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Title: Vsh or Element to Mineral Methods: which to use?

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Summary

Log interpretation has progressed from a volume of shale idea to correct for non-permeable zones, commonly called a "Vsh" method on which most commercial programs are presently based, to a "Element-Mineral" (EM) method that corrects resistivity in shale using cation exchange capacity (CEC). The EM method was developed in the 1980's and has been refined with new tool measurements ever since. The question of what method to use has often been asked. This paper is a summary to provide some information.

The considerations are:

1) Element-Mineral derived CEC is an upgrade to Vsh.

2) One can do more with element-mineral methods than with Vsh because more information is available; For example, sandclass from elements, grain density from elements, Rw from SP [because CEC corrects the Ro for clay effects].

3) When elements are not recorded, they can be predicted from offset wells to make full use of the element to mineral method. Predicted data has caveats: a major assumption is the depositional environments are similar. This means the elements associated with the minerals are similar. For example, in reducing environments like the Montney, sulphur is present and is associated with pyrite. Hence, sulphur and some iron is bound in the pyrite and the program would calculate pyrite. On the other hand, the association of sulphur in a non-reducing carbonate environment is more likely anhydrite. Hence, an example is one should not predict elements from a shale gas environment and use the predicted element in a lithic Mannville environment. One can manually reduce the predicted sulphur and the program will work satisfactorily but one must be aware of the element-to-mineral association. No problem for log-recorded element-tools like ECS™, Litho_Scanner™, GEM™ and Flex™; I am just referring to predicted elements.

4) Comparisons of the two methods, Vsh and EM, can be made. Sometimes they agree and sometimes they do not. Four examples are shown from tar, shale, lithic-Mannville and Milk River environments.

5) Which method is "best"? Both methods can be "locally" adjusted to fit core in a well. So, fitting to core is the best method. However, when core is not available, which is best? The software one has available will probably determine what one routinely uses. What is "best" is whatever works for you.

6) Software is available for the element to mineral method. One can treat it as free shareware by joining a user group if one desires to do that. Contact the author.

Introduction

The Vsh and EM methods are discussed with the benefits of each. In practice, the method chosen is often more related to one's software availability. Since the Vsh method has been available longer than the EM method, most software commercially available is based on the Vsh method. However, all major service companies that offer measurements of elements also have programs to use elements. In addition, some petrophysicists have built their own programs, such as the "Petrophysics Designed to Honour Core" (PDHC) available through the author.

Theory and/or Method

The Vsh method depends on a shale correction applied to an empirical-saturation model and porosity to obtain effective saturation and porosity. Historically, Vsh is derived from almost any curve that responds to shale: GR, SP, N_D, resistivity etc. On the other hand, the EM method converts elements to minerals. Then uses the clay minerals to provide a combined cation exchange capacity and clay water which is used in a scientifically-derived saturation model.

Inputs and Methods Used

The Vsh methods are standard in commercially-available programs.

The EM method is from the papers available in Ref. 3, 4, 5, 6. In addition, the EM method has been taught at CWLS schools since 2010. An outline is available from the author (roberteverettsupercomputer@gmail.com) and is in Ref. 13.

Examples

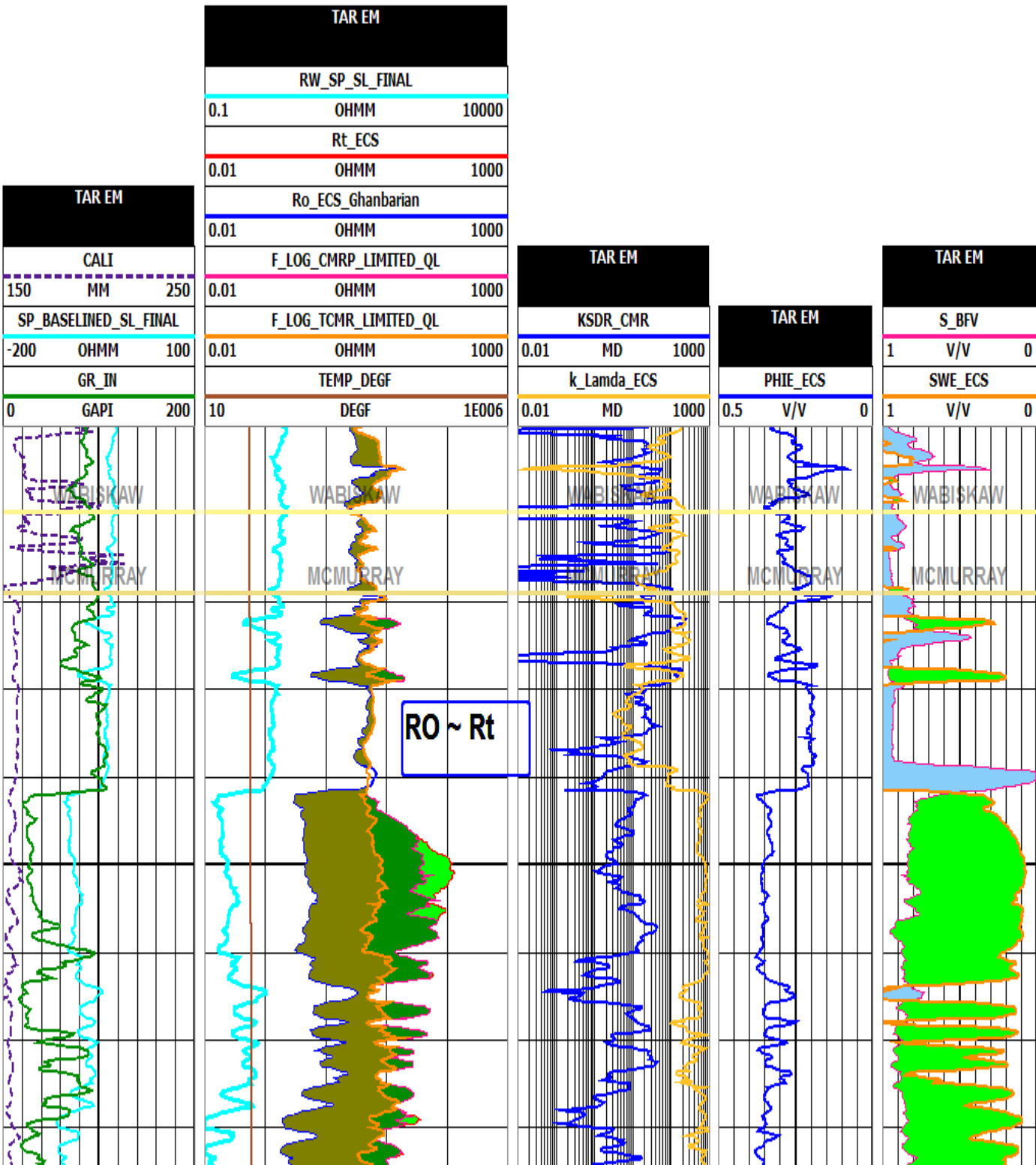
There are three examples shown with plots of Sw, porosity and permeability.

Tar sands enviroment

(of course, the weight fraction of Bitumen is also calculated but not shown below)

Bitumen Vsh method

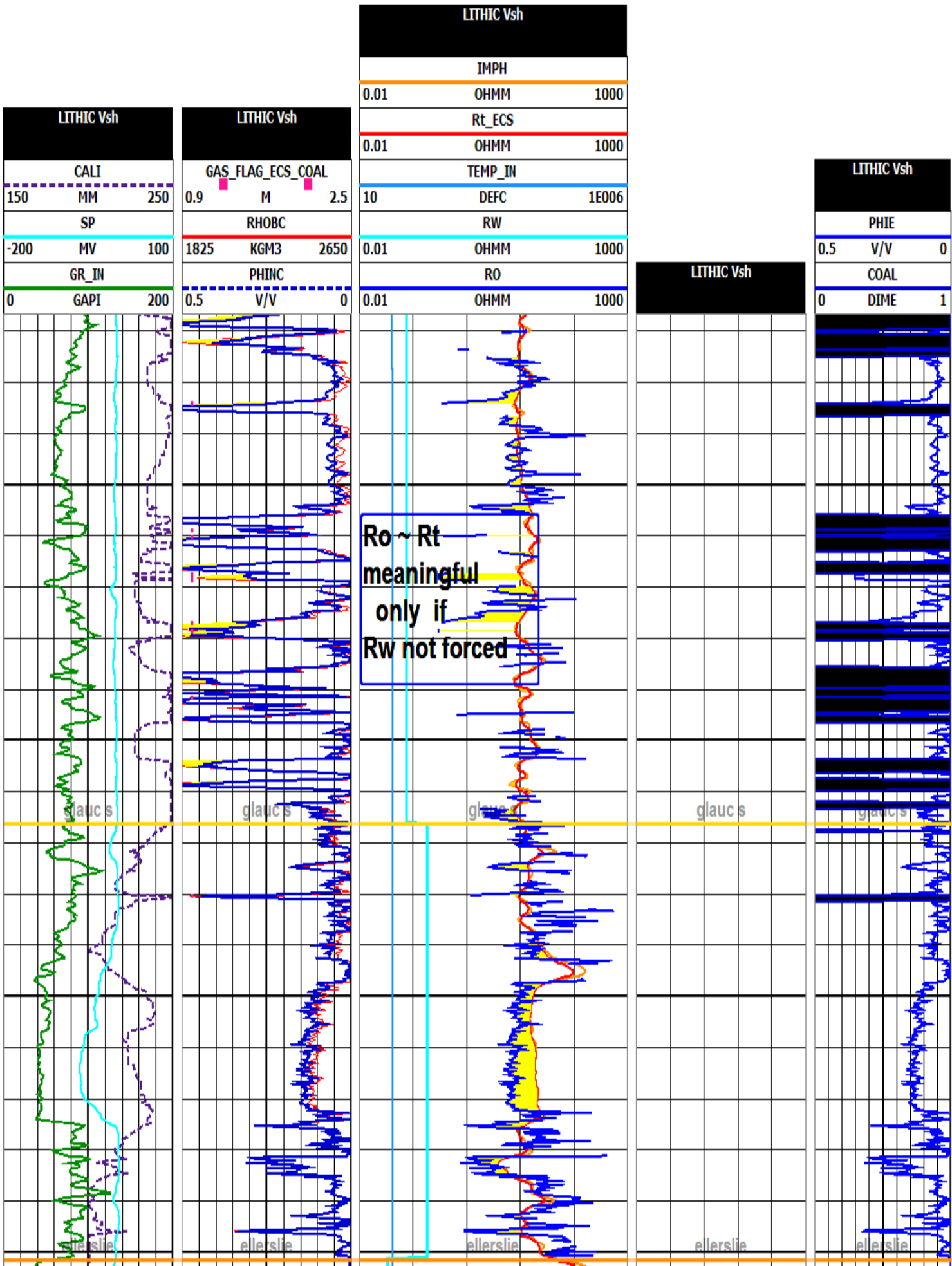
Bitumen, heavy oil, EM method


TAR EM
CALI
150 MM 250
SP_BASELINED_SL_FINAL
-200 OHMM 100
GR_IN
0 GAPI 200
TAR EM
RW_SP_SL_FINAL
0.1 OHMM 10000
Rt_ECS
0.01 OHMM 1000
Ro_ECS_Ghanbarian
0.01 OHMM 1000
F_LOG_CMRP_LIMITED_QL
0.01 OHMM 1000
F_LOG_TCMR_LIMITED_QL
0.01 OHMM 1000
TEMP_DEGF
10 DEGF 1E006
WABISKAW
MCMURRAY
RO ~ Rt
TAR EM
KSDR_CMR
0.01 MD 1000
k_Lamda_ECS
0.01 MD 1000
TAR EM
PHIE_ECS
0.5 V/V 0
TAR EM
S_BFV
1 V/V 0
SWE_ECS
1 V/V 0

Lithic Mannvile environment

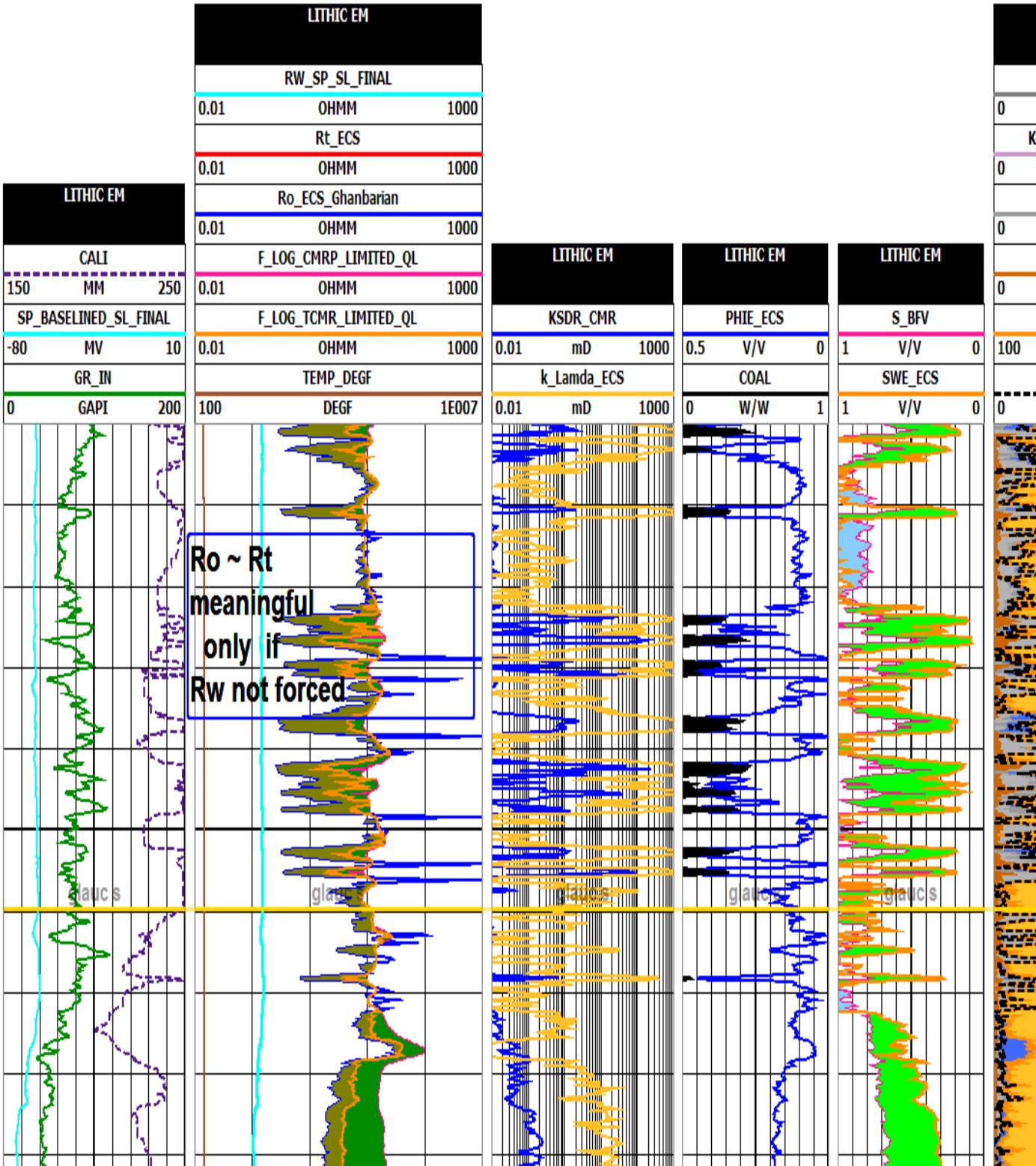
Vsh method

This well was done with great effort over several months using HDS software and an analyst who never gives up. Note that Rw (0.2@FT) and Vsh (~30%) are manipulated to obtain an “acceptable” Sw.


LITHIC Vsh
CALI
150 MM 250
SP
-200 MV 100
GR_IN
0 GAPI 200
LITHIC Vsh
GAS_FLAG_ECS_COAL
0.9 M 2.5
RHOBC
1825 KGM3 2650
PHINC
0.5 V/V 0
LITHIC Vsh
IMPH
0.01 OHMM 1000
Rt_ECS
0.01 OHMM 1000
TEMP_IN
10 DEFC 1E006
RW
0.01 OHMM 1000
RO
0.01 OHMM 1000
Ro ~ Rt
meaningful
only if
Rw not forced
LITHIC Vsh
LITHIC Vsh
PHIE
0.5 V/V 0
COAL
0 DIME 1
glauc s
ellerslie

EM method

The addition of predicted NMR curves enhances the output, providing KSDR, bound fluid volume for irreducible saturation, S_BFV and an estimate of producibility from the formation factors * Rw (i.e. Ro_TCMR, Ro_CMRP). The right-most mineral plot shows a more complex mineralogy, with traces of pyrite and small fractions of dolomite and calcite, as well as muscovite (mica). Incidentally, discontinuous pyrite does not affect resistivity. Rw is ~ 0.1@25C, according to Susan Johnson, Opus Engineering, salinity expert. However, a higher Rw, 0.1@FT, was used to obtain the same Sw as the Vsh model. This was accomplished by multiplying the SP by 0.5. Also note the clay in the pay zone is almost zero (~ 0 - 5%). There is some dolomite (~5%).

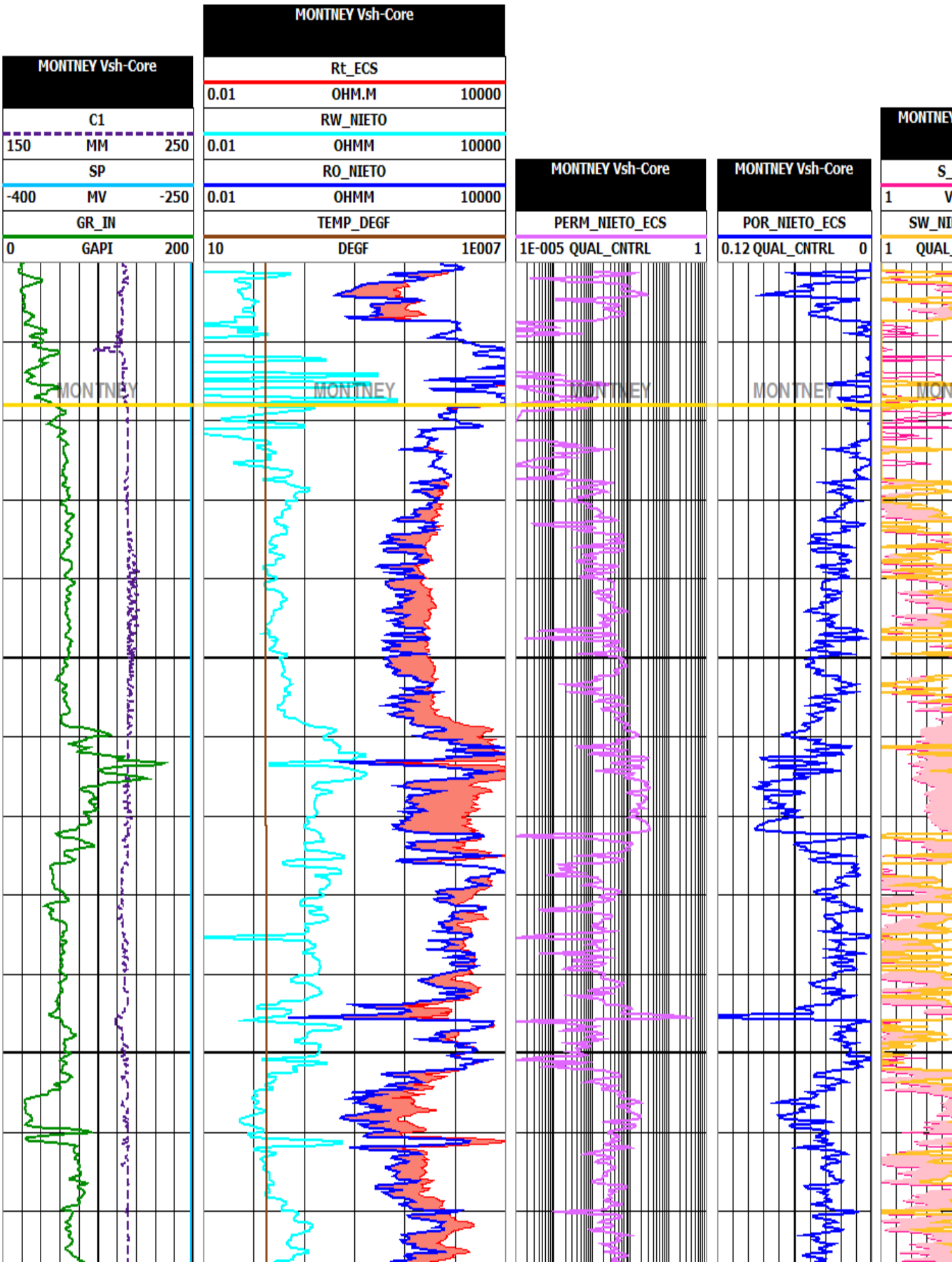

LITHIC EM
CALI
150 MM 250
SP_BASELINED_SL_FINAL
-80 MV 10
GR_IN
0 GAPI 200
LITHIC EM
RW_SP_SL_FINAL
0.01 OHMM 1000
Rt_ECS
0.01 OHMM 1000
Ro_ECS_Ghanbarian
0.01 OHMM 1000
F_LOG_CMRP_LIMITED_QL
0.01 OHMM 1000
F_LOG_TCMR_LIMITED_QL
0.01 OHMM 1000
TEMP_DEGF
100 DEGF 1E007
Ro ~ Rt
meaningful
only if
Rw not forced
LITHIC EM
KSDR_CMR
0.01 mD 1000
k_Lamda_ECS
0.01 mD 1000
LITHIC EM
PHIE_ECS
0.5 V/V 0
COAL
0 W/W 1
LITHIC EM
S_BFV
1 V/V 0
SWE_ECS
1 V/V 0
0
K
0
0
0
100
0

Unconventional shale, Montney environment

Vsh method

This is not really a Vsh method and it is not an EM method. It is a core method from another well. The curves were computed relying heavily on core using Dean Stark methods. Core was carefully preserved. Note the good fit of perm to core. Note also the Sw is higher than the Sw from the EM method: the Rw is higher for the Vsh-core-calibrated method. There are a couple of caveats:

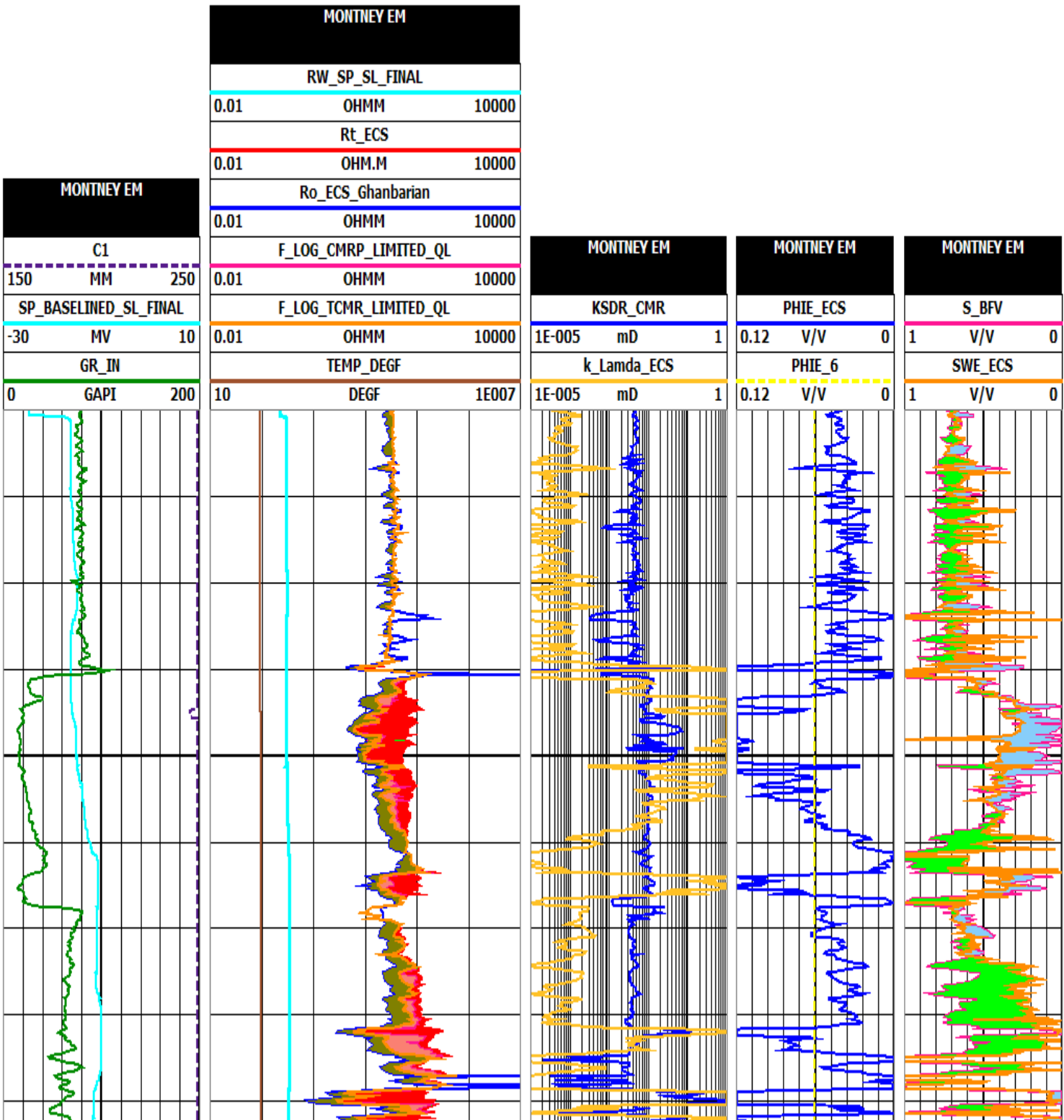
1) The Sw was computed from a formula (Ref. 12) that does not involve Rw. The Dean Stark core work was not on this well. The question, of course, is does the core work on another well also apply to this well?
2) The Ro and Rw shown are a reverse-calculation of Sw, using an Archie formula with m=n=M_ZERO and a Ghanbarian formation factor (Ref. 9).


MONTNEY Vsh-Core
C1
150 MM 250
SP
-400 MV -250
GR_IN
0 GAPI 200
MONTNEY Vsh-Core
Rt_ECS
0.01 OHM.M 10000
RW_NIETO
0.01 OHMM 10000
RO_NIETO
0.01 OHMM 10000
TEMP_DEGF
10 DEGF 1E007
MONTNEY
MONTNEY Vsh-Core
PERM_NIETO_ECS
1E-005 QUAL_CNTRL 1
MONTNEY
MONTNEY Vsh-Core
POR_NIETO_ECS
0.12 QUAL_CNTRL 0
MONTNEY
MONTNE
S_
1 V
SW_NI
1 QUAL_
MON

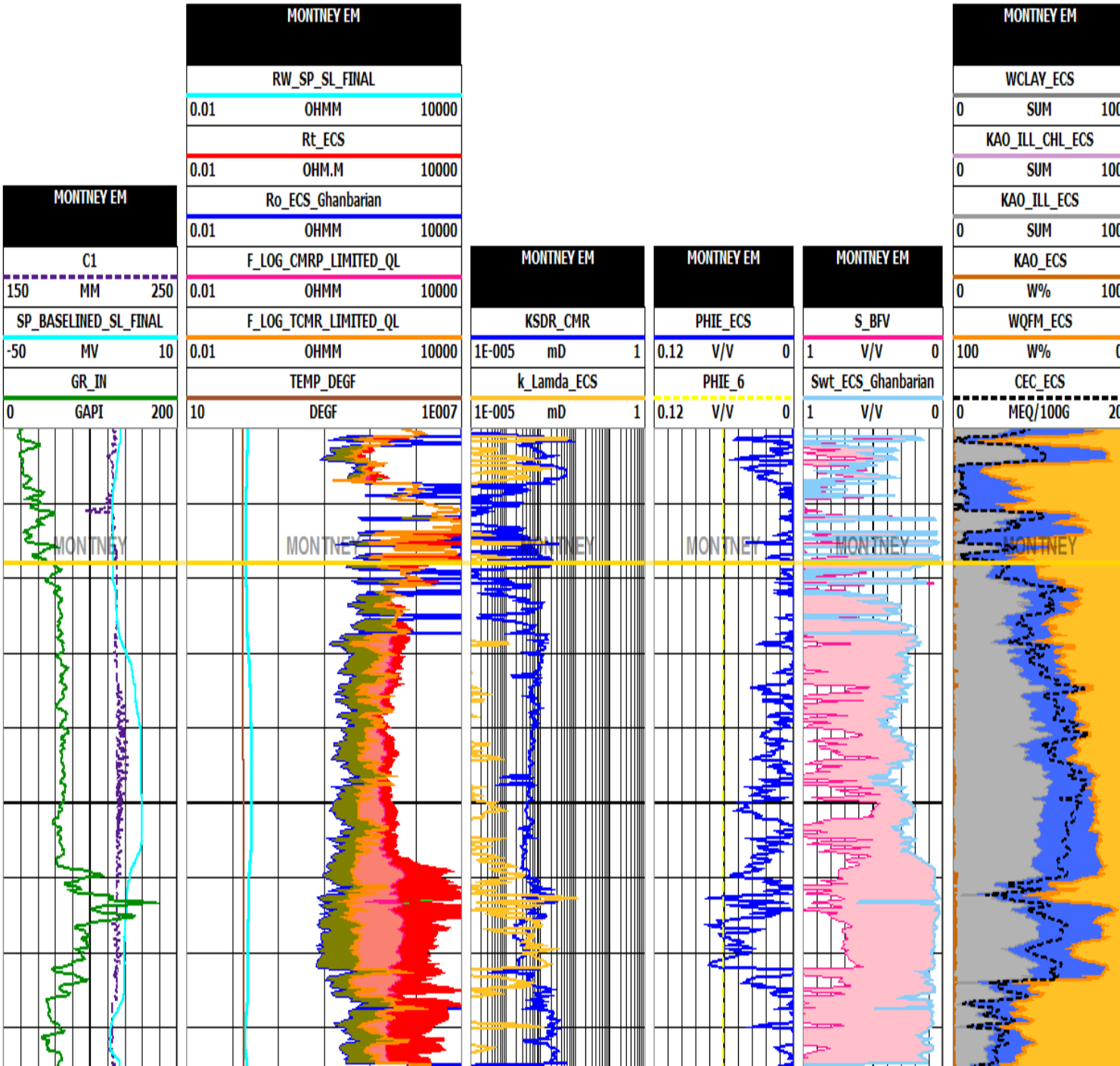
EM method

The EM method shows lower perm than the core-calibrated method above. The EM method provides mineralogy and the core-calibrated method does not.

1) The las file used was extended high enough to validate Rw in shales with Ro and Rt. Note that Pe was not recorded above 1900m.

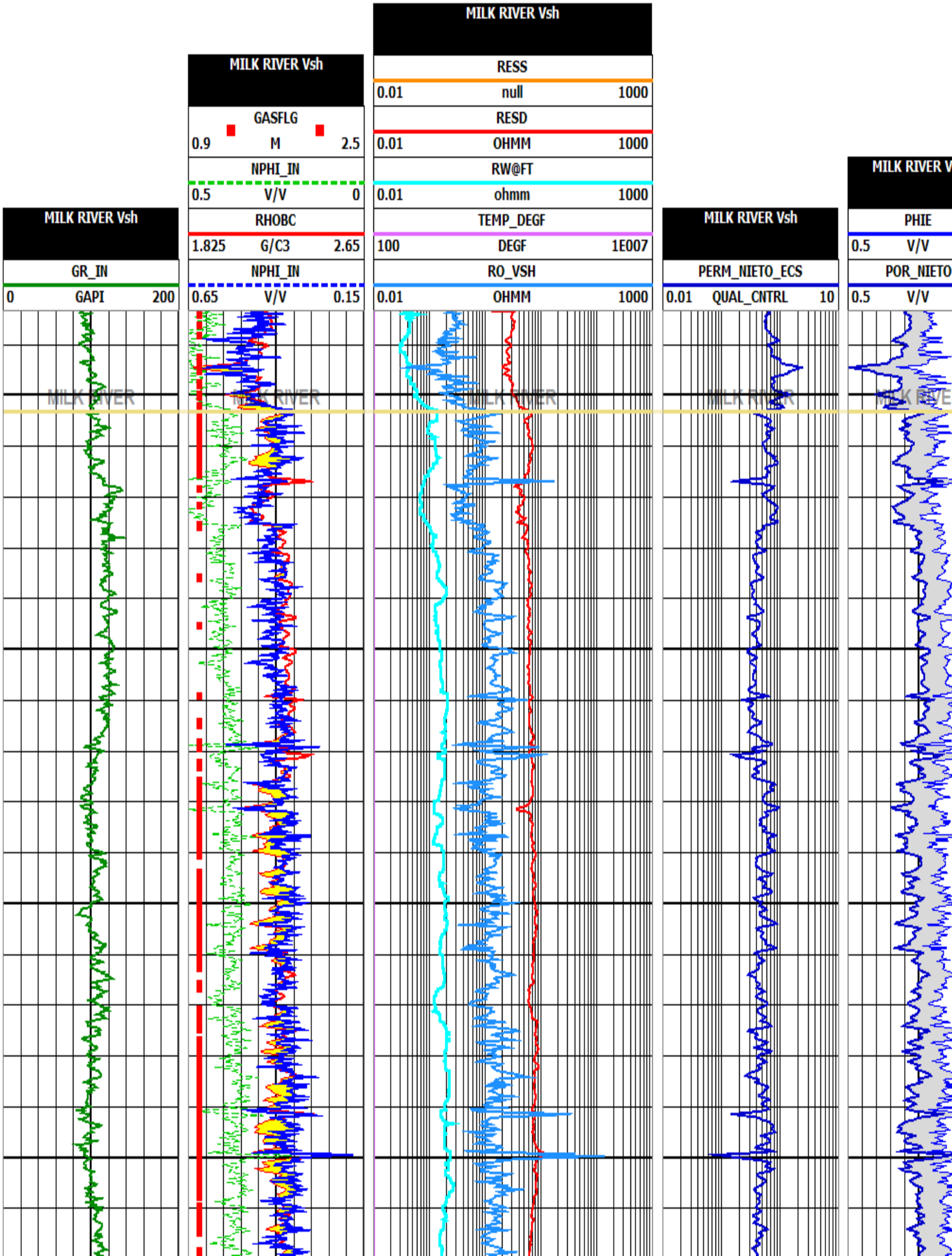

MONTNEY EM
C1
150 MM 250
SP_BASELINED_SL_FINAL
-30 MV 10
GR_IN
0 GAPI 200
MONTNEY EM
RW_SP_SL_FINAL
0.01 OHMM 10000
Rt_ECS
0.01 OHM.M 10000
Ro_ECS_Ghanbarian
0.01 OHMM 10000
F_LOG_CMRP_LIMITED_QL
0.01 OHMM 10000
F_LOG_TCMR_LIMITED_QL
0.01 OHMM 10000
TEMP_DEGF
10 DEGF 1E007
MONTNEY EM
KSDR_CMR
1E-005 mD 1
k_Lamda_ECS
1E-005 mD 1
MONTNEY EM
PHIE_ECS
0.12 V/V 0
PHIE_6
0.12 V/V 0
MONTNEY EM
S_BFV
1 V/V 0
SWE_ECS
1 V/V 0

2) The main zone is below for the EM method;
    a. note the mineralogy: Measured Pe was affected by barite so Magnesium & PEGE were used to find dolomite. Calculated Pe from elements (PEGE). The magnesium showed less dolomite; hence, the difference is attributed to Fe substituting for Mg in the dolomite.
    b. The Sw is lower than the core method.
    c. The perm is less than the core method.


MONTNEY EM
C1
150 MM 250
SP_BASELINED_SL_FINAL
-50 MV 10
GR_IN
0 GAPI 200
MONTNEY EM
RW_SP_SL_FINAL
0.01 OHMM 10000
Rt_ECS
0.01 OHM.M 10000
Ro_ECS_Ghanbarian
0.01 OHMM 10000
F_LOG_CMRP_LIMITED_QL
0.01 OHMM 10000
F_LOG_TCMR_LIMITED_QL
0.01 OHMM 10000
TEMP_DEGF
10 DEGF 1E007
MONTNEY EM
KSDR_CMR
1E-005 mD 1
k_Lamda_ECS
1E-005 mD 1
MONTNEY EM
PHIE_ECS
0.12 V/V 0
PHIE_6
0.12 V/V 0
MONTNEY EM
S_BFV
1 V/V 0
Swt_ECS_Ghanbarian
1 V/V 0
MONTNEY EM
WCLAY_ECS
0 SUM 100
KAO_ILL_CHL_ECS
0 SUM 100
KAO_ILL_ECS
0 SUM 100
KAO_ECS
0 W% 100
WQFM_ECS
100 W%
CEC_ECS
0 MEQ/100G 20
MONTNEY
MONTNEY
MONTNEY
MONTNEY
MONTNEY

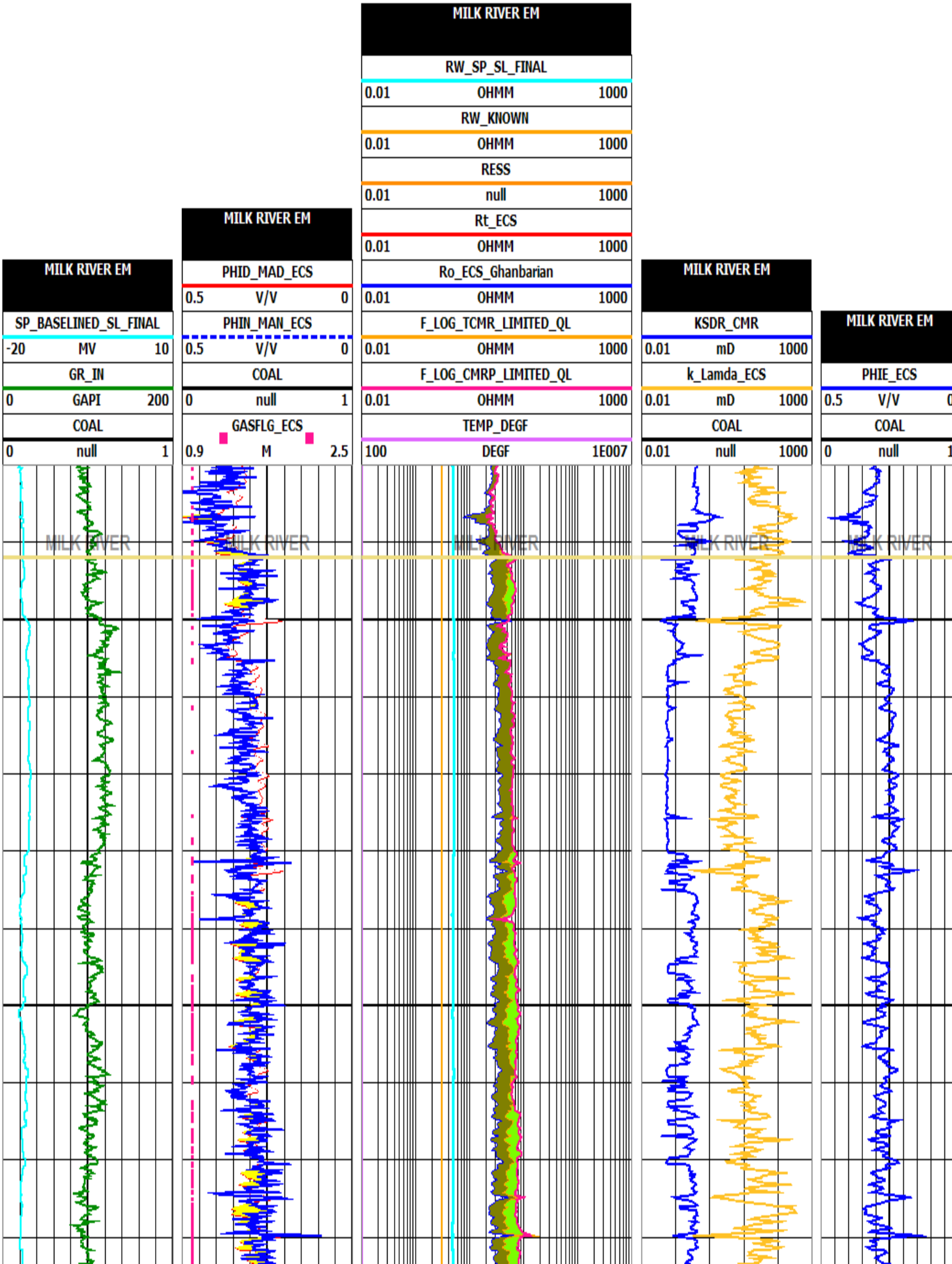
Milk River Alderson -- distal to foreshore environment

Vsh method. Note the shifted neutron of -15 pu is used to find the gas zones. Porosity and Permeability using the Nieto formula works nicely. Vsh was derived by Ross Crain: Vsh is the minimum of GR, N-D and conductivity. Rw and Ro were back-calculated. The Buckles formula was used for Sw to avoid having to know Rw. However, note that Ro and RESD do not match above Milk River, as they should, if the clay compensation was correct.


MILK RIVER Vsh
GR_IN
0 GAPI 200
MILK RIVER Vsh
GASFLG
0.9 M 2.5
NPHI_IN
0.5 V/V 0
RHOBC
1.825 G/C3 2.65
NPHI_IN
0.65 V/V 0.15
MILK RIVER Vsh
RESS
0.01 null 1000
RESD
0.01 OHMM 1000
RW@FT
0.01 ohmm 1000
TEMP_DEGF
100 DEGF 1E007
RO_VSH
0.01 OHMM 1000
MILK RIVER Vsh
PERM_NIETO_ECS
0.01 QUAL_CNTRL 10
MILK RIVER V
PHIE
0.5 V/V
POR_NIETO
0.5 V/V
MILK RIVER
MILK RIVER
MILK RIVER
MILK RIVER
MILK RIVE

EM method.

The matrix-adjusted neutron shows gas when there is less than 5 pu difference. Note that Ro=Rt (RESD) in the shale above the Milk River. Hence, Rw from the SP is correct (i.e. Rw fits the model). A simplified mineral model is used; the full mineral model also shows mica, feldspars and dolomite


MILK RIVER EM
SP_BASELINED_SL_FINAL
-20 MV 10
GR_IN
0 GAPI 200
COAL
0 null 1
MILK RIVER EM
PHID_MAD_ECS
0.5 V/V 0
PHIN_MAN_ECS
0.5 V/V 0
COAL
0 null 1
GASFLG_ECS
0.9 M 2.5
MILK RIVER EM
RW_SP_SL_FINAL
0.01 OHMM 1000
RW_KNOWN
0.01 OHMM 1000
RESS
0.01 null 1000
Rt_ECS
0.01 OHMM 1000
Ro_ECS_Ghanbarian
0.01 OHMM 1000
F_LOG_TCMR_LIMITED_QL
0.01 OHMM 1000
F_LOG_CMRP_LIMITED_QL
0.01 OHMM 1000
TEMP_DEGF
100 DEGF 1E007
MILK RIVER EM
KSDR_CMR
0.01 mD 1000
k_Lamda_ECS
0.01 mD 1000
COAL
0.01 null 1000
MILK RIVER EM
PHIE_ECS
0.5 V/V
COAL
0 null
MILK RIVER
MILK RIVER
MILK RIVER
MILK RIVER
MILK RIVER

In summary, the key to finding pay zones in the Milk River (with Alderson) is to shift the field neutron by -15 porosity units and look for cross-over with the density porosity. In the EM model, gas occurs when the matrix adjusted curves separate by less than 5 pu. Note the CEC falls close to the WCLAY, because the clay is computed as mainly illite with a CEC of 25 meq/l; hence, on the scale selected of 0-20 meq/l, the CEC happens to fall near the Wclay on a 0-100 w/w scale.

In addition, Appendix 1 has a Cretaceous sand environment to illustrate how to obtain the formation water resisitivity from the spntaneous potential. This method differs from past practice. The SP deflection is measured from a calculated zero, rather than from a shale baseline. Furthermore, the SP is coorected for drift usuqally caused by the casing that short-circuits the return to the mud fish. All the EM examples utilize this method to determine Rw. The reason is, when the resistivity has been corrected by CEC, the Ro can be compared to Rt and in a shale [with no organic carbon]; the Ro must equal Rt, thus verifyinbg the correct Rw has been implemented. The Vsh method makes this verification very difficult as usually the Vsh does not exactly correct the Ro in shales.

Conclusions

The EM method is an updated method from the Vsh method. As such, there are additional routines available that result in a more complete computation, resulting in improved water saturation, porosity, permeability and net to gross results.

The Vsh and EM methodologies are just different methods to do the same thing: correct for clay effects on water saturation, porosity and permeability. Science has yielded formulas like Shell's Waxman-Smits-Thomas and Schlumberger's Dual Water; empiricism has provided Simandoux, Indonesian and modified Dual Water plus localized adaptations. Universal models only [seem to] exist when one applies EM. Any model can be improved with localized adaptatations to core measurements.

When should one use Vsh instead of element to mineral methods?

1) If 6000 wells, use Vsh and check key wells with EM. One probably only wants to find sweet spots. The preparation involved in estimating missing data when only triple combo logs have been run, such as elements, NMR, DTS, U, K, Th, is too time consuming for more than 10-100 wells at a time.

2) If no prediction of missing curves is possible, use Vsh. I use Geological Analysis by Maximum Likehood Systems (GAMLS, Ref. 1) to predict missing data as it is easy and accurate.

3) If no knowledge of ECS/Flex/Gem nor of NMR, use Vsh. There is a learning curve to EM methods. Contact author.

4) If Vsh is "good enough", use Vsh.

5) If Vsh software is all you have, use Vsh.

6) If there is core with excellent measurements, derive equations directly from the core (as John Nieto, Canbriam Energy Inc., does, Ref. 12; "We were very careful with our core acquisition for D-S. *OBM, Sleeved core, end capped, Shipped chilled to Lab (not frozen), Immediate plug cutting (2am!), Immediate immersion in Soxhlet extractors, Dummy plugs, Clean toluene. Months of cleaning , then drying. (per AAPG))"*

7) One can think of the EM method as just a way to get Vsh in units that are more related to the rock and can be cross-checked with core. In summary, we use what is available and do the best we can. For me, that is EM. For others it is core or Vsh.

Acknowledgements

Aminex PLC has graciously provided permission to publish using some of their data.

> "I am more than happy for you to publish your findings and I am always happy to further the technical abilities of our industry. A nice mention or acknowledgement of Aminex .... doesn't hurt either!"

The rest of the data was obtained via sources that provide released information.

References

1) Eslinger, E., and R. V. Everett, 2012, 'Petrophysics in gas shales', in J. A. Breyer, ed., Shale Reservoirs—Giant resources for the 21st century: AAPG Memoir 97, p. 419–451.

2) Eslinger, E., and Boyle, F., 'Building a Multi-Well Model for Partitioning Spectroscopy Log Elements into Minerals Using Core Mineralogy for Calibration', SPWLA 54th Annual Logging Symposium, June 22-26, 2013.

3) M. M. Herron, SPE, D. L. Johnson and L. M. Schwartz, Schlumberger-Doll Research, 'A Robust Permeability Estimator for Siliciclastics', SPE 49301, 1998 SPE Annual Technical Conference and Exhibition held in New Orleans, Louisiana, 27–30 September 1968.

4) Susan L. Herron and Michael M. Herron, 'APPLICATION OF NUCLEAR SPECTROSCOPY LOGS TO THE DERIVATION OF FORMATION MATRIX DENSITY' Paper JJ Presented at the 41st Annual Logging Symposium of the Society of Professional Well Log Analysts, June 4-7, 2000, Dallas, Texas.

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.

8) Everett, R. V. 'London Petrophysical Society June Newsletter 2017'.

9) Ghanbarian, B, Hunt, A. g., Ewing, R. P. Skinner, T. E., 'Universal scaling of the formation factor in porous media derived by combining percolation and effective medium theories' Geophysical Research letters, 10./2014GL060180, Ghanbarian-alavijeh.2@wright.edu

10) Herron, S. L., Herron, M. M., Pirie, Iain, Saldungaray, Craddock, Paul, Charsky, Alyssa, Polyakov, Marina, Shray, Frank, Li, Ting, 'Application and Quality Control of Core Data for the Development and Validation of Elemental Spectroscopy Log Interpretation', SPWLA, 55th Annual Logging Symposium, Abu Dhabi, United Arab Emirates, May 18-22, 2014.

11) Freedman, R., Min, C. C., Gubelin, G., Freeman, J. J., McGuiness, T., Terry, R., Rawlence, D., 'Combining NMR and Density Logs for Petrophysical Analysis in Gas-Bearing Formations'. SPWLA 1998.

12) Nieto, J., Bercha, R., Chan, J., 'Shale Gas petrophysics – Montney and Muskwa, are they Barnett look-alikes?' SPWLA JUNE 21-24, 2009

13) Everett, R. V. 'Steps to compute using PDHC' CWLS Advanced Interpretation School May, 2017-2018 notes.

Appendix 1: Determining Rw from SP: validating Rw from the SP and EM-Derived Ro

Step 1

A value for the "known Rw" is calculated. A known Rw can come from an estimate, water catalog, DST, formation tester, etc. It represents an Rw at only one depth in the well that samples were taken from. Our estimate for this well is to solve for Rw assuming 100% Sw in a zone below the gas/water contact. Remember this value will be cross-checked later so we do not have to be precisely accurate at this stage. For Rw_known, use 0.2 at formation temperature (~ 110C (230F)). In the formulas, "TEMP_DEGF" is some version of 0.0198*DEPTHFT+42.805, that provides a bottom hole reservoir temperature that is estimated about 10 to 20 degrees F above the highest log-recorded temperature [the hole temperature is less because of mud circulation, of course].

Then Rw_known=0.2*(230+6.77)/(TEMP_DEGF+6.77).

Also calculate Rmf from a temperature gradient, [RMF]*([measured temperature] +6.77)/(TEMP_DEGF+6.77).

Also, Rw of 0.05@308F, 0.05*(308+6.77)/(TEMP_DEGF+6.77); this value is a "ballpark" for all reservoirs and happens to be the value for the Cardium, by serendipity. We will use it only to get an approximate zero line, rather than using a shale baseline.

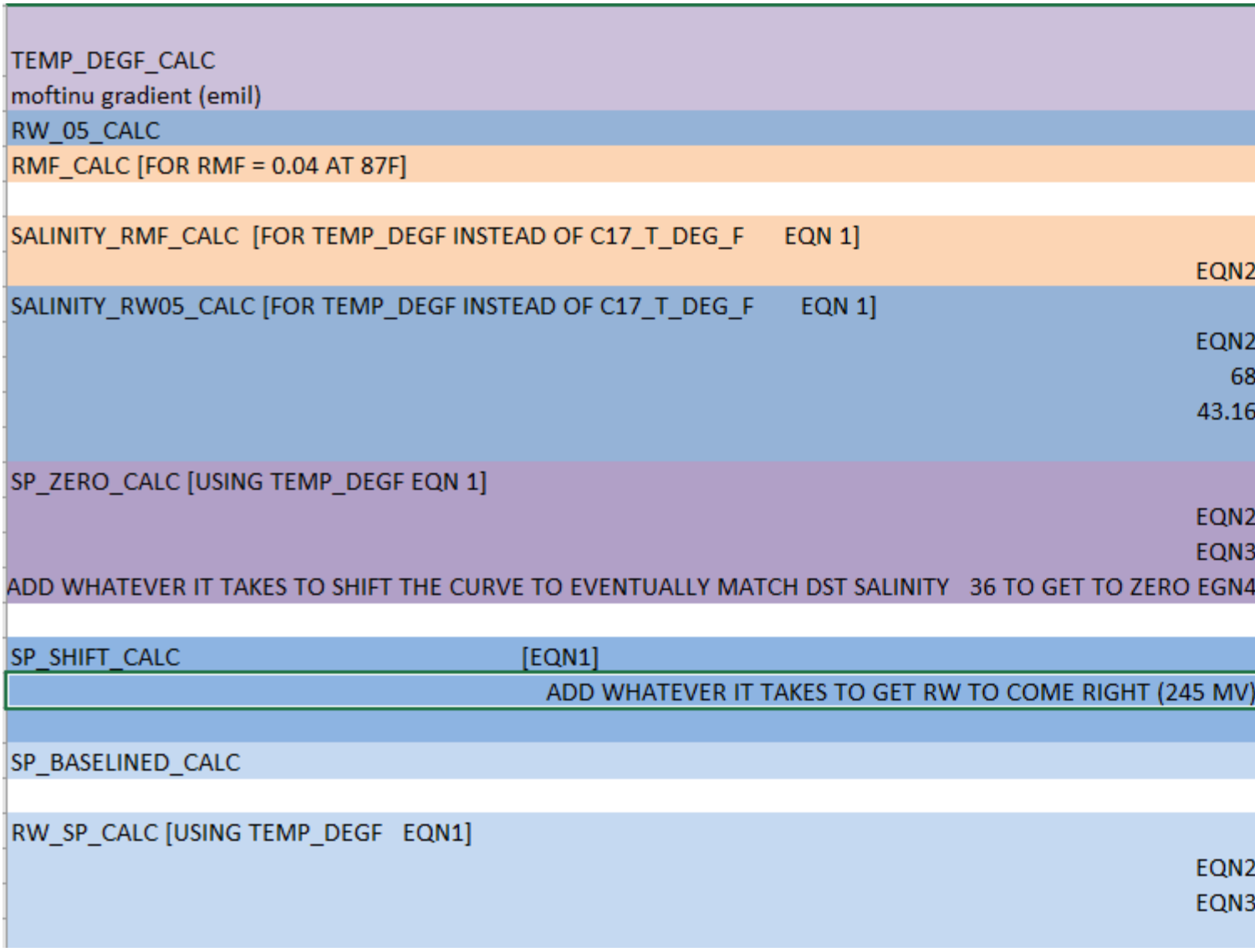
Step 2

The next step is to find SP_ZERO. You solve for it from SP_ZERO_CALC=-k*log(RMF/RW_05). This will not give an exact zero average over the interval but will get you into the ballpark. Note we do not use a shale baseline for a zero line; we want a non-zero Rw in shales as well as sands. The first attempt is:

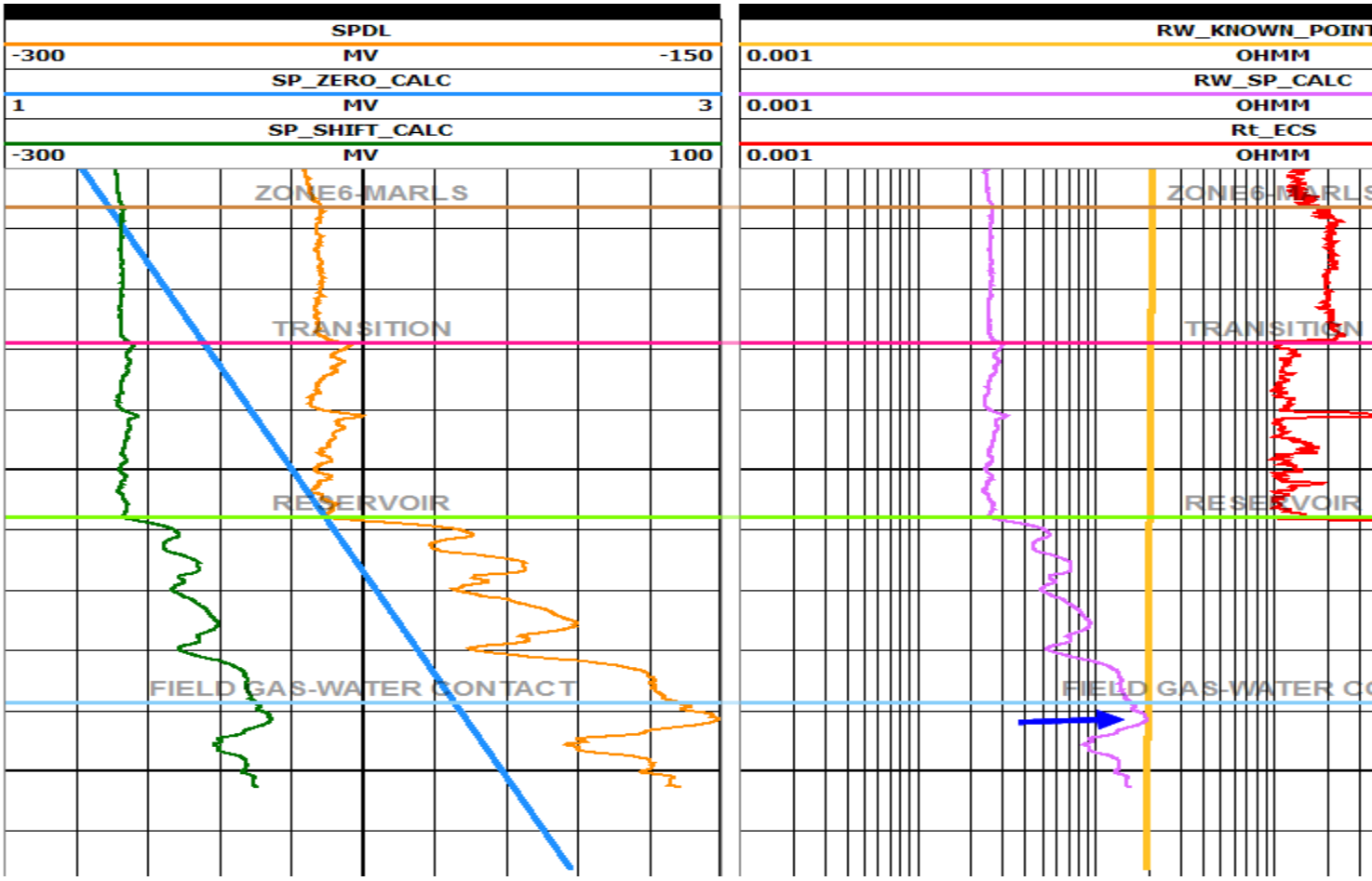
Note the above calculated value does not average at zero as the left and right values are 42 and 56. Now, add a constant until the left and right average values are the same. i.e. the average is zero over the interval selected, such as -3 and +3 averages.

The plot above shows the left and right values on the plot are the same, so the average is zero. This is where you want to be. Now plot Rw_05, RW_KNOWN and Rt on the log track; plus, SP [SPDL], SP_ZERO_CALC and temperature in the left, linear track.

Now plot an initial Rw_SP_CALC and see how close it comes to the Rw_KNOWN_POINT2. Keep changing SP_SHIFT_CALC until Rw_SP_CALC just touches Rw_KNOWN_POINT2. The formulas are:

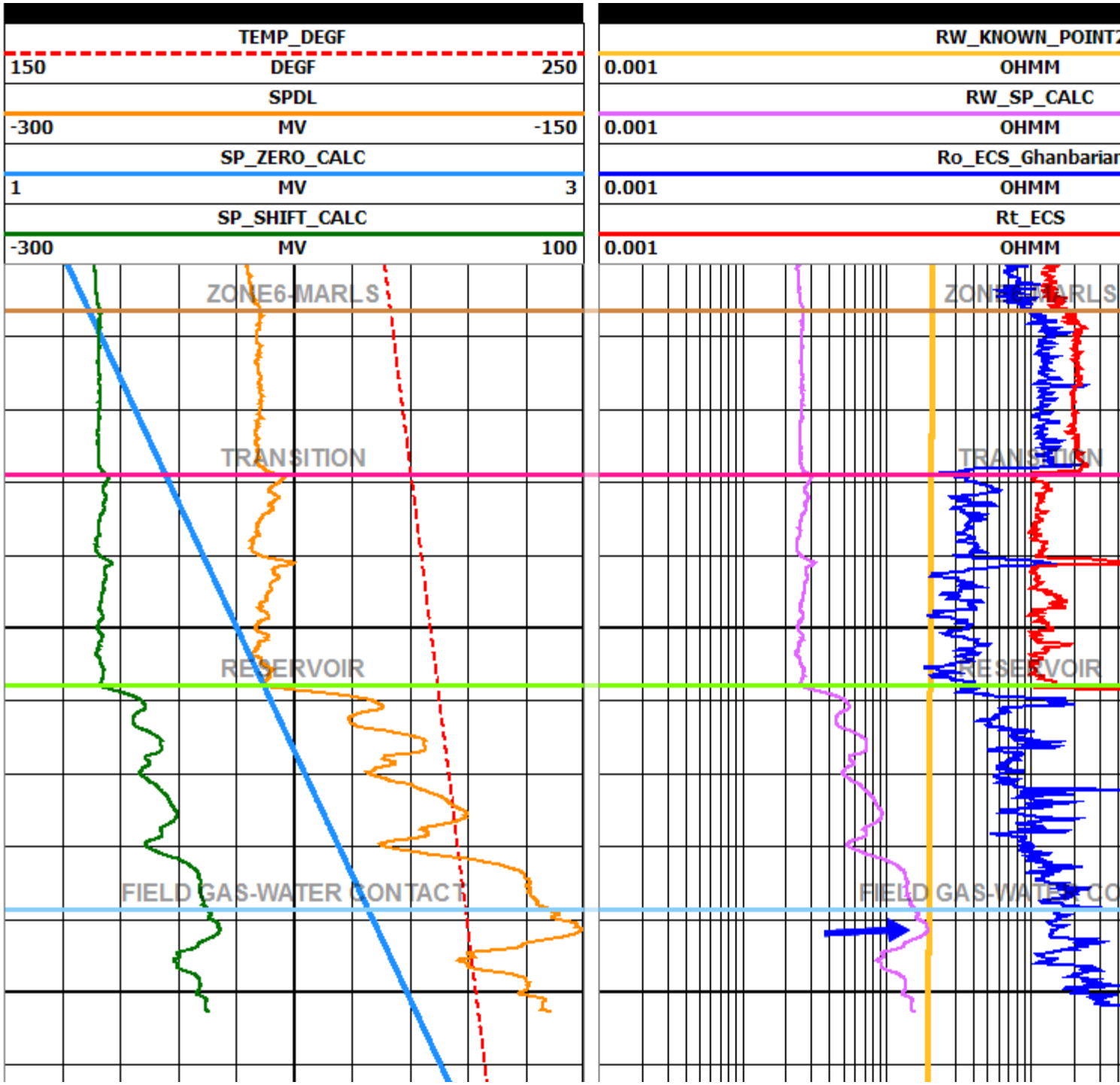


We apply another "ADD" to SP_SHIFT_CALC to move the RW_SP_CALC to the right. This is trial and error until we get the two curves to agree at the arrow. Using 0.2, we must apply a shift to the right. By trial and error, we find that a shift of +245mv seems to work OK. Arrow shows where we match.



Note the purple line just nudges the yellow line. So, at this point in the Rw_SP method, we go to the Ro [Ro_ECS_Ghanbarian] calculation step to see if the logic holds up that the Rw [so far] is the correct final Rw to use.

We have a variable Rw moderated by the SP. Compare Ro and Rt in a wet zone anywhere in the hole; this may be in shales [the only zones that are wet in Lithic and Tar lithologies are shales]. In this well, the zone above the 'transition zone' is wet, so we will go there.



The result is, our Ro is too low compared to Rt in the wet Marl zone; therefore, the Rw must be too low. Note that the water saturation is not 100% (i.e. Ro<Rt) at the field gas water contact, even though water is produced. The reason the field produces water from this zone is that [NMR, CMR™] "free porosity" is greater than the hydrocarbon filled porosity (CMRP>HCPV). Hence, there is free water. In addition, the free water is fresher than water in the gas zone. The fresh water probably comes from meteoric water since the higher the Sw, the higher the relative perm is to water. Having meteoric water appears to be common in a rift basin. Also, meteoric water is common in the Belly River and Milk River of the Western Canadian Sedimentary Basin.

Now cycle, try SP_SHIFT_CALC have a value added to them. Not "rocket science", just paste an "add" and try:

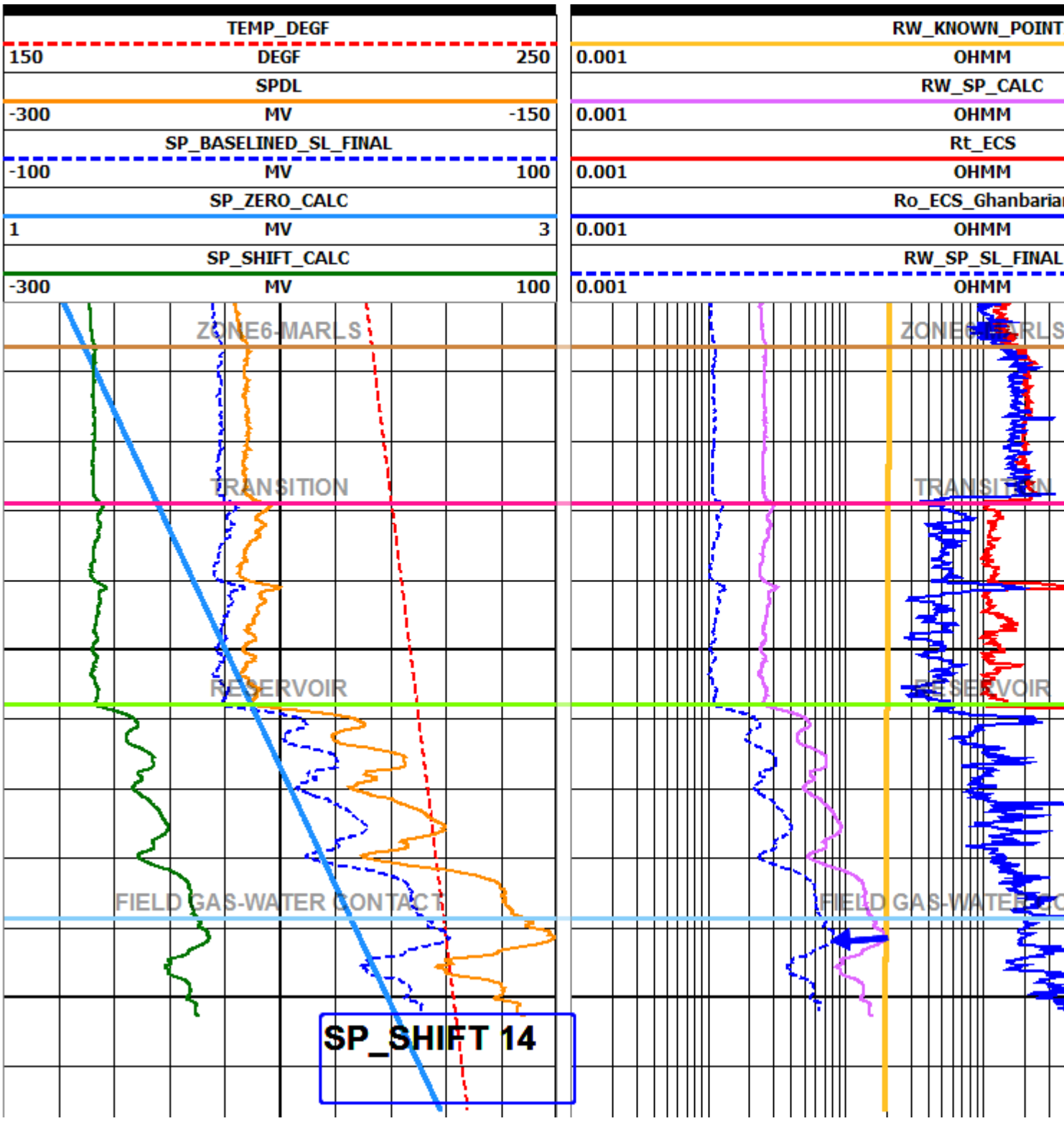
1) SP_SHIFT_CALC, ADD 10 (Rw too low)

keep cycling...2, 3, 4, etc., until you get Rw acceptable:

14) SP_SHIFT_CALC, ADD an amount to make Rw acceptable. Our check that we have the correct Rw, is to ensure that in the resistivity of the entire interval, Ro <= Rt. Note the transition zone has Ro<Rt as we would expect since there are hydrocarbons in the transition zone. Immediately above the transition zone, we have Ro very close to Rt indicating the zone is wet. The point of the exercise is that one should review the entire well that one has available. One must allow for SP drift, especially as one approaches casing. One can see that the correct Rw is not 0.2 but rather 0.08 at formation temperature at the blue arrow. In the pay zone, Rw is about 0.02 at temperature.

15) If one is convinced the RW_KNOWN is correct, then one may have to squeeze the amplitude of the SP deflection to obtain a fit. In cases of the Lithic environment, muds are very fresh and the SP deflection is huge but the SP equation is beyond its limit of a dilute NaCl environment, custom analysis may be needed. The same methodology applies. Just reduce the deflection amplitude to fit the data.

Result looks like:



In summary, this is a powerful method. We are privileged to have it coded.

APPENDIX 2 Ghanbarian code

For utility of readers familiar with code who may like to update, the Ghanbarian formation factor is presented in coding language, since the formulas may not be as clear in the paper. One can just cut and paste or modify to suit their code. The paper (Ref. 9) explains the details. In summary, the Ghanbarian formation factor provides an improved formation factor relationship, based on

Percolation theory, so we have chosen to use it. The variable “ba5” is total porosity determined from the EM-derived grain density.

The variable “c501” is an option to use the formation factor or not.

```
// ********CUSTOM CODE*********
// TODO: customized analysis - 2014_Ghanbarian_FormationFactor.pdf
// https://trello-attachments.s3.amazonaws.com/53adc190ec2c26b9f4ef9432/53c0373bfeb064ac50f551fb/f2dcae771a473797c5ed77c4f3654d1c/
// if (PHIt < PHI < PHIx) {
//    F = ((1-PHIt)*(PHIx-PHIt)) / (PHI-PHIt)^2
// } else if (PHIx < PHI < 1) {
//    F = (1-PHIt)/(PHI-PHIt)
// }
// where PHIt is approx 0.1 * PHI
final double porosity = ba5;
final double thresholdPorosity = 0.1 * porosity;
final double cFG5;
if (thresholdPorosity < porosity && porosity < ip_input_param.get("$c$501")) {
    cFG5 = ((1 - thresholdPorosity)*(ip_input_param.get("$c$501") - thresholdPorosity))
            / Math.pow((porosity - thresholdPorosity), br5);
} else {
    cFG5 = (1 - thresholdPorosity) / (porosity - thresholdPorosity);
}

ecs_out.put("FormationFactor_Ghanbarian", cFG5);
```

Readers who want more detail are advised to contact Jamie Everett, MSc., jamie@everett-energy_software.com

END