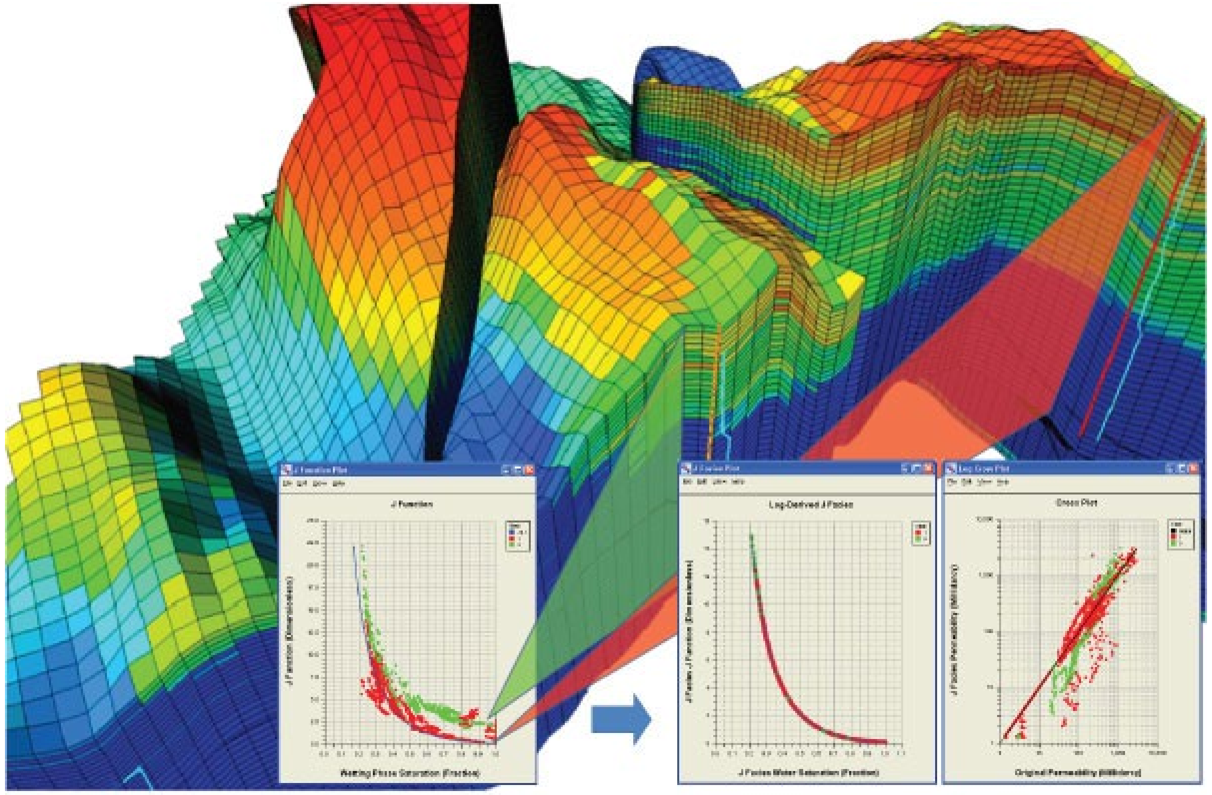
Geo2Flow: Compartments, Saturations, and Permeabilities



1. *Identifying flow compartments.*
2. *Calculating 3D saturations that honor logs.*
3. *Estimating permeabilities constrained by saturations.*

Dr. Daniel J. O'Meara

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Look How Little You Need To Get Started…

Required Input

- Porosity logs
- Water saturation/resistivity logs
- Geomodel (Grid)
- Fluid densities
- 3D Porosity

→ **Geo2Flow**

Optional Input

- Lab cap. pressure curves
- Lab poro-perm data
- Detailed geomodel
- Permeability logs
- Facies or “Indicator” logs
- Reservoir pressures (MDT)
- Detailed PVT
- 3D Facies or “Indicator”

→ **Geo2Flow**

Output

- 3D oil, gas, water saturations and volumes
- 3D net-to-gross and net porosity
- 3D horizontal permeability
- 3D vertical permeability
- Fluid contacts
- Reservoir compartments
- J Facies Log (Rock Types)
- Improved Permeability Log
- Archie Exponent logs

Main Reasons For Using Geo2Flow

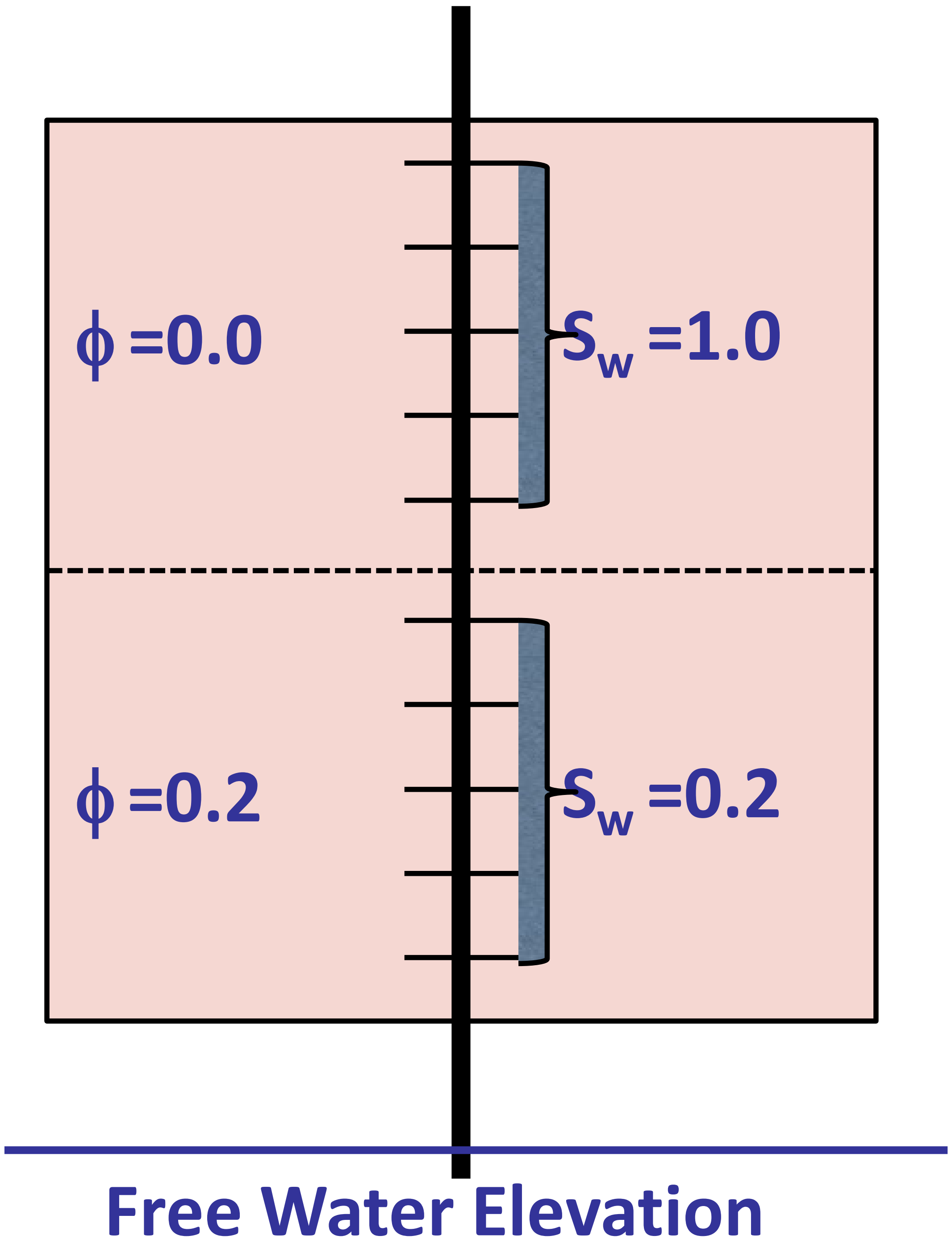
Compartments	3D Saturations	3D Permeabilities

• How connected?
• Identify free water levels.
• Multiple data sources.
  • Core data.
  • Logs.
  • Pressures.
• Closely linked to Petrel:
  • Fault segments.
  • Zones.
	• How much?
	• Honors physics of capillarity.
	• Honors saturation logs, within known errors.
	• Flexible reinterpreting of resistivity logs.
	• Estimates relative permeability curves.
		• How fast?
		• Constrained by saturations.
		• Takes advantage of well-behaved J Functions rather than noisy poro-perm.
		• Calculates horizontal and vertical.
		• Upscales: core, log, geocell, gridblock.

- *All three must be modeled together because they are coupled.*
- *Typical modeling is "silo-ized".*
  - *Reservoir engineers interpreting MDT to determine free water levels.*
  - *Petrophysicists using saturation-height functions.*
  - *Geologists using geostatistics with noisy poro-perm correlations.*
- *Workflows encourage "what if" scenarios to explore uncertainties.*
- *Brings together geologists, petrophysicists, and reservoir engineers, naturally.*

Upscaling Saturation

10 Log Measurements



What is average saturation?

1. 0.4
2. 0.6 **Volumetric**
3. 0.2 **Correct**
4. Haven't a clue.

$$\overline{S} = \frac{\sum_{i=0}^{n} S_i \, \phi_i \, V_i}{\sum_{i=0}^{n} \phi_i V_i}$$

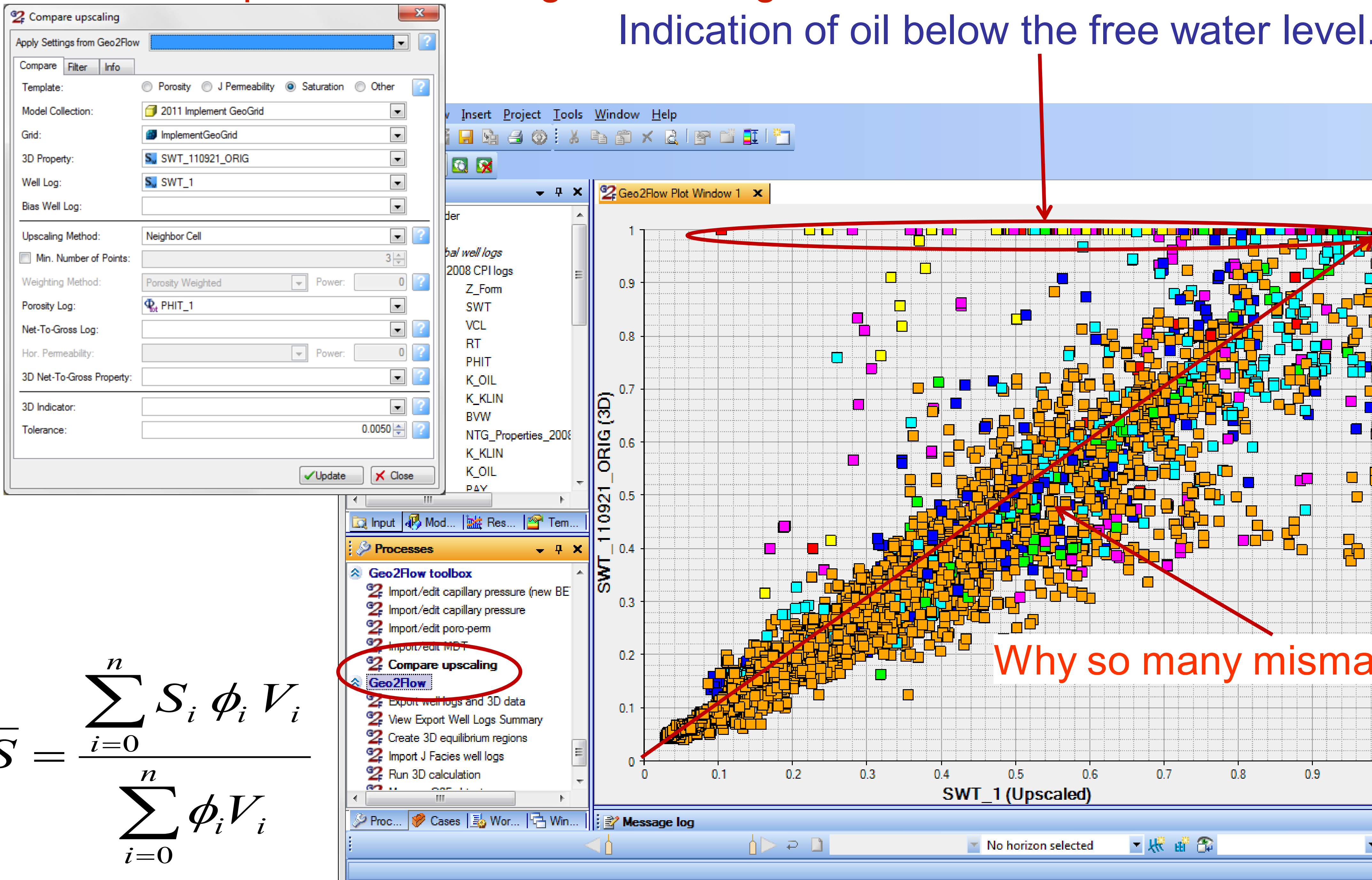
Pore Volume

A Little History…

- At Shell, beginning in 1986.
  - First geomodeling: PROFAM -> Monarch -> GeoCap.
  - GeoSim: 4 million cell unit mobility flow simulation: sweep
- With Stratamodel, 1992-2002.
  - StrataSim: 36 million cell model of Ekofisk (1996).
- Worked with Gocad, RMS, and Petrel.
- Expect models to honor observations and physics.
- "How do we check that 3D saturations honor Sw logs?"
  - "We don't".
  - Devised the following plot to check.

Peer Review: Does 3D Saturation Match Upscaled Sw Log?

- Use Geo2Flow's "Compare Upscaling" plug-in to check whether your 3D saturation matches the pore volume weighted Sw log.



$$\overline{S} = \frac{\sum_{i=0}^{n} S_i \, \phi_i \, V_i}{\sum_{i=0}^{n} \phi_i V_i}$$

- Most models without Geo2Flow show a poor match.

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Saturation Comparison: Why Not Match Every Time?

➔ *Imagine history-matching with a noisy match.*

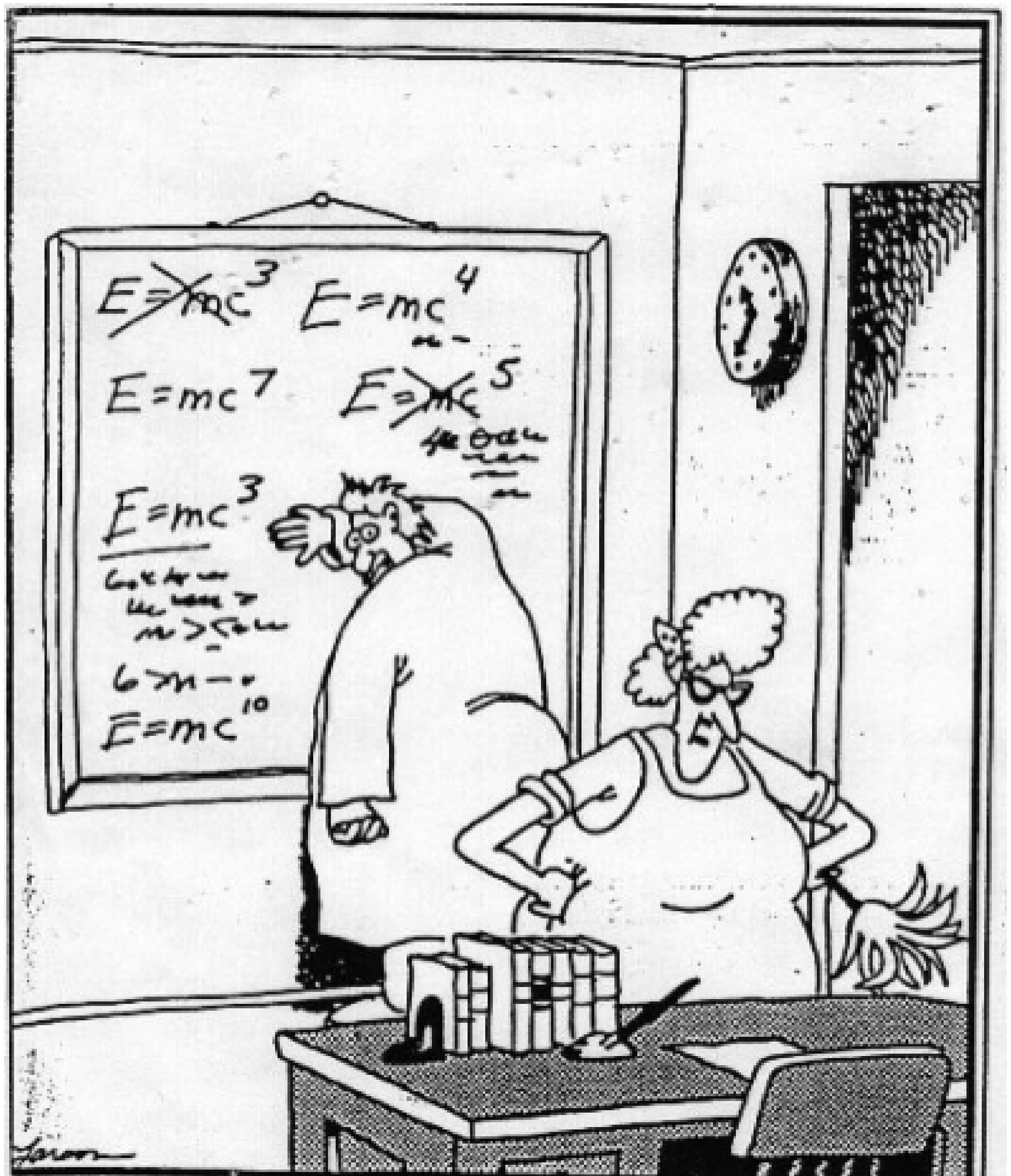
➔ *Cheating: a perfect match can be obtained by treating saturation like porosity …purely geostatistically.*

- *Non-physical saturations: not matching J Functions.*
- *Good match is a necessary but not sufficient sign of a good model*

➔ *A poor match can be caused by:*

- *Incorrect free water levels (compartmentalization).*
- *Saturation-height functions that do not depend on permeability*
- *Assumption that lab functions apply to upscaled geomodel.*
- *Failure to use a pore volume weighted saturation log.*

Einstein's Maid – The Far Side by Gary Larson



"Now that desk looks better. Everything's squared away, yessir, squaaaaaared away."

→**Dimensional Consistency**

$$E=mc^3 \qquad \frac{ML^2}{T^2}[=]M\left(\frac{L}{T}\right)^3$$

$$E=mc^4 \qquad \frac{ML^2}{T^2}[=]M\left(\frac{L}{T}\right)^4$$

$$E=mc^2 \qquad \frac{ML^2}{T^2}[=]M\left(\frac{L}{T}\right)^2$$

→**If Einstein were a petroleum engineer…**

$$E=5.4\times 10^{-15}mc^2$$

m [=] pound-mass
c [=] feet/day
E [=] British Thermal Units

Dimensionless Numbers

→ **The sound barrier. Supersonic flight.**

$$\text{Mach Number} = \frac{V_{object}}{V_{sound}} = \frac{\text{Speed of object}}{\text{Speed of sound}}$$

→ **Turbulent flow; swirling eddies.**

$$\text{Reynold's Number} = \frac{\rho V L}{\mu} = \frac{\text{Inertial}}{\text{Viscous}}$$

→ **Chemical flooding: decreasing residual oil saturation.**

$$\text{Capillary Number} = \frac{\mu V}{\sigma} = \frac{\text{Viscous Forces}}{\text{Surface Forces}}$$

J Functions Are Dimensionless

$$\overset{F/\cancel{L}^{2}}{} \qquad \cancel{L}$$

$$J(S_w) = \frac{P_c}{\sigma \cos\theta}\sqrt{\frac{k}{\phi}} \qquad L^2 \qquad [=] \text{ Dimensionless}$$

$$F/L$$

➔Seem obvious? What's wrong with the following?

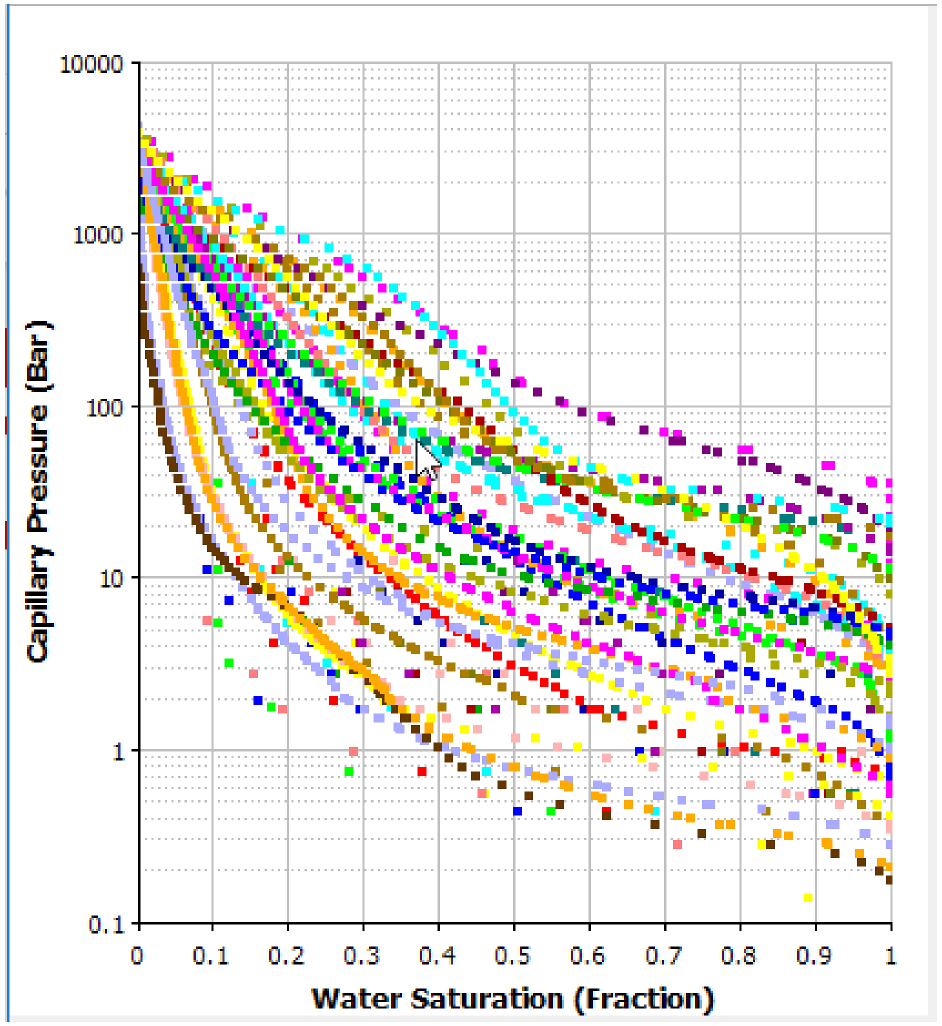
$$F/L^2 \qquad L^{2n}$$

$$J(S_w) = \frac{P_c}{\sigma \cos\theta}\left[\frac{k}{\phi}\right]^n \qquad [=] \; L^{2n-1}$$

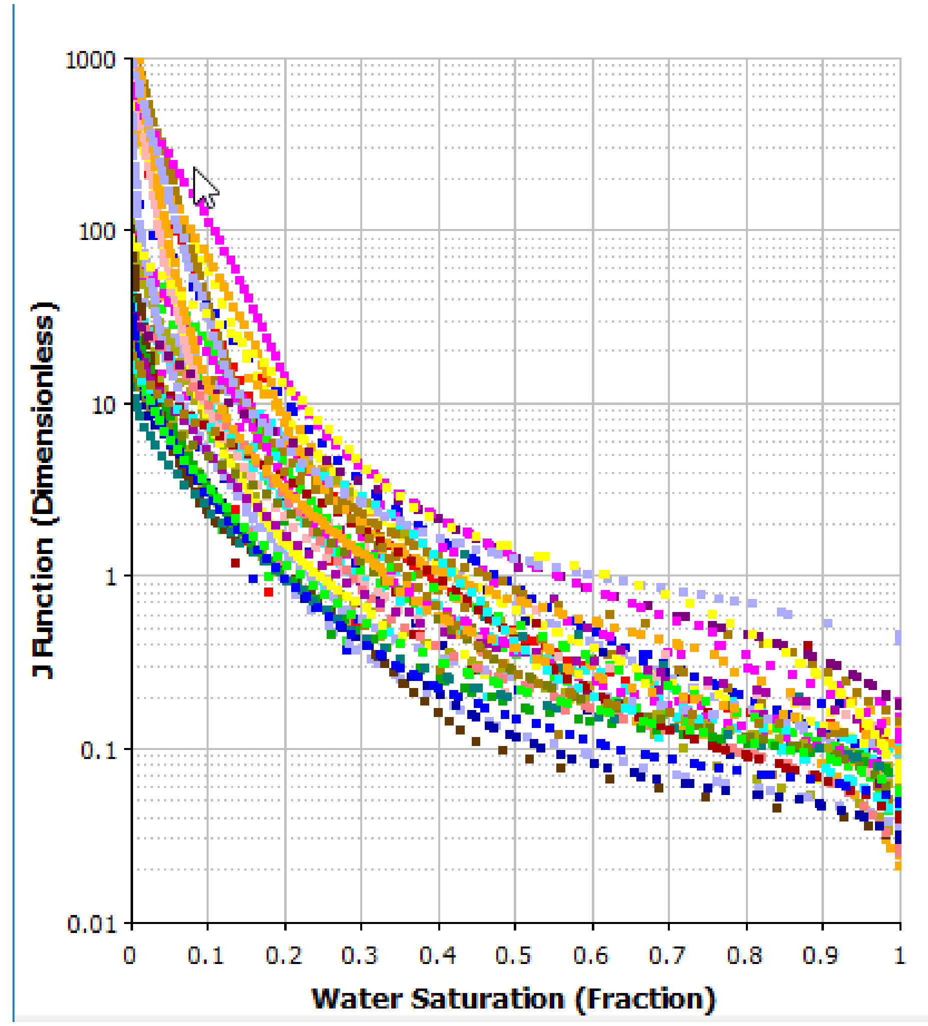
$$F/L$$

Quick J Function Review – Why Use Them?

Capillary Pressure (0.02-400 md.)



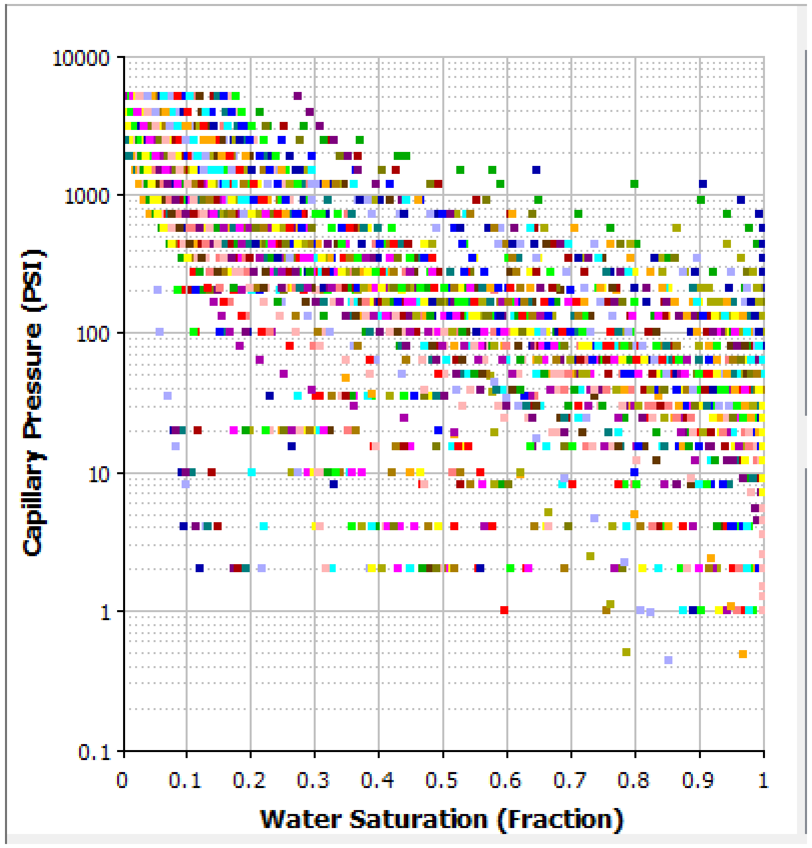
J Function (per rock type)



→Dimensionless J Function collapses many capillary pressure curves.

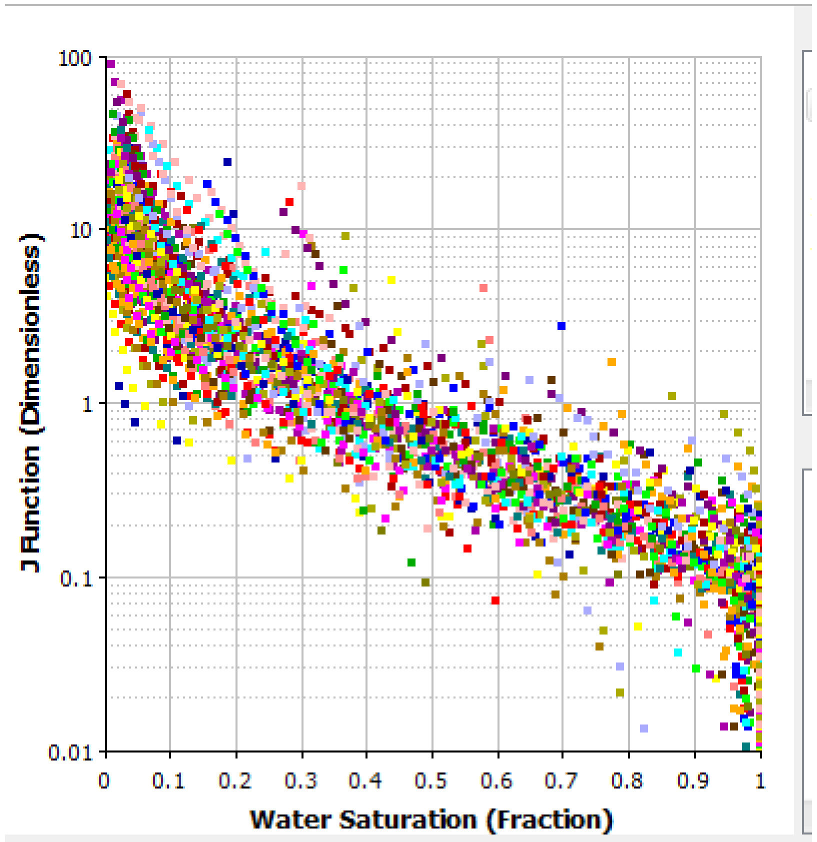
But Do They Work for Carbonates?

Capillary Pressure (0.01-3400 md.)



Entry Pressures (0.5-1000 psi)

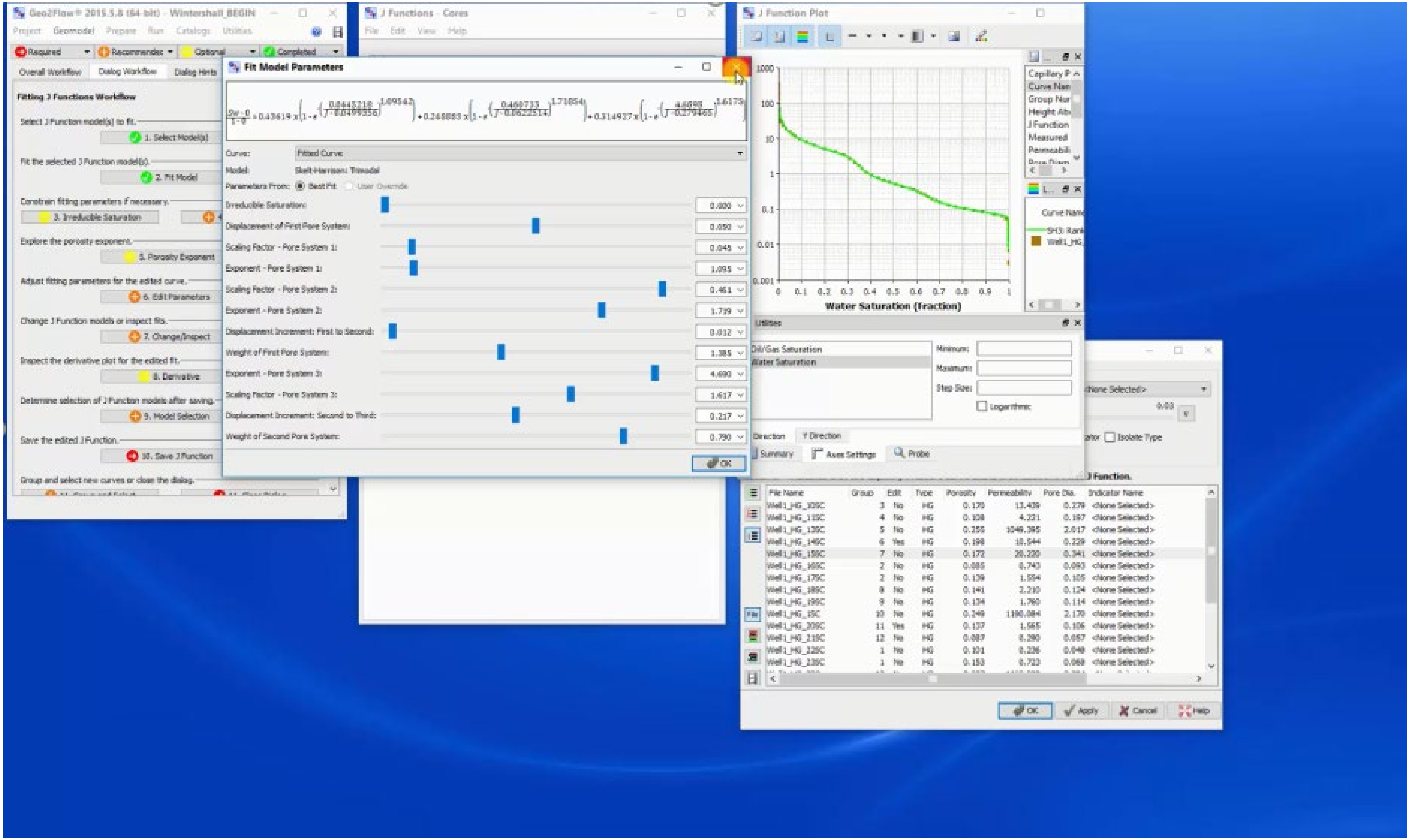
J Function (per rock type)



Entry Values (0.05-0.20)

→Dimensionless J Function collapses many capillary pressure curves.

Geo2Flow: Fitting Capillary Pressure Data



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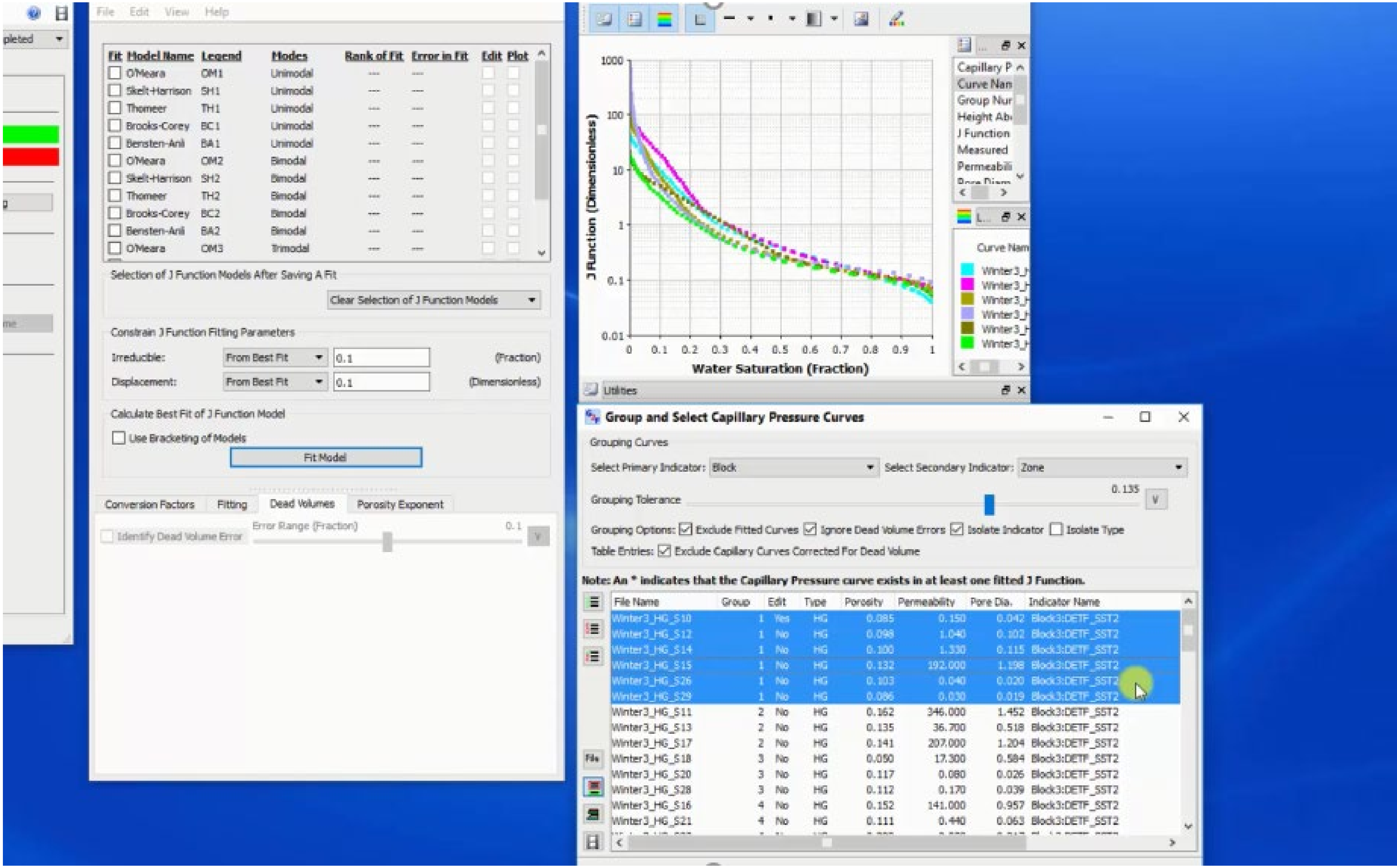
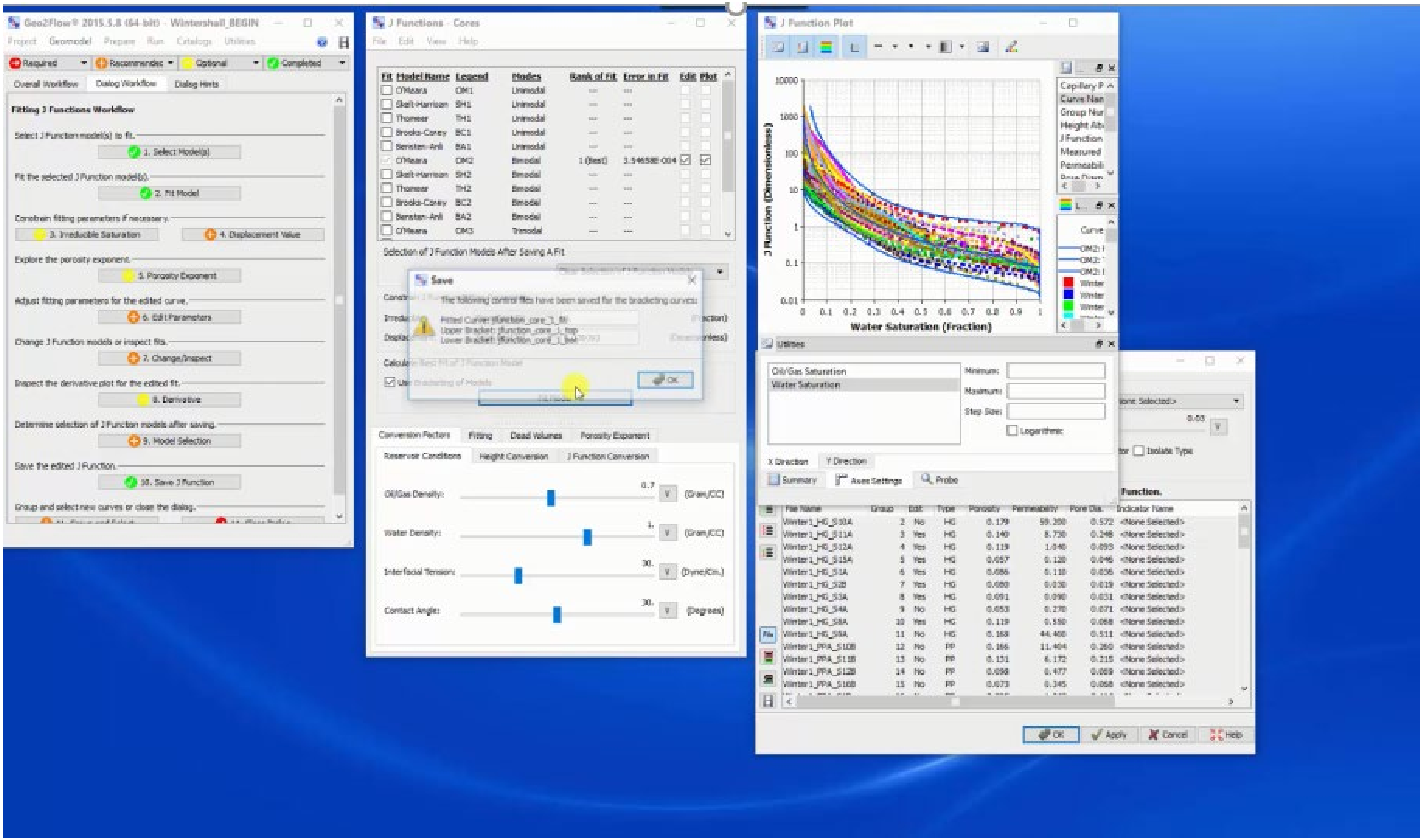
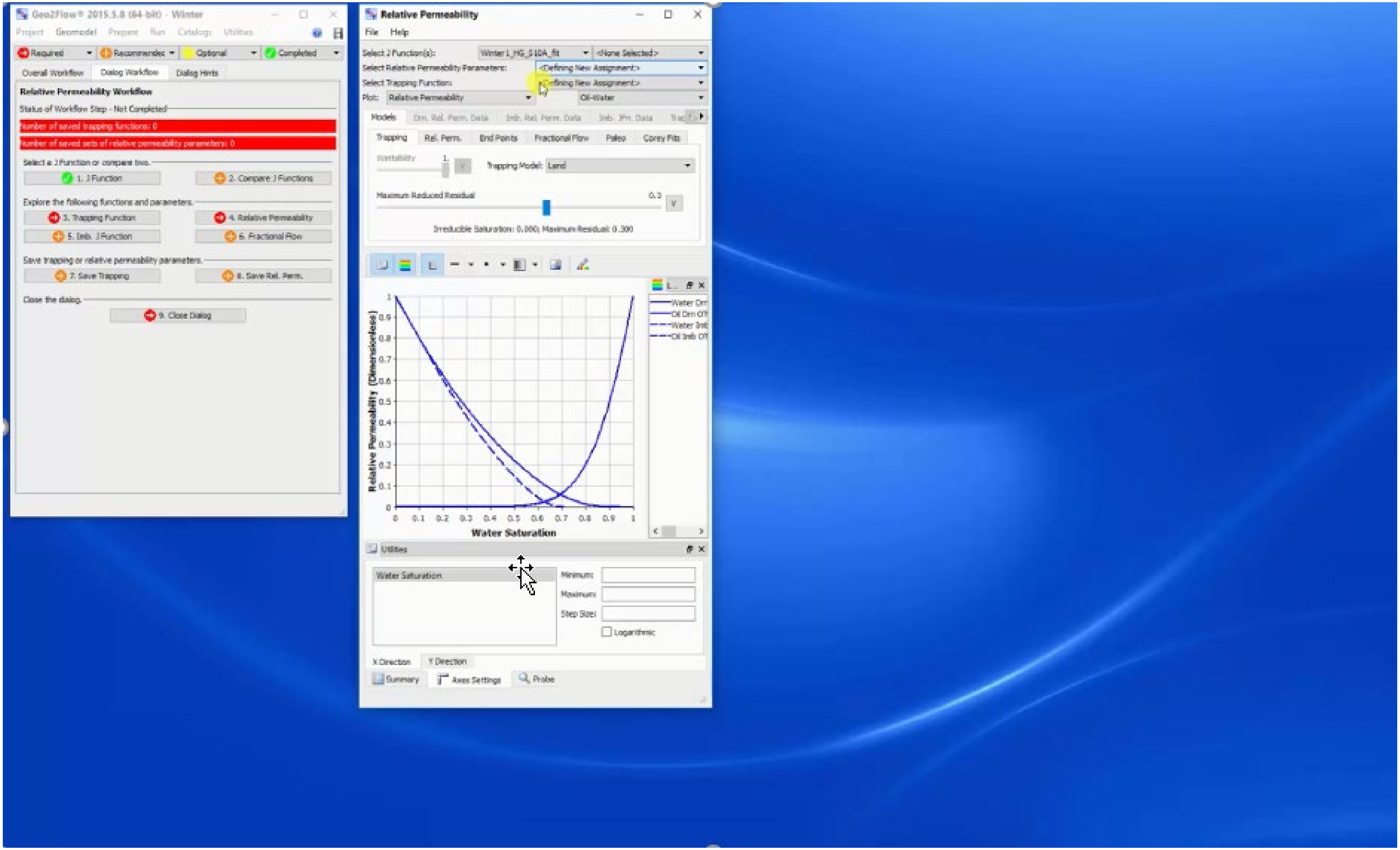
Geo2Flow: Grouping by Indicator



Geo2Flow: Bracketing Capillary Pressure Data



Geo2Flow: Relative Permeability



Geo2Flow Uses Log-Derived J Functions

$$P_c = \Delta\rho\, g\,(z - z_0)$$

Correlation or Log

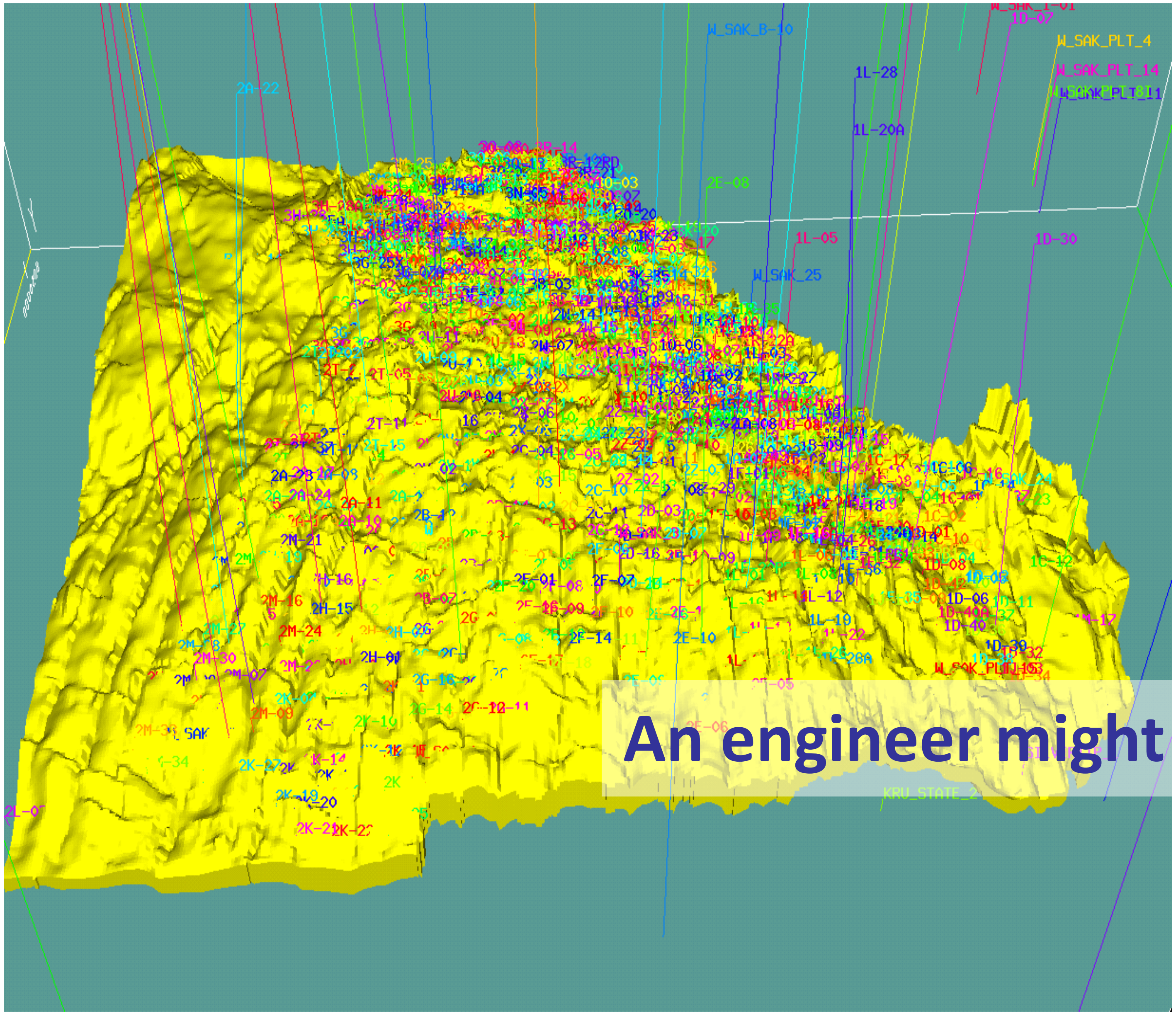
$$J(S_w) = \frac{P_c}{\sigma \cos\theta}\sqrt{\frac{k}{\phi}}$$

From Log

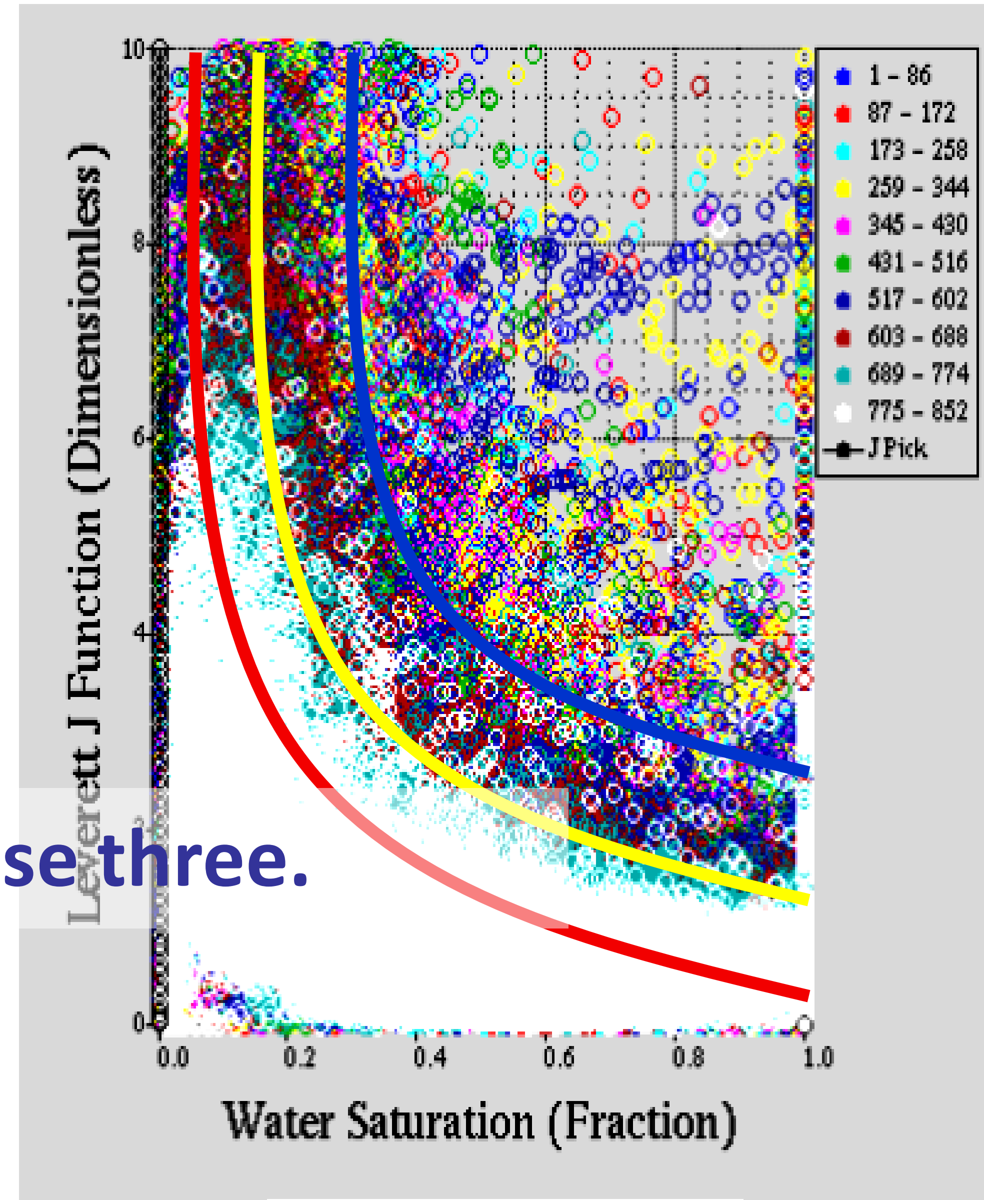
- $\sigma \cos\theta$: not necessary with log-derived J Functions.

Can You See J Function Patterns in This Field?

Highly faulted model



How many J Functions?



An engineer might use three.

➔ All of the scatter leads translates directly to errors in reserves.

Scatter caused by compartments

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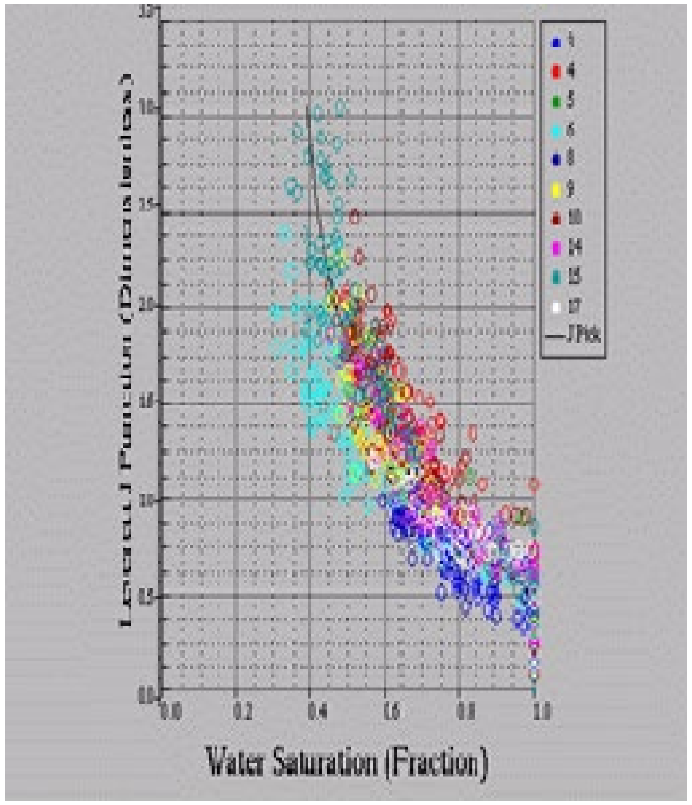
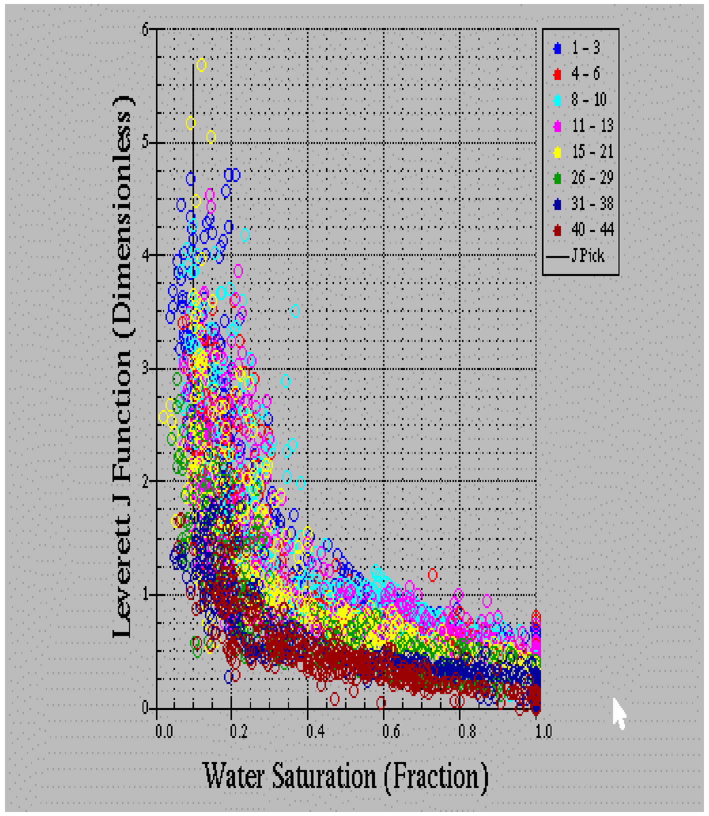
Geo2Flow Reveals Compartments

➔Three compartmentalizing fault blocks in one zone.

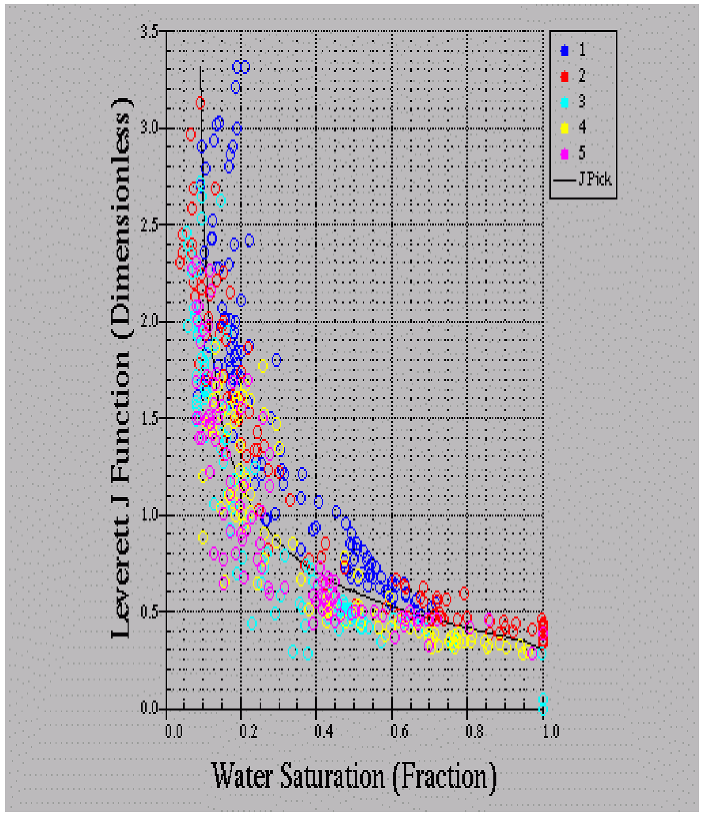
10 Wells, Zone 1



26 Wells, Zone 1



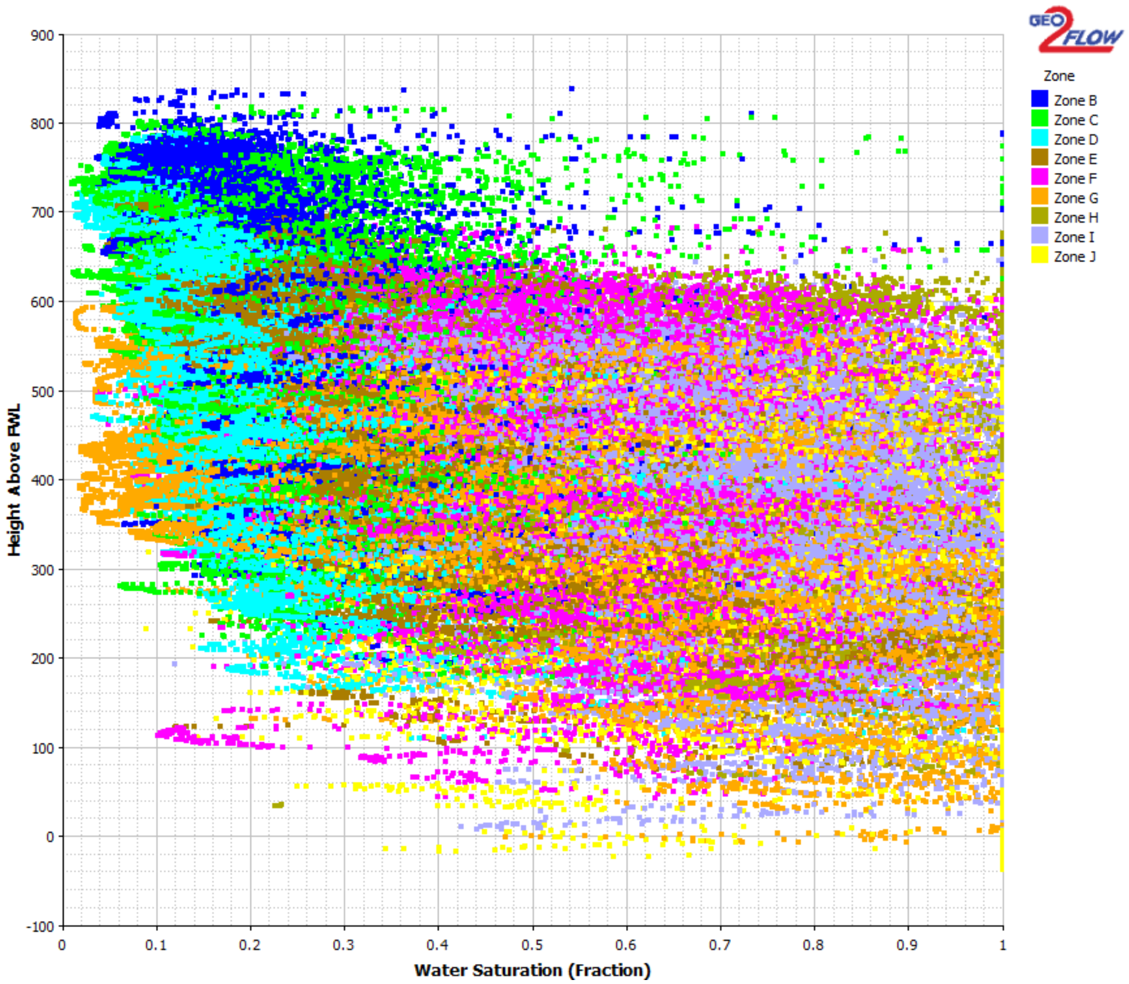
5 Wells, Zone 1

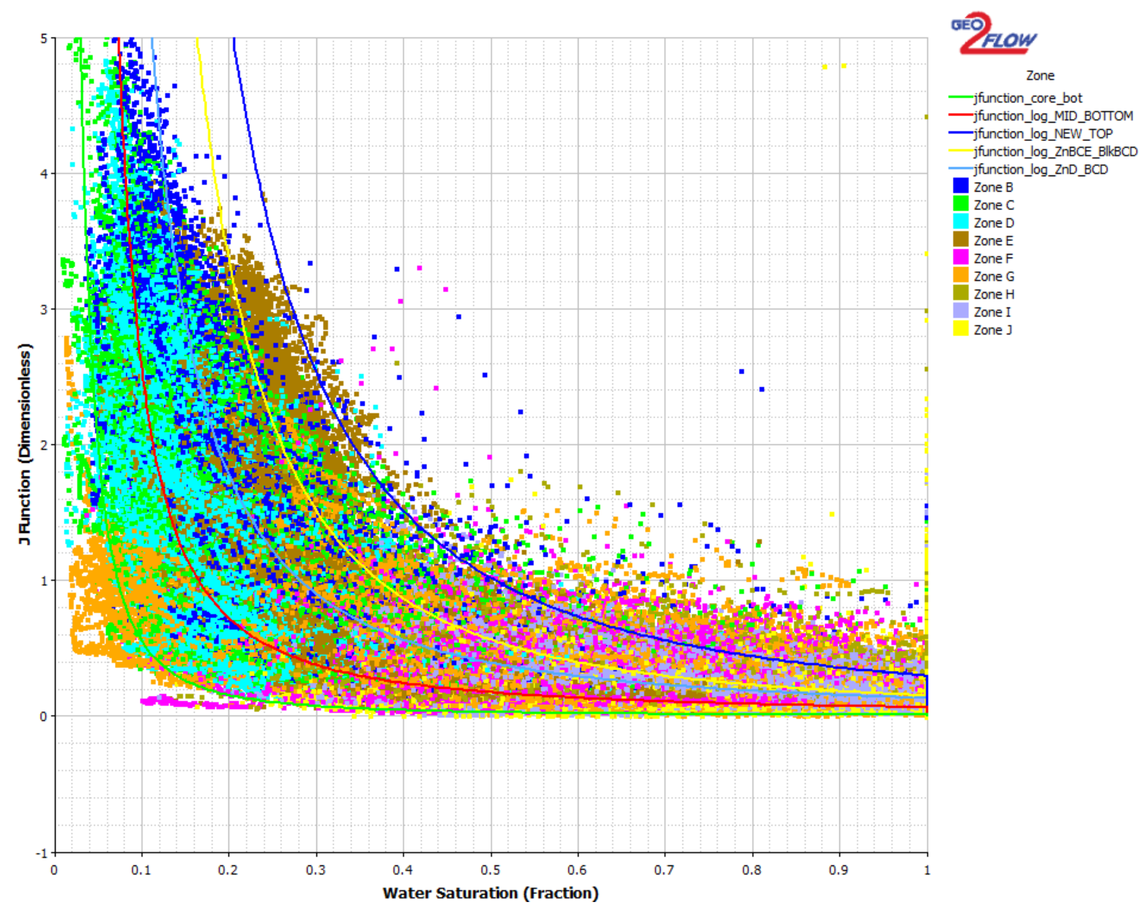


➔Worst of the scatter removed because compartmentalizing faults have been identified.

➔Remaining scatter due to differing rock types.

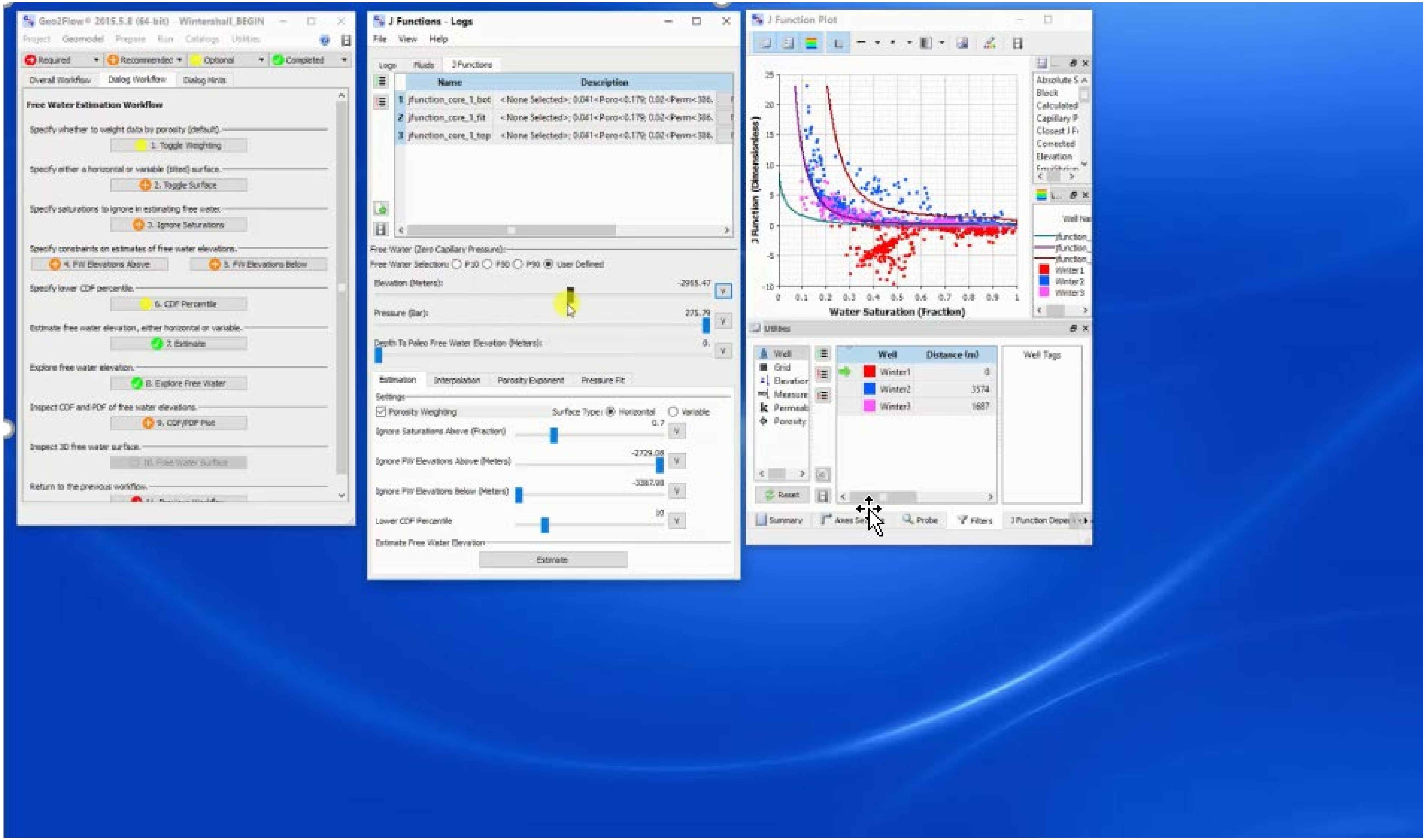
J Functions versus Saturation-Height (Carbonate)





- Remarkably well-behaved J Functions (right).
- Log-derived J Function data (points) fit within core-derived J Functions (curves).
- Ill-behaved height vs. saturation (left).

Exploring the Data: Equilibrium Regions and Dependencies



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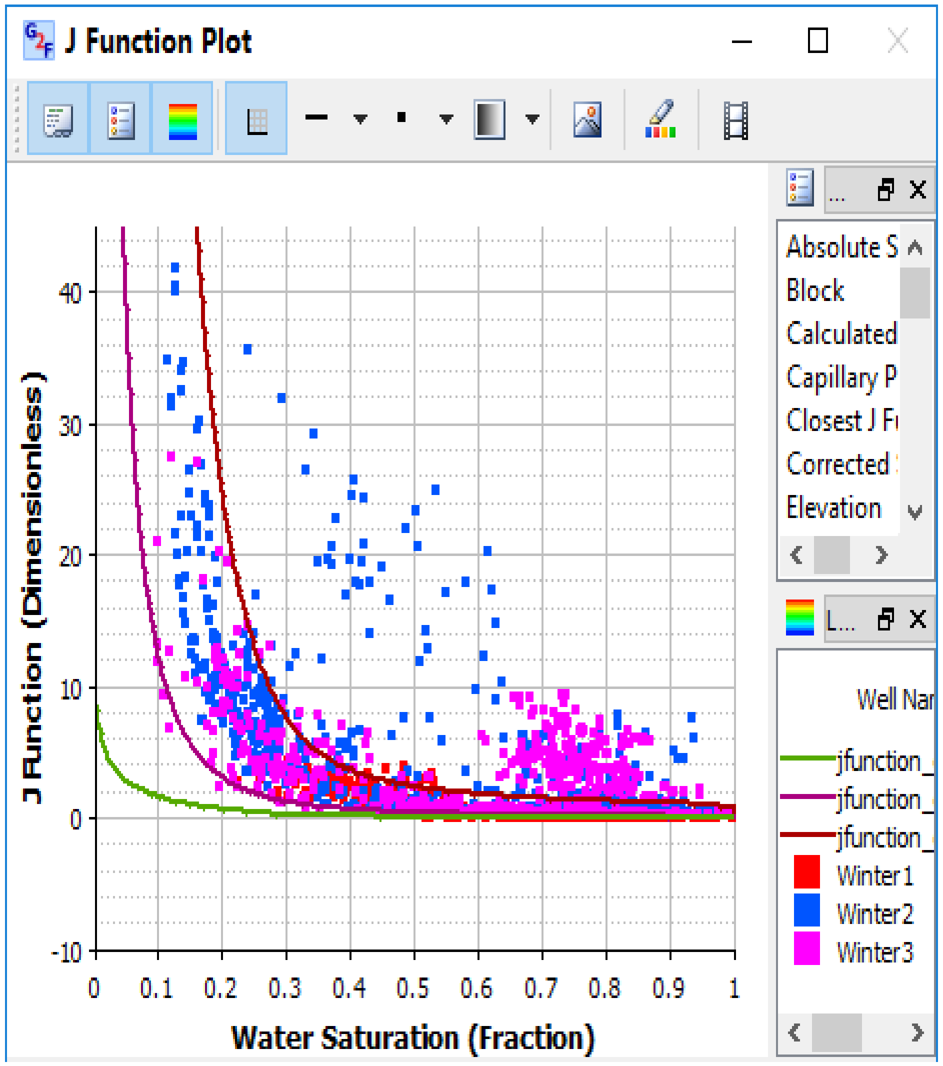
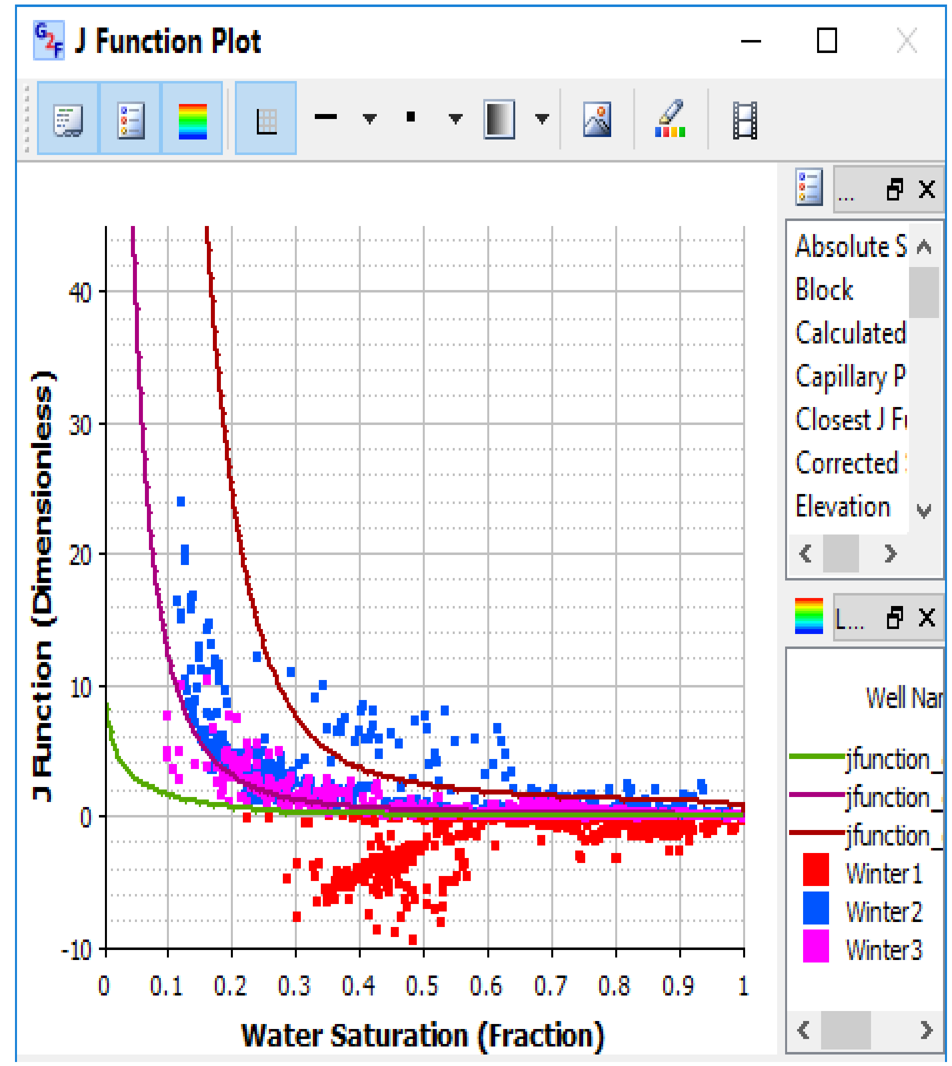
One Free Water Elevation or Two?

Free Water: -3117 m.



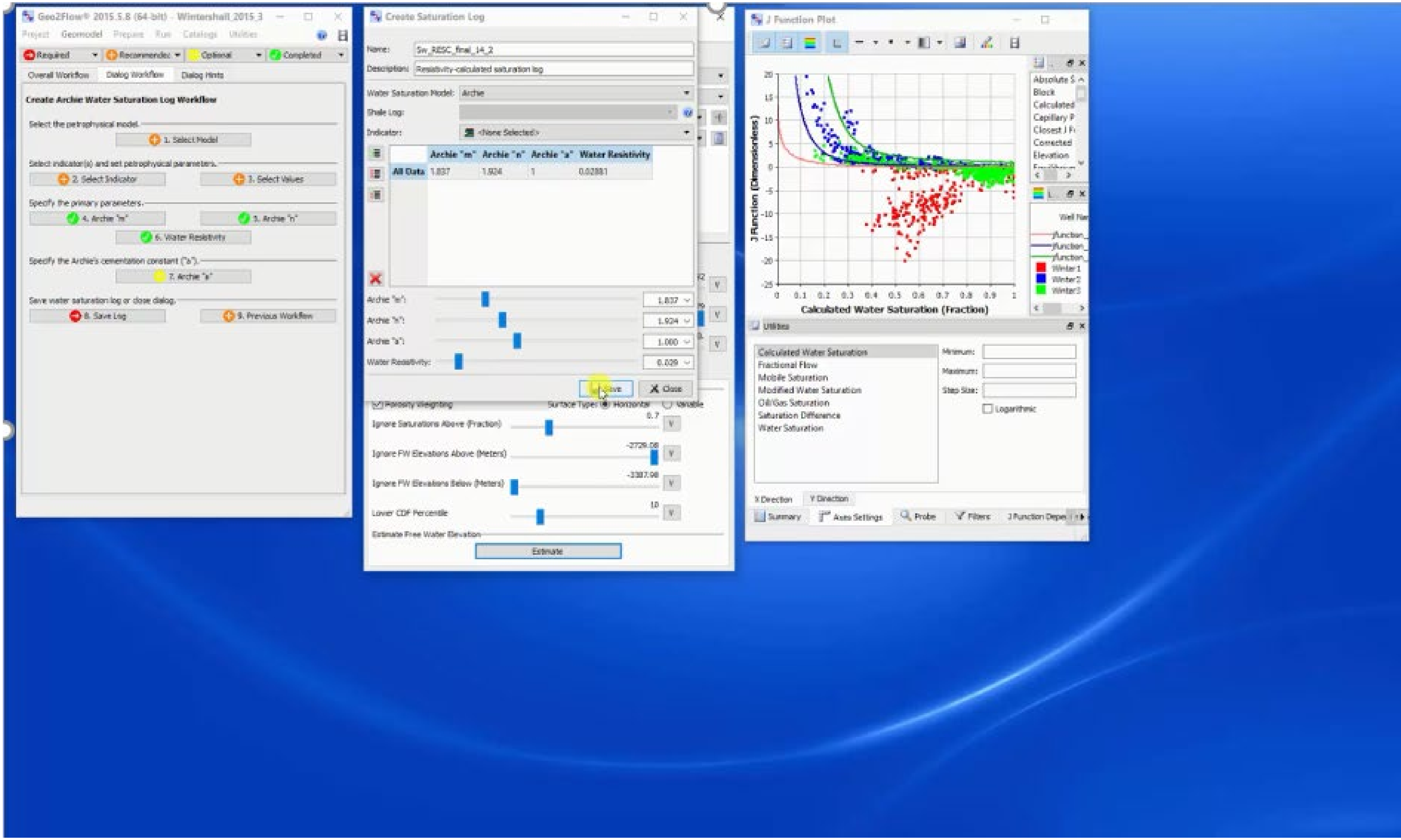
Free Water: -2973 m.



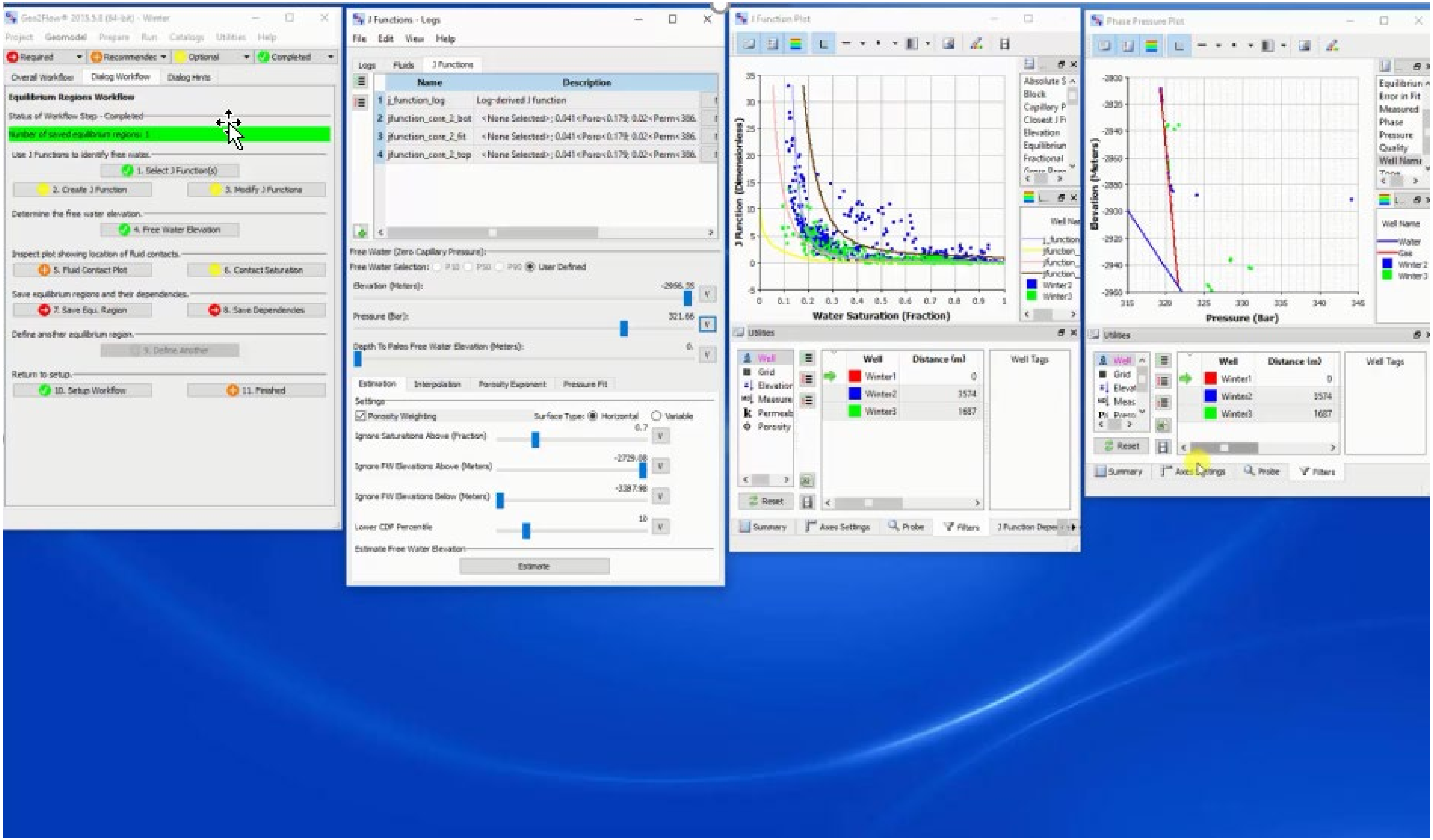
➔ **Color-coding by well.**

➔ **Note: Better match of core-derived J Functions on right.**

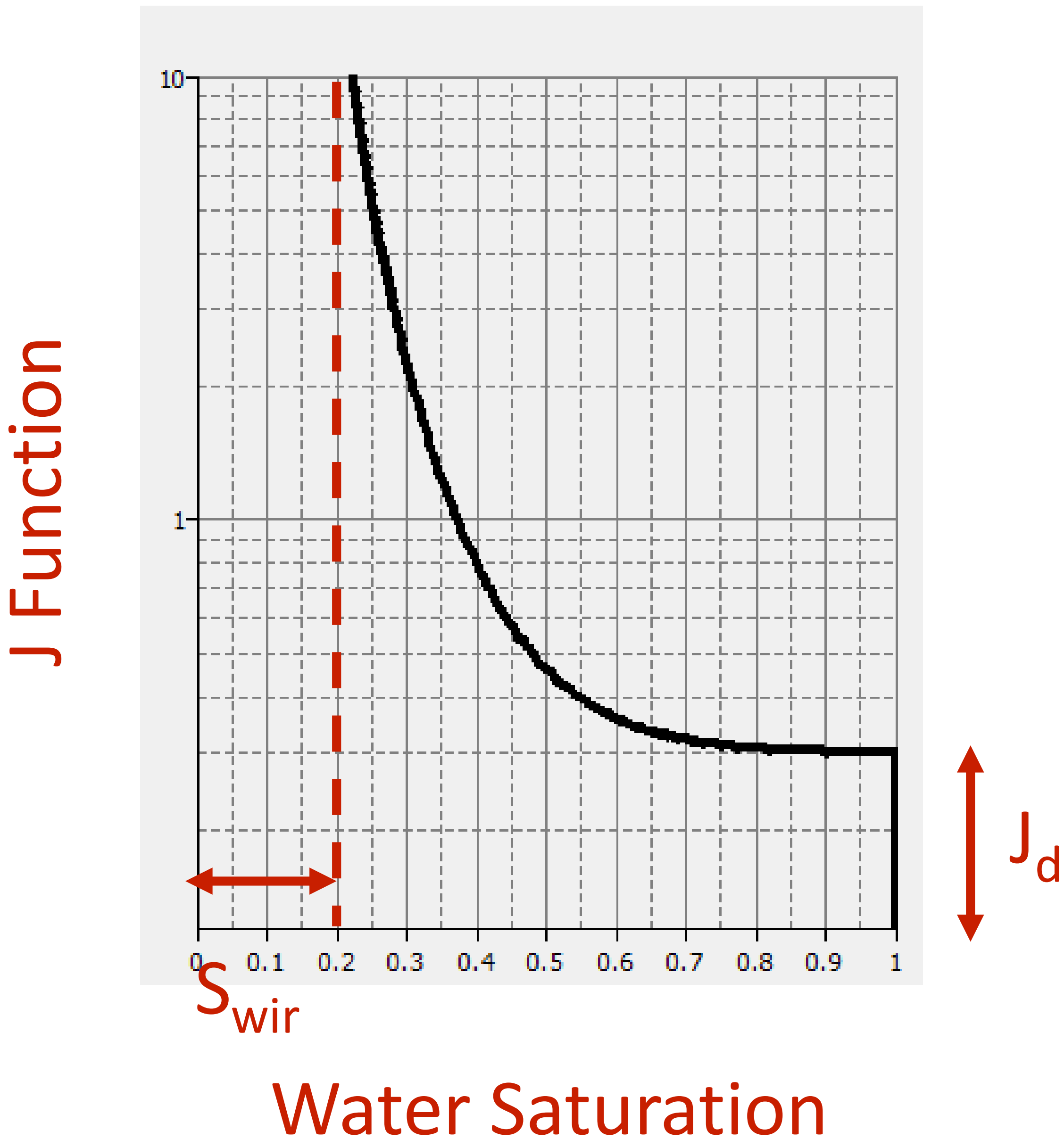
Water Saturation From Resistivity Compared With J Functions



Using MDT and J Functions simultaneously



Why is the Contact Not Flat?



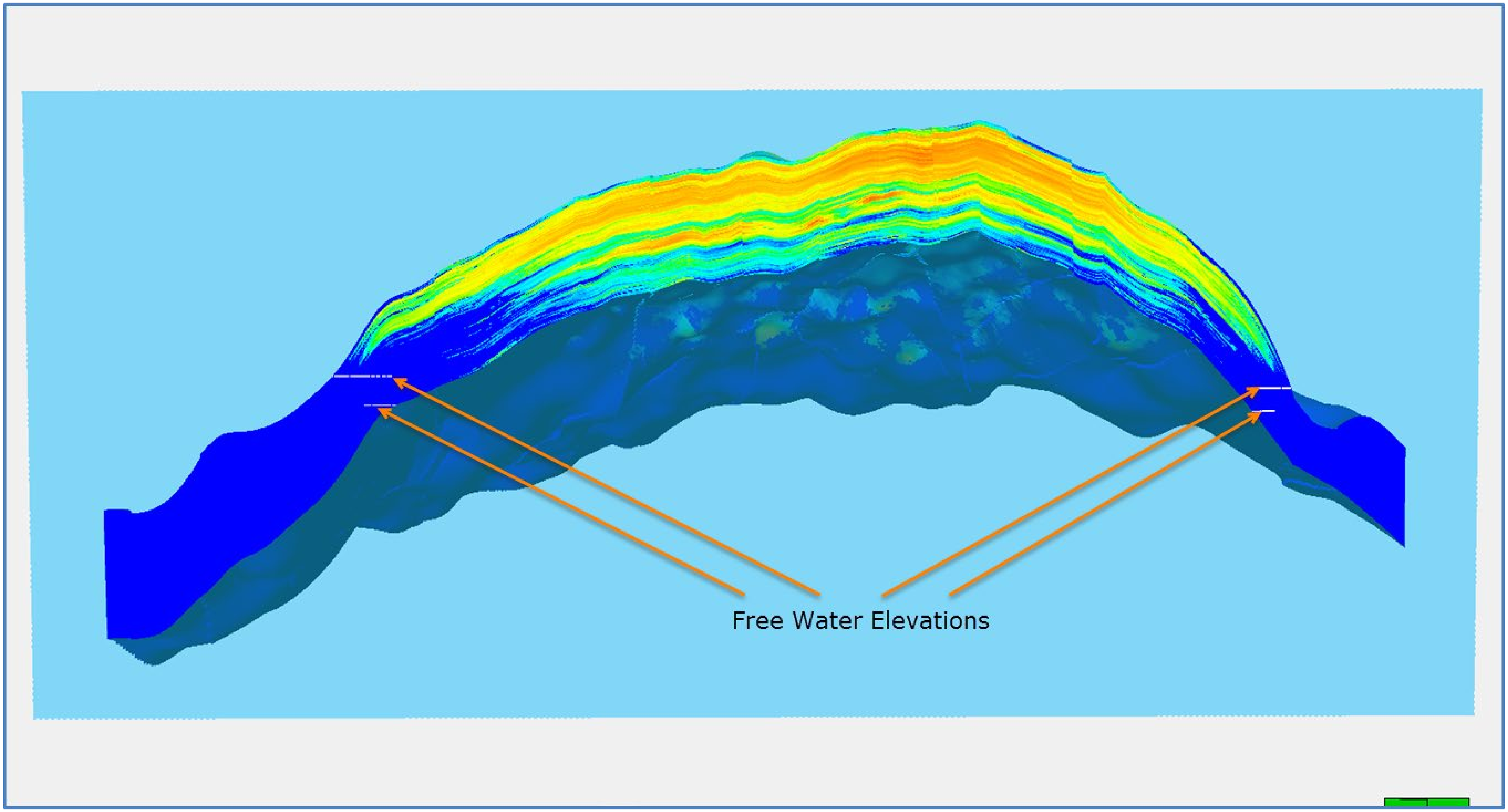
➔ Assume a single J Function.

- Equation for contact (z) above free water:

$$J_d = \frac{\Delta \rho g \left(z - z_0\right)}{\sigma \cos\theta} \sqrt{k / \phi}$$

- **Key Point:** If permeability and porosity vary in 3D, then so does height of the contact above the free water elevation.

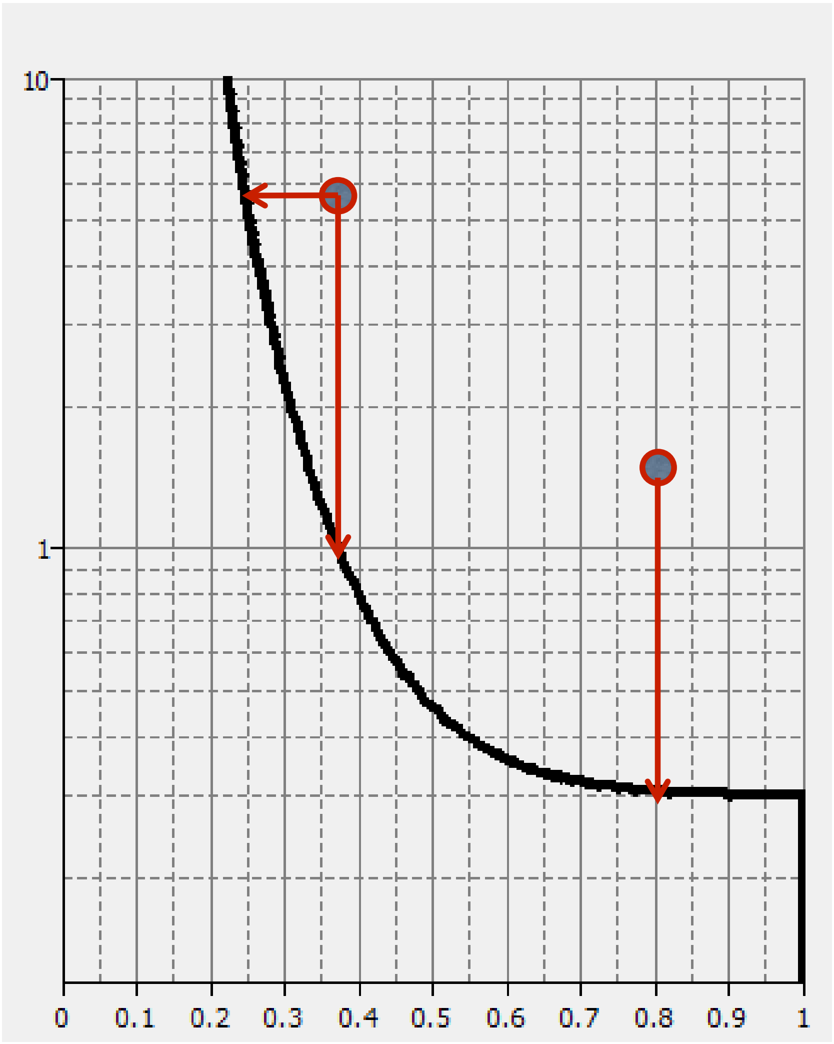
Identification of Free Water Levels for Compartments



➔ Note: oil-water contacts are significantly shallower than free water levels.

Use Log-Derived J Point To Estimate Free Water Elevation

J Function



Water Saturation

➔ Estimate z_0 that puts point on curve.

$$z_0 = z - \frac{J\sigma\cos\theta}{\Delta\rho g}\sqrt{\frac{\varphi}{k}}$$

➔ Points near steep portion of curve introduce more error.

➔ Weight points according to inverse slope.

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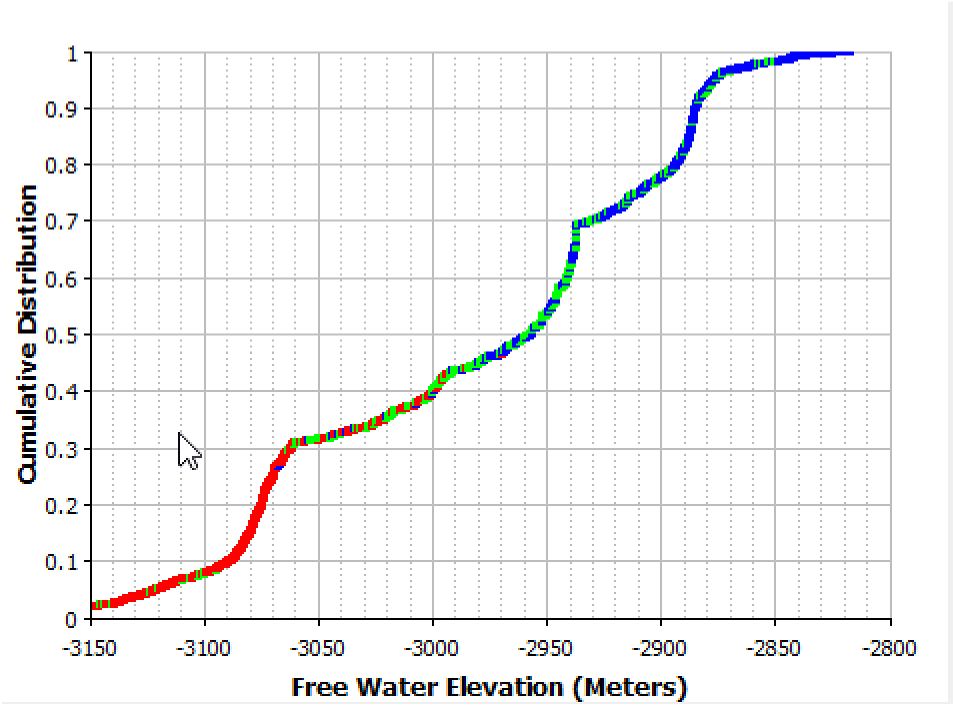
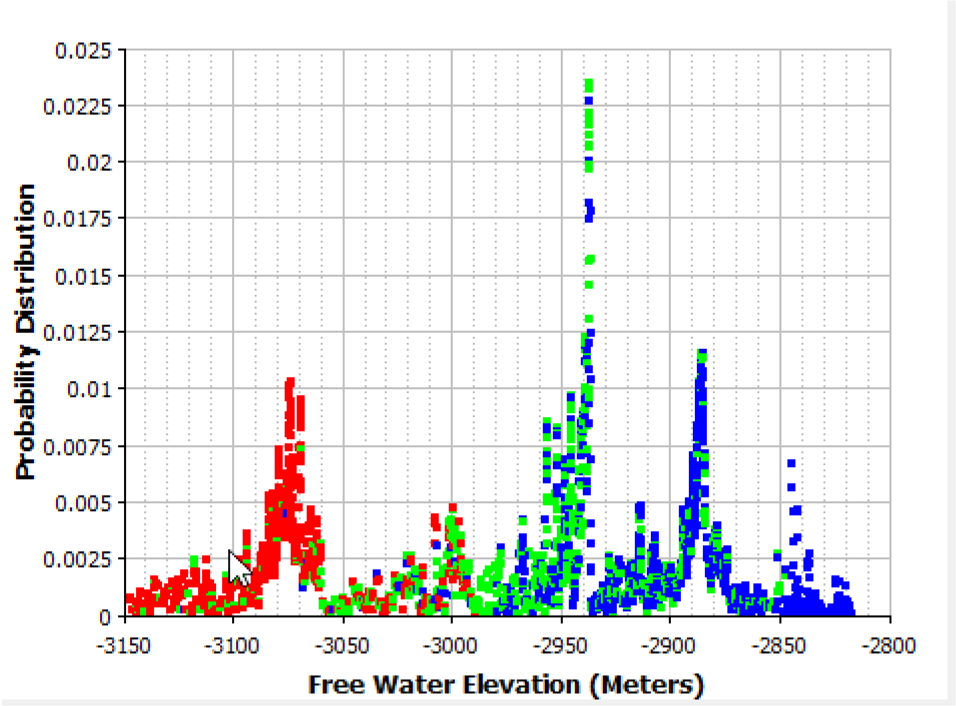
CDF and PDF for Multiple Free Water Elevations

➔ Multiple free water elevations.

- Constrain be shallowest oil down to.
- Constrain be shallowest free water up to.





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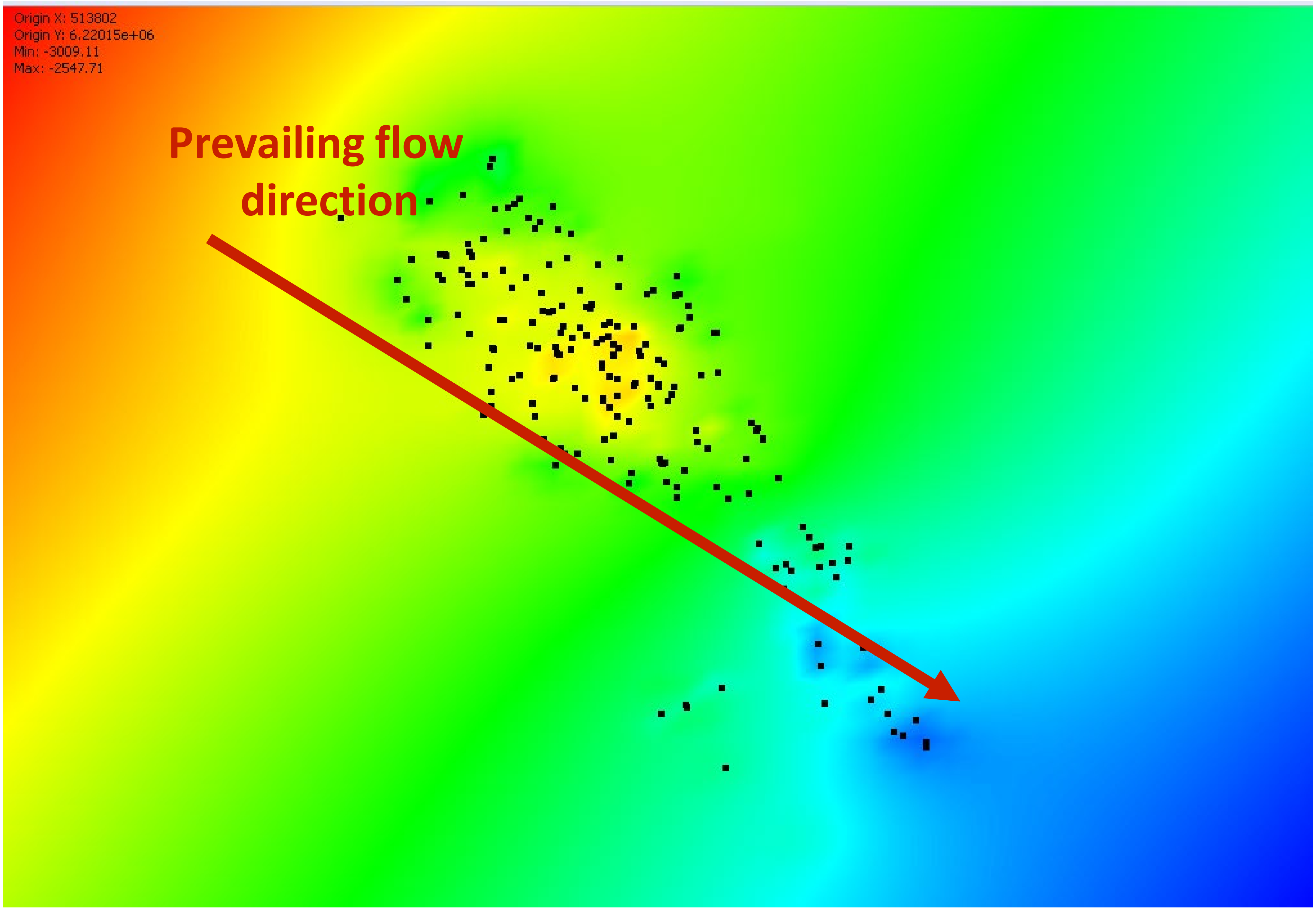
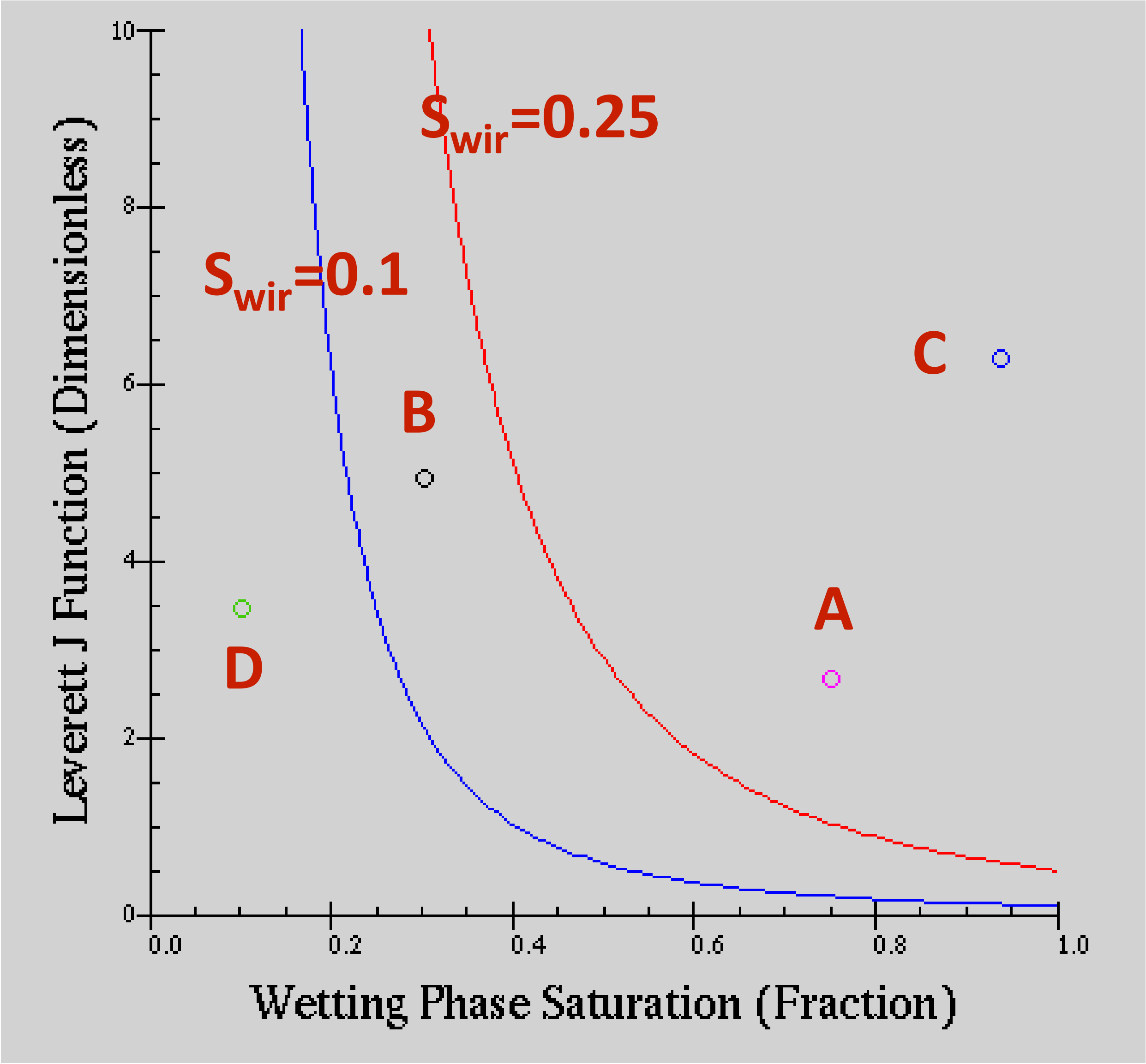
Tilted Free Water Surfaces in Geo2Flow



➔Geo2Flow estimates surfaces in equilibrium regions, defined by zones and blocks.

Two Log-Derived J Functions Have Been Identified



Consider four data points pictured here.

➔ How do you explain mismatches?

➔ Consider errors in S_w and J.

- What reinterpretations would you make?

With Error Bounds, Move Points

➔ Modify the Permeability

- Poro-perm plots are notoriously noisy.
- Vertically moves points to J Functions.

➔ Modify the Irreducible Saturation.

- NMR logs claim to measure variable S_{wir}.
- Horizontally moves J Functions to points.

➔ Modify Archie's exponents of Sw logs.

- Horizontally moves points to J Functions.

Move Points With New Free Water Elevation

➔Modify the Free Water Elevation.

- Free Water Elevations are partition-dependent, not well-dependent.
- Infer new compartment from fault blocks or zones.

FWE=-1687 m. **FWE=-1659 m.**

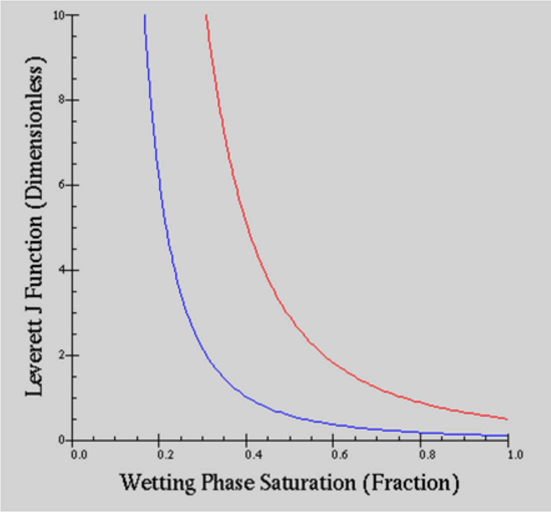
Alternatives to Moving Points

➔ Identify a new J Function.

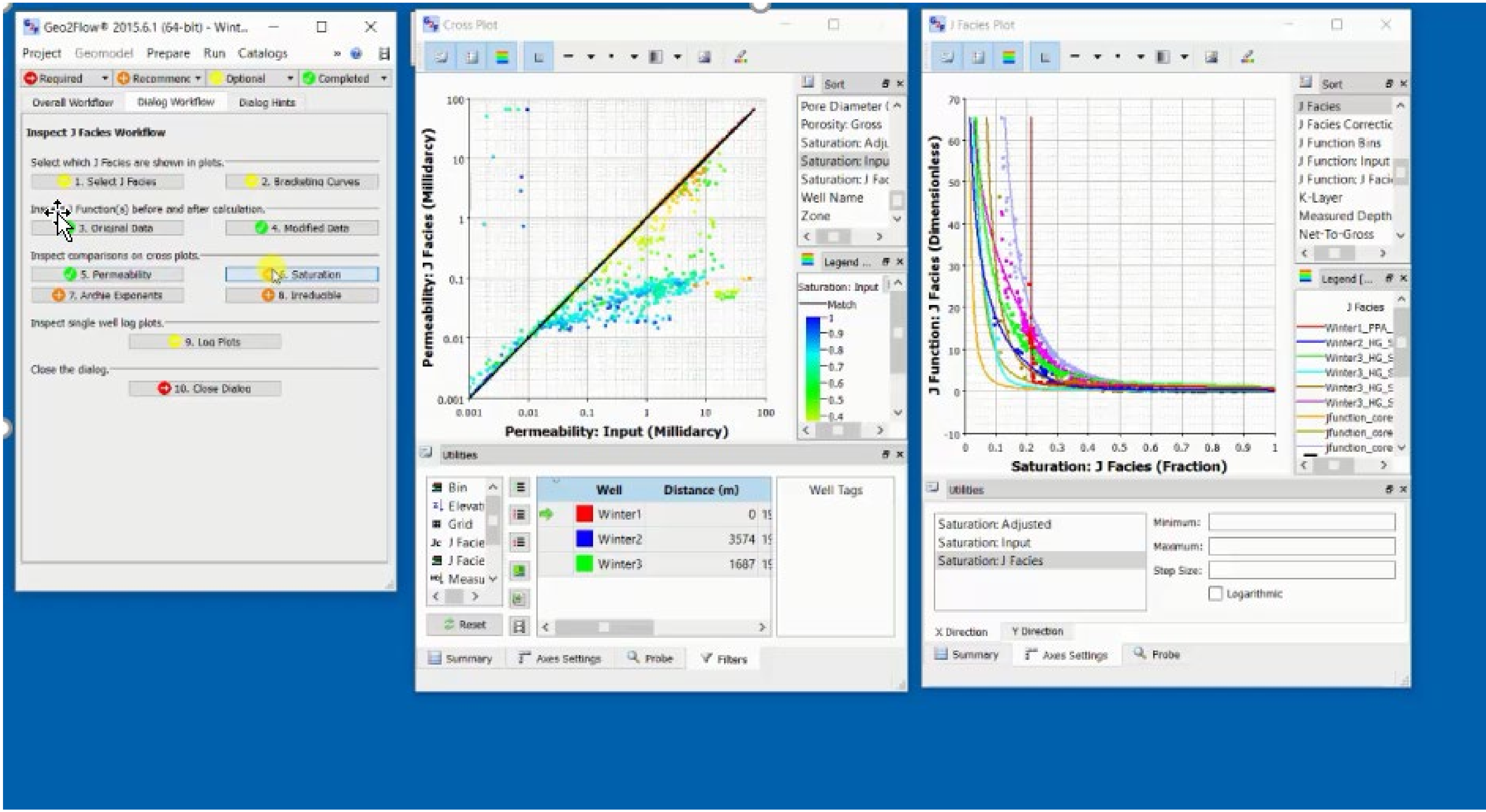
- Correlate with lithologies, if they are described in geological model.
- Laboratory capillary pressures?
- Likelihood of not encountering new rock type in coring program.

➔ Discard data point.

- Last resort: outside error bounds.



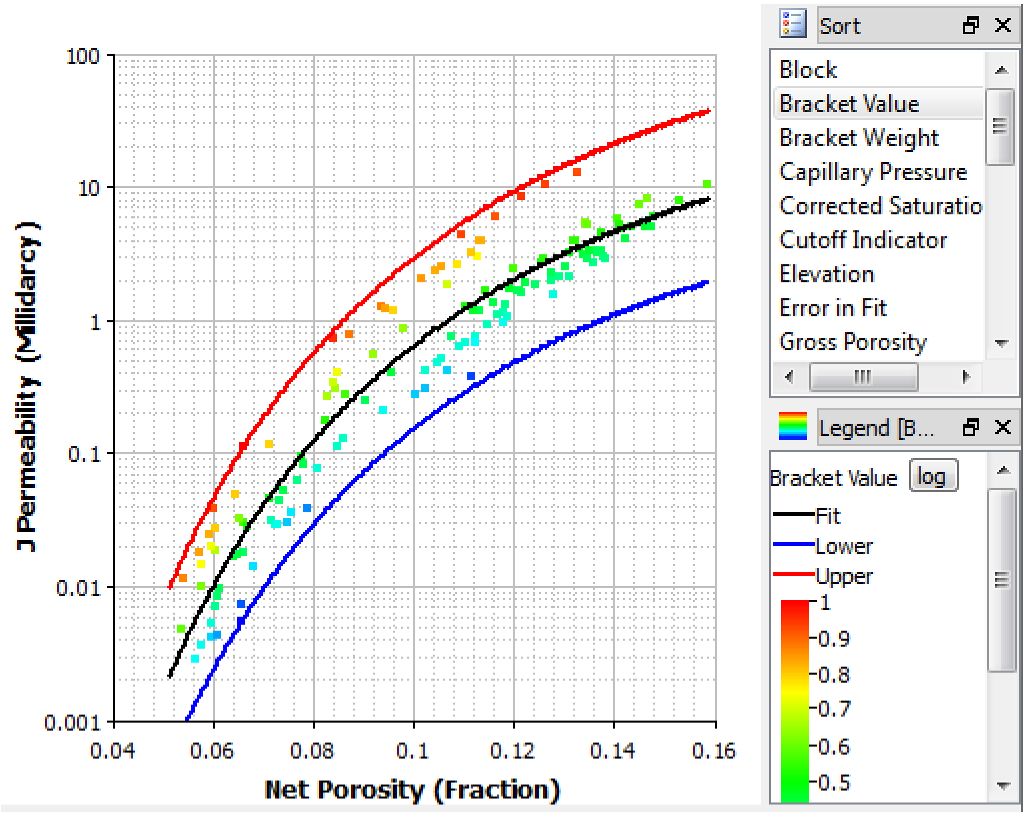
Resolving Permeability, Archie Exponents, And Irreducible



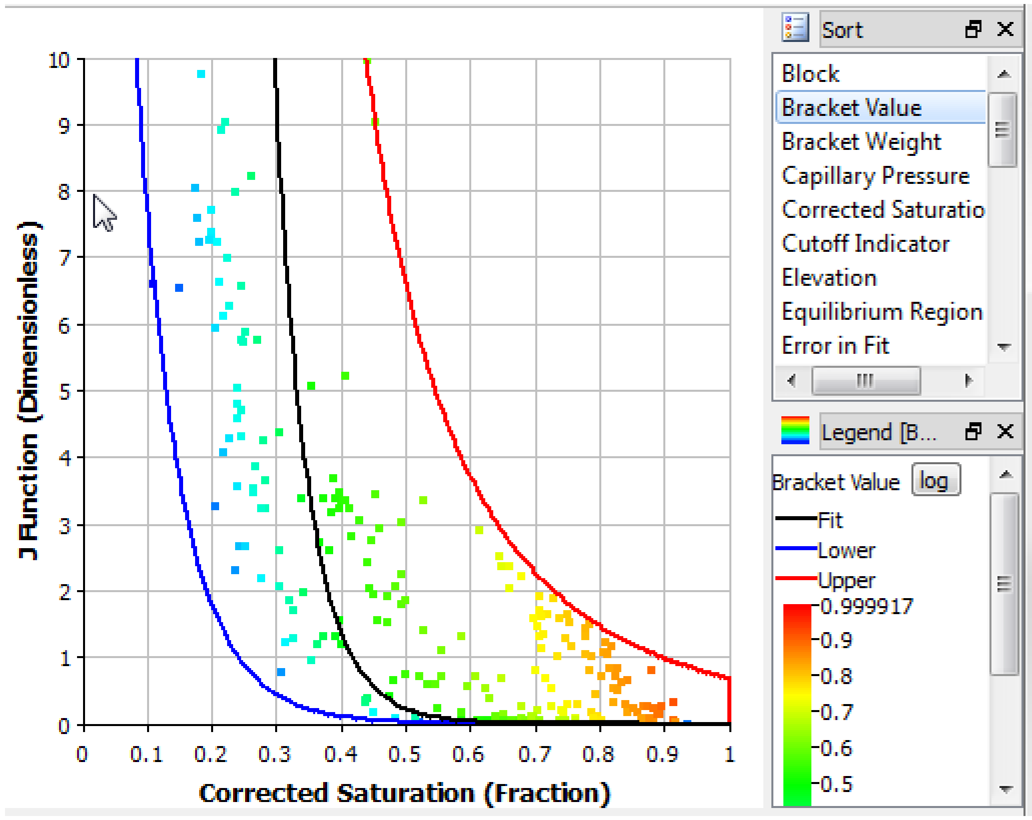
Geo2Flow 3D Modeling

➔Emphasizes governing equations.

- Geostatistics is assigned to handling variability around equations.
- “Bracketing” captures variability around equations.



Upscaled Poro-Perm



Upscaled J Function

➔**Upscaled into Petrel cells.**

Permeability: Core vs. Upscaled - Equations

From Core

$$\log k = a + b\,\phi$$

$$\frac{\sum_{i=0}^{n} V_i \log k_i}{\sum_{i=0}^{n} V_i} = \frac{\sum_{i=0}^{n} V_i \,(a + b\,\phi_i)}{\sum_{i=0}^{n} V_i}$$

Geometric Average Permeability

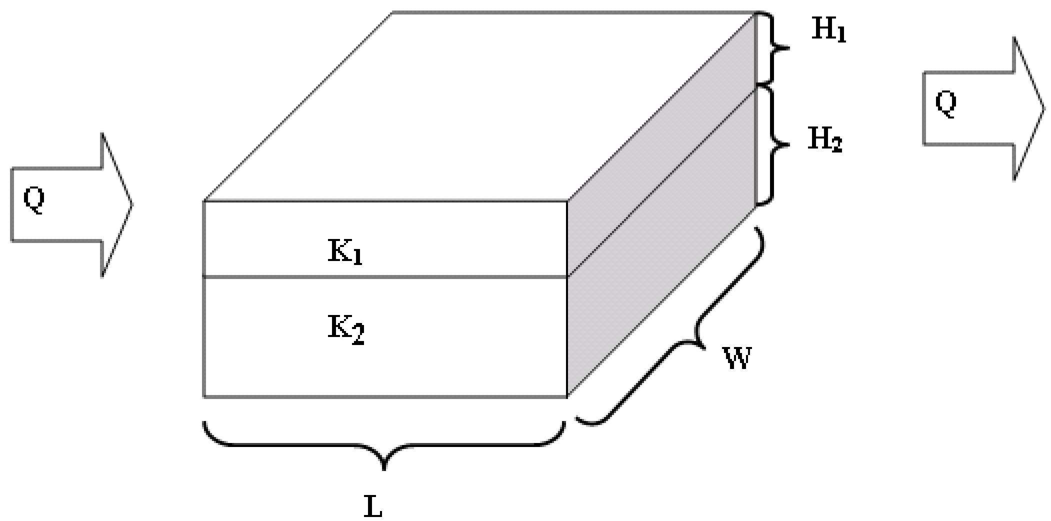
Volumetric Average Porosity

Upscaled

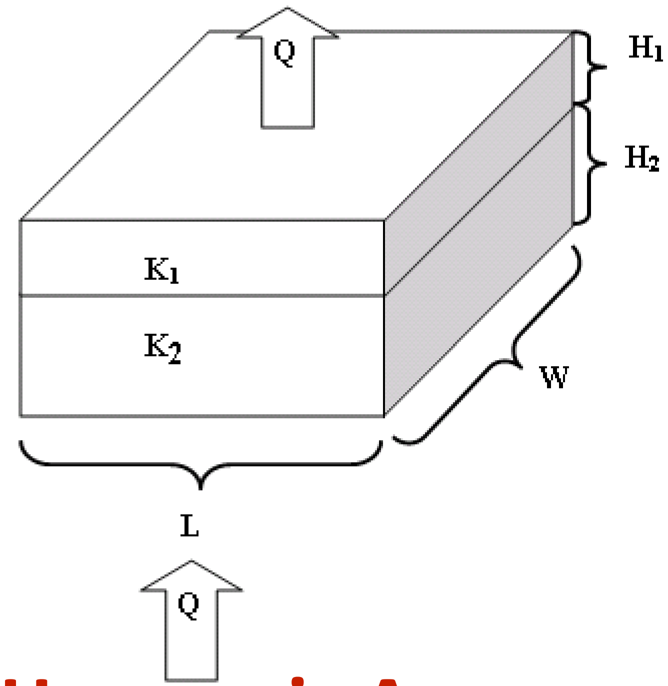
$$\log \overline{k} = a + b\,\overline{\phi}$$

Upscaling Permeability: A Simplified View

Horizontal Flow



Vertical Flow



Arithmetic Average

Harmonic Average

$$\overline{K}^n = \frac{H_1 K_1^n + H_2 K_2^n}{H_1 + H_2}$$

→Harmonic (n=-1) < Geometric (n=0) < Arithmetic (n=1).

- Horizontal (well test) permeability - Arithmetic.
- Vertical permeability – Harmonic.

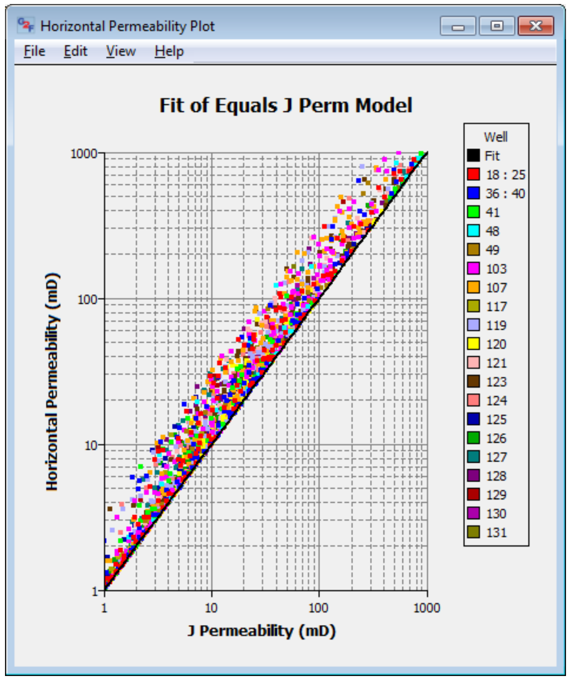
3D Permeability in Geo2Flow

➔ Geometric Average: called J Facies Permeability.

- Best for upscaling J Functions (most scale invariant).

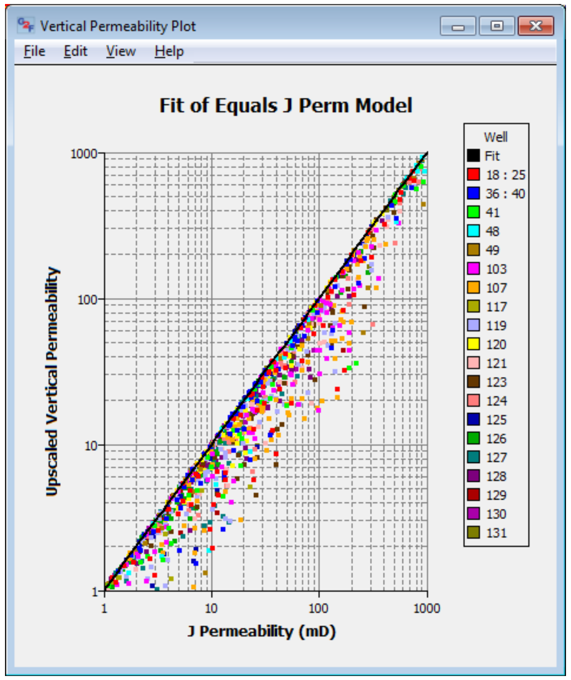
➔ Horizontal permeability.

- Linear correlation with J Permeability at wells.
- Always greater than J Permeability

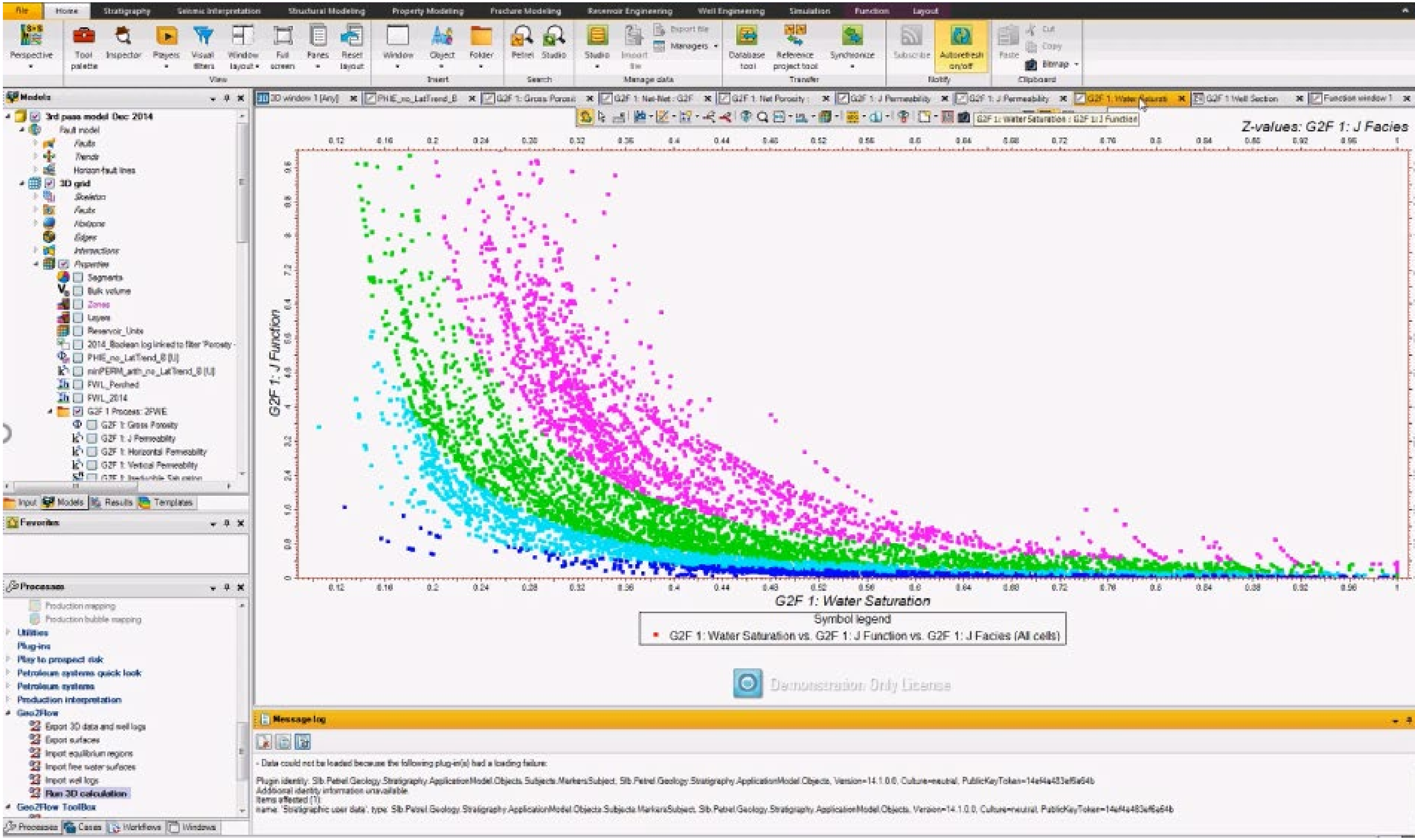


➔ Vertical permeability.

- Linear correlation with J Permeability at wells.
- Always less than J Permeability



3D Calculation and Outputs



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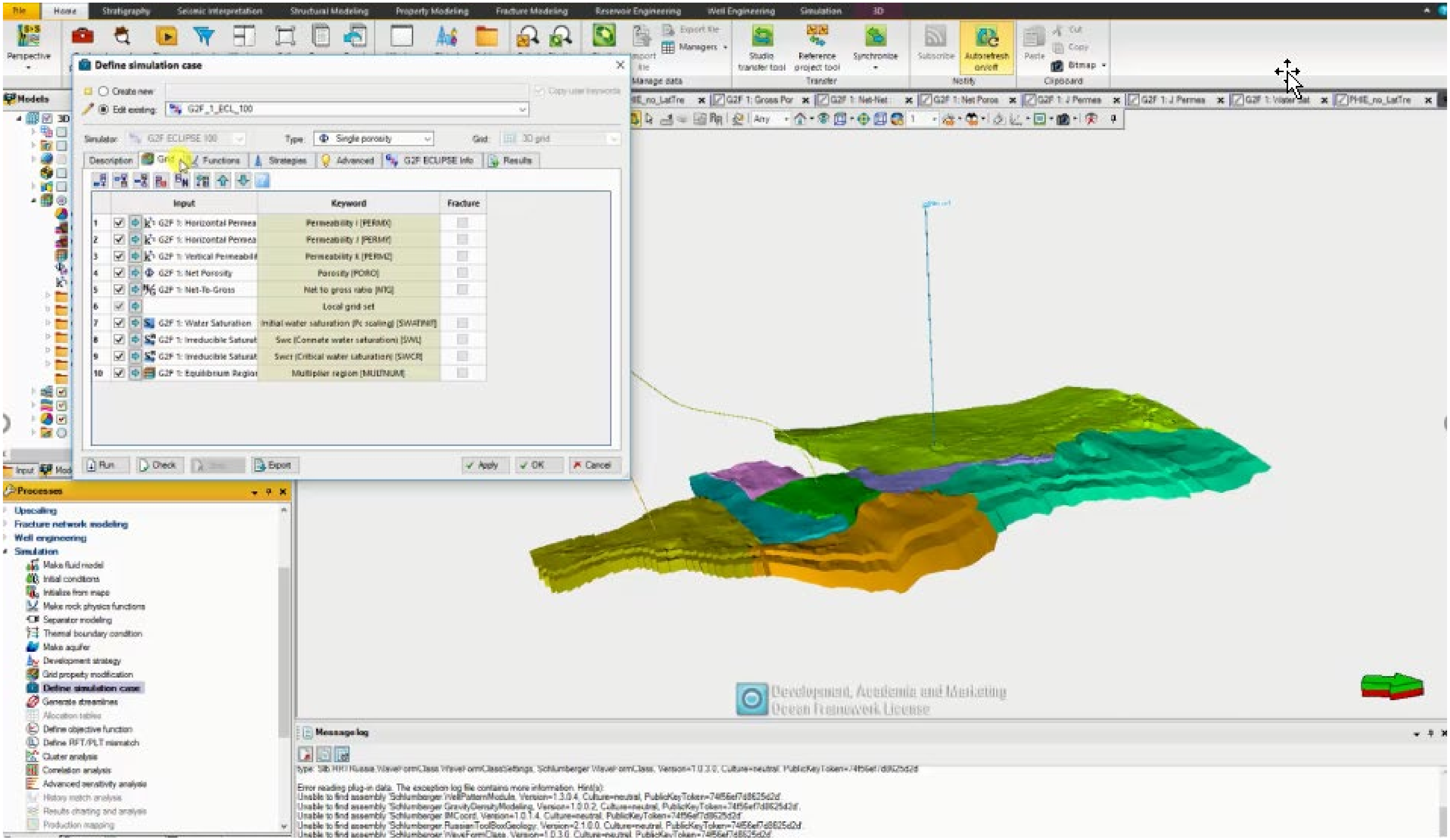
Define Simulation Case



What Do You See In Geo2Flow?

"Your aim determines what you see." – Jordan Peterson

→Scientifically strong: patented.

→Identifies reservoir compartments.

→Matches simulation models to saturations logs.

→Constrains permeability with saturations.

→Stronger history-matching from physically consistent inputs.

→Helps assess true uncertainties, not just easy ones to study.

→Stimulates interdisciplinary cooperation through workflows.

→Voluminous documentation and videos for training.

Extensive Documentation: www.geo2flow.com

- ➔ *Science plus technology.*
- ➔ *Detailed Glossary (over 200 entries).*
- ➔ *Frequently Asked Questions.*
- ➔ *Whitepapers.*
- ➔ *Instructional videos.*