Bhandari and Tanya Gupta, students of B.Tech(Applied Petroleum Engineering) have written their thesis on “MWD and LWD Interpretation” under my supervision and have successfully completed the project within stipulated time.

They have demonstrated high performance levels and dedication during the completion of their thesis.



Mr. Arun Chandel

(Mentor)

ABSTRACT

The two techniques used to calculate the geometry of the hole and the characteristics of the formation penetrated are MWD and LWD. MWD stands for Measurement While Drilling in the oil industry. It provides real time data while drilling, which makes the drilling more efficient. The various MWD tools used are either contained inside a drill collar or are built into the collar themselves. The MWD technique is basically used to measure the azimuth and the inclination. These are calculated using the survey instruments. The survey instruments are magnetometers, accelerometers and the gyroscopes. Also, there are steering tools used in MWD. The proper methodology has been included in the report. There are six types of tools used in the industry which are incorporated in the report with their specifications. The case study mainly includes the calculation of True Vertical Depth, North direction, East direction, Departure and the Dog Leg Severity using different calculation methods.

LWD stands for Logging While Drilling. It's a technique in which well logging tools are used to get information of the formation being penetrated. The main objective of wireline logs is to get rock and reservoir properties and Hydrocarbon Evaluation. Visual graphical representation of the data is done in the form of logs whose interpretations are done to get valuable and practical information. This report includes various LWD tools used to compute lithology and the fluid content in the formation.

The formula sheet and the log data have been attached in the report. The calculated results are tabulated and recommendations have been suggested in the following report.

AKNOWLEDGMENT

We would like to express our deepest gratitude to Dr. Shri Hari, Dean, COES, UPES for allowing us to perform the project work. We have received maximum co-operation and help from UPES faculty members.

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Chapter 1

INTRODUCTION

1.1 Project Background

Measurement While Drilling (MWD)

Measurements while drilling play an increasingly important role in modern drilling practices. They allow an operator almost immediate feedback regarding both the geometry of the hole being drilled and the characteristics of the formation penetrated. MWD technique is used to determine the azimuth and the inclination. Without MWD this kind of information is available only from the conventional logging tools such as deviation surveys and logs that, a priori, must be run after the drilling has taken place. These conventional logging tools are no longer effective when the angle exceeds 60 degrees to retrieve information. MWD is of particular benefit in that it can be applied when drilling directional wells and/ or when overpressured formations are of concern.

BY having the kind of information MWD can supply more or less in real time, the driller may take appropriate action such as changing the weight on bit, increasing the mud weight, or pulling out of the hole for a conventional logging run once the objective formation has been reached.

Logging While Drilling (LWD)

Well logging, also known as **borehole logging** is the practice of making a detailed record (a *well log*) of the geologic formations penetrated by a borehole. The log may be based either on visual inspection of samples brought to the surface (*geological logs*) or on physical measurements made by instruments lowered into the hole (*geophysical logs*). Well logging is done when drilling boreholes for oil and gas, groundwater, minerals, and for environmental and geotechnical studies.

The oil and gas industry records rock and fluid properties to find hydrocarbon zones in the geological formations intersected by a borehole. The logging procedure consists of lowering a 'logging tool' on the end of a wireline into an oil well (or hole) to measure the rock and fluid properties of the formation. An interpretation of these measurements is then made to locate and quantify potential depth zones containing oil and gas (hydrocarbons). Logging tools developed over the years measure the electrical, acoustic, radioactive, electromagnetic, nuclear magnetic resonance, and other properties of the rocks and their contained fluids. Logging is usually performed as the logging tools are pulled out of the hole. This data is recorded to a printed record called a "well log" and is normally

transmitted digitally to office locations. Well logging is performed at various intervals during the drilling of the well and when the total depth is drilled, which could range in depths from 300 m to 8000 m (1000 ft to 25,000 ft) or more.

Open hole operations, or reservoir evaluation, involves the deployment of tools into a freshly drilled well. As the toolstring traverses the wellbore, the individual tools gather information about the surrounding formations. A typical open hole log will have information about the density, porosity, permeability, lithology, presence of hydrocarbons, and oil and water saturation.

Cased hole operations, or production optimization, focuses on the optimization of the completed oil well through mechanical services and logging technologies. At this point in the well's life, the well is encased in steel pipe, cemented into the well bore and may or may not be producing. A typical cased hole log may show cement quality, production information, formation data. Mechanical services use jet perforating guns, setting tools, and dump bailers to optimize the flow of hydrocarbons.

There are basically two types of logging used to get information about the geologic formation penetrated by borehole.

- **Logging While Drilling (LWD)**

In the 1980s, a new technique, logging while drilling (LWD), was introduced which provided similar information about the well. Instead of sensors being lowered into the well at the end of wireline cable, the sensors are integrated into the drill string and the measurements are made while the well is being drilled. While wireline well logging occurs after the drill string is removed from the well, LWD measures geological parameters while the well is being drilled. However, because there are no wires to the surface, data are recorded downhole and retrieved when the drill string is removed from the hole. A small subset of the measured data can also be transmitted to the surface in real time via pressure pulses in the well's mud fluid column. This mud telemetry method provides a bandwidth of much less than 100 bits per second, although, as drilling through rock is a fairly slow process, data compression techniques mean that this is an ample bandwidth for real-time delivery of information.

- **Wireline log**

A continuous measurement of formation properties with electrically powered instruments to infer properties and make decisions about drilling and production operations. The record of the measurements, typically a long strip of paper, is also called a log.

Measurements include electrical properties (resistivity at various frequencies), sonic properties, active and passive nuclear measurements, dimensional measurements of the wellbore, formation fluid sampling, formation pressure measurement, wireline-conveyed sidewall coring tools, and others. In wireline measurements, the logging tool (or probe) is lowered into the open wellbore on a multiple conductor, contra-helically armored wireline. Once lowered to the bottom of the interval of interest, the measurements are taken on the way out of the wellbore. This is done in an attempt to maintain tension on the cable (which stretches) as constant as possible for depth correlation purposes. Most wireline measurements are recorded continuously even though the probe is moving. Certain fluid sampling and pressure-measuring tools require that the probe be stopped, increasing the chance that the probe or the cable might become stuck. LWD tools take measurements in much the same way as wireline-logging tools, except that the measurements are taken by a self-contained tool near the bottom of the bottomhole assembly and are recorded downward (as the well is deepened) rather than upward from the bottom of the hole (as wireline logs are recorded).

1.2 Project Aim

MWD

Many different MWD systems are in commercial use today, they all have the capability of receiving the receiving encoded control commands which are sent by turning on and off mud pumps, changing the rotating speed of drill pipe or by other advanced telemetry technology such as wired pipe. Most important objective is to calculate azimuth and the inclination. MWD measuring systems have following common characteristics:

- A downhole sensor sub
- A power source
- A telemetry system
- Surface equipment

There are transmission techniques or telemetry system like negative pulse telemetry, positive pulse telemetry and the continuous phase telemetry used for the transmission of the data from the borehole to the surface for the analysis.

The downhole sensor subs contain instrumentation capable of measuring parameters like:

- Torque and Weight on Bit, measured near the drill bit
- Borehole pressure and temperature
- Tool-face angle
- Natural formation gamma ray activity
- Formation acoustic travel time

- Formation resistivity
- Hole deviation from vertical
- Hole azimuth with respect to geographical coordinates

Also, The MWD tools make the part of the bottomhole assembly (BHA). They are either incorporated in drill collars or are build into the collars. Major tools required are accelerometer; magnetometer and gyroscope which are used in MWD will be discussed further.

LWD

The aim of LWD is to analyze and evaluate a processed log data of the well using various logging tools and equations.

1.3 PROJECT OBJECTIVE

MWD

The main objectives are:

1. Calculate the azimuth and inclination of the directional well
2. Calculate True Vertical Depths and the measured Depths
3. Calculate Northing and Easting
4. Calculate dog Leg Severity DLS

LWD

The main objectives are:

1. Identification of lithology by quick look interpretation
2. Determination HC bearing zones
3. Calculation of porosity by various methods
4. Calculation of water saturation and formation water resistivity
5. Conclusions and Recommendations

1.4 SCOPE OF THE PROJECT

MWD

The report includes the description of the MWD tools and description of the telemetry systems. This report also describe several methods to compute the position of the well bore at each well bore using the tangential, balanced tangential, average, radius of curvature and

minimum curvature methods. It also includes the case study showing the complete calculations for the above stated methods. MWD tools provide information about the conditions at the drill bit.

- Rotational speed of the drillstring
- Rotation smoothness
- Type and severity of any vibration downhole
- Downhole temperature
- Mud flow volume

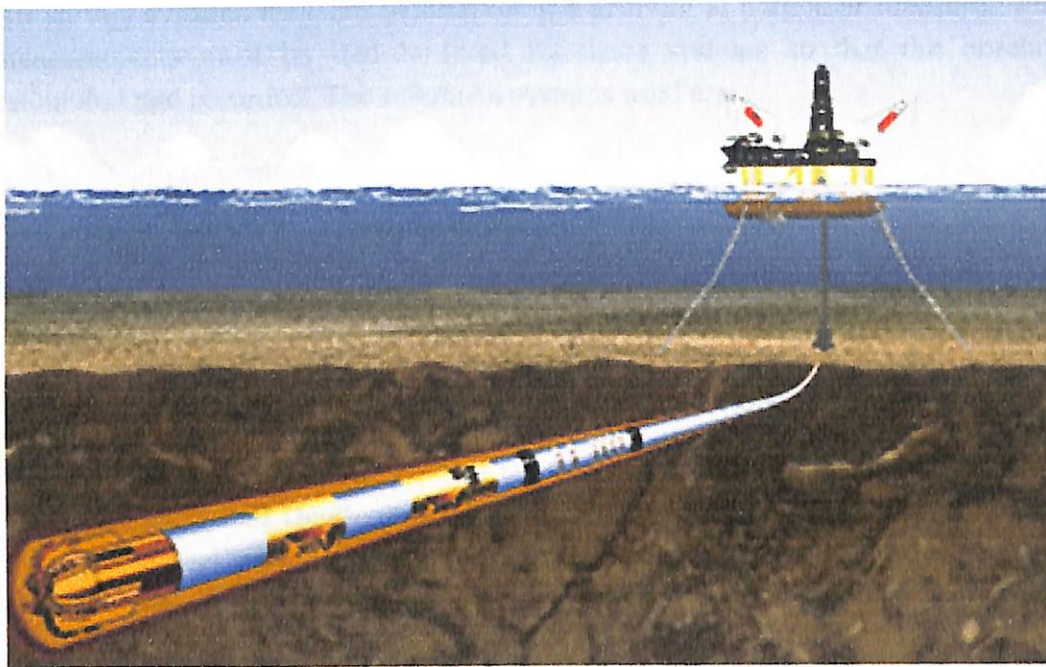


Figure 1

LWD

The report also includes the description of LWD tools used for the interpretation of the logs. This technique uses several logs which are described in this report. They are Gamma ray log (GR), Resistivity logs(RT), Neutron log (NPHI), Density log (RHOB) and Compressional sonic log (DT). The report also include case study that uses the above method to identify lithology and to calculate electrical properties (resistivity at various frequencies), sonic properties, density and neutrons porosity, water saturations and perforation intervals containing oil and gas zones.

Pressure While Drilling (PWD) is another technique used to determine the geometry to the hole and the characteristics of the formation penetrated but it is not in the scope of this report.

1.5 PROJECT METHODOLOGY

MWD

A Directional well is drilled from the surface to reach a target area along the shortest possible path. Owing to the changes in the rock properties, the hole path rarely follows a single but, instead, changes its inclination and direction continuously.

➤ Reference Systems and Coordinates

All survey systems measure inclination and azimuth at particular measured depths. These measurements must be tied to fixed reference systems so that the borehole may be calculated and recorded. The reference systems used are:

- Depth references
- Inclination references
- Azimuth references

Depth reference system:

There are two kinds of depths to calculate borehole course:

1. Measured Depth

Measured Depth or “Along Hole Depth” is the distance measured along the actual course of the wellbore from the surface reference point to the target or survey point. This depth is always measured with pipe tally, wireline depth counter, or mud loggers’ depth counter.

2. True Vertical Depth TVD)

TVD is the vertical distance from the depth reference level to a point on the borehole course.

Inclination reference system:

Well Inclination is the angle between the vertical and a tangent to the well path at any point.

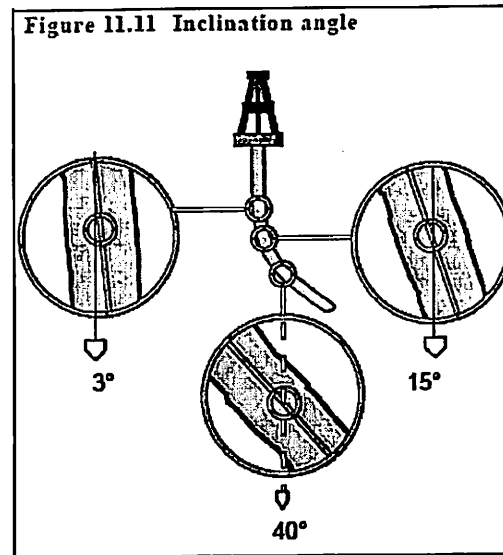


Figure 2

Azimuth reference system:

There are three azimuth reference system used for directional surveying:

Magnetic North: reference system gives azimuth using 'magnetic type' tools.

True (geographic) North: This is the geographic North Pole lies on the axis of rotation of the Earth shown on maps by the meridians of longitude.

Grid North: In order to represent the part of the surface of Earth on a flat well plan, projection systems are used.

Two of the projection systems most commonly used in the Petroleum Industry are the **Universal Transverse Mercator (UTM)**, and the **Lambert conical orthomorphic**.

Universal Transverse Mercator (UTM) system

In this projection, the surface of the spheroid chosen to represent the Earth is wrapped in a cylinder which touches the spheroid along a chosen meridian (A meridian is a circle running around the Earth passing through both geographic North and geographic South Poles.)

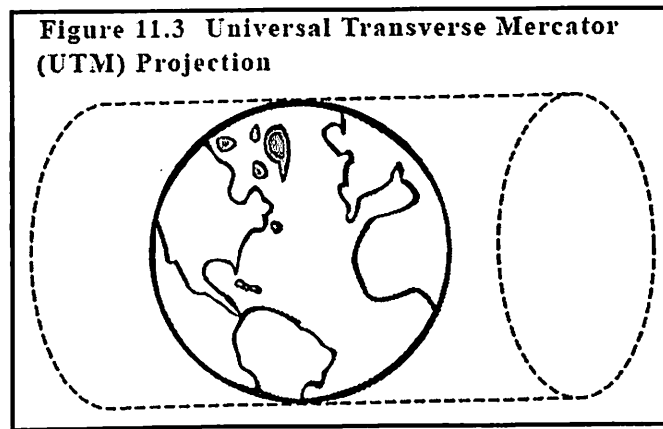


Figure 3

The grid lines on a map form a rectangular grid system, the northerly direction of which is determined by one specified meridian of longitude. This direction is called Grid North.

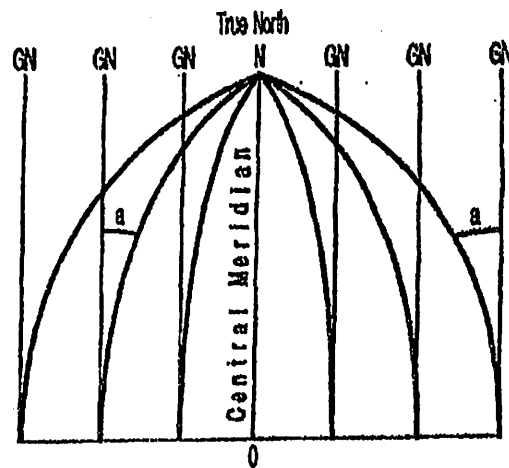


Figure 4

The reference meridians used are 6 degrees apart starting at the Greenwich meridian (chosen as the reference meridian with 0 degrees of longitude), which means the world is divided into 60 zones. The zones are numbered 0 to 60 with zone 31 having the 0 degrees meridian (Greenwich) on the left and 6 degrees East on the right.

For the polar regions North of 84 deg N and South of 80 deg S, a specialized projection system, called the Polar Stereographic grid, is used.

Coordinates in UTM system are measured in meters. UTM coordinates are given as Northings and Eastings and are always positive numbers and measured in meters.

The Northing coordinate is the distance from the equator and the easting coordinate is the distance from a line 500,000 m west of the central meridian for that sector.

Northings

The equator is chosen as the latitude of origin in all zones. For the northern hemisphere, false northing numbers are given to latitudes beginning with 0 meters at the equator and increasing towards the north. For the southern hemisphere, the equator is given arbitrary of northing value of 10,000,000 meters to avoid negative numbers.

Northings in the southern hemisphere decrease towards the south the pole.

Eastings

The central meridian of each zone is given an arbitrary easting coordinate of 500,000 meters east to avoid negative numbers. False easting numbers are then given to each vertical grid line, decreasing westwards and increasing eastwards in each zone.

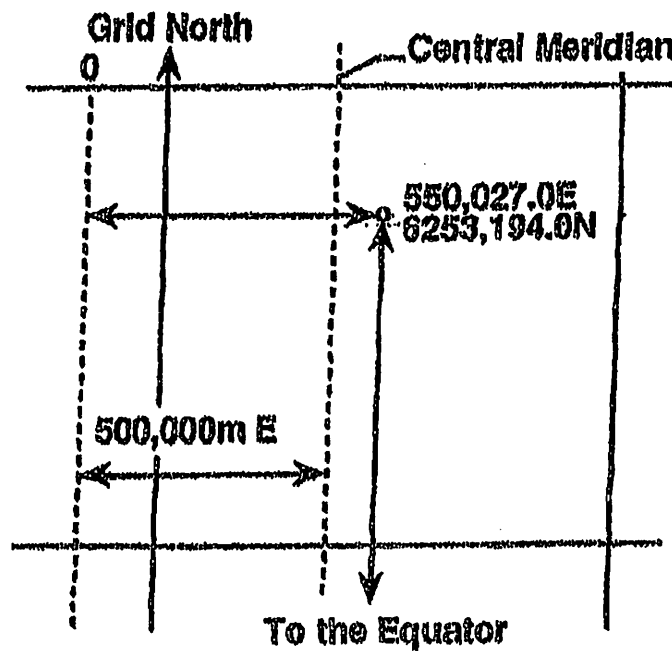


Figure 5

Lambert conical orthomorphic

This projection system is most suited in USA in which a cone as opposed to a cylinder covers the spheroid and produces a presentation with meridians as convergent lines and parallels as arcs of circles.

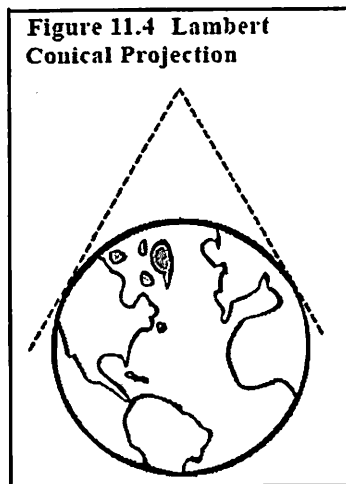


Figure 6

➤ Field Coordinates

Azimuth

Azimuth is the angle measured in a horizontal plane between the direction of the north and a point on the well path. Azimuths are usually expressed in angles from 0-360, measured from zero north. Azimuths can also be expressed in a quadrant system from 0-90 measured from north in the northern quadrants and from south in the southern quadrants. The azimuth reading of 135 equates to S45 E in quadrant readings.

For directional survey there are three azimuth reference systems. Magnetic North in which all magnetic type tools initially give azimuth reading referenced to magnetic north, True (geographic) North and grid north.

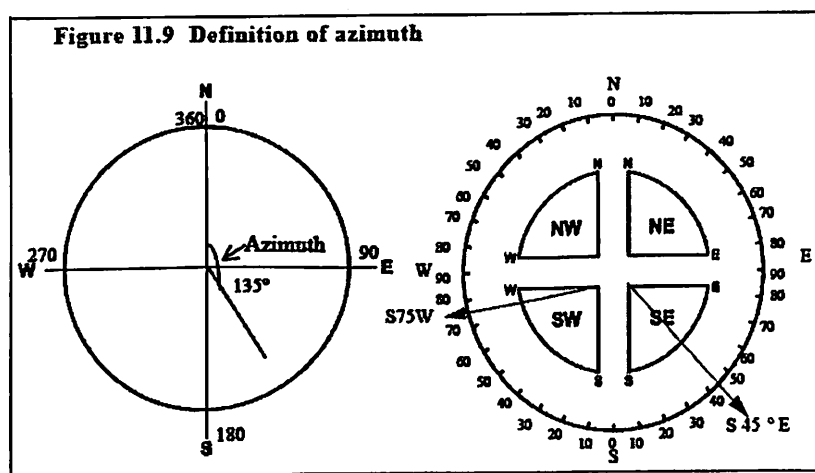


Figure 7

Northings:

It is the horizontal distance measured between the survey point and the reference point, to the north. A distance to the South is considered to be negative.

Eastings:

It is the horizontal distance between the survey point and the reference point, to the east. A distance to the West is considered to be negative.

➤ Azimuth and Departure

Rectangular coordinates of a target are derived from subtracting the grid coordinates of the surface location from those of the target. It is usually given in feet/meters North/South and east/west of the local reference point.

The rectangular coordinates can be used to determine the departure (horizontal displacement) between the surface location and the bottomhole target as follows:

$$\text{Departure} = ((\Delta E/W)^2 + (\Delta N/S)^2)^{1/2}$$

Where

Δ denotes difference in coordinates between E/W or N/S

Polar coordinates can be derived from the rectangular coordinates. They are expressed as a distance (departure) and as a direction (either quadrant or azimuth). Polar coordinates are derived from the rectangular coordinates as follows:

$$\text{Azimuth} = \tan^{-1} ((\Delta E/W \text{ coordinates}) / (\Delta N/S \text{ coordinates}))$$

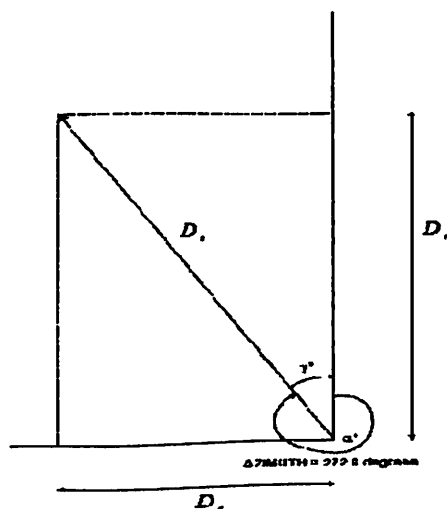


Figure 8

Using the above figure, the horizontal displacement or departure and azimuth can be calculated as :

$$\text{Departure} = D_t = \sqrt{D_e^2 + D_n^2}$$

$$\text{Azimuth}(\alpha) = \tan^{-1} \left(\frac{D_e}{D_n} \right)$$

➤ Directional well profile

A directional well profile is the planned well trajectory from the surface to the target by projecting the wellbore onto two plotted planes. The information required for determining the geometric well profile are:

- The position of the surface location
- The position of the target location
- The true vertical depth (TVD).

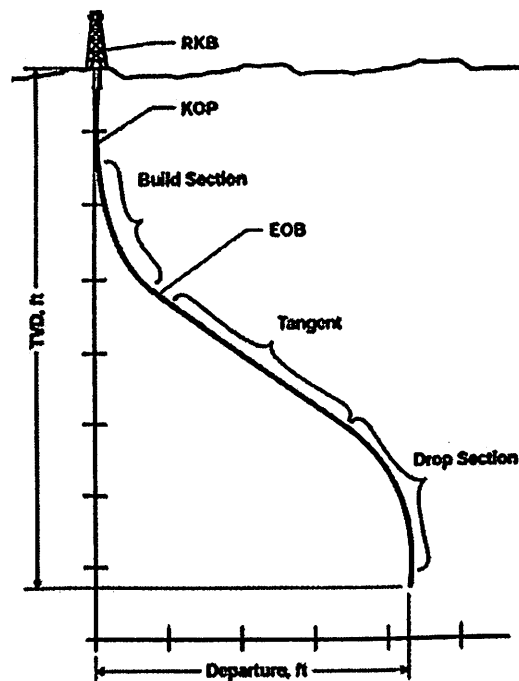


Figure 9

Well Profile Terminology

1. Kick Off Point (KOP)

The kickoff point is the location at a given depth below the surface where the wellbore is deviated in a given direction.

2. Build-up section

It is the curved section between KOP and EOB. A build section is frequently designed at a constant buildup rate (BUR) until the desired hole angle or end-of-build (EOB) target location is achieved.

3. End-Of-Build-up (EOB)

It is the point where build-up section ends.

4. Tangent Section

Curved section to get tangent angle and hold section (no inclination variation). The function of the tangent is to maintain angle and direction until the next target is reached.

5. Drop Section

This section comes after the tangent section. The purpose of a drop is to place the wellbore in the reservoir in the optimum orientation with respect to formation permeability or in-situ formation stress.

6. Inclination angle

The angle formed between the wellbore axis and the vertical at any point.

7. Measured depth

The distance traversed by the wellbore from one reference point (RKB) to the survey point. It is denoted by MD.

8. True vertical depth

It is the vertical path measured from one reference point (RKB) to the survey point. Denoted by TVD is usually referenced to the rotary table, but may also be referenced to mean sea level.

9. Northing

It is the horizontal distance measured between one survey point to the reference point, measured to the north. The distance to the south is denoted as being negative.

10. Easting

It is the horizontal distance measured from one survey point to the reference point, measured to the East. The distance to the west is denoted as being negative.

BUILD UP AND DROP OFF RATES

The buildup and the drop section is usually designed at a constant buildup rate (BUR). The maximum permissible build up /drop off rate is normally determined by one or more of the following:

- The total depth of the well
- Maximum torque and drag limitations
- Mechanical limitations of the drill string or casing
- Mechanical limitations of logging tools and production strings.

$$\begin{aligned}C &= 2\pi R_c \\&= 360 \times 100 / \text{BUR} \\ \text{BUR} &= 360 \times 100 / 2\pi R_c \text{ in } ^\circ/100 \text{ ft} \\ R_c &= 18000 / \pi \text{BUR in feet} \\ \text{TVD}_1 &= R_c \times \sin I_1 \\ \text{TVD}_2 &= R_c \times \sin I_2 \\ \Delta \text{TVD} &= \text{TVD}_2 - \text{TVD}_1 \\ &= R_c (\sin I_2 - \sin I_1) \\ \Delta \text{TVD} &= 5729.58 (\sin I_2 - \sin I_1) / \text{BUR}\end{aligned}$$

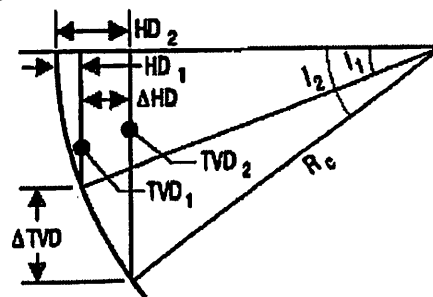


Figure 10

The optimum build up and drop off rates in predictable directional wells are in the range of 1.50 to 30 per 100 ft, although much higher build up rates are used for horizontal and multilateral wells.

➤ Types of well profile

There are three types of directional wells:

Type I : A directional well of this type is deflected at a shallow depth and the inclination is locked in until a target zone is penetrated. Wells of this type are used for:

1. Moderate depth drilling
2. Single-zone production
3. Wells requiring no intermediate casing
4. Deep wells requiring large lateral displacement

Type II : This type is also called the S-type well, as its shape resembles the letter S. The well is deflected at a shallow depth until the maximum required inclination is achieved. The well path is then locked in and, finally, the inclination is reduced to a lower value, or, the well is returned back to vertical by gradually dropping off the angle. This is practiced in multi-zone production and for relief wells.

Type III : This is similar to type I, except the well is deflected at a much deeper position in order to avoid a salt dome. Practised in sidetracking and wildcat drilling.

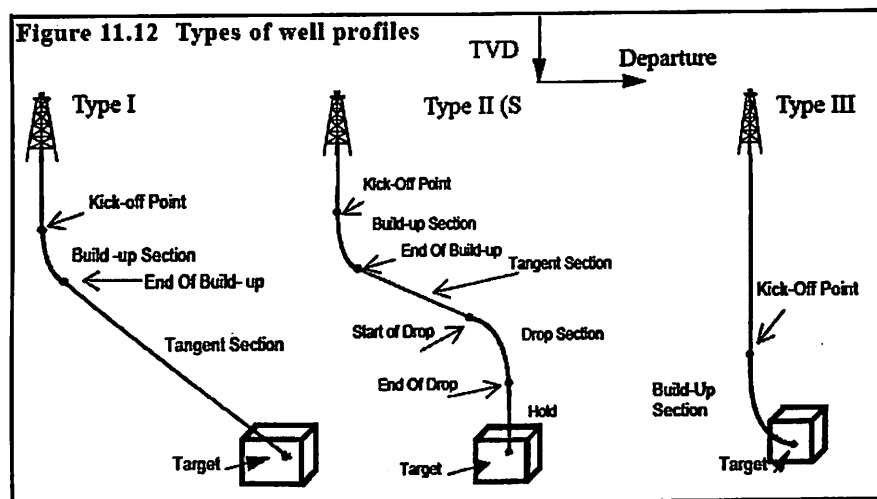


Figure 11

LWD

Qualitative methods are used to identify the lithology:

A pure sandstone formation exhibits following characteristics:

- a) At zero porosity it has a density value of 2.65 gm/cc.
- b) GR value in clean sandstone is very low.

The GR, density-neutron and sonic logs of well 'X' show such characteristics; hence the bulk lithology of the region can be identified as sandstone.

Shale is identified based on the following characteristics

- a) High gamma ray values. A positive separation between density-neutron logs
- b) Low resistivity value (approximately 1ohm)

Hence the formation is sandstone with some shale intercalation.

Crossplots like density-neutron and sonic-porosity are also used for the qualitative determination of Lithology. Crossplots provide visual insight into the type of mixtures that form the particular lithology. When the lithology is a binary mixture (e.g. sandstone-lime or lime-dolomite or sandstone-dolomite) the point plotted from log readings will fall between the corresponding lithology lines.

1.6 PROJECT LIMITATIONS

Limitations of MWD

- If the tool fails at certain depth while drilling, then it would generally be faster to pull the tool out of the hole than it would be to rig up wireline and retrieve the tool. Hence, retrieving a tool using wireline is not necessarily faster than pulling the tool out of the hole.
- If the tool detached from the wireline, then it will fall back down the drillstring which may cause serve damage to a tool and the drillstring components in which it seats.
- The process results in the increase of total cost of operation.

Limitations of LWD

- Due to low vertical resolution, thin beds cannot be always identified.
- In case of any borehole damage, the logs do not always show accurate results.
- Depth shift effects can cause ambiguities in log interpretation.

CHAPTER 2

LITERATURE REVIEW

MWD

The most important tools for the MWD are magnetometers, gyroscope and the accelerometer. The survey instruments are used to find the azimuth and the inclination of the well bore. These instruments use magnetic field and the gyroscope to determine the azimuth of the well bore.

1. **Magnetic Instruments-** The magnetic instruments works on the principle of earth's magnetic field. The instrument reading could be affected by the factors which influence the magnetic field. Corrections should be used to correct the reading. The corrections used are as follows:
 - a) Magnetic declination
 - b) Non magnetic drill collar selection

The description for these corrections is as follows:

- a) **Magnetic declination-** Magnetic survey instrument makes use of magnetic compass which points magnetic north. Generally the magnetic north is not as same as the true geographical north i.e. North Pole. Therefore, the magnetic surveys are adjusted between magnetic north and the geographical north. Also, the angle formed by the true geographical north and the magnetic north is known as the magnetic declination.

The magnetic north can be east or west or in the same direction with respect to the geographical north when at a location on earth. The azimuth reads from the magnetic north. Hence, the correction should be made according to the proper magnetic declination. If the geographical location lies on the 0° declination then no correction is needed in the instrument reading. 0° declination line is known as agonic line. A location west of the agonic line has a magnetic needle pointing to east. Example: for 10° , the location will be 10 degrees east. East declination is measured clockwise from the true geographical north. Incase the location is of the agonic line then the declination is subtracted from the instrument reading. The corrected direction is finally reported in the survey.

When the survey instrument is taken out of the well then the declination of the gas well is read from the instrument directly. Then this reading is corrected with the magnetic declination for that location. Finally the corrected readings are reported in the survey of that well. Table 1 represents whether the corrections are added or subtracted from the instrument reading based on the quadrant applicable to the well direction. The modern instruments are computer based and the declination is fed to the computer. The reported survey already includes the declination.

Table 1

SURVEY READING	EAST DECLINATION (ADD TO AZIMUTH)	WEST DECLINATION (SUBTRACT FROM AZIMUTH)
NE	+	-
SE	-	+
SW	+	-
NW	-	+

b) Non Magnetic Drill Collar Section-

The magnetic field around the tool influences the magnetic survey instruments due to the presence of ferro magnetic material in the formation and collar, drillpipe or other BHA's. This influence can be reduced to minimize interference with earth magnetic field but cannot be completely eliminated. The earth's magnetic field is measured by placing a non magnetic drill collar inside the survey instrument. We can also use more than one drill collar to minimize the magnetic interference. Non magnetic drill collars are also called monel drill collars.

The geographical location of the well also influences the number and length of non magnetic drill collars needed. The earth's magnetic field is dictated by the location and hence the quality of survey reading. Close to the earth's poles, the horizontal intensity is small but is high near the equator.

Horizontal intensity is a function of magnetic dip angle and is given by

Horizontal Intensity= Magnetic field strength* cosine (magnetic dip angle)

The angle that the magnetic needle makes with the horizontal plane at any location on earth will determine the magnetic dip angle. At the magnetic poles this angle is 90° and is close to zero near the equator and so at the magnetic poles, the horizontal intensity is smallest and highest near the equator. A wellbore which is oriented towards the east or west will require more drill collars than surveying of a well bore pointing to the magnetic north or south.

The earth's magnetic field alone is not used to determine the non magnetic drill collar length and compass spacing. But the total magnetic field which is the vectorial sum of the earth's magnetic field and the magnetic field caused by the magnetized portions of the drillstring determines it.

Steering Tool

The earliest electronic tool developed was Steering Tool. The survey reading was conveyed using a single conductor wireline to the surface from the down hole tool. The steering tool was developed to monitor the wellbore orientation when drilling with a motor. It consists of two sets of built in sensors: one to sense the earth's magnetic field (magnetometers) and another to spot the gravitational pull (accelerometers).

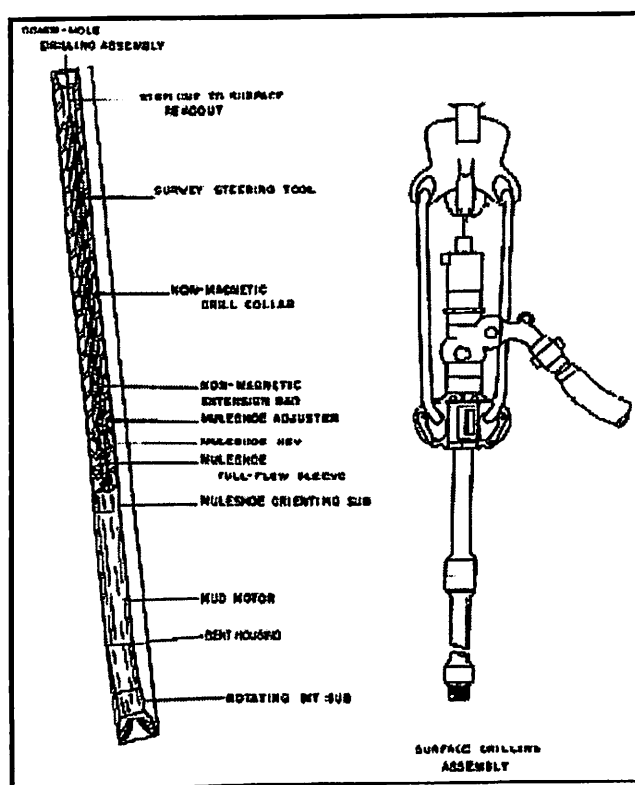


Figure 12

The figure above (fig 2) shows some of the equipment used along with a steering tool. It shows a pack off being used at the top of the drill pipe and the Kelly being removed from the drill string.

Demerits:

1. The pulling and running of the steering tool takes a long time.
2. The drill string can't be rotated while the steering tool is still in the hole.
3. A lot of time is wasted if the tool has to be pulled out of the hole or any connection has to be made.

MWD has substituted most of the steering tools. However, in underbalanced drilling operations where a compressible fluid is contained in the drill string, an electromagnetic MWD will fail and the steering tool can be utilized instead.

Gyroscopic Survey Tools

A spinning gyro is used by the gyroscopic instruments to find out the direction of the well. The gyroscopic instruments used are of four types: inertial grade, conventional gyro, ring laser, and rate or north seeking.

Places such as cased hole or areas where magnetic interference is encountered, where magnetic survey instruments cannot be employed, gyro instruments are used in such places.

A conventional gyro, which is a film based instrument, is available as a single-shot instrument, but it has limited use in surveying and orienting deflection tools in areas where magnetic interference is come across (such as in cased hole and near other wellbores). Gyro's are usually employed as multi-shot instruments on electric wireline and a surface computer processes the in data. The gyro's are also accessible in MWD tools.

Measurement While Drilling (MWD) Tool

The MWD tool utilizes the same accelerometers and magnetometers as the steering tool and the electronic multishot. The solitary variation is that it sends the data to the surface on mud pulses as demonstrated in fig 3.

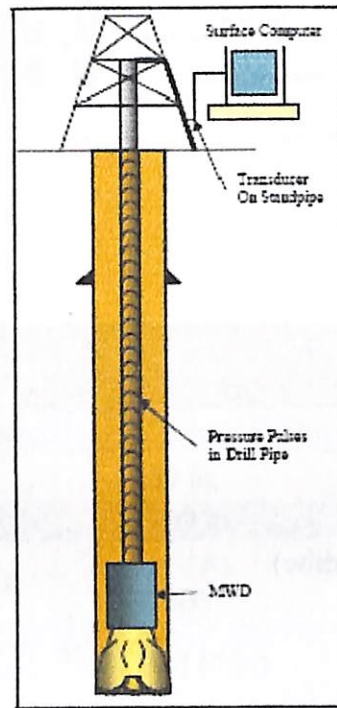


Figure 13

Schematic of MWD Transmission System

Electronic sensors in the MWD tool are used to measure the unprocessed directional data. A microprocessor is used to translate the data to a binary code or compute the survey and translate it to the binary code, based on the MWD tool. Fig 4 shows the layout of a typical positive pulse MWD with typical specifications.

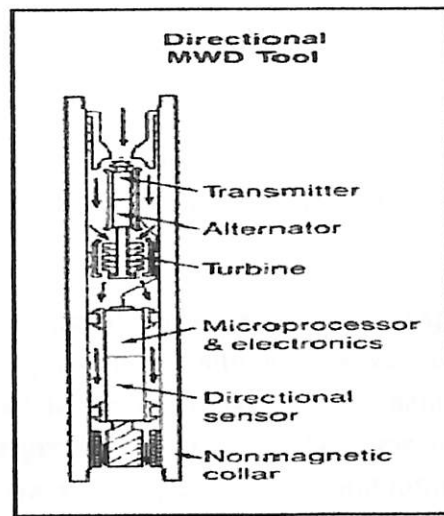


Figure 14

Table 2

Collar Size	.75 in.	.25-in normal flow
PI collar size:	.75 in.	.25 in.
Collar OD:	.89 in.	.41 in.
Collar ID:	.109 in.	.109 in.
Makeup length	3 ft. (without WOB)	3 ft. (without WOB)
Collar weight without tool:	330 (lbm)	590 (lbm)
Hydraulic connection tensile strength ratio:	.00	.20
Hydraulic connection tensile strength ratio:	.14	.20
Moment of inertia:	7.4 in. ⁴	12 in. ⁴
Collar dogleg:	deg/100 ft, 4 rotating at 100 rpm	deg/100 ft, rotating at 100 rpm
Max. collar dogleg:	5 deg/100 ft, iding	2 deg/100 ft, iding
Flow range:	25-800 gpm	00-800 gpm
Maximum torque:	operating 2,000 ft-lbf	3,000 ft-lbf
Maximum weight on bit:	1,000/L ²	94,000/L ²
Maximum tensile load:	50 klbf	65 klbf

A signal is then transferred to the pulser from the microprocessor. The location of the pulser determines if the tool is sending a one or zero. The mechanical pressure pulses traveling up the drill string are changed into an electronic signal by the transducer on the stand pipe. The binary code interpreted by the surface computer demonstrates the survey data.

The following ordinary types of pulser systems are exploited in the petroleum industry : positive pulse, negative pulse and continuous waves as illustrated in fig 5. Some of the drilling fluid is allowed to be bypassed into the annulus by the negative pulse which diminishes the surface pressure containing the same effect as a total entity in the drill string. The continuous wave has a pair of stator and rotor blades. When the blades are lined up, there is less obstruction in the flow stream and lower pressure. However, there is restriction in the flow path and increased surface pressure when the rotor blades aren't lined upwards. Since these blades rotate at a steady speed and only to a certain degree, pulse position modulation is encountered.

Each system has certain pros and cons. The positive pulse is more lenient to mud solids. Not only does it have the smallest data transmission rate, moreover it is less influenced by pump noises. On the contrary, the negative pulse system has a slightly elevated data transmission rate and here the pump noise is also not that big an issue. Moreover, it also calls for a reduced amount of power. There also must be sufficient pressure differential between the tool and the annulus in order to operate efficiently. In case of a continuous wave, the data transmission rate is much greater but pump noise is harder to filter out.

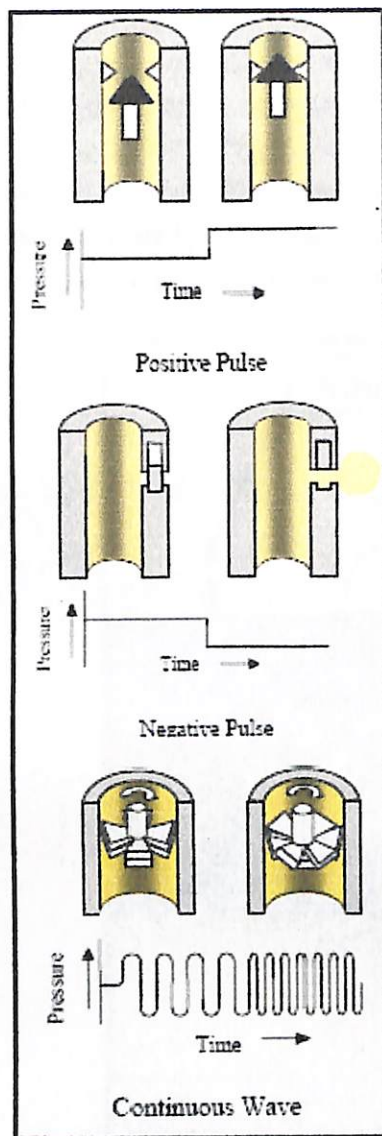


Figure 15 Pulser diagram of MWD transmitter

MWD can be powered with the help of an accelerator as demonstrated in fig 4 or lithium batteries can also be used to power it. The battery driven tools can operate only for a finite interval of time till the batteries are exhausted. Usually a battery driven MWD can function upto 300 hours depending on the temperature and the tool employed.

The instrument doesn't have power in case an alternator runs the instrument, unless the pump is on and there is least pump rate at which they will operate.

Electromagnetic MWDs also make use of the directional package utilized in mud pulse MWD. To send data to the surface, electromagnetic waves (low frequency radio waves) are

employed as illustrated in fig 6. The electromagnetic waves are conveyed by the transmitter and are received by an antenna array placed at the surface. The survey data is collected and displayed by the surface computer. The data transmission rates aren't significantly unlike the mud pulse MWD. The electromagnetic MWD is influenced by the resistivity of the formation and this MWD doesn't work as deep as mud pulse MWD. It operates better in fresh water formations. The signal gets attenuated in evaporate formations such as salts so it does not operate in the evaporate zone.

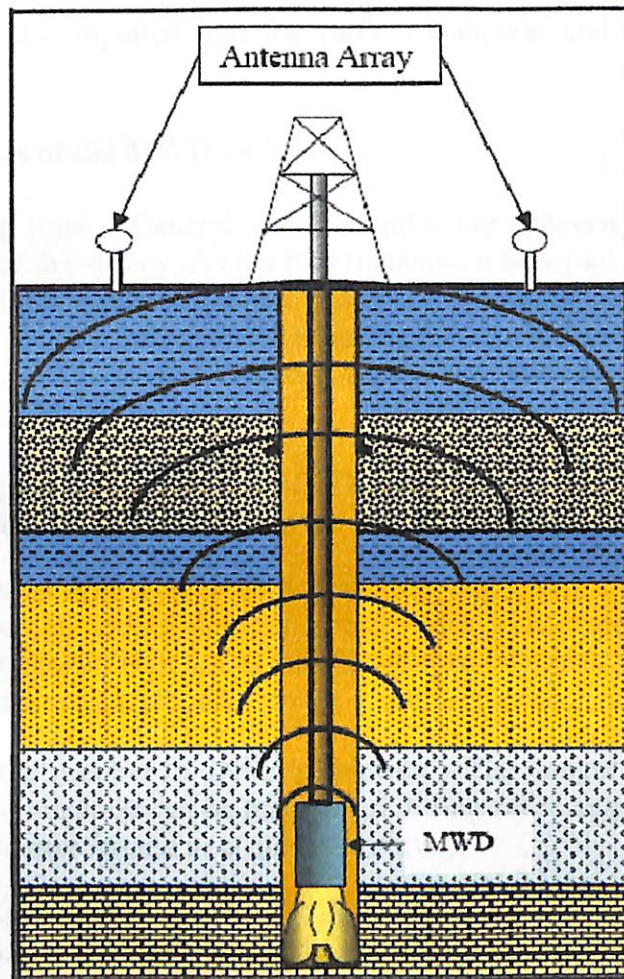


Figure 16

The most important benefit of electromagnetic MWD is that it can operate in underbalanced drilling processes. The data can still be conveyed through air, mist, foam and aerated fluid. The application of downhole motors is very tough on the MWD in air and mist drilling. If the motor is used, ample fluid should be provided to diminish the pulsation.

The entire drillstring requires to be drawn out incase the MWD tool stops working. In some instances only a segment of the tool can be drawn out from the non-magnetic drill collar with the help of a wireline and then be replaced after being serviced. If however, the tool

becomes jammed in the hole, atleast some portion of the tools can still be salvaged with the help of a wireline.

MWD can also be employed to obtain toolface data. The toolface is generally updated every 30 seconds depending upon how the tool has been preprogrammed. The tool face of the downhole motor tool usually is not in alignment with the tool face of the MWD. The disparity between the tools is quantified and then entered into the surface computer. The surface computer is used to correct the tool face reading of the MWD to the motor. The declination is also inputted into the surface computer and it automatically corrects the surveys.

The advantages of the MWD tools are:

1. Savings in Rig time – Generally, 4-5 minutes are necessary to attain a survey with an interpretation of the survey. As the tool transmits a new tool face after every 2 minutes, it decreases the time requires to adjust the downhole motors. The call for the steering tools and wireline operations are eradicated as the tools will also execute the identical tasks as the tool. The need for the tool to condition the hole prior to surveying is eliminated as the data is transferred with the pump on.
2. The drill string can be rotated with MWD in the hole:-the drill string can be rotated without a wireline in the hole. This facilitates the progress of the steerable motor assembly.
3. Tools are attuned with contemporary drilling operations - The installation of the tools doesn't require any special devices or procedures. The tools are accommodated in their separate non-magnetic drill collar which can also be replaced by the non-magnetic collar used with other survey methods.
4. Reduction in the number of Drilling hazards - The danger of pipe sticking diminishes. Uninterrupted circulation can be maintained during surveying and only 1.5 minutes with no pipe movement are required to acquire the survey.

Even though MWD saves a lot of rig time, it is only cost effective if the overall cost of the drilling operation is trimmed down. The larger the every day operating cost, the more likely an MWD system will be inexpensive. In almost normal directional drilling operation, the MWD is cost effective.

The variety of MWD tools exploited by the petroleum companies presently are:-

1. Pilot retrievable/reseatable MWD systems
2. Negative pulse transmitter
3. Ultra-slim transmitter
4. E-link transmitter
5. Guardian PDD sensor
6. Sentinel vibration sensor

Pilot MWD tool

This tool is an example of positive pulse measurement while drilling tool. Its modular design and configuration in a wide range of collar diameters and flow rates helps provide an optimum performance. The tool can be fully retrieved and resealed which allows it to be extracted and replaced successfully without tripping. In difficult drilling environments, LIH liability is minimized which saves valuable rig time in the event of downhole complications.

Description of the tool

Survey data is transmitted to the surface using a bottom mounted, retrievable/reseatable pulser in the pilot MWD system by actuating a pilot valve which restricts mud flow through the drill string interior which creates a positive pressure pulse. The pilot valve is actuated by a motor working in conjunction with a gear and a leadscrew arrangement which exerts 100 lbs seating force. To offer high accuracy and reliability tri-axial, Flux Gate Magnetometers with Q-Flex type accelerometers are used in the pilot orientation module.

Features

- LIH is minimized with full Retrievability and Reseatability.
- Plugging is minimized and tolerance to LCM is increased due to the 100 lbs-force exerted by the servo motor assembly.
- Depending on tool/battery configuration, a battery life of in excess of 400 hours can be obtained using highly efficient gear-leadscrew configuration
- For a wide range of flow rates and 3 ½ in to 12 in O.D. collars, single tool is configurable.

Pilot MWD Tool



Figure 17

Table 3

Specification

MEASUREMENT	Range	Accuracy
Azimuth	0-360°	+/- 0.5°
Inclination (up to 80° Inc)	0-180°	+/- 0.1°
Toolface (up to 10° Inc only)	0-360°	+/- 0.5°
MECHANICAL	Imperial Units	Metric Units
UBHO Sub O.D.	3.5 to 12in	89 to 305mm
UBHO Sub Length	36in (longer on request)	914mm
Probe O.D.	1 7/8in	47.625mm
Tool Length	17ft 11.3in / 23ft 3.5in (Single Battery / Dual Battery)	5469mm / 7099mm
Minimum Flow Rate	130 GPM in water	0.5 m ³ /min
Maximum Flow Rate	1060 GPM in water	4 m ³ /min
Max Temperature	150°C	302°F
Operating Pressure	20,000 psi	137.9Mpa
Shock	1000g/0.5 millisecond	
Vibration	25g RMS 30-500Hz Random, 30g 50-300Hz Sine	
Mud Sand Content	Less than 1% recommended	
Lost-circulation Material	Up to 50lb/bbl premixed Medium Nut Plug or Cedar Fiber	

Negative pulse transmitter

This negative pulse transmitter is a product of Geolink and is used to transmit the MWD data from downhole to surface by generating a sequence of small pressure losses in the circulating system.

Description

The flow path between the drill string interior and the annulus is opened by a solenoid which actuates the small normally closed valve present in the transmitter. A pressure drop of 30 to 50 psi is generated at the surface with a valve open time of 0.5 seconds.

Features

- Highly reliable in harsh drilling environments due to rugged Beryllium-copper construction.
- The downhole programmable transmission modes and signal are consistent.

- It is cost effective in maintenance with minimum wear parts.
- A user friendly interface is provided with the Geolink navigator surface software.

Negative Pulse Transmitter



Figure 18

Table 4

Specification

Transmitter Sub O.D.	4.75 to 9.5in, (larger on request) (121 to 241mm) (This tool has a hexagonal section. The span from face to face is actually 2.4in)
Transmitter Sub Length	63.5in (longer on request) (1613mm)
Flow Rates	Up to 1200 US gals/min 76 l/sec
Differential Pressure	Recommended min. 350 psi below tool (2.413 Mpa)
Temperature	Maximum 150°C (302°F)
Hydrostatic Pressure	Maximum 20,000 psi, (137.9 MPa)
Shock	1000g/0.5 millisecond
Vibration	20g RMS 30-300 Hz Random, 30g 50-300 Hz Sine
Mud Sand Content	Less than 0.5% recommended
Lost Circulation Material	Up to 30 lb/bbl Medium Nut Plug - added evenly

Ultra-slim transmitter

In order to transmit the data from downhole to the surface, a sequence of small pressure losses is generated in the circulating system using the Ultra-slim negative pulse transmitter.

Description

A solenoid actuates a small normally closed valve in the transmitter to open the flow path between the drill string and the annulus. A pressure drop of about 30 to 50 psi is generated at the surface with a valve open time of 0.5 seconds. The on or off of the mud pumps in order to control the tool functions is detected by an integral pressure switch.

Features

- It is reliable for use in the most demanding environments.
- It is suitable for working in deep wells as it provides a consistent signal.
- The transmitter is easy to operate due to its simple design.
- It is cost effective in maintenance with minimum wear parts.
- It has a high strength with an enlarged inner diameter due to its proprietary thread design.
- It is excellent for horizontal side tracks with its capability of short radius work.

Ultra-Slim Transmitter



Figure 19

Table 5

Specification

Transmitter Sub O.D.	3.5in (88.9mm)
Transmitter Sub Length	30in (76.2mm)
Max Flow Rates	150 USGPM (9.5 l/sec)
Differential Pressure	Recommended min. 350 psi below tool (2.413 Mpa)
Temperature	Maximum 150°C (302°F)
Hydrostatic Pressure	Maximum 20,000 psi (137.9 MPa)
Shock	1000g/0.5 millisecond
Vibration	20g RMS 30-300 Hz Random, 30g 50-300 Hz Sine
Mud Sand Content	Less than 0.5% recommended
Lost Circulation Material	Up to 30 lb/bbl Medium Nut Plug - added evenly mixed

E-link transmitter

It generates a sequence of electromagnetic pulses which are sent via the formation to transmit the downhole data to the surface. This transmits the data up to four times faster than with the mud pulse systems, and is detected at the surface using antennae and specialized equipment.

Description

A dipole is formed by the E-link transmitter; the main part of the drill string makes up the upper pole and the insulated BHA section below the section makes up the lower pole. A propagation signal is used to transmit the data to the surface and is detected using antennae and specialized equipment. An integral flow switch which activates the required tool function change detects pump cycles and full redundancy is provided by a fall back continuous loop mode.

Features

- It is ideal under balanced drilling applications because of its reliable and consistent signal.
- The downhole programmable transmission frequency provides signal optimization.
- A user friendly interface is provided with the Geolink navigator surface software.
- It has a fast make up and breakdown due to its simple design which save a lot of rig time.
- It has a low cost maintenance an easy operation because of the absence of any moving parts.
- Its downhole programmable speed is 4 times that of the mud pulse.

E-Link Transmitter

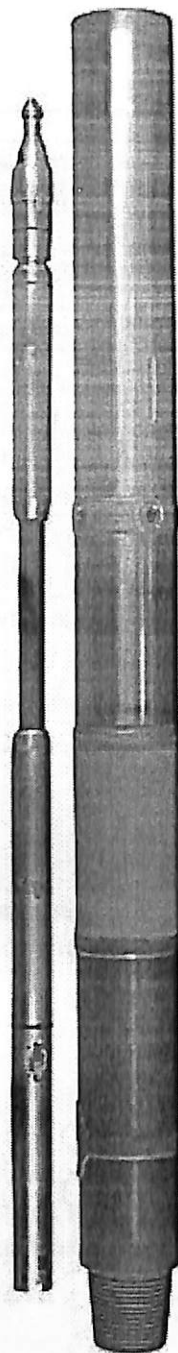


Figure 20

Table 6

Specification

Transmitter Sub O.D.	4.75in, 6.5in (12mm, 165mm)
Transmitter Sub Length	84in (Longer on request) (2134mm)
Transmission Data Rates	Up to 4 BPS (Downhole Programmable)
Signal Frequency	Up to 20 Hz (Downhole Programmable)
Power	Independent Lithium Cartridge - Lifetime > 250 hours
Flow Rates	Up to 1200 US gals/min (76 l/sec)
Lithology	Highly conductive or resistive lithology may dissipate or block signal
Temperature Rating	Maximum 150°C (302°F)
Hydrostatic Pressure	Maximum 20,000psi (137.9MPa)
Shock	1000g/0.5millisecond
Vibration	20g RMS 30-300 Hz Random, 30g 50-300 Hz Sine
Mud Type	Multiphase flow regimes, Minimum fluid phase 33 gpm (2.08 l/sec) , Nitrogen up to 1,600ft ³ /min (45m ³ /min)
Mud Sand Content	Less than 0.5% recommended
Lost Circulation Material	No Limit

Guardian PDD sensor

Continuous monitoring of the annular and pipe pressures can be done by coupling the guardian PDD (pressure during drilling) sensor to any of the sondex drilling measurement while sensors.

Description

A separate drilling sub houses the Guardian PDD sensor which is situated between the MWD assembly and the resistivity tool or below the Directional/Gamma MWD assembly. The annulus and drill pipe pressures are measured independently by two sensors. The tool has the ability to transmit the acquired data in real time and the tool is self powered.

Features

- Due to its comprehensive environmental calibration, it is highly accurate.
- Reliable and robust.
- It is also available in slim hole sizes.

Guardian PDB Sensor



Figure 21

Table 7

Specification

Measurement	Range	Accuracy
Annular Pressure	0-15 kpsi (20 kpsi on request) 0-103 Mpa(138 Mpa on request)	+/- 0.25% over range
Drill Pipe Pressure	0-15 kpsi (20 kpsi on request) 0-103 Mpa(138 Mpa on request)	
Resolution	0.25 psi / 1,723.7 pascal	
Other		
Max. Data Sampling	Every 4 seconds (Either Annular or Drill Pipe Pressure only) Every 8 seconds (Both Annular and Drill Pipe Pressures)	
Memory Capacity	~230 to 260 hours (Sampling rate dependent)	
Battery Life	~600 hours (Variable with sensor power level and sampling rate)	
Environmental		
Temperature	Operating: 0-150°C Survival: -20 - 165°C	
Pressure	15,000 psi (20,000 on request)	
Vibration	20g RMS 30-300 Hz Random, 30g 50-300 Hz Sine	
Shock	1000g 0.5ms, half sine	

Sentinel vibration sensor

With the help of this sensor, the downhole shock and vibration can be continuously monitored. With the help of this, the rate of penetration (ROP) can be maximised and the bit and string damage can be minimized.

The various data required to monitor the data output from the LWD or MWD system is displayed by the real-time screen which includes axial and vibration levels mirrored on the driller's display.

Description

Two solid state accelerometers are used in these sensors which are mounted orthogonally in the X (lateral) and Z (axial) axes of the MWD tool, on the survey electronics assembly. The shock levels measured by the accelerometers over a period of 16 seconds consecutively is monitored by the survey electronics assembly. It also categorizes the current level as either high (damage likely), moderate (warning), or low (safe) for both lateral and axial readings. For the former two cases, the tool will transmit a single pulse at the end of each dynamic transmission. A graphical representation of the data is provided on the rig floor display allowing the driller to monitor and make appropriate changes to parameters while drilling. The penetration rate can also be optimised by smooth and shock and vibration free drilling and this also prevents damage to downhole tools and drill string.

Features

- It has a low maintenance and is highly reliable and robust.
- It provides an easy interpretation with its graphical representation.
- The data can be plotted against depth or can be displayed in real time on the RFD.
- Only potentially damaged conditions are reported and it has a simple operation.
- It can be fitted as a standard in all sizes.

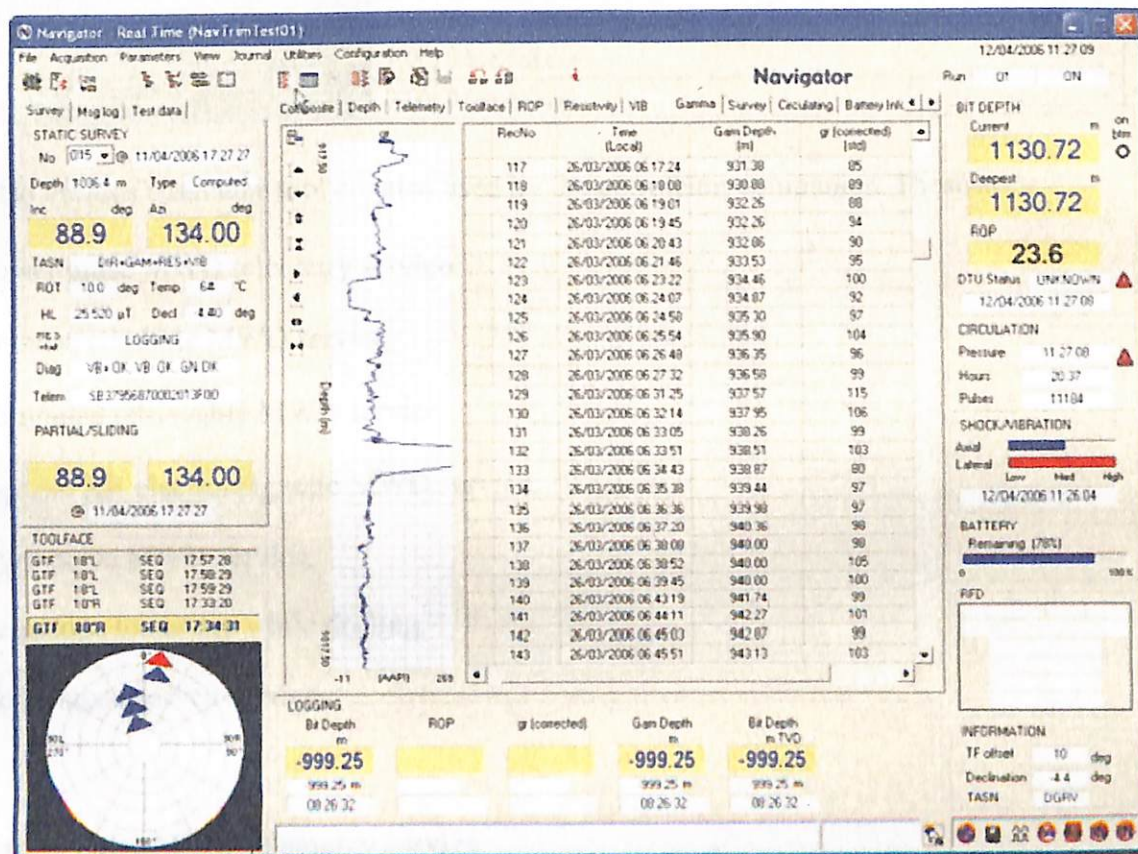


Figure22

Table 8

Specification

Measurement	Range	Resolution
Shock	+/- 105g	40mg
Environmental		
Temperature	Operating: -40 – 150°C Survival: -65 – 165°C	
Shock (powered)	1000g 0.5ms, half sine	
Shock (Unpowered)	2000g 0.5ms, half sine	

Also various telemetry tool are also used by the petroleum companies. These are:-

- Power pulse MWD telemetry service.
- Impulse slimhole MWD service.
- Slimpulse retrievable MWD service.
- E-pulse XR electromagnetic MWD service.
- Gyro pulse MWD service.
- Telescope telemetry while drilling.
- Continuous survey service.

Power pulse MWD telemetry service

The power pulse MWD telemetry system sets the standard for reliability and data transmission rates. Using continuous mud wave telemetry, transmission rates of 6 to 16 bits per second can be attained. Continuous monitoring of the inclination and azimuth takes place. Additional measurements include an optional gamma ray sensor and a downhole shock counter, an optional downhole weight on bit and torque sub.

Improved signal to noise ratios have been achieved by Schlumberger-patented zero gap modulators. The effects of drilling pumps, motors, and other rig associated noise undergo a reduction with the perked up transmission quality. The signal frequency is varied downhole to make the tool work at all depths in spite of the mud type.

Impulse slimhole MWD service

With uninterrupted data obtainable during drilling, this service may minimize doglegs. The tool memorizes the surveying quality control which is then checked downhole and transmitted as quickly as possible. Since state of the art telemetry systems are available, the measured data is transmitted at speeds of up to 6 bps. For hole sizes 5 ¼ in and larger, resistivity, survey and gamma measurements are provided with the standard tool.

By using an electromagnetic antenna array of 5 transmitters and two receivers, formation resistivities can be evaluated at numerous depths. To achieve true borehole compensated formation resistivity, the receivers can be positioned both above and below the transmitters.

Slimpulse retrievable MWD service

For drilling in high efficiency environments, this tool provides a cost effective solution. Using this tool, the inclination, gamma ray real time, directional and toolface measurements can be attained. Inclination and continuous direction measurements can also be obtained while rotating to facilitate trajectory control and reduce stationary measurements. To optimize update rates for improved trajectory control, an automatic switch between a sliding frame and a rotating frame is done by the telemetry data.

Considerable rig time can be saved by eliminating pipe trips for directional equipment because the tool can be fully retrieved and resealed. To create a direct acquisition for the high volume market, this tool is coupled with a reduced hardware and manpower requirements.

E-pulse XR electromagnetic MWD service

This tool helps to increase directional control by providing the real time information. The electronics module can be retrieved in case the drill string gets stuck and hence the lost-in-hole risk is minimized. These transmit the bottomhole data at rates of 12 bps and signal loss does not occur due to lost circulation material.

It takes only half a minute to send command to the downhole tool which can also be turned off to optimize battery life and allow long runs. This tool is not jammed by solids present in the drilling fluid. Reliable inclination, direction and toolface orientation can be achieved. Also gamma ray, collar rpm, and shock measurements can also be taken. It has a low pressure drop which reduces the pump stress and the generator fuel consumption. So, a small size rig can be used. Also no antennas or repeaters are required for signal transmission even in deep wells.

Gyro pulse MWD service

Conventional magnetic MWD and real time gyro orienting are simultaneously offered while using a Gyro pulse MWD service. The gyro in all phases of the operation is powered by the turbine in power pulse systems except in gyro compassing. These are more accurate than multiple gyro single shot runs, because of their greater frequency. Real time inertial and gravity toolface, while sliding, is also provided by the gyro service.

Telescope telemetry while drilling

Information required for optimizing well placement, improving drilling efficiency, reducing risk, and increasing production are provided by Telescope telemetry while drilling. Comprehensive downhole information reducing drilling risk and improving drilling efficiency is provided with measurements and data give from multiple tools.

The amount of real time information is maximized using this technique and allows us to log the borehole sections in great detail. Continuous directional and inclination measurements are obtained with this technique more accurately.

Continuous survey service

The azimuth and the drift measurements while drilling are provided by the Continuous survey service. Accurate directional measurements from the MWD tool in real time are transmitted with the help of the developments in applications of digital filtering techniques to magnetometer and accelerometer data. A true dog leg measurement is made with the help of this data across separate sliding and rotating sequences.

The real hole trajectory can be seen with this service, to better manage the microdoglegs, which results in more efficient drilling, fewer problems running casing, and longer reach capability.

LWD

LWD tools work on the same principle as conventional wireline logging tools. While drilling with a mud motor, these tools are run above the motor assembly above (30-40 ft). These tools require special methods of interpretation to calculate pore pressures and to compute overpressured zones. These tools detect and correlate geologic markers and formation tops and also evaluate formations as they are being drilled.

Types of log

1)Lithology log

- Gamma ray log
- Spontaneous potential log

2)resistivity log

- Latero log
- Induction log

3)porosity log

- Density log
- Neutron log
- Sonic log

1.3 GAMMA-RAY LOG

INTRODUCTION

Gamma-ray measurements detect variations in the natural radioactivity originating from changes in concentrations of the trace elements uranium (U) and thorium (Th) as well as changes in concentration of the major rock forming element potassium (K). Since the concentrations of these naturally occurring radioelements vary between different rock types, natural gamma-ray logging provides an important tool for lithologic mapping and stratigraphic correlation. Gamma-ray logs are important for detecting alteration zones, and for providing information on rock types. For example, in sedimentary rocks, sandstones can be easily distinguished from shales due to the low potassium content of the sandstones compared to the shales.

In sedimentary rocks, potassium is the principal source of natural gamma radiation, primarily originating from clay minerals such as illite and montmorillonite. In igneous and metamorphic geologic environments, the three sources of natural radiation may contribute equally to the total gamma radiation detected by the gamma probe. Often in

base metal and gold exploration areas, the principal source of the natural gamma radiation is potassium, because alteration, characterized by the development of sericite, is prevalent in some of the lithologic units and results in an increase in the element potassium in these units. The presence of feldspar porphyry sills, which contain increased concentrations of K-feldspar minerals, would also show higher than normal radioactivity on the gamma-ray logs. During metamorphism and hydrothermal alteration processes, uranium and thorium may be preferentially concentrated in certain lithologic units.

Older gamma-ray logs are recorded in "counts" whose numbers vary according to the tool design. Almost all modern gamma-ray logs are recorded in API (American Petroleum Institute) units, which make a common standard for log comparison. The scale was chosen so that a value of zero would mean no radioactivity and a value of 100 would match a typical Mid-continent shale. In practice, shales can be somewhat variable in their radioactivity according to their silt content, types of clay mineral, and the occurrence of small amounts of uranium.

APPLICATION

- Identification of shale.
- Open-hole as well as cased-hole correlation(as γ rays have a good penetrating power)
- Computation of shale volume.
- Different types of clay can be identified and discriminated
- Environment of deposition can be inferred depending on Th:U ratio(Th is present in terrestrial realm and U is mainly presenting marine realm)
- Depositional environment determination by identifying fining or coarsening upward sequences.
- To supplement the information given by the electric log (identification of formations, estimating the amount of clay in sands, etc.)
- To locate radioactive ores, uranium in particular.
- To help locate clay and fresh water sands.

For more precession in identification of different elements of cementing materials and clay minerals NGS-Logs are used Radioactivity is the emission of rays caused by the spontaneous change of one element into another. Although several types of rays are emitted, only gamma rays have enough penetration to be of practical use in logging the natural radioactivity of rocks.

1.4 SP LOG (SPONTANEOUS POTENTIAL LOG)

INTRODUCTION The spontaneous potential tool measures natural electrical potentials that occur in boreholes and generally distinguishes porous, permeable sandstones from intervening shales. The "natural battery" is caused when the use of drilling mud with a different salinity from the formation waters, causes two solutions to be in contact that have different ion concentrations. Ions diffuse from the more concentrated solution (typically formation water) to the more dilute. The ion flow constitutes electrical current, which generates a small natural potential measured by the SP tool in millivolts.

When the salinities of mud filtrate and formation water are the same, the potential is zero and the SP log should be a featureless line. With a fresher mud filtrate and so, more saline formation water, sandstone will show a deflection in a negative potential direction (to the left) from a "shale base line". The amount of the deflection is controlled by the salinity contrast between the mud filtrate and the formation water. Clean (shale-free) sandstone units with the same water salinity should show a common value, the "sand line". In practice, there will be drift with depth because of the changing salinity of formation waters. The displacement on the log between the shale and sand lines is the "static self-potential" SSP.

The SP log is used to: (1) detect permeable beds, (2) detect boundaries of permeable beds, (3) determine formation water resistivity (R_w), and (4) determine the volume of shale in permeable beds. An auxiliary use of the SP curve is in the detection of hydrocarbons by the suppression of the SP response. The concept of static spontaneous potential (SSP) is important because SSP represents the maximum SP that a thick, shale-free, porous and permeable formation can have for a given ratio between R_{mf} / R_w . The SP value that is measured in the borehole is influenced by bed thickness, bed resistivity, invasion, borehole diameter, shale content, and most important is the ratio of R_{mf} / R_w . measurement of SP is controlled by various factors.

1. Bed thickness.
2. Bed resistivity.
3. Borehole diameter.
4. Invasion profile.
5. Shale content in permeable bed.

APPLICATION

- Lithology identification.
- Estimate formation water salinity
- Bed boundaries delineation.
- Shale volume determination. $V_{sh} = 1 - (SP/SSP)$.
- Formation water resistivity (R_w) determination.
- Correlation of data with other log to get complete petrophysical and geophysical characteristics of the well.

Spontaneous potential (SP) and gamma ray log. Although they record different physical properties, the two logs are comparable because of their sensitivities to shale and so both can be used to differentiate between sandstones and shales. The stronger sandstone differentiation at greater depths on the SP log is caused by greater salinities in the deeper sandstones.

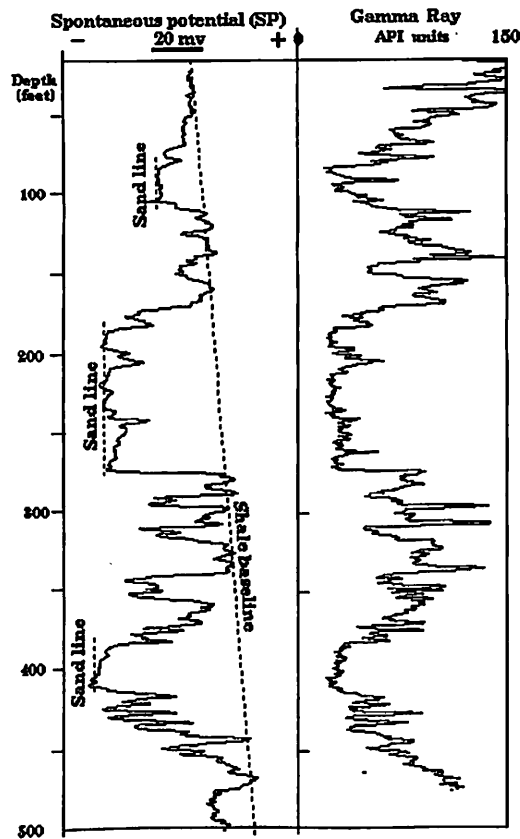


Figure 23

1.5 RESISTIVITY LOGS

INTRODUCTION

Resistivity of a body or sample is defined as a physical property of a material to resist or oppose the movement of charge through the material. Well logs, which depend on electrical resistivity and is function of porosity, pore fluid content, mineralogy and temperature in rocks are resistivity logs. Two types of logs are generally used, laterolog and induction log.

1.5.1 LATEROLOG

Laterolog tools send an electric current from an electrode on the sonde directly into the formation. The return electrodes are located either on surface or on the sonde itself. Complex arrays of electrodes on the sonde (guard electrodes) focus the current into the formation and prevent current lines from fanning out or flowing directly to the return electrode through the borehole fluid. Most tools vary the voltage at the main electrode in order to maintain a constant current intensity. This voltage is therefore proportional to the resistivity of the formation. Because current must flow from the sonde to the formation, these tools only work with conductive borehole fluid. Actually, since the resistivity of the mud is measured in series with the resistivity of the formation, laterolog tools give best results when mud resistivity is low with respect to formation resistivity, i.e., in salty mud.

1.5.2 INDUCTION LOG

Induction logs use an electric coil in the sonde to generate an alternating current loop in the formation by induction. This is the same physical principle as is used in electric transformers. The alternating current loop, in turn, induces a current in a receiving coil located elsewhere on the sonde. The amount of current in the receiving coil is proportional to the intensity of current loop, hence to the conductivity (reciprocal of resistivity) of the formation. Multiple transmitting and receiving coils are used to focus formation current loops both radially (depth of investigation) and axially (vertical resolution). Since the 90's all major logging companies use so-called array induction tools. These comprise a single transmitting coil and a large number of receiving coils. Radial and axial focusing is performed by software rather than by the physical layout of coils. Since the formation current flows in circular loops around the logging tool, mud resistivity is measured in parallel with formation resistivity. Induction tools therefore give best results when mud resistivity is high with respect to formation resistivity, i.e., fresh mud or non-conductive fluid. In oil-base mud, which is non conductive, induction logging is the only option available.

APPLICATION

It is mainly used to identify lithology and pore filling fluids. Subsurface stratigraphic units can be traced laterally. It is also used for well log correlation. Formation resistivities are usually from 0.2 to 1000 ohm-m. Resistivities higher than 1000 ohm-m are uncommon in permeable formation but are observed in impervious, very low porosity formations.

OBJECTIVE

Resistivity log is generally shown on logarithmic scale. The resistivity of hydrocarbon is higher than the resistivity of formation water. The resistivity of fresh water is also high and it decreases with increasing salinity. The formation resistivity depends on the formation fluid and porosity. If the rock has low porosity or rock is compact then resistivity of formation is high. We can calculate water saturation using Archie equation.

$$S_w = [(a / \phi^m) * (R_w / R_t)]^{(1/n)}$$

S_w : water saturation, R_w : formation water resistivity, R_t : observed bulk resistivity

ϕ porosity, 'a' is a constant (often taken to be 1), m: cementation factor (varies around 2)

1.6 POROSITY LOGS

The three porosity logs are

- Density Log
- Neutron Log
- Sonic Log

DENSITY LOG

Density logging tools contain a Cesium-137 gamma ray source which irradiates the formation with 662-KeV gamma rays. These gamma rays interact with electrons in the formation through Compton scattering and lose energy. Once the energy of the gamma ray has fallen below 100 KeV, photoelectric absorption dominates: gamma rays are eventually absorbed by the formation. The amount of energy loss by Compton scattering is related to the number electrons per unit volume of formation. Since for most elements of interest (below $Z = 20$) the ratio of atomic weight, A , to atomic number, Z , is close to 2, gamma ray energy loss is related to the amount of matter per unit volume, i.e., formation density.

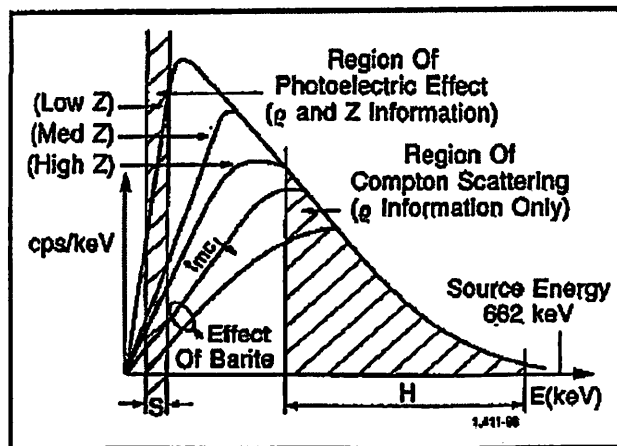


Figure 24

The density log responds to the electron density of the formations. For a substance consisting of a single element, the electron density index, ρ_e , is related to the bulk density, ρ_b ,

$$\rho_e = \rho_b * (2 * Z / A)$$

where ρ_b is the actual bulk density, Z is the atomic number (number of electrons per atom), and A is the atomic weight (ρ_b / A is proportional to the number of atoms per cubic centimeter of the substance). For a molecular substance, the electron density index

is related to the bulk density:

$$\rho_e = \rho_b * 2 * (\Sigma Z' s / \text{Mol Wt})$$

where $\Sigma Z' s$ is the sum of the atomic numbers of atoms making up the molecule (equal to the number of electrons per molecule) and Mol. Wt. is the molecular weight.

When the density tool is calibrated in freshwater-filled limestone formations, the

apparent bulk density, ρ_a , as read by the tool is related to the electron density index, ρ_e , by:

$$\rho_a = 1.0704 \rho_b - 0.1883$$

A gamma ray detector located some distance from the source, detects surviving gamma rays and sorts them into several energy windows. The number of high-energy gamma rays is controlled by compton scattering, hence by formation density. The number of low-energy gamma rays is controlled by photoelectric absorption, which is directly related to the average atomic number, Z , of the formation, hence to lithology. Modern density logging tools include two or three detectors, which allow compensation for some borehole effects, in particular for the presence of mud cake between the tool and the formation.

Since there is a large contrast between the density of the minerals in the formation and the density of pore fluids, porosity can easily be derived from measured formation bulk density if both mineral and fluid densities are known.

APPLICATIONS OF DENSITY LOG

- (1) Measurement of density of formation
- (2) Calculation of porosity
- (3) When combined with sonic travel times, it is used to calibrate seismic data
- (4) Detection of gas in reservoir when used in combination with neutron log
- (5) PEF is good indicator of lithology

Effect of shale

Interpretation can be affected by shale or clay in the formations. Although the properties of shale vary with the formation and locality, typical densities for shale beds and laminar shale streaks are of the order of 2.2 to 2.65 g/c.c.. Shale densities tend to be lower at shallow depths where compacting forces are not as great. Dispersed clay or shale disseminated in the pore spaces may have a somewhat lower density than the interbedded shales.

Effect of Pressure

The bulk density of shale increases with compaction. However, departure from this trend is observed in over-pressured zones; shale density decreases with increasing depth. This decrease often appears in shales as much as several hundred feet above high-pressure permeable sands. A high-density zone (the sealing barrier) usually lies at the top of this interval of decreased density.

Equipment

To minimize the influence of the mud column, the skid-mounted source and detector are shielded. The openings of the shields are applied against the wall of the borehole by an eccentricing arm. The force exerted by the arm, and the plow-shaped design of the skid, allow it to cut through soft mudcakes. Any mudcake or mud remaining between the tool and the formation is "seen" as part of the formation and must be accounted for. A correction is needed when the contact between the skid and the formations is not perfect (mudcake or irregularities in the borehole wall). In unfavorable cases this correction can be fairly large. If only one detector is used, the correction is not easy to determine because it depends on the thickness, the weight, and even the composition of the mudcake or mud interposed between the skid and the formations. In the FDC

compensated formation density tool, two detectors of differing spacing and depth of investigation are used.

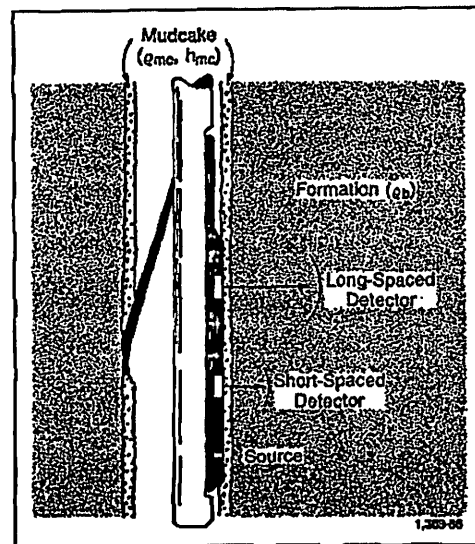


Figure 25

Schematic drawing of the dual spacing formation density-logging device (FDC)

The distance between the face of the skid and the extremity of the eccentering arm is recorded as a caliper log, which helps to assess the quality of contact between the skid and the formation.

1.6.2 NEUTRON LOG

Neutron porosity logging tools contain an Americium-Beryllium ($\text{Am}_{241} - \text{Be}_9$) neutron source, which irradiates the formation with neutrons having a mean energy of 4.2 MeV or Californium (Cf_{252}) source. These neutrons lose energy through elastic collisions with nuclei in the formation. Once their energy has decreased to thermal level, they diffuse randomly away from the source and are ultimately absorbed by a nucleus. Hydrogen atoms have essentially the same mass as the neutron; therefore hydrogen is the main contributor to the slowing down of neutrons. A detector at some distance from the source records the number of neutron reaching this point. Neutrons that have been slowed down to thermal level have a high probability of being absorbed by the formation before reaching the detector. The neutron counting rate is therefore inversely related to the amount of hydrogen in the formation.

Hydrogen Index is measured which is given as:

$$\text{HI} = (\text{number of H atoms}) / (\text{volume}) * (\text{number of H-atoms in 1 c.c. H}_2\text{O})$$

Dissolved sodium chloride (NaCl) takes up space and thereby reduces the hydrogen density. An approximate formula for the hydrogen index of a saline solution at 75° F is

$$H_w = 1 - 0.4P$$

Where P is the NaCl concentration in ppm/ 10^6 . More generally, independent of temperatures

$$H_w = \rho_w (1 - P).$$

Since hydrogen is mostly present in pore fluids (water, hydrocarbons) the count rate can be converted into apparent porosity. Modern neutron logging tools usually include two detectors to compensate for some borehole effects. Porosity is derived from the ratio of count rates at these two detectors rather than from count rates at a single detector.

APPLICATIONS OF NEUTRON LOG

- (1) Computation of Shale Volume
- (2) Porosity Determination
- (3) Locate gas when combined with Density or acoustic Log
- (4) Identify lithology when used with other porosity devices

The combination of neutron and density logs takes advantage of the fact that lithology has opposite effects on these two porosity measurements. The average of neutron and density porosity values is usually close to the true porosity, regardless of lithology. Another advantage of this combination is the "gas effect." Gas, being less dense than liquids, translates into a density-derived porosity that is too high. Gas, on the other hand, has much less hydrogen per unit volume than liquids: neutron-derived porosity, which is based on the amount of hydrogen, is too low. If both logs are displayed on compatible scales, they overlay each other in liquid-filled clean formations and are widely separated in gas-filled formations.

EQUIPMENT

Various Logs detect the followings:

1. Capture gamma rays
2. Slow (thermal) neutrons
3. Partly slowed (epithermal) neutrons.

Equipment used currently is the CNL tool series, which includes the CNL compensated neutron and the Dual-Energy Neutron Log (DNL). The current tools use Americium-Beryllium (AmBe) sources to provide neutrons with initial energies of several million electron volts.

The CNL tool is a mandrel-type tool especially designed for combination with any of several other tools to provide a simultaneous neutron log. The CNL tool is a dual-spacing, thermal neutron-detection instrument. The surface equipment to produce a linearly scaled recording of neutron porosity index processes the ratio of counting rates from the two detectors. The effects of borehole parameters are greatly reduced by taking the ratio of two counting rates similarly affected by these perturbations.

The CNL tool can be run in liquid-filled holes, either cased or uncased, but cannot be used in gas-filled holes. Since thermal neutrons are measured in the CNL tool, the response is affected by elements having a high thermal neutron capture cross section. The tool is sensitive to shale in the formation since shales usually contain small amounts of boron and other rare earth elements having a particularly high thermal neutron capture cross section. If excessive, this effect can mask the tool response to gas in shaly formations.

To improve the response to gas and to enhance interpretation in the presence of thermal neutron absorbers, the DNL tool incorporates two epithermal neutron detectors in addition to the two thermal neutron detectors. Two separate porosity measurements are obtained, one from each pair of detectors. In clean formations the measured porosities generally agree. In shaly formations containing a large number of thermal neutron absorbers, the porosity measured by the epithermal detectors reads lower and agrees more closely with density derived porosity. A comparison of the two porosity measurements indicates the shale or clay content, or the formation fluid salinity

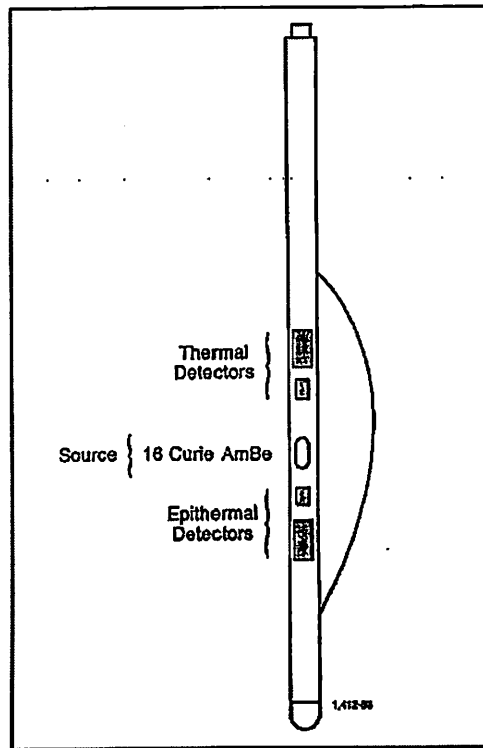


Figure 26

DNL Tool Configuration

. At a given source-detector spacing, epithermal neutron count rate is approximately an order of magnitude less than that for thermal neutrons. Therefore, to have reasonable epithermal neutron count rates, the epithermal detectors have been placed nearer to the neutron source than the thermal neutron detectors. The thermal neutron-detector configuration duplicates that of the standard CNL tool.

Since the two pairs of detectors are placed at different spacings and neutrons are detected at different energy levels, the environmental effects can be expected to be significantly different on the two neutron measurements. If the ratio processing used on the thermal neutron measurement is used for the epithermal measurement, the computed porosity is quite sensitive to borehole effects. As a result of a detailed study of detector response to many environmental variables, an epithermal neutron processing technique has been developed that uses individual detector count rates. The method greatly reduces borehole effects on the epithermal neutron-porosity measurement.

The combined epithermal and thermal neutron Dual Porosity measurements provide improved porosity determination. Since the epithermal measurement is relatively free of neutron absorber effects, it yields improved gas detection in shaly reservoirs. A comparison of the two neutron responses also provides information on the presence of materials with significant thermal neutron capture cross sections.

1.6.3 SONIC LOG

The acoustic velocity log or sonic log is a porosity log that measures interval transit time (Δt) of a compressional sound wave traveling through one foot of formation. Transit time is the time required for the wave to travel 1ft of the formation. The transit time will be more in case of liquid and vice versa. Less transit time will indicate low porosity, i.e., it is proportional to the porosity. The sonic log device consists of one or more sound transmitters, and two or more receivers. Interval transit time (Δt) in microseconds per foot is the reciprocal of the velocity of a compressional sound wave in feet per second. The interval transit time (Δt) is dependent upon both lithology and porosity. Sonic porosity can be used to determine porosity in consolidated sandstones and carbonates with intergranular porosity (grainstones) or intracrystalline porosity (sucrosic dolomites). In sonic logging only the first arrivals are noted.

$$\text{Porosity } (\Phi) = \{(t - t_{ma}) / (t_f - t_{ma})\}$$

Where, t = measured time

t_f = transit time in water

t_{ma} = transit time in matrix when porosity is zero

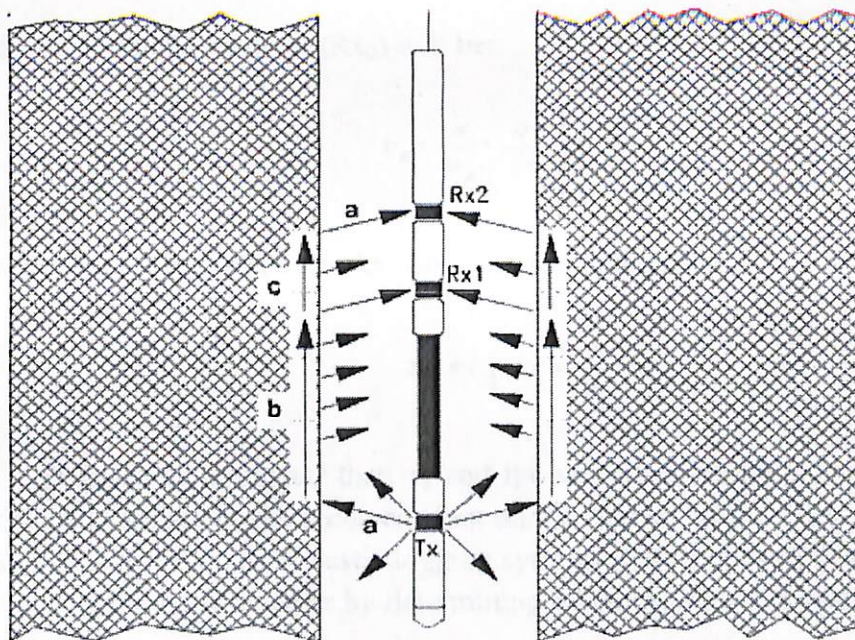


Figure 27

Schematic diagram of principles of acoustic velocity logging tools.

A compressional (P) wave is generated in the borehole fluid by pulsing of the transmitter (Tx). P-waves are characterized by pressure oscillations that are parallel to the direction of propagation. Liquids can only support P-waves, however, solids can support both P-waves and S-waves (shear waves), in which the oscillations are perpendicular to the direction of

propagation. The P-wave generated in the borehole radiates away from the transmitter in all directions. At the borehole wall, acoustic energy is reflected back into the borehole and refracted into the rock. Because solids can support both P-waves and S-waves, some of the acoustic energy that is refracted into the rock is converted to S-waves. Some of the energy that strikes the wall at the critical angle for P-waves (determined by the P-wave velocities in the rock and borehole fluid) will propagate as a P-wave along the borehole wall. Likewise, some of the energy that strikes the wall at the critical angle for S-waves (determined by the S-wave velocity in the rock and the P-wave velocity in the fluid) will propagate as an S-wave along the borehole wall. As these P- and S-waves travel along the borehole wall, energy is reradiated back into the borehole at the critical angles as P-waves. The energy that is reradiated back into the borehole is detected at the receivers.

If the compressional wave velocity in the borehole fluid is v_f and in the rock is v_p , and if the probe is centered in the borehole, the travel time from the transmitter (Tx) to the near receiver (Rx₁) is:

$$t_1 = \frac{a}{v_f} + \frac{b}{v_p} + \frac{a}{v_f}$$

The travel time to the far receiver (Rx₂) will be:

$$t_2 = \frac{a}{v_f} + \frac{b+c}{v_p} + \frac{a}{v_f}$$

The travel time in the rock between the two receivers, is therefore:

$$\Delta t = t_2 - t_1 = \frac{c}{v_p}$$

Because v_p is greater than v_s and the velocities of the guided modes, the P-wave through the rock arrives at the receivers first and is known as the "first arrival". The interval travel time that is recorded by acoustic logging systems corresponds to this first arrival. The first arrival is detected at each receiver by determining when the signal crosses a threshold level set by the operator.

There are a few other types of sonde with more complicated sets of transmitters and receivers. For instance Borehole compensated sonic (BHC) with two transmitters and four receivers; and long spacing sonic tool (LSS) with two transmitters and two receivers. The Sonic is one of the "porosity logs" along with the neutron and density logs; it does not need a radioactive source so it can be used in water source wells when radioactive sources cannot be run. The sonic log is

used in combination with other logs (e.g. density and neutron) for estimation of the (total) porosity:

High-Resolution Borehole Compensated (HBC) Sonic Tool

The HBC sonic tool measures formation acoustic velocity to provide enhanced information about formation porosity and lithology. The HBC sonic tool measures the time a pulsed acoustic wave takes to travel a fixed distance along the length of a borehole. The resulting interval transit time (Δt) is presented or can be converted to porosity using several transform types.

The HBC sonic tool incorporates an additional pair of acoustic receivers, spaced at 4 in. (102 mm), in the standard Borehole Compensated Sonic (BCS) tool. The

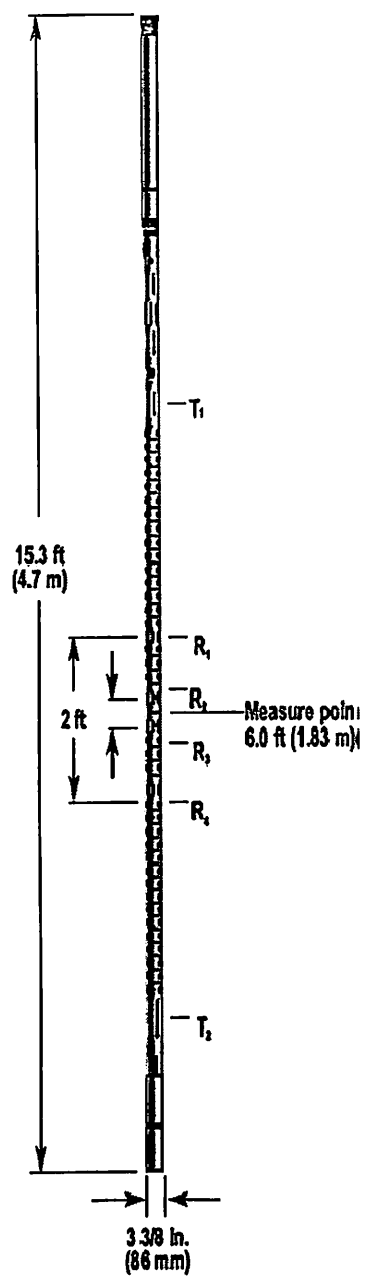


Figure 28

High-Resolution Borehole Compensated (HBC) Sonic Tool

LONG SPACING SONIC (LSS)

The LSS relies on the "depth derived" borehole compensation principle because the sonde would be too long if it used the same configuration as the BHC tool. Two transmitters spaced two feet apart are located eight feet below two receivers which are also two feet apart. Hole size compensation is obtained by memorizing the first DT reading and averaging it with a second reading measured after the sonde has been pulled up to a fixed distance along the borehole. The LSS provides an improved measurement of the sonic travel time. Thanks to its longer spacing (10-12 feet) the sonde has a deeper investigation depth and the measurement is not influenced by the altered zone close to the borehole. In fact, drilling operations in the altered zone produce a decrease of acoustic velocity below that of the virgin zone. Full waveforms are always recorded for each receiver. Shear velocity can be recorded with delay beyond P-wave arrival during a separate run.

APPLICATIONS

Porosity and "pseudodensity" log

The sonic transit time can be used to compute porosity by using the appropriate transform and to estimate fracture porosity in carbonate rocks. In addition, it can be used to compute a "pseudodensity" log over sections where this log has not been recorded or the response was not satisfactory.

Seismic impedance

The product of compressional velocity and density is useful in computing synthetic seismograms for time-depth ties of seismic reflectors.

Sonic waveforms analysis

If a refracted shear arrival is present, its velocity can be computed from the full waveforms, and the frequency content and energy of both compressional and shear arrivals can also be determined.

Fracture porosity

Variations in energy and frequency content are indicative of changes in fracture density, porosity, and in the material filling the pores. In some cases compressional-wave attenuation can also be computed from the full waveforms.

LIMITATIONS:

Environmental Effects

One common problem is cycle skipping: a low signal level, such as that occurring in large holes and soft formations, can cause the far detectors to trigger on the second or later arrivals, causing the recorded Δt to be too high. This problem can also be related to the presence of fractures or gas. Transit time stretching appears when the detection at the further detector occurs later because of a weak signal. Finally, noise peaks are caused by triggering of detectors by mechanically induced noise, which causes the Δt to be too low. Reprocessing programs that can eliminate the aberrations described above are available both at sea and on-shore.

Depth of Investigation and Vertical Resolution

The depth of investigation cannot be easily quantified: it depends on the spacing of the detectors and on the petrophysical characteristics of the rock such as rock type, porosity (granular, vacuolar, fracture porosity), and alteration. For source-detector spacings of 3-5 ft, 8-10 ft, and 10-12 ft the depth of investigation ranges from 2 in to 10 in (altered/invaded and undisturbed formation, respectively), 5 in to 25 in, and 5 in to 30 in. The vertical resolution is 2 ft (61 cm).

Log Presentations

ΔT and ΔTL are interval travel-times in microseconds per foot for the near and far receiver pairs, respectively. In very slow formations ΔTL provides the more reliable measurement as the refracted wave is not seen at the near receivers. The acoustic data is usually presented as compressional (V_p) velocity and, where available, as shear velocity (V_s) in km/s.

CHAPTER 3

OVERVIEW OF EQUATIONS AND METHODS USED IN CASE STUDY

MWD

Directional surveys are normally run at intervals of 100ft (30m) to monitor the well progress while drilling. If the well is found to deviate from its planned direction, correction measures can be taken to bring the well back onto course. Hence, survey data provide a pictorial image of the path of the well and the data are normally plotted on the graph as that of the planned course.

There are various methods to determine the well geometry (Azimuth and Inclination) from the measured survey data. The following are the most common types:

1. Tangential method
2. Balanced tangential method
3. Angle averaging method
4. Radius of curvature method
5. Minimum curvature method

Relevant data required for each method for each method include inclination angle, I , azimuth, A , and measured hole depth, MD. The intention is to calculate the true vertical depth, VD, the horizontal displacement or departure, D , and easting and northing co-ordinates of the new hole position.

Tangential method

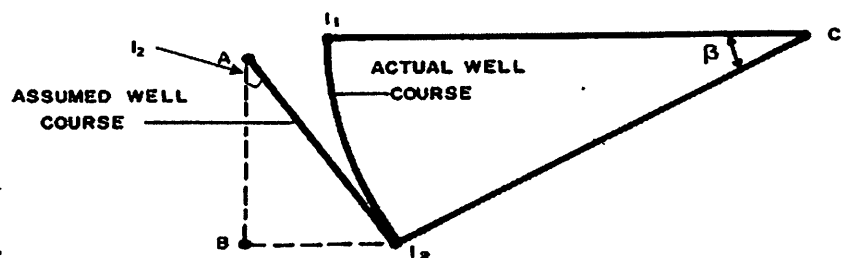
The principle of the tangential method is to use the inclination and azimuth (direction) angles at the lower end of the course only for determining VD, D , easting and northing.

$$\Delta VD = \Delta MD \cos I_2$$

$$\Delta D = \Delta MD \sin I_2$$

$$\Delta E = \Delta D \sin A_2 = \Delta MD \sin I_2 \sin A_2$$

$$\Delta N = \Delta D \cos A_2 = \Delta MD \sin I_2 \cos A_2$$



Where ΔMD = increment of course length

ΔVD = increment of horizontal displacement or departure

ΔE = increment of easting co-ordinate

Figure 29

ΔN = increment of northing co-ordinate

This method has the advantage of being the most simple to use. The errors are proportional to the magnitudes of measured angles and course length. This method is now obsolete.

Balanced tangential method

The balanced tangential method uses the measured angles at the top and bottom of the course, which results in tangentially balanced survey calculations and, in turn, a smoother well-bore profile.

Referring to the figure, inclination angles I_1 and I_2 and azimuth angles A_1 and A_2 are measured at two survey stations. The measured hole course, ΔMD , is divided into two equal increments of $\Delta MD/2$. The top increment is used in conjunction with angles I_1 and A_1 to calculate horizontal displacement D_1 , vertical depth increment, ΔVD_1 , and the increments of easting and northing, ΔE_1 and ΔN_1 , respectively. Similarly, the bottom increment of $\Delta MD/2$ is used to calculate ΔD_2 , ΔVD_2 , ΔE_2 and ΔN_2 .

Thus,

$$\Delta D_1 = \left(\frac{\Delta MD}{2}\right) \sin I_1$$

$$\Delta D_2 = \left(\frac{\Delta MD}{2}\right) \sin I_2$$

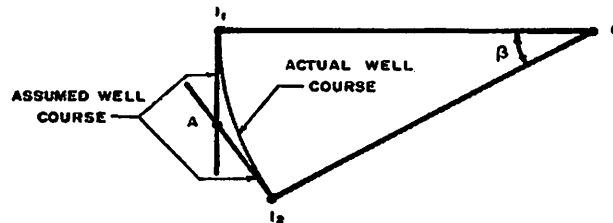


Figure 30

Angle averaging method

In the angle averaging method inclination angles I_1 and I_2 and the direction angles A_1 and A_2 are averaged and used for the calculation of departure, total vertical depth, and easting and northing increments. This method is simple and provides accurate means of calculating wellbore surveys.

Referring to the figure, average values of inclination and direction angles are $\frac{(I_1+I_2)}{2}$ and $\frac{(A_1+A_2)}{2}$.

Thus,

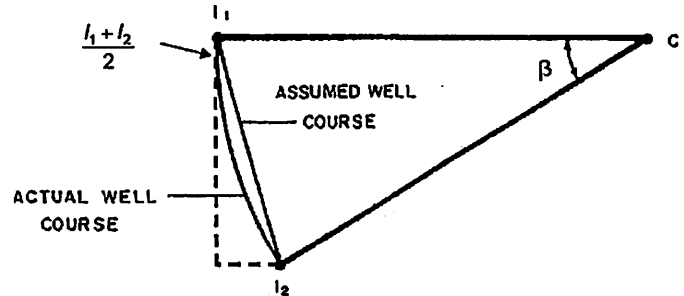
Figure 31

$$\Delta D = \Delta MD \sin \left(\frac{I_1 + I_2}{2} \right)$$

$$\Delta VD = \Delta MD \cos \left(\frac{I_1 + I_2}{2} \right)$$

$$\Delta E = \Delta MD \sin \left(\frac{I_1 + I_2}{2} \right) \sin \left(\frac{A_1 + A_2}{2} \right)$$

$$\Delta N = \Delta MD \sin \left(\frac{I_1 + I_2}{2} \right) \cos \left(\frac{A_1 + A_2}{2} \right)$$



Radius of curvature method

The radius of curvature method uses the top and bottom angles to generate a space curve having a spherical arc shape which passes through the two stations. This effectively assumes that the well bore is smooth, which makes the method less sensitive to changes in position, especially if a serve dog-leg exists in the interval.

Rate of change in inclination = $\frac{I_2 - I_1}{\Delta MD}$, where I_2 and I_1 are in radians.

Radius of curvature = 1 / Rate of change in inclination

$$R = \frac{1}{\frac{I_2 - I_1}{\Delta MD}} = \frac{\Delta MD}{I_2 - I_1}$$

Since I_1 and I_2 are measured in degrees, it is necessary to convert them to radians by multiplying by the factor $\frac{360}{2\pi}$. Thus

$$R = \frac{\Delta MD}{I_2 - I_1} \times \frac{360}{2\pi} = \frac{360 \Delta MD}{2\pi (I_2 - I_1)}$$

$$V_1 = R \sin I_1 = \frac{360 \Delta MD}{2\pi (I_2 - I_1)} \sin I_1$$

$$V_2 = R \sin I_2 = \frac{360 \Delta MD}{2\pi (I_2 - I_1)} \sin I_2$$

Therefore,

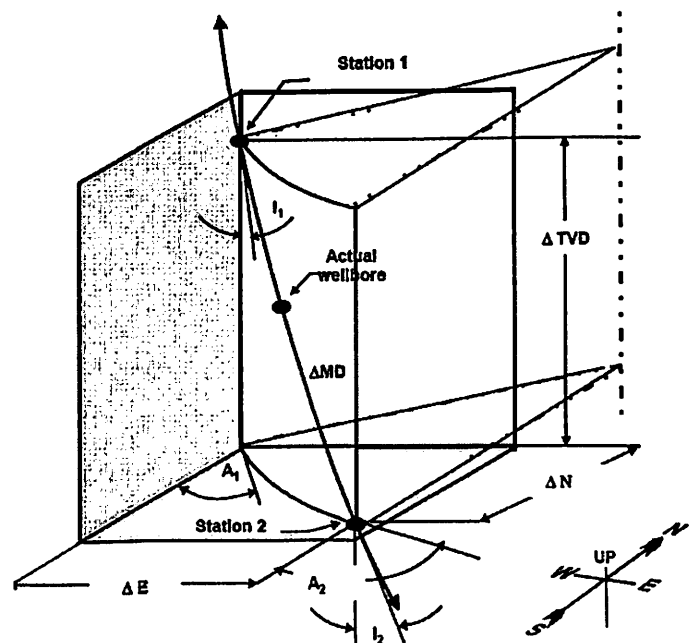


Figure 32

$$\Delta VD = V_2 - V_1 = \frac{360 \Delta MD}{2\pi(I_2 - I_1)} (\sin I_2 - \sin I_1)$$

$$\text{Departure, } D = D_2 - D_1$$

$$D_2 = R \cos I_1$$

$$D_1 = R \sin(90 - I_2) = R \cos I_2$$

$$\Delta D = D_2 - D_1 = R(\cos I_1 - \cos I_2)$$

$$\Delta D = \frac{360 \Delta MD}{2\pi(I_2 - I_1)} (\cos I_1 - \cos I_2)$$

Length or departure is assume to be curves, and consequently the radius of curvature in the horizontal plane is given by

$$R_1 = \frac{1}{\frac{A_2 - A_1}{\Delta D}} = \frac{\Delta D}{A_2 - A_1} = \frac{360 \Delta MD}{2\pi(A_2 - A_1)} \frac{(\cos I_1 - \cos I_2)}{(I_2 - I_1)}$$

I_1, I_2, A_1, A_2 are in degrees and must be converted to radians. Hence,

$$R_1 = \frac{(360)^2 \Delta MD}{(2\pi)^2 (A_2 - A_1)} \frac{(\cos I_1 - \cos I_2)}{(I_2 - I_1)}$$

The northing and easting co-ordinates are:

$$\begin{aligned} \Delta N = N_2 - N_1 &= R_1 \sin A_2 - R_1 \sin A_1 \\ &= R_1 (\sin A_2 - \sin A_1) \end{aligned}$$

$$\Delta N = \frac{(360)^2 \Delta MD}{(2\pi)^2 (A_2 - A_1)} \frac{(\cos I_1 - \cos I_2)}{(I_2 - I_1)} (\sin A_2 - \sin A_1)$$

Similarly,

$$\begin{aligned} \Delta E &= E_2 - E_1 \\ &= R_1 \cos A_1 - R_1 \cos A_2 \\ &= R_1 (\cos A_1 - \cos A_2) \end{aligned}$$

$$\Delta E = \frac{(360)^2 \Delta MD}{(2\pi)^2 (A_2 - A_1)} \frac{(\cos I_1 - \cos I_2)}{(I_2 - I_1)} (\cos A_1 - \cos A_2)$$

Minimum curvature method

The minimum curvature method is one of the most accurate calculation methods. It relies on the principle of minimizing the total curvature within the physical constraints of the wellbore. This will then produce smooth, circular arc. A ratio factor is used to smooth the wellbore path between the two stations. The ratio factor, RF, is defined by the curvature or dog-leg of the wellbore section, as follows,

$$RF = \left(\frac{2}{DL} \right) (\text{in radians}) \times \tan \left(\frac{DL}{2} \right) (\text{in degrees})$$

Where

DL = dog-leg angle (It is the measure of the amount of change in inclination or direction of a borehole.)

$$\cos DL = \cos(I_2 - I_1) - \sin I_1 \times \sin I_2 [1 - \cos(A_2 - A_1)]$$

Dog-leg severity (DLS) is the ratio of dog-leg angle, DL, to the 100 feet of the course length.

The minimum curvature method equations are similar to those of the balanced tangential method, except that the survey data are multiplied by a ratio factor, RF, to produce the required smoothing effect.

Thus,

$$\Delta VD = \frac{\Delta MD}{2} (\cos I_1 + \cos I_2) RF$$

The northing and Easting are:

$$\Delta N = \frac{\Delta MD}{2} (\sin I_1 \cos A_1 + \sin I_2 \cos A_2) RF$$

$$\Delta E = \frac{\Delta MD}{2} (\sin I_1 \sin A_1 + \sin I_2 \sin A_2) RF$$

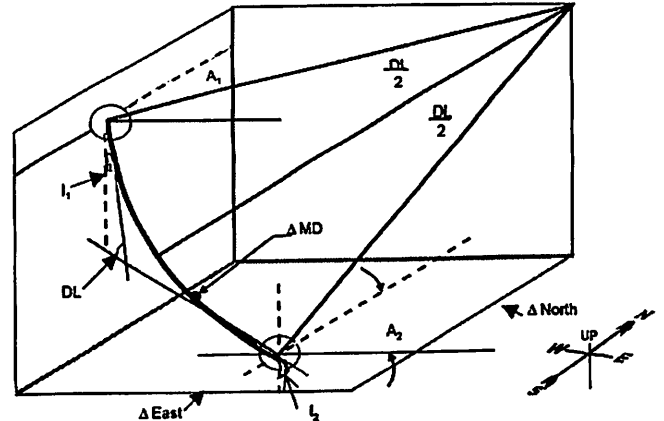


Figure 33

LWD

Depth matched and borehole corrected curves are used for petrophysical evaluation of the well. The following input curves are used in the processing of well 'X':

- Gamma ray log (GR)
- Resistivity logs (RT)
- Neutron log (NPHI)

d) Density log (RHOB)

e) Compressional sonic log (DT)

Along with these methods, equations are also used to calculate:

$$\text{Density porosity} = F = \left(\frac{\text{RHOBmatrix} - \text{RHOBlog}}{\text{RHOBmatrix} - \text{RHOBfluid}} \right)$$

$$\text{Sonic porosity} = F = - \left(\frac{\text{DTlog} - \text{DTmatrix}}{\text{DTfluid} - \text{DTmatrix}} \right)$$

$$\text{Water Saturation} = S_w = \sqrt{\frac{R_w}{\phi^2 R_t}}$$

CHAPTER 4

CASE STUDY ANALYSIS

Interpretation of MWD

For solving the case study, the following table's equations are used to calculate inclination and azimuth from various methods discussed above.

Table 9

Tangential	
$\Delta TVD = \Delta MD \times \cos I_2$	Equation 2-1
$\Delta North = \Delta MD \times \sin I_2 \times \cos A_2$	Equation 2-2
$\Delta East = \Delta MD \times \sin I_2 \times \sin A_2$	Equation 2-3
Balanced Tangential	
$\Delta TVD = \frac{\Delta MD}{2} (\cos I_1 + \cos I_2)$	Equation 2-4
$\Delta North = \frac{\Delta MD}{2} [(\sin I_1 \times \cos A_1) + (\sin I_2 \times \cos A_2)]$	Equation 2-5
$\Delta East = \frac{\Delta MD}{2} [(\sin I_1 \times \sin A_1) + (\sin I_2 \times \sin A_2)]$	Equation 2-6
Average Angle	
$\Delta TVD = \Delta MD \times \cos \left(\frac{I_1 + I_2}{2} \right)$	Equation 2-7
$\Delta North = \Delta MD \times \sin \left(\frac{I_1 + I_2}{2} \right) \times \cos \left(\frac{A_1 + A_2}{2} \right)$	Equation 2-8
$\Delta East = \Delta MD \times \sin \left(\frac{I_1 + I_2}{2} \right) \times \sin \left(\frac{A_1 + A_2}{2} \right)$	Equation 2-9
Radius of Curvature	
$\Delta TVD = \frac{(180)(\Delta MD)(\sin I_2 - \sin I_1)}{\pi(I_2 - I_1)}$	Equation 2-10
$\Delta North = \frac{(180)^2 (\Delta MD)(\cos I_1 - \cos I_2)(\sin A_2 - \sin A_1)}{\pi^2(I_2 - I_1)(A_2 - A_1)}$	Equation 2-11
$\Delta East = \frac{180^2 (\Delta MD)(\cos I_1 - \cos I_2)(\cos A_1 - \cos A_2)}{\pi^2(I_2 - I_1)(A_2 - A_1)}$	Equation 2-12
$\Delta DEP = \frac{180(\Delta MD)(\cos I_1 - \cos I_2)}{\pi(I_2 - I_1)}$	Equation 2-13
$r = \frac{180}{(\pi)(DLS)}$	Equation 2-14
$\Delta MD = \frac{I_2 - I_1}{B_r}$	Equation 2-15

Minimum Curvature	
$\Delta TVD = \left(\frac{\Delta MD}{2} \right) (\cos I_1 + \cos I_2) (FC)$	Equation 2-16
$\Delta North = \left(\frac{\Delta MD}{2} \right) [(\sin I_2 \times \cos A_2) + (\sin I_1 \times \cos A_1)] (FC)$	Equation 2-17
$\Delta East = \left(\frac{\Delta MD}{2} \right) [(\sin I_2 \times \sin A_2) + (\sin I_1 \times \sin A_1)] (FC)$	Equation 2-18
$D1 = \cos(I_2 - I_1) - \{\sin I_2 \times \sin I_1 \times [1 - \cos(A_2 - A_1)]\}$	Equation 2-19
$D2 = \tan^{-1} \sqrt{\left(\frac{1}{D1^2} \right) - 1}$	Equation 2-20
$FC = \frac{2}{D2} \times \tan\left(\frac{D2}{2}\right)$	Equation 2-21
Note: Use inclinations and azimuths in radians only	
Calculations for Closure Assuming Wellhead Coordinates are 0.00°N and 0.00°E	
$Closure\ Direction = \tan^{-1} \left(\frac{East}{North} \right)$	Equation 2-22
$Closure\ Distance = \sqrt{(North)^2 + (East)^2}$	Equation 2-23
Vertical Section	
$VS = \cos(Az_{vs} - Az_d) \times (Closure\ Distance)$	Equation 2-24
Dogleg Severity	
$DLS = \left(\frac{100}{\Delta MD} \right) \cos^{-1} \{(\sin I_1 \times \sin I_2) [(\sin A_1 \times \sin A_2) + (\cos A_1 \times \cos A_2)] + (\cos I_1 \times \cos I_2)\}$	Equation 2-25
or	
$DLS = \frac{200}{\Delta MD} \sin^{-1} \sqrt{(\sin I_1)(\sin I_2) \left[\sin\left(\frac{A_2 - A_1}{2}\right) \right]^2 + \left[\sin\left(\frac{I_2 - I_1}{2}\right) \right]^2}$	Equation 2-26

Question: calculation of the following

- a) delta northing
- b) delta easting
- c) departure
- d) dog leg severity
- e) delta TVD

Table 10

MD	SD	INC	AZM
0.00		0.6	146.1
376.57	357.57	0.4	82.4
386.09	367.09	0.7	81.7
395.32	376.32	1.0	81.8
405.01	386.01	1.7	70.4
414.60	395.60	2.7	71.0
424.30	405.30	3.7	73.0
433.87	414.87	4.6	73.1
443.49	424.49	5.8	73.8
452.99	433.99	6.9	73.3
462.53	443.53	8.0	66.7
472.17	453.17	8.8	63.7
481.64	462.64	9.4	61.0
491.16	472.16	10.1	59.3
500.73	481.73	10.9	57.0
510.26	491.26	11.8	55.2
519.89	500.89	13.1	54.5
529.24	510.24	14.7	54.8
538.92	519.92	15.9	54.3
548.61	529.61	16.4	54.4
558.06	539.06	16.8	54.7
567.75	548.75	16.7	54.5
577.45	558.45	16.8	54.6
587.06	568.06	16.8	55.5
596.71	577.71	16.8	55.6
606.12	587.12	17.0	55.9
615.66	596.66	17.1	56.0
625.25	606.25	17.0	56.1
634.84	615.84	17.0	56.3
644.38	625.38	16.9	56.0
654.07	635.07	16.7	56.0

663.61	644.61	16.6	55.9
672.69	653.69	16.8	55.3
682.34	663.34	17.1	55.0
691.70	672.70	17.2	54.6
701.20	682.20	17.3	54.5
710.65	691.65	17.0	54.5
720.15	701.15	16.9	54.7
729.72	710.72	16.7	54.8
739.28	720.28	16.7	55.0
748.81	729.81	16.6	55.1
758.34	739.34	17.0	55.0
767.39	748.39	17.2	55.4
776.93	757.93	17.3	55.0
785.96	766.96	17.1	55.2
795.49	776.49	17.0	55.4
805.18	786.18	17.0	55.7
814.70	795.70	17.0	55.4
824.22	805.22	16.8	55.9
833.62	814.62	16.7	55.7
843.18	824.18	17.0	56.3
852.90	833.90	17.1	56.3
862.52	843.52	17.1	56.3
872.03	853.03	17.0	56.3
881.50	862.50	16.8	56.4
891.10	872.10	17.3	56.9
900.88	881.88	17.6	56.7
910.44	891.44	17.9	57.0
920.03	901.03	17.9	57.1
929.62	910.62	17.8	57.1
939.37	920.37	17.8	57.5
948.93	929.93	17.7	57.3
958.53	939.53	17.9	57.5
968.05	949.05	17.9	58.0
977.75	958.75	18.1	57.8
987.51	968.51	18.2	58.1
997.11	978.11	18.3	57.7
1006.78	987.78	17.9	56.7
1015.90	996.90	17.7	55.6
1025.33	1006.33	17.7	55.2

Interpretation of LWD

The log given below is from a new well drilled into an old oilfield. The field contains some water injection wells to increase reservoir pressure and maintain oil production from producing wells.

The following input curves are used in the processing of well 'X':

- a) Gamma ray log (GR)
- b) Resistivity logs(RT)
- c) Neutron log (NPHI)
- d) Density log (RHOB)
- e) Compressional sonic log (DT)

Questions:

1. Using the information from the gamma ray and density/neutron, sketch in the approximate lithologies in the blank grid marked 'lithology'. (Use the lithology coding found at the top of the log).
2. Does the sonic log show any difference between sand and shale formations? (Answer 'yes' or 'no')
3. Read off the density log reading at 12870' and compute the density porosity using the relation:

$$\text{Density porosity} = F = \left(\frac{\text{RHOBmatrix} - \text{RHOBlog}}{\text{RHOBmatrix} - \text{RHOBfluid}} \right) \dots\dots\dots (\text{Equation 2.27})$$

Use: RHOBmatrix = 2.65 (sandstone) and RHOBfluid = 1

4. Read off the sonic log reading at 12870' and compute the sonic porosity using the relation:

5. Sonic porosity = $F = - \left(\frac{DT_{log} - DT_{matrix}}{DT_{fluid} - DT_{matrix}} \right) \dots\dots\dots$ (Equation 2.28)

Use: $DT_{matrix} = 55$ (sandstone) and $DT_{fluid} = 190$

Does the sonic log porosity match the density porosity within 3 porosity units ie. within 0.03 (Answer 'yes' or 'no').

6. Read off the Resistivity at 12870' and compute the water saturation S_w at this depth using the density porosity and the relation:

$$S_w = \sqrt{\frac{R_w}{\phi^2 R_i}} \dots\dots\dots$$
 (Equation 2.29)

2.29)

Use $R_w = .1$ for whole reservoir

Compute the water saturation S_w at 12930'.

7. Predict what fluid will flow from 12870' and 12930'.

Estimate which zones in this well you would perforate to maximise oil production, and minimise water production, knowing that no water is likely to flow when $S_w < 50\%$. Avoid selecting low permeability zones that are unlikely to flow – perforating costs money, and this would be wasted by perforating non-productive zones!

CHAPTER 5

RESULTS AND DISCUSSION:

MWD INTERPRETATION

The formulae used from table 9 are:-

Balanced tangential:

- For calculation of TVD equation 2-4 is referred.
- For calculation of TNOR equation 2-5 is referred.
- For calculation of TEAST equation 2-6 is referred.

Average angle:

- For calculation of TVD equation 2-7 is referred.
- For calculation of TNOR equation 2-8 is referred.
- For calculation of TEAST equation 2-9 is referred.

Radius of curvature:

- For calculation of TVD equation 2-10 is referred.
- For calculation of TNOR equation 2-11 is referred.
- For calculation of TEAST equation 2-12 is referred.

Minimum curvature:

- For calculation of TVD equation 2-16 is referred.
- For calculation of TNOR equation 2-17 is referred.
- For calculation of TEAST equation 2-18 is referred.
- For calculation of reference factor equation 2-21 is referred.

Balanced Tangential Method

Table 11

MD	INC	del MD	AZM	TVD	TDP	TNOR	TEAST	DLS
0.00	0.6	0.0	146.1	0	0	0	0	0
376.57	0.4	376.6	82.4	376.56	3.286146	-1.46267	2.402615	0.14721
386.09	0.7	9.5	81.7	386.07	3.37753	-1.44988	2.493097	3.15199
395.32	1.0	9.2	81.8	395.30	3.514455	-1.43026	2.628608	3.25031
405.01	1.7	9.7	70.4	404.99	3.742744	-1.36998	2.847705	7.70247
414.60	2.7	9.6	71.0	414.57	4.110869	-1.24872	3.195281	10.4302
424.30	3.7	9.7	73.0	424.26	4.652317	-1.08284	3.710606	10.3718
433.87	4.6	9.6	73.1	433.80	5.344856	-0.881	4.37308	9.40469
443.49	5.8	9.6	73.8	443.38	6.216694	-0.63324	5.208958	12.4912
452.99	6.9	9.5	73.3	452.82	7.267361	-0.33534	6.216497	11.5935
462.53	8.0	9.5	66.7	462.28	8.50427	0.091916	7.375095	14.5908
472.17	8.8	9.6	63.7	471.82	9.912476	0.68397	8.652264	9.45969
481.64	9.4	9.5	61.0	481.17	11.41021	1.379853	9.978054	7.77497
491.16	10.1	9.5	59.3	490.55	13.02239	2.182932	11.37577	7.94975
500.73	10.9	9.6	57.0	499.96	14.76634	3.104145	12.85614	9.43571
510.26	11.8	9.5	55.2	509.30	16.6418	4.151004	14.41197	10.148
519.89	13.1	9.6	54.5	518.71	18.71778	5.346692	16.10898	13.5899
529.24	14.7	9.4	54.8	527.78	20.96369	6.645834	17.941	17.1296
538.92	15.9	9.7	54.3	537.12	23.51784	8.127556	20.0214	12.4713
548.61	16.4	9.7	54.4	546.43	26.21312	9.698421	22.21158	5.16794
558.06	16.8	9.5	54.7	555.48	28.91286	11.26418	24.41089	4.32886
567.75	16.7	9.7	54.5	564.76	31.70548	12.88187	26.68724	1.19115
577.45	16.8	9.7	54.6	574.05	34.50098	14.50324	28.96452	1.07289
587.06	16.8	9.6	55.5	583.25	37.27858	16.09437	31.24111	2.70683
596.71	16.8	9.6	55.6	592.49	40.06773	17.67215	33.54111	0.29951
606.12	17.0	9.4	55.9	601.49	42.80324	19.21167	35.80226	2.31867
615.66	17.1	9.5	56.0	610.61	45.60042	20.77785	38.11987	1.09235
625.25	17.0	9.6	56.1	619.78	48.41227	22.34819	40.45236	1.08665
634.84	17.0	9.6	56.3	628.95	51.21611	23.90795	42.78231	0.60974
644.38	16.9	9.5	56.0	638.08	53.99738	25.45715	45.09215	1.39257
654.07	16.7	9.7	56.0	647.35	56.79809	27.02329	47.41404	2.06398

663.61	16.6	9.5	55.9	656.49	59.53153	28.55378	49.67884	1.0904
672.69	16.8	9.1	55.3	665.19	62.14076	30.02796	51.83168	2.90812
682.34	17.1	9.6	55.0	674.42	64.95409	31.63562	54.14039	3.23822
691.70	17.2	9.4	54.6	683.37	67.71411	33.2266	56.3957	1.65208
701.20	17.3	9.5	54.5	692.44	70.53125	34.86052	58.6906	1.09794
710.65	17.0	9.5	54.5	701.47	73.3178	36.47868	60.95917	3.1746
720.15	16.9	9.5	54.7	710.56	76.08741	38.08307	63.21674	1.2185
729.72	16.7	9.6	54.8	719.72	78.85344	39.67948	65.47559	2.11157
739.28	16.7	9.6	55.0	728.87	81.6006	41.25911	67.72318	0.60117
748.81	16.6	9.5	55.1	738.00	84.33118	42.82336	69.9613	1.09154
758.34	17.0	9.5	55.0	747.13	87.08564	44.40131	72.21898	4.20821
767.39	17.2	9.0	55.4	755.78	89.7467	45.91996	74.40412	2.56375
776.93	17.3	9.5	55.0	764.89	92.5757	47.53452	76.72713	1.62625
785.96	17.1	9.0	55.2	773.51	95.24594	49.06231	78.91711	2.30964
795.49	17.0	9.5	55.4	782.63	98.0402	50.65303	81.21438	1.21643
805.18	17.0	9.7	55.7	791.89	100.8733	52.25566	83.55059	0.90517
814.70	17.0	9.5	55.4	801.00	103.6567	53.83017	85.84581	0.92134
824.22	16.8	9.5	55.9	810.10	106.4241	55.39176	88.1306	2.59703
833.62	16.7	9.4	55.7	819.11	109.1332	56.91445	90.3712	1.22789
843.18	17.0	9.6	56.3	828.26	111.9043	58.46392	92.6686	3.62724
852.90	17.1	9.7	56.3	837.55	114.7543	60.04521	95.03964	1.02881
862.52	17.1	9.6	56.3	846.74	117.5829	61.61468	97.39296	0
872.03	17.0	9.5	56.3	855.84	120.3713	63.1618	99.71277	1.05152
881.50	16.8	9.5	56.4	864.90	123.1243	64.68727	102.0044	2.13412
891.10	17.3	9.6	56.9	874.07	125.939	66.23452	104.3557	5.42755
900.88	17.6	9.8	56.7	883.40	128.8718	67.84042	106.8097	3.12818
910.44	17.9	9.6	57.0	892.51	131.7863	69.4341	109.2499	3.28066
920.03	17.9	9.6	57.1	901.63	134.7338	71.0373	111.7233	0.3205
929.62	17.8	9.6	57.1	910.76	137.6734	72.634	114.1914	1.04275
939.37	17.8	9.8	57.5	920.05	140.6539	74.2442	116.6996	1.25413
948.93	17.7	9.6	57.3	929.15	143.5684	75.81443	119.1549	1.22513
958.53	17.9	9.6	57.5	938.29	146.5031	77.39552	121.6272	2.1785
968.05	17.9	9.5	58.0	947.35	149.4291	78.95688	124.1018	1.61426
977.75	18.1	9.7	57.8	956.58	152.4266	80.54975	126.641	2.15805
987.51	18.2	9.8	58.1	965.85	155.4669	82.16308	129.218	1.40235
997.11	18.3	9.6	57.7	974.97	158.4733	83.76068	131.7647	1.66964

1006.78	17.9	9.7	56.7	984.16	161.4775	85.38779	134.29	5.23748
1015.90	17.7	9.1	55.6	992.84	164.2654	86.94054	136.6053	4.28989
1025.33	17.7	9.4	55.2	1001.83	167.1325	88.56855	138.9653	1.28964

Angle Average Method

MD	del MD	INC	AZM	TDP	TVD	TEAST	TNOR	DLS
Surface		0.6	146.1	0	0	0	0	
376.57	357.6	0.4	82.4	3.120347	357.5564	0.0272298	3.1202285	0.155037
386.09	9.5	0.7	81.7	3.211731	367.0759	0.028107	3.2116083	3.151992
395.32	9.2	1.0	81.8	3.348656	376.3049	0.0301383	3.348518	3.250309
405.01	9.7	1.7	70.4	3.57695	385.9922	0.0355168	3.5767488	7.702465
414.60	9.6	2.7	71.0	3.945089	395.5752	0.0496489	3.9446165	10.43015
424.30	9.7	3.7	73.0	4.486558	405.26	0.0798745	4.4852408	10.37176
433.87	9.6	4.6	73.1	5.179118	414.805	0.1299936	5.1759853	9.404689
443.49	9.6	5.8	73.8	6.051004	424.3854	0.2090148	6.0442824	12.4912
452.99	9.5	6.9	73.3	7.101719	433.8271	0.3252257	7.0885518	11.59346
462.53	9.5	8.0	66.7	8.338685	443.2865	0.4856118	8.3150752	14.59083
472.17	9.6	8.8	63.7	9.746925	452.8231	0.6913318	9.7082085	9.459688
481.64	9.5	9.4	61.0	11.24468	462.1739	0.9282142	11.187114	7.77497
491.16	9.5	10.1	59.3	12.85689	471.5564	1.2012407	12.776035	7.949754
500.73	9.6	10.9	57.0	14.60088	480.9662	1.5190583	14.490826	9.435713
510.26	9.5	11.8	55.2	16.4764	490.3098	1.8881643	16.329668	10.14796
519.89	9.6	13.1	54.5	18.55251	499.7134	2.3357474	18.356955	13.58989
529.24	9.4	14.7	54.8	20.79865	508.7896	2.8753314	20.537313	17.12959
538.92	9.7	15.9	54.3	23.35294	518.1265	3.5493399	23.001073	12.47128
548.61	9.7	16.4	54.4	26.04824	527.4341	4.2990464	25.59001	5.167935
558.06	9.5	16.8	54.7	28.74799	536.4902	5.070335	28.177247	4.328864
567.75	9.7	16.7	54.5	31.54062	545.7691	5.8751582	30.851381	1.191146
577.45	9.7	16.8	54.6	34.33612	555.0575	6.6808119	33.528276	1.072887
587.06	9.6	16.8	55.5	37.11371	564.2574	7.4836254	36.187322	2.706828
596.71	9.6	16.8	55.6	39.90287	573.4955	8.2897804	38.857436	0.299515
606.12	9.4	17.0	55.9	42.63838	582.4991	9.0849985	41.474807	2.318668
615.66	9.5	17.1	56.0	45.43557	591.6198	9.9051507	44.149055	1.092346
625.25	9.6	17.0	56.1	48.24741	600.7883	10.729601	46.837319	1.086651
634.84	9.6	17.0	56.3	51.05126	609.9593	11.549366	49.518649	0.609743
644.38	9.5	16.9	56.0	53.83252	619.0849	12.360208	52.179093	1.392567
654.07	9.7	16.7	56.0	56.63324	628.3613	13.169704	54.860275	2.063983

663.61	9.5	16.6	55.9	59.36668	637.5013	13.952903	57.479114	1.090396
672.69	9.1	16.8	55.3	61.97592	646.1983	14.702694	59.978297	2.908117
682.34	9.6	17.1	55.0	64.78925	655.4291	15.522885	62.669417	3.238219
691.70	9.4	17.2	54.6	67.54927	664.373	16.336744	65.306719	1.652083
701.20	9.5	17.3	54.5	70.36642	673.4457	17.172145	67.997149	1.097939
710.65	9.5	17.0	54.5	73.15298	682.4755	17.993831	70.659809	3.174603
720.15	9.5	16.9	54.7	75.92258	691.5628	18.801272	73.309098	1.218497
729.72	9.6	16.7	54.8	78.68862	700.7243	19.600744	75.957077	2.111574
739.28	9.6	16.7	55.0	81.43578	709.8811	20.390171	78.588375	0.601172
748.81	9.5	16.6	55.1	84.16636	719.0116	21.172549	81.204469	1.091541
758.34	9.5	17.0	55.0	86.92083	728.1348	21.96868	83.841379	4.208213
767.39	9.0	17.2	55.4	89.5819	736.7847	22.75114	86.384807	2.563751
776.93	9.5	17.3	55.0	92.41091	745.8956	23.590058	89.086564	1.62625
785.96	9.0	17.1	55.2	95.08115	754.5218	24.379671	91.63739	2.309644
795.49	9.5	17.0	55.4	97.8754	763.6329	25.198963	94.308835	1.216429
805.18	9.7	17.0	55.7	100.7085	772.8995	26.027276	97.018125	0.905175
814.70	9.5	17.0	55.4	103.4919	782.0036	26.841057	99.679883	0.921338
824.22	9.5	16.8	55.9	106.2593	791.1124	27.645571	102.32785	2.597027
833.62	9.4	16.7	55.7	108.9684	800.1136	28.426308	104.92195	1.227894
843.18	9.6	17.0	56.3	111.7395	809.2631	29.229567	107.57411	3.627245
852.90	9.7	17.1	56.3	114.5895	818.5559	30.065194	110.29882	1.028807
862.52	9.6	17.1	56.3	117.4182	827.7507	30.896936	113.00244	0
872.03	9.5	17.0	56.3	120.2065	836.8427	31.714509	115.66828	1.051525
881.50	9.5	16.8	56.4	122.9595	845.9037	32.514798	118.30234	2.134124
891.10	9.6	17.3	56.9	125.7743	855.0818	33.340108	120.9934	5.427552
900.88	9.8	17.6	56.7	128.707	864.4117	34.219566	123.7912	3.128178
910.44	9.6	17.9	57.0	131.6215	873.5166	35.108093	126.56696	3.280656
920.03	9.6	17.9	57.1	134.5691	882.6424	36.014042	129.37183	0.320497
929.62	9.6	17.8	57.1	137.5087	891.7708	36.915102	132.16991	1.042753
939.37	9.8	17.8	57.5	140.4892	901.054	37.826236	135.00776	1.254132
948.93	9.6	17.7	57.3	143.4037	910.1589	38.714764	137.78352	1.22513
958.53	9.6	17.9	57.5	146.3384	919.2994	39.61188	140.57771	2.1785
968.05	9.5	17.9	58.0	149.2644	928.3586	40.511216	143.36211	1.614263
977.75	9.7	18.1	57.8	152.2619	937.5838	41.437484	146.21286	2.158053
987.51	9.8	18.2	58.1	155.3022	946.8582	42.384554	149.10189	1.402347
997.11	9.6	18.3	57.7	158.3086	955.9753	43.326041	151.95704	1.669635
1006.78	9.7	17.9	56.7	161.3128	965.1668	44.259388	154.81262	5.237481
1015.90	9.1	17.7	55.6	164.1007	973.8502	45.111648	157.4671	4.289894
1025.33	9.4	17.7	55.2	166.9678	982.8338	45.983321	160.19841	1.289639

Radius of Curvature Method

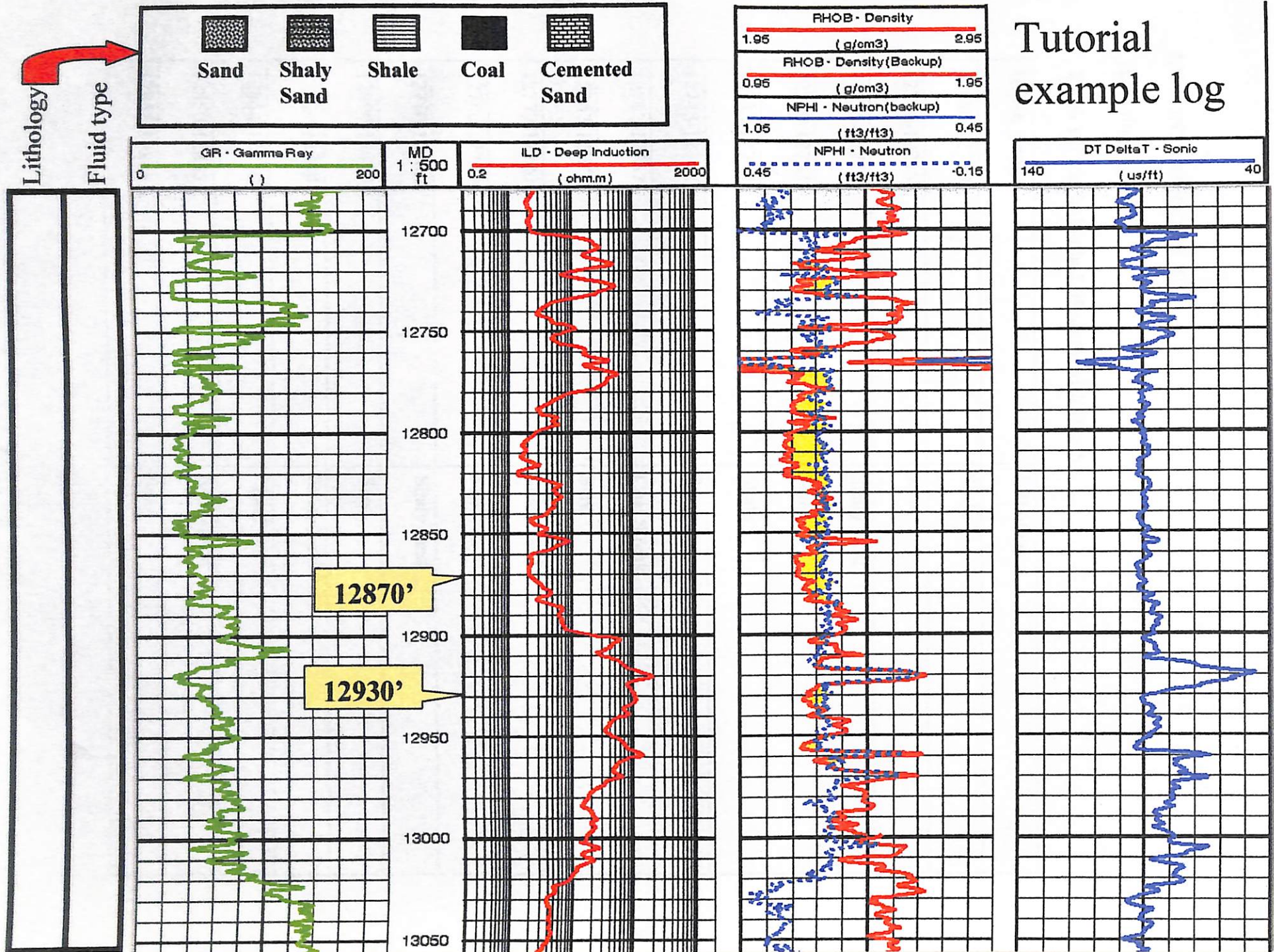
MD	del MD	INC	AZM	TVD	NOR	TNOR	TEAST	TDP
Surface	0.0	0.6	146.1	0	0	0	0	0
376.57	357.6	0.4	82.4	357.556	1.216593	-1.2166	-2.70074	-3.1203
386.09	9.5	0.7	81.7	367.076	0.012639	-1.204	-2.79124	-3.2117
395.32	9.2	1.0	81.8	376.305	0.019648	-1.1843	-2.92675	-3.3487
405.01	9.7	1.7	70.4	385.992	0.054752	-1.1296	-3.14799	-3.5769
414.60	9.6	2.7	71.0	395.575	0.121673	-1.0079	-3.49544	-3.9451
424.30	9.7	3.7	73.0	405.26	0.167312	-0.8406	-4.01037	-4.4865
433.87	9.6	4.6	73.1	414.804	0.201905	-0.6387	-4.67284	-5.1791
443.49	9.6	5.8	73.8	424.385	0.248352	-0.3903	-5.50858	-6.051
452.99	9.5	6.9	73.3	433.826	0.297535	-0.0928	-6.51627	-7.1017
462.53	9.5	8.0	66.7	443.285	0.422827	0.33005	-7.67798	-8.3386
472.17	9.6	8.8	63.7	452.822	0.590617	0.92067	-8.95619	-9.7468
481.64	9.5	9.4	61.0	462.173	0.694995	1.61566	-10.2828	-11.245
491.16	9.5	10.1	59.3	471.555	0.802411	2.41807	-11.681	-12.857
500.73	9.6	10.9	57.0	480.965	0.920232	3.3383	-13.1623	-14.601
510.26	9.5	11.8	55.2	490.308	1.046009	4.38431	-14.719	-16.476
519.89	9.6	13.1	54.5	499.712	1.195222	5.57954	-16.4164	-18.552
529.24	9.4	14.7	54.8	508.788	1.2995	6.87904	-18.2484	-20.798
538.92	9.7	15.9	54.3	518.124	1.481437	8.36047	-20.3291	-23.353
548.61	9.7	16.4	54.4	527.432	1.570904	9.93138	-22.5193	-26.048
558.06	9.5	16.8	54.7	536.488	1.565832	11.4972	-24.7186	-28.748
567.75	9.7	16.7	54.5	545.767	1.617712	13.1149	-26.9949	-31.54
577.45	9.7	16.8	54.6	555.055	1.62137	14.7363	-29.2722	-34.336

Minimum Curvature Method

MD	del MD	INC	AZM	DLS	RF	TVD	TNOR	TEAST	TDP
Surface		0.6	146.1	0	0	0	0	0	0
376.57	357.6	0.4	82.4	0.155037	1.000008	357.559	-1.3889	1.23719	3.120343
386.09	9.5	0.7	81.7	3.151992	1.000002	367.078	-1.3761	1.29473	3.211726
395.32	9.2	1.0	81.8	3.250309	1.000002	376.307	-1.3565	1.37445	3.348651
405.01	9.7	1.7	70.4	7.702465	1.000014	385.994	-1.2962	1.50986	3.57694
414.60	9.6	2.7	71.0	10.43015	1.000025	395.577	-1.1749	1.72343	3.945066
424.30	9.7	3.7	73.0	10.37176	1.000026	405.262	-1.009	2.02275	4.486513
433.87	9.6	4.6	73.1	9.404689	1.000021	414.807	-0.8072	2.38994	5.179052
443.49	9.6	5.8	73.8	12.4912	1.000037	424.387	-0.5594	2.85673	6.05089
452.99	9.5	6.9	73.3	11.59346	1.000031	433.829	-0.2615	3.40333	7.101557
462.53	9.5	8.0	66.7	14.59083	1.000049	443.288	0.16576	4.01308	8.338466
472.17	9.6	8.8	63.7	9.459688	1.000021	452.825	0.75782	4.67415	9.746672
481.64	9.5	9.4	61.0	7.77497	1.000014	462.175	1.45372	5.35055	11.24441
491.16	9.5	10.1	59.3	7.949754	1.000015	471.558	2.25681	6.06832	12.85659
500.73	9.6	10.9	57.0	9.435713	1.000021	480.968	3.17804	6.82718	14.60054
510.26	9.5	11.8	55.2	10.14796	1.000024	490.311	4.22492	7.62734	16.476
519.89	9.6	13.1	54.5	13.58989	1.000043	499.715	5.42066	8.51585	18.55197
529.24	9.4	14.7	54.8	17.12959	1.000065	508.79	6.71989	9.48531	20.79789
538.92	9.7	15.9	54.3	12.47128	1.000037	518.127	8.20167	10.5621	23.35204
548.61	9.7	16.4	54.4	5.167935	1.000006	527.435	9.77254	11.6744	26.04732
558.06	9.5	16.8	54.7	4.328864	1.000004	536.491	11.3383	12.789	28.74705
567.75	9.7	16.7	54.5	1.191146	1	545.77	12.956	13.9225	31.53968
577.45	9.7	16.8	54.6	1.072887	1	555.058	14.5774	15.0651	34.33518
587.06	9.6	16.8	55.5	2.706828	1.000002	564.258	16.1685	16.2097	37.11277
596.71	9.6	16.8	55.6	0.299515	1	573.496	17.7463	17.3603	39.90193
606.12	9.4	17.0	55.9	2.318668	1.000001	582.5	19.2858	18.4994	42.63743
615.66	9.5	17.1	56.0	1.092346	1	591.621	20.852	19.6622	45.43462
625.25	9.6	17.0	56.1	1.086651	1	600.789	22.4223	20.8258	48.24647
634.84	9.6	17.0	56.3	0.609743	1	609.96	23.9821	21.9922	51.05031
644.38	9.5	16.9	56.0	1.392567	1	619.086	25.5313	23.1418	53.83157
654.07	9.7	16.7	56.0	2.063983	1.000001	628.362	27.0974	24.296	56.63229
663.61	9.5	16.6	55.9	1.090396	1	637.502	28.6279	25.4244	59.36573
672.69	9.1	16.8	55.3	2.908117	1.000002	646.199	30.1021	26.5032	61.97496
682.34	9.6	17.1	55.0	3.238219	1.000002	655.43	31.7098	27.6654	64.78828
691.70	9.4	17.2	54.6	1.652083	1.000001	664.374	33.3007	28.7935	67.5483
701.20	9.5	17.3	54.5	1.097939	1	673.446	34.9347	29.9434	70.36545

710.65	9.5	17.0	54.5	3.174603	1.000002	682.476	36.5528	31.0681	73.152
720.15	9.5	16.9	54.7	1.218497	1	691.563	38.1572	32.1951	75.9216
729.72	9.6	16.7	54.8	2.111574	1.000001	700.725	39.7536	33.3187	78.68763
739.28	9.6	16.7	55.0	0.601172	1	709.882	41.3333	34.4438	81.4348
748.81	9.5	16.6	55.1	1.091541	1	719.012	42.8975	35.5603	84.16538
758.34	9.5	17.0	55.0	4.208213	1.000004	728.135	44.4755	36.7015	86.91983
767.39	9.0	17.2	55.4	2.563751	1.000001	736.785	45.9941	37.8029	89.58089
776.93	9.5	17.3	55.0	1.62625	1.000001	745.896	47.6087	38.9649	92.4099
785.96	9.0	17.1	55.2	2.309644	1.000001	754.522	49.1365	40.055	95.08014
795.49	9.5	17.0	55.4	1.216429	1	763.634	50.7272	41.2018	97.87439
805.18	9.7	17.0	55.7	0.905175	1	772.9	52.3298	42.372	100.7075
814.70	9.5	17.0	55.4	0.921338	1	782.004	53.9043	43.5175	103.4909
824.22	9.5	16.8	55.9	2.597027	1.000002	791.113	55.4659	44.6568	106.2583
833.62	9.4	16.7	55.7	1.227894	1	800.114	56.9886	45.7725	108.9674
843.18	9.6	17.0	56.3	3.627245	1.000003	809.264	58.5381	46.9352	111.7385
852.90	9.7	17.1	56.3	1.028807	1	818.557	60.1194	48.1241	114.5885
862.52	9.6	17.1	56.3	0	1	827.751	61.6888	49.3008	117.4171
872.03	9.5	17.0	56.3	1.051525	1	836.843	63.236	50.4574	120.2055
881.50	9.5	16.8	56.4	2.134124	1.000001	845.904	64.7614	51.5973	122.9585
891.10	9.6	17.3	56.9	5.427552	1.000007	855.082	66.3087	52.793	125.7732
900.88	9.8	17.6	56.7	3.128178	1.000002	864.412	67.9146	54.0289	128.706
910.44	9.6	17.9	57.0	3.280656	1.000002	873.517	69.5083	55.261	131.6205
920.03	9.6	17.9	57.1	0.320497	1	882.643	71.1115	56.4984	134.568
929.62	9.6	17.8	57.1	1.042753	1	891.771	72.7082	57.7291	137.5076
939.37	9.8	17.8	57.5	1.254132	1	901.055	74.3184	58.986	140.4881
948.93	9.6	17.7	57.3	1.22513	1	910.16	75.8886	60.209	143.4026
958.53	9.6	17.9	57.5	2.1785	1.000001	919.3	77.4697	61.4532	146.3373
968.05	9.5	17.9	58.0	1.614263	1.000001	928.359	79.0311	62.6939	149.2633
977.75	9.7	18.1	57.8	2.158053	1.000001	937.584	80.6239	63.969	152.2608
987.51	9.8	18.2	58.1	1.402347	1	946.859	82.2373	65.263	155.3011
997.11	9.6	18.3	57.7	1.669635	1.000001	955.976	83.8349	66.5369	158.3075
1006.78	9.7	17.9	56.7	5.237481	1.000007	965.167	85.462	67.779	161.3117
1015.90	9.1	17.7	55.6	4.289894	1.000004	973.851	87.0148	68.9229	164.0996
1025.33	9.4	17.7	55.2	1.289639	1	982.834	88.6428	70.1001	166.9666

Tutorial example log



LWD INTERPRETATION

Lithology in Well

Table 12: Variation in Lithology with Depth

Depth Range	Lithology
12680-12700	Shale
12700-12715	Sand
12715-12720	Shaly sand
12720-12733	Sand
12733-12748	Shale
12748-12762	Sand
12762-12767	Coal Streak
12767-12777	Sand
12777-12780	Shaly sand
12780-12790	Sand
12790-12800	Shaly sand
12800-12830	Sand
12830-12840	Shaly sand
12840-12850	Sand
12850-12855	Shaly sand
12855-12883	Sand

12883-12900	Shaly sand
12900-12913	Shale
12913-12918	Calcite streak
12918-12950	Shaly sand
12950-12955	Shaly sand
12955-12960	Calcite streak
12960-12965	Shaly Sand
12965-12970	Calcite streak
12970-13000	Shaly sand
13000-13005	Sand
13005-13010	Shaly sand
13010-13050	Shale

1. Does the sonic log show any difference between sand and shale formations? (Answer 'yes' or 'no')

Answer: Yes

2. Read off the density log reading at 12870' and compute the density porosity using equation 2.27:

Answer:

$\text{RHOB}_{\text{log}} = 2.17$ (at depth = 12870 Ft)

Using the formula given (Equation 2.27) ,

Density porosity = $(2.65 - 2.17) / (2.65 - 1) = .2909$

Thus,

Porosity(Φ)= 29.09%

3. Read off the sonic log reading at 12870' and compute the sonic porosity using Equation 2.28:

Answer:

DTlog=92(at the depth 12870 Ft)

Sonic Porosity= $(92-55)/(190-55) = .2740$

Thus,

Porosity (Φ)=27.40%

4. Does the sonic log porosity match the density porosity within 3 porosity units i.e. within 0.03(Answer 'yes' or 'no')

Answer: Yes.

5. Read off the Resistivity at 12870' and compute the water saturation S_w at this depth using the density porosity and Equation 2.29:

Answer:

R_t =4 ohm meter (at the depth 12870 Ft)

Φ =27.40%

S_w = .5451 or 54.51% (Using Equation 2.29)

6. Compute the water saturation S_w at 12930'.

Answer:

R_t =100 ohm meter (at depth 12930 Ft)

Using Equation 2.27, Density porosity = $(2.65-2.20)/(2.65-1) = .2727$

Φ =27.27%

Thus,

S_w =.11596 or 11.6% (using the Equation 2.29)

7. Predict what fluid will flow from 12870' and 12930'.

Answer: The interval 12870' to 12930' is marked with a lithology of mostly shaly sand. The neutron and density plot is showing a cross over indicating towards a gas zone however this cannot be confirmed. The resistivity value is dropping and rising, although the value of

resistivity is not significant. Moreover the sonic log shows approximately the same variation in this zone as compared to the zones identified for gas. We require the data for the invaded zone resistivity to get a better analysis.

This can either be due to the presence of shale (clay bound water) compromising the resistivity. A good way to find out the fluid flow will be a MDT analysis. This would give us the fluid present in this zone. Also we can analyze the pressure gradients from the **Stethoscope** tool. The pressure gradients which we will get will help us define the fluid present.

8. Estimate which zones in this well you would perforate to maximise oil production, and minimise water production, knowing that no water is likely to flow when $S_w < 50\%$. Avoid selecting low permeability zones that are unlikely to flow – perforating costs money, and this would be wasted by perforating non-productive zones!

Answer: The zones for perforation are as follows

- 12972'-13010' indicating oil zone.
- 12705'-12717' indicating gas zone.
- 12723'-12732' indicating gas zone.
- 12925'- 12957' indicating gas zone.
- 12960'-12965' indicating gas zone.
- Total pay thickness= 96ft

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

Conclusions for MWD interpretation

- The tangential method is the least accurate method and results in errors greater than all the other methods. This method is not used to calculate directional surveys.
- The angle average method is fairly accurate and easy to calculate. The errors are small but do have problems at low inclinations with large changes in azimuth.
- Radius of curvature method is considered to be accurate but if the inclination or azimuth are equal for both survey points, a division by zero will result in an error and radius, r , will become infinitely long. So, the minimum curvature or average mangle method can be used to make calculations.
- Minimum curvature method is the most accurate method used for directional surveys as they do not treat the change in inclination and azimuth separately as do the radius of curvature method. They have no problem with the change in azimuth or inclination being equal to zero.

Recommendations for MWD interpretation

- Angle average method should not be used for vertical wells.
- The minimum curvature method should be used for near vertical wells and for the vertical portions of a directional wells.
- The mud properties should be proper or else the telemetry system would not work efficiently.

Conclusions for LWD interpretation

- Selection of matrix density, fluid density, parameters might cause uncertainty in the interpretation. These parameters may cause some variation in porosity. Thus, the uncertainties in saturation exponent and cementation factor might cause some variation in water saturation.
- The given log shows that there are various gas zones in the formation.
- There are also one oil zone in the formation.
- There are, however, various shale beds separating gas zones from oil zones, that is, there is no visible gas-oil contact.
- There are also a few calcite streaks and a coal streak in the given formation.
- The log also shows that the average porosity in the gas zone is around 27.27% whereas the average water saturation is around 11.6%.

- The zone from 12770'-12890' is a tricky zone. The fluid present is uncertain. Thus inconclusive.

Recommendations for LWD interpretation

- Oil zone should be perforated first and then the gas caps should be exploited.
- MDT analysis of the zone from 12770'-12890' should be done.. We can also go for the stethoscope tool to get the fluid pressure gradients which will help in fluid identification.

The Rxo log is also required to understand better the well fluid invasion compromising the hydrocarbon zone

CHAPTER 7

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