New Developments in Carbon/Oxygen (C/O) Logging

Walter H. Fertl
Dresser Petroleum Engineering Services
Houston, Texas

ABSTRACT

Carbon/Oxygen (C/O) logging applicable in cased wellbores measures energy and intensity of inelastic and capture gamma rays resulting from pulsed neutron irradiation of subsurface formations. Continuous C/O logs therefore define the relative abundance of elements, such as C, O, Si, Ca, H, etc., which in turn relates to lithology, porosity, and hydrocarbon saturation distribution in potential reservoir rocks independent of formation water salinities.

Basic concepts and environmental correction will be reviewed with special emphasis being placed on practical field experiences both in sandstone and carbonate reservoirs. Such field applications include exploration for bypassed oil in old wells, location and monitoring of oil in low or unknown formation water salinities, monitoring sweep and displacement efficiency of waterfloods and EOR projects, residual oil determination, evaluation of heavy oil and tar sand reservoirs, etc.

PULSED NEUTRON LOGGING

For over fifteen years, pulsed neutron logging devices utilizing several different gating systems that measure the macroscopic cross section (Σ) for thermal neutron capture in a borehole environment have been highly successful in differentiating high salinity formation waters from hydrocarbons behind casing on both a qualitative and quantitative basis. Hence, they can be used to monitor time-related variations of water, oil, and gas saturations in reservoirs under primary or enhanced recovery schemes. The resulting information is invaluable input in reservoir engineering and workover projects.

While such Neutron Lifetime[1,2,3] and Thermal Decay Time[4,5,6] devices have their optimum range of applications in saline, high porosity reservoirs, they cannot be used to evaluate and/or monitor hydrocarbon saturations where the macroscopic cross section of formation water is not significantly different from that of the hydrocarbons, or in cases where salinity is constantly changing and unknown (fresh water or steam floods, etc.).

Response of the Continuous Carbon/Oxygen (C/O) Log, which is also a pulsed neutron device, however, is not affected by such salinity constraints.

CARBON/OXYGEN INSTRUMENTATION

The source of neutrons is an accelerator-type source, which produces 14 MeV neutrons by the deuterium-tritium (D,T) reaction. This neutron source is pulsed at repetition frequency of 20,000 cycles per second (20 KHz). The schematic of the instrumentation, tool specifications, and source-detector operating cycle are given in Figure 1.[7]

BASIC CARBON/OXYGEN RESPONSE CHARACTERISTICS

Gamma rays, produced during neutron inelastic scattering and thermal neutron capture, are measured which relate to the relative amounts of certain elements present in the borehole and adjacent formation.

Inelastic scattering is the nuclear force interaction between a neutron and the nucleus of an element. In the *carbon* (C) inelastic scattering reaction the predominant gamma ray is produced at 4.43 MeV. Similarly, *oxygen* (O) produces gamma rays with the most predominant energy level (i.e., full energy peak) at 6.13 MeV. The *C/O ratio* then recorded is the ratio of the total number of gamma rays in specific energy windows which encompass the full energy peak (FEP) plus the first (FEP minus 0.51 MeV) and the second (FEP minus 1.02 MeV) escape peaks of carbon and oxygen, respectively.

This C/O ratio is a function of lithology, porosity, and amount of oil in the reservoir, independent of salinity (Fig. 2). Note that the resolution of the C/O Log increases with higher porosity.

Calcium (Ca) and *silicon* (Si), which also emit gamma rays from neutron inelastic scattering, are recorded as *Ca/Si ratio.* This Ca/Si ratio again is independent of salinity, is insignificantly affected by porosity, and provides lithology information (Fig. 3). By combining C/O and Ca/Si data, the oil saturation can be determined by quick-look overlay techniques and/or digital analysis.

Within a few microseconds after the neutron source bursts, the fast 14 MeV neutrons are slowed down (thermalized) by collision with nuclei. When a nucleus absorbs (captures) such a thermal neutron, gamma rays are emitted (capture gamma rays). Calcium, silicon, chlorine, hydrogen, and iron are typical examples.

The log-recorded silicon curve and Si/Ca ratio are such capture gamma ray information.

The Si/Ca ratio is lithology, porosity, and salinity dependent (Fig. 4). By combining C/O and Si/Ca data, the oil saturation can be determined by quick-look overlay techniques and/or digital analysis provided salinity does not significantly change over the interval or such changes are well known. Under such conditions, use of C/O and Ca/Si data is preferred. However, the Si/Ca ratio still can be used to calculate a Salinity Index to monitor behind casing the extent of mixing of injection and initial formation waters of contrasting salinity on both vertical and lateral basis in secondary recovery projects.

CALIBRATION

The surface calibration is made using a conventional neutron source with the source still in its carrying container. The container is made of paraffin with an outer shell of iron. Both container and source provide a number of known energy peaks, namely, iron with a photo peak at 7.64 MeV, carbon at 4.43 MeV, hydrogen at 2.2 MeV, and silicon at 1.78 MeV. Gain and linearity of the equipment is adjusted using these energy peaks:

Element	**Energy, MeV**	**Channel Number**
Silicon	1.78	51
Calcium	1.96	57
Hydrogen	2.2	64
Carbon 2nd Escape	3.41	99
Carbon 1st Escape	3.92	113
Carbon Photo Peak	4.43	128
Iron 2nd Escape	6.62	189
Iron 1st Escape	7.13	204
Iron Photo Peak	7.64	218

During logging operations, several of the elements are always present. Iron is present in the casing and hydrogen is always a prominent peak. Depending on the rock type, silicon or calcium will also be distinctive. Thus, both high- and low-end energies are continuously defined. This provides a continuous downhole check of the instrument calibration every time a spectrum is generated by the surface instrumentation.

LOG PRESENTATION AND DIGITALLY TAPED INFORMATION

The following logging curves are normally displayed on film.

Si - Silicon curve for the capture gamma ray energy window of 2.35 - 5.08 MeV.

Monitor - Monitor curve reflects source output stability.

Si/Ca - Ratio of silicon to calcium for the capture spectrum (silicon window 3.17 - 4.65 MeV, calcium window 4.86 - 6.62 MeV).

C/O - Ratio of carbon to oxygen for the inelastic spectrum (carbon window 3.17 -4.65 MeV, oxygen window 4.86 - 6.62 MeV).

Ca/Si - Ratio of calcium to silicon for the inelastic spectrum (calcium window 2.50 -3.30 MeV, silicon window 1.54 - 1.94 MeV).

C/I - Capture/inelastic ratio, porosity curve.

Optional Curves - Count rate data from any of the above mentioned windows may also be displayed.

In addition to the standard Continuous C/O Log, stationary measurements can be taken and complete inelastic and capture gamma ray energy spectra can be digitally taped at the wellsite in both continuous and stationary logging mode. The most common logging practice tapes spectral data at one-foot intervals. These taped data can be used to retrieve count rate and ratio data for selected energy windows, including hydrogen, iron, etc.

A standard gamma ray adaptor can be run on top of the C/O device to provide an auxillary gamma ray correlation curve.

RESPONSE ACCURACY

As for any other nuclear logging instrument, statistical variations are inherent in recorded C/O logging data. Typical guidelines are as follows:

Ratio	Standard Deviation	Conditions
Inelastic C/O	C/O ± 0.007	5 minutes stationary*
	C/O ± 0.015	TC = 30 sec, continuous* < 3 ft/min
Inelastic Ca/Si	similar to C/O ratio	
Capture Si/Ca	Si/Ca ± 0.009	*stationary
	Si/Ca ± 0.002	*continuous

INTERPRETIVE CONCEPTS

Constant Lithology and Porosity - In this case the measured C/O value directly relates in linear fashion to S_o, the oil saturation in the reservoir such as[8]

$$S_o = (C/O_{log} - C/O_{wtr}) / \Delta C/O$$

where Δ C/O is the span between 100 percent water and 100 percent oil for a given porosity as illustrated in Figure 2.

Quick-Look Overlay Techniques - Overlay techniques based on C/O and Si/Ca curves and/or C/O and Ca/Si curves provide quick and reliable evaluation at the wellsite.[9,10,11]

If the Si/Ca curve is used with the C/O curve, one of the two must be reversed and both curves normalized to each other in shales, water zones, or intervals of known production with any required environmental effects to be taken into consideration. Then the hourglass-type separation of the two curves is proportional to the oil saturation over the interval of interest. Proper scaling of the recorded ratios will present S_o-values at 20 percent or 25 percent per chart division.

Under more complex conditions the Ca/Si curve is preferably used with the C/O curve. For this overlay technique no curve reversal is necessary and only proper curve normalization is required. Again, however, environmental effects need to be taken into consideration. Then the separation between Ca/Si and C/O curves is proportional to oil saturation and proper scaling of the recorded ratios will present S_o-values at 20 percent or 25 percent per chart division.

Digital C/O Analysis - Advanced digital interpretation techniques[12,13] utilize crossplotting techniques based on the following mathematical relationships:

$$S_o = (C/O + m_1 Si/Ca - I_{w1})/\Delta C/O$$
$$S_o = (C/O - m_2 Ca/Si - I_{w_2})/\Delta C/O$$

where

C/O = inelastic gamma ray C/O ratio
Si/Ca = capture gamma ray Si/Ca ratio
Ca/Si = inelastic gamma ray Ca/Si ratio
I_{w_1} = intercept of waterline at C/O axis on C/O versus Si/Ca crossplot
I_{w_2} = same on C/O versus Ca/Si crossplot
m_1 = slope of waterline on C/O versus Si/Ca crossplot
m_2 = same on C/O versus Ca/Si crossplot
$\Delta C/O$ = span of C/O values between water and oil lines

In addition to oil saturation, other important reservoir properties are calculated, including permeability, water/oil ratio estimates, anticipated water cut, and stock tank barrel of oil per acre-foot.[12]

ENVIRONMENTAL EFFECTS

As discussed previously, C/O logging measurements respond to fluid saturation, porosity, and formation lithology. In high-porosity reservoirs the depth of investigation is approximately to a distance of 8.5 inches away from the borehole wall in 6-5/8-inch casing. Hence, environmental effects have to be considered in any quantitative C/O analysis, including the following:

Invasion - For invasion effects to dissiminate, the C/O Log should not be run immediately after casing has been set. Depending on the drilling operation, mud, and reservoir characteristics, a waiting period from a few days to several weeks may be advisable.

Open Perforations - In a producing well killed through open perforations the C/O interpretation will be affected over the perforated interval.

Casing Type and Size - Fiberglass pipe has less effect than steel casing (Charts 14a-b-c[14]). Very large casing sizes (13-3/8 inch and larger) at the most give marginal answers.

Casing Fluids - Distinct, accountable shifts in C/O Log ratios occur at borehole fluid interfaces.

Cement Thickness - Increasing cement sheath thickness reduces all C/O Log ratios; C/O and

Si/Ca in similar fashion and Ca/Si to a larger degree (Charts 15a-b-c[14]). Thus, interpretation of C/O Log data may prove pessimistic in presence of thick cement sheaths.

Completion Integrity - Effectiveness of cement jobs is crucial. Presence of poor cement bond to casing and/or formation (particularly in severely washed-out sections) causes channeling, depletion, or recharge in multi-reservoir intervals which may be at different formation pressures behind casing.

Underreamed, Gravel Pack/Slotted Liner Completions - Due to constraints caused by depth of investigation and fluid distribution in massive gravel packs, information as to true reservoir conditions may be marginal.

Magnetized Casing Collars - Will cause spikes on the C/O Log ratios, most noticeable on the Ca/Si and least on the Si/Ca ratios.

Oil Density - C/O ratio values will slightly increase with decreasing gravity (<API°) of crude oils.

CASED HOLE POROSITY

The importance of accurate, reliable porosity measurements by well logs cannot be overemphasized. Generally, modern logging suites fill these requirements very adequately.

However, in many old wells that are now being considered for either recompletion or for enhanced recovery techniques, we do not have adequate logs for the required evaluation.

Table I lists several through-casing porosity determination techniques which are currently available, points out the basic concepts involved, and focuses on possible constraints.[15] Basically, a wide variety of neutron, acoustic, density, and several pulsed neutron logging concepts (including log-inject-log) allow through-casing porosity estimates. In addition, the same also holds true for the judicious selection and application of proper mathematical transforms.

Figure 5 favorably compares porosity information from the Continuous Carbon/Oxygen Log (i.e., its silicon count rate curve) versus Compensated Neutron Logs in low-porosity West Texas formations[16] and high-porosity zones along the U.S. Gulf Coast[7] and in California.[13]

Figure 6 illustrates the excellent agreement of porosity information obtained from the C/I ratio (as recorded by the Continuous Carbon/Oxygen Log) and the Compensated Neutron Log.[14] Porosity values from the C/I ratio are independent of instrument and neutron source output variations and, hence, superior to silicon-derived porosity information.

C/O APPLICATIONS AND FIELD EXAMPLES

Successful applications and field experiences including associated possible constraints are summarized in Table II.

Several specific field case examples are discussed next.

Recompletion in Seven Rivers and Queen Sands

In this well, located in Howard County, Texas, water has been injected into the Seven Rivers and Queen sands for a long time. The C/O Log, run to locate possible bypassed oil, shows the thicker sands to be watered out, with several thinner potentially oil-bearing stringers sandwiched between tight anhydrite streaks (Fig. 5). Selectively perforated as shown, this interval was successfully put on production at 40 BOPD plus 50 BWPD.[16]

Glorieta Completion

Glorieta development was limited by lack of mud shows, poor DST response, and high, indiscernible water saturation values from open-hole logs. Successful C/O application in the moderately porous carbonate reservoirs (Grayburg, San Andres, Holt, Glorieta, and the Upper Penn) has been reported for the Johnson (Glorieta) Field in central Ector County, Texas.[17] For example, the open-hole log evaluation for the well shown in Figure 6 indicated S_w values ranging from 80 percent to 100 percent in Zone 3 (water productive) and S_w from 37 percent to 68 percent in Zone 2 (probably water productive). On open-hole logs, Zones 1 and 3 look almost identical, suggesting similar production. However, subsequent C/O evaluation, successfully supported by subsequent production data, shows how open-hole data in this case are totally misleading. Figure 6 shows the C/O and Ca/Si overlay, normalized below the known oil/water contact at 5542 feet and potentially hydrocarbon-bearing intervals being shaded.

Based on this information, the well was perforated from 5414 feet to 5431 feet in Zone 1 and from 5492 feet to 5498 feet in Zone 3. Zone 2 was not perforated due to its lower apparent hydrocarbon saturation and the operator's desire to minimize water production. The lower interval in Zone 3 was not opened because of its close proximity to the oil/water contact. Following a 3000 gallon acid job, the well tested at 271 BOPD and no water on a 10/64-inch choke with GOR of 173.

Core Versus C/O Log-Derived Oil Saturation in Heavy Oil Reservoir

Since in heavy oil reservoirs the flushing and invasion effects are negligible, the C/O Log will provide a continuous and economically more attractive record of oil saturation compared to extensive and expensive core analysis. Figure 7 shows a comparison of oil saturation values from cores and the C/O Log in a well located in California.[9]

Evaluation and Monitoring of Heavy Oil Steam Flood

An open-hole and cased-hole logging program will evaluate the Poso Creek heavy oil reservoir, located in Kern County, California, before and during steam flood operation.[13] Changes in oil saturation during the steam flood operation will be evaluated with the C/O Log; steam breakthrough will be monitored with the silicon curve, C/I ratio, and temperature log. Figure 10 compares oil saturation from whole core analysis, dielectric (open-hole), and C/O (cased-hole) logging data.

Distinction Between Oil and Fresh Water

In this old well located in Texas, only an electric log from 1949 was available prior to running the Continuous C/O Log.[12] Formation waters are fresh and known to vary in salinity with depth. Under these conditions the old electric log and, for that matter, modern induction logs, cannot differentiate between oil and fresh water. Pulsed Neutron Dual Detector Neutron Lifetime® (DNLL) and Thermal Decay Time (TDT) Logs can't make this distinction either.

The Continuous C/O Log, however, clearly differentiates between the oil and fresh water as seen in Figure 11.

Upper Cretaceous Niobrara Formation

This complex lithology is very difficult to evaluate by means of conventional log analysis.[11] In this old, cased well, a completion attempt has been scheduled based on spectral gamma ray (Spectralog) and pulsed neutron (Carbon/Oxygen) data. The Spectralog is used to obtain a reliable shaliness estimate despite the presence of high and greatly varying U-concentrations. The target zone was perforated in intervals of low clay volume and sufficient oil saturations, the latter measured by the C/O Log (Fig. 12). Without any stimulation the formation was tested in excess of 800 BOD and 1.8 MMCFD through a 12/64-inch choke.

REFERENCES

1. Youmans, A.H., Hopkinson, E.C., Bergan, R.A., and Oshry, H.J. Neutron Lifetime, A New Nuclear Log. *Transactions,* AIME-SPE Meeting, 1964; *Journal Petroleum Technology,* March 1964.

2. Serpas, C.J., Wichmann, P.A., Fertl, W.H., DeVries, M.R., and Randall, R.R. The Dual Detector Neutron Lifetime Log® - Theory and Practical Applications (Paper C). *Transactions,* SPWLA, 1977.

3. Randall, R.R., Fertl, W.H., and Hopkinson, E.C. *Time-derived Sigma for Pulsed Neutron Capture Logging* (SPE 9614). Paper presented at the SPE of AIME Regional Middle East Meeting, Bahrain, March 1981.

4. Wahl, J.S., Nelligan, W.B., Frentrop, A.H., Johnstone, C.W., and Schwartz, R.J. The Thermal Neutron Decay Time Log. *Journal Petroleum Technology,* December 1970.

5. Clavier, C., Hoyle, W.R., and Meunier, D. *Quantitative Interpretation of TDT Logs,* (SPE 2658). Paper presented at the 44th SPE Of AIME 44th Fall Meeting, Denver, Colorado, September 28 - October 1, 1969.

6. Hall, J.E., Johnstone, C.W., Baldwin, J.L., and Jacobson, L.A. *A New Thermal Neutron Decay Logging System - TDT-M* (SPE 9462). Paper presented at the 55th SPE of AIME Fall Meeting, Dallas, Texas, September 21-24, 1980.

7. Hopkinson, E.C., Fertl, W.H., and Oliver D.W. *The Continuous Carbon/Oxygen Log - Basic Concepts and Recent Field Experiences* (SPE 9613). Paper presented at the SPE of AIME Regional Middle East Meeting, Bahrain, March 1981.

8. Wichmann, P.A., Hopkinson, E.C., and McWhirter, V.C. The Carbon/Oxygen Log Measurement. *The Log Analyst,* 17(6): 25-30, November - December 1976.

9. Heflin, J.D., Lawrence, T.D., Oliver, D., and Koenn, L. California Applications of the Continuous Carbon/Oxygen Log. *Transactions,* API Joint Chapter Meeting, Bakersfield, California, October 25-27, 1977.

10. Lawrence, T.D. *Continuous Carbon/Oxygen Log Interpretation Techniques* (SPE 8366). Paper presented at 54th SPE of AIME Fall Meeting, Las Vegas, Nevada, September 1979.

11. Heflin, J.D., and Nettleton, K.A. *Formation Evaluation Utilizing Gamma Ray Spectral Analysis* (SPE 9024). Paper presented at the SPE of AIME Rocky Mountain Regional Meeting, Casper, Wyoming, May 14-16, 1980.

12. Fertl, W.H., and Frost, E. *Recompletion, Workover, and Cased-Hole Exploration in Clastic Reservoirs Utilizing the Continuous Carbon/Oxygen (C/O) Log - The CHES III Approach* (SPE 9028). Paper presented at the SPE of AIME Southwest Texas Regional Meeting, Corpus Christi, Texas, April 10-11, 1980.

13. Roux, C., Fertl, W.H., Frost, E., Stedman, D., and Elliott, D. *Well Logs Evaluate and Monitor Heavy Oil Steam Flood in Kern County, California.* SPWLA 22nd Annual Logging Symposium, Mexico City, June 23-27, 1981.

14. Oliver, D.W., Frost, E., and Fertl, W.H. Continuous Carbon/Oxygen (C/O) Logging - Instrumentation, Interpretive Concepts, and Field Applications. *Transactions,* SPWLA, 1981.

15. Fertl, W.H. *Well Logging and Its Applications in Cased Holes* (SPE 10034). Paper presented at the SPE of AIME International Petroleum Exhibition and Technical Symposium, Beijing, China, March 18-26, 1982.

16. Flynn, J., Conley, S., Frost, E., and Fertl, W.H. *Cased-Hole Exploration and Recompletions in West Texas Based on the Continuous Carbon/Oxygen (C/O) Log* (SPE 9714). Paper presented at the SPE of AIME Permian Oil and Gas Recovery Symposium, Midland, Texas, March 12-13, 1981.

17. Barton, W., and Flynn, J.M. *Applications of the Carbon/Oxygen Log in Johnson (Glorieta) Field* (SPE 8453). Paper presented at the 54th SPE of AIME Fall Meeting, Las Vegas, Nevada, September 23-26, 1979; also *Journal Petroleum Technology,* 33(1): 145-150, 1981.

18. Vercellino, W.C., Skaggs, L.L., Bishop W.D., DeVries, M.R., McWhirter, V.C., and Wichmann, P.A. *Clastic Formation Evaluation Program in Cased Holes for Both Fresh and Saline Formation Waters To Determine Hydrocarbon Content* (SPE 5508). Paper presented at 50th SPE of AIME Fall Meeting, Dallas, Texas, September 28 - October 1, 1975.

19. Schultz, W.E., and Smith, H.D. Carbon/Oxygen Log Monitors Athabasca Tars and Recovery. *Oil and Gas Journal,* December 31, 1979, pp. 165-168.

20. Bradel, E. Problems and Experiences with Petrophysical and Technical Cable Tool Surveys in Cased Boreholes. *Erdoel Erdgas, Z.,* 96(8): 295-300, August 1980 (in German).

21. Sacco, E.L. Carbon/Oxygen Log Application in Shaly Sand Formation Contaminated with Tuffite Minerals (Paper HH). *Transactions,* SPWLA, 1978.

22. Rieke, H.H., Oliver, D.W., Fertl, W.H., and McCord, J.P. *Successful Application of Carbon/Oxygen Logging to Coalbed Exploration,* (SPE 9464). Paper presented at the 55th SPE of AIME Fall Meeting, Dallas, Texas, September 21-24, 1980.

TABLE I
CASED-HOLE POROSITY (Ø) DETERMINATIONS (Fertl, 1982)

Log type	Instrumentation	Remarks on basic principles, interpretive concepts, constraints
NEUTRON	neutron source-capture gamma rays detection	Capture gamma ray intensity roughly proportional to thermal neutron density
	neutron source-thermal neutron detection	Thermal neutrons measured directly
	neutron source-epithermal neutron detection	Reduction of perturbing effects of thermal neutron absorption characteristics
		$Ø_N$ = function of [rock matrix, porosity, amount and type of fluid in pore space (mud filtrate, oil, gas)]
		Environmental effects need to be taken into account when compared to open-hole porosity information
ACOUSTIC (SONIC)	several acoustic transmitter-receiver configurations	**Interval transit time** (Δt) is measured
		Δt = function of (rock matrix, porosity, amount and type of fluid in pore space, compaction, secondary porosity)
		Requires good cement bond to both casing **and** formation
		Detrimental attenuation effects in unconsolidated, gas-bearing clastic formations
DENSITY	gamma ray source-scattered gamma ray detection	**Electron density** (ρ_e, number of electrons per cc) is measured, related to true **bulk density** (ρ_b, gm/cc)
		$\rho_e = \rho_b \dfrac{2 \cdot \text{Atomic Number Z}}{\text{Atomic Weight A}}$
		ρ_b = function of [rock matrix, porosity, amount and type of fluid in pore space (mud filtrate, oil, gas)]
		Requires good borehole conditions and reliable cement job
PULSED NEUTRON	*Neutron Lifetime *Thermal Decay Time Several multiple fixed and sliding gate systems	Porosity computed as the **ratio** (Ratio curve from count rates of short-spaced (near) and long-spaced (far) detector
	High energy (14 MeV) pulsed neutron source-thermal neutron or gamma ray detection	Response of Ratio curve is similar to porosity index from compensated neutron logs
	*Log-Inject-Log Chemical Flood Method	Multiple pulsed neutron runs Runs at $S_w = 1 -$ ROS and after chemical flood ($S_w = 1.0$)
		$Ø = (\Sigma_2 - \Sigma_1)/(\Sigma_{w_2} - \Sigma_{w_1})$
	Chlorinated Oil Injection	Runs at $S_w = 1 -$ ROS and after injection of chlorinated oil (**apparent** $S_w = 1.0$)
	*Continuous Carbon/Oxygen (C/O) Tool Inelastic and capture gamma ray measurements	**Silicon count rate** curve is similar in response to compensated neutron log (as a count rate curve it will vary in absolute value for each instrument and source output)
		Ratio of capture gamma ray spectrum to a portion of the inelastic spectrum. This **capture/inelastic (C/I) ratio** is calibrated in porosity units. Independent of instrument and source output variations

CASED-HOLE POROSITY (Ø) DETERMINATIONS (continued)

Log type	Instrumentation	Remarks on basic principles, interpretive concepts, constraints
	*Gamma-Ray Spectrometer (GST) Tool	Porosity-Indicator Ratio (PIR) PIR = H/(Si + Ca)
	Inelastic and capture gamma ray measurement	Pulsed neutron logs exhibit shallow depth of investigation Mud filtrate invasion needs to be dissipated prior to logging in newly cased wells Severe washout effects, poor cement jobs and other environmental effects need to be considered
TRANSFORMS	*Mathematical correlations between different log responses to estimate porosity	Resistivity, Sigma, natural radioactivity, spontaneous potential $\longleftrightarrow$ Ø
	*Estimated maximum porosity ($Ø_{max}$) corrected for reservoir shaliness (V_{SH})	$Ø = Ø_{max}(1 - V_{SH})$ Use appropriate shaliness indicators as available
	*Depth-related porosity trends with and without shaliness corrections	Requires extensive area experience

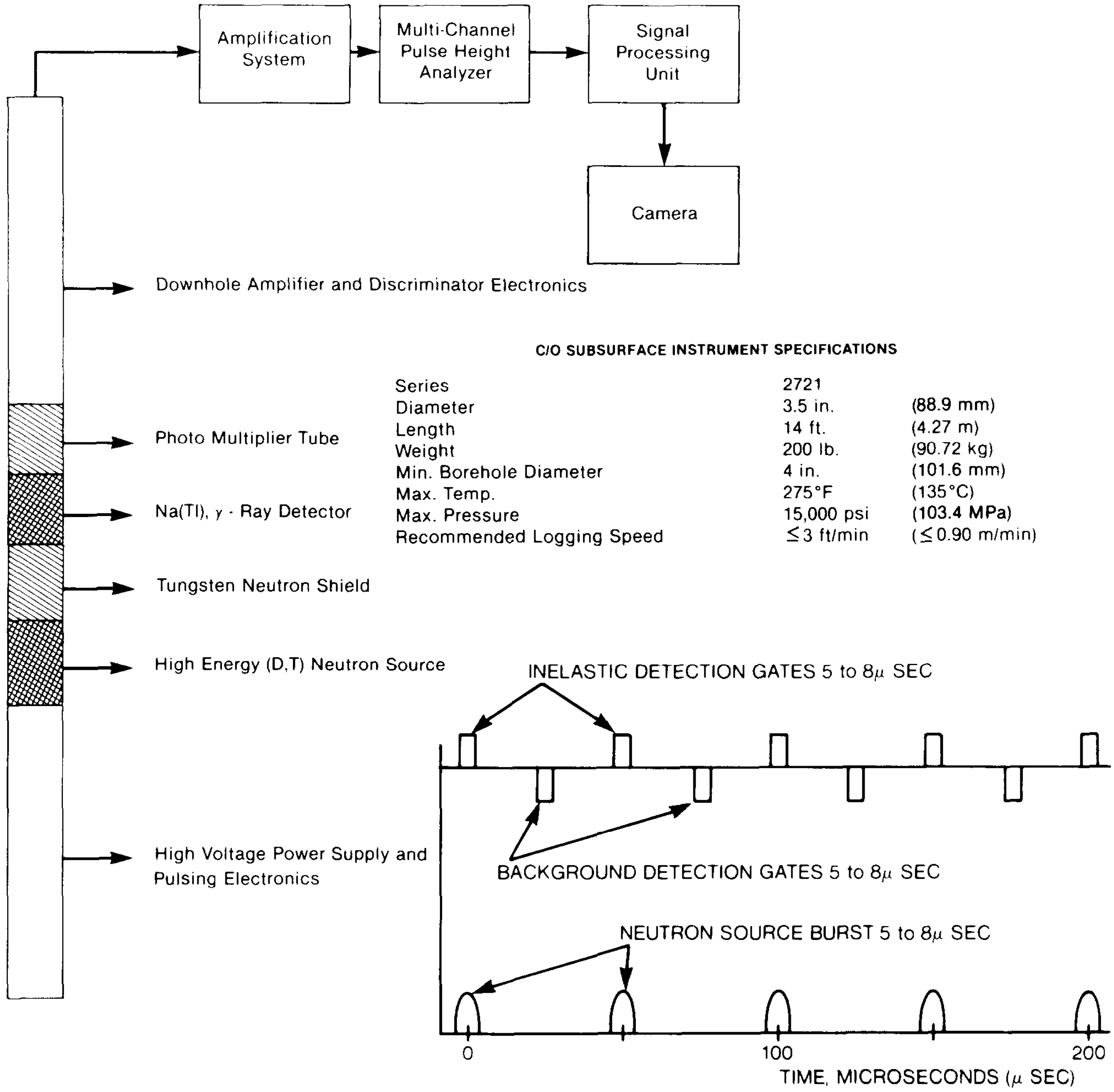
TABLE II

APPLICATIONS, FIELD EXPERIENCES & POSSIBLE CONSTRAINTS WITH THE CONTINUOUS CARBON/OXYGEN LOG

Applications	General remarks/constraints	Field experience/observations
Detection & quantitative evaluation of oil reserves in presence of fresh, brackish, mixed, and/or unknown formation water salinities.	Drastic salinity variations over short vertical distances may require interpretive use of Si/Ca **and** Ca/Si ratios with the C/O measurement.	North America (United States, Canada), South America (Argentina, Venezuela), Norwegian and United Kingdom North Sea, Continental Europe (West Germany), Saudi Arabia.
Exploration for overlooked or previously not commercially attractive hydrocarbon resources in abandoned and/or workover wells.	Prerequisite is integrity of well completion (i.e., good cement job, no casing leaks, severe washouts, etc.).	Particularly effective in old, shallow, low-salinity, multipay oil fields, supposedly watered-out (stratified) reservoirs, etc. Excellent results obtained in U.S. Gulf Coast region, West Texas, New Mexico, Mid Continent, Rocky Mountains, California, etc.
Evaluation of oil reserves in newly drilled wells where open-hole (OH) logs are not available.	Due to mechanical or safety-related hole problems no OH logs were run.	Universally applicable in medium to high porosity reservoirs. Published field cases include Gorieta and Clearfork Formations in Mitchell and Lubbock Counties, Texas.[16]
Evaluation of newly drilled wells where OH-logs give inconclusive information.	Time lag required after casing is run to eliminate possible invasion effects due to mud filtrate.	Universally accepted in medium to high porosity reservoirs. Published field cases include Glorieta Formation in Lubbock County, Texas, Ector County, Texas;[17] multi-fault block oil field, onshore Louisiana, etc.[12]
Evaluation of clean and/or shaly oil-bearing reservoirs where open-hole and other cased-hole logs provide information inconsistent with reservoir performance.		
Monitoring of displacement and sweep efficiency in primary/secondary/tertiary recovery projects. Reservoir performance and depletion checks.	Well completion integrity is a must.	Multi-well, field-wide monitoring of vertical and lateral reservoir performance. Input parameters in reservoir engineering studies and reservoir simulation models.
Hydrocarbon/water contacts. Detection and monitoring in presence of low or unknown formation water salinities.	Time-lapse logging. Multiple repeat runs (three or more) to improve results.	Applicable and used in many areas, domestic and overseas.
Waterfloods. Monitoring of oil saturation depletion, reservoir stratification, encroachment and fresh water breakthrough.	Time-lapse logging. Salinity Index can be calculated (i.e., extent of mixing of injection and initial formation waters of contrasting salinity can be monitored on vertical and lateral reservoir basis).	Universally applicable. Salinity Index has been used successfully in U.S. Mid Continent oil fields. C/O application is dramatically superior to the requirement of special plastic-casing and induction logging monitoring.
Chemical Enhanced Oil Recovery (micellar-polymer, polymer caustic). Monitoring of flood efficiency, oil depletion, stratification, breathrough patterns, etc.	Time-lapse logging. Well completion integrity is prerequisite.	Domestic field experiences.
Gaseous Enhanced Oil Recovery (CO_2 miscible, hydrocarbon miscible, other gases). Monitoring of the flood efficiency, oil depletion, stratification, breakthrough patterns, etc.	Time-lapse logging. Gas saturation estimates possible in the swept zones.	Domestic field experiences.

APPLICATIONS, FIELD EXPERIENCES, & POSSIBLE CONSTRAINTS WITH THE CONTINUOUS CARBON/OXYGEN LOG (Continued)

Applications	General remarks/constraints	Field experience/observations
Thermal Enhanced Oil Recovery (cyclic steam "huff & puff" injection, steam flood, in-situ combustion). Monitoring of flood efficiency, oil depletion, stratification, breakthrough patterns, etc.	Time-lapse logging. Heavy oil/low gravity oil reservoirs, tar sands. Temperature constraints, very large casings and underreamed, gravel-pack completions.	Extensive field experiences in the U.S. (California, Texas, Louisiana, Mid Continent, Rocky Mountains).[9,18,13] Canada (Athabasca, McMurray Fm.).[19] Europe (Emsland, West Germany);[20] South America.
Residual Oil Saturation (ROS) based on Log-Inject-Log techniques.	Accurate salinity control of injection fluid not critical. Assure well completion integrity. Low rate injection to avoid formation fracturing and crude oil stripping around wellbore.	Numerous domestic applications in Alaska and lower 48 states.
Oil Resource Evaluation in mixed and complex lithologies where formation water salinities may pose constraints on conventional formation evaluation (carbonates, oil shales, granite wash, tuffaceous sands, etc.).	At least medium reservoir porosity. Frequently very helpful is supplementary information from natural gamma ray spectral logging, such as Spectralog.	United States, Canada, Europe, South America. Carbonates (Permian Basin, U.S.; Florida, Rocky Mountains).[16] Tuffaceous Clastics (Argentina);[21] Granite Wash (Texas, Oklahoma). Niobrara, Mowry Shale, Phosphoria Fms in Rocky Mountains.[11] Oil Shales, Rocky Mountains.
Distinction between gas bearing clastic reservoirs and coal seams (i.e., lignites, etc.).	Gas sands and low-rank coals exhibit similar standard log responses. Coupled with frequent mud gas shows, this results in the testing of "gas" prospects which in fact are lignite beds.	Important in U.S. Gulf Coast region, and elsewhere, when evaluating old wells or proposed hydrocarbon prospects based on old electric logs and/or mud logs only.
Coal seam evaluation.	In cased (old) wells. Estimate of coal rank, BTU content. Constraints include severely washed-out coal seams.	Field studies in Pittsburg County, Oklahoma based on both Continuous C/O and stationary log measurements.[22]



C/O SUBSURFACE INSTRUMENT SPECIFICATIONS

Series	2721	
Diameter	3.5 in.	(88.9 mm)
Length	14 ft.	(4.27 m)
Weight	200 lb.	(90.72 kg)
Min. Borehole Diameter	4 in.	(101.6 mm)
Max. Temp.	275°F	(135°C)
Max. Pressure	15,000 psi	(103.4 MPa)
Recommended Logging Speed	≤3 ft/min	(≤0.90 m/min)

FIGURE 1
Schematic of C/O instrumentation, subsurface instrument specifications, and source-detector operating cycle (Hopkinson et al., 1981).

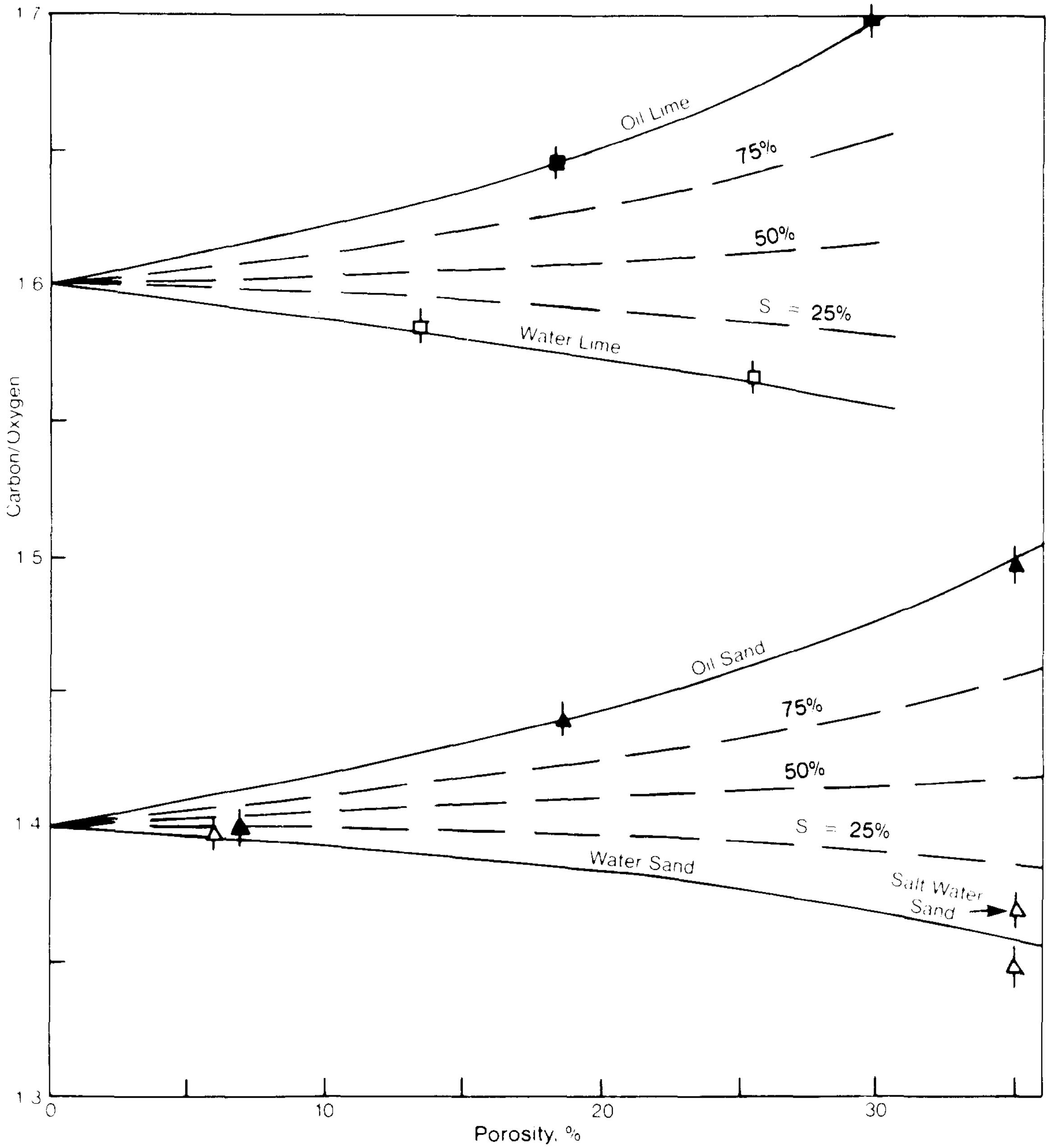


FIGURE 2
C/O laboratory calibration (Oliver et al., 1981).

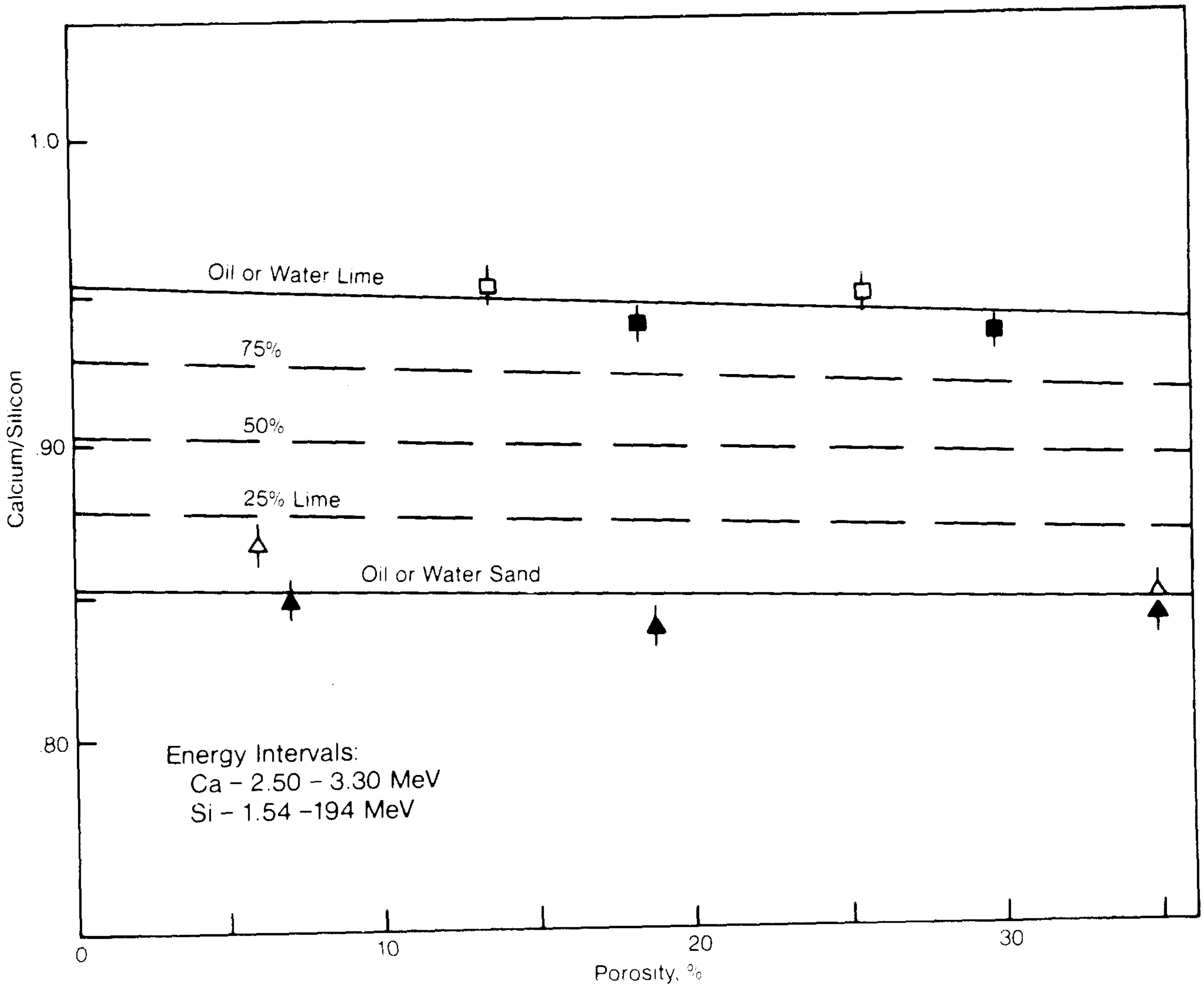


FIGURE 3
Ca/Si inelastic ratio, laboratory calibration (Oliver et al., 1981).

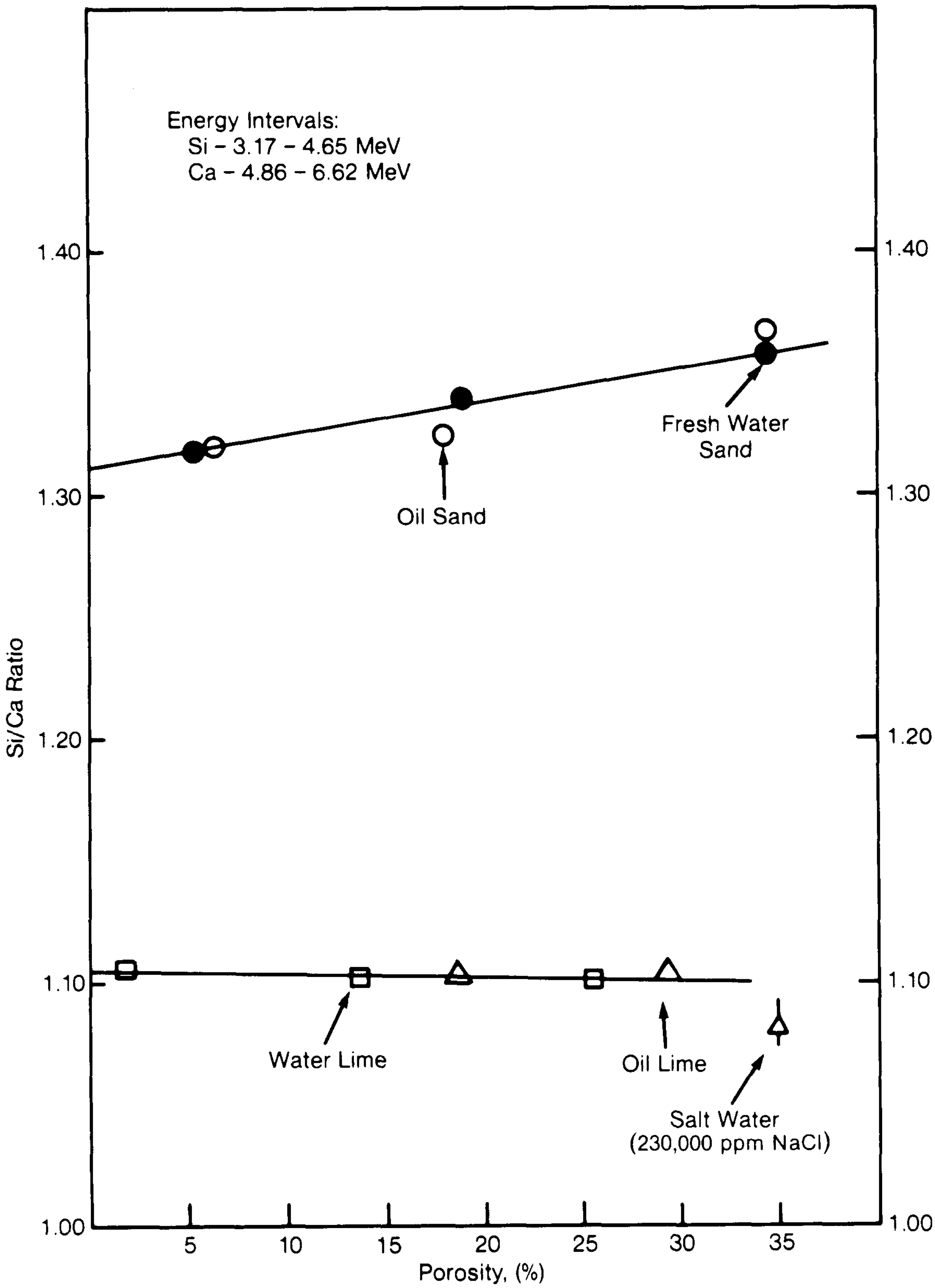


FIGURE 4
Si/Ca capture ratio, test pit formation (Oliver et al., 1981).

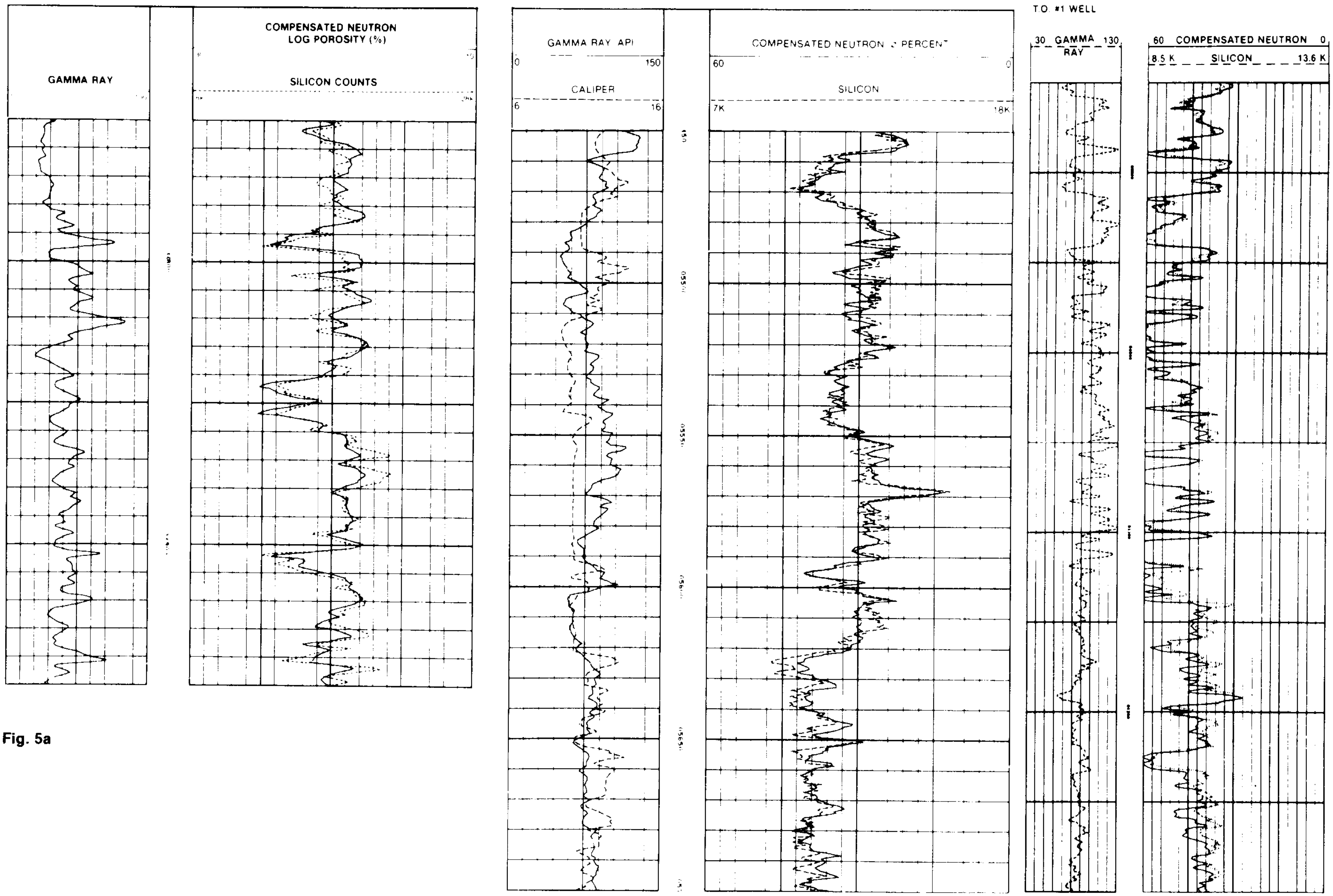


Fig. 5a

Fig. 5b

Fig. 5c

FIGURE 5
Comparison of silicon count rate curve and Compensated Neutron Log; (5a) complex reservoir rocks, West Texas (Flynn et al., 1981); (5b) clastic sequence, U.S. Gulf Coast (Hopkinson et al., 1981); (5c) sand-shale sequence, Kern County, California (Roux et al., 1981).

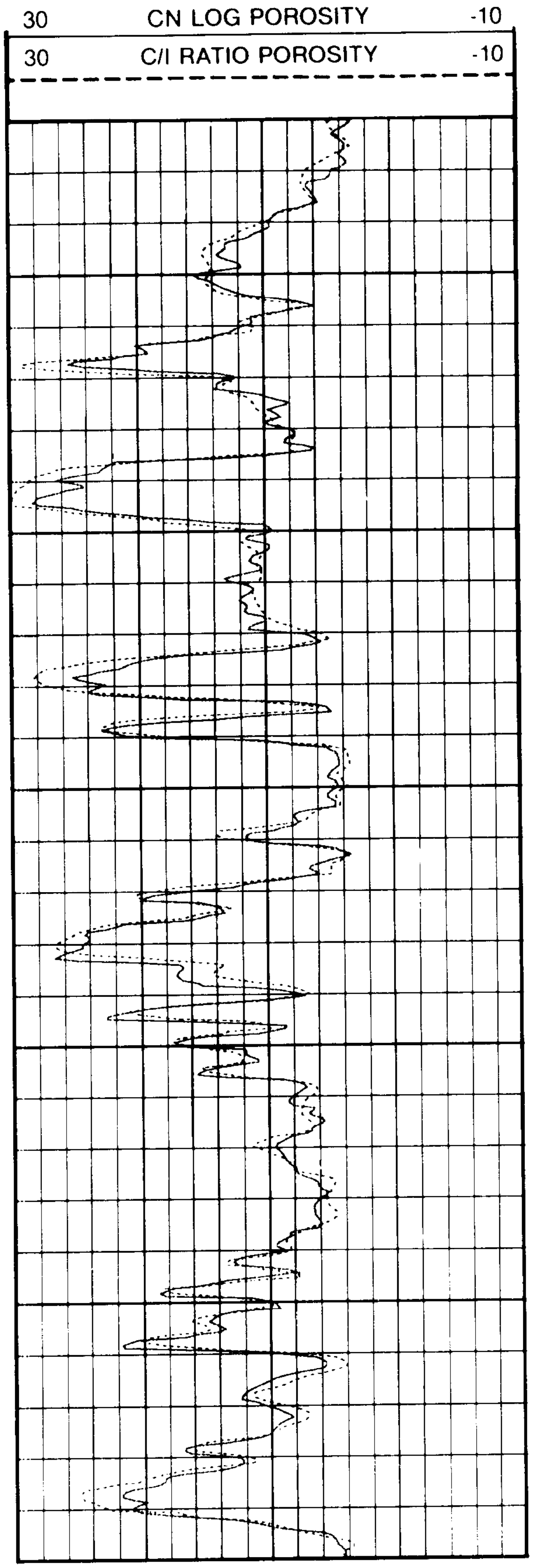


FIGURE 6
Comparison of C/I ratio versus Compensated Neutron Log (Oliver et al., 1981).

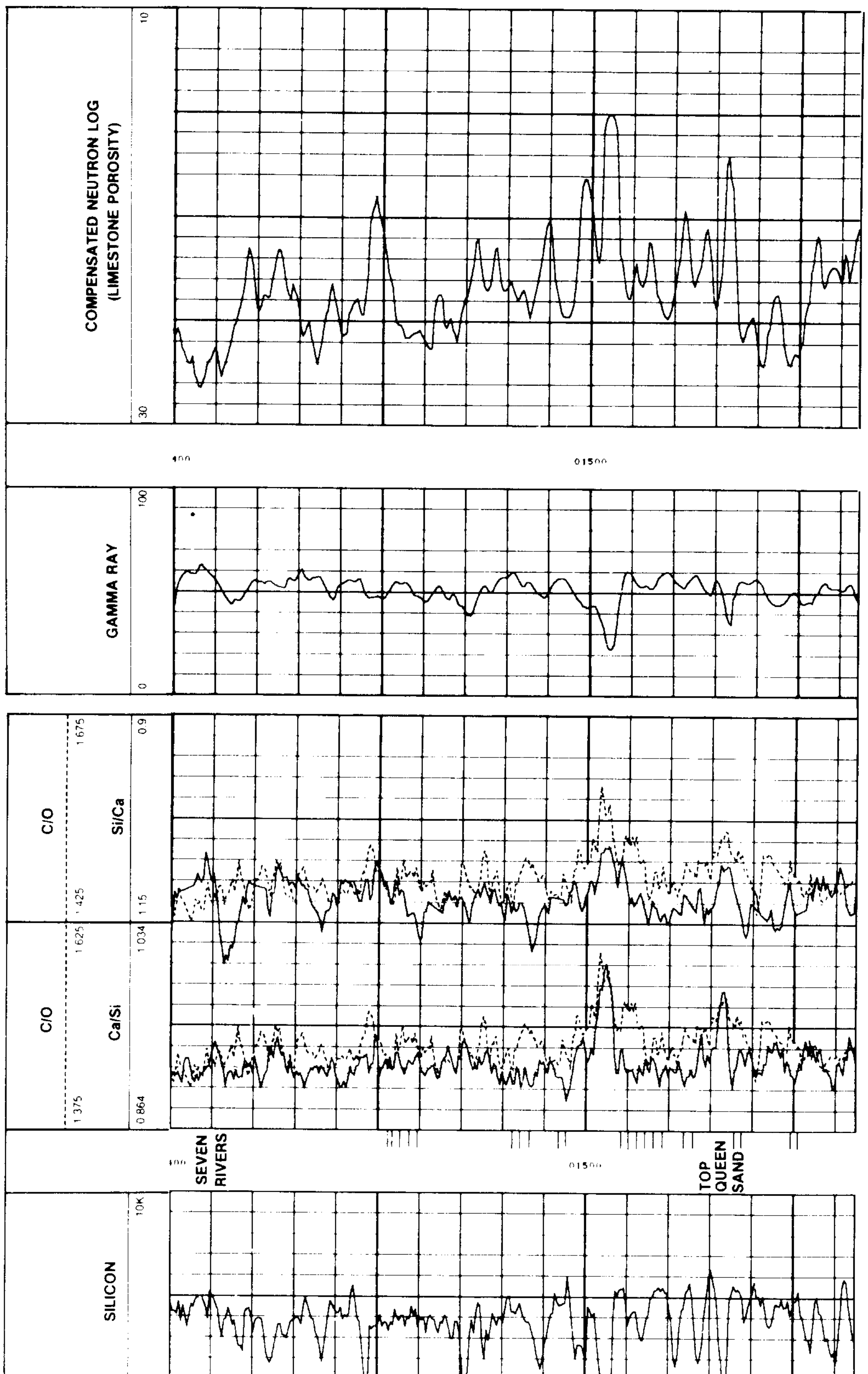


FIGURE 7
Recompletion in Seven Rivers and Queen sands, Howard County, Texas (Flynn et al., 1981).

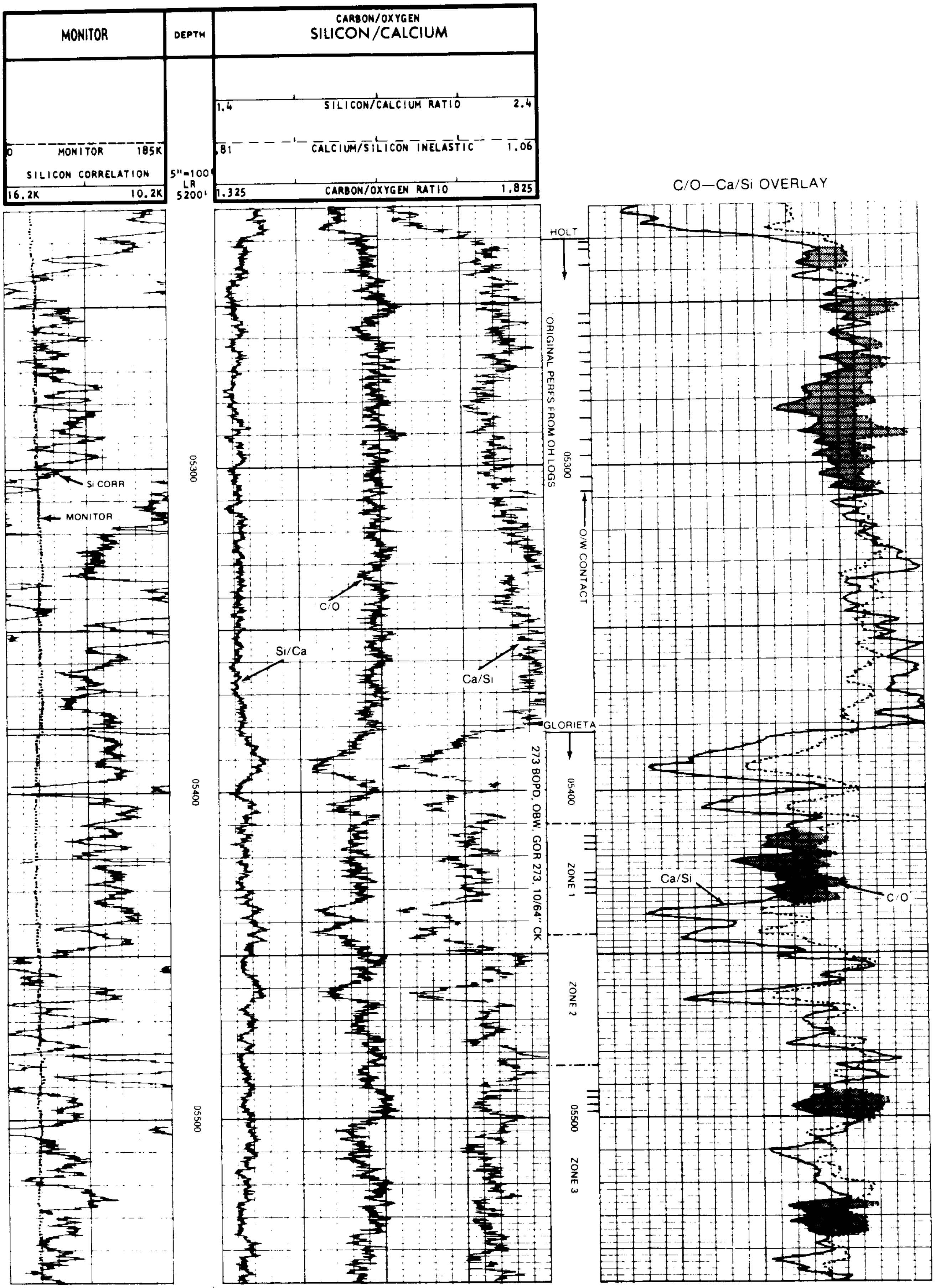


FIGURE 8

C/O Log and C/O versus Ca/Si overlay, Johnson Deep Unit No. 1 Well, Ector County, Texas (Barton and Flynn, 1979).

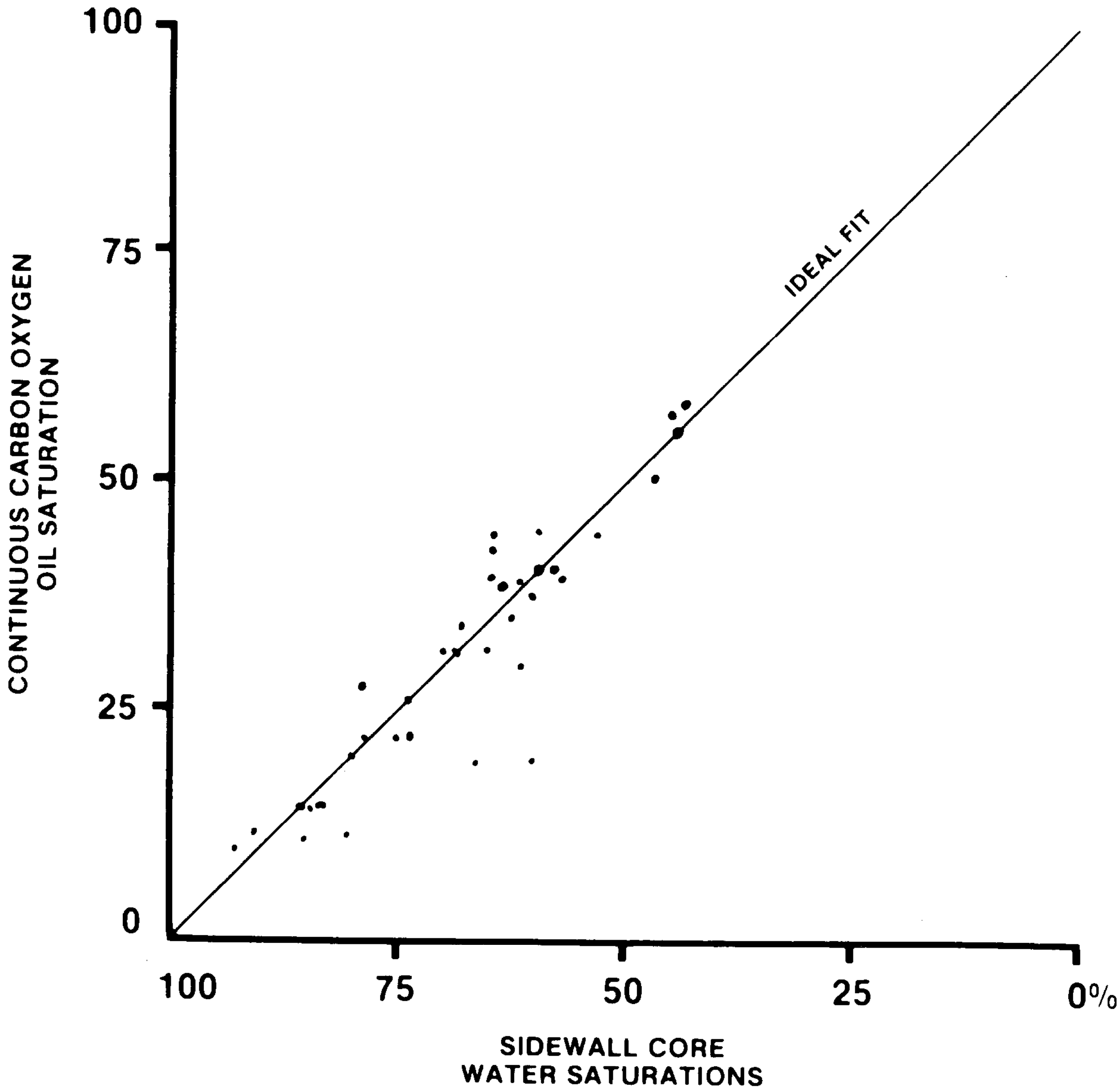


FIGURE 9
Core versus log-derived oil saturation in heavy oil reservoir, California (Heflin et al., 1977).

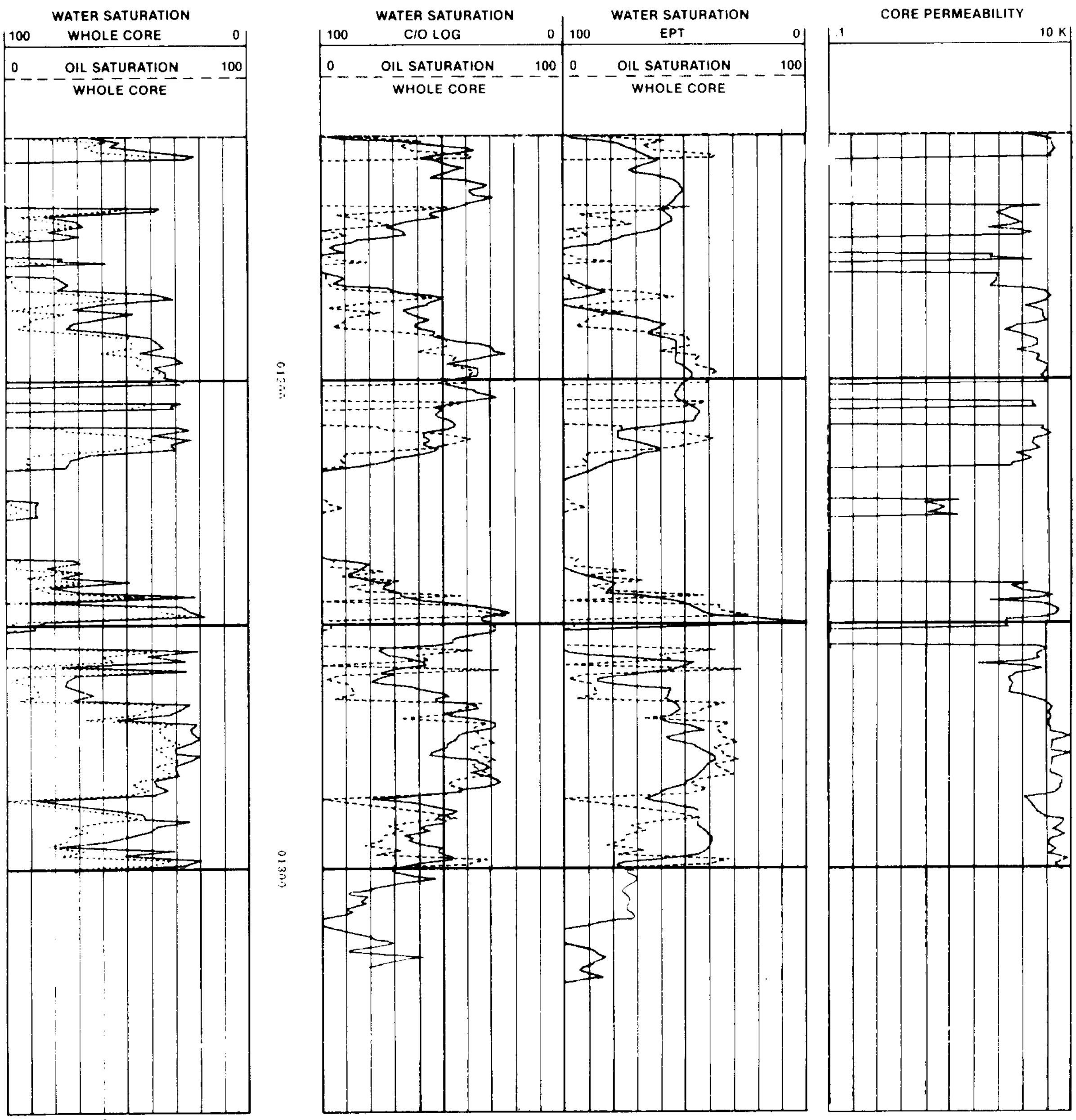


FIGURE 10
Oil saturation distribution in heavy oil, Poso Creek Reservoir, Kern County, California, based on whole core, open-hole (Dielectric), and cased-hole (C/O) logging data (Roux et al., 1981).

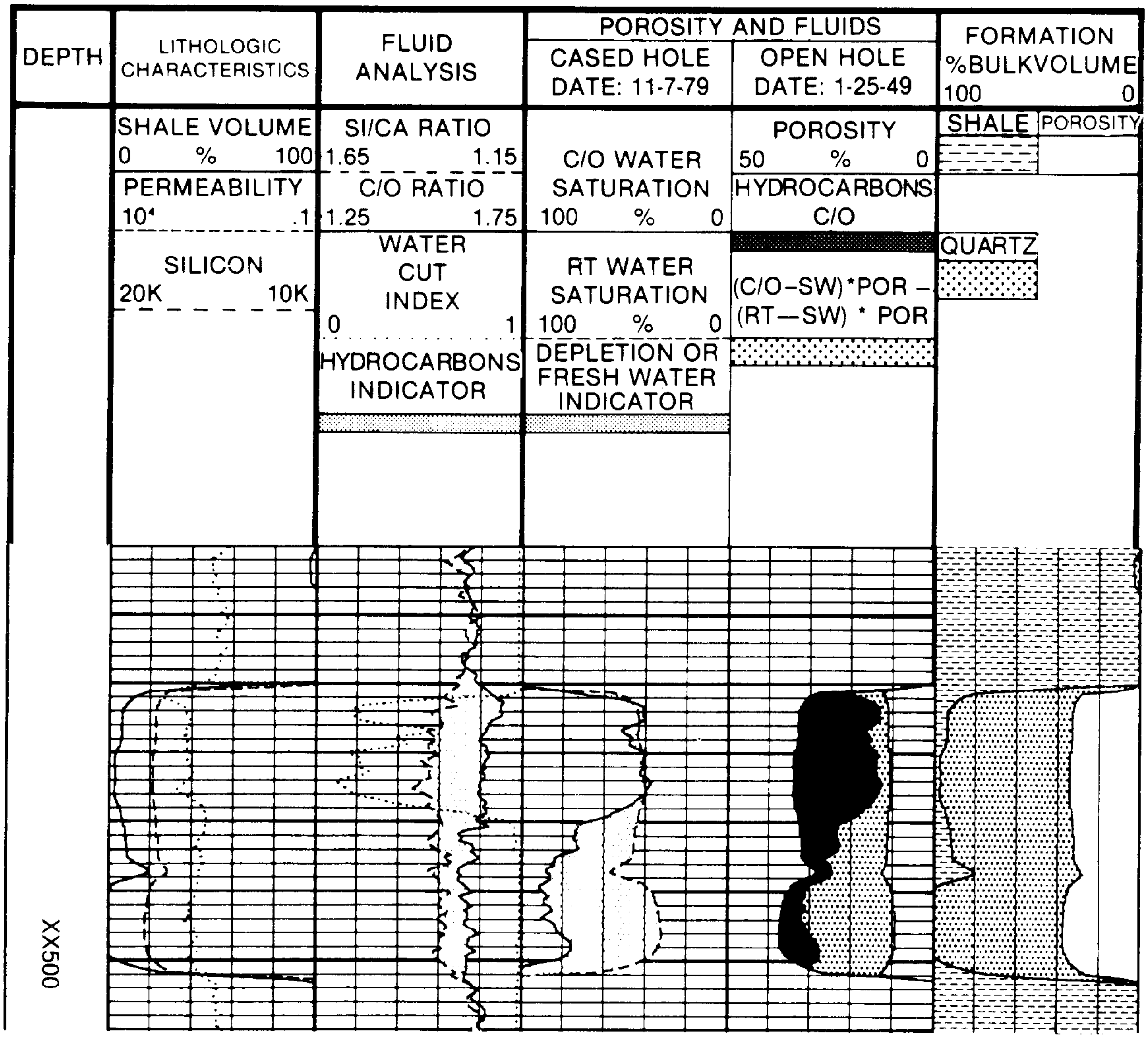


FIGURE 11
Distinction between oil and fresh water, Texas (Fertl and Frost, 1980).

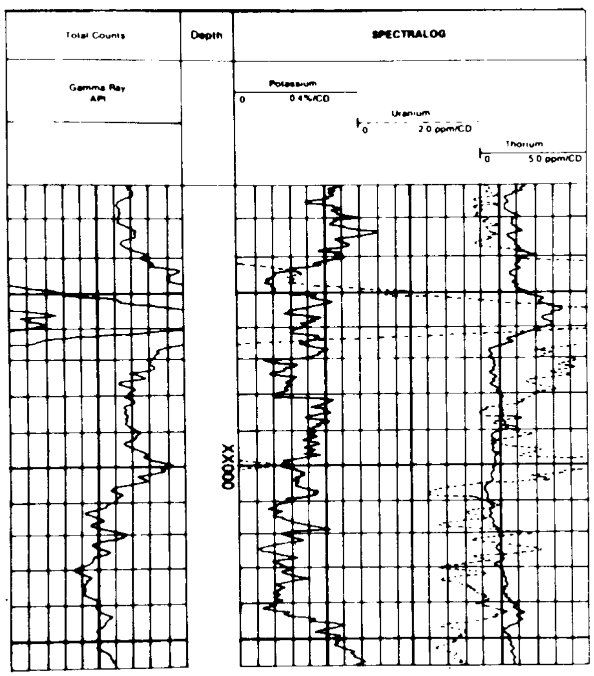


Fig.12a

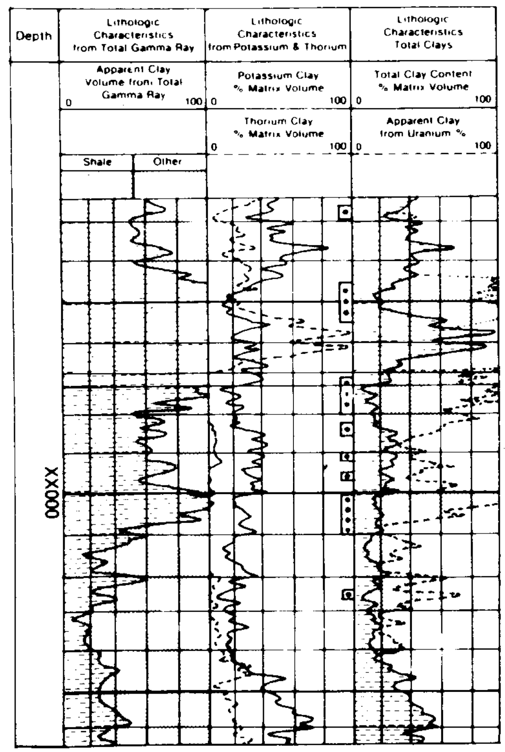


Fig. 12b

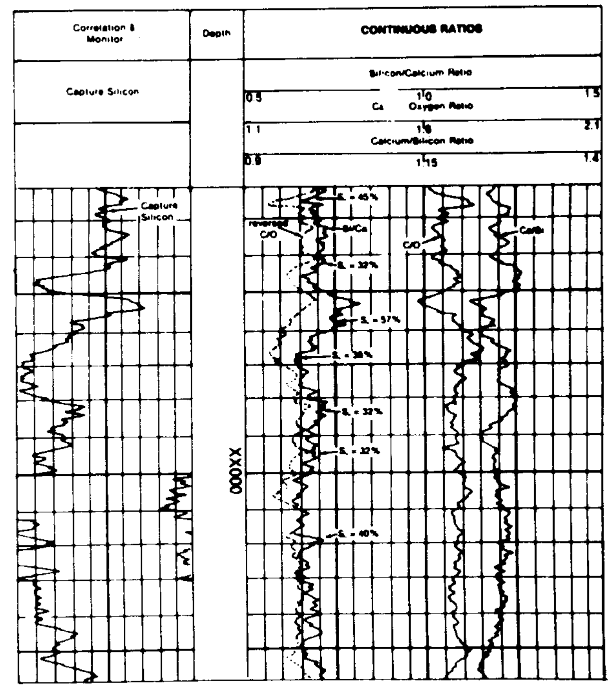


Fig. 12c

FIGURE 12
Natural spectral gamma ray (Spectralog) information (12 a & b) and Continuous C/O Log (12c) over Cretaceous Niobrara interval. Initial tests through perforations shown in Figure 12b produced 800 BOD on 12/64 choke without any stimulation (Heflin and Nettleton, 1980).