



Avak Creek Oil Occurrence, Alaska

Summary Report

Submitted to

U.S. Environmental Protection Agency

&

Alaska Department of Environmental Conservation

Submitted by

U.S. Geological Survey

Alaska Petroleum Systems Project

Palma Botterell, Research Petroleum Geochemist

pbotterell@usgs.gov

Dave Houseknecht, Supervisory Research Geologist

dhouse@usgs.gov

Mike Moldowan, CEO of Biomarker Technologies, Inc.

jmmoldowan@biomarker-inc.com

October 28, 2024

Summary

Geochemical analyses of the Avak Creek oil samples reveal they are geochemically consistent with seeps on Cape Simpson (25 to 40 miles east of Avak Creek), several exploration-well tests, and many produced crude oils across the North Slope. The inferred source rock from which most of the oil was generated is interpreted to be the Lower Cretaceous Hue-GRZ, mostly Aptian to Albian in age (~126-110 Ma), in the early stages of oil generation. There does not appear to be any significant geochemical difference between shoreline and tundra samples, suggesting a single source for the Avak Creek oil occurrence.

Further, the geochemical signatures of the Avak Creek oil samples are generally not consistent with processed oils, refinery waste products, or synthetic products. Results of biomarker acids analyses reveal that anaerobic biodegradation occurred in the subsurface, suggesting that the Avak Creek oils, or at least some portion of them, emanated as natural seeps that leaked/migrated from underground reservoirs, as opposed to a crude oil spill.

Introduction

In July 2024, A rapidly developing petroleum environmental issue emerged involving an “unknown release” of oil in a lake and tundra near Avak Creek on Native lands near Utqiagvik (formerly Barrow), the administrative center for the North Slope Borough. The U.S. Environmental Protection Agency (USEPA) and Alaska Department of Environmental Conservation (ADEC) contacted the U.S. Geological Survey (USGS) to determine whether this newly discovered oil occurrence is a previously undocumented, natural oil seep or some type of contamination (e.g., recent unsuccessful plugging of a 49-year-old exploration well, crude oil spill, refinery waste product, etc.). Existing preliminary data from the U.S. Coast Guard Marine Safety Lab was inconclusive in determining the likely origin of the oil. Avak Creek samples (Fig. 1) were provided by the USEPA and ADEC for further geochemical analyses. Funding for these analyses was provided mainly from the USGS Energy Resources Program.

Dave Houseknecht investigated the regional and local geologic framework. Palma Botterell characterized the oil geochemistry, in comparison to local Cape Simpson area seeps and to other previously characterized oils across the North Slope. The geological framework of the Avak Creek site was constructed using seismic and well data, plus basin modeling results, to identify local petroleum source rocks; map the structural geometry and faults; identify areas where source rocks are immature, mature, and overmature; and infer likely oil-migration pathways into the area. Geochemical interpretations of the likely origin of the newly discovered oil occurrence were made by integrating both subsurface data (seismic surveys and exploration well penetrations) and geochemical data from local and regional oil seeps, exploration well tests, and produced oils across the North Slope, Alaska (Fig. 2). Analytical work and interpretations were done primarily in collaboration with Mike Moldowan (CEO, Biomarker Technologies, Inc., BTI), with additional laboratory support from Jody Wycech (Project Chief of the USGS Petroleum Geochemistry Research Lab, PGRL) and Paul Lillis (USGS, emeritus).

Geologic Framework

Northernmost Alaska includes a unique, high standing subsurface feature known as the “Barrow High” (Fig. 3). The Barrow High represents the eastern portion of the broader Arctic Platform (Connors and Houseknecht, 2022, their Figure 3), a high standing area of pre-Mississippian basement rocks that extends more than 150 miles west from Point Barrow beneath the western Beaufort Sea and northeastern Chukchi Sea. Basement rocks of the Arctic Platform stand hundreds to thousands of feet higher than surrounding basement rocks beneath the Alaska North Slope to the south and east, the Chukchi Sea shelf to the west, and the Canada Basin offshore to the north.

Younger sedimentary deposits in these surrounding basins range from Mississippian (MISS in Fig. 6) to Miocene in age. Through hundreds of million years, as sediments accumulated over the Barrow High and Arctic Platform, those younger strata thin onto – and many pinch out completely – as they were deposited higher onto the Barrow High and into shallower water of the high standing region. Manifestation of these strata thinning and pinching out onto the southern flank of the Barrow High are shown in Figures 4 and 5.

The stratigraphy of the younger rocks is shown in Figure 6A, which shows the stratigraphy typically present across most of the Alaska North Slope. However, in the Barrow High many of these strata are absent either because they were never deposited or because they were later eroded (Fig. 6B). Thus, the Iko Bay #1 exploration well, drilled by the U.S. Navy in 1975 and just one mile east of the Avak Creek oil occurrence, penetrated only a fraction of the strata present across most of the North Slope before entering basement rocks at a depth of 2,705 ft. Rocks penetrated by the Iko Bay #1 are shown as yellow vertical lines in Figure 6B.

As a result of this depositional pattern, all Mississippian and younger strata thicken progressively southward beneath the North Slope and northward into the Canada Basin. A consequence of this basinward thickening is that each formation was buried deeper farther into the basins and, thus, heated to higher temperatures farther from the Barrow High – Arctic Platform. The increase in maximum temperature is expressed as higher “thermal maturity,” a measure of the maximum temperature to which a formation was exposed. In petroleum source rocks, the thermal maturity, in turn, controls the stage of petroleum generation that has occurred.

Figure 7 is a map of Arctic Alaska from the Brooks Range on the south to the central Canada Basin on the north, and from the Chukchi Sea on the west to Canada on the east. The colored contours represent the level of thermal maturity of the base of the Brookian tectonostratigraphic sequence, including strata of petroleum source rock S3b (Fig. 6). In the area of shallowest burial on the Barrow High, as well as areas to the west and east, the thermal maturity at the base of the Brookian sequence is less than 0.7% thermal maturity (scale is percent vitrinite reflectance, % VR), or the area that is mainly blue in Figure 7, which indicates the “Early Mature” oil window. This signifies that oil generation was in early stages of development when source rock S3b was at maximum temperature, which occurred during the Late Cretaceous. To the south, source rock S3b was buried deeper and heated to higher temperature, and the modeled thermal maturity lies between 0.7 and 1.0% VR (green part of map). This indicates a “Mid Mature” stage of oil

generation during the Late Cretaceous. Still farther south, source rock S3b was buried deeper and heated to higher temperature, and the modeled thermal maturity lies between 1.0 and 1.3% VR, indicating a “Late Mature” stage of oil generation. The areas of “Mid Mature” and “Late Mature” represent stages of maximum oil generation from source rocks. Still farther south, source rock S3b lies at modeled thermal maturity values higher than 1.3% VR, which is considered the Main Gas Generation Window. In this stage, any oil remaining in the pink area of the map will have been cracked to natural gas. Moreover, natural gas may be generated directly from any remaining kerogen in the source rock. Inasmuch as any source rocks in strata older than S3b will have been buried deeper and heated to higher temperature than S3b, those older source rocks will have passed through the stages of oil and gas generation described above earlier than S3b.

Finally, the inset map in the upper right of Figure 7 is a magnified view of the area near Avak Creek, which is indicated by the red star. The three exploration wells indicated by red diamonds, the South Meade, Kuyanak, and West Dease wells, are the most pertinent to interpreting the petroleum generation history of the Avak Creek area and those will be considered in the next section.

Local Geology of the Avak Creek Area

The local geology of the Avak Creek area is known from numerous petroleum exploration wells and natural gas development wells drilled since the late 1940s, and from two-dimensional (2-D) seismic data collected since the 1950s (Fig. 8). One seismic line is particularly important – a south-north line collected by the U.S. Navy in 1978; the northern part of this seismic line directly crosses the Avak Creek oil occurrence and nearly crosses the Iko Bay #1 exploration well (Fig. 8). An image of the seismic line highlighted in Figure 8 is shown in Figure 9. Strata correlated into this seismic line from surrounding areas and confirmed by the strata penetrated by the Iko Bay #1 well are shown in the legend and as labels in the figure; those range from the top of basement rocks (at bottom) to the Lower Cretaceous Nanushuk Formation (at top; Fig. 9).

The seismic image clearly shows that south of Avak Creek, the top of basement and overlying strata dip (tilt) to the south, forming a homocline (geological term for strata that display a uniform dip in one direction). Directly beneath Avak Creek, a north-dipping normal fault is present, and that fault is accompanied by two south-dipping, subsidiary normal faults. Farther north, near the end of the seismic line, a second north-dipping normal fault is present. All these normal faults display relatively minor offset (tens to a few hundred feet); nevertheless, the faults clearly offset the strata and result in dip reversal on a local scale. Directly beneath Avak Creek, strata are folded into a gentle arch (anticline), the northern flank of which is accommodated by the north-dipping normal fault with the two south-dipping subsidiary normal faults. Two intersecting seismic lines, a short northwest-southeast line and a longer northwest-southeast line (Fig. 8) confirm that the subtle anticline beneath Avak Creek also displays subtle anticlinal closure in that orientation. Thus, the anticline beneath Avak Creek has subtle, four-way closure. Between the two north-dipping normal faults (Fig. 9), the top of basement and overlying strata display a sag (syncline) in which the Iko Bay 1 well was drilled.

Strata present above basement include several distinctive units labeled as horizons in the legend below the seismic image in Figure 9. Among these are two petroleum source rocks, the Triassic Shublik Formation (labeled S1 here and in Fig. 6) and the Lower Cretaceous pebble shale unit and gamma-ray zone (PSU and GRZ, respectively, and together labeled S3b here and in Fig. 6). Whereas it is common for the older Shublik Formation (S1 in Fig. 6) to expel oil that migrates through deeper strata, it is common for the younger PSU and GRZ (S3b in Fig. 6) to expel oil that migrates through inclined “clinoform” strata, which downlap directly onto the source rocks. Moreover, those strata display origin dip, reflecting their deposition on marine slopes, which merges at shallower depth the overlying Nanushuk Formation, which is the rock exposed at the surface throughout northern NPR-A. The Fig. 9 inset shows this migration pathway from the S3b source rock to the overlying Nanushuk Formation reservoir rock (Houseknecht, 2019).

Alternatively, if oil and gas were generated in these S3b (or the S1) source rocks, the geologic setting is ideal to promote lateral migration of buoyant oil and gas northward into the anticline beneath Avak Creek and then vertically upward along the normal fault toward the surface. In fact, if porous reservoir rocks and impermeable sealing rocks are present in the anticline beneath Avak Creek, one or more small pools of oil and gas may be present in the anticline immediately south of the normal fault. In reality, both suggested migration pathways are viable alternatives for the Avak Creek setting.

Geochemical Characterization

Samples were analyzed by a suite of classical geochemical analyses including API gravity and sulfur content, bulk carbon isotopes of saturated and aromatic hydrocarbon fractions, quantitative whole oil gas chromatography-flame ionization detection (GC-FID), GC-mass spectrometry (GC-MS) of isolated saturated and aromatic hydrocarbon fractions (biomarkers) (e.g., Peters et al., 2005). Advanced Geochemical Technologies (AGTs; Dahl et al., 1999; Moldowan et al., 2015) performed by BTI comprise enhanced biomarker assessments by tandem mass spectrometry (GC-MS-MS), quantitative diamondoid analysis (QDA), quantitative extended diamondoid analysis (QEDA), and compound specific isotopic analysis (CSIA) of hopane and sterane biomarkers (CSIA-Bh and CSIA-Bs, respectively). Age-diagnostic and source-sensitive biomarker parameters, largely based on GC-MS-MS data, provide an assessment of the thermal maturity, age ranges, organic matter input, and depositional environment of the source(s) of the oil-window components. Diamondoid results provide a platform to assess possible mixed charge contributions and to determine source(s) of both post-mature and oil-window components of extracts and oils. Results of CSIA-Bh and -Bs also provide greater insight into the paleoenvironments of the generative sources.

“Biomarker Acids Analysis” also was used in this study to provide evidence for the origin of the surface expressions of the Avak Creek oil occurrences; whether they likely are natural seeps migrating from subsurface sources (reservoirs or directly from the source rock) or were simply spilled petroleum from anthropogenic activities. This analytical technique looks at severity of

biodegradation and signs of subsurface anaerobic biodegradation versus aerobic biodegradation that may occur at the surface.

Overall geochemical results from all the analyses demonstrate that the Avak Creek sample data are consistent with geochemical fingerprints of natural crude oils we have analyzed from production wells and seeps across the North Slope.

Figure 10 highlights the progression of analytical chromatograms from GC-FID (whole oil) analysis to GC-MS analysis (biomarkers in isolated saturated and aromatic hydrocarbon fractions) to GC-MS-MS analysis of biomarkers. This demonstrates that with more advanced instrumentation we were able to significantly remove overlapping hydrocarbons and peak interferences and accomplish more accurate hydrocarbon peak identification and quantification.

Whole oil GC-FID chromatograms of the Avak Creek samples show similar results to initial data generated by the USCG MSL. The unresolved complex mixture (UCM) of bio resistant compounds indicate biodegradation, with the *n*-alkanes having been completely biodegraded. Isoprenoids also have been affected; however, peaks are still detectable at the top of the UCM. Loss of volatile, low molecular weight peaks (<C₁₀) likely is due to evaporation. GC-MS-MS biomarker profiles show that the Avak Creek samples look very similar to what we would expect from natural crude oil samples. Biomarkers (steranes and hopanes) do not appear to be biodegraded. It also is important to note that we do not see any significant differences among Avak Creek samples collected from both shoreline and the tundra field site locations. Additionally, no unusual peaks were observed; data looks like standard profiles of petroleum hydrocarbons.

All Avak samples show consistent values across key bulk compositional and molecular geochemical parameters (biomarkers, CSIA, and diamondoids) commonly used to infer source rock characteristics such as depositional environment, organic matter input, geologic age, and thermal maturity (Figs. 11-16).

Thermal maturity of the Avak Creek samples is in the early oil window (~0.7-0.8 %R_o), consistent with the thermal maturity of the Hue-GRZ in this area. The geochemical results from the Avak Creek samples are exactly where we would expect them to be in terms of thermal maturity (Fig. 11). Regarding lithology of the generating source rock, all the Avak Creek samples are plotting in the middle of this distribution of oils from across the North Slope, emphasizing that their geochemical signatures are strongly indicative of natural crude oil (Fig. 12).

The Avak Creek samples cluster together and to nearby (Cape Simpson) Cretaceous oils and seeps, suggesting a common source. This generating source rock is suggested to be the Early Cretaceous Hue-GRZ, mostly Aptian to Albian in age (~126-110 Ma), in the early stages of oil generation. Taxon-specific and age-related biomarker parameters, including the absence of Oleanane (older than the Late Cretaceous, Moldowan et al., 1994) but presence of Biscadinane (Moldowan, unpublished data showing Jurassic and younger occurrence of biscadinane), brackets the age of the Avak Creek source rock as Early Cretaceous (Fig. 13). The Avak Creek samples also show a significantly higher contribution of terrestrial organic matter relative older Jurassic and Triassic typed oils. This likely supports the age of the generating source rock and unique depositional environment discussed above.

The Hue-GRZ in this area include clastic-rich, siliclastic strata deposited in a more proximal depositional environment allowing for a higher contribution of terrigenous organic matter. In the Avak sample area, the Hue-GRZ was deposited on a submarine ridge (the Barrow Arch) in a surrounding deepwater marine basin. This created a unique, isolated depositional setting with local evidence of exposure surfaces and burrows indicating shallow water.

CSIA Isotopic fingerprints of both hopanes (-Bh) and steranes (-Bs) are consistent fingerprints among the Avak Creek samples (and share a similar profile to the Cape Simpson Seismic Line seep (Figs. 14-15). CSIA-Bh results of the Avak Creek samples suggest a more stratified water column with anoxic benthic waters during deposition. CSIA-Bs results provide additional supporting evidence in support of a significant terrigenous organic matter contribution, as indicated by the isotopically heavy C₂₉ values. The Avak Creek sample group is also distinct with elevated (heavier) C₂₈ sterane isotopes.

QEDA fingerprints are consistent among the Avak samples (Fig. 16). They also cluster with Cretaceous-typed oils, including nearby Simpson well oils, Cape Simpson seeps, and Fish Creek seep). While there is also overlap with the diamondoid profile of another clastic-rich Jurassic Kingak-sourced oil, the Kingak source rock can be ruled out as an option for generating the Avak Creek oils as it is not locally present in the sample area.

Biomarker Acids Analysis identified the presence of tricyclic terpanoic acids and $\beta\beta$ -hopanoic acids in the Avak Creek samples. These compounds are products of biodegradation (not generated by kerogen of the source rock) that only occur in anaerobic conditions, such as biodegradation that occurs in a subsurface reservoir; they have not been identified in aerobic conditions. Results thus suggest that the Avak Creek fluids, or at least some portion of them, emanated as seep that leaked/migrated from underground reservoirs. Additionally, 25-norhopanoic acids, indicators of intense anaerobic degradation, were absent in the Avak Creek samples. This suggests that the biodegradation of these fluids in subsurface reservoirs did not exceed the moderately high level of biodegradation (Rank 7, Figure 3.62, page 254 in Peters and Moldowan, 1993) needed to produce these compounds.

Permafrost

Quantitative modeling of burial history and petroleum generation indicates that crude oil and natural gas have been generated in source rocks of the Barrow High and the Colville foreland basin to the south during the Cretaceous. Generation began in the Colville foreland basin of southern National Petroleum Reserve in Alaska (NPR-A) during the Early Cretaceous and migrated northward through time such that generation in the Barrow High occurred during the Late Cretaceous (Houseknecht et al., 2012). In contrast, permafrost developed very recently, during the past 2 to 3 million years; (Carter and Hillhouse, 1992). These results suggest that deterioration of permafrost only would have an impact on mobilizing crude oil and natural gas if that petroleum migrated out of source rocks, accumulated in shallow traps, and then was remobilized.

Crude oil seeps have known on Cape Simpson for hundreds of year or more and clearly have a surface expression. However, shallow core tests completed by the U.S. Navy demonstrate that

oil also is trapped in reservoirs at shallow depths (10s to 100s ft). We suggest, therefore, that the Avak Creek oil occurrence resulted from a similar process. That is, we propose that crude oil and gas were generated in Lower Cretaceous source rocks (S3b in Fig. 6), migrated northward into the Cape Simpson and Avak Creek areas, and were trapped there at shallow depth. As erosion occurred through the millennia, some of the shallowly trapped oil was liberated to become seeps on Cape Simpson whereas others remained trapped at shallow depth, as indicated by the U.S. Navy drilling on Cape Simpson, and even at the Iko Bay #1 well. The development of permafrost likely froze the shallow oil in place until warming over the past 20 years induced deterioration of the upper permafrost, which resulted in remobilization of the shallow oil and gas. We therefore recommend continued monitoring of the Avak Creek oil occurrence to determine if a significant volume of oil continues to be mobilized.

References

- Botterell, P.J., Houseknecht, D.W., Lillis, P.G, Barbanti, S.M., Dahl, J.E, and Moldowan, J.M., 2021. Geochemical Advances in Arctic Alaska Oil Typing – North Slope Oil Correlation and Charge History. *Marine and Petroleum Geology* **127**, 104878.
- Carter, L.D., and Hillhouse, J.S., 1992, Age of the Late Cenozoic Bigbendian marine transgression of the Alaskan Arctic coastal plain: Significance for permafrost history and paleoclimate: *in* Bradley D.C., and Ford A.B., eds.. US Geological Survey Bulletin 1999, Washington, D.C., p. 44–51, <https://pubs.usgs.gov/bul/1999/report.pdf>
- Clow, G.D., 2014, Temperature data acquired from the DOI/GTN-P deep borehole array on the Arctic slope of Alaska, 1973–2013: Studies of Earth Systems Science Data, v. 6, p. 201–218, <https://essd.copernicus.org/articles/6/201/2014.pdf>
- Clow, G. 2015. Permafrost Temperature Data from a Deep Borehole Array on the Arctic Slope of Alaska, Version 1. [Indicate subset used]. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. <https://doi.org/10.5065/D6N014HK>
- Dahl, J.E., Moldowan, J.M., Peters, K.E., Claypool, G.E., Rooney, M.A., Michael, G.E., Mello, M.R., and Kohnen, M.L., 1999. Diamondoid hydrocarbons as indicators of natural oil cracking. *Nature* **399**, 54–57.
- Houseknecht, D.W., 2019, Petroleum systems framework of significant new oil discoveries in a giant Cretaceous (Aptian–Cenomanian) clinothem in Arctic Alaska: American Association of Petroleum Geologists Bulletin, v. 103, p. 619–652, DOI: 10.1306/08151817281
- Houseknecht, D.W., Burns, W.M., and Bird, K.J., 2012, Thermal maturation history of Arctic Alaska and southern Canada basin: *in* N.B. Harris and K.E. Peters (eds.) Thermal History Analysis of Sedimentary Basins—Methods and Case Histories, SEPM Special Publication 103, p. 199–219, ISBN 978-1-56576-315-9, , <https://doi.org/10.2110/sepm.sp.103.199>

- Moldowan, J.M., Sundararaman, P., and Schoell, M., 1986. Sensitivity of biomarker properties to depositional environment and/or source input in the Lower Toarcian of SW-Germany. *Organic Geochemistry* **10**, 915–926.
- Moldowan, J.M., Fago, F.J., Carlson, R.M.K., Young, D.C., Duvne, G., Clardy, J., Schoell, M., Pillinger, C.T., and Watt, D.S., 1991. Rearranged hopanes in sediments and petroleum. *Geochimica et Cosmochimica Acta* **55** (11), 3333–3353.
- Moldowan, J. M., Dahl, J., Huizinga, B. J., Fago, F. J., Hickey, L. J., Peakman, T. M. and Taylor, D. W., 1994. The molecular fossil record of oleanane and its relation to angiosperms. *Science* **265**, 768–771.
- Moldowan, J.M., Dahl, J., Zinniker, D., and Barbanti, S., 2015, Underutilized advanced geochemical technologies for oil and gas exploration and production-1. The diamondoids. *Journal of Petroleum Science and Engineering* **126**, 87–96.
- Peters, K.E. and Moldowan, J.M. 1993, “The Biomarker Guide. Application of Molecular Fossils in Petroleum Exploration,” Prentice-Hall, Englewood Cliffs, New Jersey, 363 p.
- Peters, K.E., Walters, C.C., and Moldowan, J.M., 2005. The Biomarker Guide, Volume 2: Biomarker and Isotopes in Petroleum Exploration and Earth History, Second Edition. Cambridge University Press, 1155 p.
- Seifert, W.K., and Moldowan, J.M., 1978. Applications of steranes, terpanes and monoaromatics to the maturation, migration and source of crude oils. *Geochimica et Cosmochimica Acta* **42**, 77–95.
- Sieskind, O., Joly, G., and Albrecht, P., 1979. Simulation of the geochemical transformation of sterols: superacid effect of clay minerals. *Geochimica et Cosmochimica Acta* **43** (10), 1675–1679.
- Sofer, Z., 1984. Stable Carbon Isotope Compositions of Crude Oils: Application to Source Depositional Environments and Petroleum Alteration. *AAPG Bulletin* **68** (1), 31–49.
- Zumberge, J.E., 1984. Source rocks of the La Luna Formation (Upper Cretaceous) in the Middle Magdalena Valley, Colombia. In: Petroleum Geochemistry and Source Rock Potential of Carbonate Rocks (J. G. Palacas, ed.). AAPG, Tulsa, OK, 127–133.

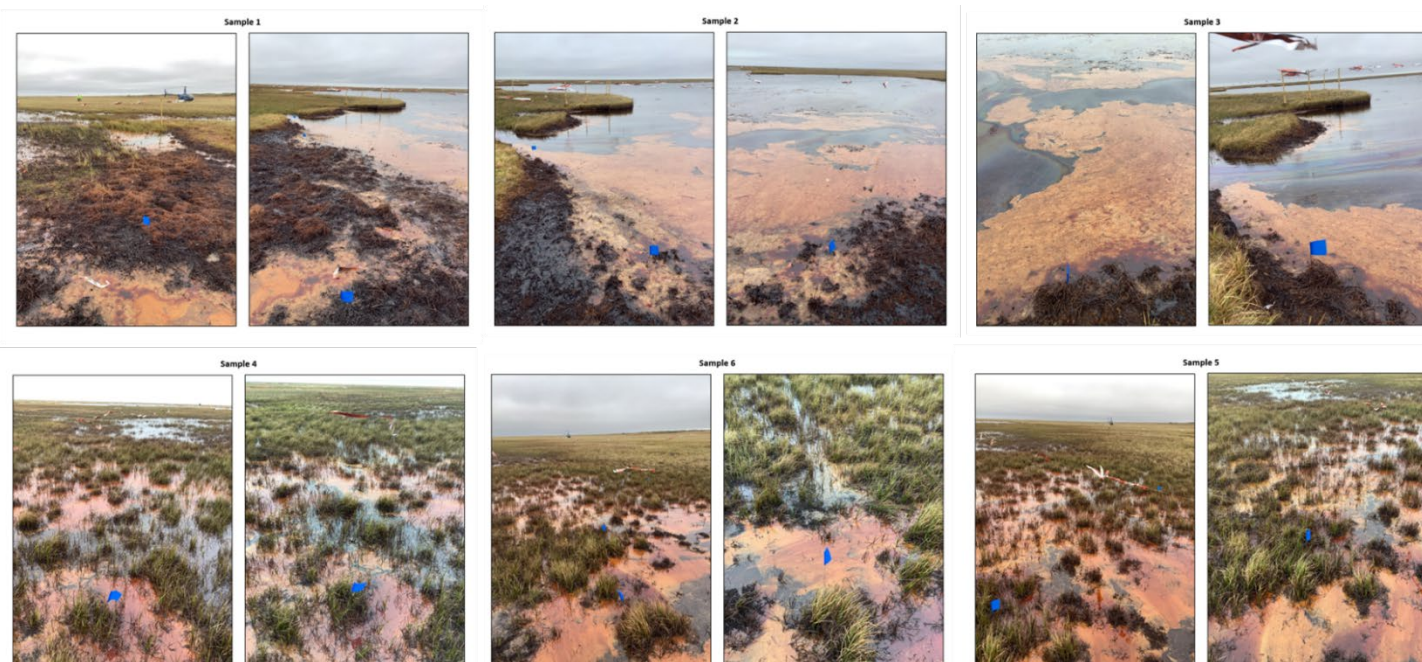
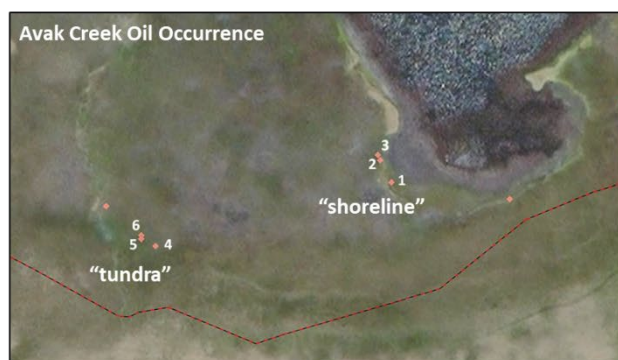
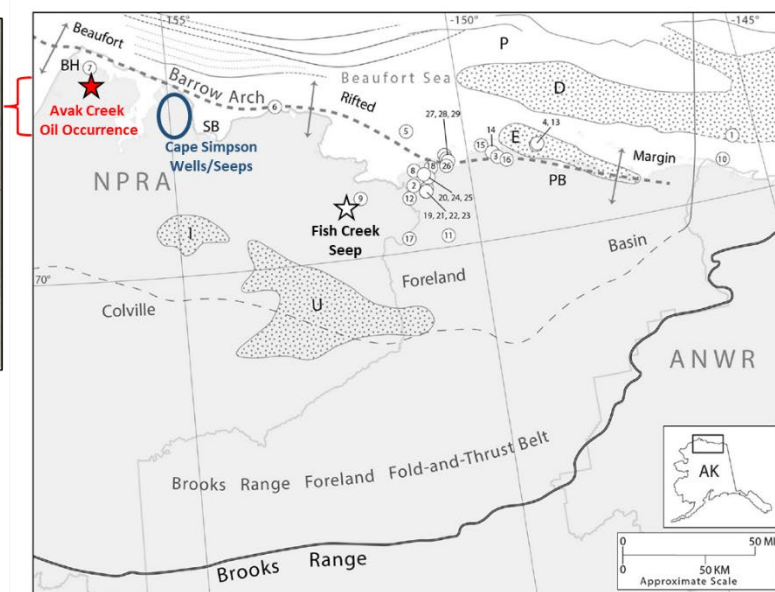


Figure 1. Avak Creek. Photographs of oil occurrence by sample site, provided courtesy of USEPA.



Avak Creek Sample Locations
photo provided by Torri Huelskoetter
U.S. Environmental Protection Agency



Map from Botterell et al. (2021)

Figure 2. Map centered on central North Slope, Alaska, showing main tectonic features, boundaries of National Petroleum Reserve in Alaska (NPRA) and Arctic National Wildlife Refuge (ANWR), and locations of Avak Creek oil occurrence, nearby Cape Simpson oils and seeps, Fish Creek seep, and oil samples in Botterell et al. (2021), listed in Table 1. Photograph of Avak Creek sample locations shown on the left, collected from the shoreline (samples #1-3) and surrounding tundra (samples #4-6), courtesy of the USEPA. Abbreviations: D, Dinkum graben; E, Endicott-Niakuk graben; I, Ikpiuk basin; P, Dinkum plateau; U, Umiat basin). BH, Barrow high; PB, Prudhoe Bay; SB, Smith Bay.



Figure 3. False-color composite Landsat image of northernmost Alaska showing in white the boundary of the National Petroleum Reserve in Alaska (NPRA). Petroleum exploration wells drilled prior to 2000 are shown as white dots and those drilled during 2000 to 2010 are shown as yellow dots. Red oval outlines the “Barrow High,” an area of high-standing basement rocks in the subsurface. Red star shows location of Avak Creek oil occurrence.

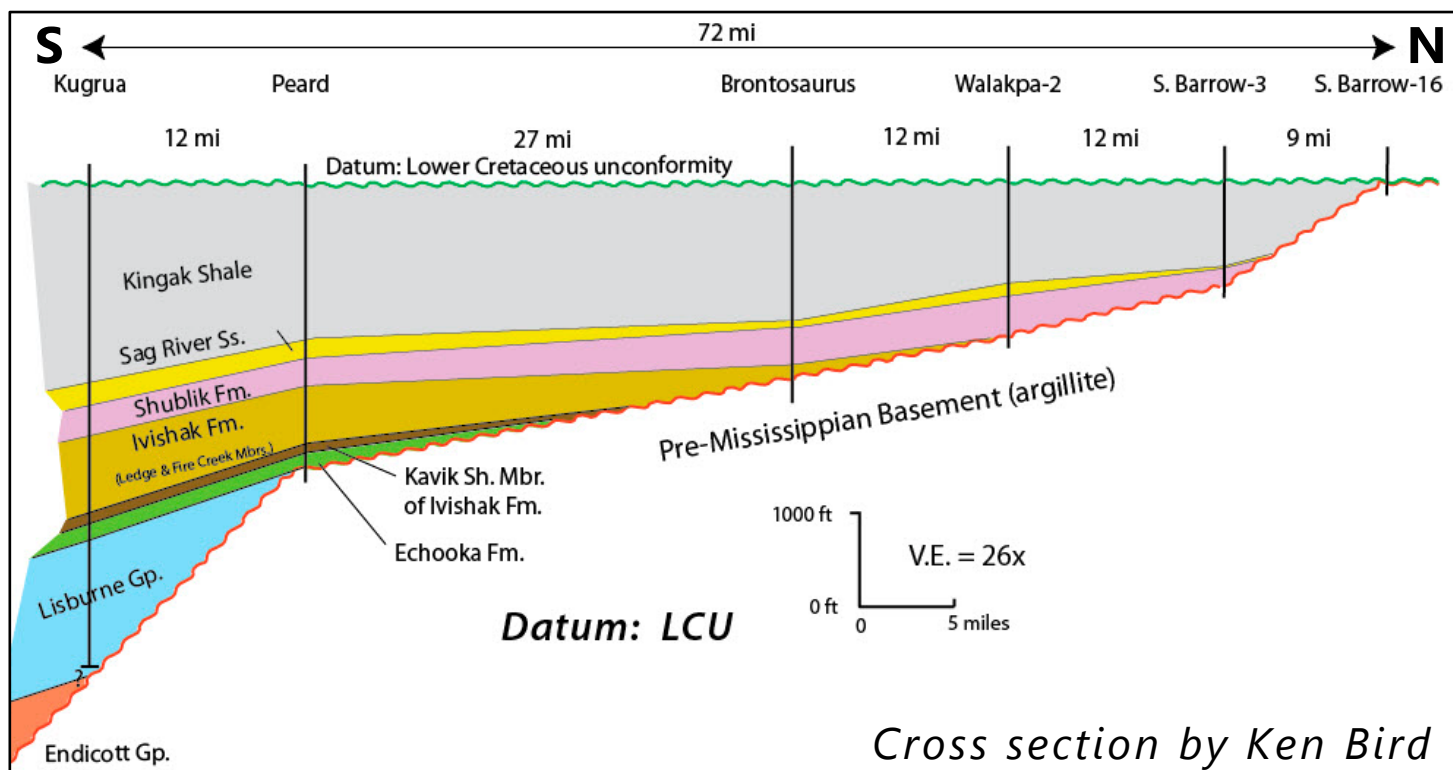


Figure 4. South to north geologic cross section showing northward onlap and pinch out Mississippian to Jurassic aged strata. See Figure 5 for ages of formations shown here. Note that datum at top of figure is Lower Cretaceous unconformity at the base of Brookian strata, which are not shown in the figure. Unpublished figure by Ken Bird (USGS retired).

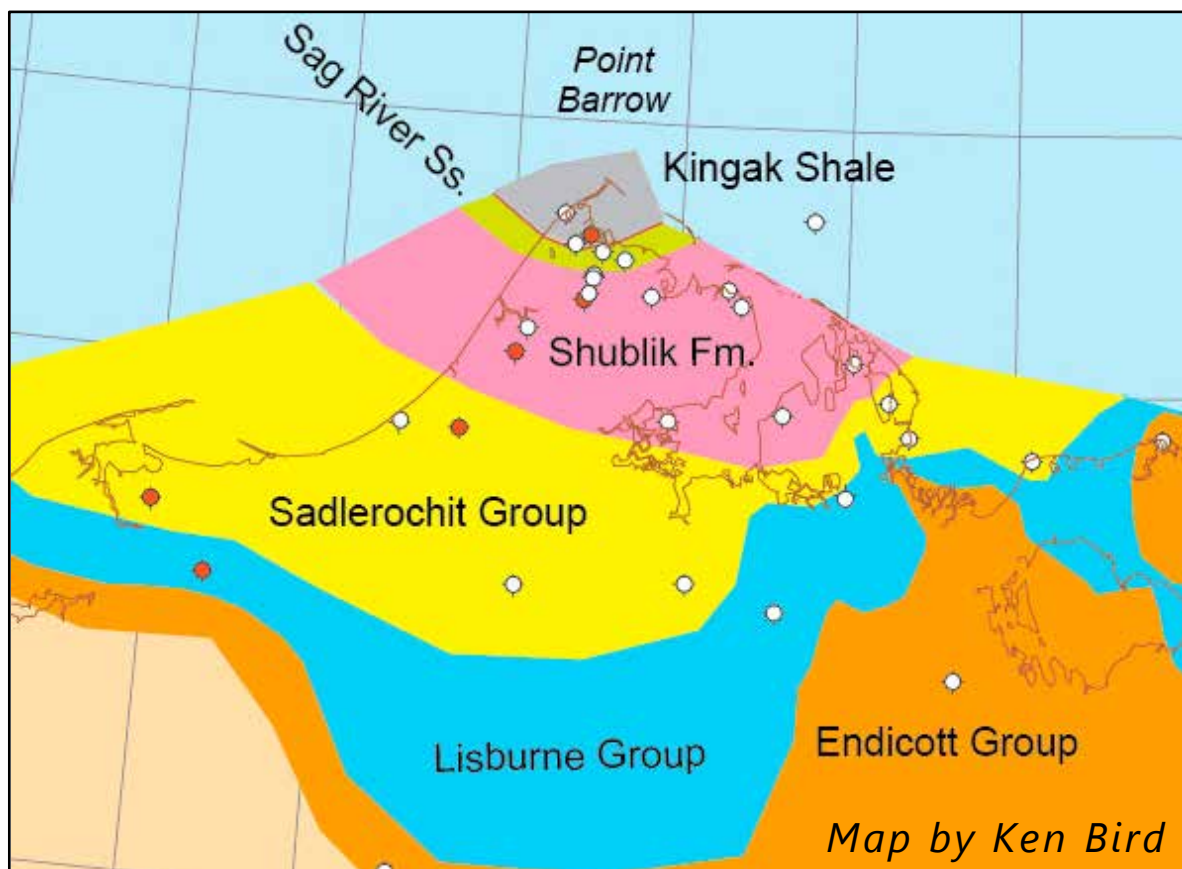


Figure 5. Map of Barrow High showing areas where Mississippian to Jurassic aged strata rest directly on Pre-Mississippian basement rocks. Unpublished figure by Ken Bird (USGS retired).

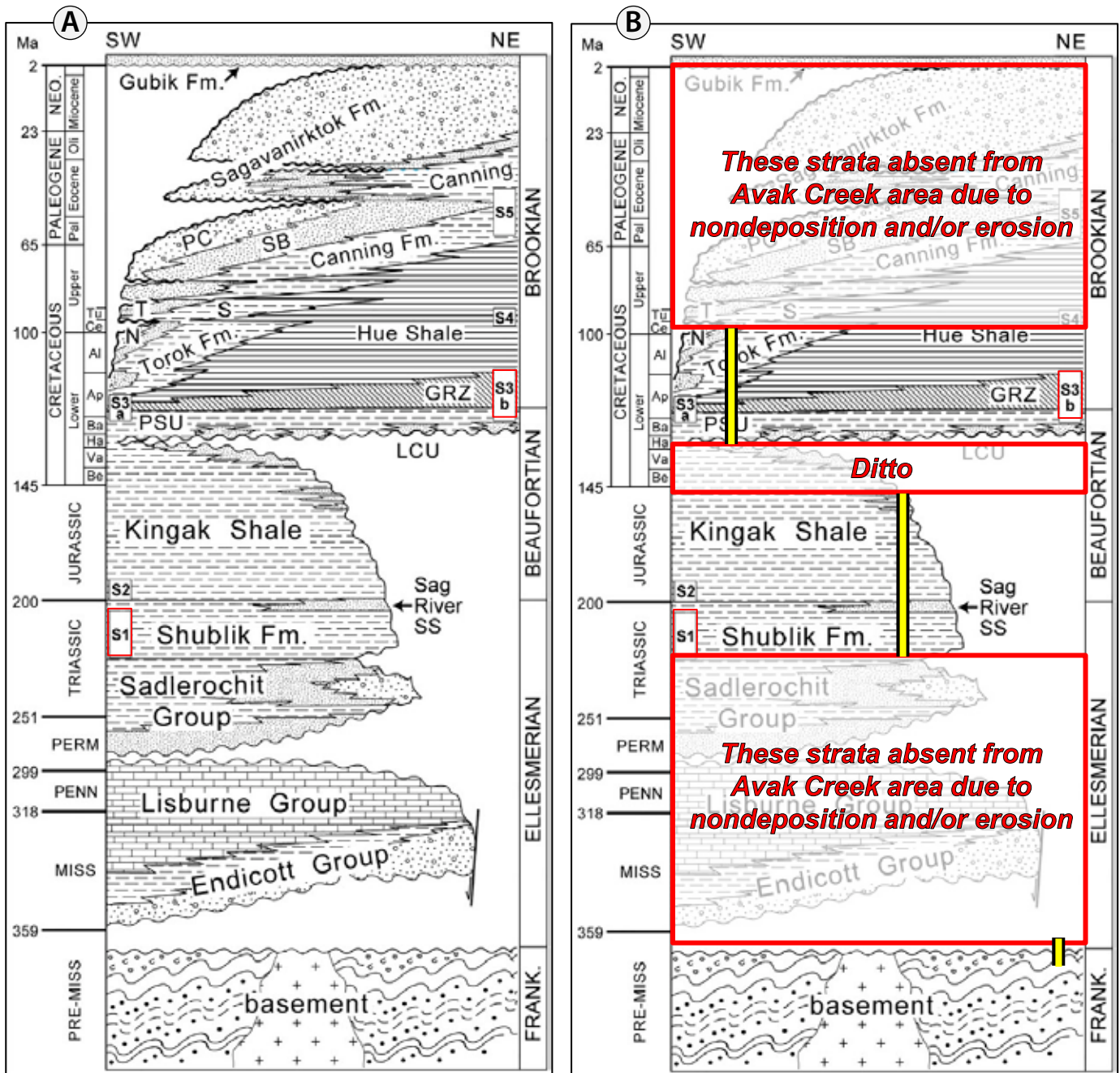


Figure 6. A. Generalized chronostratigraphy of Arctic Alaska showing tectonostratigraphic sequence names at right. Series names are shown only for Cretaceous, Paleogene, and Neogene systems. Only stage names pertinent to text are shown. Petroleum source rocks common on the Alaska North Slope include (S1) Shublik Formation, (S2) lower Kingak Shale, and four Brookian units that include (S3a) composite of proximal pebble shale unit (PSU) and gamma ray zone (GRZ) of Hue Shale, (S3b) composite of distal PSU and GRZ, (S4) Cenomanian to Turonian part of Hue Shale, and (S5) distal Paleocene to lower middle Eocene part of Canning Formation. Regional geology and seismic interpretation indicate that only S1 and S3b (highlighted by red) are likely present in the vicinity of the Avak Creek oil occurrence. Note: Time scale is nonlinear! FRANK, Franklinian; LCU, Lower Cretaceous unconformity; Be, Berriasian; Va, Valanginian; Ha, Hauterivian; Ba, Barremian; Ap, Aptian; Al, Albian; Ce, Cenomanian; Tu, Turonian. Abbreviated formation names include: N, Nanushuk; PC, Prince Creek; S, Seabee; SB, Schrader Bluff; T, Tuluva. Figure from Botterell et al. (2021). B. Same figure as A, but red boxes denote strata absent in Avak Creek area due to nondeposition on Barrow High or erosion following deposition. Vertical yellow lines show strata that were penetrated by the Iko Bay #1 exploration well.

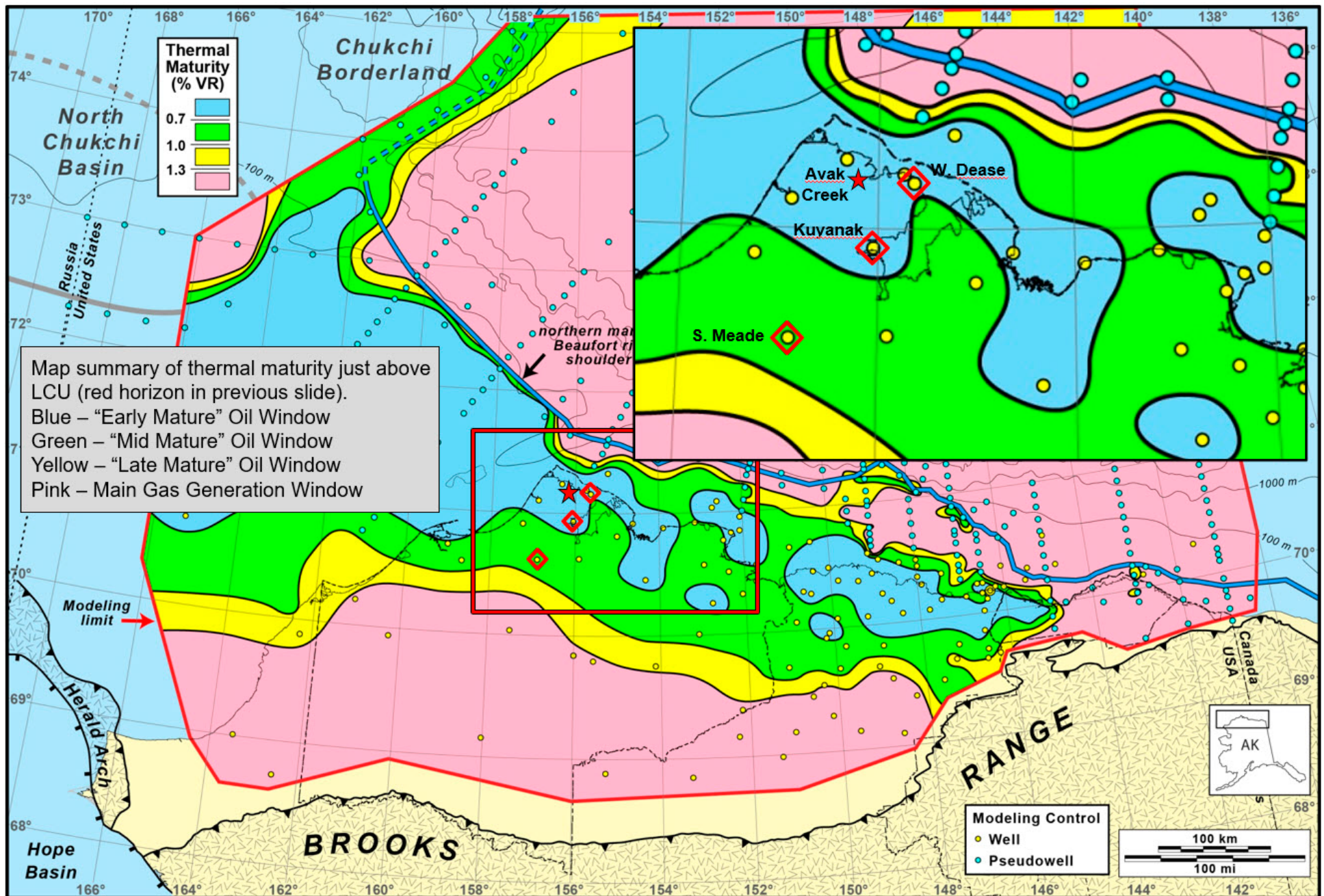


Figure 7. Regional map of thermal maturity at base of Brookian strata, corresponding to stratigraphic level of source rock S3b (Figure 6). The colors on this map relate to thermal maturity as indicated by vitrinite reflectance levels shown in legend near upper left of figure, with explanation in legend at middle left. Enlarged segment of map (upper right) shows details in study area shown in red rectangle. Figure adapted from Houseknecht, et al. (2012).

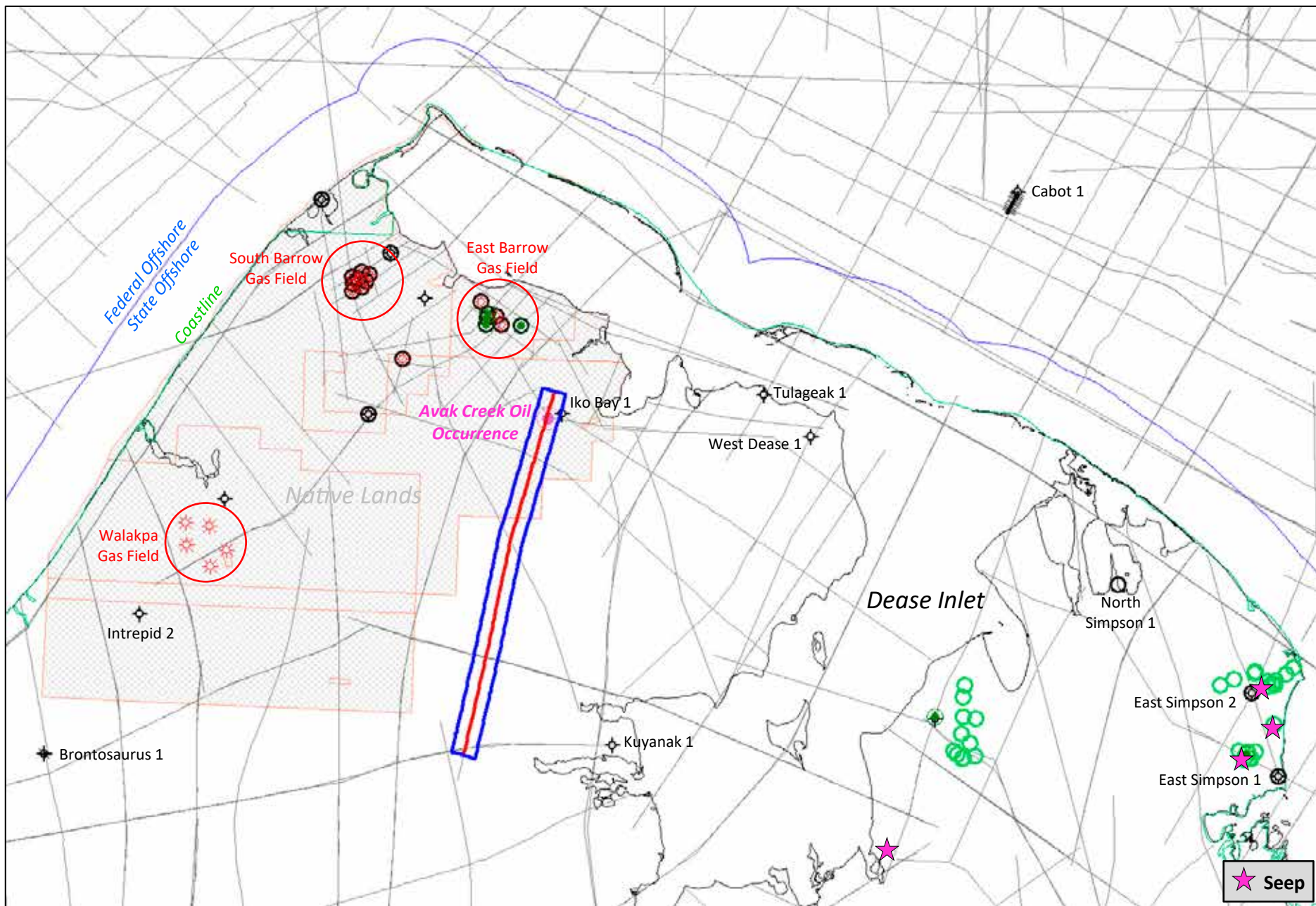
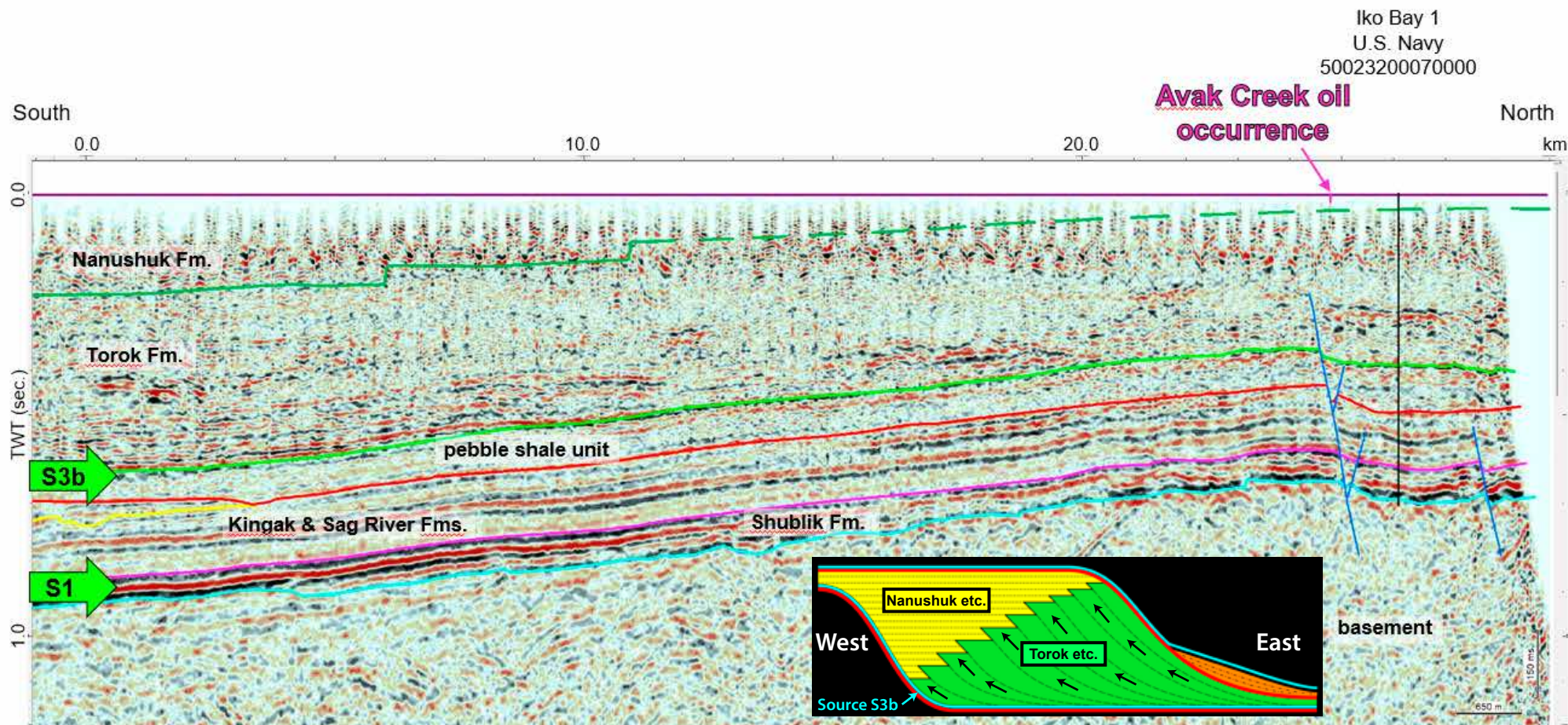


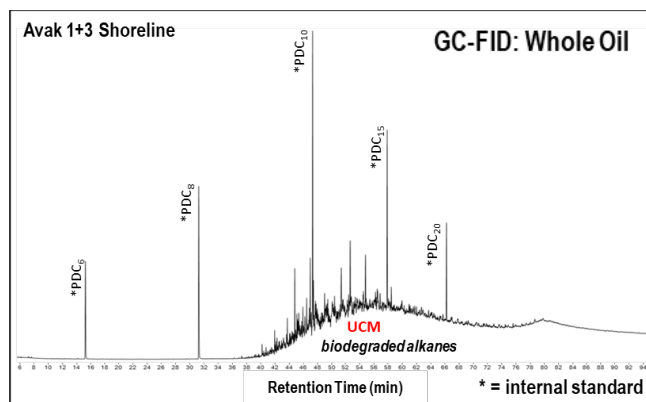
Figure 8. Map of Avak Creek area showing selected exploration wells with names, two-dimensional (2-D) seismic lines (dark gray), known seeps on Cape Simpson (magenta stars), and Simpson Core Tests drilled by U.S. Navy (green circles). Location of Avak Creek oil occurrence shown by pink circled dot just west of Iko Bay 1 exploration well. Red line with blue border is location of seismic line shown in Figure 9.



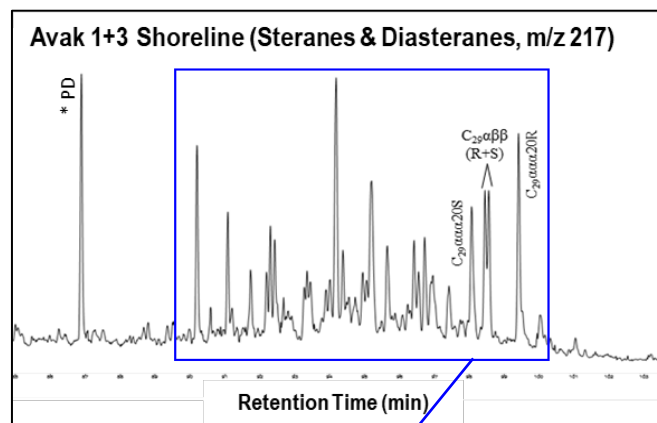
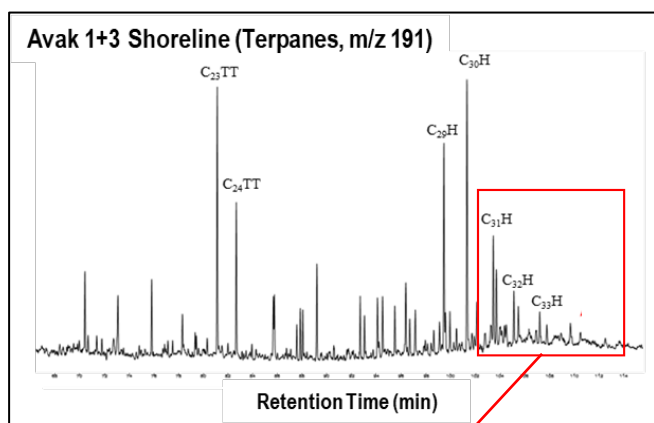
1 second Two Way Time (TWT) equals approximately 1,000 meters (3,281 feet) depth; Iko Bay 1, KB 40 ft, GL 28 ft, TD 2,731 ft (elev. 2,691 ft)

Horizons	Petroleum Source Rocks	Normal Faults	Well Identification Information
Torok toplap	Pebble shale unit & GRZ		Iko Bay 1 – well name and number
Hue – GRZ	Shublik Formation		U.S. Navy – operator
Lower Cretaceous Unconformity (LCU)			50023200070000 – UWI (unique well identifier), formerly API (American Petroleum Institute) number
Kingak K2 Top			
Shublik Formation			
Basement Top			

Figure 9. South-north seismic image crossing Avak Creek oil occurrence and Iko Bay 1 well, both near north end of line. Oil and gas generated south of Avak Creek likely migrated northward into the Avak Creek area. Migration was driven by buoyancy and likely occurred westward along clinoform surfaces (arrows in inset image) within Torok Formation and into Nanushuk Formation near surface. The arch and associated normal faults beneath Avak Creek are favorable for migration of crude oil into the area of the oil occurrence. Legend below seismic line shows horizons correlated on seismic line; stratigraphic positions of those horizons and the petroleum source rocks also are shown in Figure 6.



GC-MS: Saturate Fraction



GC-MS-MS: Saturate Fraction

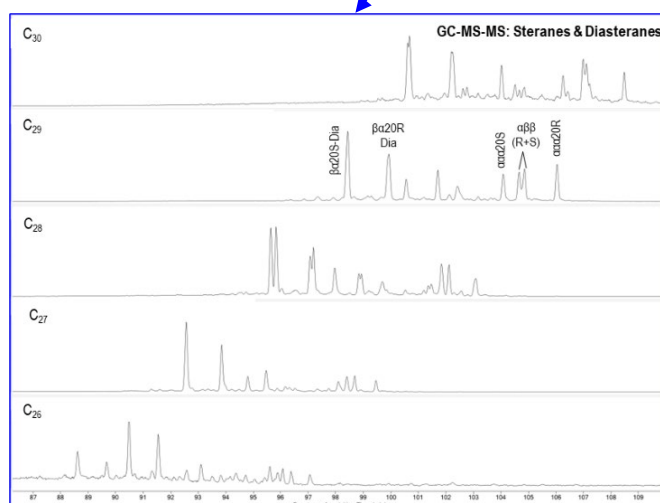
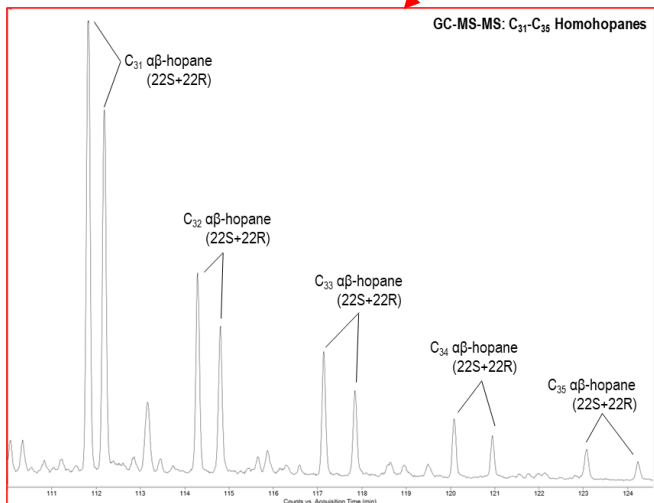


Figure 10. Analytical Chromatograms: GC-FID (whole oil) → GC-MS (saturate fraction) → GC-MS-MS (saturate fraction). Advanced instrumentation allowed for removal of overlapping hydrocarbons and peak interferences to provide a more accurate view of hydrocarbon profiles and identification of hydrocarbon peaks.

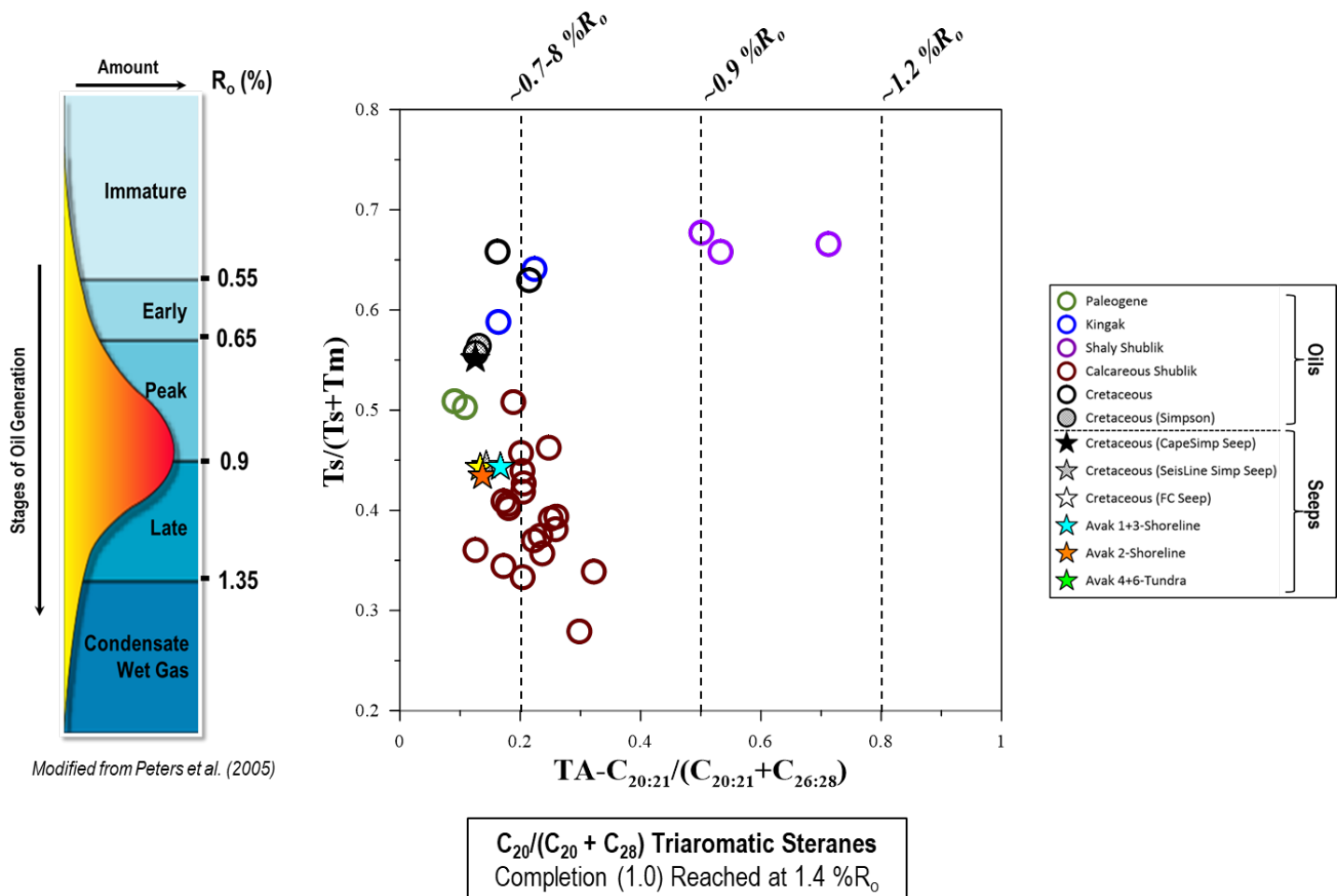


Figure 11. Thermal Maturity. Increasing values of $TA-(C_{20:21})/(C_{20:21}+C_{26:28})$ relative to $Ts/(Ts+Tm)$ reflect a general increase in thermal maturity as indicated by dashed lines and estimated vitrinite reflectance values at top according to the TA - R_o relationship defined in Peters et al. (2005).

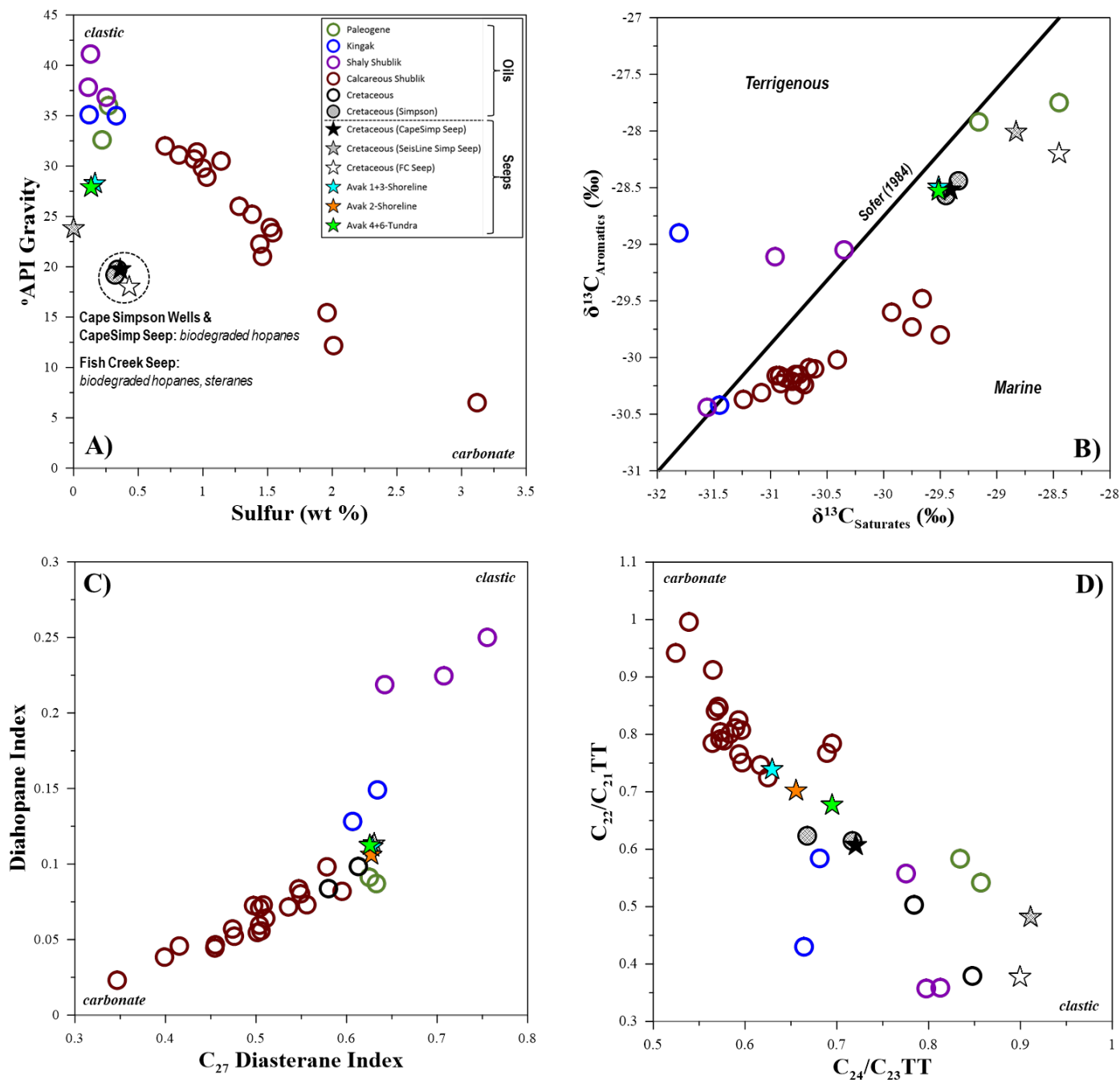


Figure 12. Lithology-sensitive bulk geochemical (A, B) and biomarker parameters (C, D). Among samples of similar thermal maturity, variation in source-related parameters represent differences in lithofacies of the inferred generating source rock among oil families (Seifert and Moldowan, 1978; Sieskind et al., 1979; Zumberge, 1984; Moldowan et al., 1986, 1991; Peters et al., 2005). Stable carbon isotopes of C_{15+} saturate and aromatic hydrocarbon fractions used to discriminate oil samples generated from a predominance of marine or terrestrial source organic matter as defined by Sofer (1984).

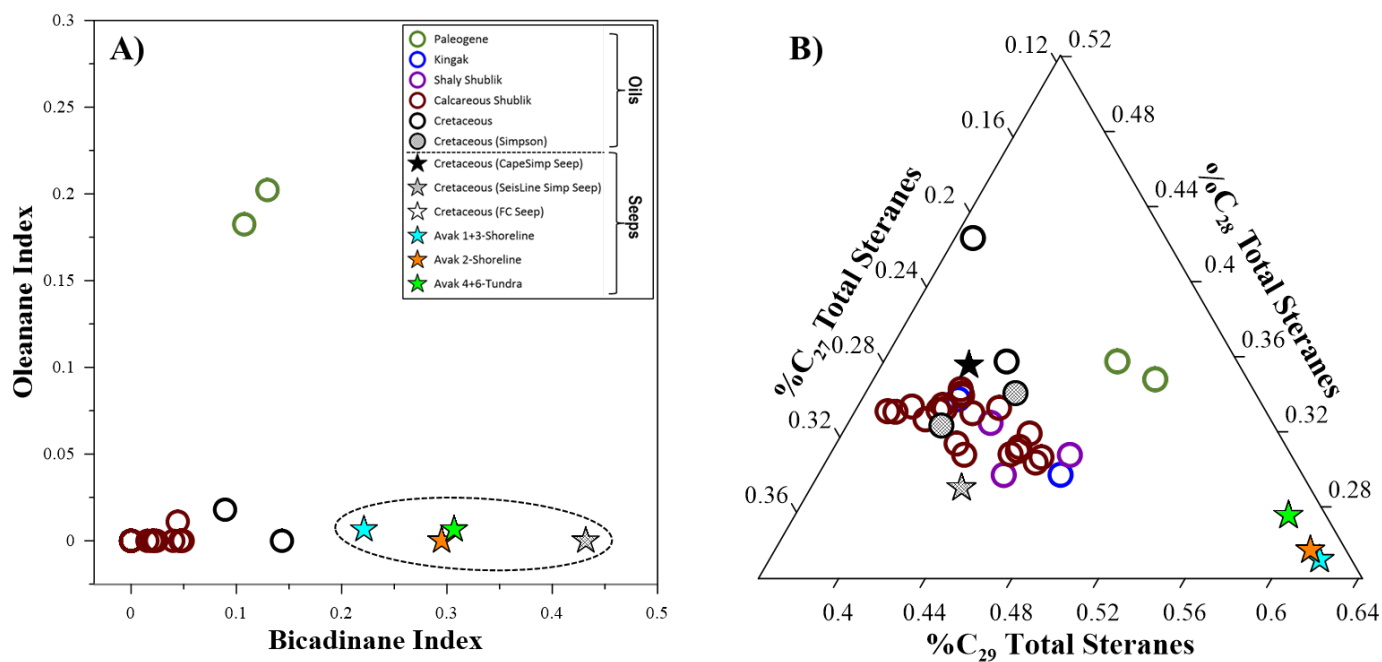


Figure 13. Source age and organic matter. Age-diagnostic (and taxon-specific) biomarker parameters used to bracket age ranges and discriminate oil families. A) Bicadinane and oleanane indices are highly specific for both Cretaceous and younger sources and terrestrial plant organic matter input. B) Sterane distributions discriminate source organic matter contributions (e.g., marine algal flora, diatoms, terrigenous plant input). Abbreviations: oleanane index ($(\alpha\text{-oleanane} + \beta\text{-oleanane})/(\alpha\text{-oleanane} + \beta\text{-oleanane} + C_{30H})$); bicadinane index ($(\text{bicadinane-T})/(\text{bicadinane-T} + C_{30H})$).

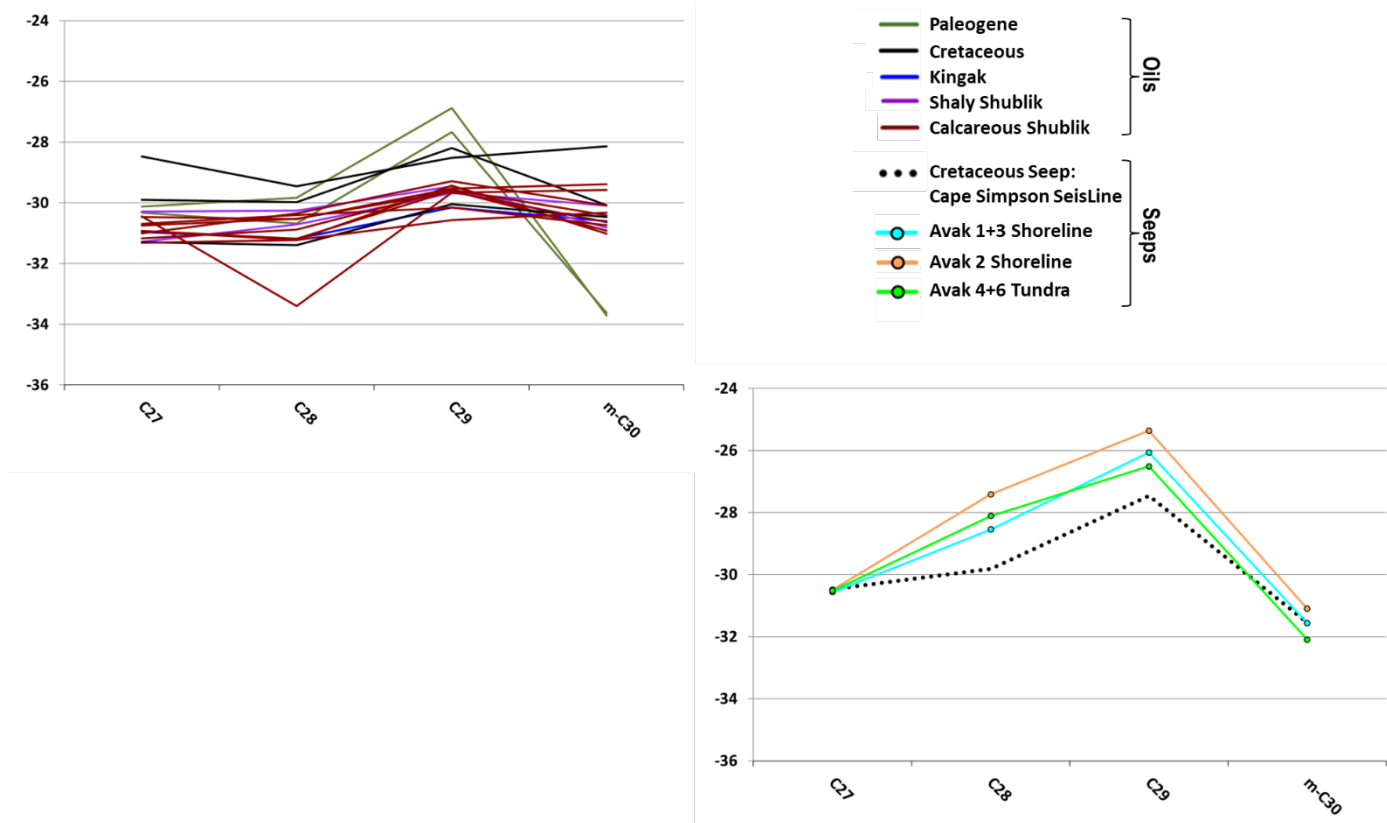


Figure 14. CSIA-Bs (sterane) Isotopic Signatures. Top Left: North Slope oils characterized in Botterell et al. (2021). Bottom: Avak Creek oil samples with nearby Cape Simpson Seismic Line seep inferred to have been generated from a Cretaceous source rock.

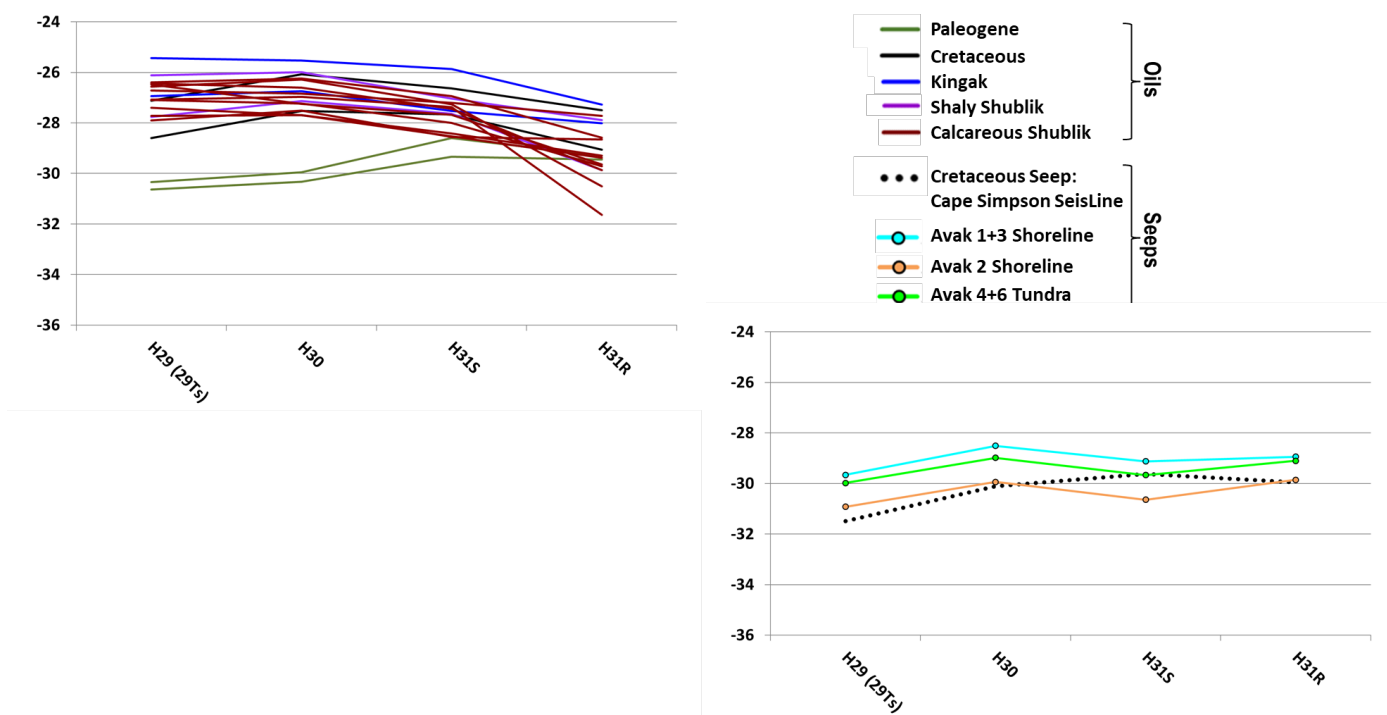


Figure 15. CSIA-Bh (hopane) Isotopic Signatures. Top Left: North Slope oils characterized in Botterell et al. (2021). Bottom: Avak Creek oil samples with nearby Cape Simpson Seismic Line seep inferred to have been generated from a Cretaceous source rock.

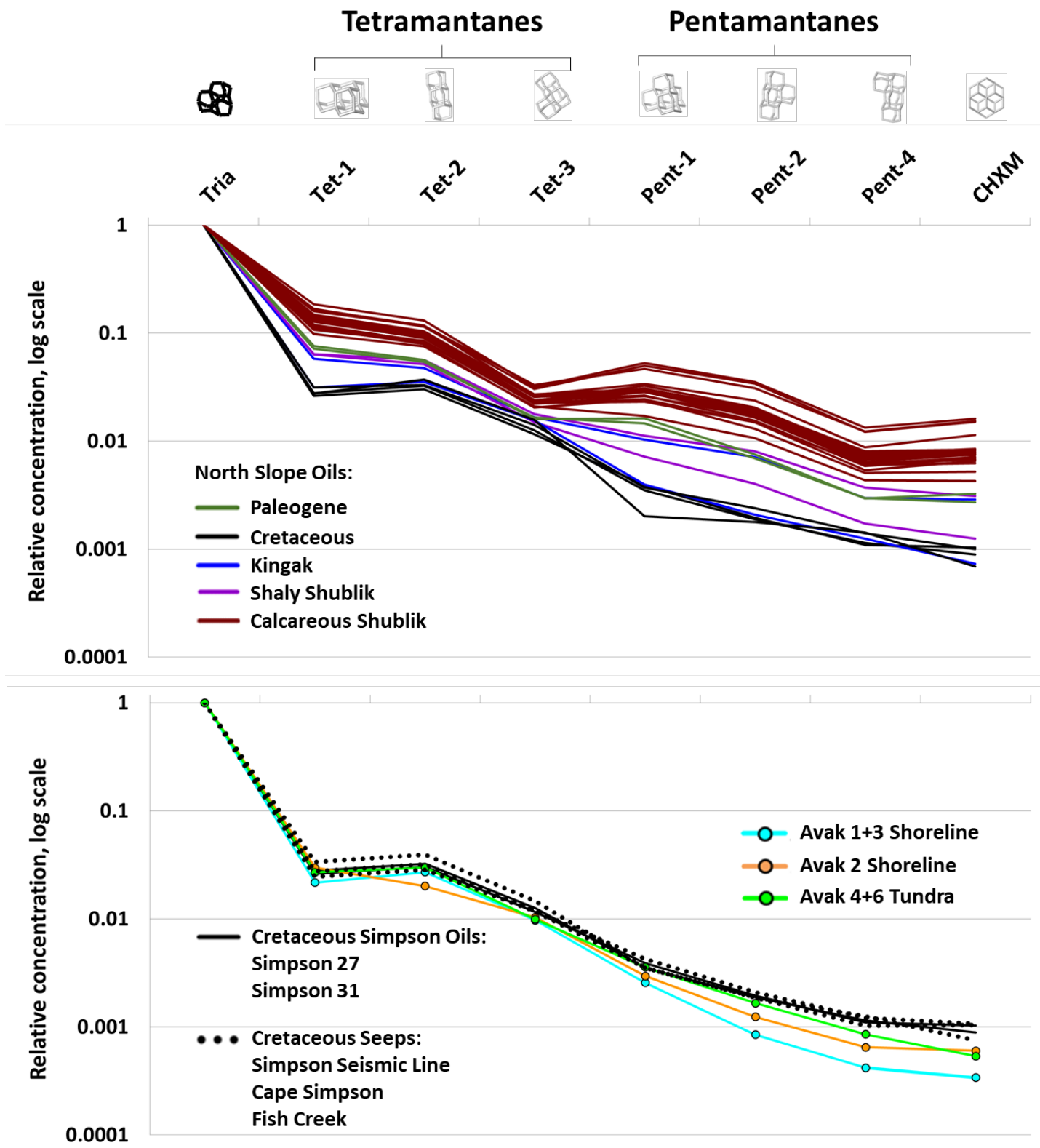


Figure 16. QEDA Fingerprints. Extended diamondoid concentrations plotted relative to triamantane. Top: North Slope oils characterized in Botterell et al. (2021). Bottom: Avak Creek oil samples with nearby oils and seeps inferred to have been generated from a Cretaceous source rock.

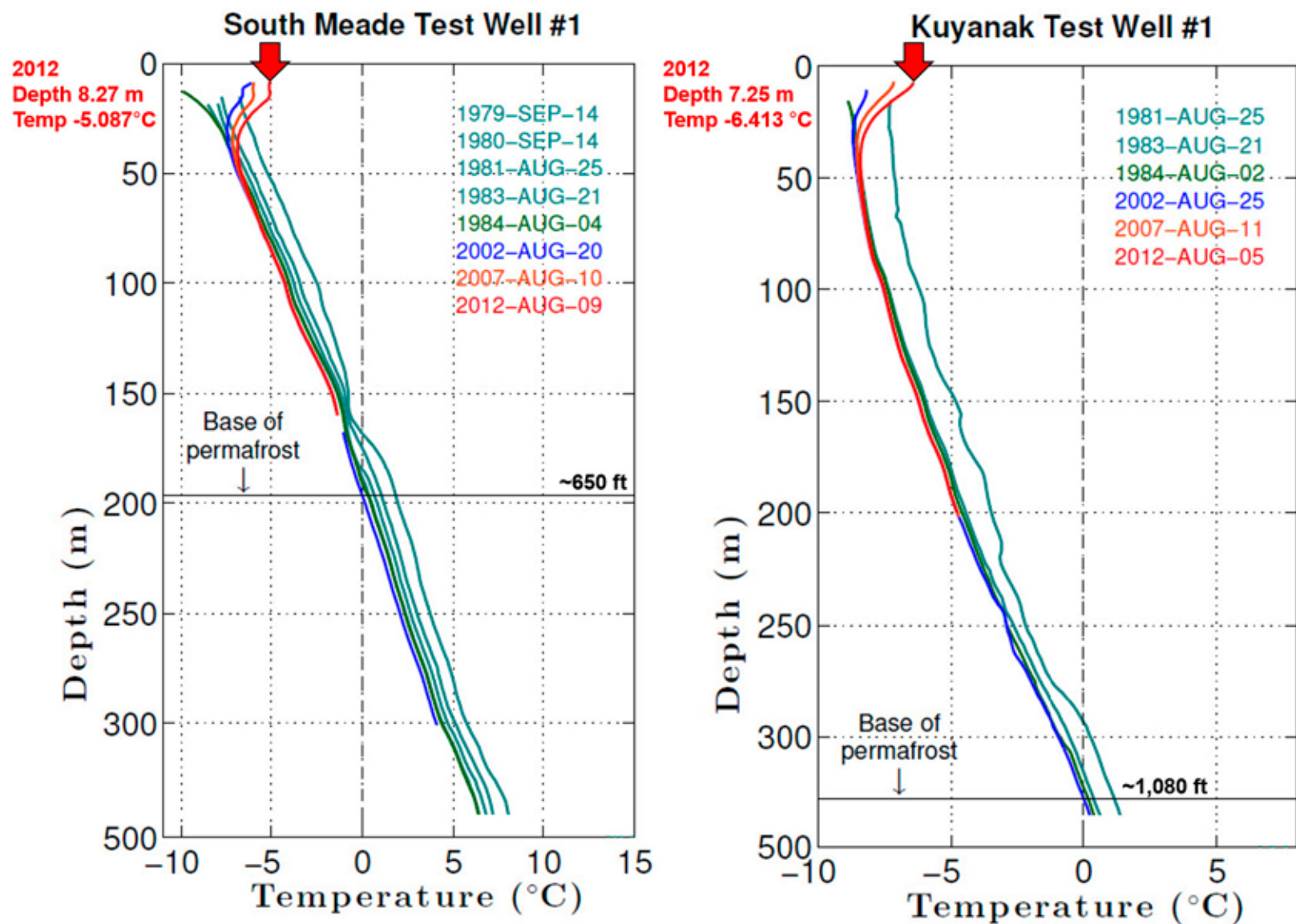


Figure 17. Subsurface temperature profiles from South Meade and Kuyanak exploration wells south of Avak Creek (see Fig. 7). The South Meade and Kuyanak wells display profiles that reflect initial cooling of shallow (less than ~35 meters) permafrost as higher temperatures induced by circulation of drilling mud during drilling subsided, followed by warming of shallow permafrost inferred as the influence of warming climate. Permafrost inferred to have formed across Arctic Alaska ~2 million years ago (Carter and Hillhouse, 1992). Data and interpretations based on Clow (2014, 2015). Plots adapted from: <https://nsidc.org/data/g10015/versions/1>