[AV]Prolific Gas Production from Low-Permeability Sandstone Reservoirs - Part II: Reconciling Basin History, Fluid Saturations, Gas Shows, and Capillary Pressure*

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Abstract

In many tight gas basins of the western USA, gas productive and non-productive sandstones are difficult to distinguish. Gas shows, calculated water saturations, and saturation-height profiles all appear similar, capillary pressure derived height functions are difficult to apply, and classic rock-typing procedures lack predictive capability.

Basin analysis of several Rocky Mountain basins in which low-permeability sandstone reservoirs produce gas suggests that hydrocarbon charge and migration occurred well in advance of maximum burial and uplift. Furthermore, these same models indicate that reservoir porosity and permeability were significantly greater than values commonly found today. We suggest that at the time of gas charge reservoir capillary pressure curves were characterized by lower displacement pressures. During burial, continued decreases in porosity and permeability caused both water saturations and gas column heights to increase. Upon uplift, gas accumulations either spilled or structurally readjusted resulting in capillary imbibition and, in some cases, secondary drainage then imbibition. Within trapped accumulations, gas expansion upon uplift also resulted in increased gas column heights.

We suggest the basin history of these low-permeability sandstones resulted in many non-productive sandstones being at, or near, residual saturations whereas many productive sandstones follow a capillary imbibition or secondary drainage-imbibition profile. Because of the complex pore geometry that characterizes many low-permeability sandstones, residual, or trapped gas, saturations fall within a similar range as the water saturations of the gas productive sandstones making the two difficult to distinguish. The lack of significant observable variation in saturation-height is a reflection of the imbibition or secondary drainage trend.

Conventional petrophysical evaluation is fundamentally based on drainage capillary principles. Low-permeability reservoirs that have experienced late uplift following an earlier phase of charge are unlikely to be characterized by capillary drainage and are more likely to be characterized by imbibition or secondary drainage and possibly imbibition.

Prolific Gas Production from Low Permeability Sandstone Reservoirs – Part II

Reconciling Basin History, Saturations, and Shows

Keith W. Shanley
Robert M. Cluff
John W. Robinson

AAPG Long Beach, April 2007

Overview

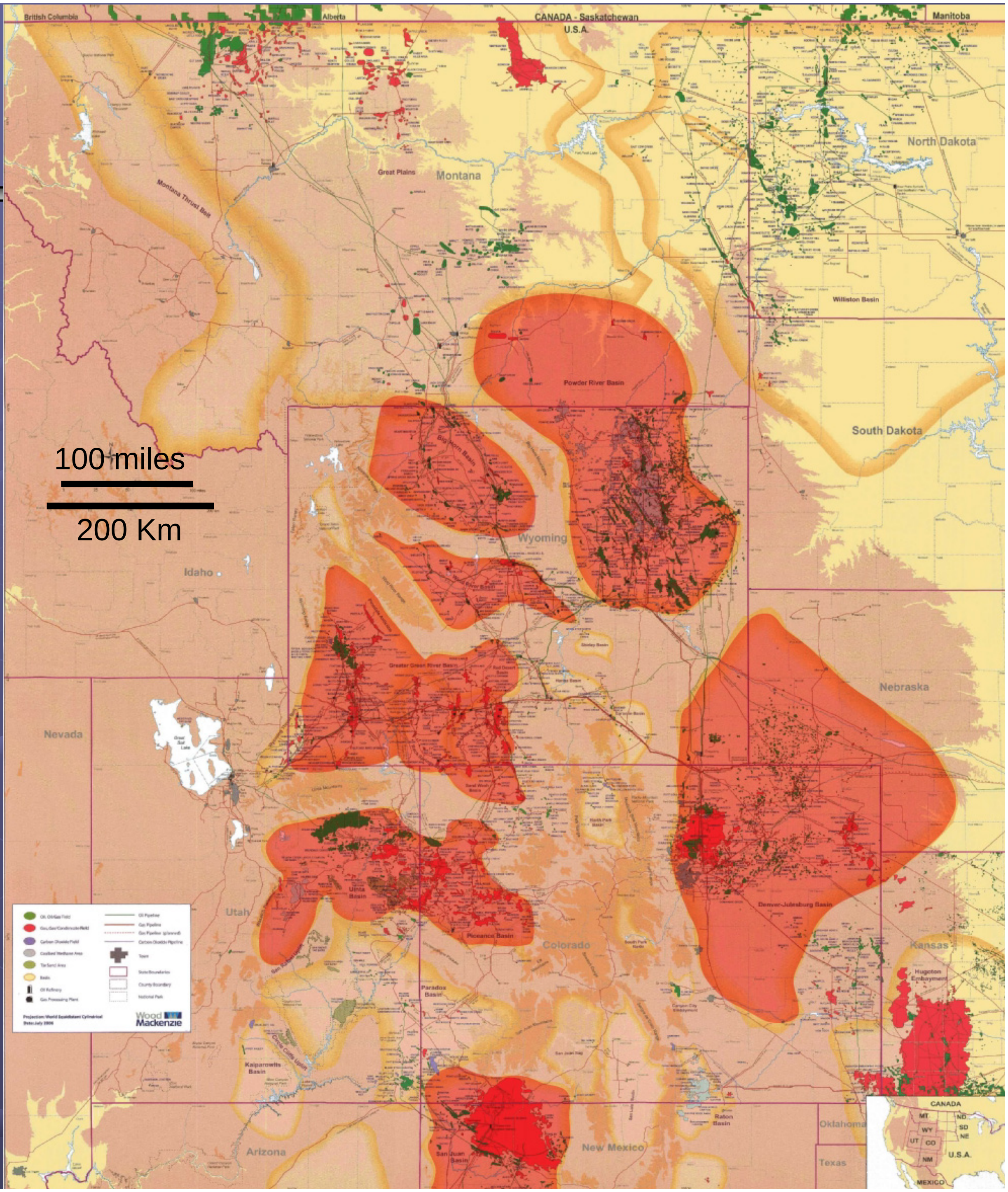
- Earlier (Part I) work focused on prolific fields (> 50 bcfe)
  - Conventional aspects of tight-gas accumulations and the importance of traps.
  - Considered consequences for risk – resource appraisals, etc.
  - Unconventional aspects concerned stress effects and multi-phase flow in low-permeability reservoirs.
    - Expanded the concept of 'permeability jail' in tight reservoirs.

- <u>Today (Part II)</u> - present a dynamic view of tight-gas
  - Incorporate & discuss
    - Burial history & HC generation
    - Implications for gas-column evolution.
    - The cause of widespread shows outside of defined traps.
    - The impact of basin-history on petrophysical 'evolution', etc.

Tight-gas basins Western USA

- Our work focuses on the Greater Green River Basin, southwest Wyoming

- Observations and conclusions applicable to other tight-gas basins in the USA and in western Canada.



Modified from Wood Mackenzie Map, 2006

Up-front conclusions

- Many tight-gas basins of western North America are characterized by -
  - early gas charge (approx. 45 - 60 Ma)
  - late structural uplift and re-organization (approx. 5 - 7 Ma).

- At the time of HC charge, many reservoirs were not tight-gas sandstones.
  - Reservoirs charged before maximum burial depth.
  - Porosity: 2x or more, what we find today.
  - Permeability: 10x – 1,000x what we find today.

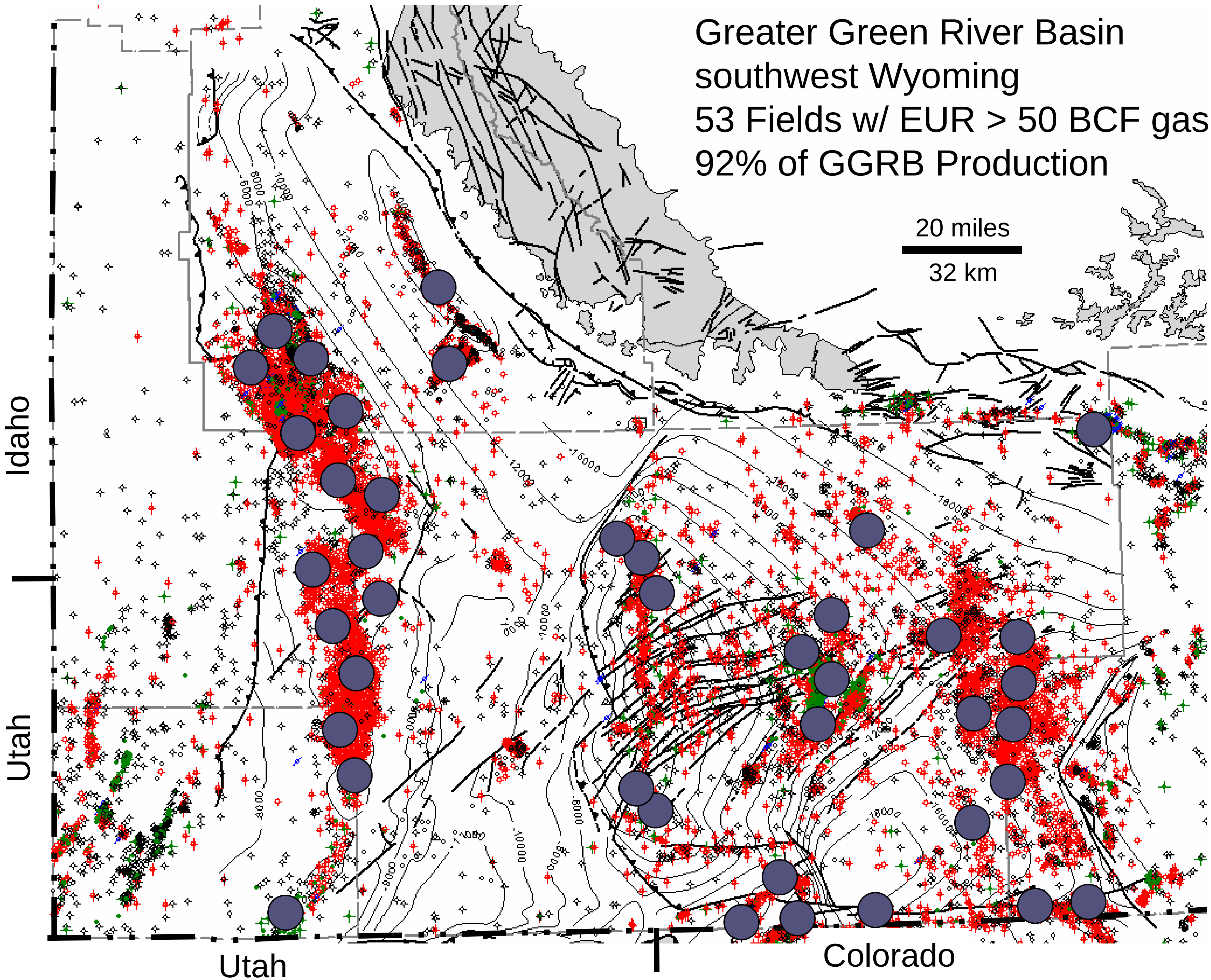
- During burial - pore-volume decreased, reservoirs became tight-gas sandstones, & many gas columns increased thickness.

- During uplift – gas columns adjusted to uplift & increased, some traps spilled, many capillary systems departed from primary drainage to imbibition (or 2^{o} drainage/imbibition)

So what?

- Large areas within tight-gas basins at residual, or near residual gas saturation.
    - Residual saturation ranges between 30 – 70% Sw
    - Distinguishing residual (non-producible) from ‘pay’ is very difficult.
- Many (most?) reservoirs not in primary drainage equilibrium
    - big challenge for petrophysical analysis –
        - Petrophysics largely based on primary drainage equilibrium.
        - Saturation vs height not applicable.
        - Rock-typing difficult as predictive tool.

- This dynamic view explains
    - Widespread gas shows yet difficulty establishing production.
    - Difficulty relating performance to Sw
    - Success of ‘late traps’
- Renewed emphasis on elements of petroleum system, in particular trap evolution & geometry and gas re-migration.

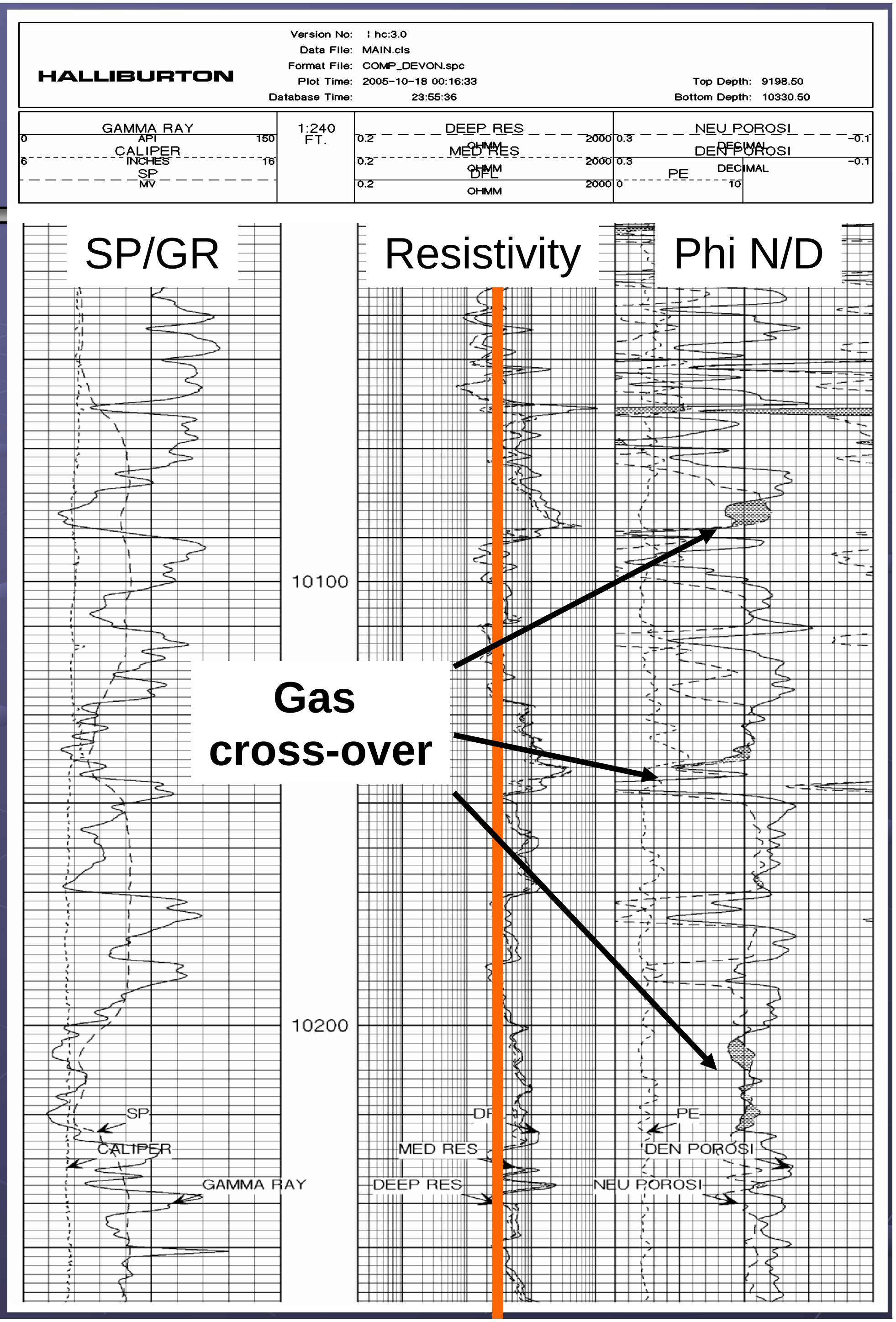

Greater Green River Basin
southwest Wyoming
53 Fields w/ EUR > 50 BCF gas
92% of GGRB Production
20 miles
32 km
Idaho
Utah
Utah
Colorado

Green River Basin

typical tight gas well

- Ericson Interval
  - Widespread, high net/gross sst.
- Mud-log shows
- High Rt –
  - 40 ohm-m line
- Gas cross-over
- Sw in ‘productive’ range
  - << 50% Sw

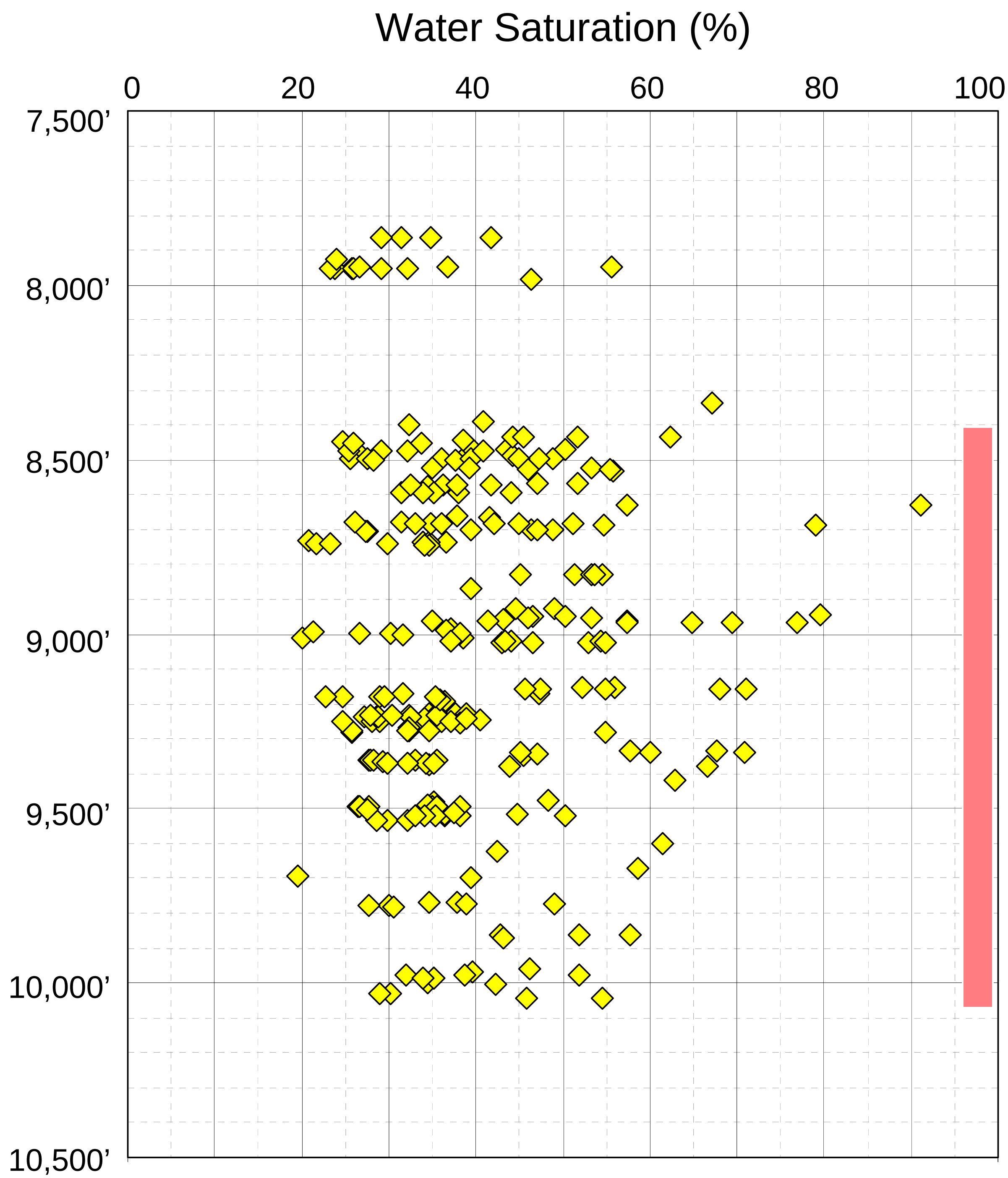
- Rarely gas productive on a sustained basis!
- Sustained water production common!



Saturation - Height Jonah Field

Jonah-Fed 2-8A

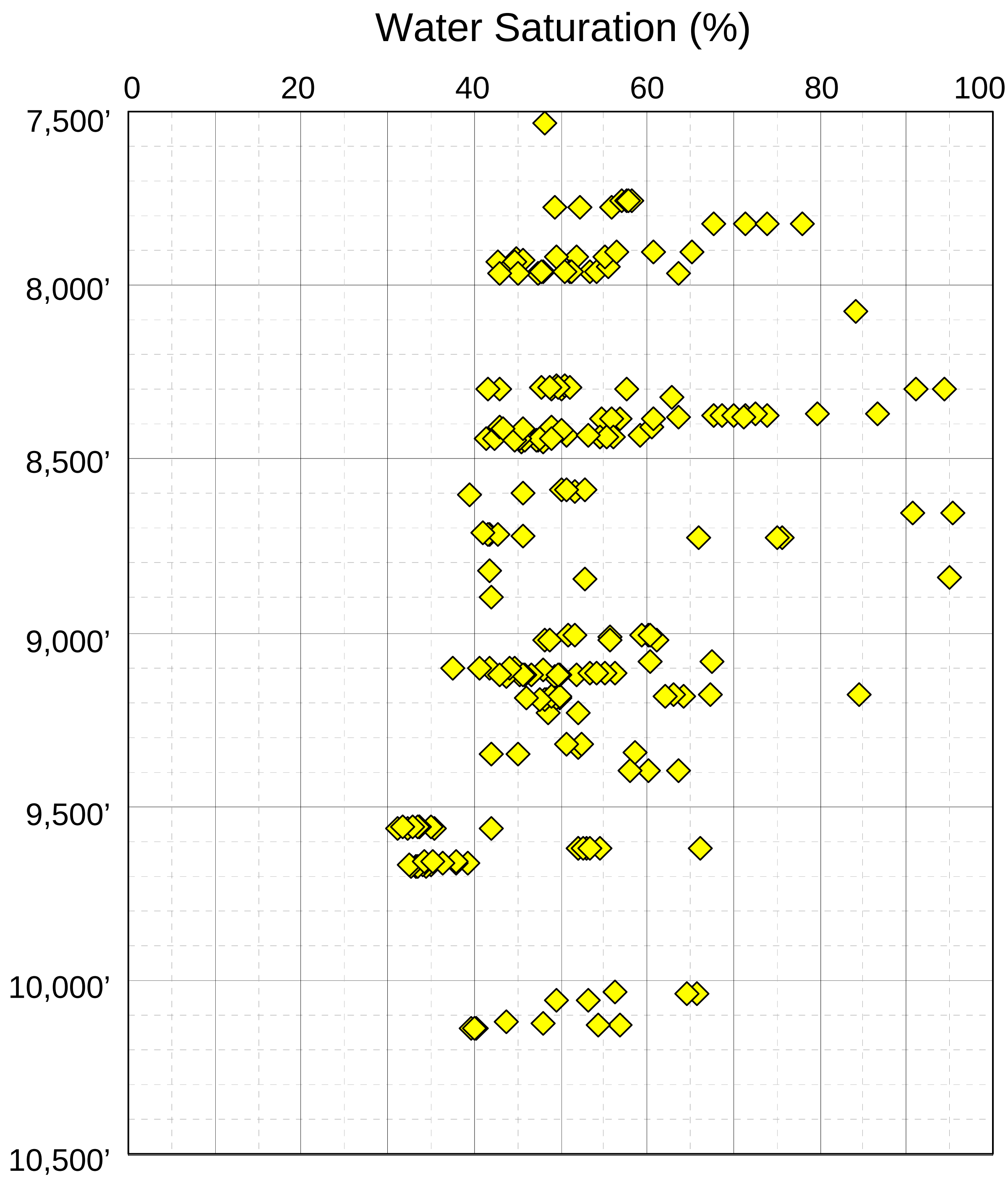
- Filtered LAS data – reduce # rock types
  - Phi 8.5 – 9.5%
  - GR < 60 API
  - Vsh < 0.5
- Sw range 30-50% across 2,500' section.
- Sw does not increase significantly with depth.
- Difficult to fit drainage Pc curves through this data.



Saturation - Height Jonah Field

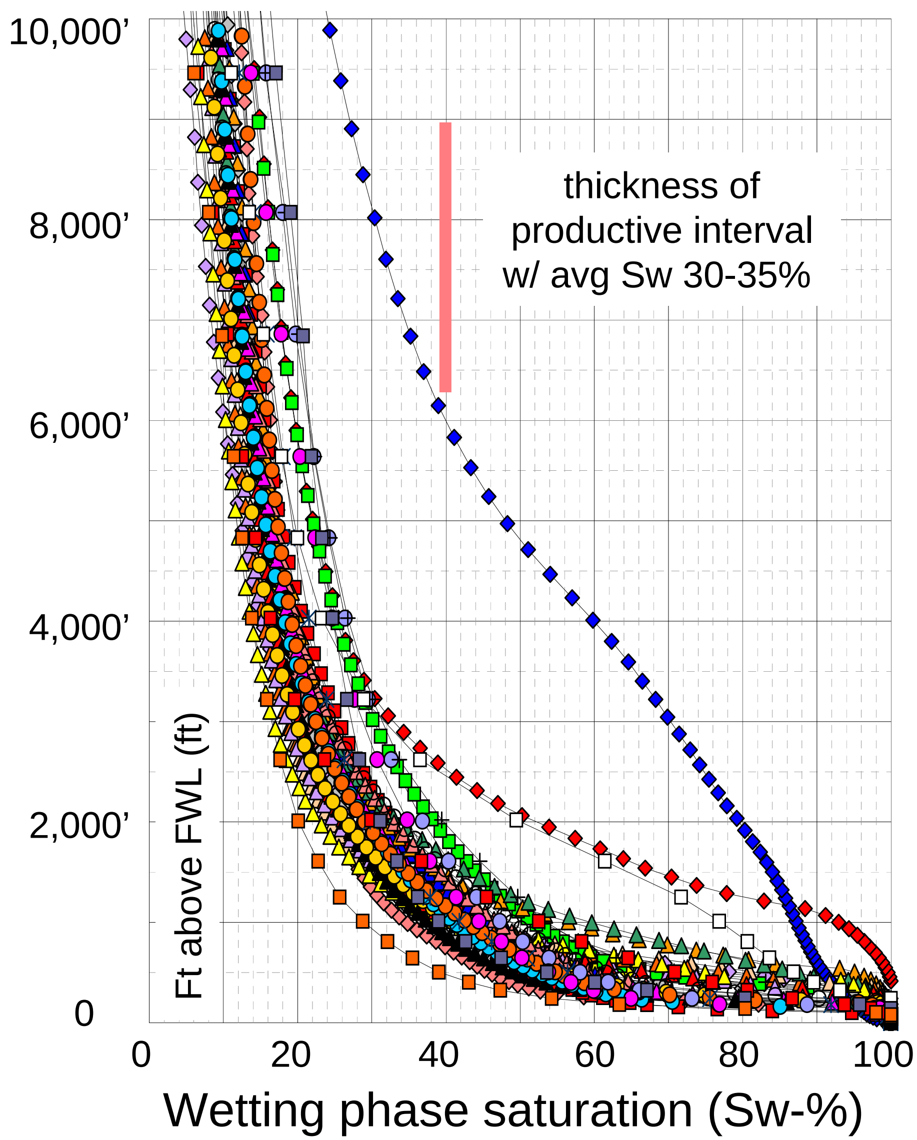
Corona Unit #7-24

- non-productive well
- Filtered LAS data – reduce # rock types
  - Phi 8.5 – 9.5%
  - GR < 60 API
  - Vsh < 0.5
- Sw approx 50%, near constant across 2,500' section.
- Sw does not increase significantly with depth.
- Difficult to fit drainage Pc curves through this data.



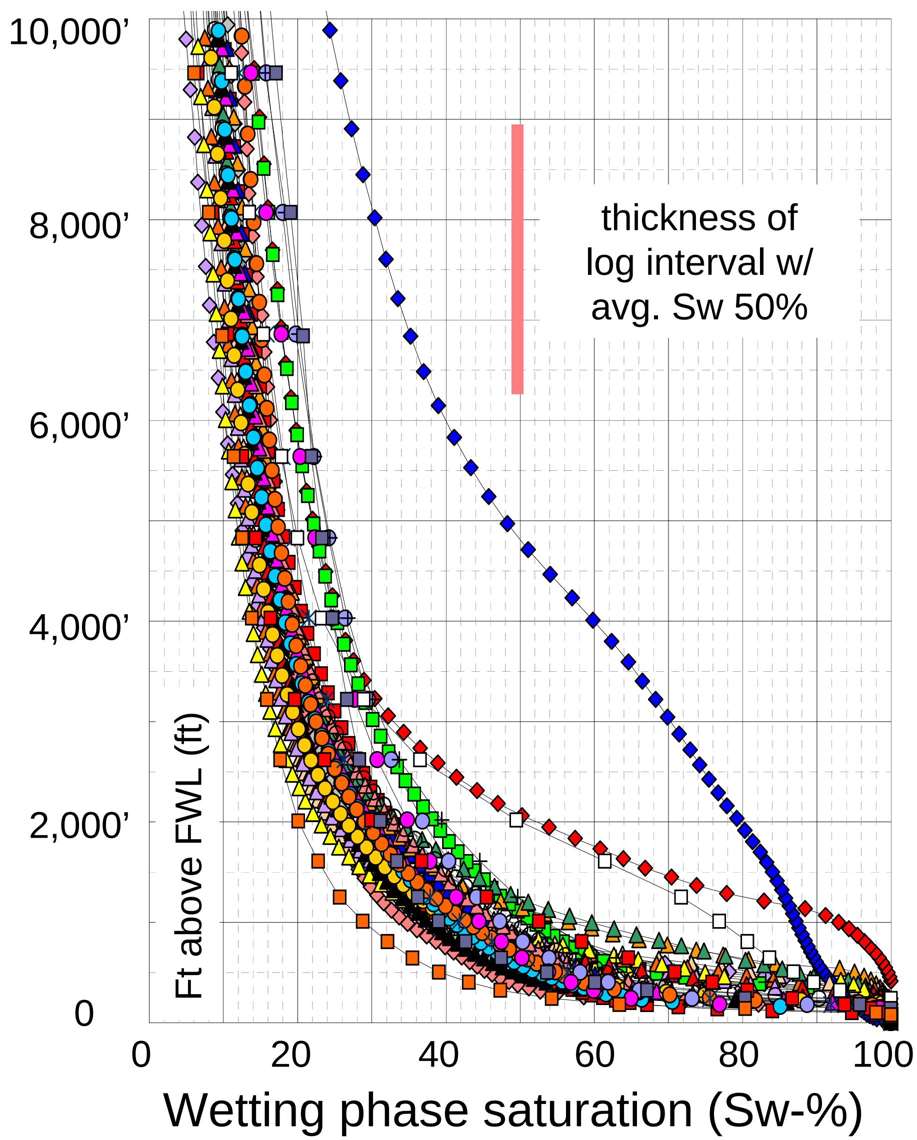
Saturation vs Height

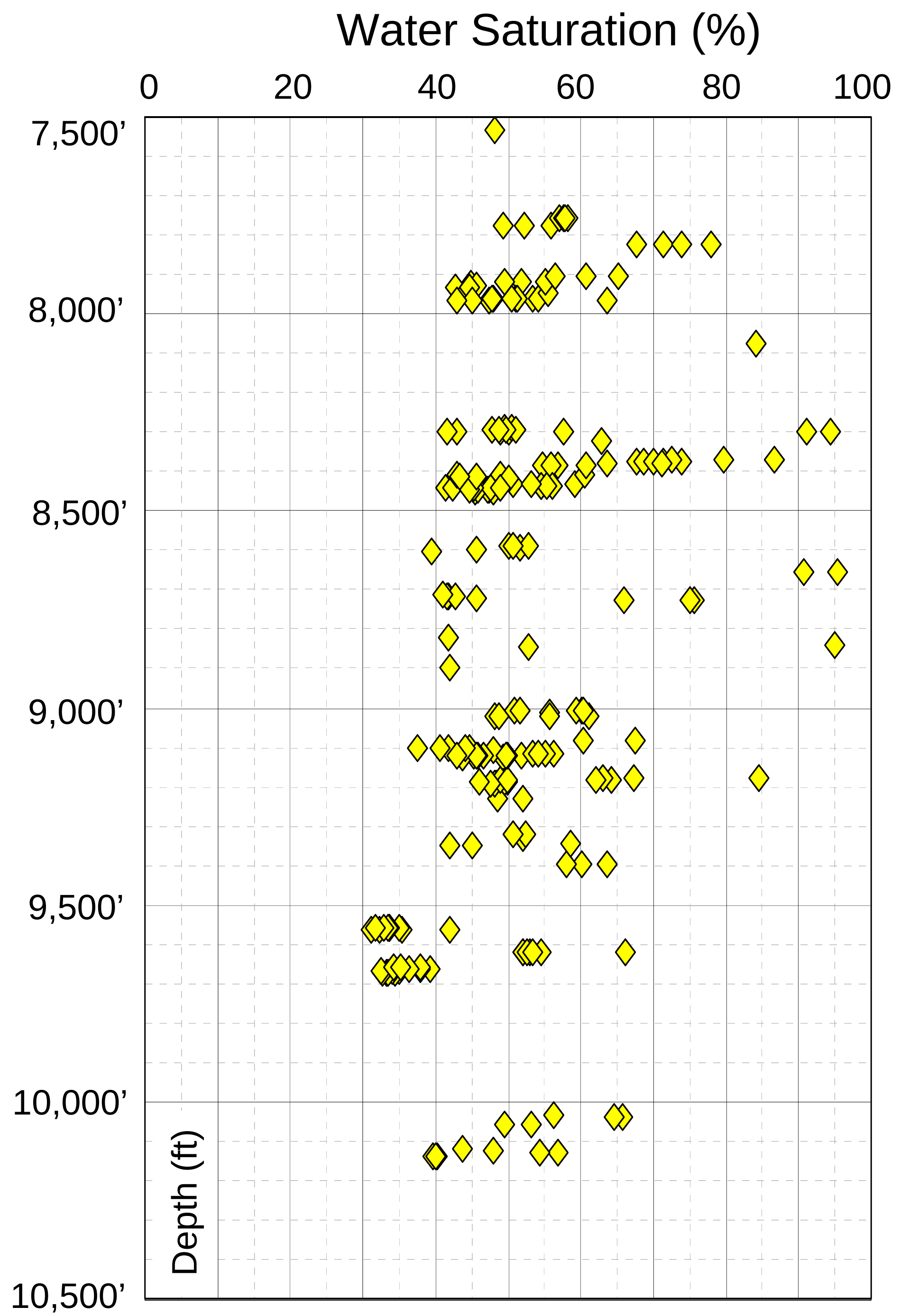
Jonah-Fed 2-8A vs Pc (n=32 Pc)



Saturation vs Height

Corona 7-24 vs Pc (n=32 Pc)





Summary of key field observations

- Most wells encounter gas shows while drilling.
  - Both within traps…and outside of trap areas
  - Many of those wells do not produce significant gas
- Rarely calculate high Sw in reservoir-quality rock even in water-bearing zones.
- Similar Sw and Sw-H trends in both producing and non-producing wells
  - Saturation models often perplexing / non-discriminating
  - Performance prediction can be very difficult
- Rock-typing has limited success in predicting reservoir performance

Briefly consider -

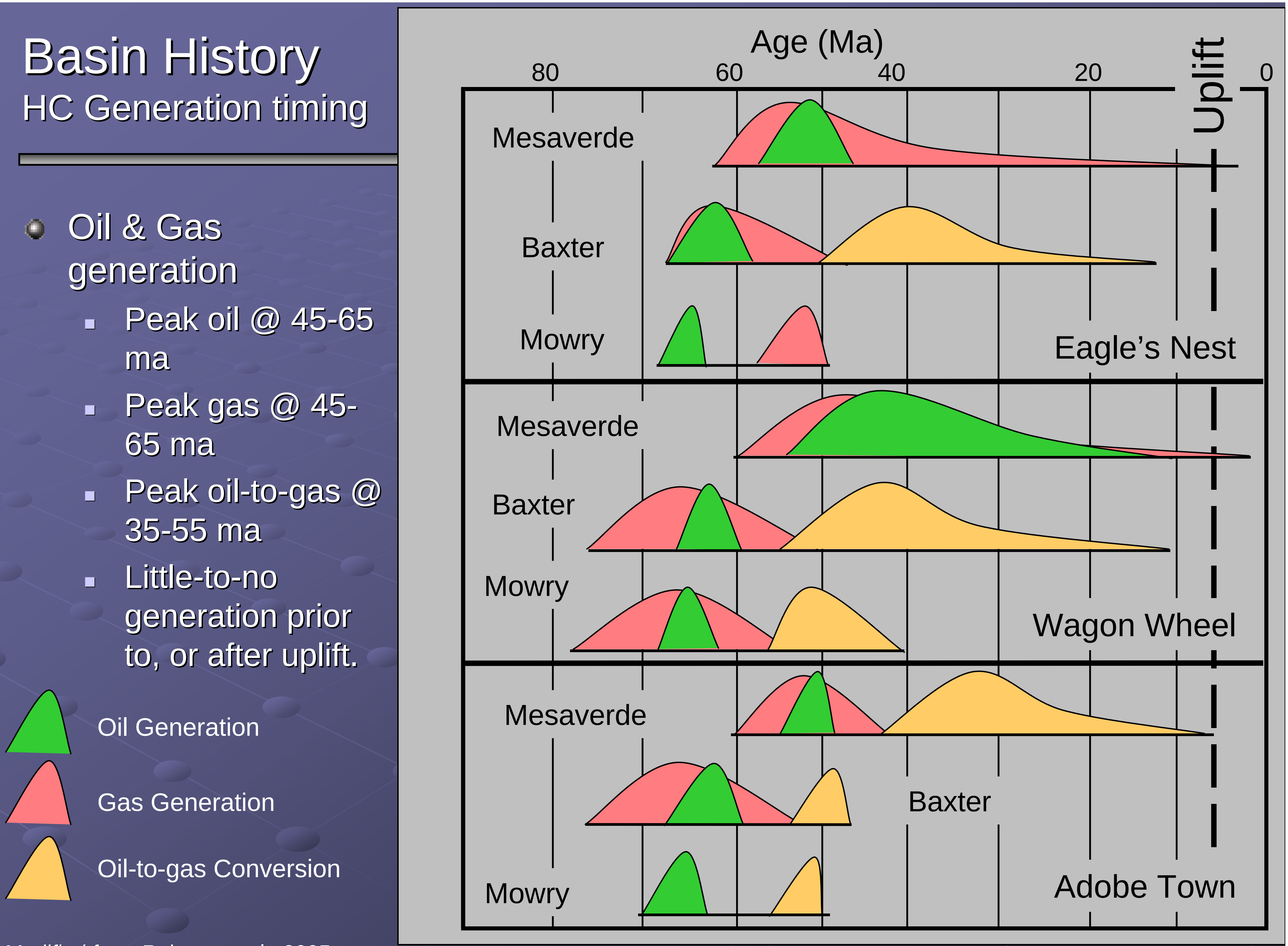
- Our perspective is that these outcomes are a reflection of basin history –
  - Relatively early charge followed by continued burial and late uplift.

- Look more closely at:
  - HC timing and charge process
  - burial -- changes in reservoir rocks and gas columns
  - uplift -- changes in gas columns & saturation trends

Basin History

HC Generation timing

- Oil & Gas generation
  - Peak oil @ 45-65 ma
  - Peak gas @ 45-65 ma
  - Peak oil-to-gas @ 35-55 ma
  - Little-to-no generation prior to, or after uplift.

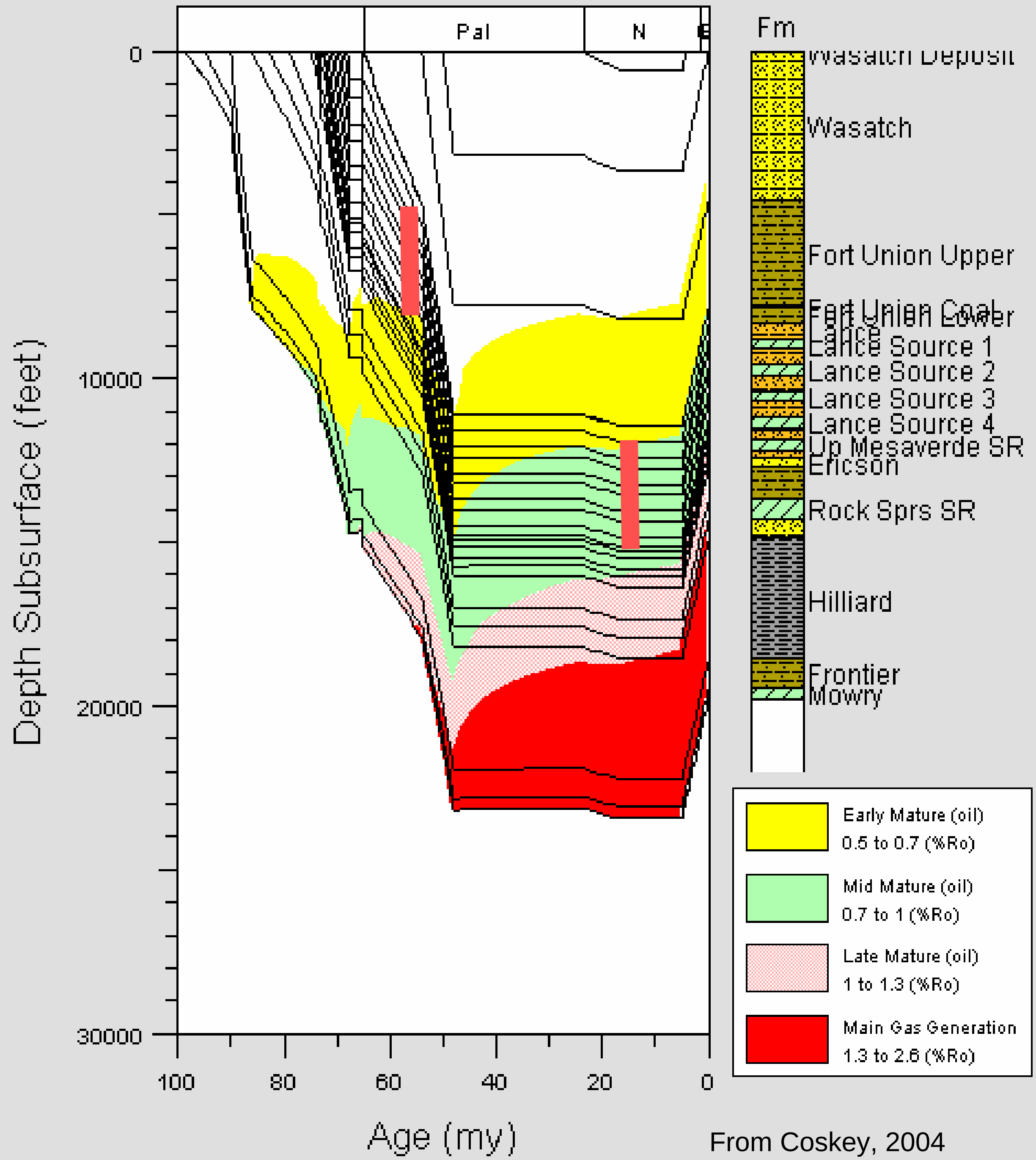


Modified from Roberts et al., 2005

Basin History
Jonah Field (SHB 13-27)

- 1-D model
- HC generation & expulsion prior to reservoir @ maximum depth of burial
  - Reservoir interval much more shallow during charge
- Late uplift shuts down HC generation

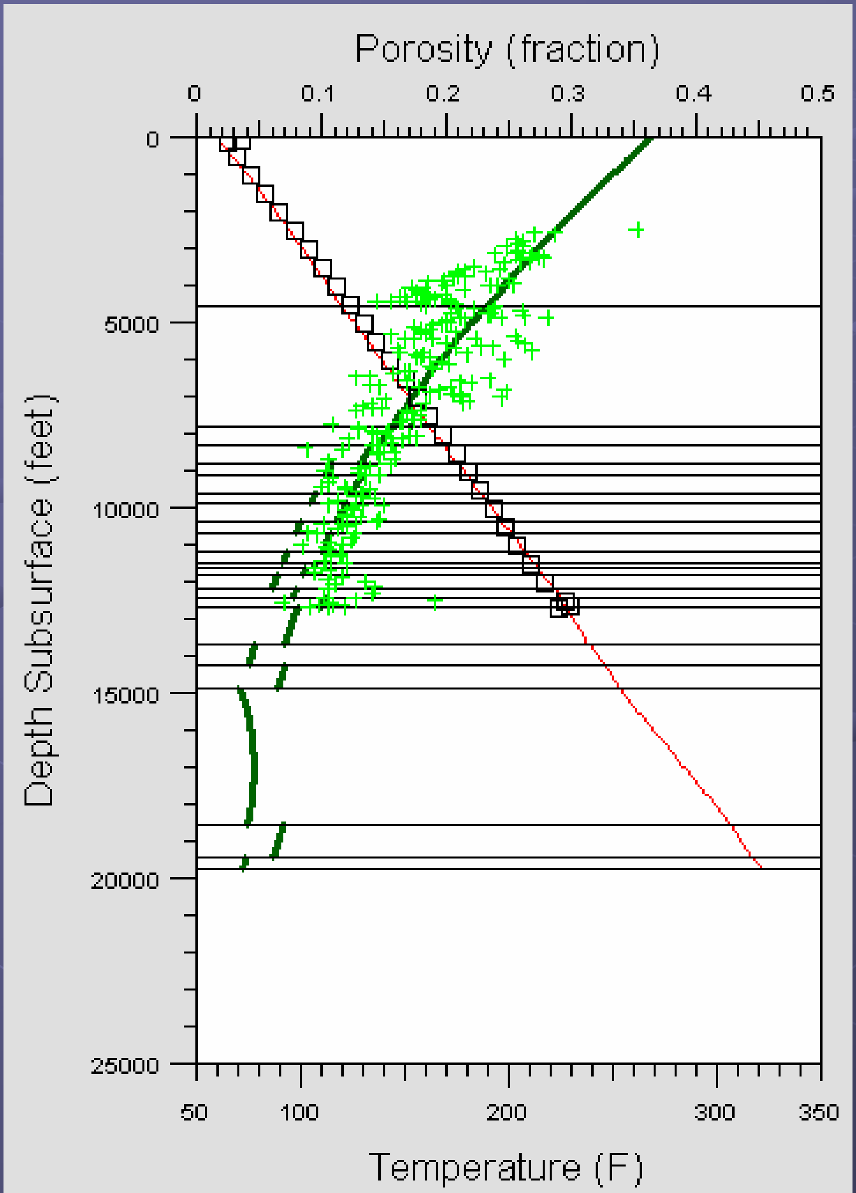
Calculation intervals:
depth @ 200 ft, Time @ 2 my



From Coskey, 2004

Basin History

Jonah-Pinedale area – Coskey, 2003-05

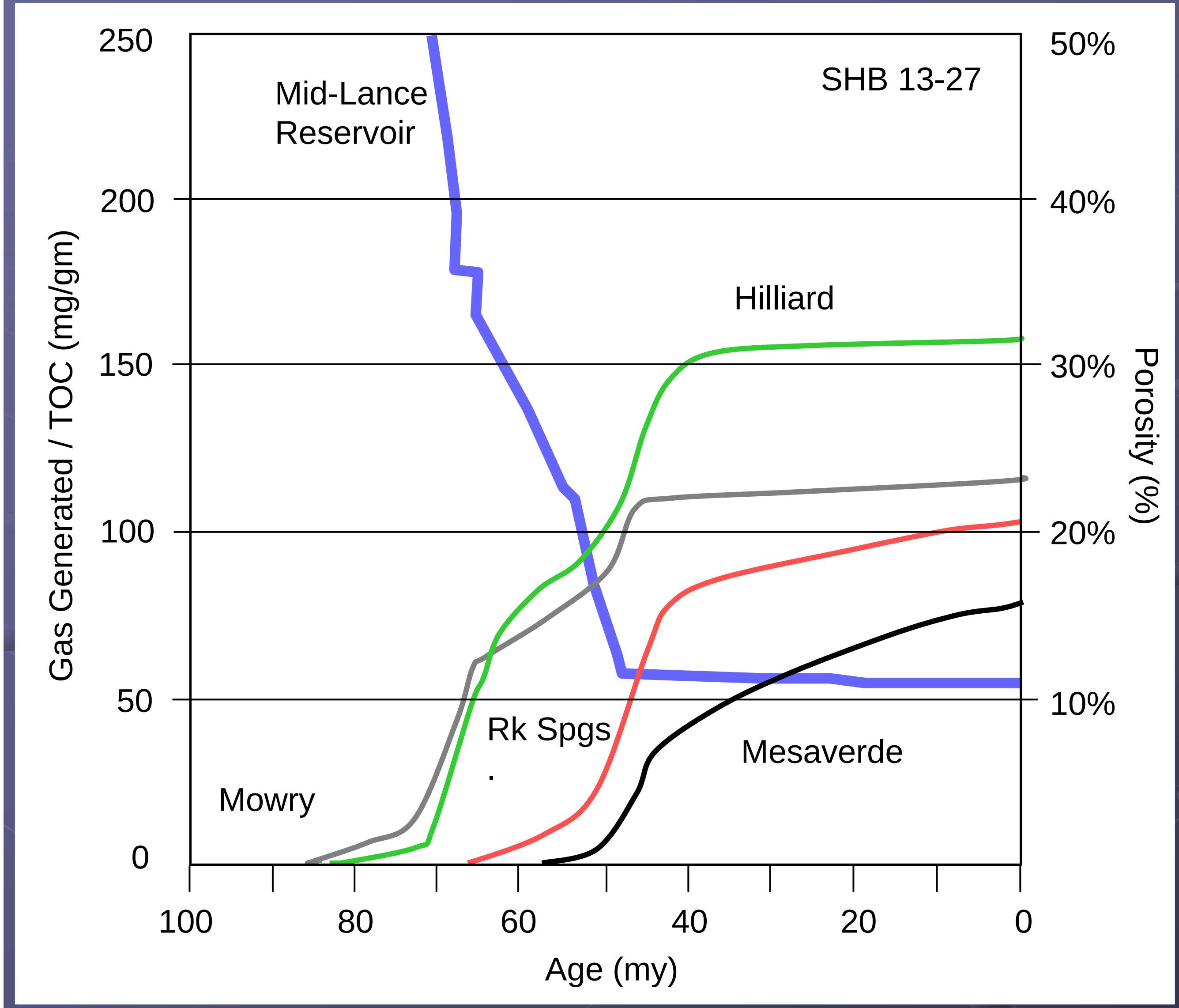


- SHB 13-27 model calibrated to:
  - BHT
  - Ro
  - also to porosity
    - understand porosity of reservoirs at time of charge and expulsion.

From Coskey, 2004

Basin History

Jonah area: Reservoir porosity vs HC charge

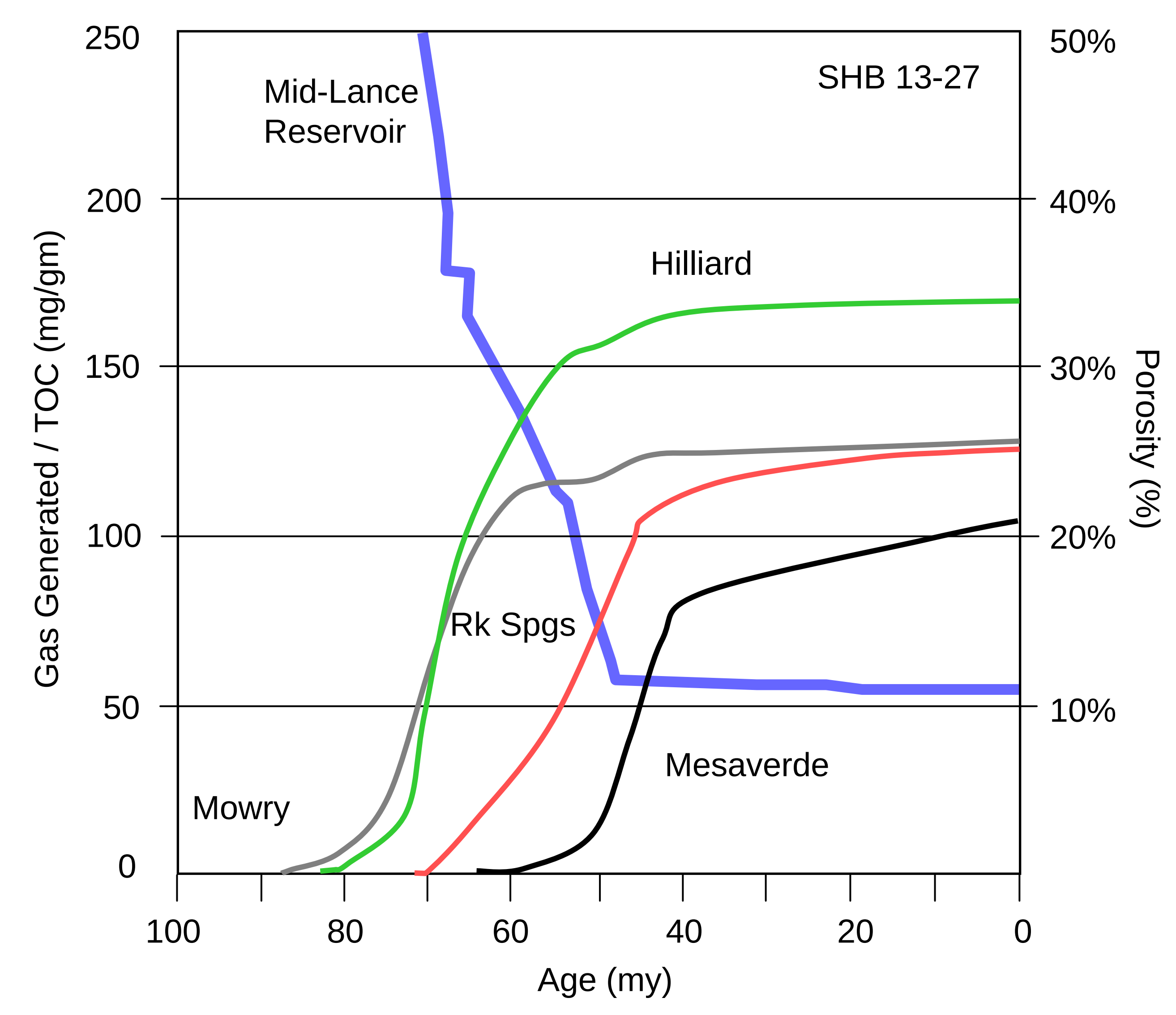


- Primary source rocks.
  - Hilliard
  - Mowry
  - Rock Springs (?)
- Source & reservoir in close vertical proximity.
- Reservoir porosity
  - 15-25%+

From Coskey, 2004

Basin History

Jonah area: Reservoir porosity vs HC charge

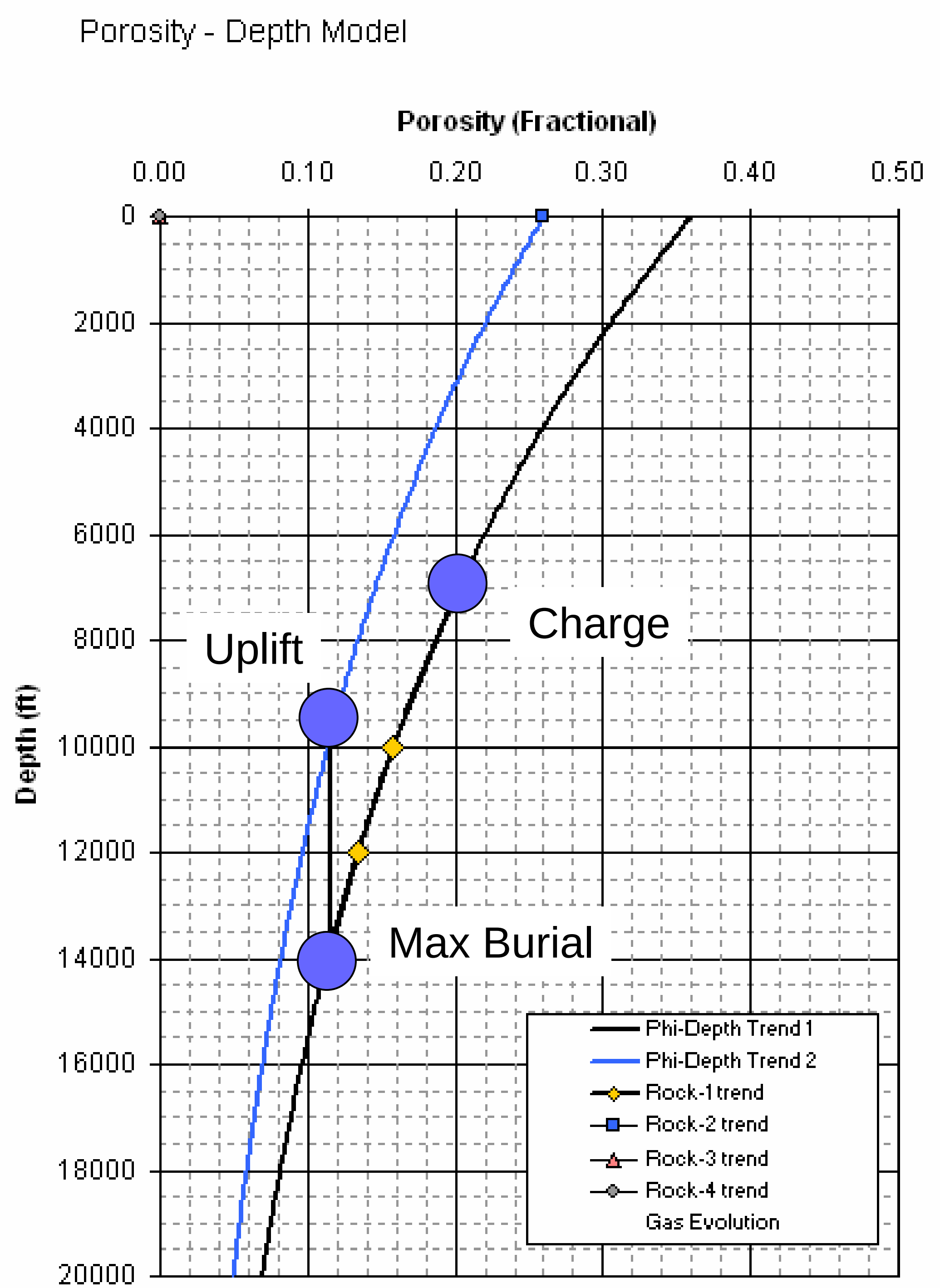


- Primary source rocks.
  - Hilliard
  - Mowry
  - Rock Springs (?)
- Deeper depth source – lateral & vertical migration.
- Reservoir porosity
  - 17-30%+

From Coskey, 2004

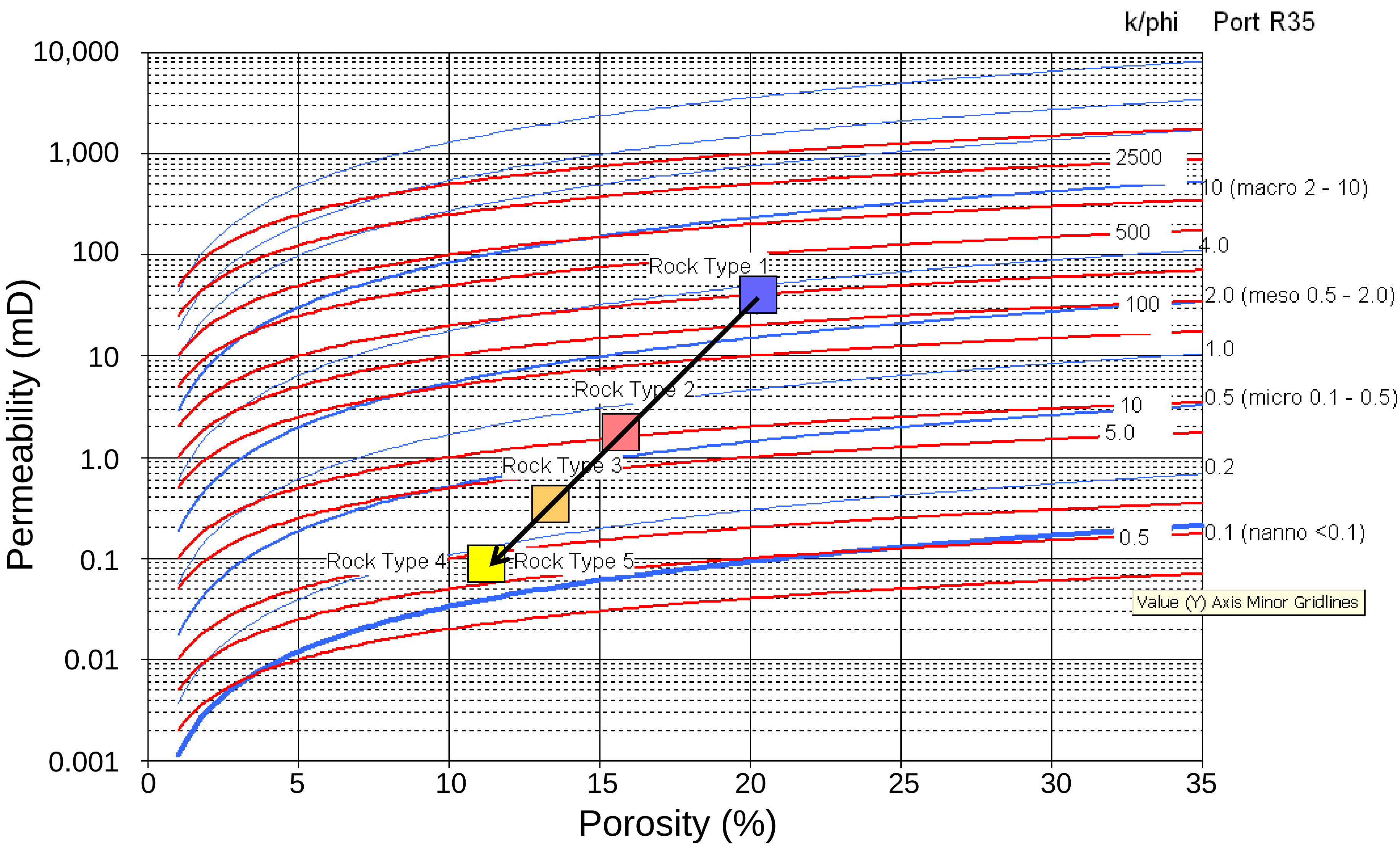
Reservoir Quality – Capillary Pressure Model

- Consider the effect of burial history on reservoir quality and Pc curves
  - Burial History model
    - Charge at 7,000’
    - Max burial to 14,000’
    - 4,500’ uplift
    - Final burial at 9.500’
  - Capillary pressure curves change with time & burial.
- The reservoirs we charged are potentially very different from the reservoirs we observe today.



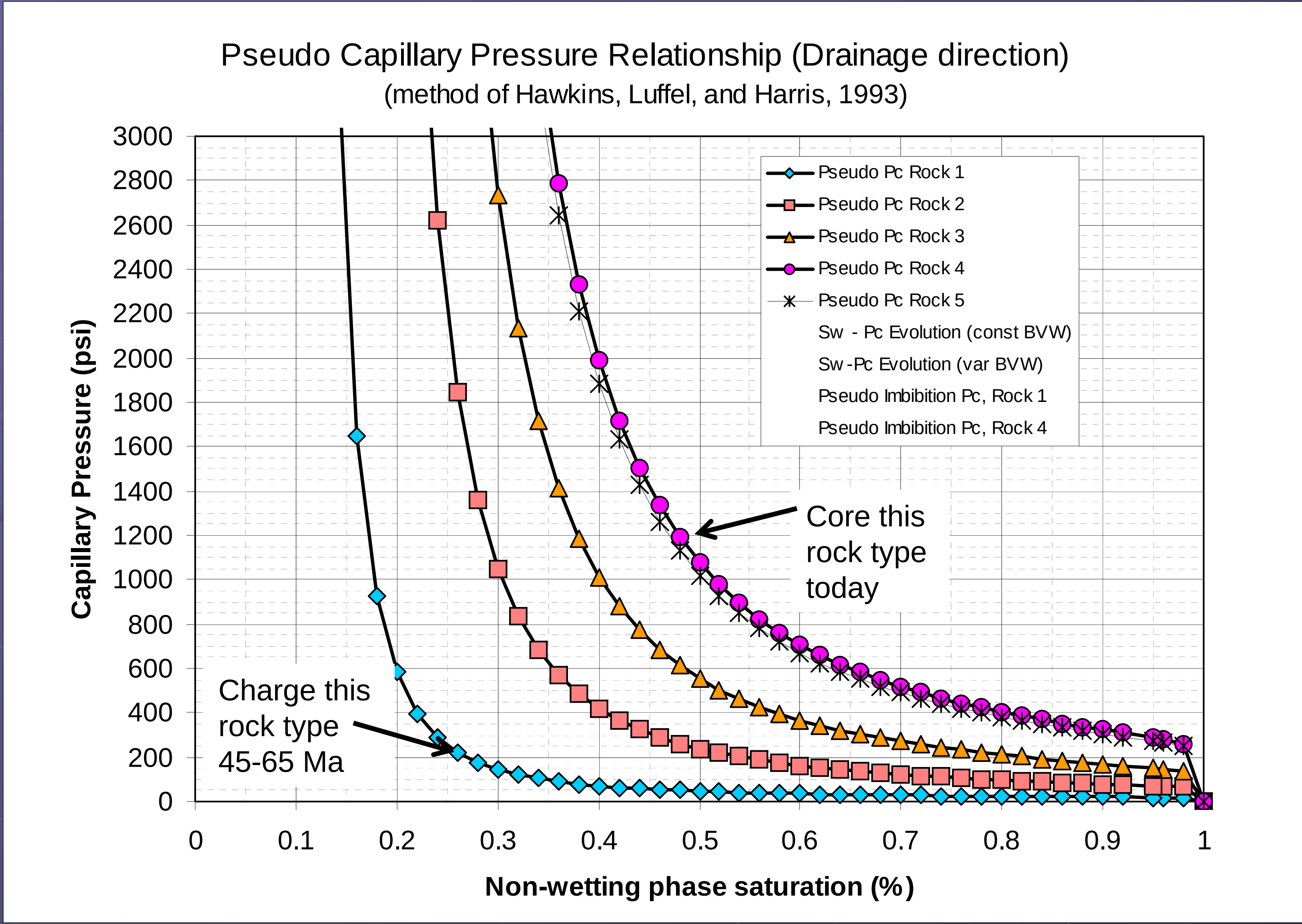
Reservoir evolution during burial

Winland rock types

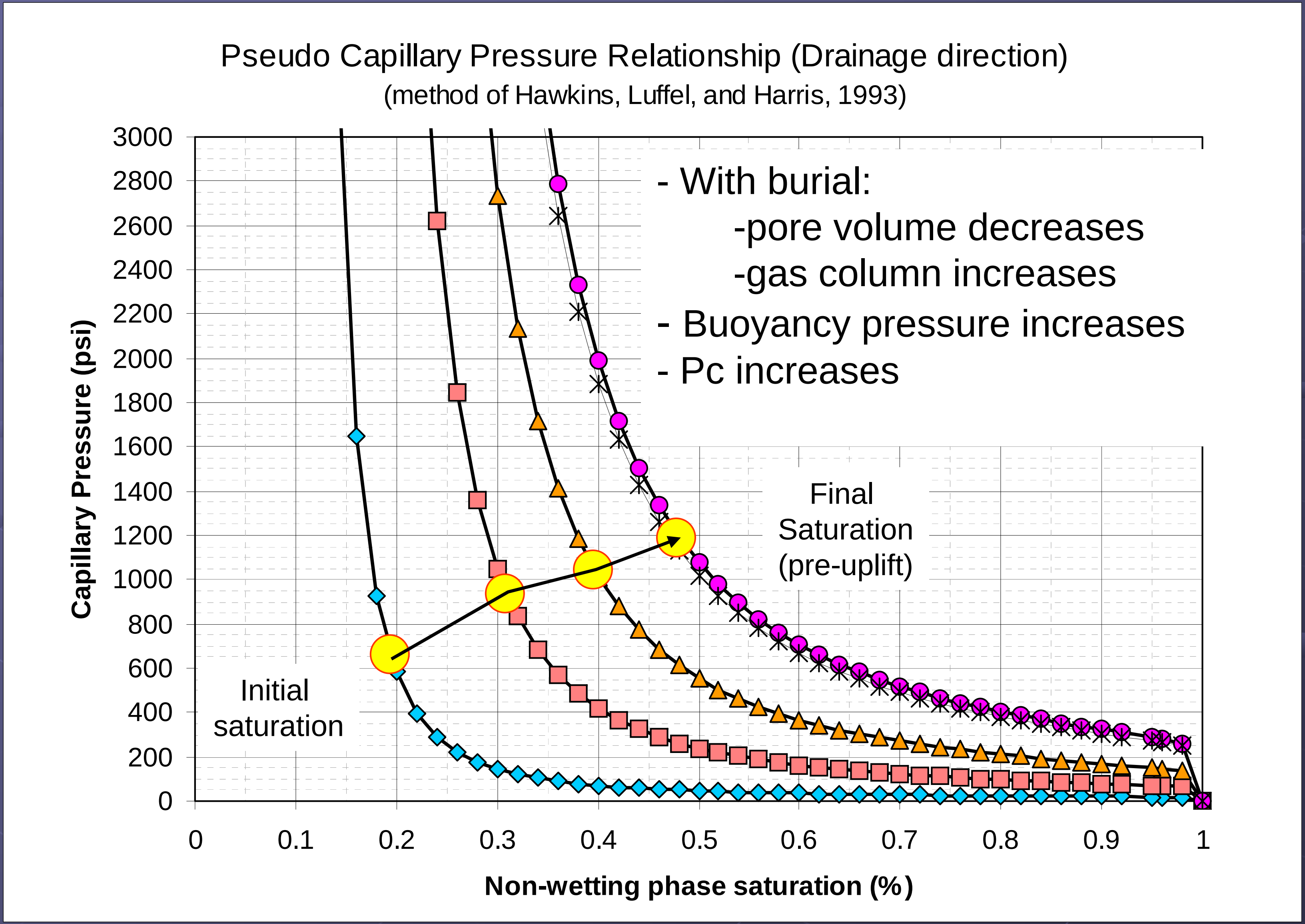


Capillary Pressure Evolution

Pseudo capillary pressure curves



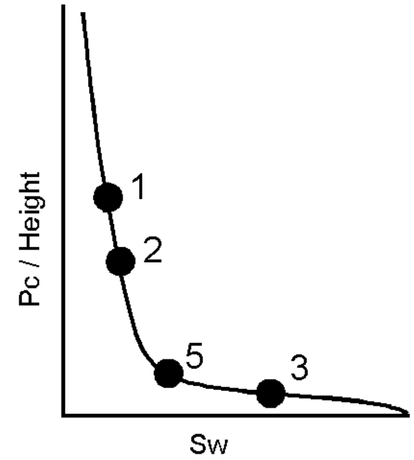
Capillary Pressure Evolution
initial saturation – final saturation

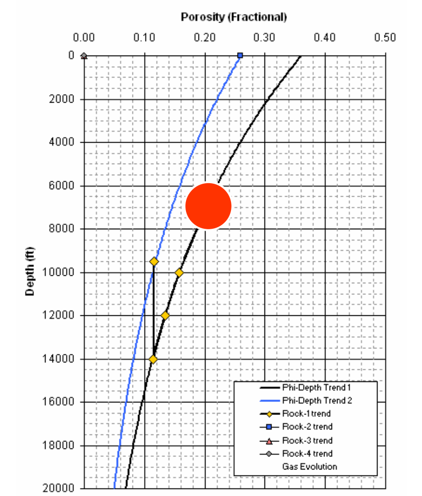


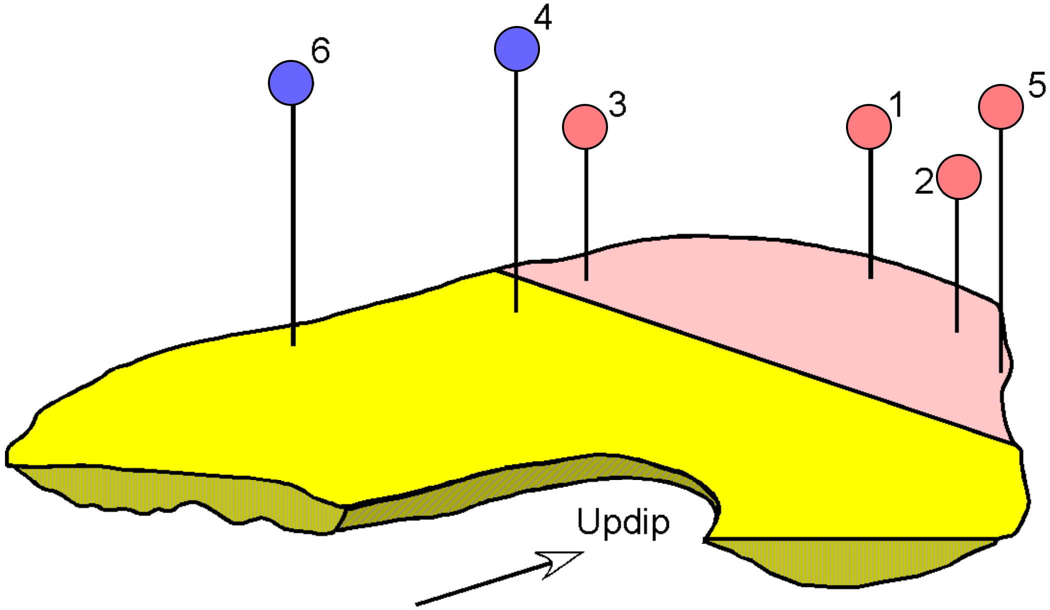
Tight-gas hydrocarbon model

Initial charge

- Initial gas charge prior to maximum depth of burial.
- Enhanced reservoir properties relative to today.
- Gas displaces water – drainage capillary process
- Saturation and height are closely related.

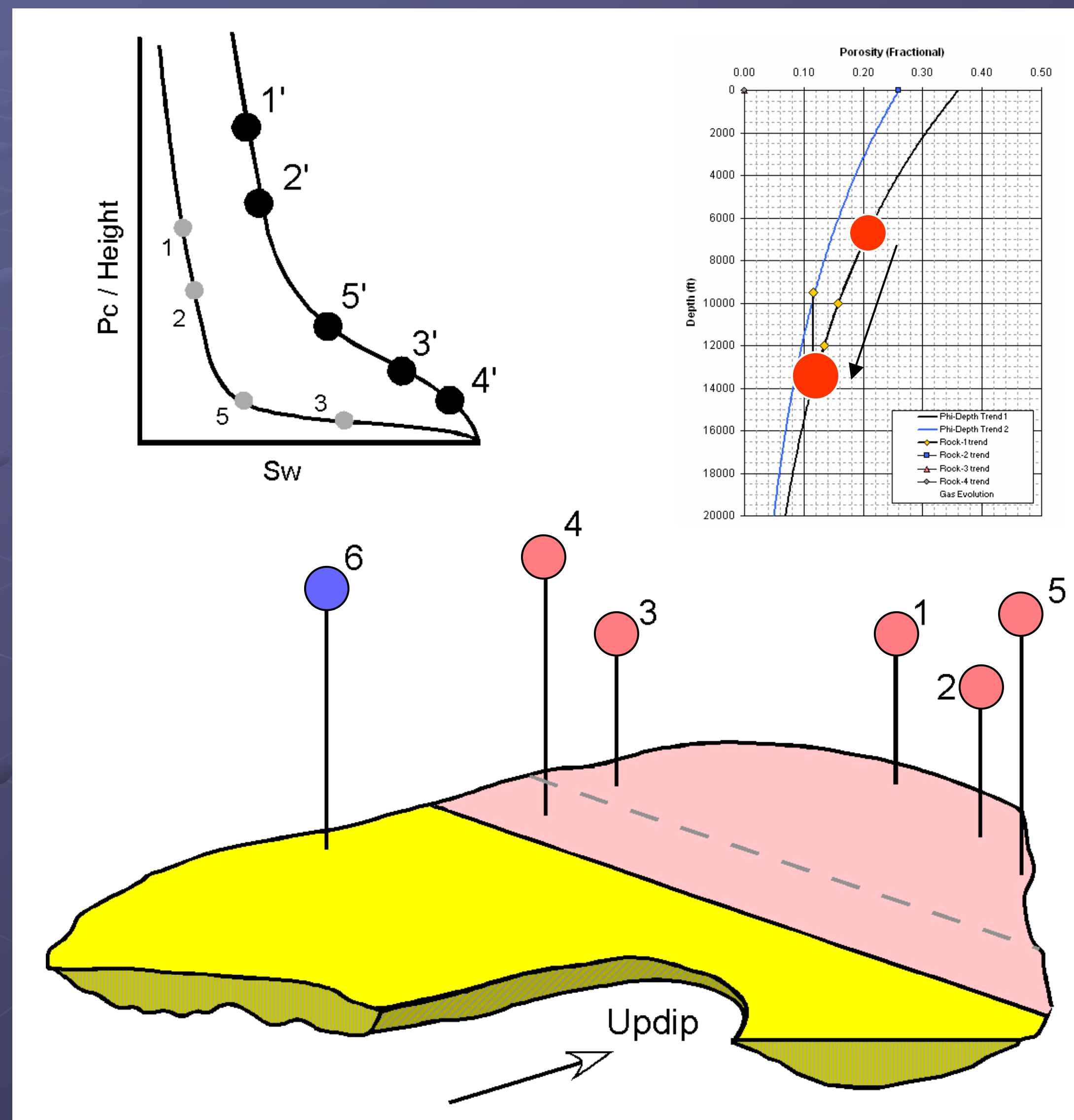






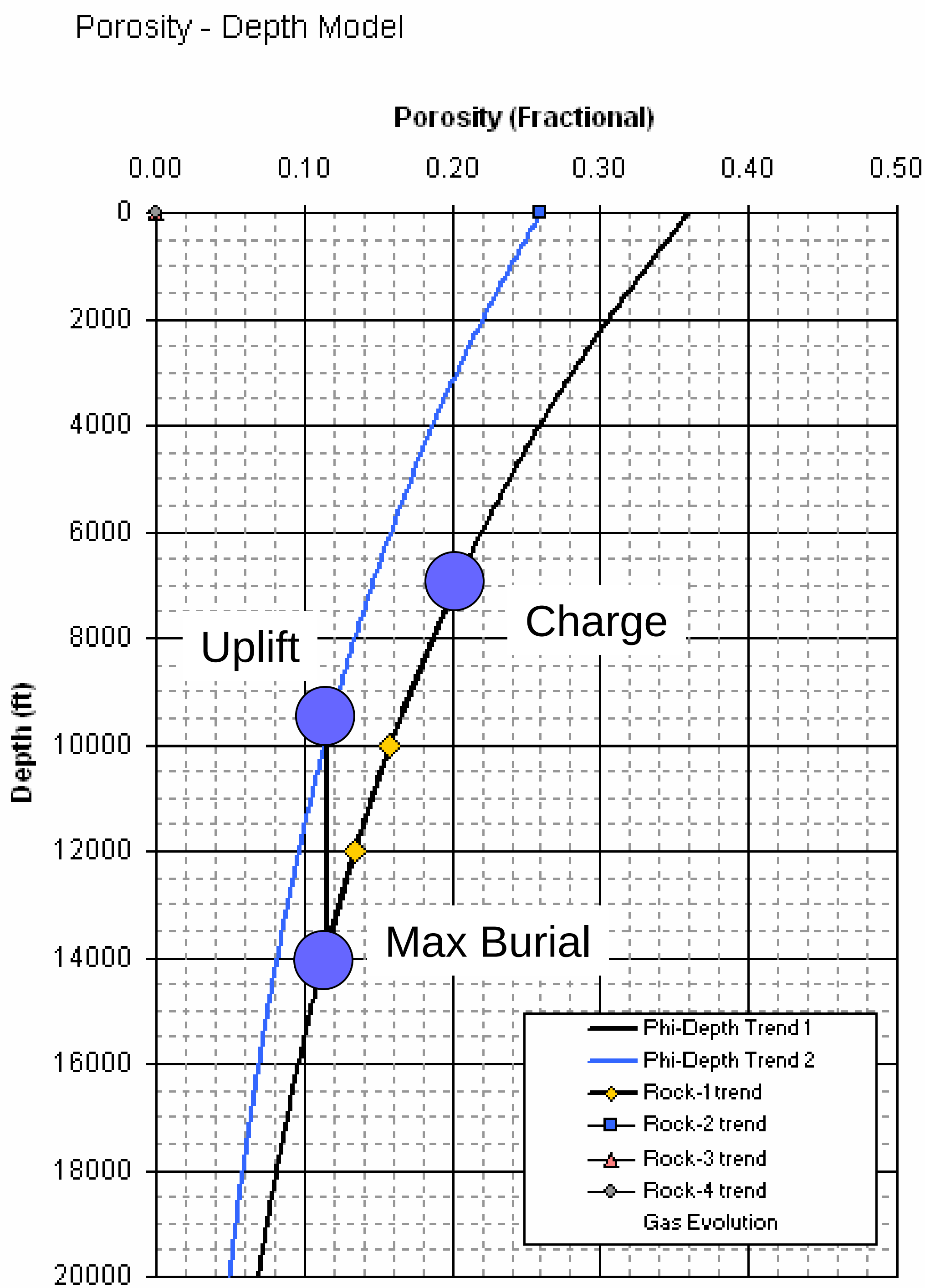
Tight-gas hydrocarbon model
with burial…

- Gas compresses
- But - gas column (H) increases due to the decreasing pore-volume in the trap.
  - How much 'h' increases dictated by trap configuration
- Diagenesis causes pore-throats to get smaller which increases Pc – causing water to be imbibed and Sw to increase.
- Saturations – move to the NE (higher Pc & Sw)
  - Both drainage & imbibition



Reservoir Quality – Capillary Pressure Model

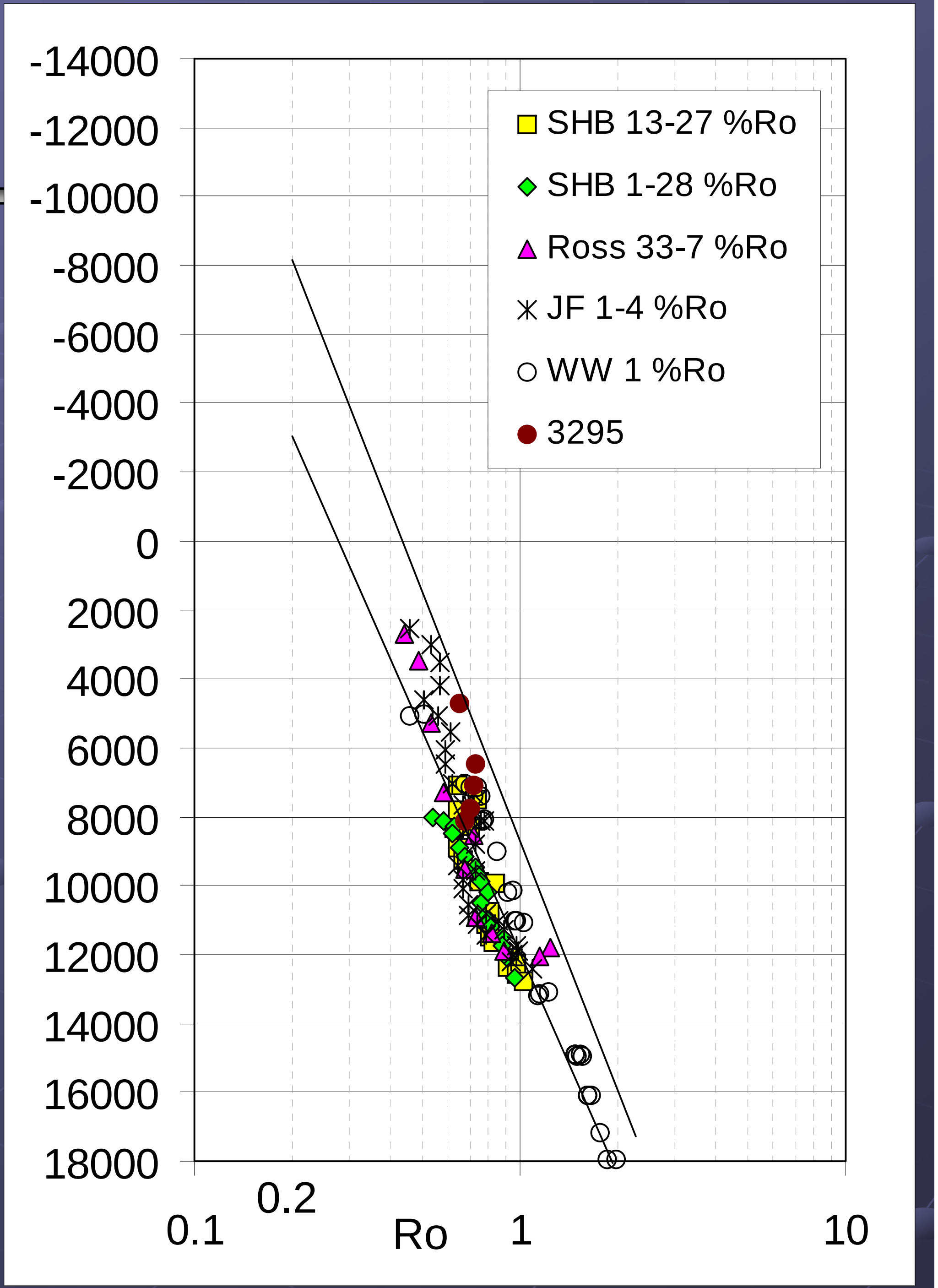
- Have considered what happens during burial.
  - Decrease in pore-volume
  - Increase in gas column thickness
- Now look at what happens during uplift and structural re-organization.



Greater Green River

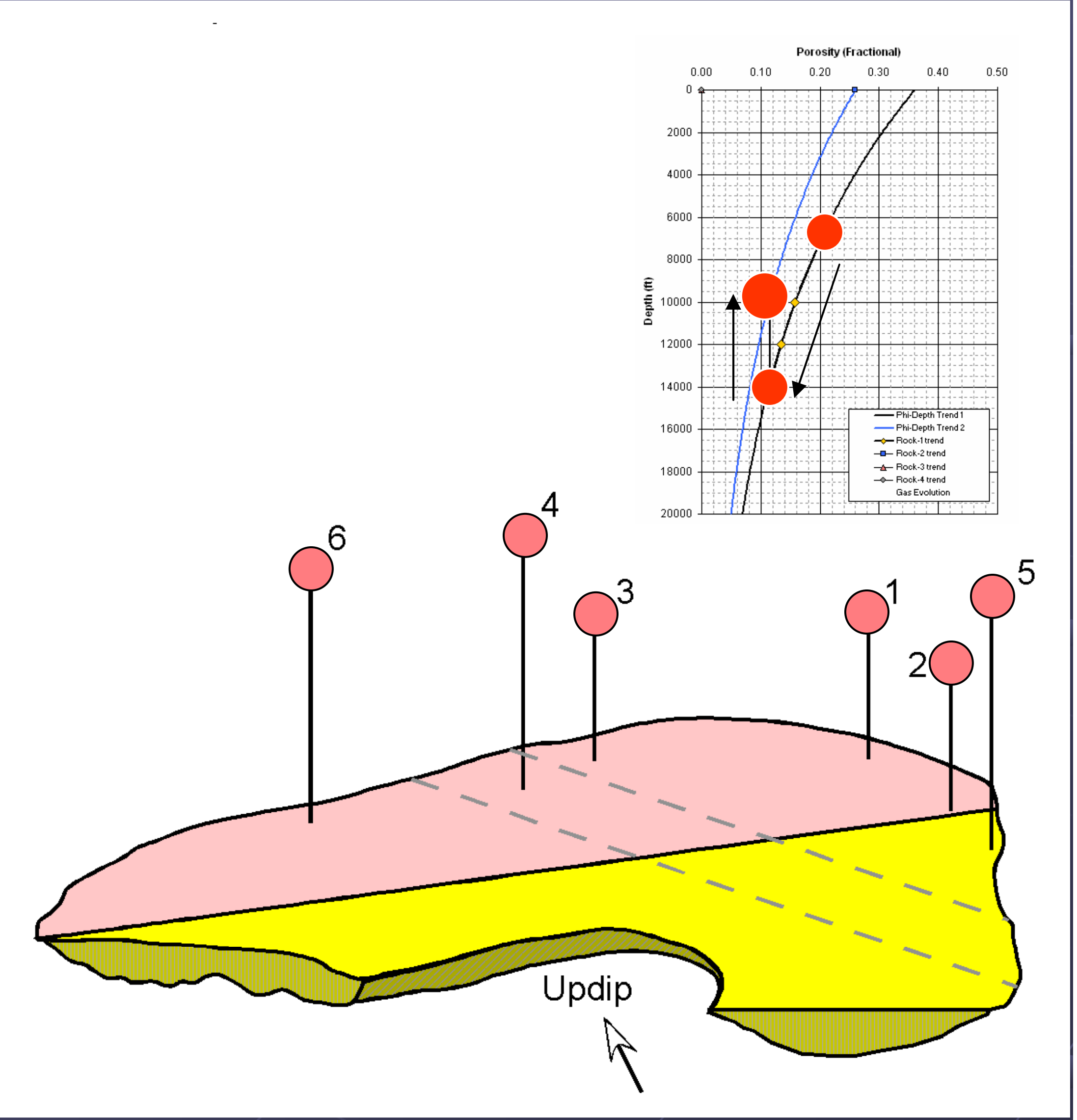
Regional uplift

- Uplift and structural re-organization @ 5-7 Ma
- Uplift estimates range 3,000 to 8,000'
- Within GGRB uplift varies spatially
- Gas columns adjust to changing structure
  - Some traps spill
  - Some re-adjust and columns move
  - Some remain the same



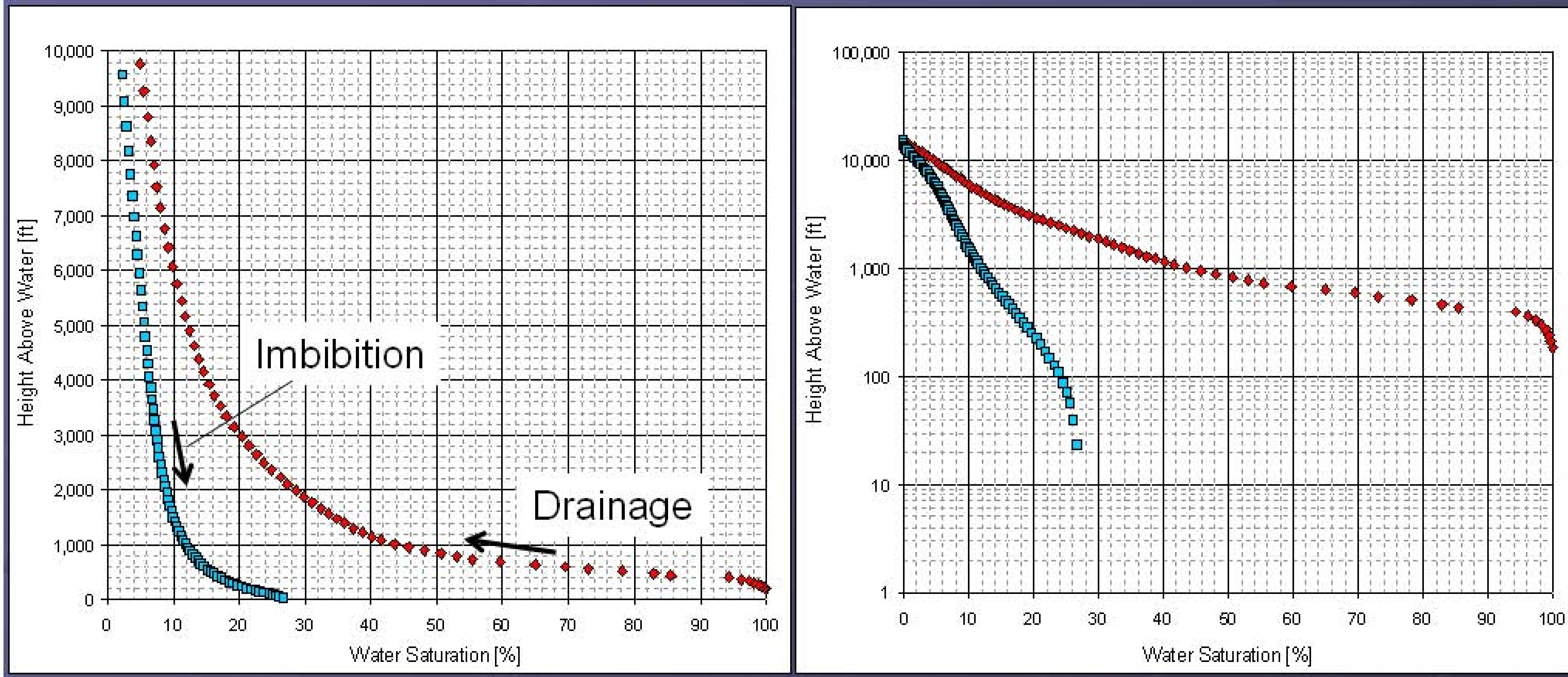
Tight-gas hydrocarbon model
Uplift…

- During uplift…if the structural attitude of the trap changes…
  - Gas could ‘adjust’ to changing structural attitude
  - Trap could spill completely
  - Trap could partially spill
- The changes in position of gas would be by both drainage (gas displacing water) and imbibition (water displacing gas) depending on trap and position within the trap.



Capillary Pressure Curves

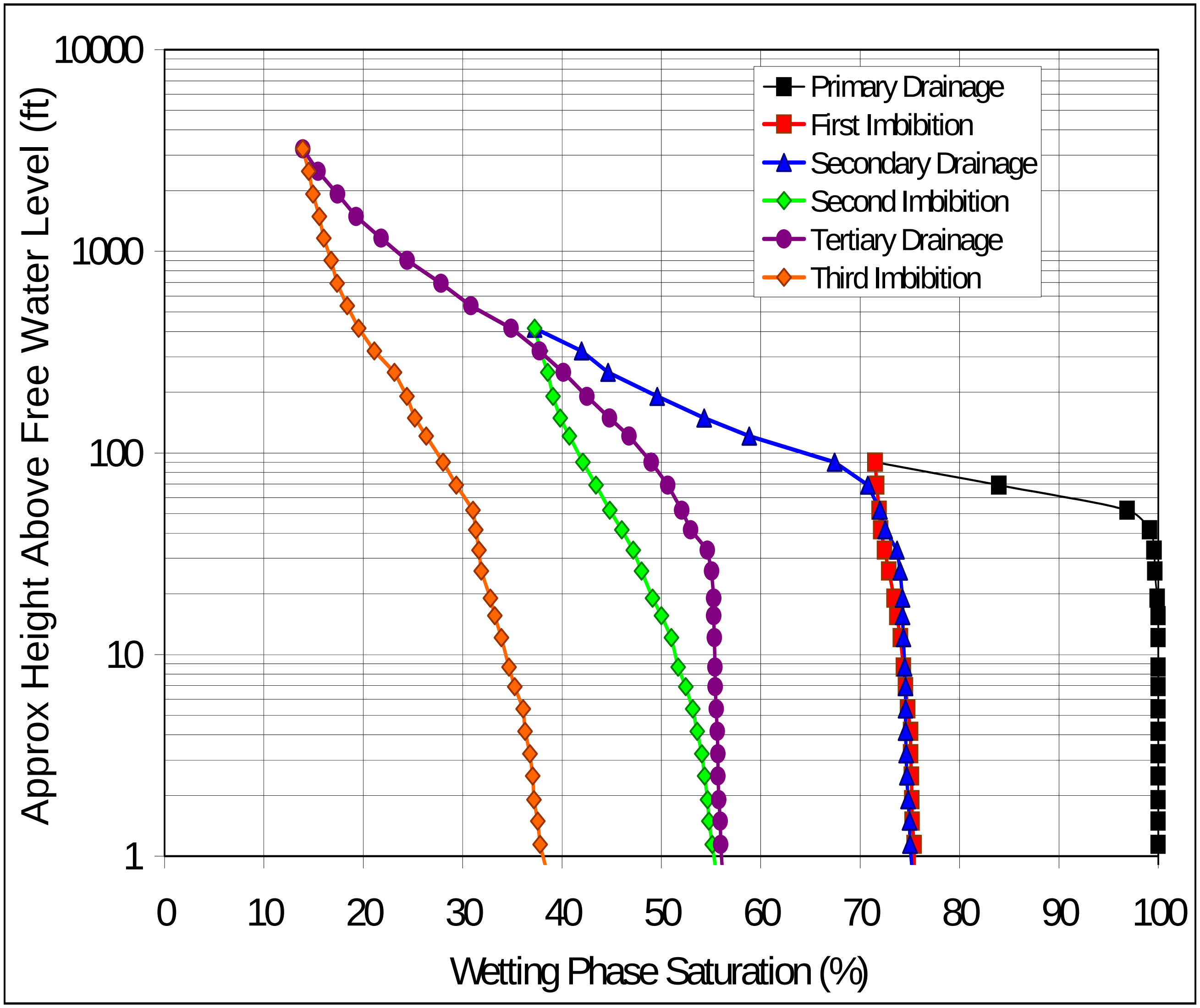
Drainage & Imbibition – Lance Fm., Pinedale - GGRB



- Hysteresis is the difference in the two paths.
- Notice that the 'final' imbibition saturation <u>does not</u> equal 100% water saturation.
- Final Sw = approx 28% at Pc = 0, often called residual saturation or trapped saturation. Final saturation depends on initial saturation.

Capillary Pressure – scanning loops

tight-gas hysteresis & residual saturation (11.3%, 0.043 mD)

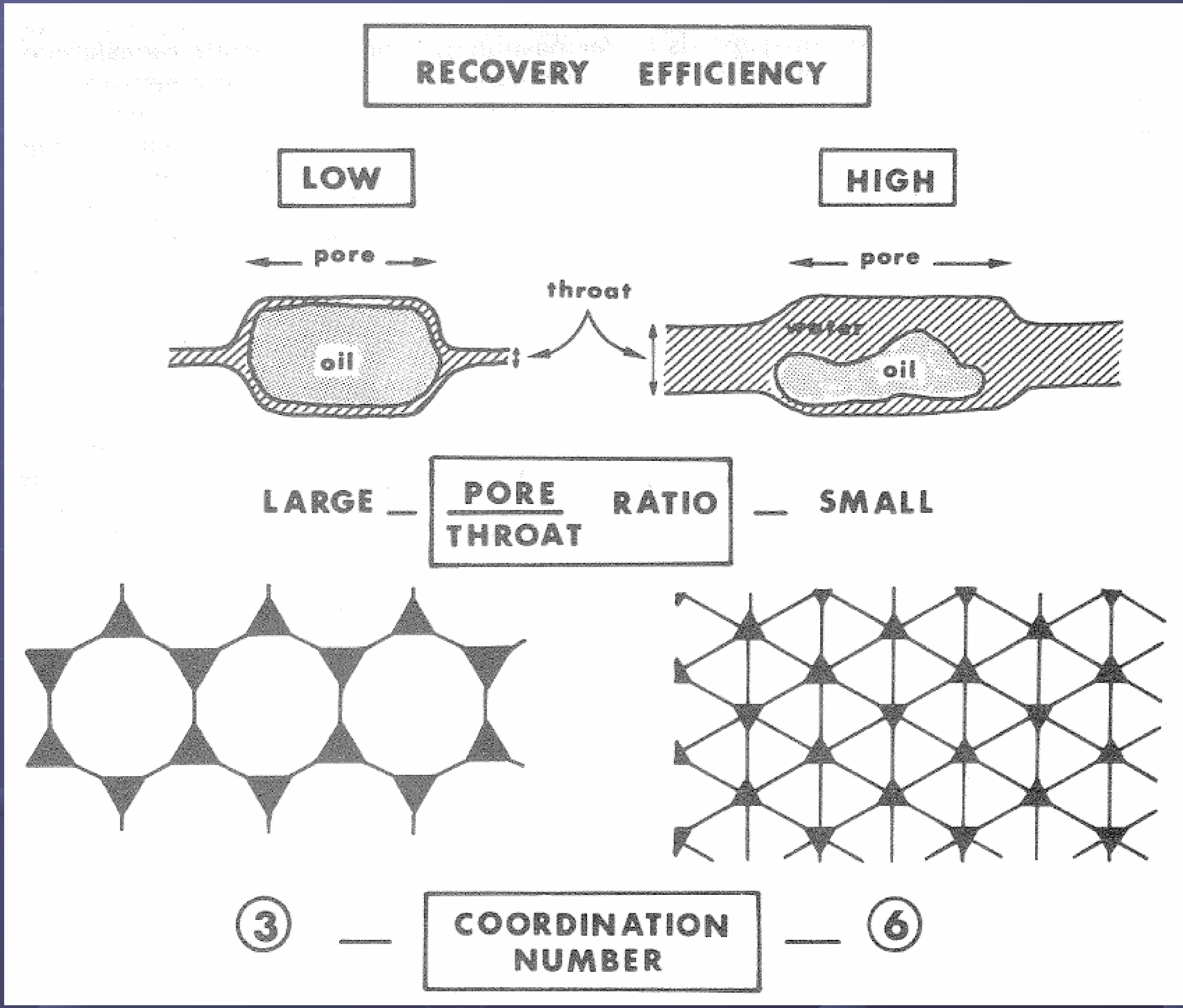


- Most previous work on imbibition related to enhanced oil recovery.
- Residual / trapped saturation depends on initial saturation
- Recent work on tight gas hysteresis reported similar results.
- Sw slope much more steep on imbibition and resulting drainage.

From Byrnes, Cluff & Webb, DOE 2007

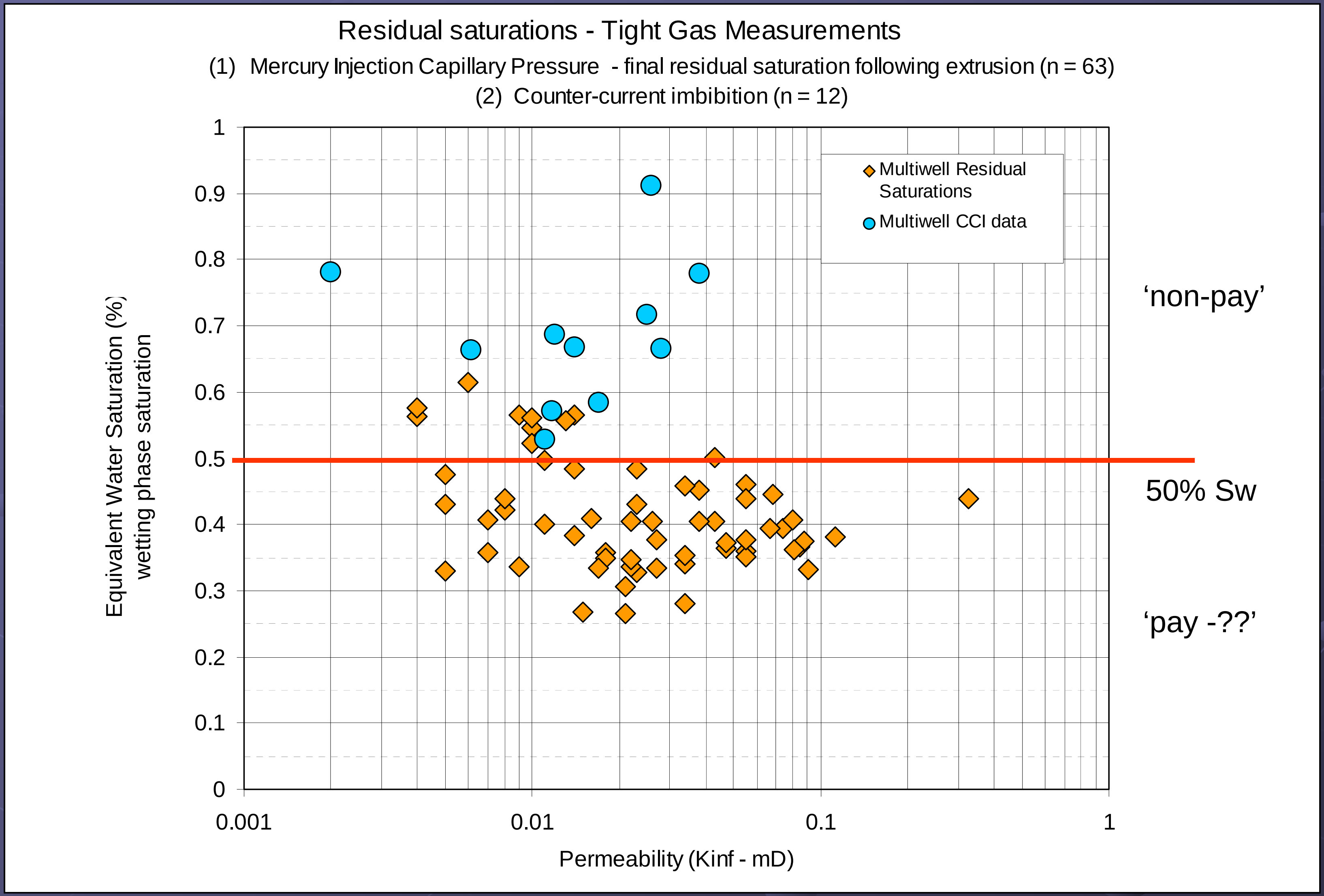
Residual Saturations
Aspect Ratio – Wardlaw & Cassan, 1978

- Work on residual largely in waterflood community
- Classic work by Wardlaw
- Residual saturation largely driven by pore / throat aspect ratio and initial saturation
- Tight-gas reservoirs have very high pore/throat aspect ratios
  - Observed through stress effect on permeability



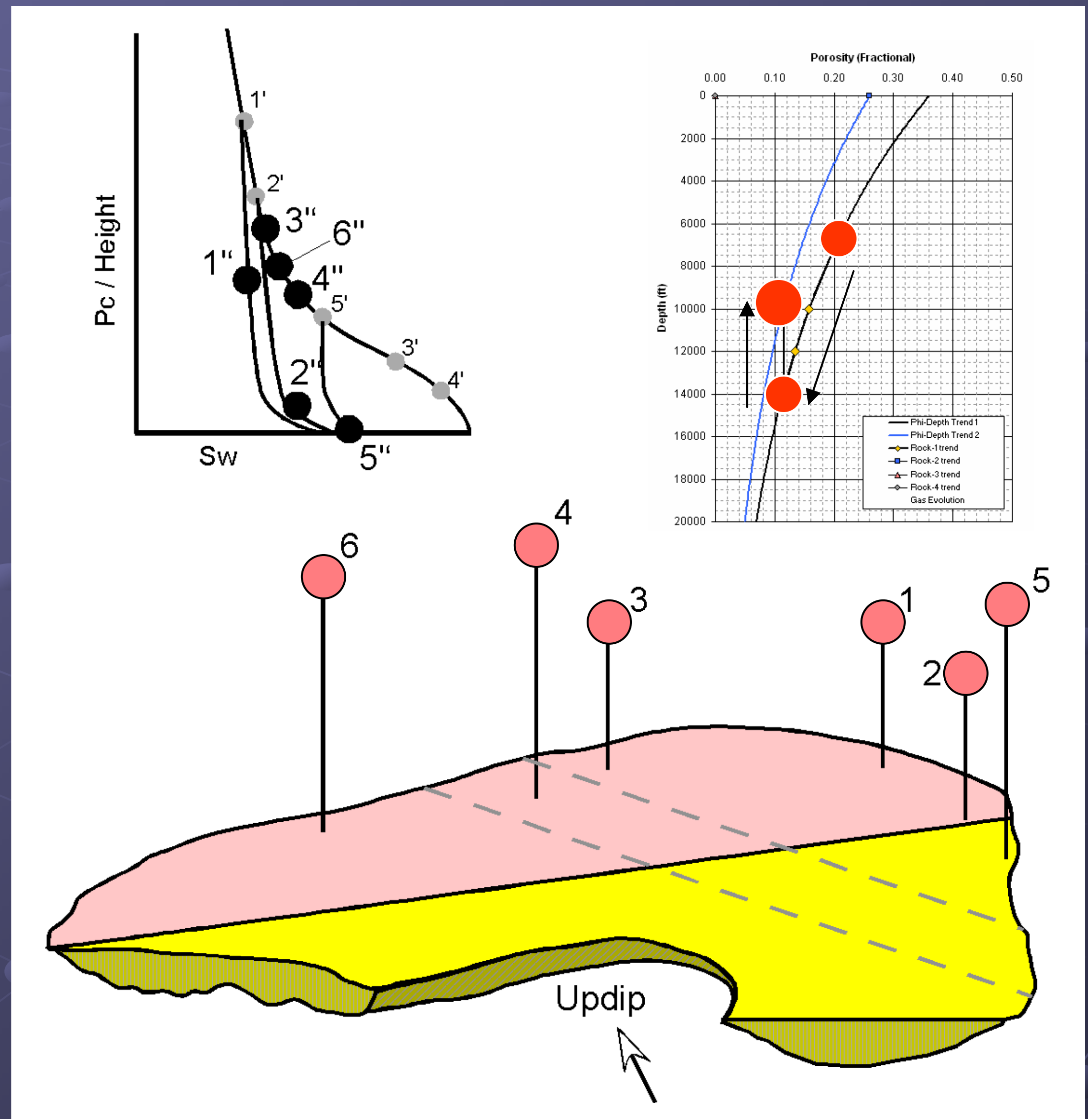
Tight gas residual saturations

Hg-saturation on extrusion & counter-current imbibition



Tight-gas hydrocarbon model
uplift, gas expansion and re-distribution

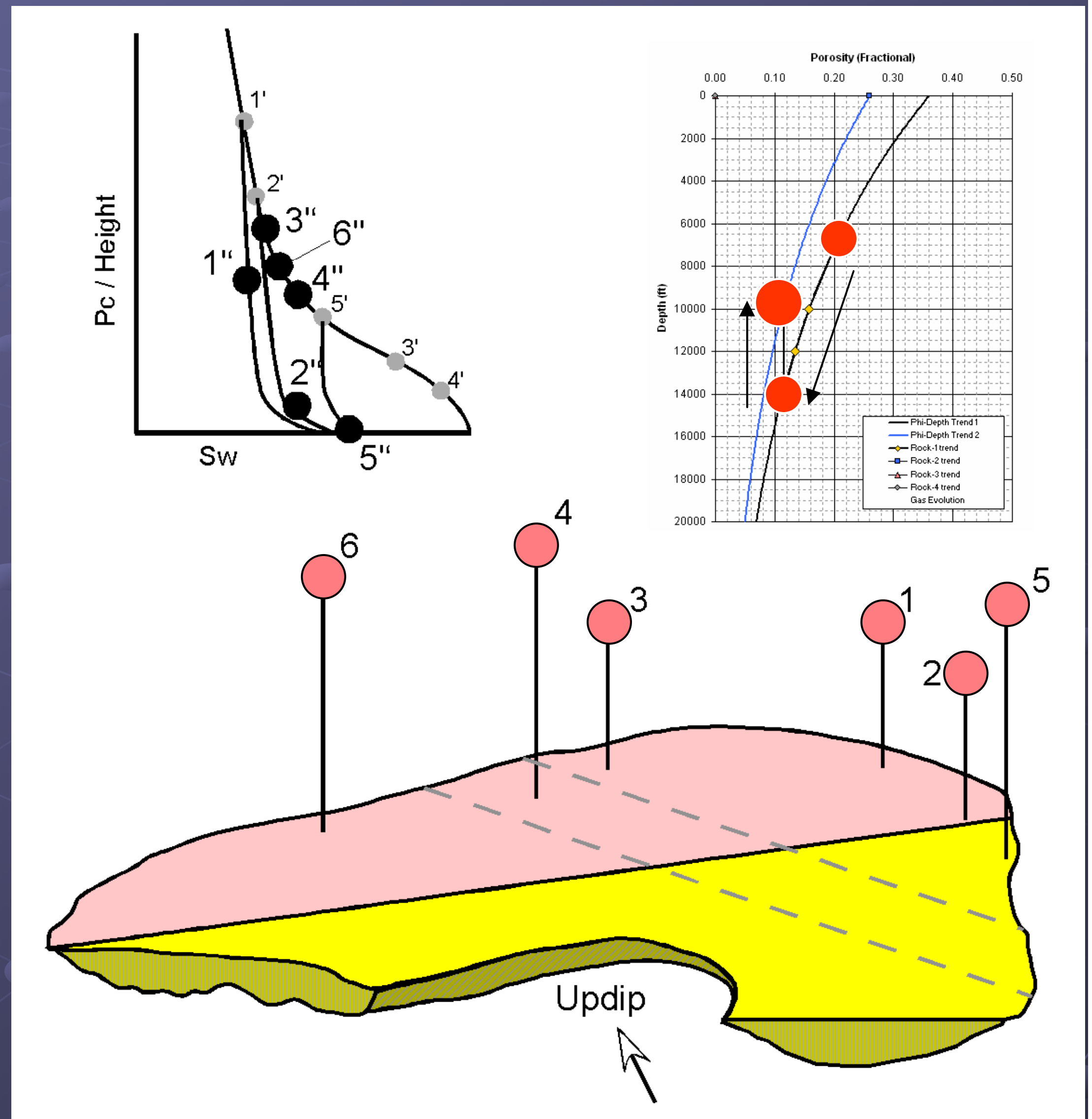
- Uplift causes –
  - Structural re-adjustment
  - Gas expansion (drop in pressure)
  - Gas re-distributed due to buoyancy.
- This causes –
  - Drainage process in some areas (3, 4 & 6)
  - Imbibition processes in some areas (1, 2 & 5)
  - Residual saturation in some areas (5)



- Notice the wide range of capillary pressures (column heights) as a function of Sw.

Tight-gas hydrocarbon model
uplift, gas expansion and re-distribution

- Within a narrow range of Sw – have a wide range of Pc and a wide range of outcomes
  - All the wells would give gas-shows while drilling
  - All the wells would calculate “pay”
  - Some of the wells would produce gas – with little water
  - Some of the wells would produce gas – with substantial water
  - Some of the wells would produce water – with little-to-no gas.



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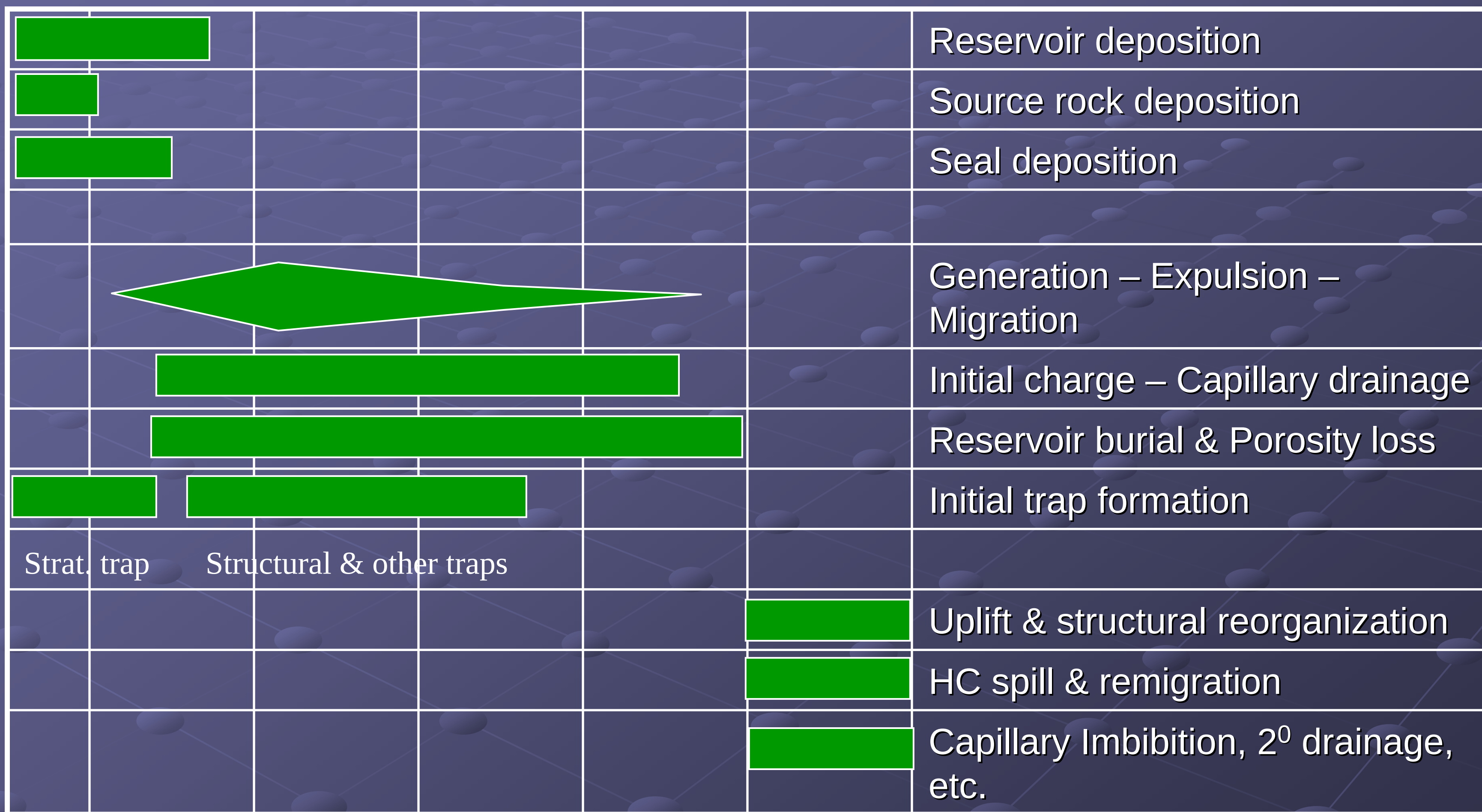
- Peter McCabe – CSIRO, Sydney, Australia

Petroleum System Event Chart

generalized for uplifted Western basins



- Several large fields are in late-stage structures (Pinedale)….
- Classic petroleum systems analysis would heavily discount these late traps.