SPWLA
Distinguished Speaker
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SOCIETY OF PETROPHYSICISTS AND WELL LOG ANALYSTS

QATAR CHAPTER

A Simple And Convincing Water Saturation vs Height Function for Reservoir Modelling

Steve Cuddy

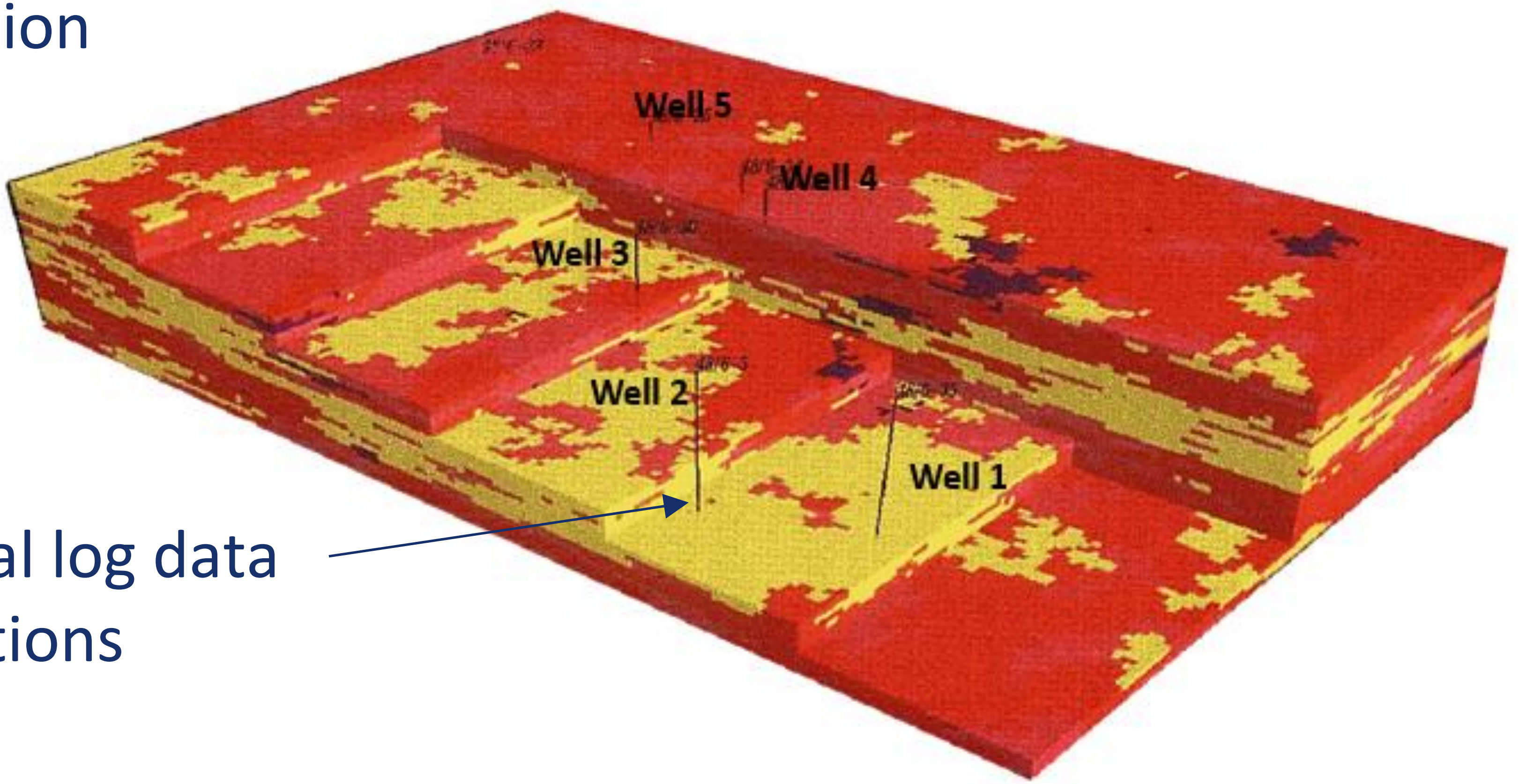
Outline

- Why we need a Water Saturation vs. Height function for reservoir modelling
- Definitions: Free-Water-Level, HWC, Net, Swirr
- Several case studies showing applications to reservoir modelling
- Why we should forget about Water Saturation and think Bulk Volume of Water

Why we need a reservoir model

The 3D reservoir model is required to calculate hydrocarbon in place and for reservoir modelling and simulation

The model requires fluid contacts, net reservoir cut-off and a water saturation vs. height function



Limited core and electrical log data available at the well locations

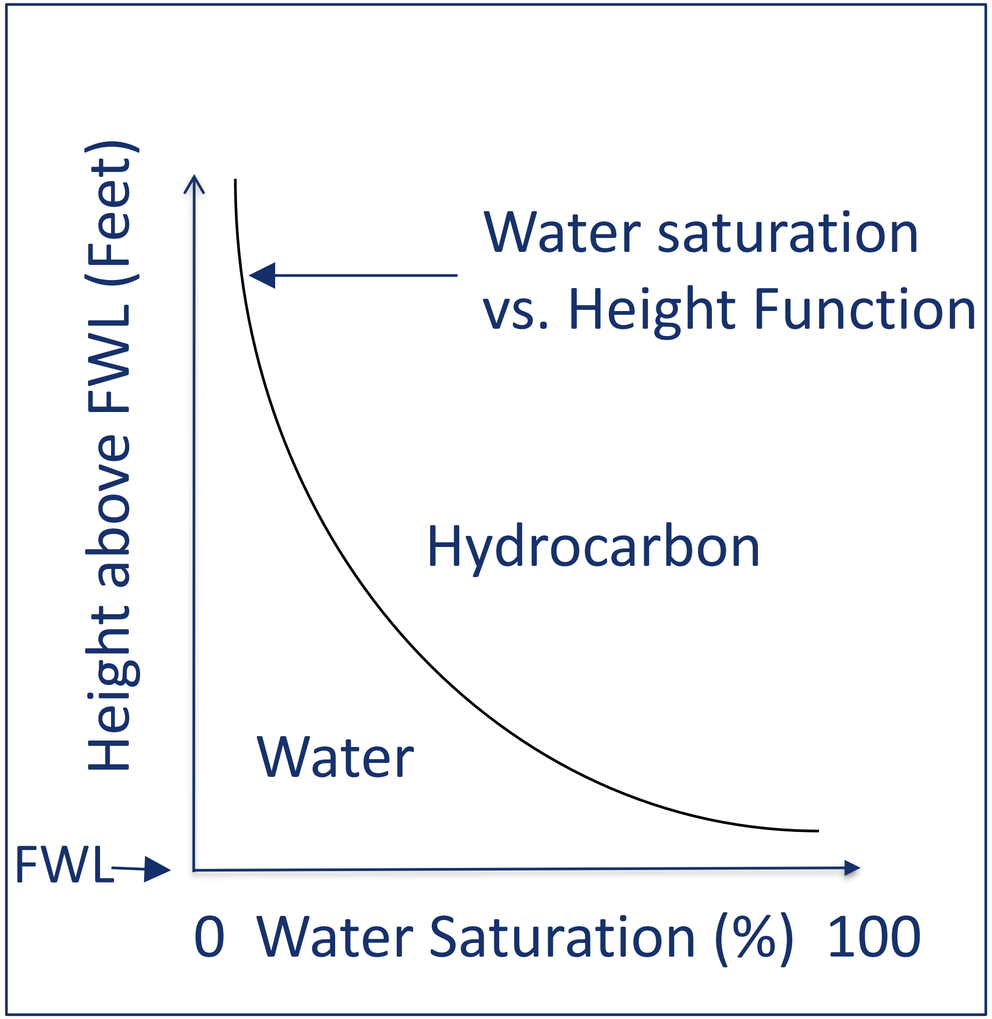
Why the reservoir model needs a Sw vs. Height Function

Used to initialize the 3D reservoir model

Tells us how water saturation varies as a function of the height above the Free Water Level (FWL)

Tells us how the formation porosity is split between hydrocarbon and water

Tells us the shape of the transition zone



What a Good Saturation Height Function Requires:

- Three independent sources of fluid distribution data are consistent
  - Formation pressure data
  - Electrical log data
  - Core data
- Must account for varying permeability and fluid contacts
- Must upscale correctly
- Should be convincing
- Should be easy to apply

Water Saturation vs. Height Function

Called the BVW or FOIL Function

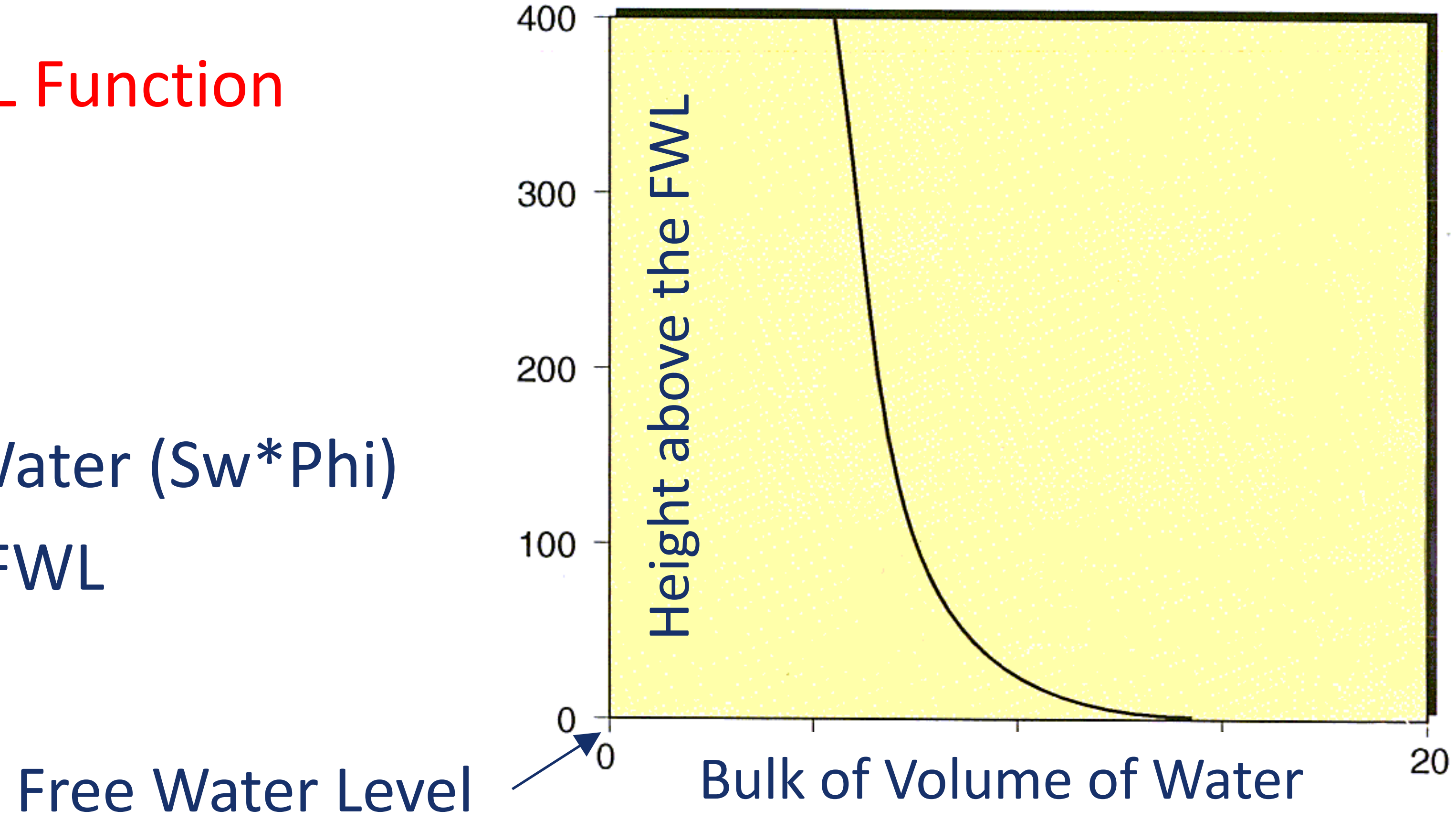
$$BVW = aH^b$$

Where:

BVW = Bulk Volume Water (Sw*Phi)

H = Height above FWL

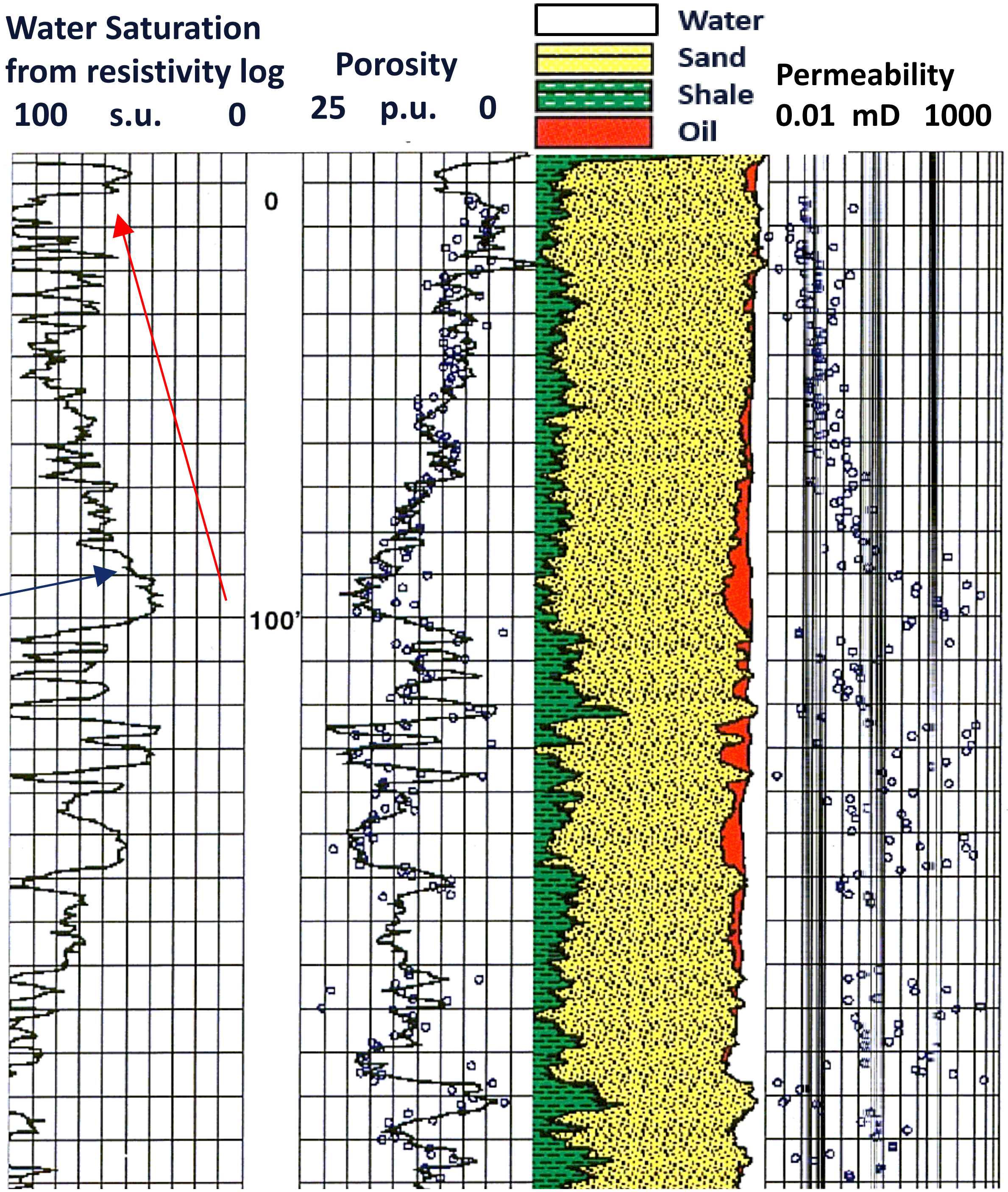
a, b = Constants



- Based on the Bulk Volume of Water (BVW)
- Independent of facies type, porosity and permeability
- Two parameters completely describe your reservoir

Sw vs. Height Challenge

- London Petrophysical Society
- North Sea supplied data
- Very difficult data set
  - Heterogeneous formation
- Sw increases with height!
- Shoot-out between several industry SwH functions
  - Comparison of Sw from Swh function and Sw from resistivity logs



Sw vs. Height Modelling Results

$BVW = aH^b$

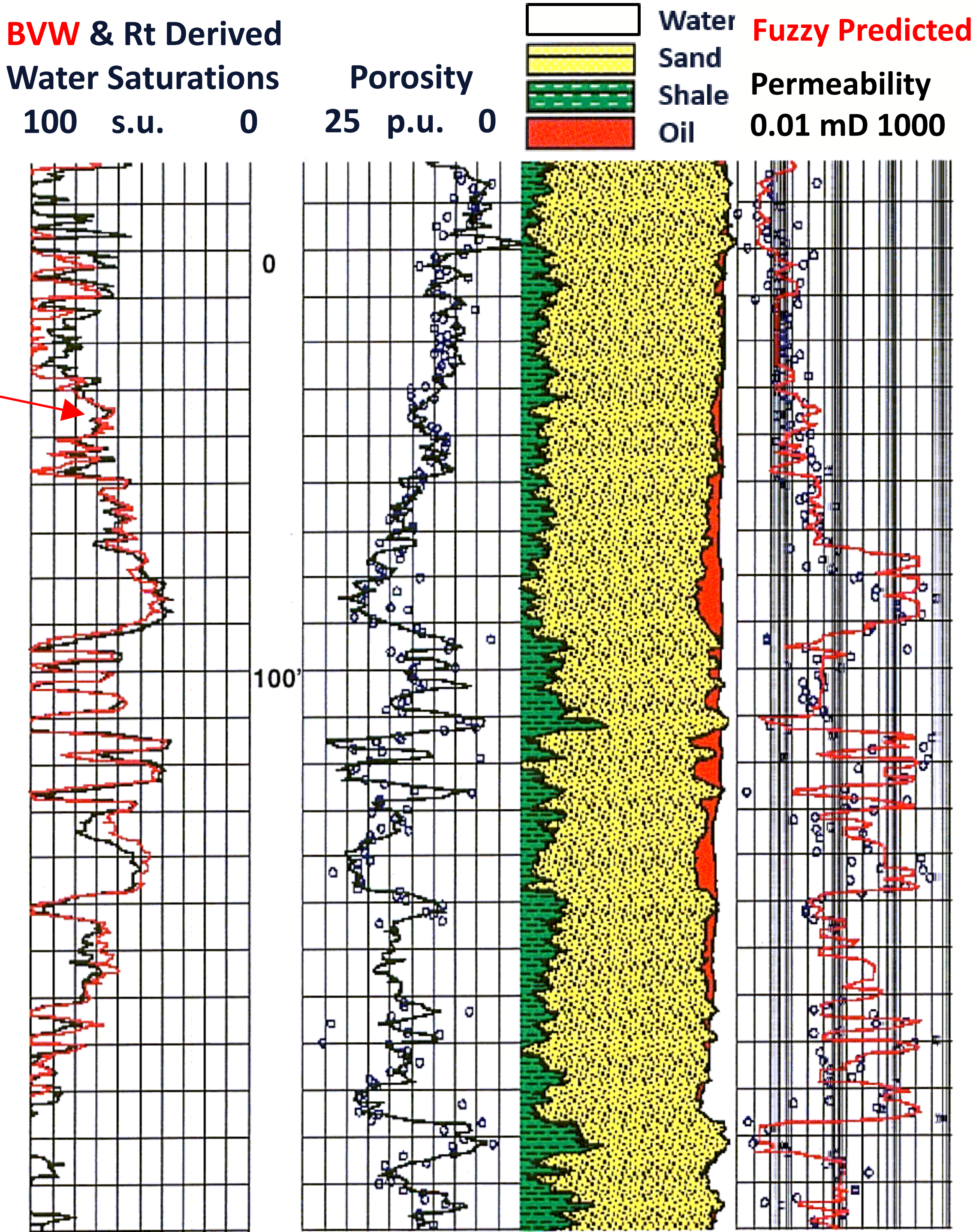
Where:

BVW = Bulk Volume Water (Sw*Phi)

H = Height above FWL

a, b = Constants

- Good match in all litho-facies types
- Permeability not required
- Defined by only 2 parameters (a,b)
- If Sw can be predicted with this accuracy
  - Do we always need resistivity logs?

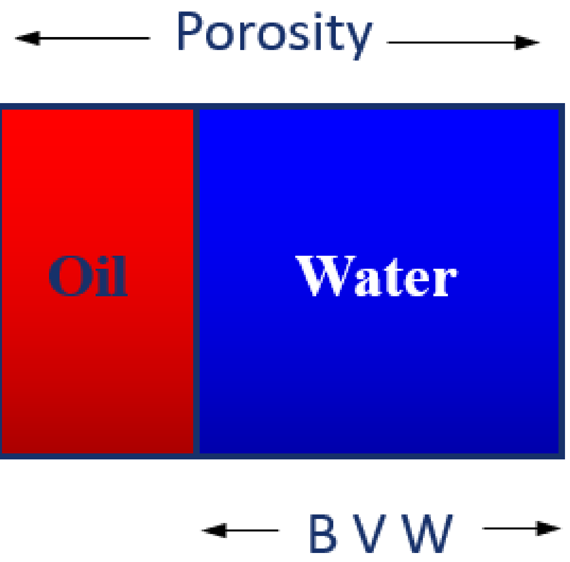


Important Definitions used in Reservoir Modelling

- Bulk Volume of Water (BVW)
- Free-Water-Level (FWL)
- Hydrocarbon Water Contact (HWC)
- Irreducible water saturation (Swirr)

The Bulk Volume of Water (BVW)

Bulk Volume of Water = Porosity x Water Saturation



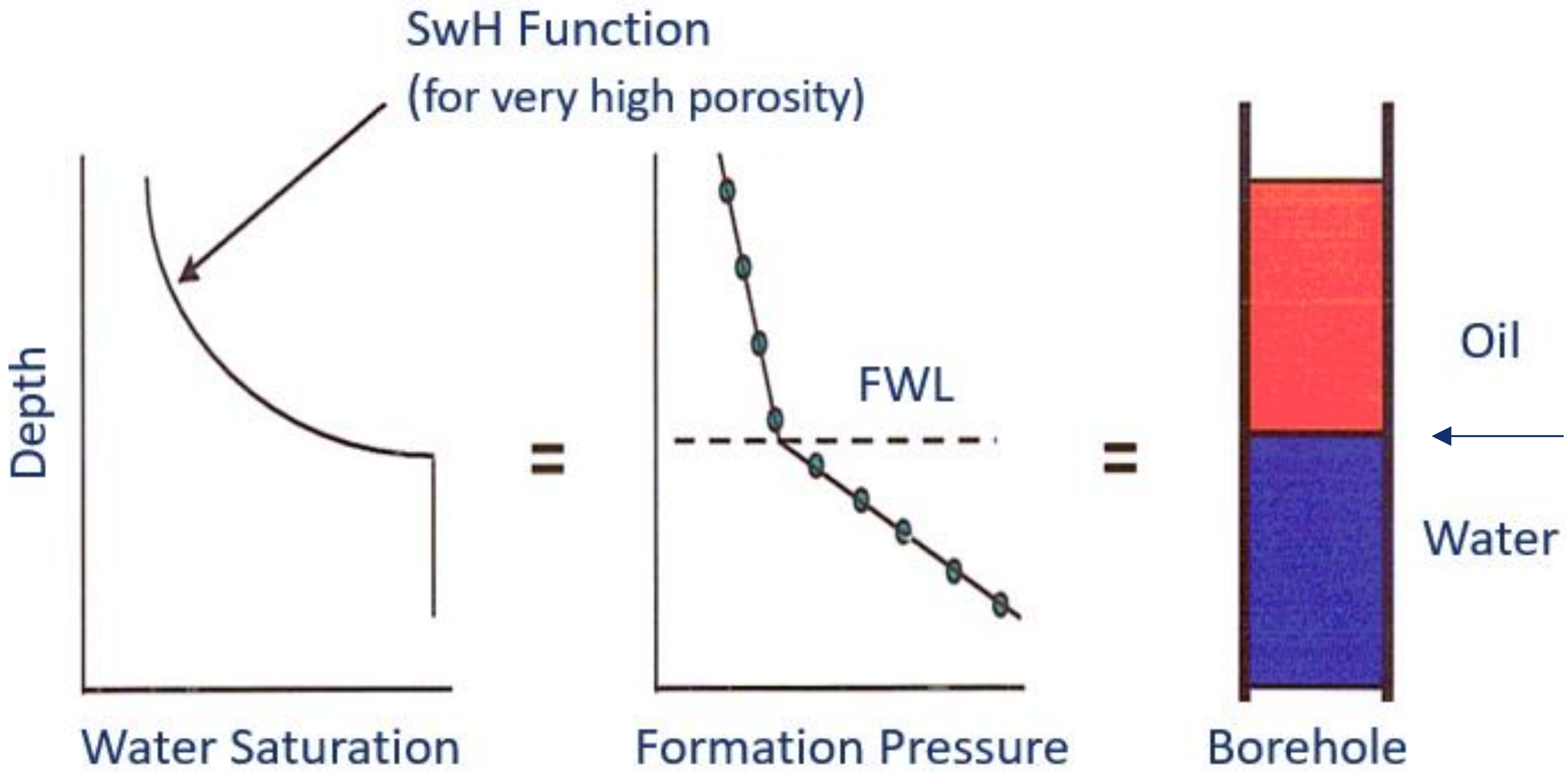
BVW = % volume of water in a unit volume of reservoir

BVW is what is measured by electrical logs and by core analysis

Electrical logs and core analysis do not measure Sw directly

The Free Water Level (FWL)

FWL is the horizontal surface of zero capillary pressure



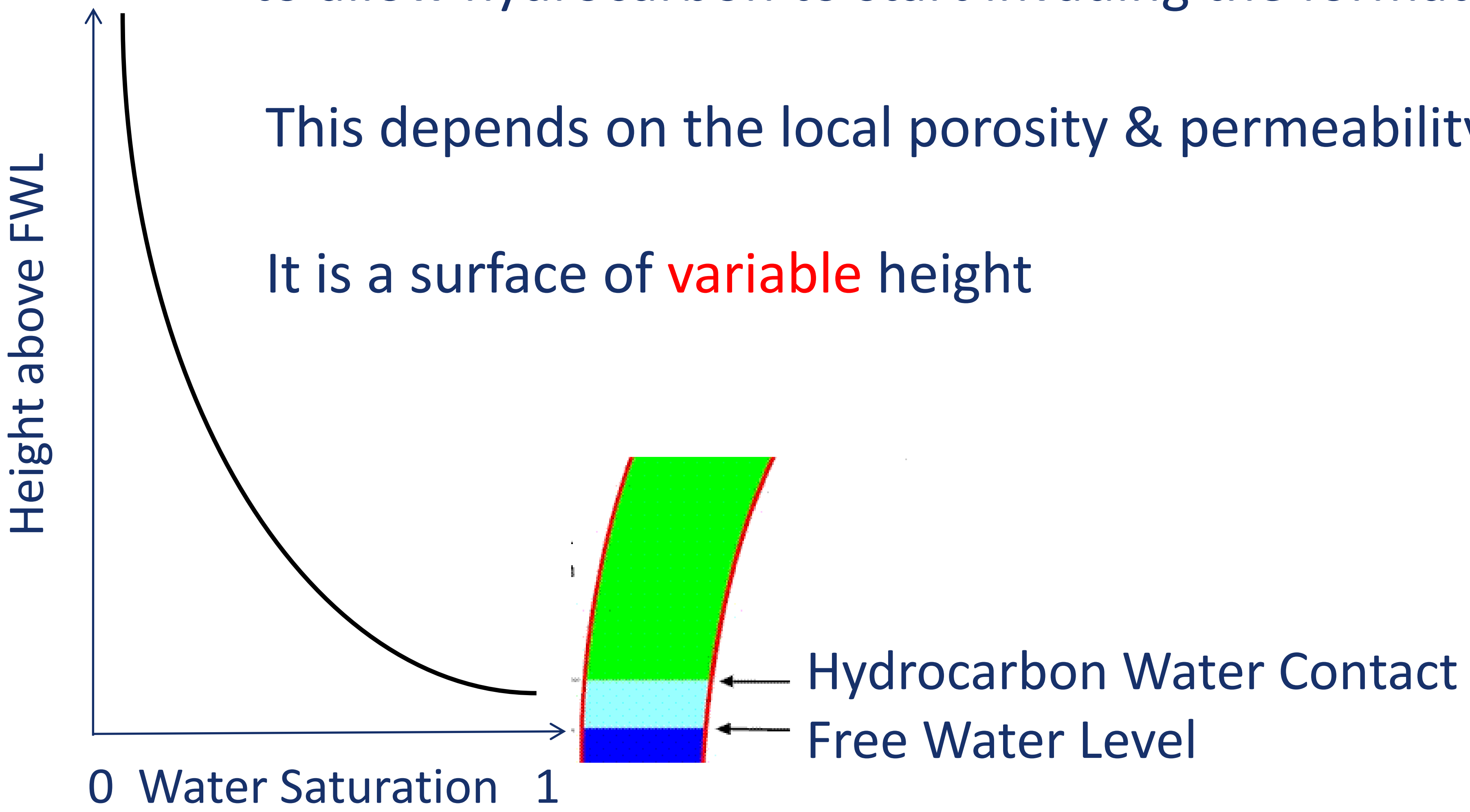
Where fluids separate in a wide borehole

Hydrocarbon Water Contact

The HWC is the height where the pore entry pressure is sufficient to allow hydrocarbon to start invading the formation pores

This depends on the local porosity & permeability

It is a surface of variable height



Irreducible Water Saturation (Swirr)

Is the lowest water saturation that can be achieved in a core plug

This is achieved by flowing hydrocarbon through a sample or spinning the sample in a centrifuge

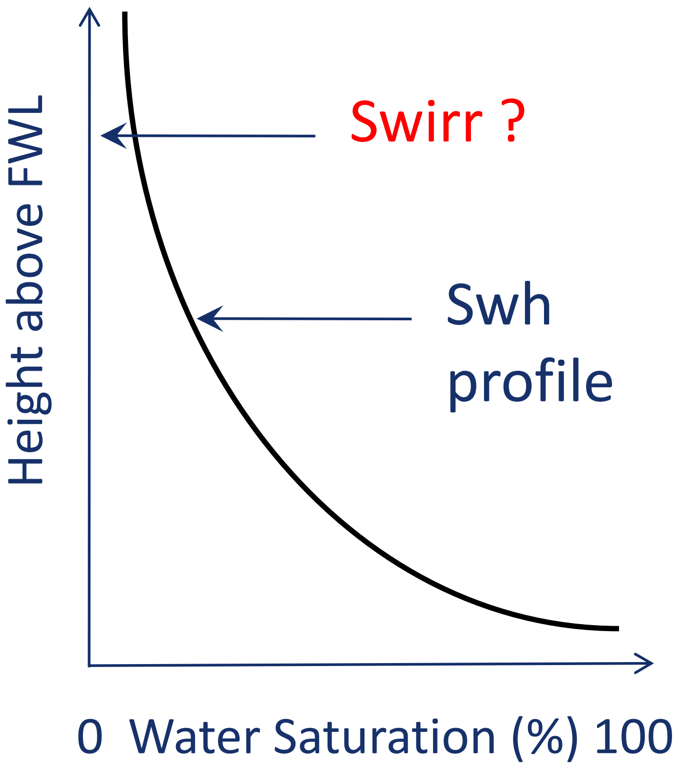
Swirr depends on the drive pressure or the centrifuge speed

Water saturation therefore depends on the height above the free water level

A minimum Swirr does not exist

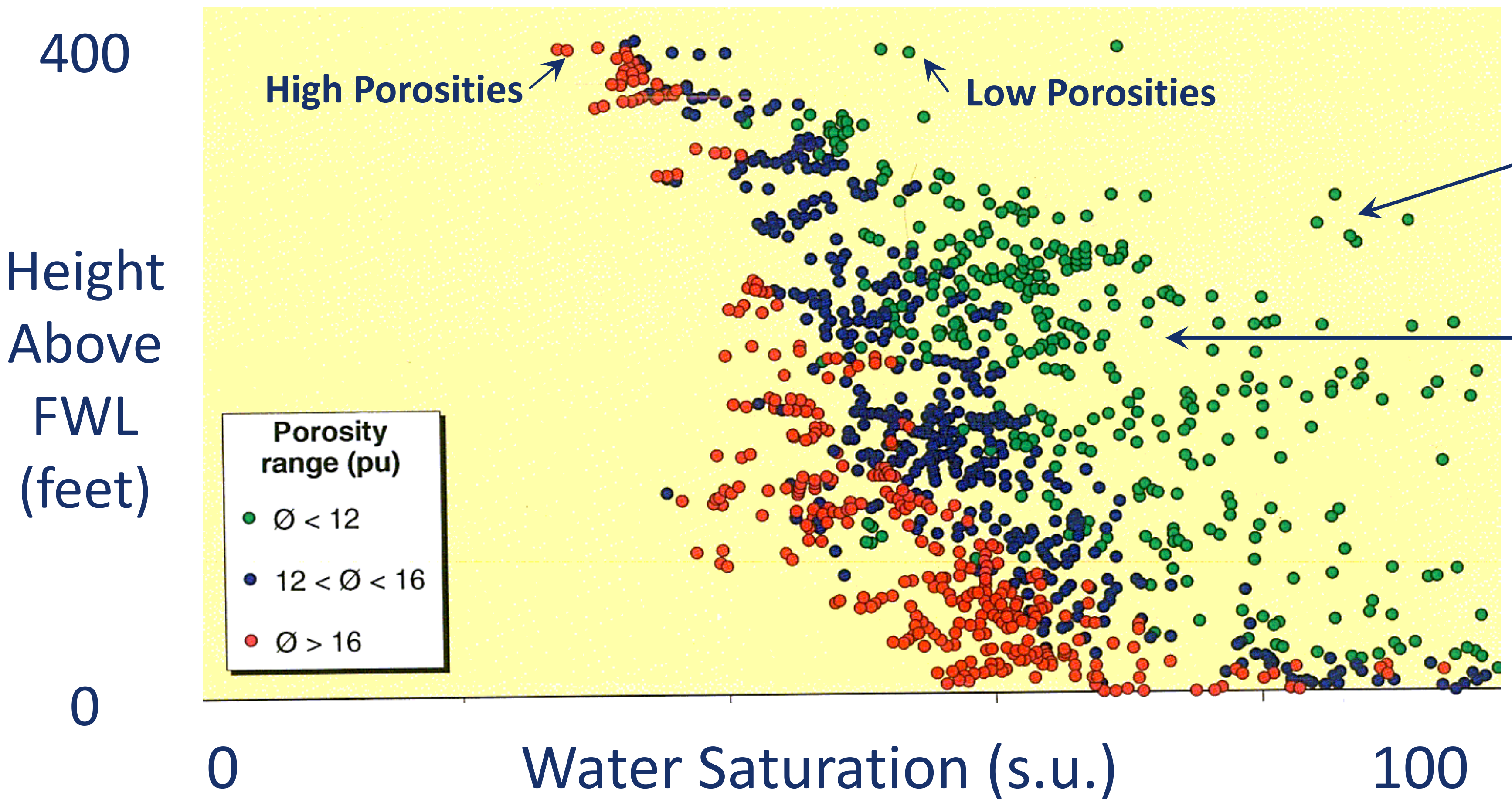
The transition zone extends indefinitely

The BVW Swh function determines Swirr as a function only of height and porosity



Water Saturation vs. Height Data

Multi-well Case Study - Southern North Sea Gas field

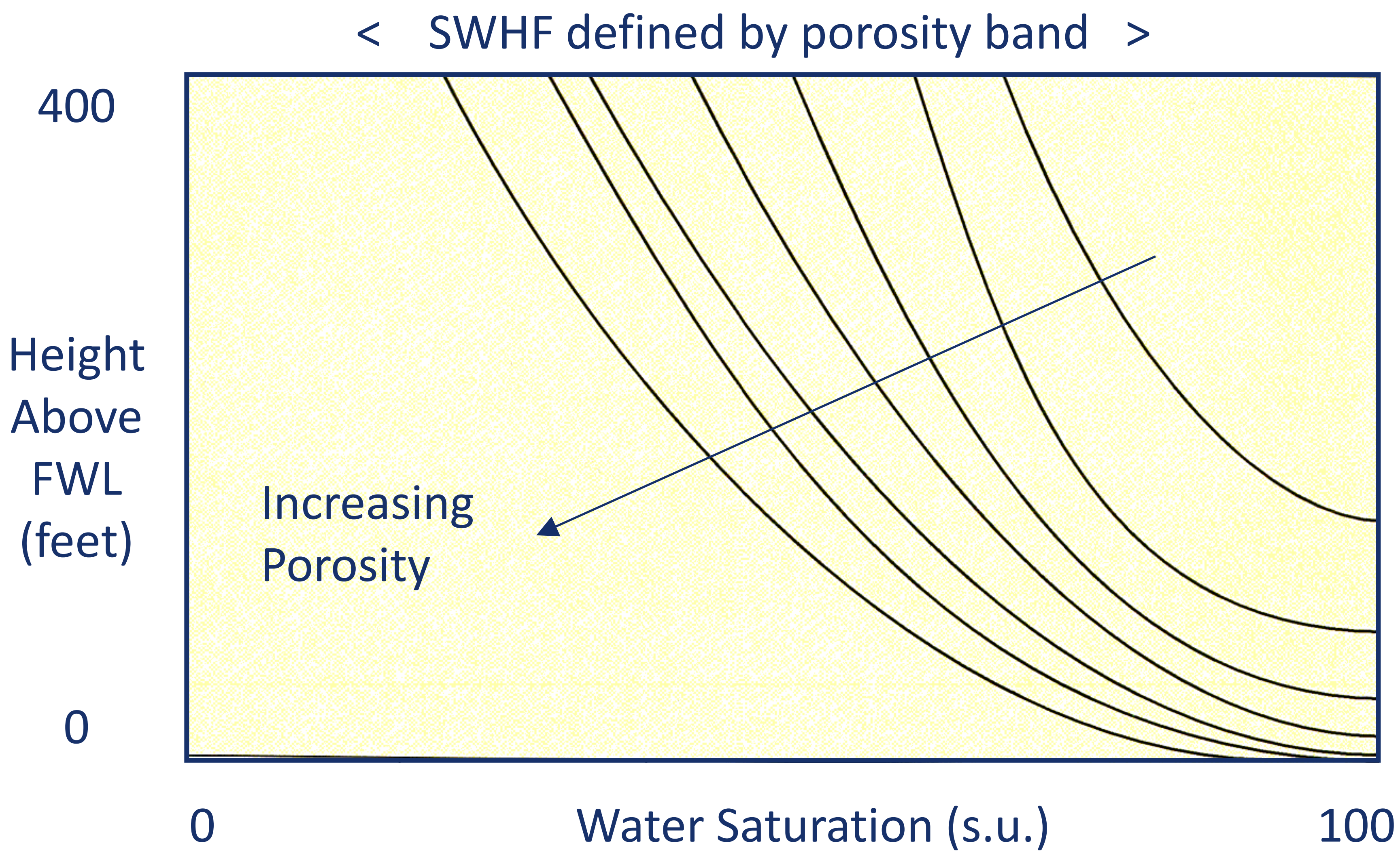


Low porosity formation is fully water saturated for hundreds of feet above the FWL

Typical Shotgun pattern

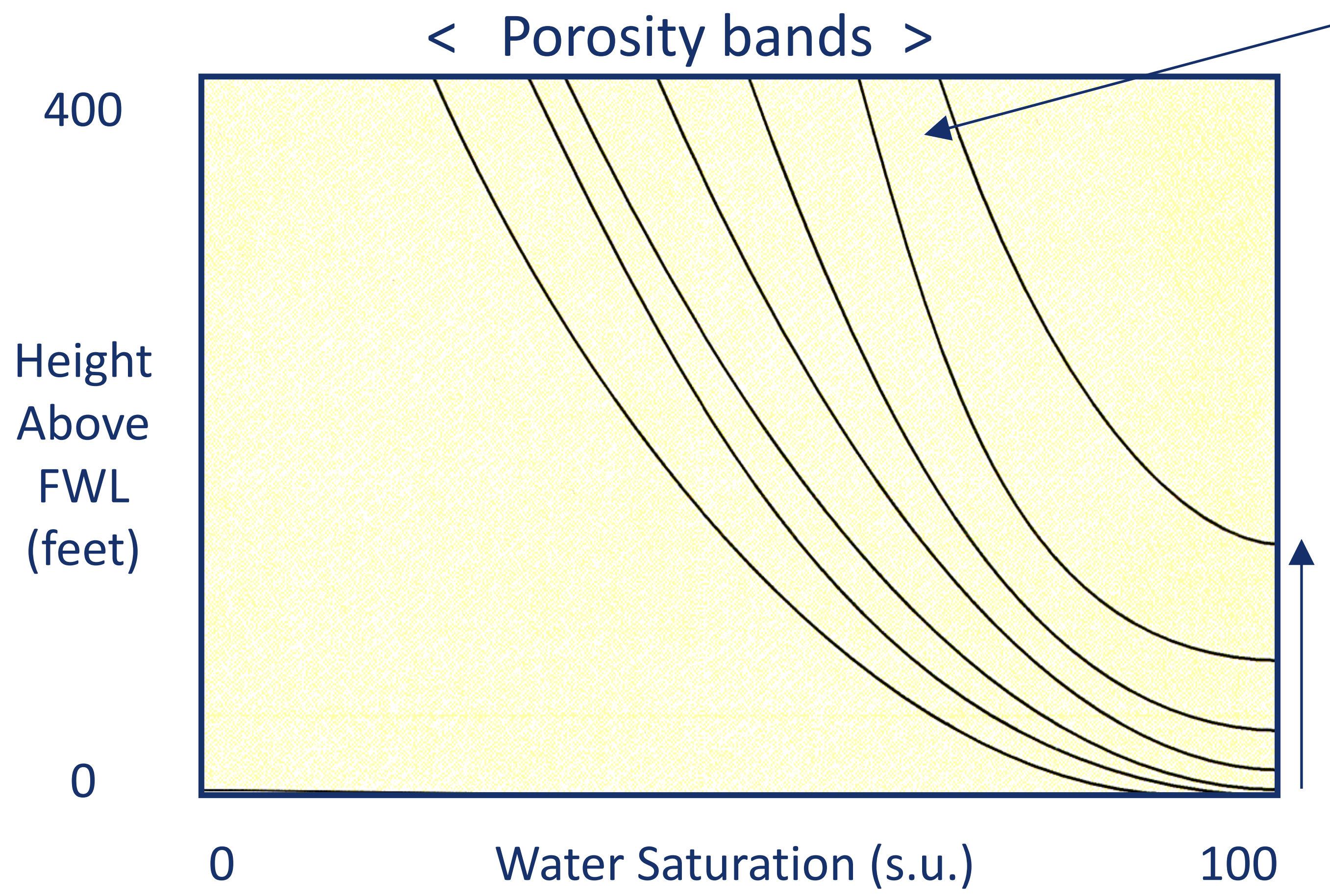
Free Water Level

Classical Water Saturation vs. Height Curves



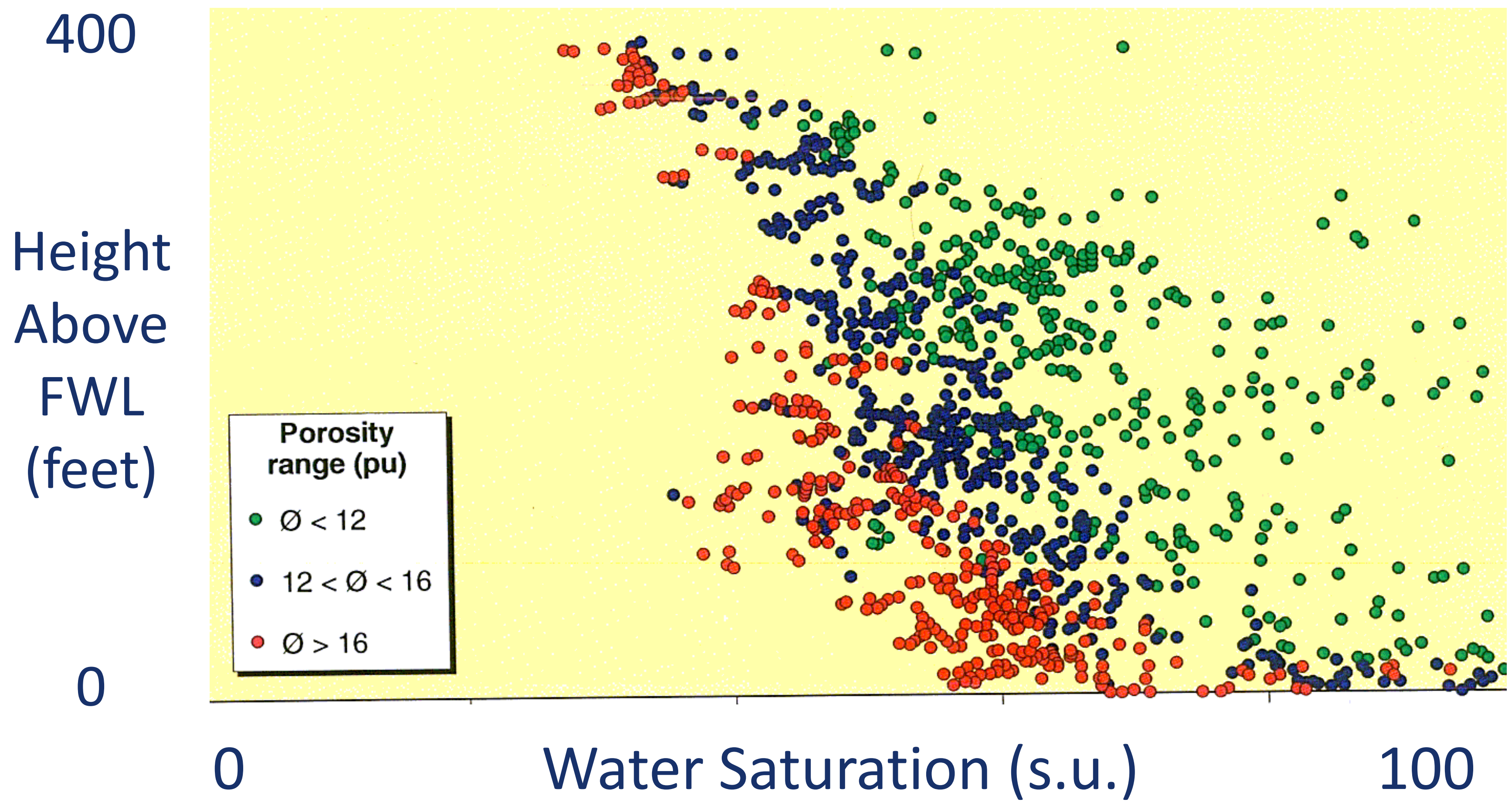
Problems with Classical Swh Functions

- Sufficient data are required for each porosity band
- Visually and mathematically unconvincing as they cross!



Defining the pore entry pressure (threshold height) can be difficult

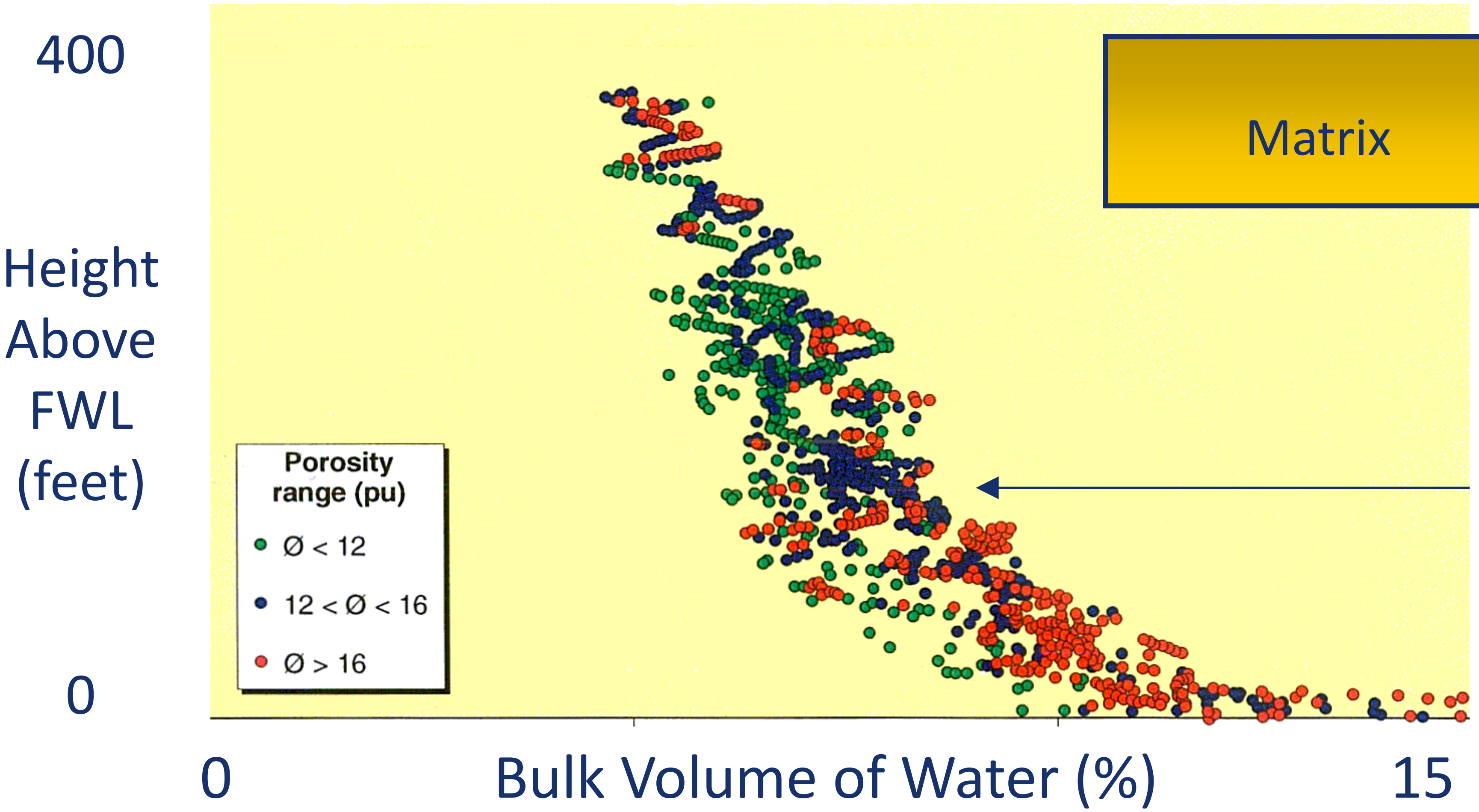
Water Saturation vs. Height Data

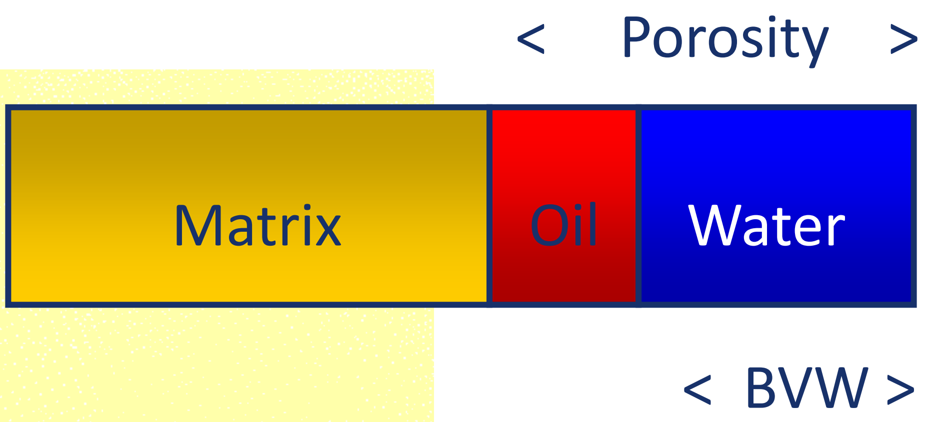


Only net reservoir data is plotted

Next slide shows what happens when Sw (x-axis) is changed to BVW

Bulk Volume of Water vs. Height Data





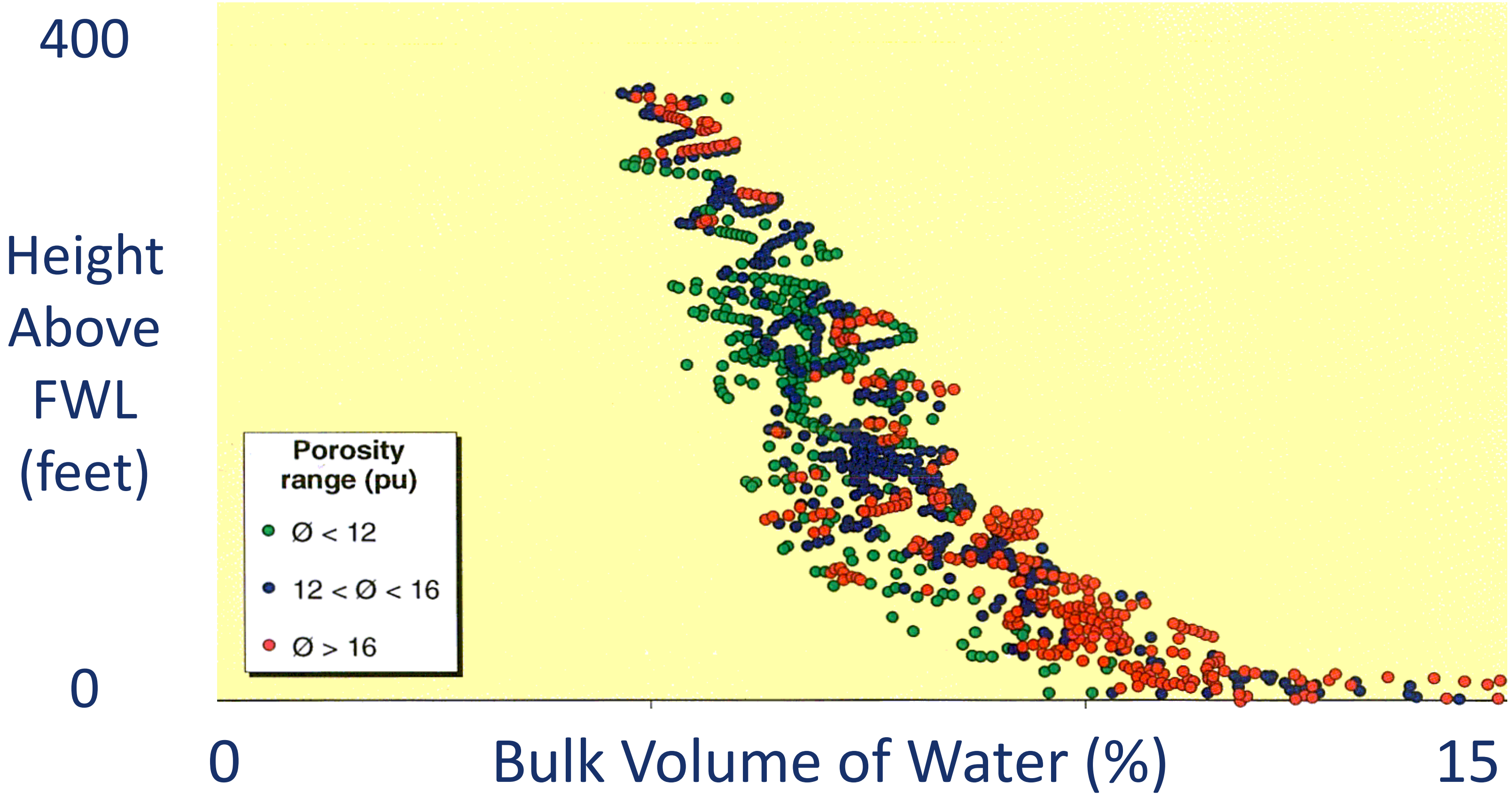
BVW trend is independent of porosity

Sw shotgun pattern collapses to a simple function of BVW vs. Height

BVW is Independent of Rock Properties

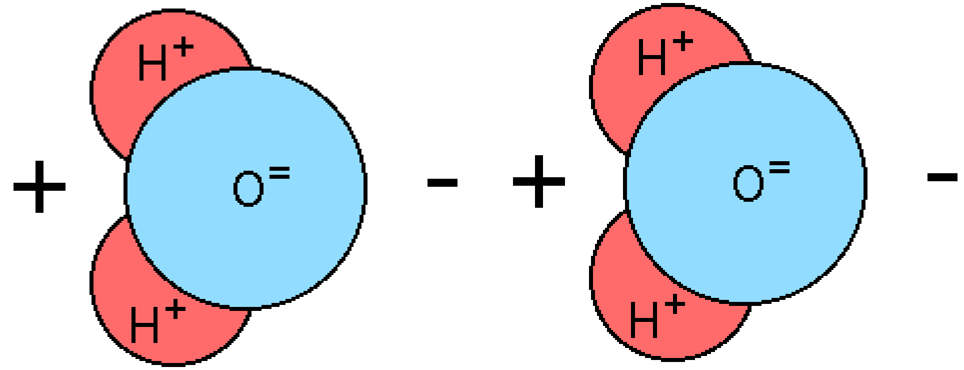
The bulk volume of water is independent of rock properties

Can be easily verified by simply plotting facies-type, porosity or permeability on the z-axis (colour) on the cross-plot



The Structure and Electrical Properties of Water

H_2O =



The water molecule is made up of 2 atoms of hydrogen and 1 atom of oxygen

The water molecule is polarized with distinct negative (oxygen) and positive (hydrogen) ends

This causes water molecules to be strongly attracted to each other and to reservoir rocks

The electrostatic force is 10^{36} times greater than the gravitational force!

Buoyancy Forces in Reservoir Fluids

Water is in the reservoir first

When hydrocarbons migrate into a trap, the buoyancy force exerted by the lighter oil (or gas) will push the water that was previously in the pore space downward

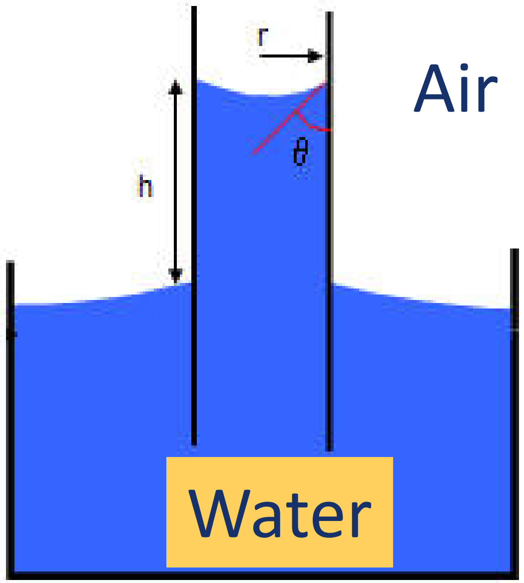
However, not all of the water is displaced; some of it will be held by capillary forces within the pores

Narrower capillaries, pores with smaller pore throats, with the larger surface area, hold onto the water the strongest

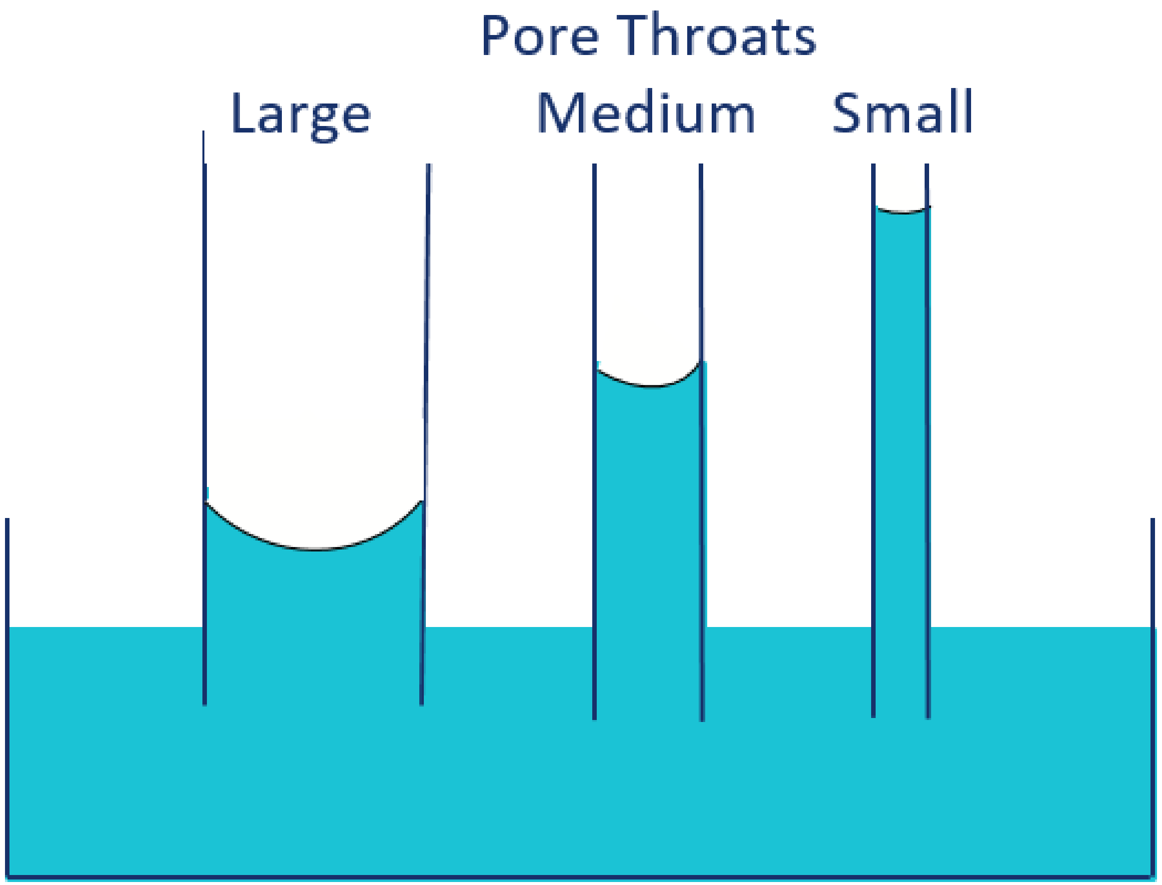
Capillary Pressure holds the Water up

When two fluids meet in a capillary tube there is a difference in pressure across their interface.

This "Capillary Pressure" is caused by the preferential wetting of the capillary walls by the water and gives rise to the familiar curved meniscus and causes the water to rise up the capillary



Capillary Pressure and Pore Size



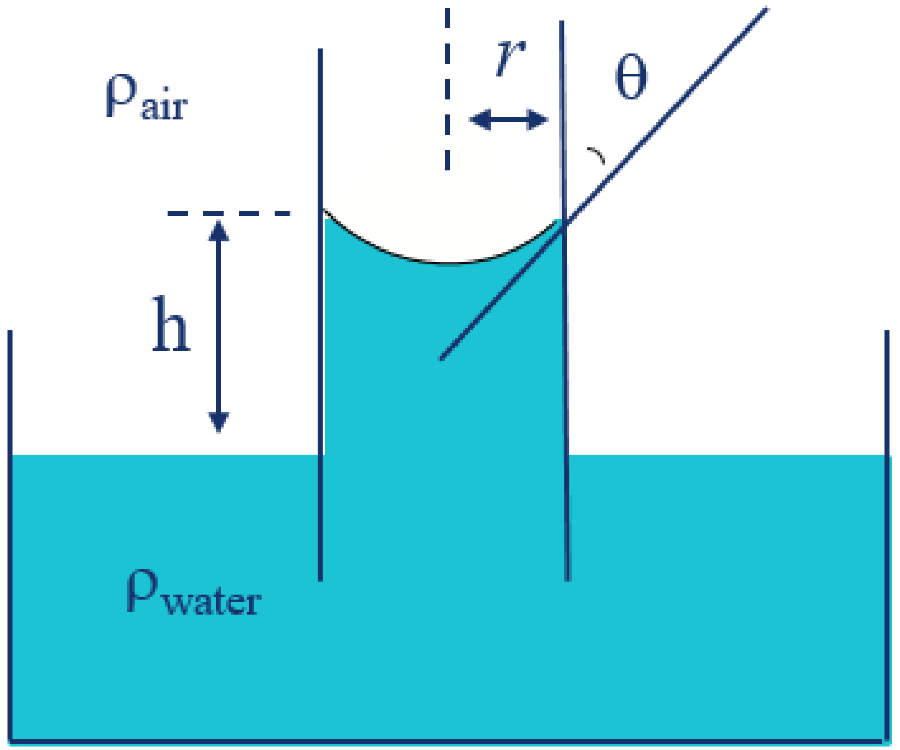
The smallest pores (throats) hold on to the most water

Consequently hydrocarbon requires more pressure to enter small pores

Capillary Pressure Equation

The height of the water in a capillary depends on the capillary pressure - which is determined by the radius of the capillary and the fluid types

$$P_C = \frac{2\sigma\cos(\theta)}{r}$$



Where:

Pc capillary pressure

r capillary radius

σ interfacial tension

θ contact angle

Gravity pulls the Water Down

The force of gravity on the column of water is determined by the difference between the water and oil densities and is called the buoyancy pressure P_b

$$P_b = (\rho_w - \rho_o)gh$$

Where:

P_b	buoyancy pressure due to gravity
ρ_w	water density
ρ_o	oil density
g	acceleration of gravity
h	height above the free water level (FWL)

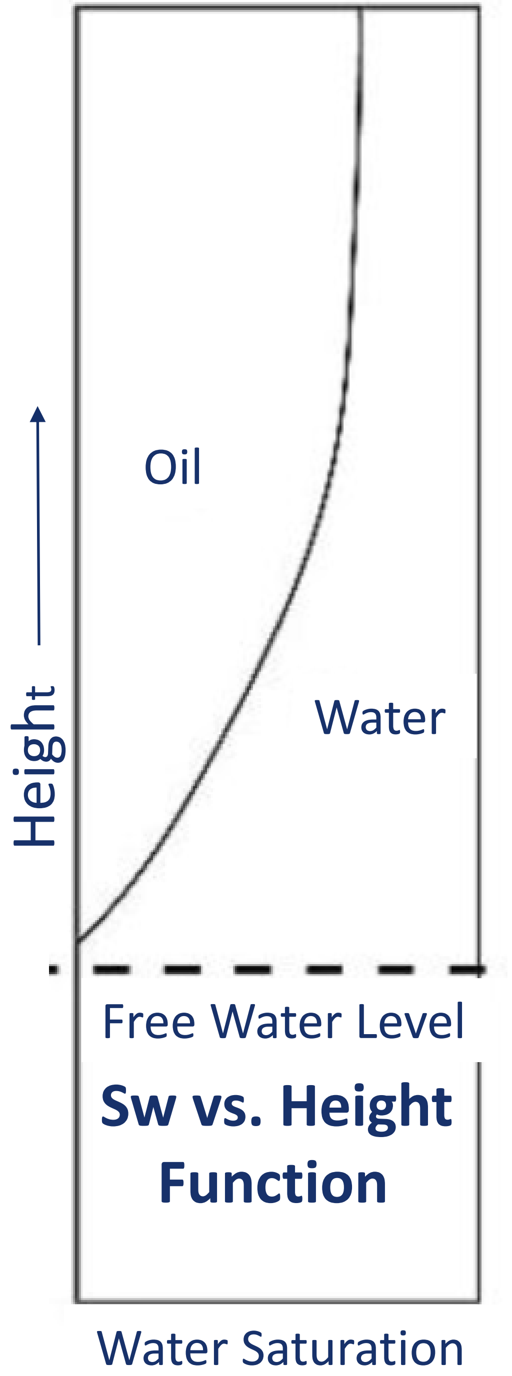
Forces Acting on Reservoir Fluids

The water at a given height in a reservoir is determined by the balance between the capillary forces holding the immobile water up to the force of gravity pulling the water down

The oil (or gas) is the mobile phase and only enters the leftover space in the reservoir pores

Consequently a given part of the pore space within the reservoir will contain both oil and water

The percentage of water in the pore space is called the water saturation (Sw)



Forces Acting on Reservoir Fluids

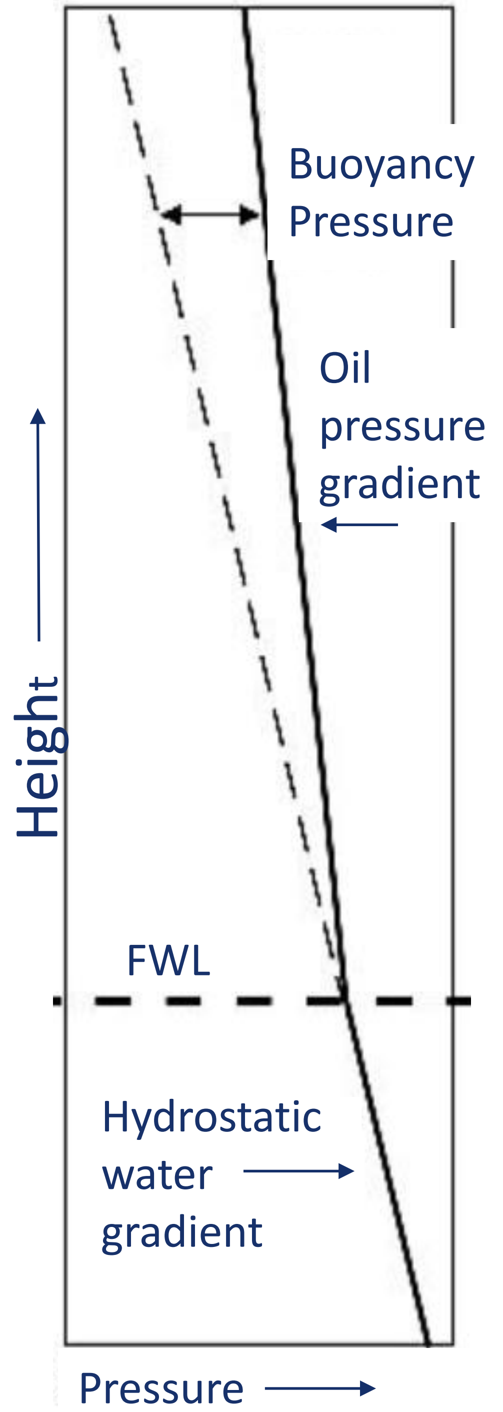
The capillary-bound water comprises a continuous column of water within the oil leg, with a hydrostatic pressure gradient

The oil is located in the remaining pore space also as a continuous phase and will have a lower pressure gradient

Although oil and water can coexist in the same localized volume of rock, the pressures acting on the two fluids are different

The intersection of the pressure gradients indicates the free water level (FWL)

The formation pressure tester only sees the mobile phase

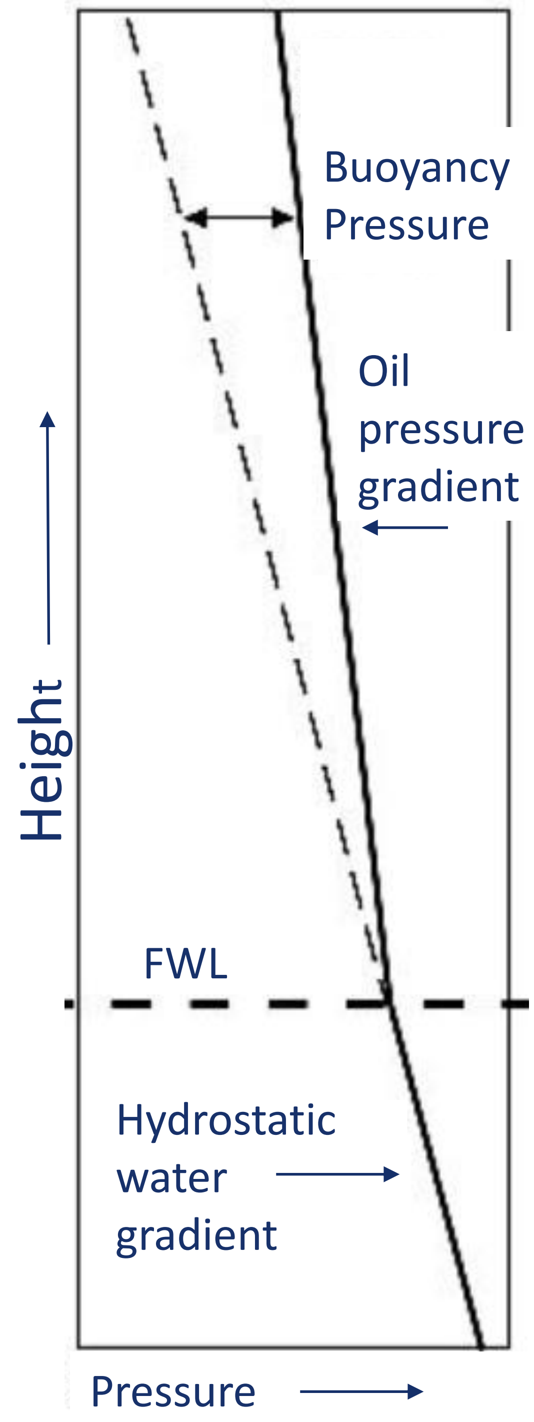


Forces Acting on Reservoir Fluids

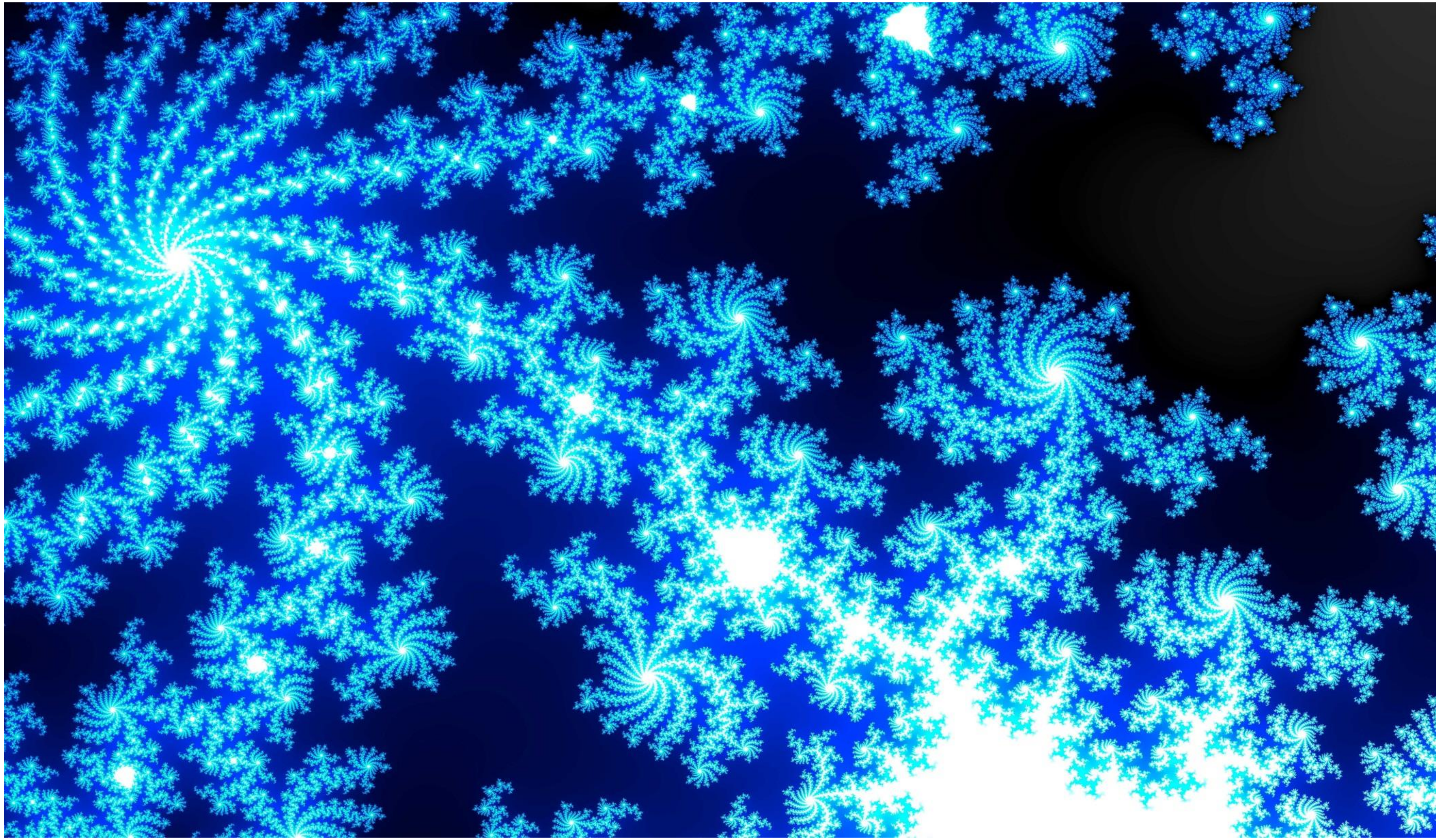
The buoyancy pressure (the difference in pressure between the oil and water phases) increases with height above the FWL

As the buoyancy pressure increases with height above the FWL, the oil phase will displace more water from increasingly smaller pore volumes

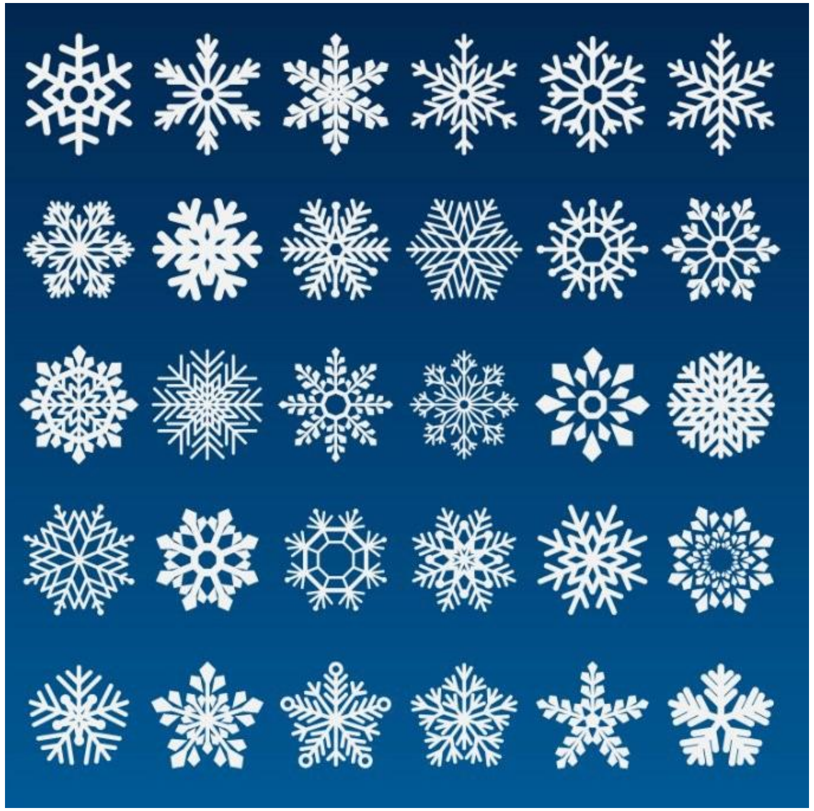
Therefore water saturation will *tend* to decrease with height above the FWL



Why Fractals are very useful in reservoir modelling



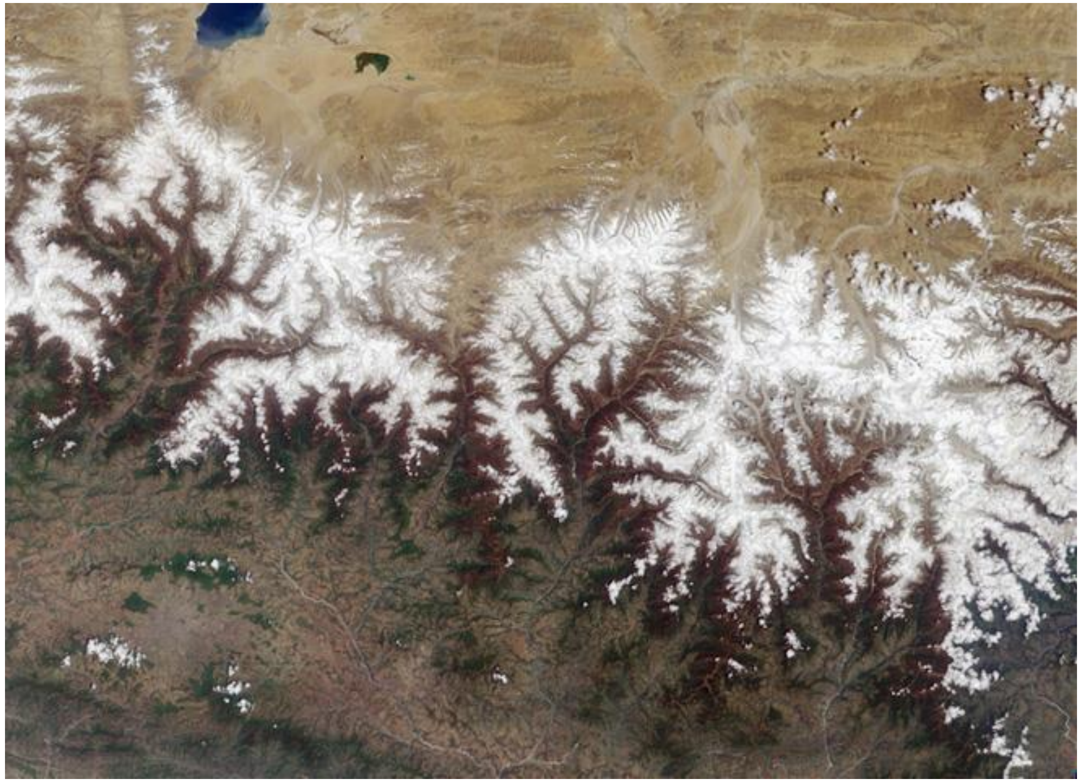
Fractals on the Small Scale



Snowflakes

Roman Cauliflower

Fractals on the Big Scale



Himalayas

River channels

Fractals on the Really Big Scale

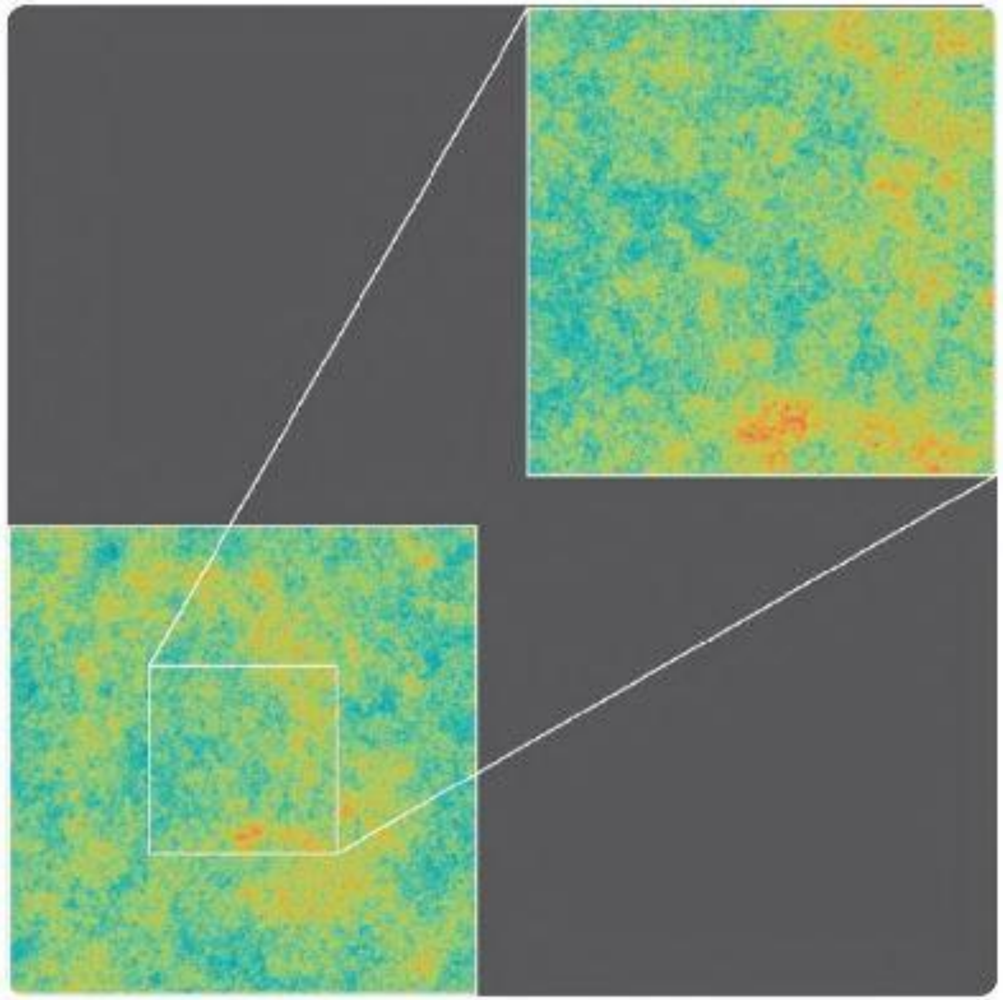
The cosmic microwave background is scale invariant

If we zoom in the patterns are indistinguishable

These patterns give rise to galactic superclusters

Galactic superclusters are built up from galaxies

The universe is fractal



Prof. Brian Cox – ‘Forces of Nature’ 2016

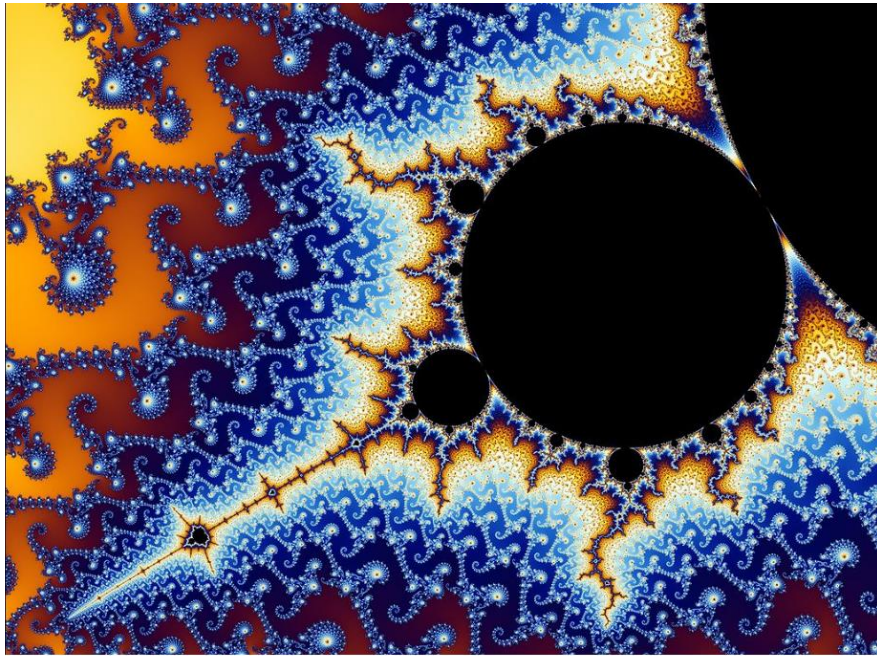
What are Fractals?

A fractal is a never-ending pattern

Fractals are infinitely complex patterns that look the same at every scale

They are created by simple repeating process

e.g. Benoit B. Mandelbrot set →



Other names for fractals are

- Self-similarity
- Scale invariance

Fractals are very useful

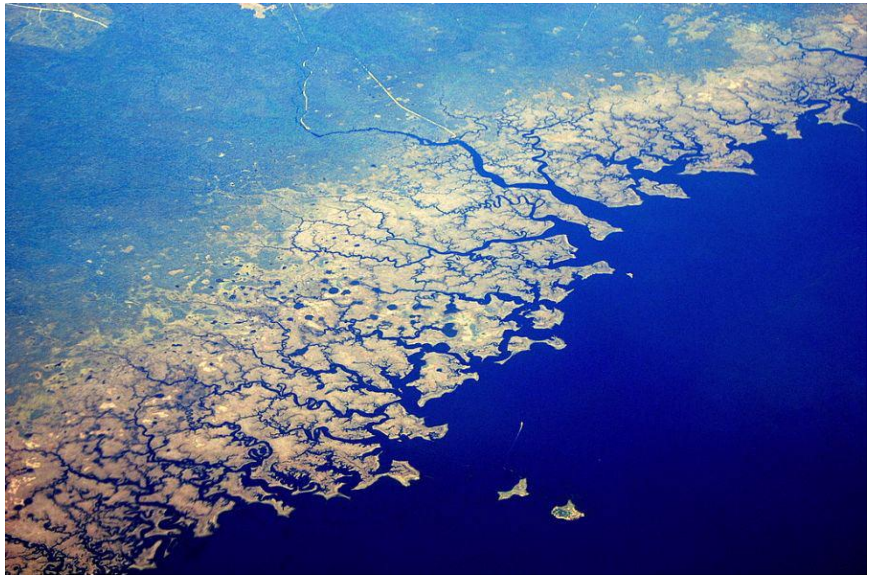
- Fractals are objects where their parts are similar to the whole except for scale
- Nature uses simple repeating processes to create complex plants – like a tree
- Trees look the same close up, as further away

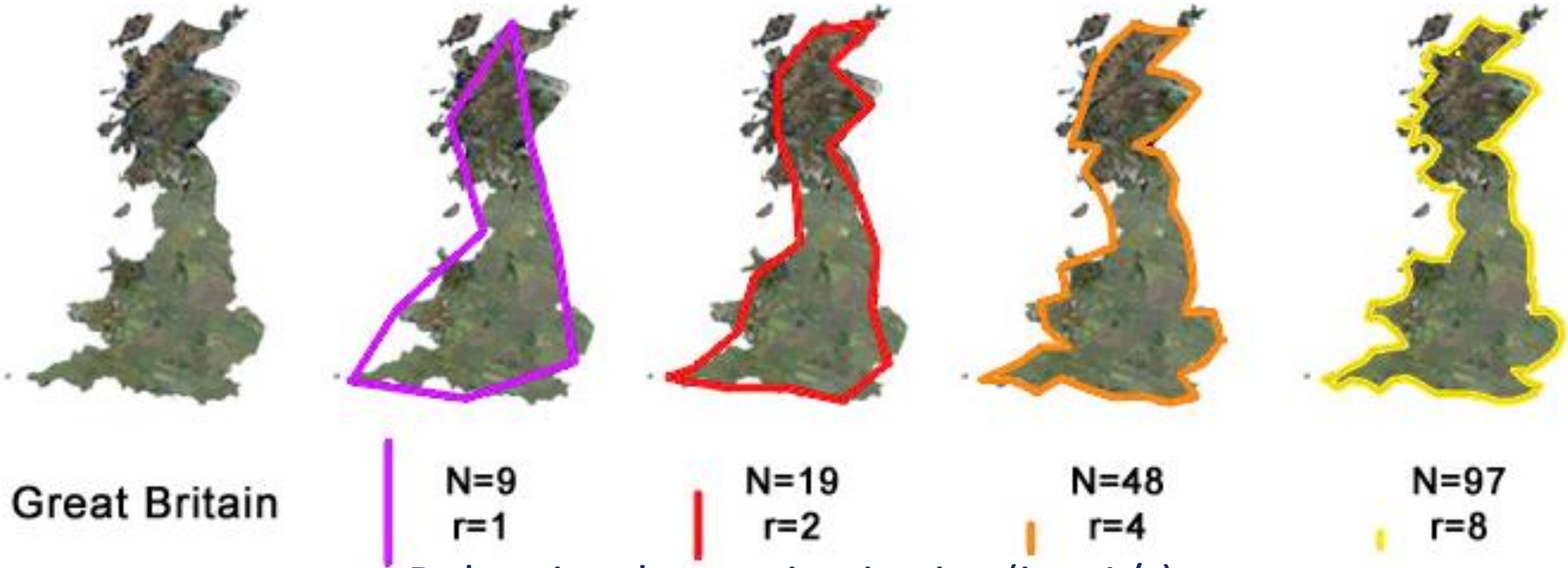
  - twigs, branches and the whole tree
- Many complex objects can be described by fractals
- Fractals are a mathematically simple way of describing complexity
- Including hydrocarbon reservoirs

How to verify if something is fractal

Coastlines show more detail, the closer you zoom in

The length Great Britain's coastline (N) depends on the length of your ruler (r)





North Sea

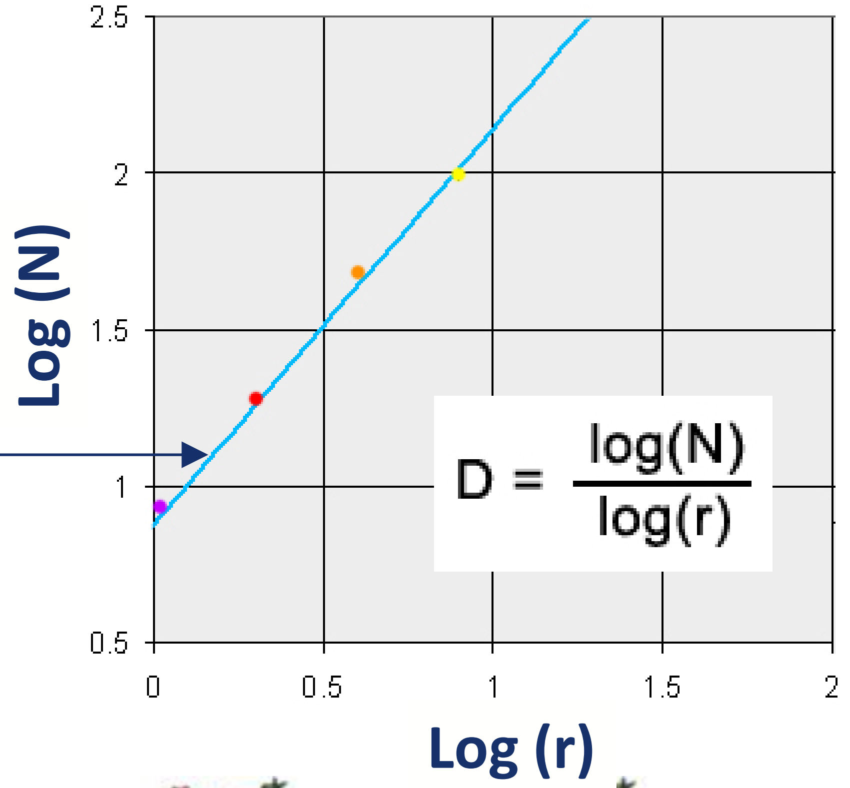
Ruler size decreasing in size (i.e. 1/r)

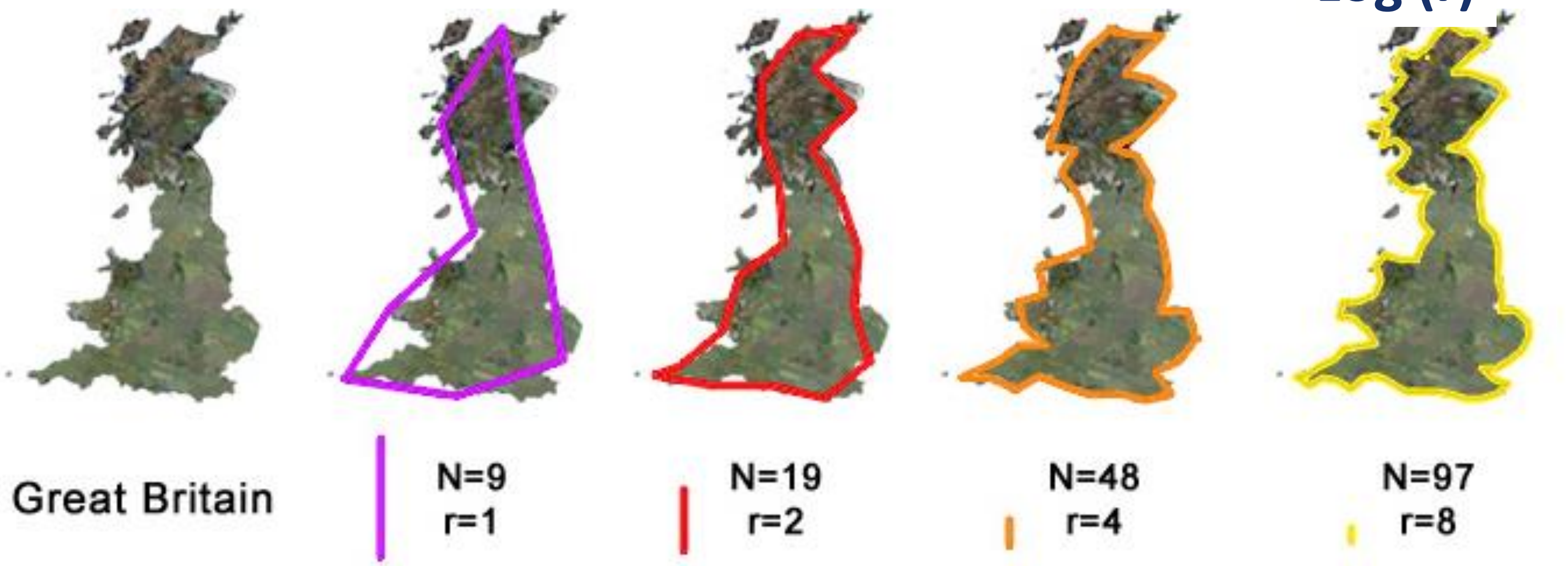
Confirming GB's Coastline is Fractal

As the ruler shrinks the measured coastline increases

The coastline is fractal because the relationship between r and N is linear when plotted on log scales

D = fractal dimension = gradient of the line





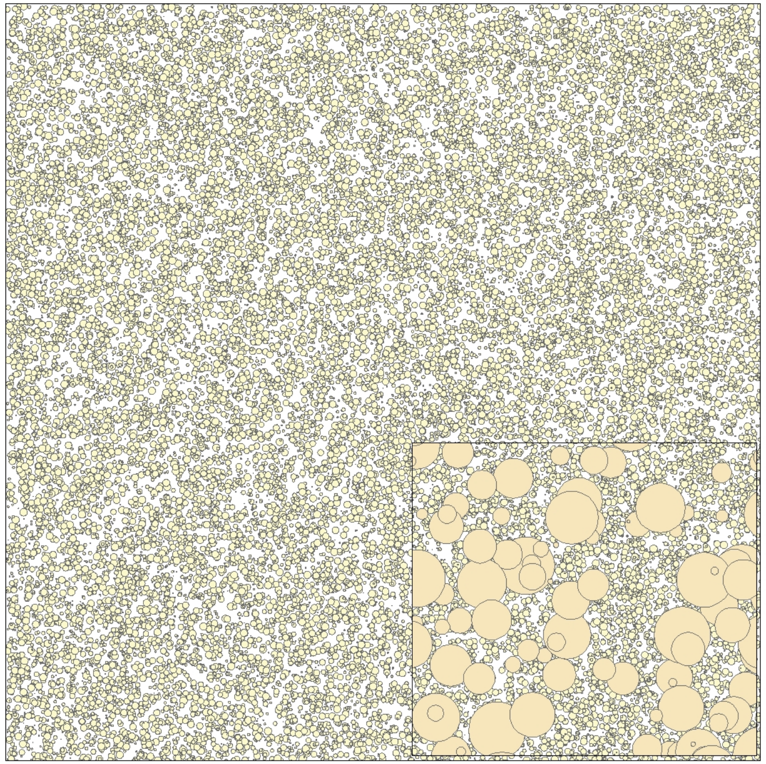
Ruler size decreasing in size (i.e. 1/r) →

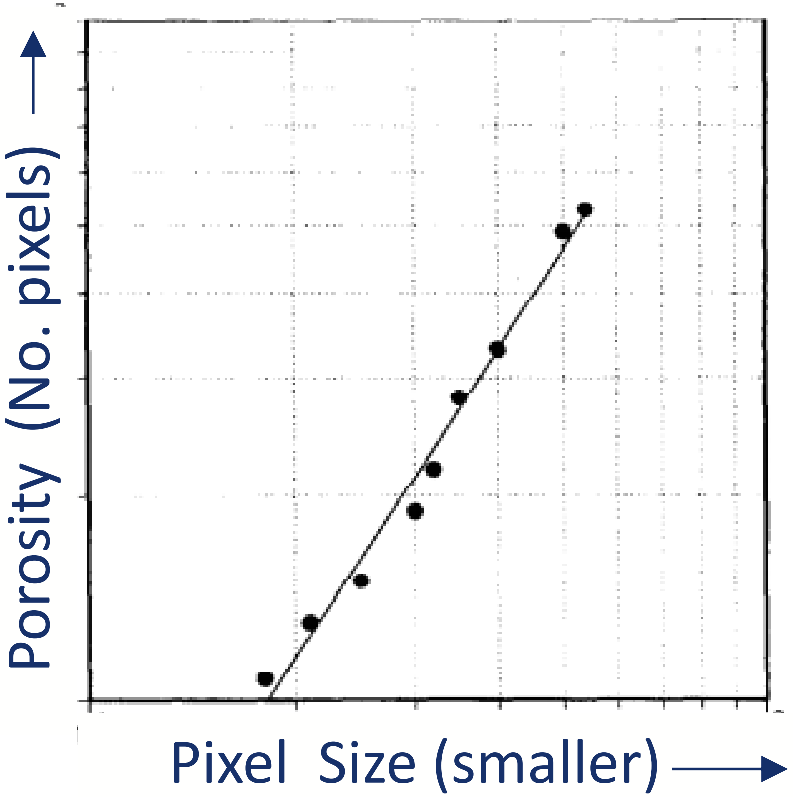
Fractals in reservoir rocks

Thin sections of reservoir rocks are imaged with a scanning electron microscope

For different magnifications the number of pixels representing porosity are counted and plotted as shown

Conclusion - Reservoir rocks are fractal in nature





e.g. Berea Sandstone

Fractals describe the rock pore network

The rock pore space can be described by the fractal formula

$$V = r^{(3-Df)}$$

Where:

V	Pore space in rock volume
r	Radius of the rock capillaries
Df	Fractal dimension (non-integer constant)

Combining with capillary pressure theory gives the BVW Swh function*

$$BVW = aH^b$$

Where:

BVW	Volume of capillary bound water in the rock
H	Height above the free water level
a & *b*	Constants

* SPWLA 58th Annual Symposium "Using Fractals to Determine a Reservoir's Hydrocarbon Distribution" (2017)

Net Reservoir Cut-off

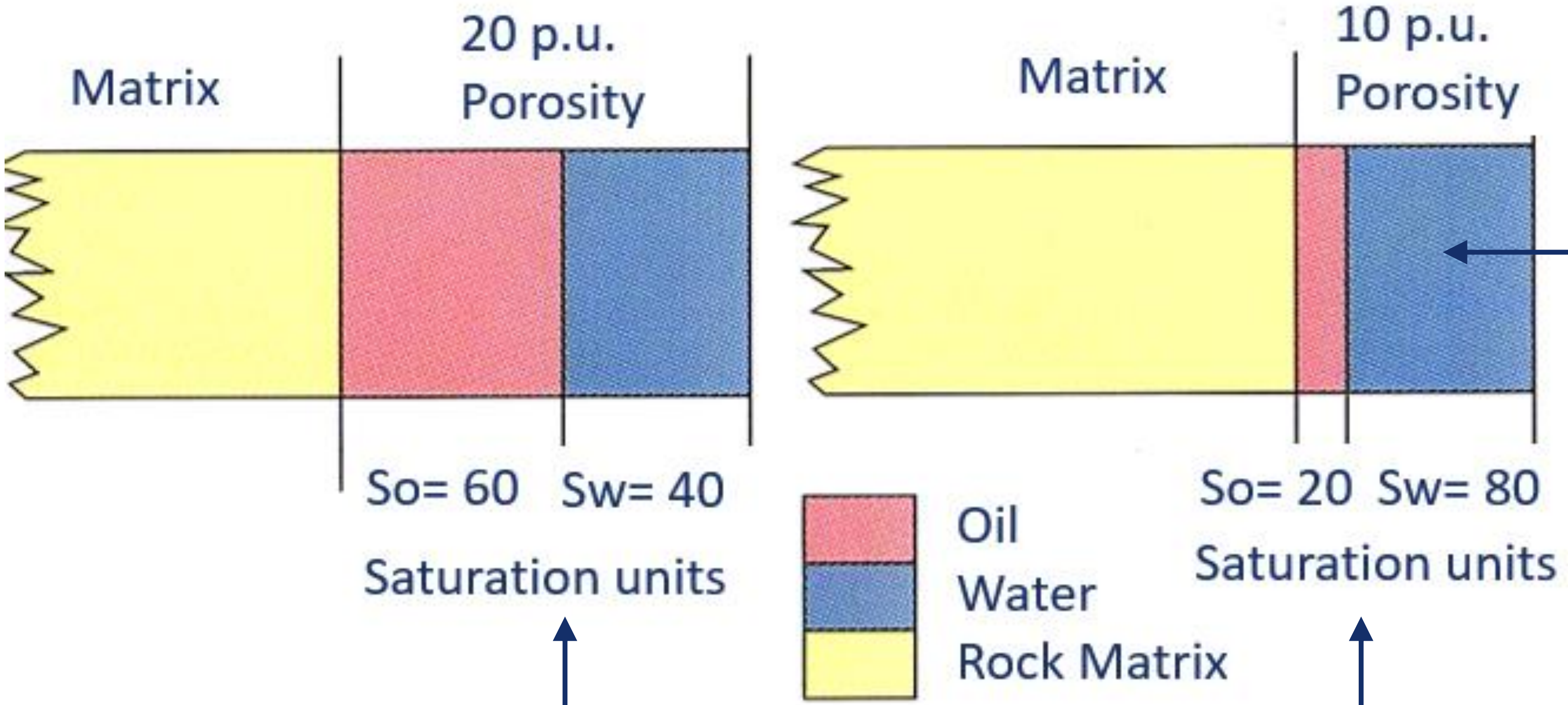
- Required for upscaling reservoir model parameters

- Net Reservoir
  - The portion of reservoir rock which is capable of storing hydrocarbon
  - Relatively easy to pick
  - Usually based on a porosity cutoff

- Net Pay
  - The portion of reservoir rock which will produce commercial quantities of hydrocarbon
  - Often used to select perforation intervals
  - Very difficult to pick
  - Depends on the oil price?

What the BVW function tells us about Net Reservoir

Bulk Volume of Water = Function (Height above the FWL)



BVW is independent of porosity

The BVW function gives the net reservoir cutoff
In this example: porosity > 9 porosity units

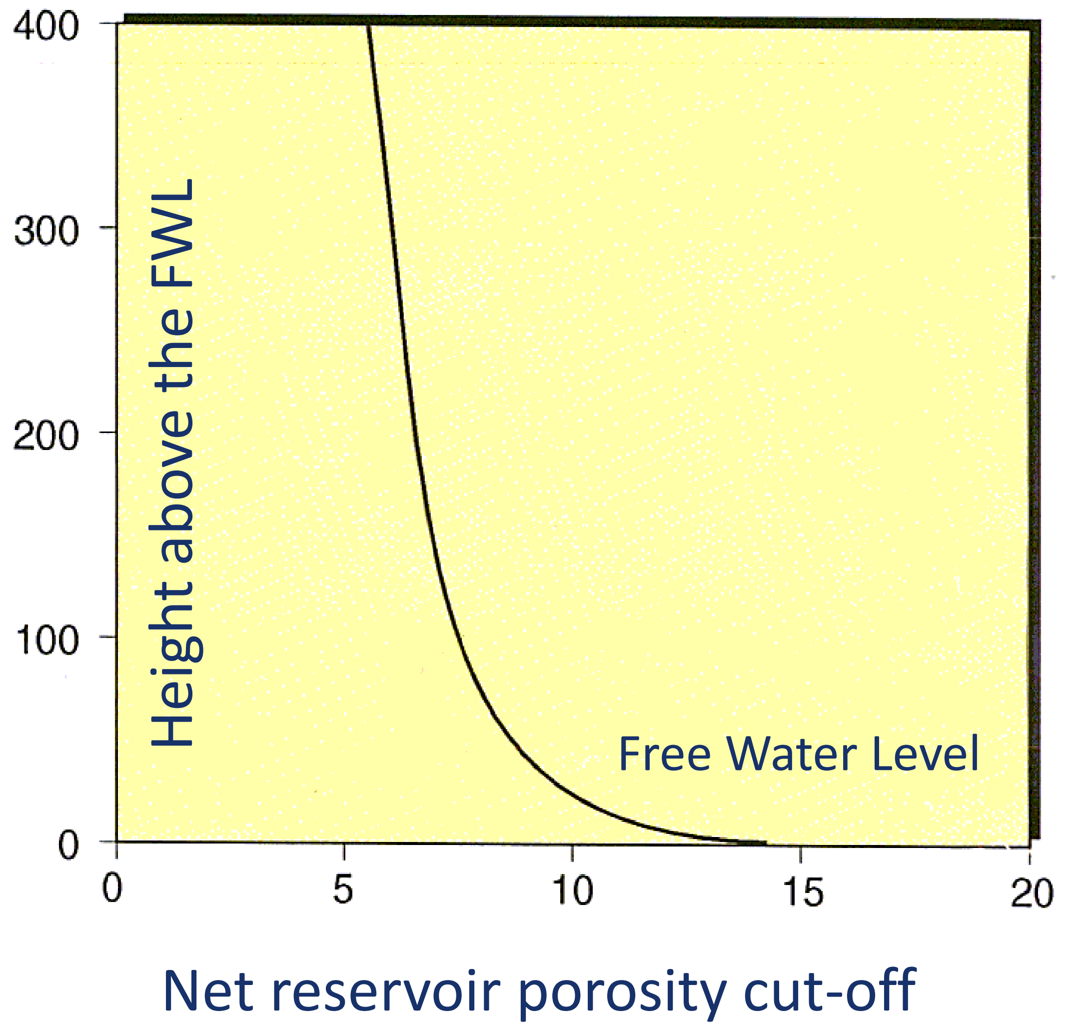
Net Reservoir Cut-off

Net reservoir is defined as the rock capable of holding hydrocarbon

The net cut-off is required for averaging porosity, permeability and water saturations in the reservoir model

The net reservoir cut-off varies as a function of height above the FWL

This is demonstrated in the next slide

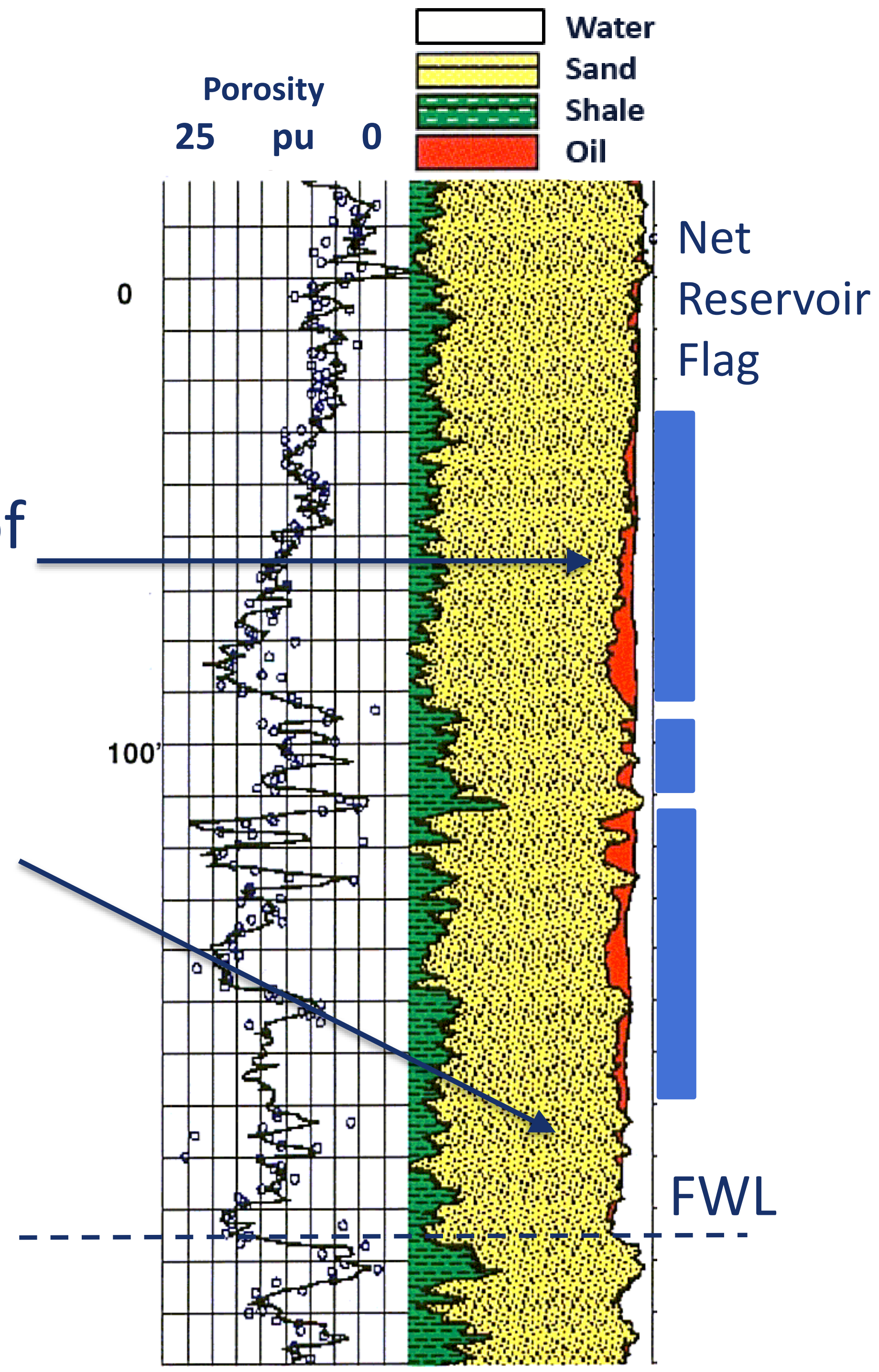


Net Reservoir Example

The Net Reservoir cut-off varies as a function of height above the free water level (FWL)

Reservoir high above the FWL has low saturations of capillary bound water and hydrocarbon enters the smaller pores – These is net reservoir

Reservoir just above the FWL, with higher porosities, contains high saturations of capillary bound water and there is a no room available for hydrocarbons – This is non-net reservoir



The BVW Function is easily calculated

BVW = a H ^{b}

The BVW function is a straight line when plotted on log scales

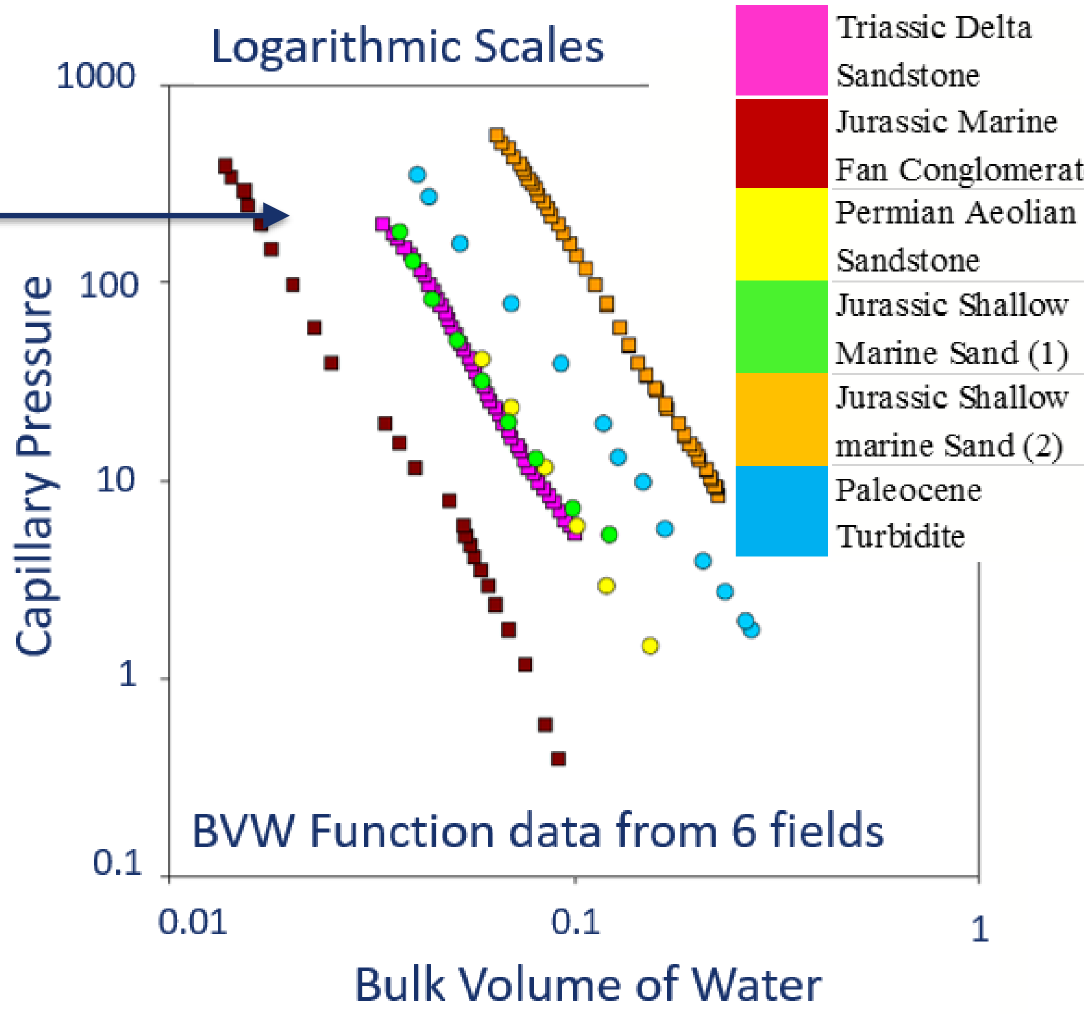
log BVW= log a + b log H

Only 2 valid core or electrical log points required to calculate the constants ‘a’ & ‘b’

Notice that all the gradients (b) are similar

- The gradient is scale invariant

Core Data from 6 different fields



Can we believe the BVW function?

Does the BVW function predict the correct Sw

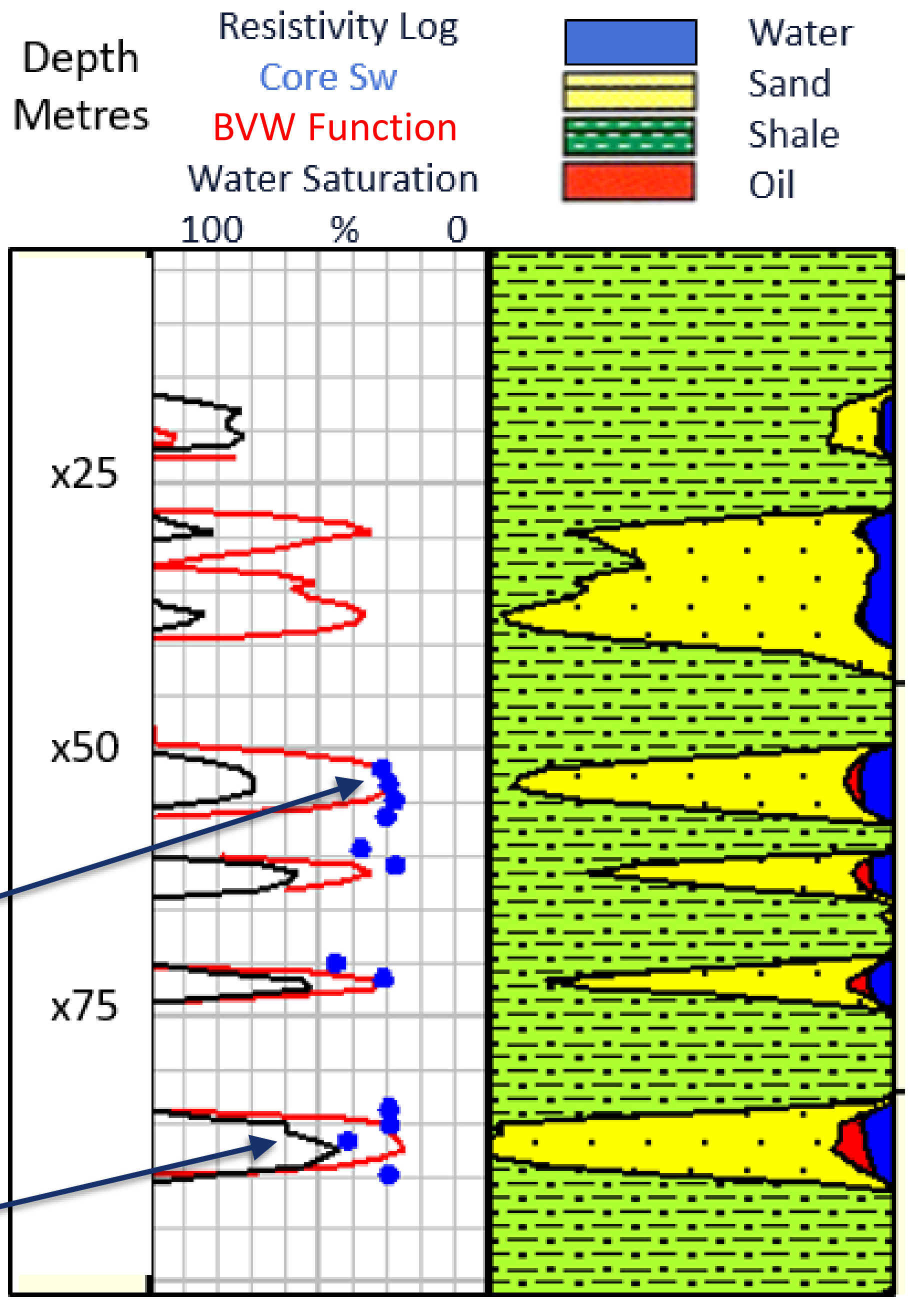
- compare resistivity, BVW function with core

Accurate core water saturations

- Dean & Stark ●
- Well drilled with oil base mud doped to identify any mud filtrate contamination
- Cored above the FWL where the capillary bound water is immobile
- Only cores centres sampled

The core confirms the water saturations determined by BVW function

Resistivity (Archie) Sw too high in thin beds



The Differential Reservoir Model

Comparison between water saturations

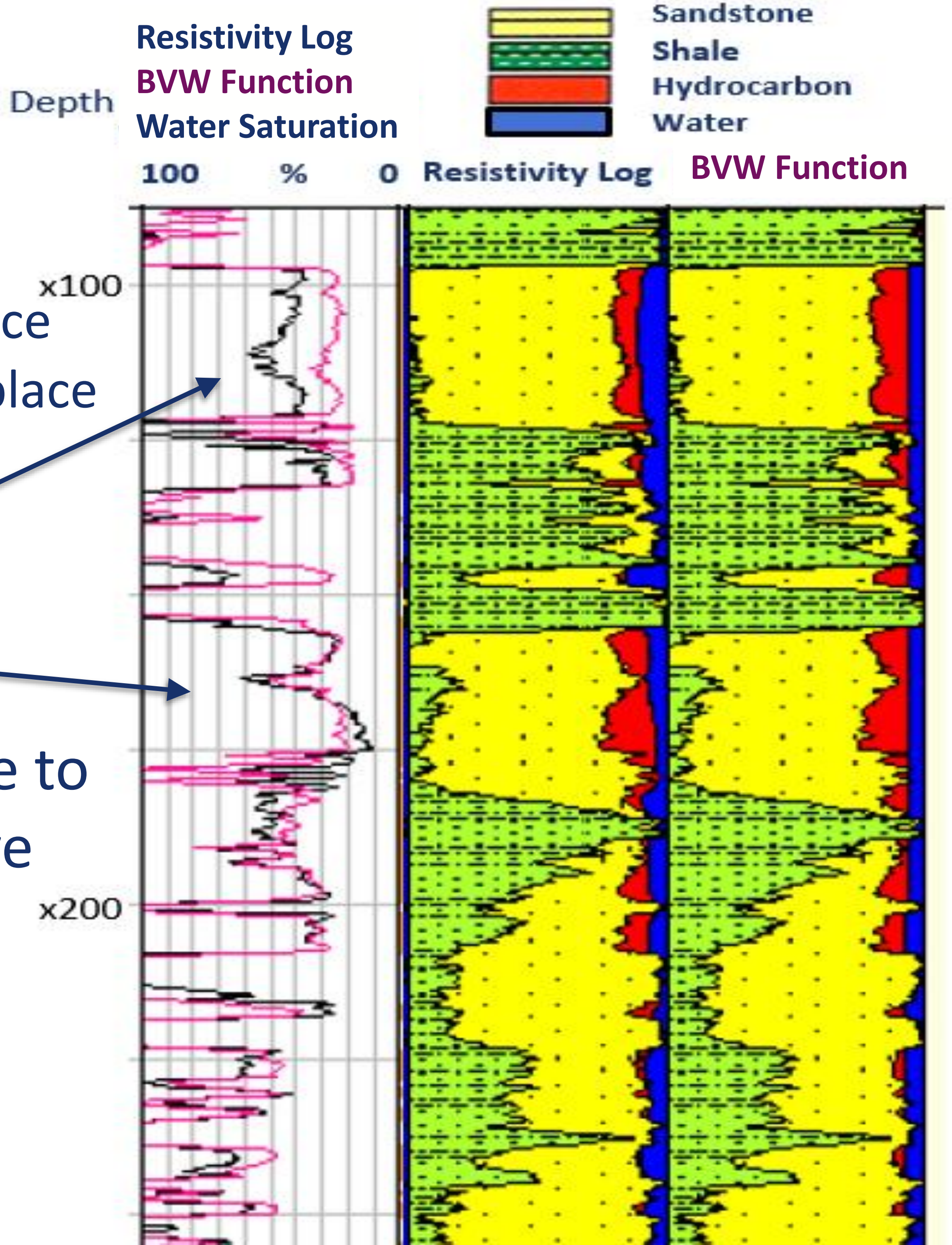
- Resistivity derived Sw represents current oil in place
- BVW function derived Sw represents initial oil in place

Swept zone showing residual oil saturations

Zone with by-passed hydrocarbon

The resistivity log is incorrect in thin beds, close to bed boundaries and where there are conductive shales

The BVW function ignores thin beds, bed boundaries and shales



Picking the Free Water Level

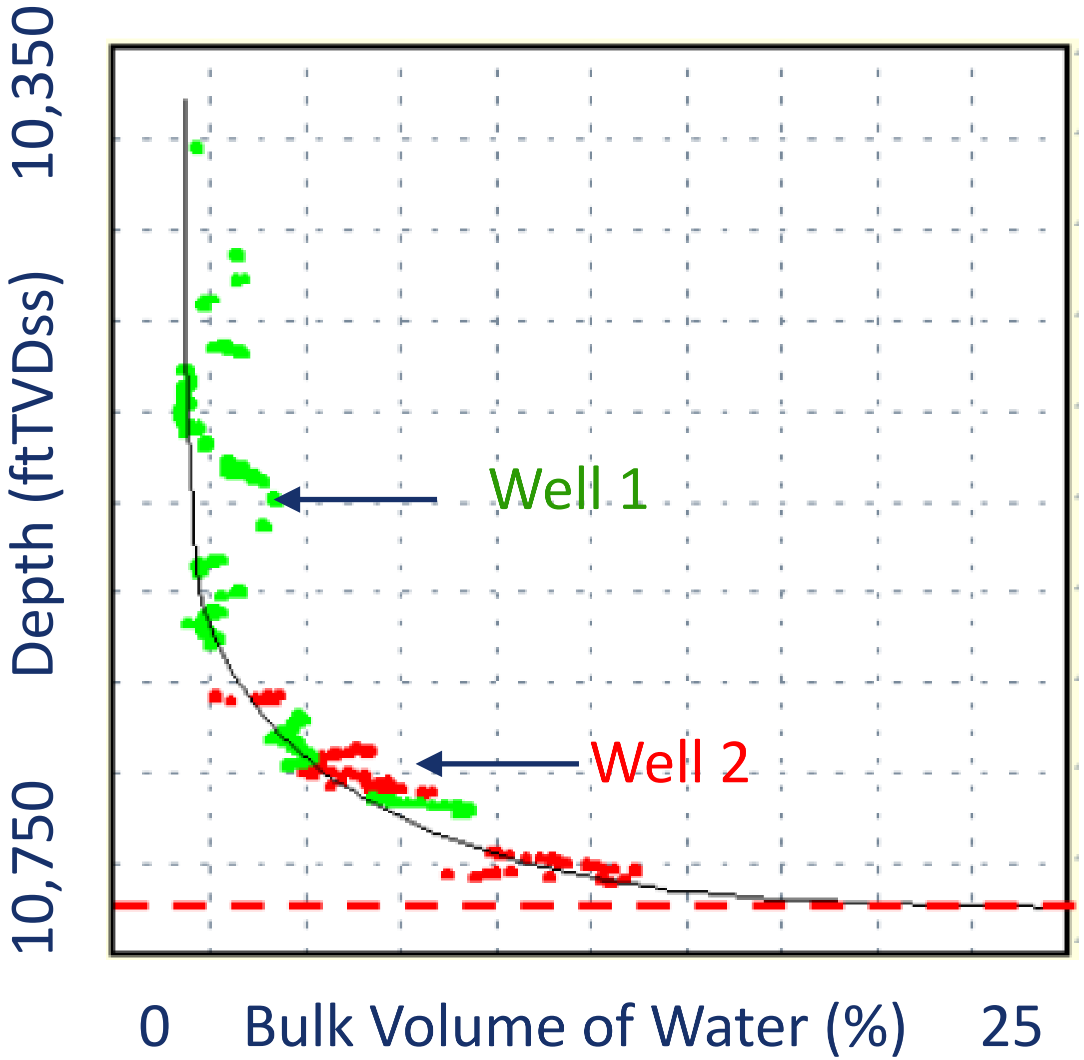
Case Study - North Sea Oil Field

Two wells that don't intercept the FWL

BVW ignores the porosity and permeability variability

BVW trend identifies the FWL and confirms the wells are probably in the same compartment

FWL=10,730 ftTVDss



Using the BVW Function to Identify the Hydrocarbon to Water Contact

$$Sw = \frac{Bulk\ volume\ of\ water}{Porosity}$$

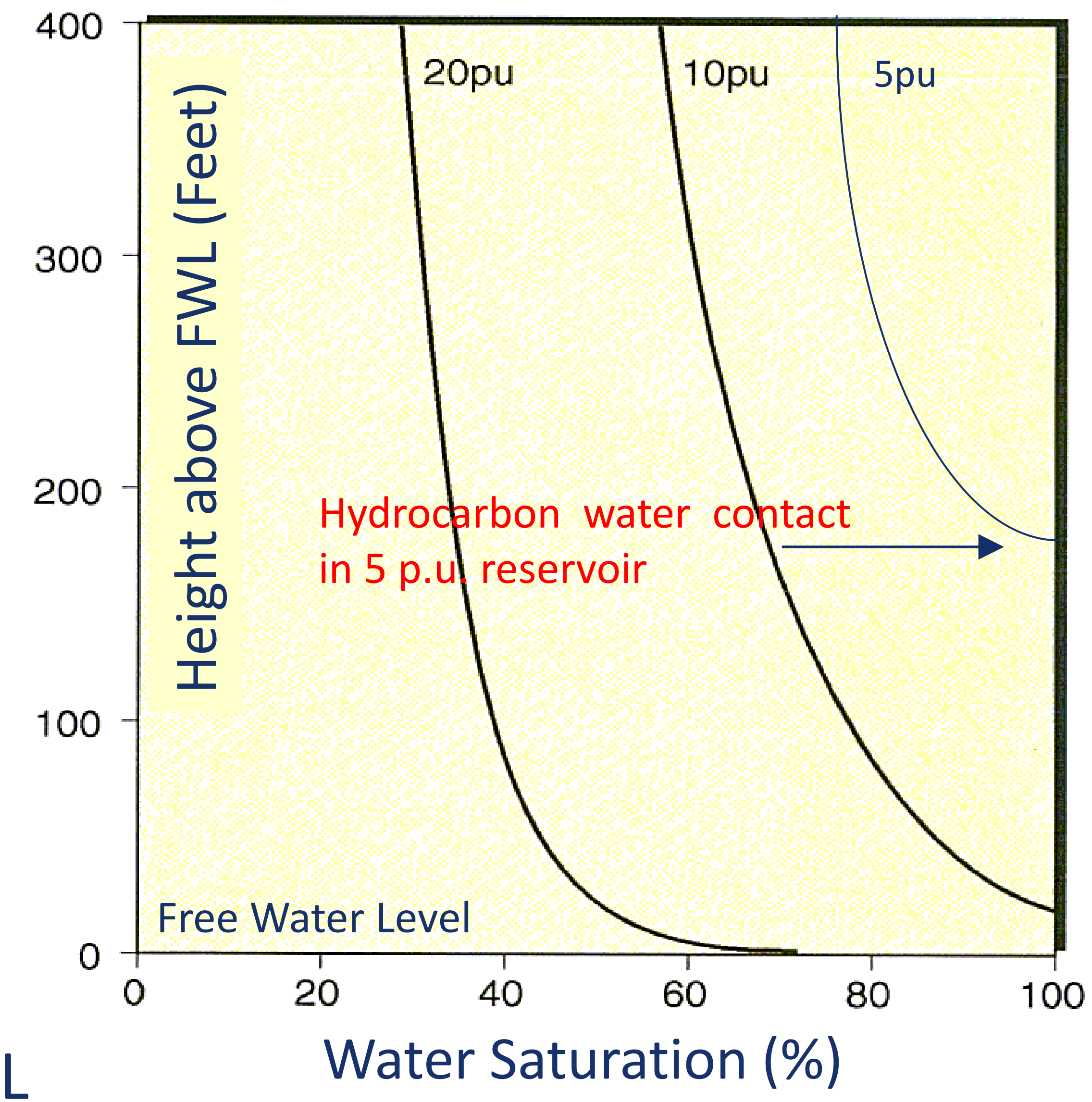
$$Sw = \frac{aH^b}{Porosity}$$

Where:

H = Height above FWL

a, b = Constants

- Single BVW function splits into multiple SWH functions
- The BVW function gives the hydrocarbon water contact as a function of porosity
- Low porosity formation is fully water saturated hundreds of feet above the FWL



Using the BVW Function for Depth control

Depth is the most important measurement

True vertical depth subsea can be +/- 30 feet

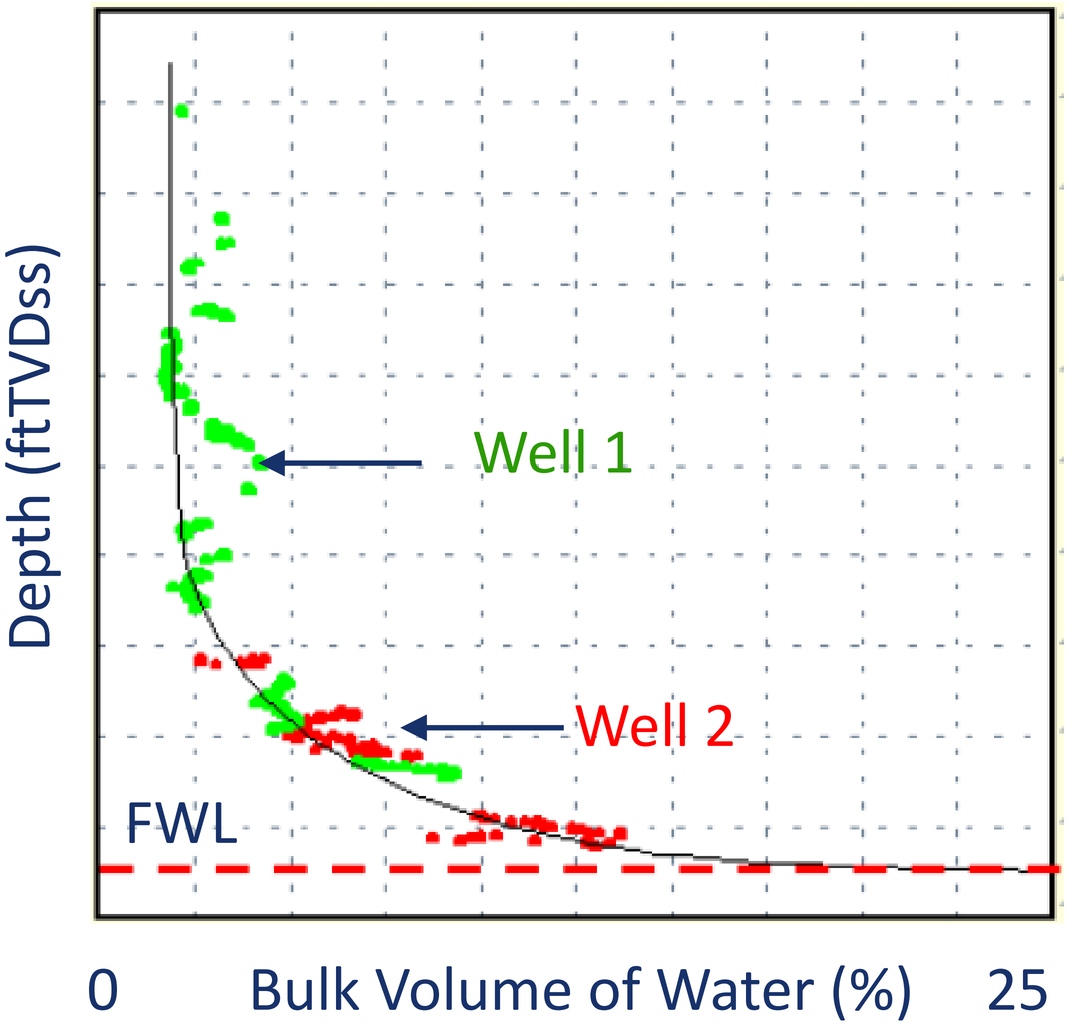
- due to survey errors
- depth measurement errors

The FWL can normalise the field's well depths

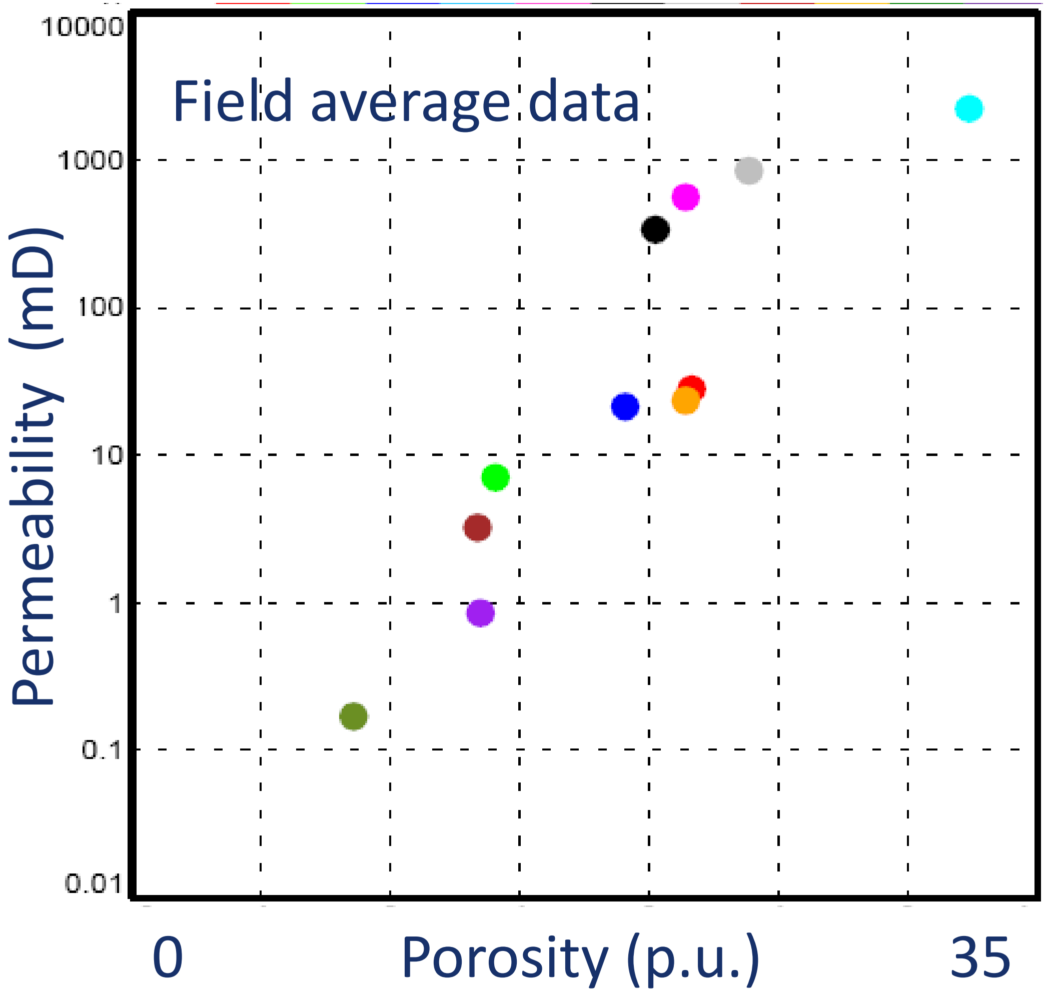
- if the wells are in the same compartment

Recent case study

- Recalibration of well depths based on the FWL changed a field's equity between two oil companies by 3%



Log and core data from 11 North Sea fields compared



Field	Fluid	Type	Porosity (pu)	Perm (mD)
	Gas	Permian Fluvial	9	0.2
	Oil	M. Jurassic Deltaic	13	3
	Oil	Devonian Lacustrine	14	7
	Gas	Permian Aeolian	14	0.9
	Oil	Palaeocene Turbidite	20	21
	Gas	Permian Aeolian	20	341
	Gas Condensate	L. Cretaceous Turbidite	24	847
	Oil	U. Jurassic Turbidite	21	570
	Oil	Palaeocene Turbidite	21	24
	Oil	Palaeocene Turbidite	22	27
	Gas	Palaeocene Turbidite	32	2207

Field Comparison Results

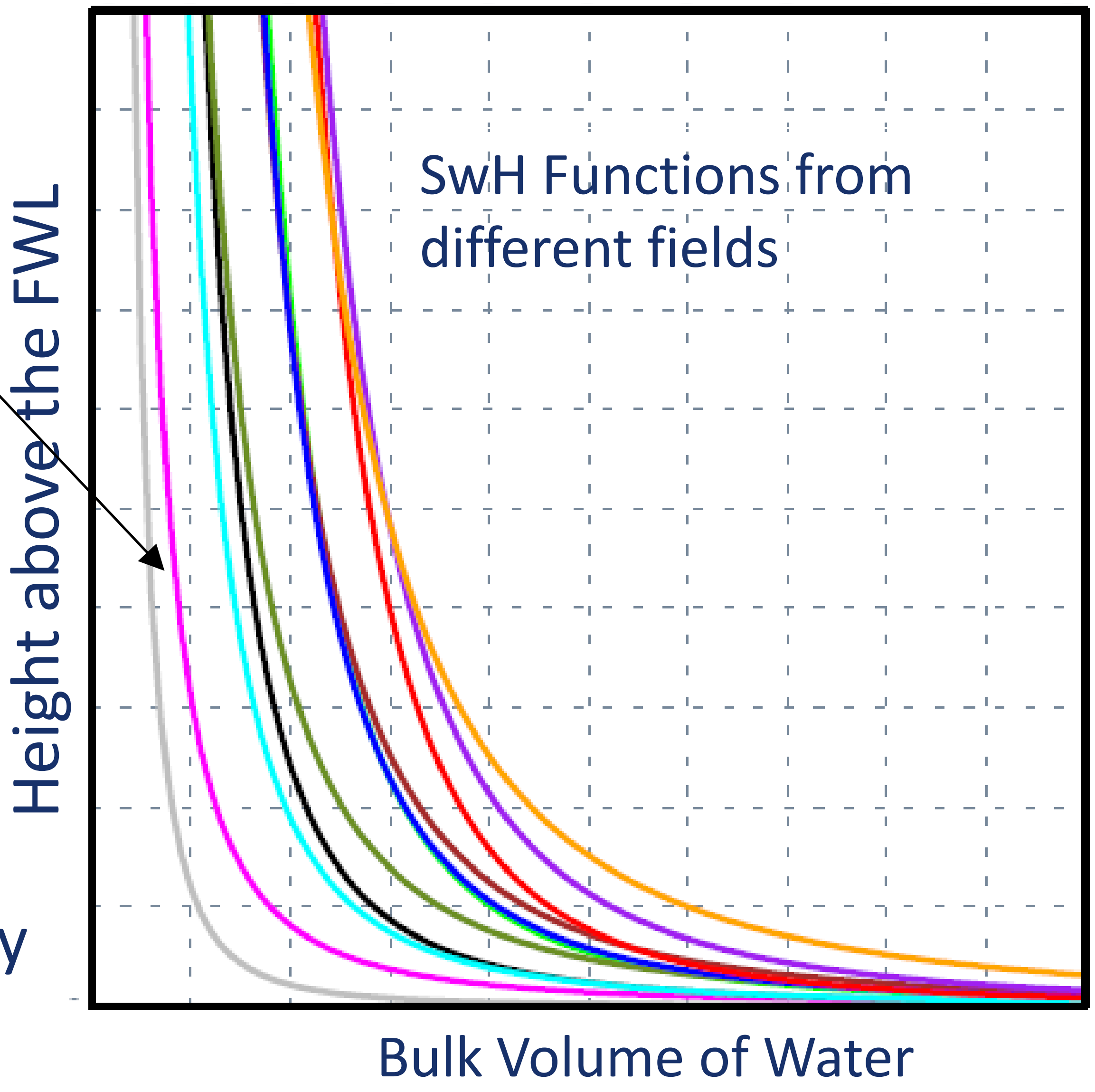
Transition zones compared

The best transition zones are on the left

- Lowest Sw for the same porosity

The shape of the transition zone is related to pore geometry rather than porosity or permeability alone

BVW Functions quantify the pore geometry

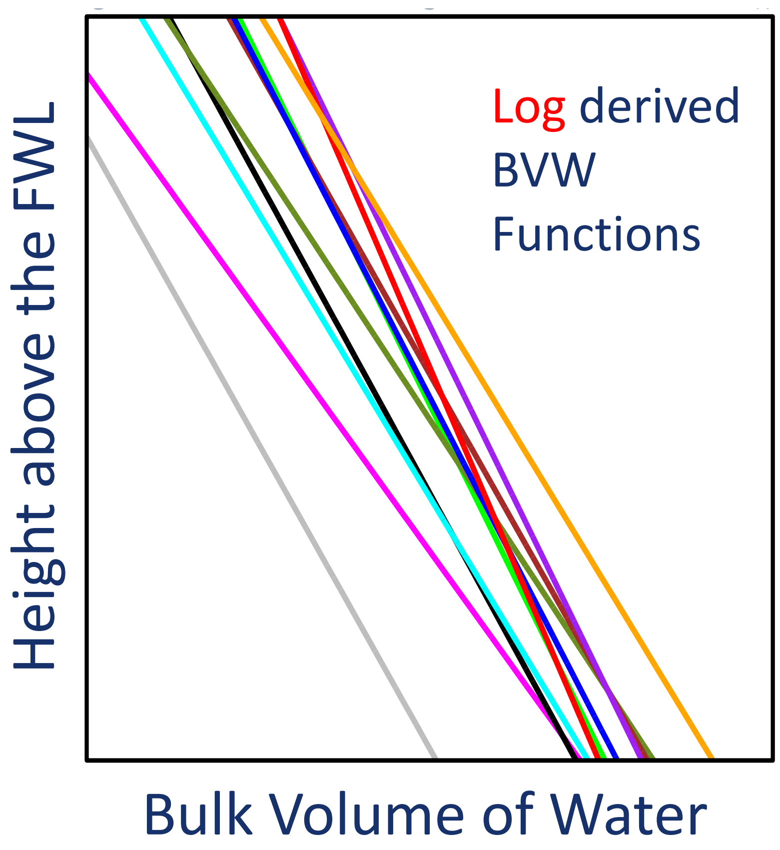


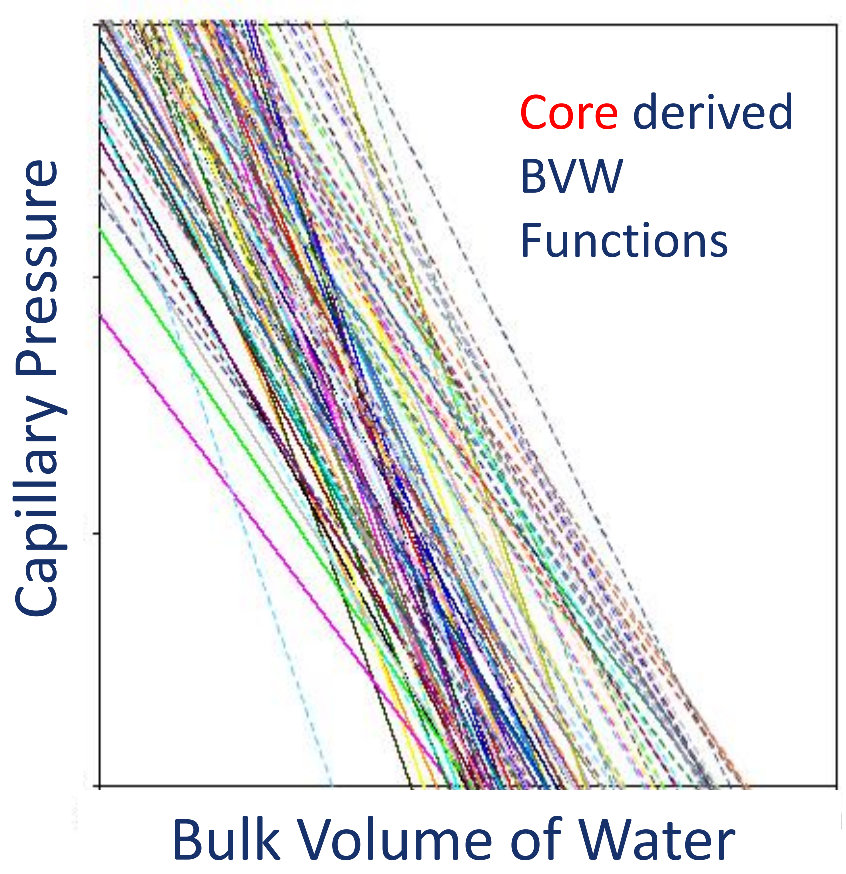
Comparison between Log and Core BVW Functions

The BVW Water Saturation vs. Height Function is linear on log-log scales

Electrical log and core functions are the same irrespective to whether they were determined from logs or core data

This confirms the fractal distribution of reservoir capillaries





Colour represents field as shown in previous key

Gradients are the same irrespective of scale

Log and core **Quality Control** each other

Upscaling Water Saturations

Sw-Height functions (SWHF) are needed to initialize the 3D reservoir model

It is essential that the SWHF predicted water saturations upscale accurately

- from ½ foot to the cell size of the reservoir model

This is done by integrating the Sw-Height function

- average Sw, unlike porosity, must be pore volume weighted

$$\overline{Sw} = \frac{\left(\overline{\Phi_1 Sw_1} + \overline{\Phi_2 Sw_2}\right)}{\left(\overline{\Phi}_1 + \overline{\Phi}_2\right)}$$

$\overline{Sw}$ = average Water Saturation

$\overline{\Phi}$ = average Porosity

$\overline{\Phi Sw}$ = average Bulk Volume of Water

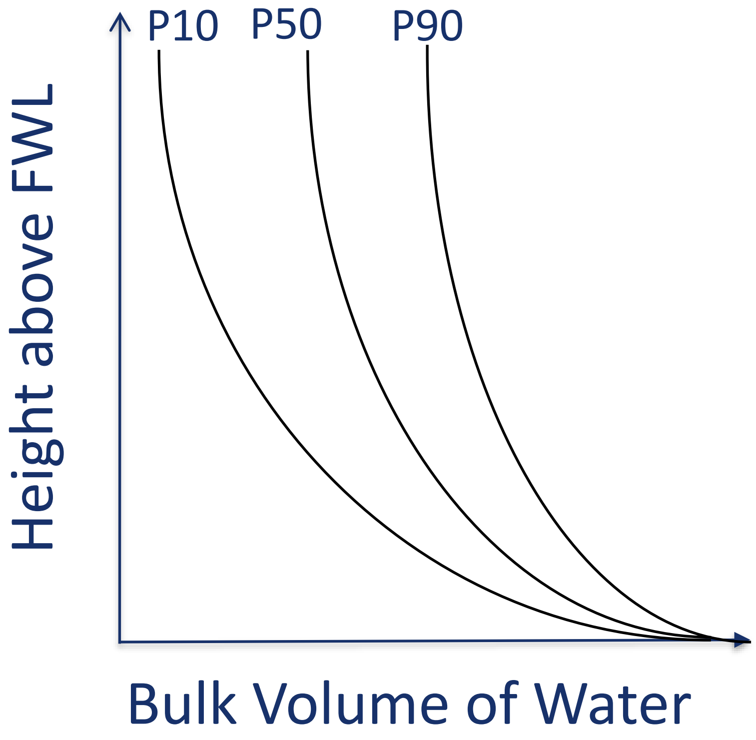
"A function that predicts *BVW* from height is especially appropriate to this application" Paul Worthington

Uncertainty Modelling

Partial differentiation of the saturation equation allows us the derive the upside (P10) downside (P90) and most likely (P50) BVW functions

These includes the uncertainty in porosity, Rt, Rw, m, n etc.

These are used to calculate upside and downside volumes of hydrocarbon in place in the reservoir model

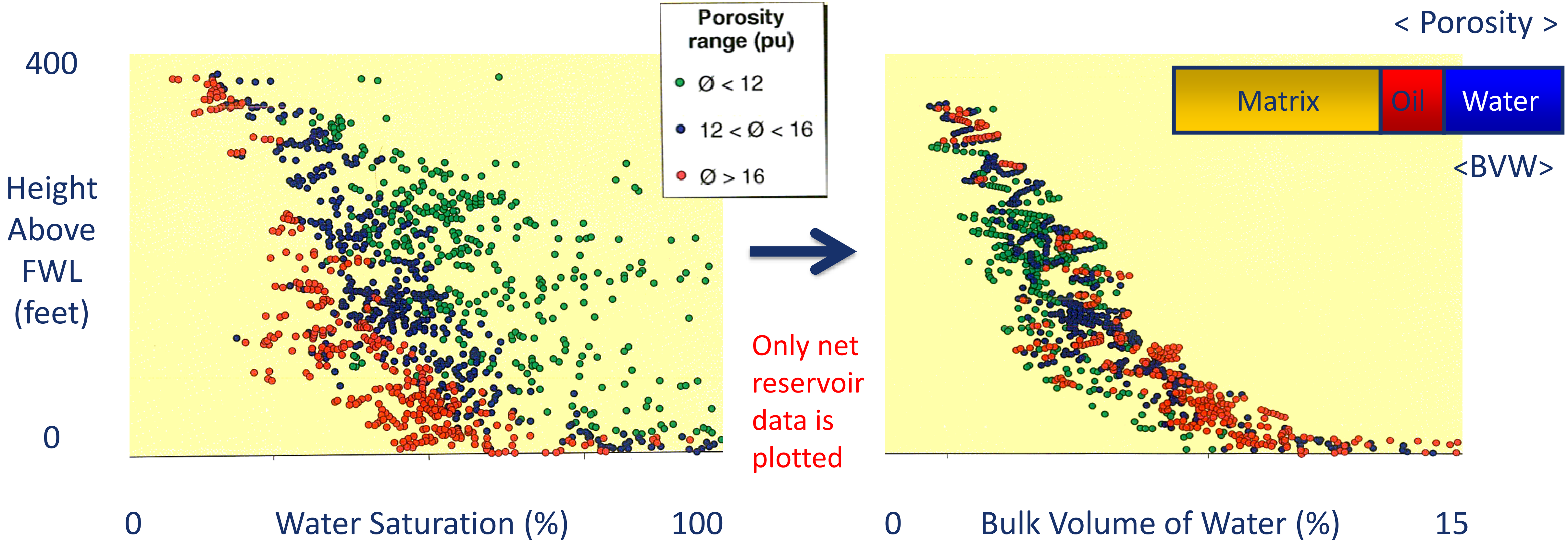


Conclusions

- BVW SWHF function derived from the fractal nature of reservoir rocks
- Can be derived from electrical logs or core data
  - Using simple linear regression of a log-log plot (only net data plotted)
  - Logs and core give the same function. Consequently they QC each other
  - This confirms fractal distribution of reservoir capillaries
- Defines the Net Reservoir Cut-off and the shape of the Transition Zone
- Determines Free Water Level and Hydrocarbon Water Contact
- Independent of rock characteristics
  - Facies type, porosity and permeability
  - You can forget about thin beds, bed boundary effects and shaliness
- Simple implementation in your reservoir model

Key Conclusion

- Forget water saturation
- Think Bulk Volume of Water



A Simple and Convincing Water Saturation vs. Height Function for Reservoir Modelling & Simulation*

Questions?

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