Chapter SR (Source Rocks)

PETROLEUM SOURCE ROCK EVALUATION BASED ON SONIC AND RESISTIVITY LOGS

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ABSTRACT

Mesozoic and Cenozoic marine siliciclastic sedimentary rocks of northeastern Alaska include important sections of organic-rich mudstone and shale. In this report, organic-rich subsurface sections of Jurassic, Cretaceous, and Paleogene age are evaluated for organic richness and petroleum source potential using the ΔlogR method of Passey and others (1990) and source potential indices (SPI) of Dembicki and Pirkle (1985). Total organic carbon (TOC) content is determined by the ΔlogR method applied to porosity and resistivity borehole geophysical logs with thermal maturity data from vitrinite reflectance. The SPI for oil and gas are calculated from thermal maturity and net richness values, net richness being the thickness of effective or net source rock times the average TOC for that interval. In net richness and SPI calculations, TOCs ≥2 wt % are used for marine source rocks, and ≥1 wt % for deltaic source rocks.

Profiles of TOC determined by the ΔlogR method are reported for ten wells, nine along the west side and southwest corner of the 1002 area of the Arctic National Wildlife Refuge plus the Aurora 1 well, to the northeast and offshore from the 1002 area. In some parts of these wells, the ΔlogR TOC profiles compare well with laboratory measured TOC results from prior studies on borehole cuttings and core, and also to the gamma-ray log, whose response in many other studies correlates positively with TOC. In other boreholes or parts of boreholes, however, the ΔlogR TOC profiles show significant departures from TOC profiles determined from cuttings, and do not show a positive correlation with gamma-ray log response. Where TOCs determined by the ΔlogR method show significant difference from TOCs determined from cuttings, the accuracy of the cuttings data is considered questionable when we can document sloughing; and the ΔlogR TOCs are considered the more representative of average TOC values, except in cases where we can document anomalous porosity or resistivity log response, or where we believe we have set the baseline incorrectly.

For the Hue Shale, including the gamma-ray zone (GRZ) on the west side of the 1002 area, TOCs determined using the ΔlogR method and TOC measurements from cuttings samples both indicate high net organic richness, particularly in the basal several hundred feet. Interval average TOCs from both methods are predominantly between 2-5 wt %, ranging up to 10 wt %. Net richness values range from 560 to 1,611. The SPI for oil generation from the Hue Shale, which has thermal maturities ranging from 0.6-1.0 $\%R_o$ is also high (392-1,611), but in areas where the Hue has been uplifted and cooled since maximum burial, the SPI does not represent present-day

potential. In the Aurora 1 well, approximately 440 ft of an age-equivalent section of the Hue Shale are present at the top of the Mesozoic section. With ΔlogR-calculated TOCs that average a minimum of 1.5 wt % and vitrinite reflectance values of approximately 1.3-1.5 % R_o, this "Hue Shale" section has a minimum net richness of approximately 600 and corresponding SPI of 180 for oil and 600 for gas.

Both TOCs measured on cuttings and TOCs calculated by the ΔlogR method for the Lower Cretaceous pebble shale unit are variable, predominantly between 1 and 3 wt %, ranging mainly up to 5 wt %. The pebble shale unit also has highly variable overall thickness (<20 to >200 ft), net richness (11-338), and SPI (11-338). Except for 2 wells near the southwest corner of the 1002 area, net organic richness is low because the pebble shale unit is thin, or in the Aurora 1 well because it is organically lean.

For the Kingak Shale, TOCs from both methods indicate uniformly low values of approximately 1-2 wt % in the 2 southernmost wells and generally higher values up to approximately 3.5 wt % in the Beli 1 and Canning River B1 wells, particularly in the upper and middle parts of the Kingak Shale. Our ΔlogR-calculated TOCs also indicate that the upper and middle parts of the Kingak are richer, and in the Canning River B1 well up to 7.5 wt % TOC. These determinations (Table SR5) suggest that the Kingak Shale has high net richness and SPI in three of the four wells if we average TOC values ≥1 wt % as the cut-off for an effective Kingak, and in two of the four wells using a 2 wt % cut-off.

The Mikkelsen Tongue of the Canning Formation is a very thick unit with mostly low TOCs between 1 and 2 wt %, but also one or more intervals of higher TOCs between approximately 2 and 4 wt %, suggested by both TOCs from cuttings and TOCs from the ΔlogR method. Net organic richness (1,336-3,393) and SPI for oil (401-1,018) are high if we assume that a thick succession with mostly low TOCs between 1 and 2 wt % is a viable petroleum source rock. Near the 1002 area, the Mikkelsen Tongue is not mature, however, we think that the lateral, age-equivalent lithofacies of the Mikkelsen Tongue, if present to the north and offshore the 1002 area, would be buried more deeply and may be a richer, or at least equally viable source of hydrocarbons.

For the Shublik Formation, low transit times on the sonic log indicate it is out of the range of calibration of the ΔlogR method, so we evaluated richness using other TOC data. TOCs measured on outcrop, cuttings, and core samples indicate that the Shublik is quite rich in some intervals, but their proportion of the total section is presently unknown. TOC values range from approximately 1-7 wt % in samples from wells and outcrop near the 1002 area, and up to 10 wt % in core samples from much farther west and north where it is also very heterogeneous in stratigraphic profile on a scale as small as 0.1 ft. Near the 1002 area, the data suggest that the average organic richness of the Shublik Formation is in the range between 1.5-4.0 wt % TOC, and probably closer to 1.5 wt %.

INTRODUCTION

Mesozoic and Cenozoic marine carbonate and siliciclastic sedimentary rocks of northeastern Alaska include substantial sections of organic-rich mudstone and shale which are considered to be the sources of petroleum in the oil and gas fields of that region (Craig and others, 1985; Bird and Molenaar, 1987; Magoon and others, 1987; Magoon and others, Chap. PS). These mudstone/shale successions include the Triassic Shublik Formation, the Jurassic and Lower Cretaceous Kingak Shale, the Lower Cretaceous pebble shale unit, the Cretaceous Hue Shale including the gamma-ray zone (GRZ), and the Tertiary Canning Formation--principally the Eocene Mikkelsen Tongue of Molenaar and others (1987). They have been described and their petroleum source parameters characterized from several outcrops in and adjacent to the 1002 area of the Arctic National Wildlife Refuge (ANWR) and/or from borehole cuttings and some core in oil and gas wells to the southwest, west, northwest, and offshore of the 1002 area (Figs. SR1, SR2) (Craig and others, 1985; Bird and Molenaar, 1987; Magoon and others, 1987; Banet, 1992; 1993; Flett and Paul, 1994; Paul, 1994; Bergman and others, 1995; written communication, 1998; Lillis and others, Chap. OA; Magoon and others, Chap. PS).

The existing outcrop and well core TOC data for the these organic-rich mudstones and shales are mainly spatially scattered samples (Magoon and others, 1987) that are not readily quantifiable in terms of stratigraphic variation in richness and thickness. Also, in most of the wells near the 1002 area, the cuttings samples are spaced at ≥50 ft intervals (Magoon and others, 1987; Nelson and others, Chap. WL). Several wells near the 1002 area were sampled approximately every 30 ft for TOC analyses from cuttings (Magoon and others, 1987), and these few wells have, so far, provided the most complete data on the stratigraphic variation in organic-richness of these potential petroleum source rocks. However, a relatively new wireline log technique, the ΔlogR method of Passey and others (1990), uses porosity and resistivity logs to produce profiles of TOC variation at a scale of approximately 3 ft or one m, the resolution of the logging tools. Thus, for the petroleum assessment of the 1002 area, we applied this method to nearby wells in order to provide a better understanding of the stratigraphic variation in organic richness and its proportions in potential source rock intervals.

In this report we evaluate siliciclastic organic-rich mudstone sections of Jurassic, Cretaceous, and Eocene age in 10 wells adjacent to the 1002 area (Fig. SR3) using the ΔlogR method of Passey and others (1990). We also qualitatively compare TOCs determined from the ΔlogR method to TOCs measured on borehole cuttings and core samples. Total organic carbon profiles produced by the ΔlogR method provide a powerful tool for evaluating source rock richness and its stratigraphic variation and have not previously been reported for the wells of this area. Creaney and Passey (1993) show several ΔlogR calculated TOC profiles for the Cretaceous Torok Formation from wells much farther west on the North Slope. The ΔlogR TOCs are then used with vitrinite reflectance data reported in Bird and others (Chap. VR) to calculate the petroleum source potential, which is expressed as source potential indices (SPI) (Dembicki and Pirkle, 1985).

The Triassic Shublik Formation has many calcareous organic-rich mudstone intervals with low transit times for which the ΔlogR method is not calibrated, therefore its organic richness in the 1002 area and vicinity is evaluated from several other sources of TOC data. TOC data are evaluated from analyses on cores published since the 1987 assessment (Kupecz, 1995; Robison and others, 1996), previously unpublished outcrop TOC data (J.T. Parrish, written communication, 3/97), and reported TOC analyses from borehole cuttings (Magoon and others (1987, Chap. PS).

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METHODS AND DATA SETS

The ΔlogR Method And Other TOC Data

The ΔlogR methodology of Passey and others (1990) determines total organic carbon (TOC) from the separation apparent when a properly scaled porosity log and resistivity log are overlain and a maturity factor applied. In water-saturated, organic-lean rocks the two curves parallel each other because both respond to variations in formation porosity. In both hydrocarbon reservoirs and organic-rich non-reservoir rocks a separation between the curves, termed ΔlogR, is present. Reservoir rocks are eliminated from the analysis by their gamma-ray response and by other well data such as the lithology from mudlog and well samples, where available.

The TOC of the source rock intervals is then calculated based on the ΔlogR separation measured in logarithmic resistivity cycles and thermal maturity expressed as LOM (level of organic metamorphism) using the following empirical relationships discussed fully in Passey and others (1990):

$$(1)\quad \Delta\log R = \log_{10}(R/R_{baseline}) + 0.02 \times (\Delta t - \Delta t_{baseline})$$

$$(2)\quad TOC = (\Delta\log R) \times 10^{(2.297 - 0.1688 \times LOM)}$$

R is the resistivity measured in ohm-m by the logging tool; Δt is the measured transit time in µsec/ft; $R_{baseline}$ is the resistivity corresponding to the $\Delta t_{baseline}$ value when the curves are baselined in non-source, clay-rich rocks; and 0.02 is based on the ratio of -50µsec/ft per one resistivity cycle.

In immature rocks the ΔlogR separation is due primarily to the response of the porosity log, e.g., the longer transit time of the sonic or acoustic log responding to the lower density organic matter. In thermally mature rocks the separation is also caused by longer transit times, but additionally by higher resistivity due to the presence of generated unexpelled hydrocarbons. We applied the method using the differential transit time log (DT), also known as the sonic or acoustic log, and the deep induction log (ILD) as recommended by Passey and others (1990). We used thermal maturity data from vitrinite reflectance measurements (Bird and others, Chap. VR) converted to LOM using the relationship in Figure VR1.

The first step in applying the method is to properly scale the porosity (DT) and resistivity (ILD) log profiles such that their relative scaling is -50 µsec/ft

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per one logarithmic resistivity cycle (see left column of Plates SR1-SR12). The profiles are then overlain and baselined in a fine-grained, non-source rock as shown in Plates SR1-SR12. Since this process counts the "non-source" shale as zero TOC, an estimate or measure of its TOC needs to be added back after the calculation of equation #2 above. We use the same value as Passey and others (1990), which is 0.8 wt % TOC, because it is in the mid-range of average TOC for shales worldwide. A baseline condition exists where the two profiles track or directly overlie each other over a significant depth range. For example, see Plate SR9 from 6,050-6,150 ft and Plate SR12 from 7,750-7,900 ft. Organic-rich intervals are then recognized by separation and non-parallelism of the two profiles, and a TOC profile is calculated using the same intervals as the digital data, in this case at 0.5 or one-foot intervals.

Establishing the baseline in a non-source shale seemed at first to be very subjective in the absence of an independent measure of TOC and especially for intervals that we thought were quite rich overall. However, in the practice of applying the method to an increasing number of wells, we think we gained the experience to apply the method consistently to get good results, although this becomes more difficult when the resistivity response increases due to the presence of hydrocarbons in rocks that have reached the thermal maturity to begin generation (0.6% R_o) (see Plates SR1 and SR6). The combined resolution of the porosity/resistivity overlay is approximately one m, thus the method does not accurately quantify the organic content of source intervals significantly thinner than one m, however, intervals as thin as 0.33 m are readily identified (Passey and others, 1990). We used wireline data digitized at either 0.5 or one-foot intervals.

TOC results from the ΔlogR method, particularly apparent anomalies, are more reliably interpreted if a suite of good wireline logs are available and if other sources of TOC data are available for comparison. So far, we have qualitatively compared our TOC results from the ΔlogR method with a large set of oil industry TOC data measured on borehole cuttings (Magoon and others, 1987; Nelson and others, Chap. WL). The complete set of wireline logs and other data for wells used in this study can be viewed in Nelson and others (Chap. WL).

TOC analyses on borehole cuttings are the best means to check the TOCs determined by ΔlogR calculations because they both represent an interval average -- even though the interval of the cuttings is usually greater than the approximate one meter resolution of the ΔlogR values. Therefore, in heterogeneous sections cuttings are better for comparison or validation than

TOC data from a point source, such as a core sample. However, the quality and representativeness of cuttings samples are more sensitive than core to factors in the well such as the mud program, casing points, and sloughing. Because we did not collect the samples or do the TOC analyses, we know little about the data set of TOCs measured on cuttings, except for the sampling interval, therefore we cautiously compared the measured TOCs to our ΔlogR-calculated TOCs.

Determination of Net Richness and Source Potential

The source potential of our sections was determined by calculating a net organic-richness based on the ΔlogR TOC profiles and then using maturity scaling factors applied to present-day thermal maturity from vitrinite reflectance using the methods of Dembicki and Pirkle (1985). Dembicki and Pirkle (1985) use "richness" to mean the thickness of an effective source rock times the average TOC for that "effective" interval. We use "net richness" in the same way they used "richness" to distinguish it from richness as organic carbon concentration. We define net or effective source rock as the thickness of rock with ≥2 wt % TOC for rocks with predominantly marine organic matter and ≥1 wt % TOC for rocks with predominantly terrigenous organic matter.

The source potental indices (SPI) are calculated from the net richness value and a thermal maturity scaling factor which becomes one when the rock is at peak generation (defined as 0.8-1.0% R_o). For example, a predominantly marine source rock that is 100 net ft thick with an average TOC of 3.5 wt % would have a net richness of 350 (100 x 3.5) and an SPI for oil of 350 (350 x 1) where vitrinite reflectance values are between 0.8-1.0 % R_o. However, for the same source interval where vitrinite reflectance is between 0.6-0.8 % R_o and a scaling factor of 0.7 is applied, the SPI would drop to 245 (350 x 0.7). Dembicki and Pirkle (1985) describe values of SPI greater than 300 as "high richness." Similarly, in evaluating potential for gas generation, a source rock with a net richness of 350 would also have an SPI of 350 where vitrinite reflectance values are between 1.2-1.5% R_o, and an SPI of 245 where vitrinite reflectance values are between 1.0-1.2 % R_o. Note that a relatively organically lean (1-2 wt %) deltaic source interval such as the Mikkelsen Tongue can have high net richness and thus high SPI values due to high net thickness of source rock with ≥1 wt % TOC.

RESULTS OF ΔlogR ANALYSES

Profiles of TOC produced from ΔlogR calculations are presented for the Kingak Shale, pebble shale unit, Hue Shale including the gamma-ray zone, and the Mikkelsen Tongue of the Canning Formation in Plates SR1-SR12. These 12 plates also show the borehole logs used, other TOC data where available from borehole cuttings or core, and the tabulations of net richness and source potential. Summary plates present both the TOCs from ΔlogR calculations and the TOC data from cuttings and core, and show its correlation with gamma-ray log response in two cross sections; Plate SR13 shows the Hue Shale -- including the gamma-ray zone (GRZ), the pebble shale unit, and the Kingak Shale, and Plate SR14 shows the Mikkelsen Tongue. Richness and source potential for these formations are discussed in the next section of this report.

In some boreholes or parts of boreholes analyzed in this study, TOCs computed from ΔlogR compare well with TOCs measured on cuttings, which is the expected result for very representative cuttings from a borehole with little or no sloughing such as the West Staines 2 well in the Hue Shale and older units (Plate SR3). However, in other boreholes or parts of boreholes, such as part of the Mikkelsen Tongue interval in the West Staines 2 well (Plate SR11), the ΔlogR TOC profiles do not compare well with cuttings data. Therefore, because we know little about the cuttings data other than the sampling interval, where the results from the two methods do not agree, the accuracy of the cuttings data is considered questionable when we can document sloughing from an enlarged borehole indicated by the caliper log, and the ΔlogR-derived TOCs are considered the more representative of average interval TOC values except in cases where we can document anomalous sonic or resistivity log response. A comparison of the TOC data sets and other observations and information about the log data and the well are also included on Plates SR1-SR12. Results are summarized for each of the formations in the following sections.

Hue Shale Including the Gamma-Ray Zone

The Cretaceous Hue Shale is evaluated by the ΔlogR method in nine wells adjacent to the 1002 area of the ANWR (Fig. SR3). Eight of these wells, including Mikkelsen Bay 1, West Staines 2, Point Thomson 2, Leffingwell 1, Beli 1, Canning River A-1 and B-1, and Kavik 1, comprise the correlation section shown in Plate SR13. The data sets for each well are displayed in Plates SR1-SR8, including net richness and source potential results that are also summarized in Tables SR1, SR2, and SR4. The most marked features of the ΔlogR TOC profiles for the Hue Shale in the eight wells on Plate SR13 are the differences in thickness of the formation; the striking vertical variation in organic carbon content, also indicated by the TOC profiles from cuttings and gamma-ray response; and the similarity in that vertical TOC distribution from one well to the next. The ninth well, Aurora 1, is located offshore and northeast of the 1002 area, and is discussed in a separate section.

Including the gamma-ray zone (GRZ), which is the lower part of the Hue Shale that has very high gamma-ray response, the thickness of the Hue ranges from 519 ft in the Point Thomson 2 well to 1,085 ft in the West Staines 2 well (Table SR1 and SR2). Correlation of the TOC profiles with gamma-ray response (Plate SR13) indicates that the upper part of the Hue Shale that is characterized by fairly low TOCs between 1-3 wt % and generally lower gamma-ray response in the West Staines 2 and Leffingwell 1 wells has been eroded in the Point Thomson 2 and Mikkelsen Bay 1 wells on the coastal plain. This upper part of the Hue Shale is also absent in the Canning River A-1 and B-1 wells and the Beli 1 well, and appears to be thinner in the Kavik 1 well.

Vertical variation in the TOC profile for the Hue Shale is striking. Below the thick, relatively organic-lean upper part of the Hue, the lowest part of the Hue, called the GRZ, was analyzed separately as well as together with the rest of the overlying Hue Shale because it is a very distinctive stratigraphic interval that has been studied extensively in outcrop and probably also in the subsurface. At the Hue Shale type locality in Ignek Valley, approximately 400 ft in the lower part of the Hue, including the GRZ and more than 200 ft above it, are very rich with TOCs generally ranging from greater than 2 wt % to approximately 6 wt % (Bird and Molenaar, 1987, p. 56). Our results also show that the lower several hundred feet of the Hue Shale, including the GRZ and strata above it, are the richest; they have calculated ΔlogR TOCs up to 9 wt %, with about the same range for TOC values measured on cuttings, except for the Hue in the Kavik 1 well which has high ΔlogR-calculated TOC values up to almost 10 wt %, but low values from cuttings. In this well the highest ΔlogR TOC values are probably erroneous due to apparent sonic log cycle-skipping (Rider, 1991, p. 81).

The very distinctive ΔlogR-calculated TOC profile for the GRZ also correlates with gamma-ray log response that uniformly shows a lower part with relatively lower API values than the very high response of the section at the top of the GRZ. The high response in the upper part is also a result of high gamma-ray signal contribution by tuff and bentonite in the section (Fig. SR4) (Bergman, 1995; Bergman and others, written communication 3/98).

Within the lower part of the Hue Shale are the most obvious apparent anomalies in the ΔlogR-calculated TOC profile, and they contribute to the vertical variation as well. These are the thin intervals of very low or "negative" calculated TOCs which correlate to relatively low resistivity, and also correspond to relatively high gamma-ray response. These intervals are present in the GRZ in all the wells and may be tuff or bentonite as described in the well history and in outcrop (Fig. SR4) (Bird and Molenaar, 1987; Bergman and others, 1995). Creaney and Passey (1993) also note that a high gamma-ray, low TOC unit is possibly a bentonite layer within the HRZ (the highly radioactive zone), which is a condensed facies of early Cretaceous age in the Torok Shale to the west of the 1002 area (Molenaar, 1988). Note however, that in some wells the TOCs measured on cuttings through these intervals do not commonly indicate low values, e.g. the Canning River wells, whereas in other wells such as the West Staines 2, the TOC values in cuttings are lower and appear to be more in agreement with the TOCs determined by the ΔlogR method. It seems reasonable to conclude that these tuffaceous or bentonitic parts of the lower Hue Shale would have lower interval average ΔlogR-calculated TOCs than the mudstone sections, but not negative values. However, the very low resistivity of these zones reduces the ΔlogR-calculated TOC profile to erroneously low or negative values in some places.

Pebble Shale Unit

As for the Hue Shale, the Lower Cretaceous pebble shale unit is evaluated by the ΔlogR method in nine wells adjacent to the 1002 area of the ANWR (Fig. SR3). The Mikkelsen Bay 1, West Staines 2, Point Thomson 2, Leffingwell 1, Beli 1, Canning River A-1 and B-1, and the Kavik 1 wells comprise the correlation section from the west and southwest shown in Plate SR13. The data sets for each well are displayed in Plates SR1-SR8, including richness and source potential results that are also summarized in Tables SR3 and SR4 where the pebble shale is added in with the Hue. The Aurora 1 well, located offshore and near the northeast corner of the 1002 area, is discussed in a separate section. The most important features of the ΔlogR TOC profiles for the pebble shale unit in the eight wells of Plate SR13 are the differences in thickness of the formation; the vertical variation in organic carbon content; and the apparent lack of similarity in vertical TOC distribution among the wells.

The thickness of the pebble shale unit is very different in each well. Defined by the gamma-ray response of the overlying GRZ, the thickness of the pebble shale unit ranges from 16 ft in the Mikkelsen Bay 1 well to more than 200 ft in two wells to the southwest, in one or both of which the section is possibly thickened structurally. It forms the basal part of a thick marine Cretaceous, mostly mudstone, succession that also includes the Hue Shale.

TOC from both sets of data is highly variable for the pebble shale unit. In some wells the ΔlogR-calculated TOCs are as low as approximately 1-2 wt % and in others as high as 4-5 wt % or more for interval averages. TOCs measured on cuttings are higher than ΔlogR-calculated TOCs in the 4 southern wells where most values are between 2-4 wt % and they range as high as 4.5 wt %. The ΔlogR-calculated TOCs are generally higher than measured TOCs in the 4 northern wells where most values are between 3-4 wt % and range as high as about 5.5 wt %. In Ignek Valley, the pebble shale unit in outcrop has TOCs up to approximately 6 wt % (Bird and Molenaar, 1987), and equally high values occur along the Canning River (Bergman, 1998--oral communication). The gamma-ray log response seems more consistent among the wells than TOC, with relatively higher values at the top and lower values at the base, except for the Canning River A-1 and Kavik 1 wells which have relatively high gamma-ray response also, or only, at the base of the pebble shale unit.

Kingak Shale

The Jurassic and Lower Cretaceous Kingak Shale is evaluated by the ΔlogR method in four wells adjacent to the southwest corner of the 1002 area of the ANWR (Fig. SR3). The Beli 1, Canning River A-1 and B-1, and the Kavik 1 wells are shown on the correlation section of Plate SR13. The data sets for each well are displayed in Plates SR5-SR8, including richness and source potential results that are also summarized in Table SR5. The Kingak in the Aurora 1 well, located offshore and northeast of the 1002 area, is discussed in a separate section.

The most notable features of the ΔlogR TOC profiles for the Kingak Shale in the four wells analyzed on the southwest side of the 1002 area are the differences in thickness of the formation; the vertical variation in organic carbon content -- or uniformity shown for the Kavik 1 well; and the apparent difference in vertical TOC distribution among the wells. The gamma-ray log response is relatively flat through the formation in all the wells except the Canning River B-1, where it has relatively lower values through an interval with the only high TOC values, ranging from approximately 3-7 wt

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% for ΔlogR TOCs and 2-3.5 wt % for measured TOCs on cuttings. Thickness of the Kingak in these wells ranges from 295 ft in the Beli 1 well to almost 1,000 ft in the Canning River A-1 well, where it is very likely thickened structurally (Plate GG3).

TOC is relatively low through most of the Kingak interval in all except the Canning River B-1 well. For the most part the Kingak ranges from approximately 1-2 wt % for both ΔlogR TOCs and measured TOCs on cuttings, and is slightly higher than this in the Beli 1 well in the upper 100 ft. However, approximately 100 ft of the upper 150 ft of the Kingak in the Canning River B-1 well have much higher TOC values, ranging from approximately 3-7 wt % for ΔlogR TOCs and 2-3.5 wt % for TOCs measured on cuttings.

Mikkelsen Tongue of the Canning Formation

The Eocene Mikkelsen Tongue of the Canning Formation is evaluated by the ΔlogR method in four wells along the coast northwest of the 1002 area (Fig. SR3). The Mikkelsen Bay 1, the West Staines 2, the Point Thomson 2, and the Alaska State C 1 wells comprise the correlation section shown in Plate SR14. The data sets used for each well are displayed in Plates SR9-SR12, and the richness and source potential are summarized in Table SR6.

The ΔlogR TOC profiles for these wells indicate that most of the Mikkelsen Tongue has fairly low TOC concentrations that range from just under 1 wt % to less than 2 wt %. However, the upper part of the Mikkelsen Tongue in all four well profiles shows an interval up to several hundred ft thick with greater TOC values, most approximately 2 wt % but some as high as 4 wt %, and even higher in the Mikkelsen Bay 1 well where the values are erroneously high due to very high transit times that are probably erroneous--possibly due to sonic log cycle-skipping (Rider, 1991). TOC data from cuttings in 2 of the 4 wells (Plate SR14) do not demonstrate unequivocally the presence of this higher TOC interval in the upper part of the Mikkelsen Tongue; one well doesn't show a marked increase and the other does. However, other wells nearby show higher measured and/or calculated TOC for the upper part of the Mikkelsen Tongue.

The extensive cuttings set for the Mikkelsen Tongue in the West Staines 2 well shows only very rare increases above the predominant 1 wt % TOC for the whole interval, but these slight increases generally correspond to intervals of higher calculated TOC. In the Point Thomson 2 well, the few TOC measurements in the upper part of the Mikkelsen Tongue show increased richness in the upper several hundred feet, suggested by two values of greater than 1.5 wt % and then a third of just over 4 wt % TOC. Moreover, the gamma-ray and sonic log response for some wells in the vicinity, e.g. Alpenglow 1, Badami 1 and 2, and East Mikkelsen 1 (see well data in Nelson and others, Chap. WL), may also indicate the presence of a slightly higher TOC interval in the upper part of the Mikkelsen Tongue.

Similar but thinner intervals of higher calculated TOC are also present in the lower part of the Mikkelsen Tongue. These intervals are indicated in some wells by higher cuttings TOC values and in other wells by gamma-ray and sonic log response, e.g. the Mikkelsen Bay 1, West Staines 2, Alaska Island 1, Alaska State D-1, Alaska State F-1, and Alaska State J-1 wells (see well data in Nelson and others, Chap. WL).

The overall gamma-ray response for the Mikkelsen Tongue is consistently higher than for the Sagavanirktok Formation above and below, but commonly it is also relatively flat--not showing excursions to higher gamma-ray response that parallel the higher TOCs indicated, except in a few wells, e.g. the Mikkelsen Bay 1, East Mikkelsen 1, and several others nearby wells. These wells are also similar to the Mikkelsen Bay 1 well in having longer transit times and relatively higher TOCs from cuttings for several hundred feet of the upper part of the Mikkelsen Tongue. The gamma-ray log response for this upper, potentially richer interval of the Mikkelsen Tongue is not consistently higher in all the wells examined; however, low gamma-ray response is also noted for a known source rock interval in the Paris basin by Creaney and Passey (1993).

Discussion

Qualitative comparison of ΔlogR TOC values with laboratory measured TOC values from cuttings or core indicate good agreement for some source rock formations or parts of a formation in some wells, and lack of agreement for other source rock formations or parts of a formation. The Hue Shale above the gamma-ray zone (GRZ), the Kingak Shale, and the Mikkelsen Tongue show the best agreement between TOC values from cuttings compared to TOCs determined by the ΔlogR method (e.g., the West Staines 2 well for the Hue Shale above the GRZ and the Mikkelsen Tongue -- excluding the part from ≈ 6,150-6,650 ft, and the Canning River A-1 and B-1 and Kavik 1 wells for most of the Kingak Shale succession) (Plates SR13 and SR14). The pebble shale unit and the GRZ show the least agreement between the TOC values from cuttings compared to TOCs determined by the

ΔlogR method (e.g., the West Staines 2 and Canning River A-1 and B-1 wells) (Plate SR13).

Our data illustrate at least 4 factors contributing to the discrepancy between TOC determined by the ΔlogR method and TOC measured on cuttings: (1) borehole sloughing; (2) unknown collection , sampling, and analytical methods/strategy for cuttings analyses; (3) anomalous sonic or resistivity log response; and (4) choice of baseline and/or maturity parameters. TOC analyses on borehole cuttings are potentially the best means to check the TOCs determined by ΔlogR calculations because they both represent an interval average -- even though the interval of the cuttings is usually greater than the approximate one meter resolution of the ΔlogR values. Thus, in heterogeneous sections the cuttings are better for comparison or validation than TOC data from a point source, such as core.

In our data set, however, the caliper log and mudlog indicate sloughing and possible contamination of borehole cuttings for parts of many wells. Therefore, because we know little about the cuttings data other than the sampling interval, where the results from the two methods do not agree, the accuracy of the cuttings data is considered questionable when we can document sloughing, and the ΔlogR TOCs the more representative of average interval TOC values except in cases where we can document anomalous sonic or resistivity log response, or where we can see that the baseline is probably off.

For those zones where erroneously calculated TOCs are produced by very low resistivity response in tuff and bentonite, note that the cutting's TOCs in some wells do not commonly indicate low values over these zones, e.g. the Canning River wells, whereas in other wells such as the West Staines 2, the cuttings values seem to be lower and more in agreement with the TOCs produced by the ΔlogR method. It seems reasonable to conclude that these tuffaceous or bentonitic parts of the lower Hue Shale would have lower interval average TOC than a mudstone part of the section, but not negative values. The very low resistivities of these zones have the effect of drawing down the ΔlogR TOC profile to erroneously low or negative values, thereby underestimating the average TOC for that zone, which should only go as low as zero for intervals of contiguous volcanics thicker than approximately one meter. If this is an accurate appraisal of how the ΔlogR method has depicted the average TOC of these intervals, then our richness and SPI estimates are low for these zones. If one can identify an interval of tuff (100%), then that interval, no matter what is calculated, should be disregarded. It should be treated the same way as a sandstone or any other non-source rock.

Another place that some of our ΔlogR calculations may be underestimating the average TOC is in wells where we are unable to set the baseline in a non-source shale, but instead have set it in a rock that probably has a higher TOC than the 0.8 wt % that we add back in during the final calculation of TOC from the ΔlogR separation. This would give us lower interval average TOC values for that part of the well where we were using that baseline.

RICHNESS AND SOURCE POTENTIAL INTERPRETATION

In this section our interpretation of net richness and source potential is discussed and summarized in Tables SR1-SR6 for the Kingak Shale, pebble shale unit, Hue Shale including the gamma-ray zone, the combined Hue Shale and pebble shale unit, and the Mikkelsen Tongue of the Canning Formation. Net richness, as described in the section on methods, is calculated with TOCs determined by ΔlogR calculations, and used in combination with thermal maturity data from vitrinite reflectance (Bird and others, Chap. VR) to calculate oil and/or gas source rock potential using the methods of Dembicki and Pirkle (1985) (Tables SR1-SR6). The Shublik's richness, which was evaluated using a different approach, is presented in a separate section and Table SR7.

Hue Shale Including the Gamma-Ray Zone

In the eight wells evaluated to the west of the Canning River and the 1002 area, the Hue Shale including the GRZ is a very rich source rock with predominantly marine organic matter (Magoon and others, Chap. PS). Interval average TOCs from ΔlogR calculations range from low values up to almost 10 wt % for both the GRZ and the upper part of the Hue Shale exclusive of the GRZ (Tables SR1, SR2, and SR4). While the lower several hundred feet of the Hue Shale, including all the GRZ, are the richest strata, the upper part is thicker and fairly organic-lean and has the lowest gamma-ray response. TOC values from both cuttings and the ΔlogR method range from approximately 1-2 wt %, but most are close to 1 wt % in the uppermost part of the Hue Shale where it is preserved. In the middle part of the Hue Shale, such as from 12,400-12,750 in the West Staines 2 well (Plates SR3, SR13), the TOCs from both methods are mostly between 2-3 wt %.

The Hue Shale exclusive of the GRZ has very high net richness values from 439-1,258 in seven of eight wells evaluated; only in the Point Thomson 2 well is it less than 300, which is used by Dembicki and Pirkle (1985) as the lower limit of their high richness category. The GRZ of the Hue also has high net richness values that range from 311-670 in six of eight wells, only in the Point Thomson 2 and Leffingwell 1 wells are the net richness values less than 300. However, the TOC values in both these wells, and therefore also the net richness, would be higher were it not for the anomalous ΔlogR results discussed previously and on Plates SR2 and SR4. Richness and net richness would also be higher in these wells if we adjusted the baseline values, which seems reasonable due to the many negative TOC values produced using the present baselines.

The Hue Shale is buried deeply enough to be currently generating hydrocarbons, though just barely in the West Staines 2, Point Thomson 2, and Leffingwell 1 wells where it also has SPI for oil greater than 300 except in the Point Thomson 2 well. The Beli 1 well and the other four wells evaluated near the southwest corner of the 1002 area achieved their maximum burial heating during Eocene time. Since then, they have been uplifted and cooled to varying degrees. These wells have high SPI values from 524-1,611 for the complete Hue Shale. Where the complete Hue Shale including the GRZ is evaluated (Table SR4), all wells have high net richness and high SPI for oil.

Pebble Shale Unit

The Lower Cretaceous pebble shale unit is defined here as the mudstone/shale succession stratigraphically below the high gamma-ray interval (GRZ) at the base of the Hue Shale and above the Thomson sand, Kemik Sandstone, or Lower Cretaceous unconformity. Among the wells we evaluated, the pebble shale unit is highly variable. It is < 20 to > 200 ft thick, and in most wells too thin to have high net richness or SPI, except for two wells in the southwest corner where it is thicker and more mature (SPI values there are 312 and 338), and in the West Staines 2 well which has the highest average TOC for the pebble shale unit (Table SR3). Our TOCs from both methods are extremely variable for the pebble shale unit, in some cases as low as approximately 1-2 wt % and in others as high as 3-4 wt % for interval averages. This variation is exemplified by net richness values that range from 11-338.

It seems reasonable that the pebble shale unit might have highly variable TOC concentration as the basal part of a transgressive marine mudstone succession that may be quite variable due to differences in depositional and diagenetic settings encountered as the basin subsided. Since it is contiguous with the Hue Shale in some places such as the Canning River, and basal Hue is distinguished mainly by the beginning of volcanic ash deposition in the

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basin, it also seems reasonable to consider it in combination with the Hue Shale as shown in Table SR4. Data in Magoon and others (1987) indicate that the pebble shale unit from outcrops near the northeast part of the 1002 area is gas prone.

Kingak Shale

In the four wells southwest of the 1002 area where we evaluated the Jurassic and Lower Cretaceous Kingak Shale, results from both methods show that TOC is generally low, 1-2 wt %, throughout most of the Kingak interval in all except parts of the section in the Canning River B-1 and Beli 1 wells where higher values up to approximately 3.5 wt % are present, particularly in the upper and middle parts of the Kingak Shale (Plates SR5-SR8 and SR13). Additionally, ΔlogR TOCs indicate that the upper and middle parts of the Kingak are richer (up to 7.5 wt % TOC) in the Canning River B-1 well. Nevertheless, the Kingak Shale is thick enough in all the wells so that resulting net richnesses using a 1 wt % cut-off are all above 300 and the SPI for oil and also gas are close to or greater than 300 except in the Beli 1 well (Table SR5). Using a 2 wt % cut-off, only the two Canning River wells have richness and SPI for oil greater than 300. Previous work on outcrop samples indicates that the Kingak Shale is gas prone in the northeast part of the 1002 area (Magoon and others, 1987).

Mikkelsen Tongue of the Canning Formation

In the 4 wells where ΔlogR TOC profiles are calculated, as well as the nearby wells discussed in this chapter, the data show that the Mikkelsen Tongue of the Canning Formation has high net organic richness if we assume that a very thick succession with fairly low TOCs between 1 and 2 wt % , is a viable petroleum source rock (Table SR6). Even without that assumption, the ΔlogR TOC profiles (Plate SR14) indicate the presence of one or more intervals of higher TOCs between approximately 2 and 4 wt % in the Mikkelsen Tongue, and this is corroborated by cuttings TOCs and gamma-ray log response in several wells. In the West Staines 2 and the Point Thomson 2 and 3 wells, Craig and others (1985) also describe a part of the Canning Formation equivalent to the Mikkelsen Tongue which has one or more rich intervals with source potential for generating oil or condensate.

In the near vicinity of the 1002 area, however, the Mikkelsen Tongue of the Canning Formation is immature with vitrinite reflectance values of approximately 0.5 % R_o. Therefore, the transgressive sediments of this part of the Canning Formation haven't been buried deeply enough to enter the generative window for conventional hydrocarbons, and their richness is more relevant to modeling the depositional system farther offshore and north of the 1002 area where it is projected to be buried deeply enough to be in the depth and temperature range for generating hydrocarbons (Craig and others, 1985). From the model proposed by Creaney and Passey (1993) to explain patterns of TOC distribution in many basins worldwide, it seems reasonable to propose that the lateral, age-equivalent lithofacies of the Mikkelsen Tongue to the north and offshore the 1002 area would be a richer, or at least equally viable source of hydrocarbons. Deposited farther offshore during the Eocene, these sediments are more likely to be finer-grained or more clayey, and more enriched in marine organic matter from deposition in a deeper marine slope or basinal setting where the organic matter would be less likely to be diluted by influx of terrigenous clastic material and could potentially accumulate a more continuous and overall richer succession of mudstone in some places, perhaps similar to parts of the Hue Shale.

Richness of the Shublik Formation

The Middle and Late Triassic Shublik Formation consists primarily of fossiliferous limestone and calcareous shale. Because of this composition and the abundance of well cemented zones that have sonic log transit times approximately less than 70 µsec/ft, for which the ΔlogR method is not calibrated (Passey and others, 1990), we did not apply this method to determining the organic richness of the Shublik in the subsurface near the 1002 area. Instead we examined and evaluated total organic carbon (TOC) data from several different studies done since USGS Bulletin 1778 (1987), as well as data included in that volume (Magoon and others, 1987) and from Detterman (1970). These results are summarized in Table SR7. We also analyzed the relationship between organic richness and total gamma-ray intensity in two Shublik subsurface sections on the North Slope in order to see if this relation could be used to evaluate the distribution of organic carbon in subsurface Shublik sections near the 1002 area.

Two important recent studies include detailed analysis of the vertical variation of total organic carbon in the Shublik Formation using core samples from wells to the west of the 1002 area (Table SR7). Kupecz (1995) analyzed 63 samples through approximately 120 ft of Shublik from the Sohio Term Well B in the Prudhoe Bay area (Fig. SR1). The average TOC for these samples, which were collected approximately every 2 ft, is 1.8 wt % (range, less than 1 wt % to approximately 6.4 wt %; median 1.4 wt %). Robison and others (1996) report 70 TOC analyses on core samples

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through 284 ft of Shublik from the Tenneco Phoenix 1 well, which is farther to the northwest and offshore (Fig. SR1). Their samples are randomly spaced from 0.1-10 ft; the initial 10 ft sampling interval was modified to be more closely spaced in certain parts of the core. TOC for all their samples averages 3.9 wt % (range 0.4-10.2 wt %; median 3.1 wt %).

The data published for these two wells probably give us the best information on the variation in total organic carbon within the Shublik Formation west of the 1002 area, although Detterman's (1970) study of 88 outcrop samples (collected every 1 ft and composited every 5 ft) at Fire Creek just south of the 1002 area (Fig. SR1) is important (more discussion below). All these data indicate that TOC distribution in the Shublik is heterogeneous and has very broad vertical variation. Variation from Kupecz's data (1995) is on at least as small a scale as 2 ft, from Robison and other's data (1996) approximately 0.1 ft, and in some parts of the Shublik it is more likely on a millimeter scale where that is the smallest scale of lamination or bedding present.

We have not determined, however, if the organic facies patterns exhibited in the areas of the Phoenix 1 and Term Well B wells are the same as in the Shublik of the 1002 area. Those facies first need to be described, including the variation in their organic richness, before we can understand how they compare to the Shublik facies from other locations. With the exception of Detterman's (1970) generalized lithostratigraphy and very systematically collected samples from Fire Creek, what we have that suggests a measure of the heterogeneity of the Shublik near the 1002 area are some data from well cuttings and some data from outcrops for which the sampling strategy is unknown. We also know that the Shublik has variable thickness near the 1002 area (Plate PS2), from a low of approximately 130 ft in wells to the southwest to a high of 500 ft or more to the south and southeast.

Of the ten wells that penetrate the Shublik to the west of the 1002 area, seven have one or more TOC measurements on cuttings samples, including the Beli 1, the Canning River A-1 and B-1, the Kemik 1 and 2, the Fin Creek 1, the Kavik 1, and the West Kavik 1 (Fig. SR 3). These well data are displayed in Nelson and others (Chap. WL) and summarized in Table SR7. The TOC values from these well cuttings are most likely either representative of average interval values or of individual rock chips. Therefore, it is unknown how representative these values are for the whole Shublik. We know little about the cuttings data other than the sampling interval, but much can be deduced about the possibility of contamination of the cuttings in these wells from the caliper log and placement of casing while the well was being drilled (see data in Nelson and others, Chap. WL).

With the exception of the Beli 1 and Kemik 2 wells, the caliper logs indicate sloughing from rock units overlying the Shublik with no casing in position to prevent contamination of the cuttings. Among the wells we report (Nelson and others, Chap. WL), the Beli 1 and Kemik 2 wells are the only ones where casing was installed just above, or within the upper part of the Shublik -- thereby preventing contamination from the sloughing of overlying Kingak and other relatively organic lean units into the Shublik cuttings (see discussion of the Kingak Shale in previous section). Possibly because of this protection, these two wells also have the highest TOC values of the seven wells. In the Beli 1 well (Plate WL12), seven TOC analyses average 1.74 wt %; the range is 0.49 wt % to 5.44 wt %. The Beli data suggest approximately the same range in TOC variation as the Term Well B; however, these samples fail to adequately represent the Shublik section. Six samples were analyzed at approximately 10 ft intervals in the upper 50 ft of the Shublik and the seventh sample is from close to the middle of the lower 104 ft. In the Kemik 2 well (Plate WL27), the four samples are more evenly spaced; the average TOC is 1.68 wt %, ranging from 0.65-3.99 wt %.

Outcrop TOC data included in Table SR7 are from one very systematically collected set of 88 samples from Fire Creek (Detterman, 1970) and other sample sets without published stratigraphic information. The latter samples include unpublished data for Fire Creek, Last Creek, and Kavik River from Parrish (written communication, 3/97) and also from Fire Creek, Last Creek, and Ignek Valley summarized in Magoon and others (1987), and available in digital form by Magoon and others (Chap. PS, data file “PS1778.xls”). Except for the study of Detterman (1970), whose TOC values may be questionable because of the analytical methods used at that time, the outcrop data generally consist of results from both fewer and more randomly distributed samples, nevertheless, probably representing the approximate range in TOCs present, but not telling us the proportion of the Shublik that these values represent.

For the Fire Creek Shublik section, Detterman's (1970) data indicate a TOC range from 0.08-2.59 wt %, with an average of 1.2 wt %; however, this represents the total 475 ft of the Shublik. His results for the upper 230 ft of the Shublik at Fire Creek are higher, averaging 1.6 wt % TOC, which is somewhat closer to the 2.0 and 2.2 averages of the other Fire Creek data sets. Probably because of compositing his samples, but maybe for other reasons as well, Detterman's (1970) highest TOC values are lower than in both other sample groups from Fire Creek (Table SR7). At Last Creek, Magoon and others (1987) report 8 TOC analyses for which the average and maximum values are inexplicably only approximately half the amount of Parrish's values for a total of 7 samples (Table SR7). Possibly the set with lower values was also composite samples such as Detterman's (1970) because the average and maximum values are almost identical to his. Parrish (Table SR7) also analyzed 13 samples from Kavik River which indicate a range from 0.74-5.46 wt % TOC, and an average TOC of 2.6 wt %, and Magoon and others (1987) report 11 samples from Ignek Valley that average 2.7 wt % TOC with a range of 0.31-7.01 wt % TOC. Outcrop data from several other areas are also included in Magoon and others (1987) and in this volume (Magoon and others, Chap PS, data are available in digital form as data file "PS1778.xls"); TOCs for these few samples fit the range for other outcrop data reported in Table SR7. Overall, the outcrop data are consistent with the well data except for the highest TOC values in the Phoenix 1 well -- to 10.2 wt % -- which is the farthest from the 1002 area. These values are higher than any outcrop samples or any other well samples that we know of (Table SR7), perhaps due to the presence of a richer facies in the vicinity of the Phoenix-1 well.

To summarize, from the studies described above, Shublik TOC variation is roughly comparable for both the surface and subsurface. Most of the TOC values in Table SR7 range from less than 1 wt % to 6 or 7 wt % TOC, except for a dozen samples in the Phoenix-1 well that range higher, to 10.2 wt % TOC. The highest values from outcrop are somewhat less than the highest subsurface values, and may be weathered. The highest TOC values from cuttings are also somewhat lower than the highest core values and may represent a mixing value of chips with higher values plus chips with lower values, as would Detterman's (1970) results (Table SR7).

In order to determine the distribution and proportion of organic facies in the Shublik, we evaluated the relationship between organic richness and total gamma-ray intensity proposed for Devonian shales in the Appalachians by Schmoker (1981) to determine the distribution of organic carbon in subsurface Shublik sections near the 1002 area of the ANWR. However, similar to the findings of Schmoker (1981) that the total gamma-ray method significantly underestimates organic matter in some intervals and that quantitative interpretation of the gamma-ray log in terms of organic matter is impossible accross large regions of the Appalachian basin, we also found the correlation between TOC and gamma-ray intensity to be inconsistent for the Shublik in the Term Well B and the Phoenix 1 Well. In the Phoenix 1 well, the gamma-ray intensity (total U counts from spectral gamma-ray log) correlates fairly well with TOC in much of the Shublik (Robison, 1996, p. 265). However, several zones exist where the gamma-ray intensity either under- or overestimates TOC in the well. Similarly, in the Term Well B, TOC analyses of the Shublik Formation (Kupecz, 1995) fail to show consistent correlation with gamma-ray log response. A major consideration in applying this relation to the Shublik Formation is that phosphatic zones in the Shublik exhibit high gamma-ray intensity interpreted as the result of U incorporation by phosphate (Kupecz, 1995), however, they may also have low TOC as shown by Robison and others (1996).

In conclusion, it is apparent from Table SR7 and the prior discussion that the Shublik Formation near the 1002 area, as well as to the west and northwest has broad vertical variation in organic richness. Clearly the Shublik also has rich, very good petroleum source rock intervals within it whose proportion of the total section is presently unknown. In comparison to existing wireline log techniques for evaluating richness and its distribution, such as gamma-ray intensity and the ΔlogR method, it seems that the best method for the Shublik is systematic sampling of cuttings, outcrop, or core on as fine a scale as possible because of the Shublik's variable composition and physical properties, and the great vertical variation in TOC. Lacking systematically collected core samples, we evaluated existing TOC data, both from Magoon and others (1987) and from other sources given in Table SR7. Based on that evaluation, we suggest that a reasonable estimate of the average organic richness of the Shublik Formation of the 1002 area is somewhere in the range between 1.5 and 4 wt %, and probably closer to 1.5 wt %. A more accurate estimate can be made by analyzing many more samples from wells or outcrop near the 1002 area of the ANWR.

THE AURORA 1 WELL

Located offshore and near the northeast corner of the 1002 area, the Aurora 1 well is important because it is the only subsurface information for the eastern part of the 1002 area (Fig. SR3). The log response, lithology, stratigraphy, and organic geochemistry of this well, which was completed in 1988, have been described and interpreted by Banet (1992; 1993), Flett and Paul (1994) and Paul (1994). However, Banet's work was done without biostratigrapic interpretation. Therefore, some of his interpretations of the stratigraphy and conclusions are different from ours, which were made using biostratigraphy in conjunction with other well data. Our interpretation of the lithostratigraphy, formation designations, and biostratigraphy for the Aurora 1 well is more similar to Paul's (1994) and Turner's (1994) interpretations, and is shown in the three lefthand columns of Plate WL8 with the lithostratigraphic interpretation of Banet (1992) summarized in column 4 of Plate WL8.

Two intervals in the Aurora 1 well are the primary focus of the following discussion of results from our evaluation of organic richness using data from the Geochemical Report of the Tenneco Oil Company (1988, publically available as of 1991) and the ΔlogR method. Note, however, that the two intervals (4,600-7,600 ft and 15,500-16,446 ft) we evaluated using the ΔlogR method straddle the oil window in the well (Fig. VR12), thus pushing this method to the limits of rigorous calibration (Passey and others, 1990). Nevertheless, the method still yields a qualitative result indicating intervals with ΔlogR separation that may be potential source rocks, as well as a profile of relative TOC for the interval evaluated.

In the lower part of the well we evaluated the interval from approximately 15,500-16,446 ft, comprising a fine-grained siliciclastic succession of Early Cretaceous age with notably high TOC values measured on sidewall cores in the Lower Cretaceous section from approximately 15,500-15,937 ft (Plate WL8). In the upper part of the well, we analyzed the section from 4,600-7,600 ft, which is lithologically comparable and age equivalent to all, or only part, of the Eocene Mikkelsen Tongue of the Canning Formation, depending on your interpretation of biostratigraphy in this well (see Plate WL8). We also evaluated existing data and interpretations regarding the richness of the Jurassic fine-grained, siliciclastic section in the well from 16,620 to total depth, and we generally agree with the conclusions in the Geochemical Report of the Tenneco Oil Company (1988). That report stated that the unit was inadequately evaluated in the Aurora 1 well because of its high thermal maturity and additives to the drilling muds.

Hue Shale and Pebble Shale Unit

In the lower part of the Aurora 1 well we evaluated the section from approximately 15,500-16,446 ft using the ΔlogR method. Approximately 440 ft of that succession from 15,500-15,940 ft, is of greater interest because of much higher TOCs measured on sidewall cores as compared to the well cuttings (Geochemical Report of the Tenneco Oil Company, 1988) (Plate WL8). The high TOCs from sidewall cores are noted by Banet (1992; 1993) who placed this interval at the base of the Tertiary and his unit 4, interpreting it as the basal part of the Brookian section. Flett and Paul (1994) also note the high SWC TOCs and place the interval from 15,480-15,930 ft in the basal Brookian, but assigning it an age of Early Cretaceous.

At first, we considered this unit to be either a locally richer facies of the lower part of the Canning Formation or the upper part of the pebble shale unit. However, further analysis of the biostratigraphic and lithologic descriptions and interpretations by M.B. Mickey (1988; reprinted herein as Plate SR15) for sidewall cores compared to cuttings indicated that this unit is lithologically more similar to, as well as age equivalent to, at least part of the Hue Shale.

Sloughing was apparently a problem in certain intervals in the well (Choromanski, 1994; Paul, 1994; Turner; 1994) resulting in contamination of cuttings and therefore erroneous lithologic, age, and geochemical interpretations if based solely on cuttings. Plate SR15, a segment of the foraminiferal plot sheet from Micropaleo Consultants, Inc., highlights the sidewall core (SWC) data in gray so that differences between the sidewall and cuttings samples are more obvious. Different foraminiferal faunas are present in the SWC as compared to the cuttings. We interpret this to indicate that the cuttings samples are contaminated or mixed with rock chips sloughing from overlying units, and conclude that any geochemical or other analyses on these cuttings are erroneous for that interval.

On Plate SR15, "paper shale" is noted in 7 SWC samples (15,514, 15,550, 15,569, 15,594, 15,747, 15,780, and 15,856) but not in any of the cuttings samples for this interval; only a few SWC in this interval lack paper shale. The paper shale lithology is typical of the Hue Shale, but not typical of the Canning Formation. A puzzling consideration is that bentonite, which is a common lithology in the Hue Shale, is noted in many of the cuttings and SWC samples from 15,950-16,270 ft in the Aurora 1 well, i.e. in the pebble shale unit below the Hue Shale (Mickey, 1988, and Plate SR15). Also, at 15,740 ft the Geochemical Report of the Tenneco Oil Company (1988) notes an abrupt organic facies change to a more promising interval down to 16,950 ft, characterized by very high concentrations of TOC and amorphous kerogen.

TOC analyses for the interval 15,500-15,940 range from 2.5-6.0 wt % on sidewall cores (n=5) and 1.3-3.0 wt % TOC on cuttings (Fig. SR5). Note that sidewall core TOCs are much lower in both the overlying and underlying units (Plate WL8). Preliminary TOCs determined by the ΔlogR method using "adjusted" thermal maturity values average about 1.5 wt % for the total interval from 15,500-15,940. However, since the method is not rigorously calibrated in this thermal maturity range, and because of how maturity is factored into the calculations, we believe that 1.5 wt % is a minimum value for the average TOC of this unit. A more important result is

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that the ΔlogR TOC profile for this unit fails to correlate well with the TOC profile plotted from cuttings values (Fig. SR5). This is another line of evidence suggesting that the cuttings are contaminated by material sloughed from above, i.e. that the lower TOC values from cuttings in the upper part of this interval are due to contamination by organically leaner material caving in from the borehole above (Plate WL8).

In summary, we correlate the fine-grained, Lower Cretaceous siliciclastic succession from approximately 15,500-15,940 ft in the Aurora 1 well to at least part of the Hue Shale based on lithology and age. This unit was unrecognized as equivalent to the Hue Shale in previous reports. Banet (1992; 1993) placed it in the lower Tertiary succession; and Paul (1994) designates it an unnamed Lower Cretaceous shale. We think that Banet's (1993, p. 16) overview for this part of the sequence,"these higher-potential samples are generally few and widely separated"; and Flett and Paul's (1994) conclusion that "contamination by drilling fluids probably caused the few high TOC values between 15,656 and 15,940 ft", are not the only, or most likely, explanations of these data. We think that the five high TOC values from sidewall cores ranging from 2.5-6.0 wt % (four are greater than 4 wt % TOC) in the approximately 440 ft succession from 15,500-15,940 ft suggest the likelihood that this Lower Cretaceous succession is organic rich.

The interval from 15,940-16,446 ft is placed in the pebble shale unit based on age, overall lithology, and stratigraphic position. However, bentonite or bentonitic material, which is commonly noted from 15,950-16,270 ft (Plate SR15), is unknown to be common in the pebble shale unit. Paul (1994) also tentatively correlates this interval to the pebble shale unit, but says that the lithology doesn't accurately fit the pebble shale unit, noting that none of the key markers are present. This interval has casing above it beginning at 15,941; however, the timing of installation of this casing is an important point because the liner/casing was installed after the well had been drilled to 16,950 ft. Therefore, the hole was open and sloughing, as indicated by the well report (Choromanski, 1994) and the caliper log, during the drilling to 16,950 ft (Plate WL8). This is probably the reason for the lack of close agreement in the TOC analyses for this interval, as for the overlying interval. SWC analyses (n=6) range from 0.9-1.2 wt % TOC, but cuttings values are higher, ranging from 1.9-3.0 wt % TOC. Preliminary calculated TOCs based on the ΔlogR method and "adjusted" maturity values average about 1.0 wt % over the whole interval, however, since this method is not rigorously calibrated for this high level of thermal maturity, the SWC are considered a more reliable indicator of TOC, and we suggest that the cuttings are indicating higher values than seen in any of the SWC because of sloughing from overlying organic rich strata. As discussed previously, the overall low organic richness that we interpret for this unit is uncommon for the pebble shale unit.

Mikkelsen Tongue of the Canning Formation

The mostly shale and claystone section from 4,600-7,600 ft in the Aurora 1 well is lithologically comparable to the Mikkelsen Tongue of the Canning Formation and is temporally equivalent to early and middle Eocene age as interpreted by Poag (Chap. BI, see also Plate WL8). Note that a different age interpretation by M. B. Mickey (1997, written communication, and Plate WL8) based on analysis of additional samples compared to his original study in 1988, extends the lower Eocene in this well from 10,490 to 13,720 ft and the middle Eocene from 4,640-10,490 ft.

With respect to whether the interval we evaluated is relatively more terrigenous or more marine in character, as might be expected for the Mikkelsen Tongue, the evidence is somewhat equivocal, but mainly suggests that it is not notably more marine. In the interval we evaluated from 4,600-7,600 ft, the SWC samples at 4,962 and 5,464 ft (but not 4,097 or 6,161 ft) show gas chromatograms of C_{15+} saturated hydrocarbons indicating a slightly more marine character as suggested by less than C_{25} saturates in relatively greater abundance. However, the Geochemical Report of the Tenneco Oil Company (1988) gives the two samples at 4,860 and 5,464 ft as examples of significant extract values (in excess of 100 ppm) that often reflect migrated hydrocarbons because their gas chromatograms are "oil like" in character and therefore contrast with the neighboring immature bitumens. They further state that "the chromatograms from 1,440-6,480 ft represent waxy, immature terrestrial bitumens with minor contributions, in some instances, of algal or bacterial source material" and that "the waxy nature of these extracts persists in the deeper samples,...".

The TOC data suggest that much of about the upper 1,700 ft of this interval is closer to 1.4 wt % TOC than to 1 wt % TOC. The range is 1.2-1.8 wt % TOC for cuttings, and approximately 1.0-1.6 wt % TOC for SWC samples (Plate WL8). TOC values determined by the ΔlogR method give basically the same results, however, the section is immature and, therefore, out of the maturity range of rigorous calibration of the method. Also, because the sonic and resistivity logs track very well through most of this interval with only minor separation, the TOCs calculated by the ΔlogR method can vary depending on the choices made for baseline sonic and resistivity values and the value for the baseline shale that is added back into the calculation. TOC values drop to about 1 wt % by about 7,100 ft and between 7,100-8,500 ft are close to 1 wt % or slightly more (Range: 1.0-1.2 wt % TOC cuttings, 0.8-1.2 wt % TOC SWC). The Mikkelsen Tongue is immature in the Aurora-1 well with respect to petroleum generation, however, as we concluded for the Mikkelsen Tongue in the other wells where we evaluated it, this unit has high net organic richness and potential as a petroleum source (where thermally mature) if we assume that a very thick succession with fairly low TOCs between 1 and 2 wt % can be a viable source rock.

CONCLUSIONS

Validation of the ΔlogR method and discussion of problematic or anomalous results have been reported by Passey and others (1990) and Creaney and Passey (1993; 1997) in many hundreds of boreholes worldwide. In our interpretation we point out the parts of our analysis where measured TOC data lack agreement with TOC determined by the ΔlogR method, and where we believe either of the results is anomalous. In our experience the method worked better and was easier to apply in rocks with maturity less than approximately LOM 10 (≈ 0.85 % R_o) because baseline values were difficult to establish as maturity increased in parts of the section which seem to lack non-source shales.

Considering the challenges of our borehole data set, we think the method worked very well overall. The correlation of calculated and measured TOC profiles with gamma-ray response for the wells we analyzed adjacent to the 1002 area of the ANWR illustrates the reliability of the ΔlogR method for determining net organic carbon richness and variability in source rock intervals, even where measured TOCs are unavailable. Also, the method can be applied if the only data available are wireline logs, and it is less expensive than extensive measurements on cuttings or core.

For the eight wells we analyzed to the west and southwest of the 1002 area of the ANWR, our profiles of total organic carbon determined using the ΔlogR method indicate that the Hue Shale including the GRZ is a very organic-rich petroleum source rock, particularly in the basal several hundred feet, with very high calculated richness that ranges from 560 to 1,611. The present-day potential for oil generation from the Hue Shale, which has maturities ranging from 0.6-1.0 R_o is also high.

In the Aurora 1 well at the northeast corner of the 1002 area, we have determined that approximately 440 ft of an age-equivalent section of the Hue Shale are present at the top of the Mesozoic section. With ΔlogR-calculated

TOCs that average 1.5 wt % (as a minimum value) and vitrinite reflectance values of approximately 1.3-1.5 % R_o, this "Hue Shale" section has a minimum richness of approximately 600 and corresponding SPIs of 180 for oil and 600 for gas. It also has TOCs measured on six sidewall core samples that range from 2.5-6.0 wt %, and "paper shale" noted in the biostratigraphy report--but only from sidewall core samples, which may indicate that the overall unit is richer than the ΔlogR average of 1.5 wt % TOC.

In most of the wells we evaluated, and using our gamma-ray log-based definition, the Lower Cretaceous pebble shale unit by itself is too thin to have high net richness or high calculated SPI except for 2 wells near the southwest corner of the 1002 area. Our TOCs from both methods are extremely variable for this unit, in some places as low as approximately 1-2 wt % and in others as high as 3-4 wt % for interval averages, and it has similarly variable richness and SPI. Since it is contiguous with the Hue Shale, it seems reasonable to count the pebble shale unit with the Hue as shown in Table SR4.

For the Kingak Shale, TOCs measured on cuttings indicate uniformly low values of approximately 1-2 wt % in the two southernmost wells and generally higher values up to approximately 3.5 wt % in the Beli 1 and Canning River B1 wells, particularly in the upper and middle parts of the Kingak Shale. Our ΔlogR-calculated TOCs also indicate that the upper and middle parts of the Kingak are richer, and in the Canning River B1 well up to 7.5 wt % TOC. These determinations (Table SR5) suggest that the Kingak Shale has high richness and source potential in half the wells using a 2 wt % cut-off for an effective source and in three of the four wells using a 1 wt % cut-off.

The Mikkelsen Tongue of the Canning Formation is a very thick unit with mostly low TOCs between 1 and 2 wt %, and cumulative high organic richness if we assume that it is a viable petroleum source rock (Table SR6). The ΔlogR TOC profiles (Plate SR14) also indicate the presence of one or more intervals of higher TOCs between approximately 2 and 4 wt %, and this is corroborated by cuttings TOCs or gamma-ray and sonic log response. In the wells where we studied the Mikkelsen Tongue to the west of the 1002 area, it is immature. However, it seems reasonable to propose that the lateral, age-equivalent lithofacies of the Mikkelsen Tongue to the north and offshore the 1002 area would be buried more deeply and may be a richer, or at least equally viable source of hydrocarbons.

The Shublik Formation near the 1002 area of the ANWR, as well as to the west and northwest has broad vertical variation in organic richness. Clearly the Shublik also has rich, very good petroleum source rock intervals within it whose proportion of the total section is presently unknown. Our evaluation is based on existing cuttings, core, and outcrop TOC data. These data suggest that a reasonable estimate of the average organic richness of the Shublik Formation of the 1002 area is somewhere in the range between 1.5 and 4 wt % TOC, and probably closer to 1.5 wt %. In comparison to existing wireline log techniques for evaluating richness and its distribution, such as gamma-ray intensity and the ΔlogR method, it seems that the best method for the Shublik is systematic sampling of cuttings, outcrop, or core on as fine a scale as possible. This method holds promise for future studies that can more accurately determine organic richness and its distribution in the Shublik Formation.

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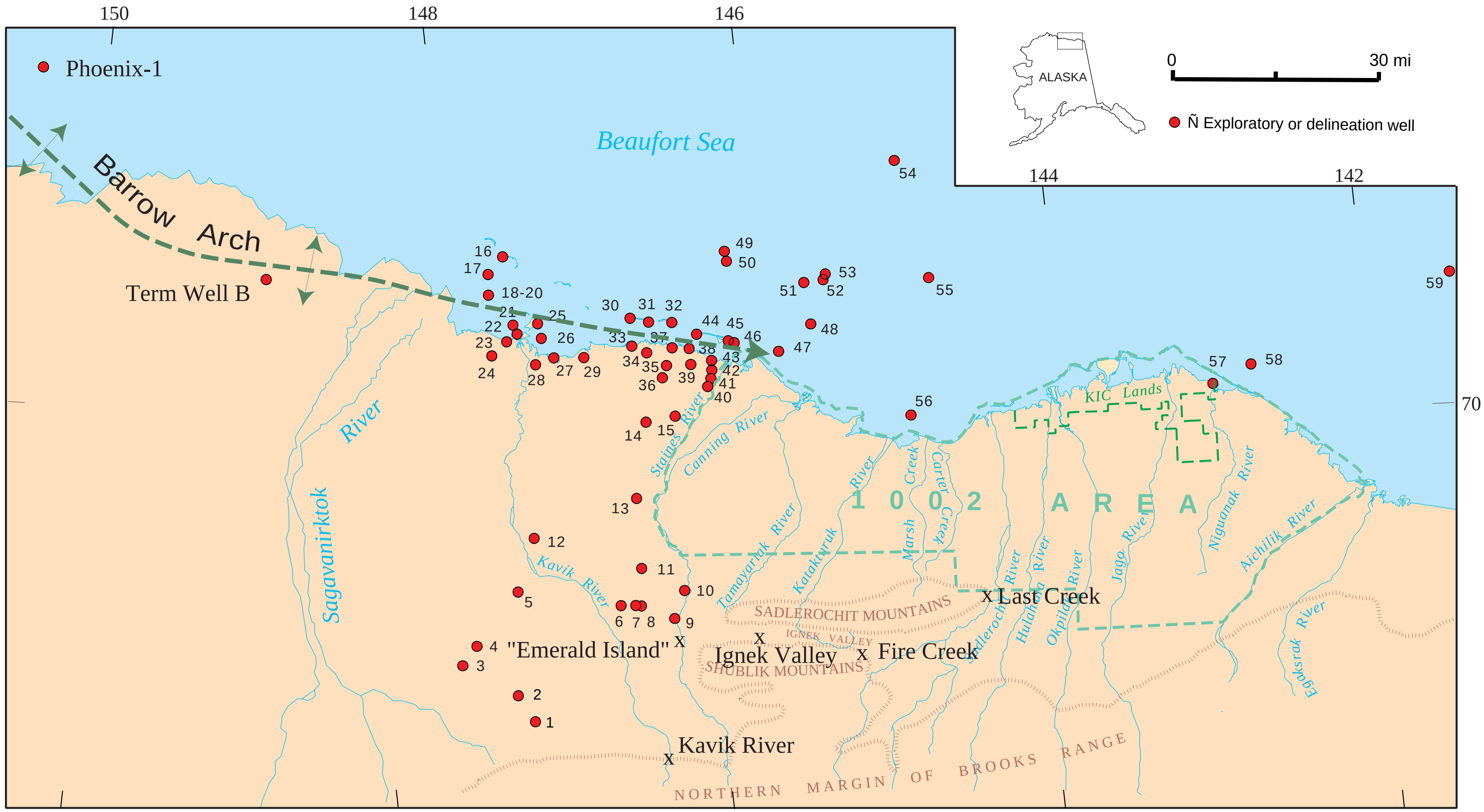

Figure SR1.-Map showing locations of key wells and stratigraphic sections near the 1002 area of the Arctic National Wildlife Refuge. See Figure SR3 for names of wells indicated by numbers.

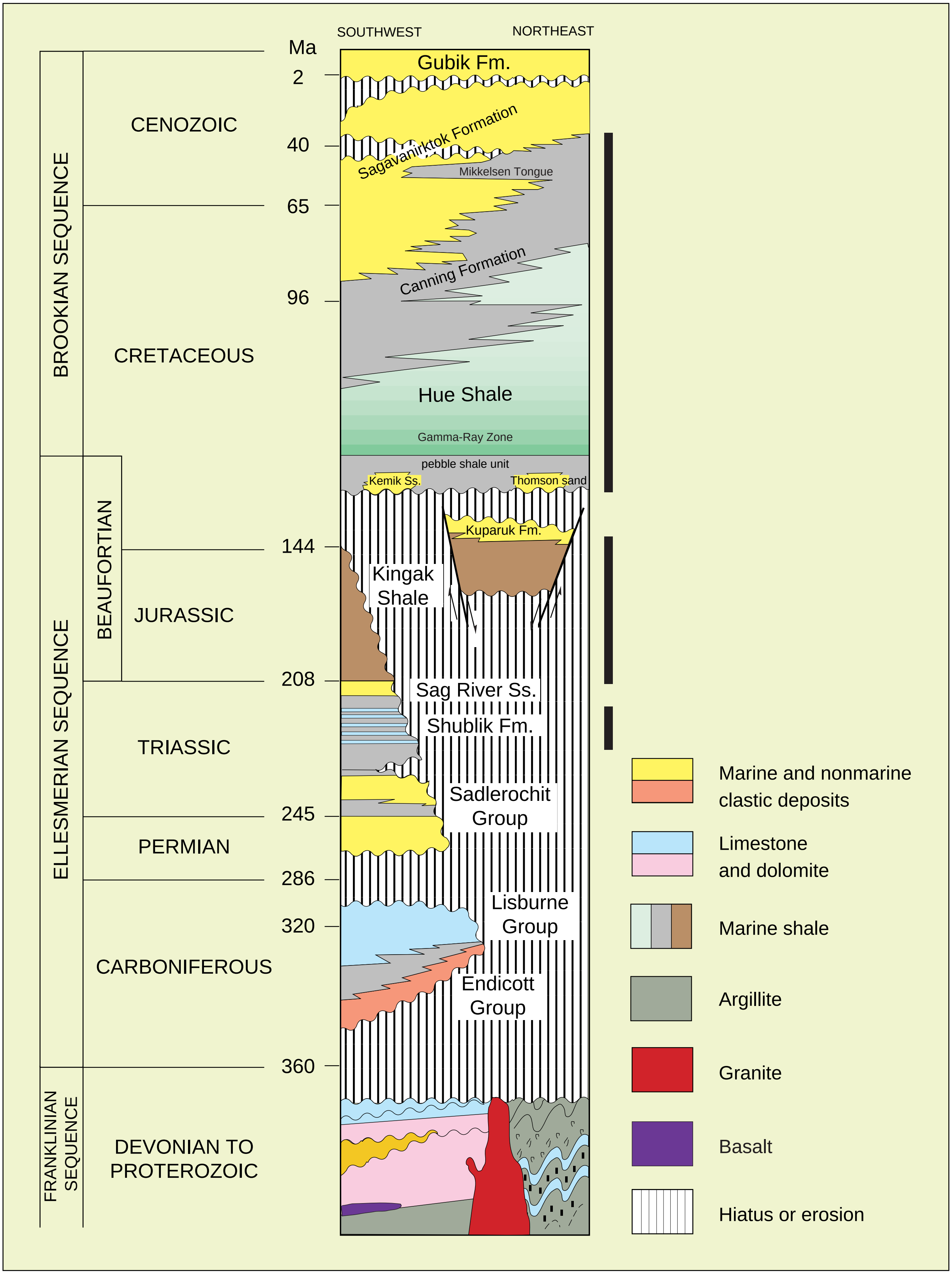

Figure SR2.–Stratigraphic column for the northern part of the Arctic National Wildlife Refuge. Principal organic-rich mudstone intervals are shown as solid black lines.

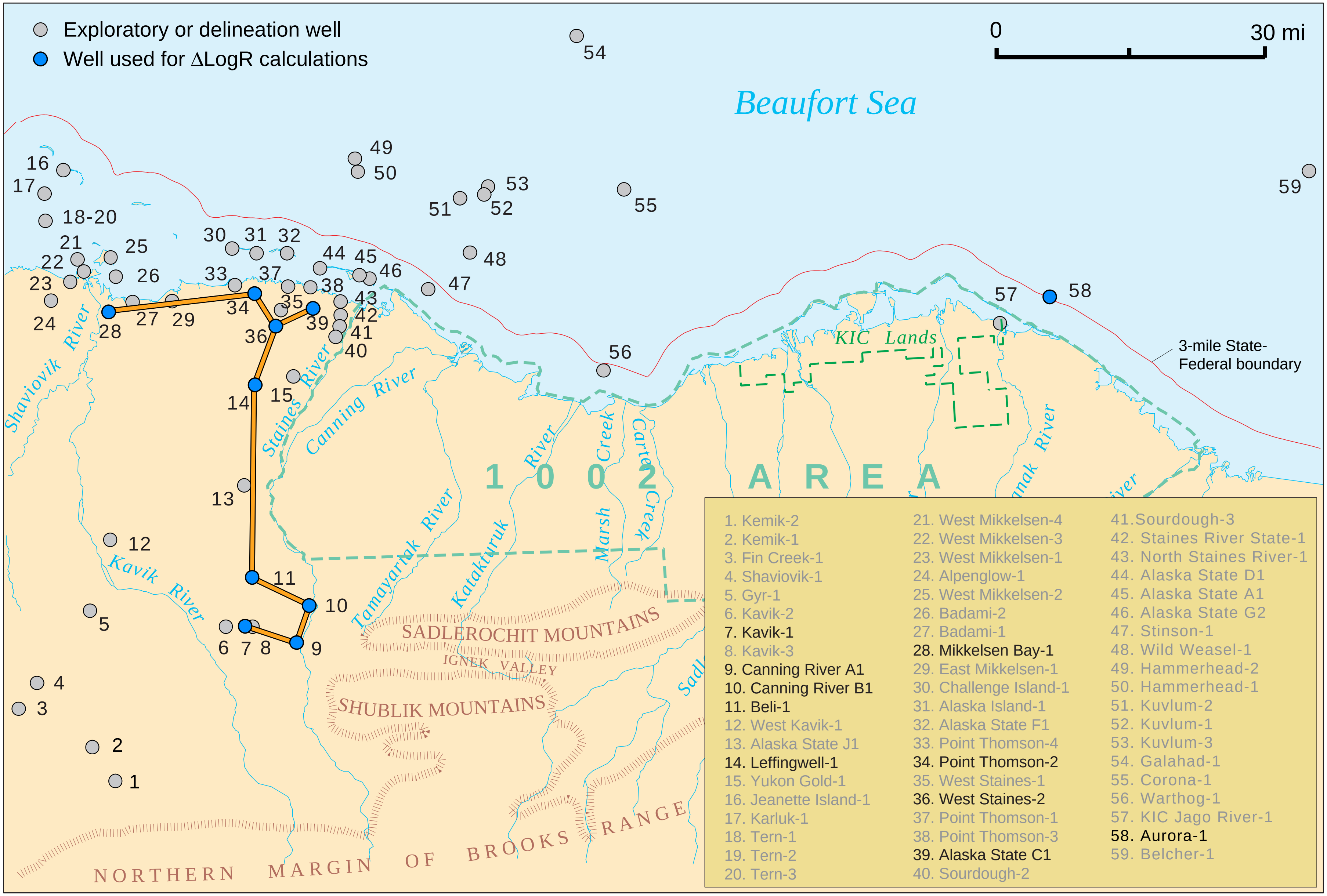

Figure SR3. Location map of wells near the 1002 area of the Arctic National Wildlife Refuge.

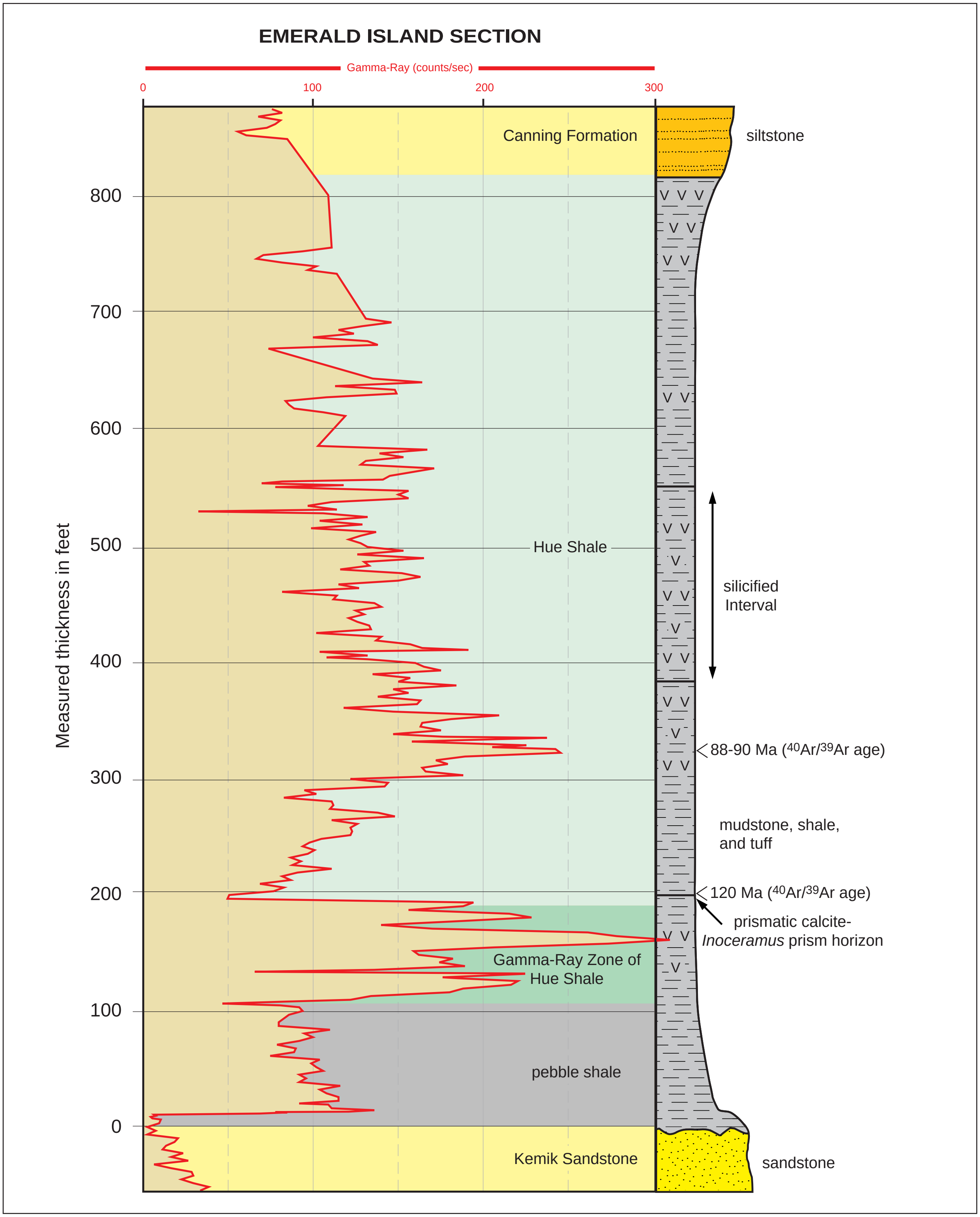

Figure SR4.–Stratigraphic column, gamma-ray profile, and radiometric age data for the "Emerald Island" section of Kemik Sandstone, pebble shale unit, and Hue Shale along the Canning River (from Bergman and others, 1995, and written communication, March, 1998).

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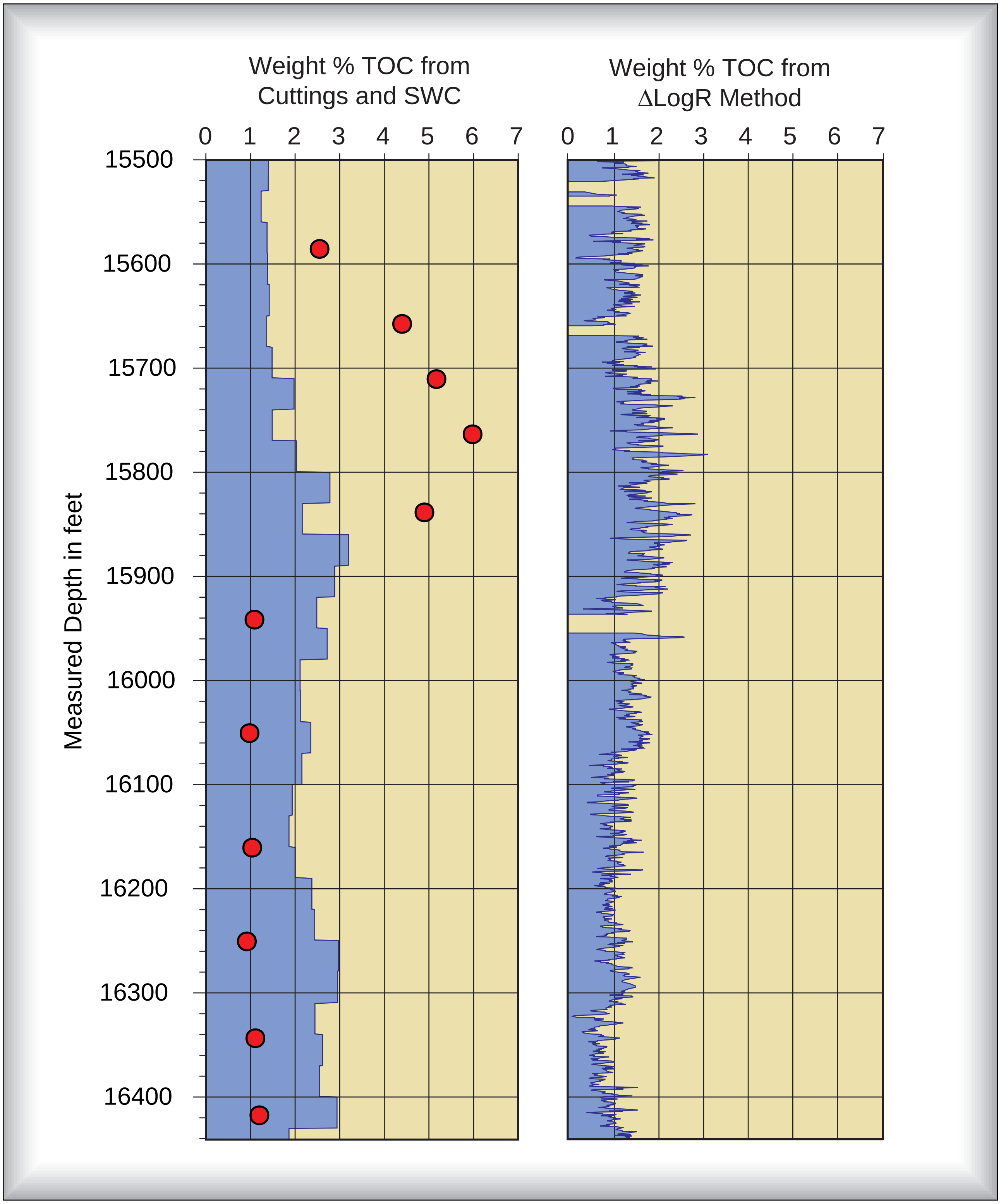

Figure SR5. TOC profiles from cuttings and ΔLogR calculations and TOC values from sidewall cores from Hue Shale and pebble shale unit equivalents in the Aurora-1 well.

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Table SR1. Richness and source potential for the Hue Shale exclusive of the gamma-ray zone.

Well Name	Mikkelson Bay 1	Point Thomson 2	West Staines 2	Leffingwell 1	Beli 1	Canning River B-1	Canning River A-1	Kavik 1
Gross thickness (feet)	372	382	928	927	545	355	440	735
Average TOC (wt %)	1.97	1.58	1.47	1.35	1.81	2.25	2.55	2.37
Net thickness (feet) (TOC>2 wt %)	169	74	161	163	171	186	344	418
Average TOC (wt %) (TOC>2 wt %)	3.41	3.63	3.72	2.83	2.57	2.91	2.81	3.01
Maximum TOC (wt%)	7.7	6.7	8.7	6.5	4.6	7.6	7	9.9
Net Richness	**576**	**269**	**599**	**461**	**439**	**541**	**967**	**1258**
Vitrinite Reflectance (% Ro)	0.9	0.6	0.6	0.6	0.6	0.95	0.9	1
Maturity factor if oil prone	1	0.7	0.7	0.7	0.7	1	1	1
Source Potential Index Oil	**576**	**188**	**419**	**323**	**308**	**541**	**967**	**1258**
Maturity factor if gas prone	0.4	0.2	0.2	0.2	0.2	0.4	0.4	0.4
Source Potential Index Gas	**230**	**14**	**20**	**92**	**88**	**216**	**387**	**503**

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Table SR2. Richness and source potential for the gamma-ray zone of the Hue Shale.

Well Name	Mikkelson Bay 1	Point Thomson 2	West Staines 2	Leffingwell 1	Beli 1	Canning River B-1	Canning River A-1	Kavik 1
Gross thickness (feet)	172	137	157	154	150	175	320	225
Average TOC (wt %)	3.93	2.59	3.66	1.85	2.3	2.15	2.39	2.24
Net thickness (feet) (TOC>2 wt %)	165	95	142	75	106	95	212	93
Average TOC (wt %) (TOC>2 wt %)	4.06	3.06	3.94	2.82	2.93	3.32	2.92	3.8
Maximum TOC (wt%)	5.7	5.2	6.5	4	5.3	8.1	7.9	9.7
Net Richness	**670**	**291**	**559**	**212**	**311**	**315**	**619**	**353**
Vitrinite Reflectance (% Ro)	0.9	0.6	0.6	0.6	0.6	0.95	0.9	1
Maturity factor if oil prone	1	0.7	0.7	0.7	0.7	1	1	1
Source Potential Index for Oil	**670**	**204**	**391**	**148**	**218**	**315**	**619**	**353**
Maturity factor if gas prone	0.4	0.2	0.2	0.2	0.2	0.4	0.4	0.4
Source Potential Index for Gas	**268**	**58**	**112**	**42**	**62**	**126**	**248**	**141**

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Table SR3. Richness and source potential for the pebble shale unit.

Well Name	Mikkelson Bay 1	Point Thomson 2	West Staines 2	Leffingwell 1	Beli 1	Canning River B-1	Canning River A-1	Kavik 1
Gross thickness (feet)	16	31	85	17	55	55	245	210
Average TOC (wt %)	3.73	1.9	3.77	2.72	1.68	1.47	2.01	2.42
Net thickness (feet) (TOC>2 wt %)	16	11	84	16	18	5	135	90
Average TOC (wt %) (TOC>2 wt %)	3.73	2.66	3.8	2.77	2.67	2.27	2.31	3.76
Maximum TOC (wt%)	4.2	3.2	5.4	3.5	3.8	2.8	3.3	9.5
Net Richness	**60**	**29**	**319**	**44**	**48**	**11**	**312**	**338**
Vitrinite Reflectance (%Ro)	0.9	0.6	0.6	0.6	0.6	0.95	0.9	1
Maturity factor if oil prone	1	0.7	0.7	0.7	0.7	1	1	1
Source Potential Index for Oil	**60**	**20**	**223**	**31**	**34**	**11**	**312**	**338**
Maturity factor if gas prone	0.4	0.2	0.2	0.2	0.2	0.4	0.4	0.4
Source Potential Index for Gas	**24**	**6**	**64**	**9**	**10**	**4**	**125**	**135**

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Table SR4. Richness and source potential for the Hue Shale plus pebble shale unit, with separate computation of richness for the entire Hue Shale (including the gamma-ray zone (GRZ)).

Well Name	Mikkelson Bay 1	Point Thomson 2	West Staines 2	Leffingwell 1	Beli 1	Canning River B-1	Canning River A-1	Kavik 1
Gross thickness (feet)	560	550	1170	1098	750	585	1005	1170
Average TOC (wt %)	2.56	1.39	1.92	1.45	1.9	2.15	2.37	2.35
Net thickness (feet) (TOC>2 wt %)	351	180	383	255	295	285	691	603
Average TOC (wt %) (TOC>2 wt %)	3.73	3.27	3.82	2.82	2.7	3.04	2.75	3.24
Maximum TOC (wt %)	7.7	6.7	8.7	6.5	5.4	8.1	7.9	9.9
Net Richness (Hue Shale + pebble shale unit)	**1309**	**589**	**1463**	**719**	**797**	**866**	**1900**	**1954**
Vitrinite Reflectance (% Ro)	0.9	0.6	0.6	0.6	0.6	0.95	0.9	1
Maturity factor if oil prone	1	0.7	0.7	0.7	0.7	1	1	1
Source Potential Index for Oil	**1309**	**412**	**1024**	**503**	**557**	**866**	**1900**	**1954**
Maturity factor if gas prone	0.4	0.2	0.2	0.2	0.2	0.4	0.4	0.4
Source Potential Index for Gas	**524**	**82**	**204**	**101**	**111**	**346**	**760**	**782**
Net Richness (Hue including GRZ)	**1249**	**560**	**1144**	**675**	**749**	**855**	**1588**	**1611**

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Table SR5. Richness and source potential for the Kingak Shale.

Well Name	Beli 1	Canning River B-1	Canning River A-1	Kavik 1
Gross thickness (feet)	295	335	960	740
Average TOC (wt %)	1.38	2.17	1.5	1.02
Net thickness (feet) (TOC>2 wt %)	77	143	144	13
Average TOC (wt %) (TOC>2 wt %)	2.59	3.4	2.39	3.14
Maximum TOC (wt %)	3.5	7.7	4	4.2
Net Richness	**199**	**486**	**344**	**41**
Vitrinite Reflectance (% Ro)	0.6	0.95	0.9	1.1
Maturity factor if oil prone	0.7	1	1	0.7
Source Potential Index for Oil	**140**	**486**	**344**	**29**
Maturity factor if gas prone	0.2	0.4	0.4	0.7
Source Potential Index for Gas	**40**	**194**	**138**	**29**
Using 1 wt % TOC cutoff:				
Net thickness (feet) (TOC>1 wt %)	180	283	813	357
Average TOC (wt %) (TOC>1 wt %)	1.92	2.46	1.61	1.3
Net Richness	**346**	**696**	**1309**	**464**
Vitrinite Reflectance (% Ro)	0.6	0.95	0.9	1.1
Maturity factor if oil prone	0.7	1	1	0.7
Source Potential Index Oil	**243**	**696**	**1309**	**325**
Maturity factor if gas prone	0.2	0.4	0.4	0.7
Source Potential Index Gas	**69**	**278**	**523**	**325**

Table SR6. Richness and source potential for the Mikkelsen Tongue of the Canning Formation.				
Well Name	**Mikkelson Bay 1**	**Point Thomson 2**	**West Staines 2**	**Alaska State C-1**
Gross thickness (feet)	1683	1577	1945	1587
Net thickness (feet) (TOC>1 wt %)	1131	772	1498	1215
Average TOC (wt %) (TOC>1 wt %)	3	1.7	2	1.8
Maximum TOC value	12.3	4.4	6	6.1
Net Richness	**3393**	**1336**	**3041**	**2187**
Vitrinite reflectance (% Ro)	0.5	0.5	0.5	0.5
Maturity factor if oil prone	0.3	0.3	0.3	0.3
Source Potential Index for Oil	**1018**	**401**	**912**	**656**
Maturity factor if gas prone	0.1	0.1	0.1	0.1
Source Potential Index for Gas	**339**	**134**	**304**	**219**

Table SR7. Total organic carbon (TOC) data for the Shublik Formation.

Sample Location and Reference	**Average TOC in weight %**	**Number of samples**	**Range of TOC values**	**Median Value**
Well Cores				
Phoenix-1 (Robison and others, 1996)	3.9	70	0.44-10.2	3.1
Term Well B (Kupecz, 1995)	1.8	63	<1 to ≈6.4	1.4
Well Cuttings				
Beli-1 (Plate WL12; Magoon and others, 1987)	1.7	7	0.49-5.44	
Kemik-2 (Plate WL27; Magoon and others, 1987)	1.7	4	0.65-3.99	
Outcrop Samples				
Fire Creek-Upper 230 ft only (Detterman, 1970)	1.6	42	0.20-2.59	
Fire Creek-complete Shublik (Detterman, 1970)	1.2	88	0.08-2.59	
Fire Creek (Parrish, unpublished data, 1997)	2.2	13	0.45-4.87	1.76
Fire Creek (Magoon, Appendix Table 2)	2.0	13	0.85-4.55	1.63
Kavik River (Parrish, unpublished data, 1997)	2.6	13	0.74-5.46	2.4
Last Creek (Parrish, unpublished data, 1997)	2.4	7	0.64-5.27	2.15
Last Creek (Magoon, Appendix Table 2)	1.2	8	0.42-2.33	1.08
Ignek Valley (Magoon, Appendix Table 2)	2.7	11	0.31-7.01	2.44

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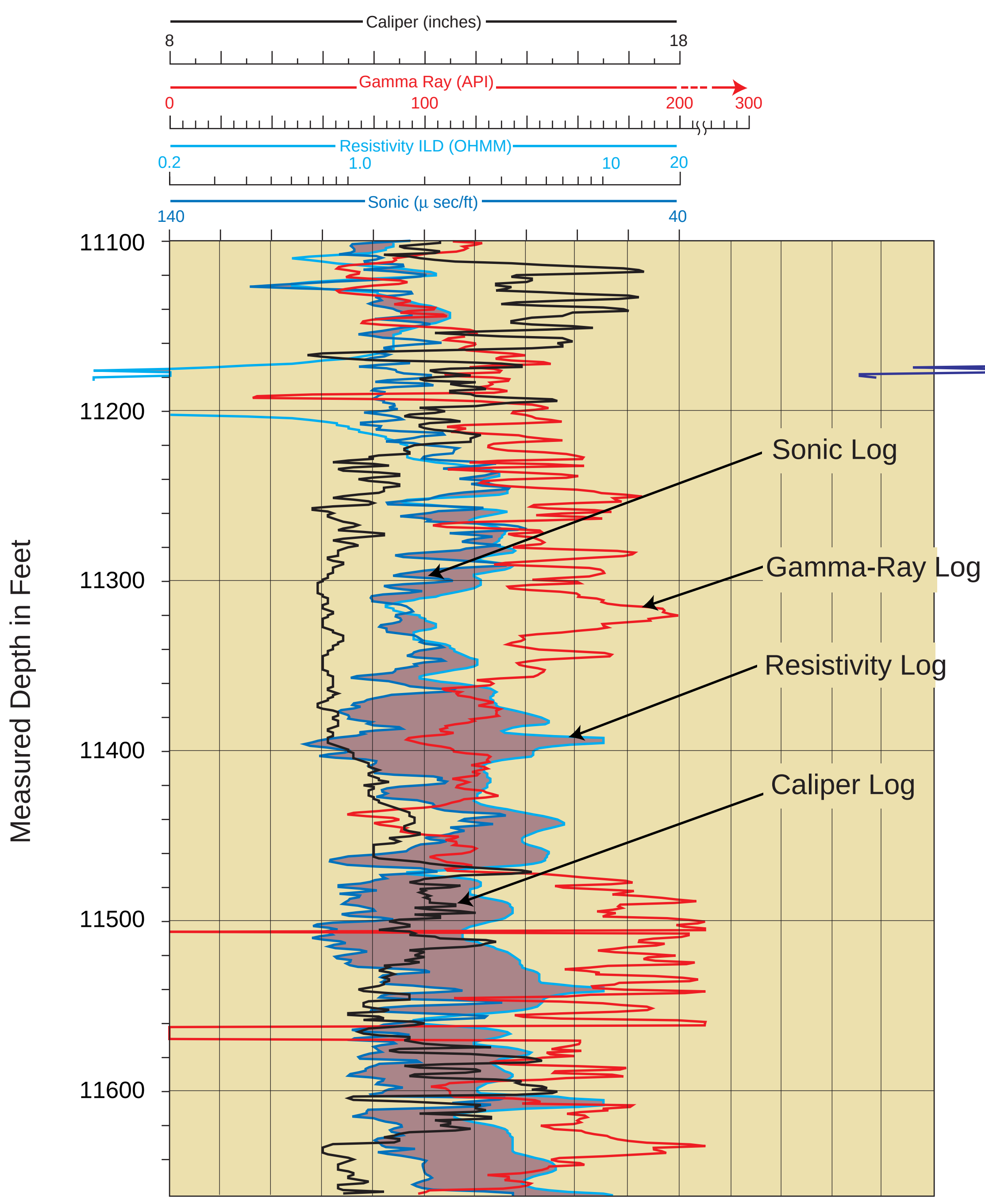
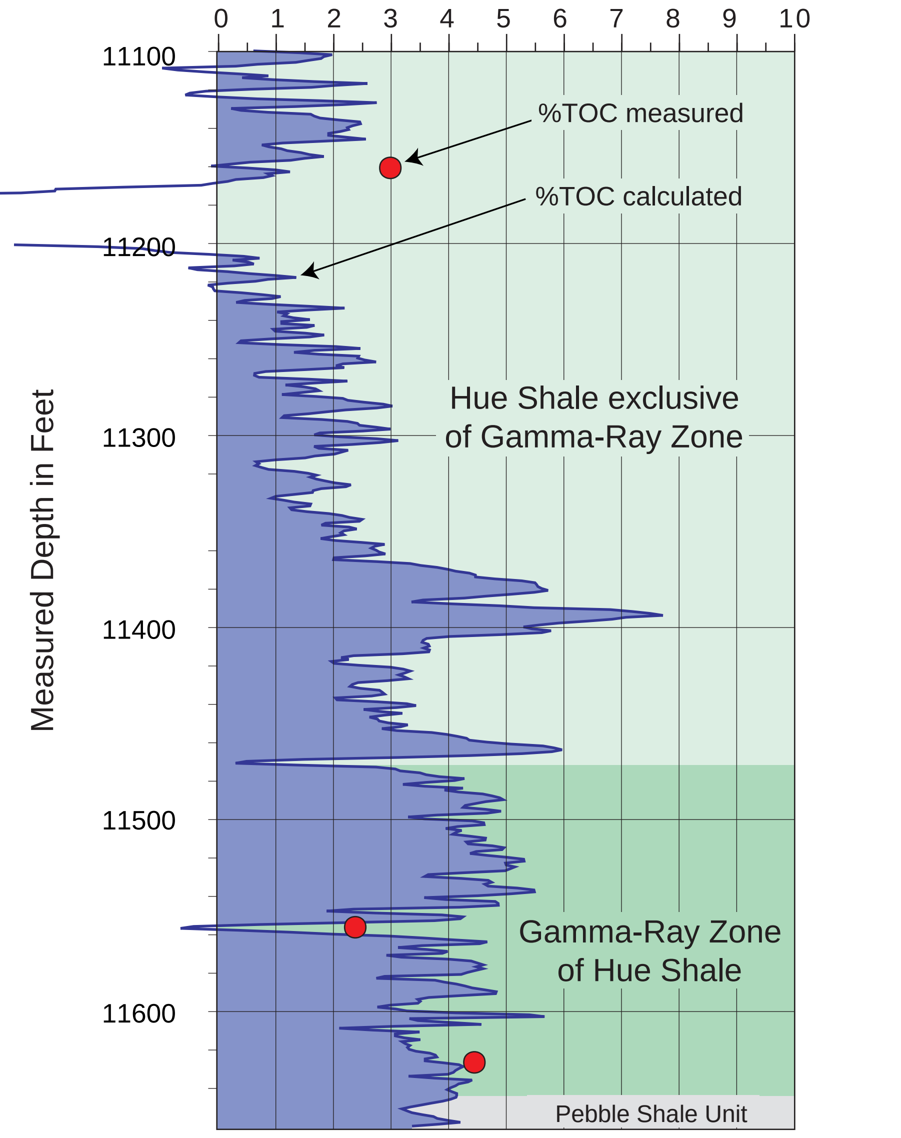


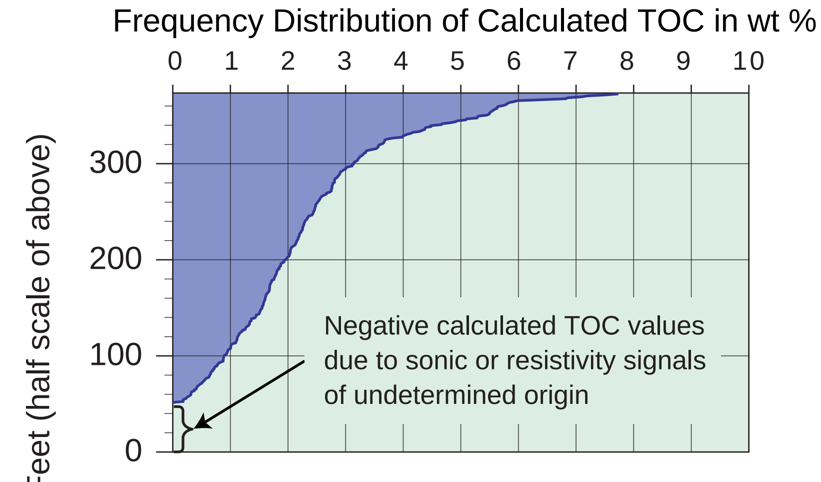
Positive ΔLogR separation resulting from sonic (DT) log's position to the left of resistivity (ILD) log when log traces are properly scaled and aligned at baseline values for DT and ILD (see Passey and others, 1990). Baseline for ΔLogR calculations is 76 µsec./ft. and 3.5 ohm-meters at 11,230-11,260 ft. Casing was set above the Hue Shale at approximately 9,775 ft.

Hue Shale and Pebble Shale Unit

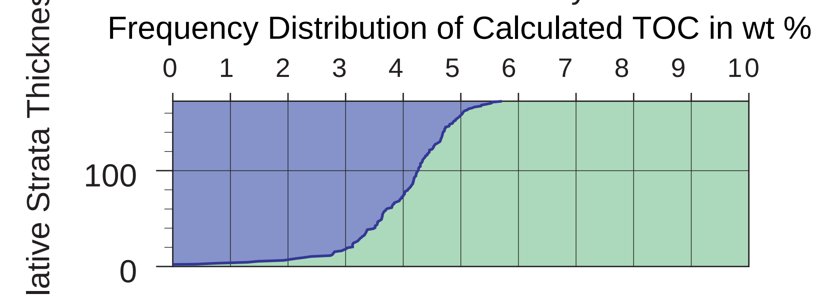
Mikkelsen Bay-1
API No. 50-029-20055
wt %TOC, measured (●) and calculated (ΔLogR method)



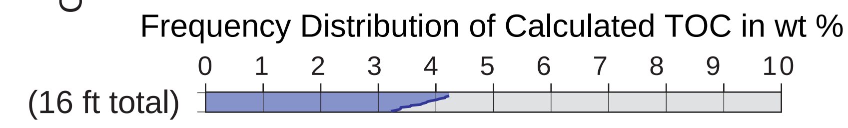
Hue Shale exclusive of Gamma-Ray Zone
Frequency Distribution of Calculated TOC in wt %



Hue Shale Gamma-Ray Zone
Frequency Distribution of Calculated TOC in wt %



Pebble Shale Unit
Frequency Distribution of Calculated TOC in wt %



Δ Log R CALCULATIONS

Data used for analysis of this well include the well history; mudlog; DT, ILD, gamma-ray, and caliper borehole geophysical logs, and three TOC values from core samples analyzed at the U. S. Geological Survey (see Lillis and others, Chapter OA). The caliper log shows significant borehole caving in the Canning Formation and upper part of the Hue Shale and also in the GRZ. In the GRZ of this well, note the interval of "negative" calculated TOC, which correlates to relatively low resistivity, and also corresponds to relatively high gamma-ray response. These intervals, which are present in the GRZ in all the wells, may be tuff or bentonite as described in the well history and in outcrop (Bird and Molenaar, 1987; Bergman and others, 1995). Creaney and Passey (1993) also note that a high gamma-ray, low TOC unit is possibly a bentonite layer within the HRZ (the highly radioactive zone), a condensed facies of early Cretaceous age in the Torok Shale to the West of 1002 area (Molenaar, 1988).

Although no set of cutting's TOC's exists for comparison to ΔlogR calculated TOCs, the few TOCs from core samples compare well with ΔlogR TOCs. Also, note the close similarity of the calculated TOC profile for the Hue Shale above the GRZ and the GRZ in this well to the lower part of the West Staines-2 well, particularly below about 12,550 ft. In addition, note the similar pattern of correlation in both wells between gamma-ray and calculated TOC curves. Based on this comparison and similar to the Point Thomson-2 well, the upper 500+ ft of the Hue Shale section present in the West Staines-2 well are eroded in the Mikkelsen Bay-1 well.

Richness and source potential indices for the Hue Shale, including the Gamma-Ray Zone (GRZ), pebble shale unit (pbsh), and Kingak Shale in the Mikkelsen Bay-1 well. Richness is from calculated TOC. Vitrinite reflectance values from Nelson & others (Ch. WL, Plate WL29). Baseline for ΔLogR calculations is 76 µsec./ft. and 3.5 ohm-meters at 11,230-11,260 ft.

	Hue, GRZ, & pbsh	*Hue Shale (Above GRZ)*	*Hue Shale (GRZ)*	*pebble shale unit*
Gross Thickness (ft)	560	372	172	16
Net Thickness (TOC≥2 wt %)	351	169	165	16
Average TOC wt %	2.56%	1.97%	3.93%	3.73%
Maximum TOC value	7.7	7.7	5.7	4.2
Average TOC≥2 wt %	3.73%	3.41%	4.06%	3.73%
Net Richness	**1309**	**576**	**670**	**60**
Vitrinite Reflectance $\%R_o$	0.9	0.9	0.9	0.9
Maturity Factor (Oil)	1	1	1	1
Source Potential Index (Oil)	**1309**	**576**	**670**	**60**
Maturity Factor (Gas)	0.4	0.4	0.4	0.4
Source Potential Index (Gas)	**524**	**230**	**268**	**24**

INTERIOR–GEOLOGICAL SURVEY, RESTON, VA–1998

TOTAL ORGANIC CARBON PROFILE AND GAMMA-RAY, RESISTIVITY, AND SONIC LOGS, HUE SHALE AND PEBBLE SHALE UNIT, MIKKELSEN BAY-1

By
Margaret A. Keller, Kenneth J. Bird, and Kevin R. Evans
1998

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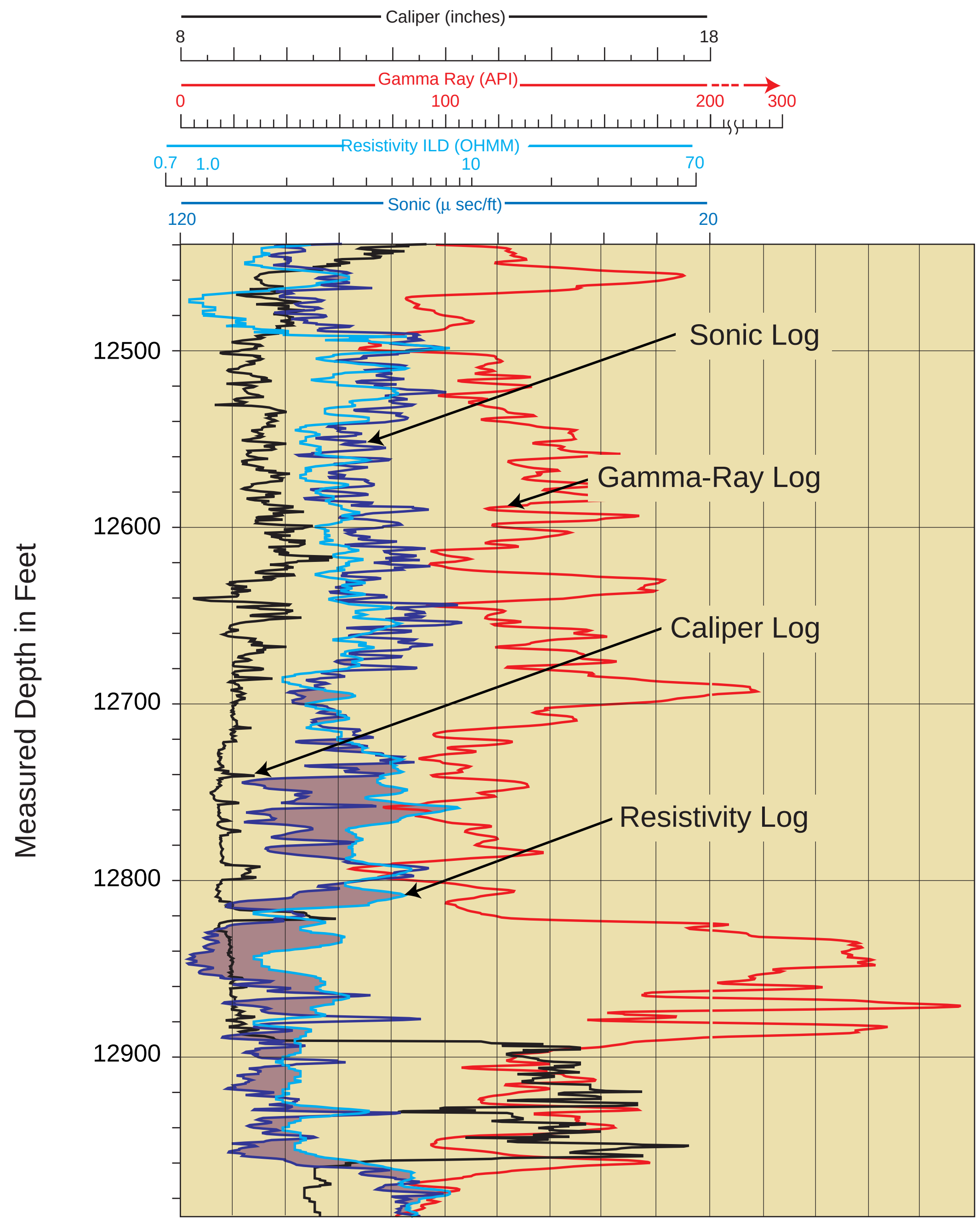
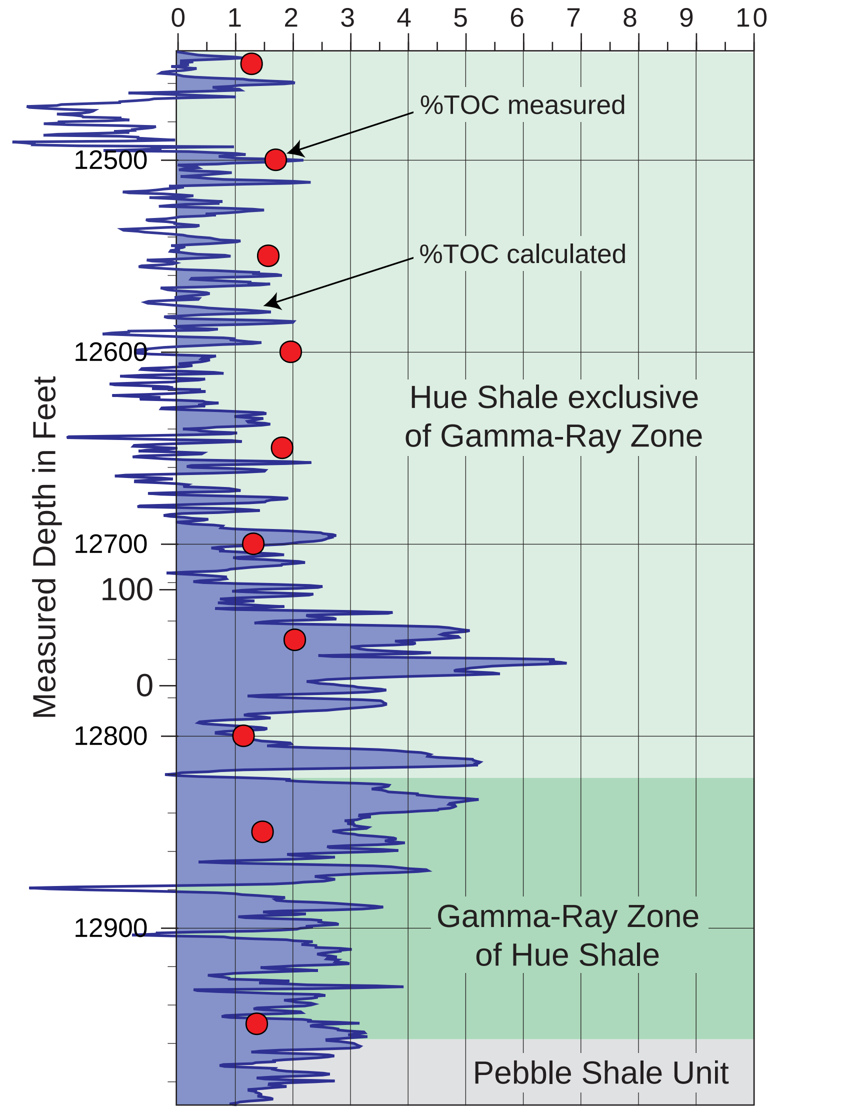
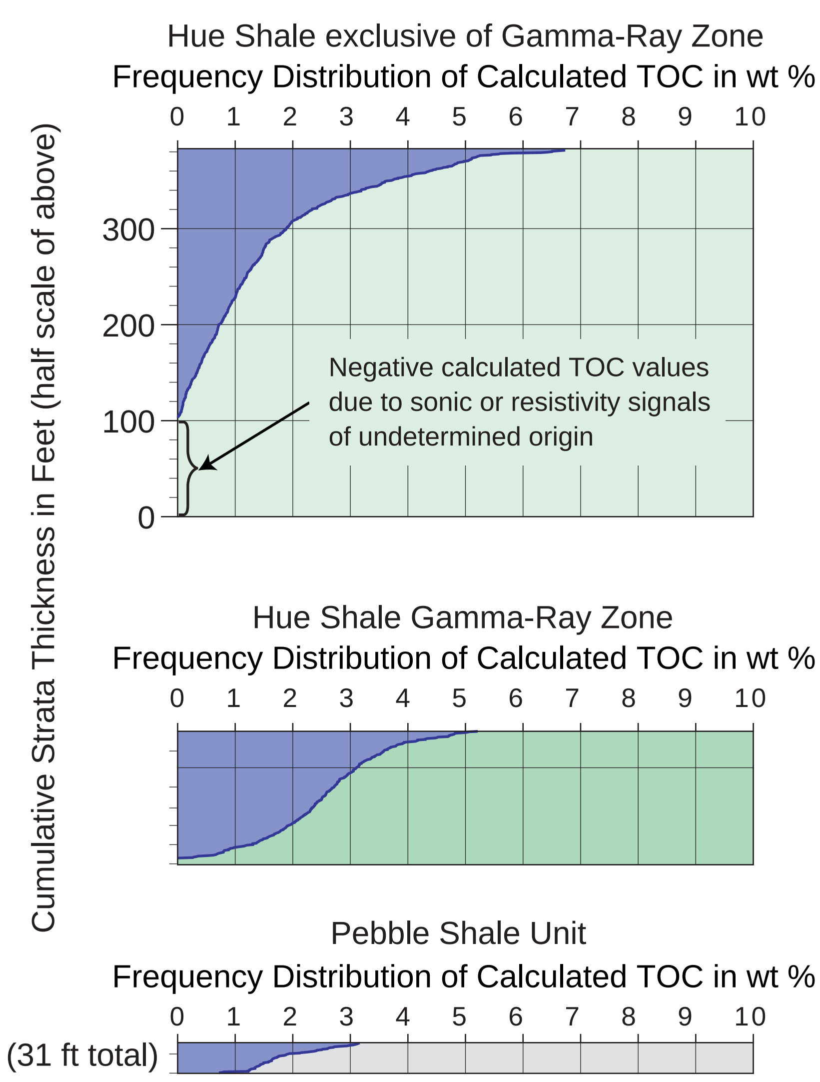
OPEN-FILE REPORT 98-34
PLATE SR2



Hue Shale and Pebble Shale Unit

Point Thomson-2
API No. 50-089-20006
wt %TOC, measured (●) and calculated (Δ Log R method)





Positive ΔLogR separation resulting from sonic (DT) log's position to the left of resistivity (ILD) log when log traces are properly scaled and aligned at baseline values for DT and ILD (see Passey and others, 1990). Baseline for ΔLogR calculation is 75 µsec./ft. and 6.2 ohm-meters at 12,400-12,440 ft. Casing was set above the Hue Shale at approximately 10,100 ft.

ΔLogR CALCULATIONS

Data used for analysis of this well include the well history; mudlog; DT, ILD, gamma-ray, and caliper borehole geophysical logs; and reported TOC values measured on cuttings. No additional information is available about the TOC values from cuttings, such as whether the samples were composited or from selected individual rock chips. However, the caliper log shows severe caving in the Canning Formation overlying the Hue and also in the lower part of the GRZ and the pebble shale.

The TOCs measured on borehole cuttings from this well do not compare well with calculated ΔlogR TOC values. This may be due to the extensive caving in this borehole and resulting sample contamination of the cuttings. Furthermore, the close similarity of the calculated TOC profile in this well to that in the nearby West Staines-2 well beginning at approximately 12,540 ft, in addition to the similar pattern of correlation in both wells between gamma-ray and calculated TOC curves, suggests that the calculated TOC values may be more reliable for this well. The correlation also shows that the upper 500+ ft of the Hue Shale section in the West Staines-2 well are eroded in the Point Thomson-2 well.

The numerous "negative" values for calculated TOC due to very low resistivities in this well may indicate that the baseline needs to be adjusted. This would uniformly add ≈ 1-1.5 wt % TOC to the curve, not changing its shape, but bringing many of the values closer to values in correlative intervals of the West Staines-2 well, and would also increase the richness and source potential indices in the table below. In the GRZ of this well, note the intervals of very low or "negative" calculated TOCs which are high conductivity or low resistivity, and also correspond to relatively higher gamma-ray response. These intervals, which are present in the GRZ in all the wells, may be tuff or bentonite as described in the well history and in outcrop (Bird and Molenaar, 1987; Bergman and others, 1995).

Richness and source potential indices for the Hue Shale, including the Gamma-Ray Zone (GRZ), pebble shale unit (pbsh), and Kingak Shale in the Point Thomson-2 well. Richness is from calculated TOC. Vitrinite reflectance values from Nelson & others (Ch. WL, Plate WL34). Baseline for ΔLogR calculations is 75 µsec./ft. and 6.2 ohm-meters at 12,400-12,440 ft.

	Hue, GRZ, & pbsh	*Hue Shale (Above GRZ)*	*Hue Shale (GRZ)*	*pebble shale unit*
Gross Thickness (ft)	550	382	137	31
Net Thickness (TOC≥2 wt %)	180	74	95	11
Average TOC wt %	1.39%	1.58%	2.59%	1.9%
Maximum TOC value	6.7	6.7	5.2	3.2
Average TOC≥2 wt %	3.27%	3.63%	3.06%	2.66%
Net Richness	**589**	**269**	**291**	**29**
Vitrinite Reflectance %R_o	0.6	0.6	0.6	0.6
Maturity Factor (Oil)	0.7	0.7	0.7	0.7
Source Potential Index (Oil)	**412**	**188**	**204**	**20**
Maturity Factor (Gas)	0.2	0.2	0.2	0.2
Source Potential Index (Gas)	**82**	**14**	**58**	**6**

INTERIOR–GEOLOGICAL SURVEY, RESTON, VA–1998

TOTAL ORGANIC CARBON PROFILE AND GAMMA-RAY, RESISTIVITY, AND SONIC LOGS, HUE SHALE AND PEBBLE SHALE UNIT, POINT THOMSON-2

By
Margaret A. Keller, Kenneth J. Bird, and Kevin R. Evans
1998

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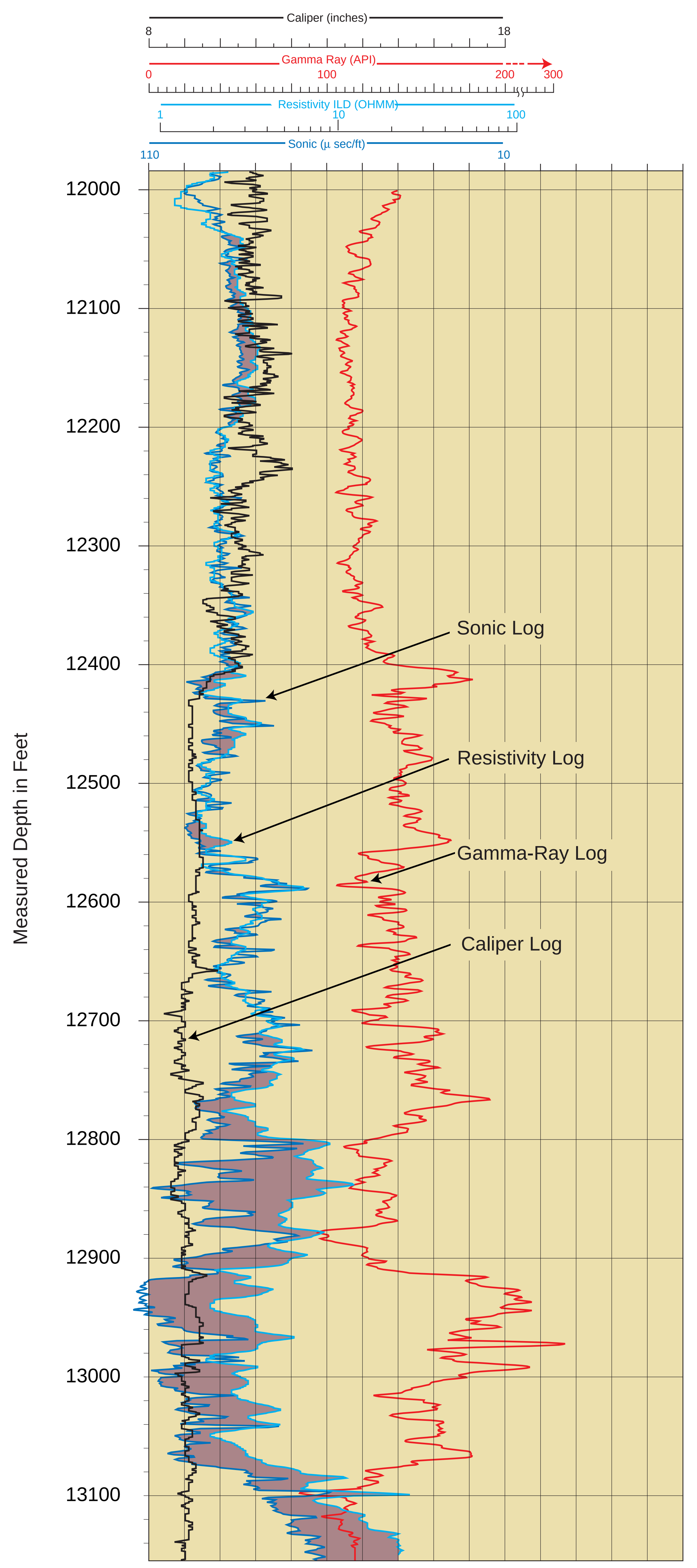
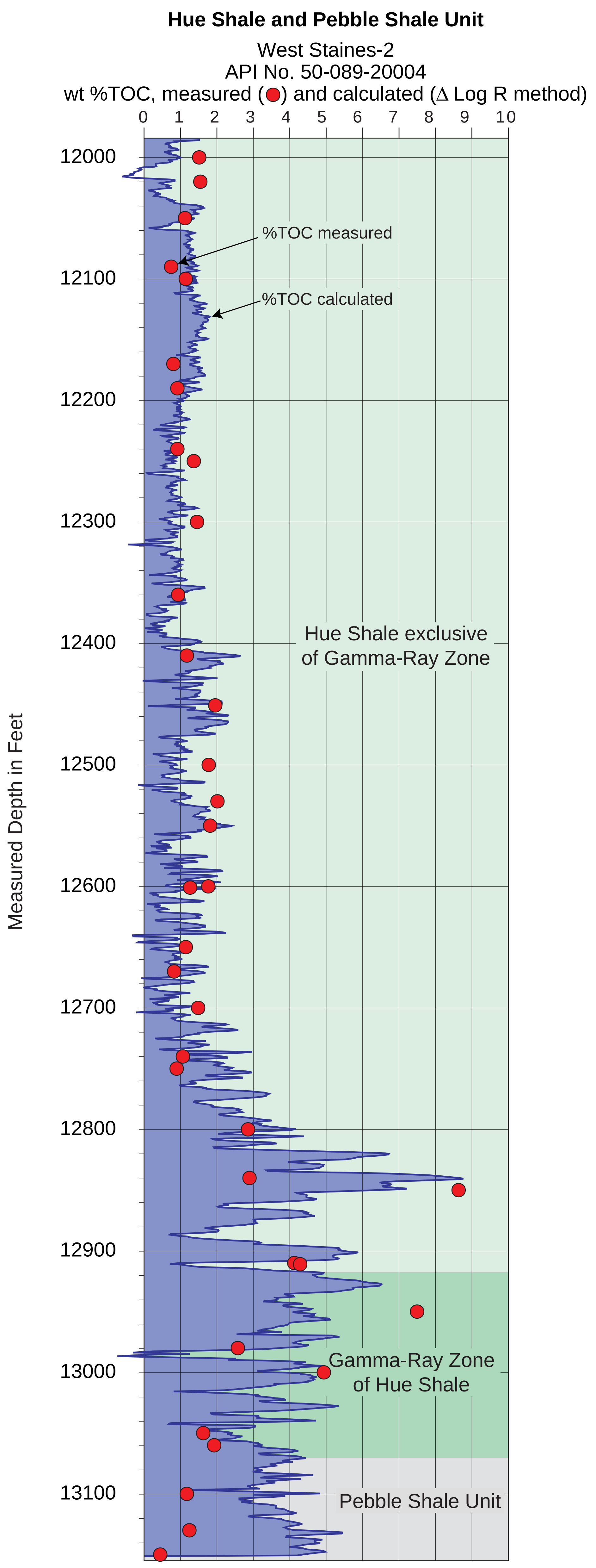
PLATE SR3



Positive ΔLogR separation resulting from sonic (DT) log's position to the left of resistivity (ILD) log when log traces are properly scaled and aligned at baseline values for DT and ILD (see Passey and others, 1990). Baseline for ΔLogR calculation is 91 µsec./ft. and 2.05 ohm-meters at 12,200-12,320 ft. Casing was set above the Hue Shale at approximately 11,250 ft.



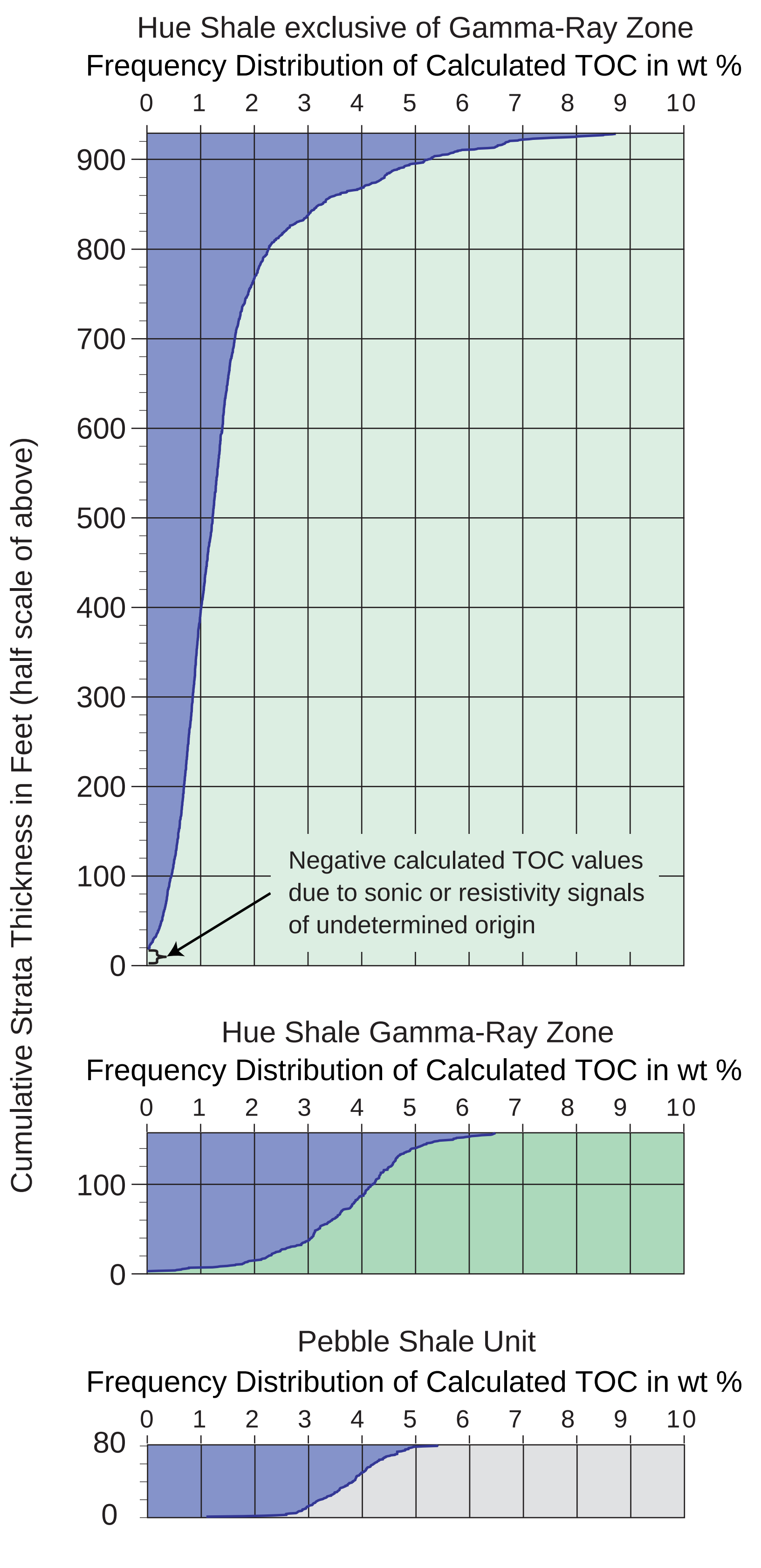
ΔLogR CALCULATIONS

Data used for analysis of this well include the well history; mudlog; DT, ILD, gamma-ray, and caliper borehole geophysical logs; and reported TOC values measured on cuttings. No additional information is available about the TOC values from cuttings, such as whether the samples were composited or from selected individual rock chips. The caliper log indicates that only minor caving occurred in the borehole; much of this is in the upper Hue Shale and in the overlying Canning Formation.

Good agreement exists between calculated TOC values and most measured TOC values, or they differ in a reasonable manner in that they represent interval averages of different intervals. The exceptions are intervals where the calculated TOC values are higher than measured TOCs, such as the basal part of the pebble shale, and intervals where calculated TOCs are lower than measured values, such as the upper part of the GRZ. Note in the GRZ the intervals of very low or "negative" calculated TOCs which are due to high conductivity/low resistivity, and also correspond to relatively higher gamma-ray response. These intervals, which are present in the GRZ in all the wells, may be tuff or bentonite as described in the well history and in outcrop (Bird and Molenaar, 1987; Bergman and others, 1995).

Richness and source potential indices for the Hue Shale, including the Gamma-Ray Zone (GRZ), pebble shale unit (pbsh), and Kingak Shale in the West Staines-2 well. Richness is from calculated TOC. Vitrinite reflectance values from Nelson & others (Ch. WL, Plate WL37). Baseline for ΔLogR calculations is 91 µsec./ft. and 2.05 ohm-meters at 12,200-12,320 ft.

	Hue, GRZ, & pbsh	*Hue Shale (Above GRZ)*	*Hue Shale (GRZ)*	*pebble shale unit*
Gross Thickness (ft)	1170	928	157	85
Net Thickness (TOC≥2 wt %)	383	161	142	84
Average TOC wt %	1.92%	1.47%	3.66%	3.77%
Maximum TOC value	8.7	8.7	6.5	5.4
Average TOC≥2 wt %	3.82%	3.72%	3.94%	3.8%
Net Richness	**1463**	**599**	**559**	**319**
Vitrinite Reflectance %R_o	0.6	0.6	0.6	0.6
Maturity Factor (Oil)	0.7	0.7	0.7	0.7
Source Potential Index (Oil)	**1024**	**419**	**391**	**223**
Maturity Factor (Gas)	0.2	0.2	0.2	0.2
Source Potential Index (Gas)	**204**	**20**	**112**	**64**



INTERIOR--GEOLOGICAL SURVEY, RESTON, VA-1998

TOTAL ORGANIC CARBON PROFILE AND GAMMA-RAY, RESISTIVITY, AND SONIC LOGS, HUE SHALE AND PEBBLE SHALE UNIT, WEST STAINES-2

By
Margaret A. Keller, Kenneth J. Bird, and Kevin R. Evans
1998

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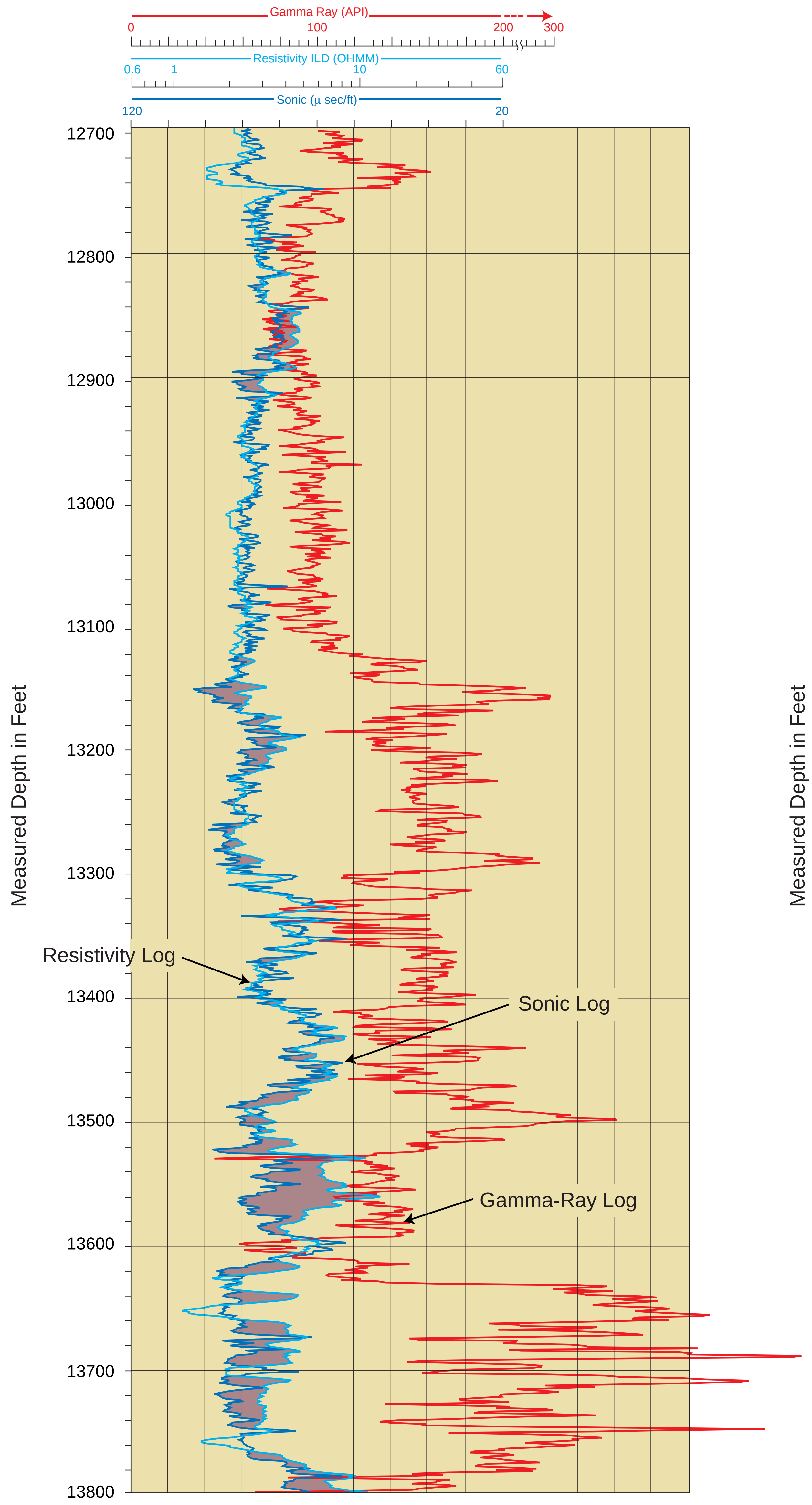
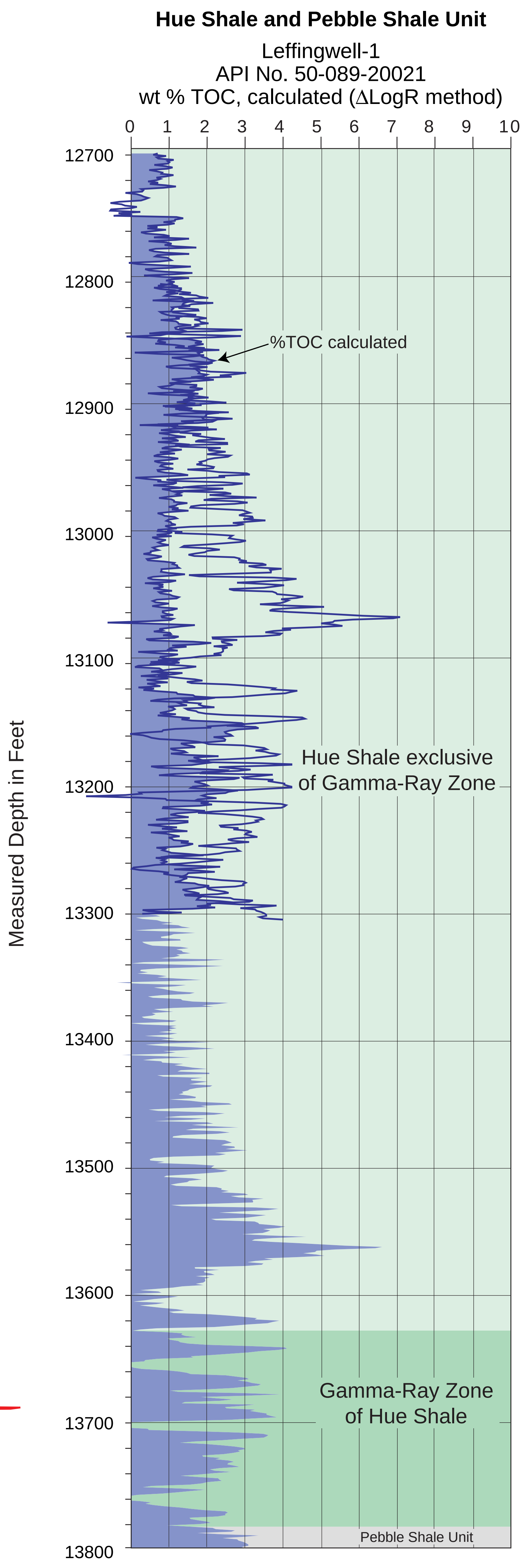




Positive ΔLogR separation resulting from sonic (DT) log's position to the left of resistivity (ILD) log when log traces are properly scaled and aligned at baseline values for DT and ILD (see Passey and others, 1990). Baseline for ΔLogR calculation is 89 µsec./ft. and 2.2 ohm-meters at 13,000-13,100 ft. Casing was set above the Hue Shale at approximately 12,300 ft.

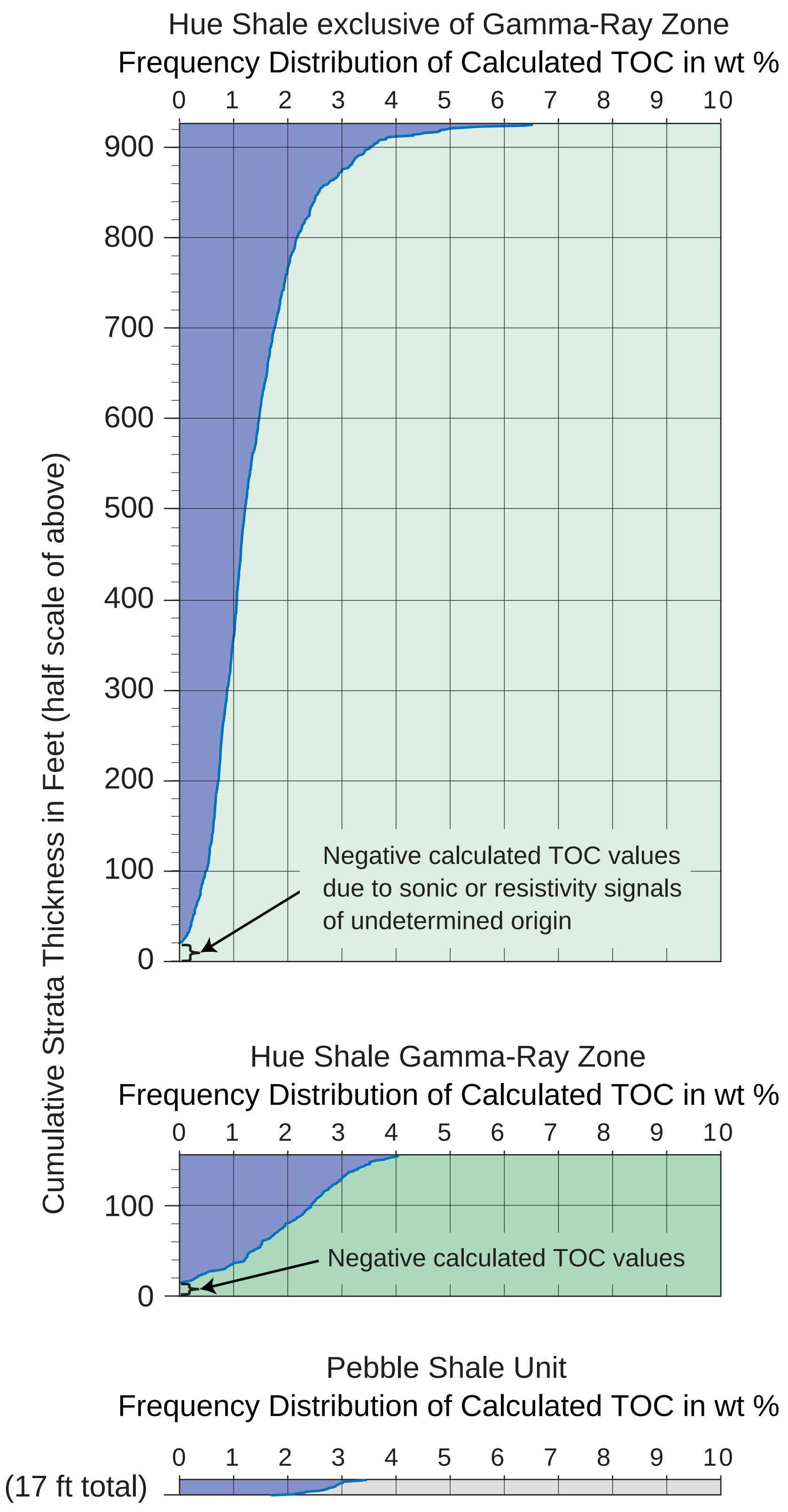
ΔLogR CALCULATIONS

Data used for analysis of this well include the well history; mudlog; and the DT, ILD, and gamma-ray borehole logs. The caliper log, which does not extend down to the Hue and Pebble shale, indicates caving in the Canning Formation overlying the Hue. Note in the GRZ of this well the intervals of low or "negative" calculated TOC's which are due to high conductivity/low resistivity, and also correspond to relatively higher gamma-ray response. These intervals, which are present in the GRZ in all the wells, may be tuff or bentonite as described in the well history and in outcrop (Bird and Molenaar, 1987; Bergman and others, 1995). Creaney and Passey (1993) also note that a high gamma-ray, low TOC unit is possibly a bentonite layer within the HRZ (the highly radioactive zone), a condensed facies of early Cretaceous age in the Torok Shale to the West of the 1002 area (Molenaar, 1988).

Although no measured TOCs on well samples have been reported to compare to calculated ΔlogR TOC values, note the close similarity of the calculated TOC profile in this well to that in the nearby West Staines-2 well, in addition to the similar pattern of correlation in both wells between gamma-ray and calculated TOC curves.

Richness and source potential indices for the Hue Shale, including the Gamma-Ray Zone (GRZ), pebble shale unit (pbsh), and Kingak Shale in the Leffingwell-1 well. Richness is from calculated TOC. Vitrinite reflectance values from Nelson & others (Ch. WL, Plate WL28). Baseline for ΔLogR calculations is 89 µsec./ft. and 2.2 ohm-meters at 13,000-13,100 ft.

	Hue, GRZ, & pbsh	*Hue Shale (Above GRZ)*	*Hue Shale (GRZ)*	*pebble shale unit*
Gross Thickness (ft)	1098	927	154	17
Net Thickness (TOC≥2 wt %)	255	163	75	16
Average TOC wt %	1.45%	1.35%	1.85%	2.72%
Maximum TOC value	6.5	6.5	4.0	3.5
Average TOC≥2 wt %	2.82%	2.83%	2.82%	2.77%
Net Richness	**719**	**461**	**212**	**44**
Vitrinite Reflectance %R_o	0.6	0.6	0.6	0.6
Maturity Factor (Oil)	0.7	0.7	0.7	0.7
Source Potential Index (Oil)	**503**	**323**	**148**	**31**
Maturity Factor (Gas)	0.2	0.2	0.2	0.2
Source Potential Index (Gas)	**101**	**92**	**42**	**9**



INTERIOR–GEOLOGICAL SURVEY, RESTON, VA–1998

TOTAL ORGANIC CARBON PROFILE AND GAMMA-RAY, RESISTIVITY, AND SONIC LOGS, HUE SHALE AND PEBBLE SHALE UNIT, LEFFINGWELL-1

By
Margaret A. Keller, Kenneth J. Bird, and Kevin R. Evans
1998

The Oil and Gas Resource Potential of the Arctic National Wildlife Refuge 1002 Area, Alaska
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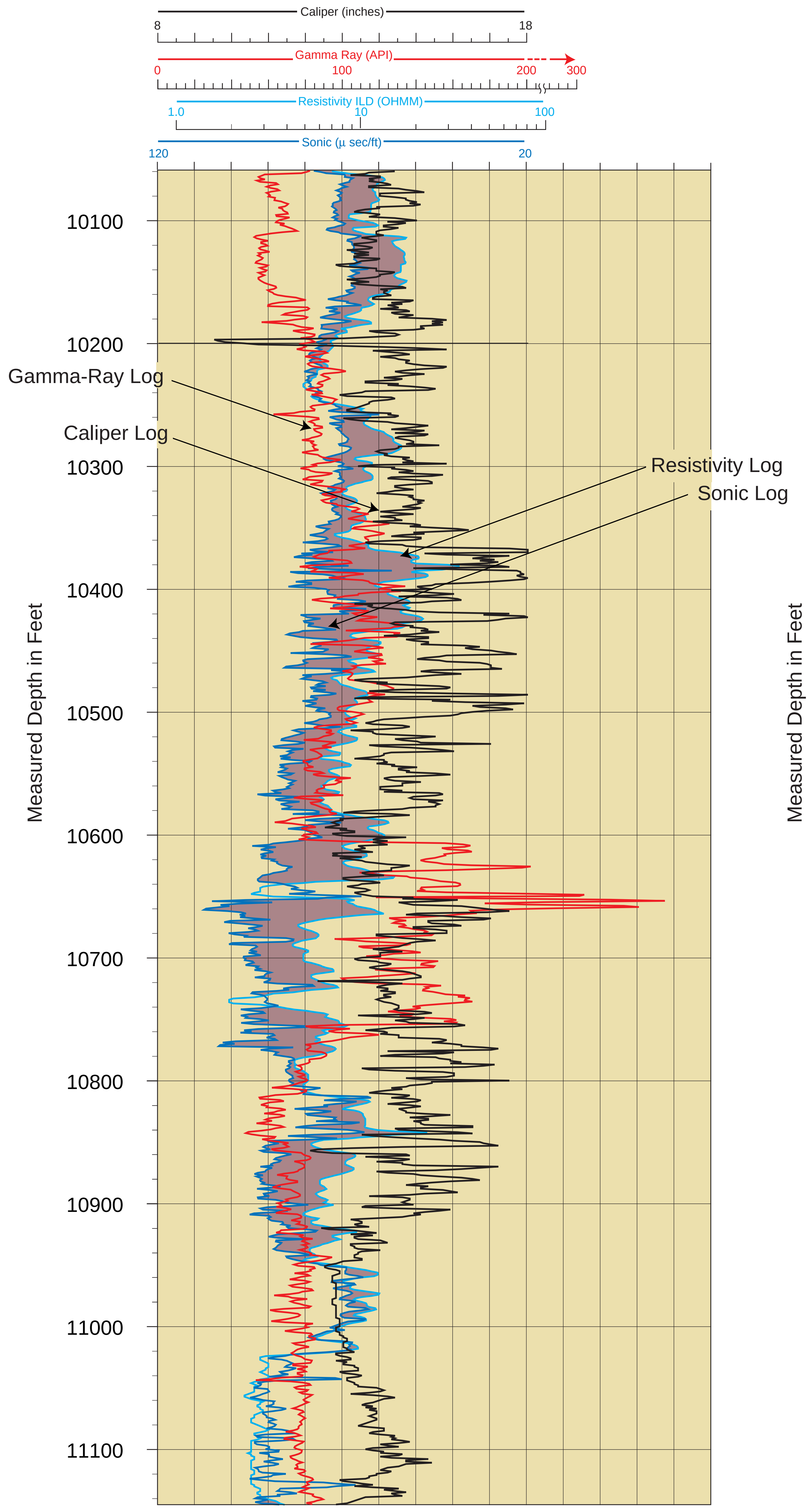
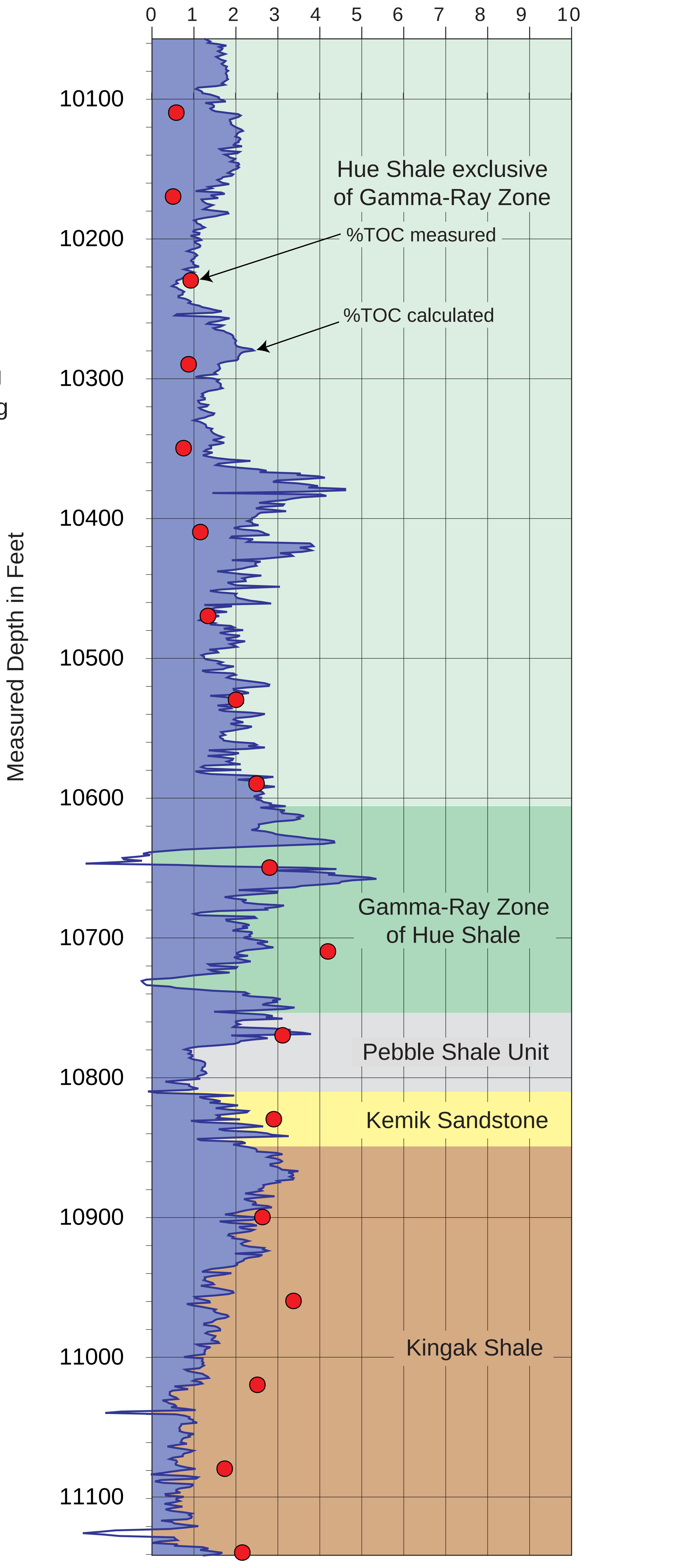
PLATE SR5



Hue Shale, Pebble Shale Unit, and Kingak Shale

Beli -1
API No. 50-179-20002
wt % TOC, measured (●) and calculated (Δ Log R method)



Positive ΔLogR separation resulting from sonic (DT) log's position to the left of resistivity (ILD) log when log traces are properly scaled and aligned at baseline values for DT and ILD (see Passey and others, 1990). Baselines for ΔLogR calculations are 78 µsec./ft. and 5.4 ohm-meters at 10,200-10,250 ft and 70 µsec./ft. and 7 ohm-meters for the Kingak Shale at 11,050-11,120 ft. Casing was set above the Hue Shale at approximately 2,680 ft.

ΔLogR CALCULATIONS

Data used for analysis of this well include the well history; mudlog; DT, ILD, gamma-ray, and caliper borehole geophysical logs; and reported TOC values measured on cuttings. No additional information is available about the TOC values from cuttings, such as whether the samples were composited or from selected individual rock chips. The caliper log indicates that caving occurred in the borehole, including the Kingak, pebble shale unit, GRZ, Hue Shale above the GRZ, and in the overlying Canning Formation. Thus, both the quality of the borehole logs, principally the sonic DT log, and the representativeness of the measured values of TOC (from borehole cuttings) are somewhat questionable. However, in general the calculated TOC values agree fairly well with measured values, or seem to differ in a reasonable manner in that they represent interval averages of different intervals.

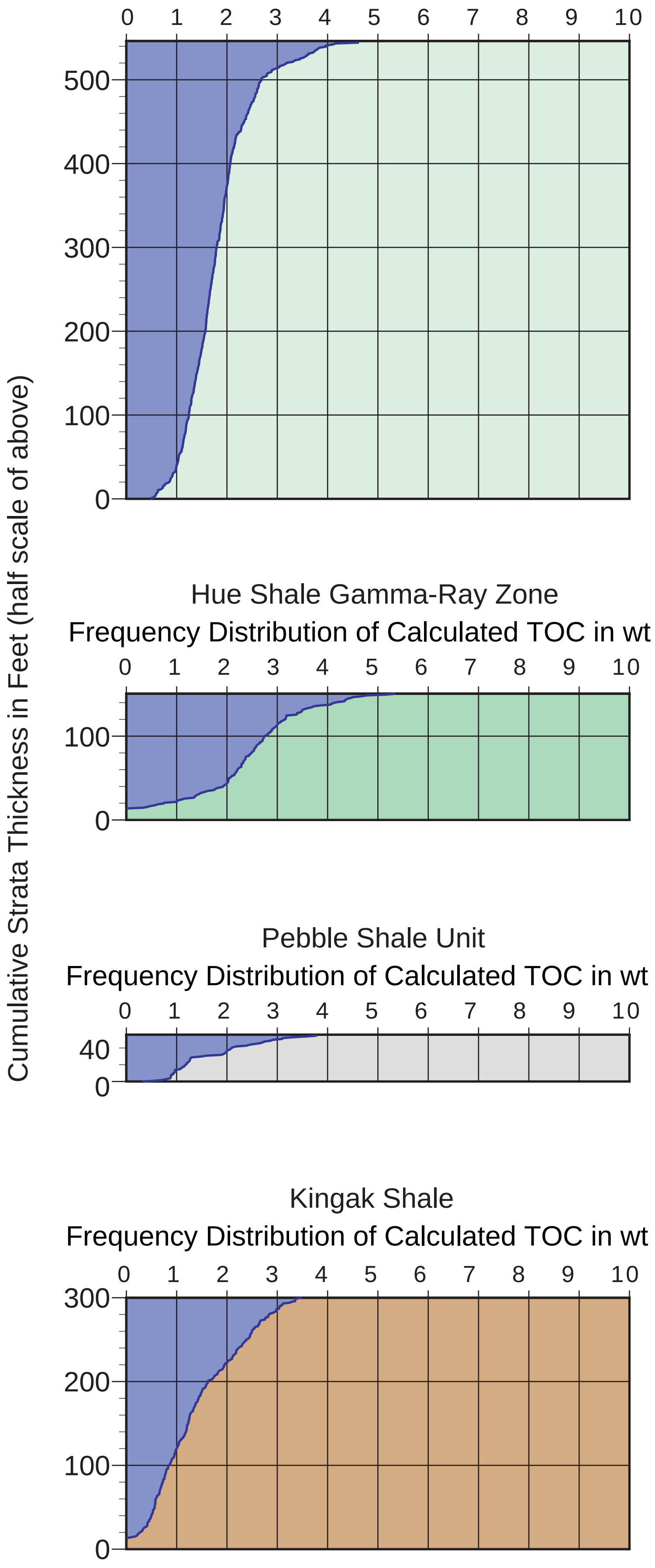
The exceptions are several intervals where the calculated TOC values are higher than measured TOCs, such as the upper part of the Hue Shale, and several intervals where the calculated TOCs are lower than measured values, such as the lower parts of the GRZ and Kingak Shale. Contamination by cuttings from overlying units with lower TOC may explain the first case, but does not seem to be the only explanation in the second case (e.g., the lower part of the GRZ at ≈ 10,710 ft and the middle part of the Kingak at ≈ 10,960 ft) where calculated TOCs are lower than measured values, and where these measured values are also higher than measured values in the adjacent overlying section. Also note in the GRZ the two intervals of "negative" calculated TOCs which are due to high conductivity/low resistivity, and also correspond to relatively higher gamma-ray response. These intervals, which are present in the GRZ in all the wells, may be tuff or bentonite as described in the well history and in outcrop (Bird and Molenaar, 1987; Bergman and others, 1995).

Hue Shale exclusive of Gamma-Ray Zone
Frequency Distribution of Calculated TOC in wt %

Hue Shale Gamma-Ray Zone
Frequency Distribution of Calculated TOC in wt %

Pebble Shale Unit
Frequency Distribution of Calculated TOC in wt %

Kingak Shale
Frequency Distribution of Calculated TOC in wt %



Richness and source potential indices for the Hue Shale, including the Gamma-Ray Zone (GRZ), pebble shale unit (pbsh), and Kingak Shale in the Beli-1 well. Richness is from calculated TOC. Vitrinite reflectance values from Nelson & others (Ch. WL, Plate WL12). Baselines for ΔLogR calculations are 78 µsec./ft. and 5.4 ohm-meters at 10,200-10,250 ft and 70 µsec./ft. and 7 ohm-meters at 11,050-11,120 ft.

	Hue, GRZ, & pbsh	*Hue Shale (Above GRZ)*	*Hue Shale (GRZ)*	*pebble shale unit*	*Kingak Shale*	*Kingak Shale**
Gross Thickness (ft)	750	545	150	55	295	295
Net Thickness (TOC≥2 wt %)	295	171	106	18	77	180
Average TOC wt %	1.9%	1.81%	2.3%	1.68%	1.38%	1.38%
Maximum TOC value	5.4	4.6	5.3	3.8	3.5	3.5
Average TOC≥2 wt %	2.7%	2.57%	2.93%	2.67%	2.59%	1.92%
Net Richness	**797**	**439**	**311**	**48**	**199**	**346**
Vitrinite Reflectance %R_o	0.6	0.6	0.6	0.6	0.6	0.6
Maturity Factor (Oil)	0.7	0.7	0.7	0.7	0.7	0.7
Source Potential Index (Oil)	**557**	**308**	**218**	**34**	**140**	**243**
Maturity Factor (Gas)	0.2	0.2	0.2	0.2	0.2	0.2
Source Potential Index (Gas)	**111**	**88**	**62**	**10**	**40**	**69**

**Tabulations using ≥1 wt % TOC.*

INTERIOR--GEOLOGICAL SURVEY, RESTON, VA--1998

TOTAL ORGANIC CARBON PROFILE AND CALIPER, GAMMA-RAY, RESISTIVITY, AND SONIC LOGS, HUE SHALE, PEBBLE SHALE UNIT, AND KINGAK SHALE, BELI-1

By
Margaret A. Keller, Kenneth J. Bird, and Kevin R. Evans
1998

The Oil and Gas Resource Potential of the Arctic National Wildlife Refuge 1002 Area, Alaska
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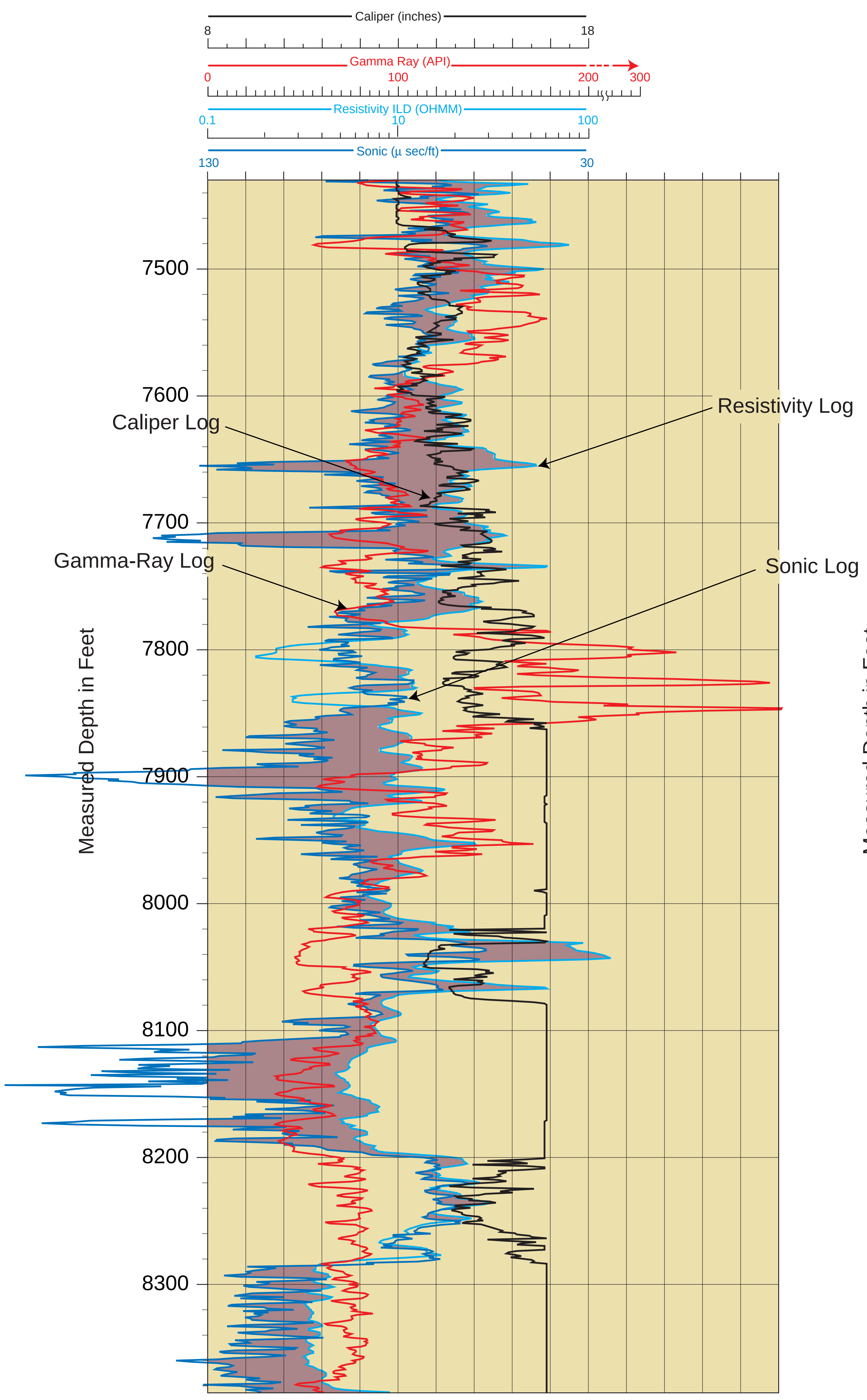
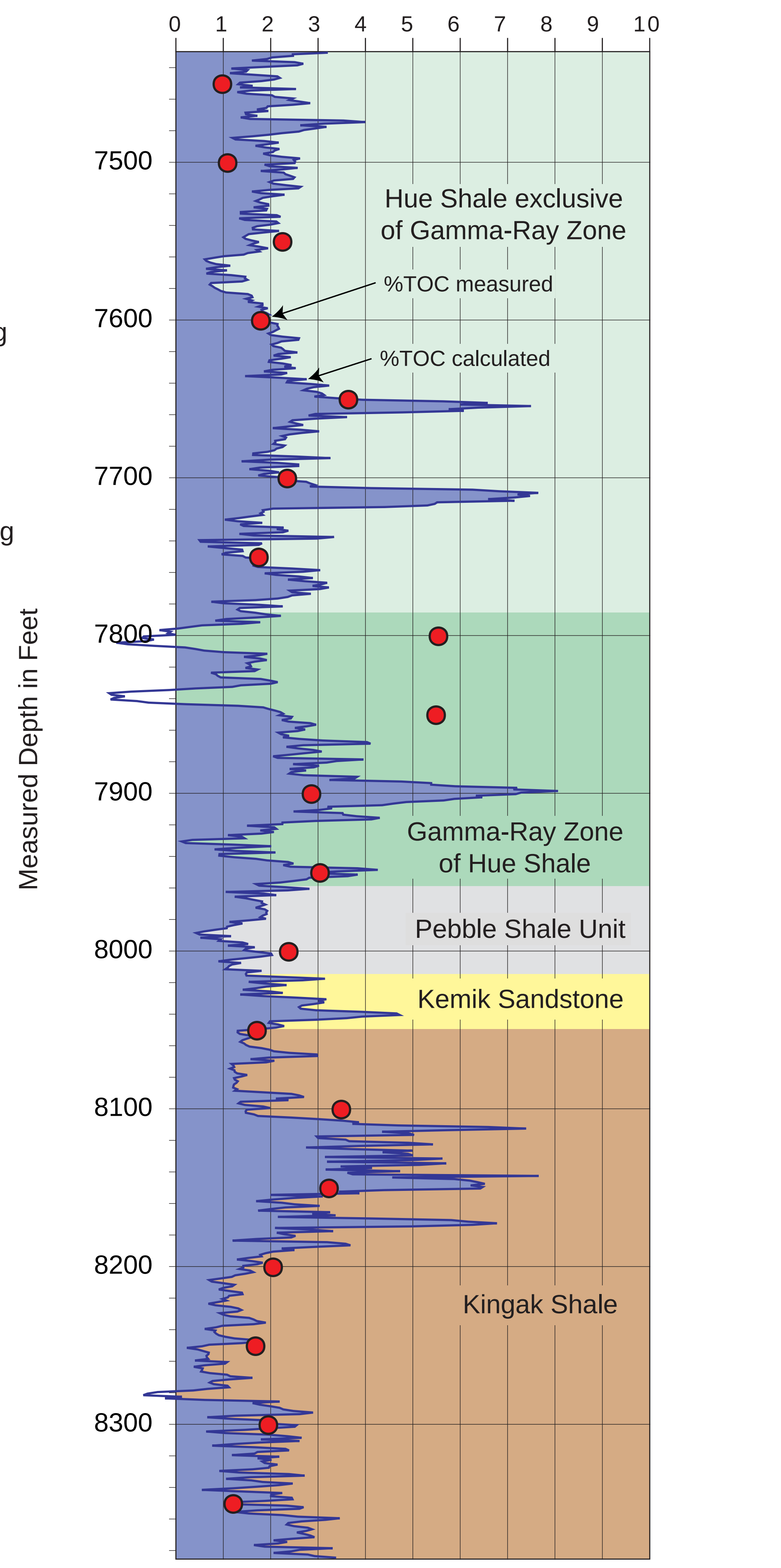
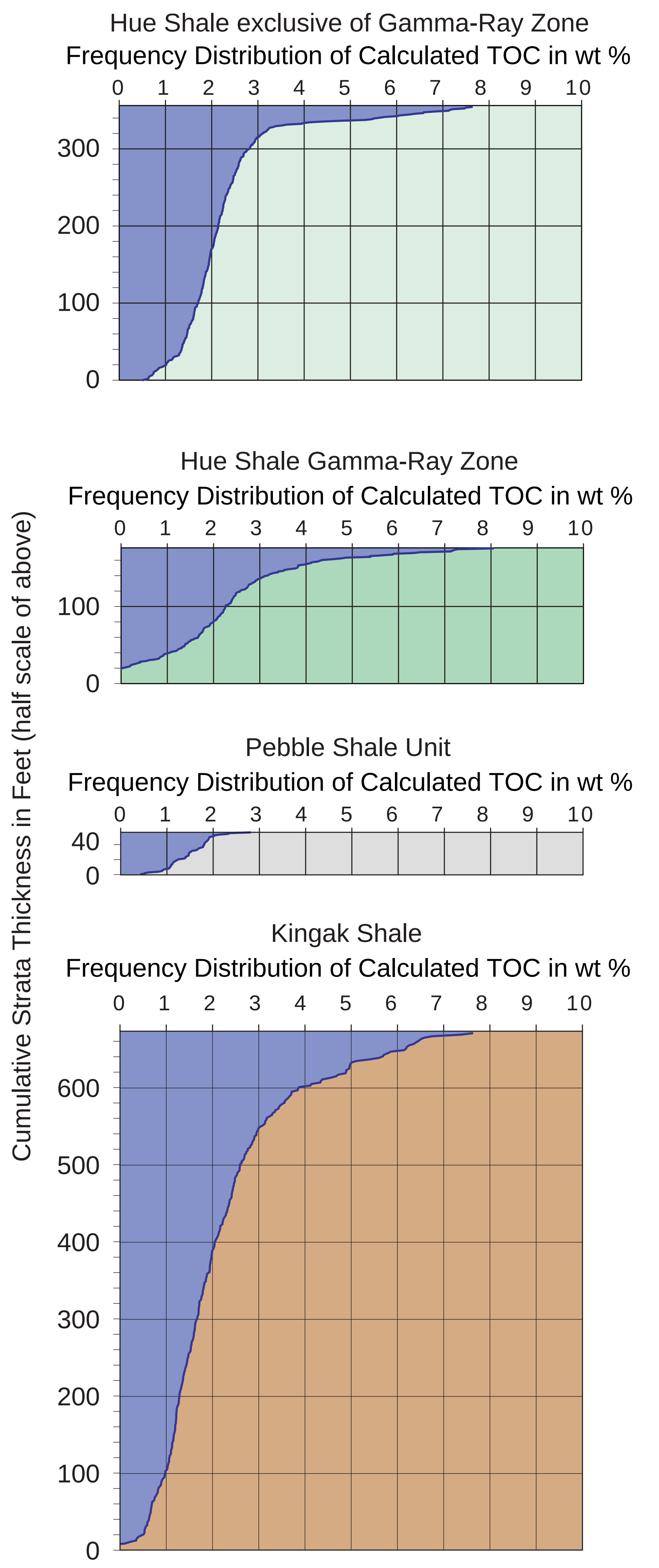


Hue Shale, Pebble Shale Unit, and Kingak Shale

Canning River B-1
API No. 50-179-20006
wt %TOC, measured (●) and calculated (Δ Log R method)



Positive ΔLogR separation resulting from sonic (DT) log's position to the left of resistivity (ILD) log when log traces are properly scaled and aligned at baseline values for DT and ILD (see Passey and others, 1990). Baseline for ΔLogR calculations is 76 µsec./ft. and 10.2 ohm-meters at 7,560-7,580 ft. Casing was set above the Hue Shale at approximately 2,500 ft.



ΔLogR CALCULATIONS

Data used for analysis of this well include the well history; mudlog; DT, ILD, gamma-ray, and caliper borehole geophysical logs; and reported TOC values measured on cuttings. No additional information is available about the TOC values from cuttings, such as whether the samples were composited or from selected individual rock chips. The caliper log indicates that caving occurred in many parts of the borehole, and severely in the Kingak, pebble shale unit, lower part of the GRZ, and in the Canning Formation overlying the Hue Shale. Therefore, both the quality of the borehole logs, principally the sonic DT log, and the representativeness of the measured values of TOC (from borehole cuttings) are somewhat questionable. However, in general the calculated TOC values agree very well with measured values, or seem to differ in a reasonable manner in that they represent interval averages of different intervals, with the exception of two anomalous TOC peaks at ≈ 7,805 ft and 7,840 ft. These peaks correlate to relatively high measured TOC values between 5 and 6 wt %, but have "negative" calculated TOCs due to very low resistivity or high conductivity, and are present in the GRZ in all the wells. They also commonly correspond to relatively higher gamma-ray response, and may be tuff or bentonite as noted in the mudlog and in outcrop for the GRZ (Bird and Molenaar, 1987; Bergman and others, 1995).

Some intervals where the calculated TOC values are much higher than measured TOCs, such as the upper part of the Hue Shale, may indicate contamination by cuttings from overlying units with lower TOC. The other explanation for most of the intervals in which the travel times exceed 150 µsec/ft (e.g. ≈ 7,890-7,910 ft and 8,110-8,180 ft) and where the calculated TOCs are also much higher than measured TOC values is cycle skipping, as described for the Canning River A-1 well.

Richness and source potential indices for the Hue Shale, including the Gamma-Ray Zone (GRZ), pebble shale unit (pbsh), and Kingak Shale in the Canning River B-1 well. Richness is from calculated TOC. Vitrinite reflectance values from Nelson & others (Ch. WL, Plate WL14). Baseline for ΔLogR calculations is 76 µsec./ft. and 10.2 ohm-meters at 7,560-7,580 ft.

	Hue, GRZ, & pbsh	*Hue Shale (Above GRZ)*	*Hue Shale (GRZ)*	*pebble shale unit*	*Kingak Shale*	*Kingak Shale**
Gross Thickness (ft)	585	355	175	55	335	335
Net Thickness (TOC≥2 wt %)	285	186	95	5	143	283
Average TOC wt %	2.15%	2.25%	2.15%	1.47%	2.17%	2.17%
Maximum TOC value	8.1	7.6	8.1	2.8	7.7	7.7
Average TOC≥2 wt %	3.04%	2.91%	3.32%	2.27%	3.4%	2.46%
Net Richness	**866**	**541**	**315**	**11**	**486**	**696**
Vitrinite Reflectance %R_o	0.95	0.95	0.95	0.95	0.95	0.95
Maturity Factor (Oil)	1	1	1	1	1	1
Source Potential Index (Oil)	**866**	**541**	**315**	**11**	**486**	**696**
Maturity Factor (Gas)	0.4	0.4	0.4	0.4	0.4	0.4
Source Potential Index (Gas)	**346**	**216**	**126**	4	**194**	**278**

**Tabulations using≥ 1 wt % TOC.*

INTERIOR–GEOLOGICAL SURVEY, RESTON, VA–1998

TOTAL ORGANIC CARBON PROFILE AND CALIPER, GAMMA-RAY, RESISTIVITY, AND SONIC LOGS, HUE SHALE, PEBBLE SHALE UNIT, AND KINGAK SHALE, CANNING RIVER B-1

By
Margaret A. Keller, Kenneth J. Bird, and Kevin R. Evans
1998

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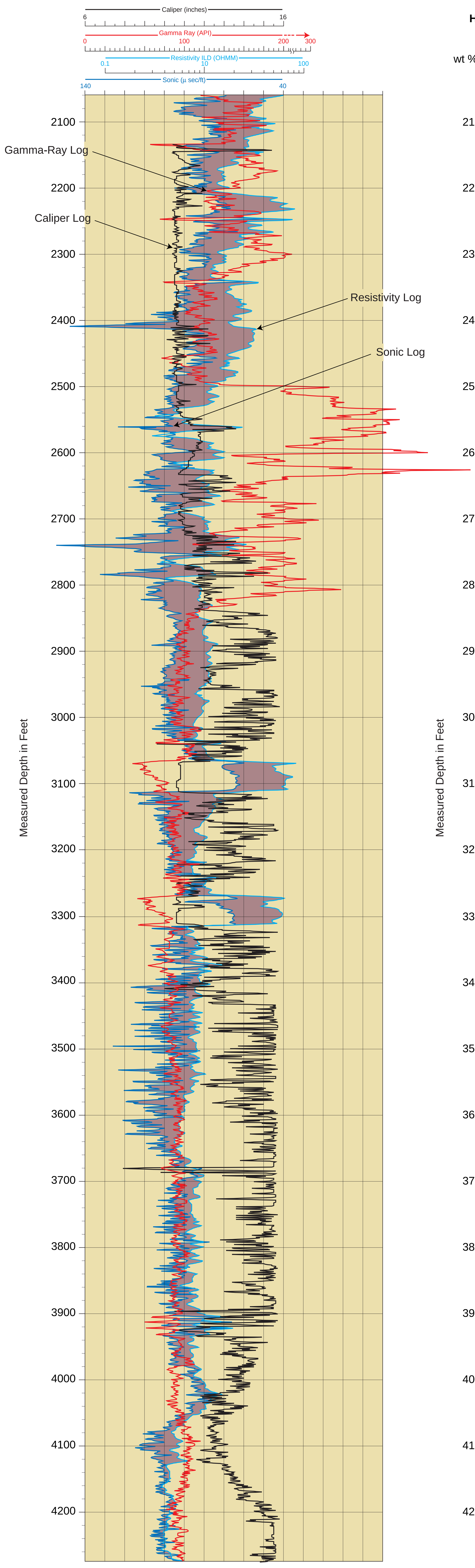
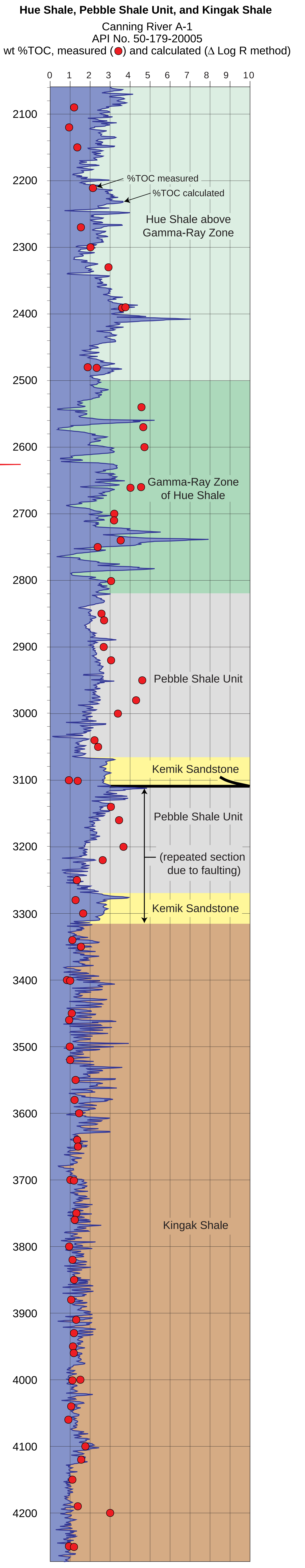
OPEN-FILE REPORT 98-34
PLATE SR7





Positive ΔLogR separation resulting from sonic (DT) log's position to the left of resistivity (ILD) log when log traces are properly scaled and aligned at baseline values for DT and ILD (see Passey and others, 1990). Baseline for ΔLogR calculations is 80 μsec./ft. and 10 ohm-meters at 4,200-4,250 ft. Casing was set at 2,138 ft in the upper part of the Hue Shale, and above the Hue Shale at approximately 500 ft.

ΔLogR CALCULATIONS

Stratigraphic and structural interpretation of the Canning River A-1 well includes a fault-repeated section of Kemik Sandstone and pebble shale. Only data from the upper succession, the Hue Shale above the Gamma-Ray Zone (GRZ), the Gamma-Ray Zone, and the pebble shale, were included in the frequency distributions (at right) and the tabulations below.

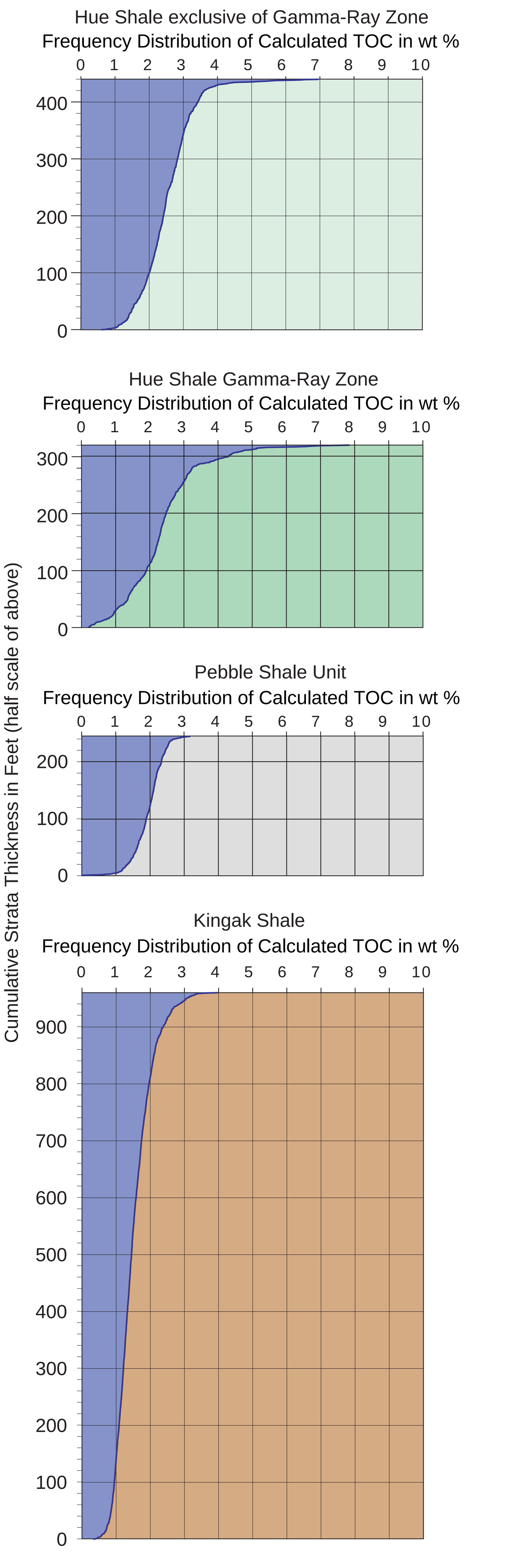
Data used for analysis of this well include the well history; mudlog; DT, ILD, gamma-ray, and caliper borehole geophysical logs; and reported TOC values measured on cuttings. No additional information is available about the TOC values from cuttings, such as whether the samples were composited or from selected individual rock chips. The caliper log indicates that caving occurred in many parts of the borehole, but most severely in the Kingak Shale, pebble shale, and parts of the GRZ. Therefore, both the quality of the borehole logs, principally the sonic DT log, and the representativeness of the measured values of TOC (from borehole cuttings) are questionable. Some intervals where measured TOC values are lower than calculated values, such as the upper part of the Hue Shale, may indicate contamination by cuttings from overlying units with lower TOC. This could not be verified with lithologic data from the mudlog because the log wasn't run until 3,480 ft, within the Kingak Shale. However, the well was cased at 2,138 ft or ≈ 80 ft below the top of the Hue Shale, and just below the points where measured values are less than half the calculated values.

In most of the Hue Shale above the GRZ and in part of the GRZ and pebble shale, the calculated TOC values agree very well with the measured values, or seem to differ in a reasonable manner in that they represent interval averages of different intervals. In at least 2 places (≈2,410 and 2,740 ft), however, cycle skipping, which is often observed on the transit-time curve in poor boreholes (Passey and others, 1990), may have produced the very long travel times (exceeding 150 μsec/ft) which yield erroneously high calculated TOC values. In other parts of the well, most notably the upper part of the GRZ, measured TOC values are much higher than calculated values; these are not likely to be contaminated because overlying measured values are much lower. This also occurs in the pebble shale. In the GRZ, these peaks of very low calculated TOCs correlating to relatively high measured TOCs of ≈5 wt %, also correspond to very low resistivity or high conductivity, and are present in the GRZ in all the wells. They also commonly have relatively higher gamma-ray response, and may be tuff or bentonite as noted in the mudlog and in outcrop for the GRZ (Bird and Molenaar, 1987; Bergman and others, 1995).

Richness and source potential indices for the Hue Shale, including the Gamma-Ray Zone (GRZ), pebble shale unit (pbsh), and Kingak Shale in the Canning River A #1 well. Richness is from calculated TOC. Vitrinite reflectance values from Nelson & others (Ch. WL, Plate WL13). Baseline for ΔLogR calculations is 80 μsec./ft. and 10 ohm-meters at 4,200-4,250 ft. Note that for intervals of this thickness, two or more baselines would probably be appropriate, however, stratigraphy and maturity in this well make baselines difficult to establish.

	Hue, GRZ, & pbsh	*Hue Shale (Above GRZ)*	*Hue Shale (GRZ)*	*pebble shale unit*	*Kingak Shale*	*Kingak Shale**
Gross Thickness (ft)	1005	440	320	245	960	960
Net Thickness (TOC≥2 wt %)	691	344	212	135	144	813
Average TOC wt %	2.37%	2.55%	2.39%	2.01%	1.50%	1.50%
Maximum TOC value	7.9	7.0	7.9	3.3	4.0	4.0
Average TOC≥2 wt %	2.75%	2.81%	2.92%	2.31%	2.39%	1.61%
Net Richness	**1900**	**967**	**619**	**312**	**344**	**1309**
Vitrinite Reflectance %R_o	0.9	0.9	0.9	0.9	0.9	0.9
Maturity Factor (Oil)	1	1	1	1	1	1
Source Potential Index (Oil)	**1900**	**967**	**619**	**312**	**344**	**1309**
Maturity Factor (Gas)	0.4	0.4	0.4	0.4	0.4	0.4
Source Potential Index (Gas)	**760**	**387**	**248**	**125**	**138**	**523**

**Tabulations using ≥ 1 wt % TOC.*



INTERIOR-GEOLOGICAL SURVEY, RESTON, VA-1998

TOTAL ORGANIC CARBON PROFILE AND CALIPER, GAMMA-RAY, RESISTIVITY, AND SONIC LOGS, HUE SHALE, PEBBLE SHALE UNIT, AND KINGAK SHALE, CANNING RIVER A-1

By
Margaret A. Keller, Kenneth J. Bird, and Kevin R. Evans
1998

The Oil and Gas Resource Potential of the Arctic National Wildlife Refuge 1002 Area, Alaska Open File Report 98-34

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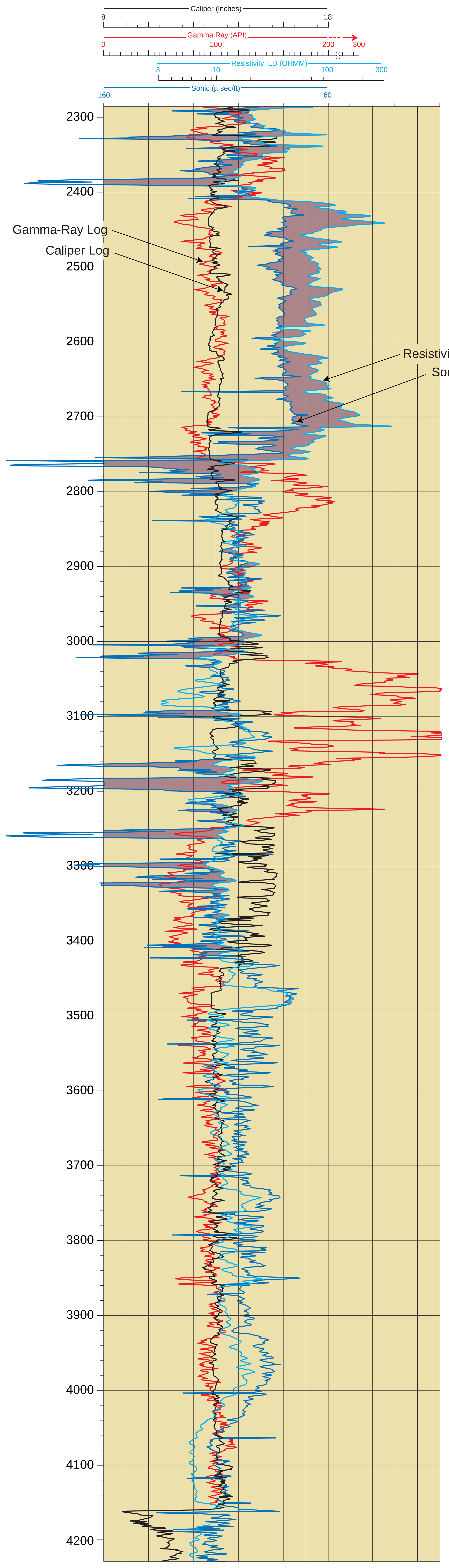
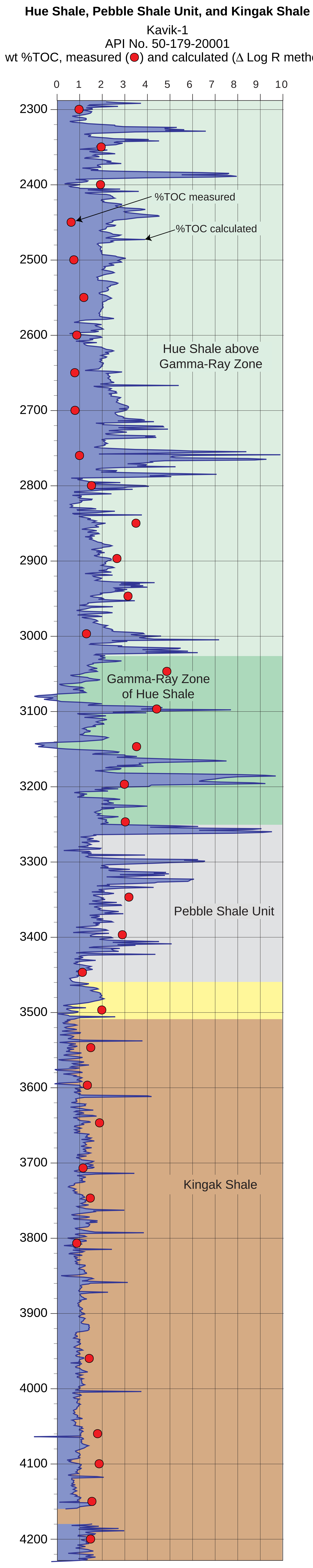
OPEN-FILE REPORT 98-34
PLATE SR8





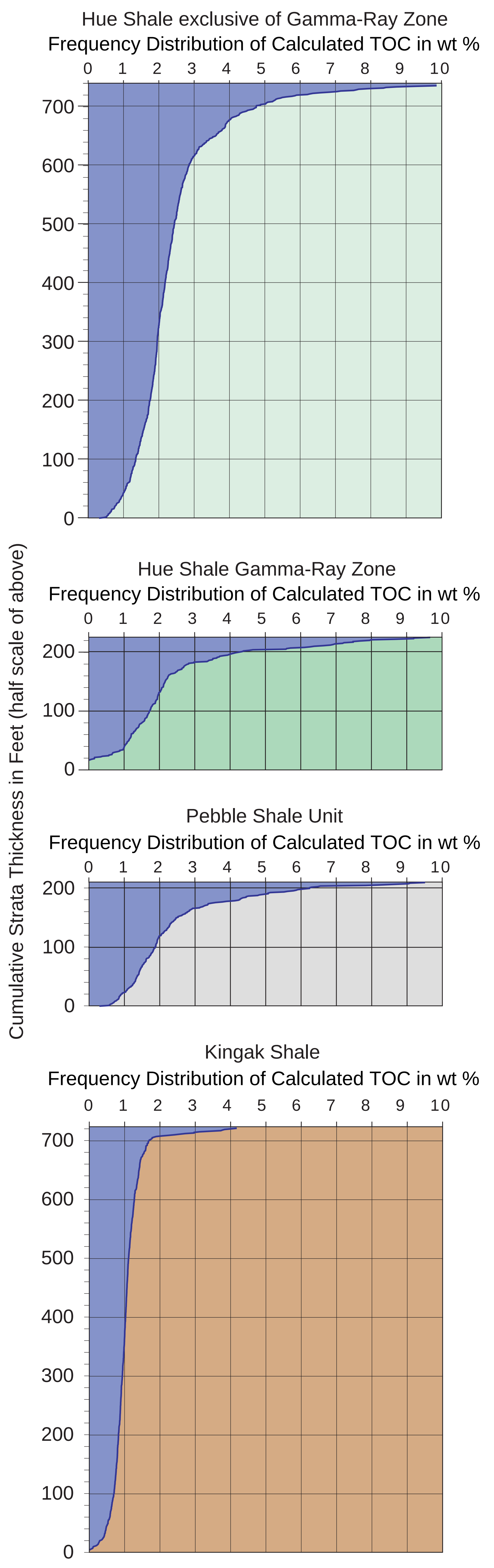
Positive ΔLogR separation resulting from sonic (DT) log's position to the left of resistivity (ILD) log when log traces are properly scaled and aligned at baseline values for DT and ILD (see Passey and others, 1990). Baselines for ΔLogR calculations are 90 μsec./ft. and 24 ohm-meters at 2,020-2,050 ft and 90 μsec./ft. and 14 ohm-meters at 3,930-3,990 ft. Casing was set above the Hue Shale at approximately 2,000 ft.

ΔLogR CALCULATIONS

Data used for analysis of this well include the well history; mudlog; DT, ILD, gamma-ray, and caliper borehole geophysical logs; and reported TOC values measured on cuttings. No additional information is available about the TOC values from cuttings, such as whether the samples were composited or from selected individual rock chips. The caliper log indicates that some caving occurred in a fairly continuous section of the lower GRZ and pebble shale interval in the borehole, and also in a few thinner intervals in the middle part of the GRZ and in the lower and upper part of the Hue above the GRZ. This does not appear to have affected the quality of the borehole logs, however, some process affected the DT log producing many thin spikes of erroneously high TOC. The DT log shows many transit time peaks to values much greater than 150 μsec/ft in the upper part of the pebble shale, the GRZ, and the Hue Shale above the GRZ in intervals just above 2,800 ft, at 2,300-2,400 ft, and just below 3000 ft. Many of these spikes except for the ones near 2,800 ft correlate to large gas kicks on the mudlog. They can also be caused by cycle skipping as described for the Canning River A-1 well.

Calculated ΔlogR TOC values only agree with measured values in isolated parts of the well. For most of the Hue Shale above 2,800 ft the ΔlogR TOCs are higher than measured TOCs, and below that they are mainly lower than measured TOCs except for the erroneous DT spikes described above. The lower values below 2,800 ft may be explained by the selection of baseline values, which are difficult to pick for this well. The calculated values can be brought more in line with measured values by adjusting the baseline. This won't improve the correlation for most of the section above 2,800 ft, where the baseline was changed, however, and particulary for the interval from 2,400-2,800 ft. The well was cased several hundred feet above the Hue at 2,000 ft and near the base of the Kingak section, so caving in the borehole above the Hue does not seem very likely either.

In the GRZ, also note the several intervals of "negative" or very low calculated TOCs which are due to high conductivity/low resistivity, and also correspond to relatively higher gamma-ray response. These intervals, which are present in the GRZ in all the wells, may be tuff or bentonite as described in the well history and in outcrop (Bird and Molenaar, 1987; Bergman and others, 1995).



Richness and source potential indices for the Hue Shale, including the Gamma-Ray Zone (GRZ), pebble shale unit (pbsh), and Kingak Shale in the Kavik-1 well. Richness is from calculated TOC. Vitrinite reflectance values from Nelson & others (Ch. WL, Plate WL22). Baselines for ΔLogR calculations are 90 μsec./ft. and 24 ohm-meters at 2,020-2,050 ft and 90 μsec./ft. and 14 ohm-meters at 3,930-3,990 ft.

	Hue, GRZ, & pbsh	*Hue Shale (Above GRZ)*	*Hue Shale (GRZ)*	*pebble shale unit*	*Kingak Shale*	*Kingak Shale**
Gross Thickness (ft)	1170	735	225	210	740	740
Net Thickness (TOC≥2 wt %)	603	418	93	90	13	357
Average TOC wt %	2.35%	2.37%	2.24%	2.42%	1.02%	1.02%
Maximum TOC value	9.9	9.9	9.7	9.5	4.2	4.2
Average TOC≥2 wt %	3.24%	3.01%	3.8%	3.76%	3.14%	1.3%
Net Richness	**1954**	**1258**	**353**	**338**	**41**	**464**
Vitrinite Reflectance %R_o	1.0	1.0	1.0	1.0	1.1	1.1
Maturity Factor (Oil)	1	1	1	1	0.7	0.7
Source Potential Index (Oil)	**1954**	**1258**	**353**	**338**	**29**	**325**
Maturity Factor (Gas)	0.4	0.4	0.4	0.4	0.7	0.7
Source Potential Index (Gas)	**782**	**503**	**141**	**135**	**29**	**325**

**Tabulations using ≥ 1 wt % TOC.*

INTERIOR–GEOLOGICAL SURVEY, RESTON, VA–1998

TOTAL ORGANIC CARBON PROFILE AND CALIPER, GAMMA-RAY, RESISTIVITY, AND SONIC LOGS, HUE SHALE, PEBBLE SHALE UNIT, AND KINGAK SHALE, KAVIK-1

By
Margaret A. Keller, Kenneth J. Bird, and Kevin R. Evans
1998

The Oil and Gas Resource Potential of the
Arctic National Wildlife Refuge 1002 Area, Alaska
Open File Report 98-34

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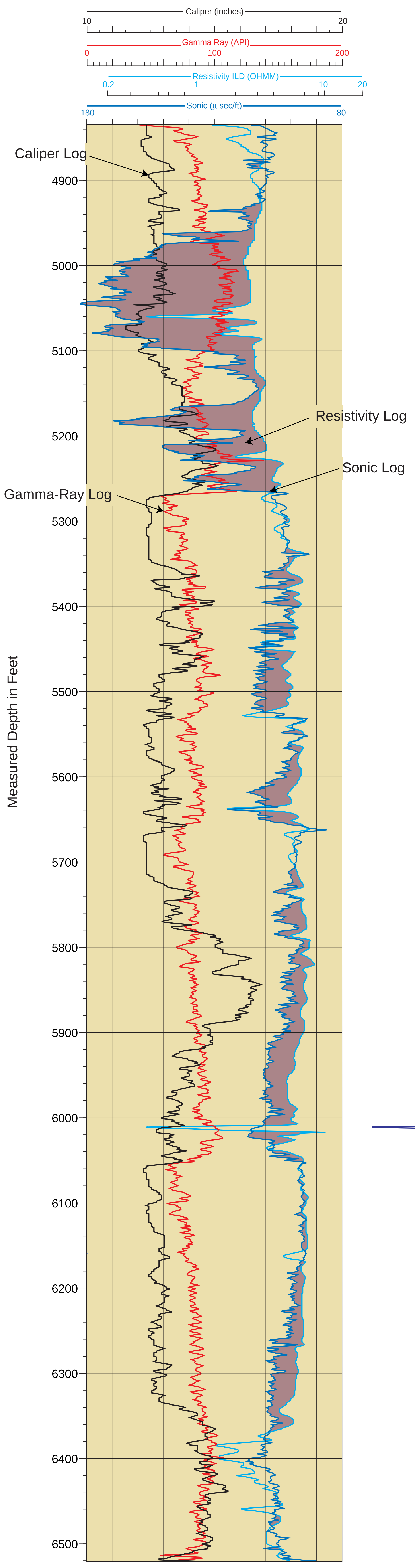
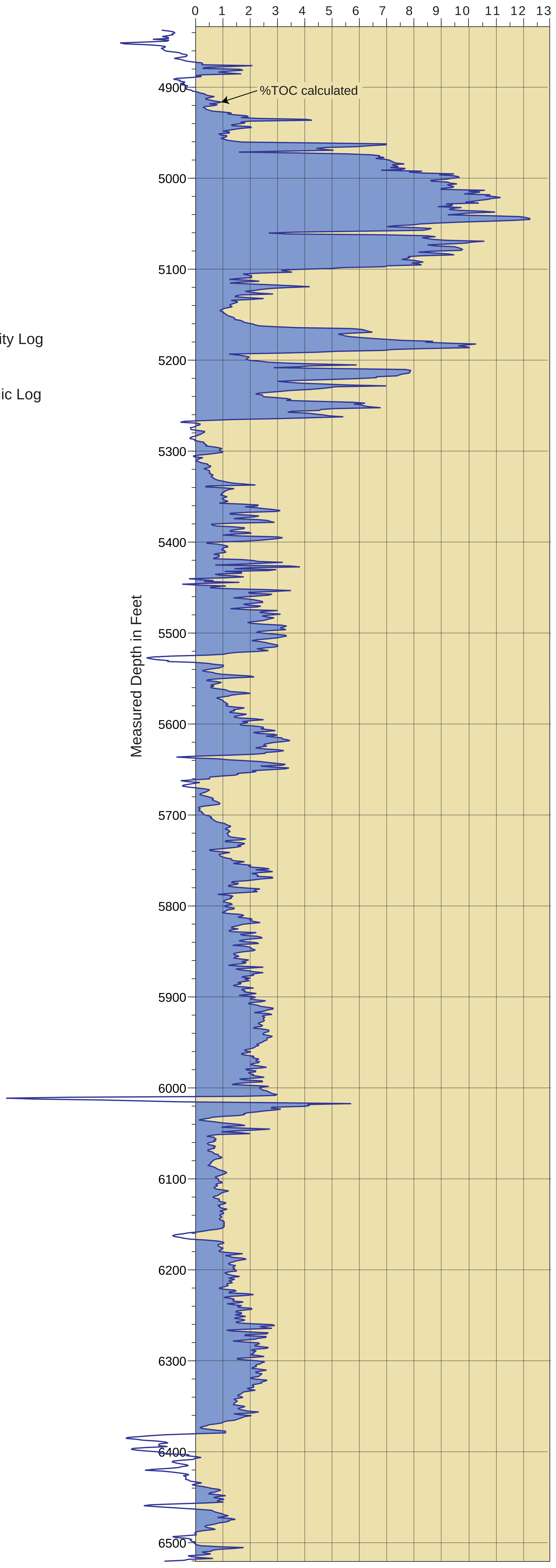
PLATE SR9



Mikkelsen Tongue of the Canning Formation

Mikkelsen Bay State-1
API No. 50-029-20055
wt %TOC, calculated (Δ log R method)



Positive ΔLogR separation resulting from sonic (DT) log's position to the left of resistivity (ILD) log when log traces are properly scaled and aligned at baseline values for DT and ILD (see Passey and others, 1990). Baseline for ΔLogR calculation is 95 msec./ft. and 7 ohm-meters at 6,050-6,150 ft. Casing was set above the Mikkelsen Tongue at 2,900 ft.

Δ Log R CALCULATIONS

Data used for analysis of this well include the well history; mudlog; and DT, ILD, gamma-ray, and caliper borehole geophysical logs. In several parts of the Mikkelsen Tongue of the Canning Formation, mainly between approximately 5,100-5,270, 5,780-5,890, and 6,340-6,520 ft but also in several thinner intervals, the caliper log shows significant borehole sloughing, which can cause the DT log to have longer transit times (Rider, 1991, p. 20). However, only the upper of these intervals from 5,100-5,270 ft corresponds to longer transit times on the DT log, and the higher gamma-ray response of that interval suggests that the longer transit times are due to the presence of lower velocity organic matter. However, in part of the interval just described, between approximately 5,180-5,270 ft, and also between approximately 4,960-5,100 ft, the longer transit times are probably erroneous because values are much greater than 150 µsec/ft. These are most likely caused by cycle skipping (Passey and others, 1990) as described for the Canning River A-1 well (Plate SR7), and therefore yield erroneous calculated TOCs that are too high. Nevertheless, the longer transit times in combination with higher gamma-ray response of these two intervals suggests the presence of lower velocity organic matter.

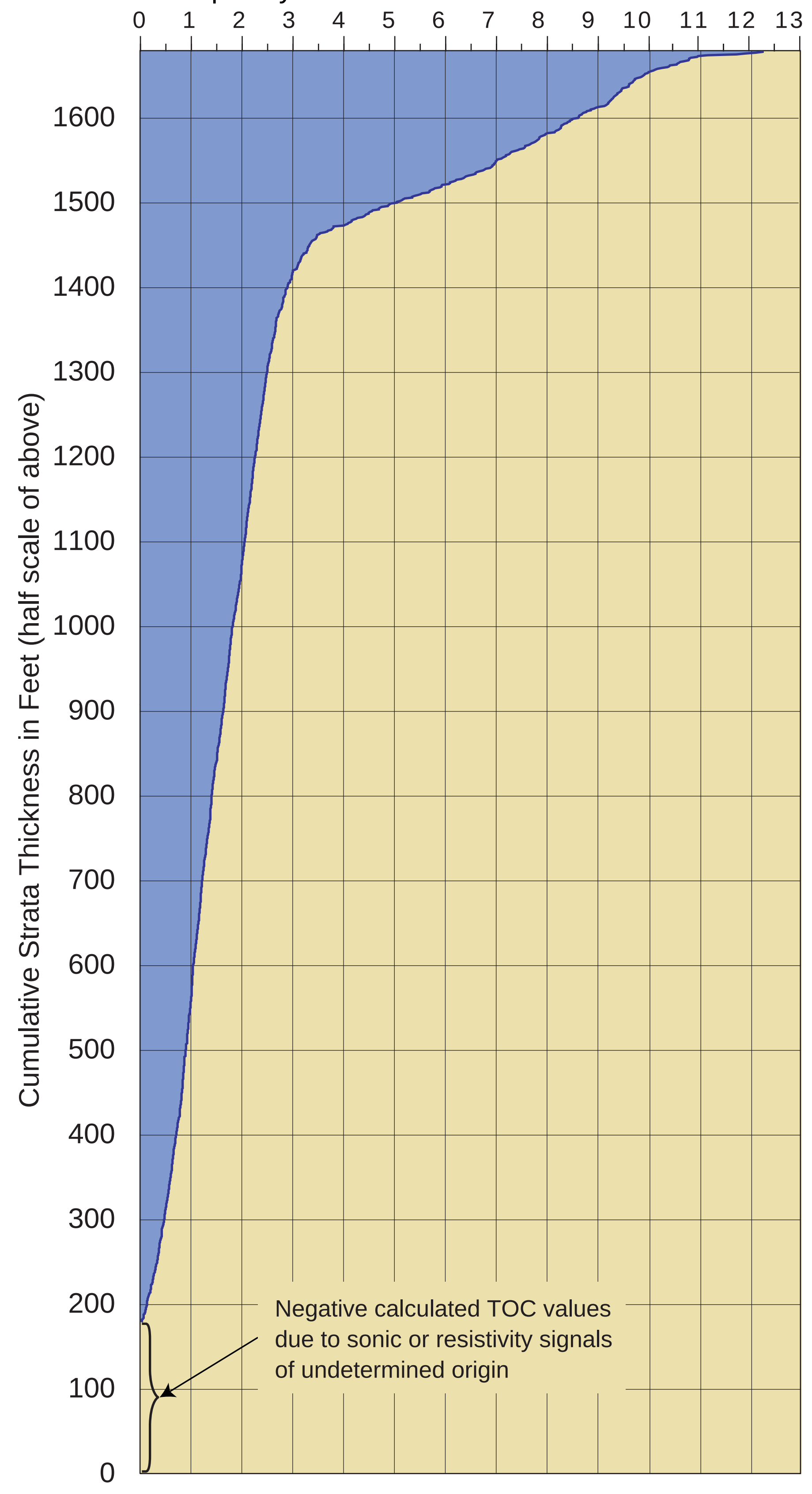
Note the several intervals of very low or "negative" ΔlogR calculated TOCs, which correlate to relatively lower resistivity or higher conductivity, but have no other consistent log characteristic. These intervals do not seem to be tuff or bentonite as described for the GRZ of the Hue Shale in the wells we evaluated on the west side of the 1002 area (Plates SR1-8).

Although no set of cutting's TOCs exists from this well for comparison to ΔlogR calculated TOCs, note that the upper part of the calculated TOC profile for the Mikkelsen Tongue in all four wells (Plate SR14) shows an interval of at least several hundred feet of relatively higher TOCs greater than 2 wt %. In addition, in the Point Thomson-2 well which had very little sloughing, the TOCs measured on cuttings in the upper part of the Mikkelsen Tongue show a trend towards higher values that corresponds to the interval of higher calculated TOCs.

Source potential indices (Dembicki & Pirkle, 1985) for oil and gas in the Mikkelsen Tongue of the Canning Formation, Mikkelsen Bay State-1 well. Richness is from calculated TOC at right. Vitrinite reflectance from Nelson & others (Ch. WL, Plate WL29). Baseline for ΔLogR calculation is 95 µsec./ft. and 7 ohm-meters at 6,050-6,150 ft.

Gross Thickness	1683
Net Thickness (TOC≥1 wt %)	1131
Average TOC≥1 wt % (Range)	3.0% (1-12.3%)
Net Richness	**3393**
Vitrinite Reflectance %R_o	0.5
Maturity Factor (Oil)	0.3
Source Potential Index (Oil)	**1018**
Maturity Factor (Gas)	0.1
Source Potential Index (Gas)	**339**

Frequency Distribution of Calculated TOC in wt %



INTERIOR–GEOLOGICAL SURVEY, RESTON, VA–1998

TOTAL ORGANIC CARBON PROFILE AND CALIPER, GAMMA-RAY, RESISTIVITY, AND SONIC LOGS, MIKKELSEN TONGUE OF THE CANNING FORMATION, MIKKELSEN BAY STATE-1

By
Margaret A. Keller, Kenneth J. Bird, and Kevin R. Evans
1998

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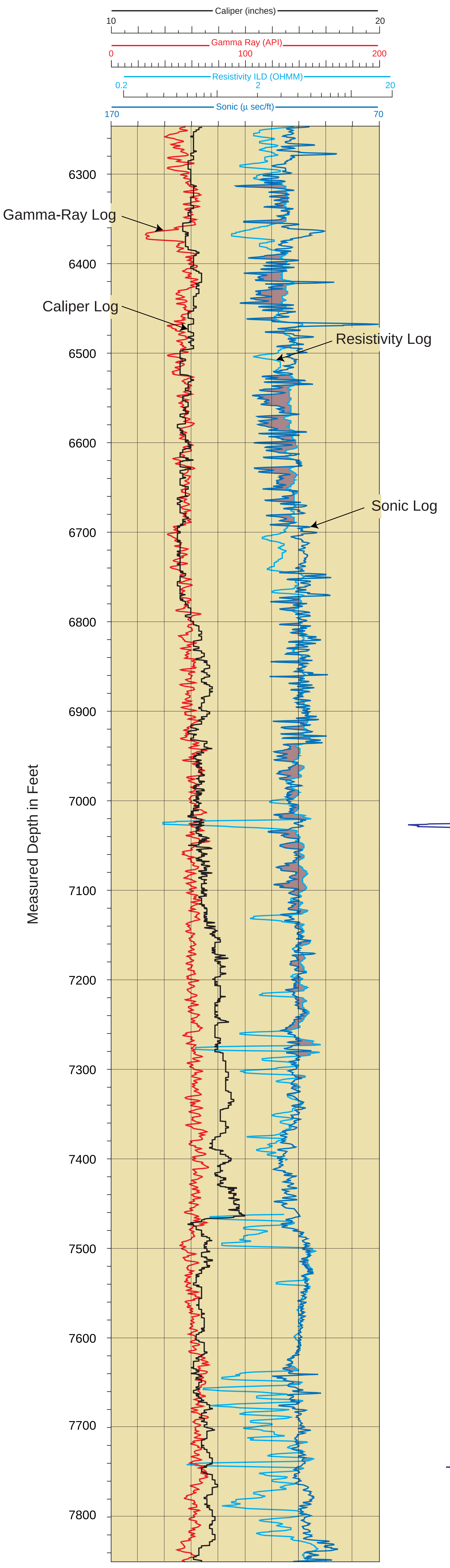
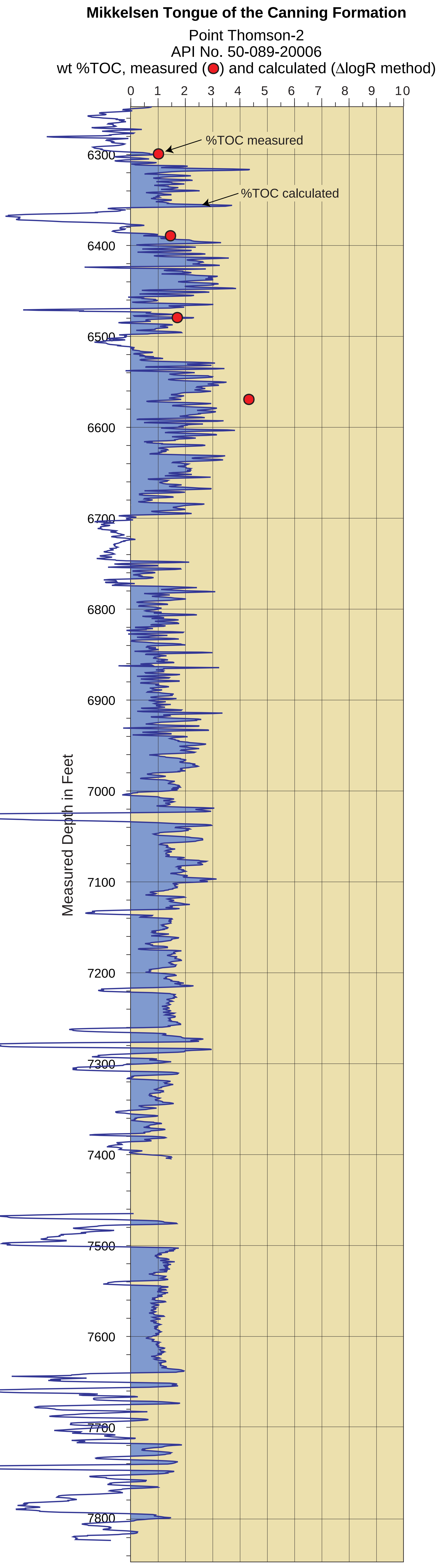
PLATE SR10





Positive ΔLogR separation resulting from sonic (DT) log's position to the left of resistivity (ILD) log when log traces are properly scaled and aligned at baseline values for DT and ILD (see Passey and others, 1990). Baseline for ΔLogR calculation is 99 msec./ft. and 4.1 ohm-meters at 6,800-6,900 ft. Casing was set above the Mikkelsen Tongue at approximately 3,400 ft.

ΔLogR CALCULATIONS

Data used for analysis of this well include the well history; mudlog; DT, ILD, gamma-ray, and caliper borehole geophysical logs; and reported TOC values measured on cuttings. No additional information is available about the TOC values from cuttings, such as whether the samples were composited or from selected individual rock chips, but since the caliper log shows very little sloughing, these data are thought to represent at least part of the interval indicated for them.

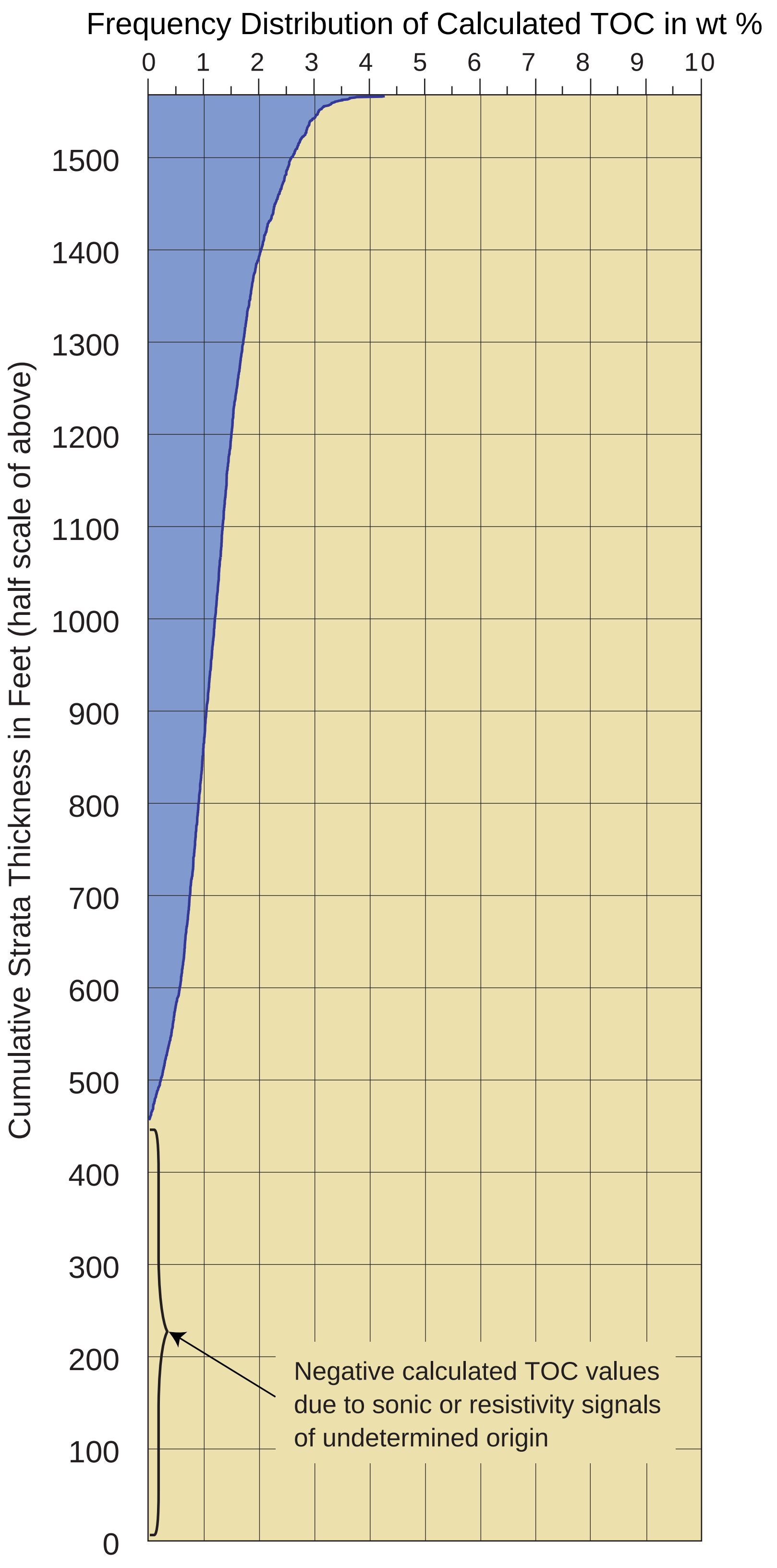
The few TOCs measured on borehole cuttings compare fairly well with calculated TOC values, although the higher measured value from cuttings at 6,570 might be indicating that the baseline needs to be adjusted. However, shifting the baseline would uniformly add approximately 1-1.5 wt % TOC to the curve, not changing its shape, but moving the other measured values farther from the calculated values, so the present baseline is probably better even with the numerous "negative" values for calculated TOC that are due to low resistivity or high conductivity in these intervals. Similar intervals are described for the Mikkelsen Tongue in the Mikkelsen Bay-1 well (Plate SR9).

Gamma-ray log response for the Mikkelsen Tongue is relatively flat and consistent in this well, even through the potential source intervals identified by the ΔlogR method. This is also the case in the West Staines-2 and Alaska State C-1 wells, in contrast to the variable response in the Mikkelsen Bay-1 well where intervals of higher gamma-ray response correspond to higher calculated TOCs. Creaney and Passey (1993) show an example of logs from the Paris basin, where the gamma-ray response is also relatively low for the source rock intervals they identified by the ΔlogR method and corroborated by measured TOC values, thus higher gamma-ray response isn't always present in source rock intervals.

Source potential indices (Dembicki & Pirkle, 1985) for oil and gas in the Mikkelsen Tongue of the Canning Formation, Point Thomson-2 well. Richness is from calculated TOC at right. Vitrinite reflectance from Nelson & others (Ch. WL, Plate WL34). Baseline for ΔLogR calculation is 99 µsec./ft. and 4.1 ohm-meters at 6,800-6,900 ft.

Gross Thickness	1577
Net Thickness (TOC≥1 wt %)	772
Average TOC≥1 wt % (Range)	1.7% (1.0-4.4%)
Net Richness	**1336**
Vitrinite Reflectance %R_o	0.5
Maturity Factor (Oil)	0.3
Source Potential Index (Oil)	**401**
Maturity Factor (Gas)	0.1
Source Potential Index (Gas)	**134**

Frequency Distribution of Calculated TOC in wt %



INTERIOR–GEOLOGICAL SURVEY, RESTON, VA–1998

TOTAL ORGANIC CARBON PROFILE AND CALIPER, GAMMA-RAY, RESISTIVITY, AND SONIC LOGS, MIKKELSEN TONGUE OF THE CANNING FORMATION, POINT THOMSON-2

By
Margaret A. Keller, Kenneth J. Bird, and Kevin R. Evans
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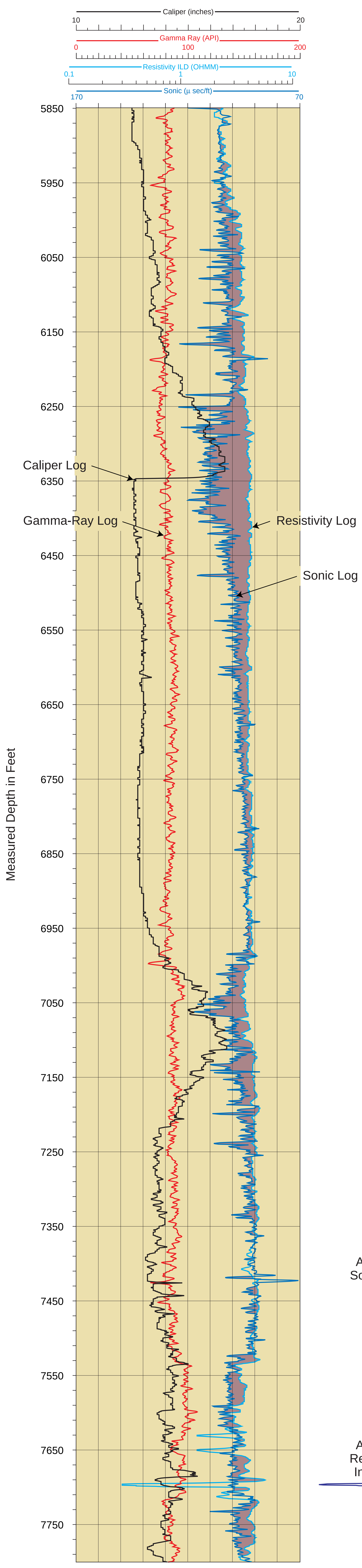
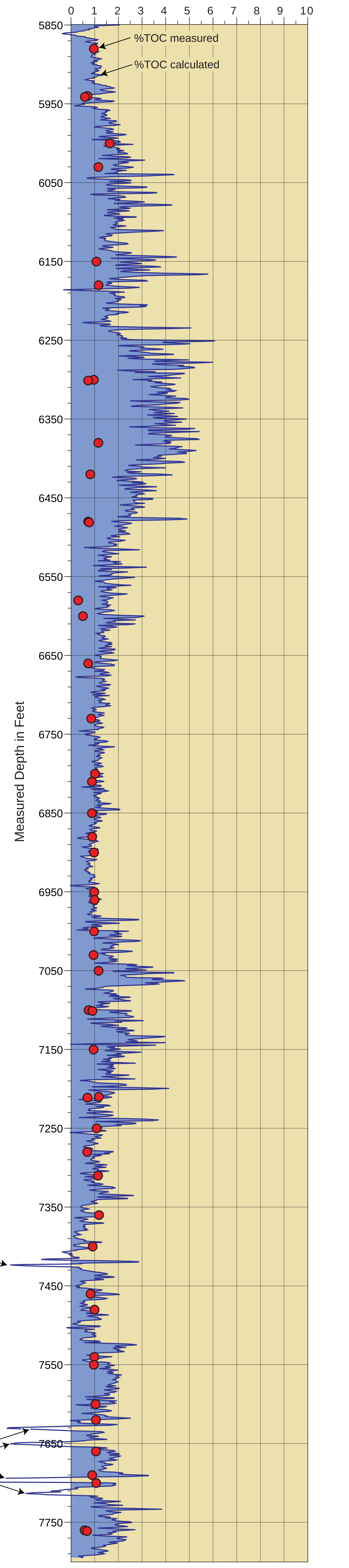
PLATE SR11



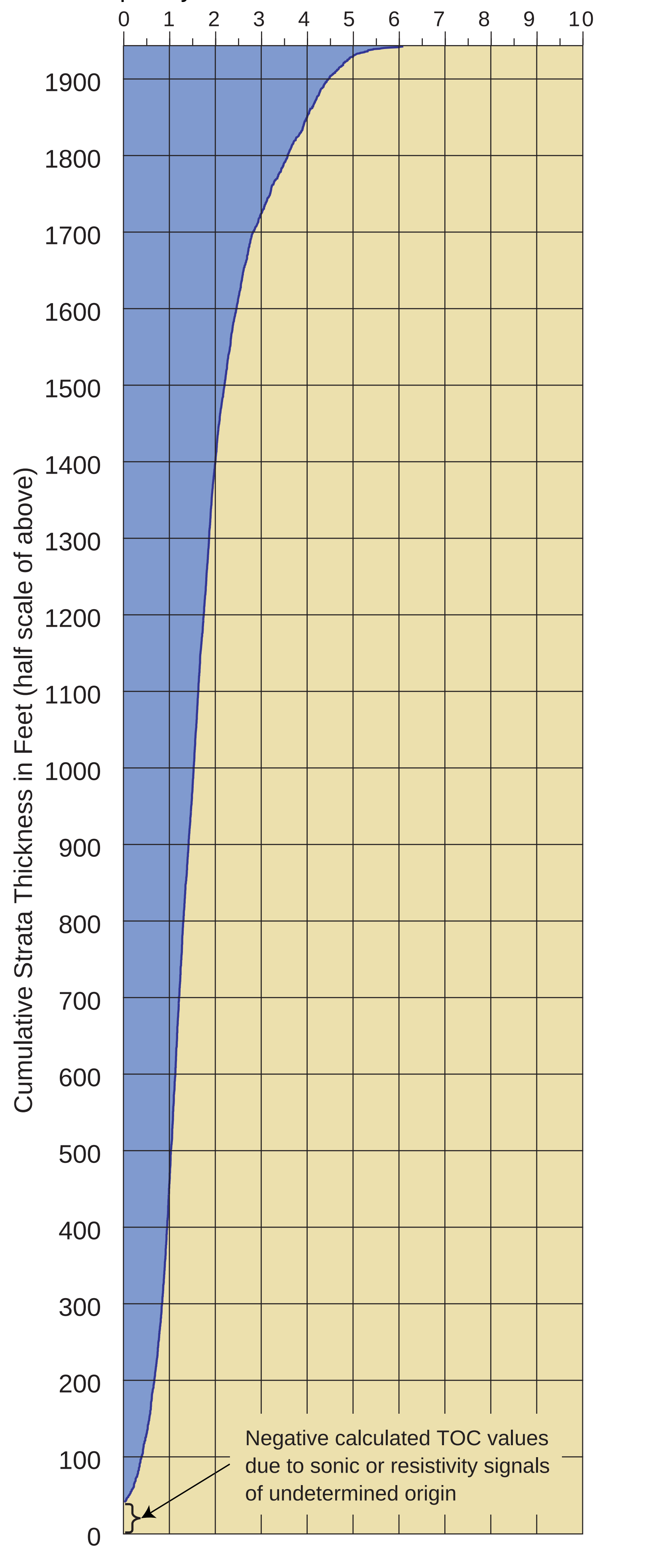
Mikkelsen Tongue of the Canning Formation

West Staines-2
API No. 50-089-20004
wt %TOC, measured (●) and calculated (Δ log R method)



Positive ΔLogR separation resulting from sonic (DT) log's position to the left of resistivity (ILD) log when log traces are properly scaled and aligned at baseline values for DT and ILD (see Passey and others, 1990). Note that two baselines were used to calculate ΔLogR values in this well. The curves are scaled to the upper baseline at 105 µsec and 2.2 ohm-meters at 5,870-5,930 ft. The lower baseline is 94 µsec and 4.1 ohm-meters at 6,900-7,000 ft. Casing was set above the Mikkelsen Tongue at 2,280 ft.

Frequency Distribution of Calculated TOC in wt %



ΔLogR CALCULATIONS

Data used for analysis of this well include the well history; mudlog; DT, ILD, gamma-ray, and caliper borehole geophysical logs; and reported TOC values measured on cuttings. No additional information is available about the TOC values from cuttings, such as whether the samples were composited or from selected individual rock chips.

The caliper log indicates that major sloughing occurred in the borehole between approximately 6,150-6,350 ft and 6,950-7,200 ft. Contamination of cuttings due to sloughing may explain the lack of agreement between ΔlogR calculated TOC values and TOC values measured on cuttings between approximately 6,300-6,600 ft.

Note the several intervals of very low or "negative" ΔlogR calculated TOCs which correspond to relatively lower resistivity or higher conductivity, but have no other consistent log characteristic. These intervals do not seem to be tuff or bentonite as described for similar log response in the GRZ of the Hue Shale in wells on the west side of the 1002 area (Plates SR1-8).

Gamma-ray log response for the Mikkelsen Tongue is relatively flat and consistent in this well, even through the main potential source interval identified by the ΔlogR method between 6,250-6,500 ft. This is also the case in the Point Thomson-2 and Alaska State C-1 wells, in contrast to the variable response in the Mikkelsen Bay-1 well where intervals of higher gamma-ray response correspond to higher calculated TOCs (see discussion of gamma-ray response on Plate SR10).

Source potential indices (Dembicki & Pirkle, 1985) for oil and gas in the Mikkelsen Tongue of the Canning Formation, West Staines-2 well. Net richness is from calculated TOC at right. Vitrinite reflectance from Nelson & others (Ch. WL, Plate WL37). Two baselines were used for ΔLogR calculation: 1) for the interval 5,000-6,500 ft., 105 µsec./ft. and 2.2 ohm-meters at 5,870-5,930 ft.; and 2) for the interval 6,500-8,000 ft., 94 µsec./ft. and 4.1 ohm-meters at 6,900-7,000 ft.

Gross Thickness	1945'
Net Thickness (TOC≥1 wt %)	1498'
Average TOC≥1 wt % (Range)	2.03% (1.0-6.0%)
Net Richness	**3041**
Vitrinite Reflectance %R_o	0.5
Maturity Factor (Oil)	0.3
Source Potential Index (Oil)	**912**
Maturity Factor (Gas)	0.1
Source Potential Index (Gas)	**304**

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TOTAL ORGANIC CARBON PROFILE AND CALIPER, GAMMA-RAY, RESISTIVITY, AND SONIC LOGS, MIKKELSEN TONGUE OF THE CANNING FORMATION, WEST STAINES-2

By
Margaret A. Keller, Kenneth J. Bird, and Kevin R. Evans
1998

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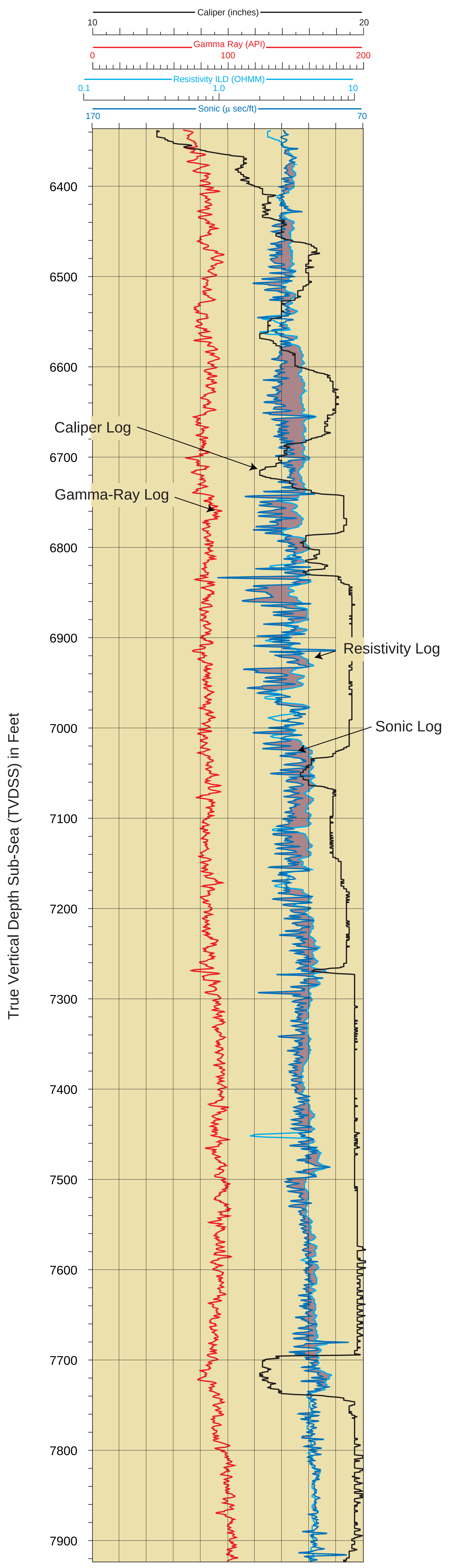
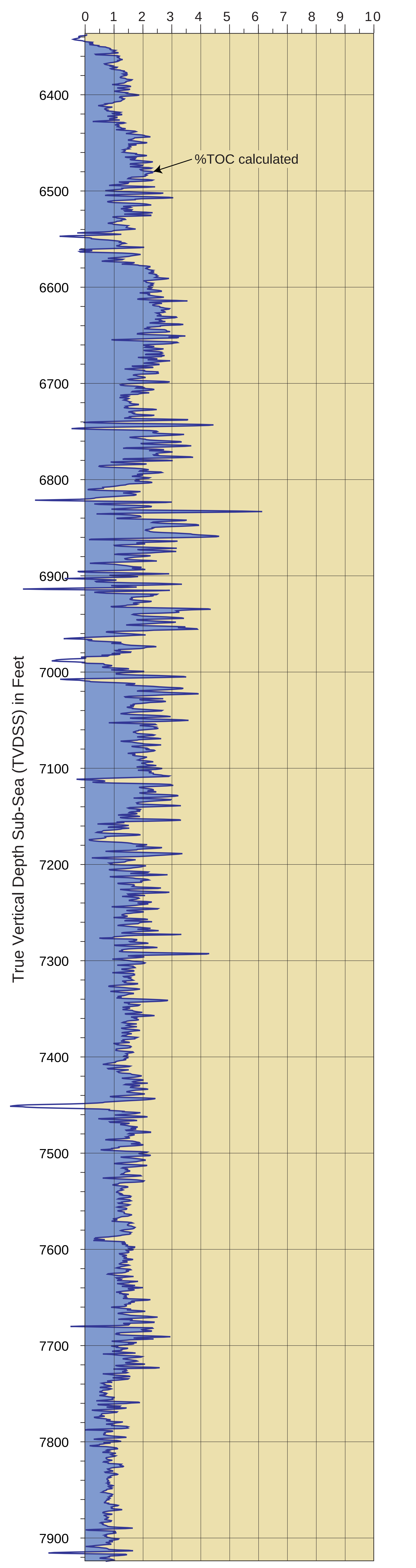


Mikkelsen Tongue of the Canning Formation

Alaska State C-1
API No. 50-089-20011
wt %TOC, calculated (Δ log R method)



Positive ΔLogR separation resulting from sonic (DT) log's position to the left of resistivity (ILD) log when log traces are properly scaled and aligned at baseline values for DT and ILD (see Passey and others, 1990). Baseline for ΔLogR calculation is 88 msec./ft. and 5.0 ohm-meters at 7,750-7,900 ft. Casing was set above the Mikkelsen Tongue at approximately 3,950 ft (TVDSS).

ΔLogR CALCULATIONS

Data used for analysis of this well include the well history; mudlog; and DT, ILD, gamma-ray, and caliper borehole geophysical logs. Throughout most of the Mikkelsen Tongue of the Canning Formation in this well, the caliper log shows significant borehole sloughing, which can cause the DT log response to exhibit longer transit times (Rider, 1991, p. 20). That may be the cause of the longer transit times on the DT log for much of this well, however, no other well data exists to corroborate that, and in most of the section below 7,300 ft where the borehole is also sloughing, the transit times are relatively shorter. Therefore, the longer transit times could also be due to the presence of low velocity organic matter.

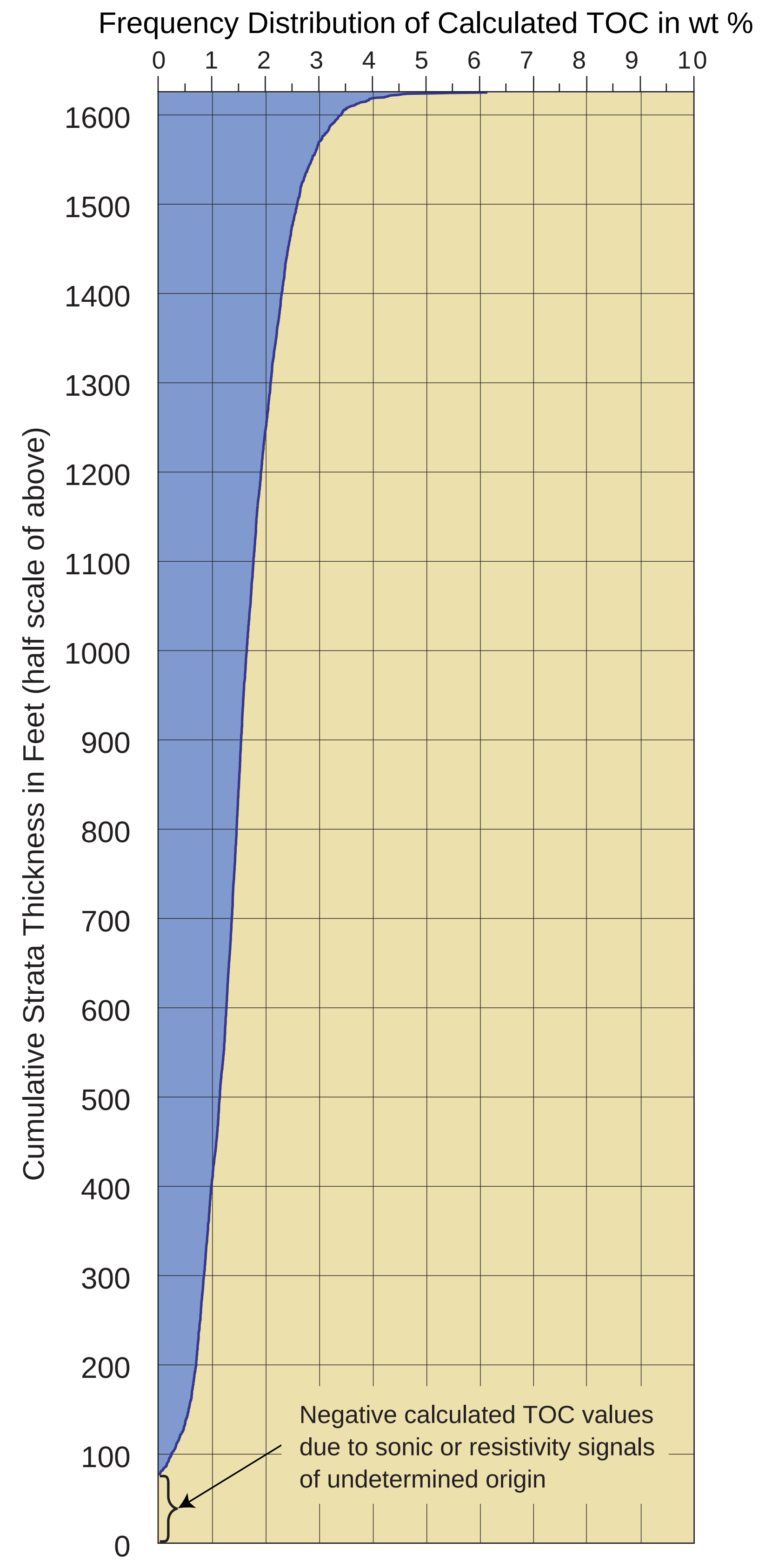
Gamma-ray log response for the Mikkelsen Tongue in this well is relatively flat and consistent even through the possible source interval between approximately 6450-7,300 ft identified by ΔlogR calculated TOCs greater than 2%. This flat gamma-ray log pattern is also exhibited in the West Staines-2 and Point Thomson-2 wells, in contrast to the variable response in the Mikkelsen Bay-1 well, where intervals of higher gamma-ray response correspond to higher calculated TOCs (see discussion of gamma-ray response on Plate SR10).

Source potential indices (Dembicki & Pirkle, 1985) for oil and gas in the Mikkelsen Tongue of the Canning Formation, Alaska State C-1 well. Net richness is from calculated TOC at right. Vitrinite reflectance from Nelson & others (Ch. WL, Plate WL4). Baseline for ΔLogR calculation is 88 µsec./ft. and 5.0 ohm-meters at 7,750-7,900 ft.; note caving in borehole through most of the Mikkelsen Tongue.

Gross Thickness	1587*
Net Thickness (TOC≥1%)	1215*
Average TOC≥1 wt % (Range)	1.8% (1.0-6.1%)
Net Richness	**2187**
Vitrinite Reflectance % R_o	0.5
Maturity Factor (Oil)	0.3
Source Potential Index (Oil)	**656**
Maturity Factor (Gas)	0.1
Source Potential Index (Gas)	**219**

*Calculated using TVDSS.

Frequency Distribution of Calculated TOC in wt %



INTERIOR--GEOLOGICAL SURVEY, RESTON, VA--1998

TOTAL ORGANIC CARBON PROFILE AND CALIPER, GAMMA-RAY, RESISTIVITY, AND SONIC LOGS, MIKKELSEN TONGUE OF THE CANNING FORMATION, ALASKA STATE C-1

By
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1998

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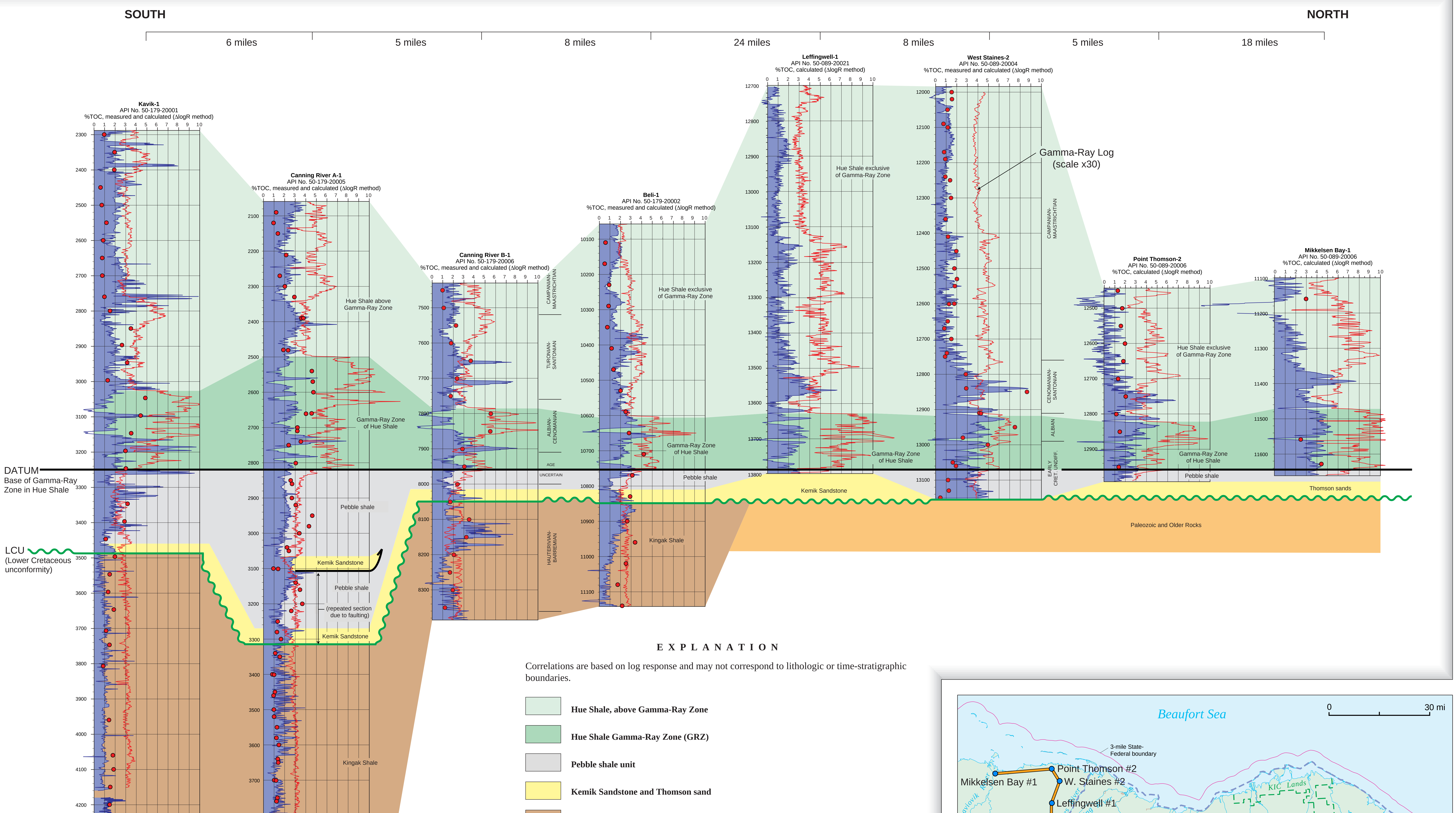
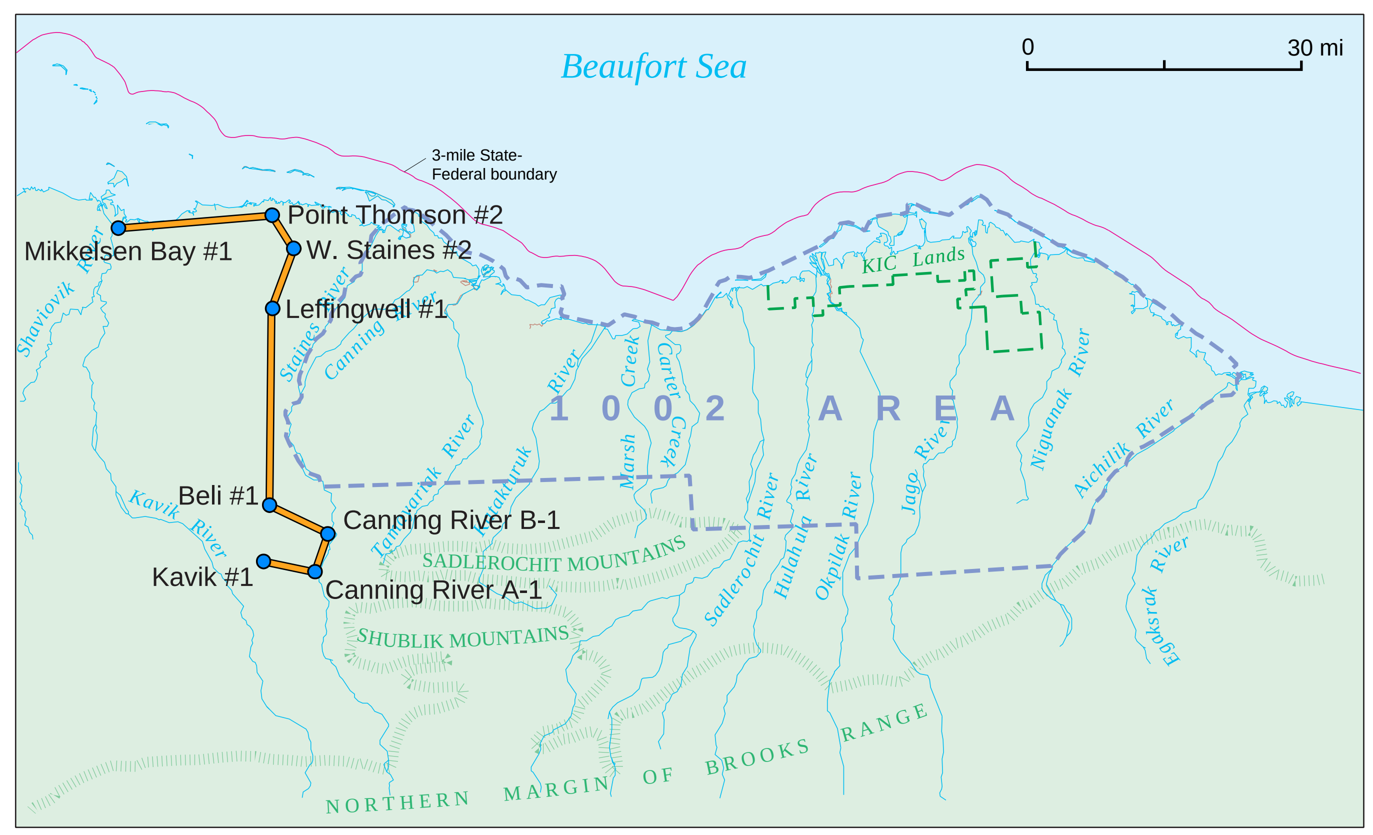


EXPLANATION

Correlations are based on log response and may not correspond to lithologic or time-stratigraphic boundaries.

- **Hue Shale, above Gamma-Ray Zone**
- **Hue Shale Gamma-Ray Zone (GRZ)**
- **Pebble shale unit**
- **Kemik Sandstone and Thomson sand**
- **Kingak Shale**
- **Paleozoic and older rocks**
- **Total Organic Carbon (TOC) in weight percent,** calculated using DT and ILD logs and ΔLogR method of Passey & others (1990)
- **Gamma-Ray Log traces,** measured in API units, equivalent to log scale x30
- **Total Organic Carbon (TOC) in weight percent,** from borehole cuttings and core
- **Lower Cretaceous unconformity (LCU)**
- **Fault,** direction of relative displacement indicated



Locations of wells in cross-section. Note distances in cross-section not to scale.

INTERIOR–GEOLOGICAL SURVEY, RESTON, VA–1998

CORRELATION OF TOTAL ORGANIC CARBON PROFILES AND GAMMA-RAY LOGS, CRETACEOUS AND JURASSIC SOURCE ROCKS

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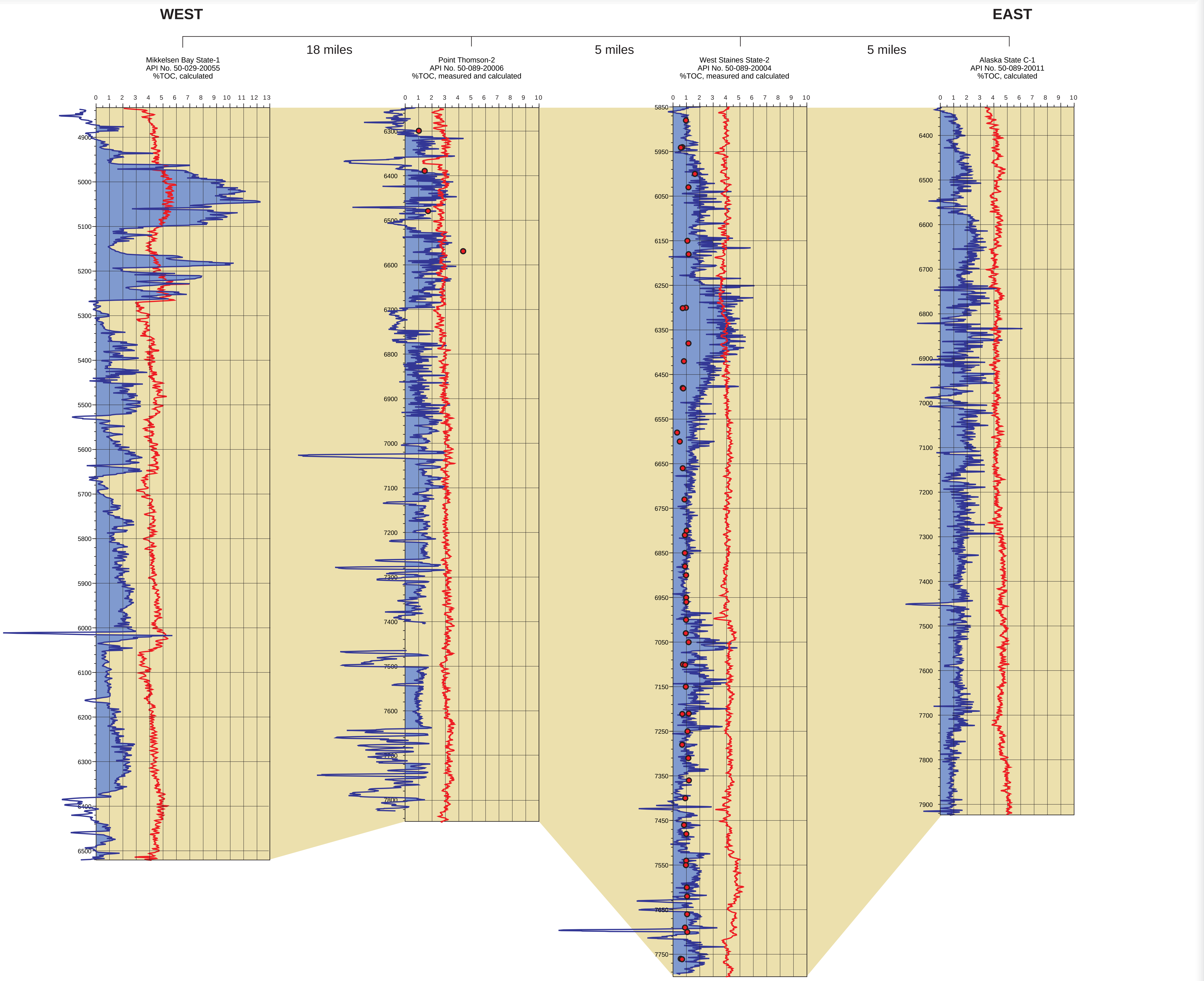
PLATE SR14



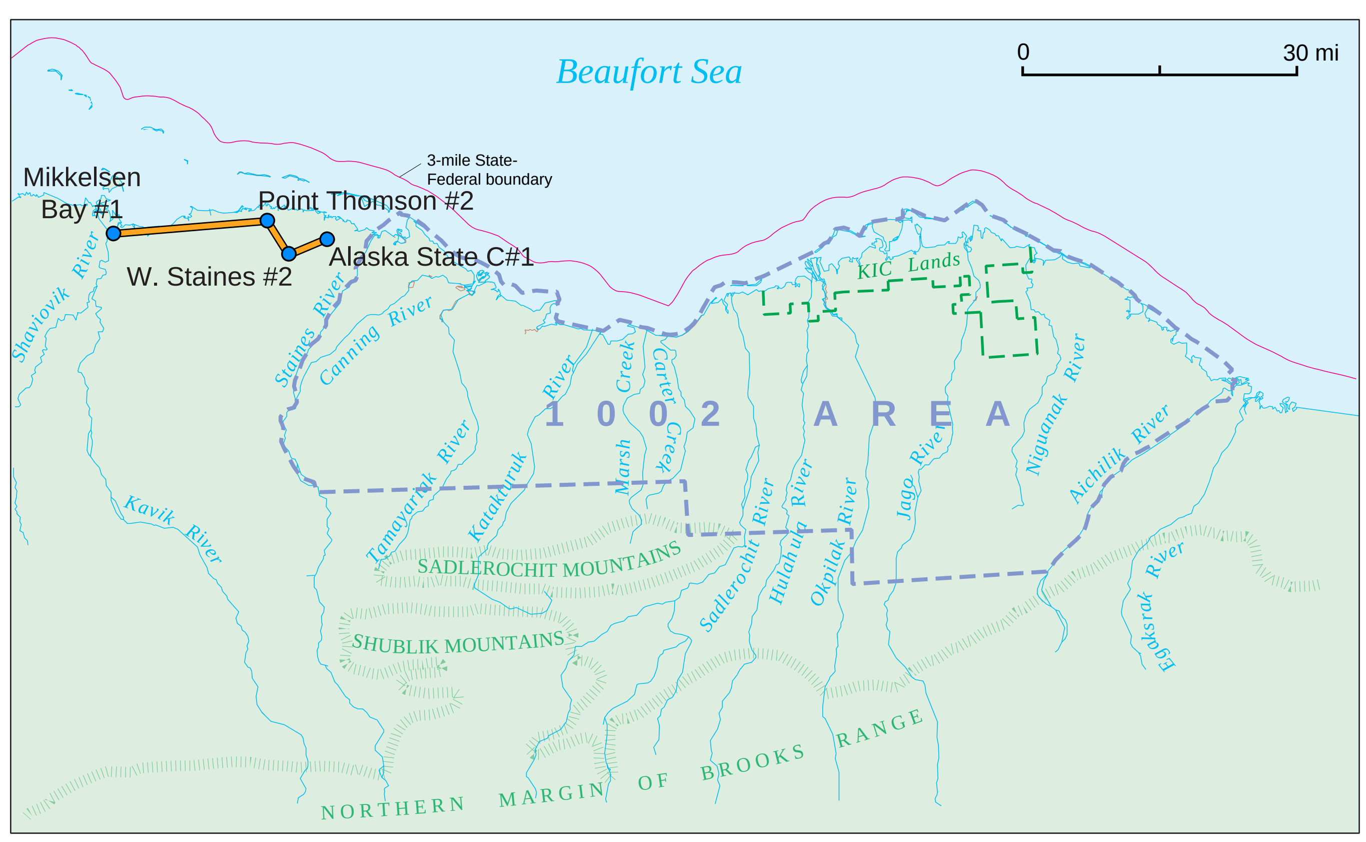
EXPLANATION

Correlations are based on log response and may not correspond to lithologic or time-stratigraphic boundaries.

Total Organic Carbon (TOC) in weight percent, calculated using DT and ILD logs and ΔLogR method of Passey & others (1990)

Gamma-Ray Log traces, measured in API units, equivalent to log scale x20

Total Organic Carbon (TOC) in weight percent, from borehole cuttings and core



Locations of wells in cross-section. Note distances in cross-section not to scale.

INTERIOR--GEOLOGICAL SURVEY, RESTON, VA--1998

CORRELATION OF TOTAL ORGANIC CARBON PROFILES AND GAMMA-RAY LOGS, MIKKELSEN TONGUE OF THE CANNING FORMATION

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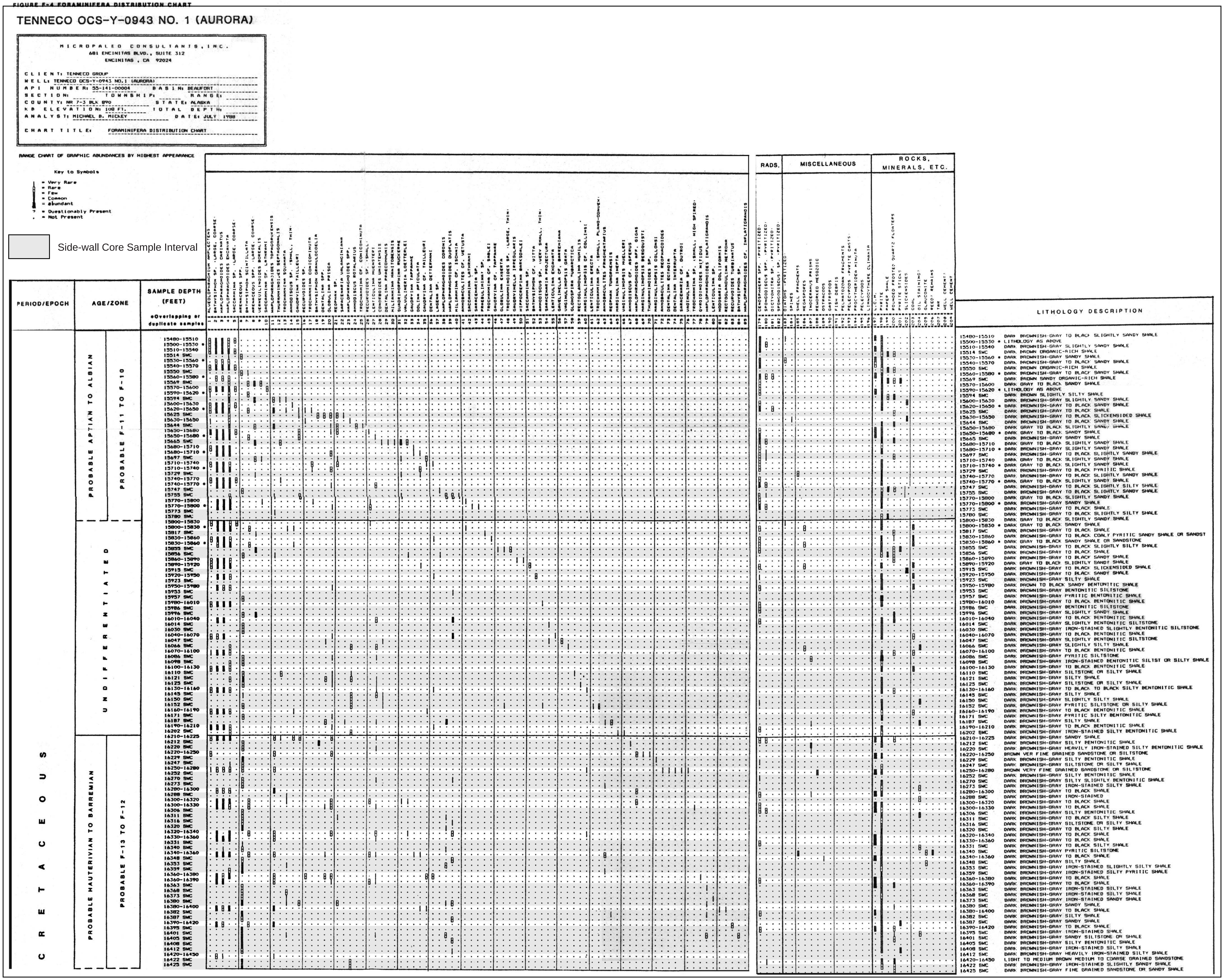
PLATE SR15



MICROPALEO CONSULTANTS INC. BIOSTRATIGRAPHY AND LITHOLOGY REPORT FOR THE CRETACEOUS HUE AND PEBBLE SHALE EQUIVALENTS IN THE AURORA-1 WELL

By

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