DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

Determination of Organic Content From Formation-Density Logs, Devonian-Mississippian Woodford Shale, Anadarko Basin, Oklahoma

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INTRODUCTION

The Woodford Shale is a "black" shale of Late Devonian-Early Mississippian age that is probably a major source of oil and gas in the Anadarko basin. Although laboratory analyses show the Woodford to be a relatively rich source rock, such data are typically too limited to regionally quantify the distribution of organic matter. To adequately sample the formation both horizontally and vertically on a basin-wide scale, large numbers of costly and time consuming laboratory analyses would be required. Such analyses are prone to errors from a number of sources, and core and (or) cuttings are frequently not available at key locations.

A method of determining organic content from formation-density logs, described by Schmoker (1979) and Schmoker and Hester (1983) in studies of Devonian-Mississippian shales of the Appalachian and Williston basins, offers a practical alternative to laboratory analyses of core or cuttings. The "density-log" method has several advantages over laboratory analyses: 1) The density log provides continuous measurement of the formation, reducing the statistical uncertainties of limited (and possibly non-random) spot sampling. 2) Density logs are more common and more readily available than core or cuttings. 3) Working with density logs is simpler and less costly than laboratory procedures.

The density-log method is shown here to be applicable to the Woodford Shale in the study area of the Anadarko basin (fig. 1). This report reviews the assumptions and methodology of the approach, and establishes the validity and limitations of the method for the Woodford Shale by comparing log-derived data to laboratory analyses.

LABORATORY ANALYSES

Woodford Shale samples were collected from 4-in.-diameter (10.2-cm) core stored at the Oklahoma Geological Survey Core Library in Norman, Oklahoma. Fifteen widely separated wells (fig. 1, table 1), for which both core and formation-density logs were available, were sampled at intervals of 1 ft (.3048 m) or less throughout the available Woodford section. For each well, composite samples representing intervals of similar density-log character were prepared for pyrolysis. Sampling parameters are reported in Table 2.

Laboratory analyses (provided by T.A. Daws of the U.S.Geological Survey) were performed using a Delsi, Inc., Rock-Eval II plus TOC pyroanalyzer, which incorporates the IFP-Fina whole-rock pyrolysis technique. (For a detailed discussion of programmed pyrolysis, see Peters (1986).) Total organic carbon (TOC), which is determined by summing pyrolyzed carbon with that of residual organic matter, is used in this report to assess the applicability of the density-log method to the Woodford Shale, and to calibrate the calculation of TOC from formation density.

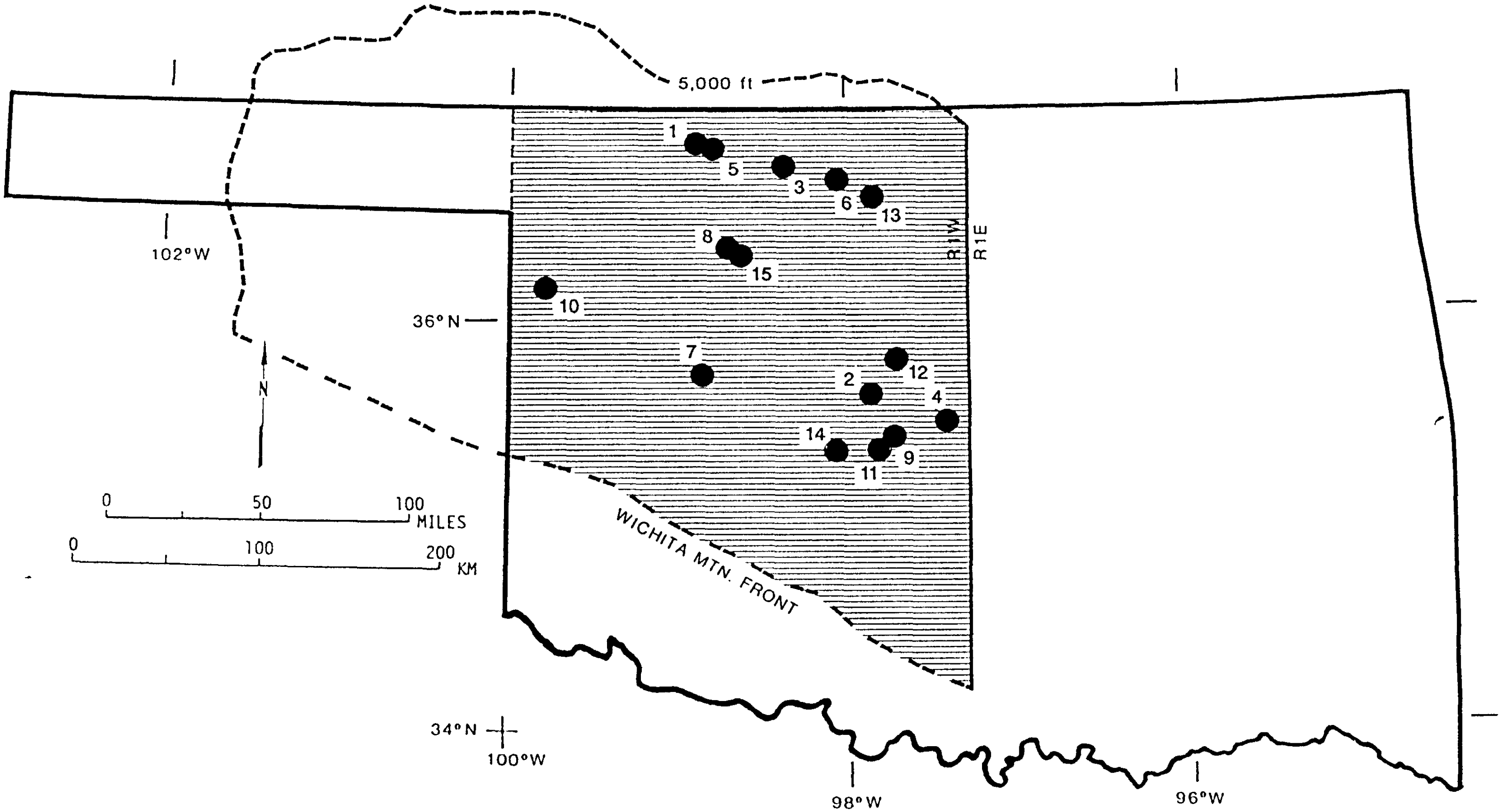

Figure 1.--Map of Oklahoma showing locations of sampled wells, and 5,000-ft (1.52-km) total-sediment isopach. Study area is shaded.

Table 1.--Identification of sampled wells

Well No.	Operator	Well Name	Location
1	Texaco Inc.	1 Helen Hampsten	Sec. 12, T27N, R16W
2	Tenneco Oil	1-5 Biller	Sec. 5, T13N, R6W
3	J. M. Huber	1 Cherokee Methodist Church	Sec. 21, T26N, R11W
4	Jones and Pellow	1 Boyd	Sec. 28, T12N, R2W
5	Calvert-Mid-America	2 Boyd	Sec. 21, T27N, R15W
6	Texaco Inc.	1 Kennedy	Sec. 9, T25N, R8W
7	GHK	1-1 Hoffman	Sec. 1, T14N, R16W
8	Tenneco Oil	A-1 J. Jordan	Sec. 3, T21N, R14W
9	Apexco	2 Curtis	Sec. 27, T11N, R5W
10	Lone Star Production	1 L.V. Hanan	Sec. 6, T19N, R24W
11	Wilshire Oil	1 Bejeck	Sec. 25, T11N, R6W
12	Eason Oil	1 Ruth	Sec. 2, T15N, R5W
13	FCD	A-1 Mary	Sec. 9, T24N, R6W
14	Resource Oil and Gas	8-1 Richardson	Sec. 8, T10N, R8W
15	Tenneco Oil	1-11 Edwards	Sec. 11, T21N, R14W

CALCULATING ORGANIC CONTENT FROM FORMATION-DENSITY LOGS

Organic matter has a density of about 1.0 g/cm^3, whereas the shale-mineral matrix in which the organic matter is contained has an average density of about 2.7 g/cm^3 (Smith and Young, 1964). Variations in organic content can therefore cause significant changes in the bulk density of the formation. Organic content can be calculated directly from formation-density measurements when density variations from other causes are taken into account.

The density-log method subdivides shale composition into four components: rock matrix, interstitial pore fluids, pyrite, and organic matter. The bulk density of the formation (ρ) is related to the densities and fractional volumes (ϕ) of these components as shown in equation 1 (Schmoker and Hester, 1983):

$$\rho = \phi_o\rho_o + \phi_p\rho_p + \phi_i\rho_i + (1 - \phi_o - \phi_p - \phi_i)\rho_m. \qquad (1)$$

The subscripts o, p, i, and m represent organic matter, pyrite, pore fluid, and matrix, respectively.

To calculate organic content from formation density, equation 1 must be reduced to a form relating the two. Schmoker and Hester (1983) addressed this problem in detail and derived a generalized equation for calculating total organic carbon (TOC, wt%) from formation density (ρ, g/cm^3):

$$\mathrm{TOC} = [(100\rho_o)(\rho - 0.9922\rho_{mi} - 0.039)]/$$
$$[(R_\rho)(\rho_o - 1.135\rho_{mi} + .675)], \qquad (2)$$

where ρ_o is the density of organic matter (g/cm^3), ρ_{mi} is the density of the interstitial-pore-fluid and mineral-grain framework (g/cm^3), and R is the ratio, by weight, of organic matter to organic carbon. The values of the parameters ρ_o, ρ_{mi}, and R, must be specifically defined for the formation and region of interest.

APPLICATION TO WOODFORD SHALE

The key points considered in this section are 1) whether the generalized model (equation 2), with its broad simplifying assumptions, is applicable to the Woodford Shale of the Anadarko basin; 2) the appropriate values for ρ_o, ρ_{mi}, and R; and 3) the accuracy of TOC calculated by the density-log method. Each question is best addressed by comparing laboratory analyses of TOC (described in a previous section) with density-log data. Data used are tabulated in Table 2.

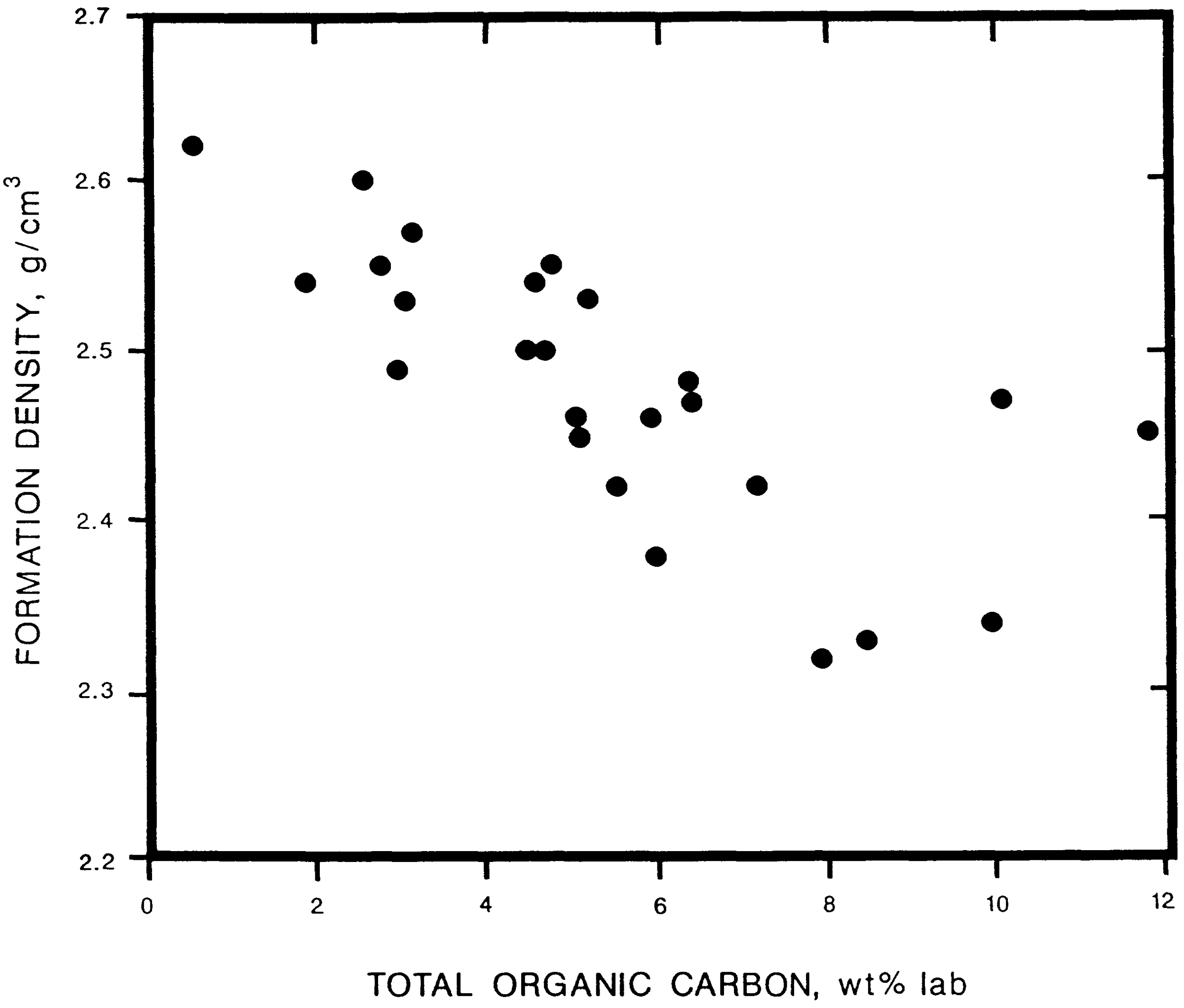

Figure 2.--Total organic carbon (TOC) derived from laboratory analyses versus log-derived formation density of sampled intervals.

Table 2.—Tabulation of data

[1 ft = .3048 m]

Well[1] No.	Median Depth (ft)	Vertical[2] Interval (ft)	Average[3] Density (g/cm^3)	Log[4] TOC (wt%)	Lab[5] TOC (wt%)	Delta[6] TOC (wt%)	No. of Samples	No. of[7] Pyrolyses
1	6,284	13	2.54	3.48	1.87	-1.61	13	13
1	6,310	9	2.57	2.79	3.14	.35	12	4
2	8,575	10	2.42	6.43	7.15	.72	21	1
2	8,595	9	2.47	5.17	6.39	1.22	21	1
3	6,083	4	2.55	3.25	4.75	1.50	5	5
4	6,479	4	2.32	9.12	7.94	-1.18	5	5
4	6,483	7	2.47	5.17	10.04	4.87	7	7
5	6,193	7	2.60	2.11	2.57	.46	8	8
5	6,200	7	2.42	6.43	5.55	-.88	7	7
5	6,205	4	2.53	3.72	3.03	-.69	4	4
6	6,276	14	2.50	4.43	4.63	.20	15	2
6	6,287	7	2.48	4.92	6.38	1.46	10	2
7	14,259	18	2.50	4.43	4.49	.06	42	6
8	8,474	6	2.49	4.68	2.98	-1.70	14	2
8	8,480	6	2.53	3.72	5.18	1.46	14	2
8	8,486	6	2.38	7.48	5.99	-1.49	14	2
9	8,519	9	2.33	8.84	8.46	-.38	15	3
10	14,327	9	2.62	1.67	.55	-1.12	21	1
11	8,896	4	2.45	5.67	11.79	6.12	5	1
12	7,139	4	2.34	8.57	9.98	1.41	5	1
13	6,338	13	2.54	3.48	4.55	1.07	13	2
13	6,352	16	2.46	5.42	5.91	.49	17	4
13	6,367	13	2.55	3.25	2.77	-.48	14	4
14	13,213	6	2.46	5.42	5.06	-.36	7	1
15	8,511	7	2.45	5.67	5.17	-.50	8	3

[1] From figure 1, table 1.

[2] Thickness of interval sampled.

[3] From formation-density logs.

[4] Log TOC = TOC calculated from formation-density logs using equation 3.

[5] Lab TOC = TOC from laboratory analyses.

[6] Delta TOC = Lab TOC - Log TOC.

[7] Values less than "No. of Samples" result from compositing of samples.

Applicability of Generalized Model

The validity of the general model described in the previous section is summarized by figure 2. Because bulk density covaries with laboratory TOC in a predictable way, a relation between the two variables can be established. Thus, for the Woodford Shale of the study area, TOC can be estimated from formation density. The width of the TOC data envelope at a given value of bulk density (fig. 2) indicates the approximate error that can be expected in the calculation of TOC from formation-density logs.

A portion of this apparent error is of a non-geologic nature and arises from uncertainties in laboratory analyses and log calibrations, and from imperfect comparisons of sampled and logged intervals. The width of the data envelope also reflects the degree to which the fundamental geologic assumptions inherent in the density-log method are not satisfied by the Woodford Shale. For example, variations in maturity or type of organic matter, changes in shale mineralogy, or compaction of the shale with burial could all contribute to the experimental error. However, figure 2 indicates that such effects are of secondary importance, and that the density-log method can yield values of TOC sufficiently accurate for regional applications to the Woodford Shales.

Values for ρ_o, ρ_{mi}, and R

Values of ρ_o, ρ_{mi}, and R for the Woodford Shale are constrained by geologic considerations. Initial selections were made on the basis of physical properties of the formation and then fine-tuned to minimize the sum of the differences between TOC determined by laboratory analyses and TOC calculated using equation 2. Values chosen are:

$$\rho_o = 1.01 \text{ g/cm}^3, \; \rho_{mi} = 2.68 \text{ g/cm}^3, \text{ and } R = 1.33.$$

Manipulating these parameters shifts the values of TOC calculated from formation density, but does not significantly affect their correlation with TOC measured in the laboratory. This relation illustrates the robustness of the model and suggests that variations in ρ_o, ρ_{mi}, and R across the study area do not significantly degrade the TOC calculations.

Substituting for ρ_o, ρ_{mi}, and R in equation 2 yields an equation for calculating TOC of the Woodford Shale that can be readily evaluated using a hand-held calculator:

$$\text{TOC} = (151.012/\rho) - (55.970). \qquad (3)$$

Accuracy of Density-Log Method

Organic-carbon content calculated from formation-density logs (using equation 3) is compared in figure 3 to that determined by laboratory analyses. Whereas figure 2 illustrates the physical basis for the density-log method, figure 3 demonstrates the execution of the idea. The overall agreement between the two independently derived values of TOC is reasonably good (fig. 3).

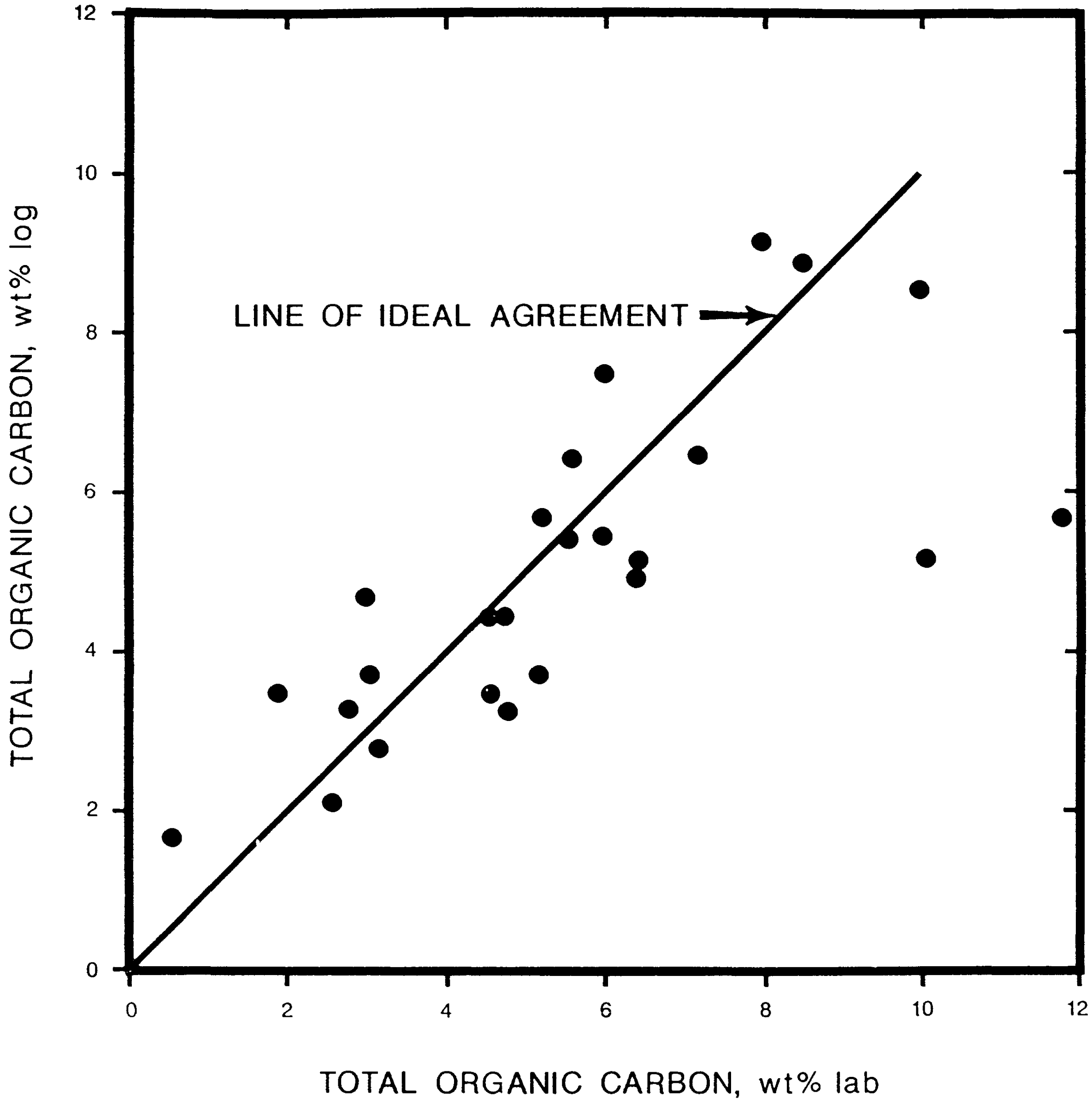

Figure 3.--Total organic carbon (TOC) derived from laboratory analyses versus values calculated from formation-density logs using equation 3.

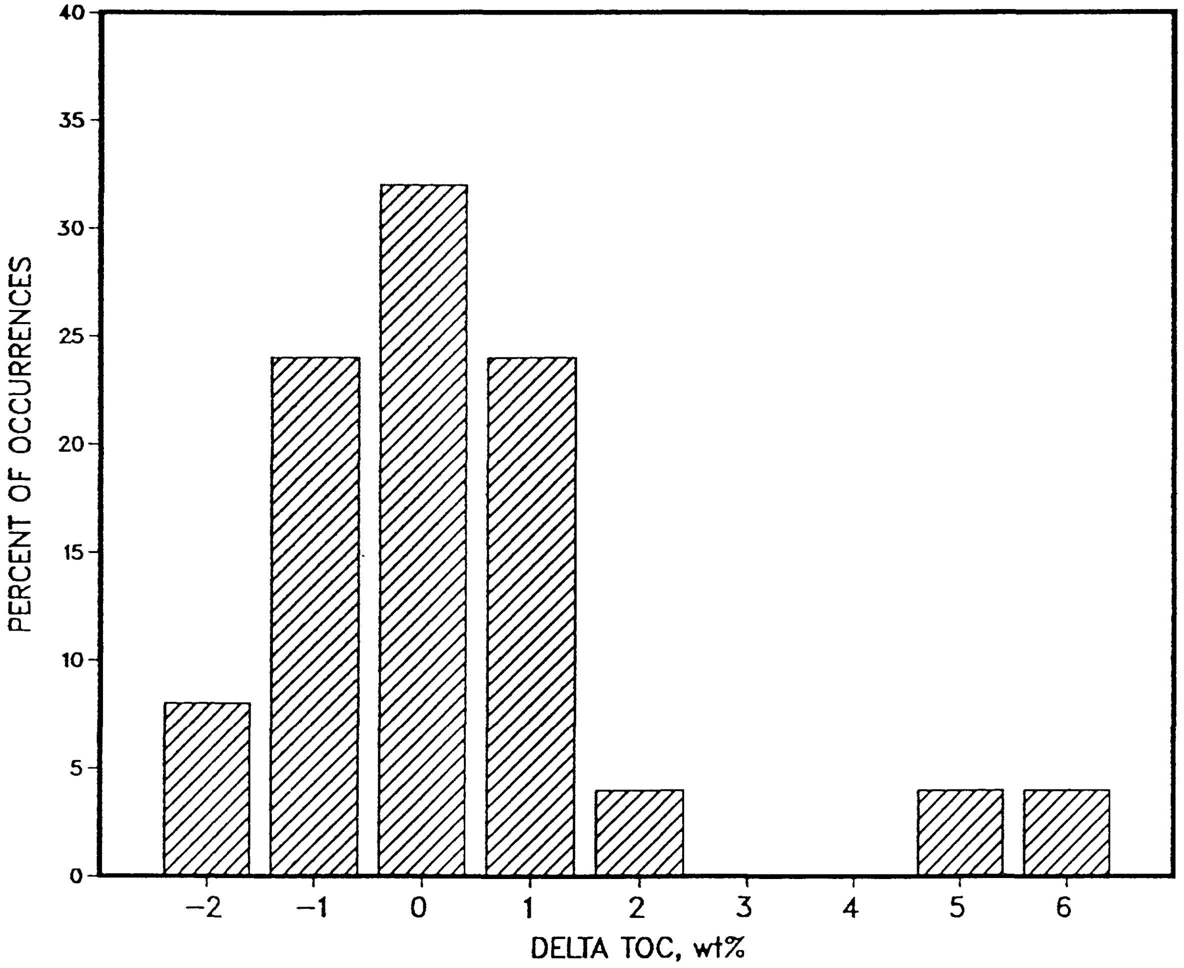

Figure 4.--Distribution of differences (Delta TOC of Table 2) between total organic carbon (TOC) derived from laboratory analyses and calculated from formation-density logs using equation 3.

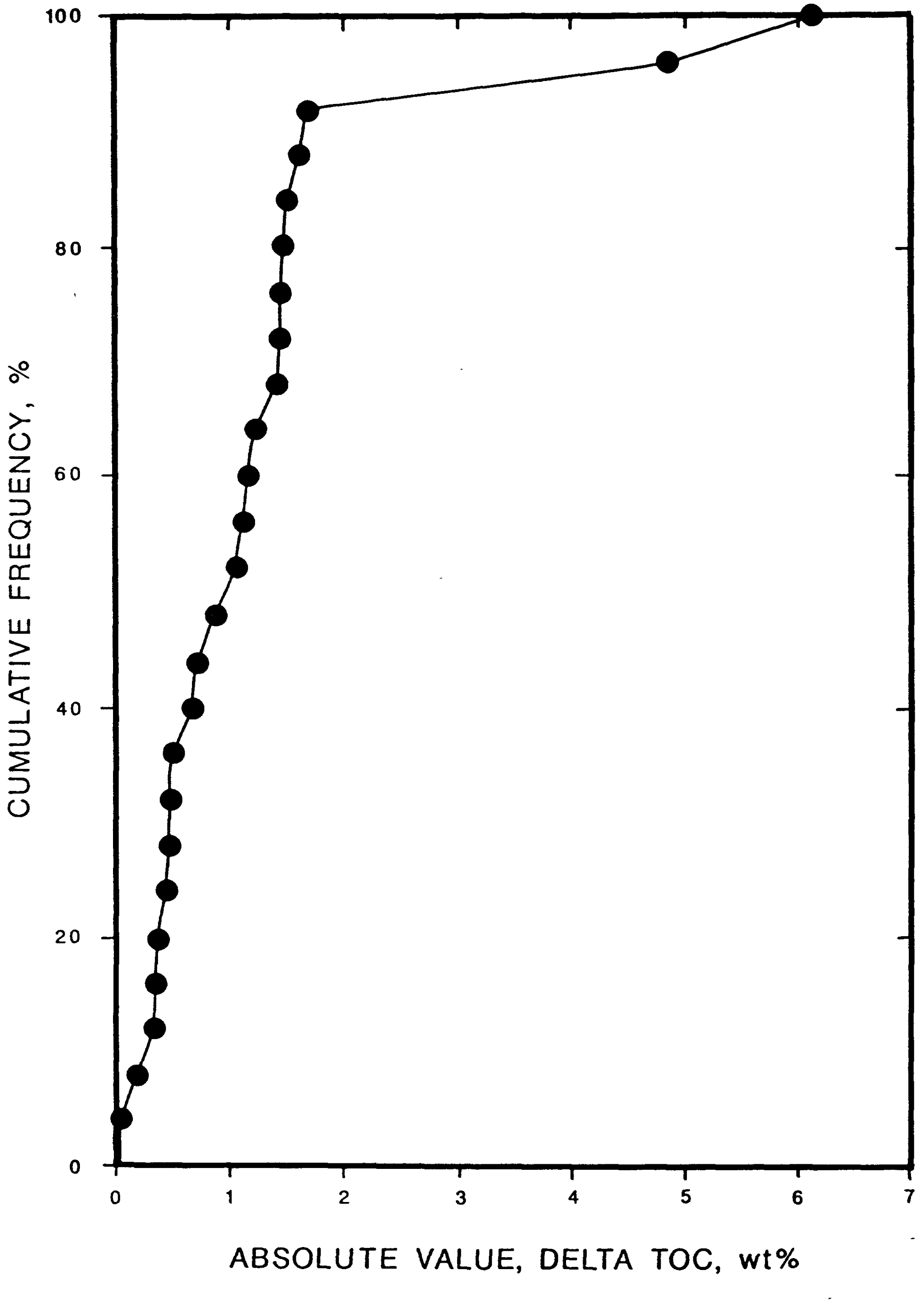

Figure 5.--Cumulative-frequence curve of absolute values of differences between total organic carbon (TOC) derived from laboratory analyses and calculated from formation-density logs using equation 3.

Two data points, however, with high laboratory-derived TOC, are clearly anomalous. Assuming that the laboratory analyses are accurate and representative, the matrix-mineral density in these two intervals is unusually high. In such isolated cases where log density is "too high", equation 3 will yield conservative estimates of TOC.

The distribution of differences between laboratory-derived and density-log-derived values of TOC (fig. 4) demonstrates that the great majority of differences are less than ±2 wt% TOC. The cumulative-frequency curve (fig. 5) shows that 68% of the differences (one standard deviation) are less than 1.4 wt% TOC, and 90% of the differences are less than about 1.6 wt% TOC.

SUMMARY

The density-log method described by Schmoker (1979) and Schmoker and Hester (1983) for determining organic content of some specific organic-rich shales offers several advantages over laboratory analyses: 1) The density log provides a continuous measurement of the formation. 2) Density logs are more common and more readily available than core or cuttings. 3) The density-log method is less costly than laboratory analyses.

The density-log method is based on the straight-forward concept that the major cause of changes in the formation density of organic-rich, well-compacted shales, is variation in organic-matter content. Based on comparisons to laboratory measurements, we conclude that this concept is applicable to the Woodford Shale of the Anadarko basin.

TOC of the Woodford Shale can be determined from formation-density logs with an accuracy, at the 90 percent confidence level, of about ±1.6 wt%, over intervals of 4 feet (1.2 m) or more. This level of accuracy is sufficient for regional source-rock studies, but may not suffice for some localized geologic applications.

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