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in the Jeanne d'Arc Basin, offshore Eastern Canada**

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INTRODUCTION

This Open File Report contains data from Rock-Eval/TOC pyrolysis of cuttings samples analyzed on a 10 meter spacing over the depth intervals noted below, from twelve wells from the Jeanne d'Arc Basin, offshore Eastern Canada.

Well name and location	Depth interval
Mobil et al Hebron I-13	910 4720 m
Mobil et al Hibernia O-35	530 4780 m
Petro-Canada et al King's Cove A-26	585 3095 m
Mobil et al Mara M-54	500 4446 m
Husky/Bow Valley et al North Ben Nevis P-93	1300 5280 m
PCI Terra Nova H-99	600 3510 m
Canterra PCI et al Terra Nova K-17	650 3250 m
Petro-Canada et al Terra Nova K-18	630 3925 m
Amoco et al West Bonne Bay C-23	640 4410 m
Petro-Canada et al Brent's Cove I-30	1020 4070 m
HMDC South Nautilus H-09	970 3910 m
Chevron et al East Rankin H-21	760 2150 m

The present report is a very belated addition to the series Open File Reports containing organic geochemistry data from the Jeanne d'Arc basin (Snowdon and Fowler, 1986; Fowler and Snowdon, 1988, 1989; Fowler et al., 1990, 1991; Fowler and Obermajer, 2001a, 2001b, 2002a, 2002b). With the exception of Brents Cove I-30 and South Nautilus H-09, borehole datasets have been available from the NRCan BASIN database (http://basin.gdr.nrcan.gc.ca/index_e.php). As for the previous Open File Reports containing Rock-Eval/TOC data, there has been little attempt to remove spurious results and caution must especially be advised in giving too much credence to parameters such as Hydrogen Index (HI) and Tmax from those samples with low total organic carbon (TOC) contents or S2 values. It should also be noted that drilling additives used in several of the wells affected the data quality negatively and made interpretation more difficult.

The tops used were those in McAlpine (1990b) or were provided later by the same author, based on lithostratigraphy outlined in McAlpine (1990a).

EXPERIMENTAL

Rock-Eval/TOC analysis provides fast and reliable characterization of the quantity and quality of sedimentary organic matter, as well as its thermal maturity. Experiments were conducted using Delsi Rock-Eval II (RE II) unit equipped with a Total Organic Carbon analysis module. The operating conditions and parameters for a RE II are provided in several GSC Open File reports. A typical RE II experiment was initiated with heating of a pulverized rock sample at 300°C for 3 min in helium atmosphere, when naturally occurring hydrocarbons (free and adsorbed) are volatilized. The oven temperature was then steadily increased to 600°C at a rate of 25°C/min and decomposition of kerogen occurs. The amount of hydrocarbons volatilized at 300°C and evolved from kerogen during the ramped heating were quantitatively determined by a flame ionization detector, and recorded as the S1 and S2 peaks, respectively. The final stage involves oxidation and combustion of the residual organic matter at 600°C. The temperature measured at the maximum of the S2 peak is referred to as Tmax. The quantity of organic CO₂ generated from 300°C to 390°C, determined by a thermal conductivity detector, comprised the S3 peak.

The percentage of carbon in CO₂ formed during oxidation and in the hydrocarbon peaks S1 and S2 is used to define the total organic carbon content (TOC), expressed as a weight percentage. The determination of the quality of organic matter is based upon the calculation of Hydrogen (HI) and Oxygen (OI) indices ($HI=100 \times S2/TOC$, $OI=100 \times S3/TOC$) which are related to the atomic H/C and O/C ratios (Espitalié et al., 1977). The OI versus HI cross plots ("pseudo van Krevelen diagrams") can be used as an organic matter type indicator at low and moderate maturities. The Tmax is an indicator of relative thermal maturity. According to Espitalié et al. (1985) the oil window is defined by the following Tmax ranges: 440°-448°C (Type I), 430°-455°C (Type II) and 430°-470°C (Type III). A cross plot of Tmax versus HI is used to constrain estimations of organic matter type and its thermal maturity, while the Production Index ($PI=S1/[S1+S2]$) is used to indicate staining of a sample or as an additional maturity parameter.

Rock-Eval/TOC parameters have reliable significance only above threshold TOC, S1 and S2 values. If TOC is less than or equal to 0.3% then all parameters have questionable significance and the experiment suggests no petroleum source potential. Oxygen Index (OI) has questionable significance if TOC is less than or equal to 0.5%. Both Tmax and Production Index ($PI = S1/(S1+S2)$), have questionable significance if S1 and S2 values are less than or equal to about 0.2 mg HC/g rock. Results can be affected by rock mineral composition. The mineral matrix may either retain hydrocarbon compounds, generally lowering the S1 or S2 peaks, while increasing Tmax, or liberate inorganic CO₂ increasing S3 and OI. These effects are important if TOC, S1 and S2 are low, and are not significant

where samples have TOC values greater than 5%. OI values greater than 150 mg/g TOC suggest either low TOC or a mineral matrix CO₂ contribution during pyrolysis. Generally, a TOC content of at least 2% is needed for a source rock. Note that TOC and Hydrogen Index decrease with increasing thermal maturity due to hydrocarbon generation. Additional guidelines on the interpretation of Rock-Eval data may be found in Peters (1986), Snowdon (1995) and Sykes and Snowdon (2002).

The following tables contain the standard measured Rock-Eval parameters (Espitalié et al., 1977, 1985) as well as several derived parameters:

TOC = total organic carbon reported as percent by weight of the whole rock;

TMAX = temperature (°C) at the top of the S2 peak;

S1 = hydrocarbons evolved (distilled or thermovaporised) at 300°C (mg hydrocarbon per g rock);

S2 = hydrocarbons evolved during heating at 25°C/min between 300°C and 600°C (mg hydrocarbon per g rock);

S3 = organic carbon dioxide evolved at 300°C and up to 390°C (mg CO₂/g rock);

PI = Production Index = $S1/(S1+S2)$;

HI = Hydrogen Index = $100 \times S2/TOC$; and

OI = Oxygen Index = $100 \times S3/TOC$.

WELL SUMMARIES

Hebron I-13

Rock-Eval/TOC data indicates no significant source rock intervals in this well. In common with other wells in the Jeanne d'Arc Basin, samples in the Tertiary section have high TOC values but low HI values. Elsewhere in the well there are occasional samples within the Hebron Well Member with high TOC contents such as at 2700 m, 2970 m, 3040 m, 3260, 3280 m and 3370 m, in the 2.44-4.12% range but relatively low HI values (140-278 mg HC/g TOC) and Tmax values (410-424°C with the exception of 3260 m sample). Samples with similar characteristics are also observed within the Hebron Well Member in the Terra Nova wells. There are several samples with TOC contents greater than 1% in the Rankin Formation but most are less than 1.25%. The best sample from 4630 m has a TOC content of 2.06% and a HI of 256 mg HC/g TOC and is mature with regard to hydrocarbon generation which suggests that there may be some minor potential in this section.

Samples with high PI (S1/S1+S2) values in the Ben Nevis and Catalina formations and Hebron Well Member correspond to zones that were tested and so likely represent migrated reservoired hydrocarbons. Intervals within the Jeanne d'Arc Formation were also tested, mostly unsuccessfully, and did not show high PI values including the DST 1 zone (4368-4381 m) which did produce oil and gas. PI values increase within the Rankin Formation towards the base of the well. This could be related to generation of hydrocarbons from this part of the Rankin Formation or migration of hydrocarbons from a mature Egret Member which should be present a little deeper than the well total depth.

Tmax generally shows a good trend of increasing with increasing depth. The Banquereau Formation at ~1000 m is immature with a Tmax of ~427-428°C. By around 3800 m in the Jeanne d'Arc Formation, the Tmax is ~430°C suggesting early maturity while the upper part of the Rankin Formation at the base of the well has Tmax values of 438-440°C indicating that it is approaching the middle of the oil window (~0.75% vitrinite reflectance equivalent).

Hibernia O-35

Rock-Eval/TOC indicates that there were no potential source rock intervals penetrated by this well. In common with other wells in the Jeanne d'Arc Basin, samples in the Tertiary section have high TOC values but low HI values. There are samples with very high PI values in the Ben Nevis – Avalon – Eastern Shoals formations corresponding to the section where the major reservoirs were tested in this well. There are somewhat elevated TOC contents (i.e. >1%) over the 3110-3270 m interval within the Catalina Fm. However, these are associated with low HI values (<150 and most less than 100 mg HC/g TOC) despite their low maturity and thus there is no hydrocarbon potential in this section. Below 3950 m, there are occasional samples with very high TOC contents in the Hibernia and Jeanne d'Arc formations. These are generally associated with low HI values (<260 mg HC/g TOC) and low Tmax values. The cause of these high TOC values is probably drilling contamination from dispersed ligno-sulphonate which was used in the drilling of this well. The amount of ligno-sulphonate used tended to increase considerably once the over-pressured Lower Cretaceous/Upper Jurassic shales were reached in wells of this age. The 4120 m sample appears to be an exception as it has a TOC content of 13.73% and a HI of 488 mg HC/g TOC and thus could represent an excellent potential source rock interval. It is thought more likely that the high HI could be because the actual TOC content is higher due to the analyzed sample being extremely contaminated and thus the beyond the instrument's calibration. A two times higher TOC content would result in a lower HI similar to the other samples

thought to be affected by the presence of ligno-sulphonate. The presence of this contamination would also explain why the Tmax is relatively constant over the lower part of the well and the difficulty different operators apparently had in measuring vitrinite reflectance on samples from this section.

The increase of Tmax with depth is a little erratic in this well, partly for the reasons of drilling contamination discussed above. Very low Tmax values in the Tertiary section indicate that it is immature. Tmax values seem to reach 430°C around 3100 m suggesting the onset of early maturity. Below this there is little variation of Tmax with depth.

Kings Cove A-26

The Tertiary section has high TOC contents and low HI values as usual for Jeanne d'Arc Basin wells. The section is then organic-lean until the Kings Cove Member, the upper part of the Jeanne d'Arc Formation, especially over 2815 to 2855 m. Here there are some samples with high TOC contents and HI values. The best two samples are 2815 m and 2825 m with TOC contents and HI values respectively of 6.10 and 4.46% and 654 and 631 mg HC/g TOC. However, these are associated with low Tmax values of 413 and 416°C. The 2822-2830.5 m interval was tested (DST 1) over the depth interval of these samples but was a misrun with only a trace of oil recovered. The low PI values and gas chromatograms for the high TOC samples seem to rule out that they have been affected by staining of heavy biodegraded oil which is one possibility to explain these data. There is a sample at the base of the well, 3085 m within the Rankin Formation, that also has a high TOC content of 2.55%, a very high HI of 740 mg HC/g TOC and a low Tmax of 421°C. While it is probable that these samples are contaminated, it is not conclusive and additional analyses are needed to determine if they are or if they really are potential source rock intervals.

Tmax does not show a good trend of increasing with depth in this well. There are low values indicating immaturity down to about the Petrel Member but after that Tmax is very erratic, probably because of the very low TOC contents in the Cretaceous section and the possible contamination in many Jurassic samples. The Fortune Bay interval appears to be an exception to this and shows Tmax values suggesting that it is early mature.

Mara M-54

No potential source rocks were indicated by Rock-Eval/TOC data for this well. The Tertiary section has high TOC contents but low HI values like elsewhere in the Jeanne d'Arc Basin. The rest of the penetrated section has mostly low TOC values. There are some high TOC contents within the Hebron Well Member such as at 3810 m and 3900 m which have TOC contents of 7.23% and 5.27% respectively but these are associated with very low HI values (40 and 35 mg HC/g TOC) despite being immature to early mature. Their Tmax values of 426 and 429°C appear to be in the range expected at this depth and do not appear anomalous. Deeper, in the B Hebron Well Member at 4290-4310 m, there are samples with TOC contents in the 1.51-3.99% range with somewhat higher HI values (162-231 mg HC/g TOC) but not high enough to indicate potential to generate significant volumes of hydrocarbons. The elevated TOC contents in these Hebron Well Member intervals may be due to thin coals.

There is a reasonable trend of increasing Tmax with increasing depth at Mara. The well is immature through most of the penetrated section, reaching early maturity towards the base of the well.

North Ben Nevis P-93

No potential source rock intervals are apparent from the Rock-Eval/TOC data in the section penetrated by this well. High TOC contents and low HI values for samples in Tertiary as seen elsewhere in Jeanne d'Arc Basin. The rest of the well is very organic-lean. This is due to the well reaching only the top of the Fortune Bay Shale and hence none of the Upper Jurassic source rocks were penetrated. The bottom two samples in the well have higher TOC contents and HI values but these are associated with very high OI values and low Tmax values and are obviously due to contamination.

It is difficult to detect stained intervals such as those tested in this well because of the high PI values from towards the top of the Nautilus Shale (~2430 m) downwards. This could be the result of oil-based drilling mud but there is no indication that this was used during the drilling of this well.

Tmax generally increase with increasing depth although somewhat erratically. There seems to be a negative correlation between PI and Tmax suggesting that drilling additives could be having some effect on Tmax. Hence caution should be used with looking at the maturity of individual samples. Looking at the overall trend in Tmax with depth, mid oil window (Tmax ~440°C) is reached around 3750 m and a Tmax of 450°C suggesting late oil window is reached around 4800 m.

Terra Nova H-99

As elsewhere in the Jeanne d'Arc Basin, there are samples with high TOC contents but with low HI values in the Tertiary. From the Tertiary until 2820 m, most samples have low TOC contents. There are some higher TOC contents (1.49-3.06%) in the Hebron Well Member over the 2630-2670 m interval. These samples have low HI values (125-203 mg HC/g TOC) and Tmax values that appear to be anomalously low. For example, the highest TOC sample from 2630 m has the lowest Tmax of 398°C. This is observed for samples in the Terra Nova K-17 and K-18 as well in the same part of the Hebron Well Member which would argue against this being contamination. A possibility is that these samples are from an interval that has coaly/carbonaceous sediments with resinous components to account for the lower Tmax values.

From 2820 m to total depth, almost every sample has a TOC content greater than 1%, usually associated with low HI values and high OI values. This may be associated with the use of X-Pel-G as a drilling additive from 2800 m and deeper. X-Pel-G is based on "pure Gilsonite Resin". Gilsonite is a natural bitumen from the Uinta Basin, Utah.

Rankin Formation samples from 3470-3510 m (t.d.) show different characteristics to the samples above them. They have high TOC and HI (>400 mg HC/g TOC) and much lower OI values. The sample from 3480 m appears to have obviously erroneous values as it has a TOC content of 64.71% and a HI of 707 mg HC/g TOC and a much higher Tmax of 440°C than surrounding samples which have Tmax values around 430°C. The other samples in this part of the well could indicate that there is a potential hydrocarbon source rock at the top of the Rankin Formation. This needs additional analyses to confirm.

The probable contamination makes it difficult to detect stained intervals such as those tested within the Jeanne d'Arc Formation between 3224-3234 m.

The Tmax shows a good trend of increasing with increasing depth down to the Nautilus Shale at ~1600 m. There is no real trend after this because of the low S2 values associated with low TOC

values and after 2800 m it is not certain whether the Tmax values reflect the contamination (i.e. gilsonite) or the maturity of the in situ organic matter. If the latter, then values of 428-434°C suggest the lower section of the well is early mature.

Terra Nova K-17

No potential source rocks were encountered in this well. As elsewhere in the Jeanne d'Arc Basin, there are high TOC contents in the Tertiary but with low HI values. There are high Production Indices in the Ben Nevis and Dawson Canyon formations corresponding to where there were production tests. There are some very high TOC contents within the Avalon Formation over the 1630-1700 m interval, including 10.27% for the 1650 m sample. However, these samples have low HI values despite being immature and very low Tmax values, such as 181 mg HC/g TOC and 398°C for the 1650 m sample. This suggests either some possible resinous coal intervals within the Avalon Formation or contamination. There are also organic-rich samples within the Hebron Well Member over the 2280-2380 m interval with the highest being 2340 m with 8.9% TOC. There is no significant hydrocarbon potential in this section as these samples have low HI values with the 2340 m sample having much the highest with 283 mg HC/g TOC. As similar organic-rich samples are found within the Hebron Well Member in other Terra Nova wells, this is probably not contamination. Lower down in the Hebron Well Member there are similar organic-rich samples with low HI values (e.g. 2500 and 2530 m) but these have anomalously low Tmax values. Once again these could be due to either coals or contamination.

In the lower part of the Fortune Bay Shale Formation and Jeanne d'Arc Formation (from ~2710 m to total depth), there are many samples with TOC contents in the 1-1.5% range, with some occasionally higher. These generally have low HI values indicating little hydrocarbon potential. Also samples with higher TOC contents have lower Tmax values. For example, the 3070 m sample which has the highest TOC content of 7.06% has a HI of 279 mg HC/g TOC and a Tmax of 411°C. This either reflects an unusual form of organic matter (e.g. a resinous coal) or contamination. The sample at 3200 m shows more conventional Rock-Eval attributes of an organic-rich sample with a TOC content of 2.7%, a HI of 481 mg HC/g TOC and a Tmax of 423°C. This perhaps represents an interval with some hydrocarbon potential in the upper Jeanne d'Arc Formation, although the Tmax is a little suppressed with regard to the overall trend in the well.

There is a reasonable trend of increasing Tmax with depth in this well. The top of the Jeanne d'Arc Formation has a Tmax of about 430°C suggesting it is early mature with respect to hydrocarbon generation.

Terra Nova K-18

As elsewhere in the Jeanne d'Arc Basin, there are high TOC contents in the Tertiary but with low HI values. Also in common with other Terra Nova wells, there are some higher TOC contents in the Hebron Well Member that are mostly associated with low HI values and low Tmax values with a general relationship of higher the HI, the lower the Tmax. For example, the 2785 m sample has a TOC content of 3.78%, a HI of 442 mg HC/g TOC and a Tmax of 382°C while the 2765 m sample has a TOC content of 6.48%, a HI of 155 mg HC/g TOC and a Tmax of 411°C.

There is a zone in the upper part of the Jeanne d'Arc Formation in this well with TOC contents greater than 1% but with generally low HI values and low Tmax values. The most organic rich of these is the

3175 m sample with a TOC content of 2.05%, a HI of 320 and a Tmax of 419°C (surrounding samples have Tmax of ~429°C). There is a minor interval with hydrocarbon potential in the lowermost Jeanne d'Arc Formation and uppermost Rankin Formation. Only the 3395 m sample stands out with a TOC content of 3.05%, a HI of 543 mg HC/g TOC and a Tmax of 430°C. The Egret Member source rock interval is present in this well and shows excellent hydrocarbon source potential. It is suggested to occur from 3635-3790 m from logs and from 3625-3805 m from Rock-Eval data. Almost all samples over this interval have TOC contents greater than 2%, ranging up to 4.84%. HI values range from 340 to 647 mg HC/g TOC indicating Type II oil-prone organic matter. Tmax values are in the 428-432°C range suggesting that the Egret Member is early mature in this well and has yet to generate a significant proportion of its potential.

Tmax shows a good trend of increasing with increasing depth in Terra Nova K-18 and suggests early maturity has been reached by the base of the well.

West Bonne Bay C-23

Samples with high TOC contents, low HI and high OI values, occur down to about 1990 m. The lower part of this interval corresponds to the upper part of the Nautilus Shale using the GSC tops but using the CNLOPB (2008) lithostratigraphic picks this would be the base of the Petrel Member and top of the Nautilus Shale. This latter lithostratigraphy would then agree with other Jeanne d'Arc Basin wells with a Tertiary-Late Cretaceous organic-rich interval with low hydrocarbon generating potential. From the top of the Nautilus Shale the well is organic-lean until the Jeanne d'Arc Formation. There are occasional samples with greater than 1% TOC within the Hibernia Formation but with no significant hydrocarbon potential. For example, the sample from 3450 m has a TOC content of 2.22% but a HI of only 185 despite being immature.

Most of the Jeanne d'Arc Formation shows somewhat elevated TOC contents in the 1-2% range with HI values in the 200-300 mg HC/g TOC range. There are a few samples with better potential, notably 4150 m and 4210 m which have TOC contents of 2.89 and 3.44% and HI values of 507 and 417 mg HC/g TOC. These samples have Tmax values of 436 and 437°C, respectively, suggesting that they are early mature. Near the base of the well in what would be the top of the Rankin Formation based on the CNLOPB (2008) lithostratigraphic picks there are three very organic-rich samples. These samples from 4390, 4400 and 4410 m have TOC contents of 10.14, 16.73 and 5.18% with HI values of 640, 690 and 574 mg HC/g TOC. Their Tmax values are what are expected for this depth of between 438 and 442°C. Hence there seems to be nothing to suggest that these results represent contamination except that the data suggests an interval with hydrocarbon potential better than seen almost anywhere else previously in the Jeanne d'Arc Basin. Dispersed lingo-sulphonate was used as an additive from 3865 m to total depth but would not be expected to have such high HI and Tmax values. Hence these three samples could represent the upper part of an excellent source rock interval at the bottom of this well but additional analyses are needed to confirm this.

There is no good trend of increasing Tmax with increasing depth in this well until the Upper Jurassic where there are higher TOC and S2 values. The Upper Jurassic is early mature with respect to hydrocarbon generation.

Brents Cove I-30

Samples with high TOC contents, relatively low HI and high OI values occur down to the base of the Petrel Member. Most of the rest of the penetrated section is organic-lean. From about 3220 m, at the top of the Fortune Bay Shale, TOC contents are mostly above 1% but rarely above 2%. These samples are associated with HI values in the 200-250 mg HC/g TOC range but high OI values and very low Tmax values, mostly in the 360-370°C range. The consistency of the Rock-Eval data for so many samples suggests background contamination, presumably from some type of drilling additive. An “enhanced polymer” was used with the drilling mud from 3287 m which corresponds to the zone that appears to be affected and may be the source of the contamination.

Some samples show Rock-Eval characteristics that suggest they are less contaminated. Samples from 3550 and 3560 m have TOC contents of 2.82 and 2.36%, HI values of 544 and 411 mg HC/g TOC, low OI values (<100 mg CO₂/g TOC) with Tmax values of 421 and 426°C, while those from 3780 and 3790 m have TOC contents of 2.32 and 2.37% and HI values of 429 and 454 mg HC/g TOC with both having a Tmax value of 428°C.

There is not a good trend of increasing Tmax values with depth for this well due to the low TOC and S₂ values or contamination. Samples with Tmax values that possibly represent the maturity of in situ organic matter within the Jeanne d’Arc Formation from ~3800 m to total depth are in the 428-430°C range suggesting early maturity.

South Nautilus H-09

There are immature samples with high TOC contents in the shallower section of this well, especially in the Banquereau Formation that have greater than 5% TOC but HI of less than 200 mg HC/g TOC. The rest of the well appears to be organic lean. There are many samples with TOC contents in the 1-1.5% range but these have HI values less than 250 mg HC/g TOC, high OI values and low Tmax values, mostly in the 350-370°C range, as well as elevated PI values (>0.2). This suggests these samples are contaminated by drilling mud. The section from the Petrel Member to the Whiterose Shale analyzed here is usually organic-lean in any case. No potential source rock intervals are present in this well.

East Rankin H-21

This well was drilled with Biovert oil-based drilling mud. Although this makes the data more difficult to interpret, it is still relatively easy to determine which intervals have source potential. Because of the Biovert, all the samples have high PI values. At the top of the well there are elevated TOC values down to the base of the Banquereau Formation, as observed elsewhere in the basin for the Tertiary/Late Cretaceous section. These are associated with low HI values and this immature interval has little hydrocarbon source potential. The rest of the well appears to be relatively organic-lean until the upper part of the Rankin Formation. From about 2000 m until the base of the well, most samples have TOC contents greater than 2%, ranging up to 5.73%. They also have high HI values which range up to 613 mg HC/g TOC and low OI values (generally less than 100 mg CO₂/g TOC). This suggests an excellent potential source rock in this interval and based on the similarity of this data with that for Rankin M-36 (Fowler and Snowdon, 1988) it appears that the Egret Member has possibly been penetrated, although it appears to be thicker at East Rankin. Tmax values are in the 408-420°C range indicating that this interval is immature.

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