Coal as Oil Source Rocks: A Brief Geochemical and Geological Review

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Summary

Hydrogen-rich coals are unusual and have been shown to generate and expel liquid hydrocarbons (oils) during pyrolysis in the lab and during thermal maturation in the subsurface of sedimentary basins. Gas chromatograph analysis of expelled hydrocarbons in the lab show an abundance of long-chained hydrocarbons with trace element and biomarker signatures typical of terrestrial organic matter. Several oil basins around the world are identified as sourced by coals or coaly sediments. The largest coal-sourced volumes are in the Gippslands Basin, southeastern Australia, with reserves of about 5 billion barrels of oil and 12 Tcf of gas. About 4 billion barrels of this coal-sourced oil has been produced.

Hydrogen-rich coals and coaly sediments capable of oil generation can be deposited at relatively high latitudes. The Tertiary Gippsland Basin coals were deposited at southern latitudes of about 65°. Paleocene coals with oil and wet gas affinities from the Nenana basin were deposited at about 65° northern latitude. Hydrogen-rich Alaskan coals along the northern Gulf of Alaska are the source of dozens of oil seeps along the Sullivan Anticline near Yakataga, Alaska. Although now at 60° latitude, these coals are part of the Yakutat block which has moved northwestward along strike-slip faults.

Hydrogen-rich, oil-prone coals similar to those in the Nenana Basin in Interior Alaska, are identified in shallow core holes around the margins of the large Yukon Flats basin. Given appropriate thermal maturation in the subsurface, it is likely these coals have generated and expelled wet gas and possibly oil. These coals and coaly sediments may be the source rocks for as yet undiscovered oil and gas accumulations of significant size.

Can Coals Generate and Expel Oil?

Depending in part on one's experience and information, generation and expulsion of oil from coal can be either accepted or controversial. Most coals are hydrogen poor and will generate only dry gas during thermal maturation, but some unusual coals are rich in hydrogen because of associated algal, resin, pollen, spore and cuticle material incorporated in the coal. Also, some vitrinite is described as hydrogen rich and thereby has a different composition and makeup than most coals. The elevated hydrogen content allows hydrogen-rich gases and liquids to form, thereby sourcing liquid oils in some basins and/or wet gas with a significant condensable fraction.

Many technical papers have considered and discussed the issue of coal as oil source rocks. Following this discussion is a selected bibliography for oil-prone coals. A much more extensive bibliography (14 pages in length) on oil-prone coals can be found at the Society for Organic Petrology website http://www.tsop.org/refs/coaloil.htm

This discussion here is not an exhaustive review of this literature, nor does it review many of the important basin and laboratory studies. Instead, this paper is offered as a brief review of certain data that support and promote the existence of oil-prone coals in Interior Alaska as viable and potentially robust oil and gas source rocks. The discussion below will follow this format.

1. Lab based hydrous pyrolysis shows hydrogen-rich coals can generate and expel oil.
2. Five billion barrels of conventional oil reserves in the Gippsland Basin, Australia, are sourced by oil-prone coal. These coals were deposited in a high southern latitude of about 65°.
3. Hydrogen-rich coal along the northern Gulf of Alaska has generated and expelled oil and is the source of dozens of surface oil seeps. Geological patterns and geochemical characteristics link the source coals and the oil seeps.
4. Coals encountered in the Nenana basin in the Nunivak #1 well and in shallow core holes along the margins of the Yukon Flats are also hydrogen-rich and similar to coals that have expelled oil. Deep burial of coal in the Nenana and Yukon Flats basin is expected to also result in oil and/or wet gas generation and expulsion.

Results of hydrous pyrolysis

RockEval analysis is a form of anhydrous pyrolysis whereby a sample is heated in a water-free environment and the expelled hydrocarbon are analyzed. Many RockEval analyses show that some coals are rich in hydrogen and the results suggest these coals may be oil source rocks when thermally mature. Hydrous pyrolysis is a similar heating experiment, but in this case the sample is heated with added water in a closed and sealed pressure vessel. Because water is ubiquitous in the subsurface of sedimentary basins, it is thought hydrous pyrolysis better reproduces thermal maturation in the subsurface. Both RockEval and hydrous pyrolysis are done on a short time frame compared to natural burial and heating. RockEval analysis normally takes less than an hour while hydrous pyrolysis may take several days to a week.

In the case of hydrous pyrolysis, any oil generated, expelled and separated during the heating run (sometimes referred to as immiscible oil) can be extracted and analyzed by gas chromatograph (GC) to determine the exact composition of the produced oil. This lab-produced oil can then be compared to natural oils. Boreham et al (2003) in their study of the Bass Basin, Australia, state:

> *"One of the most reliable indicators for oil-proneness in terrigenous organic matter is its ability to generate high molecular weight linear alkanes as revealed by pyrolysis techniques"* (also referencing Wilkins and George, 2002 and references therein).

Ruble et al (2001) performed hydrous pyrolysis analyses on a variety of potential source rocks from lacustrine sediment which dominate the Tertiary Green River Formation, Uinta Basin, Utah. The oils produced from the various lithologies were analyzed by GC and results are shown in Figure 1. Although the Green River oil production is dominantly from lacustrine source rocks, minor hydrogen-rich coals also occur.

The chromatograms in Figure 1 show a variety of light to heavy hydrocarbons from these source rocks, including the hydrogen-rich coal. These results leave no doubt that coal of appropriate composition can generate and expel oil in the laboratory which is generally similar to oil from conventional mudstones, marlstones and shale.

Similar data is presented in Figure 2 which shows chromatograms of pyrolysis products from coals and claystones from Bass Basin, southeastern Australia. These source rocks expel liquid oil when heated and are the source of about 5 billion barrels of oil reserves in the adjacent Gippsland basin. The hydrogen index (HI) of each sample is noted in Figure 2 and visual inspection shows the amount of oil generated is qualitatively related to HI. The Gippsland oils are waxy crudes with low sulfur and rich in saturated fraction. Oil gravities range from 15° to 64° API (Bishop, 2000), but most crudes appear to be between about 30° and 45° API (Summons et al, 2002, see figures therein)

Figure 1. Chromatograms of source rocks from the Green River Formation, Uinta Basin, Utah. Source: Ruble et al, 2001. The added lithologies were also from Ruble et al (2001).

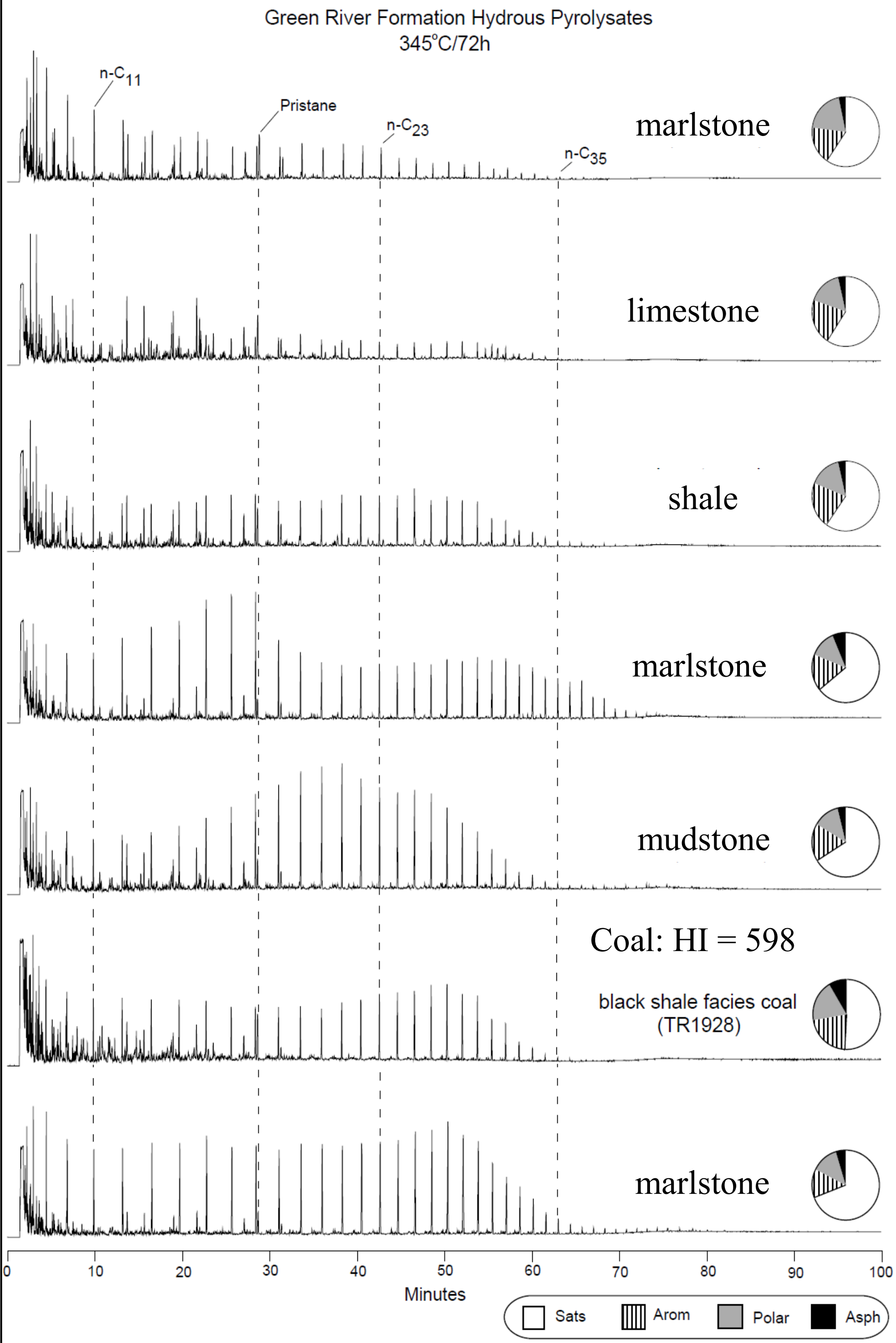


Figure 10. Whole-oil gas chromatograms and fractional compositions for immiscible oils generated during 345°C/72 hr hydrous pyrolysis experiments from various source rock lithofacies collected from the Green River Formation in Indian Canyon. Samples are in stratigraphic order from shallow (top) to deep (bottom). See Table 1 for further details. Conditions of analysis are described by Ruble (1996).

Figure 2. Chromatograms of coal and claystone pyrolysis, Bass Basin, Australia. Boreham et al, 2003.

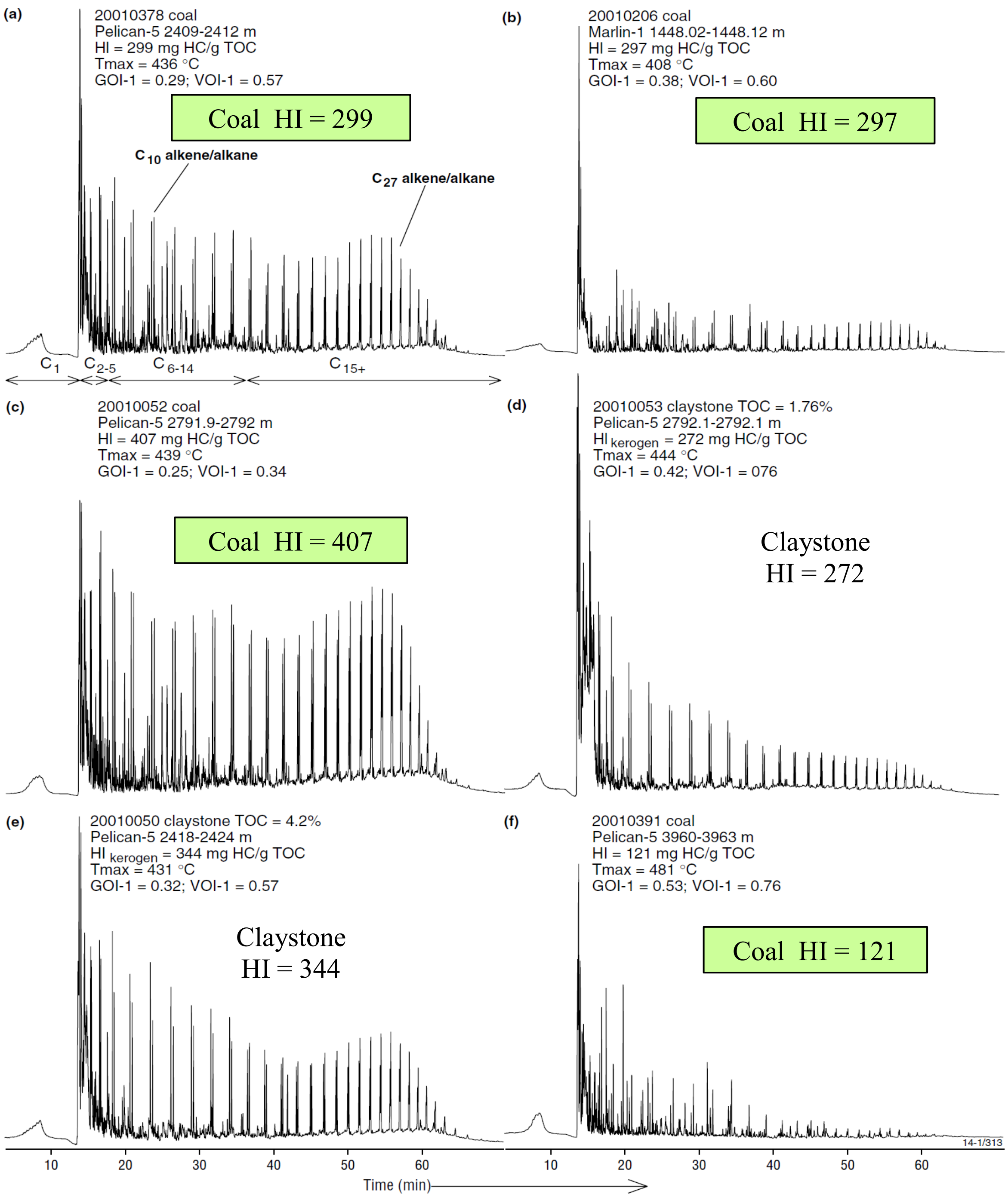


Figure 8. Py-GCMS chromatograms for coals from Pelican–5, Bass Basin; a), c), f) and Marlin–1, Gippsland Basin, b), and, claystones (kerogen) from Pelican–5, d) and e). For claystones note the slight increase in $HI_{kerogen}$ compared to HI for the whole rock (Table 2).

Producing basins with coal source rocks

Southeast Australia contains some of the best and most prolific examples worldwide of oil-prone coals sourcing large conventional oil accumulations. The offshore Gippsland Basin has about 5 billion barrels of oil reserves and 12 Tcf of gas reserves, all related to a coal or coaly source, and has historically provided most of the domestic oil and gas produced in Australia. The following comments addresses source rocks in the Gippsland and other Australian basins.

"Coals and coaly shales of Late Cretaceous through Eocene age are the source rocks for oil and gas that accumulated predominately in anticlinal traps." Bishop (2000), abstract, p. 1, referring to the Gippsland Basin

"The results of analyses of oils and potential source rocks indicate that terrestrial source rocks—coals and lower coastal plain coaly shales—show excellent correlation with the produced oils of the Gippsland Basin." Bishop (2000), p. 17

"Coals of the Latrobe Group are thought to be the principal, effective source for all oils in the Gippsland Basin…." Summons et al (2002), p. 29

"The well-known effective source rocks of the Cooper and Eromanga basin oils are exclusively terrestrial in nature with oil-prone coals and carbonaceous shales prevalent in Cretaceous-, Jurassic- and Permian-aged sequences." Summons et al (2002), p. 27

"In eastern Australia the Gondwanan Supersystem source rocks are non-marine, and associated with coal measure sequences." Summons et al (2002), p. 18

A wide variety of geological and geochemical data support the conclusion of coals and coaly shales as the oil source of the prolific Gippsland oil province. Geologically, the coals and coaly shales are widespread stratigraphically and laterally and no other fine grained sequence in the Gippsland basin has been identified with oil source potential. Geochemically, a long list provides evidence linking coals and coaly sediments with oils. The characteristics of the oils are:

1. Low sulfur
2. High Ni/V
3. Waxy signature to n-alkanes
4. Rich in saturated hydrocarbons
5. Low in asphaltenes
6. Low in NSO (nitrogen, sulfur, oxygen) compounds
7. High pristine/phytane ratios
8. High C_{29} sterane and high $C_{29}/C_{27}+C_{28}+C_{29}$ sterane ratios
9. Correlated biomarkers between oils and coals

The biomarker data (Figure 3) is informative as a visual inspection shows the similarity of coals and coaly shales and the produced oils. Figure 3 shows a comparison of GCMS traces for natural oils and oil generated in the lab from coal and claystone from Bass Basin during pyrolysis. Bass Basin is located southwest and adjacent to the prolific Gippsland Basin, Australia, and these basins share many structural and stratigraphic characteristics, including coal and coaly source rocks.

Figure 3. Oil and Coal Biomarker Correlations Bass Basin, Australia (Boreham et al 2003)

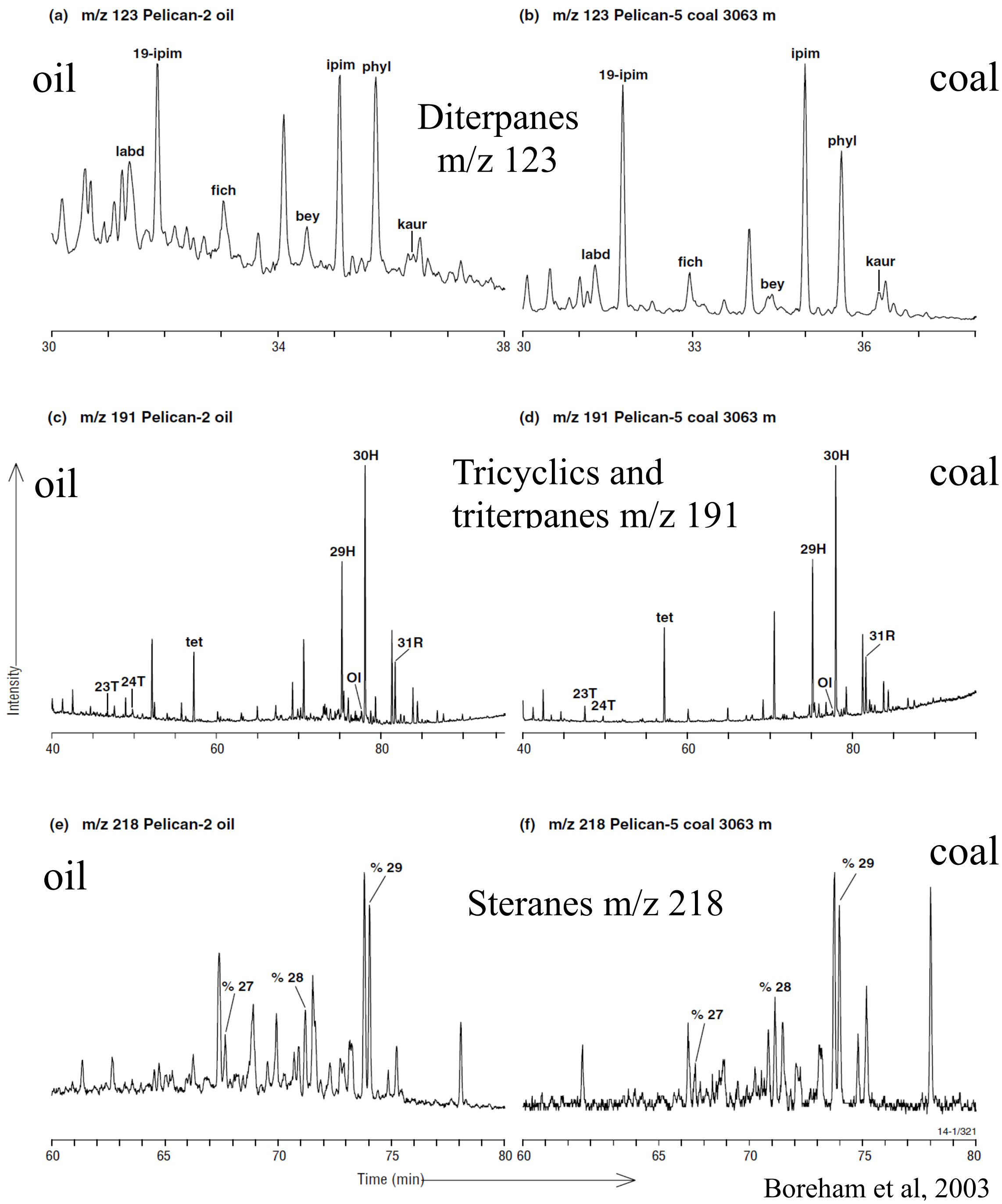
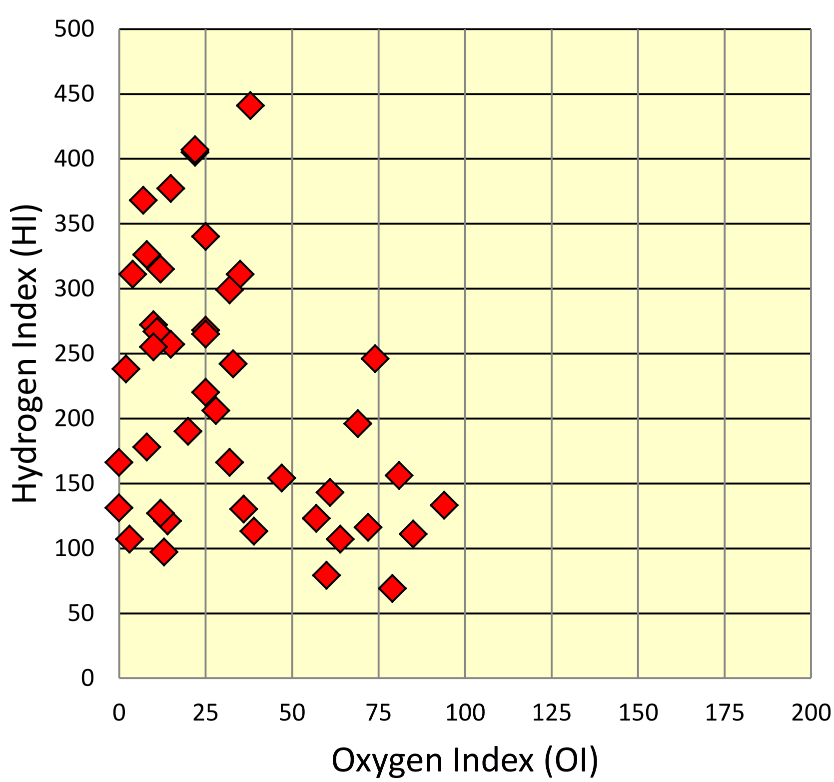


Figure 16. GCMS traces for saturated hydrocarbons for Pelican–2 oil and Pelican–5 coal from 3063 m showing a) and b), diterpanes m/z 123); c) and d), tricyclics and triterpanes m/z 191; and, e) and f), steranes m/z 218. Note: for peak identifications see Table 3.

The geochemical similarities between coals, coaly sediments and produced oils in the Bass and Gippsland Basins, the geological coincidence of coals and coaly sediment distribution with appropriate thermal maturity and the location of discovered oils, and the absence of an alternative viable source horizon, is strong evidence for coals and coaly sediments generating and expelling large volumes of oil.

RockEval results show the coals and coaly shales from the Bass Basin have Hydrogen Index (HI) values generally between 100 to 400. Figure 4 displays these results.

Figure 4. HI of Coals and coaly sediments, Bass Basin, Australia (data from Boreham, 2003)



Paleogeographic Reconstructions

It is noteworthy that Australia in the Late Cretaceous and Tertiary was geographically located at a high southern latitude.

"Sustral Supersystem sequences are Jurassic to Cainozoic in age. Throughout that time, the region was located in high southerly latitudes and experienced a humid, temperate climate." Summons et al (2002), p.21

Coals of Paleocene to Early Eocene age are particularly oil-prone, and Boreham et al (2003, p. 143) state of these coals in the Bass Basin:

"Consistently, the most oil-prone and volumetrically significant coals are of Paleocene-Early Eocene age (65-50.5 Ma)…."

Reconstructions show the southeastern region of Australia at about 65° south latitude in the Paleocene. The oil-prone coals and coaly sediments in Interior Alaska are also Paleocene (Nenana basin) while oil-prone coals along the northern Gulf of Alaska (Kulthieth Formation) are Eocene in age. The Alaskan Interior basins today and throughout the Tertiary were located at approximately 65° north latitude. In terms of paleogeographic latitude and oil-proneness of Paleocene coal and coaly sediments, there are significant similarities between Interior Alaska and southeastern Australia. Since coals deposited at high southern latitudes sourced large volumes of oil in Gippsland and Bass Basins, coals deposited at high northern latitudes in Alaska could potentially do the same. This same argument concerning latitude may not apply to the northern Gulf of Alaska coals because this crustal unit is part of the Yakatat Block which has moved northward along the margin of North America during the Tertiary.

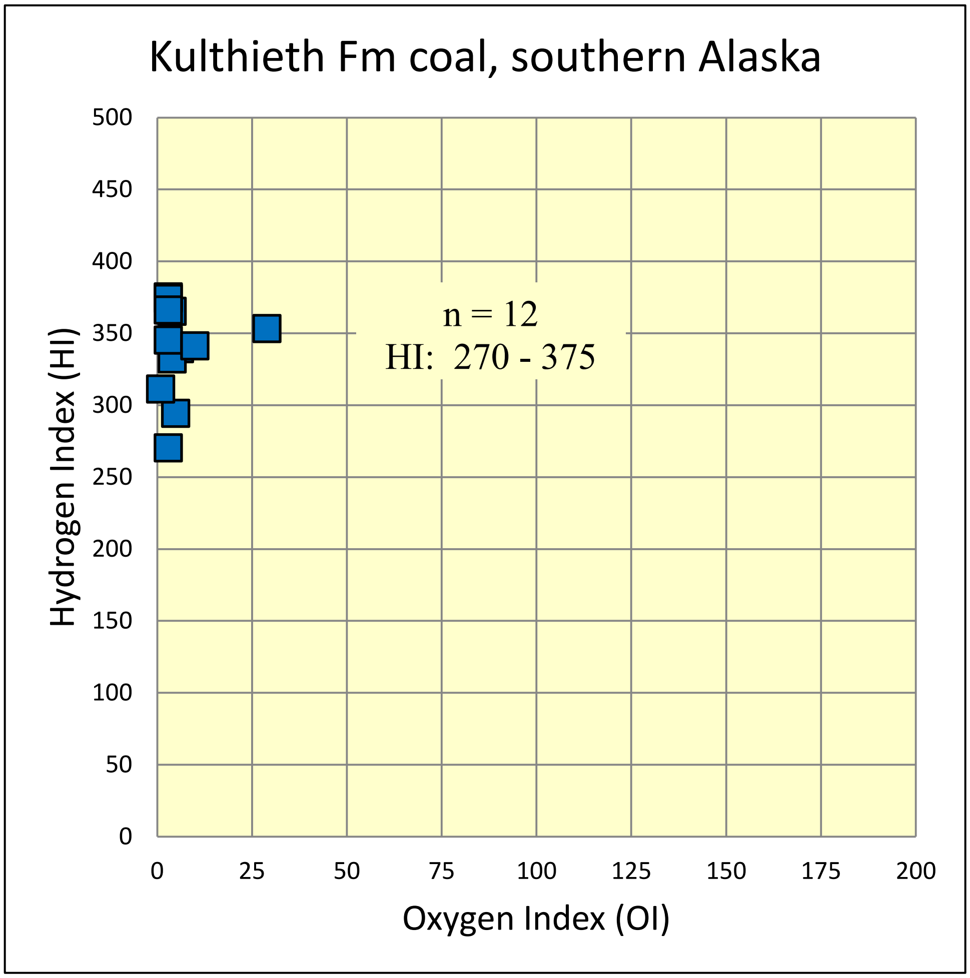
Oil from Coals: Yakataga, northern Gulf of Alaska

The Eocene Kulthieth Formation and numerous associated oil seeps along the northern Gulf of Alaska are evidence that coals and coaly sediments in Alaska can generate and expel oil. The northern Gulf of Alaska in the general region of Yakataga is a south-directed thrust belt which exposes progressively higher maturity rocks to the north. Extensive mapping and discussion by Miller (1957), Plafker (1967), and Miller (1971) show the geometry and stratigraphy of these thrust sheets.

Coals and coaly sediments of the Eocene Kulthieth Formation are usually overmature in outcrop due to past burial by thrusting. However, several localities contain rocks that are immature to marginally mature and these were evaluated for their oil source potential by Van Kooten et al (2002) and Short et al (2007). Relatively low maturity samples were collected from the western edge of the thrust complex near the headwaters of the Kosakuts River and from outcrops recently exposed by glacial retreat in Tann Fiord near Icy Bay at the eastern margin of the thrust complex. Additional oil-prone coal was found in the subsurface in the White River #2 well on the Sullivan anticline and as reworked detrital clasts in the Pliocene-Pleistocene Yakataga Formation.

RockEval results from the Kulthieth Formation coals and coaly sediments are shown in Figure 5. The modified van Krevelen diagram (Figure 5) shows the samples have HI values from 270 to 375. Comparison with Figure 4 above shows the Kulthieth coals overlap most of the higher end of the range of coals from the Bass Basin.

Figure 5. HI vs OI for coals and coaly sediments from the Kulthieth Formation, northern Gulf of Alaska. Analyses from Van Kooten et al (2002) and unpublished data.



Numerous surface oils seeps occur along the Sullivan Anticline near Yakataga and these seep oils are sourced by coals and coaly sediments from the Kulthieth Formation. Detailed mapping by Miller (1957) shows 33 oil seeps and 4 gas seeps along about 17 miles of the Sullivan Anticline. Oil volumes at most seeps are small, but Munday Creek and Johnston Creek seeps cover areas of approximately 1-2 acres. Total oil discharge at these seeps appears to vary with rainfall as increased precipitation helps to flush hydrocarbons from fractures and sediments. During one visit by the author in 1995, seepage at Johnston Creek was estimated at about 1 barrel per day. Although some oils are biodegraded, oil analyses reported by Van Kooten et al (2002) and Short et al (2007) show compositions and biomarkers consistent with a coaly, terrestrial source. In particular, cholestane (C_{27}) < methylcholestane (C_{28}) < ethylcholestane (C_{29}) < oleanane < hopane in both oils and coals, and oils and coals have $C_{29} > C_{28} > C_{27}$ steranes and similar sterane ratios dominated by C_{29}. Seep oils contain high oleanane and high pristine/phytane ratios where not degraded. A marine shale source rock (Oligocene-Miocene Poul Creek Formation) found about 60 miles to the west at Katalla and Kayak Island has different biomarker characteristics than the oils at the Sullivan Anticline. These geochemical data combined with the geographical coincidence of oil-prone coals and oil seeps provides a strong argument for Kulthieth coals and coaly sediments generating and expelling oil in southern Alaska.

Oil from Coals: Nenana Basin, Alaska

Like the coals and coaly sediments from southeastern Australia and the northern Gulf of Alaska, coals of Paleocene age encountered in the Nunivak #1 well are hydrogen-rich and appear to be oil-prone. The Paleocene section drilled in Nunivak #1 is about 3000' thick and the base was not penetrated. In Nunivak #1, Paleocene coal occurs from 8110' to about 10,450'. Over this interval of 2340', the wellsite mudlog records an equivalent footage of 368' of coal yielding a percentage of 15% of the Paleocene section being visually described as coal. Undoubtedly, much of this logged footage includes coaly sediments as well as coals.

RockEval results of Paleocene coals and coaly sediments from Nenana Basin are shown in Figure 6. The Hydrogen Index (HI) of these samples is generally between 200 and 300 although one sample reaches 379. As a comparison, Figure 7 shows a modified van Krevelan diagram with samples from southeastern Australia, the northern Gulf of Alaska, and the Nenana basin plotted together. The similarity of these data sets is clear.

Shallow cores taken by Exxon around the margins of the Yukon Flats basin occasionally encountered coal and several of these coals were analyzed by RockEval. Four coal or coaly sediment samples yield HI = 178-308. Although few samples in number, it appears the Yukon Flats may also contain hydrogen-rich coals which may be a source of oil and/or wet gas in this large Interior basin.

Figure 6. Modified van Krevelan diagram showing Paleocene coals and coaly sediments from Nunivak #1, Nenana basin, Alaska.

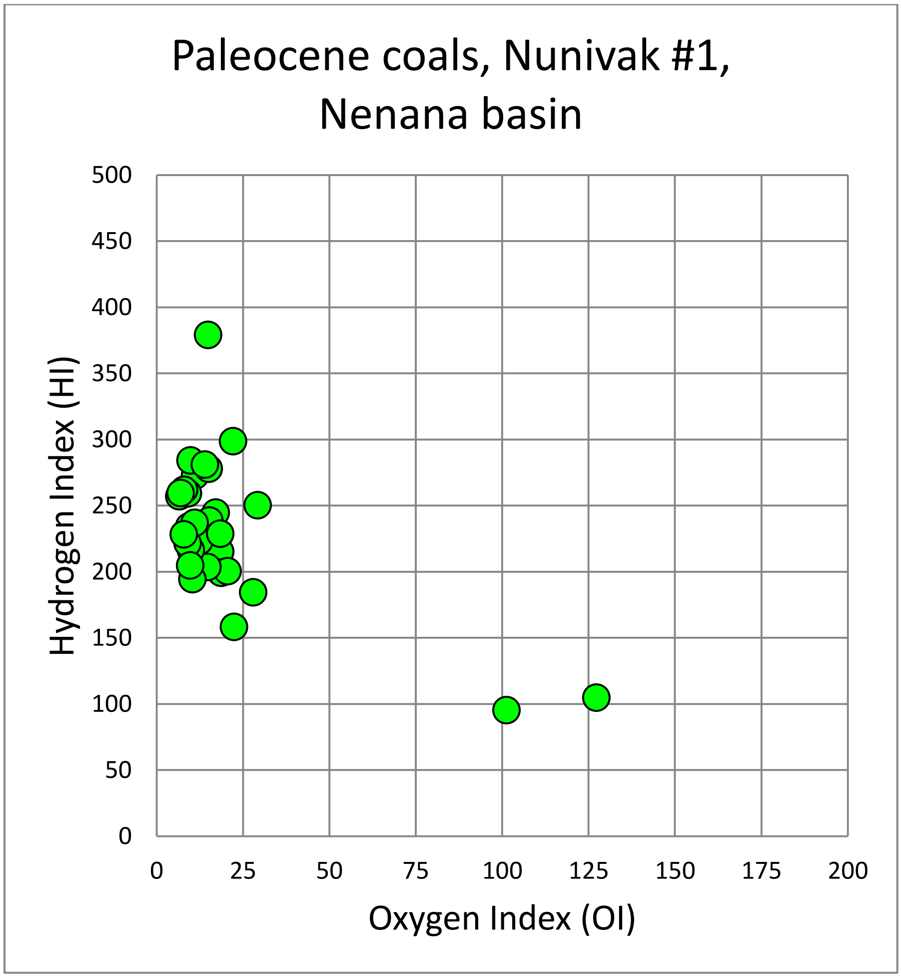
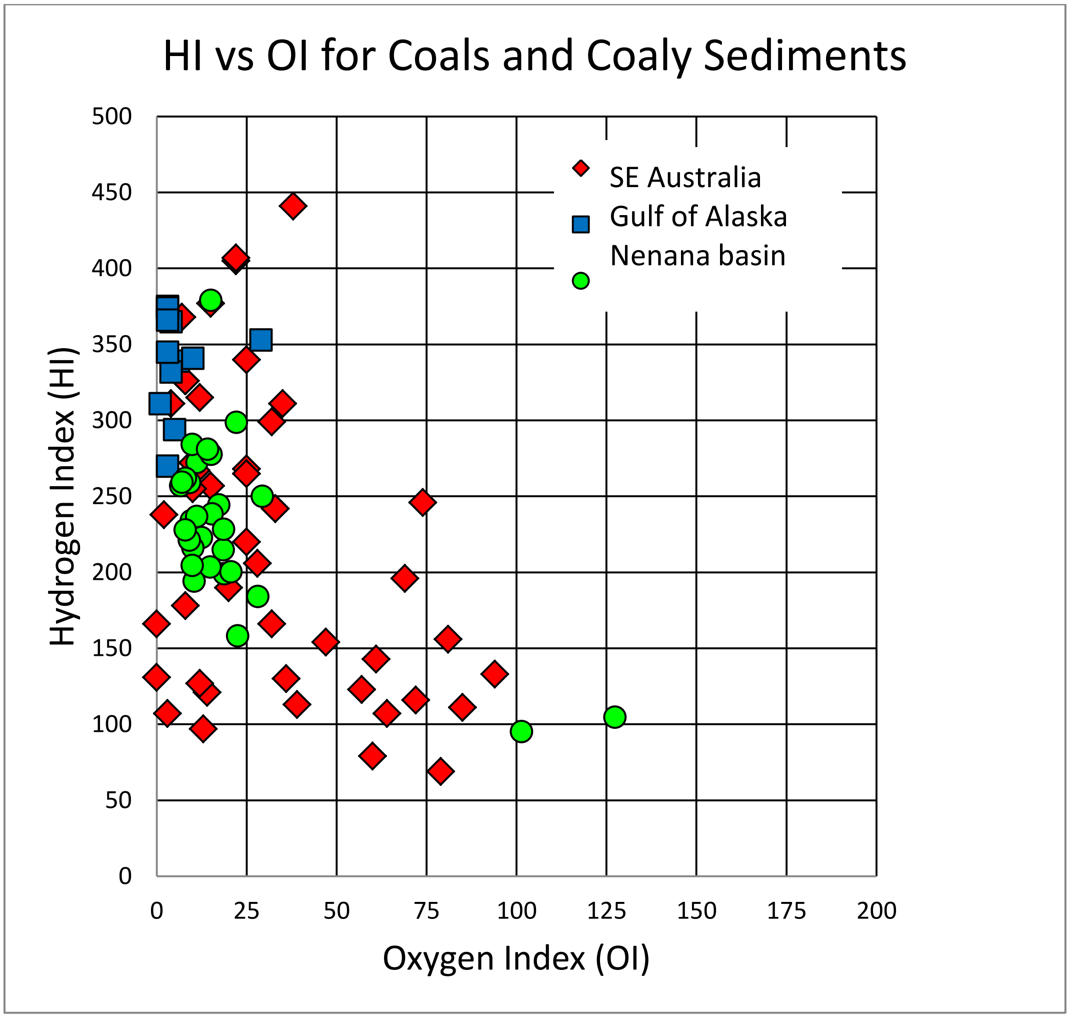


Figure 7. Comparison of coals and coaly sediments from southeastern Australia, the Gulf of Alaska, and Nenana basin, Alaska.



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