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COMPREHENSIVE ANALYSIS OF THE CARBON/OXYGEN LOG
SUPRI TR-28

By

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ABSTRACT

A study is presented on the analysis of induced gamma ray spectroscopy logs. This report reviews the current interpretation methods and presents a cross-plotting technique to compute hydrocarbon saturation. Most published studies on these logs provide only a semi-quantitative analysis with little theoretical basis. This technique follows a theoretical model proposed by previous investigators. The technique assumes that:

- 1) Each reservoir component (i.e., matrix lithologies and fluids) has a specific ratio of elemental ratios; and
- 2) The total log response is a linear function of each ratio in the matrix, the hydrocarbon, the formation water and the shale.

The cross-plotting technique has three unknowns: porosity, volumetric fraction of shale and oil saturation. Porosity and volumetric fraction of shale are obtained from a standard set of open hole logs. Oil saturation is then computed from a linear equation that approximates the bulk carbon-to-oxygen (C/O) response. The equation contains four terms representing both matrix and fluid responses in the reservoir. The coefficient of each term is obtained from one of the following cross-plots:

<u>Coefficient</u>	<u>Cross-Plot</u>
$(C/O)_{ma}$	C/O vs ϕ
$(C/O)_w$	C/O vs ϕ
$(C/O)_{sh}$	C/O vs GR (or V_{sh})
$(C/O)_h$	C/O vs $\sqrt{C_t}$

The only constraint upon this approach is that porosity must be fairly constant in the reservoir to apply the C/O vs $\sqrt{C_t}$ cross-plot. However, for most non-carbonate reservoirs of good porosity this constraint should not be of great concern.

An example is given using the empirical cross-plotting approach. The example is from an observation well of a steam-foam pilot in Kern County, California. The Dresser Atlas "Continuous Carbon/Oxygen Log"™ is being run periodically in the observation wells of this pilot to monitor the recovery process. A comparison is made between the cross-plot method and other methods now used by Dresser Atlas.

1. INTRODUCTION

Gamma rays produced by the interaction of neutrons with nuclei are an important fraction of the radiation found whenever neutrons are transported through various materials. The measurement of these induced gamma rays can be used to identify the elements in these materials as well as their gamma production cross-sections. This knowledge is of interest to both the coal¹ and petroleum industries² for reasons of elemental analysis of earth formations.

The petroleum industry has been interested in induced gamma ray spectroscopy (IGS) in order to measure the mineral content and hydrocarbon-fluid saturation in a reservoir rock. Moreover, the industry has wanted a device that could measure hydrocarbon saturation in cased-hole formations of low salinity (less than 5000 ppm of NaCl).

In these low salinity formations, the formation resistivity can be very large. Induction logs have an uncertainty of ± 2 mmoh/m, and consequently the resistivity error may be great as conductivity approached zero.³ To prevent any errors of more than 20%, the measured resistivities should be less than 100 ohm-m. However, resistivities in low salinity reservoirs may be several thousand ohm-meters. As a result, resistivity logs are useless for computing oil saturations.

Nuclear logs that measure the rate of decay of thermal neutrons are also of limited use because these logs are affected by the chlorine nuclei in the formation water. The computed saturations from these devices become questionable at water salinities less than 100,000 ppm.³ However, the IGS logs based on the relative carbon and oxygen yields can identify hydrocarbon zones under conditions of very low or unknown salinity.

The heavy-oil reservoirs of Kern County, California are an example of shaly sand formations where steam flooding is the acceptable method of recovery. In these reservoirs, the injected steam lowers the formation-water salinity to very low levels. In order to estimate the efficiency of the recovery processes, periodic measurements of the oil saturations are needed. The carbon/oxygen log has been used in these fields, but with limited success.

The Stanford University Petroleum Research Institute (SUPRI) in cooperation with the Petro-Lewis Corporation is providing technical direction and research support for a pilot of steam-surfactant flooding in the Kern River Field of Southern California.⁴ The pilot involves two inverted five-spots; one five-spot will be injected with steam only and the other with slugs of surfactant and steam. To compare the performances of the two patterns, IGS logs will be run periodically in the observation wells to monitor changes in fluid saturations.

To further our understanding of the interpretation of the IGS logs, research began on the development of improved methods of analysis. This report reviews the current techniques and describes the deficiencies of each method. An empirical approach is suggested by the author as an alternative. The new approach is evaluated with field data from a Petro-Lewis well in the North Kern Front Field of Kern County, California. The well is located on a lease designated for an enhanced recovery field demonstration. The demonstration is a jointly funded venture between Petro-Lewis Corporation and the U.S. Department of Energy.

The results of the analysis of this field data by means of this empirical approach are compared with oil saturations from other sources.

2. LITERATURE REVIEW

A survey of the literature has been made to determine the extent of published information on the theory and interpretation of induced gamma ray spectroscopy devices.

Some of the earliest work on the analysis of gamma ray spectra of naturally radioactive elements in sedimentary formations was done by Brannon and Osoba.⁵ Their work demonstrated that the relative concentration of radioactive elements could be determined by gamma ray spectral analysis. The success of this research suggested to Muench and Osoba⁶ that spectral analysis of induced radioactivity could identify elements that are not normally radioactive. The element chlorine was the easiest to detect because of its large neutron capture cross-section. However, elements of small neutron capture cross-section (e.g., carbon) were difficult to detect with a chemical source for neutrons.

Tittman and Nelligan⁷ refined the technique by using an accelerator-type of neutron source to bombard the formation with fast neutrons. Their technique included separating neutron-capture contributions from inelastic reactions. Their laboratory study showed induced gamma ray spectra for an oil-saturated sand and a water-filled sand. They noted that the spectra were the result of interfering yields from many elements. Their scintillation counter was not able to resolve lines of spectra which were too close to each other; in practice, the spectra were somewhat smeared.

Hoyer⁸ realized that the neutron accelerator could be used to emit pulses of fast neutrons into the formation. This technique was used to discriminate neutron capture reactions from inelastic scattering reactions. By detecting only the prompt gamma rays produced by neutron inelastic reactions, the relative abundance of carbon, oxygen, calcium and silicon were obtained from a gamma ray spectrum.

Both natural and induced gamma ray spectra taken from actual oil wells were presented by Caldwell et al.⁹ Slow-neutron capture gamma ray spectra were taken by stationary measurements in boreholes under controlled conditions of porosity and fluid saturation. Salt water was differentiated from oil or fresh water on the basis of capture gamma rays from chlorine.

Hoyer and Rumble¹⁰ also presented their experience of using an induced gamma ray spectroscopy log in the field. They used this logging system to identify elements that are components of formation lithologies and fluids (i.e., Si for sandstone, S for anhydrite, Al for shale, C/O ratio for oil). The ratio of induced gamma rays from carbon and oxygen, C/O, was arbitrarily defined and used to indicate the oil content of formations.

An instrument system for stationary measurements of the relative carbon content of reservoir rocks was developed by Culver *et al.*¹¹ The response of the instrument to oil saturation, porosity and borehole conditions was evaluated by laboratory measurements in test pits and simulated boreholes.

Schultz and Smith¹² discussed a gamma ray spectroscopy logging system that was used to obtain continuous measurements in a borehole. For porosities greater than 15%, the oil saturation was obtained by cross-plotting the carbon/oxygen ratio and the porosity. This paper gave the first attempt at a quantitative interpretation of the log.

Lock and Hoyer¹³ and Wichmann *et al.*¹⁴ tried a pattern-recognition technique to identify oil zones by cross-plotting the carbon/oxygen ratio with the silicon/calcium ratio. Boundary lines were formed on the plot between regions of high oil saturation and high water saturation (Fig. 2.1). Sacco¹⁵ also used a pattern-recognition technique for a shaly sandstone formation contaminated with tuffite. He cross-plotted the carbon/oxygen ratio with the percentage of potassium ions in the formation to identify hydrocarbon-bearing zones. Unfortunately, none of these methods provided quantitative results.

Fig. 2.1: PATTERN RECOGNITION TECHNIQUE¹³

However, Vercellino *et al.*¹⁶ proposed a simple linear equation for homogeneous formations of constant lithology and porosity to compute oil saturations:

$$S_o = \frac{(C/O)_{\log} - (C/O)_w}{(C/O)_{oil} - (C/O)_w} \quad (1)$$

Heflin *et al.*¹⁷ applied Eq. 1 to sand-shale reservoirs of high porosity in California and claimed that in most cases the relationship was reliable.

Lawrence¹⁸ summarized the methods of interpretation of Dresser Atlas' Carbon/Oxygen Log. Four empirical methods are discussed including a computer cross-plot method. In addition, a discussion is given of hydrocarbon density compensation, porosity compensation and shale correction. All of these methods are limited because they do not explicitly include the effect of lithology with porosity and oil saturation on the response of the tool.

Hertzog et al.¹⁹ and Hertzog²⁰ offer a different approach using a better tool design than previous investigators. The problems of interfering elements in the spectral yields have been diminished by a weighted least-squares analysis. The logging system can compute an oil saturation and indicators of salinity, lithology and porosity.

3. DISCUSSION OF INDUCED-NEUTRON REACTIONS

An important principle of induced gamma ray spectroscopy is that an element bombarded with neutrons emits gamma radiation of a characteristic energy for that element.⁸ Therefore, an element may be identified by the analysis of the energy spectrum of the neutron-induced gamma radiation. To understand this principle, the life history of an average neutron leaving an accelerator-type source in a sonde is reviewed.

During the brief life of a high-energy neutron, gamma rays from nuclear collisions are produced in two ways. The first are so-called "fast neutron" collisions in which the neutron travels at a high velocity into the borehole and the formation. These fast neutrons may collide either elastically or inelastically. Moreover, these fast neutrons may cause alpha-particle emission²⁰ (also called alpha-particle stripping). The second way gamma rays are produced is when neutrons are slowed to "thermal" velocities after multiple elastic and inelastic collisions. These free neutrons are eventually "captured" by formation nuclei. An example of each nuclear reaction is given below:

(Elastic)	$^{16}\text{O}(n,n)^{16}\text{O}$
(Inelastic)	$^{16}\text{O}(n,n'\gamma)^{16}\text{O}$
(Capture)	$^{35}\text{Cl}(n,\gamma)^{36}\text{Cl}$
(Alpha Emission)	$^{16}\text{O}(n,\alpha)^{13}\text{C}$ or $^{16}\text{O}(n,\alpha\gamma)^{13}\text{C}$

An elastic collision does not produce gamma radiation, and therefore cannot be used to identify elements in the formation. There is a transfer of some kinetic energy from the neutron to the struck nucleus, depending on the angle of collision. But each collision results without any change in the nuclear state of the target nucleus.

Inelastic collisions occur shortly after fast neutrons are emitted from the source. When an inelastic collision occurs, one or more gamma rays are emitted from the struck nucleus. These reactions occur only when the neutron has sufficient threshold energy to raise the target nucleus to an excited nuclear state. The half life of these excited states is approximately (10^{-6}) microseconds.²⁰ Note that the prime in the example above indicates a recoiled neutron (n') and represents a loss of energy to the nucleus (Fig. 3.1).

Neutrons, which have been slowed to thermal velocities, diffuse through the formation until they are captured. The probability for neutron capture is described in terms of the capture cross-sectional area, σ . The unit of capture cross-section is the barn ($1 \text{ barn} = 10^{-24} \text{ cm}^2$). The

capture cross-sectional area is proportional to the time that the neutron spends near the struck nucleus.²⁰

The emission of neutron-induced alpha particles (${}^4\text{He}_2$) can occur with or without radiation. In the example given above, Hertzog²⁰ states that this reaction contributes significantly to the total observed gamma ray spectrum from oxygen.

Fig. 3.1: FAST NEUTRON INELASTIC SCATTERING³⁸

4. INDUCED GAMMA RAY SPECTROSCOPY TOOLS

The nuclear engineering literature is filled with publications on the design of pulsed neutron generators, and various types of gamma ray detectors.²¹⁻²³ Similar instruments have been adapted to a borehole environment to look for minerals associated with uranium deposits.^{24,25} A detailed discussion of all these devices is beyond the scope of this text. However, the devices that are applied to hydrocarbon-bearing formations are presented. Currently, two major well-log service companies have logging instruments designed for measuring induced gamma rays in a borehole: Dresser Atlas and Schlumberger Well Services.

4.1 DRESSER ATLAS

Instrument Design.

The current version of the carbon/oxygen logging instrument is originally modeled after the tool design of Schultz and Smith.¹³ A schematic diagram of the logging sonde is presented in Fig. 4.1. The tool specifications are given in Table 4.1. The Dresser Atlas tool consists of a neutron generator and a gamma ray detector. The neutron generator accelerates deuterium ions onto a tritium target ($^3\text{H}[\text{d},\text{n}]^4\text{He}$) to produce 14 MeV neutrons. A high voltage power supply within the sonde supplies the accelerating potential. At a rate of 20,000 bursts per second, the high energy neutrons are pulsed into the formation. The average neutron yield is of the order of (10^8) neutrons/sec.¹⁸

Fig. 4.1: DRESSER ATLAS C/O LOGGING SYSTEM³⁸

Table 4.1

DRESSER ATLAS TOOL SPECIFICATIONS³⁸

Series	2721	
Diameter	3.5 in	(8.89 cm)
Length	14 ft	(4.27 m)
Weight	200 lb	(90.72 kg)
Min. Borehole Diameter	4 in	(10.16 cm)
Max. Temp.	275 ^o F	(135 ^o C)
Max. Pressure	15,000 psi	(103.4 MPa)
Recommended Logging Speed	≤ 3 ft/min	(≤ 0.90 m/min)

The gamma ray detector consists of a thallium-activated sodium iodide (NaI[Tl]) crystal, photomultiplier tube and preamplifier. Together, these components are kept at a constant temperature of 0°C inside a Dewar vessel. The photomultiplier tube, activated by the NaI crystal, generates an electrically pulsed signal of an amplitude proportional to the gamma ray energy. The signals are transmitted to the surface where the types and relative amounts of elements are determined on the basis of pre-selected energy windows from the gamma ray spectra.

The gamma rays are counted from inelastic and capture reactions of neutrons with various elements. The neutrons of sufficient energy to create inelastic reactions exist for very brief periods ($< 10 \mu\text{s}$). To measure the inelastic gamma rays, the detector is gated and synchronized with the neutron generator. Figure 4.2 illustrates the operating cycle of the source and the detector. As indicated, the neutron source operates simultaneously with the inelastic gate.

Fig. 4.2: OPERATING CYCLE OF SOURCE AND DETECTOR³⁸

Many of the gamma rays, due to capture of thermal neutrons, are measured in the inelastic gate. To correct for this effect, the capture gamma rays are counted at a later interval and subtracted from the inelastic spectrum.¹⁷ The inelastic spectrum (Fig. 4.3) is then partitioned into energy windows of carbon (3.27-1.86 MeV) and calcium (2.5-3.3 MeV).^{11,12}

Fig. 4.3: INELASTIC SPECTRUM WITH ENERGY WINDOWS

A 4.43 MeV carbon gamma ray incident on the NaI(Tl) crystal deposits its energy through the generation of free electrons from the photoelectric, Compton and pair-production effects. The resulting spectrum consists of the full energy or "photo" peak at 4.43 MeV and usually possesses one or two "escape" peaks.¹² The carbon escape peaks of 3.92 and 3.41 are due to gamma rays that are lost to the detector crystal following positron-electron pair production.¹⁰ When a positron and electron collide and are annihilated, one or two quanta of radiation may be lost. The photo peak of oxygen occurs at 5.62 and 5.11 MeV. The silicon window is used to encompass the prominent effect of the first and second escape peaks (3.22 and 2.71 MeV, respectively) rather than the 3.73 MeV photo peak.

The gamma rays from thermal-neutron capture are used also as an indicator of the relative abundance of silicon and calcium. The energy windows for these two elements are exactly the same as those for carbon and oxygen, respectively, in the inelastic spectrum.

Carbon/Oxygen Log Response. The Dresser Atlas instrument estimates the lithologic type and fluid saturation in a formation by computing a ratio of gamma ray counts. The relative abundance of carbon to oxygen is computed as a ratio of inelastic gamma ray counts, C/O. The ratio is sensitive to changes in oil saturation and to minerals that contain carbon in their molecular structure (e.g., calcite-- CaCO_3). To account for relative changes of carbon in a quartz sandstone-carbonate mixture, a ratio of silicon to calcium gamma rays is computed.

The atomic ratio silicon to calcium is estimated from either inelastic gamma ray counts, Ca/Si, or from capture gamma ray counts, Si/Ca. These ratios are not inversely related to each other as implied by the nomenclature. Although Culver *et al.*¹¹ could not decide which ratio is

a better indicator of lithology, Smith and Schultz¹² realize that the capture Si/Ca ratio is salinity dependent. Calcium and chlorine emit capture gamma rays of the same energy level; therefore the capture Si/Ca ratio decreases as salinity increases. McWhirter³⁰ takes advantage of this fact and uses the capture Si/Ca ratio as a quantitative measure of salinity in ppm of NaCl. The inelastic NaCl ratio is independent of salinity and is a better indicator of lithology.¹²

Unfortunately, there is speculation about the usefulness of the capture Si/Ca ratio. Neuman and Oden²⁶ present their evaluation of the tool and conclude that the capture Si/Ca ratio is unrelated to the abundance of calcium in the reservoir. They believe this ratio reflects the differences in oxygen abundance in the formation and therefore correlates with oil in place.

An example of the Carbon/Oxygen Log presentation is given in Fig. 4.4.

Fig. 4.4: CARBON/OXYGEN LOG PRESENTATION¹⁸

Carbon/Oxygen Log Calibration. The calibration of the Dresser Atlas Carbon/Oxygen Log is done on the surface using a conventional neutron source. The source is surrounded by paraffin wax with an outer shell of iron. Measurements are then made with a number of known energy peaks (Fig. 4.5): 1) Iron (Fe) with a photo peak at 7.64 MeV; 2) Oxygen (O) at 6.13 MeV; 3) Carbon (C) at 4.43 MeV; 4) Hydrogen (H) at 2.2 MeV; and 5) Silicon (Si) at 1.78 MeV. The energy peaks are assigned

Fig. 4.5: SPECTRUM WITH KNOWN ENERGY PEAKS²

to specific channels so that the same peaks occur in the same energy channel during the logging process.

4.2 SCHLUMBERGER WELL SERVICES

The Schlumberger instrument is called the Gamma-Ray Spectrometer Tool (GST). It consists of a neutron generator, a NaI[Tl] detector and a multichannel analyzer. The tool is linked to a logging truck that contains a computer system capable of real time analysis while accumulating the logging data.¹⁹ Table 4.2 is a description of the GST tool.

Table 4.2

SCHLUMBERGER TOOL SPECIFICATIONS²⁰

GST TOOL DESCRIPTION	
Length	37 feet (11.3 m)
Diameter	3.625 inch (9.21 cm)
Logging Cable	Heptacable
Maximum Pressure	20,000 psi (13.8 kPa)
Temperature	300 ^o F (150 ^o C)
Data Acquisition	Bidirectional-Telemetry and Cyber Service Unit (CSU), a computer-based data acquisition system
Detector/Size	NaI(Tl) 2 1/2 inch x 4 inch (6.4 cm x 10 cm)
Combinable with:	CCL, SGT (Gamma Ray)
Modes	Capture-Tau/Inelastic
Logging Speed	600 ft/hr (183 m/hr)/Stationary (5 min)

The neutron generator accelerates about 3×10^8 neutrons/second of 14 MeV energy. The neutrons bombard the borehole and the surrounding formation which emit both inelastic and capture gamma rays. These rays are discriminated from each other by either the "inelastic timing mode" or the "capture-tau mode."

The inelastic mode has a 100 microsecond timing cycle that is used to generate neutrons and to measure inelastic and capture gamma rays from

the formation. Figure 4.6 shows three spectral gates of the mode: 1) the inelastic or "burst gate" defined by the position and width of the neutron burst; 2) the capture "background gate" which corrects the inelastic spectra for the capture components from previous bursts; and 3) the longer "capture gate" which acquires capture spectra for the elemental analysis of the formation and the borehole environment.

The borehole components in the capture spectra are minimized by the capture-tau mode (Fig. 4.7). This mode waits for all of the early borehole-related capture components to decay before making a capture gate

The diagram illustrates the timing of two signals over a period of 61 multiples of τ .

SPECTROMETRY: This signal consists of rectangular pulses. The first pulse is labeled "CAPTURE τ ". The second pulse is labeled "NEUTRON BURST" and is split into two sub-pulses labeled "CAP". Subsequent pulses are labeled "CAP" at 44, 46, and 48. The signal then drops to a "BACKGROUND" level until the end at 61.

SIMULTANEOUS τ MEASUREMENT: This signal also consists of rectangular pulses. The first pulse is split into two sub-pulses labeled "I" and "II". Subsequent pulses are labeled "I" and "II" at 10, 12, 45, 46, and 48. The signal then drops to a "III" level until the end at 61.

TDT EQUATION:
$$TDT \text{ EQUATION} = N / 2 \cdot N + N = 0$$

- 13 -

measurement. The timing of the neutron bursts, the wait period and the detection are adjusted continuously by the simultaneous measurement of the Formation Thermal Decay Time, τ .^{*} This is accomplished by a similar gating sequence to that of the TDT-K tool.

The analysis of the spectral data is based on a weighted least-squares (WLS) fitting of the observed spectrum with response functions. The observed spectrum is divided into m equal-width energy intervals along the abscissa and n gamma rays (for the i^{th} energy interval) along the ordinate; the spectrum can be described as m -dimensional vectors, $\hat{P}$. Each response function (Fig. 4.8) or "standard-descriptor spectra," $\hat{P}_j$, is the total detector response to gamma rays of a particular element expected in the formation. A formation spectrum, $\hat{P}$ is represented as a linear combination of a complete set of s standard spectra, $\hat{P}_j$ ($j = 1, 2, 3, \dots, s$). Therefore, the $m \times s$ spectral-descriptor matrix, P , can be related to $\hat{P}$ such that:

$$\hat{P} = \sum_{j=1}^s P_{ij} X_j ; \quad (i = 1, 2, \dots, m)$$

where X_j represents the fractional contribution of the standard spectrum-descriptor vector, P_j , to the total measured spectrum, $\hat{P}$. The standard-descriptor spectra of carbon and oxygen, calcium, silicon, and iron are required for the background-corrected, inelastic spectra. The standard spectra of hydrogen and silicon, calcium, chlorine and iron are needed for the capture spectrum.

Westaway et al.²⁷ state that the set of standards required for the weighted least-squares analysis is environmentally dependent. The environmental effects are the temperature and the composition of the fluid and matrix in the formation. Higher operating temperatures of the NaI crystal cause spectral peaks to broaden. Changes in the amounts of elements such as sulfur, not normally used in real-time fitting, are necessary if the formation contains sulfur-bearing minerals such as anhydrite or gypsum.

Gamma Ray Spectrometer Log Response. Once the elemental yield coefficients, X_j , of the j^{th} element of the observed spectrum are computed and

^{*} τ is related to the formation macroscopic cross section, σ , by $\tau = 1/v\Sigma$.

ELEMENT RESPONSE FUNCTIONS

Fig. 4.8: STANDARD-
DESCRIPTOR
SPECTRA¹⁹

Table 4.3

ELEMENTAL YIELDS OF GST LOG²⁷

YIELD RATIO	INTERACTION	NAME	LABEL
C/O	Inelastic	Carbon-Oxygen Ratio	COR
Cl/H	Capture	Salinity-Indicator Ratio	SIR
H/(Si + Ca)	Capture	Porosity-Indicator Ratio	PIR
Fe/(Si + Ca)	Capture	Iron-Indicator Ratio	IIR
Si/(Si + Ca)	Capture & Inelastic	Lithology-Indicator Ratio	LIR

recorded on tape, certain elemental yield ratios are also computed (Table 4.3). These ratios are used to measure the reservoir properties.²⁷

The carbon/oxygen ratio is used as an oil saturation indicator. The salinity indicator is based on the capture chlorine-to-hydrogen yield ratio. This response is used to indicate the borehole fluid content and the formation water saturation (Fig. 4.9). The porosity indicator is

Fig. 4.9: RESPONSE OF SIR AS A FUNCTION OF SALINITY $\times S_w$ ²⁷

computed as a ratio of hydrogen yield to the silicon plus calcium yield. This indicator is a function of total porosity divided by the matrix fraction (Fig. 4.10). The capture iron indicator estimates the shale content in a formation.¹⁹ Laboratory measurements have not been made but field tests show that this indicator varies between zero in clean formations to one in shales. In cased holes, the iron indicator shifts upward about one unit due to the iron casing. The inelastic lithology indicator is not greatly affected by salinity, oil saturation or formation porosity. Therefore, this ratio is used to interpret the carbonate-to-sandstone contribution in the carbon/oxygen ratio (Fig. 4.11).

Fig. 4.10: RESPONSE OF PIR AS A FUNCTION OF TOTAL POROSITY AND MATRIX FRACTION²⁰

Gamma Ray Spectrometer Log Calibration. Laboratory calibration measurements have been made in water- and oil-saturated sandstone and limestone formations to observe the response of elemental yields and their ratios. Water of various salinities was used as the casing fluid and to saturate the formations.

However, there is no mention in the Schlumberger papers^{19,20,27} of how the tool calibration is maintained while recording the data. Hertzog²⁸ explains that an energy calibration is done but he is unable to explain details of the calibration process because this information is considered proprietary.

Fig. 4.11: RESPONSE OF LITHOLOGY INDICATOR RATIO¹⁹

5. ANALYSIS OF INDUCED GAMMA RAY SPECTROSCOPY LOGS

A close examination of the literature reveals that very little work has been done to develop a quantitative analysis of induced gamma ray spectroscopy logs (IGS). Although IGS logs have been run commercially in oilfields for several years,* most publications of analysis have given semi-quantitative methods. We shall review the current methods of analysis, and then continue with the proposed method of the authors.

5.1 LAWRENCE-OVERLAY METHOD

Dresser Atlas' analysis of the "Continuous Carbon/Oxygen Log" is based on Eq. 1:

$$S_o = \frac{(C/O)_{log} - (C/O)_w}{(C/O)_{oil} - (C/O)_w} \quad (1)$$

This equation assumes a linear relationship between log response and oil saturation based on initial values of the carbon/oxygen ratios in water, $(C/O)_w$, and oil, $(C/O)_{oil}$, saturated zones. In addition, the equation can only be applied to formations of constant lithology and porosity.

Lawrence¹⁸ presents a paper that modifies Eq. 1 for cases of changing lithology and porosity. The equations he presents are empirically derived from laboratory test-pit data. The laboratory data consist of the C/O tool response in typical oilfield lithologies of porosities ranging from 2 to 35 percent of bulk volume. The laboratory formations are saturated with either oil, fresh water, salt water or borated water. The gravity of the oil is approximately 30° API (0.87 gm/cm³). This data is plotted in Fig. 5.1.

Unfortunately, the test-pit data considers only pure lithologies. Therefore, Lawrence assumes that the data fall on parallel, straight lines of equivalent porosity. His "water line" follows the linear equation,

$$(C/O)_w = m(Si/Ca)_w + I_w \quad (2)$$

where m is the slope and I_w is the intercept of the "average water line."

* Dresser Atlas' Carbon/Oxygen Log was introduced in 1973.

Fig. 5.1: LABORATORY TEST PIT DATA: C/O VS Si/Ca¹⁸

The distance from the "water line" to lines of oil saturation less than 100% is approximated by:

$$(C/O)_{\log} - (C/O)_w = 0.6(S_o \phi)^{1.11} \quad (3)$$

For the condition of 100% oil saturation, $(C/O)_{\log} = (C/O)_{oil}$ and Eq. 3 becomes:

$$(C/O)_{oil} - (C/O)_w = 0.6 \phi^{1.11} \quad (4)$$

Dividing both sides of Eq. 3 by $0.6 \phi^{1.11}$ and then substituting Eq. 2 yields:

$$S_o^{1.11} = \frac{(C/O)_{\log} - m(Si/Ca)_w - I_w}{0.6 \phi^{1.11}} \quad (5)$$

Equation 5 is the general empirical equation for the "Overlay Method." From the test pit data, m is equal to -0.8 and I_w is 2.36 . Lawrence¹⁸ believes that the slope should remain constant, but that I_w is a function of borehole environment.

To obtain I_w for different borehole conditions, the "computer cross-plot method" or the " I_{wa} method" are recommended.¹⁸ The computer cross-plot of the inelastic C/O ratio versus the capture Si/Ca ratio is used to locate a water line of best fit (Fig. 5.2). The water line is drawn with the slope of -0.8 and is extrapolated to the intercept, I_w , on the C/O axis.

Fig. 5.2: COMPUTER CROSSPLOT OF C/O VS Si/Ca TO FIND I_w ¹⁸

$$I_{wa} = (C/O)_w + 0.8(Si/Ca)_w \quad (6)$$

CORRELATION & MONITOR		CONTINUOUS RATIOS	
SILICON	X100'	CARBON/OXYGEN RATIO	
MONITOR		SILICON/CALCIUM RATIO	
		APPARENT WATER LINE INTERCEPT	
<p>MONITOR</p> <p>SILICON</p>		<p>Normalized Reverse Si/Ca</p> <p>C/O</p>	<p>Iw = Iwa MINIMUM (WATER LINE)</p> <p>Iwa</p>
	X200'		

Fig. 5.3: I_{wa} VS DEPTH TO PICK MINIMUM I_w ¹⁸

To determine how well the laboratory test pit data fits the "overlay method," values of inelastic C/O and capture Si/CA were read from Fig. 5.1 and used to compute oil saturations with Eq. 5 (Fig. 5.4). These calculated values of oil saturation are compared with the known oil saturations identified as oil lines of Fig. 5.1; for this comparison, the terminology of "oil lines" is assumed to represent oil saturations of 100%.

Fig. 5.4: $S_o / (\text{True } S_o)$ VS SAND FRACTION

Table 5.1 lists the data as well as the percentage error. As shown, the errors are small for the laboratory sand, but become significant for other lithologic mixtures of sand and limestone. Moreover, the greatest errors are for low-porosity lithologies. Although Fig. 5.4 represents a limited amount of data, the plot does lead one to question that Eq. 5 may not be accurate for various combinations of porosity, lithology and oil saturation.

Table 5.1

"SENSITIVITY ANALYSIS" OF OVERLAY METHOD FOR $(S_o)_{\text{true}} = 1.0$

V_{sd}	ϕ	$(Si/Ca)_w$	$(C/O)_{oil}$	$(S_o)_{calc}$	Error, %
0.0	0.06	0.959	1.630	1.32	32.0
	0.19	0.980	1.670	0.97	-3.0
	0.35	0.981	1.769	1.02	2.0
0.25	0.06	1.018	1.581	1.25	25.0
	0.19	1.040	1.620	0.95	-4.7
	0.35	1.052	1.717	1.04	4.6
0.5	0.06	1.075	1.535	1.22	22.0
	0.19	1.100	1.569	0.92	-7.4
	0.35	1.122	1.660	1.04	4.7
0.75	0.06	1.133	1.487	1.18	18.0
	0.19	1.160	1.519	0.90	-9.6
	0.35	1.191	1.606	1.06	-4.4
0.8	0.06	1.144	1.477	1.14	14.4
	0.19	1.170	1.509	0.89	-10.9
	0.35	1.206	1.594	1.04	4.9
0.9	0.06	1.167	1.459	1.15	15.0
	0.19	1.195	1.489	0.89	-11.0
	0.35	1.233	1.573	1.05	5.0
0.95	0.06	1.178	1.449	1.10	10.9
	0.19	1.206	1.477	0.86	-13.8
	0.35	1.246	1.561	1.04	4.5
1.0	0.06	1.188	1.438	0.99	0.1
	0.19	1.237	1.469	1.03	1.0
	0.35	1.550	1.758	1.03	3.0

5.2 ATOMIC DENSITY METHOD

A theoretical analysis of induced gamma ray spectroscopy (IGS) logs has been considered as another alternative by various investigators.^{12,18,19,28} By computing the atomic density of various elements in the reservoir, the expected behavior of the log is modeled as a function of lithology, porosity, oil density, oil saturation and reservoir water salinity. A review of the significance of these reservoir parameters using the interpretation model of this section is given in Section 5.2.1. The atomic density is computed with the following equation:

$$\text{Atomic Density} = N (\text{No. of atoms/molecule})(\rho/\text{MW}) \quad (7)$$

The contributions of atomic density in both the fluid, F, and the matrix, M, can be computed using Eq. 7.

Let us consider a hydrocarbon above the bubble point with the molecular formula of $(\text{CH}_x)_n$. The ratio of hydrogen to carbon, x, can be approximated by:

$$x = 4 - 2.5 \rho_h \quad (8)$$

With a known value of ρ_h , an atomic density of carbon in oil, F_c , can be computed:

$$F_c = n N (\# \text{ carbon atoms/molecule})[\rho_o/n(\text{MW}_o)] \quad (9)$$

and the atomic density of carbon in the matrix, M_c :

$$M_c = N (\# \text{ carbon atoms/molecule})(\rho_{ma}/\text{MW}_{ma}) \quad (10)$$

Combining Eqs. 9 and 10 in terms of the atomic density of carbon in a formation of constant lithology:

$$C = F_c \phi S_h + M_c(1 - \phi) \quad (11)$$

Similarly for oxygen:

$$O = F_o \phi S_h + M_o(1 - \phi) \quad (12)$$

Dividing Eq. 11 by Eq. 12 yields a theoretical carbon/oxygen ratio, C/O:

$$C/O = \frac{F_c \phi S_h + M_c (1 - \phi)}{F_o \phi (1 - S_h) + M_o (1 - \phi)} \quad (13)$$

Likewise, a theoretical silicon calcium ratio, Si/Ca, is:

$$Si/Ca = \frac{\lambda_{Si} F_{Si} \phi (1 - S_h) + M_{Si} (1 - \phi)}{\lambda_{Ca} F_{Ca} \phi (1 - S_h) + M_{Ca} (1 - \phi)} \quad (14)$$

For complex lithologies, Eqs. 13 and 14 can be written as:

$$C/O = \frac{F_c \phi S_h + \sum_{i=1}^k (M_c)_i V_i}{F_o \phi (1 - S_h) + \sum_{i=1}^k (M_o)_i V_i} \quad (15)$$

$$Si/Ca = \frac{\lambda_{Si} F_{Si} \phi (1 - S_h) + \sum_{i=1}^k (M_{Si})_i V_i}{\lambda_{Ca} F_{Ca} \phi (1 - S_h) + \sum_{i=1}^k (M_{Ca})_i V_i} \quad (16)$$

For low salinity reservoirs (e.g., salinity < 5000 ppm) λ approaches zero and Eq. 16 becomes:

$$Si/Ca = \frac{\sum_{i=1}^k (M_{Si})_i V_i}{\sum_{i=1}^k (M_{Ca})_i V_i} \quad (17)$$

Equation 17 becomes numerically unstable for 100% quartz sandstone, but can be handled with an algebraic manipulation to $Si/(Si + Ca)$:

$$\frac{Si}{(Si + Ca)} = \frac{1}{1 + \frac{1}{Si/Ca}} \quad (18)$$

Equations 15 and 18 were used to generate a plot of C/O versus $Si/(Si + Ca)$ for a limestone-sandstone system (Fig. 5.5). This graph was produced with the test-pit data of Fig. 5.1. The similarities of each plot are:

- 1) The lines of water saturation drop below the zero porosity line with increasing porosity;
- 2) The carbon/oxygen ratios of limestone are greater than sandstones; and
- 3) The distance between lines of oil saturation and lines of water saturation increases with increasing porosity.

The differences between Figs. 5.1 and 5.5 are:

- 1) The theoretical response curves of Fig. 5.5 are non-linear; and
- 2) The test-pit ratios are not in the same numeric range as the theoretical ratios.

Fig. 5.5: C/O VS $Si/(Si + Ca)$ FOR A LIMESTONE-SANDSTONE SYSTEM

The similarities between the cross-plots are encouraging; however, the discrepancies between the theoretical and measured ratios preclude a direct analysis of Dresser Atlas' C/O log with the theoretical equations. Both Lawrence¹⁸ and Schultz and Smith¹² recognize this disparity as a consequence of: 1) interference in the energy windows from gamma rays of other elements; 2) the loss of some of the primary

carbon and oxygen gamma rays from their respective energy windows by energy degradation; 3) neutron interactions within the detector; and 4) pulse pile-up which can cause an apparent increase in gamma ray energy.

Hearst²⁹ presents a plot of a measured C/O ratio versus a theoretical ratio as one way of relating the measured results with the theoretical results (Fig. 5.6). From this empirical approach, a correlation can be developed to correct the measured or apparent ratios with the true atomic ratios. As yet, there is not enough test pit data to produce such a correlation for the Dresser Atlas C/O log.

The relationship between the physical atomic concentrations and the measured elemental ratios is complex. Westaway *et al.*²⁷ recognize the complexity as a function of neutron flux distribution, interaction cross-sections, and the environment of the borehole and the formation. A modified version of Eq. 13 accounts for these factors:

$$C/O = A \frac{F_c \phi S_h + M_c(1 - \phi) + B_c}{F_o \phi(1 - S_h) + M_o(1 - \phi) + B_o} \quad (19)$$

Hertzog and Plasek¹⁹ consider Eq. 19 to be a preliminary interpretation model. This model assumes that the observed elemental yields can be computed from the nuclear cross-sections and the atomic density averaged over the borehole and the formation volume. The terms B_c and B_o represent the carbon and oxygen background contribution from the borehole environment. These terms consider the effects of the type of borehole fluid (i.e., oil or water filled), the size of casing and the effect of the cement sheath.

Figure 5.7 illustrates the response of the Schlumberger tool to hydrocarbon saturation, porosity and lithology; each curve is generated from Eq. 19. The oil saturation error bars of 11 percent correspond to statistical variations. The range and magnitude agree well with the theoretical response.

Plot of carbon/oxygen count ratio vs carbon/oxygen atomic ratio and weight-fraction CO₂ equivalent.

Fig. 5.6: HEARST PLOT OF $(C/O)_{29}^{true}$ VS $(C/O)_{measured}$

Fig. 5.7: HERTZOG'S C/O VS ϕ EXPERIMENTAL DATA²⁰

5.2.1 Effect of Reservoir Properties on Elemental Ratios

Although the logging systems discussed in this report provide different output, each system is affected by the same reservoir properties. These properties are lithology, hydrocarbon density, porosity, hydrocarbon saturation and formation water salinity. We discuss the significance of these properties using Eqs. 7, 8, 15 and 16 as the interpretation model.

Lithology. A limestone-quartz sandstone system is considered. Other lithologies such as dolomite ($\text{CaMg}(\text{CO}_3)_2$) and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) are not presented, but each can be modeled in a similar fashion. Figures 5.8 and 5.9 illustrate the behavior of lithology on the $\text{Si}/(\text{Si} + \text{Ca})$ and C/O ratios, respectively. Figure 5.8 is produced from Eqs. 17 and 18:

$$\text{Si/Ca} = \frac{\sum_{i=1}^k (M_{\text{Si}})_i V_i}{\sum_{i=1}^k (M_{\text{Ca}})_i V_i} \quad (17)$$

$$\frac{\text{Si}}{\text{Si} + \text{Ca}} = \frac{1}{1 + \frac{1}{\text{Si/Ca}}} \quad (18)$$

These equations assume that the salinity of the formation water is zero. Under these conditions hydrocarbon density, porosity and hydrocarbon saturation are independent of the $\text{Si}/(\text{Si} + \text{Ca})$ response.

Fig. 5.8: LITHOLOGY BEHAVIOR: $Si/(Si + Ca)$

Fig. 5.9: LITHOLOGY, POROSITY AND HYDROCARBON SATURATION EFFECT ON C/O RATIO

Figure 5.9 is prepared from a theoretical ratio of carbon-to-oxygen atoms:

$$C/O = \frac{F_c \phi S_h + \sum_{i=1}^k (M_c)_i V_i}{F_o \phi (1 - S_h) + \sum_{i=1}^k (M_o)_i V_i} \quad (15)$$

For this case the carbon/oxygen ratio is independent of water salinity. At a 25% porosity, a water-saturated limestone and an oil-saturated sandstone have identical C/O ratios. Above a 25% porosity, the C/O values of an oil-saturated sandstone exceeds those of an oil-saturated limestone. Smith and Schultz¹³ understood this problem and realized that the lithology must be known before hydrocarbon saturation can be computed.

Porosity and Reservoir Salinity. A reservoir porosity has as much of an effect on log response as lithology. The only exception to this statement is when the formation water salinity approaches zero. In that event, the Si/(Si + Ca) ratio is independent of porosity (Fig. 5.10). At higher salinities the Si/(Si + Ca) ratio is no longer independent of porosity. Although, from Fig. 5.11 the salinity effect is not significant.

Fig. 5.10: Si/(Si + Ca) VS POROSITY FOR DIFFERENT LITHOLOGIES AND WATER SATURATIONS

Fig. 5.11: Si/(Si + Ca) VS POROSITY SHOWING SALINITY EFFECT

The carbon/oxygen ratio is independent of formation water salinity. The exception to this rule is when CO_2 and HCO_3^- are dissolved in the formation water. Desai and Moore^{31, 33} show that the concentrations of these ions may reach 30,000 to 40,000 parts per million (ppm) in solutions of 200,000 of total dissolved solids. Insufficient time prevents the authors from studying this effect in detail.

Figures 5.9 and 5.12 show how the C/O ratio is affected by porosity. For oil-saturated sandstones the C/O ratio increases with increasing porosity. When limestone is mixed with sandstone, the C/O ratio decreases with increasing porosity for a constant hydrocarbon saturation.

As expected, the C/O ratio approaches infinity (i.e., the atomic density of oxygen is zero) when porosity is 100%. The C/O ratio at infinity can be handled numerically with an algebraic manipulation:

$$\frac{1}{C + 0} = \frac{1}{1 + \frac{1}{C/O}} \quad (20)$$

A graph of $C/(C + 0)$ versus porosity illustrates its behavior at $\phi = 100\%$ (Fig. 5.13).

Fig. 5.12: C/O VS S_o SHOWING POROSITY EFFECT

Fig. 5.13: $C/(C+O)$ VS POROSITY

Hydrocarbon Density. The number of carbon atoms per unit volume of hydrocarbon is a function of hydrocarbon density (see Eq. 9). Therefore, hydrocarbon density affects the carbon/oxygen ratio as well. Figures 5.14 and 5.15 show the effect of hydrocarbon density on the C/O ratio for an oil-saturated sandstone and an oil saturated limestone, respectively. API gravities of 10 and 50 are indicated on the graphs which are related to hydrocarbon specific gravity (or hydrocarbon density) by:

$$\gamma_h = \frac{141.5}{131.5 + {}^\circ\text{API}} \quad (21)$$

Fig. 5.14: C/O VS POROSITY SHOWING HYDROCARBON EFFECT: SANDSTONE

Fig. 5.15: C/O VS POROSITY SHOWING HYDROCARBON EFFECT: LIMESTONE

Hydrocarbon Saturation. The $Si/(Si + Ca)$ ratio is virtually unaffected by hydrocarbon saturation in high salinity reservoirs. At a porosity of 40% and a concentration of 30,000 ppm of Ca^{++} , the change in the $Si/(Si + Ca)$ ratio, from 0.0 to 100% oil saturation is only 1.25% (Fig. 5.11). In reservoirs with fresh water, this ratio is entirely independent of hydrocarbon saturation (Fig. 5.10).

As expected, hydrocarbon saturation affects the C/O ratio. For any given porosity other than 0.0%, the C/O ratio increases with increasing oil saturation.

5.2.2 General Correlation of Carbon/Oxygen Ratio

For the sake of completeness, two correlations are presented. The first is lithology-dependent (with the hydrocarbon density constant), and the other is hydrocarbon-density dependent (with the lithology constant). The hydrocarbon density is expressed here as an API gravity. The curves presented in Figs. 5.16 through 5.19 form straight lines on log-log plots of $S_o/[C/(C + O)]$ versus porosity. The plots summarize the effects of reservoir properties on the theoretical $C/(C + O)$ ratio.

Fig. 5.16: LITHOLOGY-DEPENDENT CORRELATION CURVES: $^{\circ}\text{API} = 10$

Fig. 5.17: LITHOLOGY-DEPENDENT CORRELATION CURVES: $^{\circ}\text{API} = 50$

Fig. 5.18: HYDROCARBON-DENSITY DEPENDENT CORRELATION CURVES: SANDSTONE

Fig. 5.19: HYDROCARBON-DENSITY DEPENDENT CORRELATION CURVES: LIMESTONE

5.3 EMPIRICAL APPROACH

An empirical approach is described as an alternative to the previous methods. The approach assumes:

- 1) The log responses are corrected for the borehole environment; and
- 2) The log responses are linearly proportional to the reservoir parameters given below.

The method is applied to the Dresser Atlas "Continuous Carbon/Oxygen Log." The method could also be extended to the Schlumberger "Gamma Ray Spectrometer Log" with some modifications, but that approach is not discussed here. Figure 5.20 is a schematic representation of a reservoir rock. If we assume that each rock component has a specific elemental ratio, then we can write:

Fig. 5.20: SCHEMATIC REPRESENTATION OF RESERVOIR ROCK

$$\begin{aligned} C/O &= (1 - \phi - V_{sh})(C/O)_{ma} + V_{sh}(C/O)_{sh} \\ &+ \phi S_w(C/O)_w + \phi(1 - S_w)(C/O)_h \end{aligned} \quad (22)$$

$$\begin{aligned} Si/Ca &= (1 - \phi - V_{sh})(Si/Ca)_{ma} + V_{sh}(Si/Ca)_{sh} \\ &+ \phi S_w(Si/Ca)_w + \phi(1 - S_w)(Si/Ca)_h \end{aligned} \quad (23)$$

$$\begin{aligned} Ca/Si &= (1 - \phi - V_{sh})(Ca/Si)_{ma} + V_{sh}(Ca/Si)_{sh} \\ &+ \phi S_w(Ca/Si)_w + \phi(1 - S_w)(Ca/Si)_h \end{aligned} \quad (24)$$

As mentioned earlier, the Dresser logging system incorporates some redundancy. Because chlorine and calcium have overlapping spectral shapes, the capture Si/Ca measurement is salinity dependent.⁹ Therefore, Eq. 23 should be applied only in low salinity reservoirs.

Equation 24 can be used under any condition of reservoir salinity. The reservoir parameters of Eqs. 22 through 24 are given below:

<u>Component</u>	<u>Parameter</u>
matrix	$(C/O)_{ma}, (Si/Ca)_{ma}, (Ca/Si)_{ma}$
hydrocarbon	$(C/O)_h, (Si/Ca)_h, (Ca/Si)_h$
water	$(C/O)_w, (Si/Ca)_w, (Ca/Si)_w$
shale	$(C/O)_{sh}, (Si/Ca)_{sh}, (Ca/Si)_w$

The unknowns of these equations are water saturation, volumetric fraction of shale, and porosity. Water saturation is the principal unknown while the other two variables can be determined from other logs.^{32,33} Before proceeding further, let us simplify these equations.

In Section 5.2.1, the effect of fluid saturation is given. From the interpretation model used to produce Fig. 5.10, the $Si/(Si + Ca)$ ratio is independent of hydrocarbon saturation. The results of measuring the capture Si/Ca ratio in test pits (Fig. 5.21) indicate that this ratio is independent of hydrocarbon saturation. Therefore, Eq. 23 can be written as:

Fig. 5.21: TEST PIT RESULTS OF Si/Ca RATIO³⁸

$$Si/CA = (1 - \phi - v_{sh})(Si/Ca)_{ma} + v_{sh}(Si/Ca)_{sh} + \phi(Si/Ca)_{fluid} \quad (25)$$

where:

$$(Si/Ca)_{fluid} = (Si/Ca)_w = (Si/Ca)_h$$

The test pit data to evaluate this behavior for the inelastic Ca/Si ratio is given in Fig. 5.22. Again, the inelastic Ca/Si ratio is independent of hydrocarbon saturation. Equation 24 can be written as:

$$\text{Ca/Si} = (1 - \phi - V_{\text{sh}})(\text{Ca/Si})_{\text{ma}} + V_{\text{sh}}(\text{Ca/Si})_{\text{sh}} + \phi(\text{Ca/Si})_{\text{fluid}} \quad (26)$$

where:

$$(\text{Ca/Si})_{\text{fluid}} = (\text{Ca/Si})_{\text{w}} = (\text{Ca/Si})_{\text{h}}$$

Fig. 5.22: TEST PIT RESULTS OF Ca/Si RATIO³⁸

In Eq. 22 the $(\text{C/O})_{\text{sh}}$ can be equal to the C/O_{ma} when both the shale and matrix (e.g., quartz sandstone) are free of carbon. Westaway *et al.*²⁷ infer this to be a function of the fairly uniform atomic densities of oxygen in many minerals. In Table 5.2 the feldspar, mica and clay

Table 5.2

SCHLUMBERGER ELEMENTAL YIELD RATIOS²⁷

	Density g/cc	Oxygen (Atoms/cc)	Carbon (Atom/cc)
Limestone	2.71	0.081	0.027
Dolomite	2.87	0.094	0.031
Quartz Sandstone	2.65	0.088	-
Anhydrite	2.96	-	-
Oil	0.85	0.056	0.061
Water	1.0		-
Feldspars			
Microcline	2.56	0.074	-
Albite	2.62	0.080	-
Anorthite	2.76	0.079	-
Micas			
Muskovite	2.83	0.085	-
Biotite	3.08	0.081	-
Glauconite			
Sample I	2.51	0.074	-
Sample II	2.65	0.075	-
Clays			
Illite	2.53	0.082	-
Kaolinite	2.42	0.084	-
Chlorite	2.77	0.082	-
Montmorillonite	2.12	0.077	-

samples have oxygen atomic densities that remain very close to 0.08 atoms-mole/cm³-molecule. Therefore, if we assume that a quartz sandstone of a given porosity and hydrocarbon saturation contains these minerals, the $(C/O)_{ma}$ should be equal to the $(C/O)_{sh}$. Figure 5.23 is a hypothetical cross-plot of a C/O log response versus gamma ray intensity. Line "A" represents the locus of points of sand and silt plus increasing amounts of clay minerals. Notice that the line is horizontal

Fig. 5.23: HYPOTHETICAL CROSSPLOT OF C/O RATIO VS GAMMA RAY INTENSITY

and that the carbon/oxygen ratio remains insensitive to the nature of the mixture. Therefore, for carbon-free minerals in the matrix and shale, Eq. 22 becomes:

$$C/O = (1 - \phi)(C/O)_{lith} + \phi S_w(C/O)_w + \phi(1 - S_w)(C/O)_h \quad (27)$$

Equation 27 is invalid when either carbonaceous shales or carbon-bearing minerals (e.g., siderite, calcite, dolomite) are present. In that event, Eq. 22 must be applied.

5.4 PARAMETER SELECTION

Before water saturation can be computed, the parameters of Eqs. 22 through 24 must be estimated by a statistical treatment of the data. This can be done with various cross-plots.

5.4.1 C/O vs Porosity Cross-plot

The parameters $(C/O)_{ma}$ and $(C/O)_w$ are obtained from a Cartesian graph of carbon/oxygen ratio and porosity. The graph works best for a data population of water saturated zones and varying porosity. Figure 5.24 is a C/O versus porosity cross-plot for a hypothetical well. The data on the bottom of the plot correspond to a water-saturated lithology. A line

Fig. 5.24: HYPOTHETICAL CROSSPLOT OF C/O RATIO VS POROSITY

drawn through these points intersects the ordinate ($\phi = 0.0$) at the value of $(C/O)_{ma}$; in this case $(C/O)_{ma} = 1.4$. $(C/O)_w$ is estimated by extrapolating this line to a porosity of 100%; on this plot $(C/O)_w$ is 1.29.

When the porosity in the zones of interest is essentially constant, the data occurs as a lump without a definable trend. For this case, either $(C/O)_{ma}$ or $(C/O)_w$ must be known to compute the other.

5.4.2. C/O vs Gamma Ray Intensity Cross-Plot

A Cartesian graph of C/O ratio versus gamma ray intensity can be used to estimate $(C/O)_{ma}$ and $(C/O)_{sh}$. To estimate $(C/O)_{ma}$, porosity must be relatively constant so that:

$$(C/O)_{w+ma} = \phi(C/O)_w + (1 - \phi)(C/O)_{ma} \quad (28)$$

Figure 5.25 shows an example of this plot for the general case of $(C/O)_{w+ma}$ not equal to $(C/O)_{sh}$. The values of these parameters are indicated on the plot.

Fig. 5.25: HYPOTHETICAL CROSSPLOT OF C/O RATIO VS GAMMA RAY INTENSITY: $(C/O)_{sh} \neq (C/O)_{w+ma}$

5.4.3 C/O vs Conductivity Cross-Plot

$(C/O)_h$ and $(C/O)_{ma}$ can be estimated from a graph of C/O and conductivity (Fig. 5.26) when ϕ is constant. The graph is based on expressing the C/O ratio as a function of the square root of conductivity. Consider the equation of water saturation as a function of C_t :³⁵

$$S_w^n = \frac{a C_t}{\phi^m C_w} \quad (29)$$

Fig. 5.26: HYPOTHETICAL CROSSPLOT OF C/O VS $\sqrt{C_t}$ TO OBTAIN $(C/O)_h$

Taking $m = n = 2$:

$$(S_w \phi)^2 = a \frac{C_t}{C_w} \quad (30)$$

or,

$$S_w \phi = \sqrt{a(C_t/C_w)}$$

Substituting Eq. 30 into Eq. 22:

$$\begin{aligned} C/O &= (1 - \phi - V_{sh})((C/O)_{ma} + V_{sh}(C/O)_{sh} \\ &+ \sqrt{a(C_t/C_w)} (C/O)_w + (C/O)_h (\phi - \sqrt{a(C_t/C_w)}) \end{aligned} \quad (31)$$

Rearranging Eq. 31:

$$\begin{aligned} C/O &= (1 - \phi - V_{sh})(C/O)_{ma} + V_{sh}(C/O)_{sh} \\ &+ \phi(C/O)_h + \sqrt{C_t} \sqrt{a/C_w} [(C/O)_w - (C/O)_h] \end{aligned} \quad (32)$$

where:

$$\text{slope} = m = \sqrt{a/C_w} [(C/O)_w - (C/O)_h] \quad (33)$$

$$\begin{aligned} \text{intercept} = (C/O)_{\text{zero}} &= (1 - \phi - V_{sh})(C/O)_{ma} \\ &+ V_{sh}(C/O)_{sh} + \phi(C/O)_h \end{aligned} \quad (34)$$

$(C/O)_{ma}$ and $(C/O)_w$ can be obtained from a C/O versus porosity cross-plot. $(C/O)_{sh}$ is estimated from a C/O versus gamma ray intensity cross-plot. Therefore, either Eq. 33 or Eq. 34 can be used to compute $(C/O)_h$.

5.4.4 Ca/Si vs Porosity Cross-Plot

Either the capture Si/Ca ratio or the inelastic Ca/Si ratio can be cross-plotted. However, because the validity of the capture Si/Ca ratio is questioned,²⁶ the inelastic Ca/Si ratio is considered.

$(Ca/Si)_{ma}$ and $(Ca/Si)_{fluid}$ can be obtained from the Cartesian graph of Ca/Si and porosity. Figure 5.27 is an example of the cross-plot for a quartz sandstone reservoir. A line drawn through this data intersects the ordinate at the value of $(Ca/Si)_{ma}$. The $(Ca/Si)_w$ parameter is estimated by extrapolating this line to a porosity of 100%.

Fig. 5.27: HYPOTHETICAL CROSSPLOT OF Ca/Si VS POROSITY

At the time of writing this report, the effect of shale on the Ca/Si ratio has not been studied in detail, although field data indicate this ratio is independent of shale (see Section 6.2).

6. CASE HISTORY

An evaluation is presented of Dresser Atlas' Continuous Carbon/Oxygen Log from a steam flooded oil field in Kern County, California. Thermal recovery has been used in this field in order to displace the heavy oil contained in the reservoir.³⁴

6.1 BACKGROUND

In a steam drive process, the steam is continuously injected into the reservoir to generate a steam bank that displaces the heavy oil towards the producing wells.⁴ The steam's heat is transferred to the reservoir fluids, the reservoir rock, and the adjacent rock above and below the reservoir. The resulting heat loss condenses some of the steam and yields a mixture of flowing hot water and steam in the reservoir. The composition of this mixture depends on the radial distance from the wellbore, the thickness of the reservoir, the injection rate, and the quality of the steam.

The success of the steam drive process relies on the ability of the steam to reduce the viscosity of the oil and to improve oil mobility. Ideally, an oil bank forms ahead of the steam zone, which increases in size until it is produced from wells surrounding the injector. To displace the oil properly, one must consider the following:

- 1) Well spacing,
- 2) Reservoir heterogeneity (e.g., facies changes),
- 3) Gravity override,
- 4) Reservoir temperature and pressure,
- 5) Relative permeabilities,
- 6) Steam quality,
- 7) Mobility ratio,
- 8) Fluid saturations, and
- 9) Reservoir rock and fluid properties.

Unfortunately, early steam breakthrough in production wells can occur in a steam drive process.⁴ The combination of gravity override, high mobility ratio of steam to oil, and steam channeling through high permeability layers sharply reduces the oil recovery achieved by the process. To correct for these effects, the steam must be diverted toward zones of higher oil saturation in the reservoir.

Fig. 6.1: CROSS-SECTION OF STEAM-FOAMING A RESERVOIR³⁴

In-situ foaming with steam is the most promising method of diverting the steam to other parts of the reservoir (Fig. 6.1). When the foam is introduced into the steam channel, the permeability to steam is reduced and diversion occurs. The diverted steam then enters oil-bearing strata where steam drive can be effective. Moreover, the heat from the steam contacts the oil, reducing its viscosity and improving mobility.

To demonstrate the efficacy of a steam-foam process, an enhanced recovery project in the North Kern Front Field of Kern County, California is being conducted jointly by the Petro-Lewis Corporation and the U.S. Department of Energy. The hope of the project is to improve upon the sweep efficiency of the reservoir over that of a conventional steam process.

To monitor the progress of the project, the Carbon/Oxygen Log is being run every 3-5 months.³⁴ The Stanford University Petroleum Research Institute (SUPRI) has been asked to evaluate the data. A description of the field is given followed by a discussion of the results.

6.2 FIELD DESCRIPTION

The site of the field demonstration is on the North Kern Front Leases of Kern County, California (Figs. 6.2 and 6.3). The leases, Witmer and Mitchel, are located about eight miles north of Bakersfield.

The leases have been stimulated via cyclic steam since 1969.³⁴ The "Conventional Steam Drive Process with Ancillary Materials" began in September 1979 and will continue until October 1982.

Fig. 6.2: MAP OF KERN COUNTY SHOWING PILOT SITE LOCATION³⁴

Fig. 6.3: MAP OF WITMER AND MITCHEL LEASES³⁴

There are about 180 completed wells with the majority of the steam-floodable sections drilled on 2.5 acre spacings. Ten-acre inverted nine-spot patterns were created from existing production wells; some of the producing wells were converted to injectors.

The productive zones are the Chanac sand (upper Miocene age) and the Etchegoin sand (Pliocene age). The characteristics of the Chanac reservoir are described in Table 6.1. At the beginning of the field demonstration the project area contained approximated 3,344,000 barrels of oil in place. The oil (13° API) is extremely viscous and produces only small volumes of gas. The average permeability is about 2210 md, but can range from 15 to 12,000 md in a single producing zone. The driving mechanism is an edgewater drive.

Table 6.1

RESERVOIR CHARACTERISTICS OF CHANAC³⁴

Producing Formation	Chanac
Age	Upper Miocene
Average Net Zone Thickness	45 feet
Average Depth to Top of Zone	1525 feet
Type of Trap	Structural-fault
Driving Mechanism	Gravity/Edgewater
Average Porosity	33%
Average Permeability	2210 md
Average Water Saturation (S_w)	36%
Average Oil Saturation ($1-S_w$)	64%
Oil Gravity	13° API
Original Oil in Place	
Barrels/Acre-Foot	1640
Barrels	4,428,000
Barrels of Oil Produced as of 1/1/79	1,062,720
% of Oil Place Recovered	24%
Well Spacing	2.5 Acres

6.3 DISCUSSION

The empirical method described in Section 5.3 is applied to the well log data of Witmer A2-7M. The location of this observation well on the Witmer lease is given in Fig. 6.4. The interval of interest is from a

Fig. 6.4: MAP OF WITMER LEASE SHOWING LOCATION OF WELL A2-7M³⁴

depth of 1450.0 to 1600.0 feet below the surface (Fig. 6.5). The well logs, variables and parameters used in the analysis are given below. The sequence in which these variables and parameters are obtained is also indicated.

<u>Log Combination</u>	<u>Variable</u>	<u>Parameter</u>
1. Neutron-Density	ϕ, V_{sh}	ϕ_{Nsh}, ϕ_{Dsh}
2. C/O-Porosity		$(C/O)_{ma}, (C/O)_w$
3. C/O-Gamma Ray		$(C/O)_{sh}$
4. $C/O - \sqrt{C_t}$		$(C/O)_h$

Fig. 6.5: C/O LOG: WITMER A2-7M

The analysis assumes the following:

- 1) A shaly (quartz) sand sequence;
- 2) Gas occurs in relatively clean sands (Fig. 6.6);
- 3) The "excavation effect" observed in the presence of gas (i.e., light hydrocarbons and/or steam) is minimal; and
- 4) Any data slightly above the "sand line" of a $\phi_N - \phi_D$ cross-plot is attributed to statistical scatter.

Fig. 6.6: $\phi_N - \phi_D$ LOG SHOWING GAS ZONES

The volumetric fraction of shale, V_{sh} , and the true porosity, ϕ , are obtained from an analysis of a neutron-density cross-plot. The equations that describe the relationship between the (ϕ_D, ϕ_N) and (V_{sh}, ϕ) coordinate systems are:^{36,37}

$$\phi = \frac{\phi_D - \frac{\phi_{Dsh}}{\phi_{Nsh}} \phi_N}{1 - \frac{\phi_{Dsh}}{\phi_{Nsh}}} \quad (35)$$

$$V_{sh} = \frac{\phi_D - \phi_N}{\phi_{Dsh} - \phi_{Nsh}} \quad (36)$$

For clean gas-bearing formations, porosity is approximated from the neutron porosity and density porosity by the relation:

$$\phi = \frac{\sqrt{\phi_N^2 + \phi_D^2}}{2} \quad (37)$$

Water saturation, S_w , is computed from known values of log variables and log parameters by rearranging Eq. 22:

$$S_w = \frac{[(C/O) - (C/O)_{ma}] - \phi[(C/O)_h - (C/O)_{ma}] - V_{sh}[(C/O)_{sh} - (C/O)_{ma}]}{\phi[(C/O)_w - (C/O)_h]} \quad (38)$$

6.3.1 C/O Cross-Plots

The cross-plots used to obtain the log parameters are shown in Figs. 6.7 through 6.10. The values of these parameters are:

$$\begin{aligned} \phi_{Dsh} &= 0.22 & (C/O)_{ma} &= 1.42 \\ \phi_{Nsh} &= 0.38 & (C/O)_w &= 1.36 \\ (C/O)_h &= 2.06 & (C/O)_{sh} &= 1.40 \end{aligned}$$

ϕ_{Dsh} and ϕ_{Nsh} are difficult to obtain for this data population. Pure shale beds are not present in the interval that was logged. Therefore, the shale point, Sh_o , is selected somewhat arbitrarily in the lower right-hand corner of the data set (Fig. 6.7).

A line that approximates 100% water saturation in clean sands is connected between $(C/O)_{ma}$ at $\phi = 0\%$ and $(C/O)_w$ at $\phi = 100\%$. The line of "best fit" is drawn through the lower-most set of data that accounts for some statistical variation (Fig. 6.8). The data points which fall above this line represent sands of lower water saturation.

Fig. 6.7: $\phi_N - \phi_D$ CROSSPLOT

Fig. 6.8: C/O VS POROSITY CROSSPLOT

Fig. 6.9: C/O VS GAMMA RAY INTENSITY CROSSPLOT

Fig. 6.10: C/O VS $\sqrt{C_t}$ CROSSPLOT (TO OBTAIN $(C/O)_h$)

$(C/O)_{sh}$ is estimated at a point representing pure shale on a C/O versus gamma ray cross-plot. In this case, pure shale beds are not in the interval of interest. However, a shale point can be extrapolated from lines A and B (Fig. 6.9); the intersection of these lines represents the shale point, Sh_* .

The values of $(C/O)_w$ and $(C/O)_{ma}$ of Fig. 6.8 can be verified with the $(C/O)_{w+ma}$ value of Fig. 6.9. Given that the average porosity in the clean sand is about 32% (Fig. 6.13), the computed $(C/O)_{w+ma}$ should equal the graphically determined $(C/O)_{w+ma}$. From Fig. 6.9, $(C/O)_{w+ma} = 1.40$. The computed value of $(C/O)_{w+ma}$ is obtained from Eq. 28:

$$\begin{aligned}(C/O)_{ma} &= (0.32)(1.36) + (0.68)(1.42) \\ &= 1.40\end{aligned}$$

Once $(C/O)_{ma}$, $(C/O)_w$ and $(C/O)_{sh}$ are estimated, $(C/O)_h$ is obtained from a C/O versus $\sqrt{C_t}$ graph (Fig. 6.10). Again, a line of "best fit" is drawn through the data population. This plot gives the best results when the porosity range is small. Two zones are selected (Fig. 6.5) of relatively constant porosity to produce the straight line of Eq. 32. Extrapolating this line to the C/O axis at $\sqrt{C_t} = 0$ yields $(C/O)_{zero} = 1.60$. Rearranging Eq. 34, $(C/O)_h$ is computed from:

$$(C/O)_h = \frac{(C/O)_{zero} - (1 - \phi - V_{sh})(C/O)_{ma} - \bar{V}_{sh}(C/O)_{sh}}{\bar{\phi}}$$

$\bar{V}_{sh}$ and $\bar{\phi}$ are the average volumetric fraction of shale and the average porosity, respectively, for zones 1 and 2. These values are computed from the data of Table 6.2:

$$\begin{aligned}\phi &= 0.30 && (\text{frac. B.V.}) \\ V_{sh} &= 0.03 && (\text{frac. B.V.})\end{aligned}$$

6.3.2 Cross-Plots of Si/Ca and Ca/Si vs Porosity

In Fig. 6.11, a Z-plot of the Ca/Si ratio vs porosity is presented with the volumetric fraction of shale along the Z axis. A linear trend is shown indicating that this ratio is independent of hydrocarbon saturation, porosity and volumetric fraction of shale. The field-data response coincides in magnitude and range with the laboratory measurements of Fig. 5.22. Although the borehole environment for both cases differs, the behavior is similar.

A plot of the capture Si/Ca ratio versus porosity is presented in Fig. 6.12. Again, V_{sh} lies along the Z axis. Considerable scatter is evident in this graph. The spread of points in this plot may be due to differing oil saturations.²⁶ A plot of Si/Ca versus porosity with oil saturation along the Z-axis would probably resolve this question.

Table 6.2

DATA FOR C/O VS $\sqrt{C_t}$

ZONE	DEPTH	ϕ_D	ϕ_N	ϕ	V_{sh}	$\sqrt{C_t}$	C/O
1	1545.0	0.291	0.303	0.274	0.08	6.40	1.43
	1545.5	0.291	0.301	0.277	0.06	6.20	1.43
	1546.0	0.297	0.301	0.292	0.02	6.03	1.43
	1546.5	0.303	0.298	0.301	0	5.92	1.44
	1547.0	0.291	0.294	0.297	0	5.75	1.45
	1547.5	0.285	0.294	0.293	0	5.59	1.43
	1548.0	0.279	0.295	0.290	0.06	5.51	1.43
	1548.5	0.279	0.295	0.297	0.10	5.47	1.43
	1551.0	0.285	0.302	0.292	0.10	5.70	1.42
	1551.5	0.291	0.305	0.298	0.09	5.91	1.40
	1552.5	0.297	0.311	0.304	0.09	6.16	1.42
2	1566.5	0.297	0.291	0.262	0.08	5.16	1.45
	1567.0	0.291	0.304	0.273	0.08	4.27	1.48
	1567.5	0.309	0.307	0.308	0	3.66	1.49
	1568.0	0.321	0.304	0.313	0	3.43	1.50
	1568.5	0.333	0.301	0.317	0	3.17	1.51
	1569.0	0.333	0.302	0.317	0	3.12	1.50
	1569.5	0.327	0.305	0.316	0	3.27	1.51
	1570.0	0.315	0.308	0.311	0	3.49	1.51
	1570.5	0.309	0.309	0.309	0	3.76	1.50
	1571.0	0.309	0.309	0.309	0	3.99	1.50
	1571.5	0.309	0.308	0.309	0	4.26	1.49
	1572.0	0.309	0.308	0.309	0	4.55	1.48
	1572.5	0.309	0.307	0.308	0	4.79	1.49
	1573.0	0.315	0.310	0.313	0	4.89	1.49
	1573.5	0.321	0.315	0.318	0	4.80	1.47
	1574.0	0.327	0.318	0.323	0	4.57	1.46
	1574.5	0.333	0.318	0.325	0	4.37	1.45
	1575.0	0.327	0.314	0.321	0	4.17	1.45

Fig. 6.11: Z-PLOT OF INELASTIC Ca/Si RATIO VS POROSITY

Fig. 6.12: Z-PLOT OF CAPTURE Si/Ca VS POROSITY

6.4 RESULTS

Using Eqs. 35 through 38, ϕ , V_{sh} and S_w are presented in Figs. 6.13 and 6.14. Two prominent oil-bearing sands occur at about 1575.0 and 1593.0 feet. The porosities for these two zones range from 32% to 35%.

Fig. 6.13: POROSITY AND VOLUMETRIC FRACTION OF SHALE VS DEPTH

Fig. 6.14: WATER SATURATION VS DEPTH

In the figures that follow, a graphical comparison is made between computing S_w from the empirical method and from two other sources: 1) true resistivity, R_t ; and 2) Lawrence's Overlay Method. A one hundred foot interval is selected from 1500.0 to 1600.0 feet.

Fig. 6.15: WATER SATURATION VS DEPTH FOR BOTH EMPIRICAL AND OVERLAY METHODS

Empirical Method vs Overlay Method

Figures 6.15 and 6.16 present a graphical comparison of water saturation data. In this example, the overlay method becomes more optimistic than the empirical approach for a water saturation less than 75%. A reasonable correlation exists between the two methods at these lower water saturated zones. The correlation coefficient, r , is equal to 0.70. Considerable scatter in the data at higher water saturations suggests a much lower value of r .

Fig. 6.16: FREQUENCY PLOT COMPARING EMPIRICAL AND OVERLAY METHODS

Fig. 6.17: WATER SATURATION VS DEPTH COMPARING EMPIRICAL AND RESISTIVITY METHODS

Empirical Method vs True Resistivity Method

The graphical comparison of water saturation data from these two methods is presented in Figs. 6.17 and 6.18. In this example, the true resistivity method gives much more optimistic results than the empirical method at $\leq 75\%$. The correlation coefficient, r , is 0.41 in the oil-saturated zones. At higher water saturation, the empirical method indicates that some oil may be present; the R_t method considers these zones to be 100% water-saturated.

Fig. 6.18: FREQUENCY PLOT COMPARING EMPIRICAL AND RESISTIVITY METHODS

Fig. 6.19: WATER SATURATION VS DEPTH COMPARING
OVERLAY AND RESISTIVITY METHODS

Overlay Method vs True Resistivity Method

Eson and Shannon³⁴ claim that "constants" were obtained from the open hole logs to produce a "computer-generated" oil saturation curve. A comparison between the "computer-generated" overlay method and the R_t method of computing water saturation is given in Figs. 6.19 and 6.20. The correlation coefficient of the data representing oil-saturated zones is 0.77. As indicated, the R_t data is more optimistic than the overlay data for $S_w \leq 60\%$.

Fig. 6.20: FREQUENCY PLOT COMPARING OVERLAY
AND RESISTIVITY METHODS

7. CONCLUSIONS

This report summarizes the current methods of analysis of induced gamma ray spectroscopy (IGS) logs. A cross-plot technique is presented which uses both IGS logs and conventional logs to compute hydrocarbon saturation. The study concludes the following:

1. A literature review shows that there is some concern over the Dresser Atlas tool design; the Carbon/Oxygen Log does not measure true C/O, Si/Ca and Ca/Si ratios.
2. Schlumberger's new "GST"[™] log appears to have a better data processing technique than the Dresser Atlas "Carbon/Oxygen Log."
3. The overlay method proposed by Lawrence should only be used qualitatively. The method is not applicable for all cases.
4. The density of the hydrocarbon has a much smaller effect on the C/O log response than that of lithology, porosity or water saturation.
5. An empirical method is presented for the analysis of induced gamma ray spectroscopy logs but more work must be done to evaluate its usefulness.

NOMENCLATURE

CHEMICAL

C = Carbon

CaCO_3 = Calcite

$\text{CaMg}(\text{CO}_3)_2$ = Dolomite

$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ = Gypsum

Cl = Chlorine

CO_3^{--} = Carbonate ion

α = Deuterium

E_γ = Energy level (MeV)

H = Hydrogen

HCO_3^- = Bicarbonate ion

He = Helium

I = Iodine

F_C = Atomic density of carbon in oil (# of C/cm^3 of oil)

F_{Ca} = Atomic density of calcium in water (# of Ca/cm^3 of oil)

F_O = Atomic density of oxygen in water (# of O/cm^3 of water)

F_{Si} = Atomic density of silicon in water (# of Si/cm^3 of water)

Fe = Iron

M_C = Atomic density of carbon in matrix (# of C/cm^3 of matrix)

M_{Ca} = Atomic density of calcium in matrix (# of Ca/cm^3 of matrix)

M_O = Atomic density of oxygen in matrix (# of O/cm^3 of matrix)

M_{Si} = Atomic density of silicon in matrix (# of Si/cm³ of matrix)

MW_o = Molecular weight of oil (g/g-mole)

n = Number of carbons in hydrocarbon chain

n = Neutron

n' = Neutron with reduced kinetic energy

N = Avogadro's number (6.023×10^{23} atoms/mole)

Na = Sodium

O = Oxygen

P = Spectral descriptor matrix

P = Observed spectrum

P_j = Standard descriptor spectra

Si = Silicon

Tl = Thallium

x = Ratio of hydrogen to carbon

X = Weight fraction of an element

X_i = Fraction yield of each element to the observed spectrum

α = Alpha particle, 4He_2

γ = Gamma ray

λ_{Ca} = Concentration of calcium ion in water (part per part)

λ_{Si} = Concentration of silicon ion in water (part per part)

σ = Capture cross-sections (barns = 10^{-28} cm²)

LOGGING

a = Constant for Archie's equation

A = Ratio of inelastic cross section

B_c = Borehole effects of carbon (# C/cm³ of oil)

B_o = Borehole effects by oxygen (# O/cm³ of water)

BH = Borehole
 BV = Bulk volume
 C/O = Carbon-oxygen ratio
 $(C/O)_h$ = Carbon-oxygen ratio of hydrocarbon
 $(C/O)_{lith}$ = Carbon-oxygen ratio of lithology
 $(C/O)_{ma}$ = Carbon-oxygen ratio of matrix
 $(C/O)_{oil}$ = Carbon-oxygen ratio of oil
 Ca/Si = Calcium-silicon ratio
 $(C/O)_{sh}$ = Carbon-oxygen ratio of shale
 $(C/O)_w$ = Carbon-oxygen ratio of water
 $(C/O)_{w+ma}$ = Carbon-oxygen ratio of water and matrix
 $(C/O)_{zero}$ = Carbon-oxygen ratio at zero resistivity
 C_t = True conductivity (mmho/m)
 F_{lith} = Lithology indicator ($Si/(Si + Ca)$)
 F_{sal} = Salinity indicator (C/O)
 F_{S_o} = Oil saturation indicator (C/O)
 F_ϕ = Porosity indicator ($H/(Si + Ca)$)
 GR = Gamma Ray log
 GST = Gamma Ray Spectrometer Tool™
 IGS = Induced Gamma Ray Spectroscopy
 I_{wa} = Apparent intercept of water line
 I_w = Intercept of water line
 n = Saturation exponent
 m = Cementation factor
 m = Slope of water line
 PV = Pore volume
 R_t = True resistivity (ohm-m)

R_w = Water resistivity (ohm-m)
 S_h = Hydrocarbon saturation
 S_o = Oil saturation
 S_w = Water saturation
 Si/Ca = Silicon-calcium ratio
 $(Si/Ca)_{fluid}$ = Silicon-calcium ratio of fluid
 $(Si/Ca)_h$ = Silicon-calcium ratio of hydrocarbon
 $(Si/Ca)_{ma}$ = Silicon-calcium ratio of matrix
 $(Si/Ca)_{sh}$ = Silicon-calcium ratio of shale
 $(Si/Ca)_w$ = Silicon-calcium ratio of water
 Sh_o = Shale point of $\phi_N - \phi_D$ cross-plot
 $sspu$ = Sandstone porosity units
 V_{sh} = Volumetric fraction of shale
 $\bar{V}_{sh}$ = Average volumetric fraction of shale
 V_l = Volumetric fraction of lithology (fraction of bulk volume)
 WLS = Weighted least squares
 γ_h = Hydrocarbon specific gravity ($^\circ API$)
 ϕ = Porosity (function of bulk volume)
 ϕ_D = Density porosity
 ϕ_{Dsh} = Density porosity of shale
 ϕ_N = Neutron porosity
 ϕ_{Nsh} = Neutron porosity of shale
 ρ_h = Density of hydrocarbon (gm/cm^3)
 τ = Formation thermal decay time
 Sh_* = Shale point of C/O vs GR cross-plot

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