Methodology to Estimate Thermal Maturity from Petrophysical Calculations of Gas/Oil Ratios

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Abstract

Thermal maturity is routinely calculated from analysis of vitrinite reflectance (Ro), and is important in the understanding of the type of hydrocarbons – oil vs gas – that will be produced. However, in areas where Ro has not been run, and where there are no producing wells, there is no current method of predicting thermal maturity from other available data.

There are direct relations between vitrinite reflectance and Gas/Oil Ratios (GOR). A prior publication of Holmes (SPWLA 1990), describes a petrophysical method of calculating GOR using density, neutron, and resistivity well log responses. Correlation of GOR with Ro has been defined by Dow (1977) and Jarvie et al (2015).

The basis for quantifying the degree of gas saturation from petrophysical analysis is the effect of gas on density and neutron log responses. Gas increases porosity on the density log, and reduces porosity on the neutron log (the so called "density/neutron cross-over effect"). Care must be taken to apply the correct lithology, since this must be known to calculate porosities from both logs. If available, descriptions from core or cuttings data should be examined. Also, responses of density, neutron, and Pe logs using a Matrix Identification Plot (comparison of apparent matrix density and Apparent Matrix Volumetric Cross Section) should be examined. Total hydrocarbon saturation is determined from a standard porosity vs Resistivity (Pickett) plot. By subtracting gas saturation, oil saturation is available, allowing for the calculation of gas/oil ratio.

In this publication, we have analyzed eight Niobrara wells from the Denver – Julesburg Basin, which have a large range of GOR as determined from production data. All wells have the requisite log suite to calculate GOR. We demonstrate good comparison between the two sets of GOR. We also have vitrinite reflectance data on all wells, provided by Grant Zimbrick of the Dolan Integration Group.

From the vitrinite reflectance data, values of GOR are shown to be significantly lower than actual GOR. This suggests that the hydrocarbons have migrated from levels of higher thermal maturity. For these wells, the most likely explanation is lateral migration from a fairly close "hot spot".

These findings are significant for a number of reasons. Thermal maturity can be estimated from petrophysically generated GOR, even if no Ro data are available. If Ro information does exist, comparisons can be made with petrophysically determined GOR, to analyze the likely provenance of the hydrocarbons. A knowledge of thermal maturity is required to calculate volumes of total organic carbon (TOC) from well logs. These calculations are equivalent to "organic porosity" which is a significant source of unconventional reservoir hydrocarbons.

Conclusions

- Estimates of petrophysically derived GOR for all eight wells examined agree quite well with measured GOR from production data

- From relations between GOR and thermal maturity (presented from Ro information –Dow, 1977; Jarvieet al 2015) it is shown that thermal maturity is also available from GOR estimates

- For all wells examined, Ro data was provided by Grant Zimbrick of the Dolan Integration Group

- Actual produced GOR ranges from 1,823 to 17,224 SCF/BO, suggesting that the source beds for the hydrocarbons are at a much higher level of maturity than the Ro data maturity level

- The most likely explanation as to source bed location is a nearby "hot-spot" to these wells

- These findings indicate that GOR data, either from produced hydrocarbons, or from petrophysical analysis, can be used to estimate thermal maturity, even if no Ro information is available

- For newly-drilled wells, the procedure allows estimates of the relative volume of oil and gas to be produced, before the well is completed.

- It is emphasized that this petrophysical estimates of GOR require an accurate knowledge of lithology and reservoir pressure

Acknowledgements

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Outline

- Objectives

- Data analyzed

- Relations among thermal maturity (LOM) and hydrocarbon generation

- Vitrinite reflectance (Ro) and organic porosity development from total organic carbon (TOC)

- Methodology to define reservoir volumes of oil and gas

- Methodology to calculate gas/oil ratios (GOR) from petrophysical analysis

Outline

- Results – Analysis of eight Niobrara wells from the Denver-Julesburg basin
  - #1 – Relative reservoir volumes of oil and gas
  - #2 – Relations among GOR, LOM, thermal maturity, hydrocarbon production, and gas/oil reservoir volumes
  - #3 – Petrophysical results, well #2 high GOR
  - #4 – Petrophysical results, well #6 low GOR
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  - #7 – Comparison of actual GOR and petrophysical estimates of GOR
- Conclusions
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Objectives

- For the eight wells analyzed, which have a wide range of gas/oil ratios (GOR), individual well levels of thermal maturity (LOM) are presented.

- Vitrinite reflectance (Ro) data, provided by Grant Zimbrick of the Dolan Integration Group, suggest much lower values of LOM

- Using LOM values from produced GOR data, depths to source beds are calculated

- Methodology is presented to determine relative reservoir volumes of oil and gas, using estimates of reservoir pressure

- Methodology of petrophysical calculations of GOR are presented, together with petrophysical GOR compared with GOR from Ro for two wells with different values of produced GOR

- Comparisons are presented for all eight wells, between actual produced GOR and petrophysically estimated GOR

Data analyzed

- The Niobrara interval from eight wells from the Denver-Julesburg Basin, north of Greely, Weld County, Colorado were analyzed

- All wells have triple-combo well logs, used to develop consistent and reliable petrophysical interpretations

- Detailed analysis of density and neutron logs were employed to calculate gas/oil ratios

- A previous publication (Holmes, et al 2021) includes interpretations used in this presentation

- All wells include rate/time production of oil, gas, and water by month

- The wells show a large range of produced gas/oil ratios (1823 SCF/BO to 17,224 SCF/BO) with only minor volumes of water

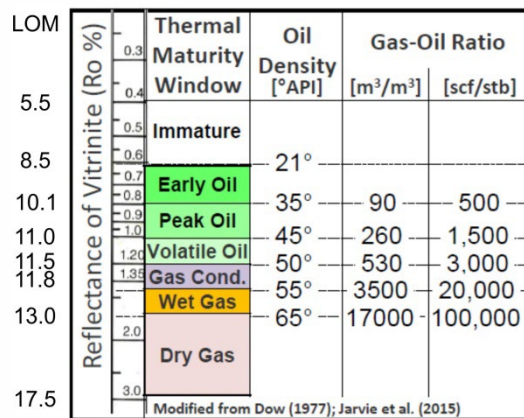# Relations among thermal maturity, hydrocarbon generation, and petrophysical analysis

- Thermal maturity is traditionally measured by vitrinite reflectance (Ro) and level or organic metamorphism (LOM). This presentation describes an alternative way to calculate thermal maturity in the absence of Ro information.
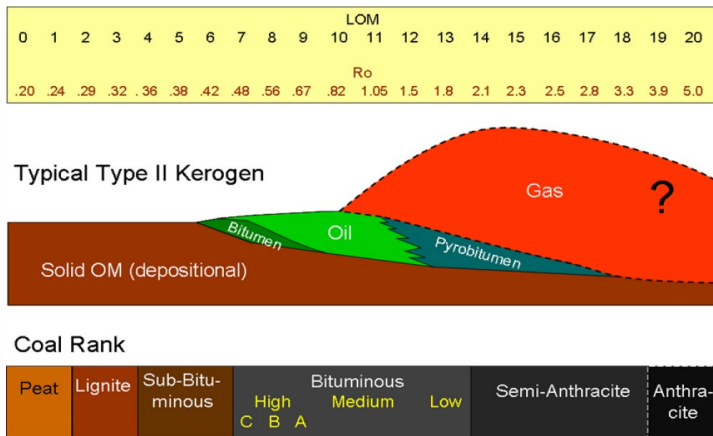
- Relations between Ro and LOM for Type II kerogen and coal rank (Passey et al, 2010).
- The classic publication of Passey (1990) describes the methodology to calculate total organic carbon (TOC) from logs. A required input is LOM.

Relations among thermal maturity, hydrocarbon generation, and petrophysical analysis

- Passey, et al (1990) describes a methodology to estimate total organic carbon (TOC) as related to LOM, from well logs (Delta Log R technique)


- Thermal maturity as it relates to hydrocarbon generation and gas/oil ratios is shown (Dow, 1977, Jarvie et al, 2015).

Vitrinite reflectance and organic porosity development

- Organic porosity is derived from total organic carbon (TOC), which is measured in weight percent

- Relations between Ro, TOC density and degree of porosity creation are shown below

- Kerogen density to vitrinite reflectance correlation (Alfred and Vernik, 2013)
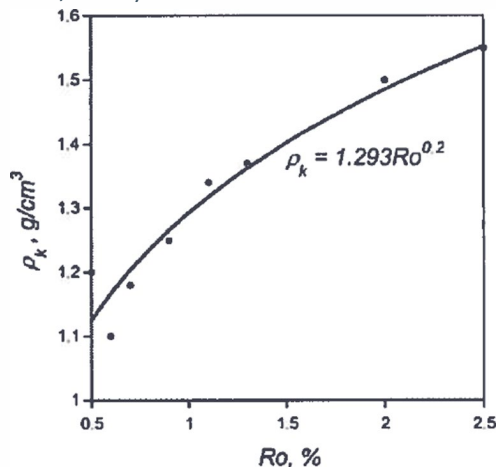
- Organic porosity development as thermal maturity increases in the Mowry (Modica and Lapierre, 2012 from Merkel, 2017)

$$\rho_k = 1.293 Ro^{0.2}$$
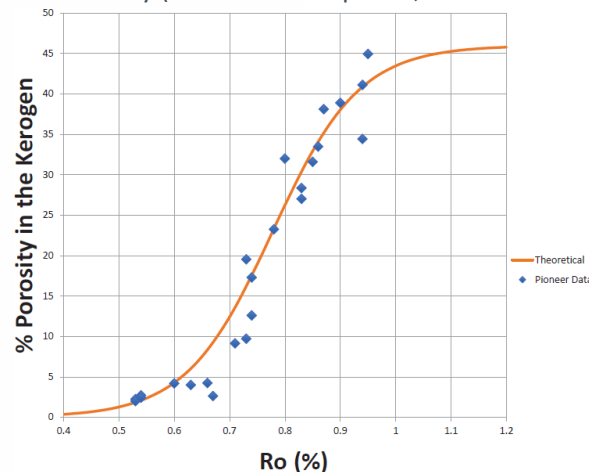
- This presentation does not discuss organic porosity. However, it is an essential component of unconventional reservoirs. The calculation requires values of thermal maturity, expressed in these publications as Ro.
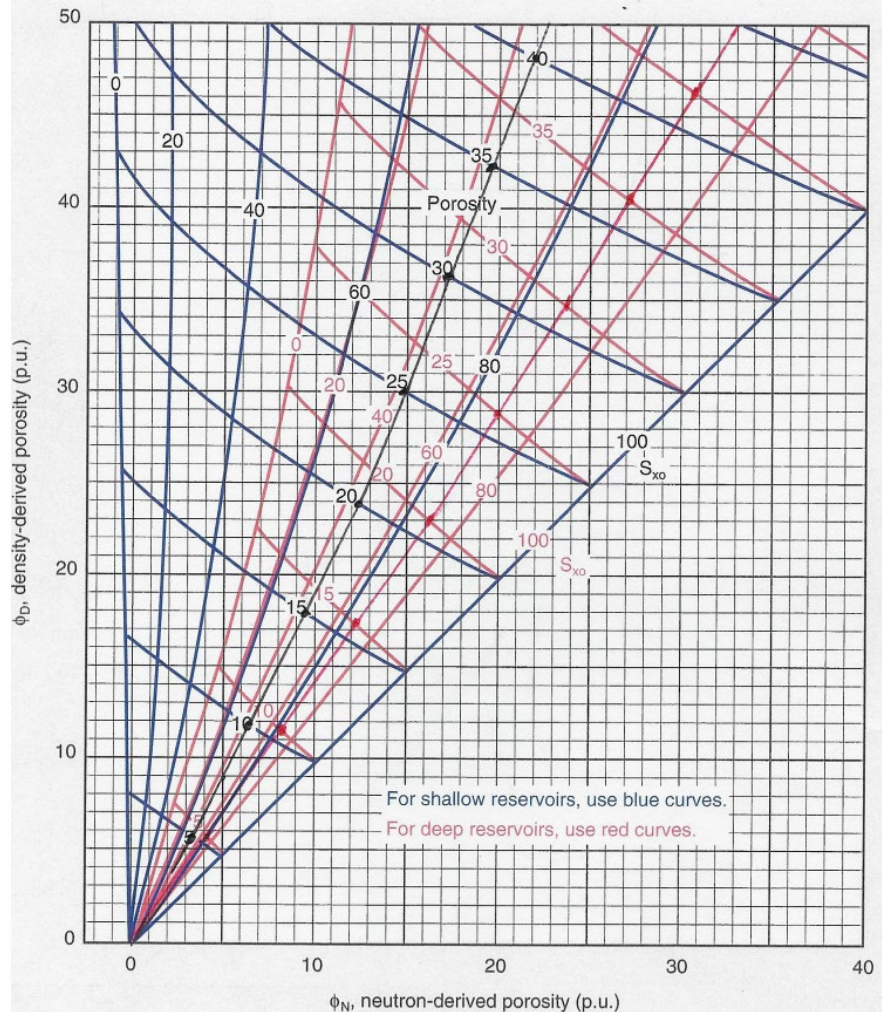
Methodology to Define Reservoir Volumes of Oil and Gas

- In order to combine oil and gas into their respective reservoir volumes, the following equations were applied:
  - Oil-Occupied reservoir void volume = Barrels Oil Produced / 7,756
  - Gas-Occupied reservoir void volume = SCF gas produced x Bg / 43,560
- For this study we used a gas formation volume factor (Bg) of 0.004 RCF/SCF
- These calculations are needed to calculate gas/oil ratios, using appropriate values of Bg, as determined from reservoir pressure

Methodology to calculate gas/oil ratios (GOR) from petrophysical analysis

In the presence of gas, the neutron porosity is reduced (gas lowers the hydrogen density) and density porosity is increased (fluid density is decreased)

To quantify the degree of gas saturation, cross plots of the density porosity vs. neutron porosity are used. The porosities need to be calibrated to the correct lithology (graph is from Schlumberger)

For shallow reservoirs, use blue curves.
For deep reservoirs, use red curves.

ϕ_D, density-derived porosity (p.u.)

ϕ_N, neutron-derived porosity (p.u.)

Methodology to calculate gas/oil ratios (GOR) from petrophysical analysis

A cross plot of measured bulk density (grain density 2.71) and neutron porosity (limestone units) provides a calculation of porosity, essentially without a need to determine gas saturation

The graph from Schlumberger, indicates that the gas correction vector is essentially the same as isoporosity vectors. However, an accurate knowledge of lithology is required.

From standard petrophysical analysis, hydrocarbon saturation is available. Oil saturation is calculated by subtracting gas saturation from hydrocarbon saturation

Details of calculation procedures were published by Holloway and Holmes (1990)

Liquid-filled holes ($\rho_f = 1.190$ g/cm^3; C$_f$ = 250 kppm)
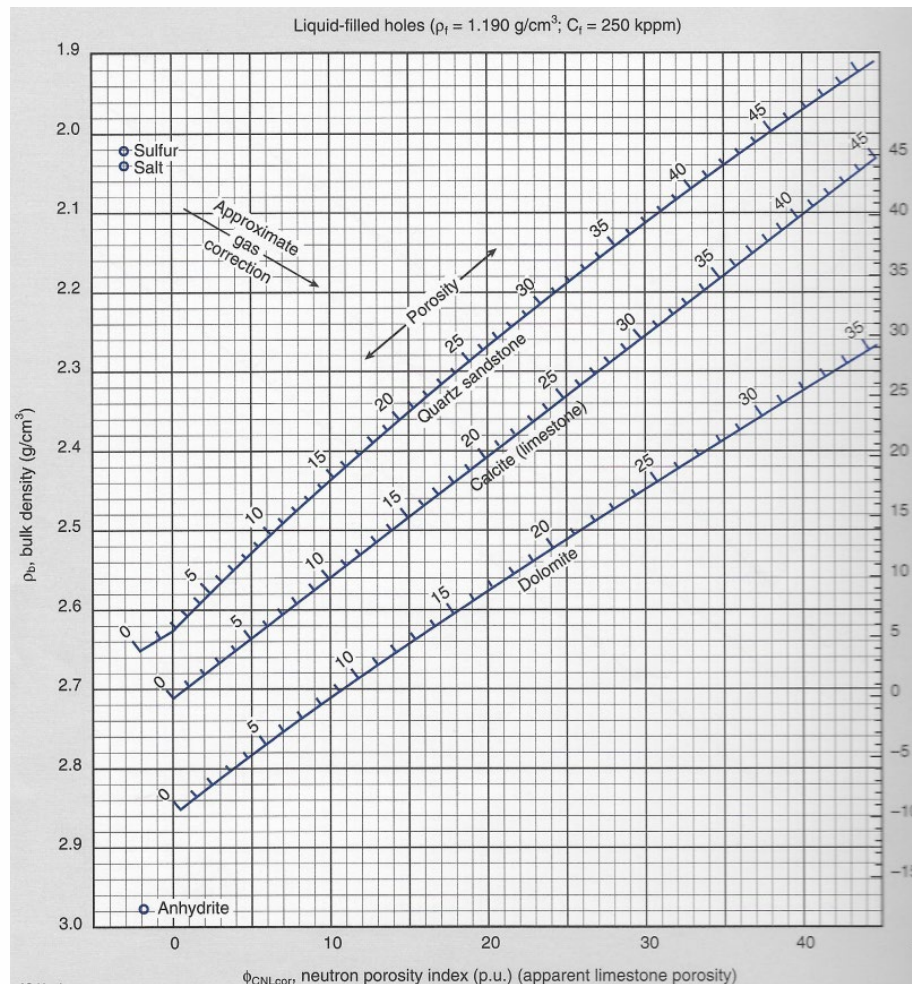
#1 Relative volumes of oil and gas

♦ For the eight wells we analyzed, all with varying degrees of gas/oil ratios (derived from cumulative volumes of produced oil and gas), we define the split in reservoir volume between oil and gas:

Well #	GOR (SCF/BO)	% oil volume	% gas volume
1	17,224	7.6	92.4
2	10,418	11.8	88.2
3	10,375	12.0	88.0
4	4,338	22.4	77.6
5	3,086	31.2	68.8
6	3,021	31.6	68.4
7	2,460	35.7	64.3
8	1,823	47.1	52.9

#2 Relations among GOR, LOM, thermal maturity, hydrocarbon production, and gas/oil reservoir volumes

♦ Relations for all 8 wells:
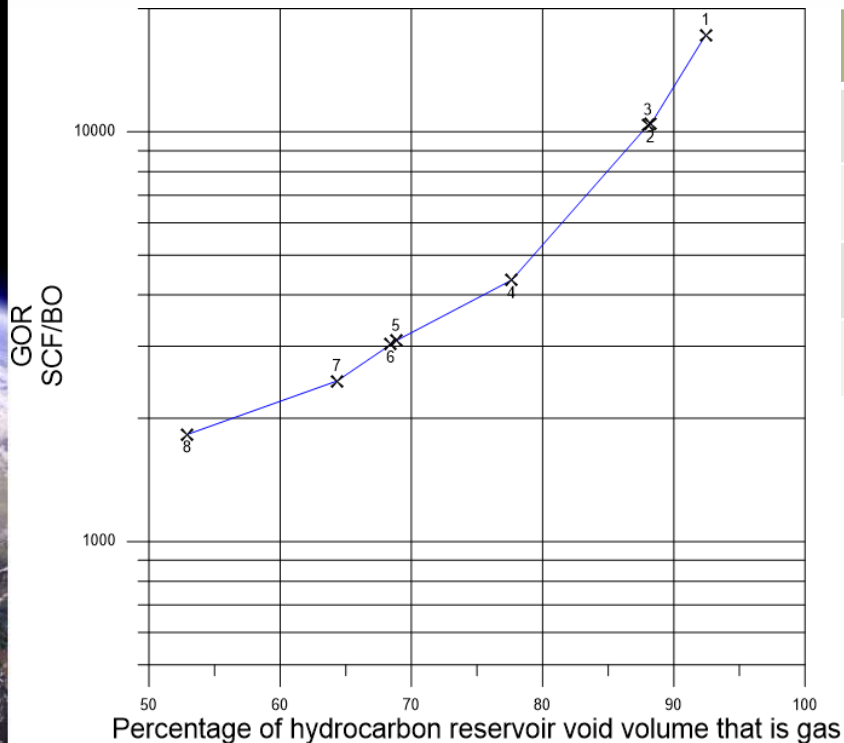
GOR Value	LOM	Hydrocarbon generated
20,000	12.0	Wet Gas
3,000	11.5	Gas Condensate
1,500	11.0	Volatile Oil
500	10.0	Peak Oil

Graph numbers refer to the eight wells

#3 Petrophysical analysis – Well #2, high GOR
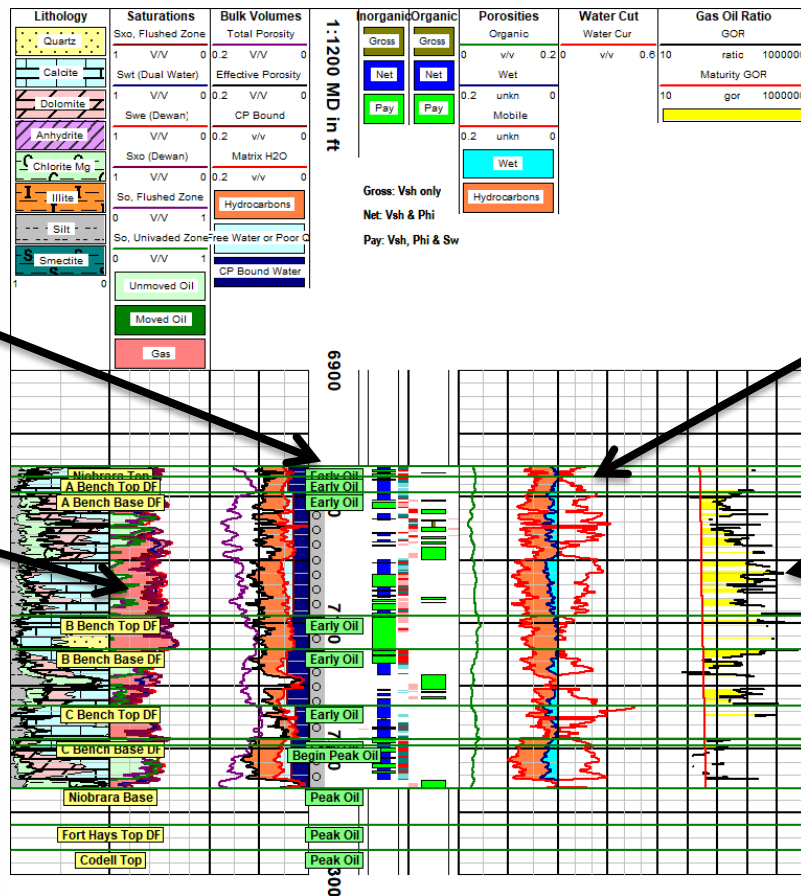
Production prediction from thermal maturity

High gas saturation

Low estimate of water cut

Calculated GOR much higher than maturity GOR

Well production:
Oil 5.953 MBO
Gas 62.022 MMCF
Water 1.655 MBW

GOR 10,418 SCF/BO

#4 Petrophysical analysis – Well #6, low GOR
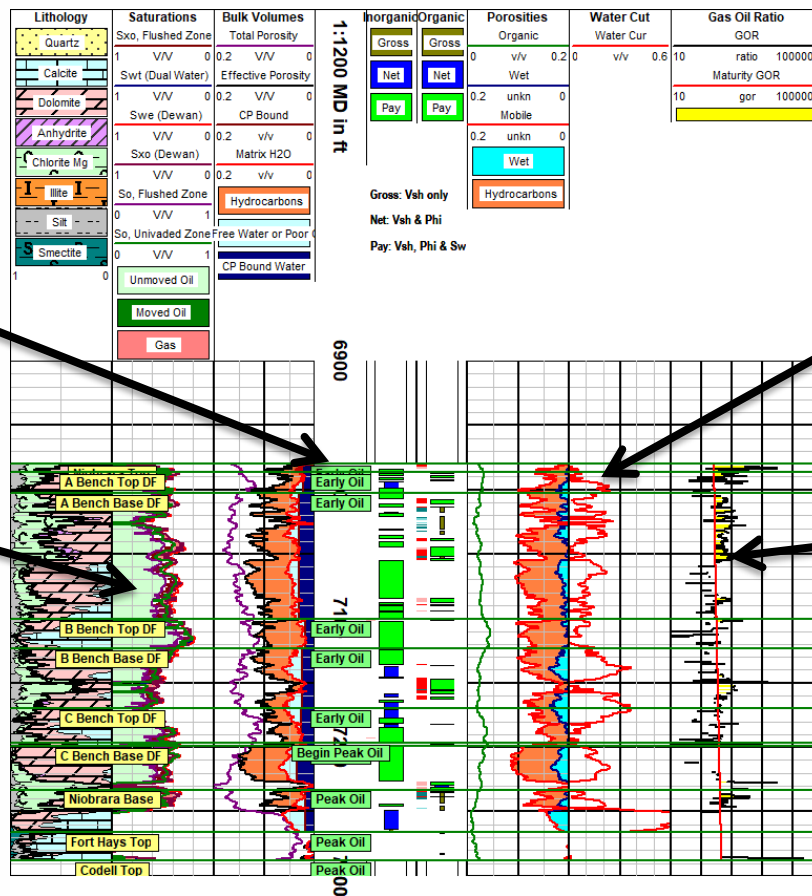
Production prediction from thermal maturity

Low estimate of water cut

Low gas saturation

Calculated GOR slightly higher than maturity GOR

Well production:
Oil   16.255 MBO
Gas   49.118 MMCF
Water   7.634 MBW

GOR   3,021 SCF/BO

#5 For all either wells, relations among Ro, LOM from Ro, GOR from Ro, actual GOR from production, and LOM from produced GOR

♦ All wells are at Ro maturity levels that suggest much lower GOR values than produced GOR, suggesting the hydrocarbon source is from formations of higher values of maturity

Well #	Actual GOR (SCF/Bo)	Niobrara LOM	Theoretical GOR (SCF/BO)	LOM from Produced GOR
1	17,224	10.0	<500	11.7
2	10,418	10.1	700	11.4
3	10,375	9.8	<500	11.4
4	4,388	10.0	<500	11.5
5	3,086	9.7	<500	11.4
6	3,021	9.8	<500	11.3
7	2,460	9.5	<500	11.2
8	1,823	9.3	<500	11.1

#6 Cross section of the eight wells showing drilled depths of the Niobrara and projected depth of the source beds

- An alternative source, and in this case a more reasonable interpretation of this, could be at the same stratigraphic level, since there are rapid changes to "hotspots" in this part of the basin

- The interpretation is based on LOM levels calculated from extending the trend of Ro-derived LOM downwards to honor LOM from produced GOR values

Cross section showing levels of LOM and GOR
GOR from maturity, SCF/BO
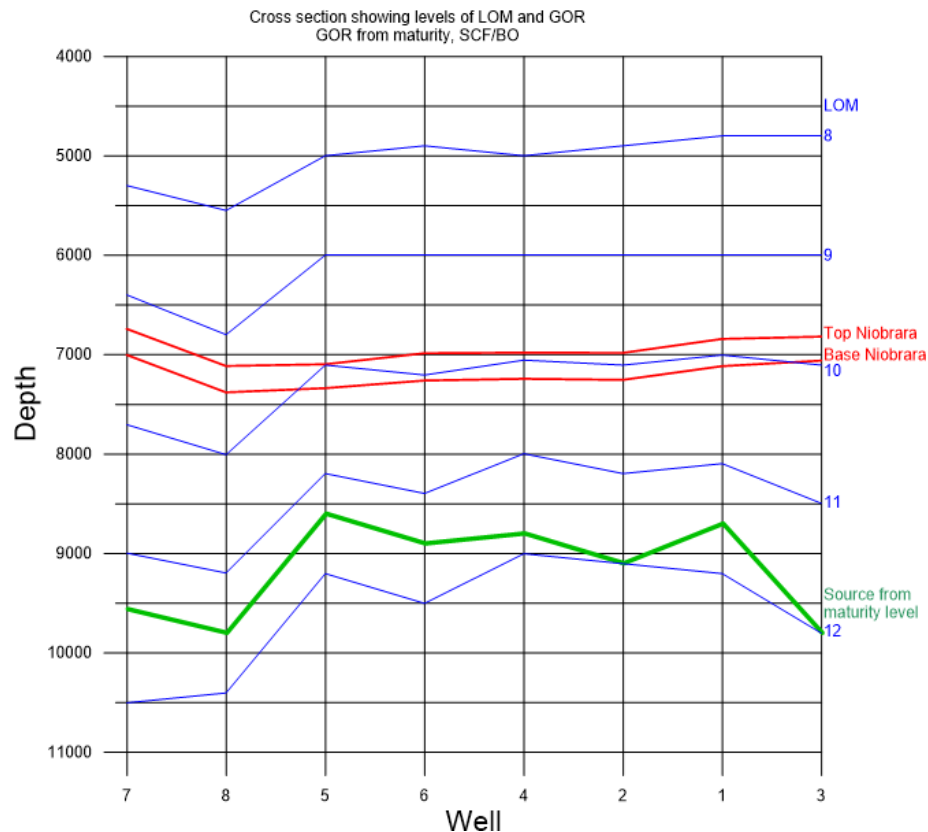
#7 Comparison of actual GOR and petrophysical estimates of GOR
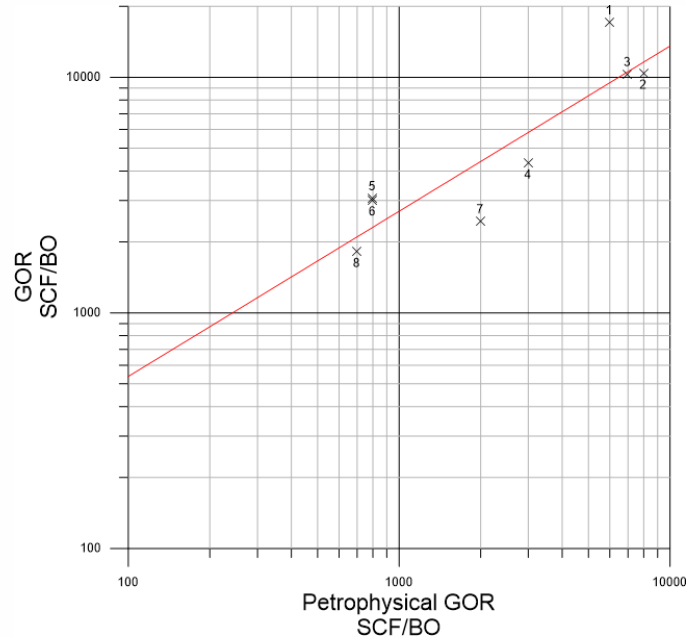
- For each well, GOR histograms of GOR were constructed for the Niobrara interval, and 50% cumulative values used

Conclusions

- Estimates of petrophysically derived GOR for all eight wells examined agree quite well with measured GOR from production data

- From relations between GOR and thermal maturity (presented from Ro information – Dow, 1977; Jarvie et al 2015) it is shown that thermal maturity is also available from GOR estimates

- For all wells examined, Ro data was provided by Grant Zimbrick of the Dolan Integration Group

- Actual produced GOR ranges from 1,823 to 17,224 SCF/BO, suggesting that the source beds for the hydrocarbons are at a much higher level of maturity than the Ro data maturity level

Conclusions

- The most likely explanation as to source bed location is a nearby "hot-spot" to these wells

- These findings indicate that GOR data, either from produced hydrocarbons, or from petrophysical analysis, can be used to estimate thermal maturity, even if no Ro information is available

- For newly-drilled wells, the procedure allows estimates of the relative volume of oil and gas to be produced, before the well is completed.

- It is emphasized that this petrophysical estimates of GOR require an accurate knowledge of lithology and reservoir pressure

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- Grant Zimbrick of Dolan Integration Group provided thermal maturity data from vitrinite reflectance

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