USGS science for a changing world
U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

OPEN-FILE REPORT 03-325
Sheet 1 of 2, Version 1.0

Petroleum Source Potential of the Lower Cretaceous Mudstone Succession of the NPRA and Colville Delta Area, North Slope Alaska, Based on Sonic and Resistivity Logs

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ABSTRACT

Resource assessment of the North Slope of Alaska by the U. S. Geological Survey includes evaluation of the petroleum source potential of Mesozoic and Cenozoic rocks using the delta log R technique (Passey and others, 1990). Porosity and resistivity logs are used in combination with thermal maturity data to produce a continuous profile of total organic carbon content in weight % (TOC). From the pattern and amount of TOC in the profile produced, the depositional setting and thus the petroleum source-rock potential (kerogen type) of the organic matter can be inferred and compared to interpretations from other data such as Rock-Eval pyrolysis.

TOC profiles determined by this technique for the contiguous interval of pebble shale unit, Hue Shale (including the Gamma Ray Zone or GRZ), and lower part of the Torok Formation indicate important potential for petroleum generation in the Tunalik 1, Inigok 1, N. Inigok 1, Kuyanak 1, Texaco Colville Delta 1, Nechelik 1, and Bergschrund 1 wells of the western North Slope region. TOC profiles suggest that this interval contains both type II and III kerogens – consistent with proposed depositional models -- and is predominantly greater than 2 wt. % TOC (cut-off used for effective source potential). Average TOC for the total effective section of the pebble shale unit + Hue Shale ranges from 2.6 to 4.1 wt % TOC (values predominantly 2-8% TOC) over 192-352 ft. Source potential for the lower Torok Formation, which also has interbedded sandstone and lean mudstone, is good to negligible in these 7 wells.

ACKNOWLEDGMENTS

We greatly appreciate the members of the USGS Alaska project team, and particularly thank Paul Lillis, Les Magoon, David Houseknecht, and Phil Nelson for helpful discussions; Phil Nelson and Joyce Kibler for digital data, and Zenon Valin for invaluable graphics assistance. We also thank Joe Macquaker, Quinn Passey, Steve Creaney, Michael Mickey, and Hideyo Haga for stimulating and helpful discussions and Les Magoon and Ken Peters for their reviews.

INTRODUCTION

On the North Slope of Alaska marine carbonate and siliciclastic sedimentary rocks of Mesozoic age include substantial sections of organic-rich mudstone and shale which are considered to be the major sources of petroleum in the oil and gas fields of this region. In the National Petroleum Reserve of Alaska (NPRA), these 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 Cretaceous Torok Formation (see stratigraphic chart from Bird, 2001b). In this study, we focus on evaluating the petroleum source potential of the contiguous Lower Cretaceous section that includes the pebble shale unit, the Hue Shale, and the lower part of the Torok Formation.

Statement of Problem

Organic-rich mudstone successions worldwide generally represent slow deposition/accumulation over millions of years and contain variation in both lithofacies and organic facies at a millimeter to sub-millimeter scale. This variation is commonly indistinguishable in outcrop or at hand specimen scale (e.g. see Macquaker and Taylor, 1996; Macquaker and others, 1998; 1999; Keller and Macquaker, 2001). For this reason, it is difficult to characterize the proportion of different facies in thick successions of fine-grained rocks that are heterogeneous but lack visually distinguishable facies. This is a common problem in mudstone successions worldwide.

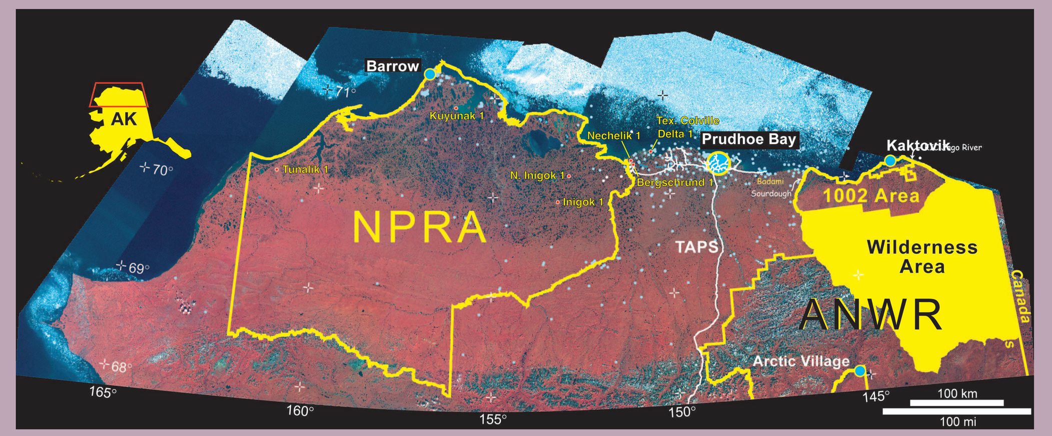
The petroleum source potential for mudstone successions has mainly been determined from scattered samples at scales from less than a meter to 10's of meters in outcrop, borehole cuttings, and conventional core. At best, these studies have produced a reconnaissance evaluation of the variation in mudstone successions. Also, significant gaps between samples preclude accurate determination of the proportion of organic-rich versus organic-lean facies within these successions, and the scale of sampling leaves doubt as to whether all the facies have been evaluated.

This Study

In this study, we derive organic richness from the characteristic physical responses of different lithofacies on wireline geophysical logs. These logs can capture a continuous profile of geophysical data from the complete source rock succession. The Δ log R technique (Passey and others, 1990), which was developed to evaluate organic richness in source rock successions, is based primarily on the sonic or density log response and secondarily on the resistivity response.

Using the Δ log R technique, we evaluate the organic richness of the Lower Cretaceous, predominantly mudstone succession in seven wells of the NPRA and adjacent area of the Colville River Delta. This succession comprises three formations that originated in different sedimentary/tectonic settings (Bird, 2001a). The provenance of the pebble shale unit was both local and from the north during the Neocomian and marks the end of the Beaufortian sequence that formed during rifting, subsidence, and ensuing transgression. The Hue Shale and Torok Formations are part of a complex assemblage of siliciclastic strata derived from the Brooks Range orogen to the south (Brookian sequence). The Hue Shale comprises distal, condensed marine mudstone. The Torok Formation consists of relatively deep marine basinal, slope, and outer-shelf mudstones and turbidite sandstones.

The pebble shale unit-Hue Shale-Torok Formation succession is rarely well exposed in outcrop and sparsely cored -- if at all, so the Δ log R technique is ideal for evaluation of total organic carbon (TOC) and the pattern of its variation in these rocks. In recent years, TOC values determined by this method have been reported for several wells in the NPRA (Creaney and Passey, 1993) and many other areas (e.g., Huang and others, 1994; Creaney and Passey, 1997). It was also used in the USGS resource assessment of the 1002 area of the Arctic National Wildlife Refuge (ANWR) to evaluate the TOC of several Cretaceous and Tertiary source rock successions (Keller and others, 1999).



METHODS & DATA SETS

The Δ log R technique of Passey and others (1990) determines TOC from the separation apparent when a properly scaled porosity log and resistivity log are overlain and a maturity factor is applied to the resulting separation. 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 Δ log R, is present. In immature rocks, the Δ log R separation is due primarily to the response of the porosity log, e.g., the longer transit time of the sonic or density log responding to the lower density organic matter. In thermally mature rocks, the separation is also created by relatively longer transit times, but additionally by higher resistivity due to the presence of generated unexpelled hydrocarbons. Reservoir rocks are eliminated from the analysis by their generally low gamma-ray response and by other well data such as the lithology and sample descriptions from a mudlog.

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

(1) Δ log R = log10(R/Rbaseline) + 0.02 x (t - tbaseline)

(2) TOC = (Δ log R) x 10(2.297 - 0.1688 x LOM)

R is the resistivity measured in ohm-m by the logging tool; t is the measured transit time in µsec/ft; Rbaseline is the resistivity corresponding to the tbaseline value when the curves are baselined in non-source, clay-rich rocks; and 0.02 is based on the ratio of -50 µsec/ft per one resistivity cycle.

The first step in applying the method is to properly scale the porosity (DT) and resistivity (ILD or LLD) log profiles such that their relative scaling is -50 µsec/ft per one logarithmic resistivity cycle. The profiles are overlain and baselined in a fine-grained, non-source rock. A baseline condition exists where the two profiles track or directly overlie each other over a significant depth range. 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 addition, since this process counts the "non-source" shale as zero TOC, an estimate or measure of its TOC must be added back after the calculation of equation #2 above. One wt % TOC, which is in the mid-range of average TOC for shales worldwide, was used in this study. 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).

For this study, we used a deep induction log (ILD, or LLD) and the differential transit time log (DT), also known as the sonic or acoustic log as recommended in Passey and others (1990) because its response is less affected by bad borehole conditions, such as caving. A suite of borehole geophysical logs (see correlation section below) was obtained for each of the 7 wells profiled, including the gamma-ray, caliper, sonic (DT), and resistivity (ILD or LLD) logs. Wireline log data was digitized at either 0.5 or one-foot intervals. Thermal maturity data is primarily from vitrinite reflectance measurements (Johnsson and others, 1999) converted to LOM using the relationship in Johnsson and others, 1999.

Example of TOC Variability All Samples From the Same Well

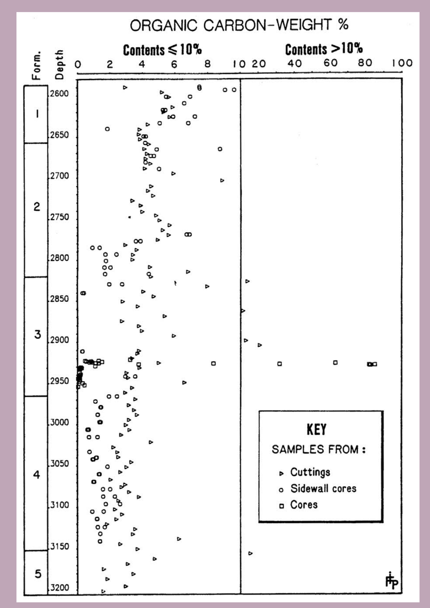


Figure from Carpentier, et.al., 1991

Evaluating Δ log R Determined TOC

TOC analyses on borehole cuttings are the best to use in evaluation of TOCs determined by Δ log R 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 Δ log R values. Therefore, in heterogeneous sections cuttings are better for comparison, calibration, or validation of Δ log R values 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. It is also fairly well known that results from analyses of cuttings often don't seem to compare well to results from core because of these many factors (figure at left from Carpentier and others, 1991). Therefore, careful consideration is recommended before TOC values from cuttings or core are used to evaluate/validate Δ log R-determined TOC values.

Generalized Stratigraphy for NPRA North of Brooks Range

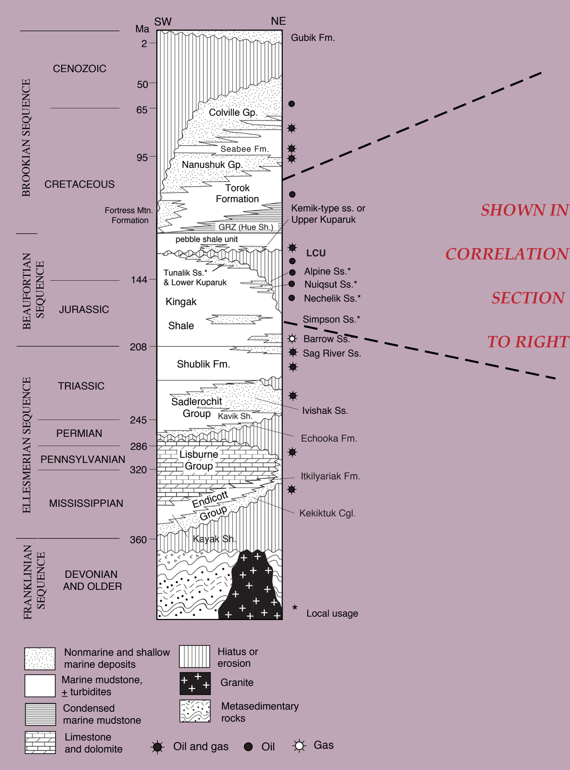
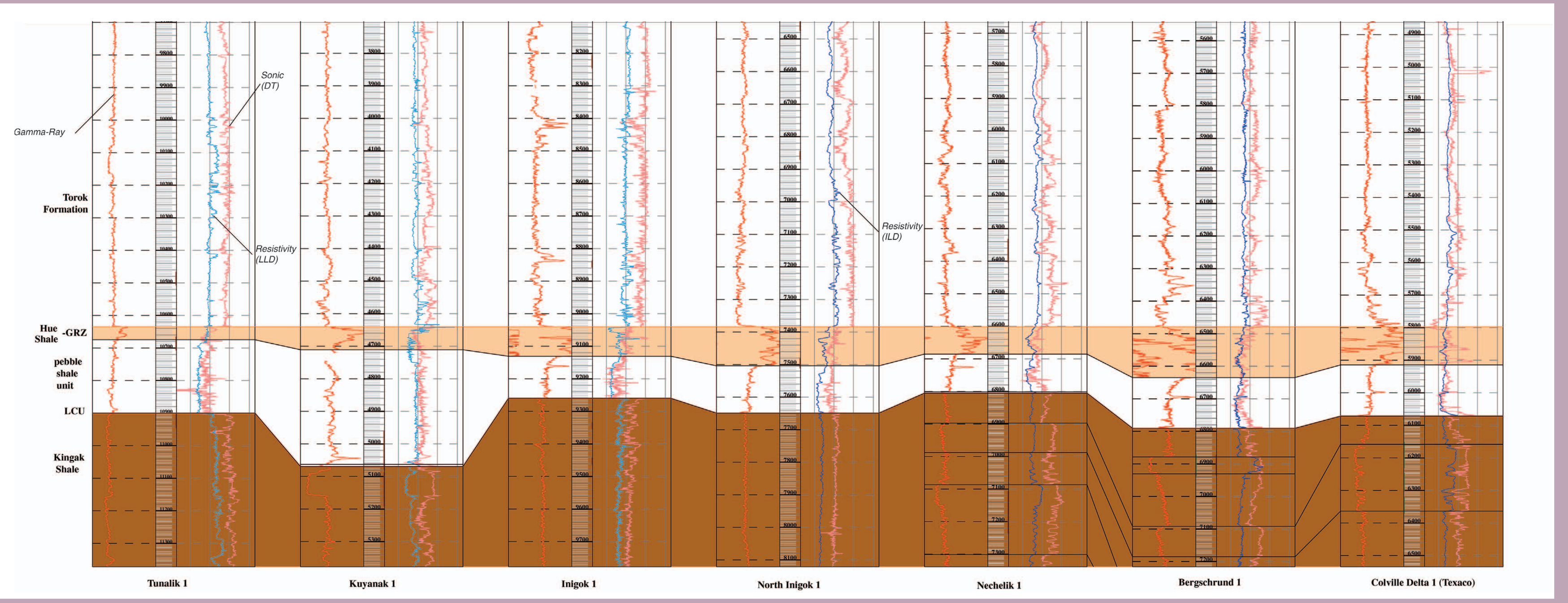


Figure from Bird, 2001b



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