Division of Geological & Geophysical Surveys

**PRELIMINARY INTERPRETIVE REPORT 2015-1**

# SOURCE-ROCK POTENTIAL OF THE LOWER CRETACEOUS PEBBLE SHALE UNIT, NORTHEASTERN ALASKA

by
Dolores A. van der Kolk, Michael T. Whalen, and Marwan A.Wartes

April 2015

Released by
STATE OF ALASKA
DEPARTMENT OF NATURAL RESOURCES
Division of Geological & Geophysical Surveys
3354 College Rd.
Fairbanks, Alaska 99709-3707

$4.00

# CONTENTS



# FIGURES



# TABLES



Cover Caption: Photograph of the Boulder Bowl locality, north of the northernmost mountains in the United States, within the Arctic National Wildlife Refuge in northeastern Alaska. View slightly to the northwest includes the black, organic-rich, pebble shale unit and the orangish-red and gray slope-forming outcrop expression of the Hue Shale. Geologist is standing on the Kemik Sandstone, near the Kemik Sandstone–pebble shale unit contact. The yellow tent in the background is pitched on pebble shale unit. Photograph by Peter Flaig

# SOURCE-ROCK POTENTIAL OF THE LOWER CRETACEOUS PEBBLE SHALE UNIT, NORTHEASTERN ALASKA

by
Dolores A. van der Kolk[1], Michael T. Whalen[2], and Marwan A.Wartes[3]

## ABSTRACT

In northeastern Alaska, the Lower Cretaceous pebble shale unit (PSU) was investigated for source-rock potential along the west side of the Canning River (outside of ANWR), along an unnamed tributary east of the Katakturuk River (Boulder Bowl), and at Marsh Creek. Samples were collected and analyzed for total organic carbon (TOC), Rock-Eval, and vitrinite reflectance ($R_o$). Results indicate that there are 12- to 31-m-thick packages of the PSU that have sufficient organic content (2–6 wt. percent TOC) to constitute good to excellent source rock. However, Rock-Eval data from these same samples suggest poor source-rock quality (Hydrogen Index [HI] < 50mg Hydrocarbon [HC]/g TOC) likely from elevated thermal maturity of the PSU as indicated by high $T_{max}$ and $R_o$ values. The average vitrinite reflectance of the sections sampled for this study ranges from 1.28 to 1.79 percent $R_o$, indicating latest oil window to gas window maturity. Results from this study are consistent with previous studies indicating that the PSU originally had good source-rock potential; however, because of advanced thermal maturity in the study area, the parameters that correspond to source-rock quality indicate considerable degradation.

## INTRODUCTION

The Lower Cretaceous pebble shale unit (PSU) and laterally equivalent strata, though widespread in the subsurface of northern Alaska, have received relatively little outcrop study. Surface exposures of the PSU are mostly limited to the northeastern Brooks Range in and adjacent to the Arctic National Wildlife Refuge (ANWR; fig. 1), where structural complications, recessive weathering, and widely scattered outcrops have impeded detailed stratigraphic and geochemical description and interpretation. This paper documents lateral variations and thicknesses of potential source rocks from relatively continuous PSU exposures. Measured sections at each locality have been evaluated for organic richness and petroleum source-rock characteristics using total organic carbon (TOC), Rock-Eval II, and thermal maturity data from vitrinite reflectance ($R_o$). Vertical profiles of TOC and Rock-Eval data are reported here for each locality (fig. 2). These new data are compared to previous source-rock analyses of the PSU reported from the Mikkelsen Bay State-1 well (fig. 1; Keller and Macquaker, 2001) and other investigations conducted from the subsurface as well as surface exposures in ANWR (Anders and others, 1987; Bird and others, 1999).

## GEOLOGIC SETTING

The informally named pebble shale unit (PSU) of northern Alaska, equivalent to the Kalubik Formation of subsurface usage (Carman and Hardwick, 1983), is an organic-rich, marine mudstone that was deposited in shelfal water depths during the later stages of rifting that led to opening of the Canada Basin during the Barremian (fig. 3; Molenaar, 1981; Bird, 1982; Molenaar, 1983; Robinson and others, 1989). Rifting is thought to have initiated in the Early Jurassic and culminated during the Early Cretaceous (Hubbard and others, 1987). Sediments of this age sourced from and deposited along the Barrow Arch rift margin are assigned to the Beaufortian sequence (figs. 1 and 3). They are genetically distinct from both the underlying, northerly-sourced Ellesmerian passive margin sequence, and from the laterally equivalent and overlying Brookian foreland basin sequence shed from the Brooks Range in the south (fig. 3, Hubbard and others, 1987). Rifting and differential uplift of the Arctic Alaska plate created at least one regional unconformity known as the Lower Cretaceous unconformity (LCU; Grantz and May, 1983) that is most conspicuous near the crest of the Barrow Arch rift margin.

In the northeastern Alaska outcrop belt, the discontinuous, transgressive sandstone above the LCU and below the PSU is known as the Kemik Sandstone (fig. 3; Molenaar and others, 1987; Mull, 1987). North of the eastern Sadlerochit Mountains and along structural strike with the study area (fig. 2), the Kemik consists primarily of a bioturbated pebbly siltstone facies interpreted by Mull (1987) as a lagoonal deposit that was shielded from wave

[1]Department of Geology and Geophysics, University of Alaska Fairbanks, P.O. Box 755780, Fairbanks, Alaska 99775-5780. Currently: The University of Texas at Austin, Bureau of Economic Geology, Jackson School of Geosciences, P.O. Box X, Austin, TX 78713-8924; dvdk@utexas.edu
[2]Department of Geology and Geophysics, University of Alaska Fairbanks, P.O. Box 755780, Fairbanks, Alaska, 99775-5780
[3]Alaska Division of Geological & Geophysical Surveys, 3354 College Road, Fairbanks, Alaska, 99709-3707

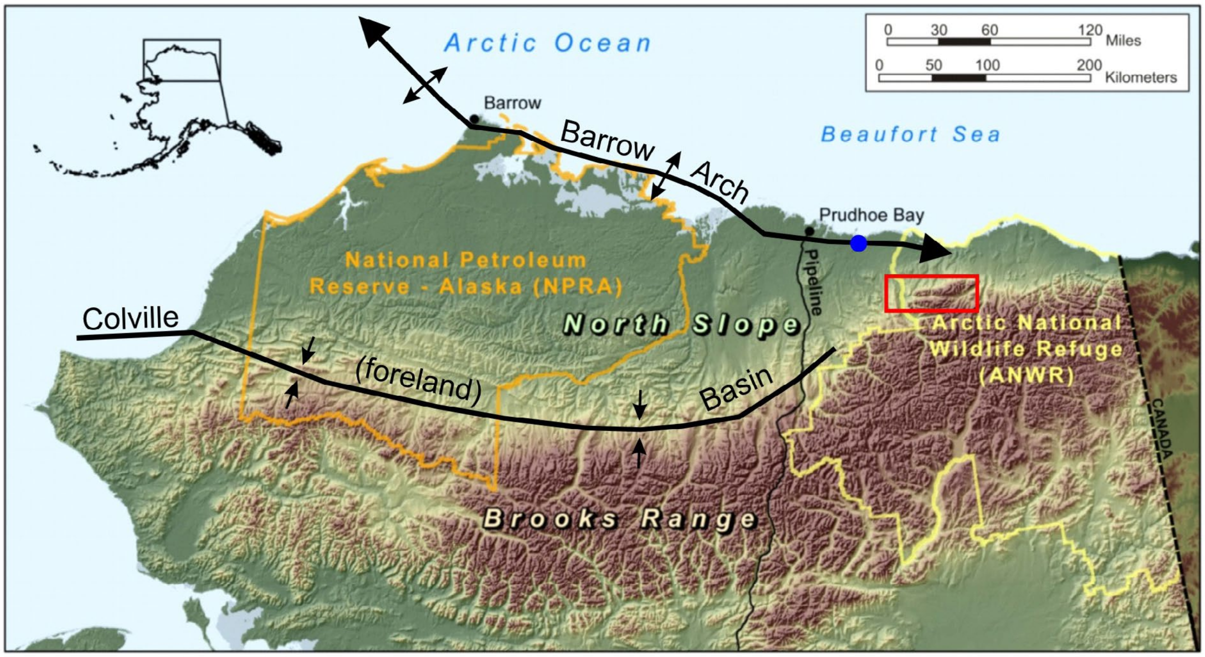



Figure 1. Regional shaded relief map (modified from Riehle and others, 1997) of northern Alaska outlining the Arctic National Wildlife Refuge (ANWR), National Petroleum Reserve–Alaska (NPRA), North Slope, and Brooks Range. Note the approximate location of the Mikkelsen Bay State No. 1 well (●), Colville (foreland) basin and Barrow Arch from Bird (2001). Red box outlines the study area; refer to figure 2 for large-scale topographic map.

energy by a barrier island facies that outcrops in Ignek Valley on the south side of the Sadlerochit Mountains. The contact between the Kemik Sandstone and overlying PSU, though described by Knock (1986) as apparently gradational, was considered mostly sharp and devoid of interfingering by Mull (1987).

Stratigraphically above the PSU is a radioactive shale interval (fig. 3) often referred to as the highly radioactive or gamma-ray zone (HRZ and GRZ, respectively; Tailleur and others, 1978; Bird, 1982; Carman and Hardwick, 1983; Molenaar and others, 1987). The HRZ is now considered the basal part of the Aptian(?) to Campanian or Maastrichtian Hue Shale (Molenaar and others, 1987; Bird and Molenaar, 1987; Bird, 1988), but had previously been considered the upper part of the PSU (Bird, 1982; 1985). HRZ sediments on the Barrow Arch are interpreted as the first stratigraphic record within the Brookian foreland basin sequence (fig. 3). The HRZ consists of condensed, organic-rich shale and bentonite deposited from suspension north of the basin's axis on the marine shelf and slope formerly occupied by the PSU (Carman and Hardwick, 1983; Molenaar and others, 1987). Sediment starvation on this shelf during HRZ deposition resulted from trapping of Brookian clastics in the basin axis to the south and subsidence of the Beaufortian rift shoulder source area (Grantz and May, 1983; Molenaar and others, 1987). The HRZ (Aptian–Albian) is highly organic with microlaminations (Carman and Hardwick, 1983) and was originally proposed as being deposited during anoxic conditions (Bird, 1985).

More recent studies and observations indicate that the PSU and Hue Shale are both microbioturbated and locally macrobioturbated marine successions that may appear uniform in outcrop, but are highly variable lithologically (Keller and Macquaker, 2001; Macquaker and Keller, 2005; D. Houseknecht, pers. commun., 2008). Even though previous studies have suggested that these units are periodically anoxic, the presence of burrowing organisms suggests that the bottom waters were either oxic or dysoxic (Macquaker and Keller, 2005). Investigations of continuous core concluded that the PSU is composed of clay-rich mudstone that is locally silt- and pyrite-bearing, carbonate-cemented mudstone, muddy sandstone, and graded tuff (Keller and Macquaker, 2001; Macquaker and Keller, 2005). As implied by its name, a primary lithologic characteristic of the PSU is the occurrence of isolated rounded and frosted quartz grains, as well as chert and quartzite pebbles and cobbles "floating" in very fine-scale bedding (sometimes less than 1 mm thick; Bird and Molenaar, 1987; Blanchard and Tailleur, 1983; Molenaar, 1988; Keller and Macquaker, 2001; Macquaker and Keller, 2005). Depositional origins previously suggested for the outsized clastic material in the PSU range from shore ice-, kelp-, or log-rafted-debris to stomach stones from ichthyosaurs (Molenaar and others, 1987; Molenaar, 1988). A more recent study suggested that a combination

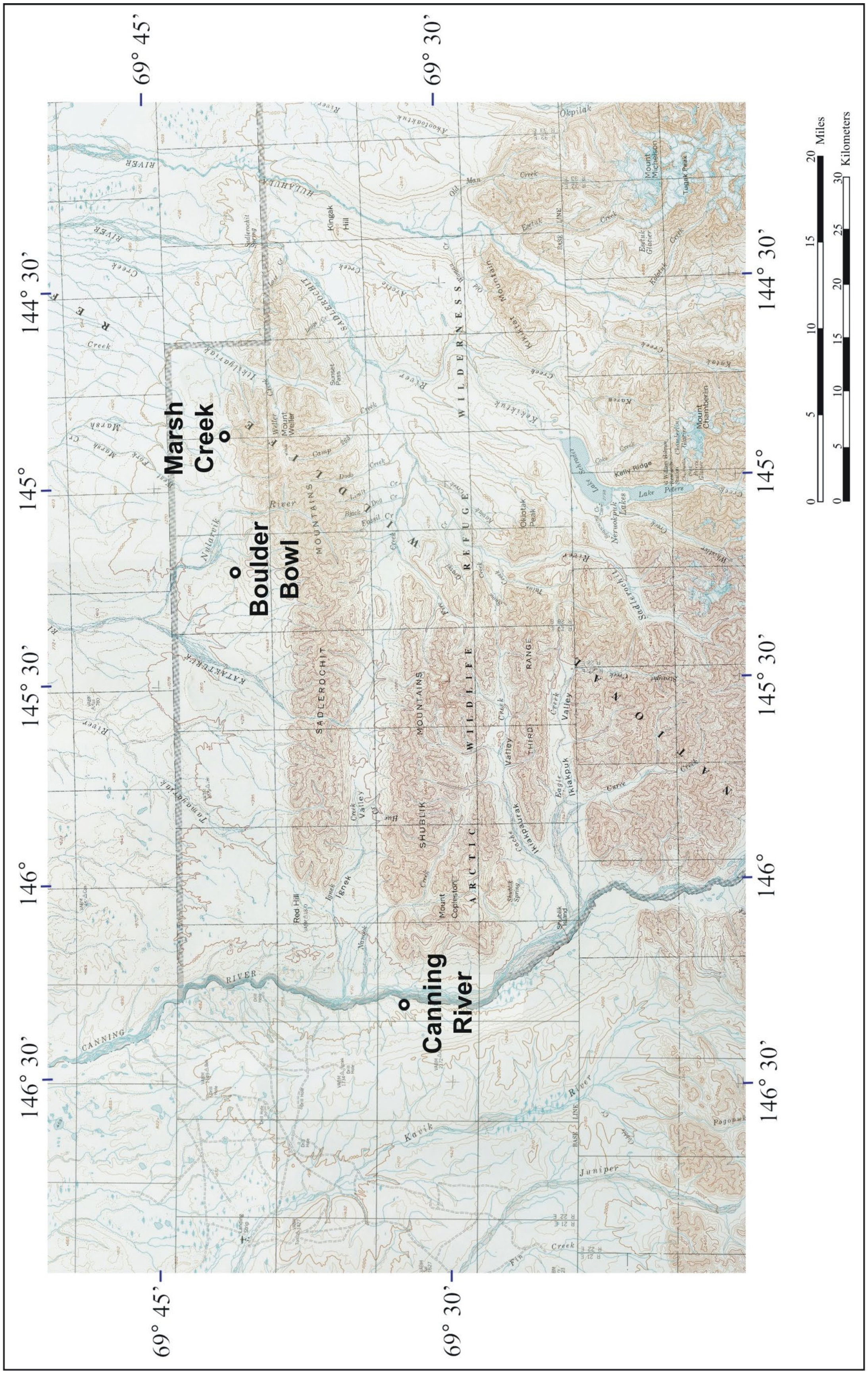



Figure 2. Central portion of the Mount Michelson Quadrangle (USGS, 1956) noting locations of the Pebble Shale Unit (PSU) relevant to this study.

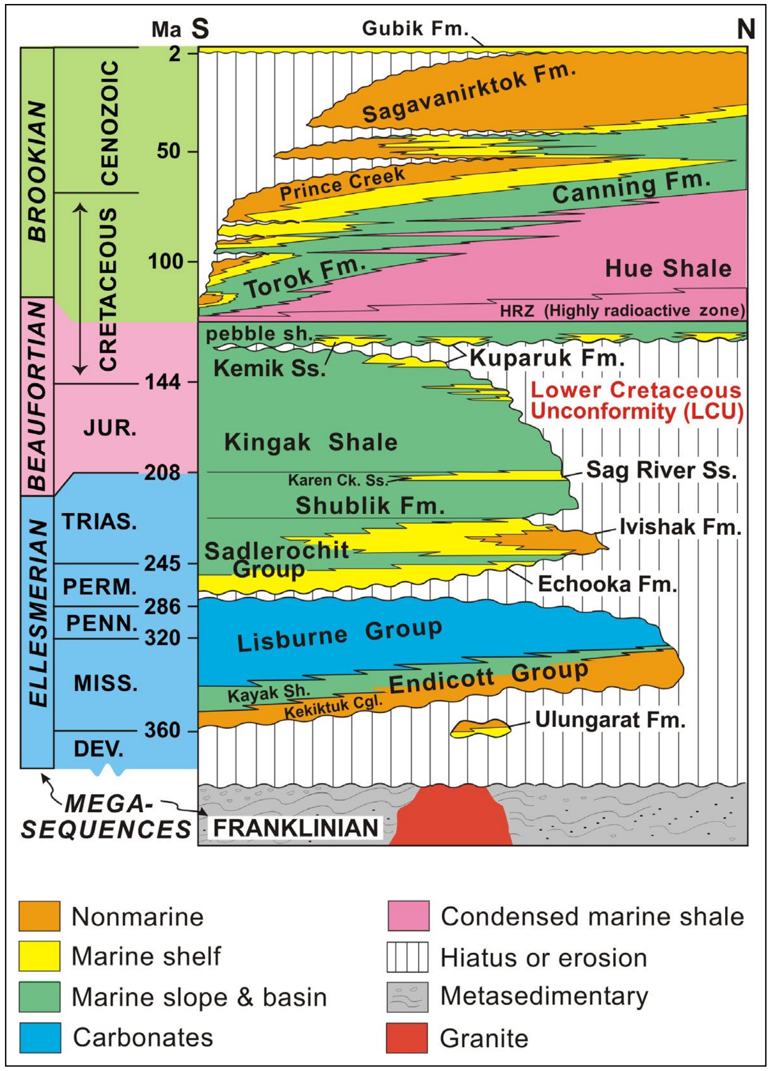



Figure 3. Chronostratigraphic column (modified from Garrity and others, 2005) showing the North Slope megasequences (Franklinian, Ellesmerian, Beaufortian, and Brookian). The Kemik Sandstone (Kemik Ss), Kuparuk Formation (Kuparuk Fm), and pebble shale unit (pebble sh) are included in the Beaufortian. The highly radioactive zone (HRZ), Hue Shale, and the Torok Formation (Torok Fm) are included in the Brookian.

of melting frazil ice, anchor ice, and fast ice played a significant role in PSU deposition (Macquaker and Keller, 2005). Furthermore, it cannot be ruled out that the frosted quartz sand grains were derived from eolian transport processes alone or that a percentage of the sand grains were deposited directly on ice and then rafted out to sea (Macquaker and Keller, 2005).

## SOURCE-ROCK PARAMETERS

Effective petroleum source rocks must satisfy several requirements as to the quantity, quality, and thermal maturity of organic matter (Peters and Cassa, 1994; Peters and others, 2005). The quantity of organic matter is expressed by measuring the total organic carbon (TOC) of a sample in weight percent (wt. percent; Peters and Cassa, 1994). The quality of the organic matter depends on the kerogen composition, which can be estimated from Rock-Eval pyrolysis. During pyrolysis, a flame ionization detector (FID) senses combustion of organic compounds in an oven. A computer controls the apparatus and records several parameters (Peters and others, 2005). The $S_1$ parameter quantifies the volatile hydrocarbons that can be thermally desorbed per gram of sample at relatively low oven temperatures. The $S_2$ parameter represents the amount of hydrocarbon generated by pyrolitic degradation of the kerogen in the sample as the temperature rises, and the $S_3$ parameter is the quantity of carbon dioxide ($CO_2$) released from the sample during temperature programming up to 390°C (Peters, 1986). $S_1$, $S_2$, and $S_3$ are all expressed in mg/g. The hydrogen index (HI) parameter represents the quantity of pyrolyzed hydrocarbon from $S_2$ relative to the TOC in the sample (HI = [$S_2$/TOC] x 100, expressed in mg HC/g TOC). Similarly, the oxygen index (OI) corresponds to the ratio of $S_3$ relative to the TOC (OI = [$S_3$/TOC] x 100, expressed in mg $CO_2$/g TOC).

A plot of HI vs. OI, called a pseudo- or modified van Krevelen diagram, is typically used to distinguish source rocks containing hydrogen-rich, oil-prone Type I and II kerogens from those containing hydrogen-poor, gas-prone Type III kerogen, and those with inert Type IV organic matter. A third ratio determined from Rock-Eval results is the production index (PI = $S_1/[S_1+ S_2]$, sometimes called transformation ratio). $T_{max}$ is the oven temperature that corresponds to the maximum rate of $S_2$ hydrocarbon generation. Both $T_{max}$ and PI have some utility in estimating a source rock's thermal maturity relative to the stages of hydrocarbon generation (Peters and others, 2005). However, thermal maturation is more reliably quantified using microscopy techniques, such as vitrinite reflectance ($R_o$). Optical properties of vitrinite, a group of gas-prone macerals derived from land-plant tissues, change due to heating and devolatilization, making the macerals more reflective. These kerogens are separated from the rock sample and analyzed with a petrographic microscope equipped with a photometer to measure the percentage of incident white light reflected (Peters and others, 2005). Approximate ranges of vitrinite reflectance are commonly used to indicate maturity with respect to oil generation (immature, 0.2–0.6 percent $R_o$; mature, 0.6–1.35 percent $R_o$; and postmature, >1.35 percent $R_o$; Peters and Cassa, 1994), but in reality these ranges vary somewhat based on kerogen composition and sample preparation.

## PREVIOUS SOURCE-ROCK WORK

During early exploration of the North Slope, workers suggested that the PSU was a source for some of the oil in the Prudhoe Bay field (Morgridge and Smith, 1972; Jones and Spears, 1976; Seifert and others, 1980; Bird 1982, 1985). As part of a large oil and source-rock correlation study coordinated by the U.S. Geological Survey, 14 out of 21 geochemical laboratories independently identified the PSU in the National Petroleum Reserve–Alaska (NPRA, fig. 1) as the probable source rock for the Umiat oil type (Claypool and Magoon, 1985). However, of the four subsurface rock samples of the "pebble shale" analyzed in this study (Magoon and Claypool, 1985, p. xiv), only two fit within the currently accepted definition (Molenaar and others, 1987) of the PSU (sample 17, Peard #1 and sample 19, Ikpikpuk #1). One of the four (sample 9, East Simpson #2) is considered to represent the overlying HRZ interval, and another (sample 10, Walakpa #2) is actually from the lower part of the Torok Formation, according to the published formation tops of Bird (1982). Commonly grouped with closely-related oils from the Cape Simpson area of north-central NPRA, Umiat oils were described as "higher gravity, low sulfur oils with no, or slight, odd-numbered n-alkane predominance and pristine to phytane ratios greater than 1.5" (Magoon and Claypool, 1980, p. 1). Isotopically, Simpson-Umiat oils were characterized as having $\delta^{13}C$ values ranging from -29.1 to -27.8 parts per thousand (ppt) and $\delta^{34}S$ values from -10.3 to -4.9 ppt (Magoon and Claypool, 1980).

In a subsequent assessment of source rocks in the ANWR area, Magoon and others (1987) adhered to a different stratigraphic nomenclature that considered the HRZ the basal portion of the Hue Shale, and excluded it from the PSU. These workers concluded that, by this definition, the PSU in ANWR contains gas-prone kerogen and would not produce oil regardless of maturity (Magoon and others, 1987). This conclusion was based on data from outcrop samples of the PSU that had low $C_{15+}$ hydrocarbon content (<15 mg/g). These data were obtained from solvent extraction and were compared with the organic-carbon content (Magoon and others, 1987). The quantity of $C_{15+}$ hydrocarbons, however, decreases with burial (Durand, 1985). Anders and others (1987) also concluded from seven wells west of the Canning River and five samples from outcrop localities in the ANWR that the PSU is hydrogen-poor, containing woody, terrestrial type III organic matter that would principally yield gas.

Other studies that considered PSU source-rock potential include a petroleum source-rock evaluation based on sonic and resistivity logs (Keller and others, 1999; Keller, 2002). Keller and others (1999) concluded that the TOC of the PSU from well logs is highly variable with some PSU intervals having TOC as low as 1–2 wt. percent and others ranging as high as 3–4 wt. percent TOC. The most recent source-rock analysis of the PSU is within the Mikkelsen Bay State #1 well (referred to herein as the Mikkelsen well; fig. 1). Rock-Eval analyses of the lower and middle part of the PSU, sampled from continuous core in the Mikkelsen well, yielded an average TOC value of 4 wt. percent (range 2–6 wt. percent) with an average HI of 336 mg HC/g TOC (range 278–449 mg HC/g TOC; Keller and Macquaker, 2001; Keller and others, 2002). These results indicate that the mudstone succession of the PSU and possibly the lower part of the Hue Shale is oil prone (Keller and Macquaker, 2001; Keller and others, 2002). As noted above, the PSU has sometimes been considered to include the HRZ (Bird, 1982; Claypool and Magoon, 1985), or has been grouped with other stratigraphic units as a single source-rock interval (Masterson, 2001; Lillis, 2003). Based on integrated analyses of carbon isotopes, biomarkers, bulk properties, and map-based burial history and migration models, Masterson (2001) concluded that the HRZ and other Cretaceous source rocks (fig. 3) are a potential co-source for 28 percent of the oil for the Prudhoe Bay field.

## PEBBLE SHALE UNIT LOCALITIES—THIS STUDY

In this study, PSU localities were selected on the basis of exposure quality and stratigraphic continuity, but were limited by the number of helicopter landings allowed in ANWR. Three outcrops[4] were examined in detail: (1) on the west side of the Canning River (outside of ANWR), (2) on an unnamed tributary east of the Katakturuk River (referred to here as Boulder Bowl), and (3) on Marsh Creek (fig. 2). The contact of the PSU with the underlying Kemik sandstone is exposed at all three study locations; however, the upper contact with the Hue Shale is not exposed at all locations. The contact between the Kemik and PSU appears sharp at the Canning River, and gradational at both the Boulder Bowl and Marsh Creek localities. The most complete section is along the Canning River, followed by Boulder Bowl where the upper portion of the PSU and base of the Hue Shale is poorly exposed. In the Marsh Creek area only 23 m of the PSU were measured, since the upper half of the PSU is deformed by a structural detachment (Mull, 1987).

The criteria used to delimit the PSU and the Hue Shale may differ slightly between field and subsurface investigations. In surface mapping, the contact between the top of the PSU and base of the Hue Shale generally defined by the lowest stratigraphic occurrence of bentonite (Bird and Molenaar, 1987; Robinson and others, 1989). However, in well logs, the PSU–Hue Shale contact is often defined by the HRZ where the gamma-ray response is >150 API units (Carman and Hardwick, 1983). At the Canning River section a 5-cm-thick altered bentonite layer was found at ~33.8 m. No bentonite layers were discovered at Boulder Bowl or Marsh Creek due to poor outcrop exposure. For the purposes of this paper, all source-rock data from this study are preliminarily grouped as PSU. Further consideration of the field, petrographic, and outcrop gamma-ray data (van der Kolk, in prep.) may result in redefining the uppermost part of the Canning River section as basal Hue Shale (HRZ).

## METHODS

In order to evaluate source-rock potential, samples of the PSU were collected from surface exposures (fig. 2) and analyzed by Intertek Westport Technology Center (Intertek) in Houston, Texas. A total of 115 samples from the Canning River, Boulder Bowl, and Marsh Creek sections were analyzed for both TOC and Rock-Eval pyrolysis. To better understand the thermal maturity of those samples and measured sections, 11 samples were further evaluated for vitrinite reflectance.

Total Organic Carbon (TOC) was analyzed using a direct combustion method with a Leco Carbon Analyzer. Pyrolytic assays were performed on whole-rock samples, using the “Rock-Eval II Plus” instrument as described by Espitalié and others (1977). Thermal maturity values were determined by isolating and concentrating kerogen from whole-rock samples, which were then embedded in epoxy, and polished for microscopic examination. Intertek measured $R_o$ using a Zeiss Photoscope equipped with a photometer, signal amplifier, and 40x oil immersion objective. The interpreted range of indigenous vitrinite was based primarily on the structure of the organic matter and the distribution of measured particles around the population mode on the frequency versus percent $R_o$ histogram with a spread of 0.4–0.6 percent $R_o$ typically being used (M. Darnell, Intertek representative, pers. commun., 2008). Angular organic matter was interpreted as buried in situ or indigenous, whereas rounded organic matter was interpreted as transported or recycled from older sediments. Kerogen type was not determined using microscopy techniques.

## DATA

Appendix A includes the complete dataset for each of the 115 PSU samples analyzed for TOC and Rock-Eval and the 11 samples analyzed for vitrinite reflectance. Appendix B shows vitrinite reflectance histograms. Tables 1–4 summarize the data for discussion purposes.

### Total Organic Carbon (TOC) Content

TOC data are summarized based on stratigraphic location in table 1. Of 115 TOC samples, 44 were analyzed from the Canning River, 46 from Boulder Bowl, and 25 from Marsh Creek. In total, mudrock (mudstone, claystone, and siltstone) within the PSU ranges from 0.61 to 6.15 wt. percent TOC (n=105, averaging 3.42 wt. percent; table 1 and Appendix A). A small percentage of organic geochemical data was measured from PSU concretions

[4]Location coordinates for base of three measured sections (NAD27AK):
Canning River locality: N69.52935°, W146.30328°
Boulder Bowl locality: N69.67866°, W145.22668°
Marsh Creek locality: N69.68308°, W144.85077°

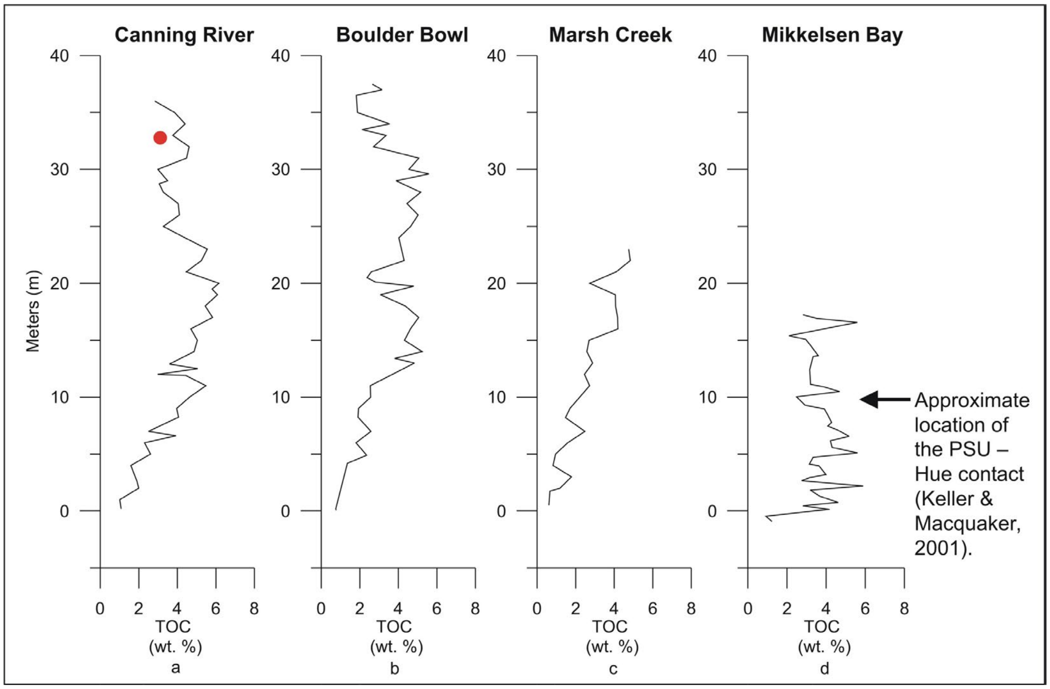



Figure 4. Total Organic Carbon (TOC) profiles for the Pebble Shale Unit (PSU) in this study: (a) Canning River, (b) Boulder Bowl, (c) Marsh Creek sections, and (d) Keller and Macquaker's (2001) investigation of the PSU within the Mikkelsen Bay State No. 1 well. Zero represents approximate contact of the PSU with the Kemik Sandstone. (●) Represents first occurrence of bentonite (~33.8 m) at the Canning River locality and base of the Hue Shale according to Robinson and others (1989).

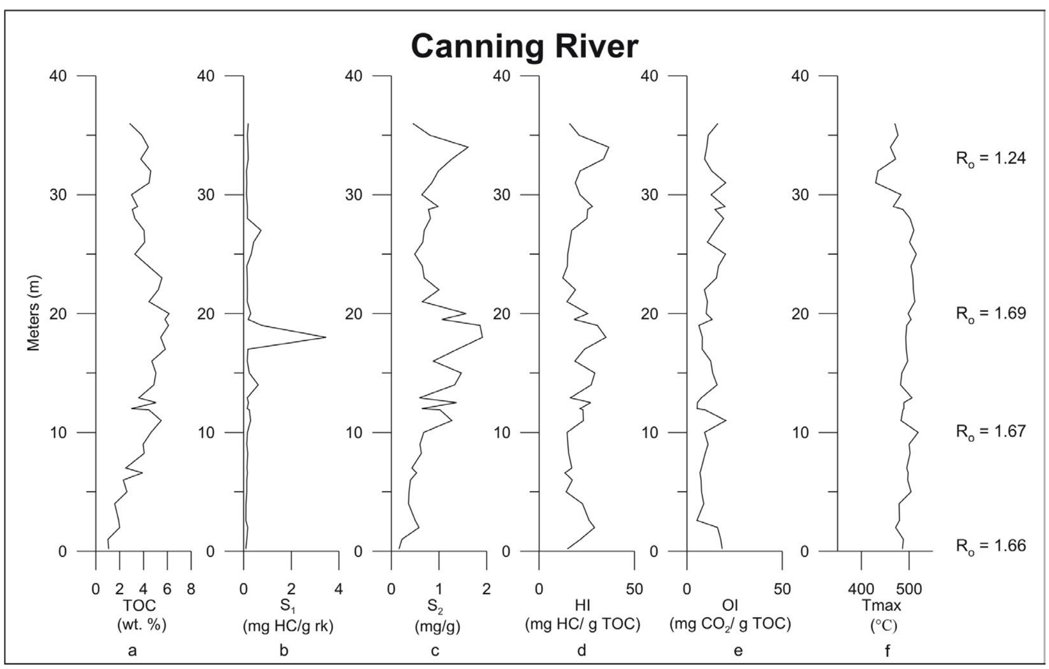



Figure 5. Total Organic Carbon, Rock-Eval, and Vitrinite Reflectance ($R_o$) measurements of the Pebble Shale Unit (PSU) from the Canning River section including: (a) Total Organic Carbon [TOC], (b) volatile hydrocarbons that can be thermally desorbed per gram of sample at relatively low oven temperatures [$S_1$], (c) amount of hydrocarbon generated by pyrolitic degradation of kerogen in the sample as the temperature rises [$S_2$], (d) hydrogen index [HI], (e) oxygen index [OI], and (f) temperature of peak $S_2$ [$T_{max}$] with corresponding $R_o$ values (n=4). Zero represents approximate contact of the PSU with the Kemik Sandstone.

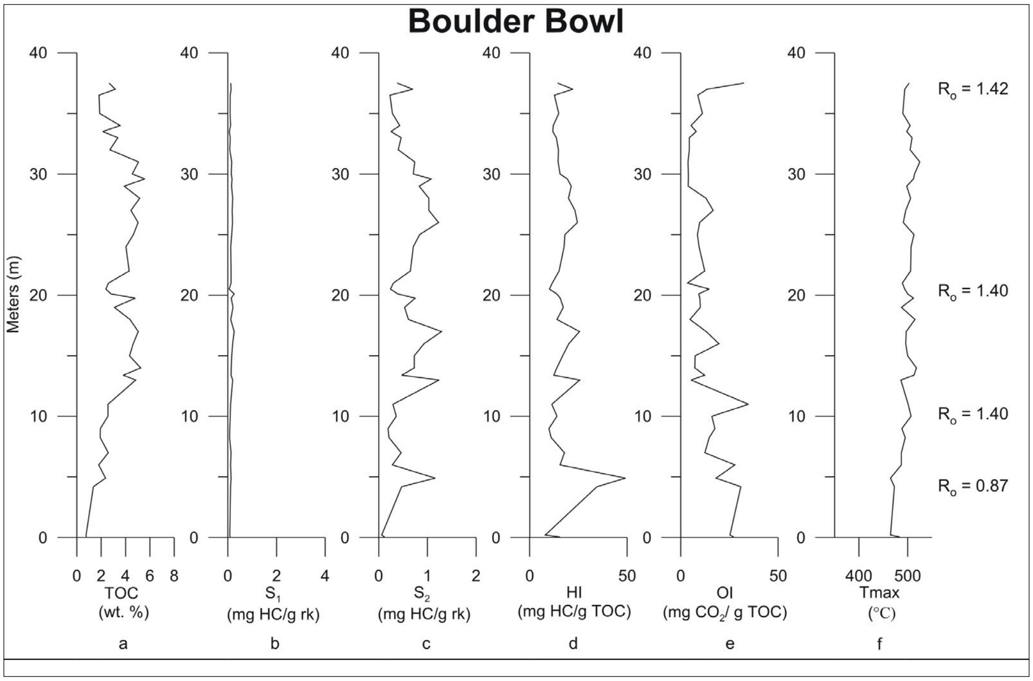



Figure 6. Total Organic Carbon, Rock-Eval, and Vitrinite Reflectance ($R_o$) measurements of the PSU from the Boulder Bowl section including: (a) Total Organic Carbon [TOC], (b) volatile hydrocarbons that can be thermally desorbed per gram of sample at relatively low oven temperatures [$S_1$], (c) amount of hydrocarbon generated by pyrolitic degradation of kerogen in the sample as the temperature rises [$S_2$], (d) hydrogen index [HI], (e) oxygen index [OI], and (f) temperature of peak $S_2$ [$T_{max}$] with corresponding $R_o$ values (n=4). Zero represents approximate contact of the PSU with the Kemik Sandstone.

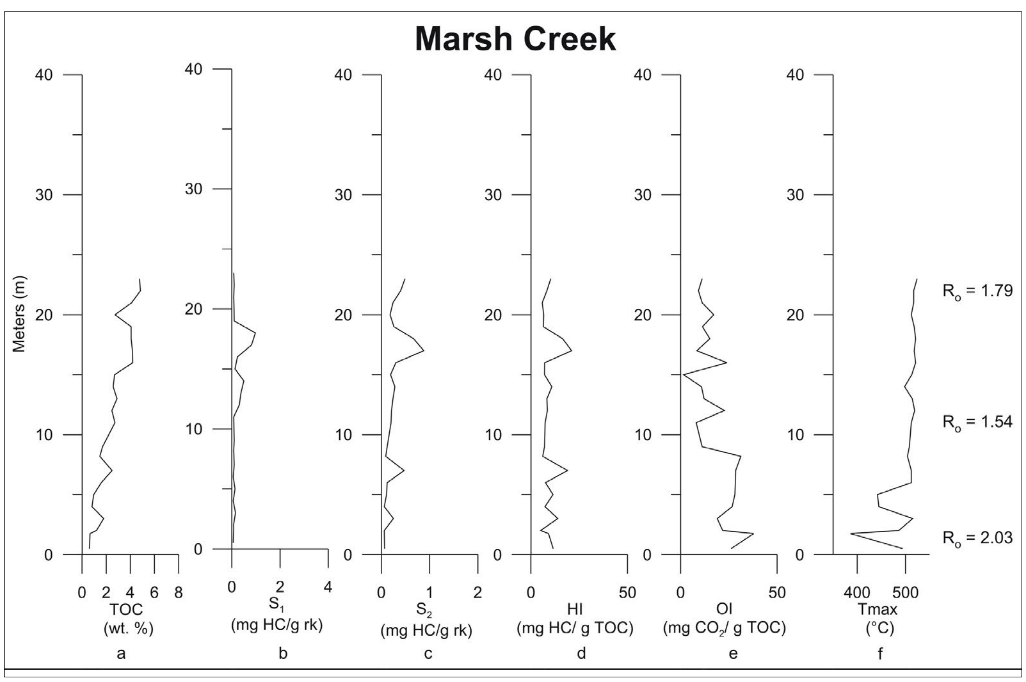



Figure 7. Total Organic Carbon, Rock-Eval, and Vitrinite Reflectance ($R_o$) measurements of the PSU from the Marsh Creek section including: (a) Total Organic Carbon [TOC], (b) volatile hydrocarbons that can be thermally desorbed per gram of sample at relatively low oven temperatures [$S_1$], (c) amount of hydrocarbon generated by pyrolitic degradation of kerogen in the sample as the temperature rises [$S_2$], (d) hydrogen index [HI], (e) oxygen index [OI], and (f) temperature of peak $S_2$ [$T_{max}$] with corresponding $R_o$ values (n=3). Zero represents approximate contact of the PSU with the Kemik Sandstone.

and cemented layers that range from 0.3 to 1.68 wt. percent TOC (n=10; averaging 0.75 wt. percent). Data from concretions and cemented layers are included in a separate table in Appendix A and are excluded from further discussions regarding the TOC data used to generate TOC profiles (figs. 4–7). TOC profiles were created to compare and contrast source-rock potential of the PSU mudrock in a stratigraphic context, both vertically and laterally. The vertical profiles show that the TOC content of the PSU generally increases by ~4 wt. percent within the first ~20 m at all three stratigraphic locations (fig. 4 a–c). TOC decreases in the upper portion of the PSU at both the Canning and Boulder Bowl localities. Structural complications precluded collecting samples above ~20 m at the Marsh Creek location (fig. 4c).

## Rock-Eval II

The same samples analyzed for TOC were analyzed using Rock-Eval II pyrolysis (table 1 and Appendix A). The minimum, maximum, and mean for each Rock-Eval parameter for all stratigraphic locations are summarized in table 2 and Appendix A. $S_1$, $S_2$, HI, OI, and $T_{max}$ are all plotted versus stratigraphic height for each location (figs. 5–7). HI values for PSU samples collected from outcrop average 17 mg HC/g TOC (ranging from 5 to 49 mg HC/g TOC). OI values for all PSU samples average 13.76 mg $CO_2$/g TOC (ranging from 1.48 to 37.92 mg $CO_2$/g TOC). The OI and HI data are plotted for all three measured sections in a modified van Krevelen diagram (fig. 8; Peters, 1986). $T_{max}$ values for all PSU localities range from 386ºC to 525°C, averaging 495°C. PI values for all PSU localities range from 0.10 to 0.64, averaging 0.22; the average value at Marsh Creek (0.42) is significantly higher than at the other two locations.

## Vitrinite Reflectance ($R_o$)

Thirteen PSU samples taken at ~10 m intervals within the stratigraphic sections were analyzed for $R_o$: four from the Canning River, four from Boulder Bowl, and three from Marsh Creek. Indigenous mean $R_o$ values are summarized in table 3, and a frequency versus percent $R_o$ histogram for each sample is provided in Appendix B. $R_o$ averages 1.57 percent at the Canning River, 1.28 percent at Boulder Bowl, and 1.79 percent at Marsh Creek.

As an internal review, four split samples (06DAV003, 06DAV029, 06DAV046, and 06DAV0180) were sent to M. Pawlewicz, who examined vitrinite within the whole-rock sample as apposed to the isolation process that Intertek utilizes (USGS, pers. commun. 2008). Even though only a few grains (n=12–18) were examined per sample, the estimated $R_o$ means were in the same general range as determinations made by Intertek. During microscopic examination of samples, Pawlewicz observed mostly solid bitumen (micron-scale) in all of the samples and in 06DAV029 as well as 06DAV180 tentatively identified Type III vitrinite. He also observed blebs of bitumen in all four samples, elongated parallel to bedding.

## DISCUSSION

In this study, PSU mudrocks average 3.42 wt. percent TOC, comparable to TOC values previously reported for the PSU in the Mikkelsen well, where the average TOC of the PSU is 4 wt. percent (ranging from 2.75 to 5.89 wt. percent TOC, n=23; Keller and Macquaker, 2001; Keller and others, 2002). The Canning River has more than 31 m of stratigraphic section with greater than 2 wt. percent TOC, whereas Boulder Bowl has 25 m and the Marsh Creek locality has more than 12 m (Appendix A; fig. 4). Despite thermal maturation, the quantity of organic matter in the PSU is on average very good, but ranges between poor to excellent based on the TOC results (Peters and Cassa, 1994; table 4; fig. 4).

Vertical TOC profiles for the three PSU outcrop localities follow consistent trends that differ from the profile from the Mikkelsen well (fig. 4). TOC is low (1–2 wt. percent) for PSU mudrock at the base of all three measured sections (figs. 4a, b, c) and slightly higher (3–4 wt. percent) at the Mikkelsen well (fig. 4d; Keller and Macquaker, 2001). There is a notable upward increase in TOC between 0 and ~20 m at all three outcrop localities that is not apparent in the Mikkelsen well (fig. 4). In ANWR, the PSU has previously been interpreted as a marine transgressive unit, based principally on the abrupt transition from shelfal deposits of the Kemik Sandstone to marine mudstone of the PSU (for example, Mull, 1987; Molenaar and others, 1987). The upward increase in TOC documented by the new data from this study is interpreted to reflect this upward deepening. It is likely that the enrichment in organic content resulted from a progressive decrease in sediment supply associated with rising relative sea level. There is also a marked decrease of TOC toward the top of the PSU in both the Canning and Boulder Bowl sections. It is possible that this decrease reflects an increase in sediment supply, either marking the onset of Brookian sedimentation or perhaps related to localized tectonic activity along the northern rift margin. An alternate explanation is that variations in organic content in the PSU may, at a fundamental level, be related to changes in the primary productivity of a sub-sea-ice ecosystem (Macquaker and Keller, 2005). Future work will test these hypotheses by examining the lithostratigraphy and gamma-ray response of the PSU and comparing them to TOC trends (van der Kolk, in prep.).

Rock-Eval data from the PSU in outcrop (figs. 5–7) differ from those reported from the Mikkelsen well, and on first inspection suggest the presence of poorer quality kerogen in outcrop (fig. 8). The HI values of outcrop samples are consistently <50 mg HC/g TOC, much lower than HI values for the Mikkelsen well, which range from 278 to 449 mg HC/g TOC (average 336 mg HC/g TOC; Keller and Macquaker, 2001; Keller and others, 2002). The low HI values of PSU outcrop samples are accompanied by low OI values, and the samples cluster tightly near the origin on a modified van Krevelen diagram (fig. 8). In actuality, this is consistent with the advanced thermal maturity of the outcrops sampled. From these data alone, it is essentially impossible to determine which kerogen types were originally present prior to maturation. Only remnants of gas-prone type III kerogen were tentatively observed in two out of four samples analyzed by M. Pawlewicz (pers. commun., 2008). Other kerogen types were unrecognizable, but all four samples have solidified bitumen. The Mikkelsen HI data are consistent with type II/III and II kerogen and indicate a mixture of marine and terrigenous organic matter deposited in a paralic (near shore marine to nonmarine) setting (Peters and others, 2005). Depending on maturity, these types of kerogen can produce oil, gas, or both. Type II kerogen is oil prone and originates from mixed phytoplankton, zooplankton, and bacterial debris, usually in marine sediments (Peters and others, 2005).

The average thermal maturity for the PSU in outcrop is 1.57 percent $R_o$ for the Canning River, 1.28 percent $R_o$ for Boulder Bowl, and 1.79 percent $R_o$ for Marsh Creek. On average, these values are slightly higher or nearly consistent with an average of 1.3 percent $R_o$ from previous results for the Canning River and Boulder Bowl localities (Bird and others, 1999). Both studies are consistent with outcrops of the PSU being overmature with respect to oil generation (Peters and Cassa, 1994). One exception is Boulder Bowl sample 06DAV083, reported by Intertek as having an indigenous $R_o$ value of 0.87 percent. This anomalously low mean value is interpreted as unreliable; consideration of the entire vitrinite population from sample 06DAV083 reveals a histogram peak at 1.4 percent that

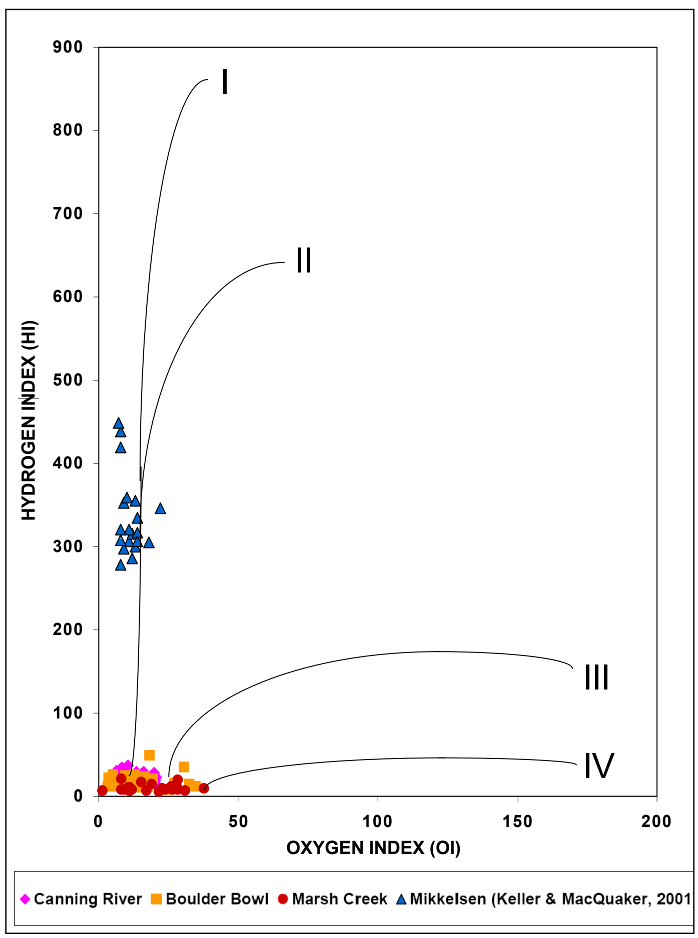



Figure 8. Modified van Krevelen diagram that compares Rock-Eval HI and OI indices of the PSU from the Canning River, Boulder Bowl, and Marsh Creek localities (this study) as well as the Mikkelsen Bay State No. 1 well (Keller and Macquaker, 2001). Arrows indicate paths corresponding to thermal maturation. The distinction among original, pre-maturation kerogen types is progressively lost with increasing maturity. These data alone do not preclude the former presence of oil- and gas-prone kerogen in the PSU in the outcrop belt.

Table 1. Summary of samples analyzed for total organic carbon (TOC) and Rock-Eval pyrolysis from mudrocks and carbonate concretions.

| Location | PSU Mudrock | | | | PSU Carbonates* | | | | Total No.of samples analyzed per location for TOC and Rock-Eval |
|---|---|---|---|---|---|---|---|---|---|
| | Total No. of samples analyzed for TOC and Rock-Eval | TOC Minimum (wt. %) | TOC Maximum (wt. %) | TOC Mean (wt. %) | Total No. of samples analyzed for TOC and Rock-Eval | TOC Minimum (wt. %) | TOC Maximum (wt. %) | TOC Mean (wt. %) | |
| **Canning River** | 42 | 1.02 | 6.15 | 3.93 | 2 | 0.57 | 0.9 | 0.74 | 44 |
| **Boulder Bowl** | 40 | 0.75 | 5.59 | 3.36 | 5 | 0.56 | 1.68 | 1.01 | 45 |
| **Marsh Creek** | 23 | 0.61 | 4.84 | 2.59 | 3 | 0.3 | 1.57 | 0.74 | 26 |

**Note**: The average TOC of mudrock within the PSU is 3.42 wt. percent (n = 105). The average TOC of carbonates within the PSU is 0.75 wt. percent (n=10).
*Carbonates include concretions and carbonate cemented layers in the PSU.
No. = number
wt. % = weight percent

Table 2. Minimum, maximum, and mean values of all Rock-Eval II parameters for PSU mudrock.

| Location | Free Hydrocarbons | | | Generatable Hydrocarbons | | | Total Hydrocarbon Generation Potential | | | Hydrogen Index | | | Generatable Carbon Dioxide | | | Oxygen Index | | | Production Index | | | Temp. of Peak $S_2$ | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $S_1$ | | | $S_2$ | | | $S_1$+$S_2$ | | | HI | | | $S_3$ | | | OI | | | "PI" | | | $T_{max}$ | | |
| Units | (mg HC / g rk) | | | (mg HC / g rk) | | | (mg HC / g rk) | | | (mg HC / g TOC) | | | (mg $CO_2$ / g rk) | | | (mg $CO_2$ / g TOC) | | | ($S_1$ / $S_1$+$S_2$) | | | (°C) | | |
| | Min. | Max. | Mean | Min. | Max. | Mean | Min. | Max. | Mean | Min. | Max. | Mean | Min. | Max. | Mean | Min. | Max. | Mean | Min. | Max. | Mean | Min. | Max. | Mean |
| **Canning River** | 0.09 | 3.46 | 0.29 | 0.16 | 1.91 | 0.85 | 0.25 | 5.37 | 1.14 | 12 | 37 | 21 | 0.10 | 1.12 | 0.47 | 5.24 | 20.44 | 12.07 | 0.10 | 0.64 | 0.22 | 430 | 519 | 490 |
| **Boulder Bowl** | 0.05 | 0.26 | 0.14 | 0.06 | 1.29 | 0.59 | 0.14 | 1.55 | 0.73 | 8 | 49 | 17 | 0.09 | 0.91 | 0.37 | 3.46 | 34.90 | 12.90 | 0.10 | 0.57 | 0.21 | 465 | 525 | 498 |
| **Marsh Creek** | 0.06 | 0.98 | 0.21 | 0.06 | 0.88 | 0.26 | 0.12 | 1.70 | 0.47 | 5 | 21 | 10 | 0.04 | 1.01 | 0.40 | 1.48 | 37.92 | 18.36 | 0.14 | 0.64 | 0.42 | 386 | 524 | 500 |

**Note:** mg = milligram; HC = hydrocarbon; g = gram; rk = rock; TOC = total organic carbon; C = Celsius; Min. = minimum; Max. = maximum

Table 3. Vitrinite reflectance ($R_o$) values for PSU mudrock.

| Location | Sample ID | Meter | Total No. of Measurements Collected | Total No. of Indigenous Measurements | $R_o$ Mean (Indigenous) | Standard Deviation (Indigenous) | Average $R_o$ Mean at Each Location |
|---|---|---|---|---|---|---|---|
| Canning River | 06DAV003 | 0.20 | 83 | 78 | 1.66 | 0.1425 | 1.56 |
| | 06DAV017 | 10.00 | 72 | 67 | 1.67 | 0.1766 | |
| | 06DAV029 | 20.00 | 86 | 85 | 1.69 | 0.1556 | |
| | 06DAV046 | 33.00 | 99 | 98 | 1.25 | 0.0900 | |
| Boulder Bowl | 06DAV083 | 4.20 | 85 | 15 | 0.87 | 0.1287 | 1.28 |
| | 06DAV091 | 10.00 | 71 | 64 | 1.40 | 0.1419 | |
| | 06DAV110 | 20.10 | 90 | 64 | 1.40 | 0.1199 | |
| | 06DAV136 | 37.50 | 98 | 70 | 1.42 | 0.0910 | |
| Marsh Creek | 06DAV149 | 0.50 | 54 | 34 | 2.03 | 0.1255 | 1.79 |
| | 06DAV164 | 11.00 | 70 | 11 | 1.54 | 0.1139 | |
| | 06DAV180 | 23.00 | 81 | 67 | 1.79 | 0.1117 | |

**Note:** Indigenous $R_o$ values are interpreted as primary, non-recycled vitrinite.
No. = number

Table 4. Summary data and interpretation of all samples analyzed for total organic carbon (TOC), Rock Eval II, and vitrinite reflectance ($R_o$)

| No. | Location | Sample ID | Meter | Total Organic Carbon | Free Hydro-carbons | Generatable Hydro-carbons | Total Hydro-carbon Generation Potential | Hydrogen Index | Generatable Carbon Dioxide | Oxygen Index | Production Index | Temp. of Peak $S_2$ | Mean Indigenous Vitrinite Reflectance | Summary Interpretation |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | TOC | $S_1$ | $S_2$ | $S_1+S_2$ | HI | $S_3$ | OI | "PI" | $T_{max}$ | $R_o$ | |
| | | | (m) | (%) | (mg HC / g rk) | (mg HC / g rk) | (mg HC / g rk) | (mg HC / g TOC) | (mg $CO_2$ / g rk) | (mg $CO_2$ / g TOC) | ($S_1$ / $S_1+S_2$) | (°C) | (%) | |
| 1 | Canning River | 06DAV003 | 0.20 | 1.08 | 0.09 | 0.16 | 0.25 | 15 | 0.20 | 18.52 | 0.36 | 486 | 1.66 | Good quantity, but poor quality and overmature. |
| 12 | Canning River | 06DAV017 | 10.00 | 4.63 | 0.16 | 0.68 | 0.84 | 15 | 0.43 | 9.29 | 0.19 | 519 | 1.67 | Excellent quantity, but poor quality and overmature. |
| 25 | Canning River | 06DAV029 | 20.00 | 6.15 | 0.30 | 1.57 | 1.87 | 26 | 0.62 | 10.08 | 0.16 | 498 | 1.69 | Excellent quantity, but poor quality and overmature. |
| 39 | Canning River | 06DAV046 | 33.00 | 3.76 | 0.19 | 1.27 | 1.46 | 34 | 0.35 | 9.31 | 0.13 | 472 | 1.24 | Very good quantity, but poor quality and late maturation. |
| 3 | Boulder Bowl | 06DAV083 | 4.20 | 1.36 | 0.11 | 0.47 | 0.58 | 35 | 0.42 | 30.88 | 0.19 | 473 | 0.87 | Fair quantity, poor quality and mature(?). See discussion about suggested re-evaluation of $R_o$ for this sample. |
| 9 | Boulder Bowl | 06DAV091 | 10.00 | 2.56 | 0.10 | 0.36 | 0.46 | 14 | 0.41 | 16.02 | 0.22 | 507 | 1.40 | Very good quantity, but poor quality and overmature. |
| 20 | Boulder Bowl | 06DAV110 | 20.10 | 2.81 | 0.26 | 0.39 | 0.65 | 14 | 0.26 | 9.25 | 0.40 | 500 | 1.40 | Very good quantity, but poor quality and overmature. |
| 40 | Boulder Bowl | 06DAV136 | 37.50 | 2.65 | 0.12 | 0.38 | 0.50 | 14 | 0.86 | 32.45 | 0.24 | 503 | 1.42 | Very good quantity, but poor quality and overmature. |
| 1 | Marsh Creek | 06DAV149 | 0.50 | 0.61 | 0.06 | 0.07 | 0.13 | 11 | 0.16 | 26.23 | 0.46 | 494 | 2.03 | Poor quantity, poor quality, and overmature. |
| 11 | Marsh Creek | 06DAV164 | 11.00 | 2.72 | 0.08 | 0.20 | 0.28 | 7 | 0.22 | 8.09 | 0.29 | 512 | 1.54 | Very good quantity, but poor quality and overmature. |
| 23 | Marsh Creek | 06DAV180 | 23.00 | 4.75 | 0.08 | 0.49 | 0.57 | 10 | 0.53 | 11.16 | 0.14 | 524 | 1.79 | Excellent quantity, but poor quality and overmature. |

Note: Quantity is assessed by wt. percent TOC, quality by the amount of HI, and maturation from $R_o$ (c.f. Peters and others, 2005).
No. in this table corresponds to the data point (i.e., line number) in Appendix A.

probably reflects the true maturity of the sample (Appendix B). This higher value (overmature) is consistent with results from the three other PSU samples collected stratigraphically above 06DAV083 at the Boulder Bowl locality.

Based on the observation of bitumen blebs elongated parallel to bedding within the rock matrix, the bitumen is interpreted as having been generated in place (M. Pawlewicz, pers. comm. 2008). This, along with high TOC values, may suggest that the PSU in the outcrop belt may have once had the potential to generate at least minor amounts of hydrocarbon liquids in addition to gas. Late- to post-mature $R_o$ values, high Tmax values, and low HI values, combined with the presence of bitumen and the possible occurrence of type III vitrinite in whole rock samples, are consistent with a history in which the PSU generated hydrocarbons and was subsequently subjected to maximum temperatures corresponding to late oil-window and gas-window maturities (Magoon and others, 1987).

Based on an analysis of geophysical well logs, Burns and others (2005) estimated the thickness of strata eroded since the time of maximum burial at 145 well sites on the North Slope. Estimated exhumation at the Mikkelsen well site is zero. In the vicinity of the Canning River section, the estimated exhumation for the Canning B-1 well site is 2,903 m (6,867 feet). The PSU within the Canning B-1 well lies at measured depths between 2,426 and 2,443 m (7,960 and 8,015 feet; Nelson and others, 1999). The maximum burial depth at the base of the PSU within the vicinity of the Canning River is thus estimated at 5,346 m (~17,540 feet). Using present-day, sub-permafrost geothermal gradients of ~30ºC/km, as has been determined for several wells in the Point Thomson area (Magoon and others, 1987, p. 147), temperatures corresponding to late oil window and gas-window maturities would be expected at depths of ~5,500–7,000 m (~18,000–23,000 ft). Assuming the same gradient, a mean surface paleo-temperature of ~0 ºC, and in the absence of permafrost, the same temperatures would have been reached at depths of ~5,000-6,670 m (~16,400-21,900 ft).

## CONCLUSIONS

115 TOC measurements from three sections of the PSU in ANWR indicate that there are 12- to 31-m-thick packages that have sufficient organic content (2–6 wt. percent TOC) to constitute good to excellent source rock. However, Rock-Eval data from these same samples suggest poor source-rock quality (HI <50mg HC/g TOC). This apparent inconsistency is explained by the elevated thermal maturity of the PSU in the outcrop belt indicated by high $T_{max}$ and vitrinite reflectance values; HI and TOC values have likely been lowered from their original levels due to conversion of hydrogen and organic carbon into hydrocarbons. The average vitrinite reflectance of the sections sampled for this study ranges from 1.28 to 1.79 percent $R_o$, indicating latest oil window to gas window maturity. High TOC values combined with the presence of bitumen and the probable occurrence of at least Type III vitrinite in whole rock samples collected in this study suggest that present-day surface exposures of the PSU likely produced hydrocarbons at one time.

These results are consistent with previous studies indicating that the PSU originally had good source-rock potential and, because of advanced thermal maturity in the study area, we cannot rule out the possibility that it may have locally been oil-prone. However, the unit's original potential is only fully apparent from Rock-Eval and TOC results in areas where PSU source rocks were not exhausted during deep burial by Brookian foreland basin sediments.

## ACKNOWLEDGMENTS

Analytical and logistical support was generously provided by the Alaska Division of Geological & Geophysical Surveys (DGGS), whose funding for recent North Slope field projects has come from a combination of state budgets and contributions from industry sponsors including Anadarko, BG Alaska, BP, Chevron, ConocoPhillips, ENI, FEX-Talisman, Petro-Canada, Pioneer Natural Resources, and Shell. P. Flaig and M. Whalen are thanked for help in the field. This work benefited greatly from numerous discussions with K. Bird, P. Decker, R. Garrard, D. Houseknecht, M. Keller, J. Macquaker, P. McCarthy, G. Mull, R. Newberry, M. Pawlewicz, and W. Wallace. P. Decker, who conducted an internal review, improved this manuscript significantly. A. Loveland is thanked for help in the creation of figure 1 and P. Flaig is thanked for help creating figure 2.

## REFERENCES

Anders, D.E., Magoon, L.B., and Lubeck, S.C., 1987, Geochemistry of surface oil shows and potential source rocks, *in* K.J. Bird, and L.B. Magoon, eds., Petroleum geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska: U.S. Geological Survey Bulletin 1778, p. 181–198.

Bird, K.J., 1982, Rock unit report of 228 wells drilled on the North Slope, Alaska: U.S. Geological Survey Open-file Report 82-278, 106 p.

Bird, K.J., 1985, The framework geology of the North Slope of Alaska as related to oil-source rock correlations *in* L.B., Magoon, and G.E. Claypool, eds., Alaska North Slope oil/source rock correlation study: American Association of Petroleum Geologists Studies in Geology 20, p. 3–29.

———1988, North Slope stratigraphic nomenclature and data summary for government—drilled wells *in* Gryc, G., ed., Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: Washington, U.S. Geological Survey Paper 1399, p. 317–353.

———2001, Alaska—A twenty-first-century petroleum province, *in* Downey, M.W., Threet, J.C., and Morgan, W.A., eds., Petroleum provinces of the twenty-first century: American Association of Petroleum Geologists Memoir 74, p. 137–165.

Bird, K.J., and Molenaar, C.M., 1987, Stratigraphy, *in* Peck, D.L., ed., Petroleum geology of northern part of the Arctic National Wildlife Refuge, northeastern Alaska: Washington, U.S. Geological Survey Bulletin 1778, p. 37–59.

Bird, K. J., Burruss, R.C., and Pawlewicz, M.J., 1999, Thermal maturity, *in* The Oil and Gas Resource Potential of the 1002 Area, Arctic National Wildlife Refuge, Alaska, by ANWR Assessment Team: U.S. Geological Survey Open-file Report 98–34, 12 p.

Blanchard, D.C., and Tailleur, I.L., 1983, Pebble shale (Early Cretaceous) depositional environments in National Petroleum Reserve in Alaska (NPRA) [abs]: American Association of Petroleum Geologists Bulletin, v. 67, p. 424–425.

Burns, W.M., Hayba, D.O, Rowan, E.L., and Houseknecht, D.W., 2005, Estimating the amount of eroded section in a partially exhumed basin from geophysical well logs—An example from the North Slope: U.S. Geological Survey Professional Paper 1732-D, p.1–18.

Carman, G.J., and Hardwick P., 1983, Geology and regional setting of Kuparuk Oil Field, Alaska: American Association of Petroleum Geology Bulletin, v. 67, no. 6, p. 1,014–1,031.

Claypool, G.E., and Magoon, L.B., 1985, Comparison of oil-source rock correlation data for Alaskan North Slope—Techniques, results, and conclusions, *in* Magoon, L.B., and Claypool, G.E., eds., Alaska North Slope oil/source rock correlation study: American Association of Petroleum Geologists Studies in Geology, v. 20, p. 48–81.

Durand, B., 1985, Diagenetic modification of kerogens: Philosophical Transactions of the Society of London, Series A, v. 315, no. 1531, p. 77–90.

Espitalié, J., Madec, M, Tissot, B., Menning, J.J., and Leplat, P., 1977, Source rock characterization method for petroleum exploration, *in* Preprints—Offshore Technology Conference, Houston, Texas: Dallas, TX, Offshore Technology Conference, v. 3, no. 9, p. 439–444.

Garrity, C.P., Houseknecht, D.W., Bird, K.J., Potter, C.J., Moore, T.E., Nelson, P.H., and Schenk, C.J., 2005, 2005 oil and gas resource assessment of the central North Slope, Alaska—Play maps and results: U.S. Geological Survey Open-file Report 2005-1182, 29 p., online only: http://pubs.usgs.gov/of/2005/1182/.

Grantz, Arthur, and May, S.D., 1983, Rifting history and structural development of the continental margin north of Alaska, *in* Watkins, J.S., and Drake, C.L., eds., Studies in Continental Margin Geology: American Association of Petroleum Geologists Memoir, v. 34, p. 77–100.

Hubbard, R.J., Edrich, S.P., and Rattey, R.P., 1987, Geologic evolution and hydrocarbon habitat of the 'Arctic Alaska Microplate': Marine and Petroleum Geology, v. 4, p. 2–34.

Jones, H.P., and Speers, R.G., 1976, Permo-Triassic reservoirs of Prudhoe Bay field, North Slope, Alaska, *in* Braunstein, J., ed., North American oil and gas fields, American Association of Petroleum Geologists Bulletin Memoir 24, p. 23–50.

Keller, M.A., 2002, Petroleum source potential of the Beaufortian succession of the NPRA and Colville Delta area, North Slope Alaska, based on sonic and resistivity logs: American Association of Petroleum Geologists Bulletin, v. 86, p.1148.

Keller, M.A., and Macquaker, J.H.S., 2001, High resolution analysis of petroleum source potential and lithofacies of Lower Cretaceous mudstone core (pebble shale unit and ?GRZ of Hue Shale), Mikkelsen Bay State # 1 Well, North Slope Alaska, *in* Houseknecht, D.W., ed., NPRA Core Workshop Petroleum Plays and Systems in the National Petroleum Reserve—Alaska, Core Workshop No. 21: Denver, Co, SEPM (Society for Sedimentary Geology), p. 37–56.

Keller, M.A., Bird, K.J., and Evans, K.R., 1999, Petroleum source rock evaluation based on sonic and resistivity logs, *in* Alaska Assessment Team, eds., The oil and gas resource potential of the 1002 Area, Arctic National Wildlife Refuge, Alaska: U.S. Geological Survey Open-file Report 98-34, p. SR1–SR35 + figures, tables, and plates.

Keller, M.S., Macquaker, J.H.S., and Lillis, P.G., 2002, High resolution study of petroleum source rock variation, Lower Cretaceous (Hauterivian and Barremian) of Mikkelsen Bay, North Slope, Alaska: U.S. Geological Survey Open-file Report 01480, 3 sheets, http://pubs.usgs.gov/of/2001/of01-480.

Knock, D.G., 1986, Thirty-seven measured sections of Lower Cretaceous Kemik Sandstone, northeastern Alaska: Alaska Division of Geological & Geophysical Surveys Public-data File 86-86b, 22 p.

Lillis, P.G., 2003, Representative bulk geochemical properties of oil types for the 2002 U.S. Geological Survey resource assessment of National Petroleum Reserve-Alaska: U.S. Geological Survey Open-file Report 03-407: http://pubs.er.usgs.gov/publication/ofr03407.

Macquaker, J.H.S., and Keller, M.A., 2005, Mudstone sedimentation at high latitudes—Ice as a transport medium for mud and supplier of nutrients: Journal of Sedimentary Geology, v. 75, p. 696–709.

Magoon, L.B., and Claypool, G.E., 1980, Two oil types on North Slope of Alaska—Implications for Exploration: American Association of Petroleum Geologists Bulletin, v. 65, p. 644–652.

———1985, Introduction, *in* L.B., Magoon, and Claypool, G.E., eds., Alaska North Slope oil/source rock correlation study: American Association of Petroleum Geologists Studies in Geology v. 20, p. xi–xiv.

Magoon, L.B., Woodward, A.C., Banet A.C, Griscom, S.B., and Daws, T.A., 1987, Thermal maturity, richness, and type of organic matter of source rock unit, *in* Bird, K.J., and Magoon, L.B., eds., Petroleum geology of the northern part of the Arctic National Wildlife Refuge, northeastern Alaska: U.S. Geological Survey Bulletin 1778, p. 181–198.

Masterson, W.D., 2001, Petroleum filling history of central Alaskan North Slope fields: Dallas, TX, University of Texas at Dallas, Ph.D. thesis, 222 p.

Molenaar, C.M., 1981, Depositional history and seismic stratigraphy of Lower Cretaceous rocks, National Petroleum Reserve in Alaska and adjacent areas, U.S. Geological Survey Open-file Report 81-1084, p. 1–45.

———1983, Depositional relations of Cretaceous and Lower Tertiary rocks, northeastern Alaska: American Association of Petroleum Geologists Bulletin, v. 67, p. 1,066–1,080.

———1988, Depositional history and seismic stratigraphy of Lower Cretaceous rocks in the National Petroleum Reserve in Alaska and adjacent areas, *in* Gryc, G., ed., Geology and Exploration of the National Petroleum Reserve in Alaska, 1974 to 1982: U.S. Geological Survey Professional Paper 1399, p. 593–621.

Molenaar, C.M., Bird, K.J., and Kirk, A.R., 1987, Cretaceous and Tertiary stratigraphy of Northeastern Alaska, *in* Tailleur, I.L., and Weimer, Paul, eds., Alaskan North Slope Geology, Volume 1: Anchorage, The Pacific Section, Society of Economic Paleontologists and Mineralogists, p. 513–528.

Morgridge, D., and Smith, W., Jr., 1972, Geology and discovery of Prudhoe Bay field, eastern Arctic Slope, Alaska, *in* King, R.E., ed., Stratigraphic oil and gas fields—Classification, exploration methods, and case histories: American Association of Petroleum Geologists Bulletin Memoir 16, p. 489–501.

Mull, C.G., 1987, Kemik sandstone, Arctic National Wildlife Refuge, northeastern Alaska, *in* Tailleur, I.L., and Weimer, Paul, ed., Alaska North Slope Geology, Volume 1: Bakersfied, SEPM (Society for Sedimentary Geology), Pacific Section and Alaska Geological Society, p. 405–431.

Nelson, P.H., Kibler, J.E., and Giberson, C.P., 1999, Chapter WL, Well data and well plots, *in* ANWR Assessment Team, ed., The oil and gas resource potential of the 1002 Area, Arctic National Wildlife Refuge, Alaska, U.S. Geological Survey Open-file Report 98-34, p. WL1-WL26.

Peters, K.E., 1986, Guidelines for evaluating petroleum source rock using programmed pyrolysis: American Association of Petroleum Geologists Bulletin, v. 70, p.318–329.

Peters, K.E., and Cassa, M.R., 1994, Applied source rock geochemistry, *in* Magoon, L.B., and Dow, W.G., eds., The petroleum system—From source to trap: American Association of Petroleum Geologists Memoir 60, p.93–117.

Peters, K.E., Walters, C.C., and Moldowan, J.M., 2005, The biomarker guide, 2d ed: Cambridge, United Kingdom, Cambridge University Press, 1,155 p.

Riehle, J.R., Fleming, M.D., Molnia, B.F., Dover, J.H., Kelley, J.S., Miller, M.L., Nokleberg, W.J., Plafker, George, and Till, A.B., 1997, Digital shaded-relief image of Alaska: U.S. Geological Survey Series I-2585, 1 sheet, scale 1:2,500,000.

Robinson, M.S., Decker, John, Clough, J.G., Reifenstuhl, R.R., Bakke, A.A., Dillon J.T., Combellick, R.A., and Rawlinson, S.E., 1989, Geology of the Sadlerochit and Shublik Mountains, Arctic National Refuge, Northeastern Alaska: Alaska Division of Geological & Geophysical Surveys Professional Report 100, 1 sheet, scale 1:63,360.

Seifert, W.K., Moldowan, J.M., and Jones, R.W., 1980, Application of biological marker chemistry to petroleum exploration—Proceedings of the 10th World Petroleum Congress, Bucharest, Romania, September 1979, Paper SP8: Philadelphia, PA, Heyden & Son Inc., v. 2, no. 10, p. 425–440.

Tailleur, I.L., Pessel, G.H., and Engwicht, S.E., 1978, Folio, eastern North Slope petroleum province: U.S. Geological Survey Miscellaneous Field Studies Map MF 928A (map with tables), 8 p., scale 1:500,000.
van der Kolk, D.A., 2010, Geochemistry, sedimentology, and stratigraphy of the Lower Cretaceous pebble shale unit, northeastern Alaska: Fairbanks, Alaska, University of Alaska Fairbanks, M.S. Thesis, 116 p.
U.S. Geological Survey, 1956 (limited revisions 1983), Mount Michelson 1:250,000 Quadrangle, Alaska: U.S. Geological Survey, Reston, Virginia, 1 sheet, scale 1:250,000.

# APPENDIX A

| No. | Sample ID | Meter | Total Organic Carbon | Free Hydrocarbons | Generatable Hydrocarbons | Total Hydrocarbon Generation Potential | Hydrogen Index | Generatable Carbon Dioxide | Oxygen Index | Production Index | Temp. of Peak $S_2$ | Mean Indigenous Vitrinite Reflectance |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | TOC | $S_1$ | $S_2$ | $S_1+S_2$ | HI | $S_3$ | OI | PI | $T_{max}$ | Ro |
| | | (m) | (%) | (mg HC / g rk) | (mg HC / g rk) | (mg HC / g rk) | (mg HC / g TOC) | (mg $CO_2$ / g rk) | (mg $CO_2$ / g TOC) | ($S_1$ / $S_1+S_2$) | (°C) | (%) |
| 1 | 06DAV003 | 0.20 | 1.08 | 0.09 | 0.16 | 0.25 | 15 | 0.20 | 18.52 | 0.36 | 486 | 1.66 |
| 2 | 06DAV004 | 1.00 | 1.02 | 0.13 | 0.22 | 0.35 | 22 | 0.18 | 17.73 | 0.37 | 488 | -- |
| 3 | 06DAV005 | 2.00 | 2.00 | 0.17 | 0.58 | 0.75 | 29 | 0.32 | 16.04 | 0.23 | 472 | -- |
| 4 | 06DAV008 | 2.60 | 1.91 | 0.09 | 0.50 | 0.59 | 26 | 0.10 | 5.24 | 0.15 | 480 | -- |
| 5 | 06DAV009 | 4.00 | 1.58 | 0.10 | 0.36 | 0.46 | 23 | 0.14 | 8.85 | 0.22 | 479 | -- |
| 6 | 06DAV010 | 5.00 | 2.61 | 0.13 | 0.37 | 0.50 | 14 | 0.20 | 7.67 | 0.26 | 504 | -- |
| 7 | 06DAV011 | 6.00 | 2.30 | 0.13 | 0.40 | 0.53 | 17 | 0.17 | 7.39 | 0.25 | 497 | -- |
| 8 | 06DAV012 | 6.60 | 3.93 | 0.16 | 0.53 | 0.69 | 13 | 0.27 | 6.87 | 0.23 | 498 | -- |
| 9 | 06DAV013 | 7.00 | 2.50 | 0.14 | 0.43 | 0.57 | 17 | 0.19 | 7.60 | 0.25 | 495 | -- |
| 10 | 06DAV014 | 8.25 | 4.06 | 0.17 | 0.63 | 0.80 | 16 | 0.39 | 9.60 | 0.21 | 502 | -- |
| 11 | 06DAV015 | 9.00 | 3.97 | 0.13 | 0.60 | 0.73 | 15 | 0.44 | 11.09 | 0.18 | 500 | -- |
| 12 | 06DAV017 | 10.00 | 4.63 | 0.16 | 0.68 | 0.84 | 15 | 0.43 | 9.29 | 0.19 | 519 | 1.67 |
| 13 | 06DAV018 | 11.00 | 5.48 | 0.29 | 1.27 | 1.56 | 23 | 1.12 | 20.44 | 0.19 | 483 | -- |
| 14 | 06DAV019 | 11.90 | 4.44 | 0.24 | 1.02 | 1.26 | 23 | 0.42 | 9.46 | 0.19 | 487 | -- |
| 15 | 06DAV020 | 12.00 | 2.98 | 0.15 | 0.64 | 0.79 | 22 | 0.16 | 5.38 | 0.19 | 489 | -- |
| 16 | 06DAV022 | 12.50 | 5.06 | 0.20 | 1.37 | 1.57 | 27 | 0.28 | 5.54 | 0.13 | 489 | -- |
| 17 | 06DAV021 | 12.90 | 3.60 | 0.15 | 0.59 | 0.74 | 16 | 0.27 | 7.51 | 0.20 | 506 | -- |
| 18 | 06DAV023 | 14.00 | 4.87 | 0.61 | 1.33 | 1.94 | 27 | 0.77 | 15.80 | 0.31 | 482 | -- |
| 19 | 06DAV024 | 15.00 | 5.04 | 0.24 | 1.47 | 1.71 | 29 | 0.68 | 13.50 | 0.14 | 485 | -- |
| 20 | 06DAV025 | 16.00 | 4.70 | 0.15 | 0.88 | 1.03 | 19 | 0.59 | 12.56 | 0.15 | 497 | -- |
| 21 | 06DAV026 | 17.00 | 5.83 | 0.18 | 1.39 | 1.57 | 24 | 0.47 | 8.06 | 0.11 | 494 | -- |
| 22 | 06DAV027 | 18.00 | 5.45 | 3.46 | 1.91 | 5.37 | 35 | 0.44 | 8.08 | 0.64 | 493 | -- |
| 23 | 06DAV028 | 19.00 | 6.09 | 0.76 | 1.86 | 2.62 | 31 | 0.38 | 6.24 | 0.29 | 495 | -- |
| 24 | 06DAV030 | 19.50 | 5.80 | 0.19 | 1.06 | 1.25 | 18 | 0.77 | 13.28 | 0.15 | 504 | -- |
| 25 | 06DAV029 | 20.00 | 6.15 | 0.30 | 1.57 | 1.87 | 26 | 0.62 | 10.08 | 0.16 | 498 | 1.69 |
| 26 | 06DAV032 | 21.00 | 4.46 | 0.15 | 0.65 | 0.80 | 15 | 0.48 | 10.76 | 0.19 | 512 | -- |
| 27 | 06DAV033 | 22.00 | 5.25 | 0.16 | 1.00 | 1.16 | 19 | 0.48 | 9.15 | 0.14 | 509 | -- |
| 28 | 06DAV034 | 23.00 | 5.55 | 0.15 | 0.69 | 0.84 | 12 | 0.86 | 15.49 | 0.18 | 508 | -- |
| 29 | 06DAV035 | 24.00 | 4.40 | 0.13 | 0.65 | 0.78 | 15 | 0.73 | 16.59 | 0.17 | 504 | -- |
| 30 | 06DAV036 | 25.00 | 3.27 | 0.32 | 0.49 | 0.81 | 15 | 0.66 | 20.18 | 0.40 | 515 | -- |
| 31 | 06DAV037 | 26.00 | 4.10 | 0.42 | 0.66 | 1.08 | 16 | 0.44 | 10.73 | 0.39 | 501 | -- |
| 32 | 06DAV038 | 27.00 | 4.04 | 0.73 | 0.69 | 1.42 | 17 | 0.60 | 14.84 | 0.51 | 510 | -- |
| 33 | 06DAV039 | 28.00 | 3.27 | 0.16 | 0.82 | 0.98 | 25 | 0.63 | 19.25 | 0.16 | 502 | -- |
| 34 | 06DAV057 | 28.75 | 3.06 | 0.16 | 0.78 | 0.94 | 26 | 0.45 | 14.73 | 0.17 | 487 | -- |
| 35 | 06DAV040 | 29.00 | 3.50 | 0.16 | 0.98 | 1.14 | 28 | 0.70 | 20.01 | 0.14 | 467 | -- |
| 36 | 06DAV041 | 30.00 | 2.99 | 0.12 | 0.64 | 0.76 | 21 | 0.38 | 12.72 | 0.16 | 483 | -- |
| 37 | 06DAV042 | 31.00 | 4.47 | 0.13 | 0.85 | 0.98 | 19 | 0.91 | 20.34 | 0.13 | 430 | -- |
| 38 | 06DAV045 | 32.00 | 4.61 | 0.12 | 0.99 | 1.11 | 21 | 0.60 | 13.02 | 0.11 | 435 | -- |
| 39 | 06DAV046 | 33.00 | 3.76 | 0.19 | 1.27 | 1.46 | 34 | 0.35 | 9.31 | 0.13 | 472 | 1.24 |
| 40 | 06DAV047 | 34.00 | 4.41 | 0.18 | 1.61 | 1.79 | 37 | 0.46 | 10.44 | 0.10 | 461 | -- |
| 41 | 06DAV048 | 35.00 | 3.86 | 0.16 | 0.81 | 0.97 | 21 | 0.43 | 11.15 | 0.16 | 477 | -- |
| 42 | 06DAV049 | 36.00 | 2.83 | 0.19 | 0.45 | 0.64 | 16 | 0.46 | 16.23 | 0.30 | 470 | -- |
| Minimum | | | 1.02 | 0.09 | 0.16 | 0.25 | 12 | 0.10 | 5.24 | 0.10 | 430 | 1.24 |
| Maximum | | | 6.15 | 3.46 | 1.91 | 5.37 | 37 | 1.12 | 20.44 | 0.64 | 519 | 1.69 |
| Mean | | | 3.93 | 0.29 | 0.85 | 1.14 | 21 | 0.47 | 12.07 | 0.22 | 490 | 1.57 |

Note: The Kemik-PSU contact and base of the Canning River section is approximately located at N 69.52935°, W 146.30328°.

| No. | Sample ID | Meter | Total Organic Carbon | Free Hydrocarbons | Generatable Hydrocarbons | Total Hydrocarbon Generation Potential | Hydrogen Index | Generatable Carbon Dioxide | Oxygen Index | Production Index | Temp. of Peak $S_2$ | Vitrinite Reflectance |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | TOC | $S_1$ | $S_2$ | $S_1$+$S_2$ | HI | $S_3$ | OI | PI | $T_{max}$ | Ro |
| | | (m) | (%) | (mg HC / g rk) | (mg HC / g rk) | (mg HC / g rk) | (mg HC / g TOC) | (mg $CO_2$ / g rk) | (mg $CO_2$ / g TOC) | ($S_1$ / $S_1$+$S_2$) | (°C) | (%) |
| 1 | 06DAV080 | 0.05 | 0.77 | 0.09 | 0.12 | 0.21 | 16 | 0.21 | 27.27 | 0.43 | 484 | -- |
| 2 | 06DAV081 | 0.20 | 0.75 | 0.08 | 0.06 | 0.14 | 8 | 0.19 | 25.33 | 0.57 | 465 | -- |
| 3 | 06DAV083 | 4.20 | 1.36 | 0.11 | 0.47 | 0.58 | 35 | 0.42 | 30.88 | 0.19 | 473 | 0.87 |
| 4 | 06DAV085 | 4.90 | 2.36 | 0.13 | 1.16 | 1.29 | 49 | 0.43 | 18.22 | 0.10 | 465 | -- |
| 5 | 06DAV087 | 6.00 | 1.80 | 0.11 | 0.28 | 0.39 | 16 | 0.50 | 27.78 | 0.28 | 487 | -- |
| 6 | 06DAV088 | 7.00 | 2.58 | 0.13 | 0.46 | 0.59 | 18 | 0.32 | 12.40 | 0.22 | 487 | -- |
| 7 | 06DAV089 | 8.25 | 1.91 | 0.07 | 0.21 | 0.28 | 11 | 0.28 | 14.66 | 0.25 | 495 | -- |
| 8 | 06DAV092 | 9.00 | 1.93 | 0.08 | 0.19 | 0.27 | 10 | 0.34 | 17.62 | 0.30 | 488 | -- |
| 9 | 06DAV091 | 10.00 | 2.56 | 0.10 | 0.36 | 0.46 | 14 | 0.41 | 16.02 | 0.22 | 507 | 1.40 |
| 10 | 06DAV095 | 11.00 | 2.55 | 0.11 | 0.29 | 0.40 | 11 | 0.89 | 34.90 | 0.28 | 501 | -- |
| 11 | 06DAV097 | 13.00 | 4.83 | 0.20 | 1.24 | 1.44 | 26 | 0.26 | 5.38 | 0.14 | 486 | -- |
| 12 | 06DAV098 | 13.40 | 3.81 | 0.13 | 0.47 | 0.60 | 12 | 0.47 | 12.34 | 0.22 | 513 | -- |
| 13 | 06DAV100 | 14.00 | 5.24 | 0.14 | 0.73 | 0.87 | 14 | 0.38 | 7.25 | 0.16 | 518 | -- |
| 14 | 06DAV101 | 15.00 | 4.32 | 0.16 | 0.73 | 0.89 | 17 | 0.32 | 7.41 | 0.18 | 500 | -- |
| 15 | 06DAV103 | 16.00 | 4.63 | 0.20 | 0.93 | 1.13 | 20 | 0.91 | 19.65 | 0.18 | 496 | -- |
| 16 | 06DAV106 | 17.00 | 5.05 | 0.26 | 1.29 | 1.55 | 26 | 0.66 | 13.07 | 0.17 | 497 | -- |
| 17 | 06DAV107 | 18.00 | 4.36 | 0.12 | 0.61 | 0.73 | 14 | 0.21 | 4.82 | 0.16 | 515 | -- |
| 18 | 06DAV108 | 19.00 | 3.07 | 0.21 | 0.53 | 0.74 | 17 | 0.31 | 10.10 | 0.28 | 487 | -- |
| 19 | 06DAV109 | 19.75 | 4.80 | 0.14 | 0.75 | 0.89 | 16 | 0.47 | 9.79 | 0.16 | 512 | -- |
| 20 | 06DAV110 | 20.10 | 2.81 | 0.26 | 0.39 | 0.65 | 14 | 0.26 | 9.25 | 0.40 | 500 | 1.40 |
| 21 | 06DAV111 | 20.50 | 2.38 | 0.05 | 0.24 | 0.29 | 10 | 0.35 | 14.71 | 0.17 | 494 | -- |
| 22 | 06DAV112 | 21.00 | 2.60 | 0.13 | 0.30 | 0.43 | 12 | 0.09 | 3.46 | 0.30 | 489 | -- |
| 23 | 06DAV113 | 22.00 | 4.30 | 0.13 | 0.65 | 0.78 | 15 | 0.53 | 12.33 | 0.17 | 506 | -- |
| 24 | 06DAV116 | 24.00 | 4.02 | 0.12 | 0.71 | 0.83 | 18 | 0.38 | 9.45 | 0.14 | 507 | -- |
| 25 | 06DAV117 | 25.00 | 4.64 | 0.16 | 0.84 | 1.00 | 18 | 0.40 | 8.62 | 0.16 | 513 | -- |
| 26 | 06DAV119 | 26.00 | 5.03 | 0.19 | 1.23 | 1.42 | 24 | 0.49 | 9.74 | 0.13 | 491 | -- |
| 27 | 06DAV122 | 27.00 | 4.44 | 0.18 | 1.03 | 1.21 | 23 | 0.74 | 16.67 | 0.15 | 496 | -- |
| 28 | 06DAV123 | 28.00 | 5.16 | 0.20 | 1.03 | 1.23 | 20 | 0.67 | 12.98 | 0.16 | 506 | -- |
| 29 | 06DAV124 | 29.00 | 3.89 | 0.15 | 0.83 | 0.98 | 21 | 0.15 | 3.86 | 0.15 | 498 | -- |
| 30 | 06DAV125 | 29.60 | 5.59 | 0.17 | 1.08 | 1.25 | 19 | 0.22 | 3.94 | 0.14 | 512 | -- |
| 31 | 06DAV126 | 30.00 | 4.55 | 0.14 | 0.71 | 0.85 | 16 | 0.18 | 3.96 | 0.16 | 514 | -- |
| 32 | 06DAV127 | 31.00 | 5.06 | 0.16 | 0.74 | 0.90 | 15 | 0.19 | 3.75 | 0.18 | 525 | -- |
| 33 | 06DAV129 | 32.00 | 2.71 | 0.08 | 0.40 | 0.48 | 15 | 0.12 | 4.43 | 0.17 | 505 | -- |
| 34 | 06DAV130 | 33.00 | 3.37 | 0.10 | 0.46 | 0.56 | 14 | 0.15 | 4.45 | 0.18 | 509 | -- |
| 35 | 06DAV131 | 33.50 | 2.11 | 0.06 | 0.25 | 0.31 | 12 | 0.17 | 8.06 | 0.19 | 498 | -- |
| 36 | 06DAV132 | 34.00 | 3.55 | 0.11 | 0.43 | 0.54 | 12 | 0.19 | 5.35 | 0.20 | 505 | -- |
| 37 | 06DAV133 | 35.00 | 1.88 | 0.09 | 0.28 | 0.37 | 15 | 0.21 | 11.17 | 0.24 | 490 | -- |
| 38 | 06DAV134 | 36.50 | 1.82 | 0.10 | 0.23 | 0.33 | 13 | 0.16 | 8.79 | 0.30 | 493 | -- |
| 39 | 06DAV135 | 37.00 | 3.16 | 0.13 | 0.70 | 0.83 | 22 | 0.43 | 13.61 | 0.16 | 494 | -- |
| 40 | 06DAV136 | 37.50 | 2.65 | 0.12 | 0.38 | 0.50 | 14 | 0.86 | 32.45 | 0.24 | 503 | 1.42 |
| **Minimum** | | | 0.75 | 0.05 | 0.06 | 0.14 | 8 | 0.09 | 3.46 | 0.10 | 465 | 0.87 |
| **Maximum** | | | 5.59 | 0.26 | 1.29 | 1.55 | 49 | 0.91 | 34.90 | 0.57 | 525 | 1.42 |
| **Mean** | | | 3.36 | 0.14 | 0.59 | 0.73 | 17 | 0.37 | 12.90 | 0.21 | 498 | 1.70 |

Note: The Kemik-PSU contact and base of the Boulder Bowl section is approximately located at N 69.67866º, W 145.22668º.

| No. | Sample ID | Meter (m) | Total Organic Carbon TOC (%) | Free Hydrocarbons $S_1$ (mg HC / g rk) | Generatable Hydrocarbons $S_2$ (mg HC / g rk) | Total Hydrocarbon Generation Potential $S_1+S_2$ (mg HC / g rk) | Hydrogen Index HI (mg HC / g TOC) | Generatable Carbon Dioxide $S_3$ (mg $CO_2$ / g rk) | Oxygen Index OI (mg $CO_2$ / g TOC) | Production Index PI ($S_1$ / $S_1+S_2$) | Temp. of Peak $S_2$ $T_{max}$ (°C) | Vitrinite Reflectance Ro (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 06DAV149 | 0.50 | 0.61 | 0.06 | 0.07 | 0.13 | 11 | 0.16 | 26.23 | 0.46 | 494 | 2.03 |
| 2 | 06DAV151 | 1.75 | 0.66 | 0.08 | 0.06 | 0.14 | 9 | 0.25 | 37.92 | 0.57 | 386 | -- |
| 3 | 06DAV152 | 2.00 | 1.19 | 0.07 | 0.06 | 0.13 | 5 | 0.26 | 21.85 | 0.54 | 486 | -- |
| 4 | 06DAV153 | 3.00 | 1.79 | 0.15 | 0.25 | 0.40 | 14 | 0.34 | 19.01 | 0.38 | 515 | -- |
| 5 | 06DAV154 | 4.00 | 0.82 | 0.06 | 0.06 | 0.12 | 7 | 0.22 | 26.75 | 0.50 | 445 | -- |
| 6 | 06DAV156 | 5.00 | 0.96 | 0.13 | 0.11 | 0.24 | 11 | 0.27 | 28.09 | 0.54 | 442 | -- |
| 7 | 06DAV157 | 6.00 | 1.59 | 0.06 | 0.12 | 0.18 | 8 | 0.45 | 28.36 | 0.33 | 512 | -- |
| 8 | 06DAV159 | 7.00 | 2.49 | 0.10 | 0.47 | 0.57 | 19 | 0.71 | 28.57 | 0.18 | 512 | -- |
| 9 | 06DAV161 | 8.20 | 1.47 | 0.08 | 0.09 | 0.17 | 6 | 0.46 | 31.21 | 0.47 | 504 | -- |
| 10 | 06DAV162 | 9.00 | 1.70 | 0.10 | 0.12 | 0.22 | 7 | 0.19 | 11.16 | 0.45 | 508 | -- |
| 11 | 06DAV164 | 11.00 | 2.72 | 0.08 | 0.20 | 0.28 | 7 | 0.22 | 8.09 | 0.29 | 512 | 1.54 |
| 12 | 06DAV165 | 12.00 | 2.46 | 0.31 | 0.21 | 0.52 | 9 | 0.56 | 22.75 | 0.60 | 519 | -- |
| 13 | 06DAV167 | 13.00 | 2.89 | 0.38 | 0.24 | 0.62 | 8 | 0.35 | 12.13 | 0.61 | 514 | -- |
| 14 | 06DAV168 | 14.00 | 2.58 | 0.50 | 0.28 | 0.78 | 11 | 0.28 | 10.86 | 0.64 | 498 | -- |
| 15 | 06DAV170 | 15.00 | 2.70 | 0.13 | 0.19 | 0.32 | 7 | 0.04 | 1.48 | 0.41 | 513 | -- |
| 16 | 06DAV171 | 16.00 | 4.19 | 0.23 | 0.30 | 0.53 | 7 | 1.01 | 24.10 | 0.43 | 521 | -- |
| 17 | 06DAV172 | 17.00 | 4.18 | 0.82 | 0.88 | 1.70 | 21 | 0.35 | 8.38 | 0.48 | 518 | -- |
| 18 | 06DAV174 | 18.00 | 4.08 | 0.98 | 0.67 | 1.65 | 16 | 0.62 | 15.21 | 0.59 | 521 | -- |
| 19 | 06DAV175 | 19.00 | 4.06 | 0.10 | 0.26 | 0.36 | 6 | 0.46 | 11.33 | 0.28 | 518 | -- |
| 20 | 06DAV176 | 20.00 | 2.74 | 0.09 | 0.18 | 0.27 | 7 | 0.47 | 17.17 | 0.33 | 512 | -- |
| 21 | 06DAV177 | 21.00 | 4.10 | 0.08 | 0.24 | 0.32 | 6 | 0.46 | 11.21 | 0.25 | 517 | -- |
| 22 | 06DAV178 | 22.00 | 4.84 | 0.10 | 0.40 | 0.50 | 8 | 0.45 | 9.30 | 0.20 | 517 | -- |
| 23 | 06DAV180 | 23.00 | 4.75 | 0.08 | 0.49 | 0.57 | 10 | 0.53 | 11.16 | 0.14 | 524 | 1.79 |
| **Minimum** | | | 0.61 | 0.06 | 0.06 | 0.12 | 5 | 0.04 | 1.48 | 0.14 | 386 | 1.54 |
| **Maximum** | | | 4.84 | 0.98 | 0.88 | 1.70 | 21 | 1.01 | 37.92 | 0.64 | 524 | 2.03 |
| **Mean** | | | 2.59 | 0.21 | 0.26 | 0.47 | 10 | 0.40 | 18.36 | 0.42 | 500 | 1.79 |

Note: The Kemik-PSU contact and base of the Marsh Creek section is approximately located at N 69.68308º, W 144.85077º.

| No. | Location | Sample ID | Meter | Total Organic Carbon | Free Hydrocarbons | Generatable Hydrocarbons | Total Hydrocarbon Generation Potential | Hydrogen Index | Generatable Carbon Dioxide | Oxygen Index | Production Index | Temp. of Peak $S_2$ | Vitrinite Reflectance |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | TOC | $S_1$ | $S_2$ | $S_1$+$S_2$ | HI | $S_3$ | OI | PI | $T_{max}$ | Ro |
| | | | (m) | (%) | (mg HC / g rk) | (mg HC / g rk) | (mg HC / g rk) | (mg HC / g TOC) | (mg $CO_2$ / g rk) | (mg $CO_2$ / g TOC) | ($S_1$ / $S_1$+$S_2$) | (°C) | (%) |
| 1 | Canning River | 06DAV006 | 3.00 | 0.57 | 0.14 | 0.17 | 0.31 | 30 | 1.75 | 304.93 | 0.45 | 511 | -- |
| 2 | Canning River | 06DAV016 | 9.80 | 0.90 | 0.08 | 0.22 | 0.30 | 25 | 2.34 | 260.61 | 0.27 | 514 | -- |
| 4 | Boulder Bowl | 06DAV084 | 4.60 | 0.90 | 0.16 | 0.30 | 0.46 | 33 | 2.16 | 240.00 | 0.35 | 505 | -- |
| 5 | Boulder Bowl | 06DAV086 | 5.40 | 0.60 | 0.08 | 0.13 | 0.21 | 22 | 1.50 | 250.00 | 0.38 | 515 | -- |
| 6 | Boulder Bowl | 06DAV090 | 8.50 | 0.56 | 0.23 | 0.08 | 0.31 | 14 | 3.01 | 537.50 | 0.74 | 511 | -- |
| 7 | Boulder Bowl | 06DAV094 | 10.85 | 1.68 | 0.12 | 0.23 | 0.35 | 14 | 2.62 | 155.95 | 0.34 | 488 | -- |
| 3 | Boulder Bowl | 06DAV128 | 31.00 | 1.32 | 0.15 | 0.27 | 0.42 | 20 | 0.62 | 46.97 | 0.36 | 469 | -- |
| 8 | Marsh Creek | 06DAV150 | 1.00 | 0.30 | 0.08 | 0.06 | 0.14 | 20 | 1.06 | 348.34 | 0.57 | 479 | -- |
| 9 | Marsh Creek | 06DAV155 | 4.50 | 0.36 | 0.06 | 0.06 | 0.12 | 17 | 0.92 | 256.34 | 0.50 | 487 | -- |
| 10 | Marsh Creek | 06DAV163B | 10.00 | 1.57 | 0.22 | 0.05 | 0.27 | 3 | 2.46 | 156.99 | 0.81 | 437 | -- |
| **Minimum** | | | | 0.30 | 0.06 | 0.05 | 0.12 | 3 | 0.62 | 46.97 | 0.27 | 437 | -- |
| **Maximum** | | | | 1.68 | 0.23 | 0.30 | 0.46 | 33 | 3.01 | 537.50 | 0.81 | 515 | -- |
| **Mean** | | | | 0.88 | 0.13 | 0.16 | 0.29 | 20 | 1.84 | 255.76 | 0.48 | 492 | -- |

Note: Carbonates include concretions and carbonate cemented layers in the PSU.

# APPENDIX B

## Intertek Westport Technology Center

### Vitrinite Reflectance - Visual Kerogen Assessment Summary

**Sample Information**

| | | | |
|---|---|---|---|
| Westport Project | WTC-06-000220 | Client | Alaska Geological Survey |
| Westport Sample | 94756 | Client Project | North Slope |
| | | Client Sample | 06DAV003 |

**Visual Kerogen Assessment**

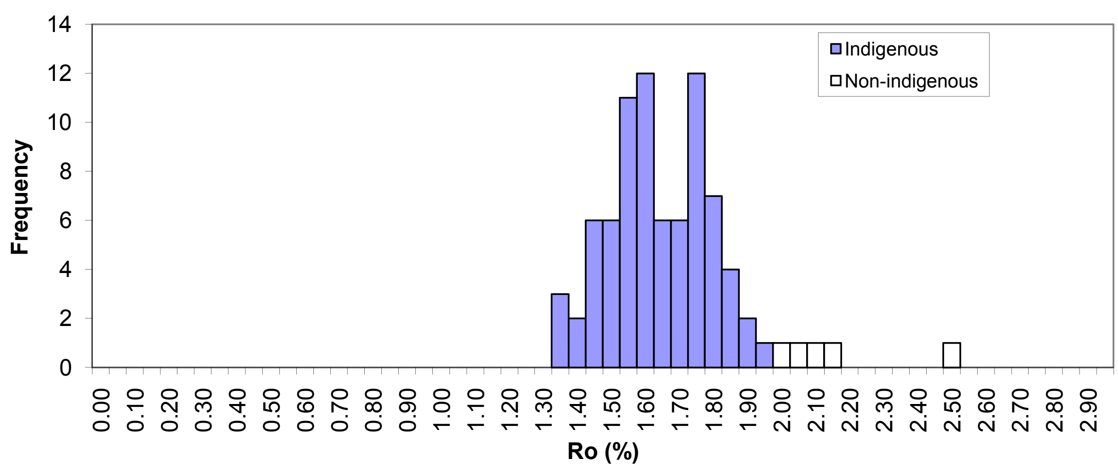
| Thermal Alteration Index |
|---|
| |

| Kerogen Types (vol%) | | | | | |
|---|---|---|---|---|---|
| Amorphous Kerogen | | | | | |
| Fluor. | Non-flour. | Alginite | Exinite | Vitrinite | Inertinite |
| | | | | | |

**Comments:**

**Vitrinite Reflectance**

| | Min | Max | Mode | Mean | Median | StDev |
|---|---|---|---|---|---|---|
| Indigenous | 1.36 | 1.95 | 1.59 | 1.66 | 1.64 | 0.1425 |
| Total | 1.36 | 2.51 | 1.59 | 1.69 | 1.65 | 0.1911 |




**Ordered Readings**    Bold = Indigenous    **Point Count** 83

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **1.36** | **1.49** | **1.56** | **1.60** | **1.65** | **1.73** | **1.78** | **1.84** | 2.11 |
| **1.37** | **1.51** | **1.56** | **1.60** | **1.65** | **1.74** | **1.79** | **1.85** | 2.18 |
| **1.38** | **1.52** | **1.57** | **1.61** | **1.66** | **1.75** | **1.79** | **1.86** | 2.51 |
| **1.42** | **1.53** | **1.57** | **1.61** | **1.66** | **1.76** | **1.79** | **1.87** | |
| **1.44** | **1.53** | **1.59** | **1.62** | **1.68** | **1.76** | **1.81** | **1.88** | |
| **1.45** | **1.54** | **1.59** | **1.62** | **1.69** | **1.77** | **1.81** | **1.91** | |
| **1.45** | **1.54** | **1.59** | **1.63** | **1.70** | **1.77** | **1.81** | **1.94** | |
| **1.46** | **1.55** | **1.59** | **1.63** | **1.71** | **1.78** | **1.82** | **1.95** | |
| **1.48** | **1.55** | **1.60** | **1.64** | **1.72** | **1.78** | **1.83** | 2.03 | |
| **1.48** | **1.56** | **1.60** | **1.64** | **1.73** | **1.78** | **1.83** | 2.07 | |

# Intertek Westport Technology Center

## Vitrinite Reflectance - Visual Kerogen Assessment Summary

### Sample Information

| | | | |
|---|---|---|---|
| Westport Project | WTC-06-000220 | Client | Alaska Geological Survey |
| Westport Sample | 94757 | Client Project | North Slope |
| | | Client Sample | 06DAV017 |

### Visual Kerogen Assessment

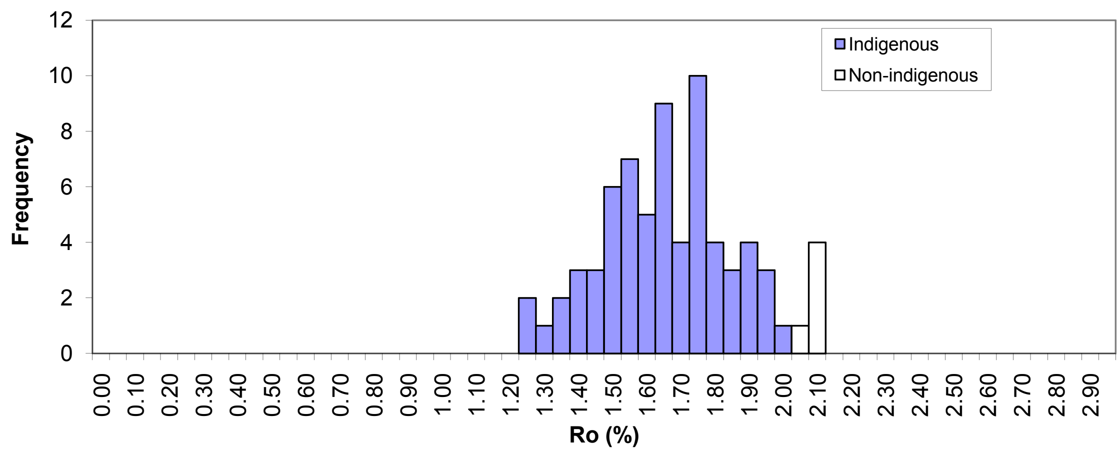
| Thermal Alteration Index |
|---|
| |

| Kerogen Types (vol%) | | | | | |
|---|---|---|---|---|---|
| Amorphous Kerogen | | | | | |
| Fluor. | Non-flour. | Alginite | Exinite | Vitrinite | Inertinite |
| | | | | | |

**Comments:**

### Vitrinite Reflectance

| | Min | Max | Mode | Mean | Median | StDev |
|---|---|---|---|---|---|---|
| Indigenous | 1.27 | 2.00 | 1.59 | 1.67 | 1.67 | 0.1766 |
| Total | 1.27 | 2.13 | 1.59 | 1.70 | 1.68 | 0.2047 |




Ordered Readings — Bold = Indigenous — Point Count **72**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **1.27** | **1.49** | **1.59** | **1.66** | **1.72** | **1.79** | **1.90** | 2.12 |
| **1.28** | **1.50** | **1.59** | **1.66** | **1.72** | **1.79** | **1.91** | 2.13 |
| **1.33** | **1.50** | **1.59** | **1.66** | **1.76** | **1.83** | **1.93** | |
| **1.36** | **1.51** | **1.59** | **1.67** | **1.76** | **1.83** | **1.95** | |
| **1.38** | **1.52** | **1.60** | **1.67** | **1.76** | **1.84** | **1.96** | |
| **1.40** | **1.52** | **1.61** | **1.67** | **1.77** | **1.84** | **1.98** | |
| **1.41** | **1.54** | **1.62** | **1.68** | **1.77** | **1.85** | **2.00** | |
| **1.43** | **1.56** | **1.62** | **1.69** | **1.77** | **1.86** | 2.08 | |
| **1.49** | **1.58** | **1.63** | **1.70** | **1.79** | **1.89** | 2.10 | |
| **1.49** | **1.59** | **1.65** | **1.70** | **1.79** | **1.90** | 2.12 | |

# Intertek Westport Technology Center

## Vitrinite Reflectance - Visual Kerogen Assessment Summary

**Sample Information**

| | | | |
|---|---|---|---|
| Westport Project | **WTC-06-000220** | Client | **Alaska Geological Survey** |
| Westport Sample | **94758** | Client Project | **North Slope** |
| | | Client Sample | **06DAV029** |

**Visual Kerogen Assessment**

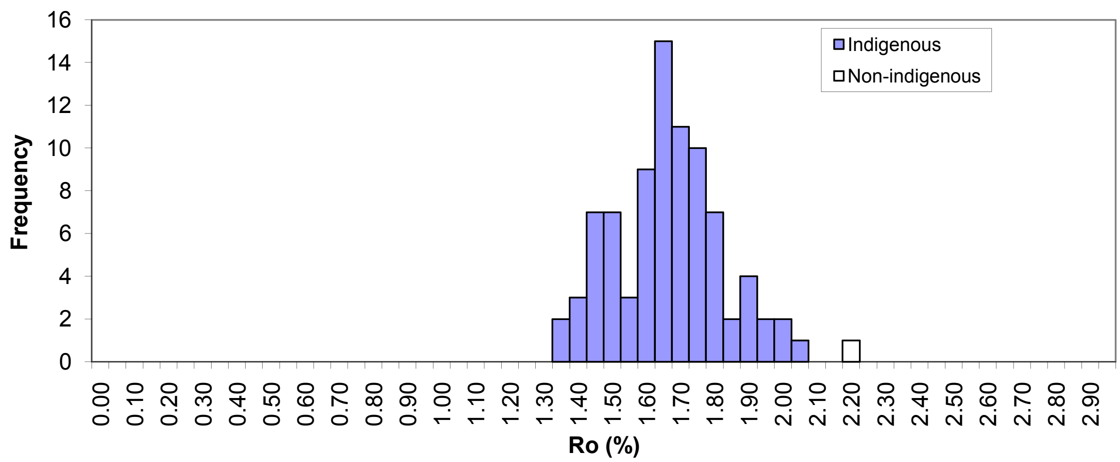
| Thermal Alteration Index |
|---|
| |

| Kerogen Types (vol%) | | | | | |
|---|---|---|---|---|---|
| Amorphous Kerogen | | | | | |
| Fluor. | Non-flour. | Alginite | Exinite | Vitrinite | Inertinite |
| | | | | | |

**Comments:**

**Vitrinite Reflectance**

| | Min | Max | Mode | Mean | Median | StDev |
|---|---|---|---|---|---|---|
| Indigenous | **1.36** | **2.06** | **1.66** | **1.69** | **1.69** | **0.1556** |
| Total | **1.36** | **2.21** | **1.66** | **1.69** | **1.69** | **0.1646** |




**Ordered Readings** — **Bold = Indigenous** — **Point Count 86**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **1.36** | **1.49** | **1.52** | **1.66** | **1.69** | **1.71** | **1.77** | **1.82** | **1.95** |
| **1.39** | **1.50** | **1.58** | **1.66** | **1.61** | **1.74** | **1.77** | **1.82** | **1.97** |
| **1.41** | **1.51** | **1.61** | **1.66** | **1.69** | **1.74** | **1.77** | **1.83** | **2.01** |
| **1.44** | **1.52** | **1.61** | **1.66** | **1.70** | **1.75** | **1.78** | **1.85** | **2.04** |
| **1.44** | **1.52** | **1.62** | **1.66** | **1.70** | **1.75** | **1.79** | **1.86** | **2.06** |
| **1.46** | **1.54** | **1.62** | **1.66** | **1.70** | **1.75** | **1.79** | **1.90** | 2.21 |
| **1.47** | **1.54** | **1.62** | **1.67** | **1.71** | **1.75** | **1.80** | **1.91** | |
| **1.47** | **1.55** | **1.63** | **1.67** | **1.71** | **1.76** | **1.82** | **1.92** | |
| **1.48** | **1.56** | **1.64** | **1.68** | **1.72** | **1.77** | **1.82** | **1.93** | |
| **1.48** | **1.57** | **1.65** | **1.67** | **1.72** | **1.77** | **1.82** | **1.93** | |

# Intertek Westport Technology Center

## Vitrinite Reflectance - Visual Kerogen Assessment Summary

### Sample Information

| | | | |
|---|---|---|---|
| Westport Project | WTC-06-000220 | Client | Alaska Geological Survey |
| Westport Sample | 94759 | Client Project | North Slope |
| | | Client Sample | 06DAV046 |

### Visual Kerogen Assessment

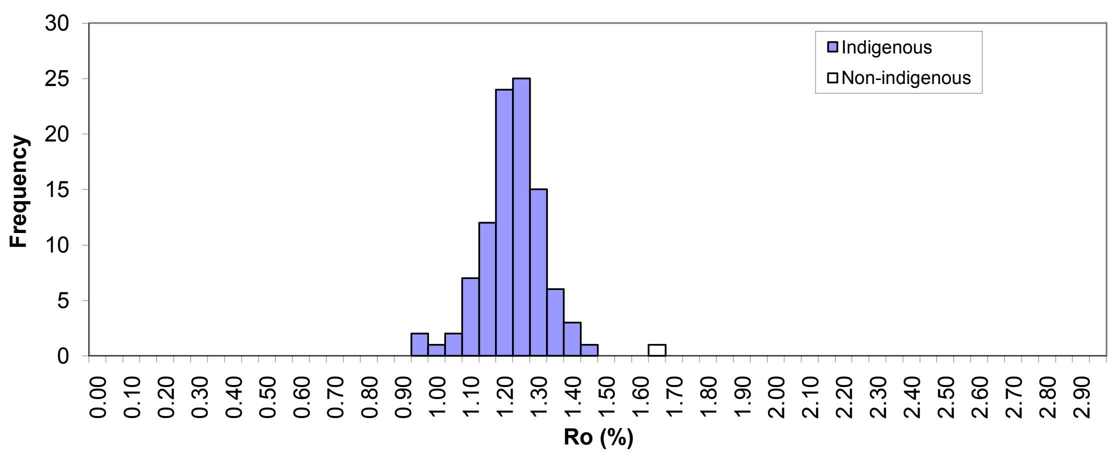
| Thermal Alteration Index |
|---|
| |

| Kerogen Types (vol%) | | | | | |
|---|---|---|---|---|---|
| Amorphous Kerogen | | | | | |
| Fluor. | Non-flour. | Alginite | Exinite | Vitrinite | Inertinite |
| | | | | | |

**Comments:**

### Vitrinite Reflectance

| | Min | Max | Mode | Mean | Median | StDev |
|---|---|---|---|---|---|---|
| Indigenous | 0.98 | 1.50 | 1.24 | 1.25 | 1.26 | 0.0900 |
| Total | 0.98 | 1.66 | 1.24 | 1.25 | 1.26 | 0.0987 |




**Ordered Readings** Bold = Indigenous **Point Count** 99

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **0.98** | **1.15** | **1.20** | **1.23** | **1.24** | **1.26** | **1.28** | **1.21** | **1.32** | **1.38** |
| **0.98** | **1.15** | **1.20** | **1.23** | **1.24** | **1.27** | **1.28** | **1.30** | **1.33** | **1.38** |
| **1.02** | **1.16** | **1.20** | **1.23** | **1.24** | **1.27** | **1.28** | **1.30** | **1.33** | **1.40** |
| **1.07** | **1.16** | **1.20** | **1.23** | **1.24** | **1.27** | **1.22** | **1.31** | **1.33** | **1.40** |
| **1.08** | **1.17** | **1.21** | **1.23** | **1.25** | **1.27** | **1.28** | **1.31** | **1.33** | **1.42** |
| **1.11** | **1.18** | **1.21** | **1.24** | **1.25** | **1.27** | **1.28** | **1.31** | **1.33** | **1.43** |
| **1.12** | **1.18** | **1.21** | **1.24** | **1.26** | **1.27** | **1.28** | **1.31** | **1.33** | **1.45** |
| **1.14** | **1.19** | **1.21** | **1.24** | **1.26** | **1.27** | **1.28** | **1.31** | **1.34** | **1.50** |
| **1.15** | **1.19** | **1.22** | **1.24** | **1.26** | **1.27** | **1.29** | **1.31** | **1.36** | 1.66 |
| **1.15** | **1.19** | **1.23** | **1.24** | **1.26** | **1.27** | **1.29** | **1.32** | **1.36** | |

# Intertek Westport Technology Center

## Vitrinite Reflectance - Visual Kerogen Assessment Summary

### Sample Information

| | | | |
|---|---|---|---|
| Westport Project | WTC-06-000220 | Client | Alaska Geological Survey |
| Westport Sample | 94760 | Client Project | North Slope |
| | | Client Sample | 06DAV076 |

### Visual Kerogen Assessment

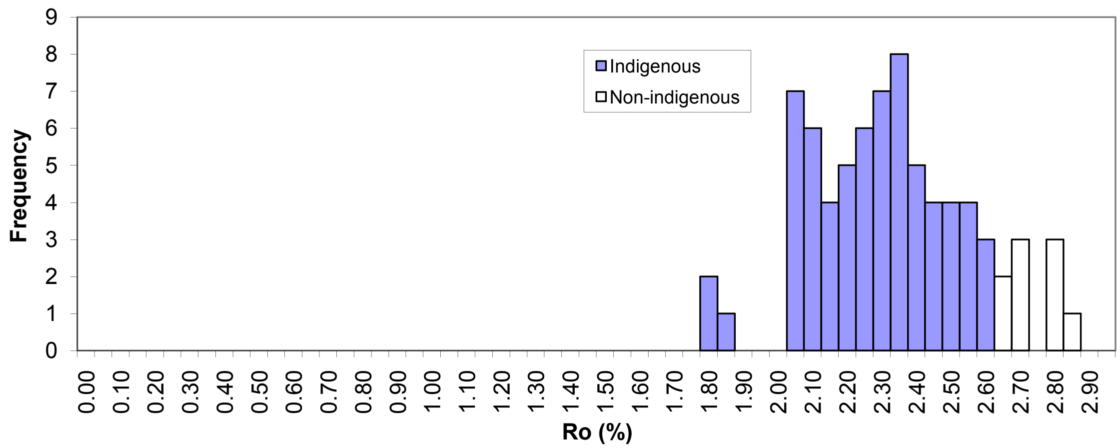
| Thermal Alteration Index |
|---|
| |

| Kerogen Types (vol%) | | | | | |
|---|---|---|---|---|---|
| Amorphous Kerogen | | | | | |
| Fluor. | Non-flour. | Alginite | Exinite | Vitrinite | Inertinite |
| | | | | | |

**Comments:**

### Vitrinite Reflectance

| | Min | Max | Mode | Mean | Median | StDev |
|---|---|---|---|---|---|---|
| Indigenous | 1.81 | 2.63 | 2.30 | 2.30 | 2.30 | 0.1888 |
| Total | 1.81 | 2.85 | 2.30 | 2.35 | 2.34 | 0.2340 |




**Ordered Readings** Bold = Indigenous **Point Count** 75

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **1.81** | **2.10** | **2.21** | **2.29** | **2.35** | **2.43** | **2.57** | 2.74 |
| **1.83** | **2.10** | **2.22** | **2.30** | **2.36** | **2.45** | **2.57** | 2.80 |
| **1.90** | **2.12** | **2.22** | **2.30** | **2.37** | **2.49** | **2.59** | 2.83 |
| **2.06** | **2.13** | **2.24** | **2.30** | **2.38** | **2.49** | **2.61** | 2.83 |
| **2.06** | **2.14** | **2.24** | **2.30** | **2.39** | **2.49** | **2.61** | 2.85 |
| **2.06** | **2.14** | **2.25** | **2.32** | **2.39** | **2.50** | **2.63** | |
| **2.08** | **2.16** | **2.25** | **2.33** | **2.40** | **2.51** | 2.67 | |
| **2.08** | **2.17** | **2.26** | **2.34** | **2.41** | **2.52** | 2.68 | |
| **2.09** | **2.19** | **2.27** | **2.35** | **2.42** | **2.53** | 2.70 | |
| **2.09** | **2.19** | **2.28** | **2.35** | **2.43** | **2.56** | 2.71 | |

# Intertek Westport Technology Center

## Vitrinite Reflectance - Visual Kerogen Assessment Summary

### Sample Information

| | | | |
|---|---|---|---|
| Westport Project | **WTC-06-000220** | Client | **Alaska Geological Survey** |
| Westport Sample | **94761** | Client Project | **North Slope** |
| | | Client Sample | **06DAV077** |

### Visual Kerogen Assessment

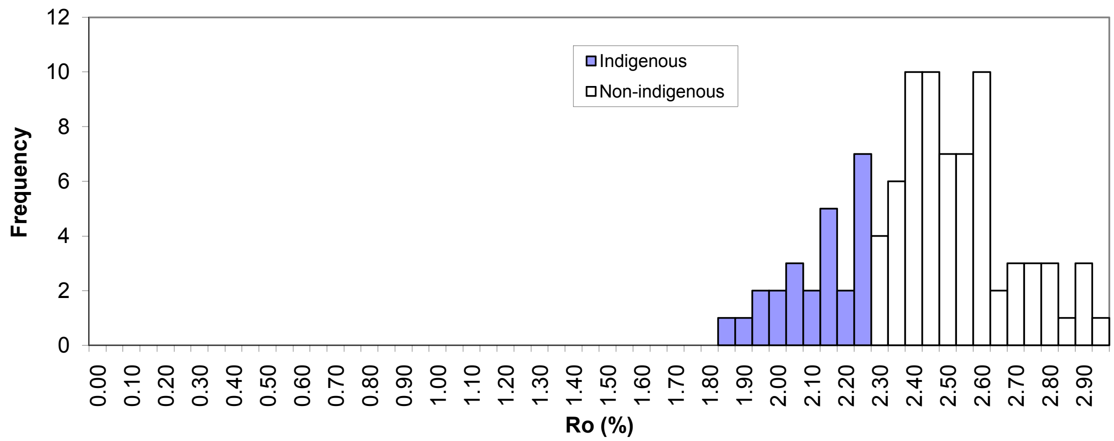
| Thermal Alteration Index |
|---|
| |

| Kerogen Types (vol%) | | | | | |
|---|---|---|---|---|---|
| Amorphous Kerogen | | | | | |
| Fluor. | Non-flour. | Alginite | Exinite | Vitrinite | Inertinite |
| | | | | | |

**Comments:**

### Vitrinite Reflectance

| | Min | Max | Mode | Mean | Median | StDev |
|---|---|---|---|---|---|---|
| Indigenous | **1.86** | **2.29** | **2.25** | **2.13** | **2.15** | **0.1244** |
| Total | **1.86** | **3.29** | **2.60** | **2.47** | **2.46** | **0.2682** |




**Ordered Readings** Bold = Indigenous **Point Count** **98**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **1.86** | **2.15** | **2.25** | 2.36 | 2.43 | 2.47 | 2.52 | 2.60 | 2.68 | 2.84 |
| **1.91** | **2.15** | **2.26** | 2.37 | 2.43 | 2.47 | 2.54 | 2.60 | 2.71 | 2.87 |
| **1.95** | **2.16** | **2.26** | 2.38 | 2.44 | 2.48 | 2.56 | 2.60 | 2.71 | 2.91 |
| **1.97** | **2.18** | **2.27** | 2.38 | 2.44 | 2.49 | 2.57 | 2.61 | 2.73 | 2.94 |
| **2.00** | **2.10** | **2.29** | 2.38 | 2.44 | 2.49 | 2.57 | 2.61 | 2.75 | 2.95 |
| **2.00** | **2.19** | 2.30 | 2.40 | 2.45 | 2.50 | 2.58 | 2.62 | 2.75 | 3.01 |
| **2.05** | **2.21** | 2.33 | 2.40 | 2.45 | 2.51 | 2.59 | 2.63 | 2.77 | 3.03 |
| **2.08** | **2.21** | 2.34 | 2.40 | 2.45 | 2.51 | 2.59 | 2.64 | 2.80 | 3.29 |
| **2.08** | **2.25** | 2.34 | 2.41 | 2.46 | 2.51 | 2.59 | 2.64 | 2.92 | |
| **2.12** | **2.25** | 2.35 | 2.43 | 2.46 | 2.52 | 2.60 | 2.66 | 2.84 | |

# Intertek Westport Technology Center

## Vitrinite Reflectance - Visual Kerogen Assessment Summary

**Sample Information**

| | | | |
|---|---|---|---|
| Westport Project | **WTC-06-000220** | Client | **Alaska Geological Survey** |
| Westport Sample | **94762** | Client Project | **North Slope** |
| | | Client Sample | **06DAV083** |

**Visual Kerogen Assessment**

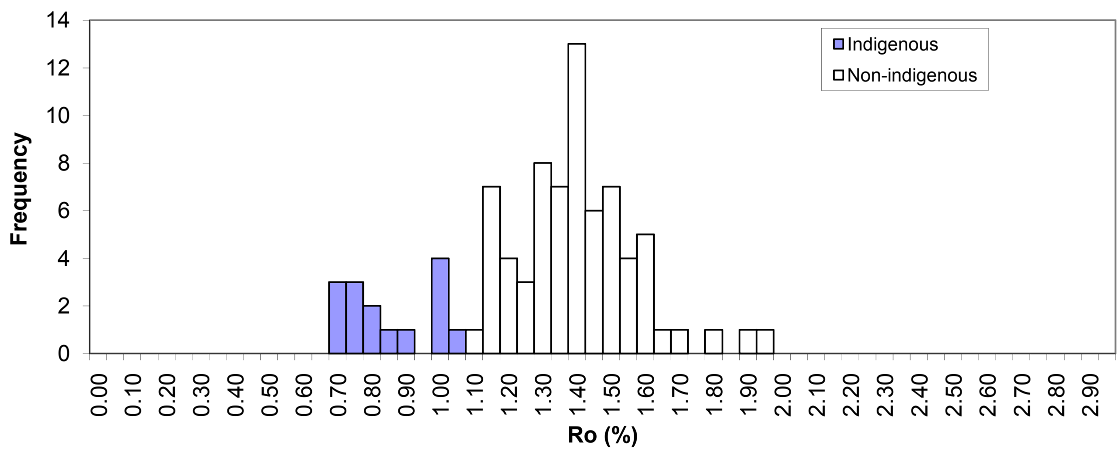
| Thermal Alteration Index |
|---|
| |

| Kerogen Types (vol%) | | | | | |
|---|---|---|---|---|---|
| Amorphous Kerogen | | | | | |
| Fluor. | Non-flour. | Alginite | Exinite | Vitrinite | Inertinite |
| | | | | | |

**Comments:**

**Vitrinite Reflectance**

| | Min | Max | Mode | Mean | Median | StDev |
|---|---|---|---|---|---|---|
| Indigenous | **0.73** | **1.10** | **0.73** | **0.87** | **0.83** | **0.1287** |
| Total | **0.73** | **1.98** | **1.37** | **1.33** | **1.37** | **0.2690** |




**Ordered Readings** — Bold = Indigenous — **Point Count 85**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **0.73** | **1.01** | 1.19 | 1.31 | 1.37 | 1.43 | 1.46 | 1.55 | 1.67 |
| **0.73** | **1.01** | 1.20 | 1.31 | 1.37 | 1.44 | 1.46 | 1.56 | 1.72 |
| **0.74** | **1.03** | 1.20 | 1.31 | 1.37 | 1.44 | 1.48 | 1.59 | 1.83 |
| **0.75** | **1.05** | 1.24 | 1.32 | 1.38 | 1.44 | 1.50 | 1.60 | 1.92 |
| **0.77** | **1.10** | 1.25 | 1.33 | 1.38 | 1.44 | 1.51 | 1.60 | 1.98 |
| **0.77** | 1.13 | 1.25 | 1.34 | 1.41 | 1.45 | 1.52 | 1.61 | |
| **0.82** | 1.16 | 1.27 | 1.35 | 1.42 | 1.45 | 1.52 | 1.61 | |
| **0.83** | 1.17 | 1.22 | 1.35 | 1.42 | 1.45 | 1.54 | 1.61 | |
| **0.85** | 1.17 | 1.29 | 1.36 | 1.42 | 1.46 | 1.54 | 1.62 | |
| **0.91** | 1.19 | 1.30 | 1.37 | 1.43 | 1.46 | 1.55 | 1.62 | |

# Intertek Westport Technology Center

## Vitrinite Reflectance - Visual Kerogen Assessment Summary

**Sample Information**

| | | | |
|---|---|---|---|
| Westport Project | WTC-06-000220 | Client | Alaska Geological Survey |
| Westport Sample | 94763 | Client Project | North Slope |
| | | Client Sample | 06DAV091 |

**Visual Kerogen Assessment**

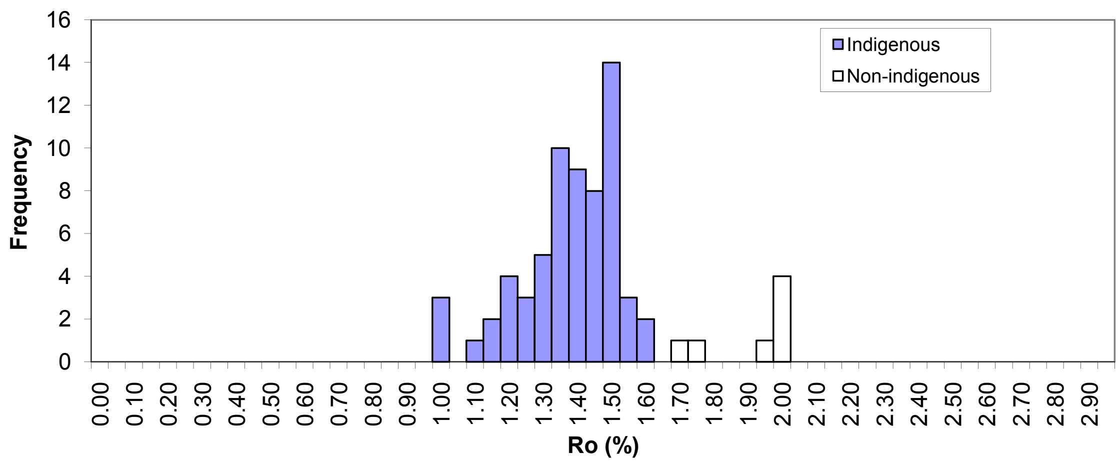
| Thermal Alteration Index |
|---|
| |

| Kerogen Types (vol%) | | | | | |
|---|---|---|---|---|---|
| Amorphous Kerogen | | | | | |
| Fluor. | Non-flour. | Alginite | Exinite | Vitrinite | Inertinite |
| | | | | | |

**Comments:**

**Vitrinite Reflectance**

| | Min | Max | Mode | Mean | Median | StDev |
|---|---|---|---|---|---|---|
| Indigenous | 1.01 | 1.63 | 1.54 | 1.40 | 1.43 | 0.1419 |
| Total | 1.01 | 2.03 | 1.54 | 1.46 | 1.45 | 0.2126 |




**Ordered Readings** Bold = Indigenous **Point Count 71**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **1.01** | **1.28** | **1.38** | **1.41** | **1.47** | **1.53** | **1.58** | 2.03 |
| **1.04** | **1.22** | **1.38** | **1.43** | **1.49** | **1.53** | **1.60** | |
| **1.05** | **1.30** | **1.38** | **1.44** | **1.49** | **1.54** | **1.61** | |
| **1.15** | **1.31** | **1.39** | **1.45** | **1.50** | **1.54** | **1.63** | |
| **1.16** | **1.34** | **1.39** | **1.45** | **1.50** | **1.54** | 1.71 | |
| **1.20** | **1.34** | **1.39** | **1.45** | **1.51** | **1.54** | 1.78 | |
| **1.22** | **1.35** | **1.40** | **1.45** | **1.52** | **1.54** | 1.99 | |
| **1.24** | **1.35** | **1.40** | **1.46** | **1.52** | **1.54** | 2.00 | |
| **1.24** | **1.36** | **1.41** | **1.47** | **1.52** | **1.55** | 2.02 | |
| **1.27** | **1.36** | **1.41** | **1.47** | **1.52** | **1.58** | 2.03 | |

# Intertek Westport Technology Center

## Vitrinite Reflectance - Visual Kerogen Assessment Summary

**Sample Information**

| | | | |
|---|---|---|---|
| Westport Project | WTC-06-000220 | Client | Alaska Geological Survey |
| Westport Sample | 94764 | Client Project | North Slope |
| | | Client Sample | 06DAV110 |

**Visual Kerogen Assessment**

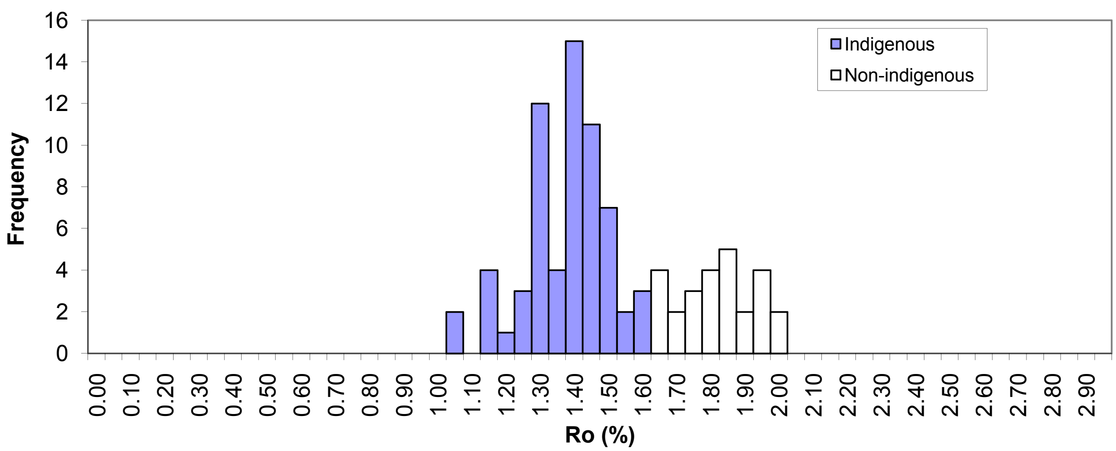
| Thermal Alteration Index |
|---|
| |

| Kerogen Types (vol%) | | | | | |
|---|---|---|---|---|---|
| Amorphous Kerogen | | | | | |
| Fluor. | Non-flour. | Alginite | Exinite | Vitrinite | Inertinite |
| | | | | | |

**Comments:**

**Vitrinite Reflectance**

| | Min | Max | Mode | Mean | Median | StDev |
|---|---|---|---|---|---|---|
| Indigenous | 1.07 | 1.62 | 1.44 | 1.40 | 1.42 | 0.1199 |
| Total | 1.07 | 2.03 | 1.44 | 1.53 | 1.47 | 0.2324 |




**Ordered Readings** Bold = Indigenous **Point Count** 90

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **1.07** | **1.31** | **1.35** | **1.42** | **1.45** | **1.49** | **1.60** | 1.77 | 1.89 |
| **1.10** | **1.32** | **1.35** | **1.42** | **1.46** | **1.50** | **1.61** | 1.78 | 1.89 |
| **1.17** | **1.33** | **1.36** | **1.43** | **1.46** | **1.51** | **1.62** | 1.80 | 1.91 |
| **1.19** | **1.33** | **1.38** | **1.44** | **1.47** | **1.51** | **1.62** | 1.81 | 1.92 |
| **1.20** | **1.33** | **1.39** | **1.44** | **1.47** | **1.51** | 1.67 | 1.83 | 1.95 |
| **1.20** | **1.33** | **1.40** | **1.44** | **1.47** | **1.51** | 1.67 | 1.85 | 1.95 |
| **1.22** | **1.33** | **1.41** | **1.44** | **1.47** | **1.52** | 1.68 | 1.85 | 1.96 |
| **1.26** | **1.34** | **1.42** | **1.44** | **1.48** | **1.53** | 1.69 | 1.86 | 1.98 |
| **1.29** | **1.34** | **1.42** | **1.44** | **1.48** | **1.54** | 1.75 | 1.86 | 2.00 |
| **1.29** | **1.34** | **1.42** | **1.45** | **1.49** | **1.56** | 1.75 | 1.87 | 2.03 |

# Intertek Westport Technology Center

## Vitrinite Reflectance - Visual Kerogen Assessment Summary

**Sample Information**

| | | | |
|---|---|---|---|
| Westport Project | WTC-06-000220 | Client | Alaska Geological Survey |
| Westport Sample | 94765 | Client Project | North Slope |
| | | Client Sample | 06DAV136 |

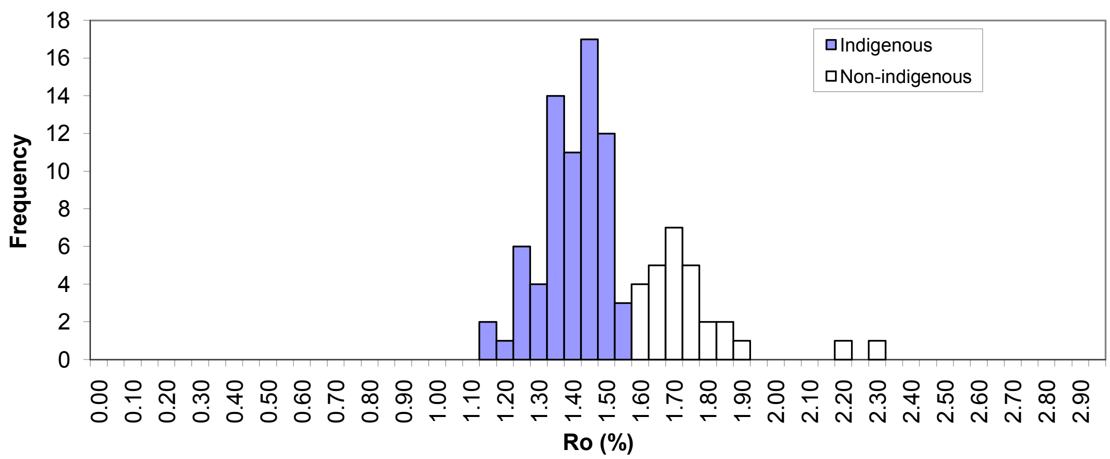
**Visual Kerogen Assessment**

| Thermal Alteration Index | Kerogen Types (vol%) | | | | | |
|---|---|---|---|---|---|---|
| | Amorphous Kerogen | | | | | |
| | Fluor. | Non-flour. | Alginite | Exinite | Vitrinite | Inertinite |
| | | | | | | |

**Comments:**

**Vitrinite Reflectance**

| | Min | Max | Mode | Mean | Median | StDev |
|---|---|---|---|---|---|---|
| Indigenous | 1.19 | 1.60 | 1.47 | 1.42 | 1.45 | 0.0910 |
| Total | 1.19 | 2.30 | 1.47 | 1.53 | 1.48 | 0.1950 |




**Ordered Readings** — Bold = Indigenous — **Point Count 98**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **1.19** | **1.32** | **1.39** | **1.44** | **1.47** | **1.49** | **1.52** | 1.63 | 1.72 | 1.80 |
| **1.20** | **1.33** | **1.39** | **1.44** | **1.47** | **1.50** | **1.52** | 1.65 | 1.72 | 1.81 |
| **1.24** | **1.34** | **1.39** | **1.45** | **1.47** | **1.50** | **1.52** | 1.65 | 1.72 | 1.85 |
| **1.27** | **1.36** | **1.39** | **1.45** | **1.47** | **1.50** | **1.52** | 1.65 | 1.74 | 1.86 |
| **1.27** | **1.36** | **1.39** | **1.45** | **1.47** | **1.50** | **1.53** | 1.66 | 1.74 | 1.87 |
| **1.28** | **1.36** | **1.40** | **1.45** | **1.47** | **1.51** | **1.54** | 1.66 | 1.74 | 1.92 |
| **1.30** | **1.37** | **1.40** | **1.45** | **1.47** | **1.51** | **1.55** | 1.67 | 1.76 | 2.20 |
| **1.30** | **1.37** | **1.42** | **1.45** | **1.48** | **1.51** | **1.56** | 1.68 | 1.77 | 2.30 |
| **1.30** | **1.38** | **1.42** | **1.46** | **1.48** | **1.51** | **1.57** | 1.70 | 1.79 | |
| **1.31** | **1.38** | **1.42** | **1.47** | **1.49** | **1.51** | **1.60** | 1.72 | 1.80 | |

# Intertek Westport Technology Center

## Vitrinite Reflectance - Visual Kerogen Assessment Summary

**Sample Information**

| | | | |
|---|---|---|---|
| Westport Project | WTC-06-000220 | Client | Alaska Geological Survey |
| Westport Sample | 94766 | Client Project | North Slope |
| | | Client Sample | 06DAV149 |

**Visual Kerogen Assessment**

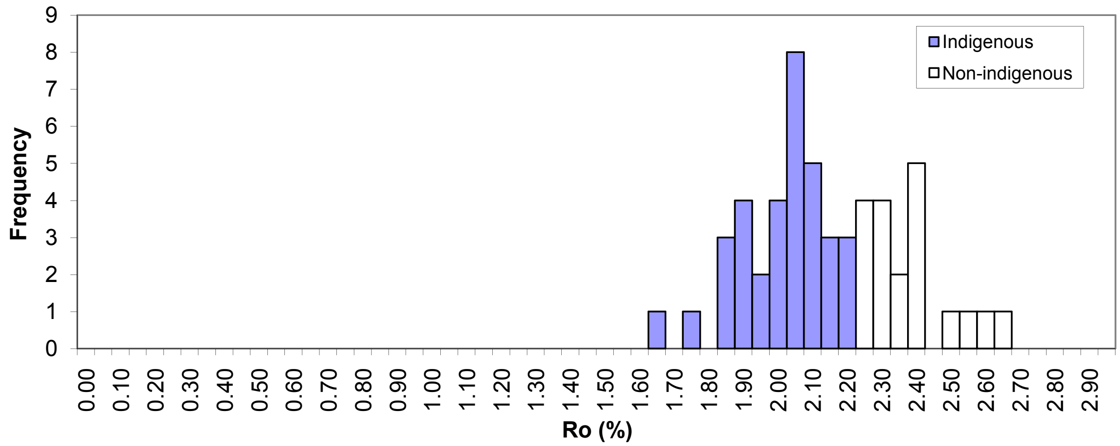
| Thermal Alteration Index |
|---|
| |

| Kerogen Types (vol%) | | | | | |
|---|---|---|---|---|---|
| Amorphous Kerogen | | | | | |
| Fluor. | Non-flour. | Alginite | Exinite | Vitrinite | Inertinite |
| | | | | | |

**Comments:**

**Vitrinite Reflectance**

| | Min | Max | Mode | Mean | Median | StDev |
|---|---|---|---|---|---|---|
| Indigenous | 1.70 | 2.23 | 2.05 | 2.03 | 2.05 | 0.1255 |
| Total | 1.70 | 3.29 | 2.05 | 2.19 | 2.14 | 0.2622 |




**Ordered Readings** Bold = Indigenous **Point Count** 54

| | | | | | |
|---|---|---|---|---|---|
| **1.70** | **1.96** | **2.07** | **2.19** | 2.32 | 2.57 |
| **1.80** | **2.00** | **2.08** | **2.20** | 2.34 | 2.64 |
| **1.87** | **2.03** | **2.09** | **2.21** | 2.36 | 2.65 |
| **1.87** | **2.03** | **2.10** | **2.23** | 2.38 | 3.29 |
| **1.89** | **2.04** | **2.11** | 2.25 | 2.40 | |
| **1.91** | **2.05** | **2.14** | 2.25 | 2.41 | |
| **1.92** | **2.05** | **2.14** | 2.29 | 2.41 | |
| **1.94** | **2.05** | **2.14** | 2.29 | 2.42 | |
| **1.94** | **2.05** | **2.17** | 2.30 | 2.43 | |
| **1.95** | **2.06** | **2.18** | 2.32 | 2.52 | |

# Intertek Westport Technology Center

## Vitrinite Reflectance - Visual Kerogen Assessment Summary

**Sample Information**

| | | | |
|---|---|---|---|
| Westport Project | **WTC-06-000220** | Client | **Alaska Geological Survey** |
| Westport Sample | **94767** | Client Project | **North Slope** |
| | | Client Sample | **06DAV164** |

**Visual Kerogen Assessment**

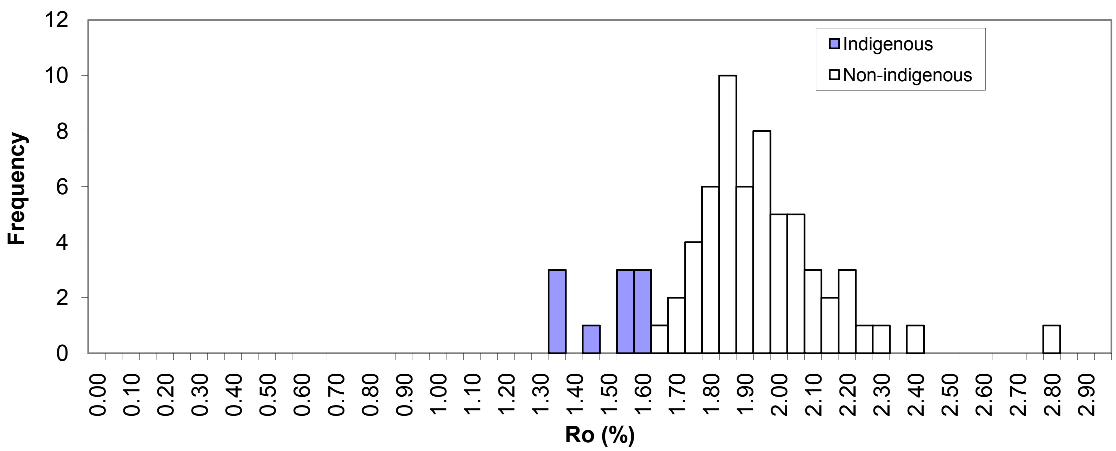
| Thermal Alteration Index |
|---|
| |

| Kerogen Types (vol%) | | | | | |
|---|---|---|---|---|---|
| Amorphous Kerogen | | | | | |
| Fluor. | Non-flour. | Alginite | Exinite | Vitrinite | Inertinite |
| | | | | | |

**Comments:**

**Vitrinite Reflectance**

| | Min | Max | Mode | Mean | Median | StDev |
|---|---|---|---|---|---|---|
| Indigenous | **1.36** | **1.66** | **1.64** | **1.54** | **1.58** | **0.1139** |
| Total | **1.36** | **2.82** | **1.90** | **1.91** | **1.91** | **0.2443** |




**Ordered Readings** — Bold = Indigenous — **Point Count 70**

| | | | | | | |
|---|---|---|---|---|---|---|
| **1.36** | **1.66** | 1.84 | 1.90 | 1.95 | 2.03 | 2.13 |
| **1.37** | 1.70 | 1.84 | 1.90 | 1.95 | 2.03 | 2.15 |
| **1.40** | 1.72 | 1.85 | 1.90 | 1.95 | 2.04 | 2.18 |
| **1.49** | 1.73 | 1.85 | 1.90 | 1.95 | 2.06 | 2.22 |
| **1.57** | 1.76 | 1.86 | 1.91 | 1.96 | 2.06 | 2.23 |
| **1.58** | 1.78 | 1.86 | 1.91 | 1.97 | 2.08 | 2.24 |
| **1.60** | 1.79 | 1.87 | 1.92 | 1.97 | 2.09 | 2.28 |
| **1.61** | 1.79 | 1.89 | 1.92 | 1.98 | 2.09 | 2.34 |
| **1.64** | 1.81 | 1.89 | 1.94 | 2.01 | 2.10 | 2.42 |
| **1.64** | 1.83 | 1.90 | 1.94 | 2.02 | 2.13 | 2.82 |

# Intertek Westport Technology Center

## Vitrinite Reflectance - Visual Kerogen Assessment Summary

### Sample Information

| | | | |
|---|---|---|---|
| Westport Project | WTC-06-000220 | Client | Alaska Geological Survey |
| Westport Sample | 94768 | Client Project | North Slope |
| | | Client Sample | 06DAV180 |

### Visual Kerogen Assessment

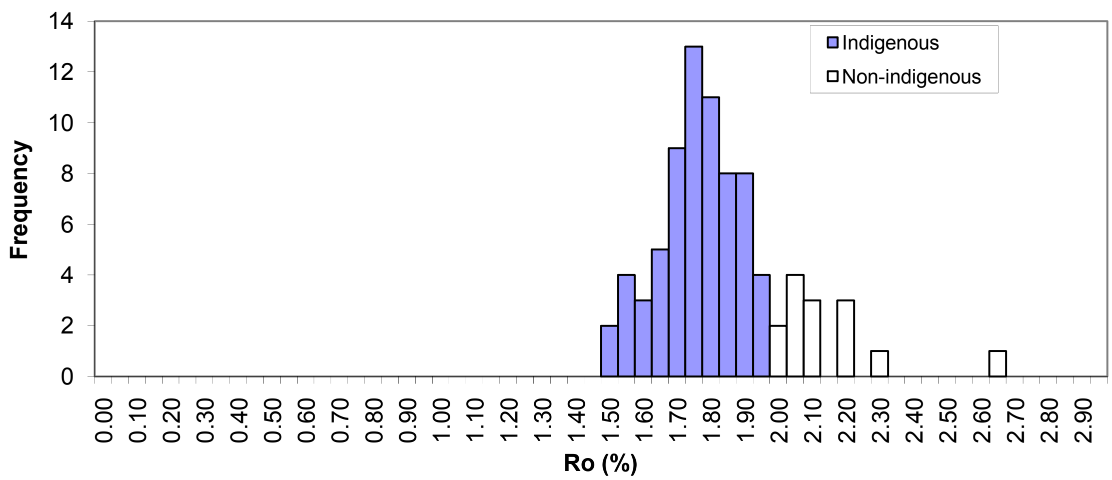
| Thermal Alteration Index |
|---|
| |

| Kerogen Types (vol%) | | | | | |
|---|---|---|---|---|---|
| Amorphous Kerogen | | | | | |
| Fluor. | Non-flour. | Alginite | Exinite | Vitrinite | Inertinite |
| | | | | | |

**Comments:**

### Vitrinite Reflectance

| | Min | Max | Mode | Mean | Median | StDev |
|---|---|---|---|---|---|---|
| Indigenous | 1.51 | 1.97 | 1.78 | 1.79 | 1.80 | 0.1117 |
| Total | 1.51 | 2.68 | 1.78 | 1.85 | 1.82 | 0.1902 |




**Ordered Readings** Bold = Indigenous **Point Count** 81

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **1.51** | **1.67** | **1.75** | **1.79** | **1.82** | **1.88** | **1.93** | 2.06 | 2.68 |
| **1.54** | **1.68** | **1.75** | **1.79** | **1.83** | **1.88** | **1.93** | 2.08 | |
| **1.56** | **1.69** | **1.75** | **1.79** | **1.84** | **1.89** | **1.94** | 2.09 | |
| **1.60** | **1.69** | **1.76** | **1.80** | **1.84** | **1.89** | **1.95** | 2.11 | |
| **1.60** | **1.71** | **1.77** | **1.80** | **1.84** | **1.90** | **1.95** | 2.13 | |
| **1.60** | **1.71** | **1.78** | **1.80** | **1.85** | **1.91** | **1.96** | 2.13 | |
| **1.61** | **1.71** | **1.78** | **1.81** | **1.85** | **1.91** | **1.97** | 2.21 | |
| **1.63** | **1.73** | **1.78** | **1.81** | **1.86** | **1.91** | 2.01 | 2.22 | |
| **1.63** | **1.74** | **1.78** | **1.82** | **1.87** | **1.91** | 2.04 | 2.24 | |
| [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | [illegible] | |