

22.01 Introduction to Ionizing Radiation
Fall 2003

Lecture Notes on "Well Logging" (S. Yip, 11/19/03)

Introduction

Study of geological formation on Earth is a fundamental scientific undertaking as well as a practical endeavor which affects human society in the most profound manner – it is the problem of energy resources worldwide, the exploration and extraction of oil and gas.

We are interested in a particular aspect of the oil-well logging science and technology, the use of nuclear techniques in the determination of hydrocarbon contents in the rock formation. In this brief look we will focus on a description of the problem and the principles underlying the measurement of neutron logs which enable the determination of the formation porosity.

I. Basic Concepts

1. A "log" in the oil industry means "a recording against depth of any of the characteristics of the rock formation traversed by a measuring apparatus in the well-bore".
2. Logs, sometimes referred to as "wireline logs" or "well-logs", are obtained by means of measuring equipment (logging tools) lowered on cable (wireline) into the well. Measurements are transmitted up the cable to a surface laboratory or computer unit; the recording of this information on film, paper, or magnetic tapes constitutes the well-logs.
3. Geology is the study of the rocks making up the Earth's crust. The aspect of geology most important to the oil industry is sedimentology, which involves a precise and detailed study of the composition, texture and structure of the rocks.
4. The geologist depends on rock samples for his basic information. Surface samples have a known point of origin and are easily available; however, the information may not be what is relevant. Subsurface samples, cuttings and cores obtained from drilling, can suffer from difficulty in characterization due to measurement imprecision, contamination, etc. An alternative is to take in situ measurements by running well-logs. In this way, parameters pertaining to porosity, lithology, hydrocarbons, and other rock properties can be obtained.
5. Porosity is the fraction of the total volume of a rock that is not occupied by solid constituents. [It is dimensionless, expressed as a percentage (30%), a decimal (0.30), or in porosity units (30 p.u.).] There are several types.

$$\text{Total porosity } \phi_t = \phi_t = (V_t - V_s) / V_t = V_p / V_t$$

where V_p, V_s, V_t are volume of empty space (pore and channel, generally occupied by oil, gas or water), solid materials, and entire rock, respectively. See Fig. 1-2.

6. Lithology refers to the nature and percentage of clays present, and traces of conductive minerals.

7. First concern is to determine the rock composition - mineralogy and proportions of the solid constituents ("matrix" and "shale") and the nature and proportions (porosity, saturation) of the interstitial fluids. See Fig. 1-2. A simple matrix lithology can consist of a single mineral such as calcite or quartz. Shale is a fine-grained sedimentary rock formed by the consolidation of clay or silt. Fluids here refer to water, air, gas, oil, tar, etc. Just how much fluid is contained in a rock depends on the space, or porosity, available.

8. With the exception of water, pore-fluids have one important property in common with the matrix minerals - poor electrical conductivity. Water, on the other hand, is a relatively good conductor by virtue of the dissolved salts. Thus resistivity of a formation is an important log measurement. Knowing the percentage of water in the rock and also the porosity one may deduce the percentage of hydrocarbon present (the hydrocarbon saturation).

9. The first well-log, an electrical resistivity measurement, was made by Marcel and Conrad Schlumberger in 1927 in France. Since then scientific and technological advances have led to the development of a vast range of highly sophisticated measuring techniques and equipment.

10. Log data constitute a "signature" of the rock: the physical characteristics they represent are the consequences of physical, chemical, and biological conditions prevalent during deposition and evolution through the course of geological history. Log interpretation therefore should have the same objectives as conventional laboratory core-analysis. This is feasible only if there exist well-defined relationships between the log measurements and the rock parameters of the interest. (This statement is applicable to any diagnostic technique in science.

II. Logging Techniques and Measurements

11. Log measurements fall into two broad categories: natural phenomena where only an appropriate detector is required, and induced phenomena where in addition one needs some means of 'exciting' the response of interest in the rock formation. See Table 2-1.

12. We will focus on nuclear measurements which are carried out by irradiating the formation with gamma rays or neutrons. Following are the principal methods.

Formation Density: γ emitted from a source is scattered (Compton scattering) in the formation and detected in the form of gamma-gamma log.

Mean Atomic Number: Photoelectric absorption measured at low γ in the form of lithodensity log.

Hydrogen Index: High-energy neutrons sent into the formation are slowed down by successive elastic collisions with atomic nuclei, particularly hydrogen. Subsequent radiation is detection in several forms -- (a) neutrons slowed down to thermal energies (neutron-thermal neutron logging), (b) γ emitted when the thermal neutrons are captured by the atomic nuclei (neutron-gamma logging), (c) neutrons not yet slowed down to thermal energies (neutron-epithermal neutron logging).

Macroscopic Thermal Neutron Capture Cross Section: Measurement of decay rate of thermal neutrons in the formation following a burst of high-energy neutron emission (thermal neutron decay time logging).

Elemental Composition: γ emitted from interaction between high-energy neutron and certain atomic nuclei are analyzed spectroscopically -- (a) inelastic neutron scattering (carbon-oxygen logging), (b) neutron capture (chlorine logging), (c) activation and subsequent radioisotope decay (activation logging).

Proton Spin Relaxation Time: Pulsed DC magnetic field momentarily aligns the magnetic moments of the protons in the formation which then precesses about the Earth's magnetic field and gradually stops. The spin relaxation time can be used to evaluate residual oil in the formation (nuclear magnetic resonance log).

13. Log measurements are made using a apparatus called the sonde which is lowered into the borehole on a cable from a winch mounted on a logging truck or offshore unit. See Fig. 2-12. Data in the form of digital magnetic tape are first processed in the logging truck on site and then taken to a remote terminal for transmission via telephone line to log processing center or base station where the tape is played back and recorded as film log. See Fig. 2-28.

14. Well-bore temperature and pressure increase with depth as a function of geothermal gradient and mud density respectively. A deep well can reach 6 km (about 4 miles or 20,000 ft), where temperature, pressure can be 150C (300F), 15,000 psi (1000 atmospheres). Thus logging tools therefore must withstand very hostile environments of extreme temperatures and pressures. In addition, presence of corrosive gases, such as HS, may require special precautions and resistant equipment.

III. Neutron Logs

15. When the formation is bombarded by high-energy neutrons, several types of interaction can occur which lend themselves to logging techniques, as shown in Table 8-1. Neutrons from a radioisotope source have energies 4 - 6 Mev whereas neutrons from an accelerator typically have energies of about 14 Mev.

16. Source neutrons undergo fast capture or slowing down by elastic scattering. Some inelastic scattering and transmutation with subsequent γ emission can occur; these are relatively unimportant for our discussion. At the end of slowing down, the thermalized neutrons can be captured or cause transmutation. Hydrogen is the most effective element for slowing down neutrons, while chlorine is most effective for thermal capture. See Tables 8-2 and 8-3, and Figs. 8-2 and 8-3.

17. The neutron energy loss vs time and the spatial distribution of the neutrons and capture γ are shown in Fig. 8-4 for a point source in an infinite homogeneous medium. The thermal neutron density is constant over the surface of any sphere centered about the source and decreases with distance from the source. Same is true of the capture γ .

18. Neutron logs are measurements of the apparent concentration of hydrogen atoms per unit volume. The three major types are neutron-gamma, neutron-thermal neutron, and neutron-epithermal neutron.

Neutron-gamma log is based on the γ emission rate due to thermal neutron capture. Measurement is made using scintillation of Geiger-Mueller detectors. See Fig. 8-6.

Neutron-thermal neutron log is a measure of the as yet uncaptured thermal neutron density in the formation. He(3) detectors are used. See Fig. 8-7.

Neutron-epithermal neutron log gives the density of epithermal neutrons (energy between 100 eV and 0.1 eV) in the formation. See Fig. 8-8.

19. Hydrogen index (HI) of a material is defined as the ratio of hydrogen concentration [atoms per cm] to that of pure water at 75F. Pure water therefore has HI of 1.0. For hydrocarbons, HI ranges from nearly zero (low pressure gas) to close to 1.0 (heavier oils).

See Table 8-4 for a number of reservoir fluids and minerals.

20. Since hydrogen content of most pure rock grains (quartz, calcite, etc.) is zero, it follows that the neutron log is a porosity measurement, provided HI of the pore-fluid is 1.0. Under non-ideal condition, corrections for fluid characteristics and rock type will be necessary.

IV. Additional Topics

21. Capture of thermal neutrons results in emission of gamma rays which have discrete values characteristic of the absorbing element. This means each element has a capture γ signature which can be detected to signify its presence. Elements of greatest interest which can be treated in this way are hydrogen, silicon, calcium, and chlorine.

22. In addition to elemental identification, measuring the count rate of the capture γ leads to the determination of the relative proportions of the elements present in the medium. This is the basis for an induced capture γ spectroscopic analysis of the constituent elements and their abundance in the reservoir rock. An example is the chlorine log which gives information about salinity.

23. There are several types of nuclear logs besides the neutron logs which we have just described. See Table 5-1. Besides nuclear techniques, other methods such as electrical resistivity and acoustic (ultrasound) are also used. See Table 2-1.

24. For further reading, the following references are suggested.

References:

- O. Serra, *Fundamentals of Well-Log Interpretation*, Elsevier, Am
J. R. Hearst and P. H. Nelson, *Well Logging for Physical Propert*
York (1985).

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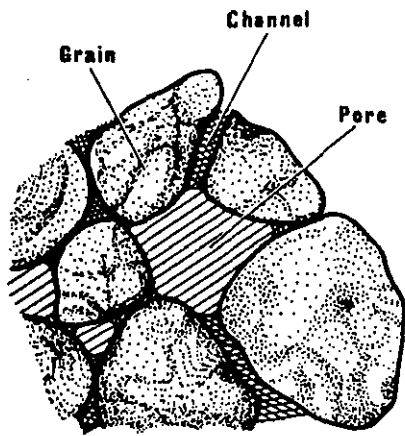


Fig. 1-2. Interstitial spaces in a clastic rock.

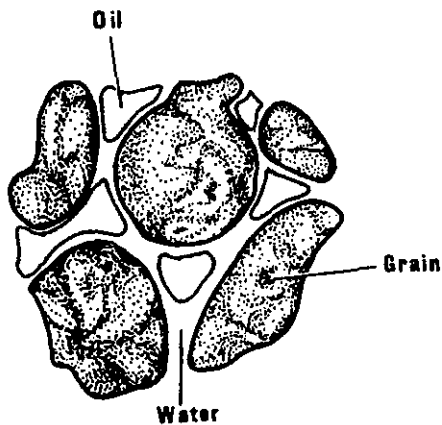


Fig. 1-16. Section of rock saturation by hydrocarbons. This particular rock is water-wet, the hydrocarbon is the non-wetting phase.

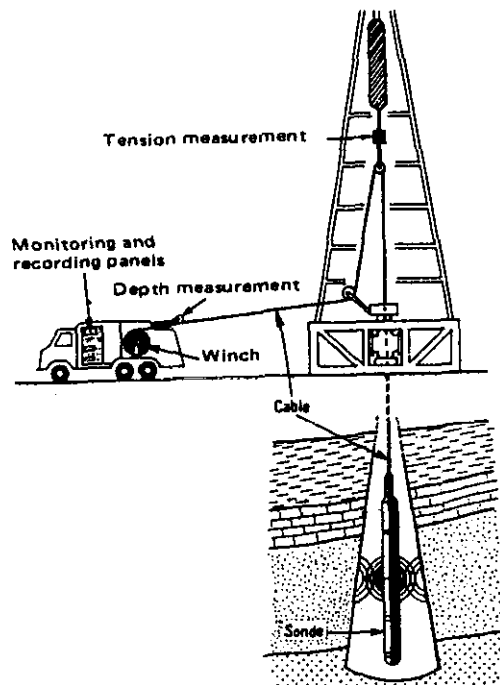


Fig. 2-12. Schematic representation of a logging "set-up" on a land-rig.

TABLE 2-1

A classification of log measurements

1. Natural or spontaneous phenomena

Basic equipment—Single detector (passive system)

Spontaneous potential	SP		
Natural gamma-ray activity			
Total	GR		
Spectrometry	NGS * (spectralog)		

Temperature	T
Hole Diameter	CAL
Deviation	DEV

2. Physical properties measured by inducing a response from the formation

Basic equipment—source (or emitter) + detector (s).

Resistivity:

(a) Long-spacing devices:

 non-focused:

 focused

(b) Micro-devices:

 non-focused

 focused

(c) Ultra long-spacing devices

Conductivity

Dielectric constant (electromagnetic propagation)

Hydrogen index (using neutron bombardment)

Neutron capture cross-section, or thermal neutron decay time (neutron lifetime) TDT *, NLL, GST *

Photoelectric absorption cross-section

Electron density

Relaxation time of proton spin (nuclear magnetic resonance)

Elemental composition (induced gamma-ray spectroscopy)

Acoustic velocity

Formation dip

Mechanical properties (amplitude of acoustic waves)

N(normal), L(ateral), ES
LL *, SFL *

ML *
MLL *, PL *, MSFL *
ULSEL

IL
EPT *
N, NE, NT *, SN(P) *
CN(L) *

LDT *

FDC *, LDT *, D, CD
NML

IGT *, GST *, HRS *

SV, SL, LSS *, BHC *, WST *

DM, CDM *, HDT *, SHDT *

A, VDL *

* Mark of Schlumberger

TABLE 5-1

Principle of the different nuclear logging techniques

Measurement principle	Schlumberger tool
<i>Natural radio-activity</i>	
Natural γ -radioactivity (total)	SGT(GR)
Natural γ -ray spectroscopy	NGT
<i>Radiation induced by neutron bombardment</i>	
Spectroscopy of γ -rays emitted by the activation of oxygen:	GST IGT
$^{16}\text{O}(n,p)^{16}\text{N}(\beta^-)$ $^{16}\text{O}^*(\gamma 6.13\text{MeV})^{16}\text{O}$	
or the activation of a wide range of elements	HRS
Spectroscopy of γ -rays emitted from fast neutron interactions (mainly inelastic):	GST IGT
eg $^{16}\text{O}(n,n'\gamma 6.13\text{MeV})^{16}\text{O}$, $t_{1/2} = 1.7 \times 10^{-11}$ sec	
Spectroscopy of γ -rays emitted by thermal neutron capture	GST IGT
Epithermal neutron density at a fixed distance from a high-energy neutron source	SNP CNT
Thermal neutron density at a fixed distance from a high-energy neutron source, by:	
(a) detection of neutrons themselves	CNT
(b) detection of gamma-rays arising from capture of the thermal neutrons	GNT
Decay rate of the thermal neutron population. The thermal neutron density is sampled at two different times between neutron bursts, by detecting the capture gamma-rays.	TDT
<i>Compton scatter of gamma rays</i>	
Gamma rays emitted from a source are scattered by the formation. The count-rate of those reaching the detector is measured.	FDC LDT*
<i>Photo-electric absorption</i>	
Low-energy gamma absorption by the photo-electric effect	LDT*
<i>Decay of proton spin precession induced by a strong magnetic field</i>	
Protons are caused to precess about the local Earth magnetic field by a strong DC magnetic pulse. This precession decays with a time characteristic of the formation fluids.	NML

* Note that the LDT makes both measurements.

TABLE 8-1

Schematic classification of neutron techniques in nuclear geophysics (from Braffman et al., 1977).

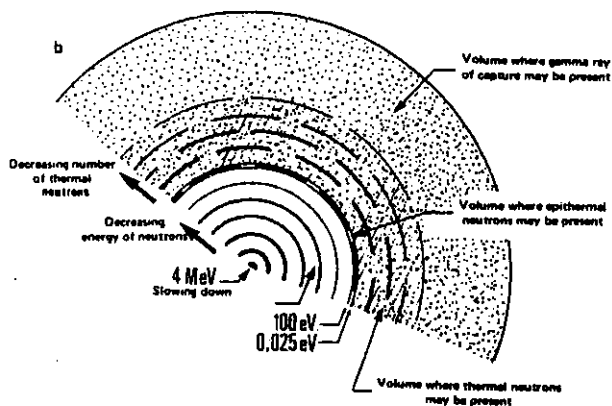
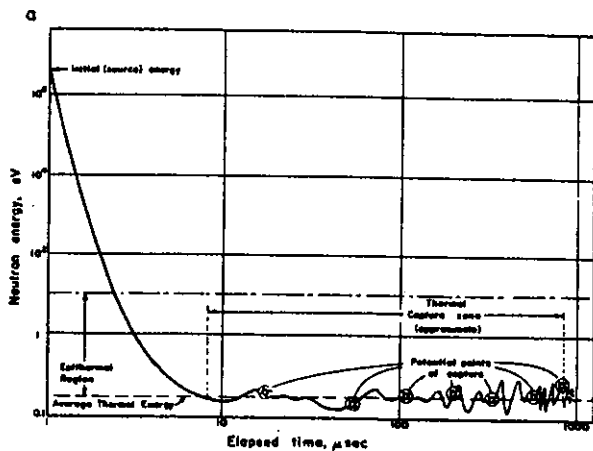
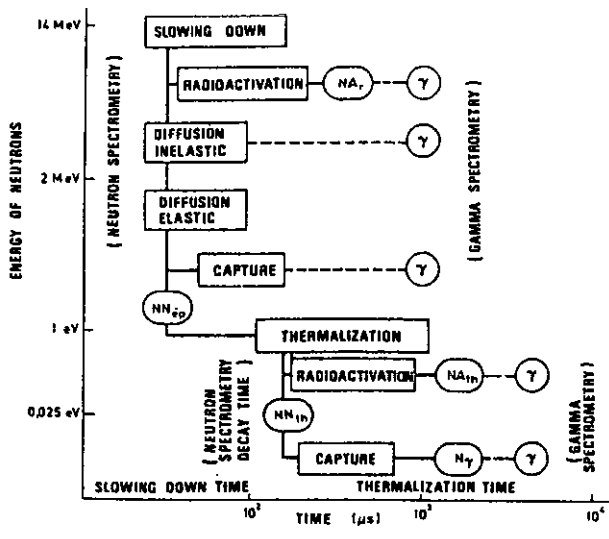


Fig. 8-4. a. Neutron energy versus time after emission (courtesy of Schlumberger). b. Schematic of spatial distribution of neutrons and gamma rays during continuous neutron emission.

TABLE 8-3

Slowing down power of elements (from I. Kaplan)

Element	Number of collisions needed to reduce the energy of neutrons from 2 MeV to 0.025 eV
Hydrogen	18
Carbon	114
Oxygen	150
Silicon	257
Chlorine	329
Calcium	368

* Nuclear Physics, Irving Kaplan.

TABLE 8-4

Hydrogen contents of some substances

Material	Number of hydrogen atoms per cm ³ (× 10 ²³)	Hydrogen Index
Water, pure		
60°F, 14.7 psi	0.669	1
200°F, 7000 psi	0.667	1
Water, salted,		
200 000 ppm NaCl		
60°F, 14.7 psi	0.614	0.92
200°F, 7000 psi	0.602	0.90
Methane CH ₄		
60°F, 14.7 psi	0.0010	0.0015
200°F, 7000 psi	0.329	0.49
Ethane C ₂ H ₆		
60°F, 14.7 psi	0.0015	0.0023
200°F, 7000 psi	0.493	0.74
Natural gas (mean)		
60°F, 14.7 psi	0.0011	0.0017
200°F, 7000 psi	0.363	0.54
N-octane C ₈ H ₁₈		
68°F, 14.7 psi	0.667	1.00
200°F, 7000 psi	0.639	0.96
N-nonane C ₉ H ₂₀		
68°F, 14.7 psi	0.675	1.01
200°F, 7000 psi	0.645	0.97
N-decane C ₁₀ H ₂₂		
68°F, 14.7 psi	0.680	1.02
200°F, 7000 psi	0.653	0.98
N-undecane C ₁₁ H ₂₄		
68°F, 14.7 psi	0.684	1.02
200°F, 700 psi	0.662	0.99
Coal, bituminous		
0.8424 (C) 0.0555 (H)	0.442	0.66
Carnalite	0.419	0.63
Limonite	0.369	0.55
Ciment	0.334	0.50 env.
Kernite	0.337	0.50
Gypsum	0.325	0.49
Kainite	0.309	0.46
Trona	0.284	0.42
Potash	0.282	0.42
Anthracite	0.268	0.40
Kaolinite	0.250	0.37
Chlorite	0.213	0.32
Kieserite	0.210	0.31
Serpentine	0.192	0.29
Nahcolite	0.158	0.24
Glauconite	0.127	0.19
Montmorillonite	0.115	0.17
Polyhalite	0.111	0.17
Muscovite	0.089	0.13
Illite	0.059	0.09
Biotite	0.041	0.06

Compared with that of fresh-water (under identical pressure and temperature conditions) in the case of fluids.

TABLE 8-2

Thermal neutron capture cross-section for the principal elements

Elements	Cross-section in barns ($= 10^{-24} \text{ cm}^2$) for neutrons ($v = 2200 \text{ m/s}$)	Energy of emitted gamma rays (MeV)	Probability of emission	Mean loss of energy by collision
Gadolinium	40,000			
Bore	771			
Lithium	71			
Chlorine	33.4	7.77	0.1	
		7.42	0.08	
		6.12	0.06	
		5.01	0.04	
Potassium	2.2			
Barium	1.2			
Iron	2.56			
Sodium	0.534			
Sulphur	0.49	5.43	0.84	
		4.84	0.20	
		6.42	0.83	0.04
		5.89	0.11	
Hydrogen	0.332	2.23	1.0	0.5
Aluminium	0.232	7.72	0.35	
		3.02	0.16	
		2.84	0.13	
		6.40	0.19	0.06
Silicon	0.16	4.95	1.0	
		4.20	0.19	
		3.57	0.94	
		2.69	0.65	
		8.16	0.09	
Magnesium	0.064	3.92	0.83	
		3.45	0.16	
		3.83	0.39	0.14
Carbon	0.0034	4.95	0.49	
		4.05	0.15	
		3.05	0.36	
Oxygen	0.0002			0.11

* From Handbook of Chemistry and Physics, 62 edition (1981-1982). Chemical Rubber Publishing Co., Cleveland, Ohio, U.S.A.

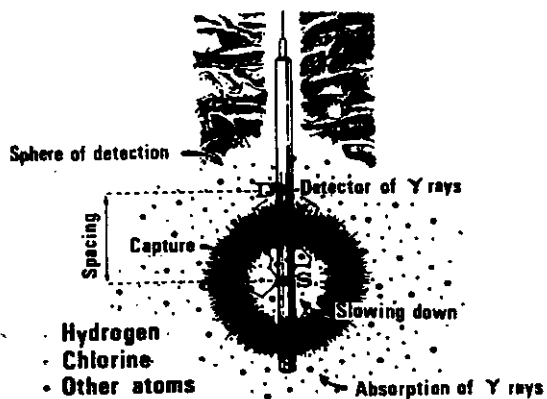


Fig. 8-6. The neutron-gamma (n, γ) logging principle.

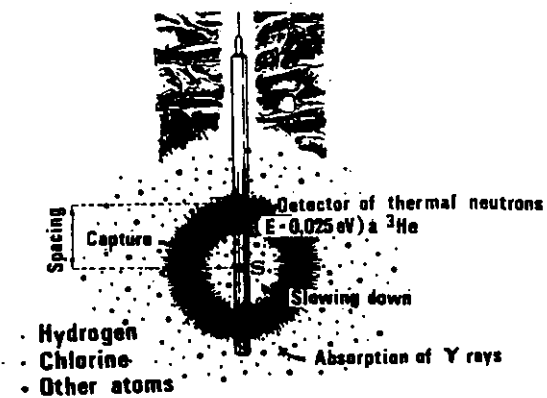


Fig. 8-7. The neutron-thermal (n, n_{th}) logging principle.

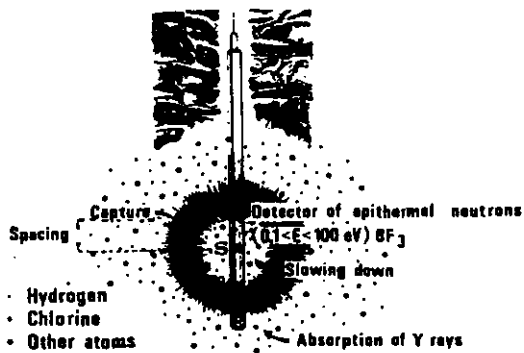


Fig. 8-8. The neutron-epithermal neutron (n, n_{epi}) logging principle.

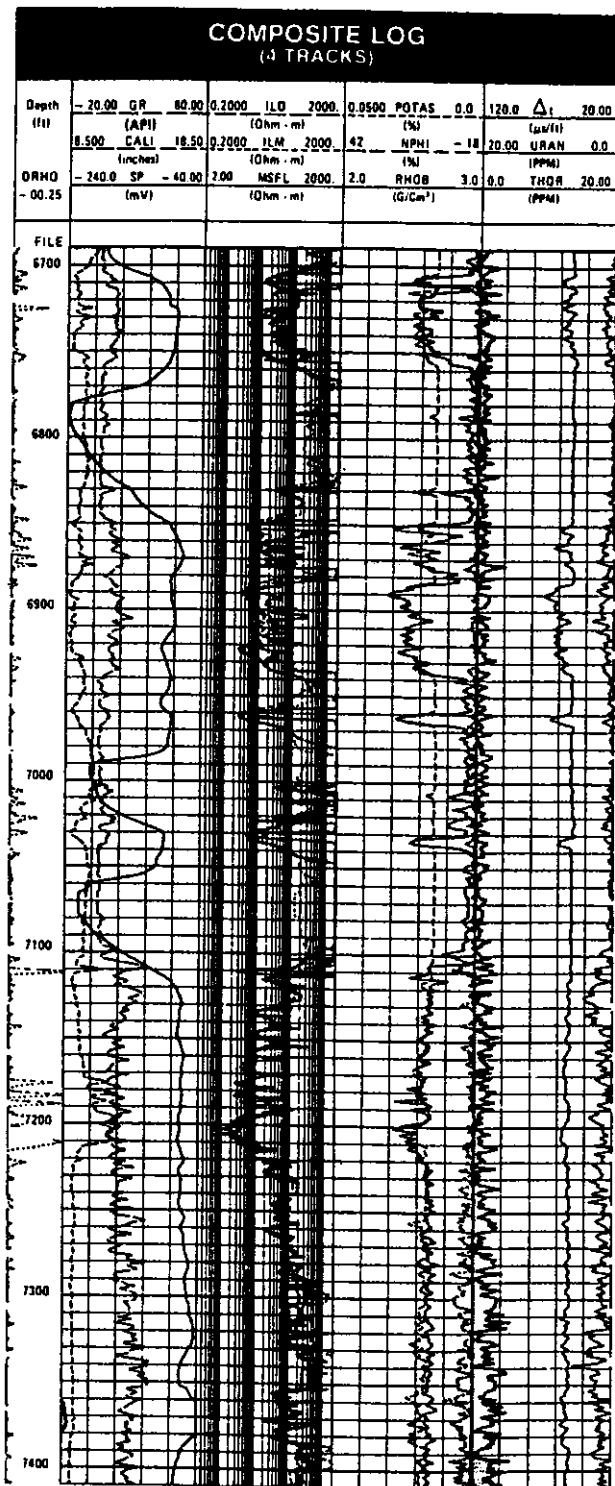


Fig. 2-28. A composite log presentation obtained with CSU.