UNICORNS IN THE GARDEN OF GOOD AND EVIL:  
Part 9 – Tight Oil Reservoirs  


Unicorns are beautiful, mythical beasts, much sought after by us mere mortals. The same is true for petrophysical models for unconventional reservoirs. This is the ninth in a series of review articles outlining the simple beauty of some practical methods for log analysis of the unusual.

TIGHT OIL RESERVOIR BASICS

Most of us are familiar with tight gas reservoirs – clean, low-porosity sandstones or siltstones that look unattractive on log analysis, at least by the conventional wisdom of the 1960s. By the end of the 1970s, we had overcome these hang-ups and exploitation in tight sands developed rapidly, along with the fracturing technology needed to make them economic.

Further progress in drilling and fracturing of horizontal wells brought us to shale gas, although most such plays are not really shales, but low-porosity siltstones or laminated shaly sands. Many are radioactive due to uranium and look like shale on logs, hence the continued reference to “shale".

Siltstones are a mixture of quartz and other minerals, predominately dolomite and calcite, but many others may be present. They are characterized by low permeability, usually less than 1 millidarcy. When filled with gas, we think of these as “tight gas” reservoirs. A conventional complex lithology log analysis model is used, and such reservoirs are not considered “unconventional”.

When shale volume increases, these reservoirs become shaly silts or silty shales; they may have sufficient organic content to become a self-sourcing reservoir. Then we use the shale gas model described in an earlier article.

The same revolution is occurring in oil exploration. Tight oil or “shale oil” is the current hot topic. Again, most such plays are siltstones or mudstones without a lot of clay in the reservoir. Siltstones with oil are a different story; “tight oil” is considered to be an “unconventional” reservoir, requiring horizontal wells and massive hydraulic fracture jobs to perform economically. Some siltstones are sufficiently sandy to produce oil in vertical wells, usually after a decent stimulation.

Conventional shale-corrected complex lithology log analysis models are used, even in shaly silts. However, a total organic carbon (TOC) assessment might also be made over the nearby source rocks and the reservoir interval.

Many siltstones are radioactive because of uranium. It pays to run a spectral gamma ray log to distinguish between uranium and clay content.

The Bakken Formation in the Williston Basin of Saskatchewan, Manitoba, and North Dakota is a classic silt and sandy silt. It is low resistivity due to high-salinity formation water with high irreducible water saturation (caused by very fine-grain size), and the lithology is a mix of quartz and dolomite (and sometimes calcite).

In Alberta and Montana, the Bakken equivalent, the Exshaw, and adjacent formations (Banff / Lodgepole and Big Valley / Three Forks) are “Tight Oil” prospects, as are the Duvernay, Second White Specks, Nordegg, and other formerly unattractive low-porosity reservoirs. In Saskatchewan, the naturally low resistivity in Bakken pay zones is further aggravated by thin clay laminations, clay-filled burrows, laminated porosity, and dispersed pyrite (Figures 1, 2).

Even more confusing is the water resistivity variation on the northwest and northeast edges of the Basin. Here, wet wells have higher resistivity than oil wells further south because the water resistivity is 5 to 20 times higher than deeper in the Basin. This results from fresher water recharge from the Black Hills of North Dakota. An adequate production testing program is the only solution to this issue, as there is no log analysis model that will predict water resistivity in this reservoir.

Water salinity in the deeper North Dakota wells reaches 325,000 ppm, making for exceedingly low water resistivity. In Saskatchewan, salinity is usually at 200,000 ppm or more, but can be as low as 25,000 ppm in the recharge area. Pore geometry in the deeper parts of the basin is more intergranular in texture and irreducible water saturation is lower than in Saskatchewan.

Typical Sw in Saskatchewan averages 50%, grading southward to about 30% in the deeper North Dakota wells. Very low apparent Sw in Saskatchewan usually means fresh water recharge, possibly with some residual oil. The “best-looking” wells are actually water producers, but have measured resistivity values 2 to 4 times higher than productive oil wells. Water resistivity values are sparse, so any water recovery should be sent to the lab and analyzed.

The low resistivity, high radioactivity, large density-neutron separation caused by dolomite and pyrite, and the high PE value (near 3) conspire to make the zone look like shale on logs. Worse, some literature
continues to name the producing zone the Bakken Shale, even though we know the middle Bakken is a radioactive dolomitic sand or siltstone. These conflicts in the conventional data suggest strongly that some special core analysis should be done – namely electrical properties, capillary pressure, X-ray diffraction, thin-section mineralogy, and anything else that can help explain the petrophysical response to these complex rocks.

The Bakken is now the biggest oil play in north America, and may ultimately be the largest ever found, even larger than the Alaska North Slope. It is sometimes termed an “unconventional” reservoir, due to the low permeability of the siltstone intervals. In North Dakota, it is also called a “resource” play because the oil was formed in place (from the Upper and Lower Bakken Shales). In Saskatchewan, the oil migrated from the deeper parts of the basin, and is not, strictly speaking, a resource play there. Alberta and Montana is also probably a resource play, but few facts have been published to date, so it is hard to tell.

Vertical wells are not overly prolific due to the low intrinsic permeability of the silty sand, but most horizontal wells perform reasonably well. In the deep, hot, over-pressured region in North Dakota, some wells are flowing 1,000 to 2,000 barrels of oil per day.

BAKKEN GEOLOGY

Oil in the Bakken in southeastern Saskatchewan has migrated from mature Bakken source rocks in North Dakota and Montana. The best reservoir is associated with the Upper Middle Bakken Sandstone Facies (BF4). Average porosity ranges from 14% to 16% and permeabilities are 20 to 80 millidarcies. The unconventional siltstone reservoir (BF2) averages 9% to 12% porosity and 0.01 to 1.0 millidarcies. In the deeper North Dakota wells, porosity is somewhat lower but permeability may be higher. All facies types have been exploited in different parts of the Basin.

These facies were deposited during the late Devonian and early Mississippian in what was then a tropical setting. The sediment is believed to have an aeolian source and was blown into the marine environment from the adjacent arid landmass to the east and reworked into the various marine facies. The organic-rich Upper and Lower Bakken shales are the source rocks for the sand and silt reservoirs.

The sands and silts are highly dolomitic, averaging about 50% dolomite. In deeper wells, calcite may replace some of the dolomite or infill some porosity.

Many of the dominant features of the Bakken are below the resolution of logging tools and are best seen in core photos and core logs, as shown in Figure 3.

BAKKEN CALCULATION MODEL

The Bakken is radioactive due mainly to uranium that migrated with the oil. This can be identified with a spectral gamma ray log and it should always be run when penetrating radioactive sands. Sadly, it is often not requested, even though the service is cheap and costs no extra rig time.

The thorium curve is best for shale volume calculations. The SP is flat and useless. Density-neutron separation is mostly due to dolomite, so it cannot be used. The gamma ray can be used in the absence of the Thorium curve by assuming uranium content is constant.

\[
1: V_{SHh} = (TH - TH0) / (TH100 - TH0)
2: V_{SHgr} = (GR - GR0) / (GR100 - GR0)
\]

The clean lines TH0 and GR0 are easy to pick (red and black lines in Figure 4). Shale lines are harder as they are often off-scale to the right or buried under a plethora of backup curves. In the absence of a good pick from the log, use:

\[
3: TH100 = TH0 + 25
4: GR100 = GR0 + 150
\]

Adjust the constants to suit your local knowledge.

POROSITY CALCULATIONS

Even though the Bakken is a complex mixture of quartz, dolomite, calcite,
and sometimes pyrite, with a little clay, the standard density-neutron complex lithology crossplot model works well:

5: PHIdc = PHID – (Vsh * PHIDSH)
6: PHInc = PHIN – (Vsh * PHINSH)
7: PHIe = (PHInc + PHIdc) / 2

For porosity values greater than 0.05 fractional, this is an adequate representation of the crossplot; some software packages will use more complicated math to fuss with that third decimal place.

Equation 7 is equivalent to Crain’s Rule #1: “Porosity is halfway between the density and neutron curves in clean zones” regardless of mineralogy, provided logs are on compatible porosity scales.

WATER SATURATION CALCULATIONS
Since there is little clay, the Archie model can be used, although it costs nothing extra to use a shale-corrected saturation equation such as Simandoux or Dual Water. Electrical properties variations between facies and with depth or diagenesis are not published. This lab work is worth the effort, as considerable increases in oil-in-place are possible with small reductions in M and N values. Fresh water recharge in the north can confuse log analysis results, so a production test is essential before drilling any horizontal wells.

PERMEABILITY CALCULATIONS
No strong correlation between porosity and permeability has been seen. Figures 5 and 6 show the scatter is large. The Wyllie

Figure 5. Permeability versus porosity scatter plots for a North Dakota well. The scatter suggests microfractures.

Figure 6. Permeability versus porosity scatter plots for a Saskatchewan well. The scatter suggests microfractures.

ROCK SHOP

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See some of my photos featured on the Rocks! Across Canada DVD from the CSPG.

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Rose equation gives rational values and can be tuned to fit smoothed core data:

8: \[ k_{\text{max}} = 100,000 \times (\Phi_{e}^6) / (SW_{ir}^2) \]

LITHOLOGY CALCULATIONS
How do we know which minerals to use in the petrophysical log analysis? Detailed sample descriptions are a good start (Figure 7). Both X-ray diffraction data and thin-section point counts can be used. Both methods are considered semi-quantitative and come from tiny samples compared to the volume measured by logs. As a result, we don’t get too excited about obtaining a close numerical match.

Standard three-mineral models using PE, density, and neutron data are used with appropriate parameters for the selected minerals. Multi-mineral solvers can be used if spectral gamma ray data is available. In this case, shale volume would be derived also.

PYRITE CORRECTIONS
Pyrite is a conductive metallic mineral that may occur in many different sedimentary rocks. It can reduce measured resistivity, thus increasing apparent water saturation. The conductive metallic current path is in parallel with the ionic water conductive path. As a result, a correction to the measured resistivity can be made by solving the parallel resistivity circuit. Although the math is simple, the parameters needed are not well known. The two critical elements are the volume of pyrite and the effective resistivity of pyrite. Pyrite volume can be found from a two- or three-mineral model, calibrated by thin-section point counts or X-ray diffraction data.

The resistivity of pyrite varies with the frequency of the logging tool measurement system. Laterologs measure resistivity at less than 100 Hz, induction logs at 20 KHz, and LWD tools at 2 MHz. Higher-frequency tools record lower resistivity than low-frequency tools for the same concentration of pyrite. The variation in resistivity is caused by the fact that pyrite is a semiconductor, not a metallic conductor. It is nature’s original transistor, and formed the main sensing component in early radios.

Typical resistivity of pyrite is in the range of 0.1 to 1.0 ohm-m; 0.5 ohm-m seems to work reasonably well. The effect of pyrite is most noticeable when Rw is moderately high and less noticeable when Rw is very low.

The math is easiest when conductivity is used instead of resistivity:

10: \[ \text{COND}_{\text{pyr}} = 1000 / \text{RES}_{\text{pyr}} \]
11: \[ \text{COND}_{\text{corr}} = 1000 / \text{RES}_{\text{d}} - \text{COND}_{\text{pyr}} \times V_{\text{pyr}} \]
12: \[ \text{RES}_{\text{dcorr}} = 1000 / \text{COND}_{\text{corr}} \]

The corrected resistivity can be plotted versus depth, along with the original log. Corrected water saturation will always be lower or equal to the original Sw. If \( \text{COND}_{\text{corr}} \) goes negative, lower \( V_{\text{pyr}} \) or raise \( \text{RES}_{\text{pyr}} \).

Figures 8, 9, and 10 are Bakken Log Examples.

(Continued on page 16...)

Figure 7. Mineral and core analysis summary for a Bakken reservoir.

(...Continued from page 13)
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ABOUT THE AUTHOR
E. R. (Ross) Crain, P.Eng. is a Consulting Petrophysicist and a Professional Engineer with over 45 years of experience in reservoir description, petrophysical analysis, and management. He has been a specialist in the integration of well log analysis and petrophysics with geophysical, geological, engineering, and simulation phases of oil and gas exploration and exploitation, with widespread Canadian and Overseas experience.

His textbook, “Crain’s Petrophysical Handbook on CD-ROM” is widely used as a reference to practical log analysis. Mr. Crain is an Honourary Member and Past President of the Canadian Well Logging Society (CWLS), a Member of Society of Petrophysicists and Well Log Analysts (SPWLA), and a Registered Professional Engineer with Alberta Professional Engineers, Geologists and Geophysicists (APEGGA).

Figure 8 Density–neutron logs on low resistivity, radioactive, dolomitic Bakken sand. Note high apparent porosity (almost coal values) in upper and lower shales. Density–neutron separation and PE show a 50-50 mix of quartz and dolomite with a few percent pyrite. XRD and sample descriptions confirm this analysis.

Figure 9. The answer plot illustrates the mineral mix and the match to core porosity and permeability that was achieved. The curves in the correlation track are, from left to right, uranium, potassium, thorium, total gamma ray.
Figure 10. Here is a different well with the pyrite correction applied to the resistivity log. The before and after versions of the resistivity are shown in Track 2, along with the pyrite fraction determined from a 3-mineral model using PE-density-neutron logs. The correction raises the resistivity about 0.5 ohm-m and reduces water saturation by about 10%. Making the pyrite more conductive would raise RESD further, but as yet no one has provided any public capillary pressure data in this area to calibrate Sw. The Swir from an NMR log would also help calibrate this problem.