

Petrophysical Summary: How to?

A log interpretation method, not commonly available, is designed to incorporate and be calibrated by core. There are two programs involved.

- 1) Geological Analysis by Maximum Likelihood Systems or Gamls. The most common use of this program is when you have, say, 50 core mineralogy data points and want to derive the same type of core result using log inputs as well as core inputs.
- 2) Petrophysics Designed to Honour Core or PDHC. This is a general mineral-based program, where, usually element measurements are available or predicted from close-by offset wells.

Our interpretation starts with the most basic inputs that can be correlated to core measurements every step of the interpretation. For example, we started with the elements, (Al, Ca, Fe, Si, and S) predicted from offset logs. We invoke an element to mineral model from the PDHC program "Petrophysics Designed to Honour Core" to derive the common minerals from the input elements. While this (elements to minerals) may seem an obvious strategy, there are more unknowns than knowns involved. It is accomplished by an iterative normalization procedure using the elements as constraints. Alternatively, a normalization procedure has been developed using the core minerals as constraints in the Geological Analysis by Maximum Likelihood Systems (GAMLS) program. When extensive core mineralogy is not available, offset logs are used to provide element input for mineralogy. The elements, Si, Ca, Al, Fe and S provide 5 constraints whereas the ubiquitously-available Vsh approach provides only one.

Derived-mineralogy attributes are used to derive cation exchange capacity, grain density and permeability and can easily be compared to core porosity and permeability when core is available.

Introduction

Why involve mineralogy? We can use the mineral attributes such as cation exchange capacity, grain density and surface area to compute S_w , porosity and permeability. Analysis will be complete if diagenesis does not modify the calculated attributes (CEC, Perm, m , n) from our model values.

In summary, mineralogy from predicted and measured elements provides a complex interpretation of porosity, water saturation and permeability. We use a flexible interpretation

program to perform checks and balances at each step of the process. The final criteria for net pay flags are given in Appendix B.

We had this information:

There was no water analysis data for the field available so it was calculated from the SP and checked so that $R_t=R_o$. Note this method can only be accurately used when clay minerals are computed from elements, to provide cation exchange capacity. The log headings from old wells are often truncated in the las file so we could not check it against a recorded temperature log or maximum recorded temperature.

Method

- a) We prepare reliable data before entering the calculation programs. This involves very detailed correlation of core data and log data. Log data, recorded by xxxx on the well, was off depth for the Spectral log and SPAR. We have special software developed to provide core to log Gamma correlation.
- b) Correct for washouts affecting the density. We compared sonic porosity to density porosity and did not find any rugosity effects on the density log. Note for future drilling and logging, a Dual density log is a good way to record. Two density tools are configured to be 90 degrees to each other. The result is one density pad is always in the minor diameter, recording good data.
- c) Before we got to the first step in computing the elements, we determined R_w from the SP. The R_w derived from the SP was calibrated with an estimated field R_w of 0.05@75F. The SP fluctuations allow the R_w to be propagated over the interval of the well; this method is outlined in the spring 2014 CWLS 'Insite' magazine, available on the CWLS website and is also taught at spring schools at the Calgary GeoConvention. Note we were lucky to obtain a valid SP in the oil base mud. This happens when the water phase is continuous in the mud.
- d) Calculate the total organic carbon (TOC). The empirical calibration equation for TOC was $(\text{Log}_{10} ((2.8*(HURA-0.3*HTHO))^{1.85}))$ to give a result in weight percent. There are several transforms in the literature, but we have found this equation is a reliable generic one. It compared nicely to core TOC.
- e) Predict missing log curves, such as the elements and NMR from all wells. When a curve is predicted, the name is usually appended with the letter, '_P', such as CMRP_3ms_P for predicted free fluid, used as there was no CMR measurement available. NMR and ECS /FLEx/GEM logs were not available.
- f) Note the TOC is not low everywhere, as expected, in the Duvernay.

Calculations in the program

1. **Minerals:** Solve for clastics, carbonates, and clays respectively from strip & log elements equivalent to the ECS curves (Al, Ca, Fe, Si, and S).
2. **Normalize:** by constraining log elements and measured GR spectroscopy (K, U, Th), to convert the Si & K to quartz, kspar, plagioclase and muscovite; Ca to dolomite, calcite; Si, Al, K and Fe to illite, smectite (none), kaolinite and chlorite (none). As expected, we did not observe any mixed layer clays (smectite/illite) or muscovite. Primarily, the clay was illite with a small amount of kaolinite and chlorite.
3. **Solve for porosity and permeability** using the Herron formulas (Ref. 3) from the calculated carbonate, clay and siliclastics groups. Solve for KSDR also.
4. **Solve for Sw** and provide estimates of irreducible (SWIRR), bound fluid saturation (S_BFV) and minimum water saturation (SW_DS_GAS_ECS) to estimate if water will be produced.

Sw calculation:

- The saturation equation used is called a Dual Water Equation, from the paper by Chris Clavier et al, (Ref 5).
- The components of the equation are:

m_zero, which is the cementation factor, dependent on m^* (m_{star}), the Waxman-Smits cementation factor:

$$\text{IF}((m_{star} \leq 2.0356), (m_{star} / (0.1256 * m_{star} + 0.7781)), ((m_{star} / (0.3764 * m_{star} + 0.2694))))$$
, where

$$m_{star} = (1.653 + (0.0818 * (\text{Surface area} * \text{RHOG})^{0.5}))$$
, where

Surface area (SO) = sum of specific SO of each mineral. This is a very critical part of the calculation.

n_zero = tortuosity factor = $m_{zero} =$

$$\text{IF}((m_{star} \leq 2.0356), (m_{star} / (0.1256 * m_{star} + 0.7781)), ((m_{star} / (0.3764 * m_{star} + 0.2694))))$$

N_{zero} and m_{zero} are used in the Dual Water saturation equation; M_{star} would be used in the Waxman-Smits-Thomas equation, but we used the DW equation. In the lab, both DW and WS give the same results. However, DW also gives Sw_b , the clay water saturation. We use Sw_b as a quality control check because Sw_t cannot be lower than Sw_b .

CEC = cation exchange capacity of each mineral summed

TPOR = total porosity from the density and grain density derived from elements.

Grain density is $RHOG_ECS = 2.62+0.049*Si+0.2274*Ca+1.993*Fe+1.193*S$

Rw_SP = the formation water resistivity derived from the Rmf and SP, straight-lined several times until a final was accepted.

RT = assumed from the deep reading resistivity

The calculation continues as below:

Porosity

Porosity is calculated from bulk density and grain density. Grain density is calculated from the Herron Element relationship

$RHOG_ECS = 2.62+0.049*Si+0.2274*Ca+1.993*Fe+1.193*S$, in addition Kerogen is added to the equation, as below. $Ker = TOC*1.2$

$RHOG_KER = IF(Ker < 1.5, (2.62+0.049*Si+0.2274*Ca+1.993*Fe+1.193*S), ((1 - Ker/100) * (2.62+0.049*Si+0.2274*Ca+1.993*Fe+1.193*S) + (Ker/100 * ((1+0.049*Si+0.2274*Ca+1.993*Fe+1.193*S)) * (1))))$

Water Saturation Detail

Water saturation is calculated from the Dual Water equation, using cation exchange capacity to calculate Qv.

[See **Clavier, C., G. Coates, and J. Dumanoir, 1977**, the **theoretical and experimental bases** for the "dual water" model for the ... **SPE Paper 6859, Society of Petroleum Engineers 52nd Annual Fall Meeting, Denver, Colorado, October 9–12, 1977**. Dewan, J. T., 1983, Essentials of modern open-hole log **interpretation**: Tulsa, Oklahoma, PennWell Publishing Company, 361 p. ... Hill, H. J., O. J. Shirley, and G. E. Klein, 1979, Bound water in **shaly sands**: Its relation to Qv and other formation ...]

From the Petrophysics Designed to Honour Core (PDHC) program:

$$CEC = \text{Sum}(Wi * CEci)$$

$$Qv = (CEC/100 * Rhog * (Rhob - 1)) / ((Rhog - 1) / Tpor)$$

$M = \text{salinity} / Rhof_bw / 58.45$, where salinity is the formation water salinity and Rhof_bw is density of bound water, usually 1. [Molarity.]

$$W = (0.22 + (0.084 / M^{0.5}))$$

$$Swb = W * Qv$$

$$B = 0.03772 * \text{Temp_degF} - 0.6516$$

$$Cb = B * Qv / Swb$$

$$F = F_Ghanbarian \text{ or } 1/TPOR^{m_zero}$$

$$Cw = 1/Rw_SP_used$$

$$TC_DW = ((Cb*Swb-Cw*Swb)/F) \text{ [Term c in quadratic]}$$

$$Co = (Cw/F)+TC_DW$$

$$Ro = 1/Co$$

$$Ct = 1/Rt$$

$$Swt = (Ct/Co)^{n_zero}$$

Hence,

$$Swt = (Ct / ((Cw/F) + ((0.03772*Temp_degF - 0.6516*Qv / (0.22 + (0.084 / \text{salinity} / 58.45^{0.5})) * (CEC/100 * Rhog * (Rhob - 1) / (Rhog - 1) / Tpor) * (0.22 + (0.084 / \text{salinity} / 58.45^{0.5})) * (CEC/100 * Rhog * (Rhob - 1) / (Rhog - 1) / Tpor) - 1/Rw_SP_used * (0.22 + (0.084 / \text{salinity} / Rhof_bw / 58.45^{0.5})) * Qv) / F)))^{n_zero}$$

The Rw_SP_USED is calculated in two parts. First an estimate is made, called RW_SP , from an estimated field value and a baselined SP. Second, this value is refined so that after a full ECS calculation is made, the CEC-Corrected Ro matches the recorded deep resistivity. The Rw process is repeated until a satisfactory match of Ro and Rt is obtained. One has to be careful as the density tool has a different vertical resolution than the deep resistivity. Hence, some experience is useful.

5. Create flags for net pay (PHIE>4% & Hydrocarbons), net porous (PHIE>4%) and gross porous (PHIE>2%) zones. Note that offset wells all use the same parameters.

Determination of Rw : How to?

Rw from SP

As you probably know, the Rw changes with depth, according to the ratio of Rmf and Rw . As you also probably know, the $SP = -k \log RMF/Rw$, so the SP records the variable Rw very nicely. However, you learned in Basic logging classes, or Ross Crain's website, that the SP:

- 1) Is reduced in hydrocarbons vs. water. This is natural because the salinity in hydrocarbons is reduced. Just not as much room for the salt. So, we will ignore this potential problem for now.
- 2) Drifts left or right as the tool approaches casing. The casing provides a short circuit to the SP fish in the mud pit. We will learn how to account for the drift.

- 3) Has no 'zero'. So we need to provide a zero. One way, we were taught in basics, is to draw a shale baseline from one shale to the next and to measure the deflection from this baseline. Sounded good. It just doesn't work. For short intervals it seems to work. However, we have developed a method that works all the time, even if there are long sections where there is considerable Rw variation.

Our method is:

SP_ZERO

- A) Find a zero by calculating an average zero. Do you know the known Rw at any depth? For example this well has a 'Rw_known' of [0.05@75F](#). If we knew RMF, then $SP_ZERO = -k \log(RMF/RW_KNOWN)$; If we don't have a clue as to what Rw is known (no water catalogs, no collected samples etc.) then use [0.05@308F](#). This, by serendipity, is a good starting point no matter where you are in the world. In this area, we have two 'known' values, 190ppk & 215ppk.). We can convert these to Rw if we have a temperature profile. The one I use is $0.0186 * \text{depth in ft} - 15 \text{ DegF}$. Other wells use $0.0196 * \text{depthft} + 42.8 \text{ DegF}$.

Then Rmf for 190ppk is $((400000/TEMP_DEGF)/(ppk*1000))^{0.88} = ((400000/204.5)/(190*1000))^{0.88} = 0.017$ ohmm and

Rmf for 215 ppk & 215 Deg F is $((400000/215)/(215*1000))^{0.88} = 0.015$ ohmm;

The estimated Rw is $(0.05*(308+6.77)/(TEMP_DEGF+6.77)) = (0.05*(308+6.77)/(204.5+6.77)) = 0.019$ ohmm at 204.5 deg F and

0.018 ohmm at 215 deg F

Bottom line, we could choose any of these Rw's as a known Rw. The mud salinity is very close to the formation water resistivity at one zone in the well. Using ASAL, when oil based mud, Then $SP_ZERO = (-1)*(61+0.133*TEMP_DEGF) * \log(RMF_ASAL_WALK2/RW_KNOWN)+15 = (-1)*(61+0.133*190) * \log(0.017/0.019)+15 = -67 \text{ mv}$

Note there is a +15mv term. This is really a variable term to make the average come out to zero, over the interval selected. When the interval is changed, this number will have to be changed.

SP_SHIFT

- B) Next, find a **SP_SHIFT**, defined as SP plus a term to make the final Rw to equal the Rw_Known at a particular depth. To start with, 'SP_SHIFT' is just the SP. If the RW_SP that we calculate does not match the Rw_KNOWN, we will come back here and add or subtract some millivolts and try again. We will iterate until we are satisfied with the match.

- C) Next find the difference between the SP_SHIFT and SP_ZERO. Call this **SP_BASELINED** = SP_SHIFT – SP_ZERO.

RW_SP

- D) Next, having ‘calibrated’ the SP deflection, we are ready to calculate Rw from the SP, where **RW_SP** = $RMF / (10^{(SP_BASELINED / (-1 * (61 + 0.133 * TEMP_DEGF))))$
- E) Now look at a plot of Rw_SP and Rw_Known. If the minimum Rw_SP = Rw_Known, you are done. If not, go back to Step B, and add or subtract the millivolts you think you need to make them match and recalculate with step C & D. Keep iterating until you get a match.
- F) Next we check to ensure $R_o \leq R_t$. First off, how do we get R_o ? As a first order guess, use the PHID_MAD as porosity [PHID_MAD is the element-corrected density porosity, from RHOB and RHGE_Walk2. Then $F = 1 / (PHID_MAD)^{m_zero}$, and $R_o = F * RW_SP$.
- G) Check several low resistivity zones to ensure this $R_o \leq R_t$. Perhaps it seems ok at bottom of hole but not at top. If this is the case, the SP may be drifting left or right. To correct the drift, add a series of corrections (shifts) to the SP to make it come out right.
- H) Are you done? Maybe. We now need to do a full calculation to get a CEC-corrected R_o and compare that to R_t . Re-cycle as in Step B to G. I have a program set up to do this recycling, by inputting shifts to the SP or correcting for drift. The Program is called Petrophysics designed to Honour Core or PDHC. The program is available in Excel or Java. Excel is slow and cumbersome. But I don’t charge for it. Java is fast, but it is not free. My son, Jamie, wrote the translation from Excel to Java and I am slowly paying him for it as we sell the Java versions. Jamie also wrote a standalone plotting program that can be combined with PDHC. The plotting program is not free either. If you already have a plotting program, you will not be interested. I like his plotting program better than others, so I use it all the time. It is in prototype beta version right now (2019).

Example for Rw_SP

Assumptions

- 1) Rw_Known is [0.05@75F](#), compute the temperature corrected value, given TEMP_DEGF – $0.0186 * DEPTHFT - 15$.
- 2) Oil based mud with ASAL_WALK2 to compute RMF, find temperature corrected RMF.
- 3) Calculate SP_ZERO
- 4) There is a recorded SP but it is not reliable, since the mud is oil-based [always record the SP as sometimes it works OK if the water in the oil based mud is in a continuous phase]. I have predicted an SP from an offset well. It is called SP_PMF, which means spontaneous potential predicted and smoothed with a median filter of 55.
- 5) Calculate SP_SHIFT
- 6) Calculate SP_BASELINED
- 7) Calculate RW_SP

- 8) Compare RW_SP to RW_KNOWN
- 9) Iterate until you are satisfied with RW_SP
- 10) Calculate initial Ro from F, PHID_MAD, RW_SP, m_zero
- 11) Balance Ro with RT; iterate as necessary to get $Ro \leq R_t$.
- 12) Make an approximate drift correction if needed.
- 13) Do full calculation to get Excel results for Ro. Iterate as necessary.
- 14) Compare results with your reported results and explain why there are differences.

Example for Rw_SP Answer

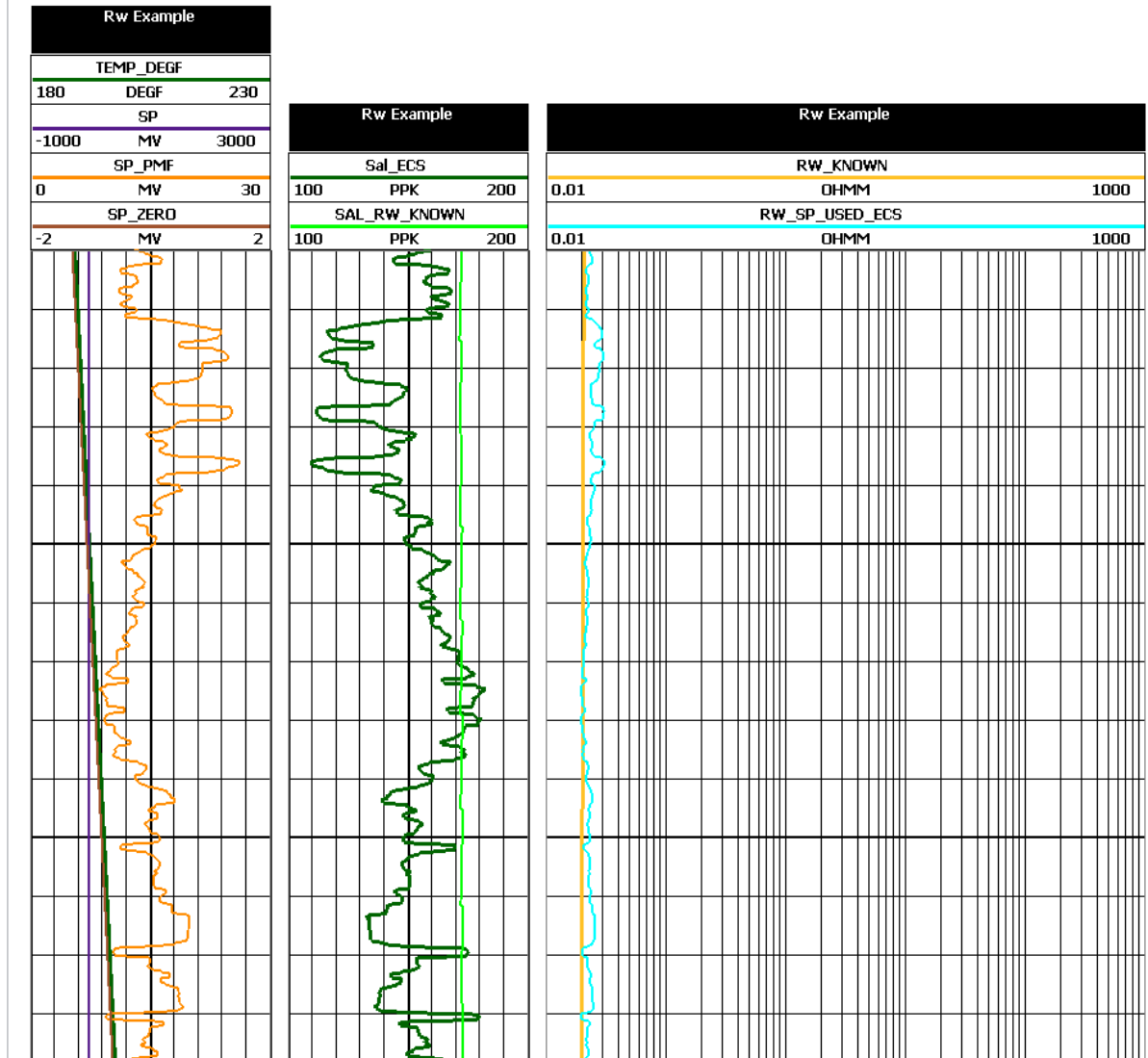
Here are my results for you to compare to, especially if you get stuck.

The math results are in the las file. The plots are below.

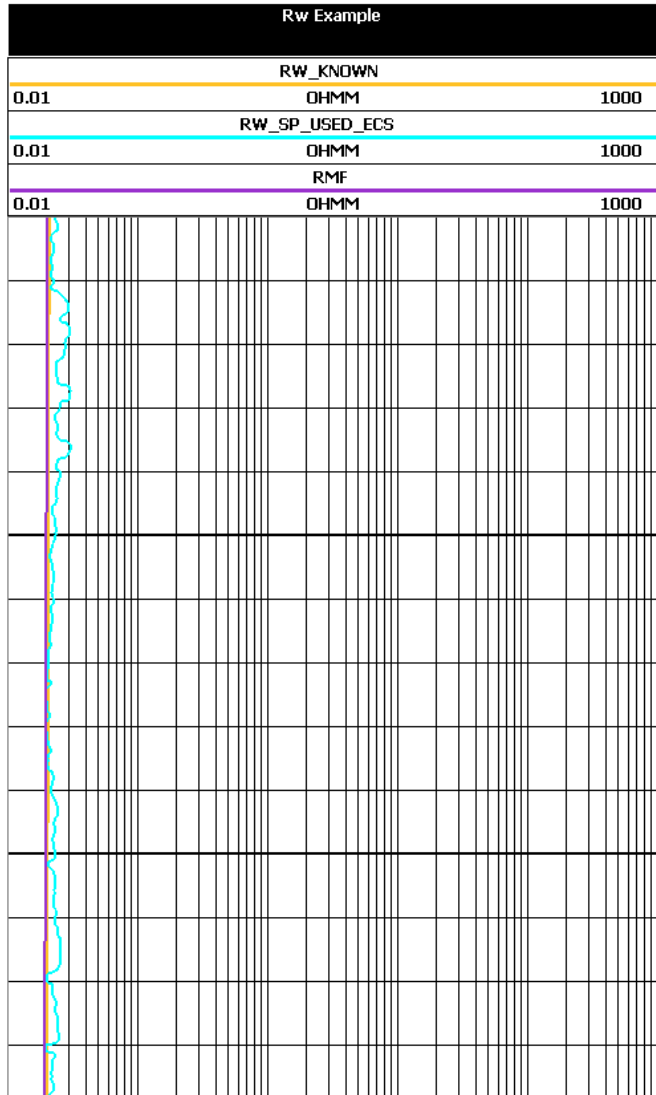
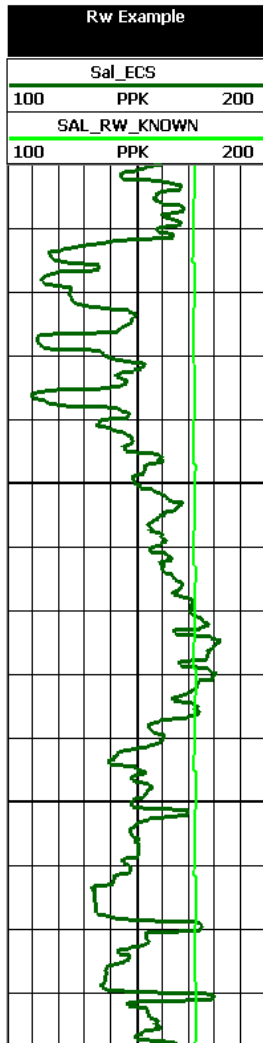
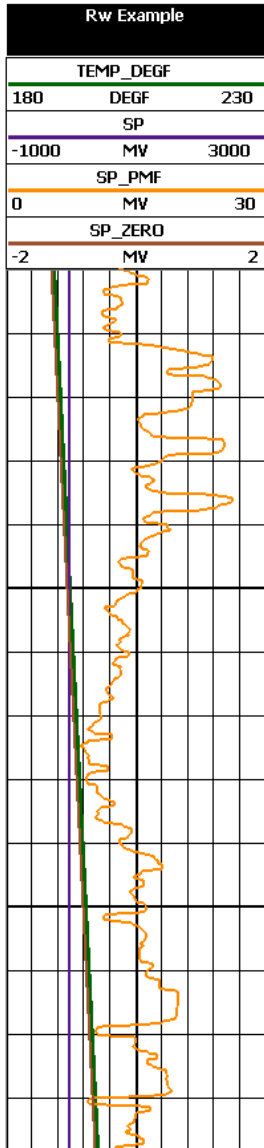
- 1) RW_KNOWN is [0.05@75F](#), compute the temperature corrected value, given $TEMP_DEGF = 0.0186 * DEPTHFT - 15$. See las file and plot.
- 2) Oil based mud with ASAL_WALK2 to compute RMF, find temperature corrected RMF; See las file and plot.
- 3) Calculate SP_ZERO; See las file and plot.
- 4) There is a recorded SP but it is not reliable, since the mud is oil-based [always record the SP as sometimes it works OK if the water in the oil based mud is in a continuous phase]. I have predicted an SP from an offset well. It is called SP_PMF, which means spontaneous potential predicted and smoothed with a median filter of 55. See las file and plot.
- 5) Calculate SP_SHIFT; See las file and plot.
- 6) Calculate SP_BASELINED; See las file and plot.
- 7) Calculate RW_SP; See las file and plot.
- 8) Compare RW_SP to RW_KNOWN; See las file and plot.
- 9) Iterate until you are satisfied with RW_SP; See las file and plot.
- 10) Calculate initial Ro from F, PHID_MAD, RW_SP, m_zero; See las file and plot.
- 11) Balance Ro with RT; iterate as necessary to get $Ro \leq R_t$.; See las file and plot.
- 12) Make an approximate drift correction if needed. See las file and plot.
- 13) Do full calculation to get Excel results for Ro. Iterate as necessary. See las file and plot.
- 14) Compare results with your reported results and explain why there are differences.

Rw_SP, Steps 1, 2, 3, 4, 5, 6, 7, 8

Note the deflections caused by mud salinity, in the calculation of SP_ZERO. Note the RW_SP matches the RW_KNOWN at the bottom and at the top.

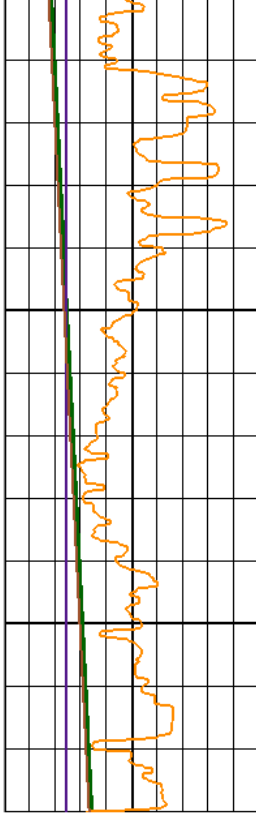


Now, add RMF using the salinity seen by ASAL. One can see that RMF is a straight line, sitting right on top of RW_KNOWN.

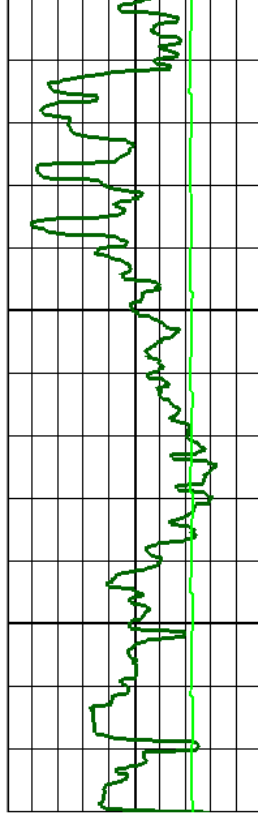


Next plot FRw from PHID, m=1.8

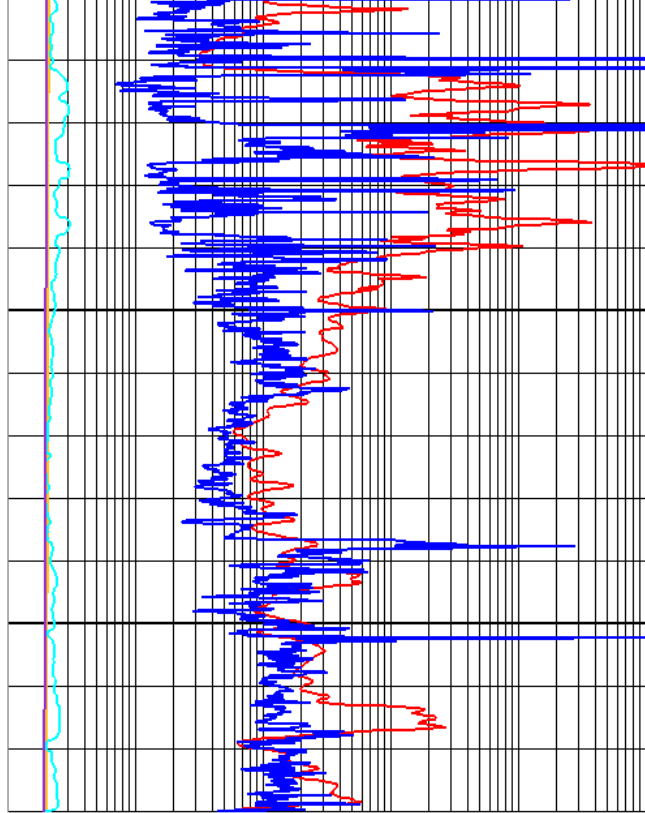
| Rw Example | | |
|------------|------|------|
| TEMP_DEGF | | |
| 180 | DEGF | 230 |
| SP | | |
| -1000 | MV | 3000 |
| SP_PMF | | |
| 0 | MV | 30 |
| SP_ZERO | | |
| -2 | MV | 2 |



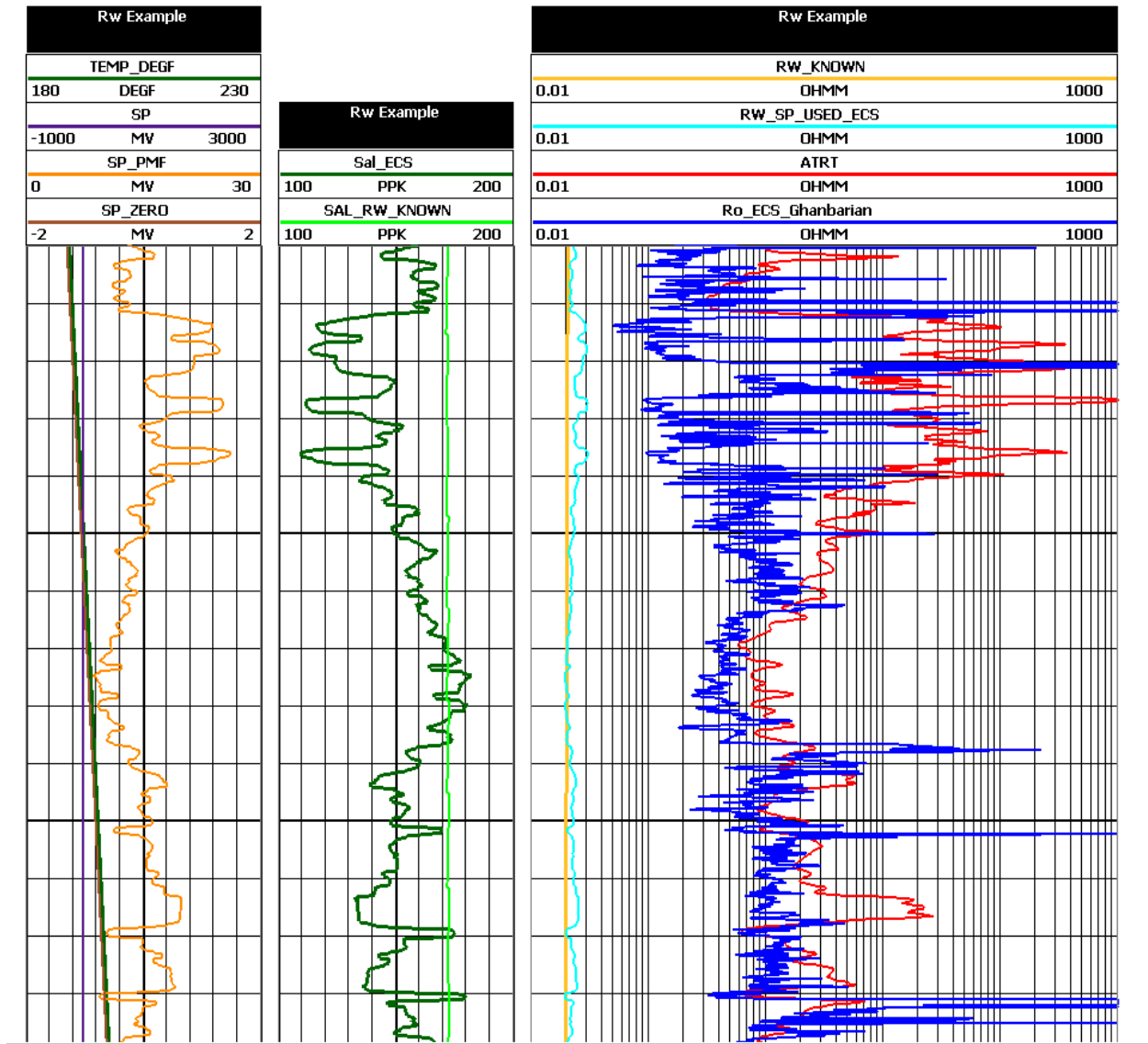
| Rw Example | | |
|--------------|-----|-----|
| Sal_ECS | | |
| 100 | PPK | 200 |
| SAL_RW_KNOWN | | |
| 100 | PPK | 200 |



| Rw Example | | |
|----------------|------|------|
| RW_KNOWN | | |
| 0.01 | OHMM | 1000 |
| RW_SP_USED_ECS | | |
| 0.01 | OHMM | 1000 |
| ATRT | | |
| 0.01 | OHMM | 1000 |
| RMF | | |
| 0.01 | OHMM | 1000 |
| FRW_PHID | | |
| 0.01 | OHMM | 1000 |



When the FRW_PHID is close to the lowest values of Rt and the RW_SP is close to Rw_KNOWN, one is finished the first step. Now one enters the full program to calculate and Ro



We see a similar result as Ro is approximately FRw_PHID. When clay is low, we will get this result.

The above plot looks reasonable as there are no big zones where $Ro > Rt$. There are zones where this happens, but they are bed resolution differences.

Next, we will look at uranium and thorium, plus TCMR (MRP) and CMRP (FFV) for quality control. We know a couple of things:

- 1) Uranium and thorium are related in a crustal sense. Uranium = $1/3$ thorium. When $HURA > HTHO * 0.3$, then there is excess uranium (excess over the normal crustal relationship). We take advantage of this ratio and calculate a total organic carbon when there is excess. We do not differentiate on whether this excess uranium is in bitumen or not. We have calibrated this TOC to core in many areas over the years, so it is our 'standard way' to calculate TOC, where

TOC_URAN = 2.8* log [IF(HURA<0,00.001,((HURA-0.3*HTHO)/1)^M_ZERO)]; the 2.8 factor is appropriate for the Duvernay and 1.4 is appropriate elsewhere.

- 2) We also use the ratio to calculate SOR (bitumen saturation). Sometimes we see there is a separation of $R_o < R_T$ and it looks constant, as if there was an R_w error. So we check the SOR as it could be bitumen. Apparently, the oil and water travel together. The uranium is very soluble in water. So when the pressure is high, the water is squeezed out and the bitumen and uranium remain.
- 3) We check the elements looking for relationships. The total rock can be characterized by pyrite + carbonate+ clastics & muscovite. What is left over from a sum to 1 is clay. This is characterized by $S/0.53 + Ca/0.4 + Si/0.467 + 1.99*Fe = 1$

Therefore, we always scale Ca with 0 to 0.4 and Si with 0 to 0.467. Fe has 5% in illite, so if Fe is higher than 5% in shales, there is excess Fe, perhaps from siderite or ankerite.

- 4) In Dr. Mike Herron's paper, he characterizes 3 types of clay, normal, high feldspar and mica. The high feldspar clay is common in the Gulf of Mexico (GOM). If you don't use the high feldspar model you end up with too much kaolinite in the GOM. Usually, except for the GOM, we don't know what model to use. So we always select the model that provides the minimum amount of clay, to start with. If we are in the Duvernay, the high mica model is appropriate.

References

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- 5) Clavier, C., Coates, G., Dumanoir, J., 'Theoretical and Experimental Basis for the Dual-Water Model for interpretation of Shaly Sands', SPE Journal Vol 24 #2, April 1984.
- 6) Herron, M.M, 'Geochemical Classification of Terrigenous Sands and Shales from Core or Log Data', Journal of Sedimentary Petrology, Vol. 58, No. 5 September, 1988, p. 820-829.
- 7) Everett, R.V., Berhane, M, Euzen, T., Everett, J.R., Powers, M, 'Petrophysics Designed to Honour Core – Duvernay & Triassic' Geoconvention Focus May 2014.
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- 11)