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A High Resolution Study of Petroleum Source Rock Variation, Lower Cretaceous (Hauterivian and Barremian) of Mikkelsen Bay, North Slope, Alaska

by

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Abstract

The pebble shale unit and lower part of the Hue Shale comprise the Lower Cretaceous, relatively condensed, organic-rich mudstone succession of the eastern North Slope of Alaska. The pebble shale unit has been interpreted to be gas-prone in the eastern North Slope region, but oil-prone to the west, where it is considered one of several sources for the Prudhoe area oil fields. The Hue Shale, particularly the lower part, is considered a good oil-prone source rock over the whole area. To evaluate variation in source potential and lithofacies and to determine controls on their deposition in the middle North Slope region, 45 core samples from the Lower Cretaceous section of the Mobil-Phillips Mikkelsen Bay State #1 well were analyzed using Rock-Eval and microscopic techniques.

On the basis of lithology the studied section (11,606-11,664 ft) is divided into the pebble shale unit and the lower part of the Hue Shale, the Hue distinguished by a major increase upsection in the abundance of tuffaceous material. Rock-Eval data indicate that both units are primarily type II, oil-prone source rocks with similar TOC, although, apparently the pebble shale unit has better oil-generating characteristics as indicated by higher hydrogen index (HI) values. The Hue Shale, however, has generated petroleum (PI approximately 0.15- 0.35; S1/TOC=0.4-1.0), resulting in reduced HI values, while the pebble shale unit has not (PI < 0.1; S1/TOC approximately 0.3). These data suggest that this Hue Shale interval has a lower activation energy than the pebble shale unit, probably related to differences in their original depositional environments reflected in their varying facies.

Introduction

Although the petroleum potential of the North Slope of Alaska has been investigated extensively [e.g., see Magoon and others (1987) and USGS Open-File Report 98-34 (1999) and references therein], very few high-resolution stratigraphic studies exist in the literature. A notable exception is a recent paper by Robison and others (1996) which documents the internal variation in Rock-Eval pyrolysis parameters and other petroleum source-rock characteristics within the Triassic Shublik Formation.

The Lower Cretaceous, relatively condensed, mudstone succession of the North Slope of Alaska is considered to be an important petroleum source rock interval (see below). This succession comprises the pebble shale unit and the lower part of the Hue Shale named the gamma-ray zone (GRZ). While the Hue Shale, and particularly the GRZ, is thought to be a good oil prone source rock, the pebble shale unit is described as gas prone in the eastern North Slope (Magoon and others, 1987), but oil prone to the west where it is one of several sources for the Prudhoe Bay area. In a prior study (Macquaker, Keller, and Taylor, 1999) of the Lower Cretaceous succession in outcrop along the Canning River (shown as Emerald Island below), lithofacies variation was documented at a millimeter to centimeter scale within the pebble shale unit. However, this section is too weathered for meaningful source rock evaluation.

In this study, we collected 47 core samples through 96 feet of section of the Mobil-Phillips Mikkelsen Bay State #1 well in order to evaluate the variation in lithofacies, petroleum source rock potential, and kerogen type at the fine scale of depositional bedding in the Lower Cretaceous succession. This well has one of the few complete cores of the Lower Cretaceous succession of the North Slope region between the NPRA and the ANWR. Our samples comprise the upper part of the Kemik Sandstone, the pebble shale unit, and the lower part of the Hue Shale or GRZ. Here we present the results from Rock-Eval pyrolysis and lithofacies analysis of this succession. See also Keller and Macquaker (2000), Macquaker and Keller (2000), and Keller and Macquaker (2001).

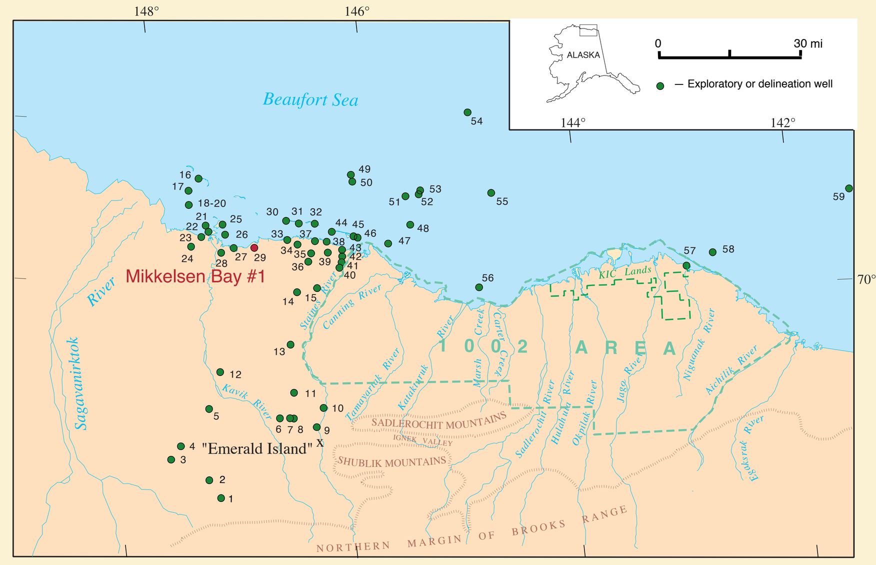
Methods

Core samples were collected approximately every 1 to 1.5 ft or wherever a facies change was visible in the core. Unusually thin polished thin sections (approximately 20 microns thick) were prepared and photographed using combined optical and electron optical (backscattered electron imagery) methods. The textures present and the mineralogy of each sample were recorded at a variety of scales using: a Polaroid 35 mm slide scanner adapted to take polished thin sections (cm to mm scale), a conventional petrographic (Nikon Labophot Pol) microscope (1.0 mm to 0.1 mm scale); backscattered electron imagery (< 0.1 mm scale) utilizing a Link four quadrant backscattered electron detector mounted on a Jeol JSM 4600 electron microscope (operating at 20Kv, 2 μA at an operating distance of 9 mm); and energy dispersive spectrometry (Link EDS detector attached to Link EXL mini computer running ZAF 4 on a Jeol JSM 4600) to confirm the mineralogical identity of individual grains. Sheet 2 shows our lithofacies data and interpretation.

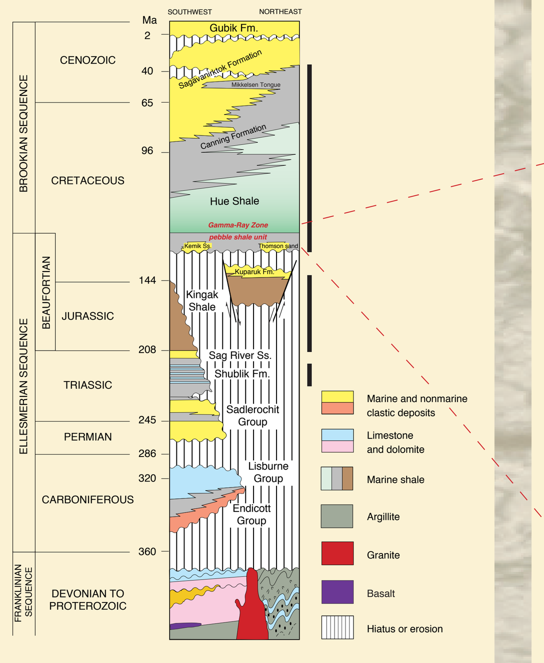
In order to evaluate petroleum source potential of the Lower Cretaceous succession, Rock-Eval pyrolysis including total organic carbon analysis was performed on 45 core samples. Approximately 1 gm of mudstone was broken from a remnant piece of the individual core samples. The core piece for this analysis, although similar to that used for the thin section study, did not necessarily contain identical strata. Strata that either contained abundant pyrite, obvious tuff, and mineralized coatings or weathered crusts were avoided.

Rock-Eval pyrolysis is the thermal distillation of free organic compounds (mostly bitumen in source rocks, oil in reservoir rocks) from the rock matrix followed by cracking of the insoluble organic matter, kerogen. The analyses reported here were run by Humble Instruments and Services Inc., using standard Rock-Eval programmed pyrolysis techniques. See Data Tables and explanation at right.

Study Area and Stratigraphic Framework

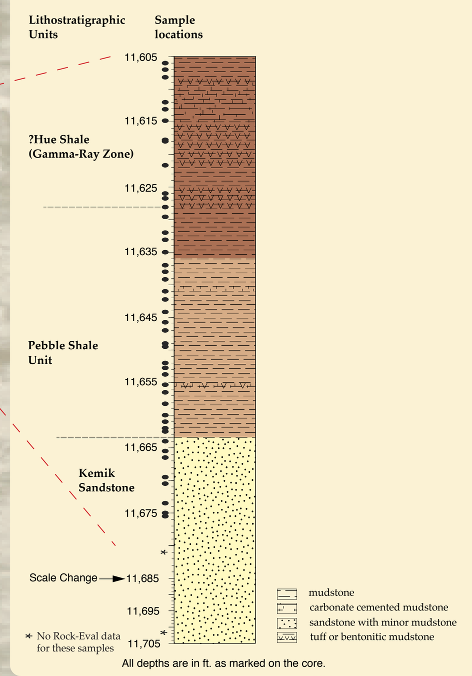


Index Map showing the location of the Mobil-Phillips Mikkelsen Bay #1 well of this study. Also shown are important wells near the 1002 area of the Arctic National Wildlife Refuge and Emerald Island, where the Lower Cretaceous succession is described by Macquaker, Keller, and Taylor (1999).



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

Lithofacies Log for Lower Cretaceous Succession from 11,605 - 11,705 ft. Mobil-Phillips Mikkelsen Bay State #1 API# 50-029-20055



Acknowledgements

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Rock-Eval and Petrophysical Data

Rock Eval Summary

Formation	TOC	S_1	S_2	S_3	T_{max}	HI	OI	S_2/S_3	PI	S_1/TOC
?GRZ and upper pebble shale unit, samples 32-47	3.5 (2.1-5.6)	1.9 (<1-3.2)	7.2 (1.9-16.1)	0.47 (0.32-1.01)	435 (430-439)	204 (59-397)	14 (6-32)	17 (1.8-44.6)	0.23 (0.11-0.4)	0.56 (0.27-0.97)
Lower part of pebble shale unit, samples 12-31	4.0 (2.8-5.9)	1.35 (0.82-2.46)	13.6 (8.24-26.42)	0.44 (0.27-0.69)	438 (435-441)	336 (278-449)	11.4 (7-22)	32.3 (15.8-60.0)	0.09 (0.05-0.16)	0.34 (0.22-0.54)
Kemik Sandstone samples 3-11	1.0 (0.68-1.36)	0.73 (0.30-0.87)	1.06 (0.58-2.0)	0.16 (0.12-0.21)	434 (429-437)	103 (64-159)	17.4 (10-31)	6.6 (2.3-12.5)	0.43 (0.27-0.64)	0.79 (0.33-1.26)

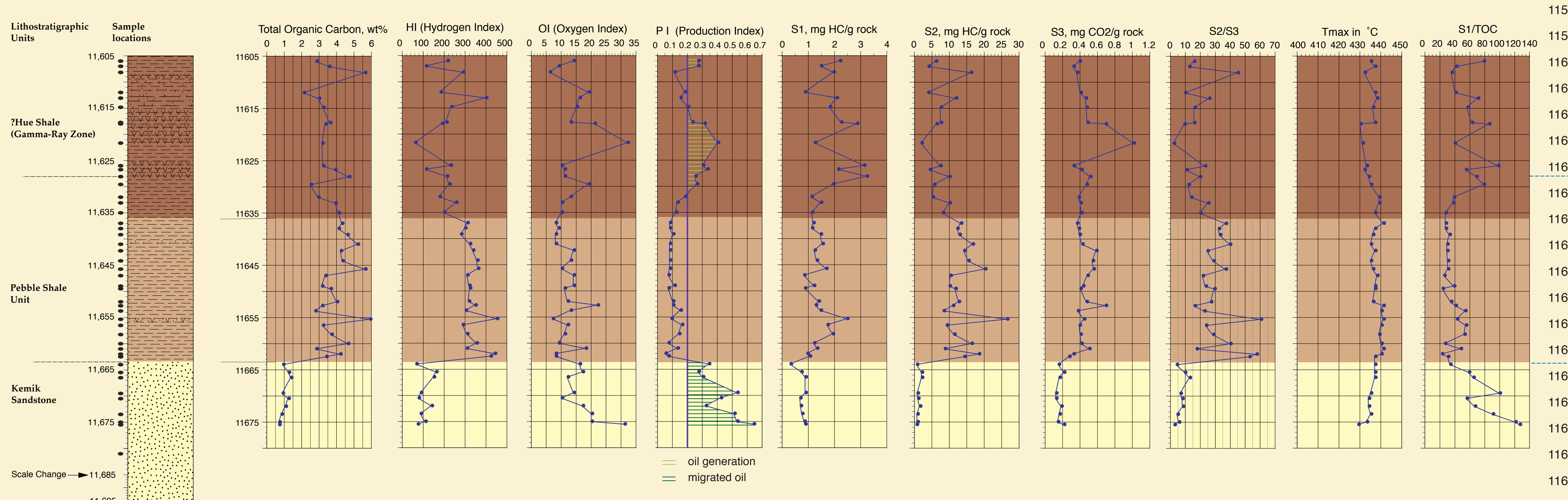
Rock Eval Data

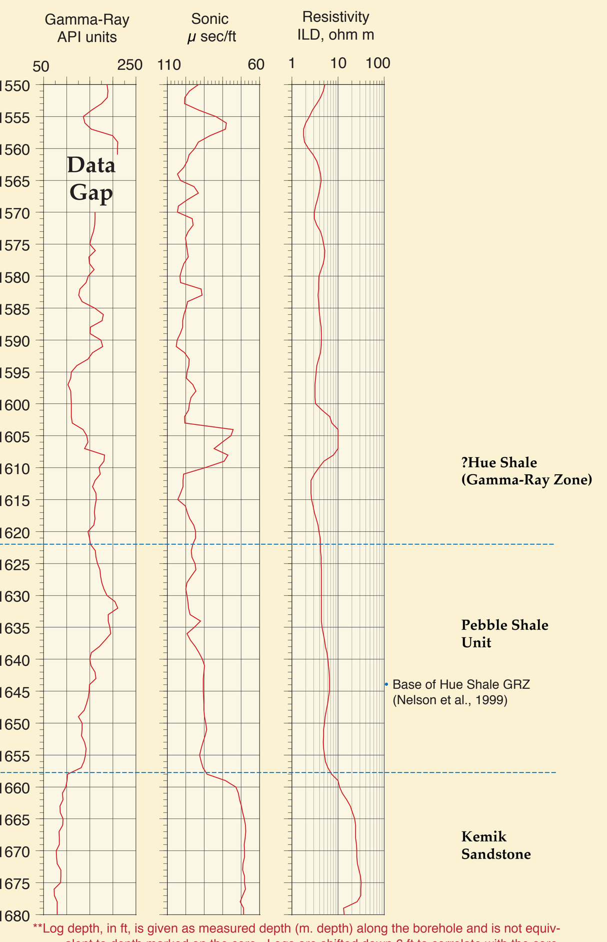
SPL									INTERPRETIVE RATIOS				
ID.		Depth, ft	TOC	S1	S2	S3	TMAX		HI	OI	S2/S3	PI	S1/TOC
47	Hue	11606	2.82	2.19	6.02	0.39	435		213	14	15.44	0.27	0.78
46	Hue	11607	3.55	1.46	3.9	0.32	437		110	9	12.19	0.27	0.41
45	Hue	11608.17	5.6	1.94	16.06	0.36	432		287	6	44.61	0.11	0.35
44	Hue	11612	2.1	0.85	3.78	0.4	437		180	19	9.45	0.18	0.40
43	Hue	11613.08	2.96	2.06	11.75	0.46	438		397	16	25.54	0.15	0.70
42	Hue	11614.83	3.21	1.8	7.4	0.47	436		231	15	15.74	0.2	0.56
41	Hue	11617.75	3.6	2.23	7.44	0.48	437		207	13	15.5	0.23	0.62
40	Hue	11618	3.33	2.84	6.22	0.69	430		187	21	9.01	0.31	0.85
39	Hue	11621.67	3.16	1.23	1.87	1.01	431		59	32	1.85	0.4	0.39
38	Hue	11626	3.2	3.11	7.29	0.32	433		228	10	22.78	0.3	0.97
37	Hue	11626.75	3.89	2.12	4.29	0.41	432		110	11	10.46	0.33	0.54
36	Hue	11628.08	4.69	3.21	9.87	0.51	434		210	11	19.35	0.25	0.68
35	pebble	11629.58	2.49	1.93	5.52	0.47	435		222	19	11.74	0.26	0.78
34	pebble	11632	2.92	1.1	5.11	0.38	439		175	13	13.45	0.18	0.38
33	pebble	11633.08	3.91	1.46	9.95	0.4	439		254	10	24.88	0.13	0.37
32	pebble	11635	4.1	1.12	8.02	0.41	437		196	10	19.56	0.12	0.27
31	pebble	11637	4.28	1.17	13.19	0.36	441		308	8	36.64	0.08	0.27
30	pebble	11638	4.09	1.12	12.16	0.38	437		297	9	32	0.08	0.27
29	pebble	11639.17	4.59	1.45	12.77	0.39	436		278	8	32.74	0.1	0.32
28	pebble	11641	5.18	1.52	16.56	0.42	435		320	8	39.43	0.08	0.29
27	pebble	11642.25	4.22	1.22	14.14	0.58	437		335	14	24.38	0.08	0.29
26	pebble	11644.17	4.31	1.3	15.32	0.54	435		355	13	28.37	0.08	0.30
25	pebble	11645.75	5.61	1.66	20.12	0.55	436		359	10	36.58	0.08	0.30
24	pebble	11647	3.33	0.82	10.21	0.48	438		307	14	21.27	0.07	0.25
23	pebble	11649	3.14	1.19	9.95	0.43	437		317	14	23.14	0.11	0.38
22	pebble	11649.5	3.63	0.85	11.61	0.4	437		320	11	29.03	0.07	0.23
21	pebble	11652	3.99	1.37	12.56	0.47	436		315	12	26.72	0.1	0.34
20	pebble	11652.75	3.15	1.26	10.91	0.69	441		346	22	15.81	0.1	0.40
19	pebble	11653.75	2.75	1.45	8.24	0.37	440		300	13	22.27	0.15	0.53
18	pebble	11655.33	5.89	2.46	26.42	0.44	441		449	7	60.05	0.09	0.42
17	pebble	11656.5	3.19	1.71	9.13	0.39	440		286	12	23.41	0.16	0.54
16	pebble	11658.25	3.68	1.91	11.28	0.4	439		307	11	28.2	0.14	0.52
15	pebble	11660	4.62	1.2	16.26	0.41	440		352	9	39.66	0.07	0.26
14	pebble	11661	2.81	1.31	8.58	0.5	441		305	18	17.16	0.13	0.47
13	pebble	11662	4.18	0.94	18.33	0.32	440		439	8	57.28	0.05	0.22
12	pebble	11662.5	3.38	1.03	14.16	0.27	437		419	8	52.44	0.07	0.30
11	Kemik	11664	0.91	0.3	0.58	0.15	437		64	16	3.87	0.34	0.33
10	Kemik	11665.5	1.23	0.71	1.96	0.21	437		159	17	9.33	0.27	0.58
9	Kemik	11666.5	1.36	0.87	2	0.16	437		147	12	12.5	0.3	0.64
8	Kemik	11669.5	0.88	0.87	0.76	0.12	435		86	14	6.33	0.53	0.99
7	Kemik	11670.5	1.21	0.67	0.91	0.12	434		75	10	7.58	0.42	0.55
6	Kemik	11672	1.05	0.69	1.44	0.18	434		137	17	8	0.32	0.66
5	Kemik	11673.5	0.82	0.74	0.7	0.16	435		85	20	4.38	0.51	0.90
4	Kemik	11675	0.69	0.83	0.74	0.14	433		107	20	5.29	0.53	1.20
3	Kemik	11675.5	0.68	0.86	0.48	0.21	429	*	71	31	2.29	0.64	1.26

*Tmax data not reliable due to low kerogen S2 value

S1, content of free organic compounds (less than approximately C_{33}), in mg HC/g rock
S2, amount of hydrocarbons (HC) generated by pyrolysis (plus some bitumen), in mg HC/g rock
S3, the organic carbon dioxide released to 390 °C, in mg CO_2/g rock
Tmax, the temperature of maximum S2 yield in °C
TOC, the total organic carbon in weight %
HI, the hydrogen index, S2/TOC, an indicator of kerogen type, in mg HC/g C_{org}
OI, the oxygen index, S3/TOC, an indicator of kerogen type, in mg CO2/g C_{org}
PI, the production index, S1/S1 + S2. An indicator of thermal maturity in a source rock, generally 0-0.4. An oil stained rock will have anomalously high PI.
S2/S3, used in the characterization of kerogen as surrogate for ratio of H/O
S1/TOC, the ratio of hydrocarbons generated, in mg HC/g C_{org}

Variation Within Succession





**Log depth, in ft, is given as measured depth (m. depth) along the borehole and is not equivalent to depth marked on the core. Logs are shifted down 6 ft to correlate with the core.

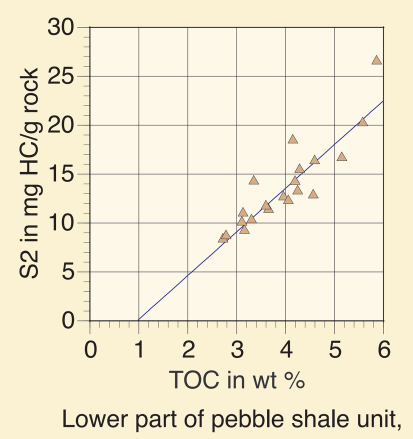
ROCK-EVAL AND PETROPHYSICAL DATA

On the basis of results from Rock-Eval pyrolysis (shown at left and above) the Lower Cretaceous succession in this well can be divided into 3 units that are fairly well stratigraphically confined. In the discussion that follows, all depths are given as marked on the core unless otherwise noted. Core depth minus 6 ft is equal to the measured depth (m. depth) along the borehole used for the logs. The upper part of the Kemik Sandstone has sonic travel times of 70 microseconds/ft or less, the highest resistivity (10-30 ohm m) of the three units, and the lowest gamma-ray response -- typically less than 80 API units. Average TOC is 1 wt %, S2 is 1.1 mg HC/g rock, and S1 is less than 1 mg HC/g rock. The production index (PI) is the highest of the succession averaging 0.43, and the hydrogen index (HI) is the lowest at 103 (64-159) mg HC/g TOC.

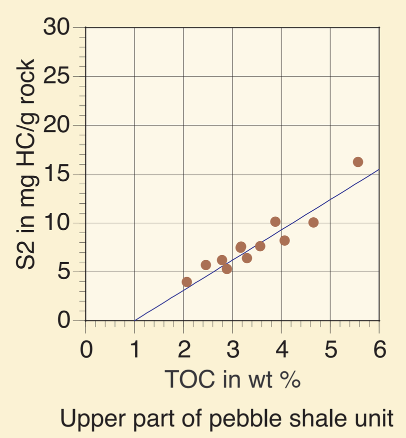
The lower part of the pebble shale unit has sonic travel times of approximately 90 microseconds/ft for the lower 19 ft and 90-100 microseconds/ft in the upper 10 ft. Resistivities are 4-6 ohm m, and gamma-ray response is significantly higher than the Kemik Sandstone, ranging from approximately 125-165 API units between 11,658 and 11,639 ft (m. depth), and then increasing to greater than 200 API units over the next 7 ft. Average TOC is 4 wt %, S2 is 13.6 mg HC/g rock, and S1 is generally 1-2 mg HC/g rock. The average production index (PI) is the lowest of the 3 units averaging 0.09, and the hydrogen index (HI) is the highest at 336 (278-449) mg HC/g TOC. On plots of S2 vs TOC (At Right) (after Langford and Blanc-Valleron, 1990) the average HI of the lower part of the pebble shale unit (samples 12-31) is 447 mg HC/g TOC. The S2/S3 ratio is the highest of the succession, generally 20-40, but as high as 60.

The upper part of the pebble shale unit and possibly the GRZ of the Hue Shale generally have sonic travel times of 95-105 microseconds/ft, but these decrease to less than 80 microseconds/ft coincident with the occurrence of carbonate cemented intervals in the core at approximately 11,615 ft. Gamma-ray response is approximately 150-180 API units, and resistivity varies from approximately 2.5-4 ohm m except in the carbonate cemented interval, where it rises to 10 ohm m. Average TOC is 3.5 wt % and S2 is 7.2 mg HC/g rock. S1 is significantly higher than in the lower pebble shale unit, and generally in the range of 2-3 mg HC/g rock. The production index (PI) is much higher than in the lower part of the pebble shale unit -- averaging 0.23, and the hydrogen index (HI) is lower -- averaging 204 (59-397) mg HC/g TOC. On plots of S2 vs TOC (At Right) the average HI of this unit, excluding 4 outliers, is 310 mg HC/g TOC. The S2/S3 ratio is generally 10-20.

Average Hydrogen Indices

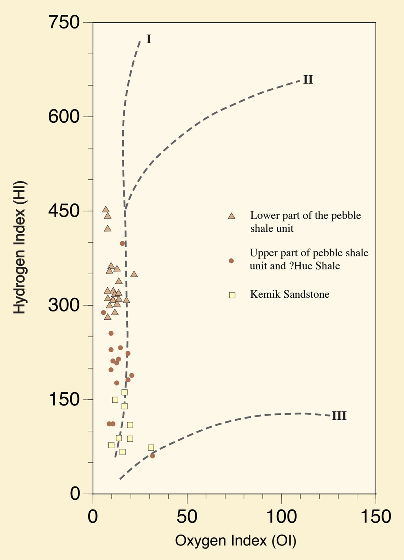


Lower part of pebble shale unit, HI= 447



Upper part of pebble shale unit and ?Hue Shale, HI= 310

Kerogen Type From HI vs. OI



DISCUSSION

Rock-Eval results and derived parameters (Peters, 1986) within the sampled succession of the Mikkelsen Bay State #1 well suggest 2 units of fairly uniform character and an upper, more variable unit. These units correspond to the upper part of the Kemik Sandstone, the lower part of the pebble shale unit, and the upper part of the pebble shale unit and possibly the lower part of the Hue Shale. The Rock-Eval characteristics of the 3 units are consistent with borehole geophysical log signatures and lithofacies. However, picking the base of the Hue Shale or gamma-ray zone in this well is problematic in that a previous gamma-ray log-based pick (Nelson and others, 1999) shows it to occur at approximately 11,644 ft (m. depth) within what we describe as the pebble shale unit. Although the interval above 11,644 ft (m. depth) has relatively higher gamma-ray response, the Rock-Eval results and lithofacies are consistent with its inclusion in the pebble shale unit, and we place the base of the Hue Shale higher in the core based on the abundance of bentonitic material, mineralized coatings, and weathering that reflect a change in composition.

For the upper part of the Kemik Sandstone, the low TOC and high PI suggest that it contains migrated hydrocarbons and is not a source rock. In the overlying mudstone succession the Rock-Eval data as well as new geochemical data (Lillis, Keller, and Macquaker, unpublished data; May, 2001) from pyrolysis GC, elemental analysis of isolated kerogen, column chromatography of bitumen extracts, and gas chromatography of the saturated hydrocarbon fraction suggest that there are 2 distinct petroleum source units. We also considered the possibility that the pebble shale unit has already generated and subsequently expelled hydrocarbons --thereby lowering its S1 values; however, we found no geochemical or geologic evidence to support this.

The lower part of the pebble shale unit is a type II, oil-prone source rock that is just entering the oil window and hasn't reached peak hydrocarbon generation, whereas the mudstones in the overlying unit have generated hydrocarbons. This upper and more variable mudstone succession, equivalent to the upper part of the pebble shale unit and possibly the lower part of the Hue Shale, is also predominantly type II, oil-prone source rocks; however, these mudstones, for the most part, have already generated hydrocarbons, thereby lowering S2, TOC, and HI and relatively increasing S1 values. This explains their low present day average HI value determined by plotting S2 versus TOC. The original S2 and TOC values for this upper unit were probably closer to or greater than present values for the lower part of the pebble shale unit, suggesting that the kinetics of hydrocarbon generation in the upper unit are faster. The one sample, #39, that might be interpreted as gas prone (Peters, 1986) because of very low S2 and HI, despite 3.16 % TOC, is from a weathered sample of the core within the upper unit.

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