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 sixth in a series of review articles outlining the simple beauty of some practical methods for log analysis of the unusual.

**TAR SAND BASICS**

Tar sands (oil sands, bitumen sands) are mined or depleted by steam-assisted gravity drainage (SAGD) or in-situ fire floods. In all situations, an adequate reservoir description is needed to assess the economics and progress of any project. A conventional shaly sand analysis using complex lithology porosity models is the foundation for the work. A shaly sand water saturation equation, such as the Simandoux model, is also needed.

The best tar sands are clean, medium- to coarse-grained, unconsolidated sands. However, they may be interbedded with finer, siltier, and shalier sands or bounded by lower quality reservoir rock. The log analysis needs to describe these variations, especially laterally continuous barriers to vertical flow of steam and oil movement.

The fluid column can be more complicated than conventional reservoirs. Here are some possibilities:

1. bitumen with or without bottom water,
2. top water over bitumen with or without bottom water.

SAGD, fire floods, or solvent floods. Gas is usually less of an issue because there is less likelihood of biogenic gas generation, but gas caps may exist in some plays.

**TAR SAND MATH**

Tar assay data from core analysis is often presented in terms of mass (weight) fraction (or percent) and sometimes also as volumes. Log analysis results are usually in volume fractions. Comparison between log and core results needs some extra math compared to conventional oil and gas evaluations. Further, net pay is often determined by a tar mass fraction cutoff instead of porosity and water saturation.

**GAS EFFECT**

First let’s look at the gas problem. If there is no gas crossover, you can skip this section. The conventional equation for porosity in a gas sand is:

\[ \phi_e = \left( \frac{\phi_i + \phi_d}{2} \right)^{1/2} \]

This equation is accurate enough for most gas zones, but in very shallow gas sands, it will underestimate porosity. The above equation must be replaced by:

\[ \phi_e = \left( \frac{\phi_i \times X + \phi_d \times X}{2} \right)^{1/2} \]

Where:

- \(X\) is in the range of 2.0 to 4.0, default = 3.0 for very shallow gas, 2.0 for conventional gas.

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PHIdc and PHInc are shale-corrected values of density and neutron porosity respectively.

The exponent X is adjusted by trial and error until a good match to core porosity is obtained.

**PARTITIONING GAS AND TAR VOLUMES**

After shale volume and porosity have been calculated, water resistivity can be found in a bottom water zone below the tar, as these rarely has any residual tar. Rw may vary somewhat in the tar sand interval and this can be adjusted if necessary by comparing calculated tar mass with core tar mass in non-gassy, relatively shale-free, intervals. Water saturation is then calculated from a shale-corrected model such as Simandoux.

Many, but not all, gas zones related to tar sands have some residual tar. Hydrocarbon saturation is partitioned between bitumen and gas by the following method:

3. \[ V_{wtr} = \Phi_h \times S_w \]
4. \[ V_{hyd} = \Phi_h \times (1 - S_w) \]
5. \[ \text{GasTarRatio} = \max(0, \min((1 - \text{TARmin}), (\text{PHIDc} - \text{PHINc}) / \text{MAX}_\text{OVER})) \]
6. \[ V_{gas} = \text{GasTarRatio} \times V_{hyd} \]
7. \[ V_{tar} = (1 - \text{GasTarRatio}) \times V_{hyd} \]

Where:
- TARmin = minimum tar volume in gas zone as seen on core analysis (could be zero).
- MAX_xOVER = maximum density neutron crossover in a gas zone (fractional).

**TAR MASS FROM LOGS**

Tar weight is calculated from log analysis as follows:

8. \[ W_{Ttar} = B_{Ttar} \times DENSHY \]
9. \[ W_{Tshl} = V_{sh} \times DENS\text{SSH} \]
10. \[ W_{Tsnd} = (1 - V_{sh} - \Phi_h) \times DENSMA \]
11. \[ W_{Twtr} = B_{Wwtr} \times DENS\text{W} \]
12. \[ W_{Trock} = W_{Ttar} + W_{Tshl} + W_{Tsnd} + W_{Twtr} \]

**TAR MASS FRACTION**

13. \[ W_{tar} = W_{Ttar} / W_{Trock} \]
14. \[ WT\%_{tar} = 100 \times W_{tar} \]

Where:
- TARmin = minimum tar volume in gas zone as seen on core analysis, could be zero.
- MAX_xOVER = maximum density neutron crossover in a gas zone (fractional).
- V_xxxx = volume fraction of a component.

WTxxx = weight of a component (grams or Kg).
W_xxxx = mass fraction of a component.
WT\%xxx = weight percent of a component.

Typical densities are DENSMA = 2,650, DENS\text{W} = DENS\text{HY} = 1,000, DENS\text{SSH} = 2,300 kg/m³.

This is the only way to rigorously calculate Tar Mass. Other equations have been used, such as the one shown below, but are less accurate, since shale volume is not explicitly enumerated:

99. \[ \text{TARmassfrac} = ((1.0 - S_w) \times \Phi_h \times DENS\text{tar}) / (DENS\text{rna} \times (1.0 - \Phi_h)) \]

In equation 99, DENS\text{rna} is a computed result from the log analysis, and is usually wrong when gas is present. It hides the shale correction term and individual rock and fluid parameters cannot be adjusted. I strongly recommend that this "simplified" version be avoided.

It should be noted that core data is usually derived from a summation of fluids process, such as Dean-Stark method, so the porosity from core matches total porosity better...
than effective porosity. The same goes for water saturation. That’s why we use tar mass and not porosity and saturation to calibrate log analysis to core data. Tar mass from log analysis is plotted along with tar mass calculated from core analysis data, on the depth plots to show the match between log analysis and core data results. The match between log analysis tar mass, porosity, and saturation with corresponding core data is usually excellent except in the very shaly, non-pay intervals, mostly because the core data provided ignores shale and its effect on net grain density. The match in zones with high gas saturation varies in quality due to the inherent inaccuracy in the gas/tar partitioning calculation on the log analysis.

DEAN-STARK CORE ANALYSIS METHOD
This method is used in poorly consolidated rocks such as tar sands and involves disaggregating the samples and weighing their constituent components. Samples are usually frozen or wrapped in plastic to preserve the contents during transport. In the lab, the still-frozen cores are slabbed for photography and description; samples are then selected and weighed. Samples are then heated and crumbled to drive off water, and weighed again. The weight loss gives the water weight. Solvents are used to remove oil or tar. The sample is weighed again and the weight loss is the weight of oil. The matrix rock is separated into clay and mineral components by flotation, dried and weighed again, giving the weight of clay and weight of the mineral grains.

15. \( W_{\text{Twtr}} = W_{\text{Tsamp}} - W_{\text{Theated}} \)
16. \( W_{\text{Tar}} = W_{\text{Theated}} - W_{\text{Minerals\&clay}} \)

By dividing each weight by its respective density and adjusting each result for the total weight of the sample, the volume fraction of each is obtained.

17. \( V_{\text{OLwtr}} = W_{\text{Twtr}} / D_{\text{ENSwtr}} \)
18. \( V_{\text{OLtar}} = W_{\text{Tar}} / D_{\text{ENStar}} \)
19. \( \Phi_{\text{core}} = V_{\text{OLwtr}} + V_{\text{OLtar}} \)

Assuming clay-bound water is driven off by heating and drying, then \( \Phi_{\text{core}} \) equals total porosity. From comparison to log analysis results, it appears that some clay-bound water remains in many cases, so \( \Phi_{\text{core}} \) lies between total and effective porosity from log analysis.

TAR MASS FROM CORE LISTINGS
If not provided on the core listing, the equivalent value of tar mass from core analysis is derived from porosity, oil saturation, and an assumed oil density:

20. \( W_{\text{Tar}} = \Phi_{\text{core}} \times S_{\text{tar}} \times D_{\text{ENStar}} \)
21. \( W_{\text{Wtr}} = \Phi_{\text{core}} \times S_{\text{wtr}} \times D_{\text{ENSwtr}} \)
22. \( W_{\text{Rock}} = \left(1 - \Phi_{\text{core}}\right) \times G_{\text{R\_DENScore}} \)

Where:
\( S_{\text{tar}} = \) tar volume relative to pore volume.

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Swtr = water volume relative to pore volume.

PHIcore = volume of water + volume of tar.

Wtar = tar mass fraction.

WTwtr = water mass fraction.

WTrockcore = rock mass fraction.

Since GR_DENScore represents a mixture of quartz and shale, this value should vary with shale volume. However, shale volume is never reported on core analysis, so the composite grain density from the rock sample is used. If grain density is not recorded in the core analysis, we must assume a constant of 2,650 Kg/m3 or lower.

**FLUID VOLUMES FROM CORE LISTINGS**

If not provided on the core listing, the equivalent value of tar volumes from core analysis are derived from porosity, tar mass fraction, and an assumed oil density:

23. Star = Wtar / (PHIcore * DENSwtr)

Or:

25. Swtr = 1.00 - Star

Where:

Star = tar volume relative to pore volume.

Swtr = water volume relative to pore volume.

PHIcore = volume of water + volume of tar.

Wtar = tar mass fraction.

WTwtr = water mass fraction.

**PERMEABILITY**

Permeability is calculated from the following equation, based on data from the core analyses.

26. Perm = 10 ^ (HPERM * PHIe – JPERM)

Vertical permeability is especially important in SAGD operations, and similar equations can be developed by plotting core porosity against vertical permeability. Both horizontal and vertical perm can be generated from log analysis porosity and plotted versus depth. An alternate approach is to do a regression of Kv versus Kh.

**TAR CUTOFFS and PAY FLAG**

A bitumen pay flag is calculated with a log analysis tar mass cutoff, usually between 0.050 and 0.085 tar mass fraction. A gas flag should also be shown on the depth plots where density neutron crossover occurs on the shale corrected log data.

**TAR IN PLACE**

Tar in place is calculated from:

27. TAR = SUM (Wtar * DENSHy * THICK) * AREA

Where:

AREA = reservoir area (m2).

THICK = rock thickness (meters).

TAR = tar in place (tonnes).

Wtar = tar mass fraction (fractional).

DENSHy = density of bitumen (g/cc).

If the oil equivalent in barrels or cubic meters is needed, the standard equation can be used:

28. OOIP = KV3 * SUM(PHIe * Star * THICK) * AREA / Bo
Where:
KV3 = 7,758 bbl for English units.
KV3 = 1.0 m³ for Metric units.
AREA = spacing unit or pool area (acres or square meters).
OOIP = oil in place as bitumen (bbl or m³).

Recovery factor for surface mining operations is very high, maybe 0.98 or better. For SAGD, RF = 0.35 to 0.50 are used. Since we can’t keep the steam away from the shaly sands, recovery will vary with the average rock quality in a SAGD project. Since water has a very high latent heat, the volume of water to be steamed is as important to the economics as the volume of bitumen. High water saturation is bad news here, just as in conventional oil.

### 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 a 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).

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<th>PHI</th>
<th>Star</th>
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<th>Vol Tar</th>
<th>Vol Wtr</th>
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Table 2. If tar mass fraction and water mass fraction are known, as well as core porosity (blue shading), all other terms can be calculated. Some core analysis reports do the math for you, some do not.