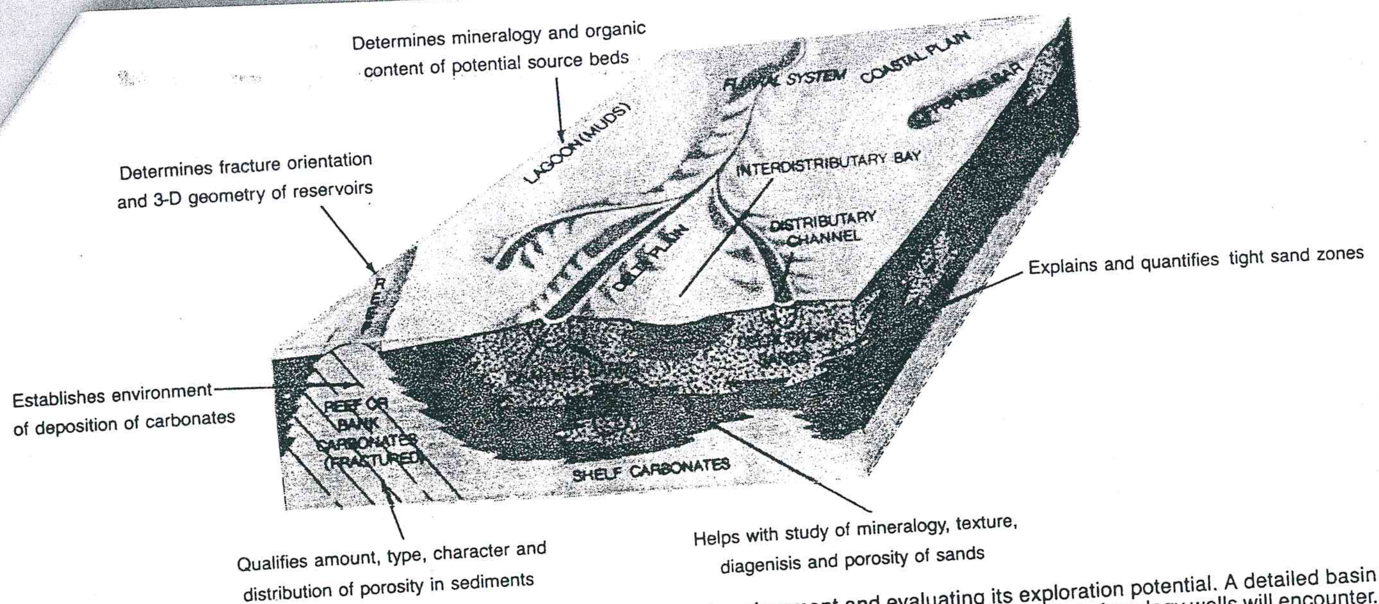


Fig. 6—A number of factors are involved in understanding a depositional environment and evaluating its exploration potential. A detailed basin analysis takes into account these factors and can give the operator a virtual three-dimensional picture of the kind of geology wells will encounter.

TABLE 3—Engineering data obtained by core analysis

- Porosity distribution and magnitude (histogram)
- Permeability distribution and magnitude (histogram)
- Permeability heterogeneity (Lorenze coefficient, variance factor)
- Porosity vs. permeability relationships
- Reservoir water saturations (oil-base cores)
- Reservoir residual oil saturations and distribution (pressure and sponge core)
- Data for calibration and refinement of downhole log calculations
  - Grain density
  - Calcimetry (limestone/dolomite ratio)
  - Acoustic velocity
  - Gamma ray characteristics (core gamma and core spectral)
  - Electrical properties ("m" and "n")
  - Mineralogy and clay type, distribution and quantity
- Special core analysis
  - Relative permeability
  - Formation wettability
  - Capillary pressure (water-retention properties)
  - Pore volume compressibility
  - Rock-injected fluid compatibility
  - Residual gas (trapped by water)
  - Performance evaluations
    - Water flood
    - Enhanced oil recovery
- Oil shale assay
  - Hydrocarbon yield
  - Water recovered
  - Spent shale
- Geotechnology (rock mechanics)
  - Compressive strength
  - Poisson's ratio
  - Young's modulus
  - Hardness
  - Tensile strength
- Oil or bitumen quantity/unit volume of reservoir (tar sands)

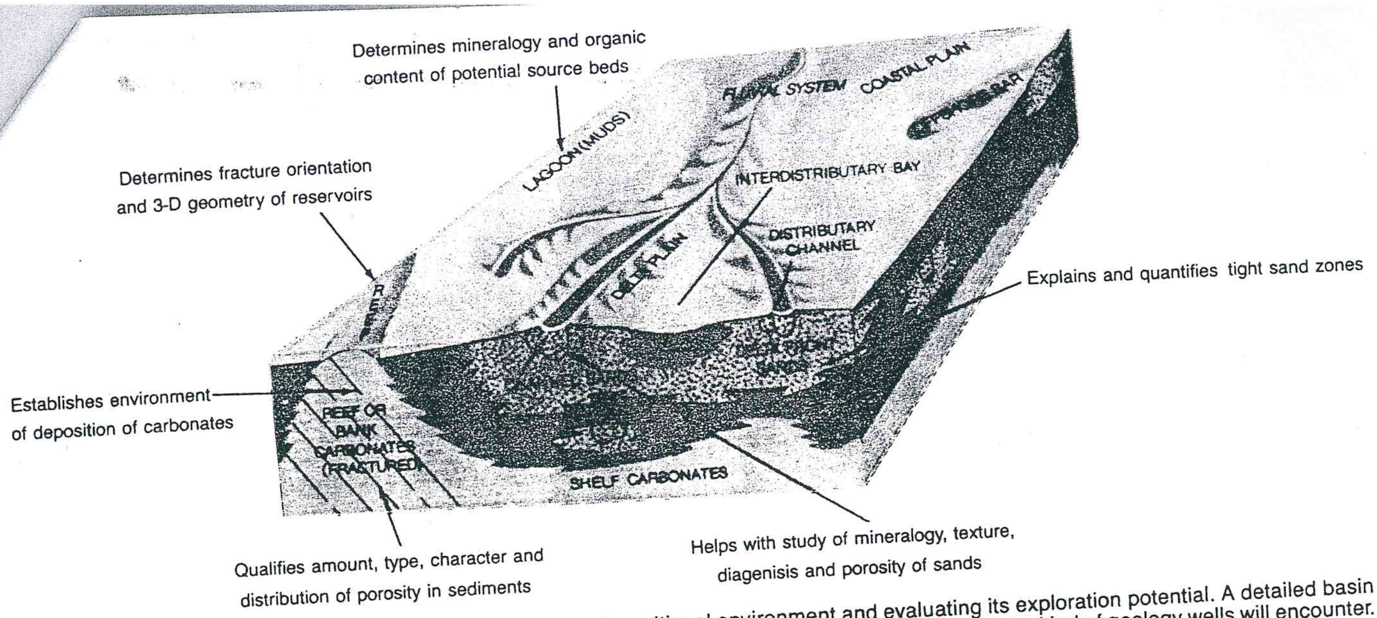
with audio lithologic description is another new and innovative means of recording and presenting core data.

Special core analysis. This field consists of several more complex and time-consuming measurements that extend and supplement the more commonly available information. A number of these tests are utilized in reservoir engineering applications, as they furnish information to quantify oil-in-place (capillary pressures), fluid flow characteristics (relative permeability—see Fig. 3) and recovery anticipated with various improved recovery schemes (waterflood and enhanced oil recovery). Log-related parameters such as formation factor-porosity and acoustical properties are also measured, and these relieve the need to use published, average values that may be inappropriate.

Drilling, completion, workover and injection fluid reactions with the reservoir rock can be evaluated with special core analysis so that suitable fluids can be selected that will not damage the formation or reduce productivity. These special tests are generally made on fewer samples than used for routine measurements, yet the variation noted in the routine data forms the basis of subsequent special core analysis sample selection.

Petrology. The study of rock composition, characteristic and origin of sediments, adds depth to information gener ated by both *conventional* and *special* core analysis. Its use ha expanded as instrumentation has improved and been re duced in cost, and as operator awareness of the cost benefi from utilizing the information has increased. Detailed co descriptions are aided by microscopic examination that i cludes thin section analysis, X-ray diffraction analys (XRD) and scanning electron microscopy (SEM). The data yield information on depositional environmen diageneses, reservoir potential, porosity type and contr potential completion damage or production problems a authigenic (formed-in-place) minerals.

An example SEM photograph illustrating the presence montmorillonite in the pore space is shown in Fig. 4. It fo warns of the potential formation damage that may occur permeability reduction from freshwater drilling, complet or injection fluids. The potential also exists for high irred ible water and abnormally low resistivity in hydrocarl productive zones. Permeability damage can be quantified sensitivity studies utilizing special core analysis fluid f tests, and irreducible water can be determined from ca



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Thick formations of constant and known chemical composition that have undergone little alteration after deposition, that contain no mineral impurities within the pore space, or that have water of constant salinity, can likely be evaluated adequately without cores for completion purposes or to determine oil-in-place. Unfortunately, this ideal case is seldom encountered in the real world, and core data are still required to evaluate subsequent improved recovery schemes.

CONSIDERATIONS PRIOR TO CORING

When sampling a particular reservoir, coring operation objectives should be clearly defined and established early. These objectives influence the type of core to be cut, its size, coring fluid to be used and the analysis to follow. Most coring devices require that a coring point be predetermined so that the tool may be attached to the bottom of the drillstring. Unless a total section in the well is to be cored, some geologic control is required. Otherwise, data such as gas shows, oil shows or drilling breaks supplied by a hydrocarbon well logger are used to indicate the coring point.

One type of wireline coring tool allows a center plug to be recovered from the drill bit so that coring can be done at any selected depth. Another tool allows recovered cores to be spatially oriented, while others allow reservoir pressure to be maintained during core recovery. All of these, run at the bottom of the drillstring, supply a continuous vertical section of core from 2 to 8 in. in diameter from which needed information may be derived.

Percussion sidewall and the sidewall drilled cores now under development have a unique advantage in that coring points are selected after the well is drilled and downhole logs have been run to identify zones of interest. Unfortunately, these devices do not furnish a continuous core, since they sample small portions of the reservoir at selected intervals. While they are of tremendous value in formation evaluation and for petrographic studies, alteration of percussion sidewall cores makes them unsuitable for the *special core analysis* tests that furnish hard engineering data. It is anticipated, however, that tools such as the new sidewall device designed to drill 1-in.-diameter cores at right angles to the wellbore will overcome this latter limitation.

CORE ANALYSIS

Conventional core analysis. Of all commonly available coring methods, this is the most important source of information in that it furnishes measured values of basic rock properties. Porosity, permeability, residual fluids, lithology and texture are some of the parameters that characterize a core vertically, and representative samples are commonly taken every foot (and more frequently when core examination indicates the need).

A quick look at these cores and their tabulated and plotted data identifies zones of greatest storage capacity (porosity), greatest flow potential (permeability) and the presence of and magnitude of residual oil (Fig. 1). Relative changes in these properties with depth are easily observed, and average properties of selected zones can be compared for relative quality. Grain size, an indication of sorting, color of the rock, presence of laminations and other important structures are described. Fractures, vugs, and color, intensity and distribution of oil fluorescence are also reported. Supplementary data such as grain density, grain size distribution, cation exchange capacity and acid solubility typically are furnished on request.

Core photography offers a permanent and objective record of both the core's appearance and fluorescence (Fig. 2). The presence of oil-saturated rock and non-fluorescing shale zones are thus documented, and a record of the preserved core is established. This is of particular value for needs that may occur years after the core is cut (i.e., net pay determination) or when well participants are located at prohibitive travel distances from the point of analysis. Color videotape

TABLE 1—Geological data obtained by core analysis

- Formation lithology (sandstone, limestone, dolomite, etc.)
- Texture (grain size, distribution, and orientation)
- Sedimentary structures (laminations, cross-bedding, root casts, worm burrows)
- Porosity type (storage capacity)
    - intergranular — vugular-moldic
    - intragranular — fracture
    - intercrystalline — microporosity
- Permeability (flow capacity)
- Rock color
- Presence or absence of oil (fluorescence)
- Formation presence and thickness (tops and bottoms)
- Formation sequence
- Formation age, facies and correlation (biostratigraphy)
- Depositional environment
- Fracture definition
    - depth and occurrence — width
    - length — mineralization
    - dip angle — staining
    - dip azimuth
- Diagenesis (chemical, physical and biologic changes after deposition)
- Geochemical (source bed studies)
    - organic richness — thermal maturity
    - type of organic matter — liquid hydrocarbon potential
- Trace elements and insoluble residues
- Paleomagnetism
- Permanent record of core appearance and fluorescence (core photo)

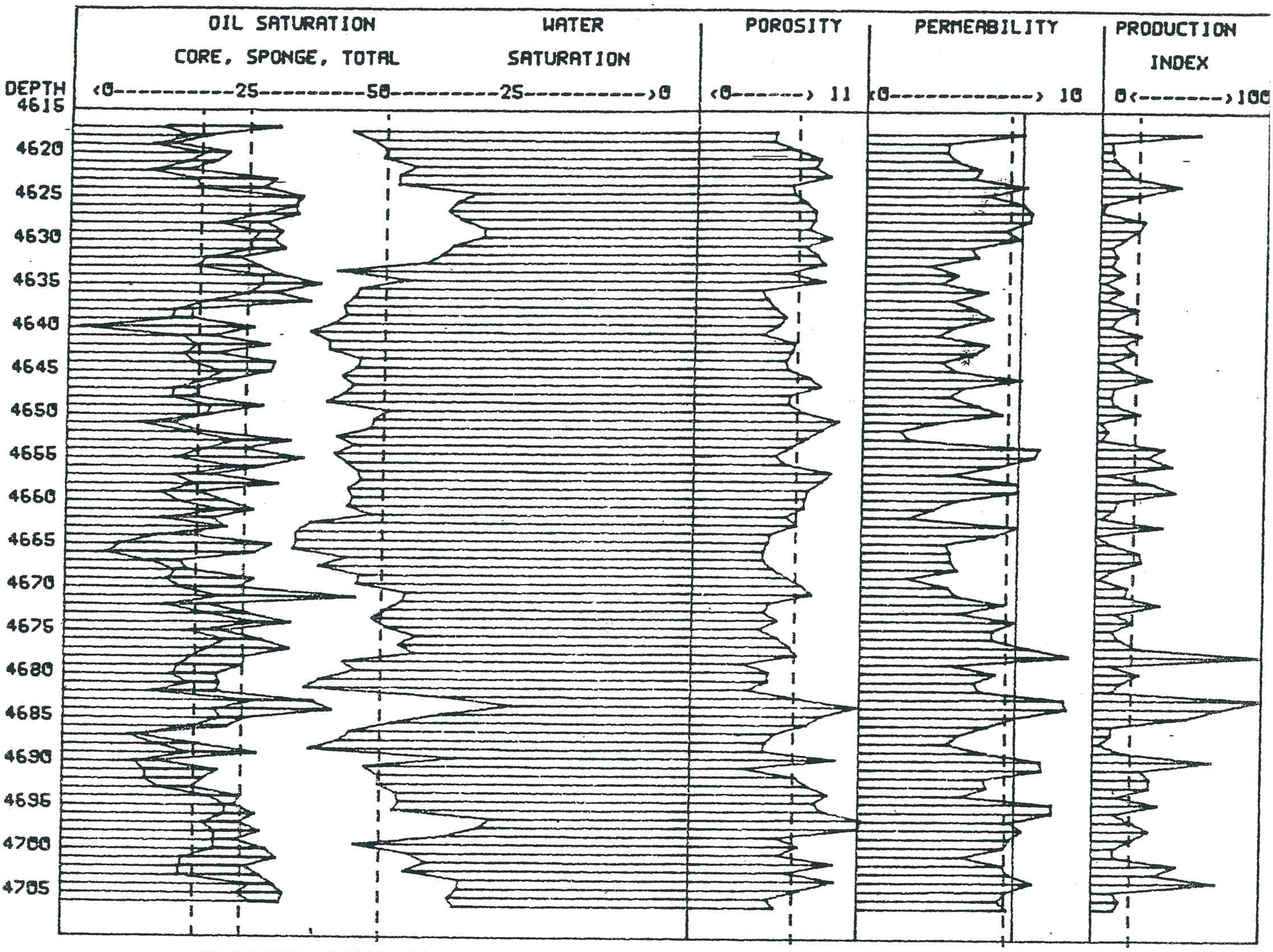
TABLE 2—Completion data obtained by core analysis

- Mineralogy (fabric and pore filling minerals type and occurrence)
- Clay morphology (form and structure)
- Clay distribution and quantity
- Porosity magnitude and distribution
- Residual oil quantity and distribution
    - Type of fluid production expected
    - Gas-oil and oil-water contacts
- Grain size distribution (gravel pack selection)
- Formation-rock compatibility with completion and workover fluids
- Vertical permeability (define need for frequency of perforations and cross flow expected)
- Horizontal permeability (selection of perforation intervals)
- Critical water estimates (quantity of water held immobile)
- Acidization susceptibility and fracture treatment design

DOWDCO SPONGE CORE DATA GRAPHICS

MAJOR OIL COMPANY SPONGE WELL #1

SAN ANDRES FORMATION ECTOR COUNTY TEXAS



AVERAGE CORE OIL: 21.5 AVERAGE TOTAL OIL: 29.8

AVERAGE SPONGE OIL: 8.3 AVERAGE WATER SATUR.: 50.7

AVERAGE POROSITY: 6.7 AVERAGE PERMEABILITY: .7

FORMATION VOLUME FACTOR: 1.1

Well Logging

A well log is a tabular or graphical portrayal of any drilling condition(s) or subsurface feature(s) encountered which relate to either the progress or evaluation of an individual well.

For example – The records of core analysis data vs. depth, shown in this handout figure are often called core logs.

Common logs ⟹
Electric logs
Radioactive logs

1. Driller's logs (including drilling time)
2. Sample logs
3. Mud logs
4. Electric logs
5. Radioactivity logs
6. Misc. logs

Electric logging – A method of formation evaluation was developed by Conrad + Marcel Schlumberger and was introduced to the US in 1920.
Electric logging became a standard practice in 1935.

An electric log – Considered as a plot of certain electrical properties of the ~~st~~ strata in contact with the well bore. These properties are measured by various electrode configurations which are lowered into the borehole on electric cables.
The standard electric log presents two different sets of graphs.

The left-hand side shows the spontaneous potential (SP), while the resistivity measurements are recorded on the right

Basic Concepts:

The resistivity of a material is the specific resistance which it offers to the flow of electric current. In this regard it is much like sp. gravity or density as opposed to weight.

$$R = \frac{rA}{L}$$

where R = resistivity of media or conductor thru which current is flowing

r = resistance of conductor

A = Cross-sectional area of conductor

L = length of conductor

The practical units of R as used in electric logging are

$$\text{ohms} \times \frac{\text{meters}}{\text{meters}} \quad \text{or simply}$$

ohm-meters...

A conductor having an area of one m^2 and a length of 1 m and offering one ohm resistance to current flow is said to have a resistivity of 1 ohm-meter.

~~Fluid Resistance~~

Fluid Resistivities

Dry sedimentary rocks are non-conductive, their resistivity is extremely high.

Shales – are conductors, their low resistivity is due to a high interstitial water content.

Oil & gas are also insulators and will not conduct an electric current.

Resistivity of water depends on its salinity & temp.

Resistivity of mud filtrate

$$R_{mf} = 0.75\ R_m$$

where R_{mf} = mud filtrate resistivity at a particular temp., ohm-meters

R_m = mud resistivity at the same temp. ohm-meters

Resistivity of mud cake

$$R_{mc} = 1.5\ R_m$$

Formation Resistivities

Any conductivity by sedimentary rock strata is attributed to interstitial fluid content.

The only exceptions to this rule are a few sands which contain glauconite & Pyrite, both of which are conductors.

For a particular porous medium:

(1) The greater the water content, the lower will be the formation resistivity.

(2) A rock which contains an oil and/or gas saturation will have a higher resistivity than the same rock completely saturated with formation water.

These (1) + (2) form the principal basis for electric log interpretation and are completely valid except for those cases when the formation water is relatively fresh (only slightly saline).

A fundamental definition is the following:

R_o = the resistivity of a rock which is 100% saturated with formation water.

$R_o > R_w$ (resistivity of formation wtr.)

(a) $$R_o = F R_w$$

where F = formation factor

Experimental evidence has shown that porosity, ϕ, and F are related by the eqn.

(b) $$F = \phi^{-m}$$

where m = cementation factor

Equations (a) + (b) are from the work of G.E. Archie — + referred to as Archie's Equations

* ✓ A rock which has an oil or gas saturation will exhibit a higher resistivity than the same rock with 100% water saturation.

Further, the greater the hydrocarbon saturation, the greater will be the resistivity.
This behavior is expressed by the empirical relationship of Archie equations:

$$S_w = \left(\frac{R_o}{R_t}\right)^{1/n} = \left(\frac{F R_w}{R_t}\right)^{1/n} = \left(\frac{\phi^{-m} R_w}{R_t}\right)^{1/n}$$

where S_w = water saturation of the rock in question

R_t = true resistivity of the formation, ohm-meters. (the word "true" is used to distinguish between this and the apparent value read from a log. Apparent values may or may not require corrections to convert them to R_t).

n = saturation exponent. For clean, water-wet rocks $n \approx 2$ is commonly used. The precise value of n for shaley or oil-wet rocks is difficult to obtain and discussion of it is beyond our treatment. The range for shaley sands is between 1 – 1.7. For oil-wet rocks, n = 2 to 16.

Radioactivity Logs

✓ All electric logs must run in an open hole, to avoid short circuits thru the steel casing. This restriction does not apply to radioactivity logs, which may be run in either open or cased holes.

Two curves are included in a complete log of ~~Types~~ this type:

measures → Gamma ray — Similar to X-ray (electromagnetic waves) are able to penetrate several inches of rock or steel. (@ a power of 10,000)

the radioactivity of sediments (defining the lithology)

Newtron Log — Newtrons exist in the nucleii of all elements except hydrogen — same mass as H atom but have no charge

Applications of Radioactivity Log

- Porosity determination:
  - Density log tool
  - Newtron log tool
  - Sonic log —

Logging Devices } or special well logs
Acoustic logs
Caliper "
Temperature logs

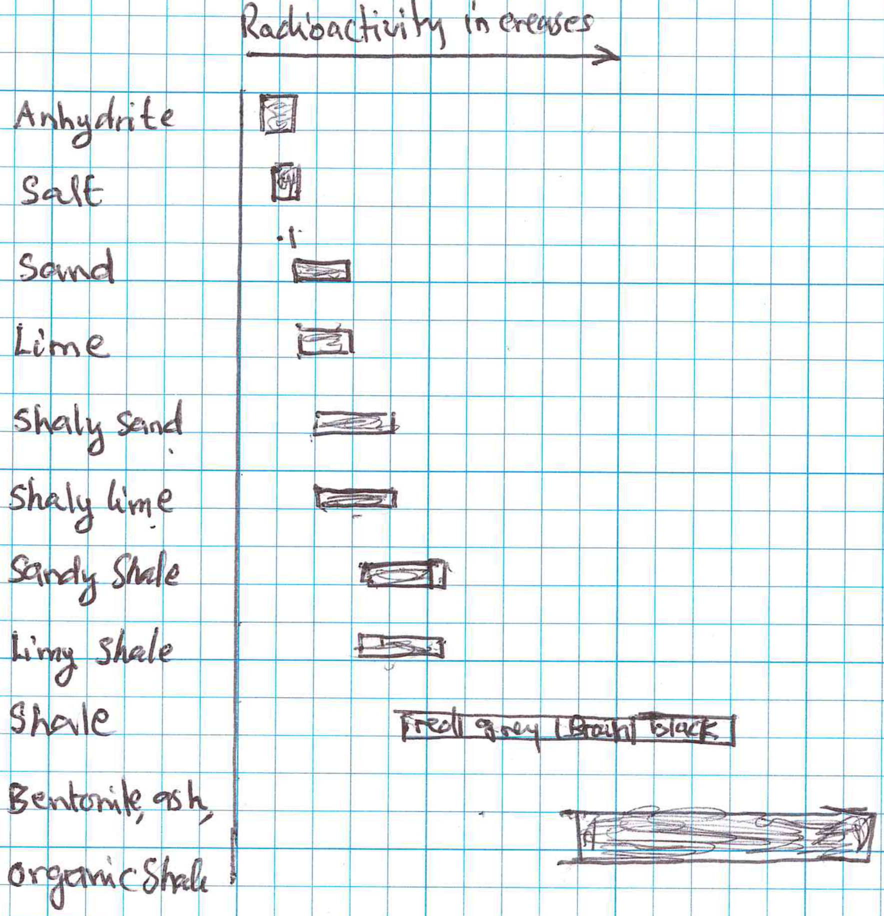
The principal radioactive families of elements are:

1- The uranium-radium series
2- The thorium series
3- The actinium series
4- The potassium isotop K^{40}.

Nearly all sedimentary rocks contain traces of of radioactive salts and, as a consequence, emit measurable radiation

This figure show the relative intensity of gamma radiation in typical Sedimentary rocks.

Relative intensity of gamma radiation of Sedimentary rocks



Relative radioactive range of rocks

Radioactive techniques have been extremely useful in logging old well which were cased and completed in the erea when the driller's log was the only recorded source of information,

Both the gamma & neutron ~~logs~~ curves give good definition of formation + porous zone boundaries.

Neutron ~~log~~ Curve is able to distinguish gas from oil or water. this is due to the lower H. density of gas at low pressures.

special Radioactive logs

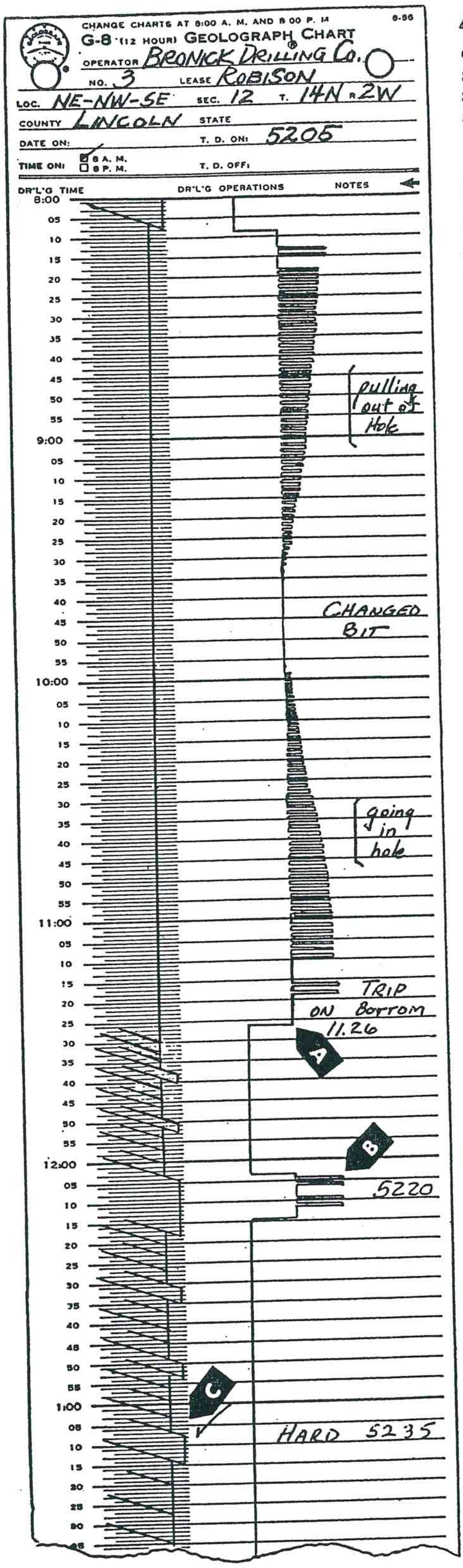
Acoustic logging (Continuous Velocity)

Caliper ~~logging~~ logs — A presentation of hole size, either

~~The Well Completion~~

diameter or area, vs. depth.

Dip Logs → A record of formation dip, both angle and direction, vs. depth.



A Line in drilling operations column moves to the left indicating that driller got on bottom with new bit and started drilling at 11:26. Total trip time, as indicated by "Trip Action", 3 hours and 17 minutes.

B This is the way a connection looks on the Geolograph chart. The driller raised the drill pipe from bottom at 12:03, broke out the kelly, picked up a single pipe (adding it to the drilling string), picked up the kelly and resumed drilling. This operation required 11 minutes, and the driller has written the depth of the hole, at that time, on the chart. Thus, every connection is a convenient datum for determining the depth of any drilling or down-time break, either immediately above or below.

C A 4-foot hard streak was encountered at 5,235 feet, as indicated by the increased spacing of the foot marks on this time chart.

D A connection was made at 5,259 feet and a vertical test was run at this point to determine the vertical deviation of the hole. The driller has noted on the chart that the test was actually taken at 5,250 feet and the deviation was ½ degree. The vertical test and connection required 34 minutes.

E Soft bed was drilled from 5,266 to 5,269 feet. Because of the thinness of this bed, no core or drill stem test was attempted.

F This section represents 5 feet of drilling. Note that every 5 feet the base line is offset for 1 foot, making a convenient marker for determining the depth of significant drilling changes.

G Connection was made at 5,287 feet. Note similarity to the record at "B".

H A hard streak was encountered from 5,288 to 5,290 feet.

I At 5,290 feet, the formation softened, drilling continued to 5,300 feet where the driller was given orders to cease drilling and circulate for samples.

J Circulating for samples started at 6:39 as indicated by movement of the line to the right. After circulating for 35 minutes, samples showed stain and odor, and a drill stem test was ordered.

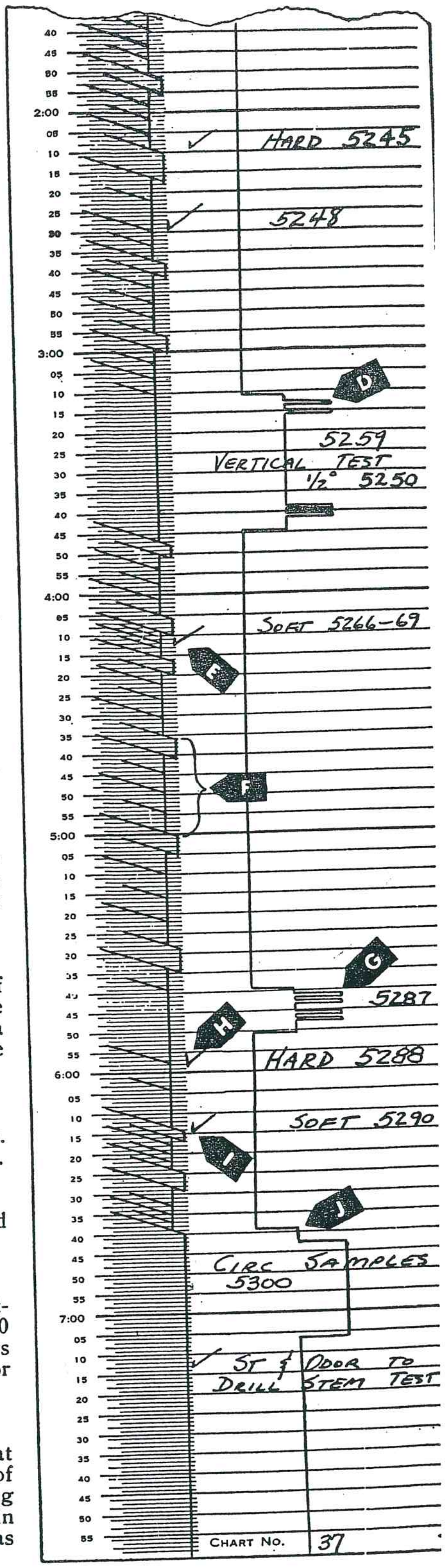


Fig. 11.1. Typical mechanical drilling log record. Courtesy Geolograph Mechanical Well Logging Service.

Drillers Logs

TABULAR DATA and INTERPRETATION

No Fracture--NF
Vertical Fracture--VF

Sample Number	Depth Feet	Perm. MD.	Porosity %	Residual Saturation % Pore Space: Oil	Residual Saturation % Pore Space: Total Water	
29	4805.5	0.0	7.5	0.0	68.0	NF
30	06.5	0.0	12.3	0.0	78.0	NF
31	07.5	2.5	17.0	0.0	43.0	NF
32	08.8	59	20.7	0.0	29.0	NF
33	09.5	221	19.1	0.0	31.4	NF
34	10.5	211	20.4	0.0	38.7	VF
35	11.5	275	23.3	0.0	34.7	NF
36	12.5	384	24.0	0.0	26.2	NF
37	13.5	108	23.3	0.0	30.9	NF
38	14.5	147	16.1	0.0	29.2	NF
39	15.5	290	17.2	0.0	34.3	VF
40	16.5	170	15.3	0.0	24.2	NF
41	17.5	278	15.9	0.0	26.4	NF
42	18.5	238	18.6	0.0	39.8	NF
43	19.5	167	16.2	0.0	39.5	VF
44	20.5	304	20.0	0.0	38.0	VF
45	21.5	98	16.9	0.0	34.3	NF
46	22.5	191	18.1	0.0	34.8	VF
47	23.5	266	20.3	0.0	31.1	VF
48	24.5	40	15.3	0.0	22.9	VF
49	25.5	260	15.1	0.0	13.9	VF
50	26.5	179	14.0	0.0	21.4	VF
51	27.5	312	15.6	0.0	28.8	NF
52	28.5	272	15.5	0.0	34.8	VF
53	29.5	395	19.4	6.2	25.3	NF
54	30.5	405	17.5	13.1	25.7	VF
55	31.5	275	16.4	17.7	22.5	NF
56	32.5	852	17.2	19.8	19.2	VF
57	33.5	610	15.5	21.9	21.3	VF
58	34.5	406	20.2	16.3	22.3	VF
59	35.5	535	18.3	19.7	24.6	VF
60	36.5	663	19.6	19.4	16.3	VF
61	37.5	597	17.7	17.5	19.8	VF
62	38.5	434	20.0	14.0	27.5	VF
63	39.5	339	16.8	20.8	19.7	VF
64	40.5	216	13.3	18.1	23.3	VF
65	41.5	332	18.0	15.6	15.6	VF
66	42.5	295	16.1	19.3	15.5	VF
67	43.5	882	15.1	19.2	21.2	NF
68	44.5	600	18.0	20.6	22.2	VF
69	45.5	407	15.7	15.3	13.4	VF
70	4847.5	479	17.8	20.8	14.6	VF
71	48.5	0.0	9.2	14.1	8.7	NF
72	49.5	139	20.5	0.0	77.1	NF
73	50.5	135	8.4	0.0	57.2	NF
74	51.5	0.0	1.1	0.0	63.6	VF

COMPLETION COREGRAPH

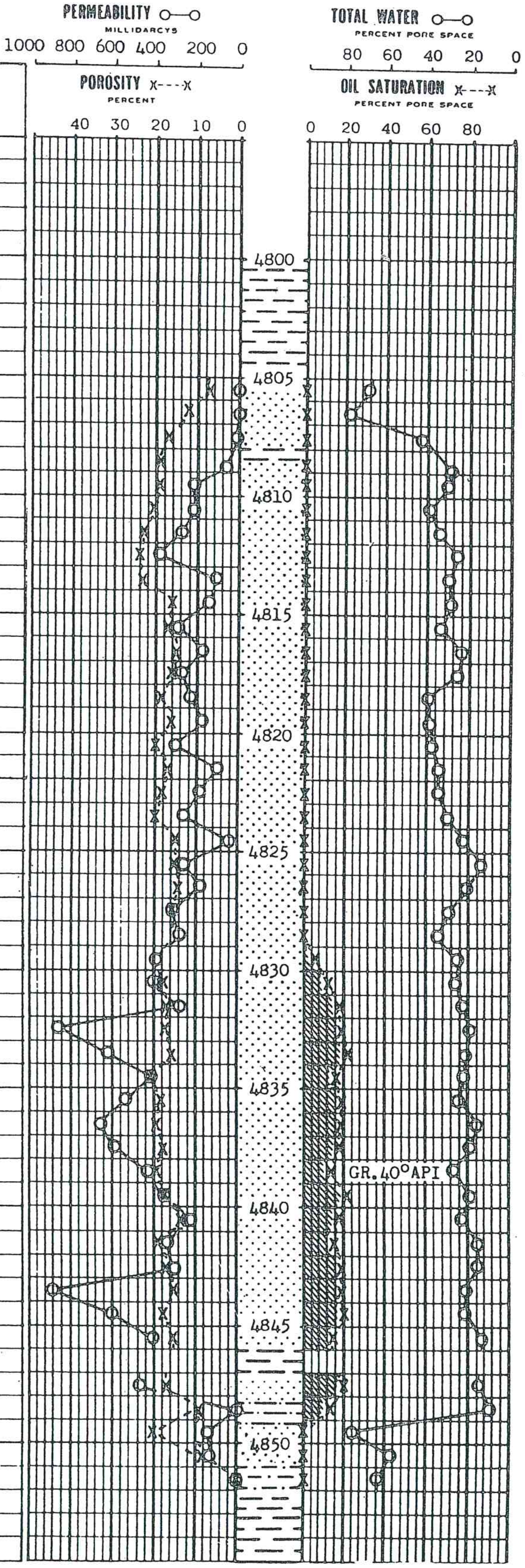


Fig. 10.30. Sample core analysis report. Courtesy Core Laboratories, Inc.

Gamma Ray Log

The Gamma Ray log is a recording of the naturally occurring gamma rays in the formations adjacent to the borehole. Since radioactive elements tend to concentrate in shales and clays in sedimentary rocks, the Gamma Ray log can be used to indicate through pipe the shale content of the formation.

The Gamma Ray tool is effective in any environment so it is the standard device for correlating cased hole logs with openhole logs.

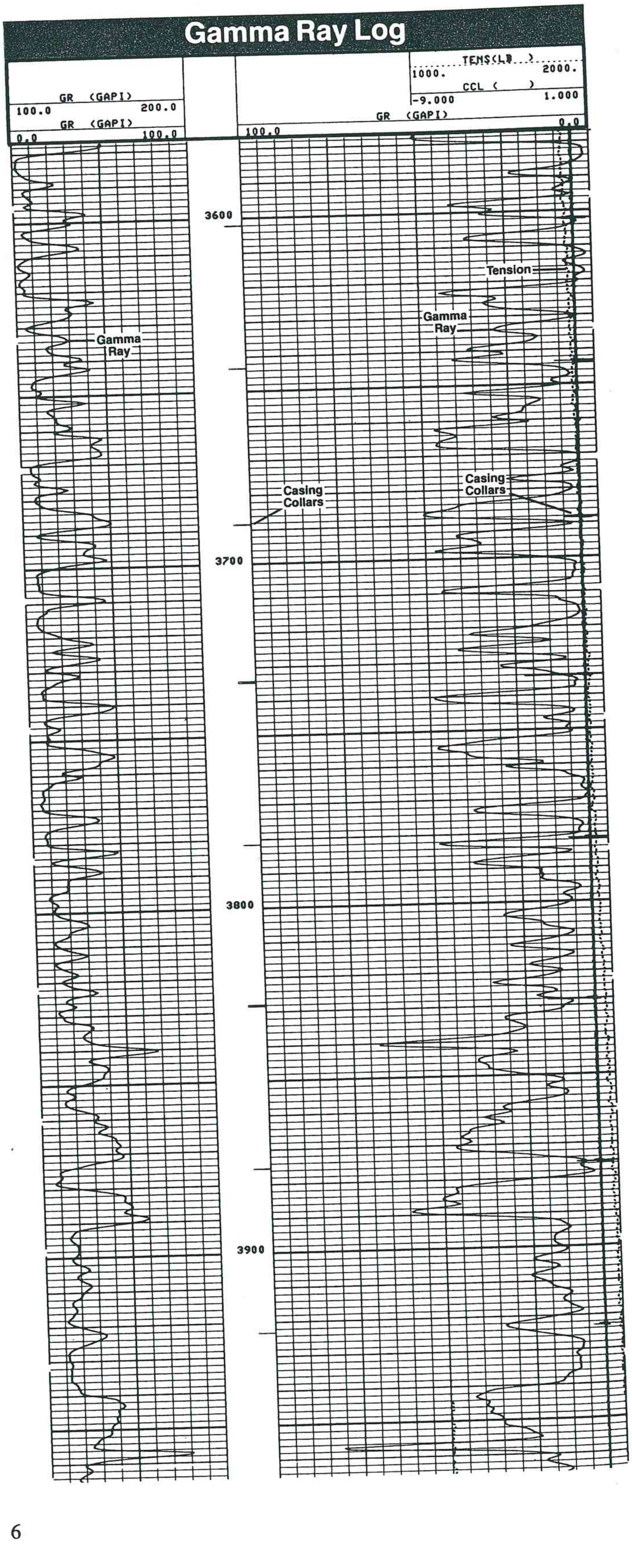
Combination perforating gun-Gamma Ray tools are available for depth control and perforating on a single trip. This combination saves significant time in certain cases where perforating is the only service required.

Principal Applications

- Depth control–correlating openhole and cased hole services
- Discrimination between shales and nonshales
- Estimation of shale content in reservoir rocks

Tool Specifications

OD in.	Max. Press. psi	Max. Temp ^{0}F
1 11/16	20,000	350
2 3/4	20,000	450
3 3/8	20,000	350



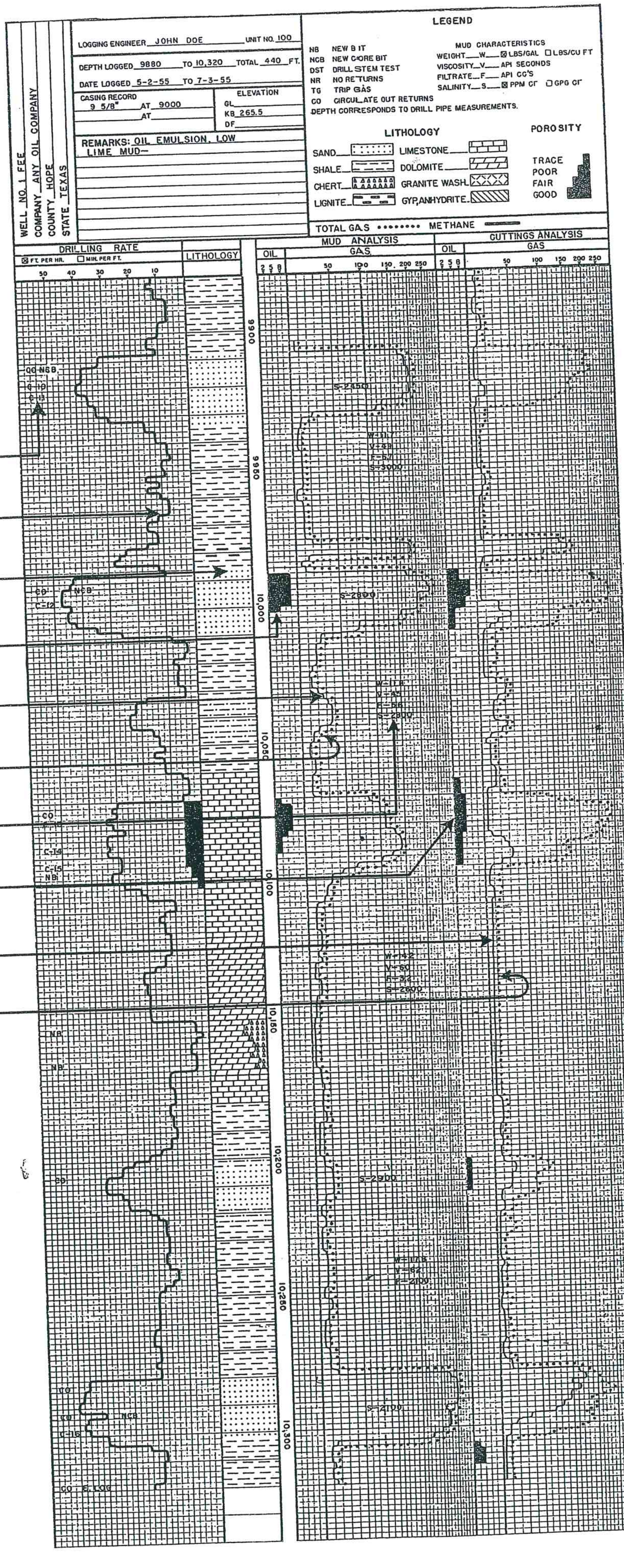


Fig. 11.2. Mud logging report. Courtesy Baroid Sales Division, National Lead Company.