Case Studies of Recognizing Bypassed and Unconventional Pay From Wireline Logs, Quality Control of Processed Logs

- NMR Petrophysics, Inc.
  ShaleBase
This course presents several case studies of unconventional or bypassed pay in shale, clastics, and carbonates. The examples will be reviewed by class attendees in teams and discussed with the class in a workshop format designed to encourage discussion and learning. The goals of the course are:

- To improve skills in recognizing unusual log signatures that can indicate an unconventional or bypassed resource.
- To improve skills in quality-control of standard logs and processed logs.
- To recognize situations where additional logs, core or other information might be needed for proper formation evaluation.
- Provide a primer on log response in shale oil and gas

Brian Stambaugh
NMR Petrophysics, Inc.
18871 Dillinger Rd.
Newell, SD 57760
281-468-7755
brian@nmrpetrophysics.com
www.nmrpetrophysics.com
www.shalebase.com
Quick Log Calcs !!!

Step 1: Take a look at the logs and determine which porosity log to use. Generally this is DPHI, unless there is gas crossover, then use the crossplot or median value of NPHI and DPHI. For organic shales porosity can be a real problem to determine! (Generally need core for reference in this case.) More on that later.

Step 2: Determine if you are looking at a sand or carbonate. If DPHI and NPHI logs are on the correct matrix – great!

Step 3: If looking at a sand and DPHI is lime subtract 2 to 3 pu from DPHI. If looking at a lime and DPHI is on sand, add 2 to 3 pu to DPHI.

Step 4: Determine Rw, ask someone with local knowledge, or find a wet zone and compute Rwa (apparent water resistivity)

\[ Rwa = ILD \times \Phi \times 2 \]

Step 5: Compute BVW (bulk volume water) in the zone of interest.

\[ BVW = \sqrt{\frac{Rw}{ILD}} \]

Step 6: Compute Sw (water saturation) if you want.

\[ Sw = \frac{BVW}{\Phi} \]

Step 7: Compare BVW to Phi, Swirr typically about 30%, higher if shaley perhaps 50 to 70%, lower if very clean.

Above assumes Archie formula \( m = n = 2, a =1 \)
Can also calculate Sw by the classic Archie formula directly

\[ Sw = \left( \frac{Rw}{Rt \times \Phi^m} \right)^{1/n} \]
Some guidelines for m and n values...
Clean sand; \( m = n = 1.9 \) to 2
Shaley sands; \( m = n = 1.8 \)
Very shaley sands; possibly lower \( m, n \), or use shaley sand eqn such as Simandoux etc
Clay coating issues; \( n < 1.5, m < 1.8 \)
Carbonates; \( m = n = 2 \)
Vuggy carbonates; \( n = 2, m = 2 \) to 4
Oil wetting; \( n \) as high as 9

**A small change in \( m \) or \( n \) can result in a large change in \( Sw \)!!!**

Some guidelines for bound water saturation (Swirr)
Clean, high porosity; Swirr 5 to 35%
Clean, low porosity; Swirr 30 to 55%
Shaley formations; Swirr 35 to 60%
Very shaley formations; Swirr 60 to 80%

Some guidelines for determination of shale content
Common shale indicators are gamma ray, SP, neutron density separation, resistivity
The key is to look at ALL the shale indicators, in general use the minimum shale indication
Pay that has not been recognized from shows or logs, often because of:
- Mineral effects on logs such as clay effects or bound water
- Faulty assumptions in log calculations, Rw, m, n
- Thin bed effects on logs
- Often “low resistivity” or “low contrast” pay
- Have you in your career seen bypassed pay? Significant?
- Please take a minute and work with the person next to you to do “quick log calcs” on the example below. Be careful – you might get the wrong answer!

This well in East Texas (Cotton Valley formation) has a sand at 9945 to 9965, that has good porosity but low resistivity. Using an Rw of 0.026, the Sw is about 100%. However, zone such as these often produce gas at high rates. It was discovered through core analysis that the sand typically had a small amount (5 to 7%) of grain-coating clay. As a result, the value of n in the Archie equation should be 1.4 rather than the standard value of 2 that was used here. Using n = 1.2 and m = 1.6 yields an Sw of about 40%. Also note that the zone at 9970 to 9990 does have lower Sw, so, this might be a another clue that the zone above could be pay…. it does not make sense to have water above gas…
As per USGS: General categories of unconventional petroleum include:

- Deep Gas
- Shallow biogenic gas
- Heavy Oil/Natural Bitumen
- Shale Gas and Oil
- Gas Hydrates
- Coalbed Methane
- The oil and natural gas resources that exist in geographically extensive accumulations.
- The deposits generally lack well-defined oil/water and gas/water contacts and include coalbed methane, some tight sandstone reservoirs, chalks, and auto-sourced oil and gas in shale accumulations.

Shannon sand / Gammon shale – southern Williston Basin
Characteristics of bypassed pay

- Subtle log signatures, “shaley looking” gamma ray and SP, suppressed resistivity…often due to increased shale volume and / or thin beds. Typical logs resolve beds 1 to 4 feet in thickness. Also, shale acts as a “short circuit” to the resistivity logs, a small amount of shale can have a large effect. The bypassed pay in the example below is a result of thin beds, and also shaliness.
- With bypassed pay one or more of the log signatures tend to be “out of balance” with the others. In conventional pay the log signatures tend to be in balance with each other.
- Also, the gamma ray can be misleading
- Your best friend…. the mud log !!!

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- Bypassed pay
- “Conventional” pay

![Graph showing characteristic differences between bypassed and conventional pay](image-url)
In this section of the course you will gain a greater appreciation for 80, 90, even 100% Sw! How can that be you ask? You will learn to look at all available data in order to locate pay zones that may have been missed.

It has been said the resistivity is not a good tool for finding oil and gas and determining Sw. There is some truth to that.

Causes of low resistivity / low contrast pay;

1) **Category 1** - Mineral effects such as from grain-coating clay. This can have the effect of lowering the saturation exponent greatly, from a typical value in the range of 1.8 or 2, down to a value less than 1.4! This drastically affects Sw.

2) **Category 2** - Grain size changes resulting in high bound water volume (Swirr).

3) **Category 3** - Laminations in the formation that are thinner than the logging tool can resolve.

Watch for these scenarios of these in upcoming examples!
This well in East Texas (Cotton Valley formation) has a sand at 9945 to 9965, that has good porosity but low resistivity. The typical Cotton Valley pay zone should have 6% or better porosity, and greater than 10 ohm-m. Using an Rw of 0.026, which is typical for this formation, the Sw in the sand at 9945 to 9965 is over 90%. However, zone such as these were found to produce gas at high rates. Mud log shows and drilling breaks prompted further study of these apparent wet zones. It was discovered through core analysis that the sand typically had a small amount (5 to 7%) of grain-coating chlorite and smectite clay.

As a result of the measured values of m and n from core analysis, the value of n in the Archie equation should be 1.2, rather than the standard value of 2, and the value of m should be 1.6 rather than 2. Using these new values yields an Sw of about 48%.

Another thought – note that the zone at 9970 to 9990 does have lower Sw using the normal m = n 2, so, this might be a another clue that the zone above could be pay…. it does not make sense to have water above gas… Again, mud logs had good gas shows in these zones that appear to be wet from the preliminary log analysis.

Bypassed pay?

Standard pay, 6% phi, 14 ohm-m, 35% Sw
This version of the processed log uses the adjusted (as per core study) values of $n = 1.2$ and $m = 1.8$. This shows the “nearer to correct” Sw of around 40% in the previously bypassed pay zone.
The area in question had a peculiar problem - too much oil production. The reservoir has outperformed its initial estimated potential by 2 ½ times. The question was, from where was the oil coming? There are some pay zones that are fairly obvious on the resistivity logs - upwards of 20 ohm-m. Also there is an obvious water zone with resistivity of 0.25 ohm-m. But what about the zones at 1-2 ohm-m. Wet?
This processed log does not show much exciting in the interval above the main pay sand. No special effort was made to properly resolve the thin beds. ILD was not corrected for thin beds.
This is a second attempt at a processed log using thin-bed corrected resistivity (Rt), shale volume model designed to respond to thin beds, and a shaley-sand Sw model (Simandoux). In this case the shaley sands and thin beds are seen in a more realistic fashion.
- For conventional pay, logs tend to be “in balance”, for example all the logs indicate the same thing.

- For unconventional or bypassed pay, one of more of the logs tend to be “out of balance”.

- Some of the logs can be misleading as far as what is and is not shale.

- Thin beds (less than 2 feet thick) are not resolved by most logs.

- Look at all of the logs to see if any of them are indicating something that does not agree with the others. Gamma ray, resistivity, neutron and density logs all provide a different look at shaliness.

- Shale or clay, in its various forms is often the cause of low contrast zones.

- Mud logs may have helped to flag the low contrast zones in these examples.
Causes of low resistivity / low contrast and bypassed pay;

1) **Category 1** - Mineral effects such as from grain-coating clay. This can have the effect of lowering the saturation exponent greatly, from a typical value in the range of 1.8 or 2, down to a value less than 1.4! This drastically affects Sw. *(Is apparent Sw correct for this category?)* NO IT IS NOT!

2) **Category 2** - Grain size changes resulting in high bound water volume (Swirr). *(Is apparent Sw correct for this category?)* PROBABLY YES

3) **Category 3** - Laminations in the formation that are thinner than the logging tool can resolve. *(Is apparent Sw correct for this category?)* MIGHT BE CORRECT ON AVERAGE, INCORRECT ON BED LEVEL (INCHES OR MM)

4) **Category 4 Bypassed Pay** - Errors in assumptions regarding Sw, pressure, permeability, and other errors.
A Different Kind of Bypassed Pay (Category 4)

Does the zone at 5760 appear to be productive from log calculations? Darn – too bad it is depleted as per the wireline Repeat Formation Tester....
Typically, permeability is a function of porosity. Also a function of grain size, pore size etc, however for clastics it is usually safe to assume that there is some relation of permeability to porosity. The graph above shows the log-derived permeability on the Y axis as a function of the porosity on the X-axis, and with shale volume on the Z or color axis. This covers a wide range of sediments over 10000 feet of borehole in East Texas. Why does the trend change with shale volume?

For the example on the previous page, with 5 to 10 MMCFD gas production, and at 4% porosity, clearly, there has to be permeability greater than the 0.001 md indicated by this graph. More than likely, the permeability is to the upper left as shown by the blue line. How can there be that much permeability? Some possibilities;

1) Natural fractures
2) Grain coating clay resulting in preservation of permeability
3) Other reasons related to geologic morphology
1) **Category 1** - Mineral effects such as from grain-coating clay. This can have the effect of lowering the saturation exponent greatly, from a typical value in the range of 1.8 or 2, down to a value less than 1.4! This drastically affects Sw.  *In some cases with grain-coating clay, such as East Texas Travis Peak, Cotton Valley, porosity and permeability are preserved and actually better than the average tight sand. In other cases such as with conductive minerals like pyrite, it may not make much difference.*

2) **Category 2** - Grain size changes resulting in high bound water volume (Swirr). *In this case, as Swirr increases, permeability generally decreases.*

3) **Category 3** - Laminations in the formation that are thinner than the logging tool can resolve. *In this case, since the laminations are typically not resolved by logs, permeability can be much higher than the logs would predict.*
This well is in the Wattenberg Field northeast of Denver. The indicated sands with high resistivity and neutron-density crossover are the known field pay zones. Typical production is 500 MCFD after frac. Any other pay sands here?
### Tight Gas Sand, Bypassed, Unconventional Pay Case Study – Denver Basin

**2nd try processed log** – shows possible pay above the known pay zones… Again the lesson here is to look at multiple shale indicators not just one – like the gamma ray. Anecdotal stories and the NMR log on the following page corroborate this zone…

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Ensure that the base (input) data is valid

- Calibrations
- Reasonable downhole response in “marker beds” or known formations
- Environmental corrections applied (invasion, borehole corrections etc)

Ensure that processed log assumptions are reasonable

- Shale volume
- Rw, m, n

Does the processed result make sense in the larger picture (mud logs, geology etc)

- If not, review with Petrophysical staff, service company….
- Is the processed log a “flag” for bypassed pay or an unconventional resource?
Considerations for Shale Gas

Typical log response in shale gas;
- high gamma ray (due to Kerogen -> Uranium)
- high resistivity (due to low Sw)
- low bulk density (due to TOC)

Critical reservoir parameters (1)
- Phi > 4%
- Sw < 45%
- Permeability > 100 nanodarcies
- TOC > 2% by weight

1) From Schlumberger Oilfield Review article “Producing Gas From Its Source”.
Considerations for Shale Gas

Log analysis

- Core data needed for reference if at all possible

- Compute TOC volume if possible by Passey method using sonic DT and ILD, or correlation to gamma ray, ILD, or RHOB

- Compute or estimate heavy mineral volume

- Need to determine matrix density as this may be heavily influenced by TOC (very light) and heavy minerals (such as Pyrite which is very dense). Then compute density porosity.

- Compute Sw

- If possible compute matrix permeability as a function of porosity, referenced to core.
Passey et al 1990, Exxon, outlined a method for computing TOC content from sonic compressional transit time (DT) combined with resistivity, and making an assumption regarding LOM (level of maturity).

This method can be used graphically by:
1) Overlaying the sonic DT with the deep resistivity or Rt
2) There should be 50 us/ft of sonic scale for each decade of resistivity scale
3) Flip the DT curve scale, for example instead of 140 to 40, it would be 40 to 140
4) Adjust the DT scale, while honoring the 50 us/ft per decade rule, in order to overlay the DT and resistivity in “non-organic” shales
5) The amount of spread between the flipped DT and resistivity provides a graphical depiction of TOC content.
6) TOC can be computed from this technique with the following equations

\[ \text{DELTALOGR} = \log(\frac{\text{ILD}}{3}) + 0.02(\text{DT} - 85), \]
where 3 = Rshale baseline, 85 = Dtshale baseline

\[ \text{TOC} = \text{DELTALOGR} \times 10^{0.297 - 0.1688 \times 10.5}, \]
where 10.5 is the LOM, could vary from 6 to 12

*There are other methods of determining TOC content, correlations to gamma ray, Rhob, ILD. The important thing is to have core reference data.*
Bakken shale log example. TOC is as high as 10%, NPHI and DPHI are on 2.71 lime lithology scale. High pore pressure at 0.62 psi/ft. Interval was DST’d with no recovery but good pressure. Some questions: What do the “excursions” on the RXO indicate? What does the Passey method indicate here? Is there a good shale zone to use as a DT and LLD overlay interval? Around 10450 +/- 10 or so ft there is DT and LLD separation – does this indicate an organic shale or something else? Could TOC content be correlated to RHOB or GR?
Summary of Key Points

Key Points – Bypassed Pay
- Some of the logs can be misleading as far as what is or isn’t shale.
- Thin beds (less than 2 feet thick) are not resolved by most logs
- Look at all of the logs to see if any of them are indicating something that does not agree with the others. Gamma ray, resistivity, neutron and density logs all provide a different look at shaliness
- Shale or clay, in its various forms is often the cause of low contrast zones. Do not write off a zone due to high Sw!
- Mud logs may can help to flag the low contrast zones

Key Points – Unconventional Resources
- Often high gamma ray
- Higher resistivity than surrounding shales
- Higher density porosity, remember that neutron porosity will be too high due to shaliness
- Sonic porosity usually too high, however this may be a flag when compared to resistivity (Passey et al)

Key Points – QC of Processed Logs
- Ensure that base data is valid, proper corrections
- Ensure that processed log assumptions are reasonable
- If not, review with Petrophysical staff, service company…
- Is the processed log a “flag” for bypassed or unconventional pay?