Water Quality Profiles From Well Logs: The Waxman-Smits Solution for Conductive Clays

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Aquifers and Water Quality

- Understanding groundwater quality and distribution is increasingly important with new legislation and regulation impacting the use and protection of this resource
- Oil and gas operations are among the sources of concern about potential effects on groundwater
- Data from oil wells and petroleum technology are making significant contributions to better knowledge of aquifers and groundwater basins in the areas where O&G operations exist
  - Well logs through shallow zones in oilfields and nearby provide an abundant data source

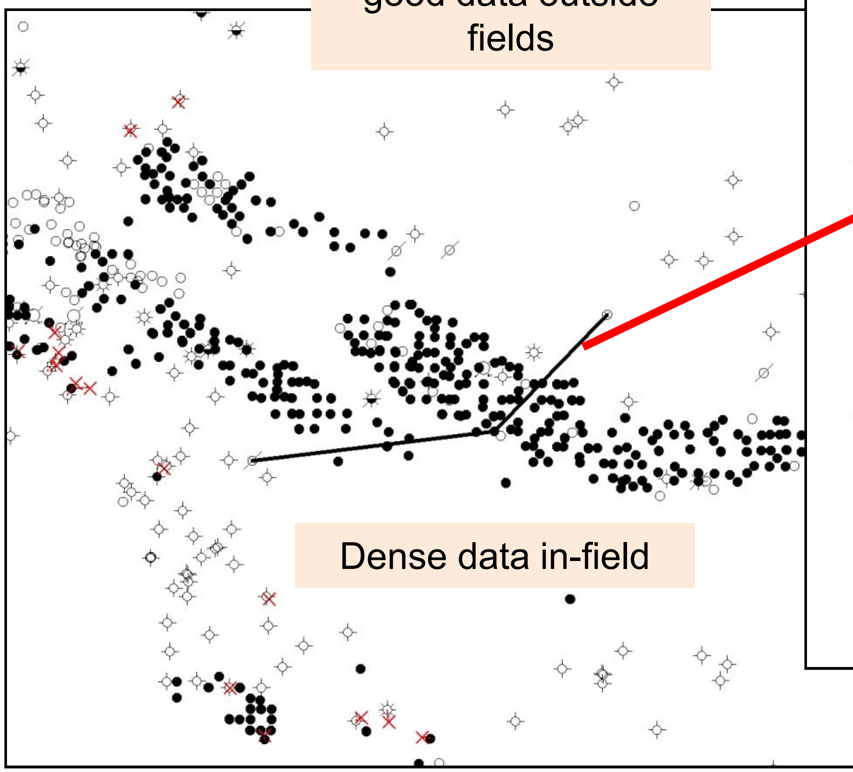
Water Quality Profiles From Logs

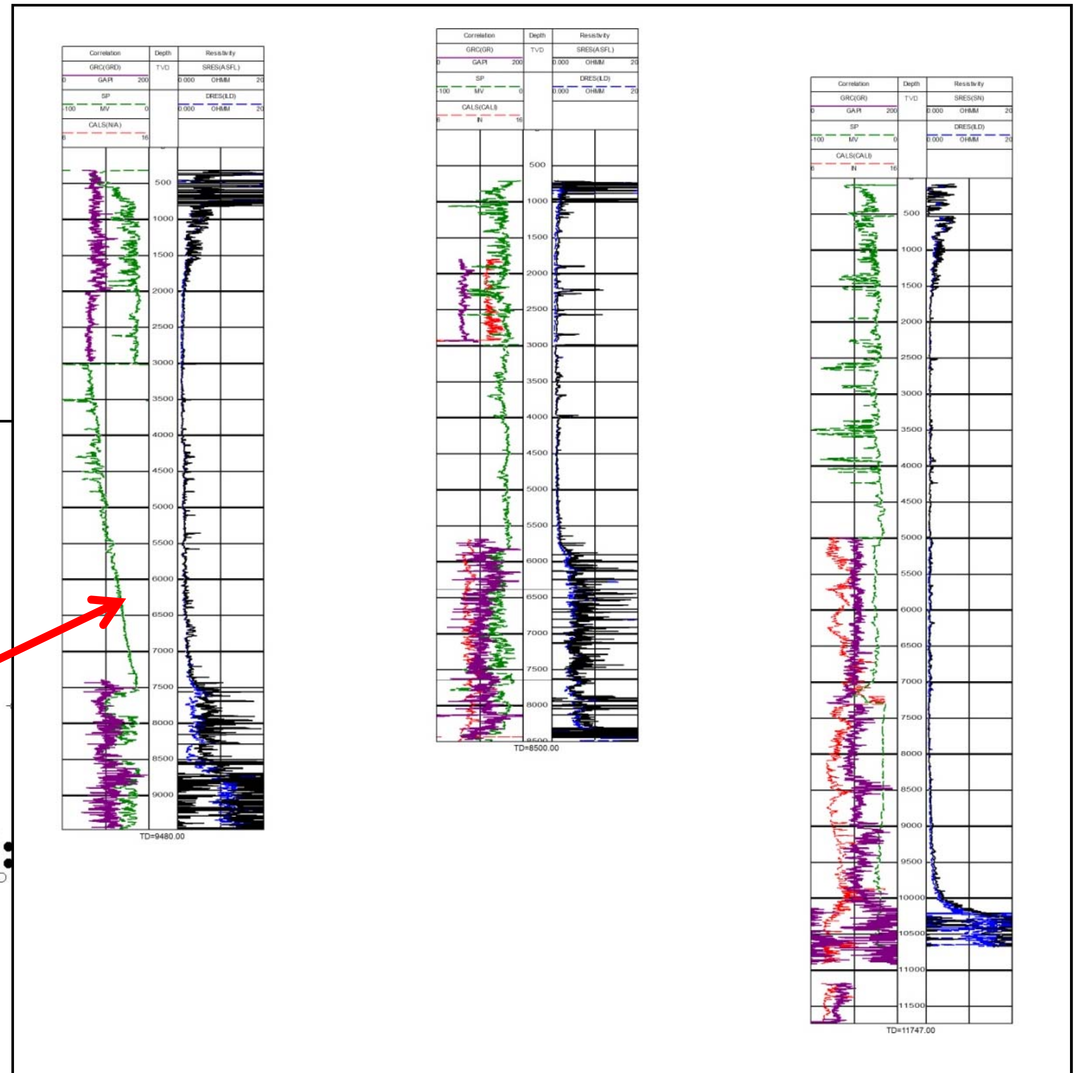
- There is great interest in deriving water quality from logs
  - Provides quantitative data over wide areas where sampling is difficult or not economically feasible
  - Fills in between analysis data points laterally and vertically
  - Assists in locating the approximate depth for base of protected waters
  - Should be calibrated to water analyses
  - **Needs to be based on good science**

Aquifers and Water Quality

- Water quality can be determined from lab analyses
  - Expensive, though necessary for detailed data on constituents of water and log calibration
  - Samples sometimes difficult or impossible to obtain where needed

Track Groundwater Quality Trends from Surface to Deep Injection Zones, In-Field and Regionally





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Water Quality Profiles From Logs

- Based on techniques developed from extensive lab research on cored rock samples, starting in the 1930's
- Although the goal was to find oil, most research was done on water-saturated sands with varying salinities
- These concepts can be applied directly to aquifers
  - Various techniques proposed
  - Most useful are resistivity-porosity relationships
  - ***Basic model does not account for clay conductivity***

Water Quality Profiles From Logs

- A water quality profile from a well log is based on deriving Rwa (Apparent Water Resistivity)
  - $Rwa = R_T/F$
    - F = Formation Factor (defined below)
    - R_T = Formation True Resistivity, for which logged Deep Resistivity is usually adequate
  - Rwa in a clean 100% wet sand is Rw
  - Rw is proportional to TDS at constant temperature

Water Quality From Logs: Conceptually Simple Based on Archie Model

$$R_o = R_T = F * R_w$$

Ro is the resistivity of a 100% wet rock, and by definition equals measured resistivity. It is a function of F, formation factor, and Rw, resistivity of the saturating water

$$F = {}^{a}/_{\phi^m}$$

Formation factor is approximated by a function of porosity, exponent “m”, and constant “a”, (“a” often assumed = 1.0)

$$R_w = {}^{R_o}/_{F}$$

Re-arranging the equation to solve for Rw

$$R_w = \phi^m * R_T$$

Substituting terms obtainable from log measurements

a = Empirical constant, ϕ = Porosity, m = Porosity exponent, R_T = True resistivity

Water Quality Profiles From Logs

- The parameter Rw, formation water resistivity, is a function of water chemistry
  - Rw is related to salinity as ppm NaCl at temperature through charts and empirical relationships
  - Na/Cl are the dominant ions in high-salinity water
  - Many fresh to brackish waters also contain significant amounts of non-NaCl ions

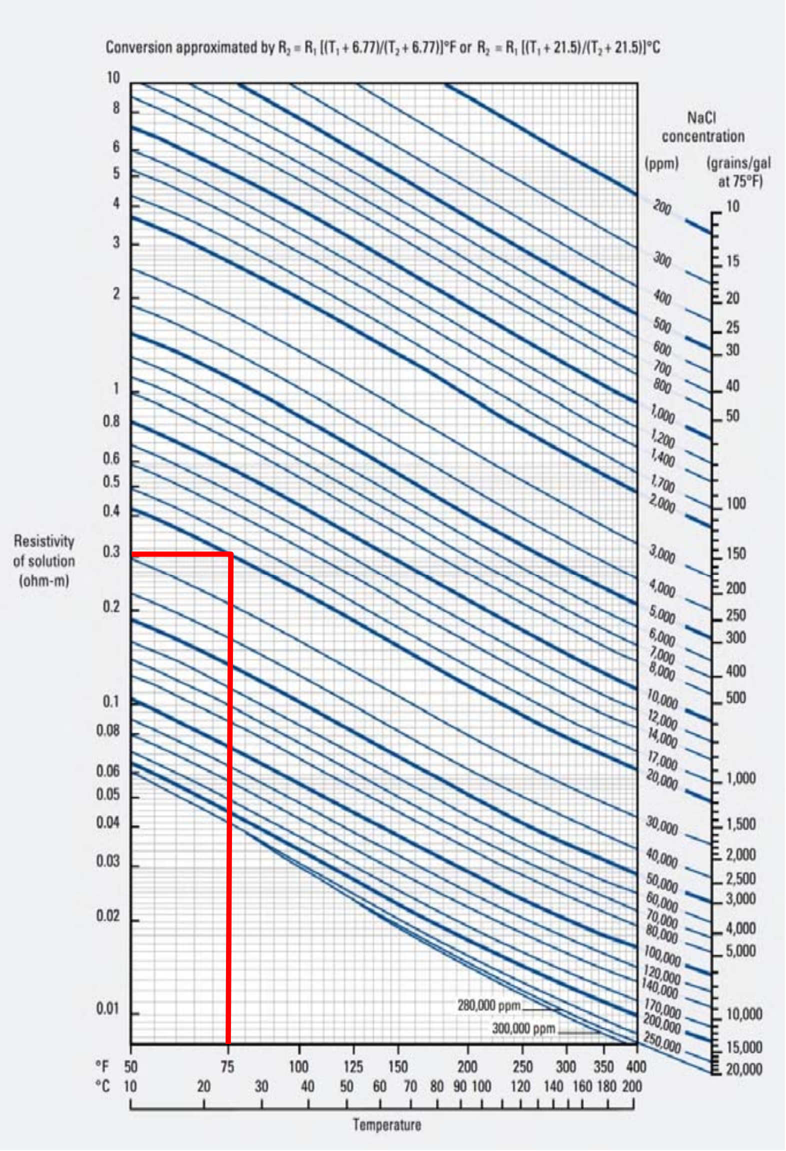
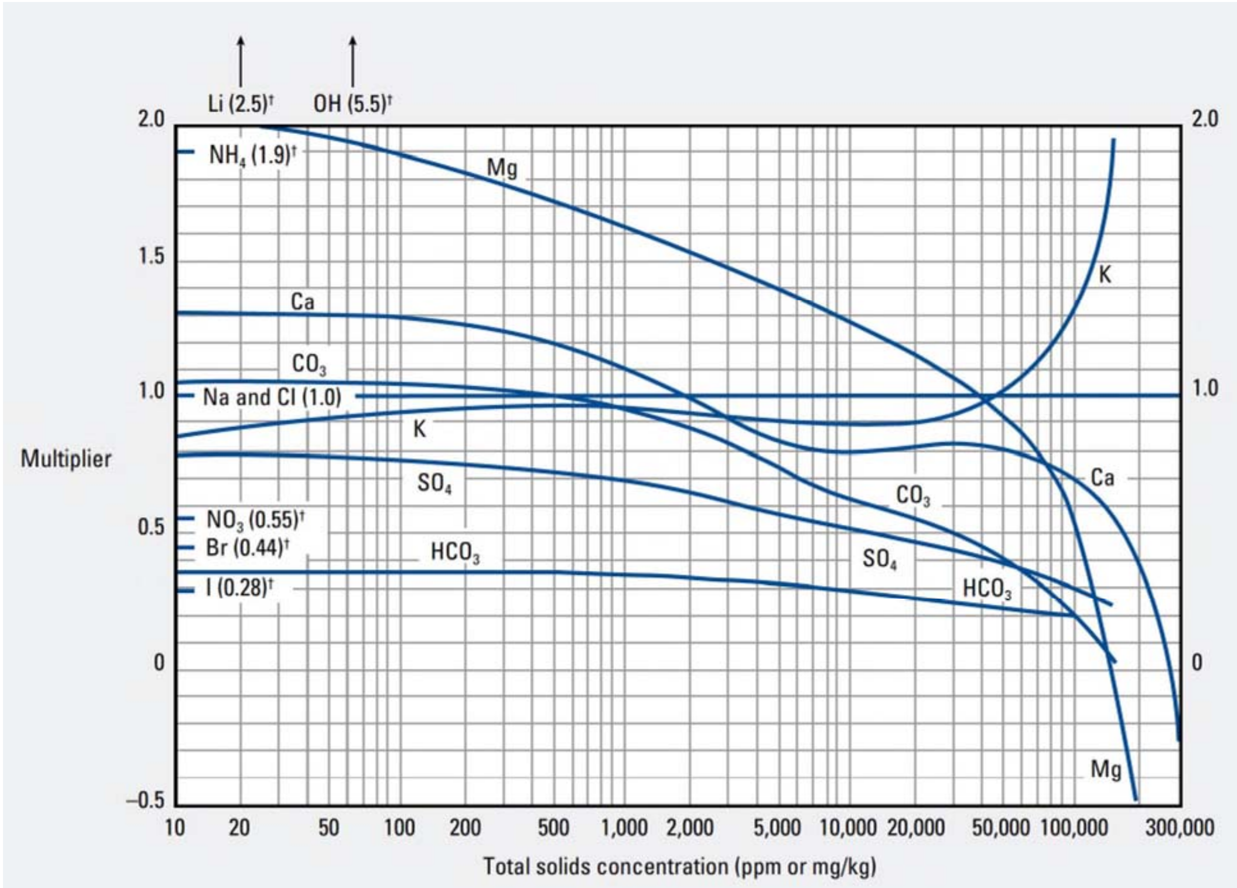


Chart: Schlumberger 2013

Waters Not Dominated by NaCl

- The chemistry of lower-TDS waters typically includes significant amounts of non-NaCl species such as Ca, Mg, CO3, $HCO3^-$, and SO4
  - These ions have different electrical activity than NaCl
- When these ions are present in large amounts, the relationship between TDS and resistivity is not the same as for a NaCl solution



This chart allows the apparent TDS as NaCl to be calculated for a water with significant amounts of other ions present. The Rw of the water can then be determined from the NaCl chart.

Schlumberger Gen-4 (2013 edition, formerly Gen-8)

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Calculating Rw From Logs

Calculate porosity from bulk density where: ϕ = porosity, ρ_{ma} = matrix density, ρ_B = log density, and ρ_{fl} = fluid density

$$\emptyset = \frac{\rho_{ma} - \rho_B}{\rho_{ma} - \rho_{fl}}$$

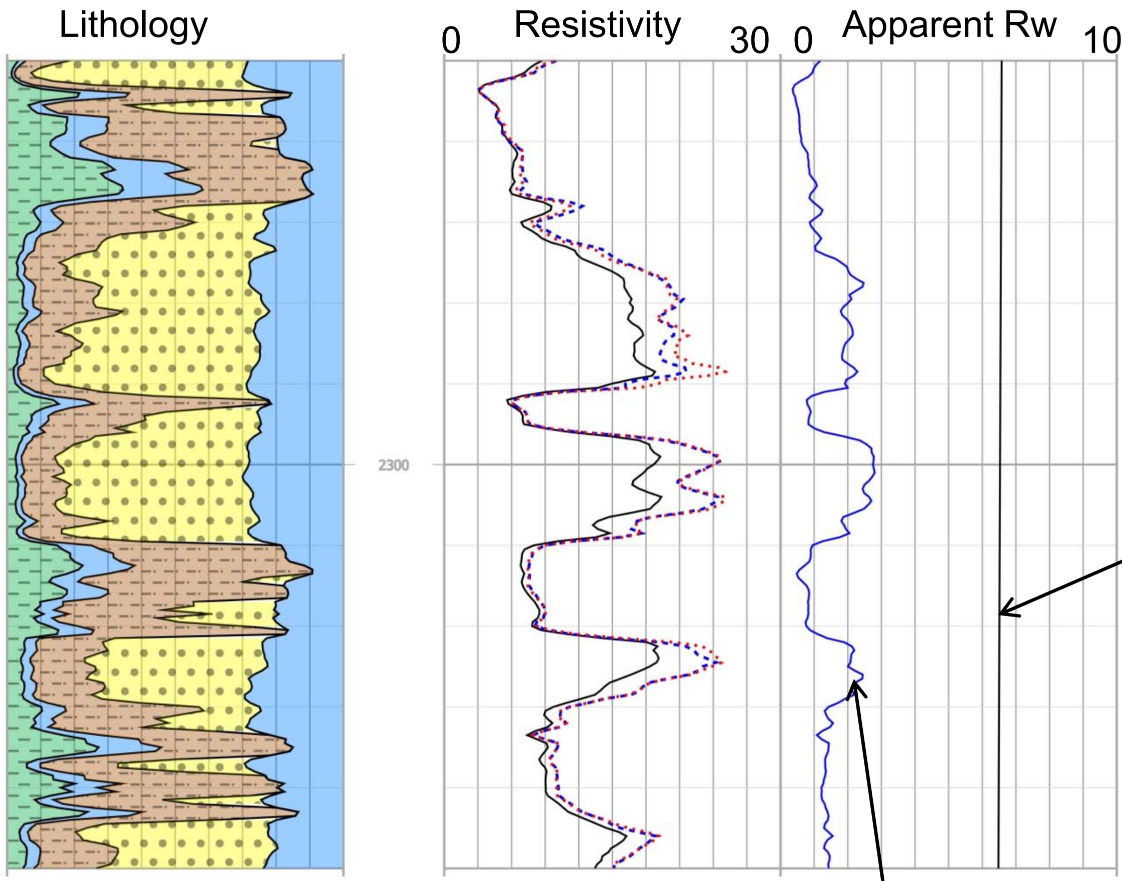
Logged deep resistivity can be used for R_T

"m" = 2.0 is a good initial setting

$$R_w = \emptyset^m * R_T$$

There is no clay correction in this calculation – it will be accurate only if the sand is clay-free

Apparent Water Resistivity (Rwa) in Wet Sands Example



Archie-Derived Rw

$$R_w = \emptyset^m * R_T$$

Laboratory Rw on water sample (at temperature)

Apparent Rw from a simple Archie analysis (blue curve) is much lower than Rw measured in the laboratory on a sample taken from this zone (black line). Apparent TDS calculated from the Archie-derived curve will be too high.

Overestimating TDS From Rwa

- In sands with low-TDS water, even after correcting for non-NaCl ion activity, Rwa analysis based on Archie often over-estimates the apparent salinity. Why?

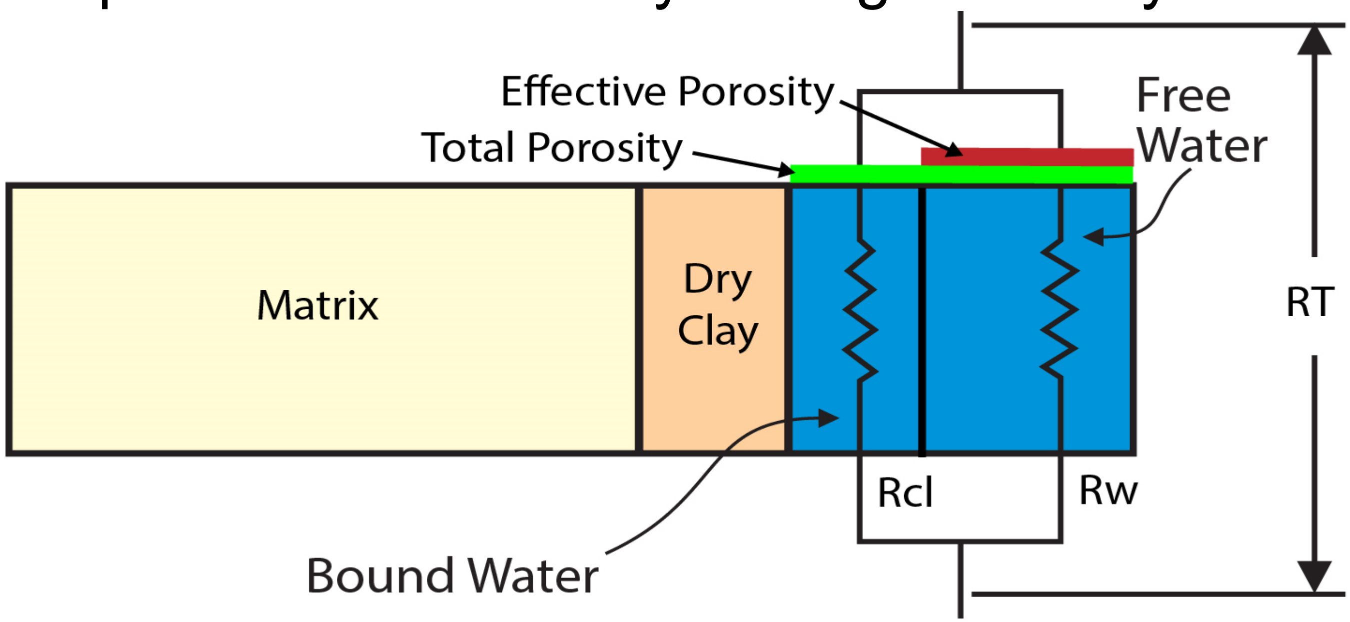
CLAY

Clays in Sandstones

- Many clay minerals are electrically conductive to varying degrees because of their chemistry
- Members of the montmorillonite/smectite series have the highest conductivity
  - These clays are common in shallow to moderate-depth aquifers

Clays in Sandstones

Decades of research primarily by Shell Oil, showed that many sandstones, even ones that appeared to be fairly clean, responded to laboratory testing like shaly sands



Conductance of electrical current through a wet sand is modeled as a parallel-conductor circuit, one path through the formation water and another through water associated with the clays.

Research Proves Parallel Current Path Resistivity Model is Applicable to Shaly Sands Worldwide

The quote below from Waxman and Thomas is an interesting comment from the researchers themselves on the similar electrical behavior they observed in all the samples they worked with

> The Waxman-Smits model…represents conduction in rocks containing clay minerals of unknown type in countless distributions…This implies that the clays are distributed throughout the pore network, resulting in a relatively uniform electric current flux…Because a great number of samples were used from reservoirs of differing character and origin…the proposed physical model [is] meaningful…

Waxman, M.H., and Thomas, E.C.,1974, Part 1, SPE Journal, pp 213-225

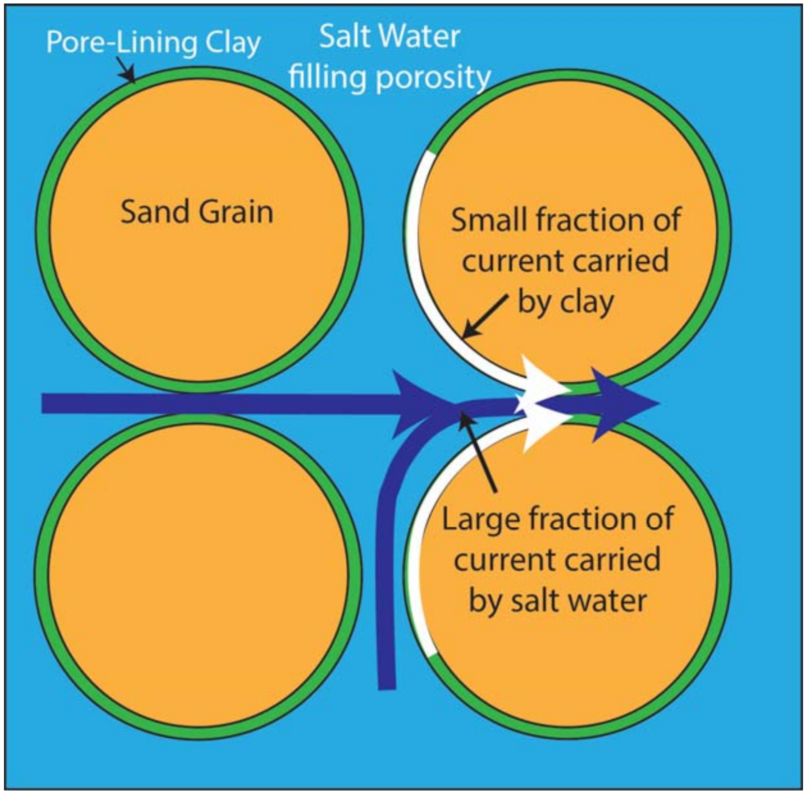
Shaly Sand Principles Adapted to Water Quality Profiles

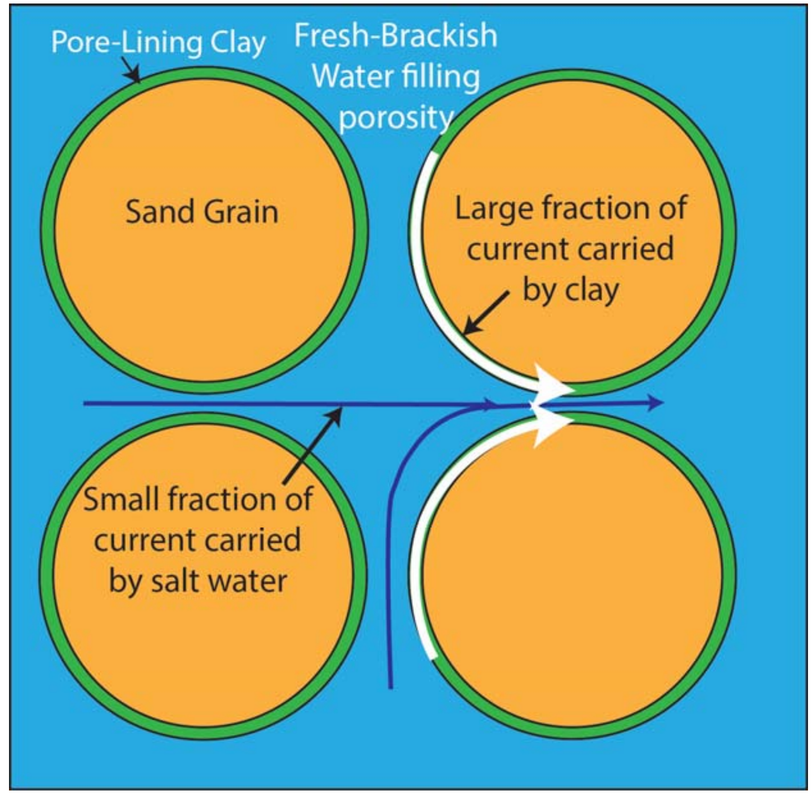
- If a clay correction is not applied to the basic Rw/Porosity/Rt relationship, water salinity will often be over-estimated
- Our shaly-aquifer log analysis model is based on 30+ years of experience with oil reservoirs having similar lithologies and containing water with varying salinity
- We have adapted it for use specifically in fresh to brackish-water aquifers containing small but significant amounts of clay

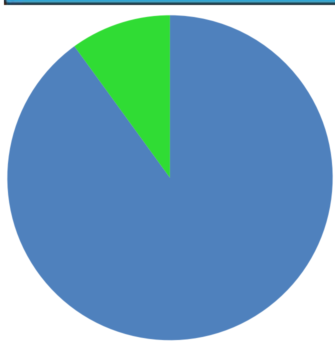
Clays in Sandstones

- Even if the rock appears to be very clean, sands (especially feldspathic) will nearly always have some authigenic clays and they will be found lining the pore system
- Clays facilitate a continuous electrical current path when located as pore lining
- As the formation water becomes less saline, an increasing proportion of total current is carried by the clay – possibly even a majority of the current!

Electrical Current Path Through Rocks

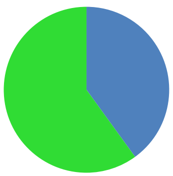






In salt water, total current flow is high and most of it is carried by the water

In fresh water, total current flow is low but most of it is carried by the clays



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Montmorillonite Pore Lining Showing Continuous Clay Phase on Grains

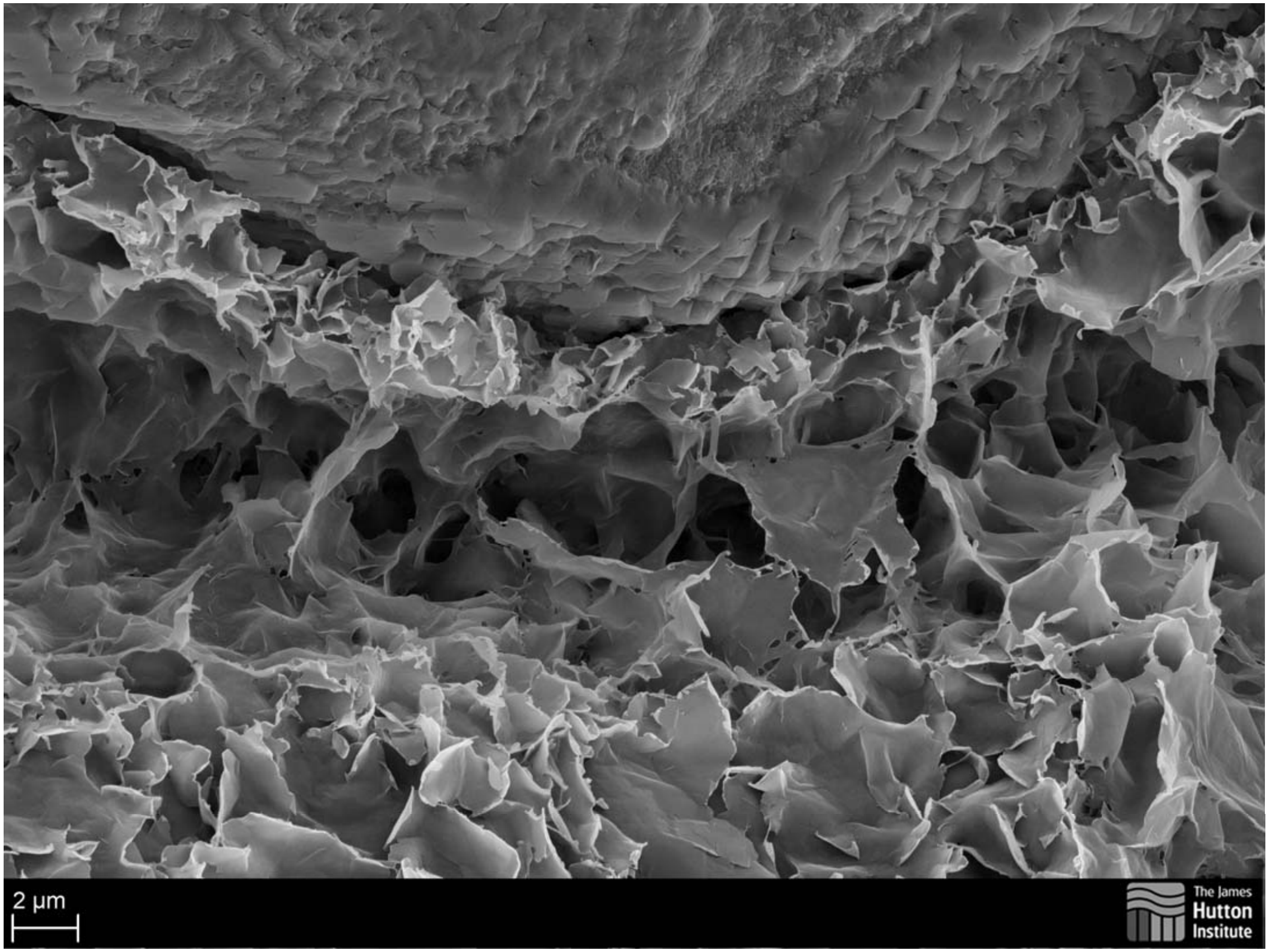
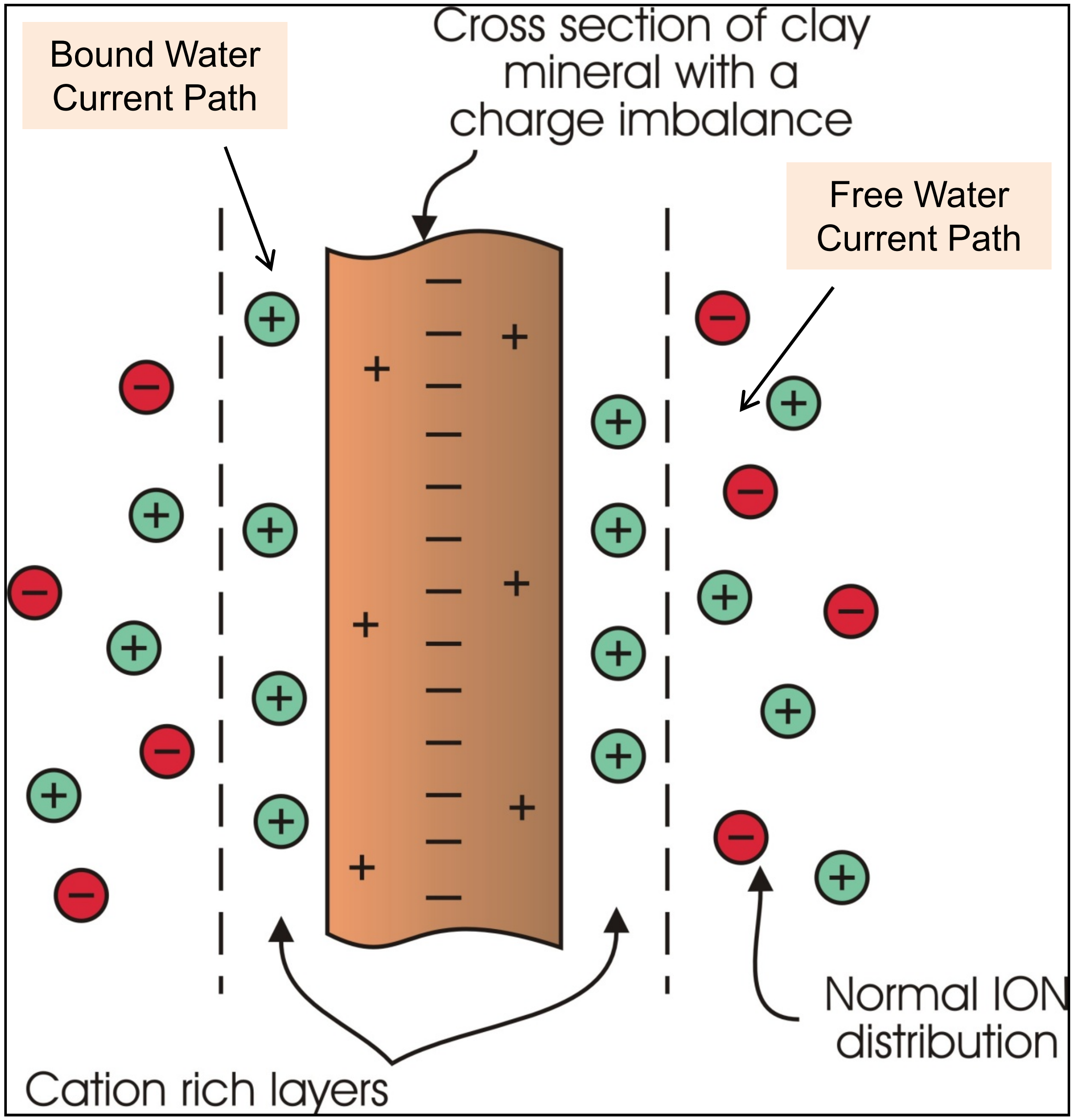


Image reproduced from the 'Images of Clay Archive' of the Mineralogical Society of Great Britain & Ireland and The Clay Minerals Society (www.minersoc.org)



The clay surface has a net negative charge and many charge sites that must be balanced by counterions (cations) that are in equilibrium with the cations and anions in the formation water. Ions move between the clay water and the free water. Though a simplification of reality, one can think of two current paths located within the bound water and free water (illustrated left).

Calculation of Clay Volume

- The accuracy of the clay volume is important for Rw and water salinity profiles
  - Many commercial software programs do not provide adequate tools for accurate clay calculations
  - May be only approximately accurate in the cleaner sands
- Nearly all California sands have at least 3%-5% clay
  - Most clay in shallower zones is authigenic montmorillonite or mixed layer species, the most conductive clays by far

Waxman-Smits Resistivity Model

- Waxman-Smits (1968) and Waxman-Thomas (1974) documented the role of clays in electrical conductance through rocks saturated with waters over a wide range of salinity and temperature
- The data indicated a temperature and salinity-dependent relationship between clay counterion concentration and formation water
- The experiments were extensive and carefully performed

Waxman-Smits Resistivity Model

- The original lab protocol used NaCl brines mostly in higher concentrations typical of oil reservoirs (NOT fresh water), and a temperature range from 25^{o} – 200^{o}C
- Later experiments extended research to low salinity brines
  - Clay-associated conductance was constant at a given temperature at high brine salinities
  - At lower salinities, clay conductance was reduced ***and not linear with temperature***
  - None of the other common shaly-sand models account for this phenomenon as thoroughly as by Waxman-Smits

Archie Model for Wet Sand in Conductivity

$$R_w = \emptyset^m * R_T = {R_T}/{F}$$

Archie model for Rw in wet sand, $R_T = R_o$

$$F = {a}/{\emptyset^m} = {R_o}/{R_w}$$

Where F = Formation Factor

Reciprocate terms into conductivity

$$F = {R_o}/{R_w} = {C_w}/{C_o}$$

F in terms of resistivity ratios and conductivity ratios

$$C_o = C_T = {C_w}/{F}$$

Calculate Co

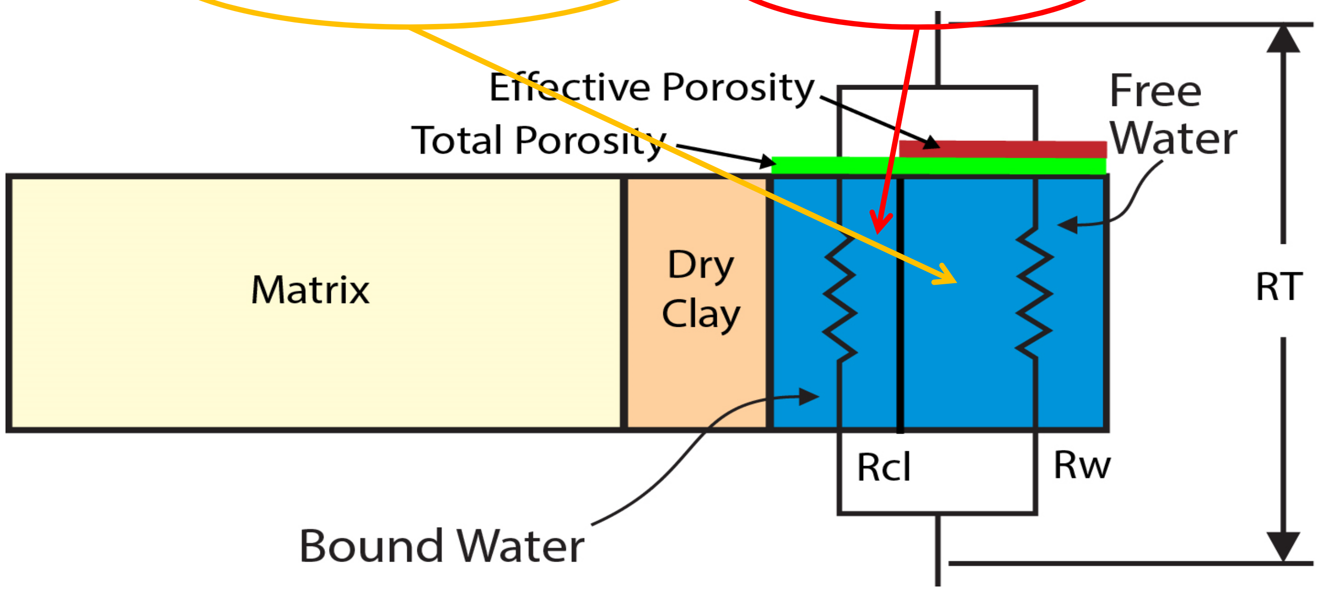
$$C_w = F * C_o = {C_o}/{\emptyset^m}$$

Calculate Cw

Waxman-Smits for Clay Correction

Note that this (like nearly all shaly sand saturation equations) consists of the standard Archie equation with a second term added to account for the excess clay conductivity

$$Co = (Cw/F^*) + ((BxQv)/F^*)$$

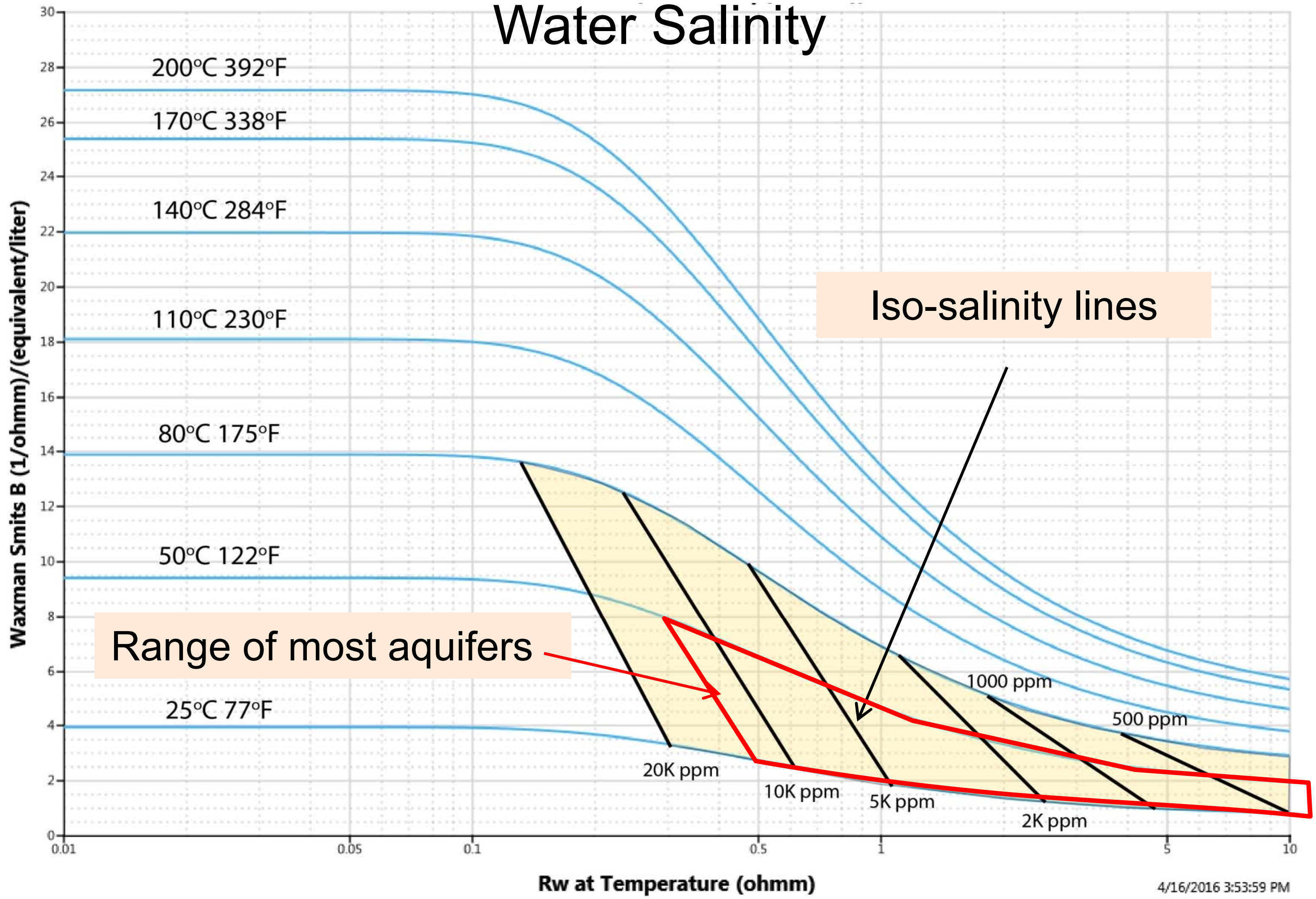


"B" = Equivalent counterion conductance

Qv = Cation concentration per unit volume of water in pore space (meq/ml)

F* = Waxman-Smits Formation Factor

Value of Parameter "B" As a Function of Temperature and Water Salinity



Maximum range of B for aquifers = 0.5 – 8.0 at temperatures <130°F

From Gravestock, 1991

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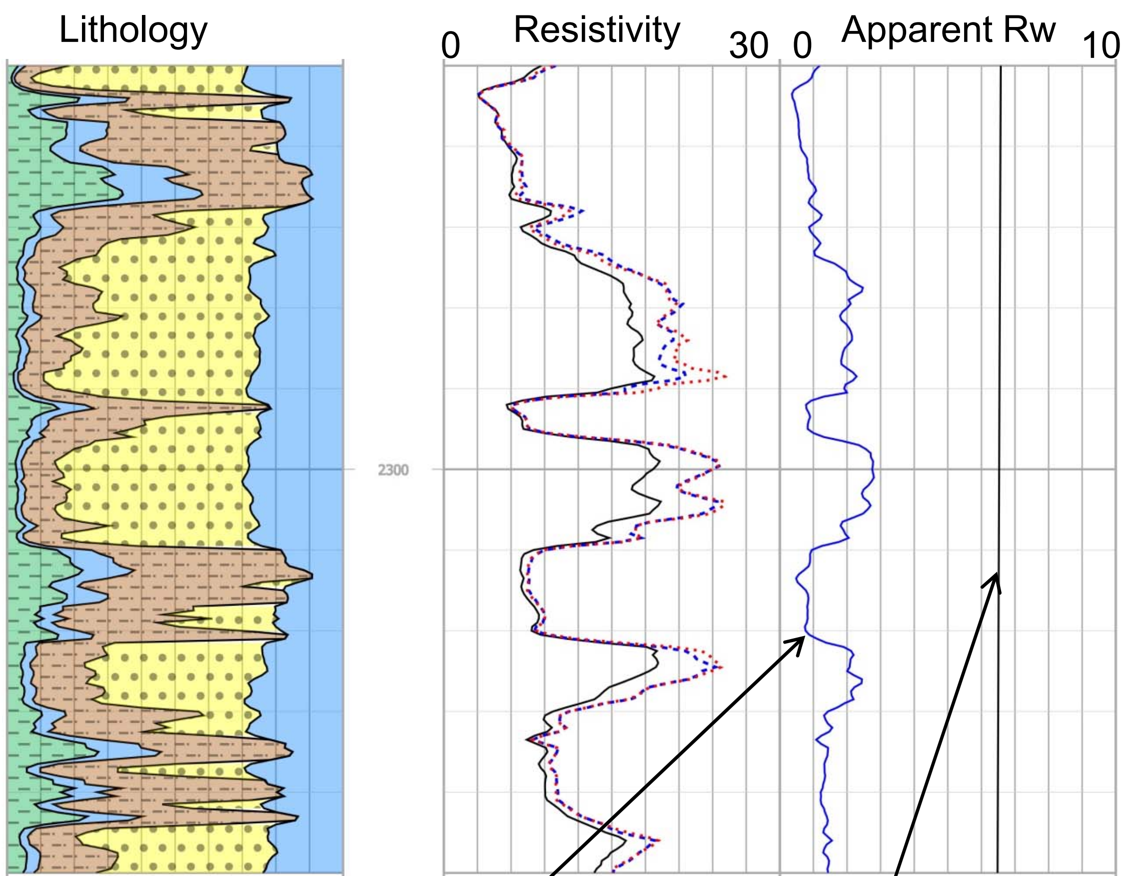
Ion	ppm
Mg	1
K	7
Na	210
Ca	14
HCO3	270
Cl	170
SO4	6
SiO2	58

Example: Major Ion Analysis of Low TDS Water

This very low TDS water (736 ppm) is only about 50% NaCl. The other dominant ion in the water is bicarbonate, which is common in brackish waters in California basins.

Rwa Without Clay Correction: Very Low Salinity (<1000 ppm)

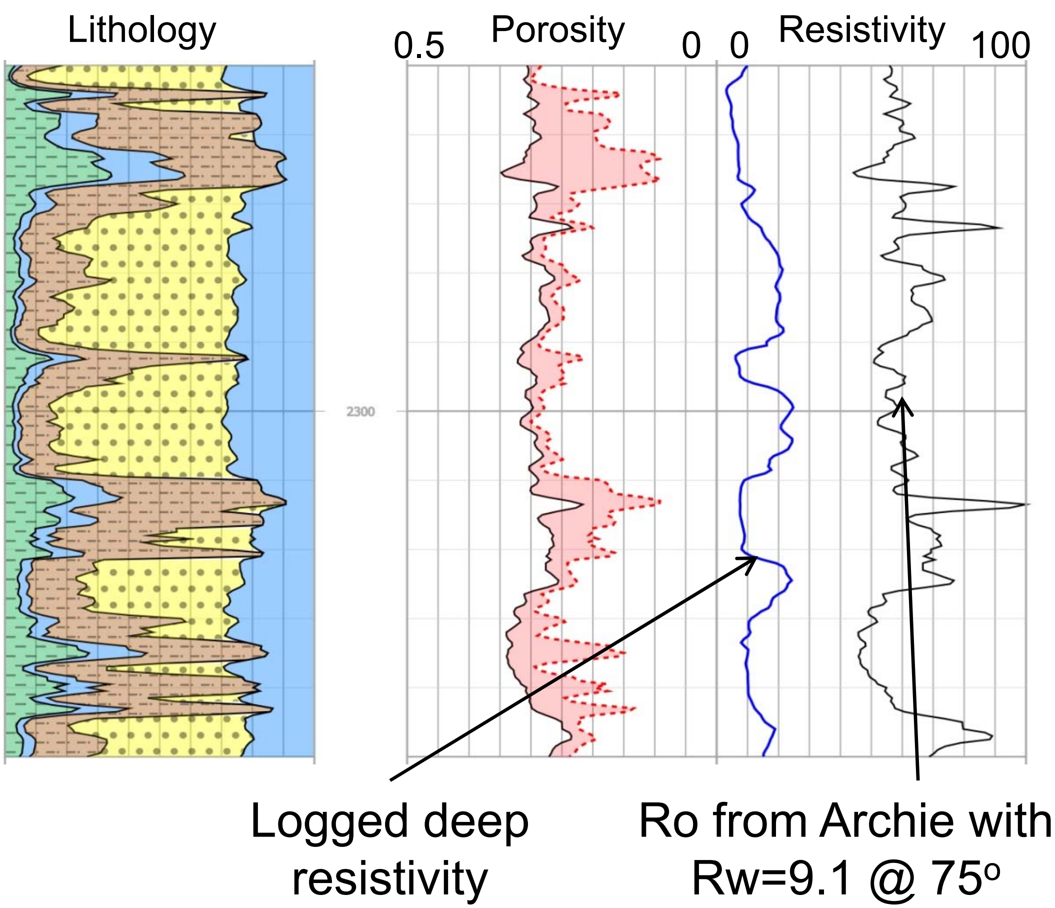


$$R_w = \emptyset^m * R_T$$

Laboratory Rw 6.5 ohm-m on water sample (at temperature)

If there were no clay conductivity included in the logged resistivity, the apparent Rw calculated from the simple Archie formula would be all that was needed. But clearly, even though total clay volume is 4%-7% in these sands it contributes significant conductivity, shown by the Rwa values so much lower than the measured Rw. TDS therefore will appear to be too high.

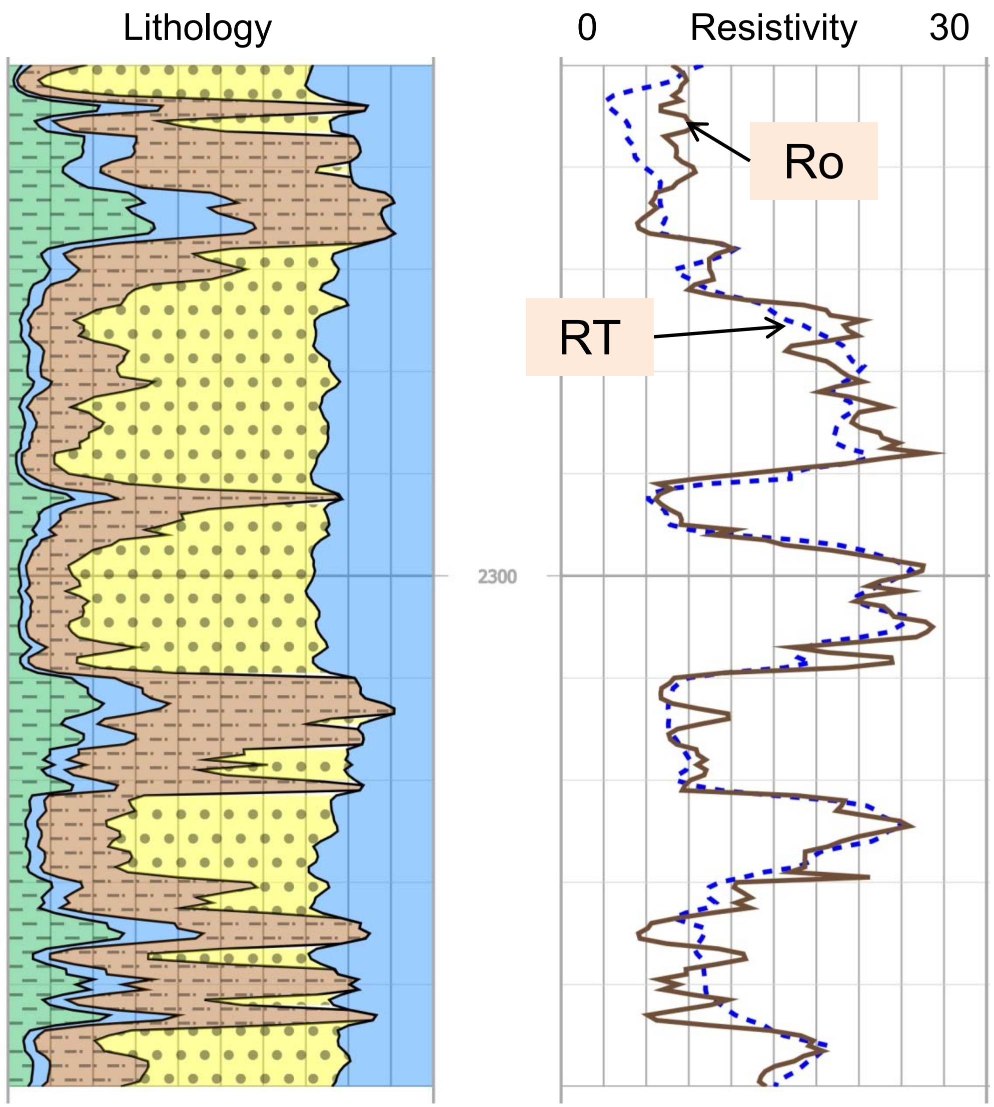
Ro Analysis Without Clay Correction: Ro = F* x Rw



Calculation of Ro is a good model validation step, since Ro should equal RT in wet sands. Using lab Rw value of 9.1 ohm-m @75º (adjusted to formation temperature) with no clay correction, the calculated Ro is about 55-65 ohm-m in sands (black curve). Log derived deep resistivity is much lower, about 25 ohm-m in the sands. This difference indicates that clays are affecting the results.

If the analysis model were correct, the black curve would overlay the blue curve (Ro=RT in wet sand). The difference is the clay conductivity.

Ro Analysis With Waxman-Smits Clay Correction



When Ro is calculated using the complete clay correction model, it is possible to achieve a very close fit between the computed Ro and the logged RT.

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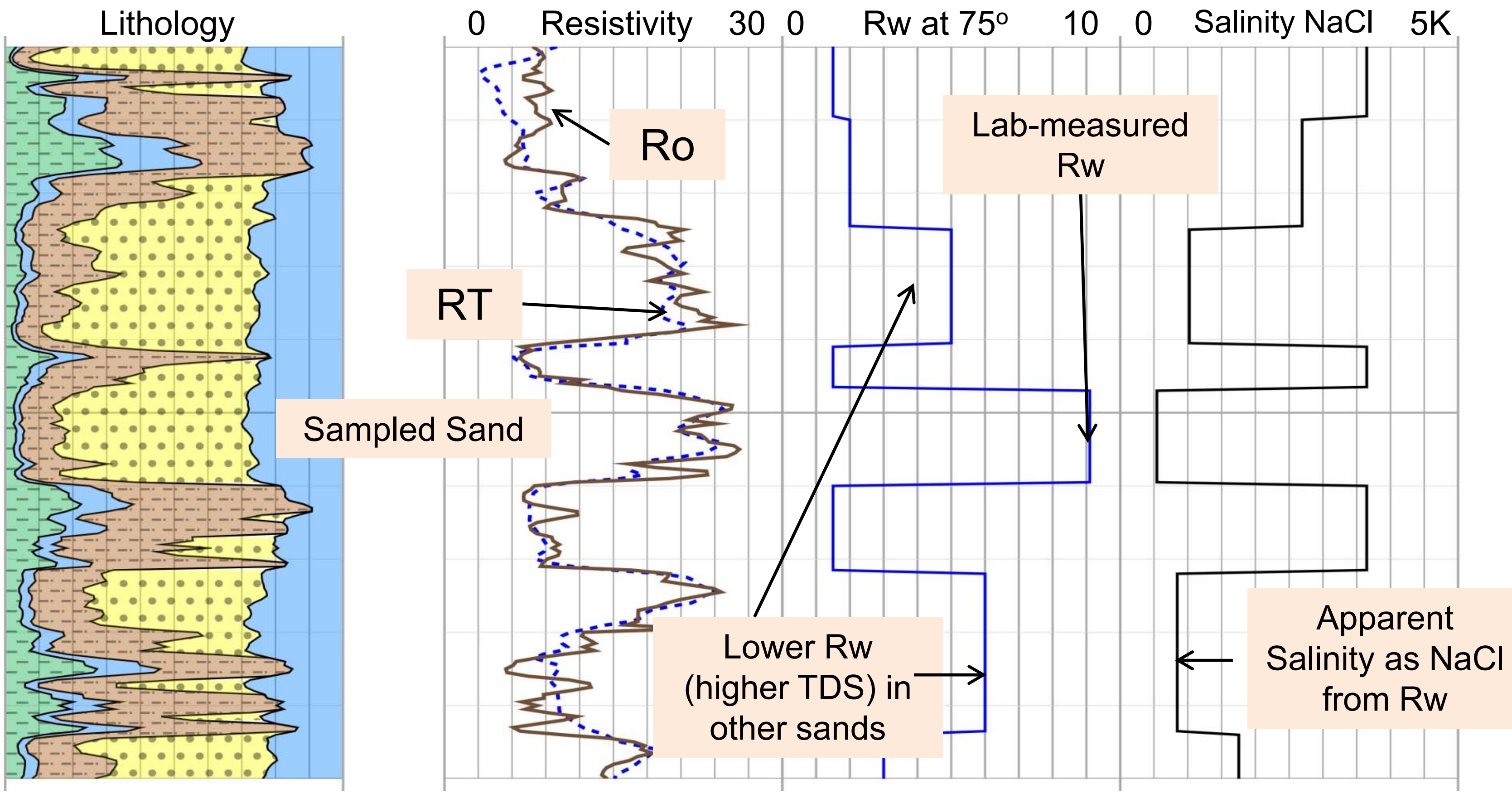
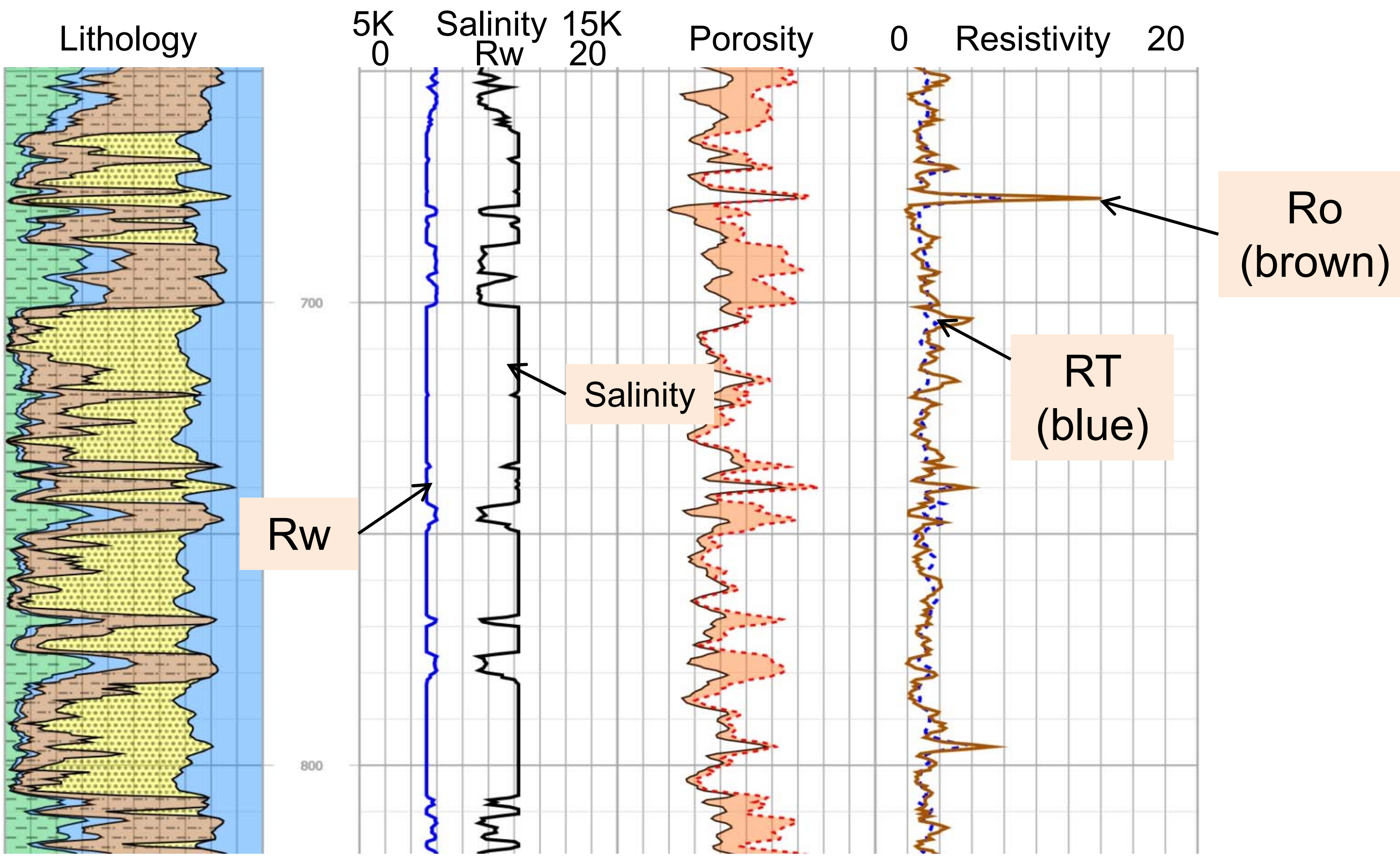
Ro Analysis With Full Waxman-Smits Clay Correction



The water resistivity curve (variable by zone) required to calculate the Ro curve from the Waxman-Smits model is shown as the blue curve. Lab-measured Rw of 9.1 ohm-m provides a good answer in the sand at 2296' but lower Rw values (higher salinity) were needed in the other sands. The water sample must have come from the 2296' sand.

Waxman-Smits Ro Analysis in Sand with ~ 11K PPM Water



Water from this interval tested at about 10,500 ppm TDS. The Rw values from analysis that provide the best match between Ro and RT correspond to an apparent NaCl salinity of about 11,150 ppm TDS.

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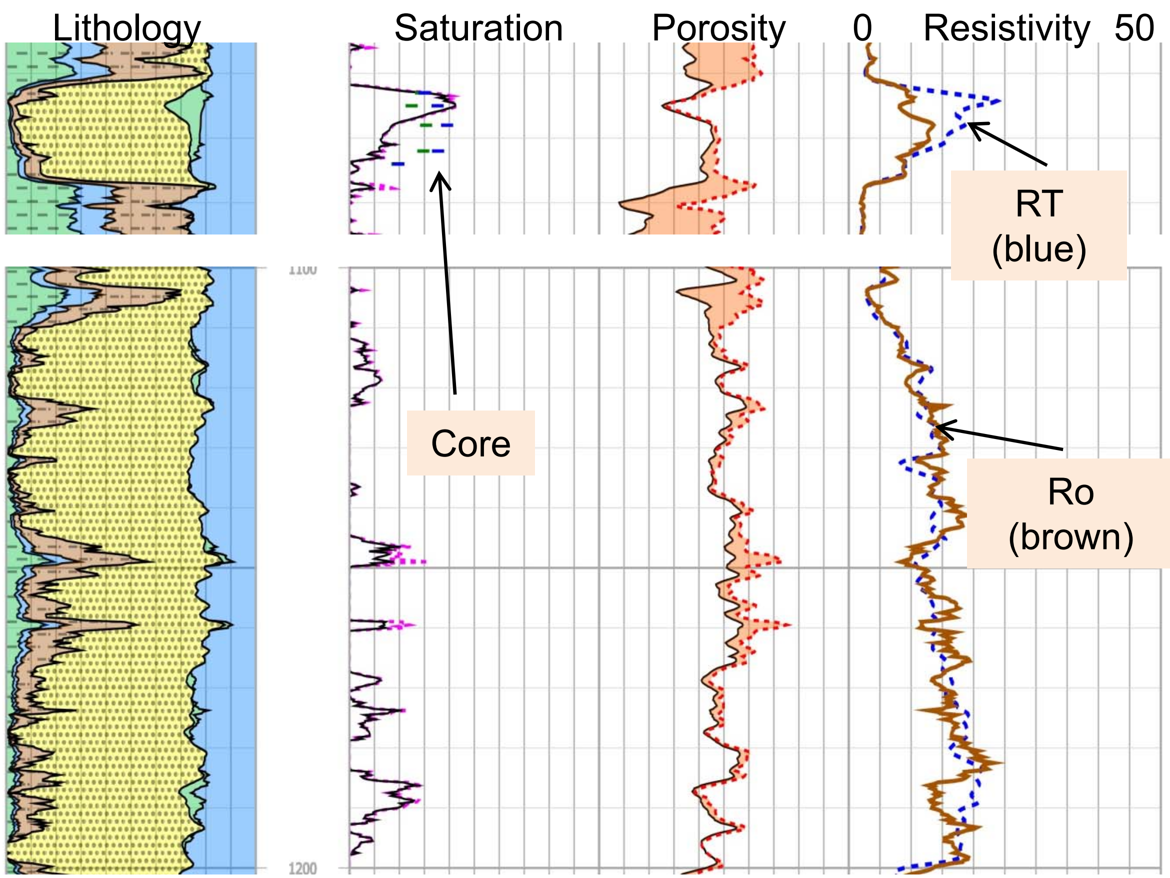
Estimating Clay Conductivity Parameters From Oil Sand With Core Data



Clay parameters were established in the upper oil-bearing sand by matching the Sw from the full WS model to the core points. These clay parameters were then applied to the suspected wet sand below. It was discovered that the sand actually has some thin intervals of residual oil saturation.

Advantages

- Theoretical and experimental framework of the WS model is well documented and based on extensive laboratory data
  - Validity can be demonstrated to regulatory agencies
- Most producing areas have an abundance of logs with usable log suites inside and outside of field limits
  - Provides data not otherwise easily obtainable
- Once calibrated to the unique ion concentrations of an aquifer, the model can be run on a large number of wells quickly
- Varying ages of wells in the same trend may provide an indication of changes in TDS over time