Predicting oil sands viscosity from well logs, NMR logs, and calculated seismic properties

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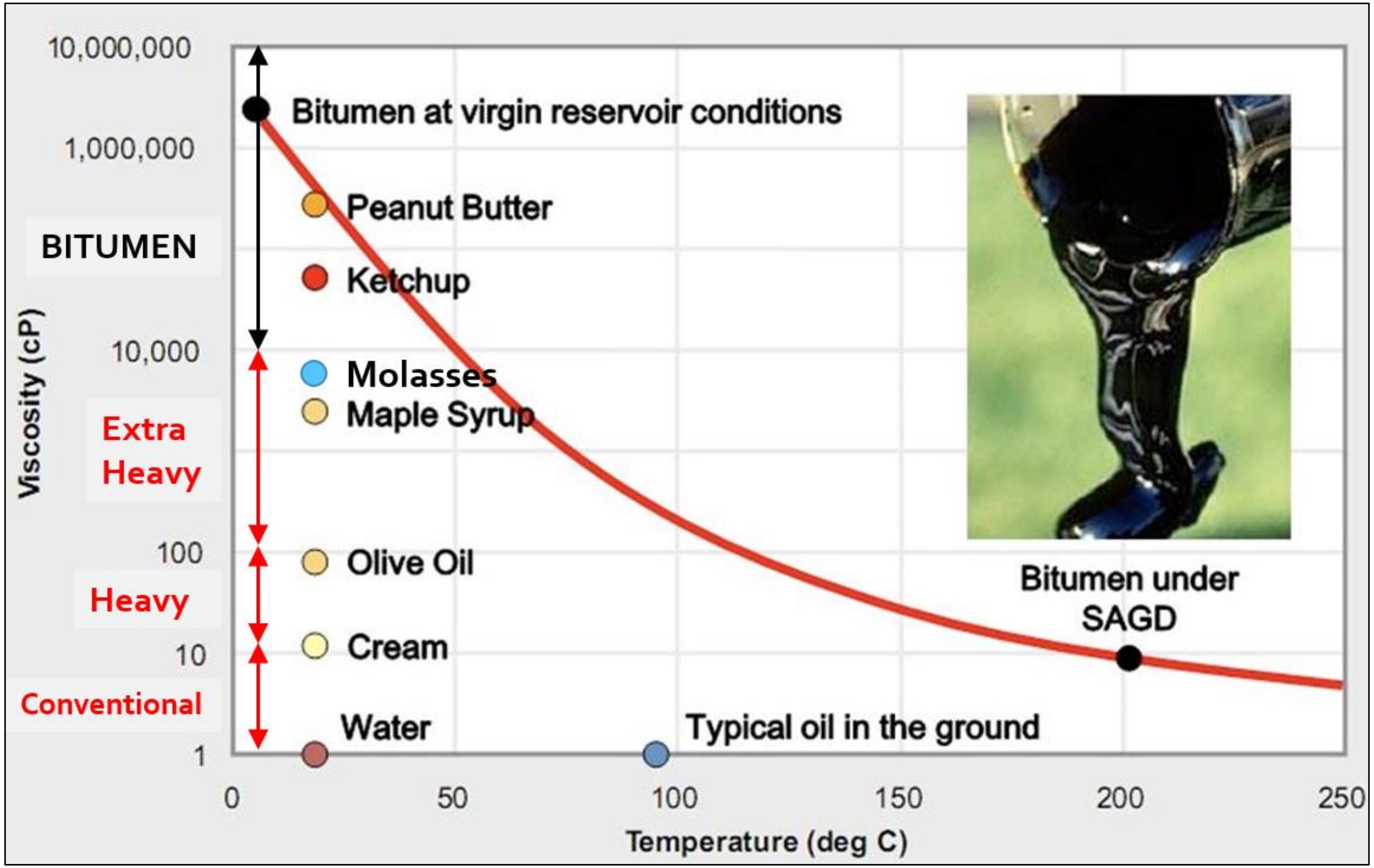
CREWES Meeting – Friday December 2nd 2016

Oil grades based on their viscosities

- Steam injection decreases the viscosity so the bitumen can flow



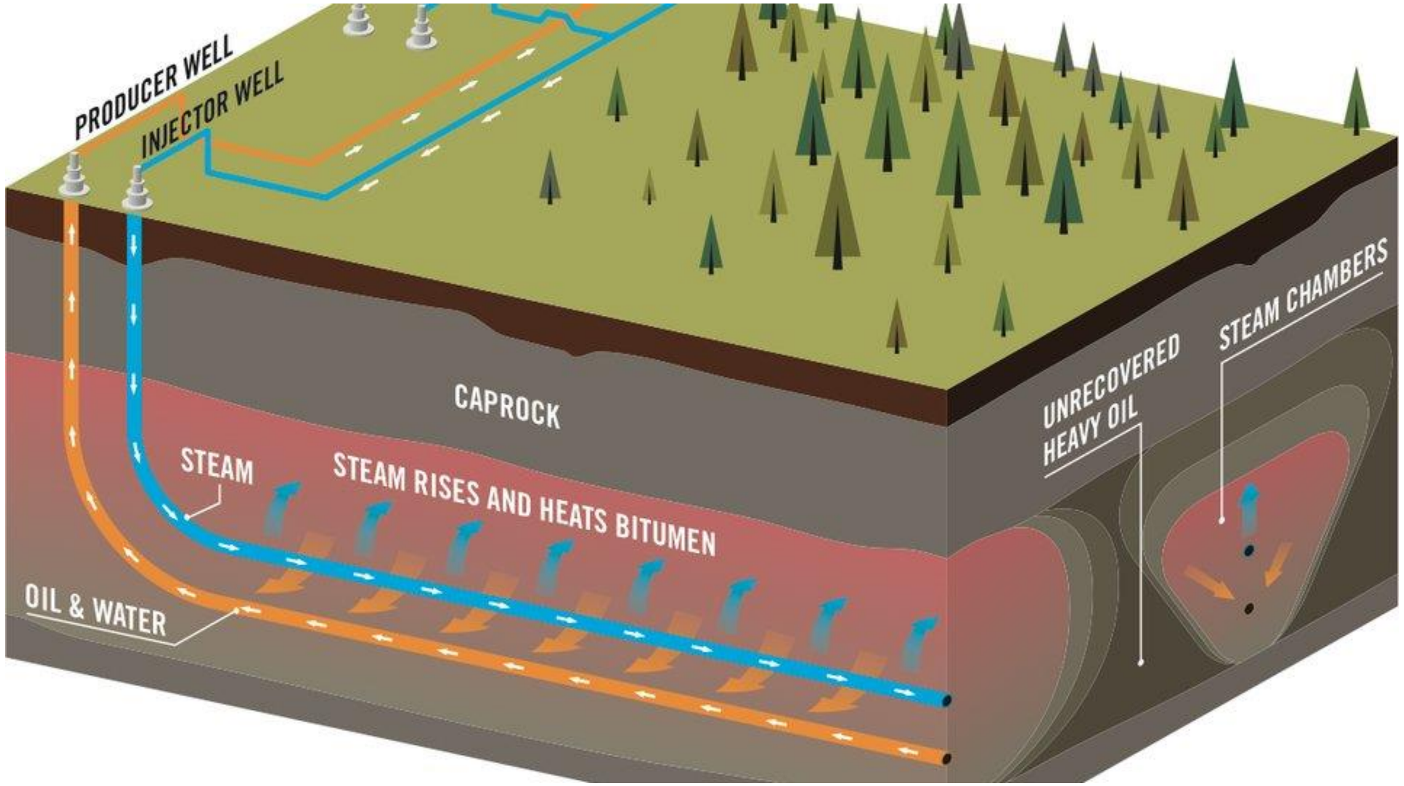
ConocoPhillips Oil Sands website

Why do we care about viscosity?

- *"Viscosity is the key parameter controlling heavy-oil production and, as we shall see, it also has a strong influence on seismic properties."* (Han & Liu & Batzle, 2008)
- Knowing viscosity beforehand will greatly aid in planning the optimal reservoir development strategy

- **<u>Ultimate goal:</u>** Develop prediction equations for viscosity (and API gravity) that can be used on any nearby well with a standard suite of logs.

<u>Steam-Assisted Gravity Drainage</u>

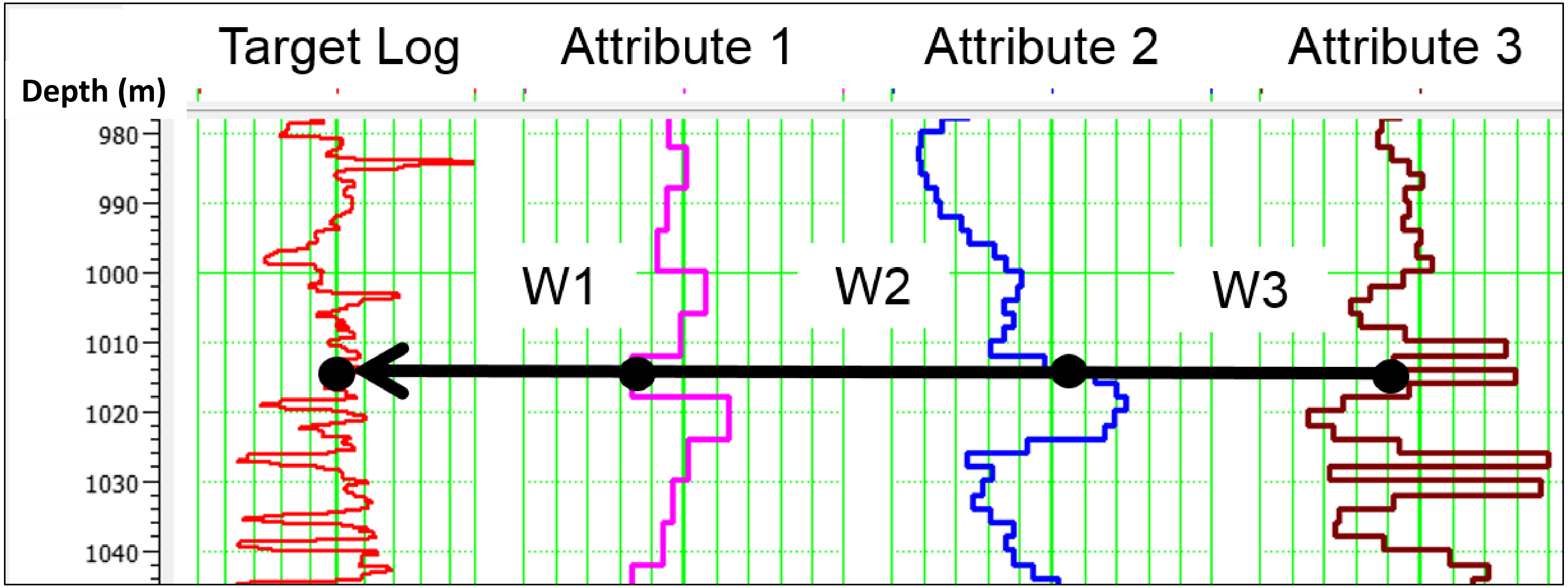


Steam chambers reduce viscosity

Theory of multi-attribute-analysis

Multi-attribute analysis

- At each time sample, the target log is modeled as a linear combination of several attributes.



Hampson-Russell Emerge™ course notes

Example: Predicting Viscosity using 3 attributes

$$V(z) = w_0 + w_1 D(z) + w_2 G(z) + w_3 R(z)$$

where: *V(z)* = Viscosity (cP)
D(z) = Bulk density (kg/m³)
G(z) = Gamma ray (API units)
R(z) = Resistivity (Ohm*m)

D, G, and R were chosen arbitrarily here

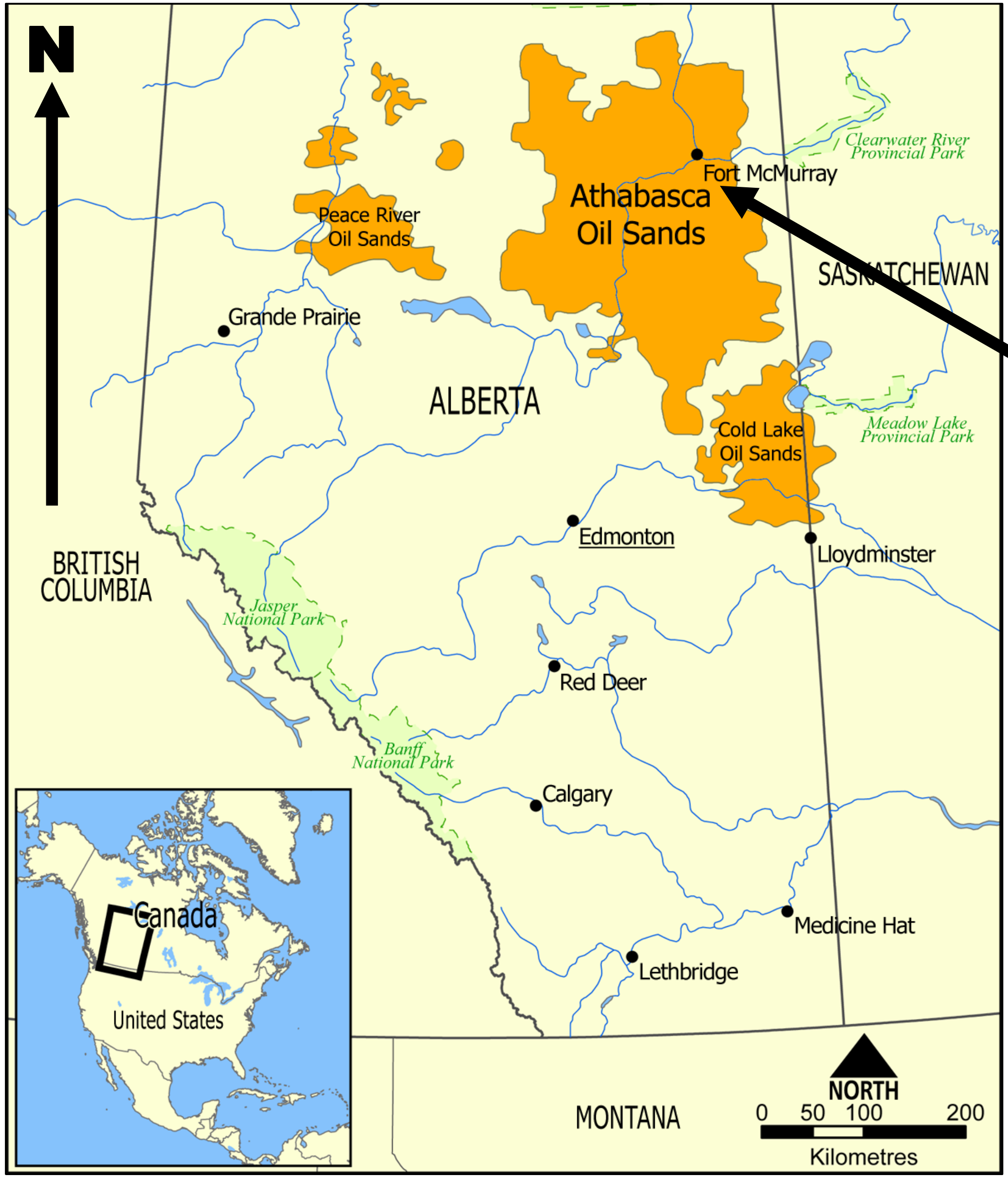
In matrix form:

$$\begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_N \end{bmatrix} = \begin{bmatrix} 1 & D_1 & G_1 & R_1 \\ 1 & D_2 & G_2 & R_2 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & D_N & G_N & R_N \end{bmatrix} \begin{bmatrix} w_0 \\ w_1 \\ w_2 \\ w_3 \end{bmatrix}$$

Or more compactly as: $\boldsymbol{V} = A\boldsymbol{W}$

The regression coefficients can be solved for using least-squares: $\boldsymbol{W} = [A^T A]^{-1} A^T \boldsymbol{V}$

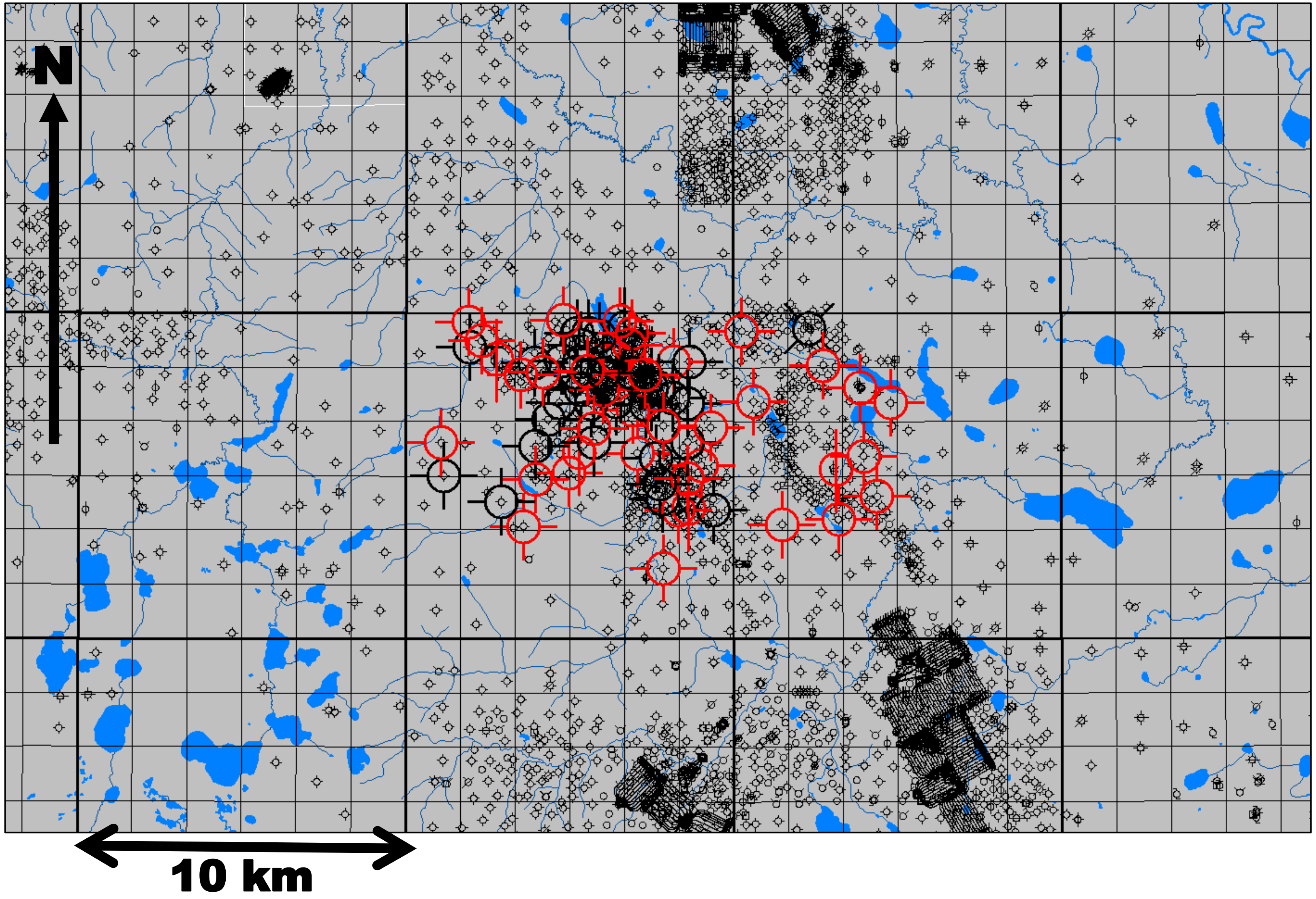
Oil Sands Study Area



Wikipedia

- Located 40km SE of Fort McMurray in the Athabasca oil sands
- McMurray formation bitumen

Oil Sands Study Area



- **78** TOTAL wells with viscosity measurements (large well symbols)
- **40** wells with viscosity measurements and all necessary logs (shown in red)
- Viscosity range from **9,000 cP to 541,000 cP**

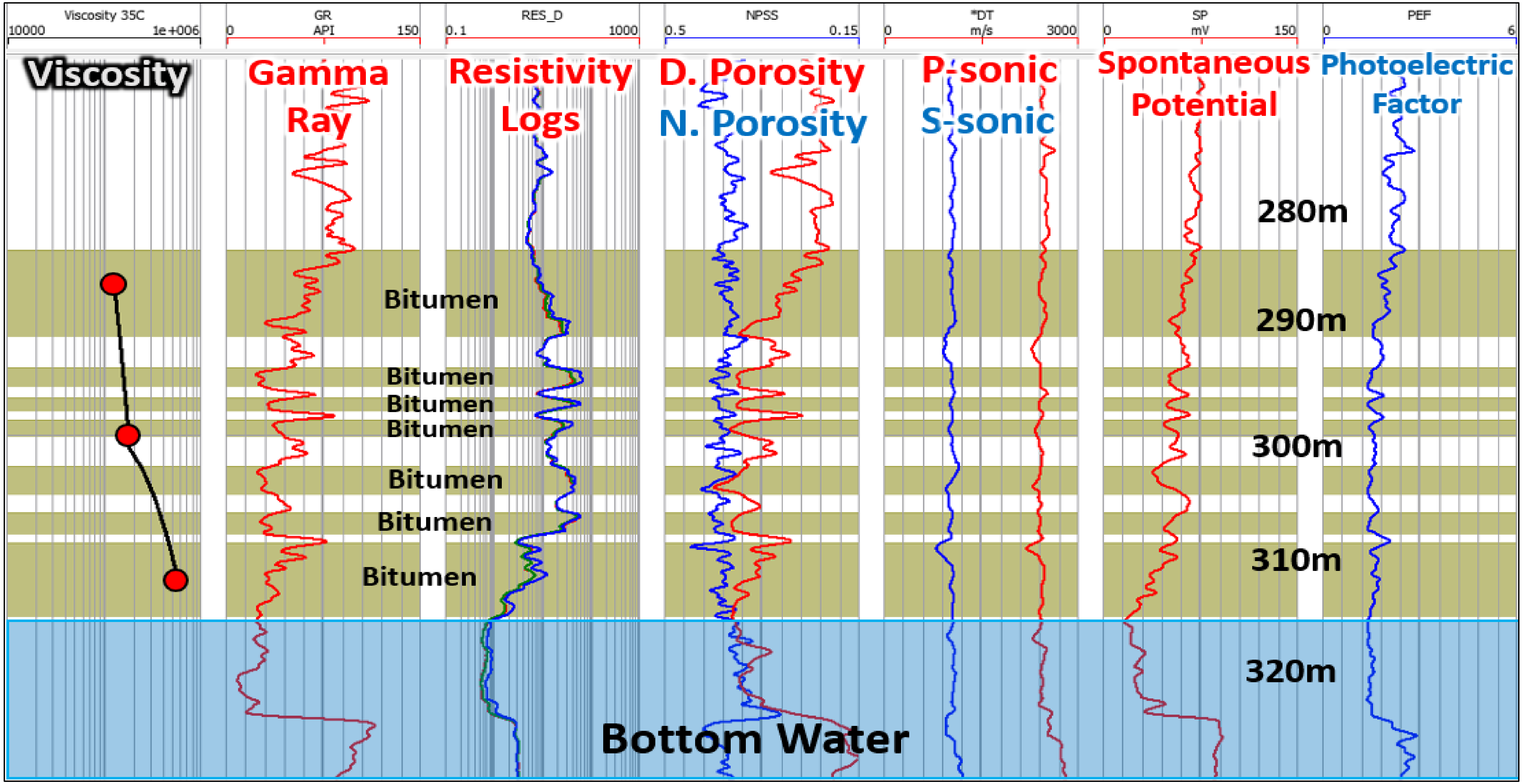
Mean: 121,000 cP

St. Dev: 100,000 cP

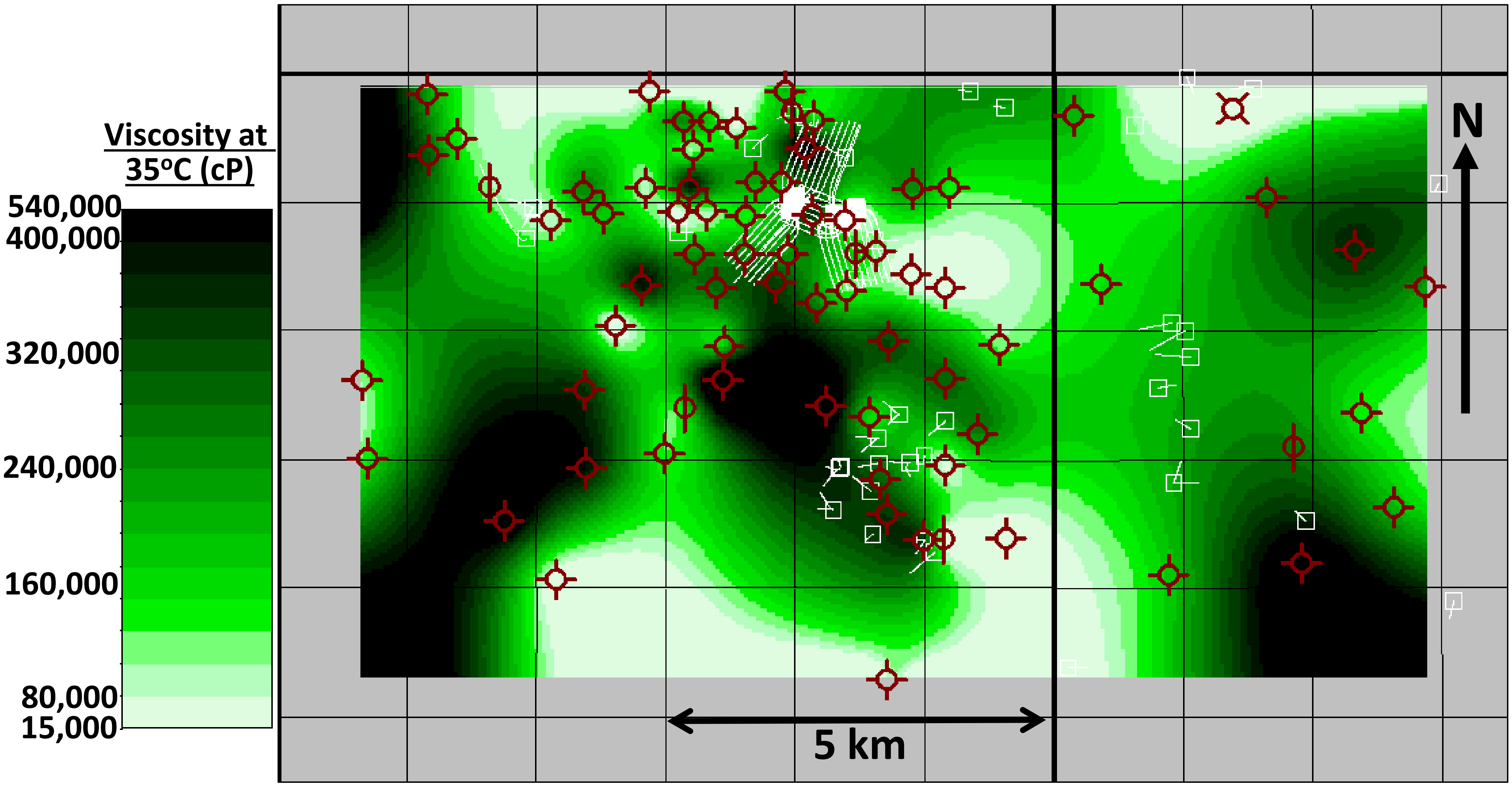
(Measured at 35^{0}C)

Type well in the study area

Study is focused to the McMurray bitumen interval



Viscosity Map – base viscosity measurements



All data wells shown in dark red

Normalizing the logs

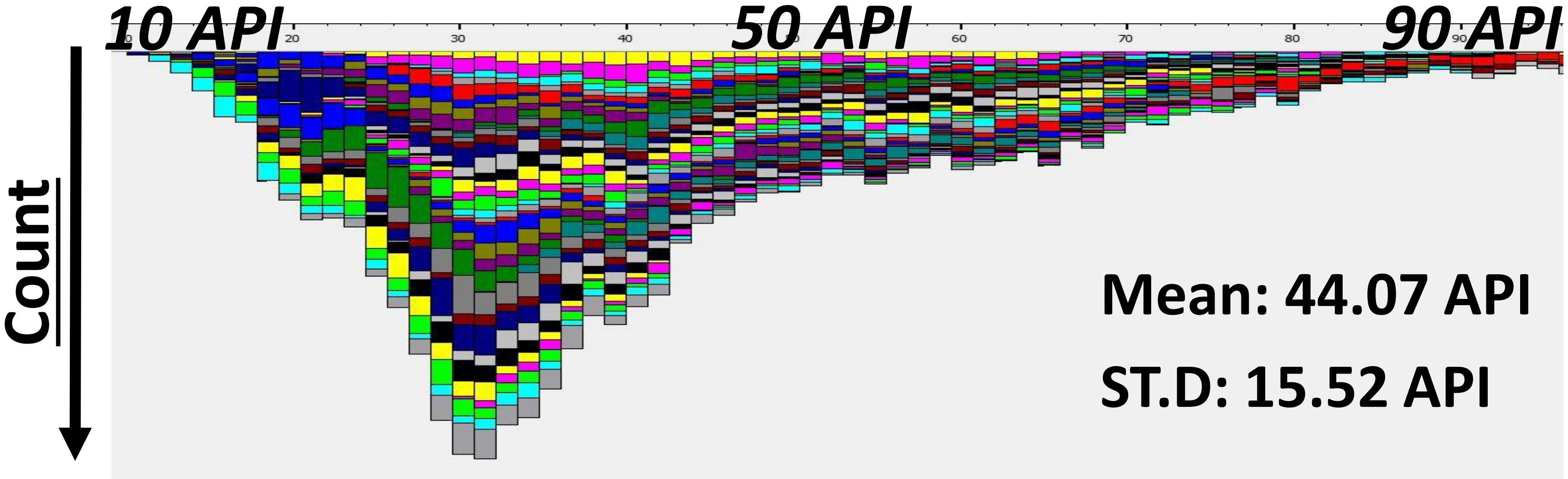
$$Output(i) = \frac{Measured(i) - Average}{Std.Dev.} * Desired.Std.Dev + Desired.Mean$$

“Well log normalization identifies and removes systematic errors from well log data so that reliable results may be obtained for reservoir evaluation, solving difficult correlation and seismic modeling problems”.

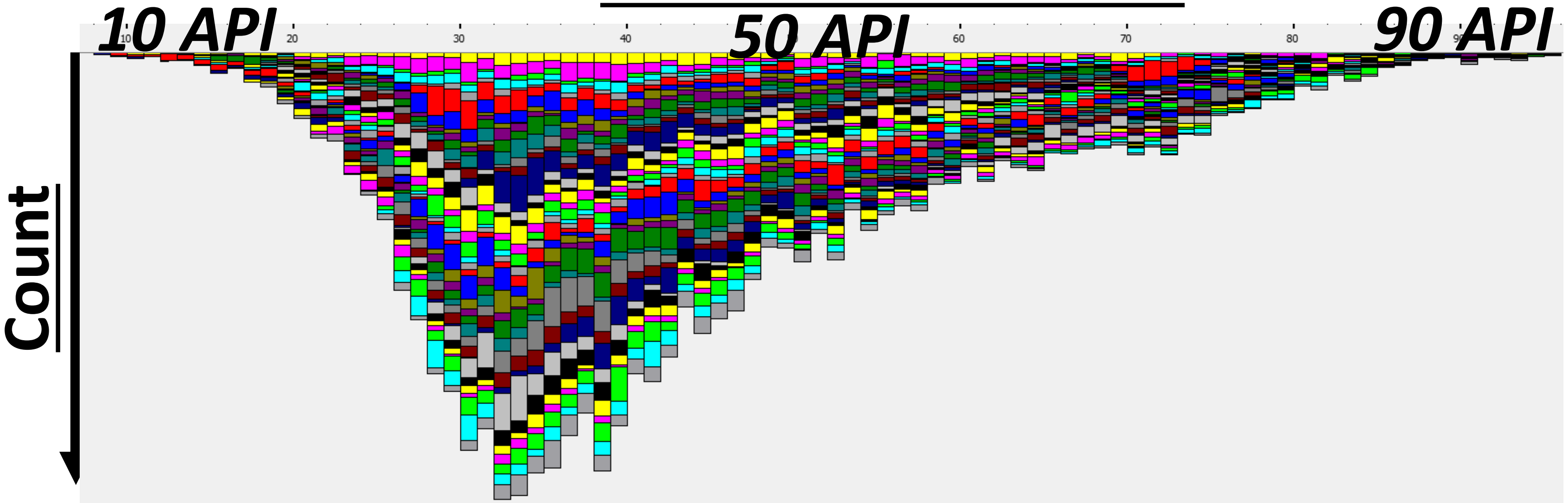
(Daniel Shier, 2004, Petrophysics)

Normalizing the Gamma Ray logs

Gamma Ray Distribution for all wells in bitumen zone



AFTER normalization



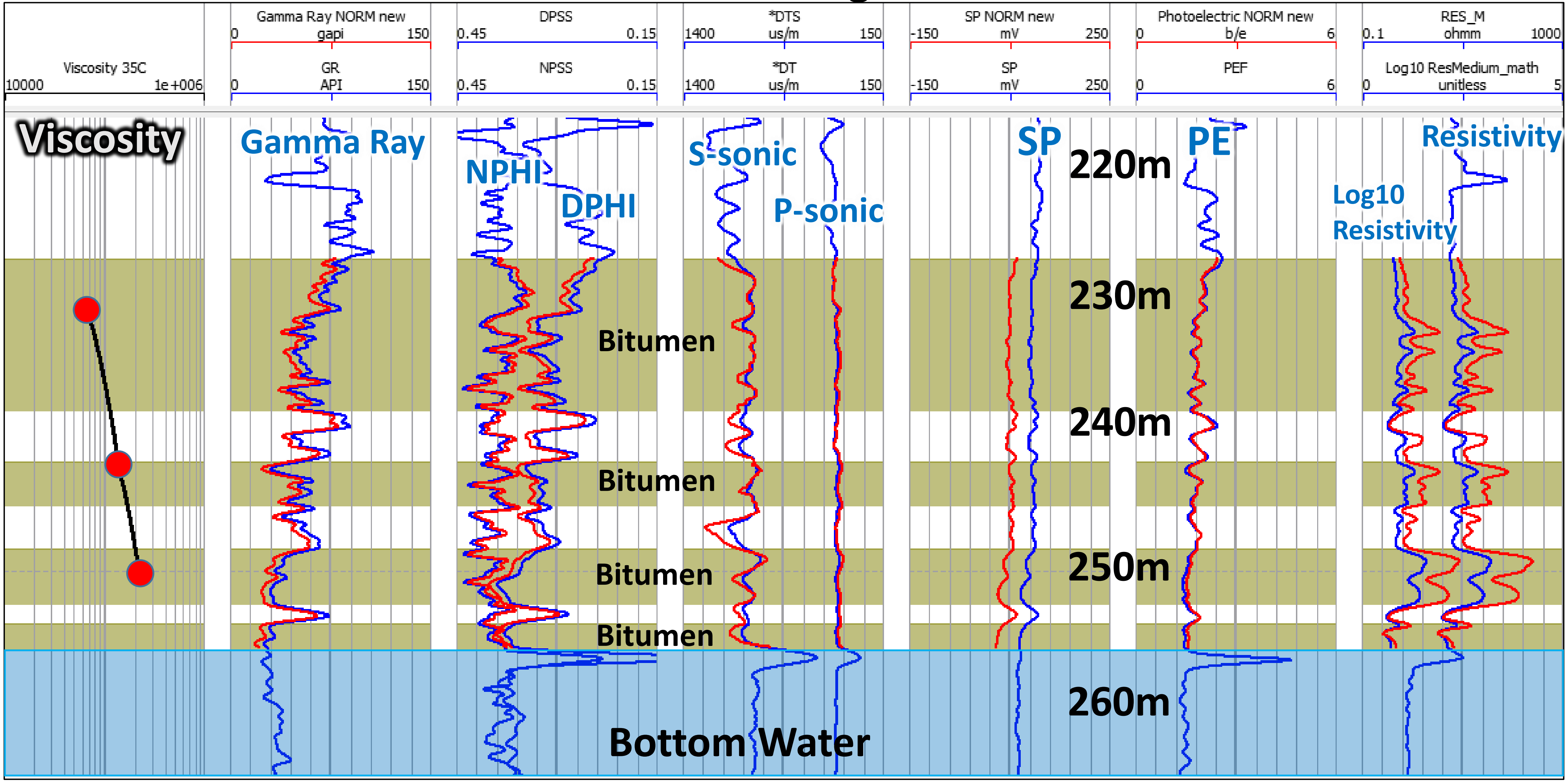
40 **project wells**

Color coded by wells

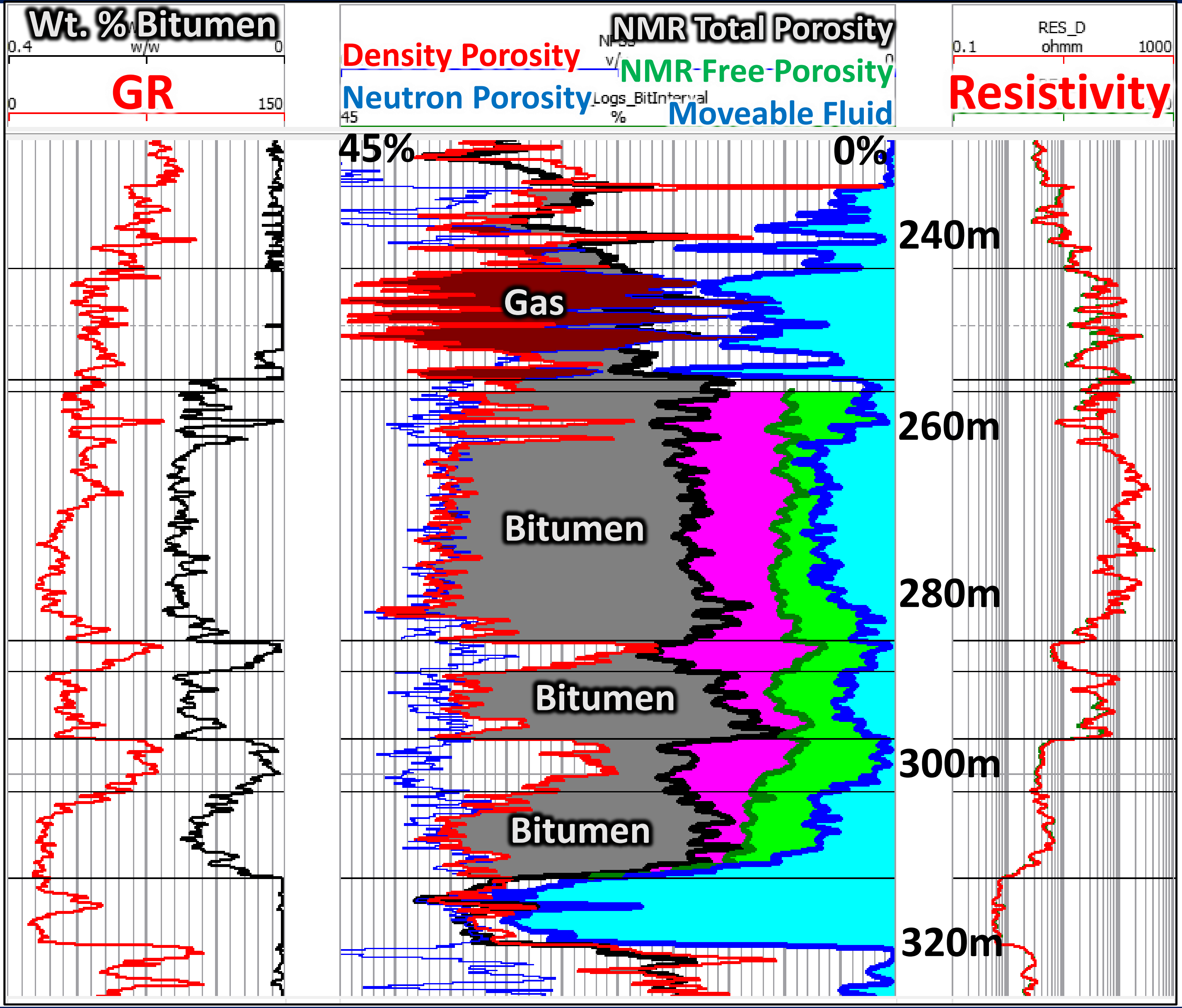
Analysis Window:
Top to base bitumen

What the normalized logs look like

Normalized logs in **red**



Oil sands well with NMR logs



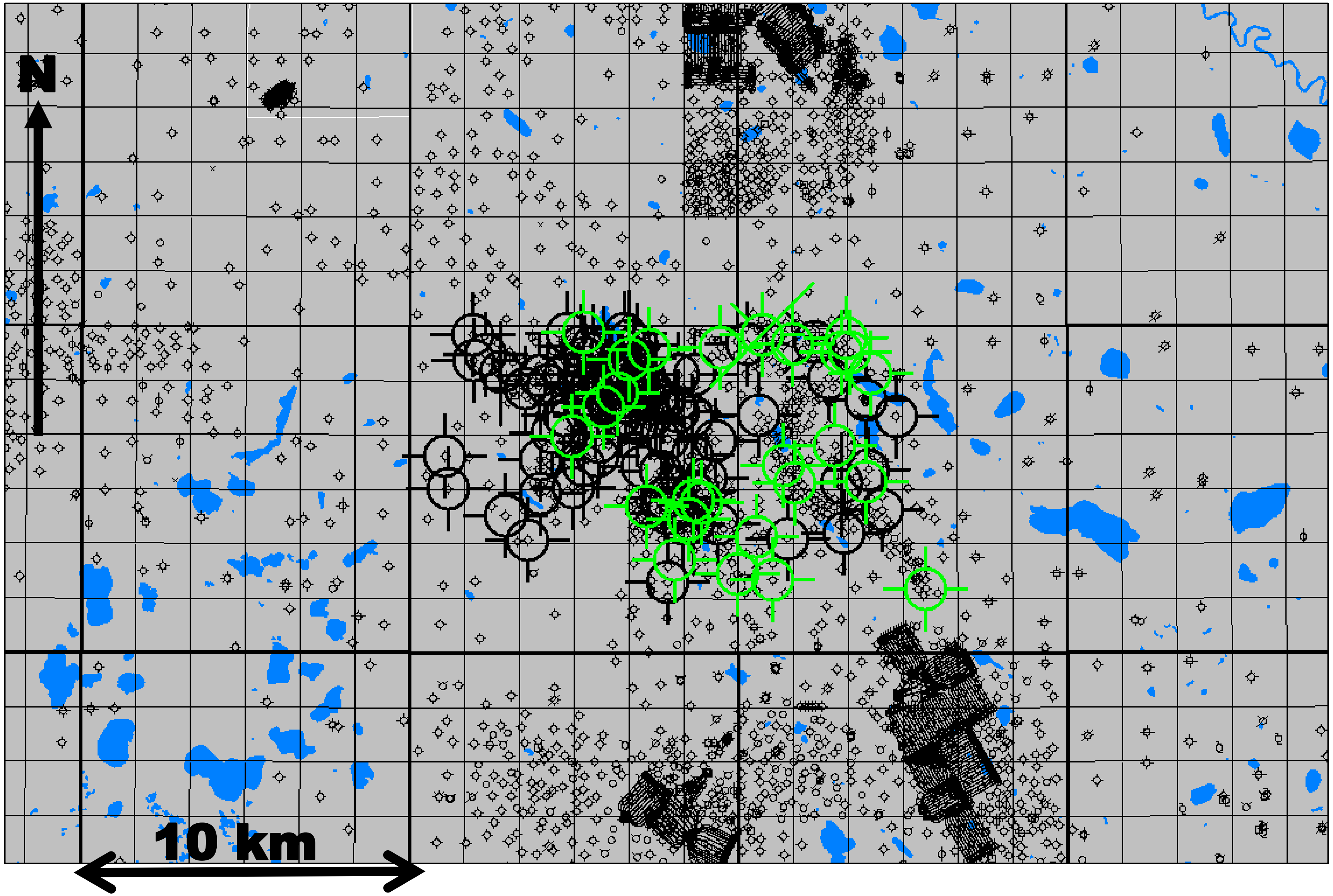
Dark gray is bitumen which NMR cannot see

Magenta is hydrocarbon in small pores with poor mobility

Green is moveable hydrocarbons in medium pores

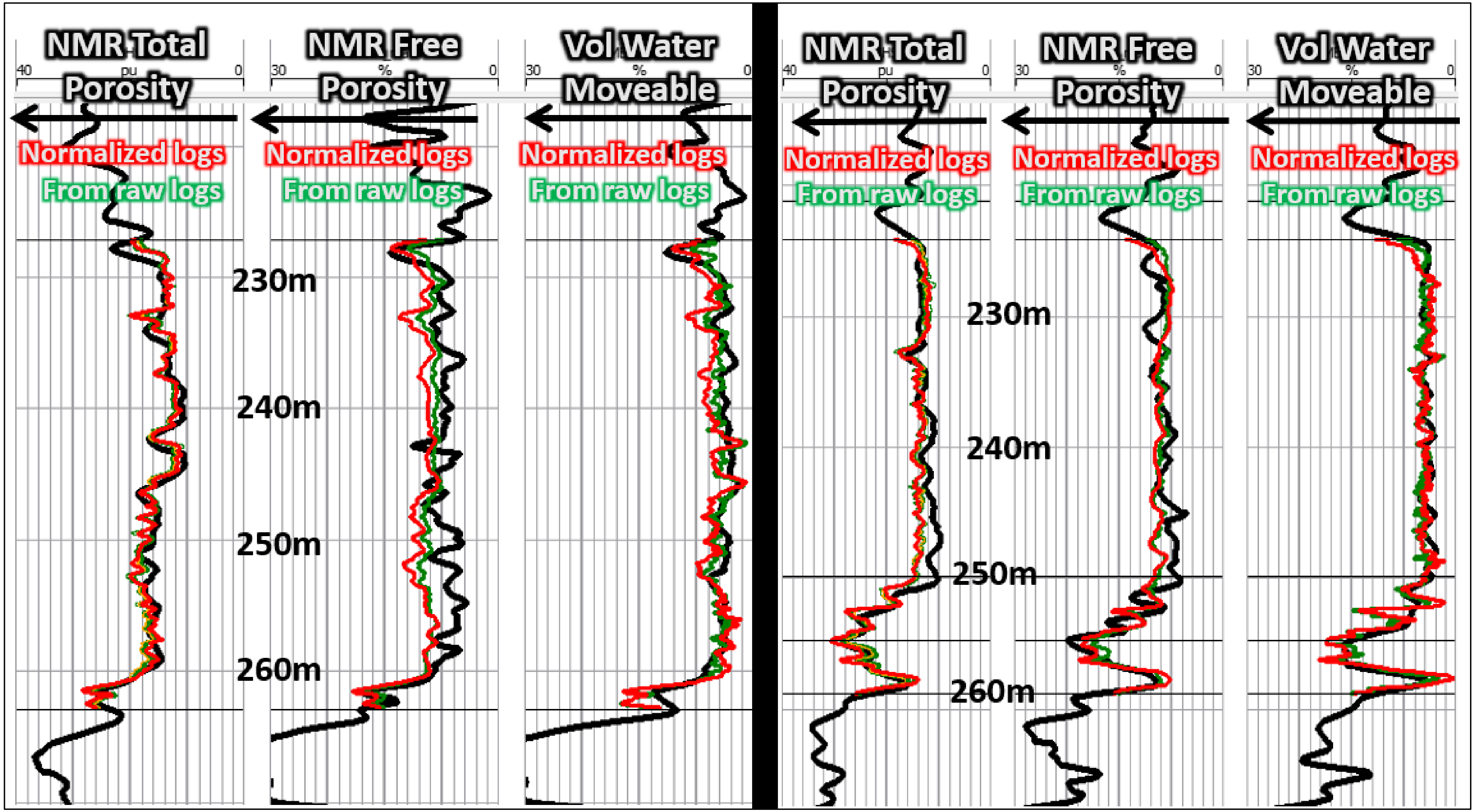
Blue is moveable fluids in large pores

Distribution of NMR Wells

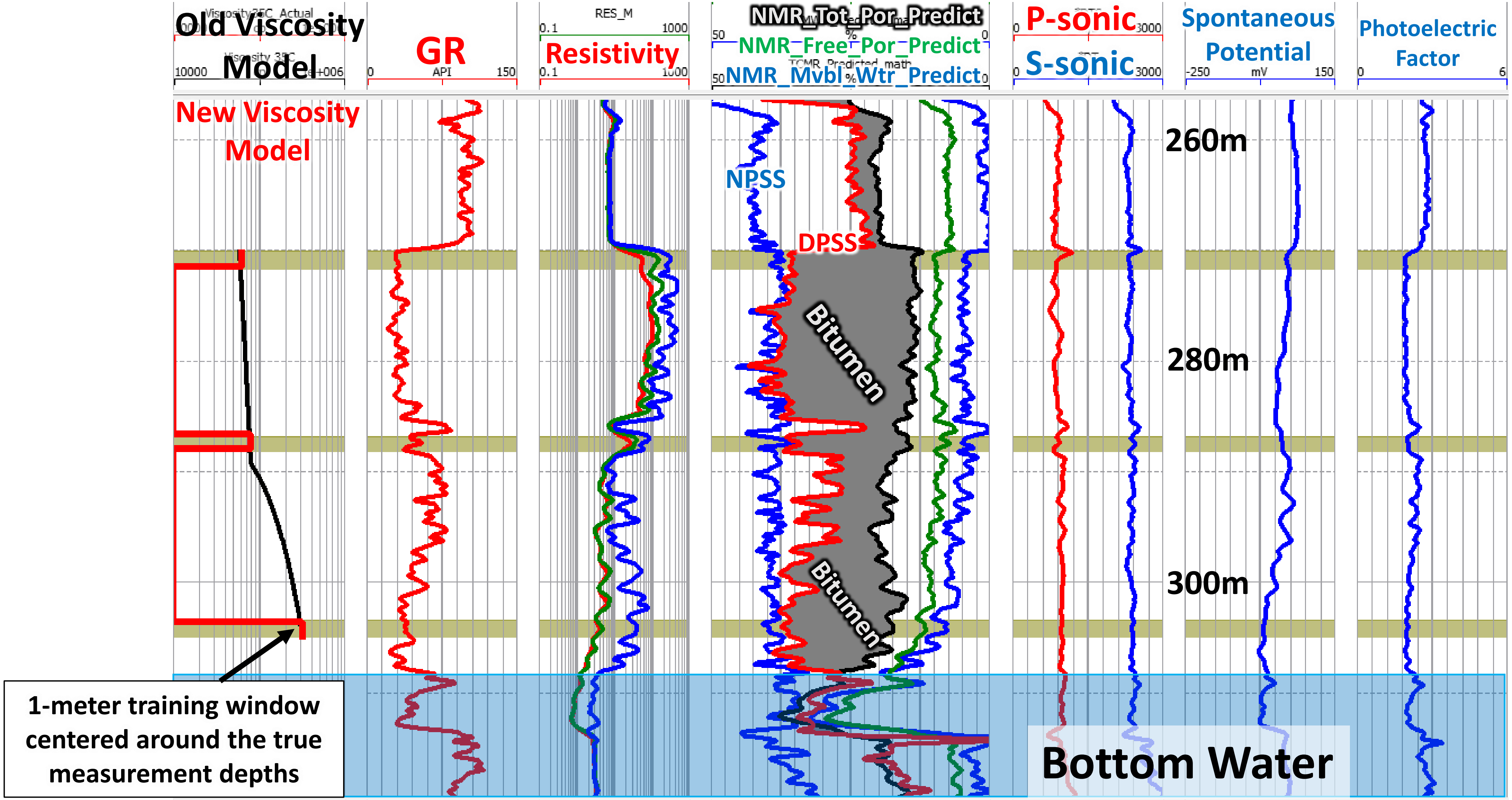


- **78** TOTAL wells with viscosity measurements (large black well symbols)
- **26** wells with NMR data (shown in green)
- None of the viscosity wells have NMR!

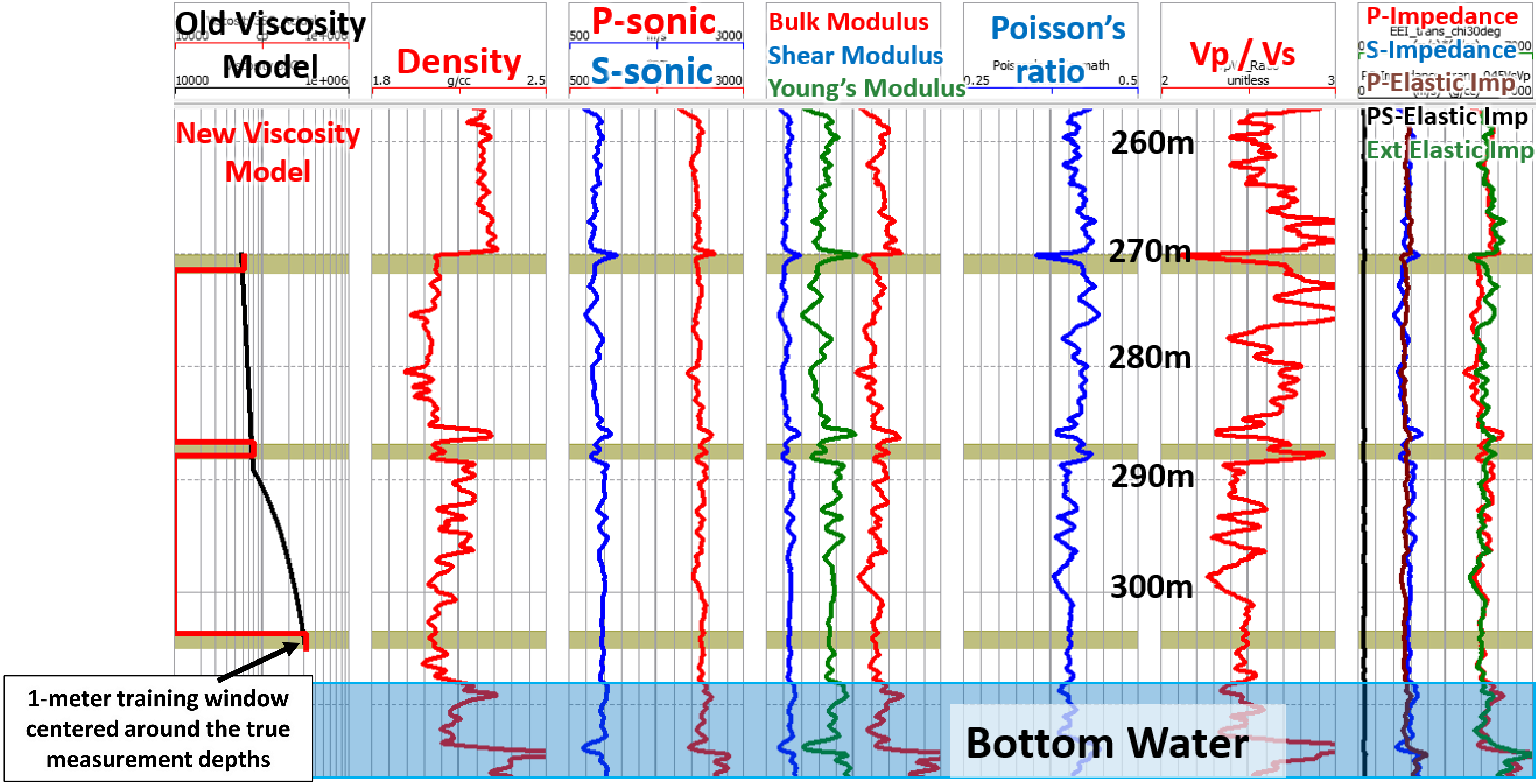
NMR Predictions from Resistivity, P-Sonic, and Gamma Ray



New Training Model – Calibrate only at viscosity measurement depths



New Training Model – Calculated Seismic Properties



Top viscosity predicting attributes

Viscosity from standard logs and NMR

New model (normalized logs):

1. $(\text{Resistivity})^{-1}$
2. ln |Gamma Ray|
3. $(\text{SP})^{-1}$
4. $(\text{NMR Total} - \text{NMR Free})^{2}$
5. $(\text{S-wave sonic})^{-1}$

Average validation error: 69,000cP
(0.69 of 1 standard deviation)

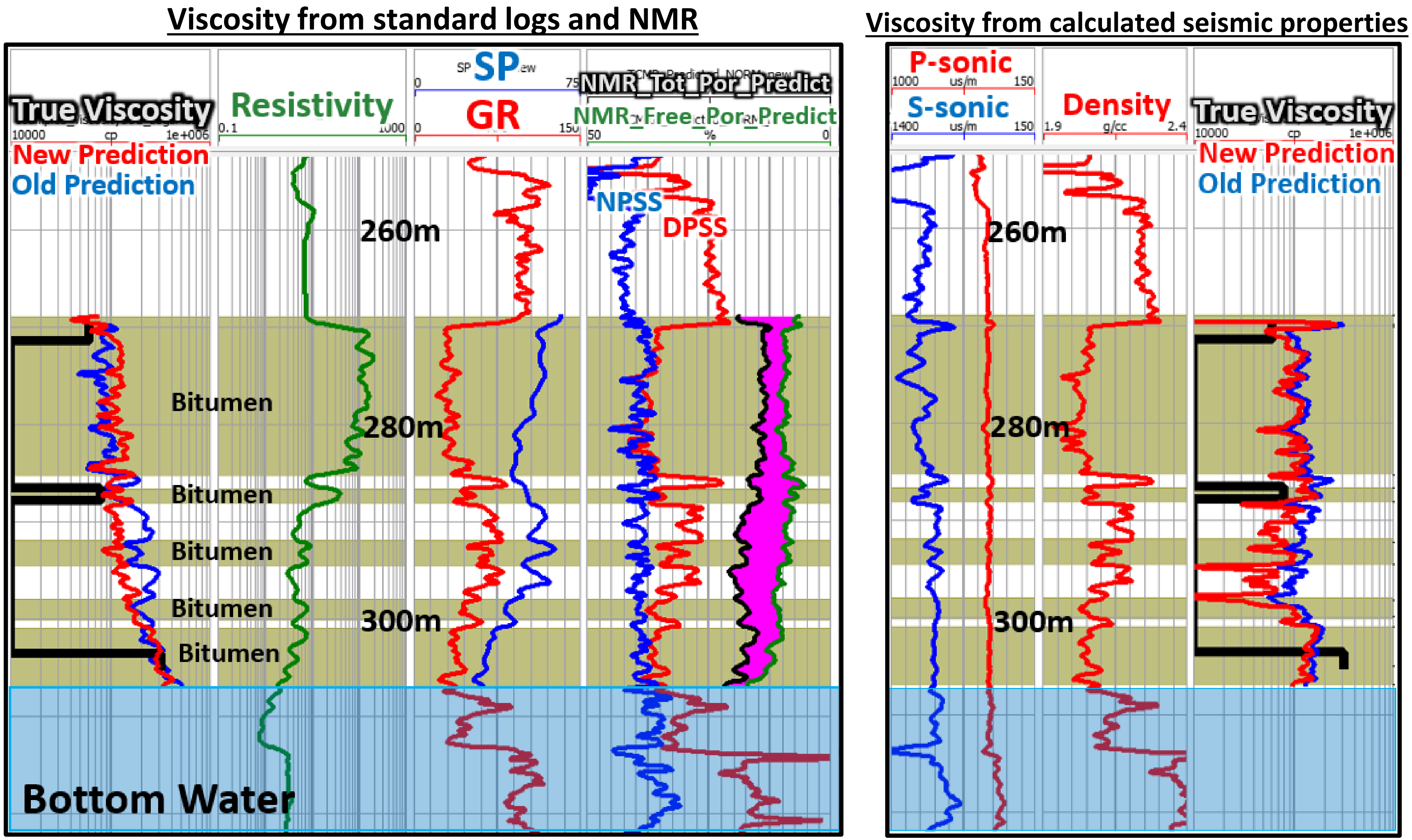
Viscosity from calculated seismic properties

New model (normalized logs):

1. $(\text{P-wave sonic})^{-1}$
2. $(\text{P-impedance})^{-1}$

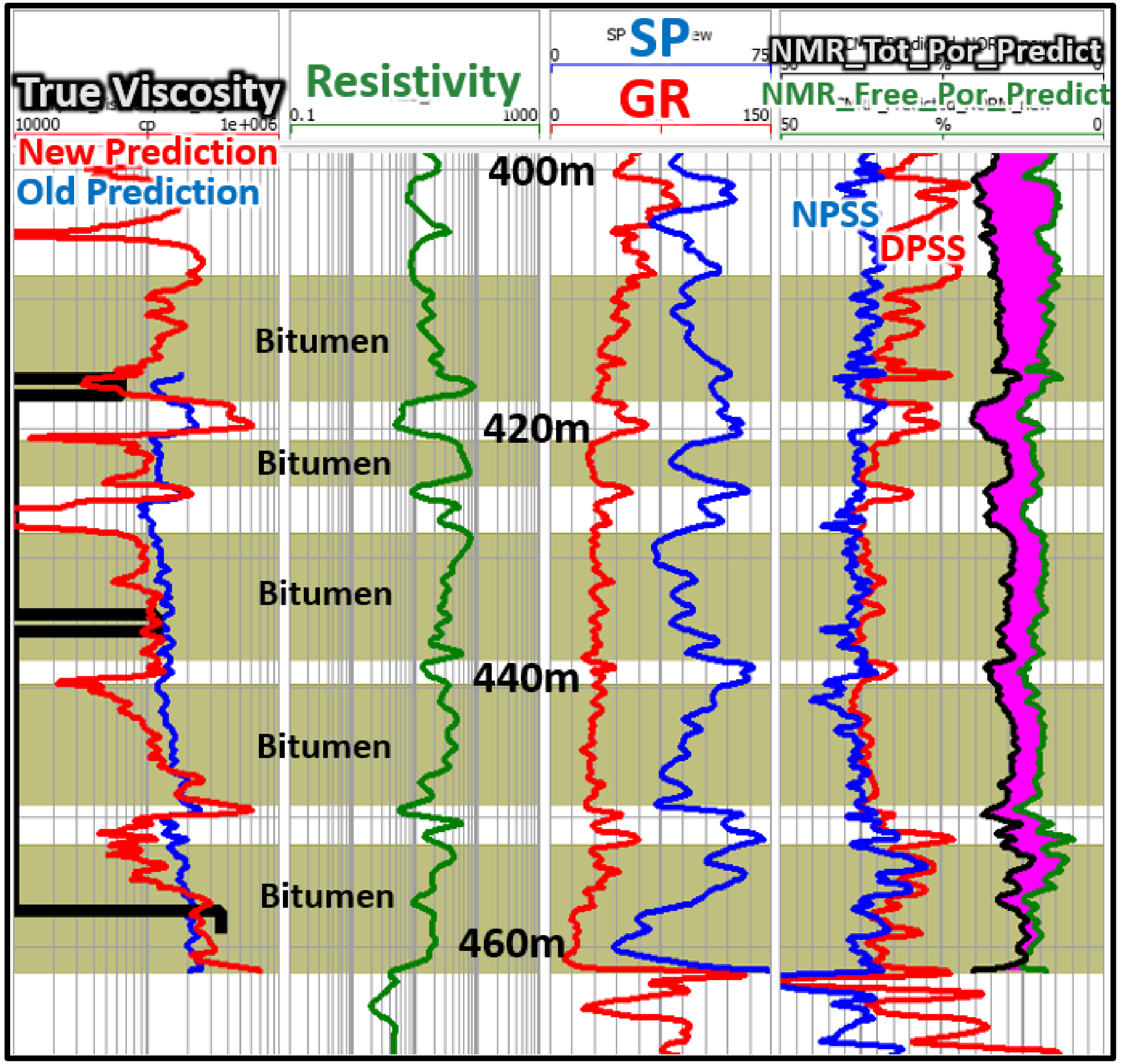
Average validation error: 93,000cP
(0.93 of 1 standard deviation)

Example Well – Smooth viscosity increase with depth

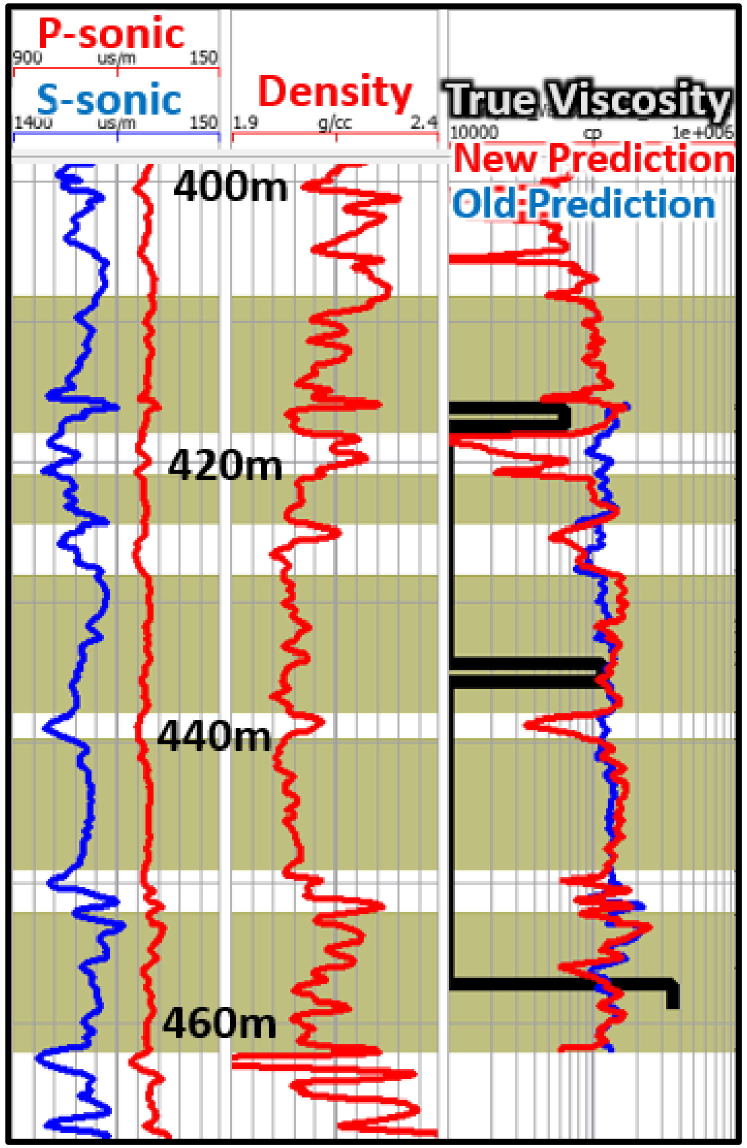


Example Well – Two viscosity gradients from 440m to 460m

Viscosity from standard logs and NMR

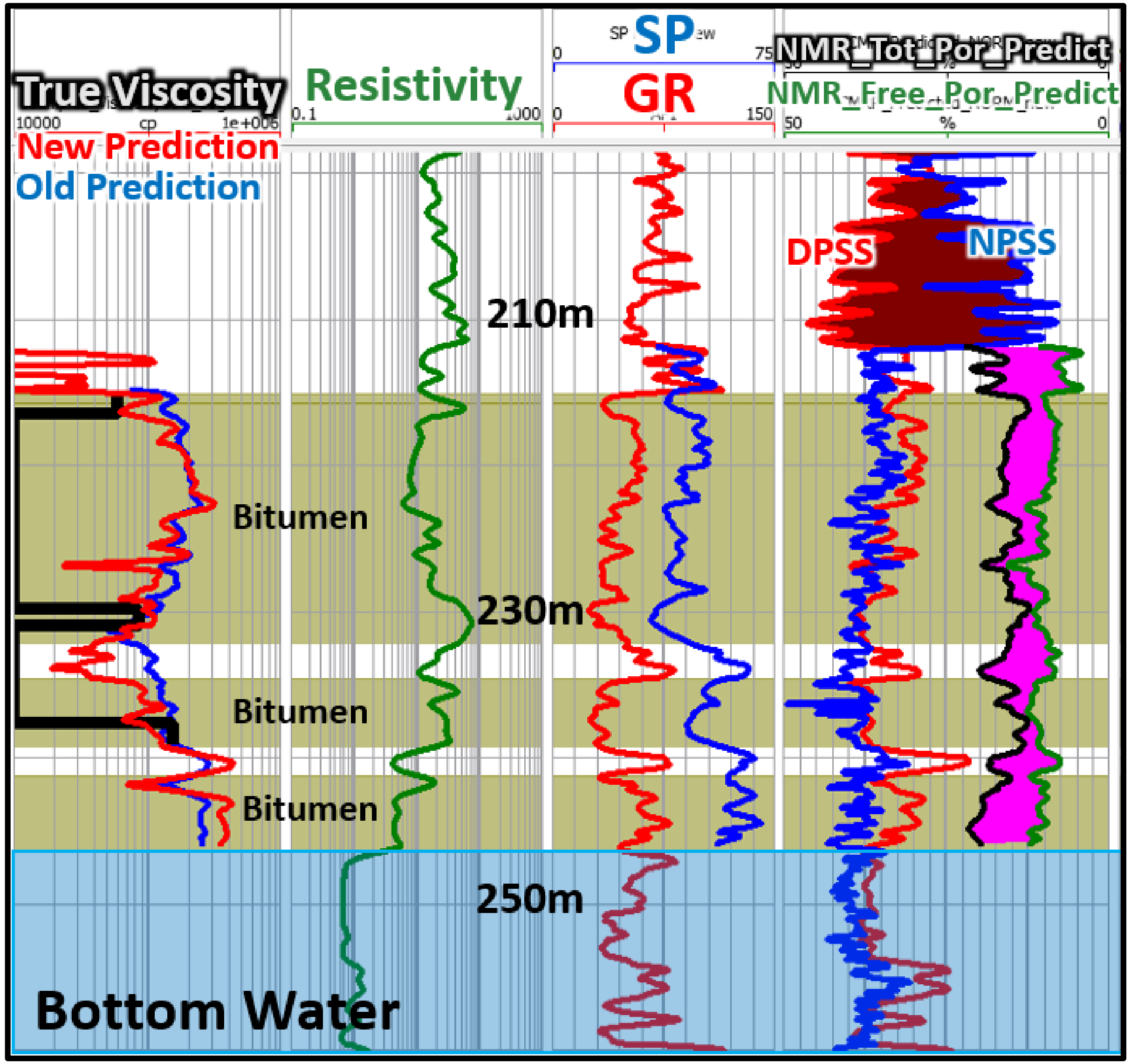


Viscosity from calculated seismic properties

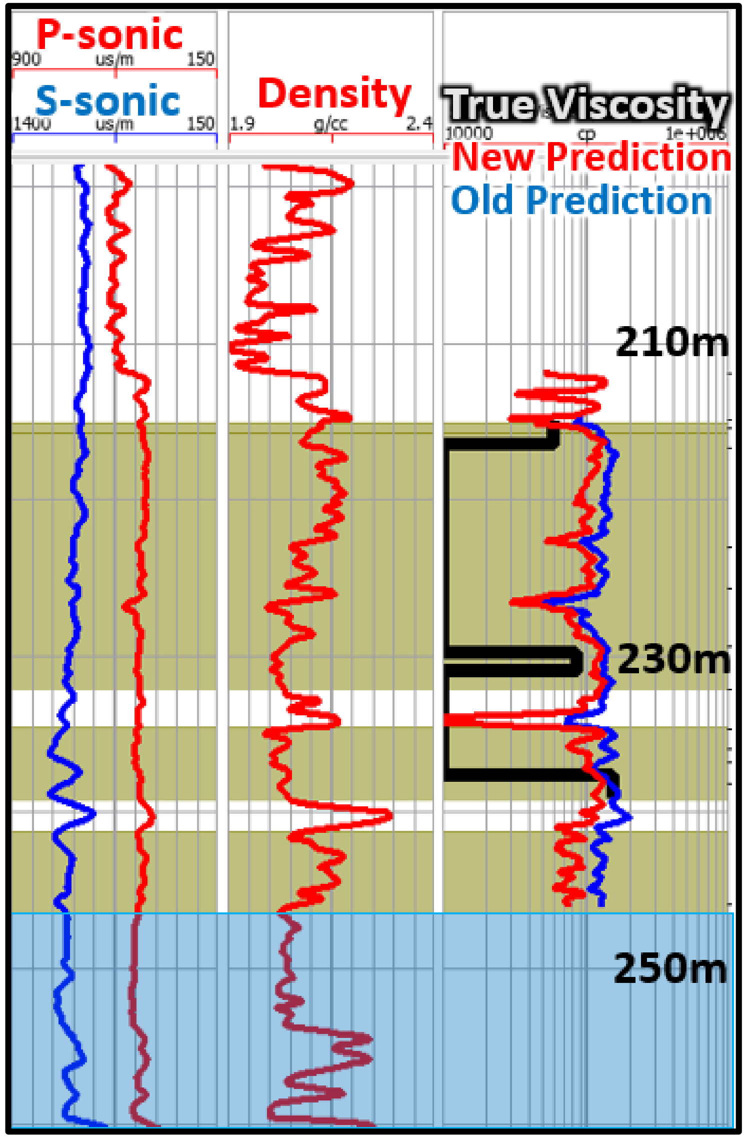


Example Well – Two modelled viscosity gradients

Viscosity from standard logs and NMR

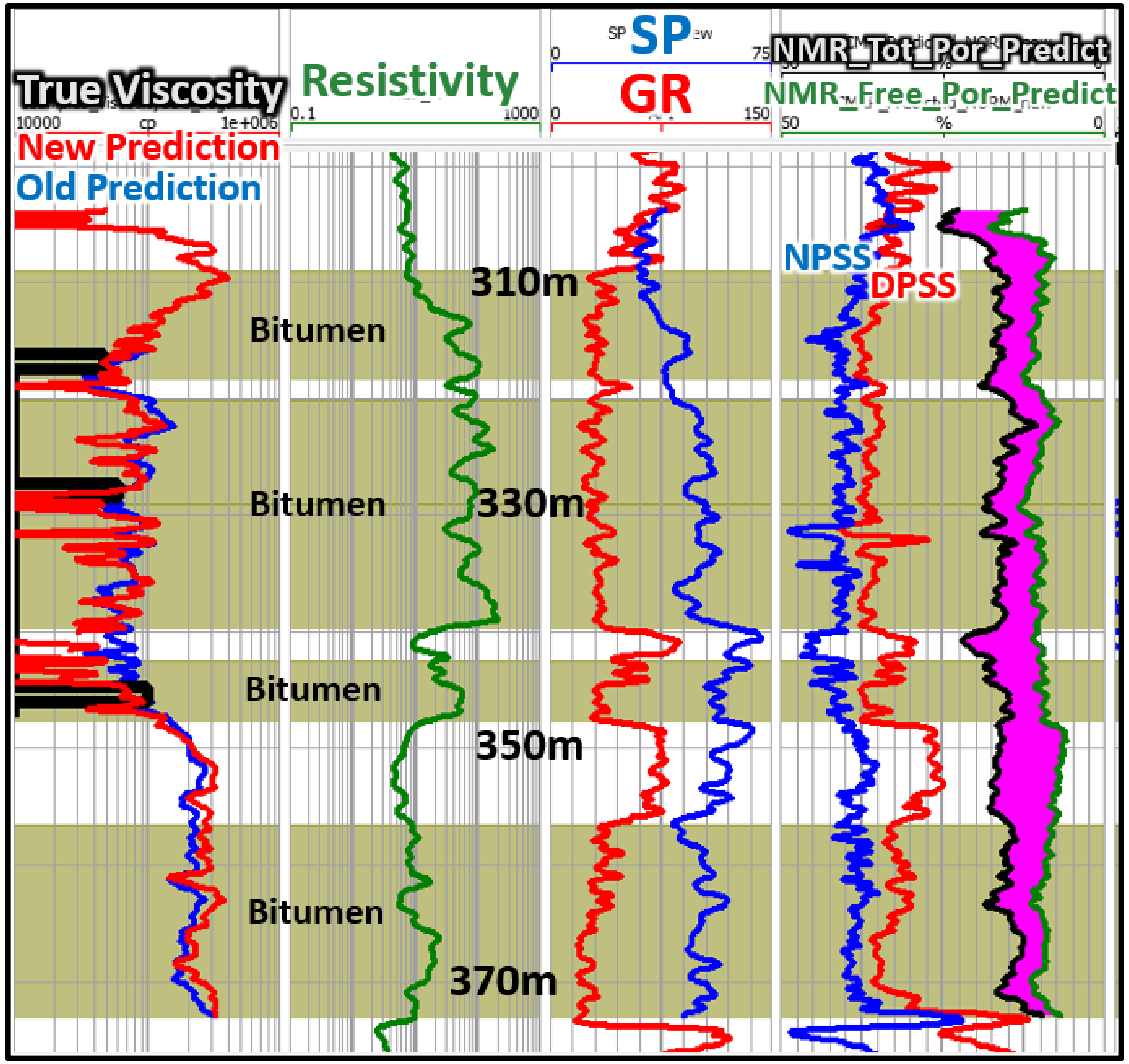


Viscosity from calculated seismic properties

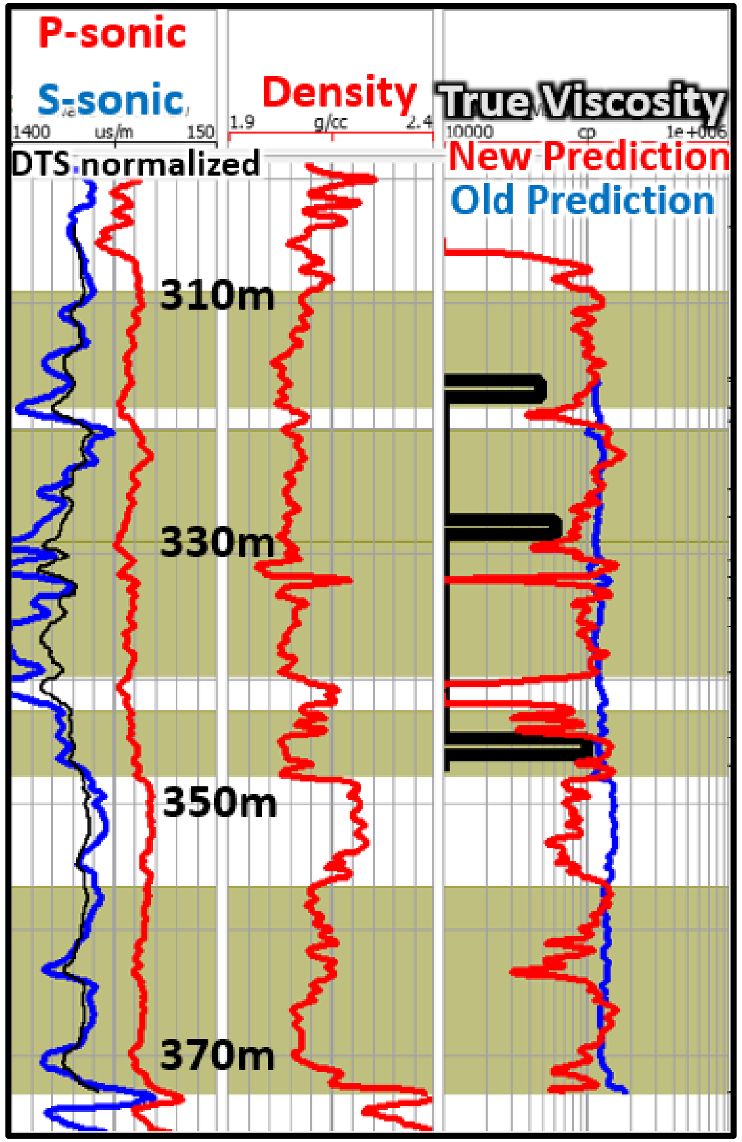


Variations above and below, slow shear sonic underestimates viscosity

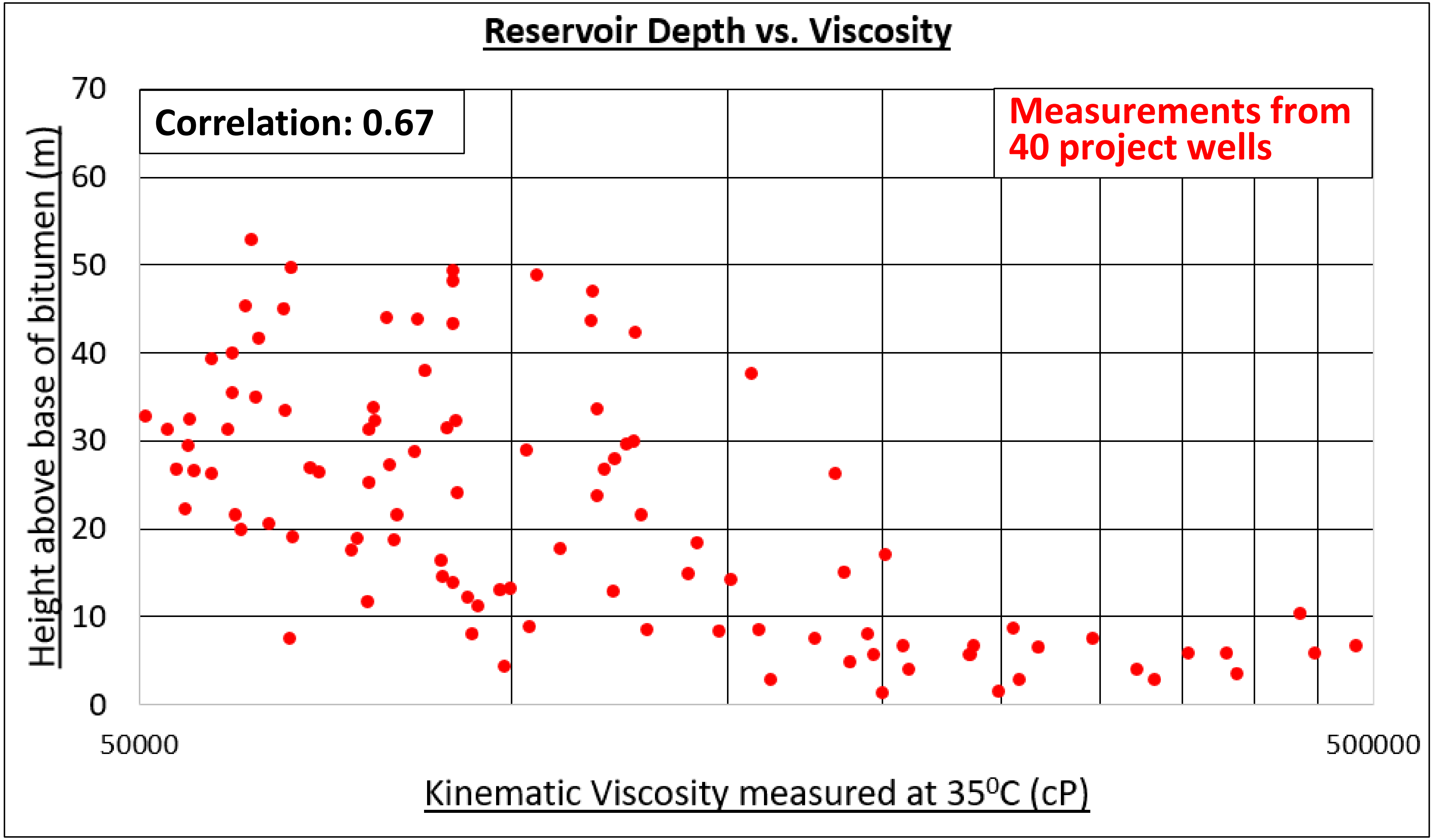
Viscosity from standard logs and NMR



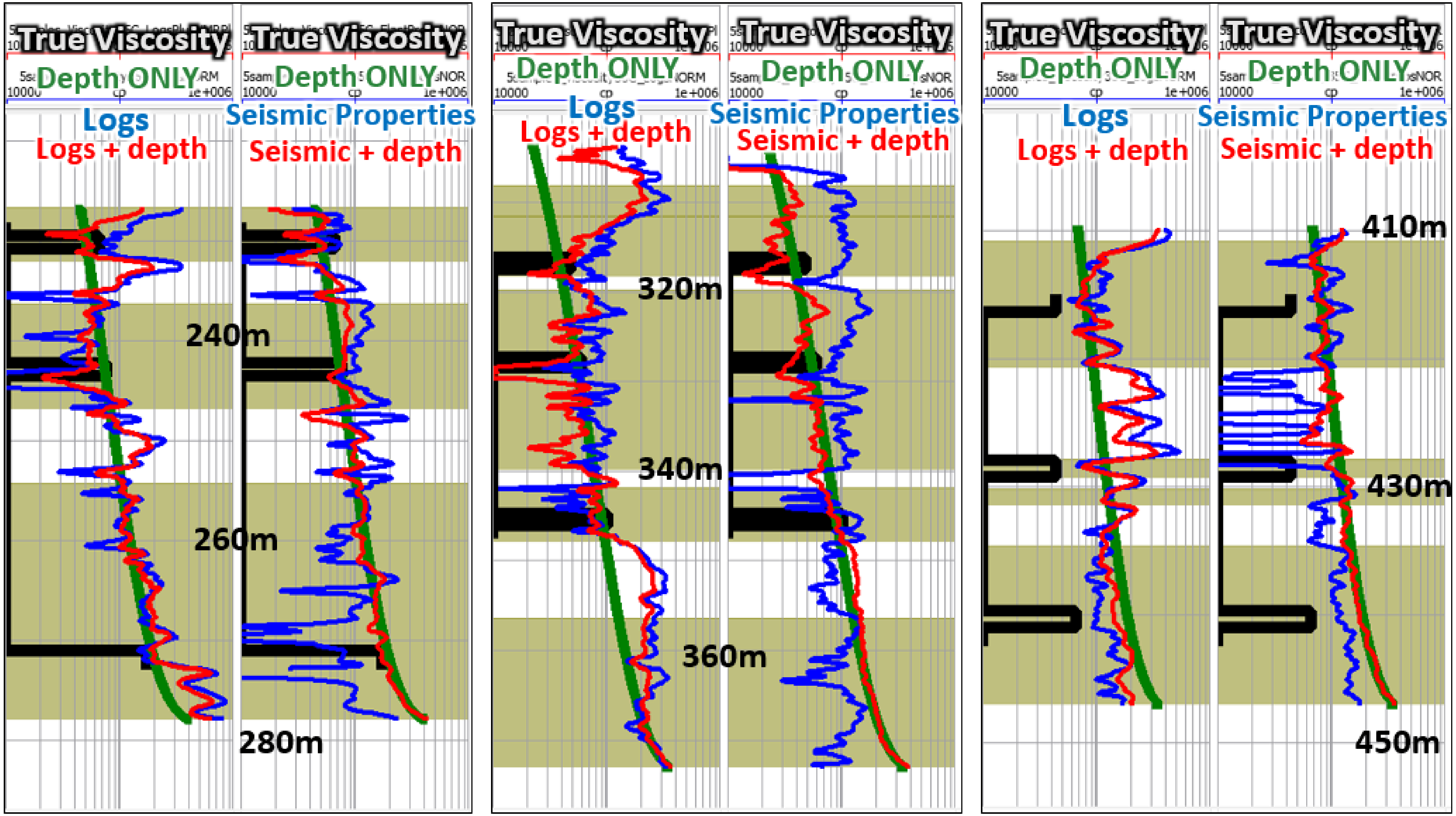
Viscosity from calculated seismic properties



What if we add depth as a viscosity predictor?



Including depth (height above bitumen base) as a predictor



Conclusions

- Standard well logs (including predicted NMR) successfully predicted viscosity with an **average error of 69,000 cP (0.69 of 1 standard deviation)**, and detected **variations between control points.**
- Seismic properties (from logs) predicted viscosity with an **average error of 93,000cP (0.93 of 1 standard deviation)**, but detected **less variations**.
- Including depth improves the prediction in most cases, but will always overestimate viscosity if the base reservoir has a low viscosity.

Acknowledgements

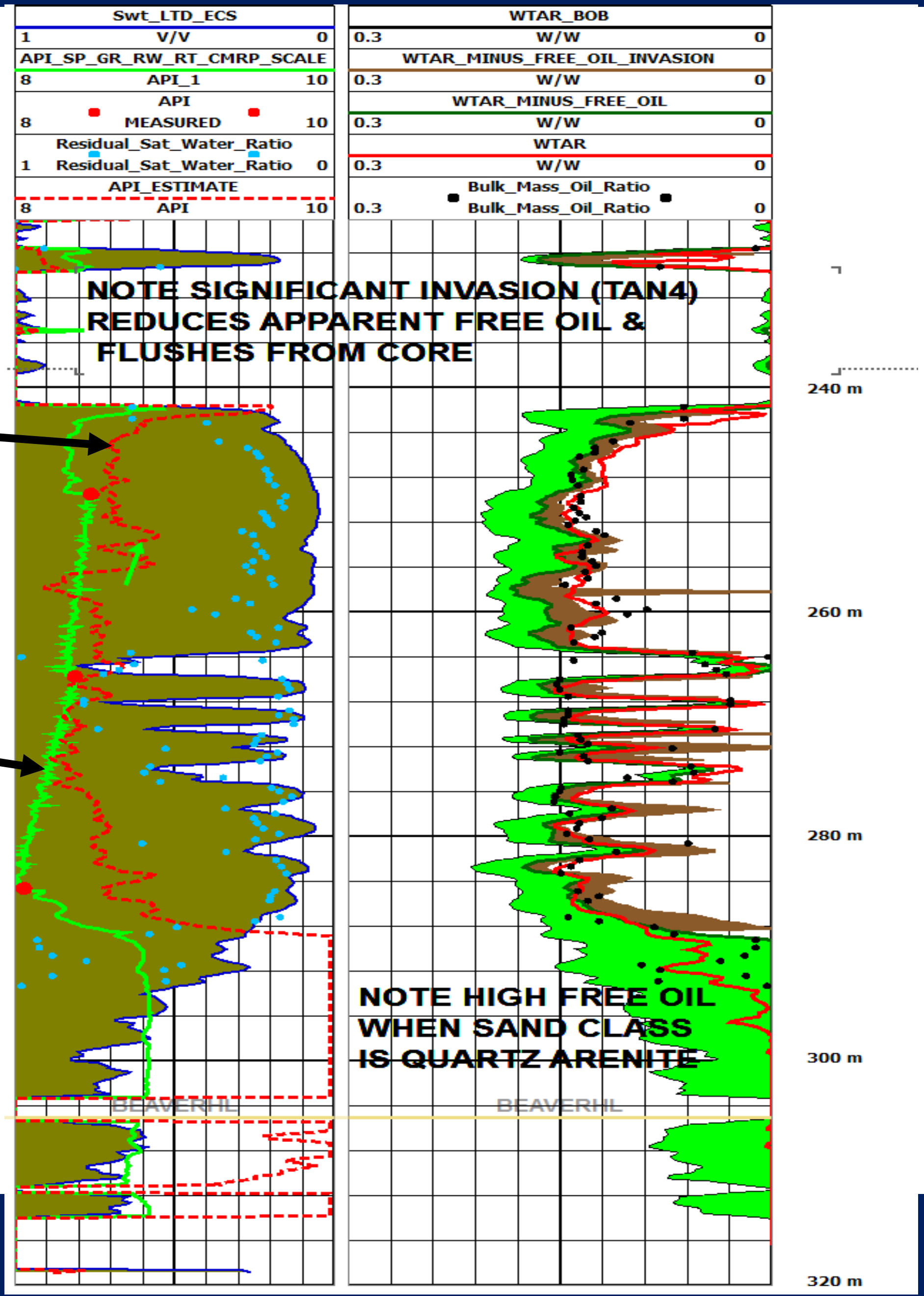
- **CREWES sponsors**
- **NSERC (**grant *CRDPJ 461179-13*)
- **David Gray, Kevin Pyke, Bob Everett, Rudy Strobl & Scott Keating**
- **CREWES staff and students**

Q & A

API prediction using only NMR for a test well

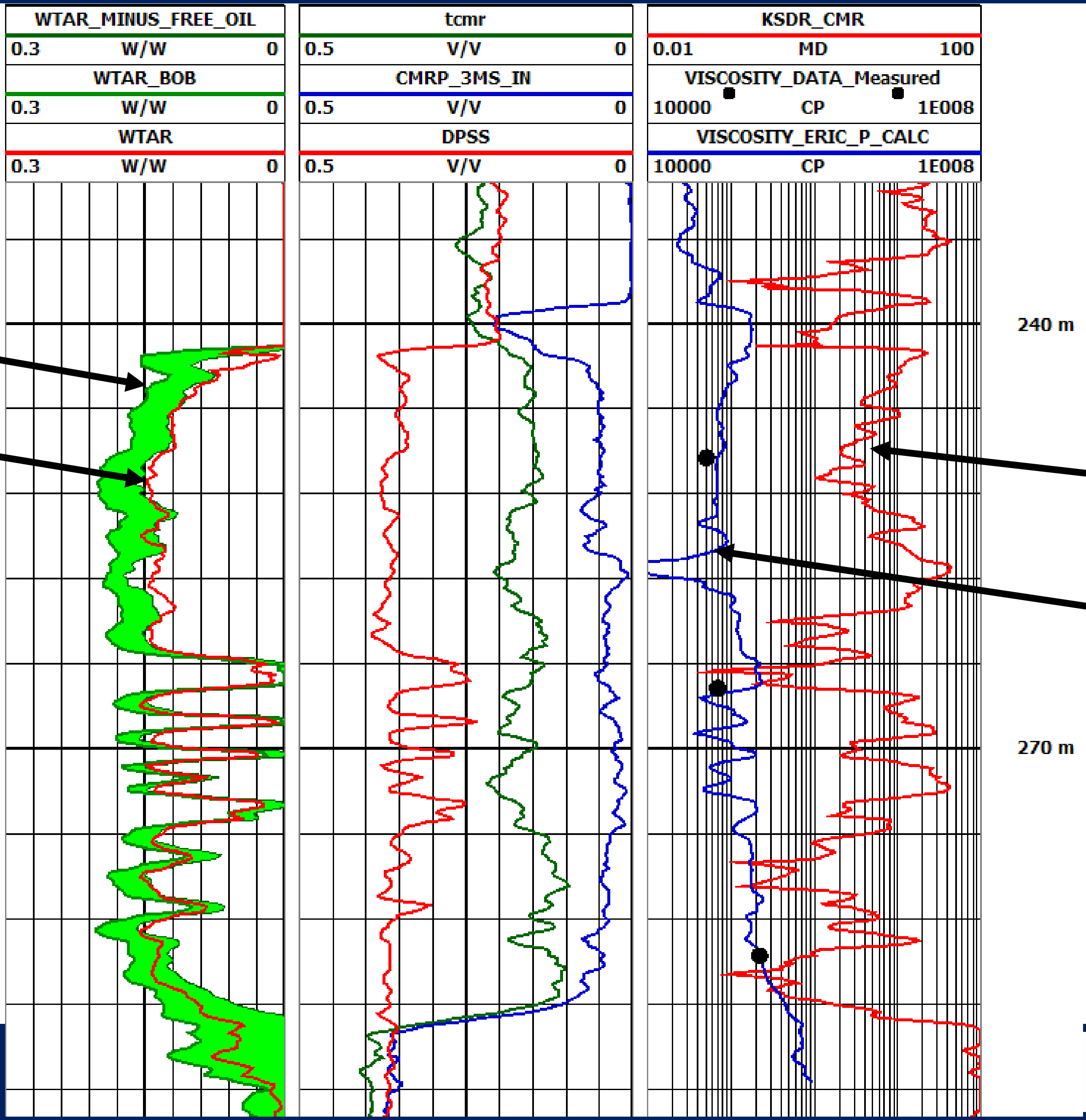
Estimated API =
10*(NMR free porosity) + 8

Estimated API from SP, GR, RW, RT, and NMR



From Bob Everett

Viscosity, Permeability, NMR, and Free Oil



Expected WTAR

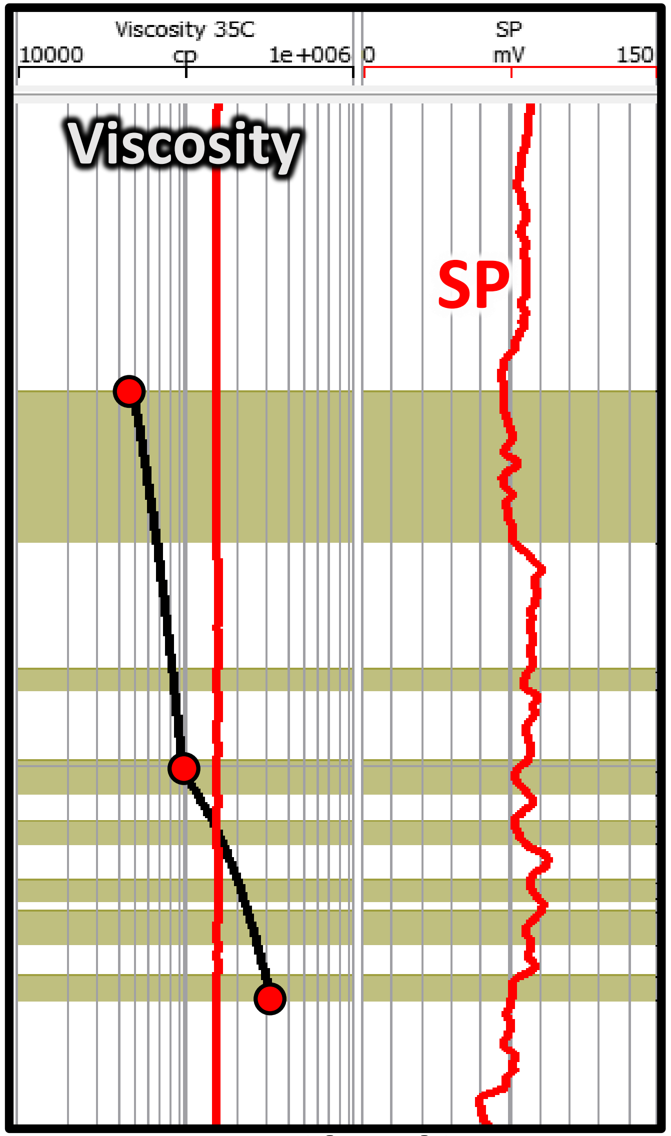
WTAR calibrated to fit core

Green space is the free oil estimated from the *movable bulk volume (CMRP)* NMR curve

Schlumberger permeability:
K = f(Total NMR Porosity)[4]

$$\eta = 24380 - 29600\sqrt{HtAboveBitumen} + 3957\sqrt{ln(|SP|)} + 610800\left(\frac{1}{ResMedium}\right) - 1643(GammaRay) + 119300000\left(\frac{1}{P - sonic}\right)$$

SP as a predictor



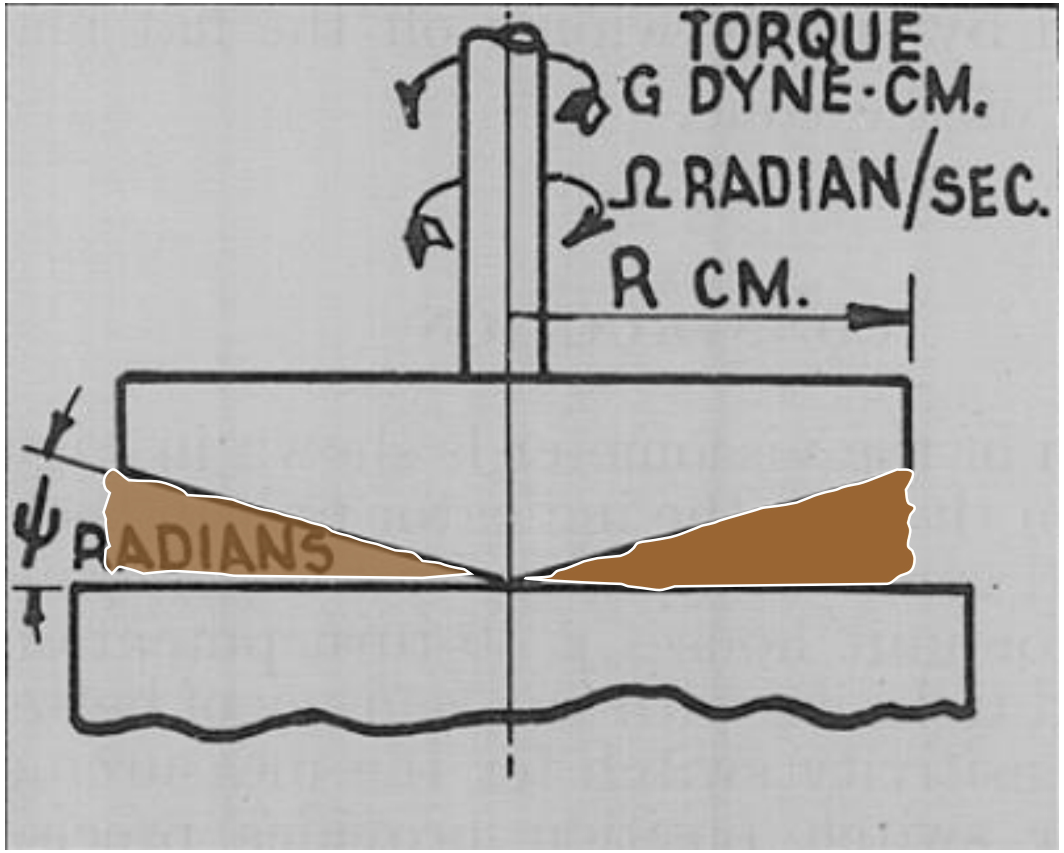
ln (|SP|)

Viscosity prediction equation using only SP:

$$\eta = 136000 + 4940 \ln(|SP|)$$

Viscosity Measurement

- **<u>Cone and Plate Viscometer</u>** is typically used for heavy oil
- The resistance to the rotation of the cone produces a torque that is proportional to the shear stress in the fluid



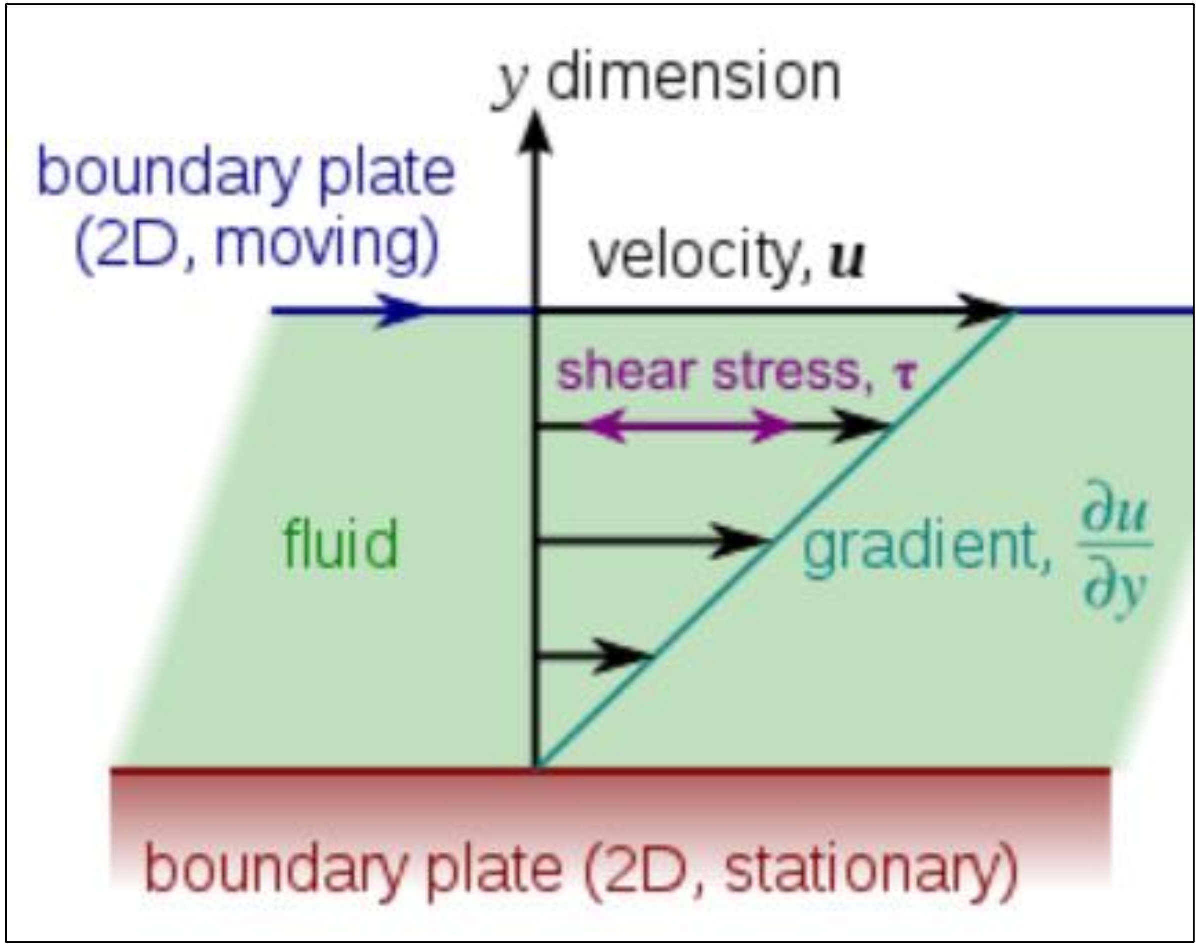
McKennell (1956)

$$Viscosity = \frac{ShearStress}{ShearRate}$$

$$\eta = \frac{3G}{2\pi R^3} \Big/ \frac{\Omega}{\psi}$$

Viscosity Concept

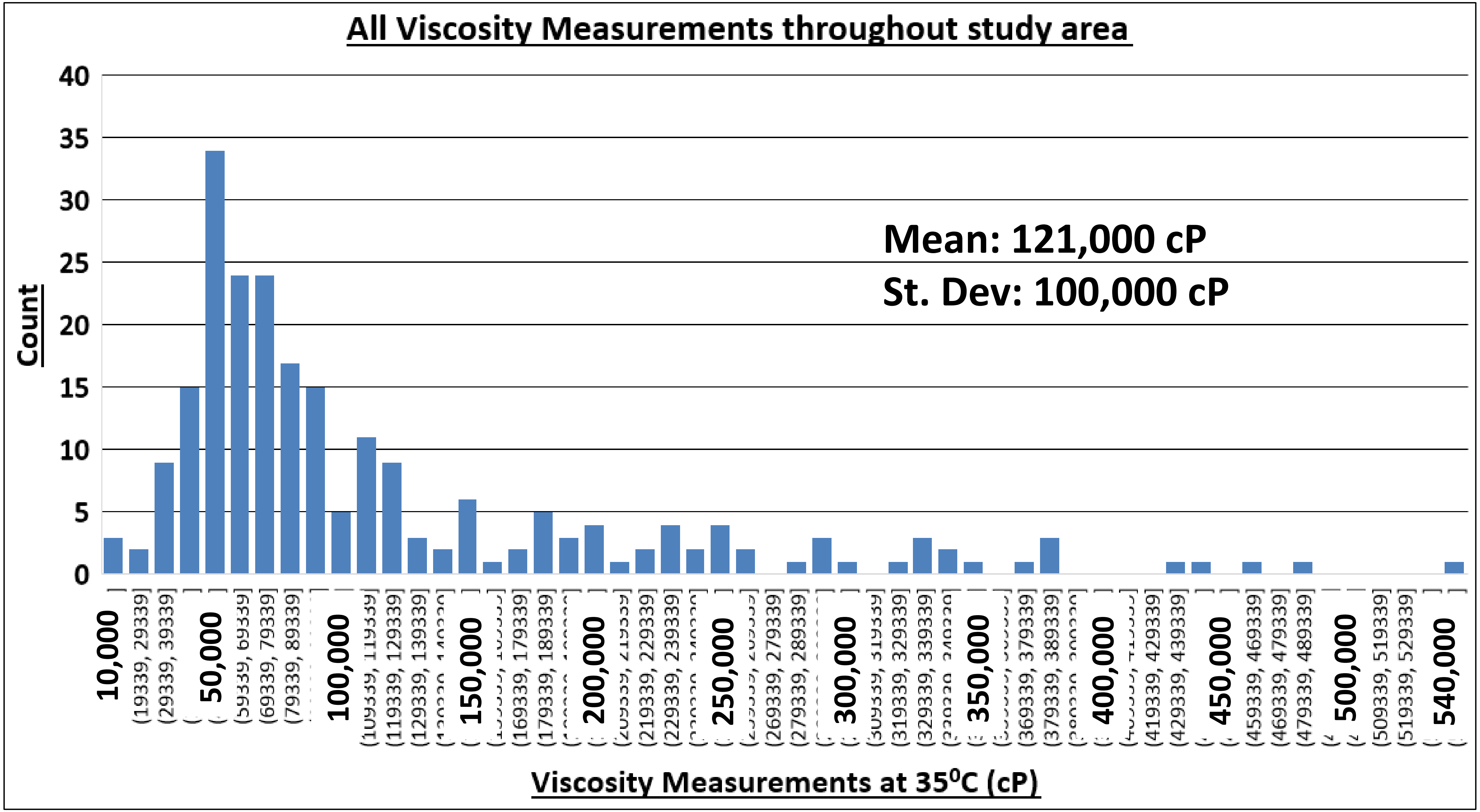
$$1\ cP = 1\ mPa \cdot s = 0.001\ Pa \cdot s = 0.001\ \frac{N}{m^2} \cdot s = 0.001\ \frac{kg}{m \cdot s}$$



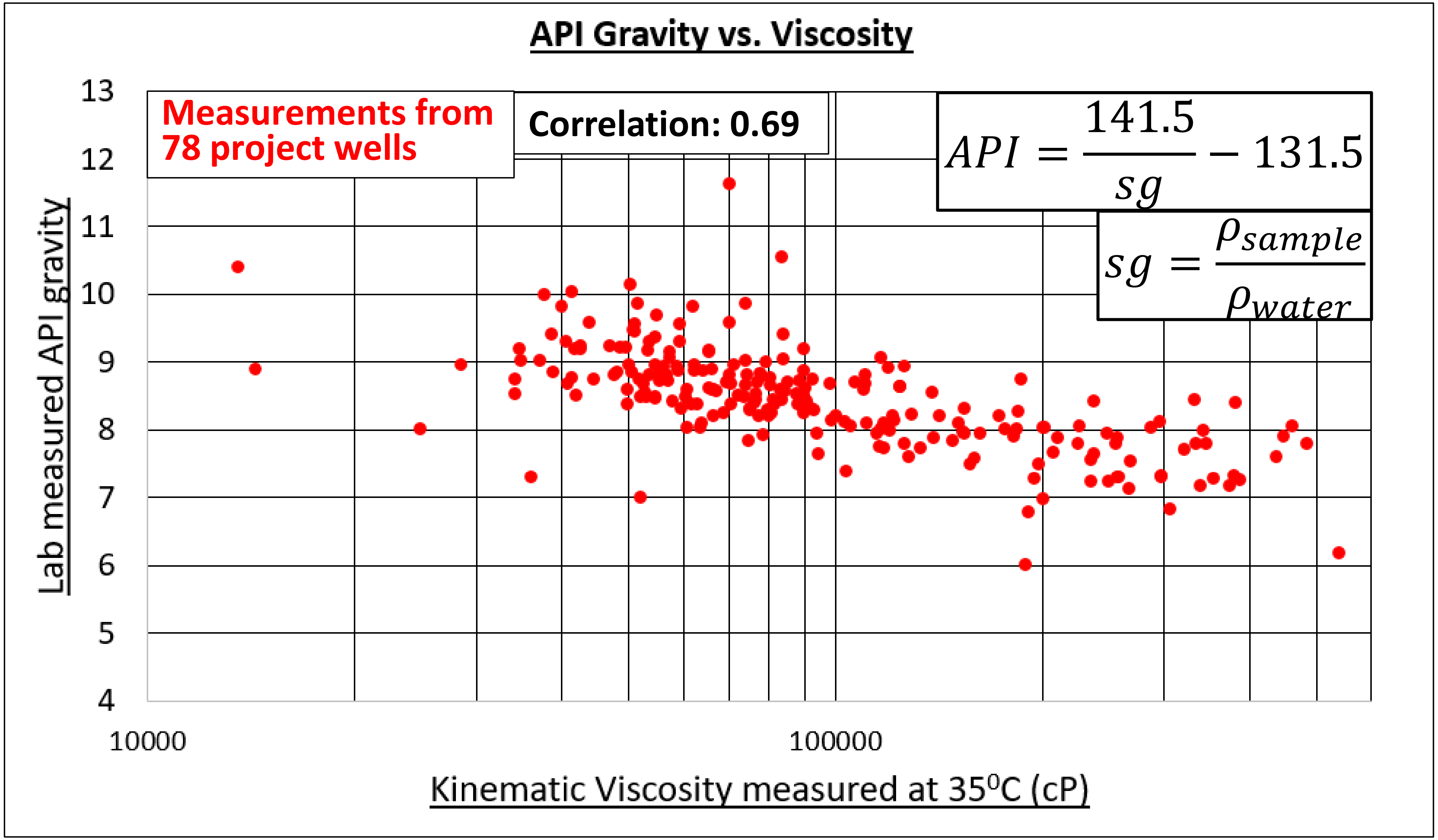
- If a fluid is placed between two plates with distance *1 m*, and one plate is pushed sideways with a shear stress of *1 Pa*, and it moves at *"u" m/s*, then it has viscosity of *"u" Pa·s*

Image credit: Wikipedia

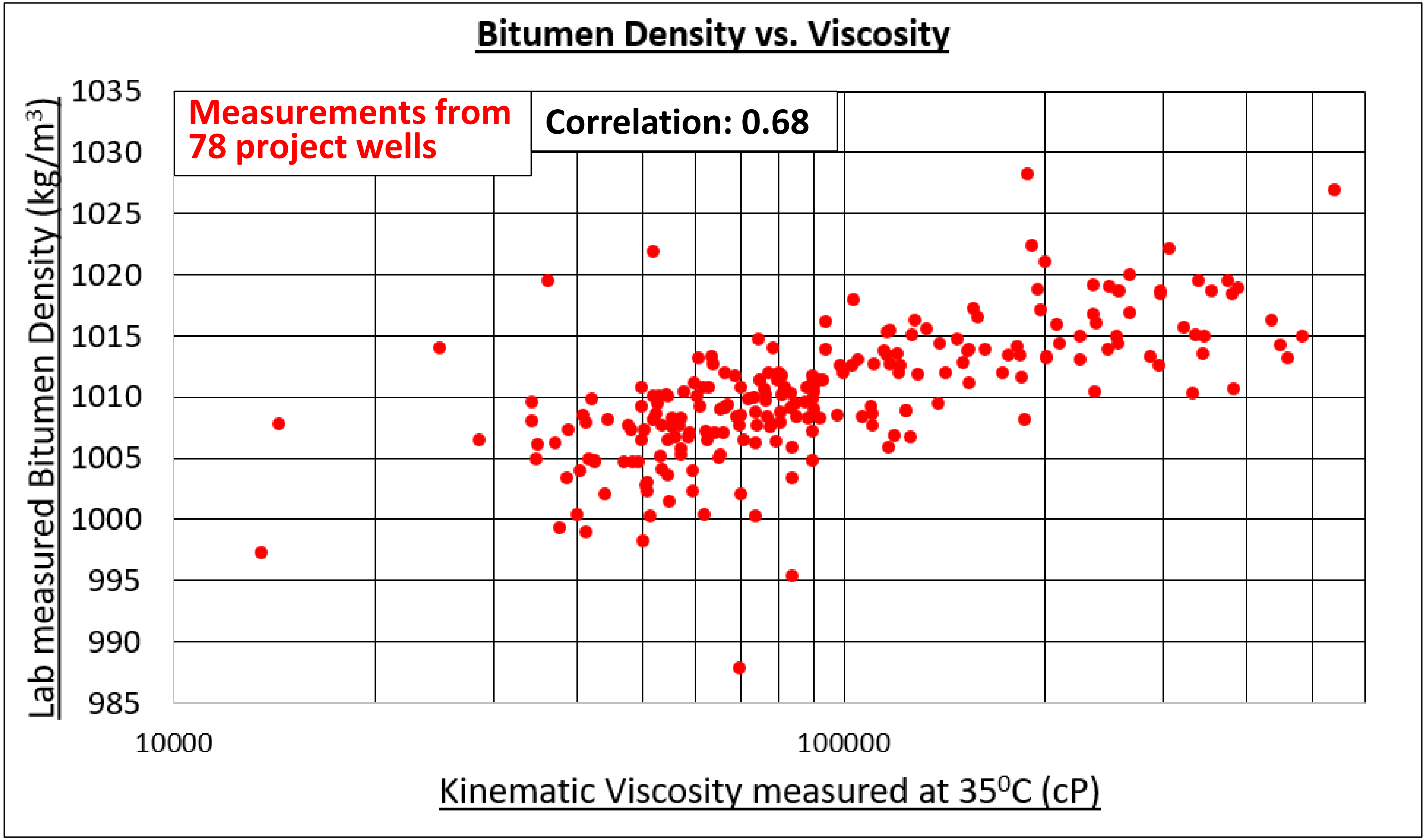
Viscosity Measurement Distribution



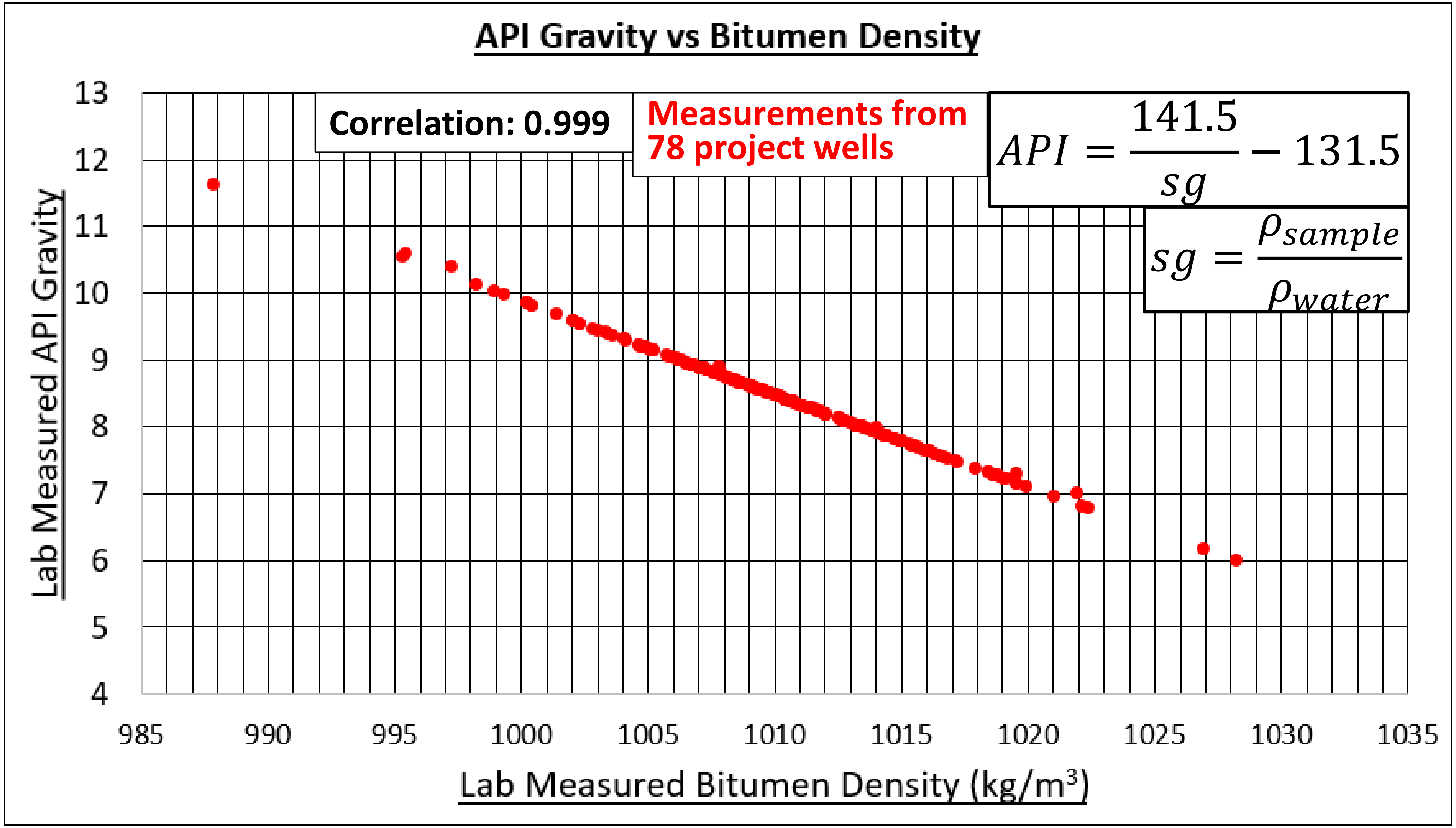
API Gravity – Viscosity Relationship



Bitumen Density – Viscosity Relationship



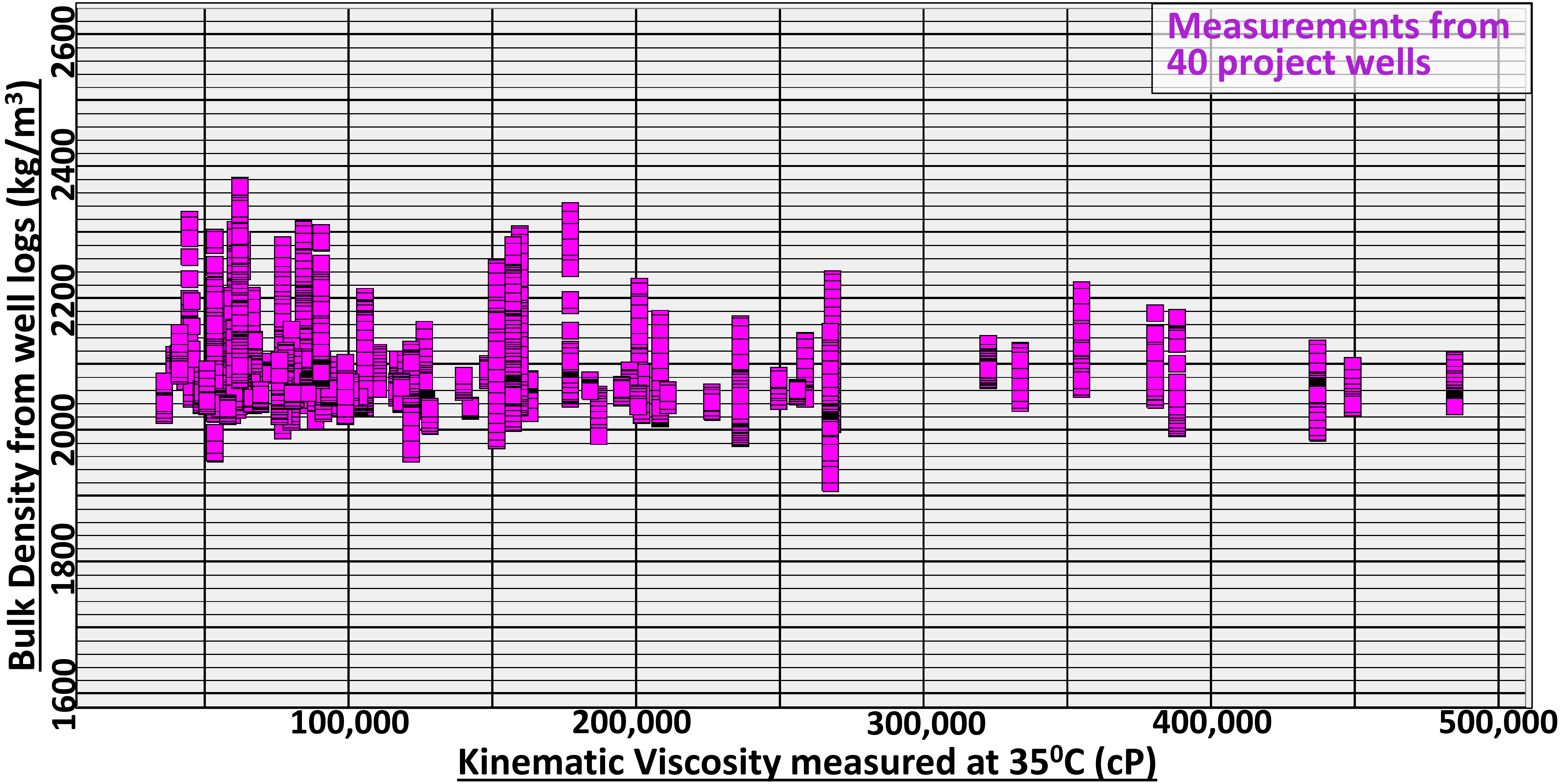
API Gravity – Bitumen Density Relationship



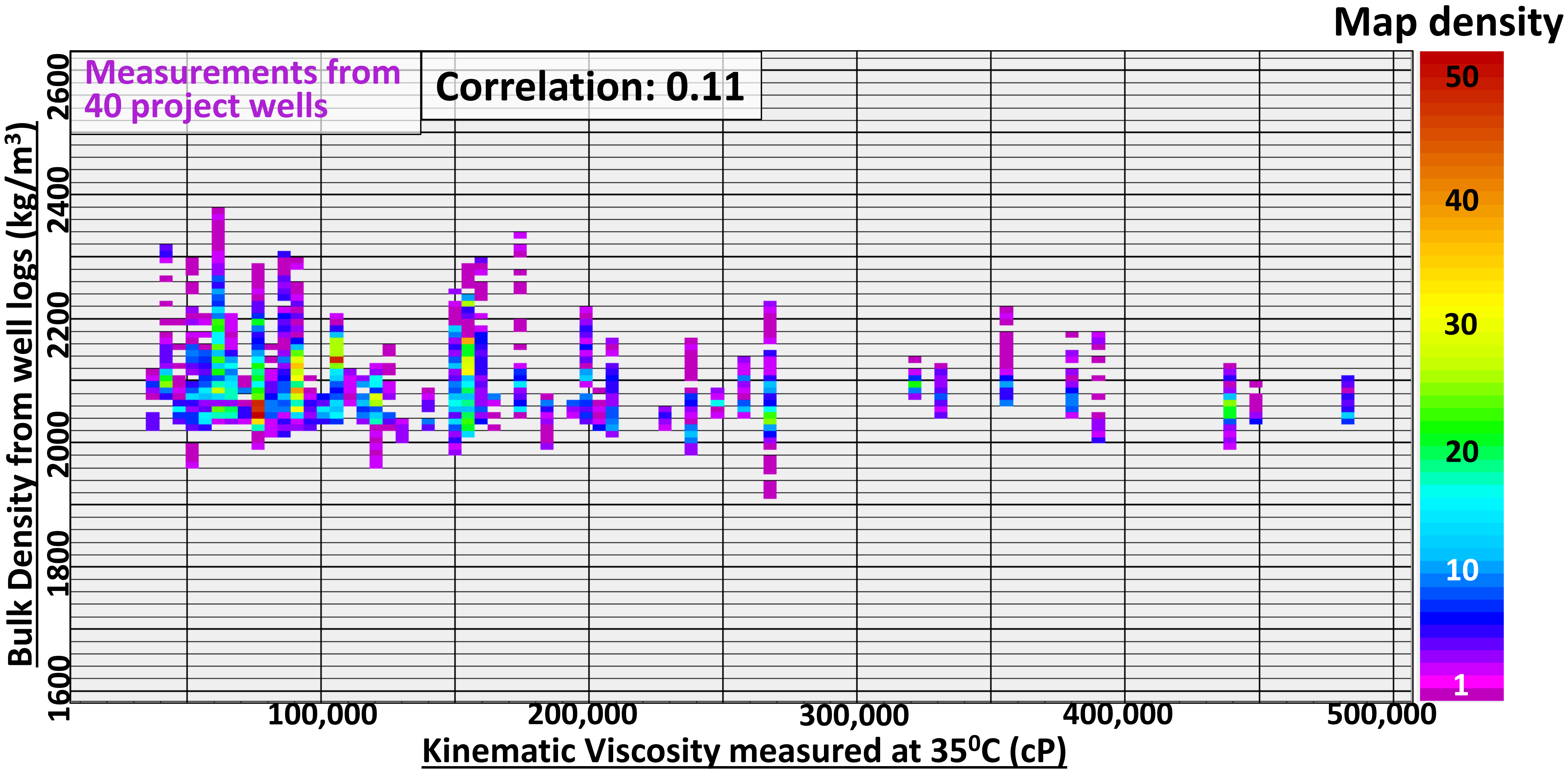
$$API = \frac{141.5}{sg} - 131.5$$

$$sg = \frac{\rho_{sample}}{\rho_{water}}$$

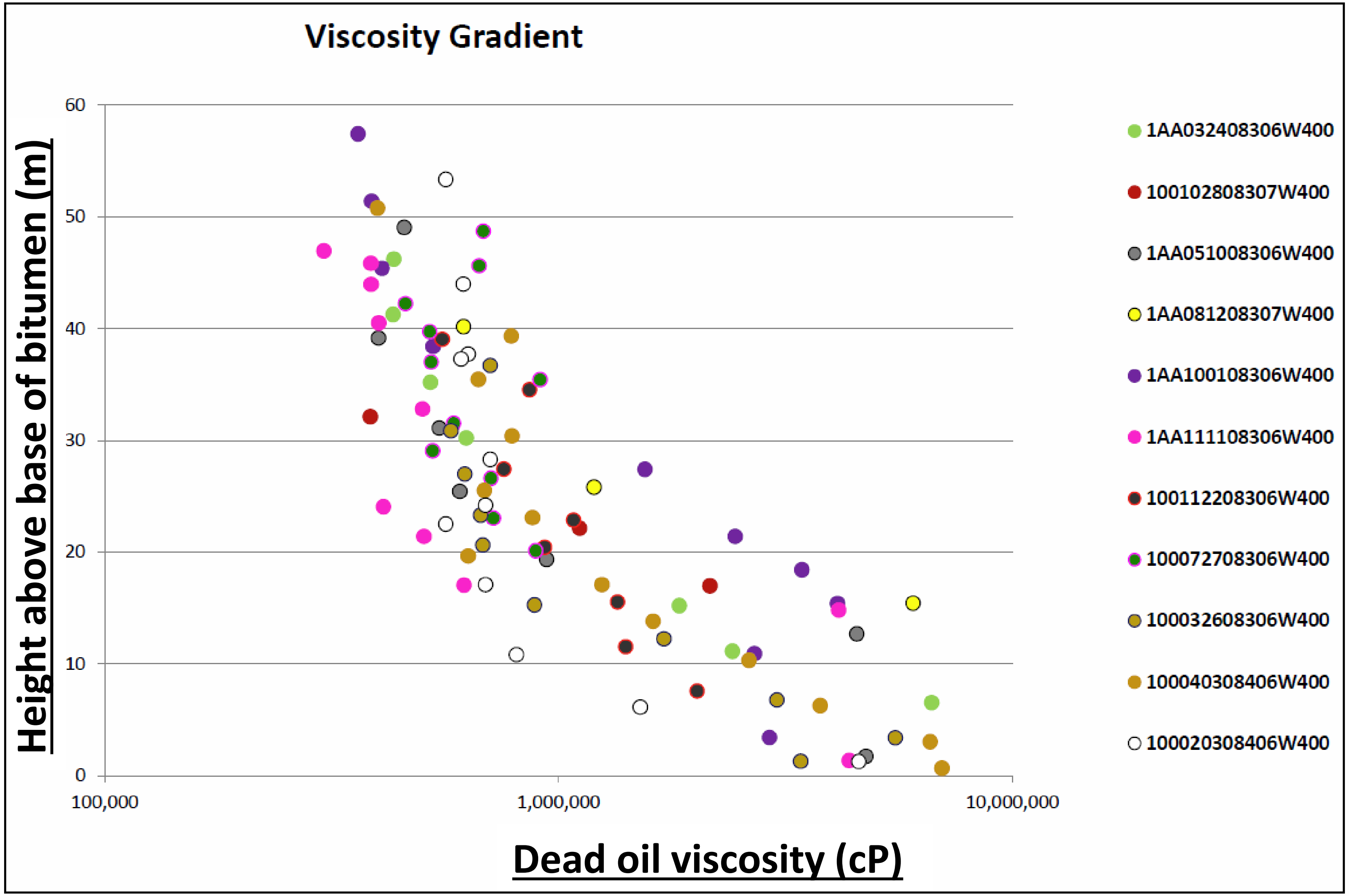
Bulk Density – Viscosity Relationship



Bulk Density – Viscosity Relationship



McMurray formation viscosity measurements



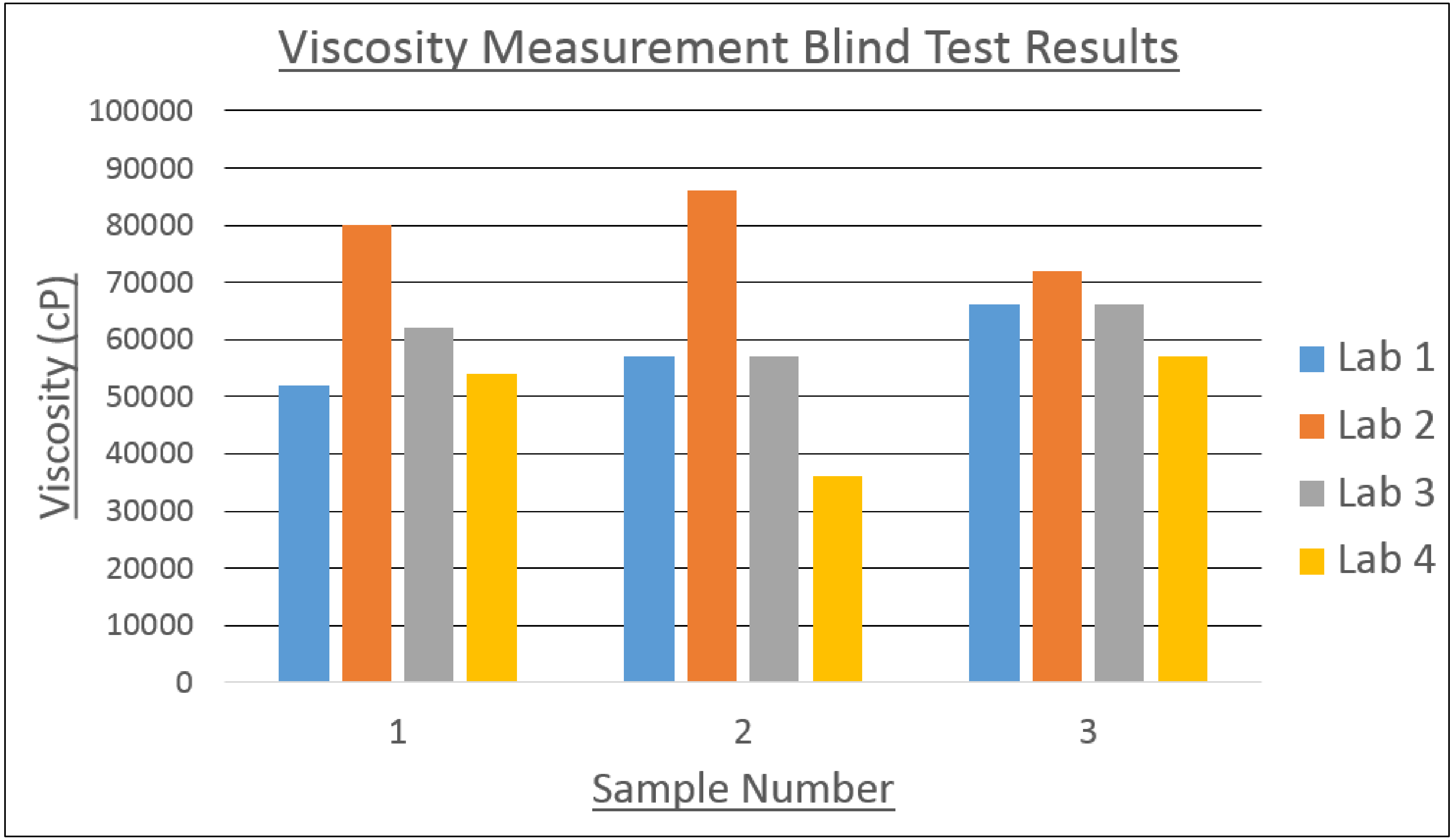
- Viscosity tends to increase with reservoir depth

- Located about 10km south of the study area

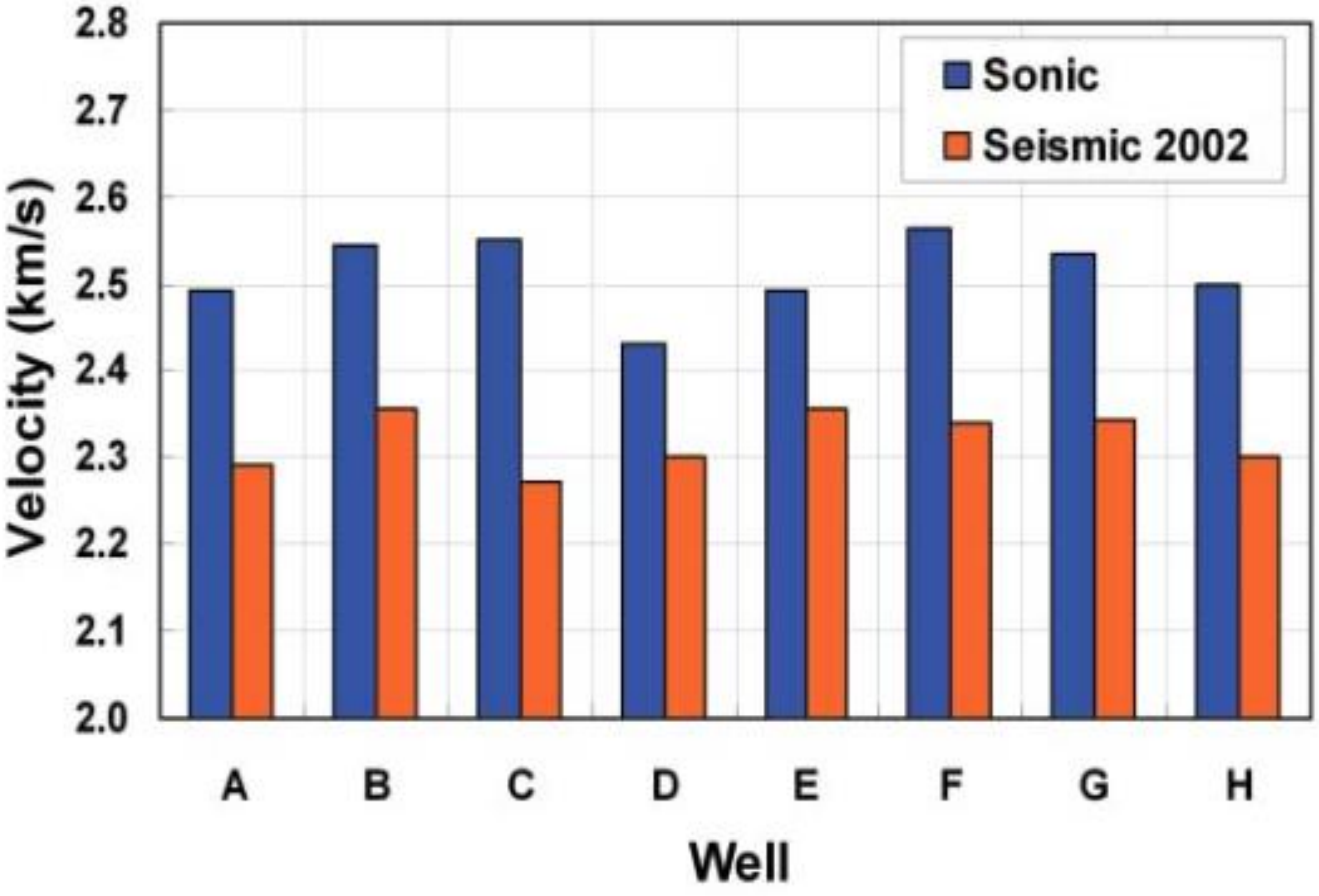
ConocoPhillips AER Report (2015)

Uncertainty of the Viscosity Measurement

Miller et al (2006): *Should you trust your heavy oil viscosity measurement?*



Velocity Dispersion



Kato & Onozuka & Nakayama (2008)

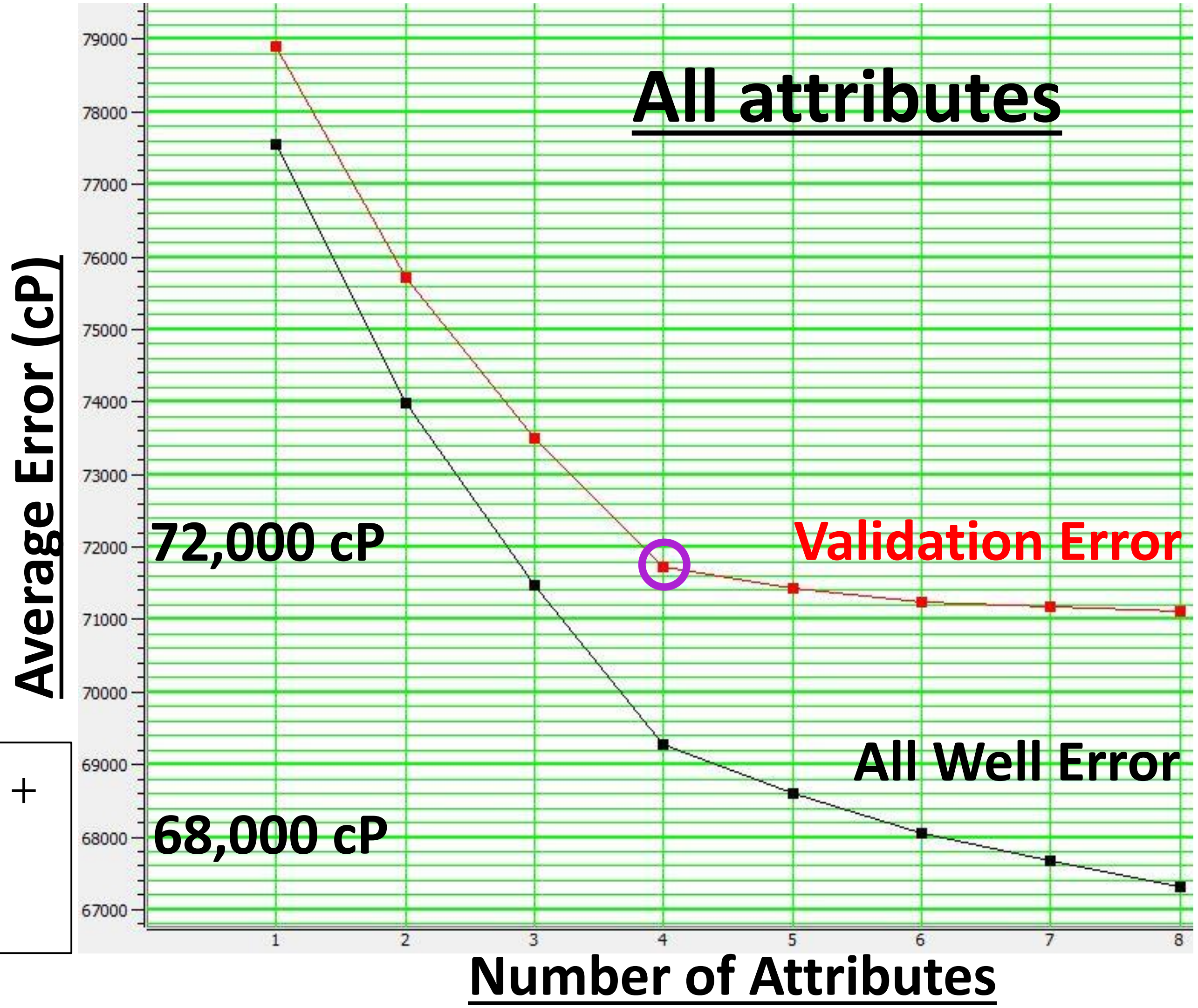
- Velocities tend to increase with measurement frequency
- Laboratory measurements give higher velocities than sonic logs or seismic data
- Example from a heavy oil field 50km SW of Fort McMurray

Predicting viscosity from un-normalized well logs

- Optimum viscosity prediction is found using **4 attributes**

Attribute	**Units**
1. 1 / (ResMedium)	*1/[ohm-m]*
2. $(GammaRay)^{1/2}$	*$[API]^{1/2}$*
3. 1 / (P-wave sonic)	*1/[us/m]*
4. ln|ResSeparation|	*ohm-m*

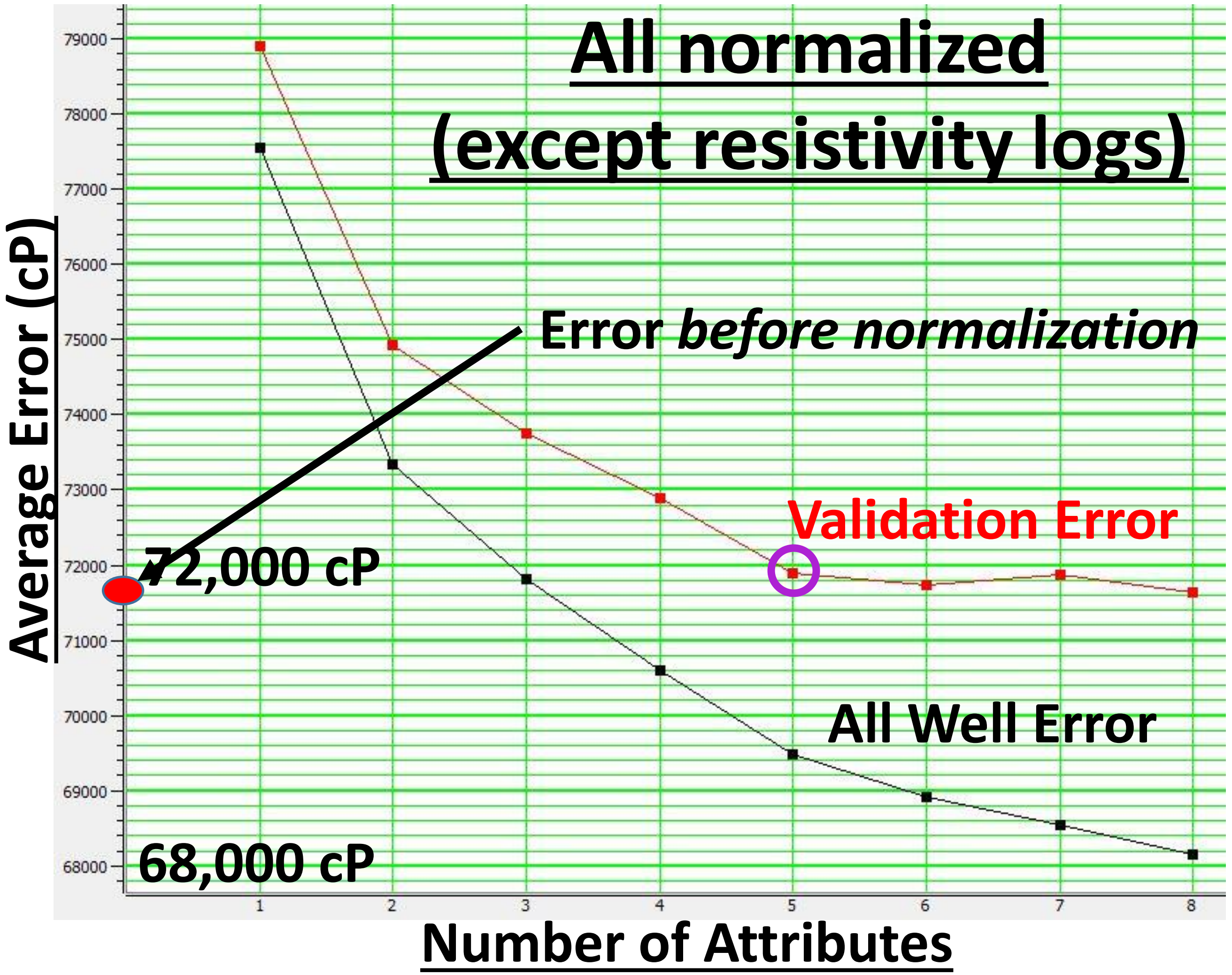
$$\text{Viscosity } [\eta] = -96870 + \left(\frac{985300}{\boldsymbol{ResMedium}}\right) - 31660\sqrt{\boldsymbol{GammaRay}} + \left(\frac{176220000}{\boldsymbol{P-sonic}}\right) - 10970\ln(|\boldsymbol{ResSeparation}|)$$



Predicting viscosity from NORMALIZED well logs

- Normalized logs do not noticeably improve the prediction

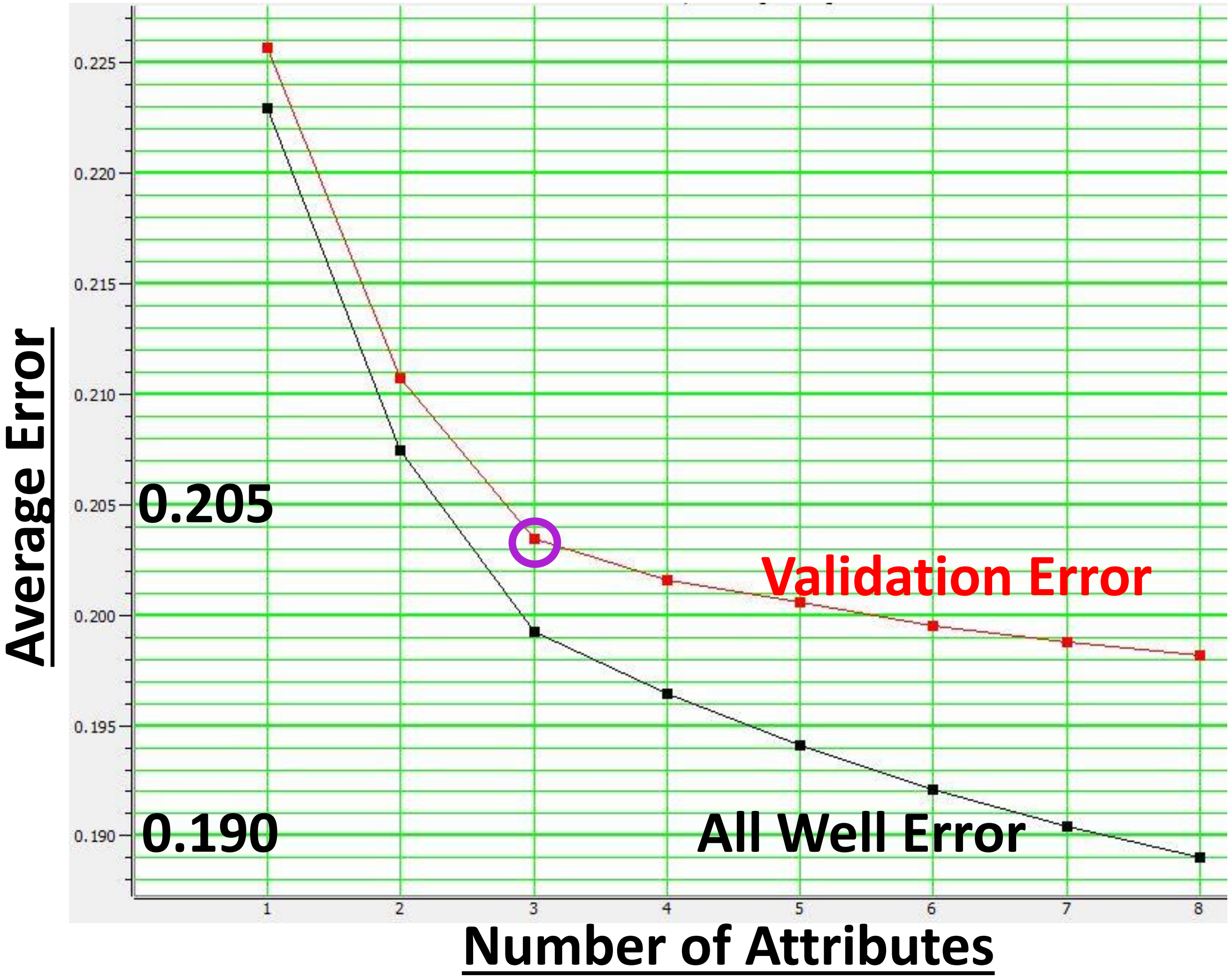
Attribute	Units
1. 1 / (ResMedium)	*1/[ohm-m]*
2. ln|GammaRay|	ln|*API*|
3. $(\text{ResShallow})^{1/2}$	*$[\text{ohm-m}]^{1/2}$*
4. 1 / (P-wave sonic)	*1/[us/m]*
5. $(\text{S-wave sonic})^{1/2}$	*$[\text{us/m}]^{1/2}$*
6. $(\text{Wt \% bitumen})^{1/2}$	*$[\%]^{1/2}$*



Predicting LOG10(viscosity) from un-normalized well logs

- Optimum log10(viscosity) prediction is found using **3 attributes**

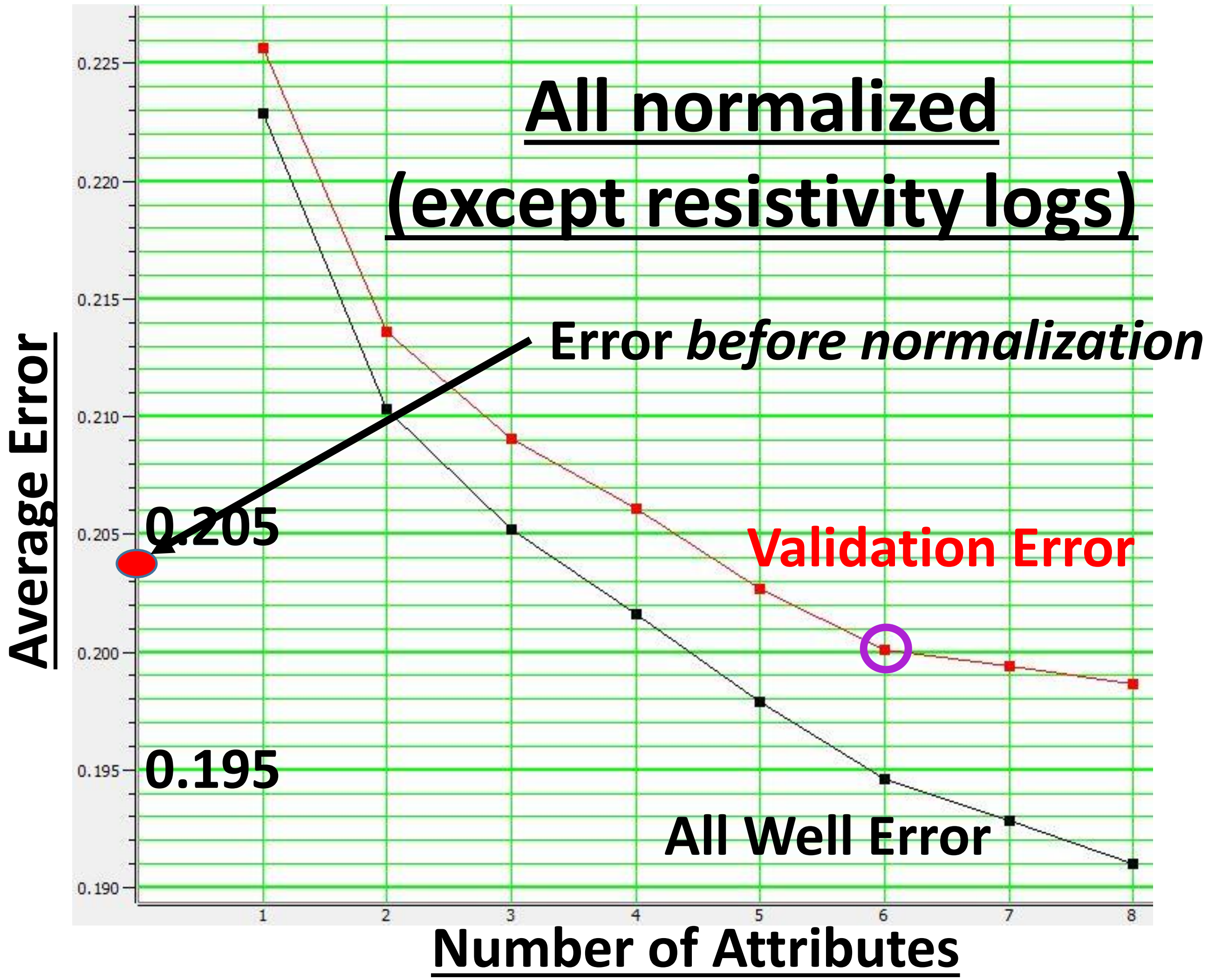
Attribute	Units
1. ln(ResShallow)	*ln[ohm-m]*
2. Gamma Ray	*[API]*
3. 1 / (P-wave sonic)	*1/[us/m]*



Predicting LOG10(viscosity) from NORMALIZED well logs

- Normalized logs do not noticeably improve the prediction

Attribute	Units
1. ln(ResShallow)	*ln[ohm-m]*
2. ln(Gamma Ray)	*ln[API]*
3. 1 / (P-wave sonic)	*1/[us/m]*
4. (S-wave sonic)^2	*[us/m]^2*
5. ResM / ResS	*[unitless]*
6. (Wt % bitumen)^2	*[%]^2*



Key Points – Viscosity from standard log suite

To predict viscosity directly, 4 well log attributes should be used:

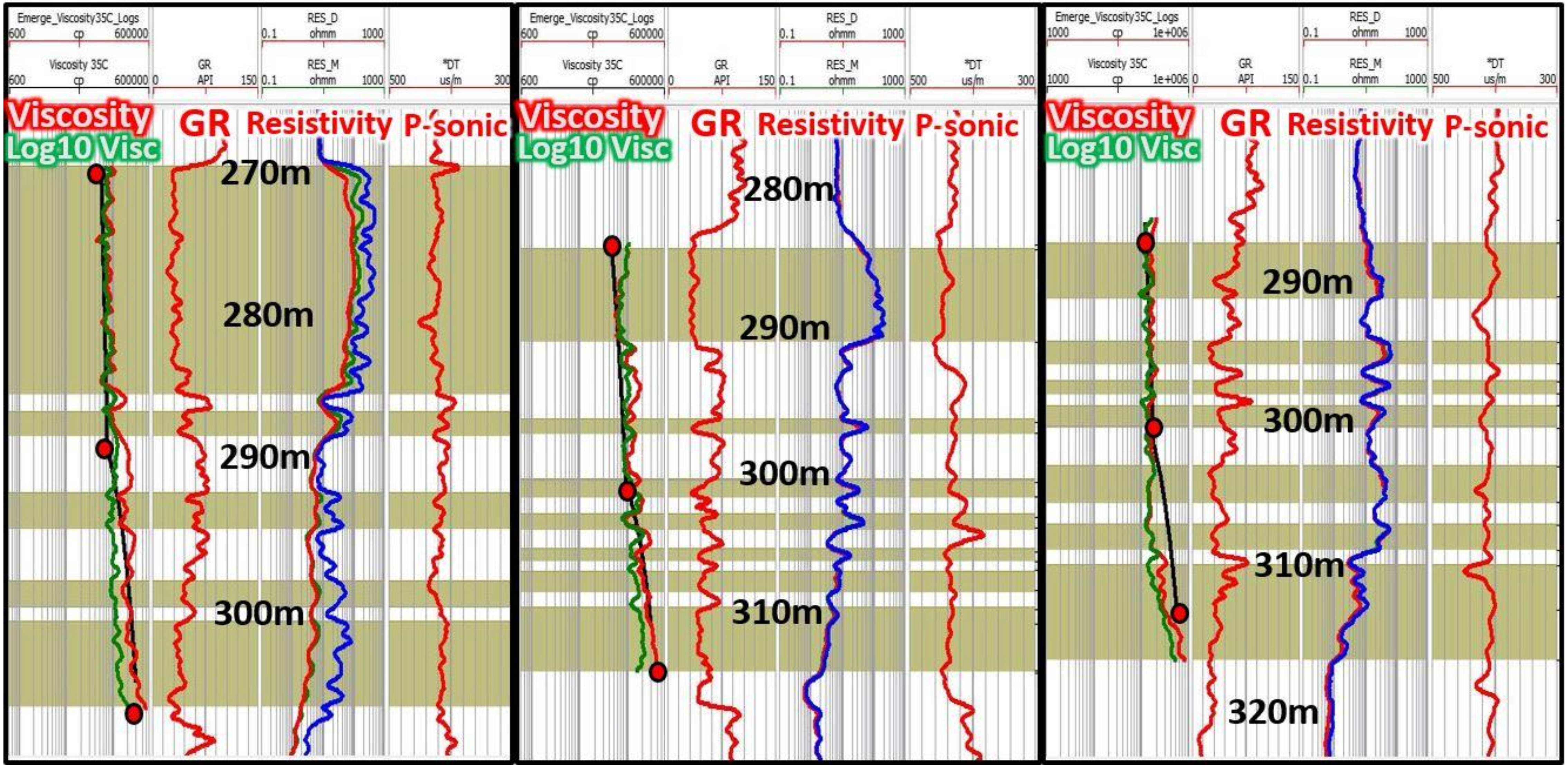
1. **1 / (ResMedium)**
2. **$(GammaRay)^{1/2}$**
3. **1 / (P-wave sonic)**
4. **ln |ResShallow|**

To predict LOG10(viscosity), 3 well log attributes should be used

1. **ln |ResShallow|**
2. **Gamma Ray**
3. **1 / (P-wave sonic)**

Normalizing the logs did not significantly improve the prediction ☹

Viscosity predictions from standard log suite



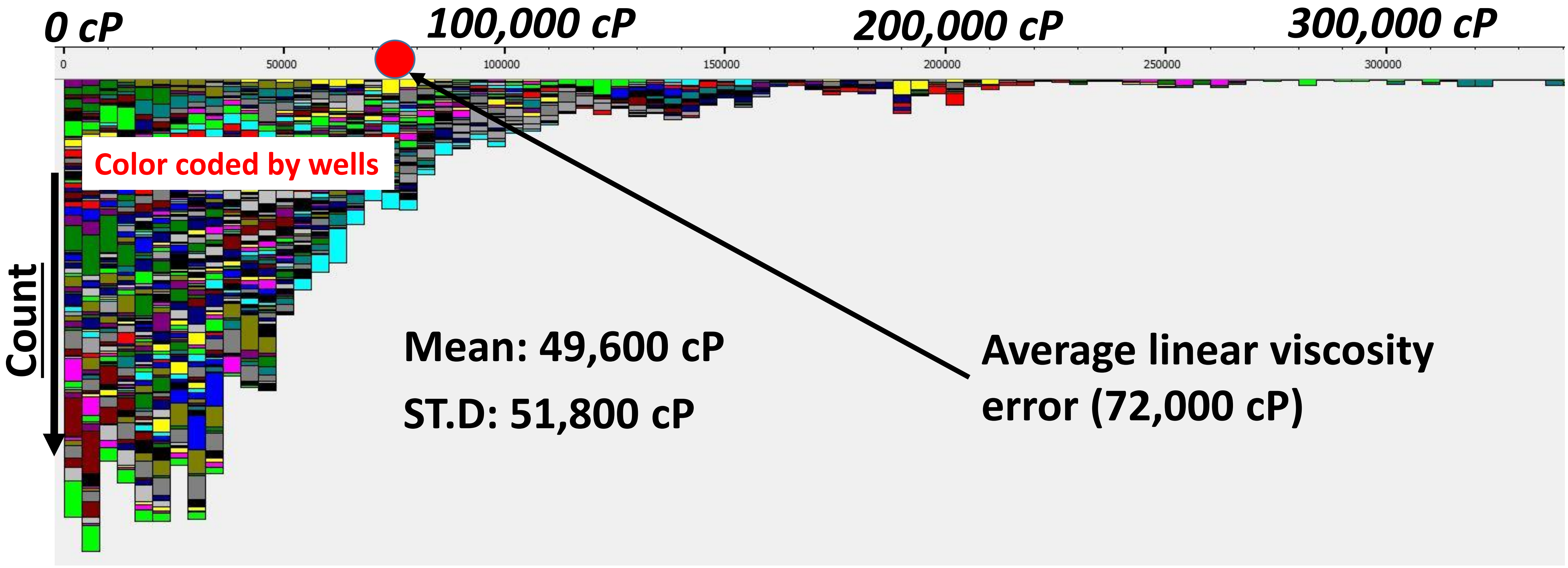
Top Error: 32,000 cP
Base Error: 45,000 cP

Top Error: 62,000 cP
Base Error: 41,500 cP

Top Error: 24,000 cP
Base Error: 204,000 cP

Should we predict Log10 Viscosity or linear Viscosity?

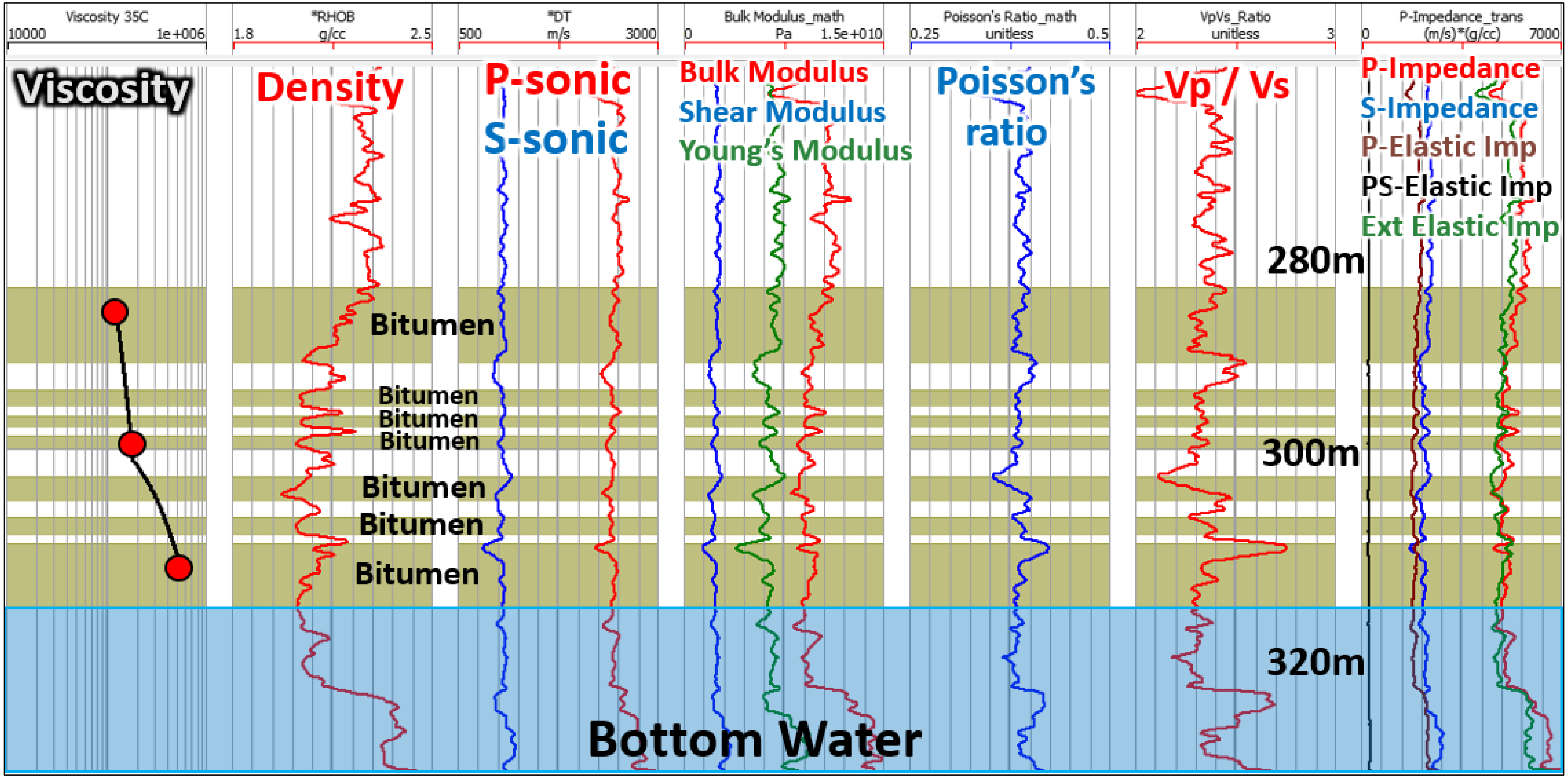
Log10 viscosity errors converted back to linear space



Log10 viscosity predictions converted back to linear space appear to give lower errors

Using Calculated Elastic Properties to predict viscosity

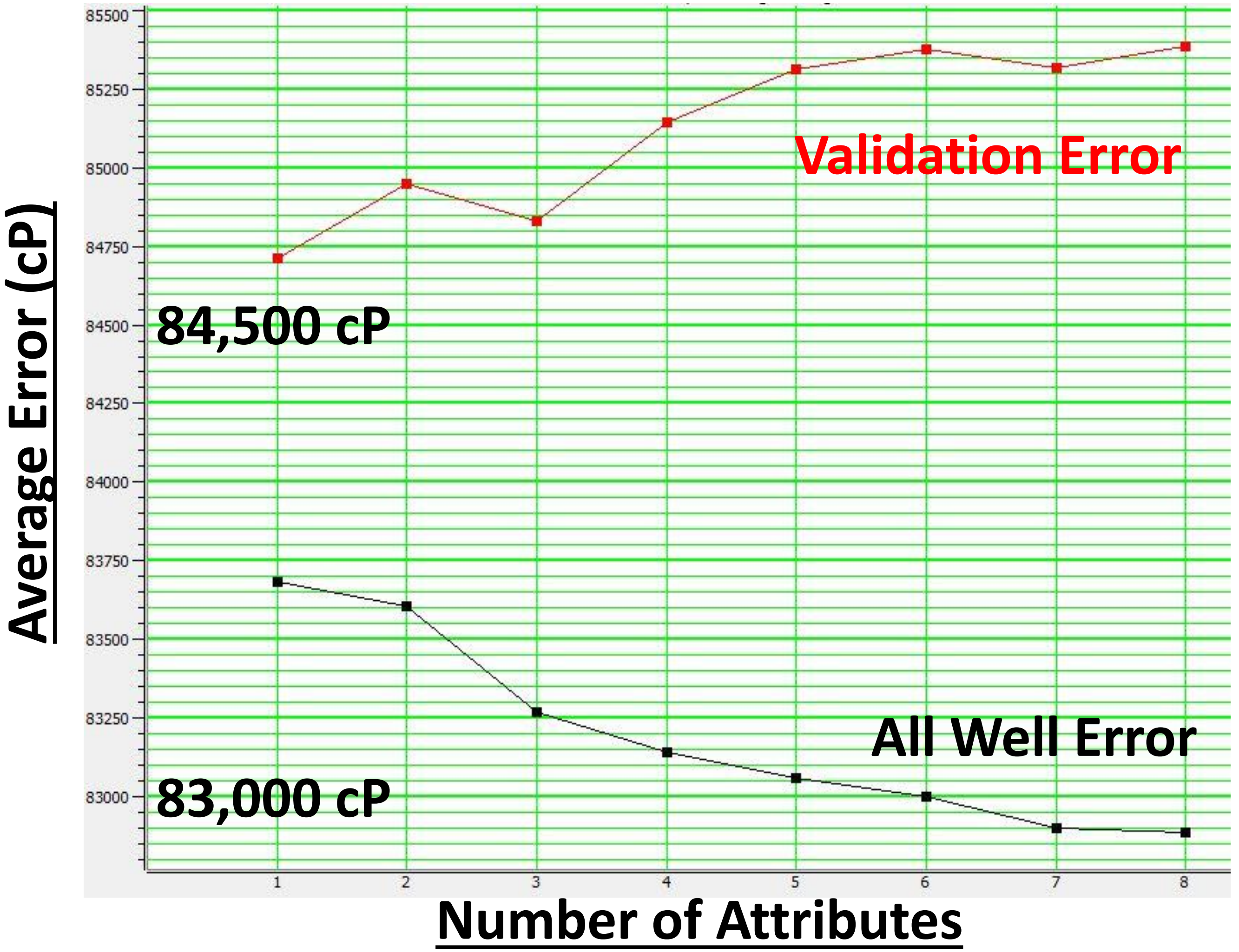
Goal: Use seismic to predict viscosity



Using un-normalized Elastic Properties to predict Viscosity

- Something is wrong with the input well log attributes

Attribute	Units
1. Bulk Modulus	*[Pa]*
2. 1 / (P-Imp.)	1/*[m/s * g/cc]*
3. (S-Impedance)^2	*[m/s * g/cc]*^{2}
4. (E. Elastic Imp)^2	*[m/s * g/cc]*^{2}

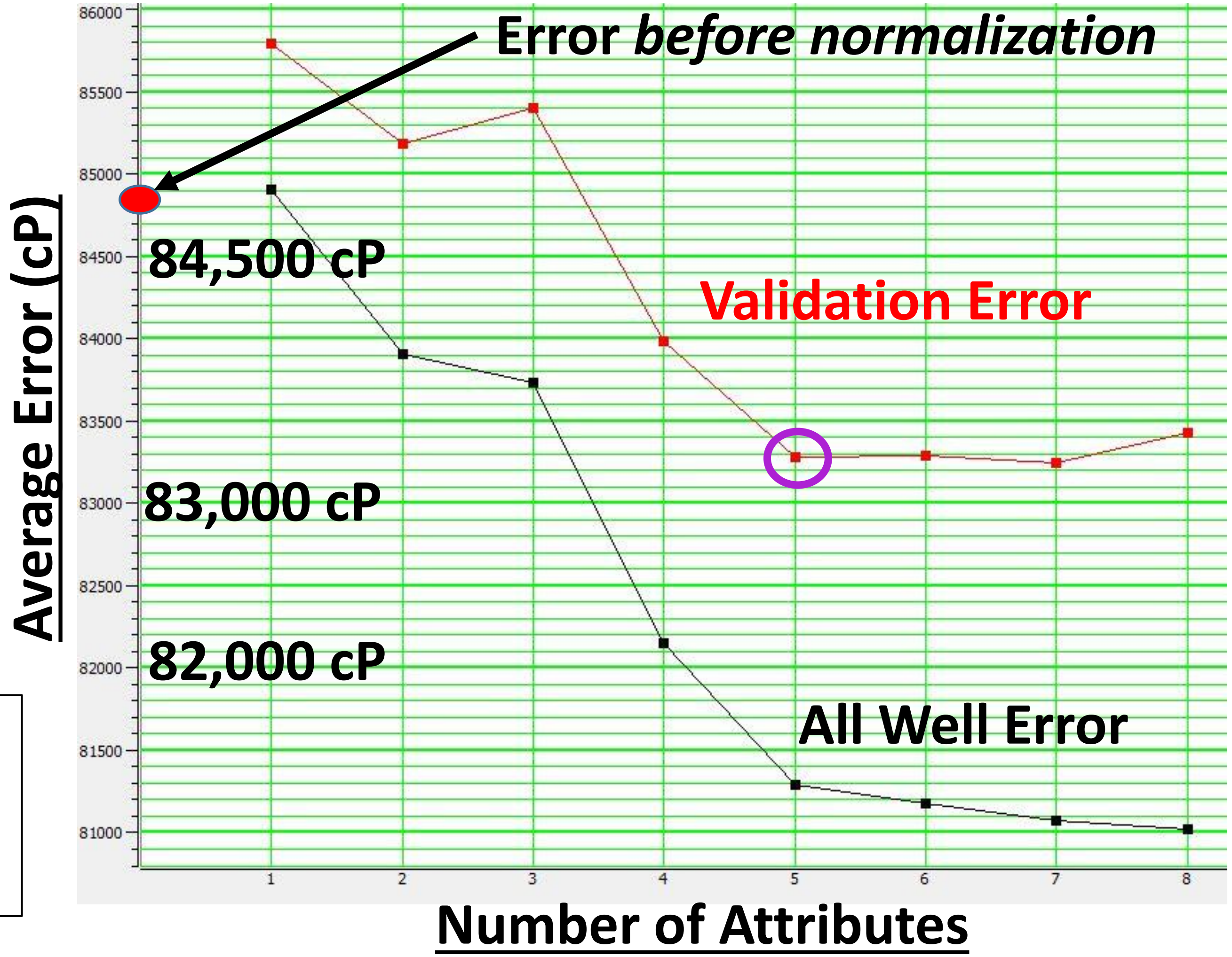


Using NORMALIZED Elastic Properties to predict Viscosity

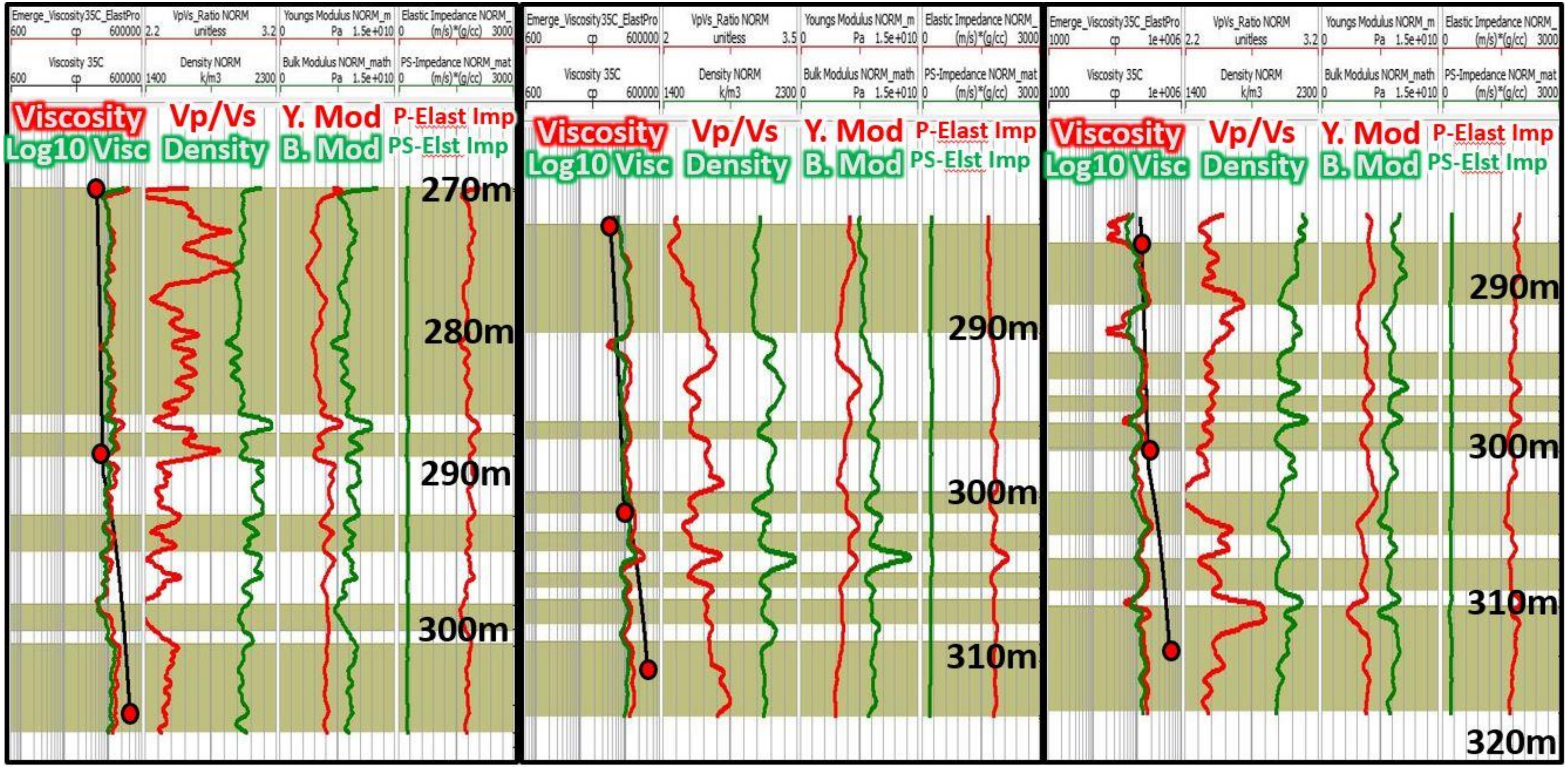
- Optimum viscosity prediction is found using **5 attributes**

Attribute	**Units**
1. **Bulk Modulus**	*[Pa]*
2. **1 / (Density)**	*1/[kg/m³]*
3. **1 / (PS-Elast Imp)**	*1/[m/s * g/cc]*
4. **(Young's Modulus)$^{1/2}$**	*[Pa]$^{1/2}$*
5. **P-Elastic Imp**	*[m/s * g/cc]*

$$\eta = -2527000 + 0.00009(\boldsymbol{BulkModulus}) - \left(\frac{695541000}{\boldsymbol{Density}}\right) + \left(\frac{413430000}{\boldsymbol{PS-Elast\ Imp}}\right) + 17.06(\boldsymbol{YoungsModulus})^{1/2} - 573.2(\boldsymbol{P} - \boldsymbol{Elastic\ Impedance})$$



Viscosity predictions from calculated elastic properties



Top Error: 70,000 cP
Base Error: 100,000 cP

Top Error: 45,000 cP
Base Error: 131,000 cP

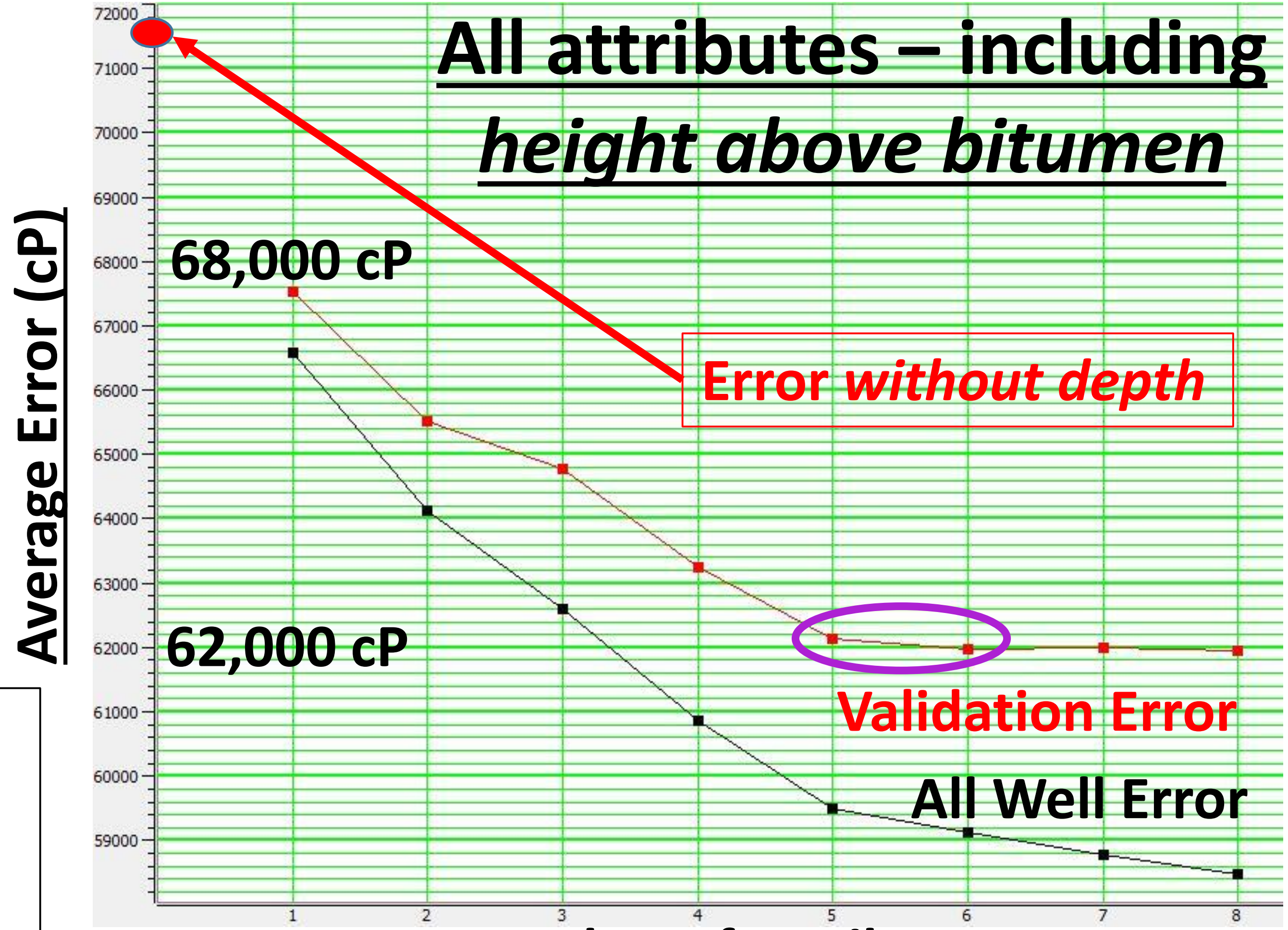
Top Error: 31,000 cP
Base Error: 255,000 cP

Adding *height above bitumen base* as an attribute

- Optimum viscosity prediction is found using **5 to 6 attributes**

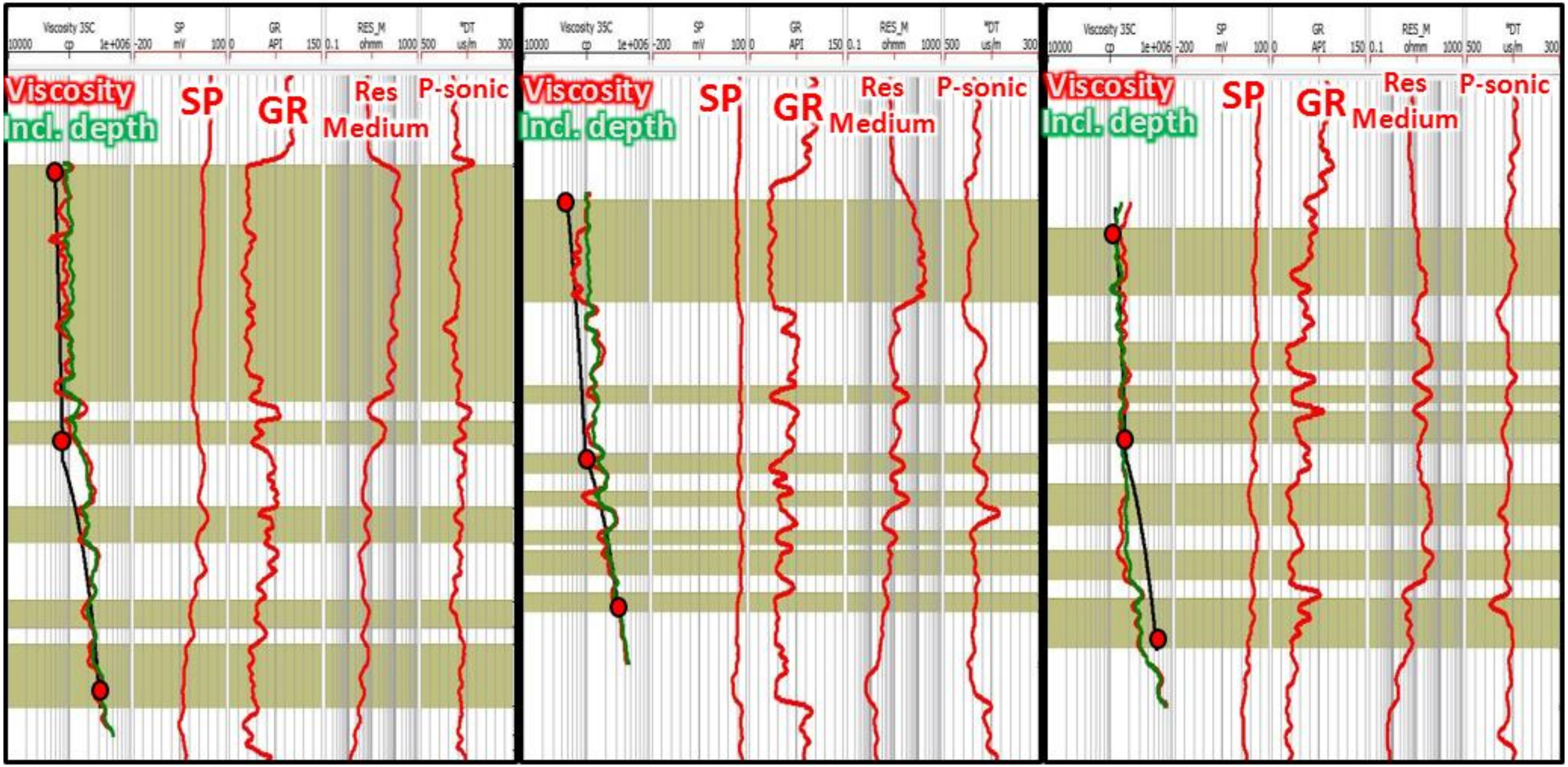
Attribute	**Units**
1. (Ht. above bitumen)$^{1/2}$	***[m]$^{1/2}$***
2. ln(|SP|)	***[none]***
3. 1 / (ResMedium)	***1/[ohm-m]***
4. Gamma Ray	***[API]***
5. 1 / (P-wave sonic)	***1/[us/m]***

$$\eta = 24380 - 29600\sqrt{HtAboveBitumen} + 3957ln(|SP|) + 610800\left(\frac{1}{ResMedium}\right) - 1643(GammaRay) + 119300000\left(\frac{1}{P-sonic}\right)$$



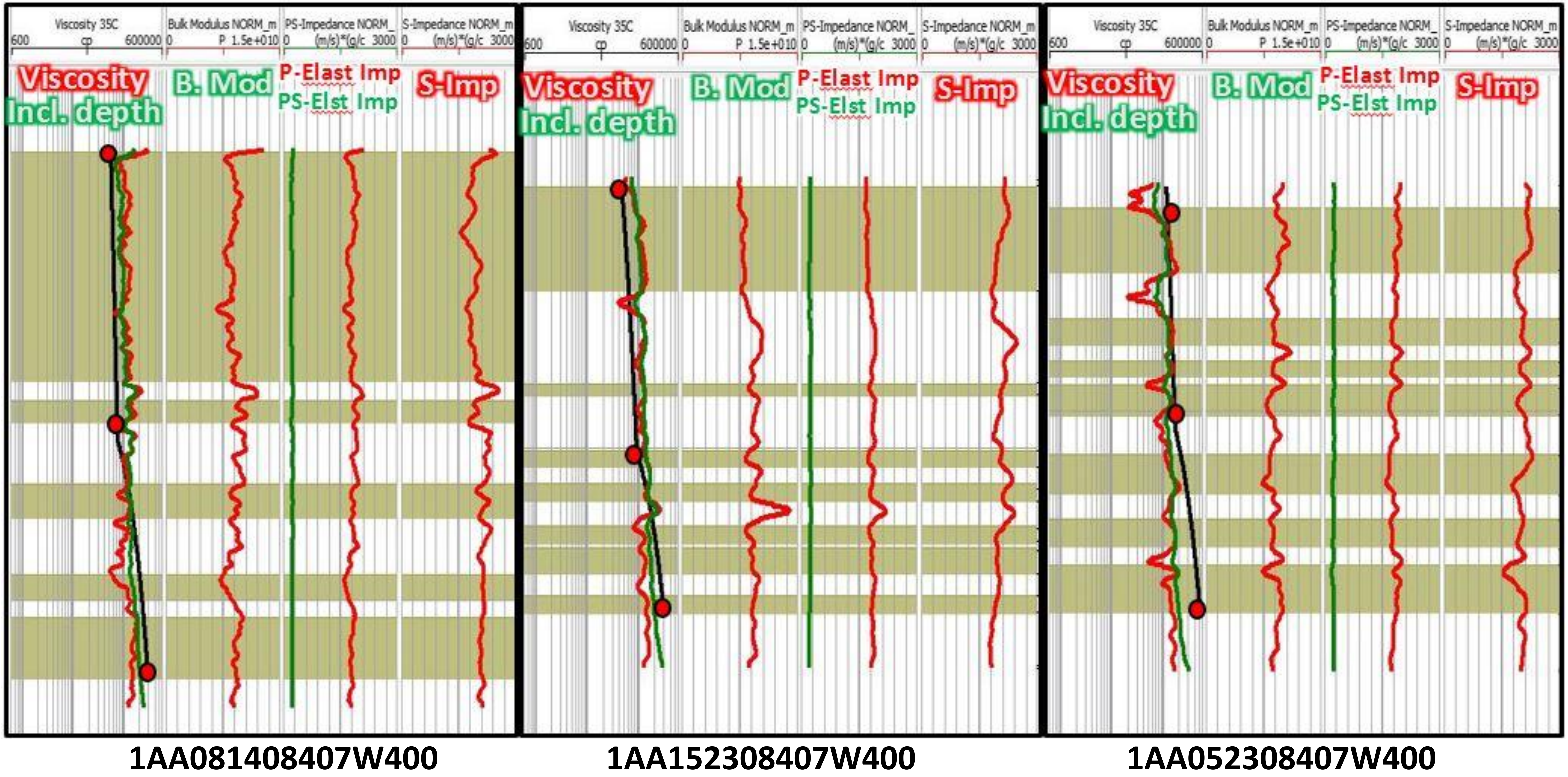
Number of Attributes

Viscosity prediction results using unnormalized logs AND depth



1AA081408407W400 1AA152308407W400 1AA052308407W400

Viscosity prediction using NORM Elastic Properties AND depth



GeoConvention 2016

GeoConvention 2016

Petrophysics Trip to Comox, BC !! (April 2016)