

Accurate, Direct Total Organic Carbon (TOC) Log from a New Advanced Geochemical Spectroscopy Tool: Comparison with Conventional Approaches for TOC Estimation*

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Abstract

Total organic carbon (TOC) is an important parameter in the evaluation of kerogen-rich unconventional reservoirs; therefore, a continuous, accurate wireline TOC log is highly desirable. Recent advances in geochemical spectroscopy logging make it possible to obtain an accurate and robust TOC log without the need to calibrate to core. A new tool simultaneously measures carbon and the major elements, calcium and magnesium, that form carbonate minerals, from which TOC is derived as the difference between total carbon and inorganic (mineral) carbon at acceptable open hole logging speeds.

This method differs considerably from the current practice of estimating TOC from conventional log measurements based on empirical approaches. Two well-established and proven techniques are the Schmoker density-log technique and the combination sonic- (or density-) and resistivity-log technique known as Δ log R. Other common methods for TOC estimation include using uranium or gamma ray logs as indicators of organic matter, although they often require a local calibration. The Schmoker density-log technique uses the bulk density log and assumes that the change in density of the formation is due to the presence or absence of low-density organic matter (~ 1.0 g/cm³). The Δ log R technique relies on separation of the sonic (or density) and resistivity curves to identify areas containing organic matter and the subsequent derivation of TOC from the separation of the two curves based on the level of organic maturity.

Each of these quantitative approaches has been compared with TOC measured by coulometry on hundreds of core samples in field tests covering a variety of formations and wells drilled with both water- and oil-based muds. The organic carbon content of the core samples ranges from 0 to over 15 wt%, and the carbonate mineral content ranges from 0 to almost 100 wt%. TOC from the geochemical spectroscopy log agrees very well with the core data, matching as well as or better than the Schmoker or Δ log R techniques for all datasets. The accuracy and robustness of the TOC derived from spectroscopy logging plays a key role in accounting for organic content when computing density and

porosity for unconventional reservoirs to ensure accurate and consistent evaluation across varying rock compositions, depositional environments, and hydrocarbon maturities.

Methods of Computing TOC from Wireline Logs

The new geochemical spectroscopy tool (Radtke et al., 2012) produces elemental concentration logs of all the major sedimentary-rock-forming elements except oxygen. It uses a pulsed neutron generator (PNG) source which enables measurement of gamma rays produced by both high-energy inelastic reactions and thermal energy capture reactions. Gamma rays are detected by a large cerium-doped lanthanum bromide (LaBr₃:Ce) gamma ray detector that is coupled to a state-of-the-art high-temperature photomultiplier. The combination of these new technologies leads to the measurement of more elements with better accuracy and precision than possible with the previous generation of tools.

An exciting new development is the ability to generate a continuous log of TOC₁. The technique is described previously (Herron et al., 2008; Herron et al., 2011) and briefly summarized here. A similar approach has been described by Pemper et al. (2009). Elemental concentrations, including total carbon (TC), are determined from the integration of inelastic and capture spectroscopy measurements. Prior to quantification, the carbon yield is corrected for carbon in the borehole (OBM). Total inorganic carbon (TIC) is determined by first computing concentrations of carbonate minerals such as calcite, dolomite, siderite, ankerite, or rhodochrosite. As a simple example, the concentrations of calcium and magnesium are used to compute calcite (CaCO₃) and dolomite (CaMg(CO₃)₂), which are in turn used to compute TOC in weight percent (wt%):

$$\text{TIC} = 0.12(\text{Cal}) + 0.13(\text{Dol}) \quad (1)$$

where Cal and Dol are the concentrations in wt% of calcite and dolomite, respectively. The difference between the total carbon and the inorganic (mineral) carbon is TOC in wt%:

$$\text{TOC} = \text{TC} - \text{TIC} \quad (2)$$

Conventional approaches for TOC estimation either use log data as qualitative TOC indicators or employ empirical relationships from logs for quantitative estimation. Qualitative log indicators of elevated TOC include elevated neutron porosity, low bulk density, high sonic transit time, and high gamma ray or uranium (Herron, 1991). However, these measurements respond to more than just organic matter and therefore, interpretation of these logs in terms of organic matter requires an assumption that other variables are constant or requires some sort of a local calibration. Because the heterogeneity of unconventional reservoirs exists on both micro and macro scales, it is difficult to use these log responses alone for more than a qualitative identification of TOC.

Two widely used empirical approaches have been developed to quantitatively estimate TOC from log data. The first was developed in Devonian shales using bulk density logs (Schmoker, 1979; Schmoker, 1980) and was later refined in Bakken shales (Schmoker, 1983). Based on the response of the bulk density measurement to low-density organic matter (~1.0 g/cm³), the Schmoker method, as it is commonly called, computes TOC:

$$\text{TOC} = (154.497/\rho_b) - 57.261 \quad (3)$$

where ρ_b is the bulk density in g/cm^3 and TOC is reported in wt%. This equation assumes a constant mineral composition and porosity throughout the formation. Although the method was developed and refined based on specific environments, it is frequently used for TOC estimation in a wide variety of shale formations.

The second approach, known as the $\Delta \log R$ technique, combines porosity and resistivity logs to estimate TOC in organic-rich rocks (Passey et al., 1990). For the porosity curve, a sonic log is typically used, although if one is not available, a bulk density log can be used. In this study, sonic logs were not available for many of the wells and therefore bulk density logs were used. Using either porosity curve, the method relies on the porosity and resistivity curves overlaying each other in organic-lean rocks, whereas in organic-rich rocks, the two curves separate. The separation between the two curves, $\Delta \log R$, gives the method its name and is calculated as follows:

$$\Delta \log R = \log_{10} (R/R_{\text{baseline}}) - \text{ScalingFactor} (\rho_b - \rho_{\text{baseline}}) \quad (4)$$

where R is the resistivity in ohm/m, R_{baseline} is the resistivity in the baseline organic-lean zone in ohm/m, ρ_b is the bulk density in g/cm^3 , and ρ_{baseline} is the bulk density in the baseline organic-lean zone in g/cm^3 . The scaling factor is calculated after baselining the two curves in the organic-lean zone, and its calculation is further discussed in the methodology section. The $\Delta \log R$ separation of the two curves is then related to the maturity of the formation to determine the TOC in wt% in the organic-rich zones:

$$\text{TOC} = (\Delta \log R) \times 10^{(2.297 - 0.1688\text{LOM})} \quad (5)$$

where LOM is the level of organic maturity (Hood et al., 1975). The LOM can be determined from a variety of measurements including vitrinite reflectance, Tmax, or Rock Eval if the type of organic matter is known. Therefore, if two formations have the same $\Delta \log R$ values but different LOM values, estimated TOC will be different. However, in over-mature shale reservoirs with LOM values greater than 10.5, the limit of calibration of maturity to TOC is reached. In these formations, a LOM value of 10.5 should be used (Passey et al., 2010).

Comparison of TOC from Different Methods

Wireline log measurements, including geochemical spectroscopy, resistivity, and bulk density, were used to compute continuous TOC logs from four wells from which core samples were available. The wells are all from unconventional shale plays in North America. Core samples were sent to the Schlumberger-Doll Research Center, where each core sample was crushed and homogenized, and then split for multiple measurements, including TOC by coulometry, which was outsourced to SGS Laboratories in Canada.

The TOC log derived from the geochemical spectroscopy data for well 1 is presented in [Figure 1](#). The computation is automated, but it requires a quality control step to assure that automatic compensation for carbon in the borehole has been properly applied. When done correctly, the TC and TIC curves overlay in an organic-free interval, as shown in Zone (a) of [Figure 1](#).

The computation of TOC using Schmoker's technique is straightforward. The application of the $\Delta \log R$ method to log data is a bit more complex. First, bulk density and resistivity curves are plotted on the same track using the default limits for each curve. Next, the two curves must be baselined in an organic-lean zone, which can be identified by finding where the two curves parallel each other ([Figure 2](#)). A gamma ray curve or knowledge of the local geology can help to identify these zones.

Once the organic-lean interval has been identified, the curves are baselined by adjusting the limits of each curve so they end up overlaying each other in the selected interval ([Figure 3a](#)). One or both of the limits can be adjusted, as long as the limits respect the range of the actual values. Separation of the two curves is seen in the organic-rich intervals ([Figure 3b](#)).

The scaling factor presented in equation (4), is now calculated from the adjusted limits of the bulk density and resistivity curves:

$$\text{Scaling Factor} = \# \text{Resistivity divisions} / (\rho_{b\text{-upper}} - \rho_{b\text{-lower}}) \quad (6)$$

where the number of resistivity divisions is an integer and is counted from the track divisions on the log plot, $\rho_{b\text{-upper}}$ is the value of the upper adjusted bulk density limit, and $\rho_{b\text{-lower}}$ is the value of the lower adjusted bulk density limit. The scaling factor is then entered into equation (4) along with the baseline bulk density (ρ_{baseline}) and resistivity (R_{baseline}) values to calculate the $\Delta \log R$ separation. Because the baseline is usually set over an interval and not at an exact depth, the R_{baseline} and ρ_{baseline} values chosen are the approximate average values for that interval. Finally, the calculated $\Delta \log R$ separation is used as an input to equation (5) along with an LOM value for the formation. Because the formations examined in this study are over-mature shales, the LOM value entered into equation (5) is 10.5 for all wells.

Comparison with Core Data

Each of the three TOC values computed from log data are compared with core TOC. However, before the comparison to core can be made with the geochemical spectroscopy tool values, the core TOC values must be adjusted. This is to account for the fact that the core organic carbon (TOC in wt%) is measured on a different basis than the log TOC values. The core TOC is measured in grams of organic carbon per grams of dry rock, which includes minerals plus kerogen, but for the geochemical spectroscopy log, TOC is reported in grams of TOC per grams of minerals. The adjusted core TOC is:

$$\text{Adj Core TOC} = 100\text{TOC}/(100 - 1.2\text{TOC}) \quad (7)$$

where 1.2 is a commonly accepted multiplier used to account for other components (H, O, N, S) of organic matter. This coefficient can be modified based on local knowledge, but such a modification is rarely needed. No adjustment to the core data is necessary to compare it with the $\Delta \log R$ and Schmoker methods.

Log plots were created to compare TOC methods side by side for well 1. The core TOC data was overlain on each of the three TOC tracks and in a fourth track the three TOC logs were overlain on each other ([Figure 4](#)).

The log-derived values of TOC were extracted at each core sample depth, and crossplots were made to compare the core data with the corresponding log value for each method. The agreement between the core data and the TOC methods was evaluated by computing the average absolute difference (aad) for each well.

Results and Discussion

Log plots displaying a measurement versus continuous depth can be useful for spotting trends in data; however, they are not ideal for determining and quantifying how well core and log data agree. Figure 4 shows an example of the log plot for well 1 only. For this well, the log plot shows that at most depths the Δ log R technique results in a narrower dynamic range of TOC values and the geochemical spectroscopy and Schmoker methods appear to generate similar TOC logs. Looking at the log plot on its own, however, it is hard to determine which method has the best agreement with the core data.

By extracting the TOC log data at each core depth, it is possible to display the core and log TOC data in crossplot and calculate the aad. [Figure 5](#), [Figure 6](#), [Figure 7](#), and [Figure 8](#) show crossplots comparing the core TOC to TOC from each of the three log methods for each well.

For well 4 the crossplots show that the geochemical spectroscopy method agrees better with the core data than the other two methods. In this well, the points on the spectroscopy plot closely follow the one-to-one line. The Δ log R and Schmoker methods, however, show biases in the TOC data. For TOC values above 5 wt%, these two methods under estimate the TOC by as much as 10 wt%. It is somewhat surprising that the Schmoker method does not show better agreement with core in well 4 because it is located in the Bakken Formation, which is one of the formations where the method was originally tested by Schmoker. The opposite bias is seen in well 2, where TOC from Δ log R and Schmoker is overestimated by as much as 6 wt%. In wells 1 and 3, it is hard to determine which of the three methods is in the best agreement with core by only looking at the crossplots. [Table 1](#) lists the computed aad values for the three TOC methods compared with core TOC for each well and all wells combined.

The combined data from all the wells ([Figure 9](#)) show the robustness and the accuracy of the geochemical spectroscopy-derived TOC log throughout multiple formations, depositional environments, and drilling conditions. In contrast, the Δ log R and Schmoker techniques are slightly less reliable, especially at TOC values over 10 wt%, without additional calibration or local knowledge.

On average, each of the three methods predicts TOC to within 2 wt%. In three of the four wells presented in this study, TOC derived from geochemical spectroscopy logs is in better average agreement with core compared with the other methods, and examination of the crossplots shows none of the biases exhibited by the other techniques.

Summary

TOC from geochemical spectroscopy logs agrees with core TOC to within and aad of 1.0 wt% in four wells covering various lithologies, drilling mud types, and organic carbon values ranging from zero to 18 wt%. The accuracy and robustness of the TOC estimated is achieved

through a combination of new technology, careful characterization, and new interpretation development. The TOC logs are valuable for identifying and quantifying organic richness in unconventional plays. In addition to the TOC logs, the geochemical spectroscopy tool provides a full suite of elemental concentrations that can be used to characterize formation mineralogy or lithology.

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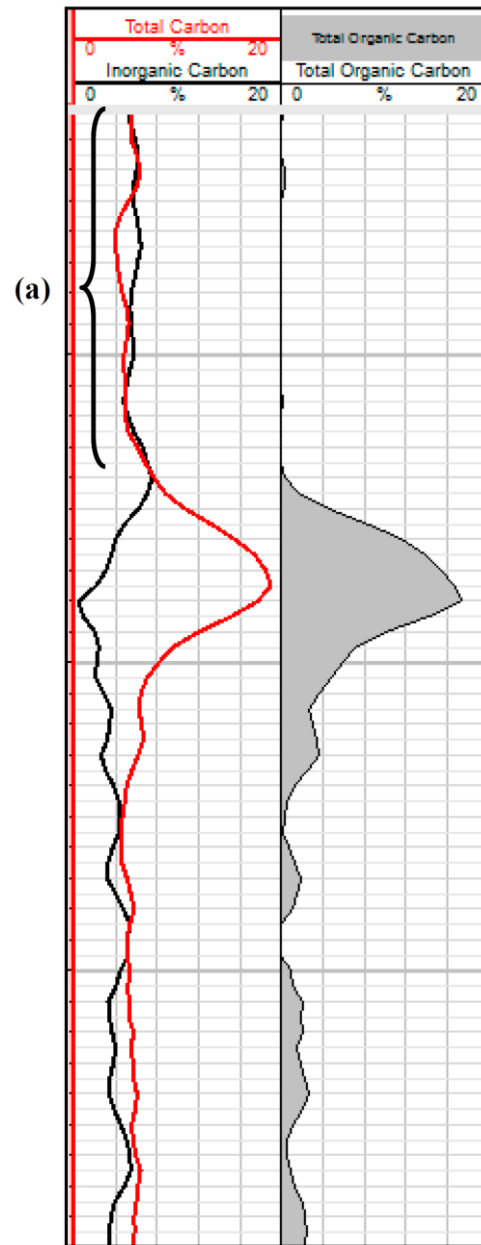


Figure 1. The total carbon and inorganic carbon logs are plotted together in track 1. The computed TOC is plotted in track 2. Zone (a) is an organic-lean zone as indicated by the overlay of total carbon and inorganic carbon.

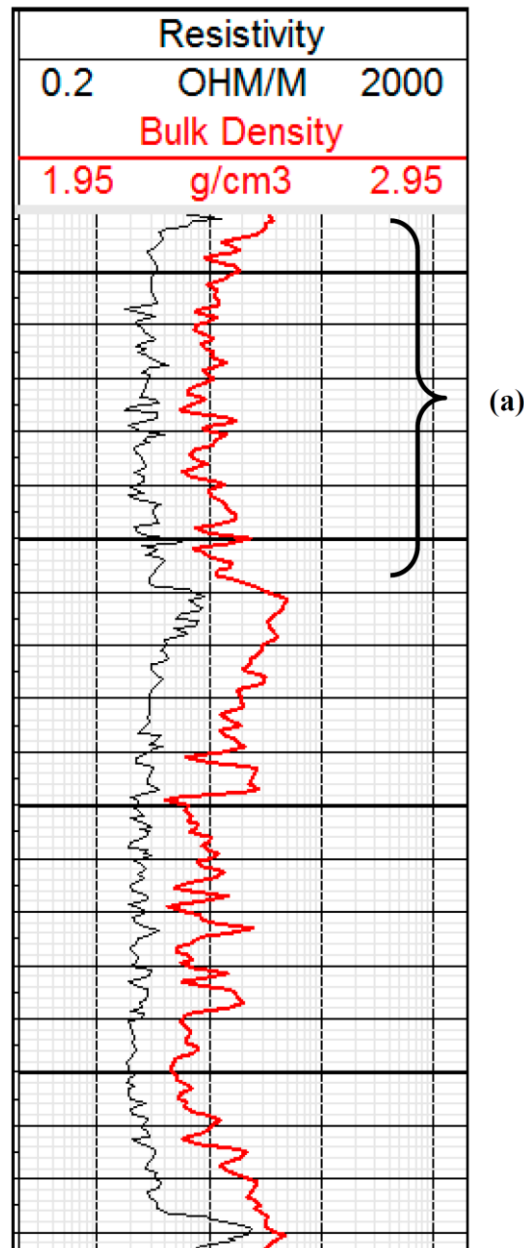


Figure 2. Zone (a) is used to baseline the density and resistivity logs for the application of the $\Delta \log R$ method.

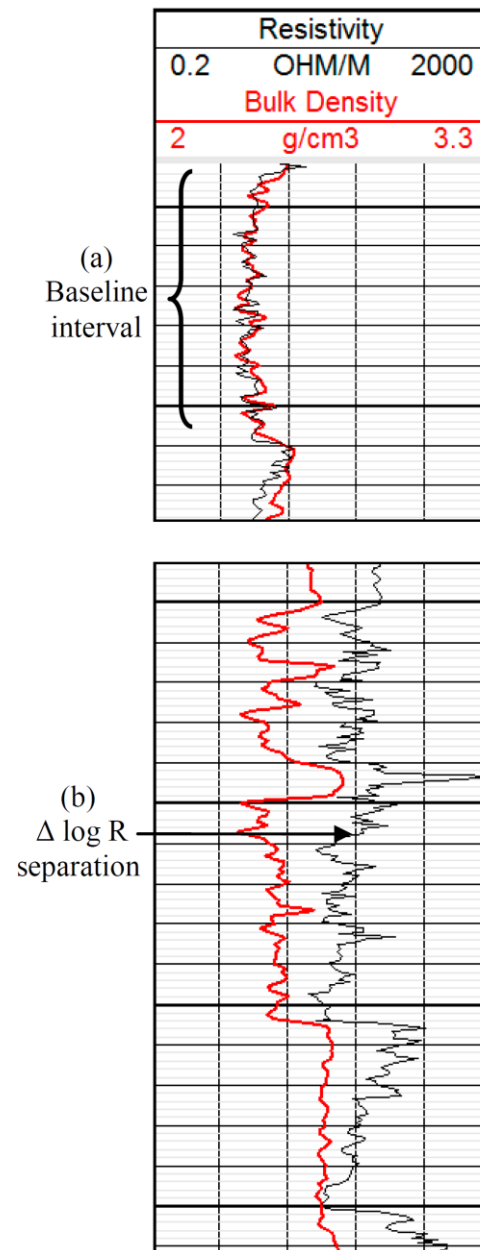


Figure 3. (a) After adjusting the limits, the bulk density and resistivity curves overlay in the identified baseline zone. (b) In a different part of the well, the two curves separate, indicating the presence of organic matter.

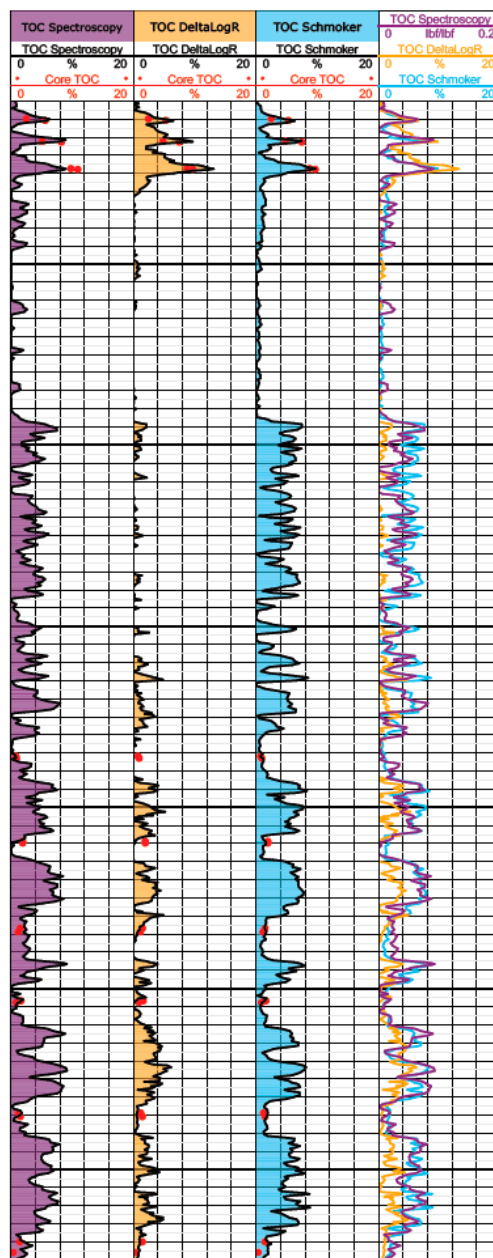


Figure 4. TOC from geochemical spectroscopy logs (track 1), $\Delta \log R$ method (track 2), Schmoker method (track 3), and core (red dots) in wt%. Track 4 plots the three TOC methods on top of each other.

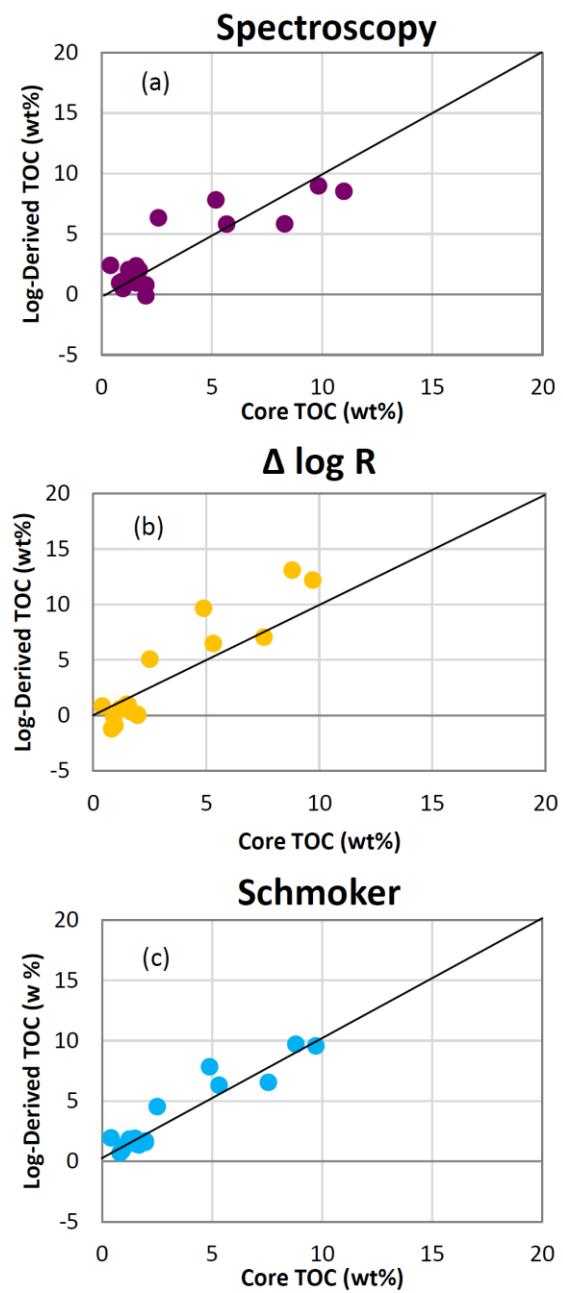


Figure 5. Crossplots for well 1 comparing core TOC versus (a) geochemical spectroscopy TOC, (b) $\Delta \log R$, and (c) Schmoker.

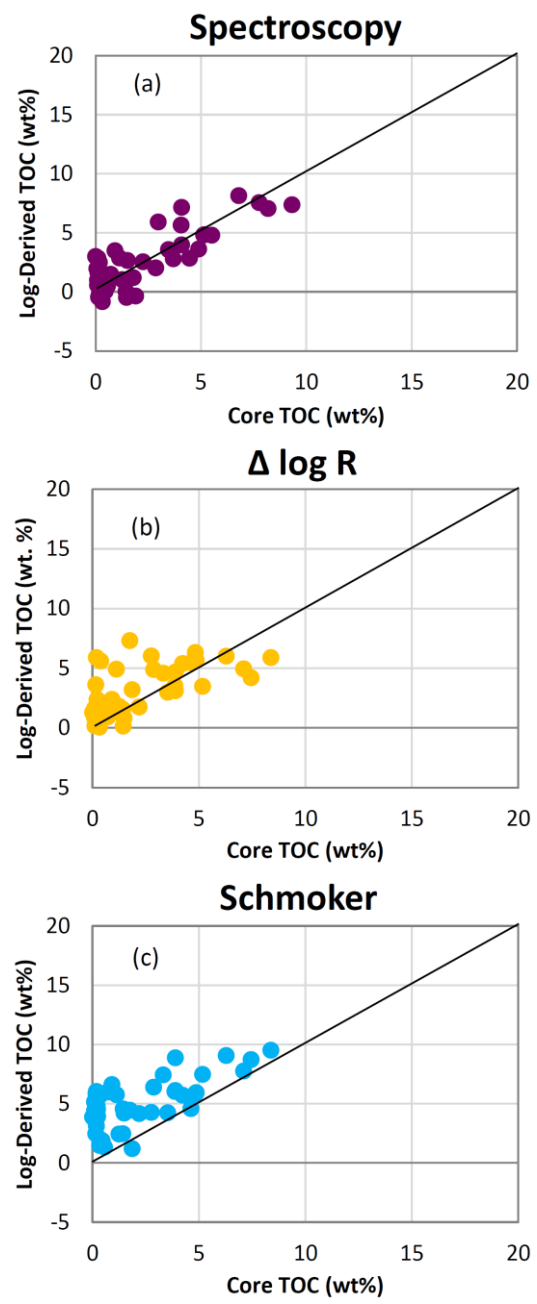


Figure 6. Crossplots for well 2 comparing core TOC versus (a) geochemical spectroscopy TOC, (b) $\Delta \log R$, and (c) Schmoker.

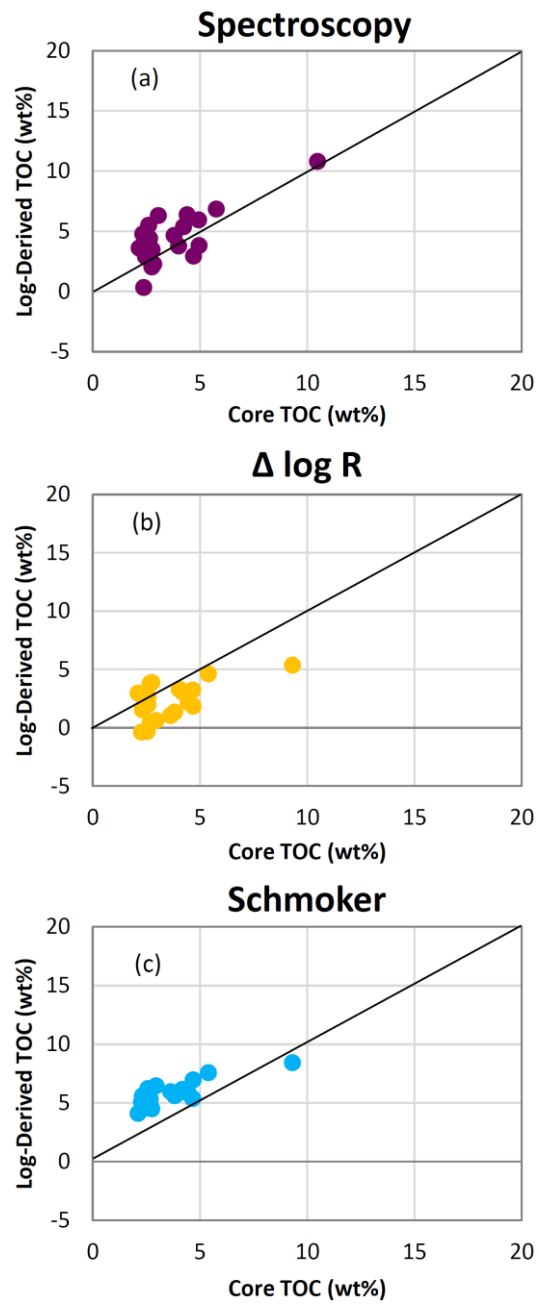


Figure 7. Crossplots for well 3 comparing core TOC versus (a) geochemical spectroscopy TOC, (b) $\Delta \log R$, and (c) Schmoker.

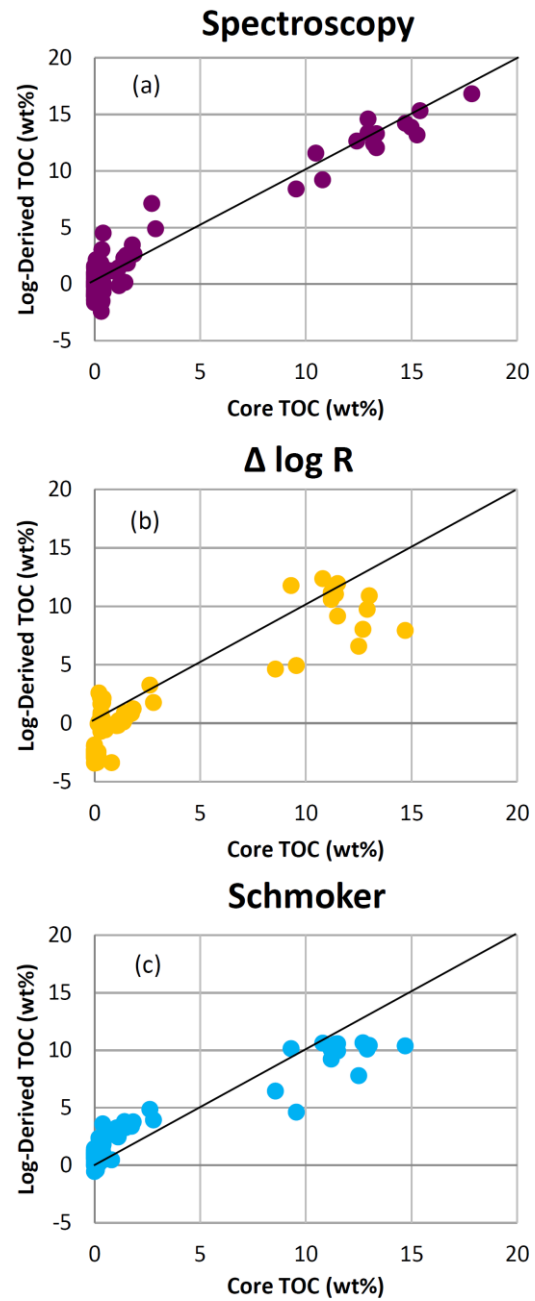


Figure 8. Crossplots for well 4 comparing core TOC versus (a) geochemical spectroscopy TOC, (b) $\Delta \log R$, and (c) Schmoker.

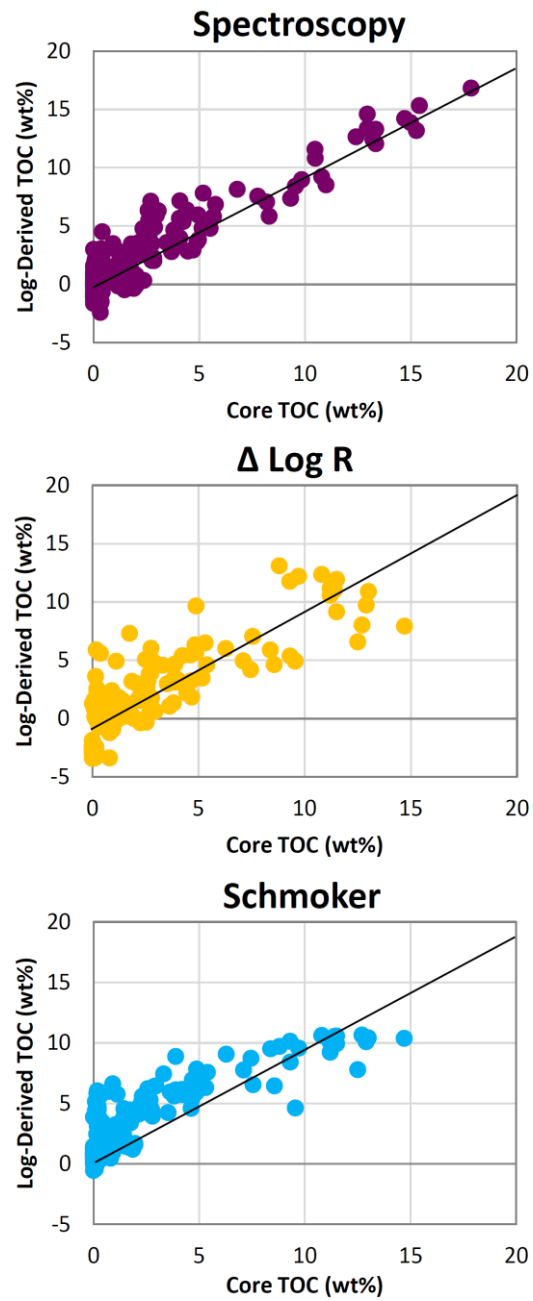


Figure 9. Combined data from all four wells comparing core TOC versus (a) geochemical spectroscopy TOC, (b) $\Delta \log R$, and (c) Schmoker.

aad (wt%)			
Well	Geochemical Spectroscopy	$\Delta \log R$	Schmoker
1	1.2	1.6	0.7
2	1.0	1.5	3.1
3	1.3	1.7	2.2
4	0.9	2.0	1.2
ALL	1.0	1.7	1.6

Table 1. Average absolute difference (aad) for each TOC method compared with core TOC for all wells individually and combined.