SPE 8454

GAMMA RAY SPECTRAL EVALUATION TECHNIQUES IDENTIFY FRACTURED SHALE RESERVOIRS AND SOURCE ROCK CHARACTERISTICS

SPE
Society of Petroleum Engineers of AIME

Walter H. Fertl, Dresser Atlas, Dresser Industries, Inc., Houston, Texas
H. H. Rieke III, West Virginia University and TWR Inc., Morgantown, West Virginia

ABSTRACT

Highly radioactive, black, organic-rich and gaseous shales are encountered in several United States geologic provinces. Such organic-rich shales are not only potential source rocks but frequently owe their localized but significant production potential to natural fracture systems in an otherwise impermeable rock. These natural fracture systems are normally concentrated in the interbedded brittle, calcareous, cherty or silty zones.

Calcareous and silty zones, both characterized by low values of potassium and thorium but by excessively high values of uranium, are easily located with natural gamma ray spectral information obtained from a highly sensitive scintillation spectrometer logging tool (i.e. Spectralog). These interpretive concepts have already assisted in many successful gas and oil well completion and recompletion attempts in the more permeable and/or fractured intervals of such shale formations.

The Spectralog also allows a continuous monitoring of the source rock potential (SRP) of shales in open and in cased boreholes. Hence, both vertical and lateral SRP variations can be studied using appropriate mapping techniques. Gamma ray spectral data also assist in detailed stratigraphic correlations, for in addition to total gamma ray counts, the Spectralog measures the individual gamma rays emitted by potassium-40 (K^{40}) the uranium series nuclide bismuth-214 (Bi^{214}) and the thorium series nuclide thallium-208 (Tl^{208}).

The present discussion focuses on the employment of gamma ray spectral logging to interpret the reservoir pore structure present in shales. Interpretive experiences include work in the Eagle Ford Shale of the Cretaceous Carbonate Trend of South Texas, in the Cretaceous Niobrara and Pierre Shales of Colorado, in the Woodford Shale of Lower Mississippian and Upper Devonian age of Oklahoma and West Texas, and in the Devonian Shales of the Appalachian Basin.

References and illustrations at end of paper.

INTRODUCTION

Conventional logging and interpretive techniques are not adequate to satisfactorily evaluate the complex and frequently fractured shale reservoirs. Novel applications of the Spectralog for characterizing these shale formations as to their reservoir properties and source rock potential will be discussed and illustrated in detail.

SPECTRALOG PRINCIPLES

Gamma rays are the radiations originating within an atomic nucleus. Radioactive decay consists of the emission or capture of elementary and composite particles with their consequent transformation into daughter nuclei characterized by different atomic numbers and in some cases by different mass numbers.

Basically, the vacuum flask assembly in the pressure housing of the Spectralog sonde contains a high-resolution gamma spectrometer. The spectrometer consists of the thallium-activated sodium iodide crystal (2 inch by 12 inch) optically coupled to a photomultiplier (PM) tuble. A downhole, high-quality electronic amplifier assures voltage amplitude proportionality when transmitting the pulses througn either a single conductor or multiconductor logging cable to the surface panels. These include an electronic amplifier, a multichannel analyzer, a digital panel and a conventional logging camera.

Pulse signals reaching the surface first pass through the electronic amplifier (its gain set during calibration). Amplified pulses are then filtered by the multichannel analyzer, which not only displays the entire spectrum but also selects pulses within preselected energy windows. Next, the digital panel computes background corrected radiation count rates from the raw logging data by means of a mathematical spectrum stripping technique.

Four count rate meters (CRM) are available to tally the total number of gamma rays measured (total count rates, counts/minute) and the background corrected count rates for potassium, uranium and thorium in each of the above energy windows. The outputs from each CRM are displayed on the camera and recorded on film as a function of depth.

Hence, in addition to total gamma ray counts, the Spectralog measures and records the gamma rays emitted by potassium-40 (K^{40}) at 1.46 MeV, the uranium series nuclide bismuth-214 (Bi^{214}) emanating gamma rays at 1.764 MeV, and the thorium series nuclide thallium-208 (Tl^{208}) emanating gamma rays at 2.614 MeV. These nuclides are of particular interest to the oil industry, since in various amounts, all are found in subsurface formations as constituents of potential-reservoir rocks. Based on an extensive literature search and on recent field observations, a data compilation has been published to document potassium, uranium and thorium distributions in various rock types.[1]

FRACTURED SHALE RESERVOIRS

Downward movement of meteoric waters into subsurface strata, concurrent reduction of oxygen, bacterial action and geochemical reactions with the host rocks are responsible for changes in the redox (Eh) potential. Mineral precipitation from subsurface waters is controlled by pH and Eh potentials.

Petroleum associated subsurface waters usually exhibit a reducing (negative) redox potential. In the presence of organic matter, hydrogen sulfide, sulfur dioxide, and the available uranium ions transported by migrating formation waters will precipitate as UO_2. Tuffaceous, arkosic, and granitic rocks are among the probable source rocks of uranium.

Precipitated uranium may concentrate along fault planes, fracture and fissure systems of some areal extent, and under the proper conditions, in any more permeable part of subsurface formations. Extensive field experience over the last two years has shown that gamma ray spectral logging techniques such as the Spectralog assist in pinpointing fractured intervals.[2] However, standard well logs still have to be taken into account for complete interpretive formation evaluation, such as porosity and water saturation determinations.

Eagle Ford Shale - Cretaceous Carbonate Trend, Texas

Over the last few years interest in exploratory drilling and recompletion attempts in old wells has been rekindled in the Cretaceous Carbonate Trend, located in both south and east Texas. With recoverable oil reserves estimated to range between two and three billion barrels, the trend extends over 370 miles in a southwesterly-northeasterly direction with a width up to 50 miles.

Primary productive formations are the Austin Chalk and Buda Limestone, which are separated by the Eagle Ford Shale. Although the latter has an additional but less significant oil-producing potential, the Eagle Ford Shale by itself cannot be considered the sole target for drilling.[2]

Normally, these target formations exhibit low porosity and low permeability. Occasionally, however, good matrix porosity ($<$12%) and permeability are encountered. Presence of a natural fracture system, supported by some matrix porosity, is the key to locating high initial flow rates which will level off at economical and stabilized production rates.

The very petroliferous Eagle Ford Shale is the source rock for much of the hydrocarbons found in the Austin Chalk and Buda Limestone. The Eagle Ford Shale is a frequently fractured, brittle, often micaceous and fossilferous shale with some siltstone and with occassionally recrystallized dolomitic lime streaks that exhibit a highly oil-saturated matrix. In some areas these carbonate stringers range in thickness from 10 to 30 feet. The SEM-photo[2] in Figure 1 shows some recrystallization in this shale at 5000x magnification.

Depending upon its location within the Cretaceous trend, in the Eagle Ford Shale the Spectralog response may vary from indicating a typically dark, organic-rich shale that exhibits high potassium, high thorium and excessively high uranium to indicating those calcareous, brittle, fractured and often productive Eagle Ford intervals that exhibit low potassium, low thorium and excessively high uranium. Uranium concentrations ranging as high as 7 parts per million (ppm) to 15ppm are frequently observed.

Drastic differences in the Spectralog response also exist between potentially productive Eagle Ford Shale sections and the Del Rio Shale underlying the Buda Limestone (Figure 2). Although the total gamma ray radiation values in the two zones are quite similar, major differences are apparent in the distribution of the potassium (K), uranium (U), and thorium (Th) concentrations (i.e., Eagle Ford: low K, excessively high U, and low Th; Del Rio: high K, high U, and high Th).[1]

Figure 3 shows the Spectralog response typical for the Eagle Ford Shale, Dimmit County.[2] The well was initially perforated over the entire Austin Chalk section based on a fracture identification log, and treated with a massive frac. However, a subsequent production test yielded only 5 barrels of oil per day (BOPD).

The operator planned to plug the well but decided to run the Spectralog prior to abandonment. Based on Spectralog information, it was recommended to selectively perforate the Eagle Ford Shale in zones of low potassium but high uranium content. Without stimulation, the well was put on production, pumping at a sustained rate of 28 BOPD from this shale section.

Figure 4 presents the Spectralog response to the Eagle Ford Shale in the Pearsall area, Frio County, Texas. Note that the total counts curve does not show any correlation to formation shaliness. Particularly between 5455 ft. and 5495 ft., the potassium curve indicates a relatively clean, calcareous Eagle Ford interval. However, uranium values increase. Selective perforating in such intervals often yields oil production.

The Spectralog response over the Austin Chalk, Eagle Ford Shale, and Buda Limestone in a well drilled in Caldwell County, Texas, is shown in Figure 5. Here the relatively thin Eagle Ford Shale is characterized by high values for potassium and thorium, and excessively high uranium. This Spectralog response is typical for organic-rich shales.

Niobrara and Pierre Shales - Cretaceous Shale Reservoirs, Colorado and New Mexico

Cumulative oil production from fractured shales is three percent of that from all formations in Colorado and eleven percent in NW - New Mexico.[3] Parts of the Niobrara, Mancos and Pierre Formations are the principal rocks that locally produce hydrocarbons. Generally speaking, hydrocarbon production from these shales comes from fractured intervals of Cretaceous age which exhibit similar reservoir characteristics. These include (1) thick, dark, organic-rich shales, (2) natural fracture systems in an otherwise essentially impermeable rock, (3) fractures concentrated in brittle, usually hard calcareous or silty zones confined to specific stratigraphic intervals and demonstrably local structural features, and (4) potential "reservoir" intervals capped, floored and/or interbedded with relatively plastic clay shales that provide the seal for the reservoir fluids and suggest an indigenous source of the latter.

Additional exploration-related details on fracture occurrence in these Cretaceous shale intervals located in the San Juan Basin, New Mexico have been discussed recently.[4] In the Verde oil field, for example, commercial oil-filled fractures appear to be confined largely to areas of maximum convex curvature, to abrupt changes in strike direction along monoclines, and to the presence of thin, brittle, quartzitic siltstones (from one inch to several feet thick) in an indurated Niobrara shale matrix. In the San Juan Basin surface indications usually show three fracture types along limbs of folds — open fractures located parallel to fold axes on the convex side of folds, the frequently tight dip fractures and the oblique fractures that are also tight. Typical examples of producing fracture reservoirs include two groups of fields as follows: the Verde, Boulder, West Puerto Chiquito and East Puerto Chiquito oil fields of the San Juan Basin in New Mexico; Buck Peak, Chromo, Coalmont, Florence-Canon City, Hidden Valley, Moffat, Rangely, Red Mesa, Tow Creek and Waddle Creek fields in Colorado.

Based on organic richness the high source rock potential of the Niobrara Formation is clearly shown by comparing its average content in barrels per acre-foot of hydrocarbon, asphalt, and kerogen with other U.S. and Canadian shales.[5]

Source rocks	Barrels per acre-foot		
	Hydrocarbon	Asphalt	Kerogen
•Mississippian and Devonian Woodford Shale	65	60	1,000
•Mississippian and Devonian Antrim Shale	50	79	1,190
•Cretaceous Niobrara Formation	**26**	**43**	**630**
•Devonian Traverse Group	24	37	230
•Mississippian Banff Formation (of Canada)	22	14	130
•Mississippian Caney Shale	19	48	730
•Tertiary Monterey Shale	12	40	380
•Permian Phosphoria Formation	11	7.0	220
•Pennsylvanian and Mississippian Springer Group	8.0	10	300
•Devonian Bell Shale	5.3	3.7	80
•Pennsylvanian Cherokee Group	5.0	11	380
•Tertiary Wilcox Group	3.7	11	170
•Ordovician Beekmantown Group	1.2	3.0	21

Figure 6 shows the Spectralog response over the Pierre Shale as logged in a well in Fremont County, Colorado. Note that the excessively high total for natural gamma ray radioactivity is caused primarily by high uranium concentration.

Woodford Shale — Oklahoma and Texas

Typically black, organic-rich shale formations include the Antrim-Chattanooga-Woodford shales of Lower Mississippian and Upper Devonian age.

Figure 7 illustrates the Spectralog response in a U.S. mid-continent area well that penetrates the Mississippian Lime, approximately 50 feet of Woodford Shale (here note $\gg$ total counts, $>$ K, $\gg$ U, $>$ Th)* and the Hunton Lime.

---

* $>$ =high, increasing; $<$ =low, decreasing; $\gg$ =very high, excessive

In southern Oklahoma, the Woodford Formation is a carbonaceous shale, dark-brown to black in color, which locally contains relatively thin beds of dark pyritic chert, silicious shales and siltstone. Hydrocarbon production from this Woodford section is controlled by the presence of natural fracture systems particularly in intervals of increased carbonate, silt and chert content.[6]

Well log responses in the Woodford Shale include excessively high, natural radioactivity, a non-definitive spontaneous potential (SP), high formation resistivity and low bulk density. The latter two are caused by kerogen in the pore space. Figure 8 shows those log responses characteristic for the Woodford section in a well in Caddo County, Oklahoma. Note the excessively high (shaded) gamma ray values and the presence of several cleaner (less shaley) zones as suggested by the density-neutron, porosity overlay. Mainly siliceous shales, these cleaner zones occur from 5955 feet to 6058 feet and are productive in the subject well. The siliceous zone is identified by the apparent-density porosity being higher than the neutron porosity. The transition from the siliceous to mostly shale interval occurs around 6058 feet with density-porosity reading lower than neutron porosity.

The kerogen effect is clearly shown by comparing log- and core-derived bulk density values. As expected, core bulk densities determined by the Dean Stark method are consistently higher than the log-derived values.

The well was selectively perforated in the cleaner intervals between 5964 feet and 6052 feet. It was put on production at 240 BOPD.

Application of the Spectralog (not available in subject well) greatly assists in locating these less shaley, potentially fractured intervals defined by decreasing values of potassium and thorium but by drastically increasing uranium concentration. Over the deep Woodford Formation in a West Texas well, the Spectralog (Figure 9) clearly suggests the presence of a rather hard shale exhibiting high natural radioactivity. The latter is primarily due to the drastic increase in uranium concentration. Typical shale response (>K, >Th) is only observed close to the top of the subject interval.

Devonian Shales, Eastern United States

Devonian Shales are source rocks and locally hydrocarbon-bearing reservoir targets which consist of quartz, clays, and accessory minerals such as calcite, pyrite, gypsum, feldspar, zircon, muscovite and titanite.

The Devonian sedimentary sequence underlies much of the approximately 200,000 square miles included within the Appalachian basin.[7] Eastern Devonian Shale characteristics[8] include the following:

Type of rock: shale with 1.0 to 15 percent organic carbon

Production: natural gas and some oil

Typical depth 3500 feet

Bottom Hole Temperature = 95°F, Bottom Hole Pressure = 500 psi

Average gross thickness: 1500 feet

Average net pay (Brown Shale section): 600 feet

Porosity: 0.1 to 4.0 percent

Permeability: 0.1×10^{-2} to 5×10^{-2} mD

Modulus of elasticity: 4.2×10^{6} psi

Potential productive area: 60,000 square miles at 4000 feet

Recent studies of Devonian Shale samples from a well in Monongalia County, West Virginia, showed a permeability of 5×10^{-3} to 2×10^{-8} mD parallel to the bedding planes and 6.6×10^{-6} mD perpendicular to bedding planes. Due to laboratory difficulties involved in these low range permeability measurements, such data should be viewed as guidelines only.

Linear correlations of compensated density and gamma ray logging data have been observed in three Devonian Shale wells, located in Lincoln County, West Virginia.[9] For gamma ray (GR, in API units on y-axis) versus density log response (ρ_b, in g/cc on x-axis) the following mathematical-regression trends were obtained:

$\rho_b = -1.2 \times 10^{-3}$ GR + 2.877 (with a standard deviation of 0.02 g/cc for intervals averaged over 20 feet).

$\rho_b = -1.29 \times 10^{-3}$ GR + 2.896 (with a standard deviation of 0.018 g/cc for 18 intervals, 20 to 170 feet thick).

Figure 10 schematically illustrates the linear correlation, but we also point out several factors which affect correlation of such logging data.

Basically, the dark, organic-rich shale intervals in the Appalachian Basin exhibit increased natural radioactivity compared to the lighter colored shales which contain less organic matter. The Spectralog run in open and/or in cased wellbores pinpoints under field conditions that this increase in radioactivity is primarily due to enrichments of elements in the uranium series. Application of such continuous uranium measurements in wellbores to determine the source rock potential of shales will be discussed later on in this paper.

A recent study[10] has shown a remarkably close relationship between the high organic carbon content associated with restricted marine environments of deposition and the low organic carbon content associated with both marine and non-marine environments. Hence, the Spectralog also can assist in biostratigraphic reconstruction studies.

Furthermore, organic geochemical studies in both the Appalachian and Illinois Basins show that the gas is not uniformly distributed. Most of the gas is "sourced" and is largely retained in the organic-rich zones. Here the presence of fractures and silty stringers improves gas recovery rates. It is clear that integrating Spectralog into logging suites designed for such formation evaluation will increase the precision of log analysis.

SPECTRALOG SOURCE ROCK EVALUATION

Prerequisite for commercial hydrocarbon occurrences is the optimum interaction of several parameters including source rocks, migration opportunities, seals, traps and proper timing of geologic events. Generally speaking, the most organic-rich sediments are deposited from areas of high organic productivity through reasonably quiet waters with a moderate sedimentation rate to beds where the supply of bottom oxygen is minimal.[11]

Investigations show that organic compounds in a host rock play a significant role in subsurface uranium accumulation. An early 1944 paper states that "use of radioactive elements as tracers in the study of sedimentation may aid in defining the source beds of oil."[12] Laboratory data for Paleozoic black shales shows linear correlations between the carbon content (in percent) and the uranium content, and the thorium/uranium ratio. In 1945 the radioactivity and the organic content of 510 samples of sediment were studied and "a marked relation between certain types of organic content and radioactivity" was observed.[13] A patent has been issued recently for the *in-situ* evaluation of the source rock potential of earth formations based on downhole gamma ray spectral logging application.[14]

The Spectralog allows a continuous monitoring of the source rock potential of shales in both open and cased wellbores. Spectralog application in hydrocarbon exploration thus becomes obvious. New and old wells can be logged to determine source rock variations both versus depth and on a regional basis using the appropriate mapping techniques.

The typical Spectralog response in source rock shales, such as high potassium and thorium with excessive uranium enrichment has already been shown in Figure 5.

Organic carbon content (in percent) versus the U/K ratio and U-content in the New Albany Shale is shown in Figure 11; whereas, comparative variations of uranium and organic carbon content versus depth are shown for Devonian Shales in Jackson County, West Virginia (Figure 12).

Recent electron microprobe investigations[15] suggest no significant difference in the organic/inorganic heterogeneities at both 100x and 1000x magnifications. This organic material exists in relatively large and distinct organic fragments or is finely divided and imparts reddish-brown coloring typical of the argillaceous intervals.

Uranium concentration versus organic carbon content in Devonian Black Shales, located in Jackson and Lincoln County, New York is shown in Figures 13 and 14. A more refined application is the Th/U ratio versus the organic carbon content in Devonian Black Shales, located in Jackson and Lincoln County, West Virginia and in Perry County, Kentucky is shown in Figures 15 and 16. Application of Th/U and/or K/U ratio concept allows a more refined intepretation since variations in formation shaliness are automatically compensated. Again, such information can be derived on a continuous basis from the Spectralog in newly drilled open holes or in old, cased boreholes. From correlations shown above, variations in the source rock potential of the Devonian Shales can be computed as a continuous log from the Spectralog response, or generally speaking, for any shale formation under study.

Spectralog-derived recognition of key beds within massive shale sequences also assists in establishing a useful interval stratigraphy. Furthermore, recent investigations in volcaniclastic sediments in the Basin and Range Province of Yavapai County, Arizona[16] and in the Devonian Black Shales of West Virginia, Kentucky and New York [17] have shown that sulfur significantly increases within the uraniferous intervals. Such empirical correlations with the uranium concentrations shown by the Spectralog suggest an additional field for further research.

CONCLUSIONS

1. The Spectralog can be run in open and in cased wellbores and provides a continuous record of total, natural gamma ray radioactivity, of potassium measurements in percent and of uranium and thorium measurements in ppm.
2. The log assists in the evaluation of formation shaliness, of lithology variations, of interval stratigraphy and of fracture detection in potential shale reservoirs.
3. The Spectralog also provides an *in-situ* evaluation of the source rock potential in shales.
4. Laboratory and field data support these novel application concepts.

REFERENCES:

1. Fertl, W. H.: "Gamma Ray Spectral Data Assists in Complex Formation Evaluation," *Trans. 6th European Formation Evaluation Symposium*, SPWLA, London, England, March 1979; also Dresser Atlas publication #3335, p. 61.

2. Fertl, W. H., Stapp, W. L., Vaello, D. B., Vercellino, W. C.: "Spectral Gamma Ray Logging in the Austin Chalk Trend," paper SPE 7431, presented at SPE 53d Annual Fall Meeting, Houston, Texas, Oct. 1-3, 1978.

3. Mallory, W. W.: "Oil and Gas from Fractured Shale Reservoirs in Colorado and NW-New Mexico," Rocky Mountain Association of Geologists, Denver, Colorado, *RMAG Special Publication #1* (1977) p. 38.

4. Gorham, F. D., Woodword, L. A., Callender, J. F., Greer, A. R.: "Fractures in Cretaceous Rocks from Selected Areas of San Juan Basin, New Mexico Exploration Implications," *AAPG Bulletin #63* (April, 1979) 598-607.

5. Hunt, J. M., Jamieson, G. W.: "Oil and Organic Matter in Source Rocks of Petroleum," *AAPG Bulletin #40* (March, 1956) 477-488.

6. King, E. E., Fertl, W. H.: "Evaluating Shale Reservoir Logs," *Oil & Gas Journal* (March 26, 1979) 166-168.

7. Harris, L. D., DeWitt, W.: "What Are Possible Stratigraphic Controls for Gas Fields in Eastern Black Shale?" *Oil & Gas Journal* (April 3, 1978) 162-165.

8. Schrider, L. A., Komar, C. A., Pasini, J.: "Natural Gas from Eastern US Shales," paper SPE 6841 presented at SPE 52d Annual Fall Meeting, Denver, Colorado, October 9-12, 1977.

9. Schmoker, J. W.: "The Relationship Between Density and Gamma Ray Intensity in the Devonian Shale Sequence, Lincoln County, West Virginia," *Source publication unknown.*

10. McIver, R. D., Zielinski, R. E.: "Geochemical Evaluation of the Eastern Gas Shales - Part I," DOE Contract #EY-76-C-04-0053, *Report MLM-2563*, p. 33.

11. Dow, W. G.: "Petroleum Source Beds on Continental Slopes and Rises," *AAPG Bulletin #62* (Sept. 1978) 1584-1606.

12. Beers, R. F., Goodman, C.: "Distribution of Radioactivity in Ancient Sediments," *Geologists Society of America Bulletin #55* (October, 1944) 1229-1254.

13. Russell, W. L.: "Relation of Radioactivity, Organic Content, and Sedimentation," *AAPG Bulletin #29* (October, 1945) 1470-1494.

14. Supernaw, I. R., McCoy, Arnold, D., Link, A. J.: "Method for *In-situ* Evaluation of the Source Rock Potential of Earth Formations," *U.S. Patent 4,071,744*, January 31, 1978.

15. Hakkila, E. A., Elliott, N. E., Williams, J. M., Wewerka, E. M.: "Electron Microprobe Studies of the Micromineral Structure of Devonian Shales," in *LA-7094-PR*, (January, 1978) 18-22.

16. Sherborne, J. E., Buckovic, W. A., Dewitt, D. B., Hellinger, T. S., Pavlak, S. J.: "Major Uranium Discovery in Volcaniclastic Sediments, Basin and Range Province, Yavapai County, Arizona," *AAPG Bulletin #63* (April, 1979) 621-646.

17. Leventhal, J. S., Goldhaber, M. B.: "New Data for Uranium, Thorium, Carbon, and Sulfur in Devonian Black Shale from West Virginia, Kentucky, and New York," *Source publication unknown.*

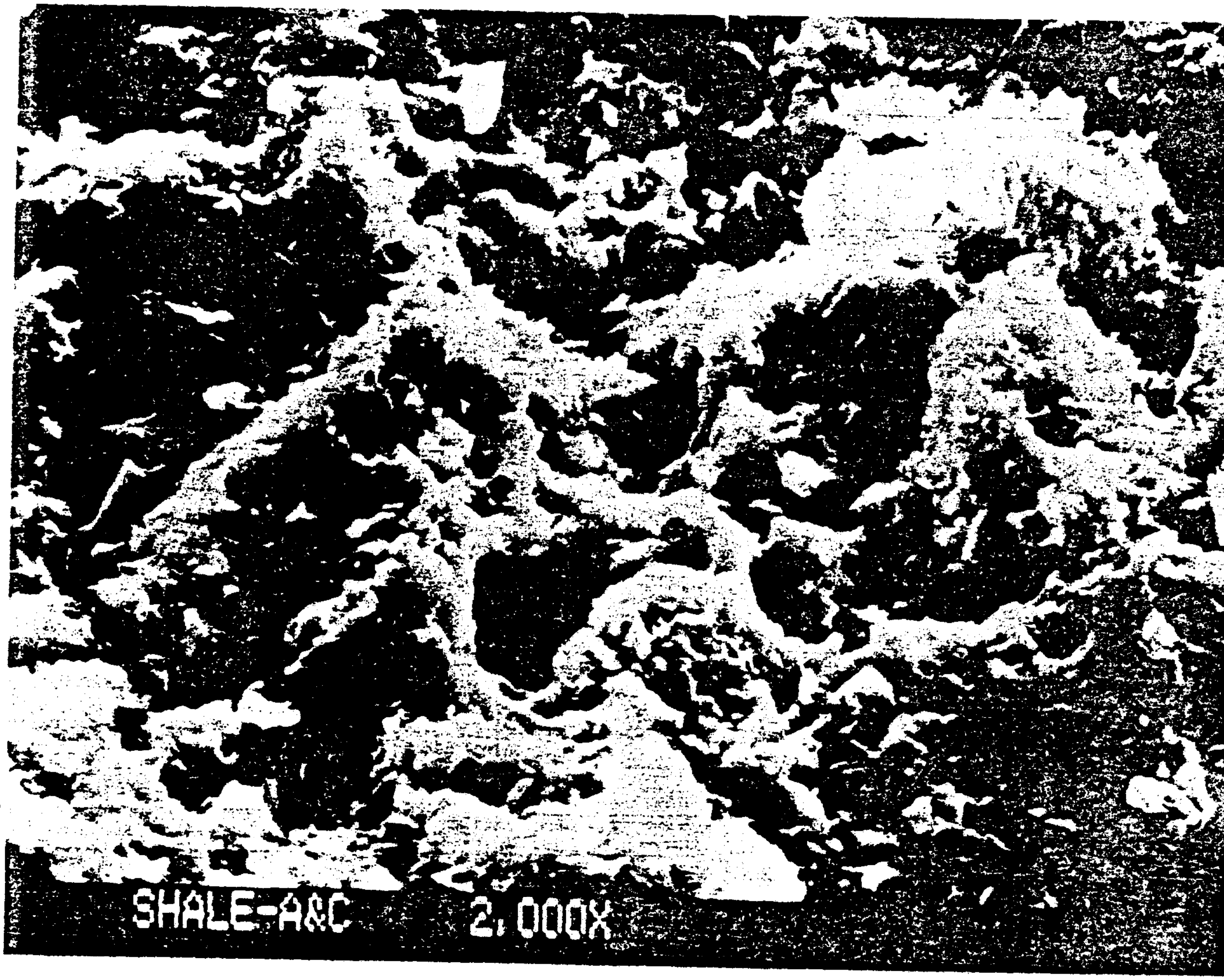

Fig. 1 - SEM of Eagle Ford Shale, cretaceous carbonate trend, South Texas. 500 x magnification. [2]

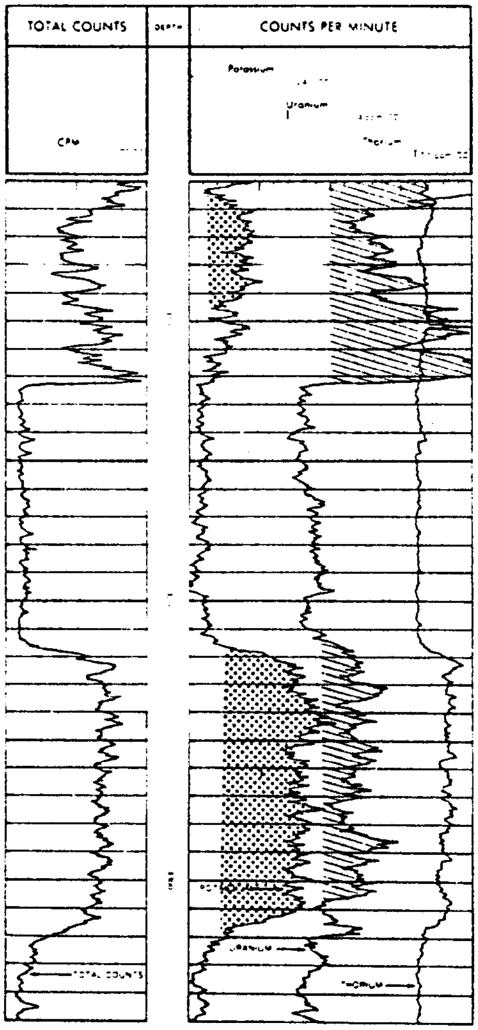

Fig. 2 - Spectralog response (a) in organic-rich, partly calcareous Eagle Ford Shale (>K, >>U,>Th) down to 4122 feet, (b) from 4122 feet to 4218 feet over the relatively clean Buda Limestone (>K,>U,>Th), and (c) in the Del Rio Shale (>>K,>U,>>Th) below 4218 feet.

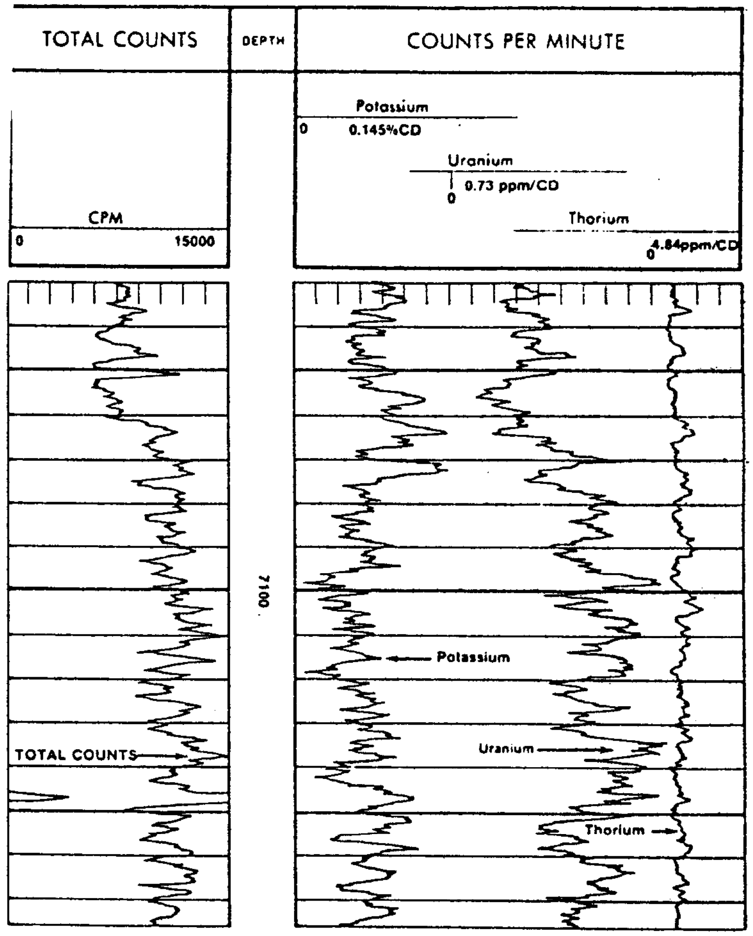

Fig. 3 - Spectralog response in productive Eagle Ford Formation, Dimmit County, Texas. Well was completed in fractured intervals exhibiting low potassium but high uranium values and put on production at 28 barrels of oil per day.[2]

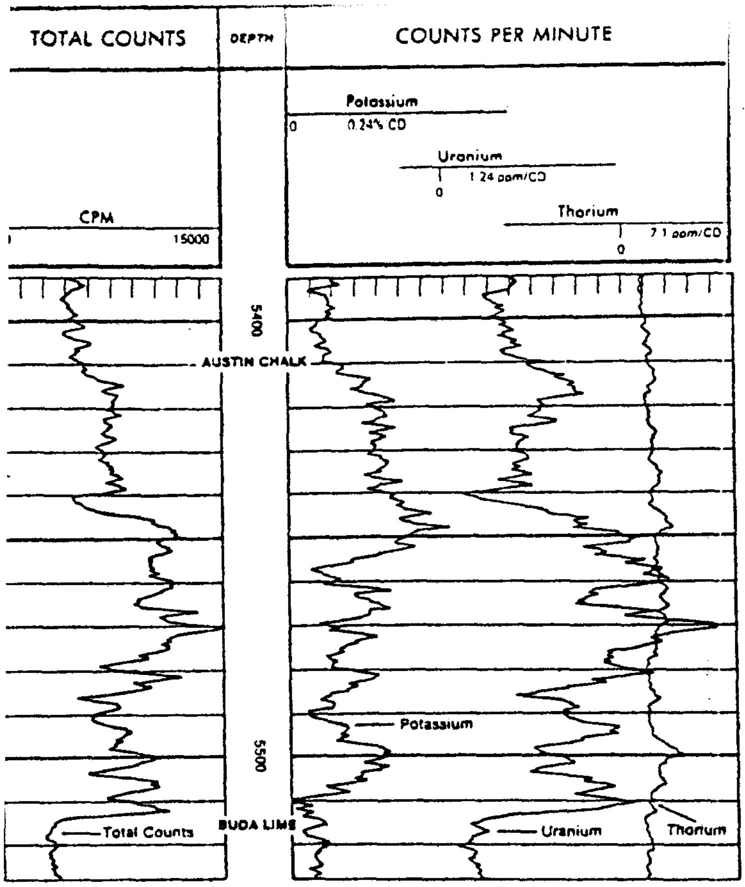

Fig. 4 - Spectralog over Eagle Ford Shale in Pearsall area, Frio County, Texas. Note that total counts (gamma ray) response is totally unrelated to formation shaliness. Potassium curve shows relatively clean, calcareous interval, which exhibits excessively high uranium concentration. Selective perforating in such zones often yields commercial production without massive well stimulation efforts.

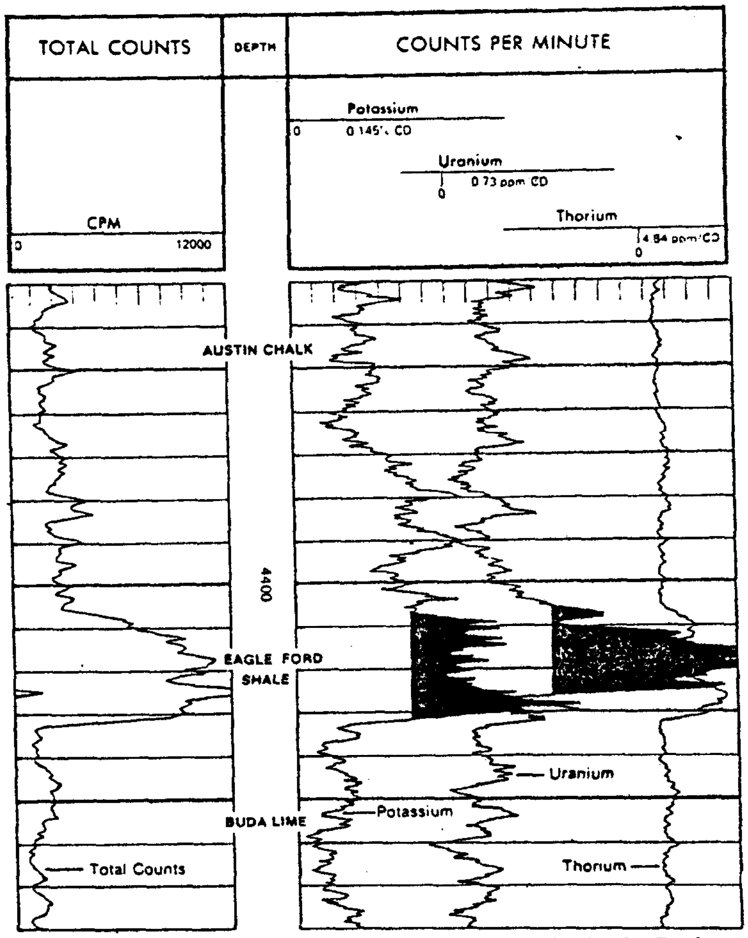

Fig. 5 - Spectralog response over Austin Chalk, Eagle Ford Shale, and Buda Limestone in cretaceous carbonate trend, Caldwell County, Texas. Eagle Ford section exhibits typical organic-rich shale response (>K,>>U, >Th) which can be applied to source rock potential determination.

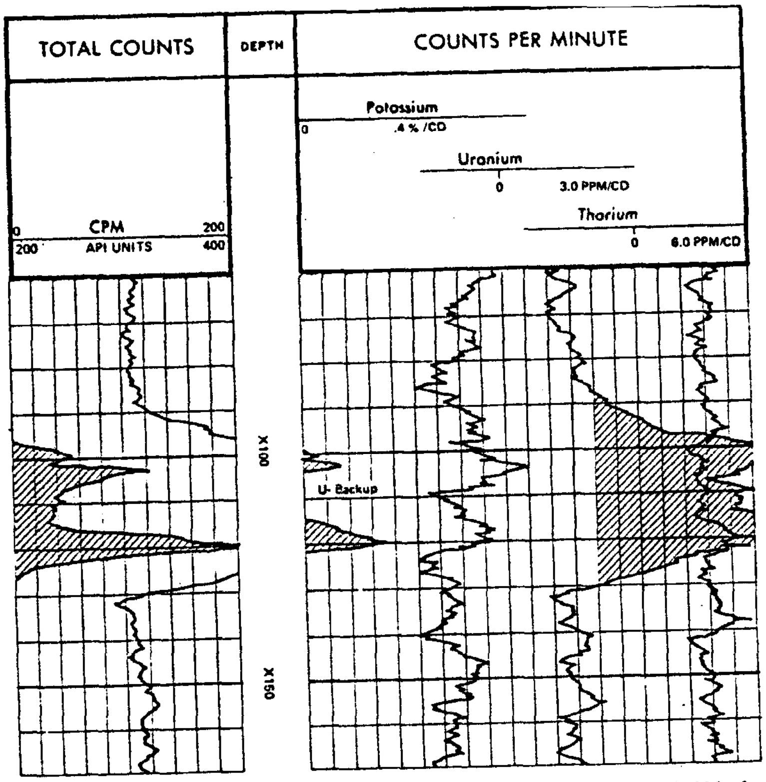

Fig. 6 - Spectralog over Pierre Shale interval in well drilled in Fremont County, Colorado.

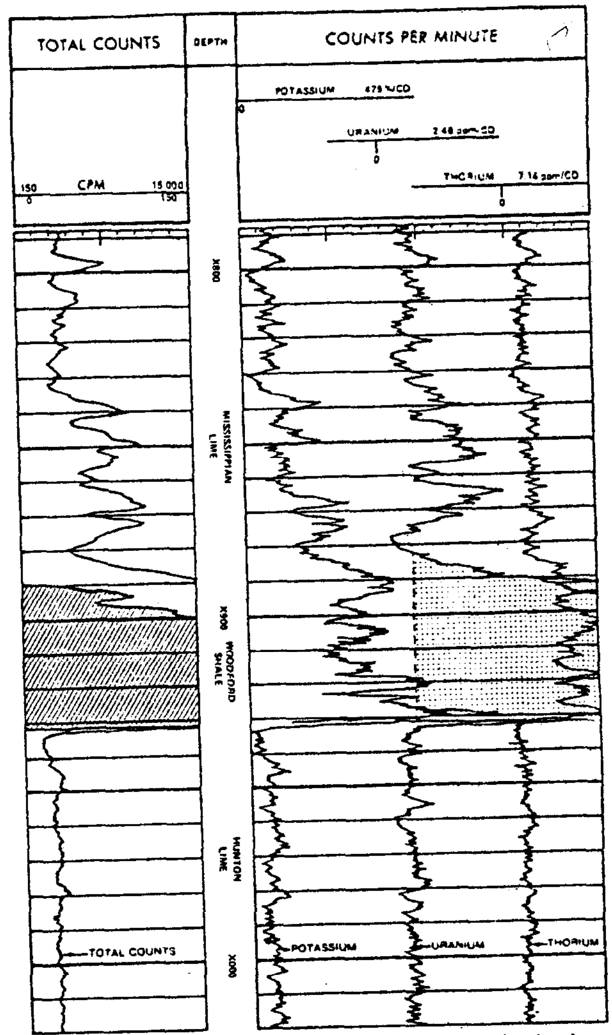

Fig. 7 - Spectralog response in Mississippi Lime, Woodford Shale, and Hunton Lime, Oklahoma.

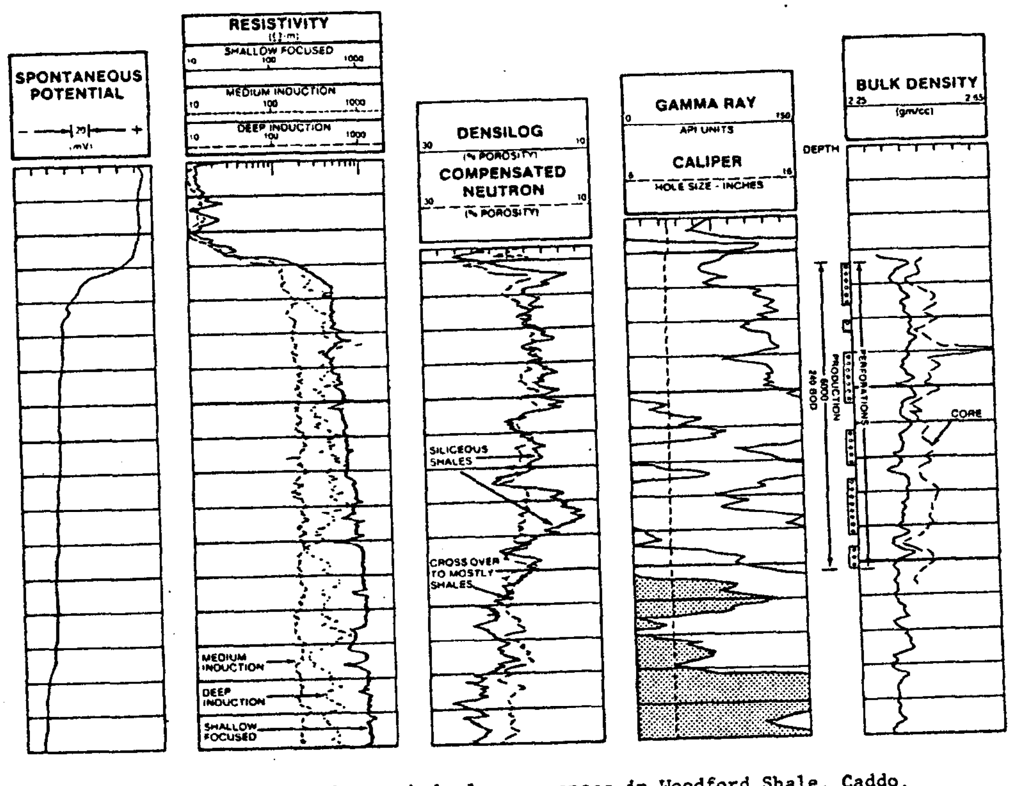

Fig. 8 - Typical open-hole log responses in Woodford Shale, Caddo, County, Oklahoma. Fractured silicious shales are perforated from 5955 feet to 6058 feet and produce at a rate of 240BOPD.[6]

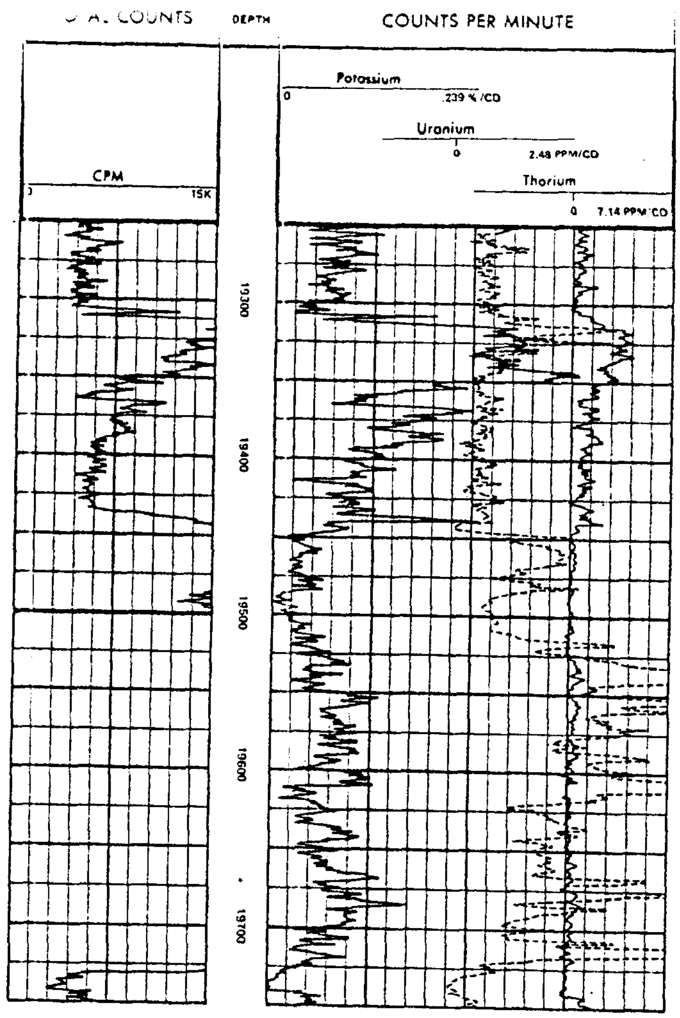

Fig. 9 - Spectralog response in deep Woodford Shale, West Texas.

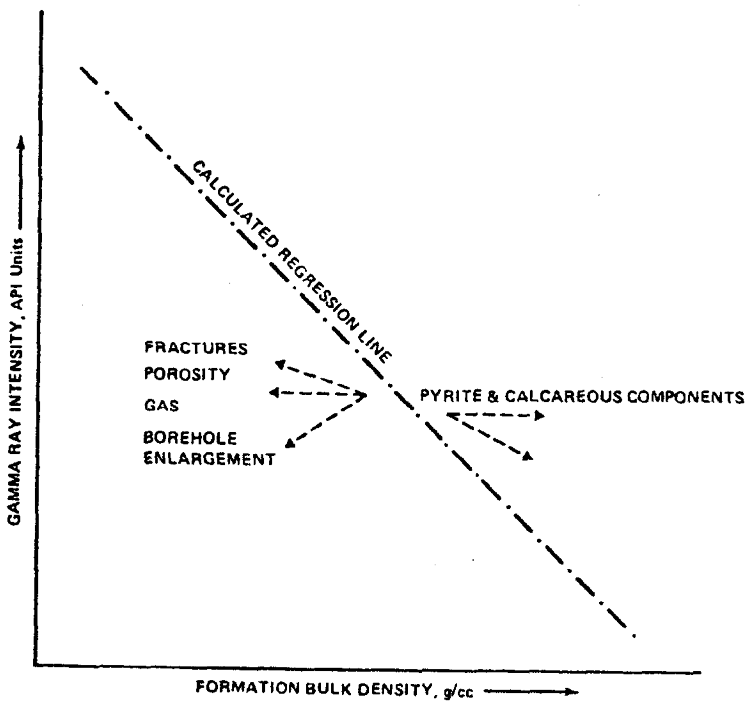

Fig. 10 - Relationship between gamma ray intensity and formation density as determined from geophysical well logs in Devonian Shales. Parameters affecting such correlations are also shown.

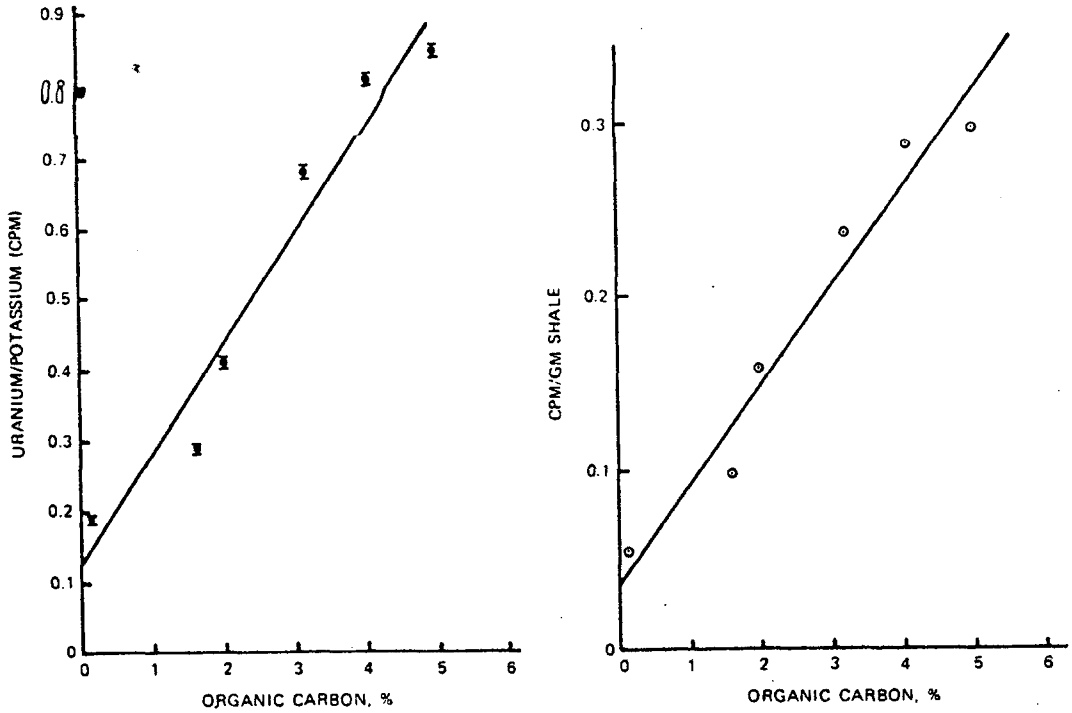

Fig. 11 - Source rock potential estimates from gamma ray spectral data, New Albany Shale.[14]

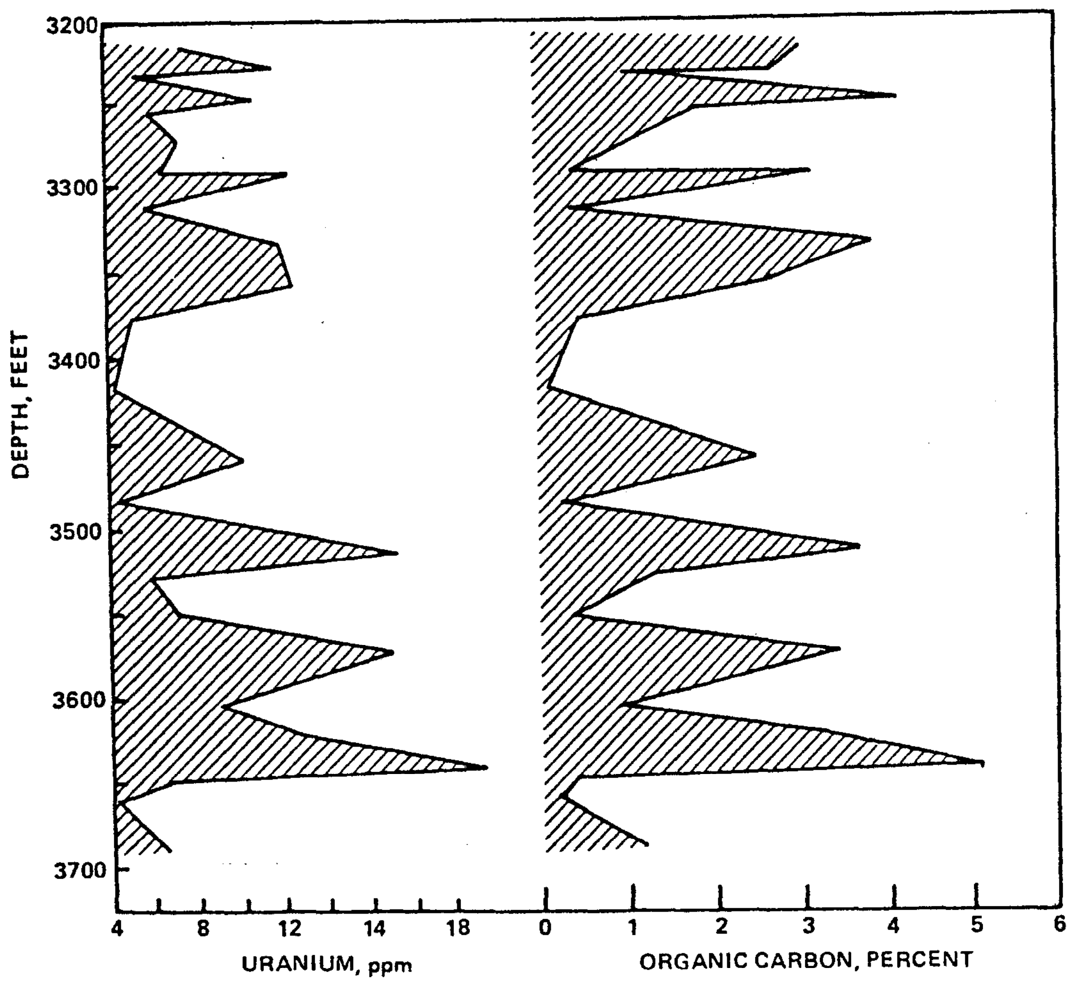

Fig. 12 - Variations in uranium and organic carbon content in Devonian Black Shales, Jackson County, West Virginia.[17]

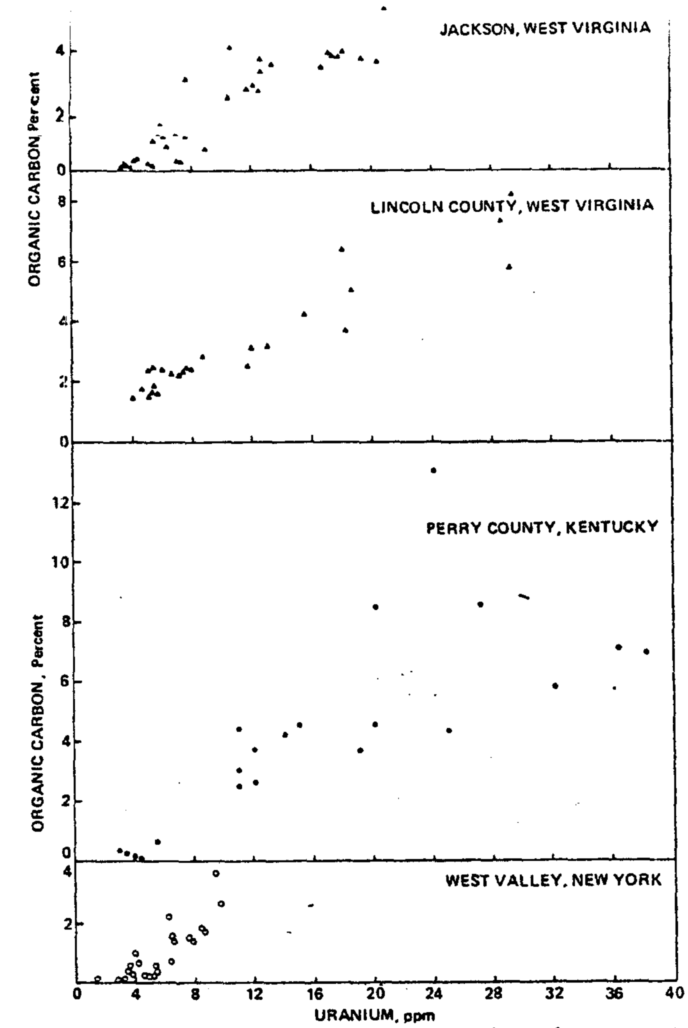

Fig. 13 - Uranium concentration vs organic carbon content in Devonian Black Shales (after data by Leventhal et al.)[17]

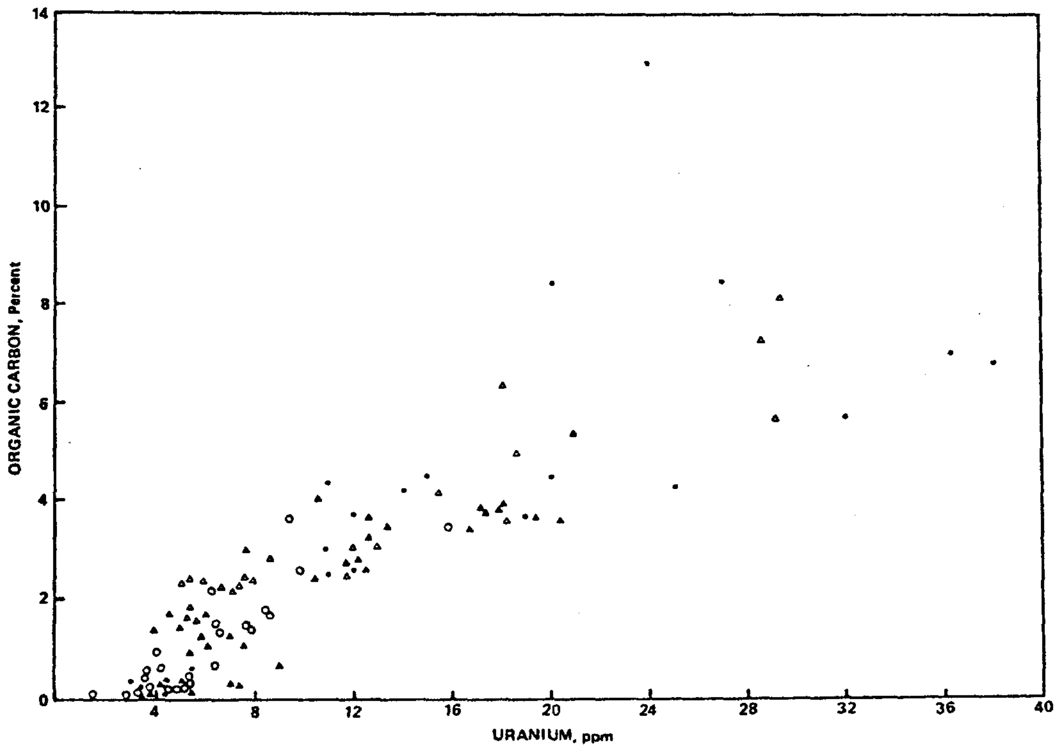

Fig. 14 - Composite data of uranium-organic relationship in Devonian Black Shales located in Jackson and Lincoln County, West Virginia; Perry County, Kentucky; West Valley, New York.[17]

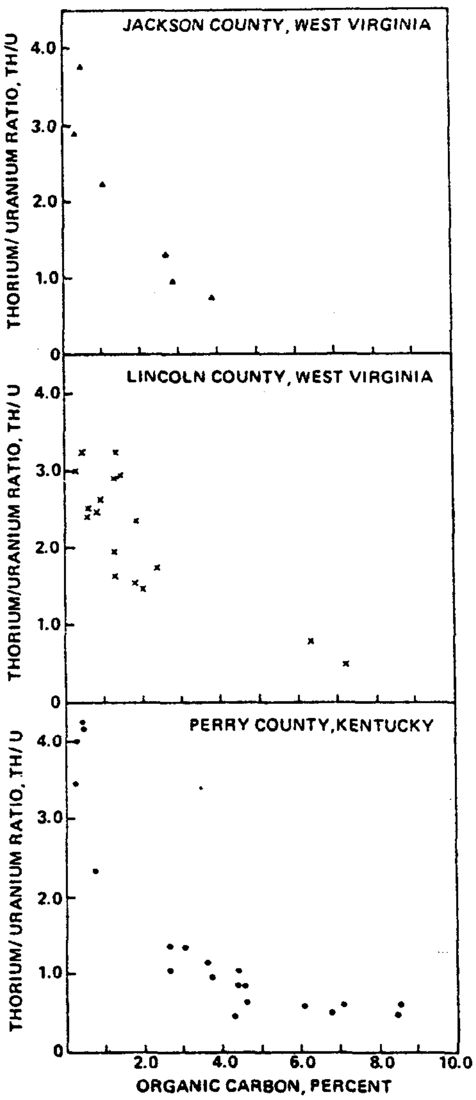

Fig. 15 - Thorium/uranium ratio vs organic carbon content in Devonian Black Shales. Jackson County and Lincoln County, West Virginia; Perry County, Kentucky (after data by Leventhal et al.).[17]

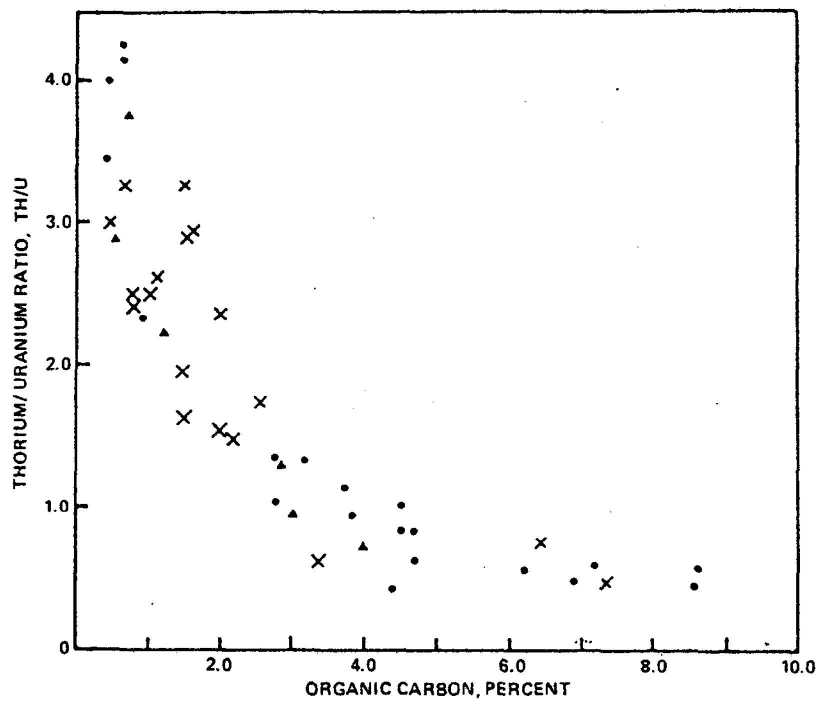

Fig. 16 - Composite data showing relationship of thorium/uranium ratio to organic carbon content in Devonian Black Shales located in West Virginia and Kentucky.[17]