Permeability Jail Revisited: What is it, and how did we ever get into it?

Robert Cluff

The Discovery Group Inc.

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What is “permeability jail”?

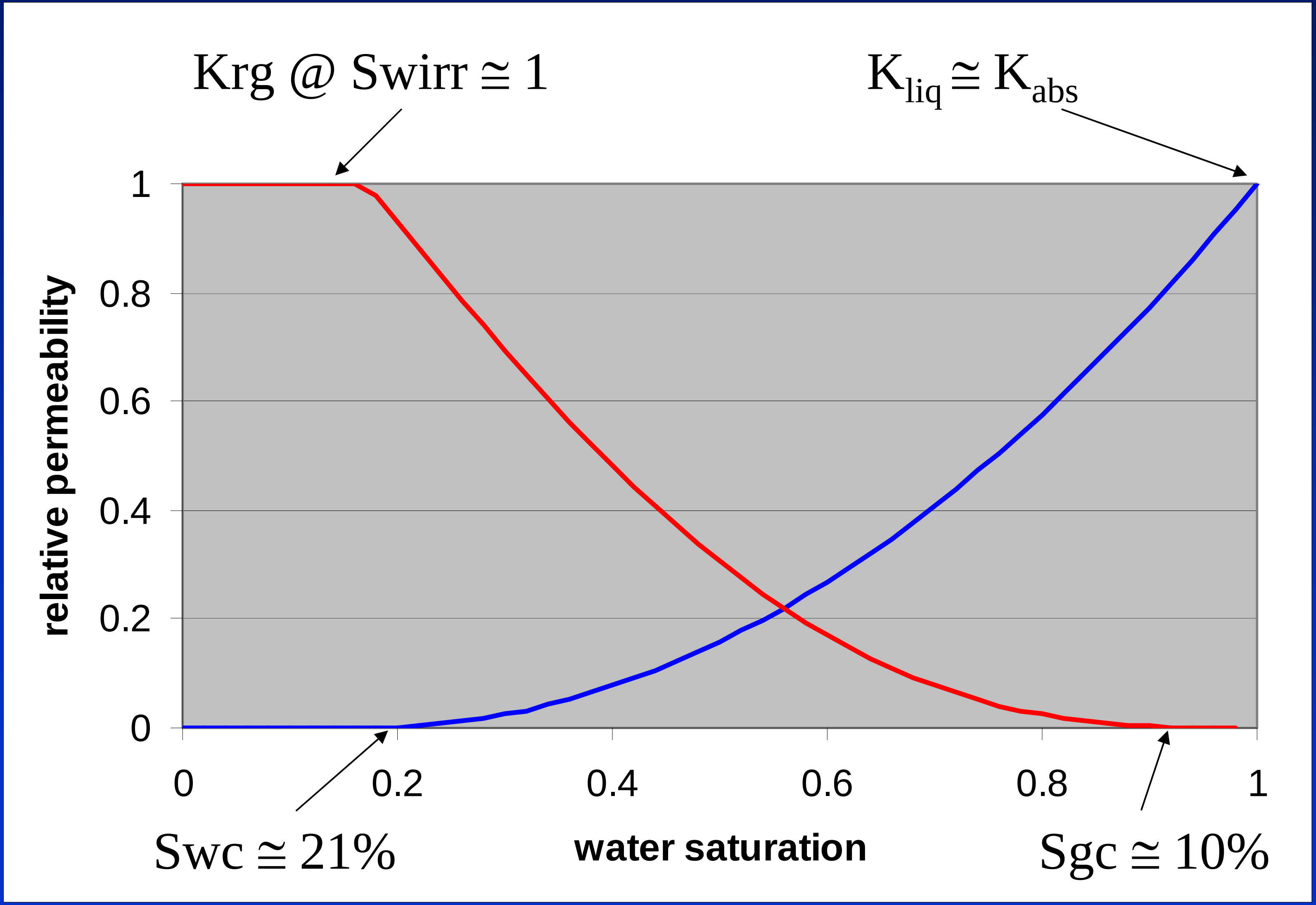
- Permeability jail is the saturation region where, in low permeability rocks, the relative permeabilities to *BOTH* gas and water are so low that neither phase has any effective flow capacity.
  - only appears below 50 to 100 μD Kabs
  - defined at <2% Krg or Krw
- Both gas and water block the other phase from moving.
- Everything is locked up, nobody is going anywhere…

Characteristics

- Minimal water production associated with non-commercial gas rates
- DST's commonly recover gas cut mud, small amounts of free gas, little (but rarely zero) water
- Associated with the downdip limits of structural and stratigraphic accumulations
  - although traps are commonly subtle
  - or former traps that have been breached or tilted out
- Very common in "basin centered gas" areas

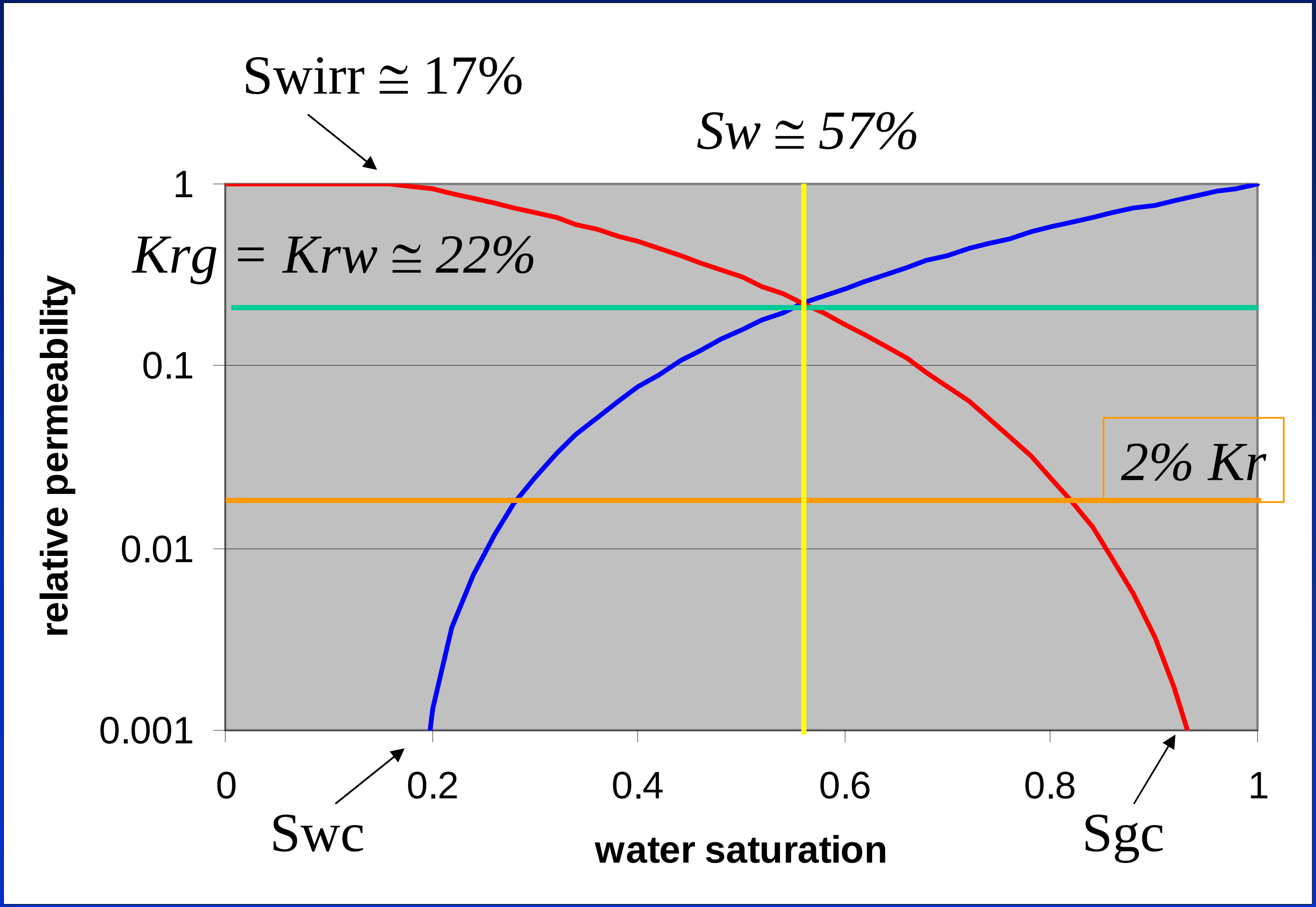
Classic Krg & Krw behavior

high permeability (10 md, 18% ϕ) sandstone



Semi-log curves are clearer….

high permeability (> 10 mD) sandstone



Let’s review some basic terms

- $K_{absolute}$, K_{abs}
  - absolute permeability
  - Specific permeability to the non-wetting phase
  - Gas (air) perm measured in dry rock (0% Sw)
    - we use it to mean Klinkenberg corrected permeability at reservoir stress conditions, a.k.a. K_{inf} , K_{∞} , K_{insitu}, $K_{k\text{-}is}$
- K_{liquid} , K_{liq}
  - liquid permeability, usually brine
  - Specific permeability to the wetting phase
  - determined at 100% Sw

More basic terms

- $K_{effective}$, K_{eff}
  - Effective permeability to one phase (gas, oil, or water) at partial water saturation
    - $K_{eg} <= K_{abs}$
    - $K_{ew} <= K_{liq} <= K_{abs}$
- Krg & Krw
  - Relative permeability to gas or water

$$Krg = K_{eg} / K_{abs} \qquad Krw = K_{ew} / K_{abs}$$

Modeling relative permeability

- Corey equations (1954):

  Effective water saturation:

  $$Swe = ((Sw\text{-}Swirr)/(1\text{-}Swirr))$$

  Relative permeability to water:

  $$Krw = Swe^4$$

  Relative permeability to gas:

  $$Krg = (1 - Swe)^2 * (1 - Swe^2)$$

- Corey equations are simple, get the shapes about right, easy to fit to lab data

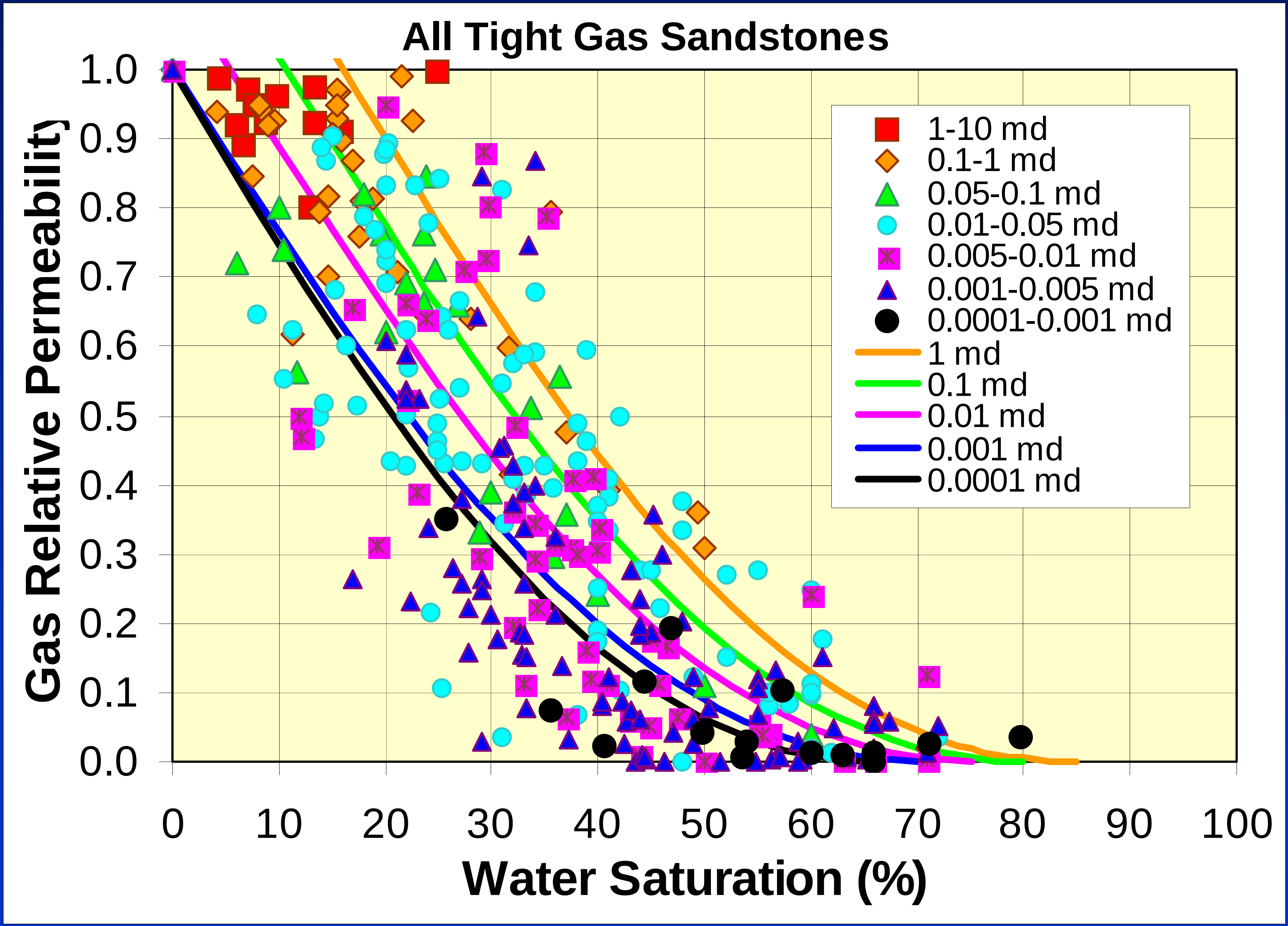
Modified Corey

- Corey suggested exponents 4 and 2 for consolidated rocks- but these are better treated as variables (*p*, *q*)
- Swirr is also a rock type specific variable
- Byrnes, 2003, suggested an alternative formula:

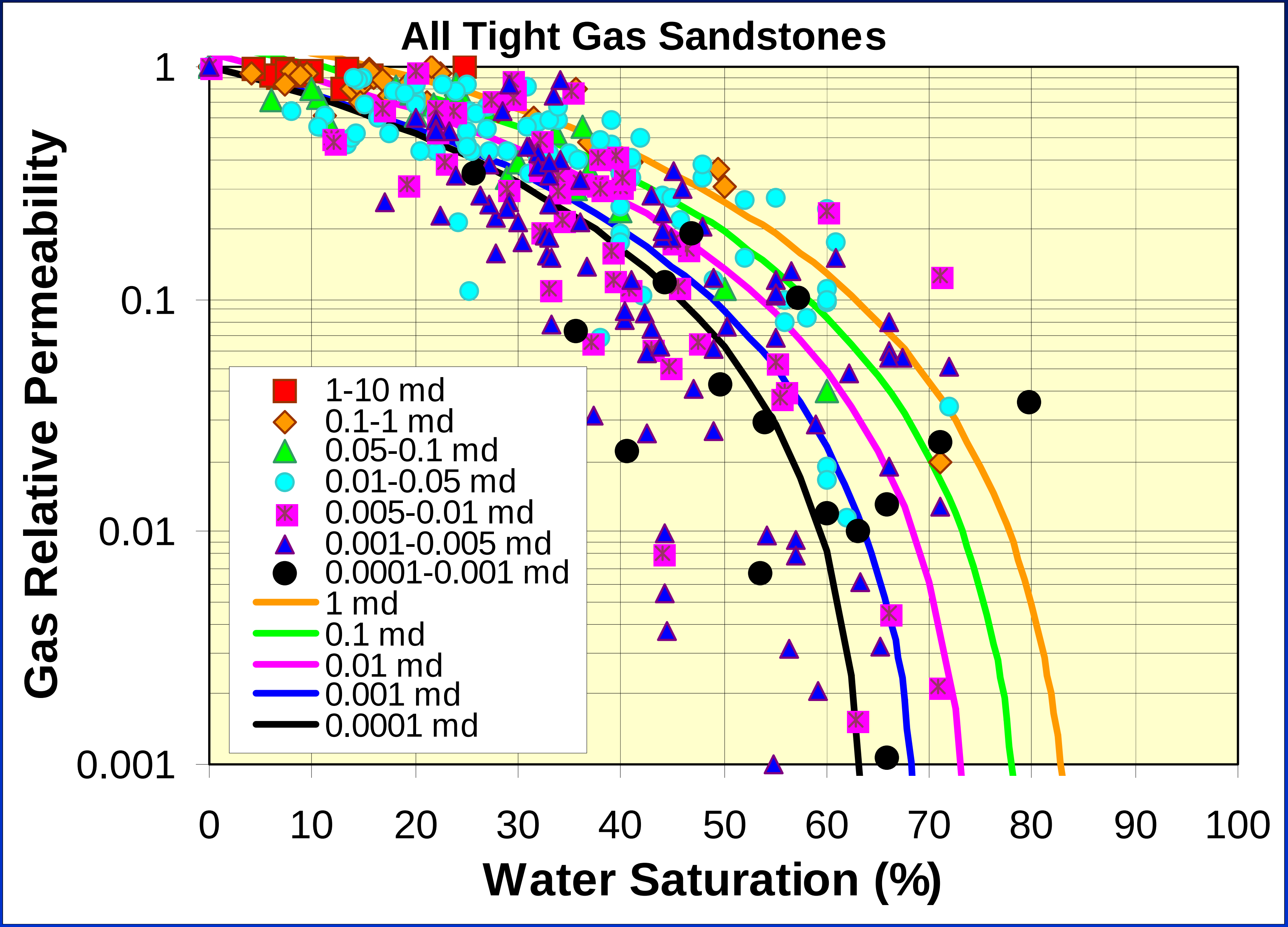
$$Krg = [1- (Sw-Swc)/(1-Sgc-Swc)]^{p} * [1 – ((Sw-Swc)/(1-Swc))^{q}]$$

  – where critical parameters are Swc, Sgc, p, and q

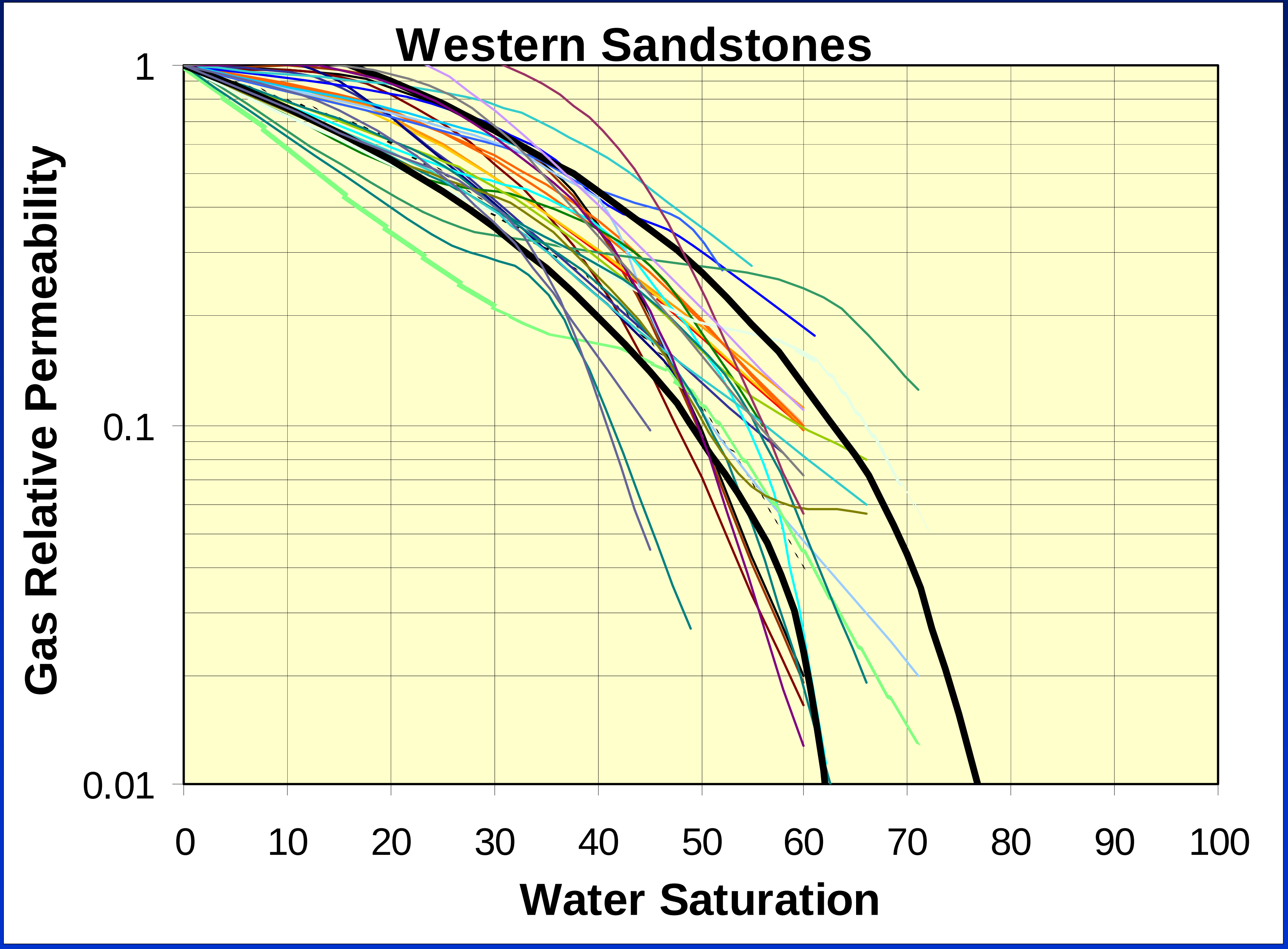
Single point Krg data (linear plot)



Single point Krg data (log plot)



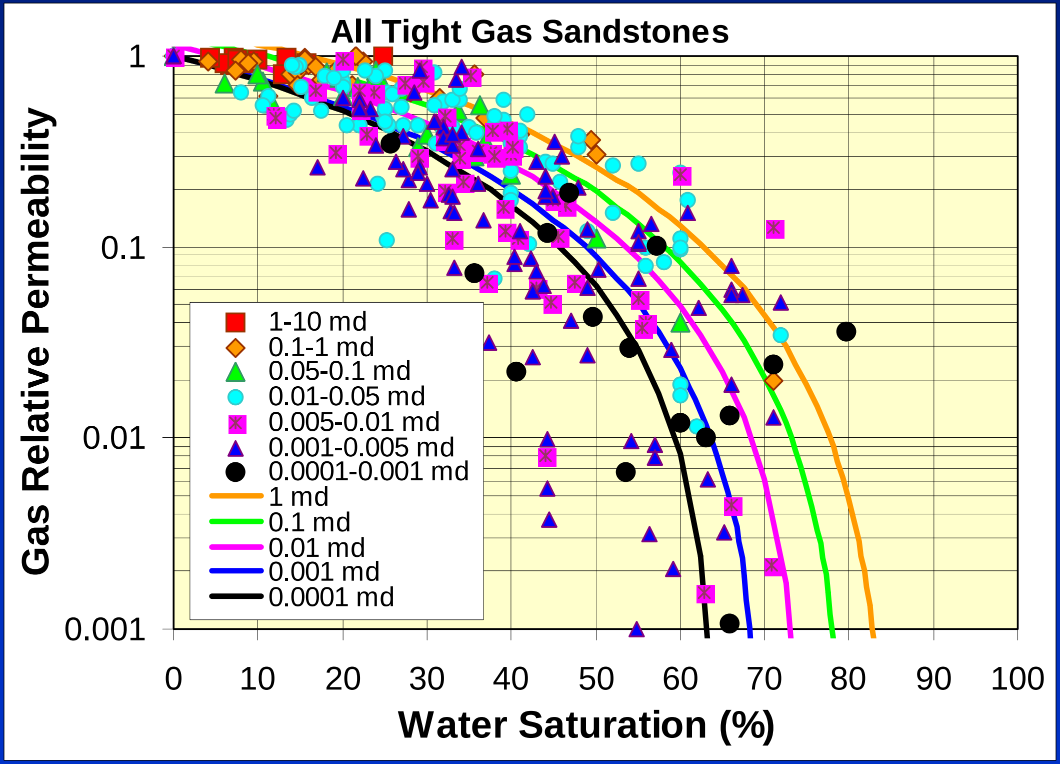
Multipoint Krg data



What do we think is going on?

1. S_{wc} decreases with decreasing $K_{k\text{-}is}$

⟵ S_{wc}



⟵ S_{gc}

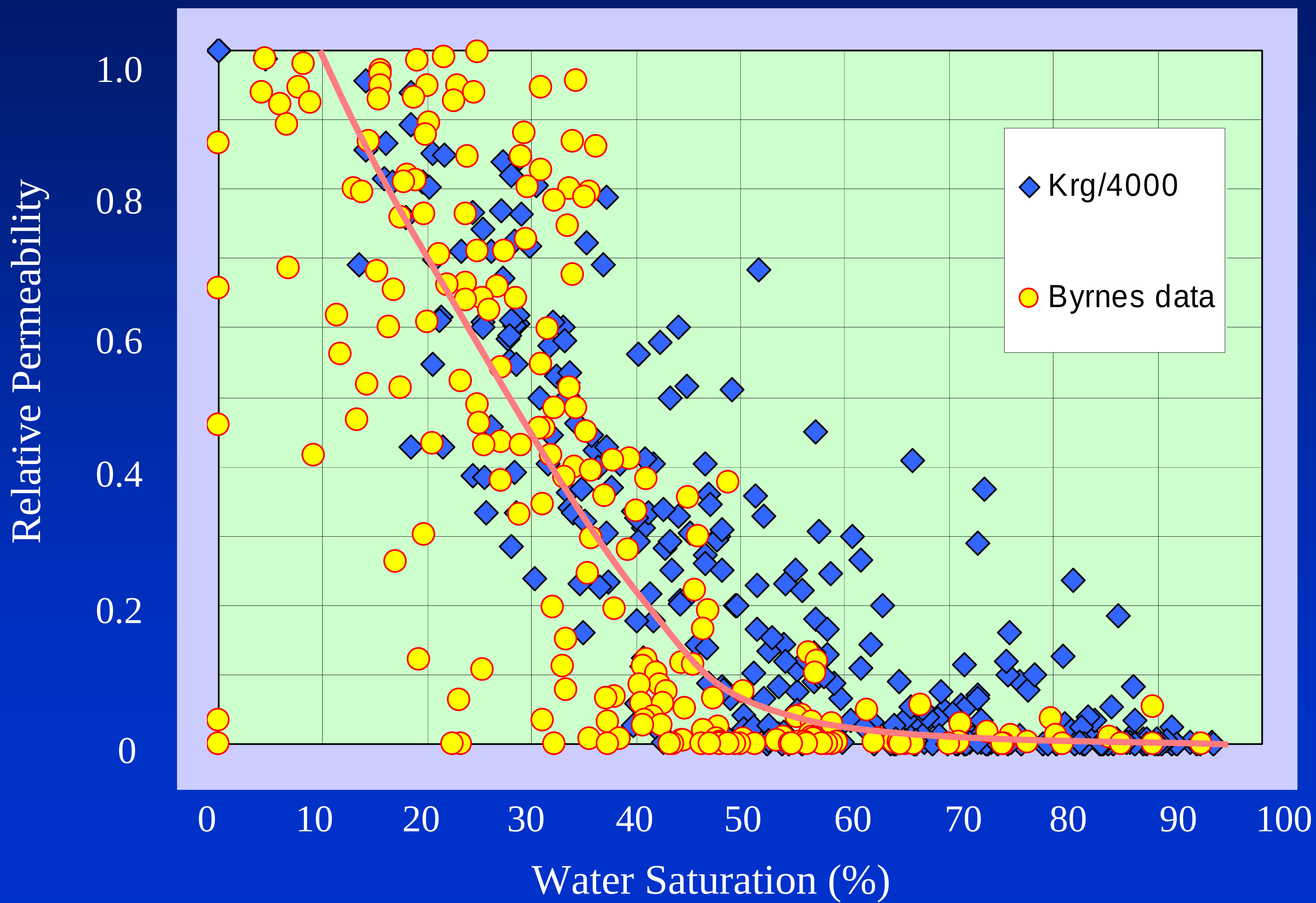
2. S_{gc} increases with decreasing $K_{k\text{-}is}$

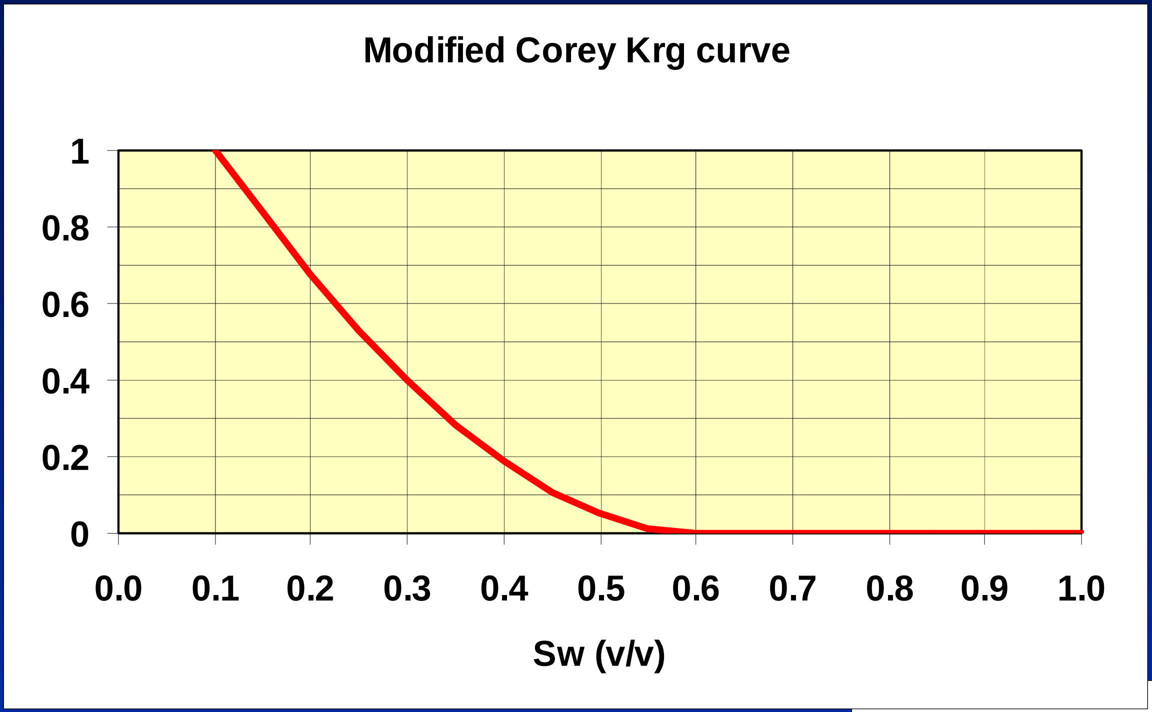
3. at any given S_w K_{rg} increases with increasing $K_{k\text{-}is}$

$K_{rg,Sw}$ ↑

4. Does the curvature change? Maybe.

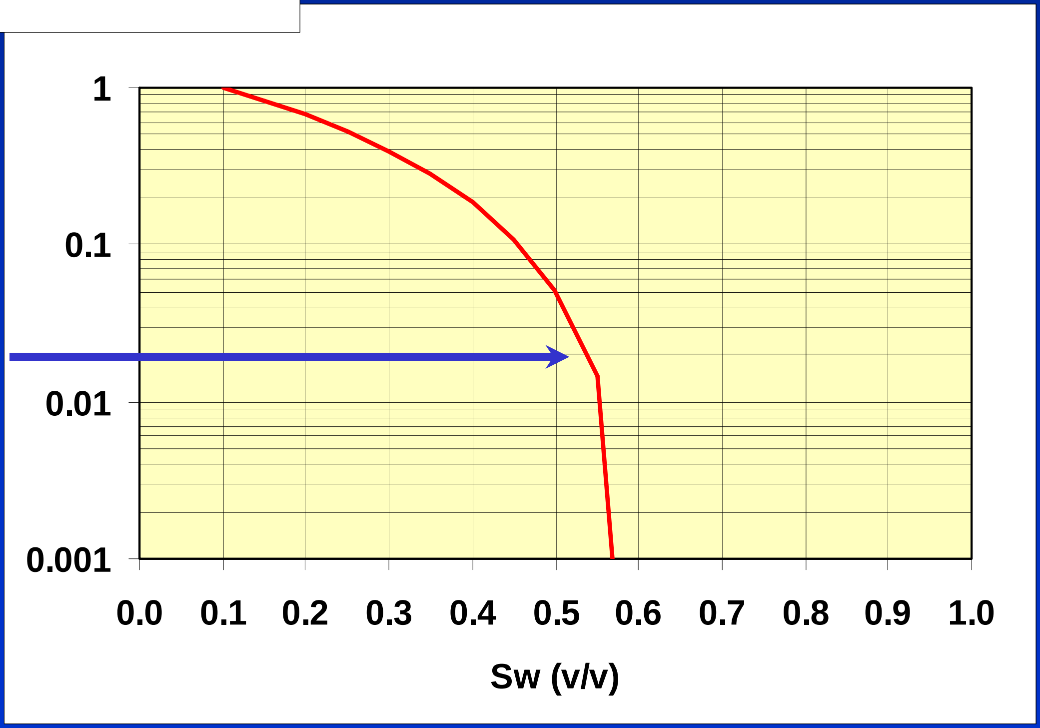
Greater Green River basin tight sands *(n = 583)*





Modeled Krg curve for a high quality tight gas sandstone (40 µD), e.g. Jonah, Rulison

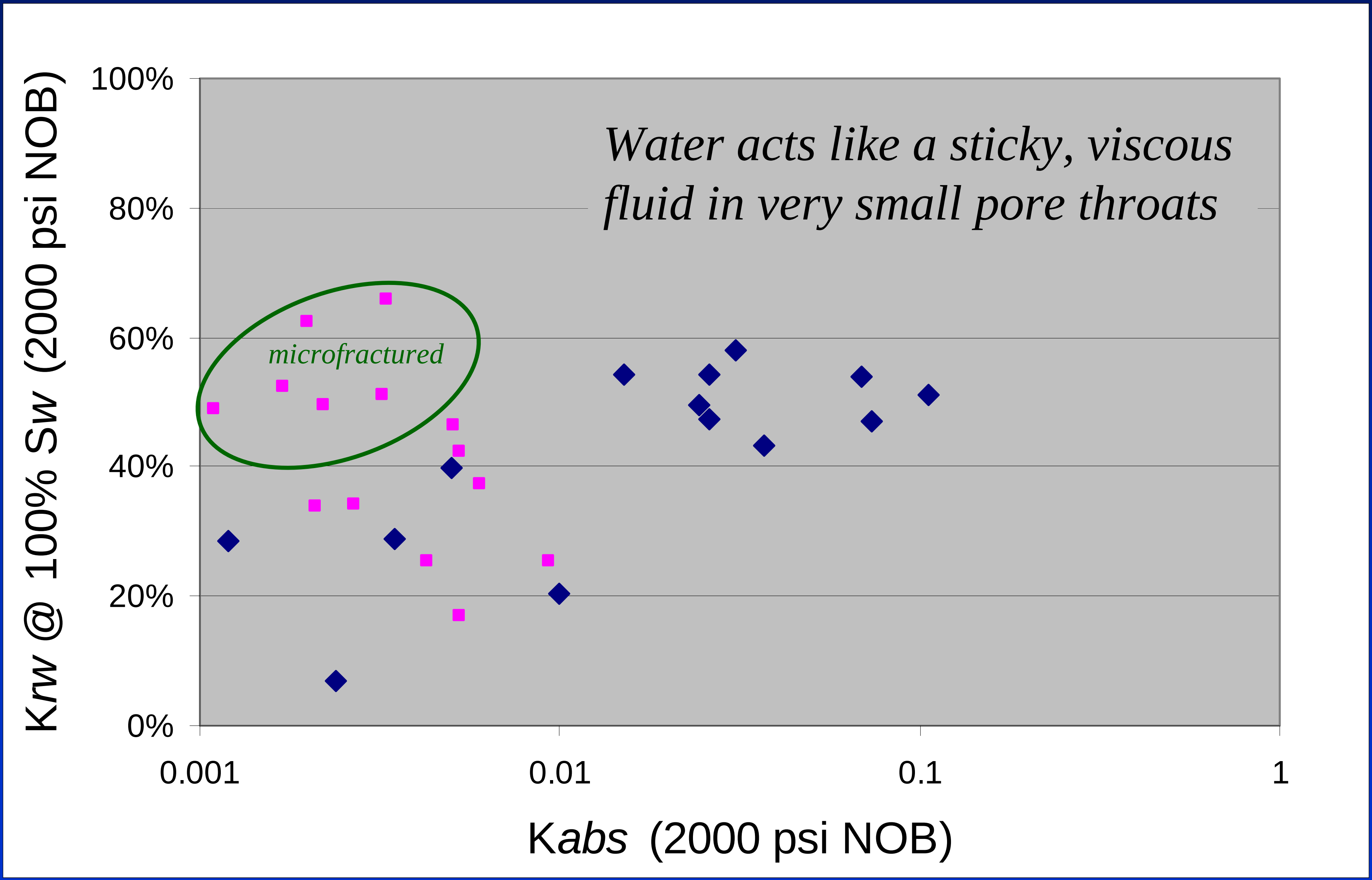
In tight sands, Krg < 2% is ~ the critical saturation where flow becomes measurable in the field (more than a few MCFD)



Permeability to water

- *We don’t have nearly as much data on this side of the problem……*
- FIELD evidence is water permeabilities are quite low, such that many people think these wells are producing “no water”
- In fact, WGR’s of 10’s to 1000’s of bbls/MMCF are common, far above water of condensation
- BUT, absolute water rates are small

K_{brine} vs. K_{abs}

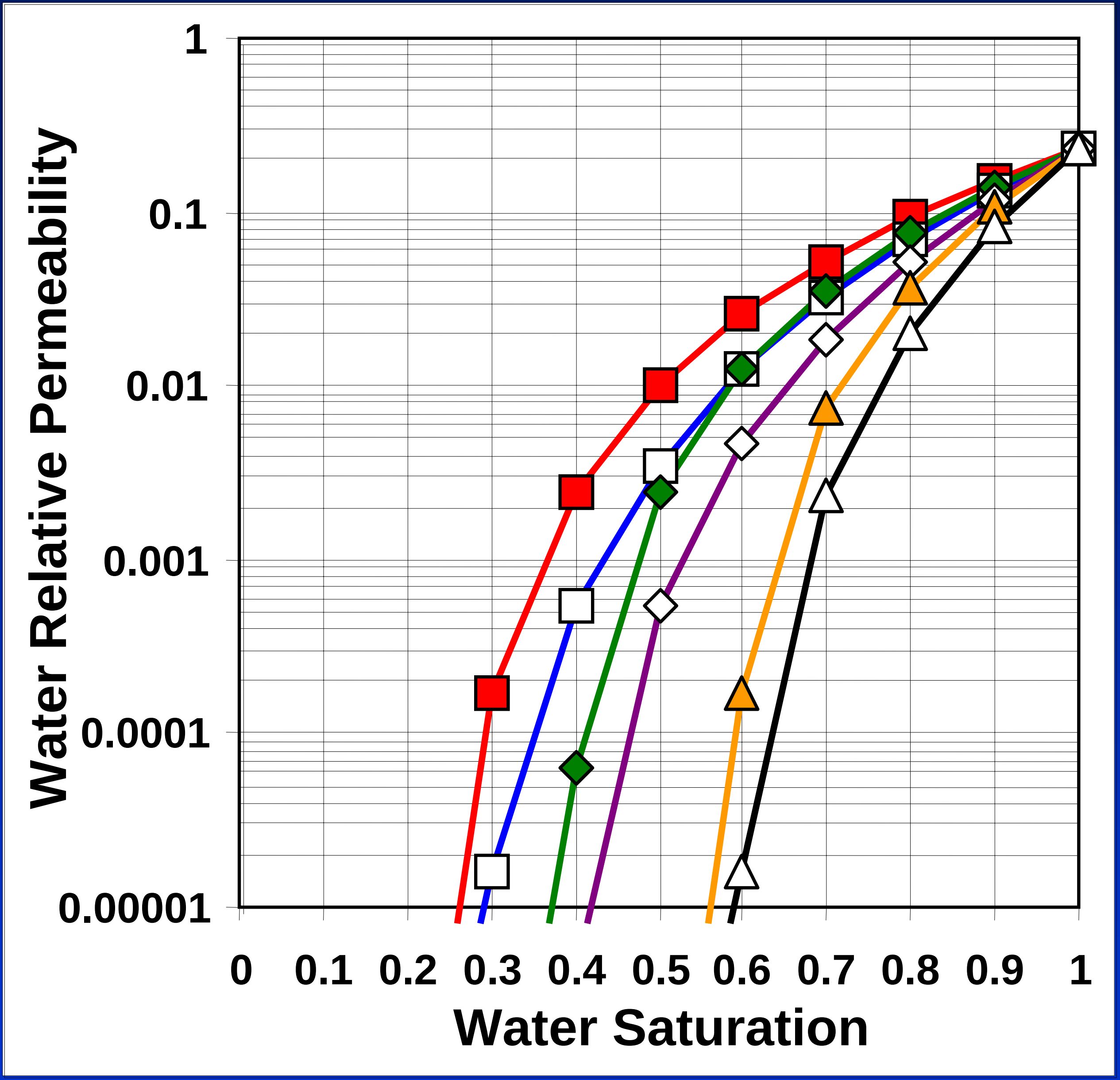


Krw summary

- Lab data show $K_w << K_{abs}$
  - e.g. Jones and Owens, 1980:

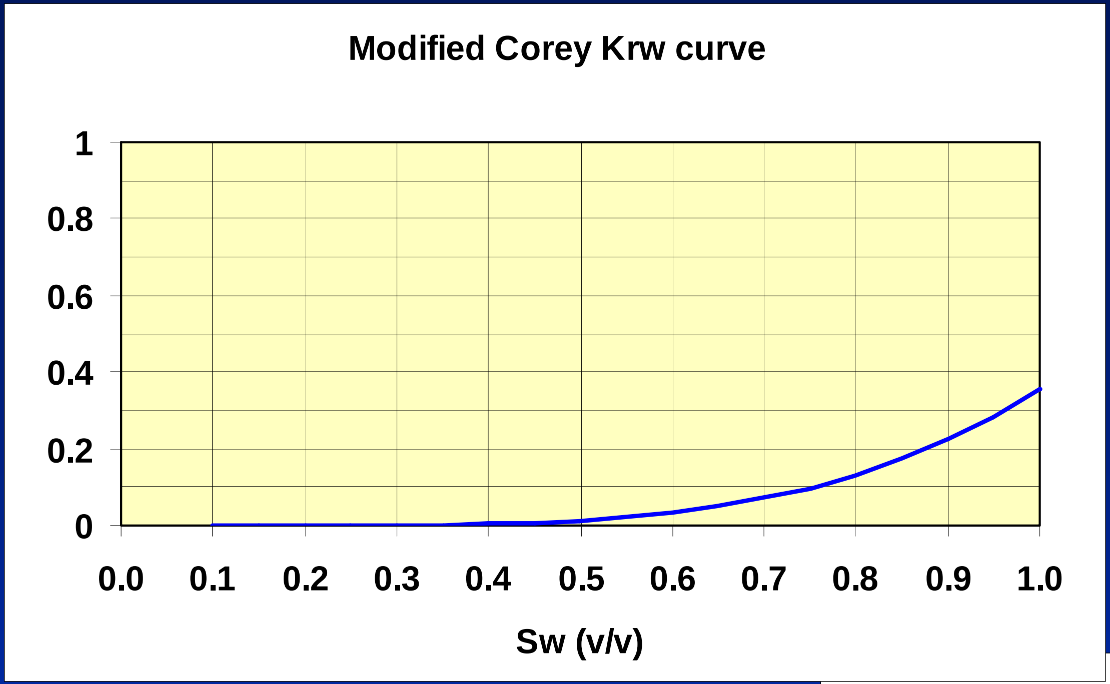
$$K_{wtr} = K_{inf}^{\ 1.32} \qquad \text{for } K_{abs} < 1 \text{ mD}$$

- As absolute permeability decreases
  - K_{water} decreases
  - We believe (but cannot prove) Swc shifts to the right (to higher Sw's) at the same time

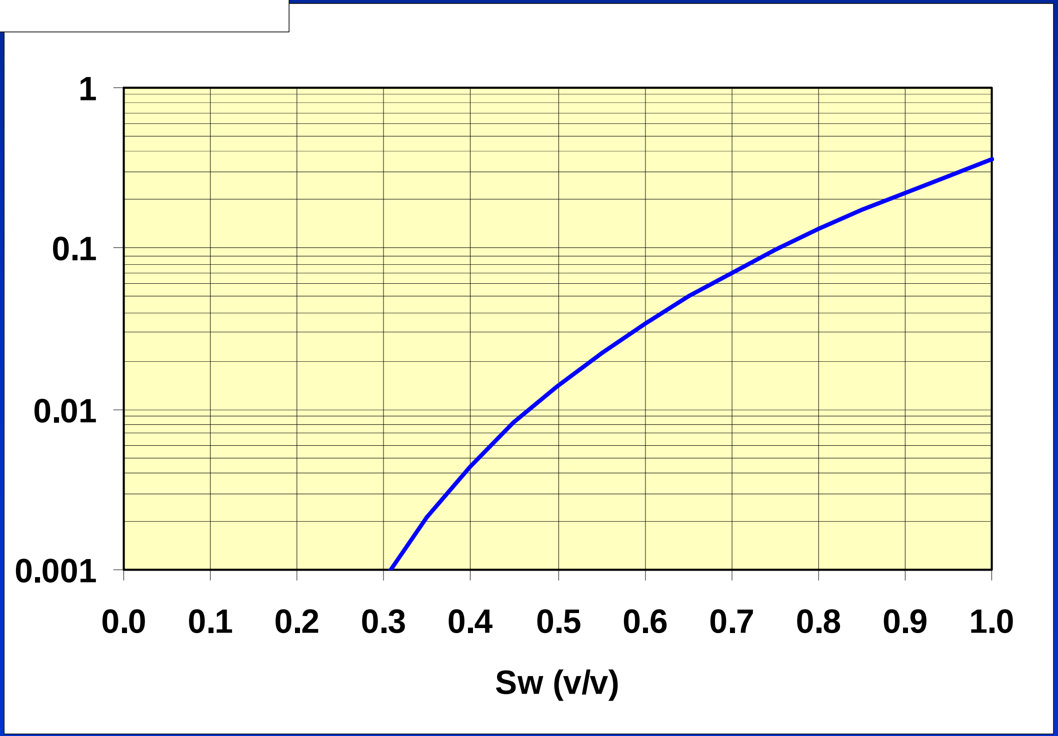


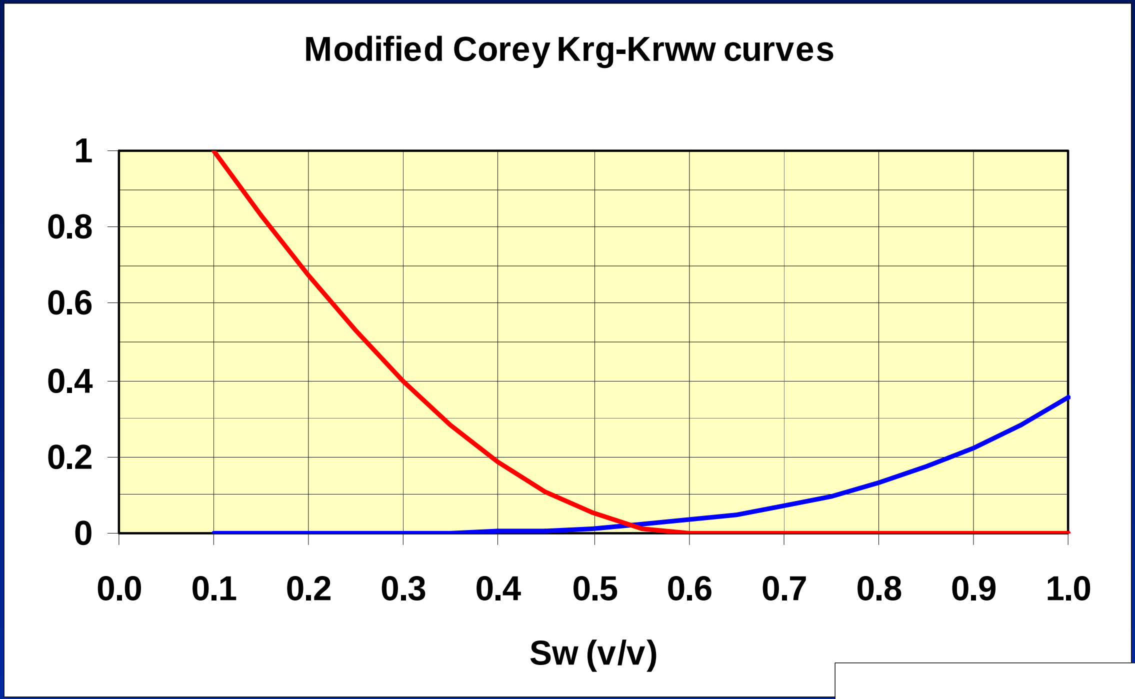
Modeled water relative permeability

Byrnes, 2003

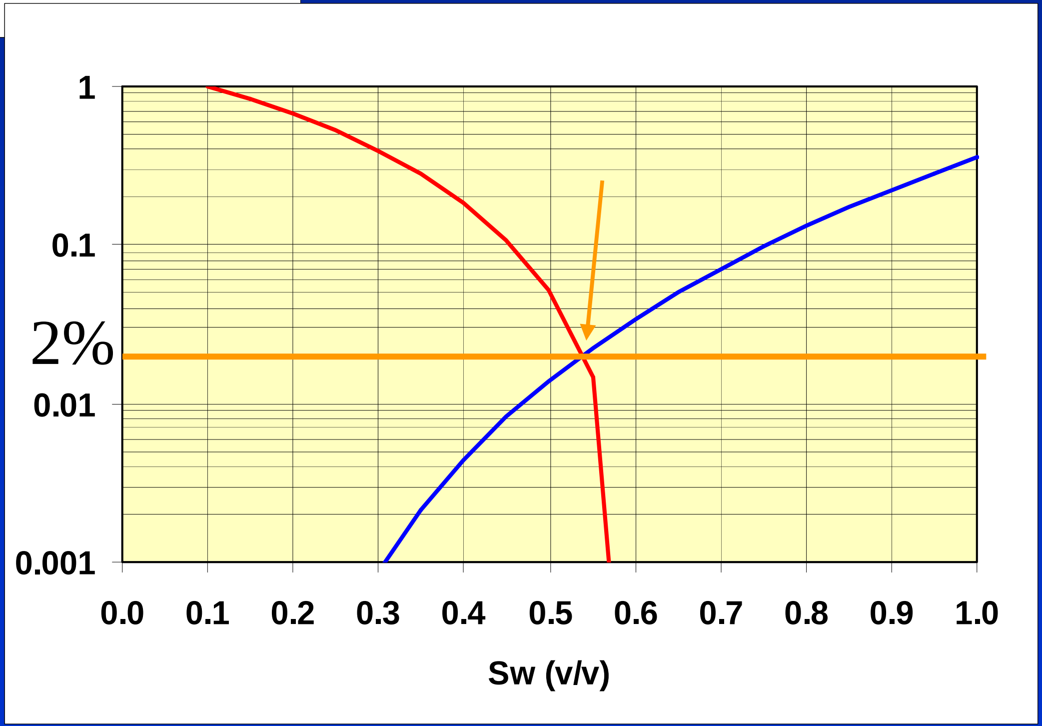


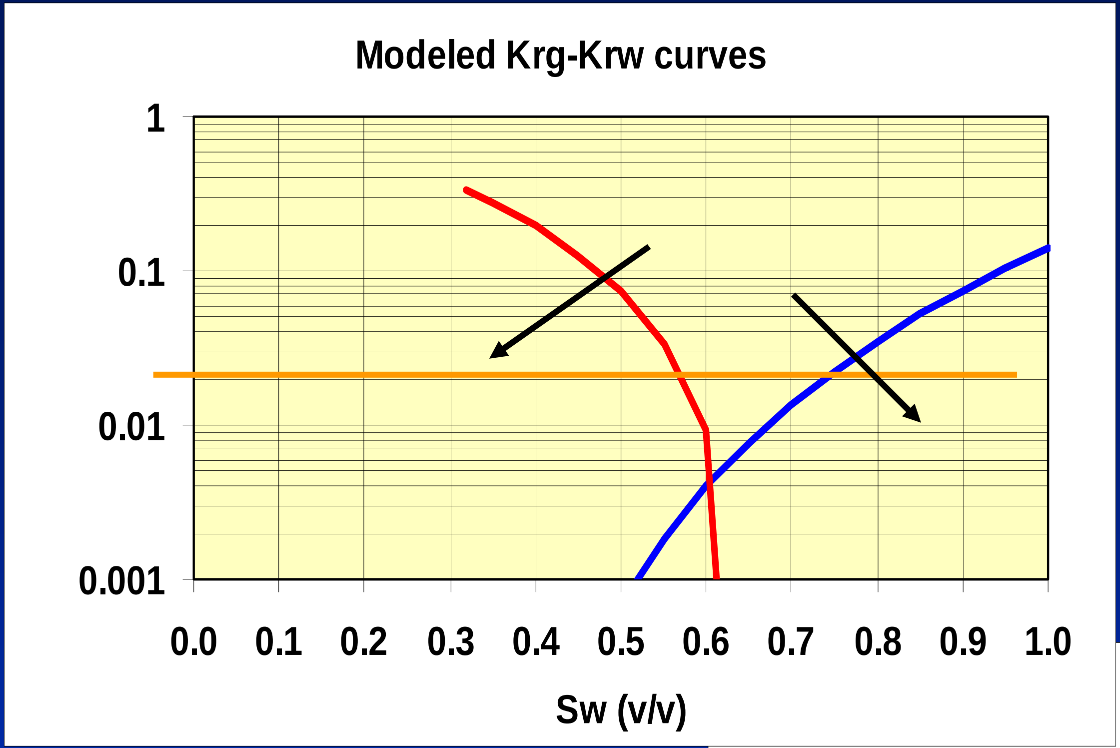
Hypothetical Krw curve for high quality tight gas reservoir rock (40 µD)
e.g. Jonah or Rulison



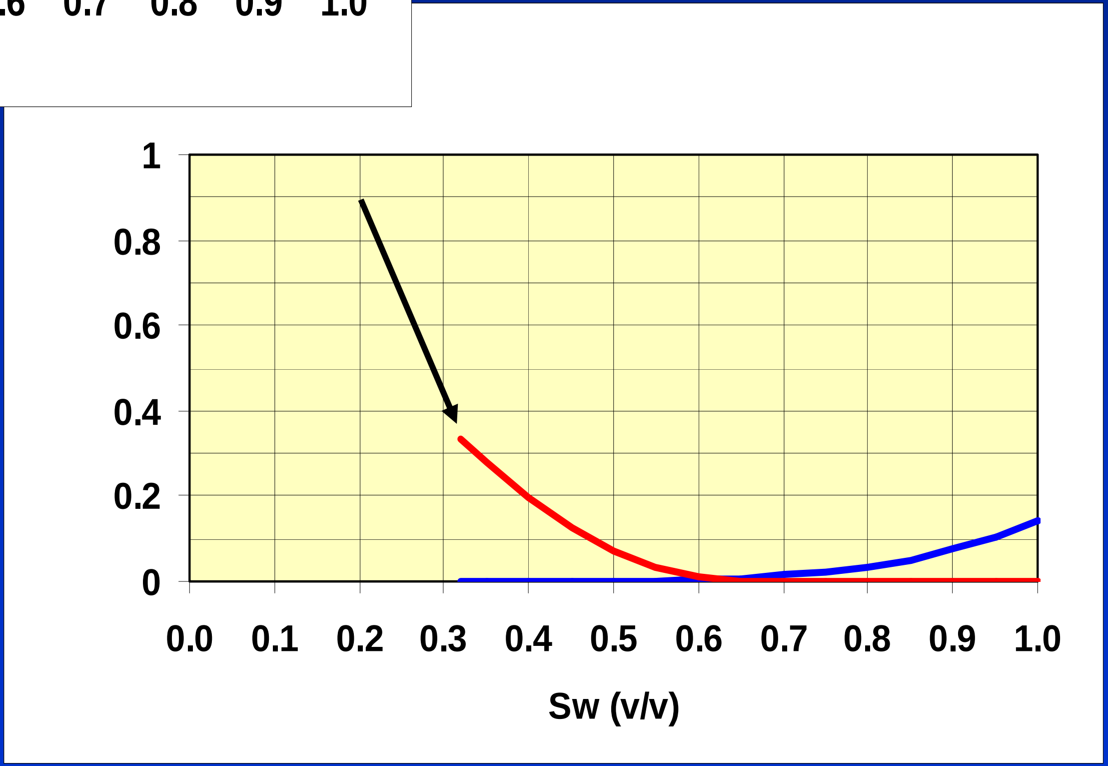


Putting them together…..



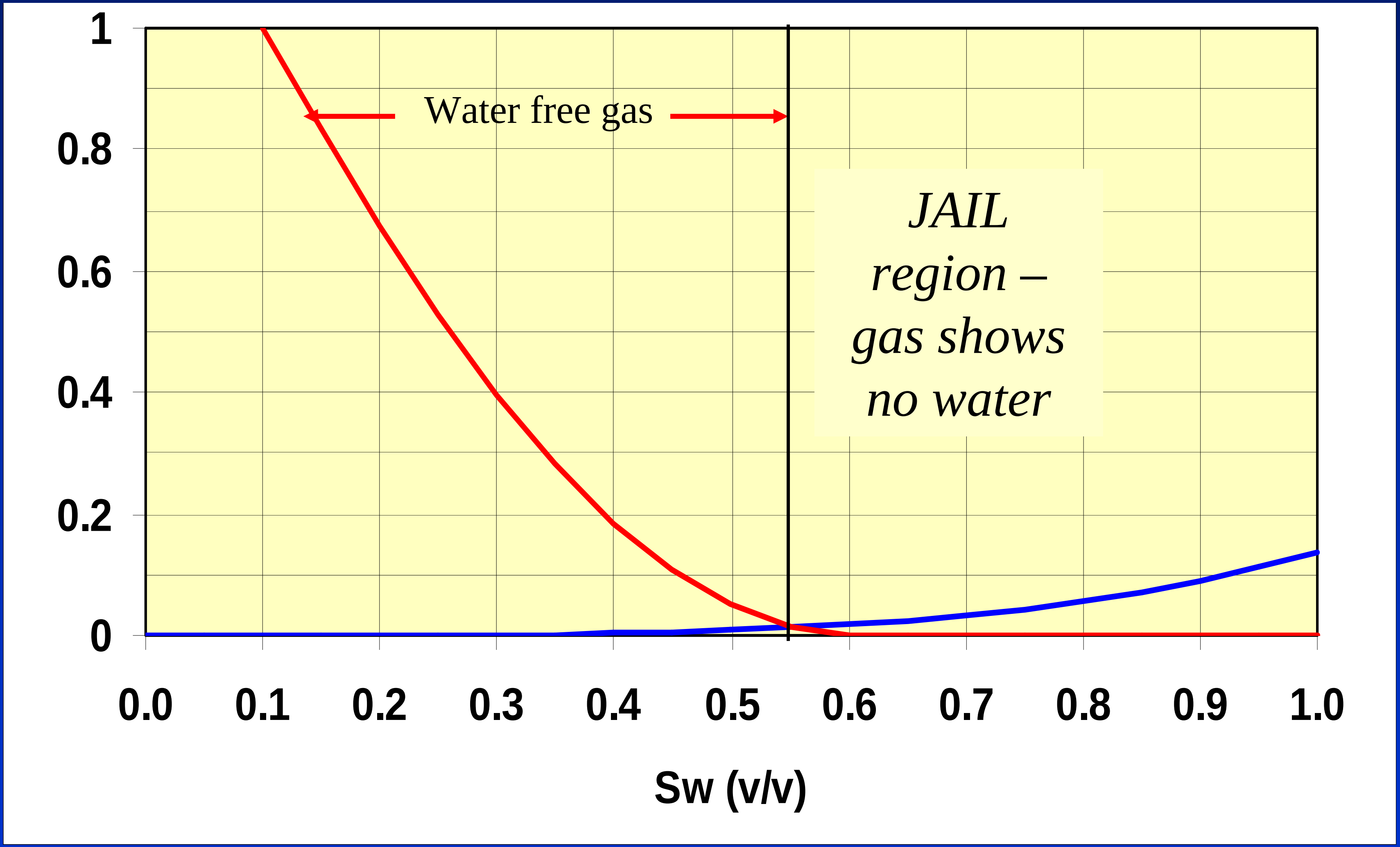


As rock gets tighter, curves increasingly diverge



6% ϕ, 3 μD model

Sw < Swc = water free gas production in tight sands



So how does the gas get into jail?

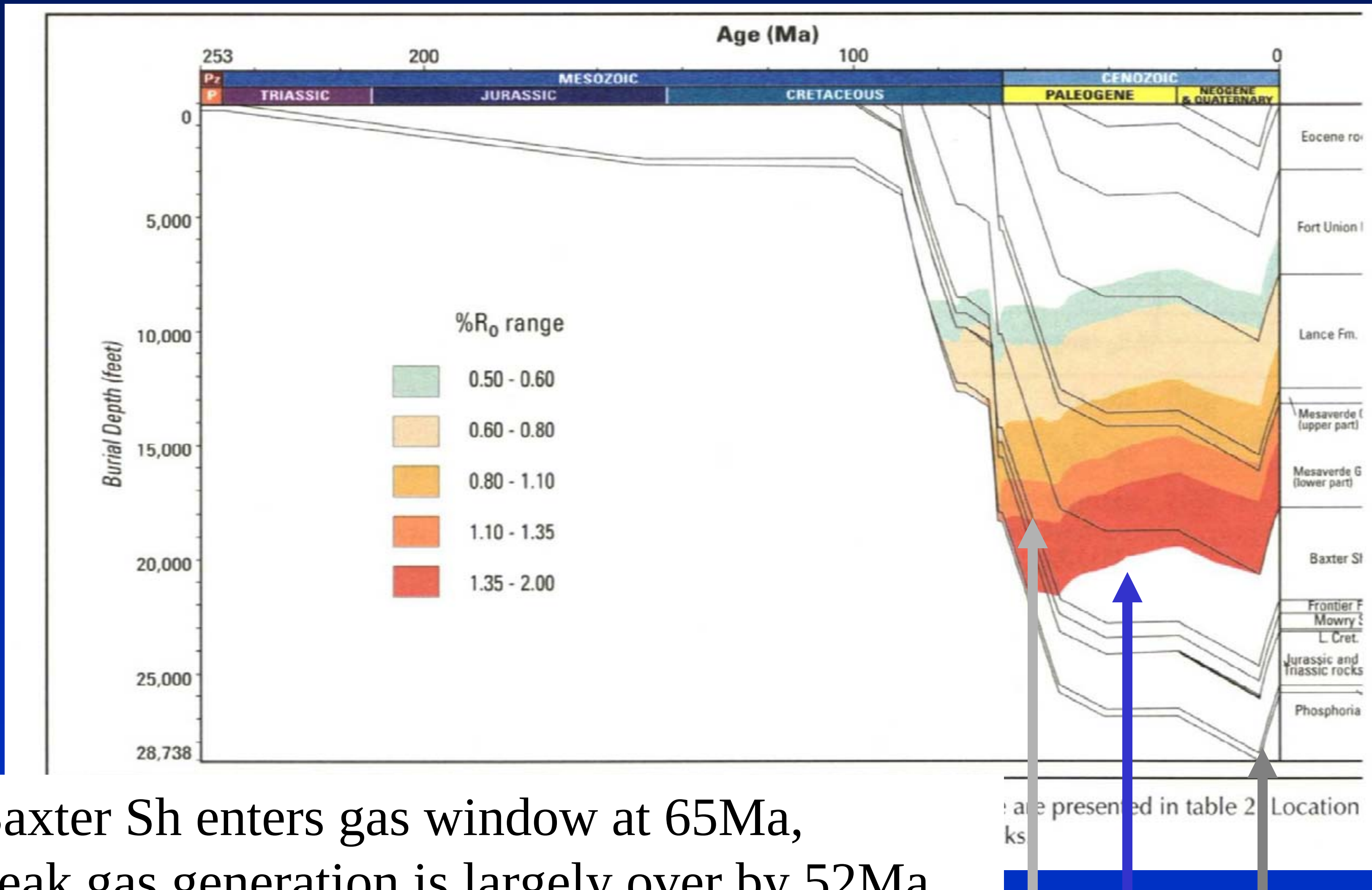
- If Permeability jail is real, you shouldn’t be able to move gas into a trap across the barrier- the entry Pc would be too high
- It seems like these would all be wet sands with less than critical gas saturation……
- OK Bob, we gotcha!

Ah, but how do you put a prisoner into a jail cell?

- You put the prisoner in a cell BEFORE you close the door.
- Permeability jail ONLY WORKS if you charge the sands early, when the reservoir quality was higher and you could freely drain the wetting phase
- *PERM JAIL IS A GEOLOGIC CONCEPT*
  - it requires early migration and charge,
  - then continued diagenesis to destroy the permeability

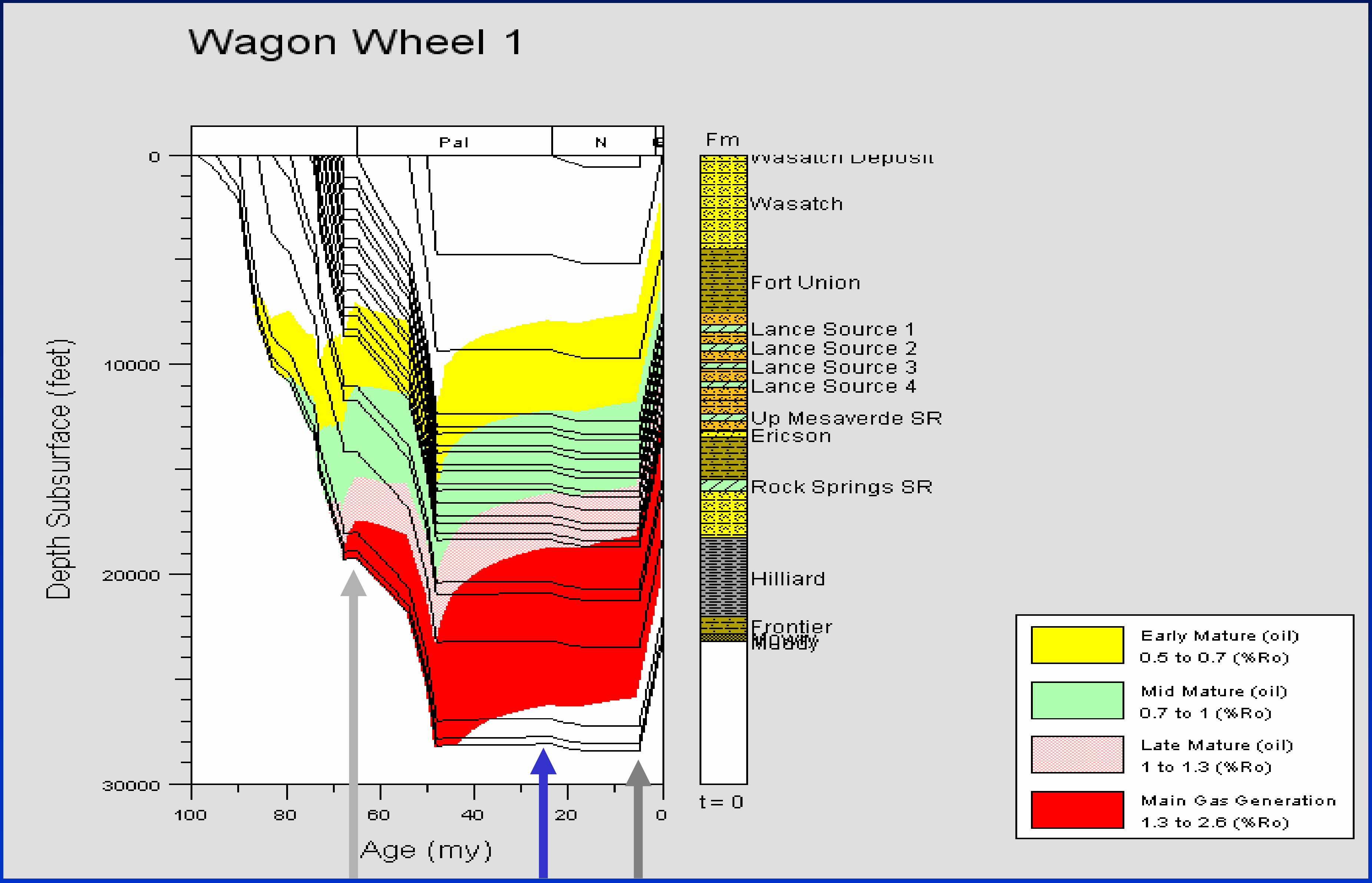
Stepwise: 1. Early gas charge

- Gas charge starts early- while rocks are still on their way down
- Generation slows, but continues, when maximum burial depths are reached and subsidence ceases
- Uplift essentially stops HC generation
  - Source rocks cool; kinetic theory of generation predicts C-C bonds have already been broken at formerly higher T's



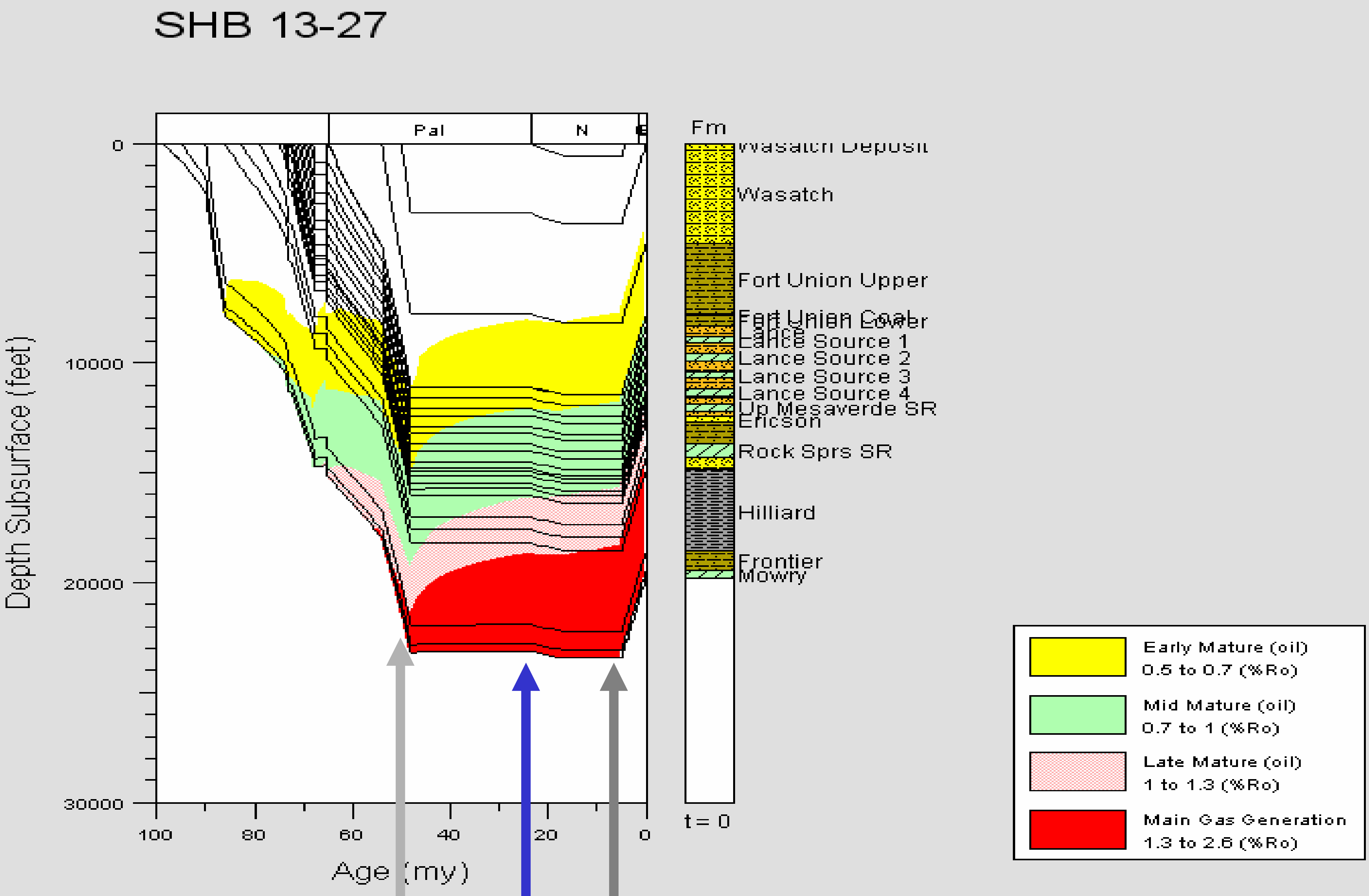
Baxter Sh enters gas window at 65Ma,
Peak gas generation is largely over by 52Ma,
Uplift commences at 5Ma and generation <u>stops</u>

Roberts, Lewan & Finn, 2004



65Ma → 6 Ma

Coskey, 2004



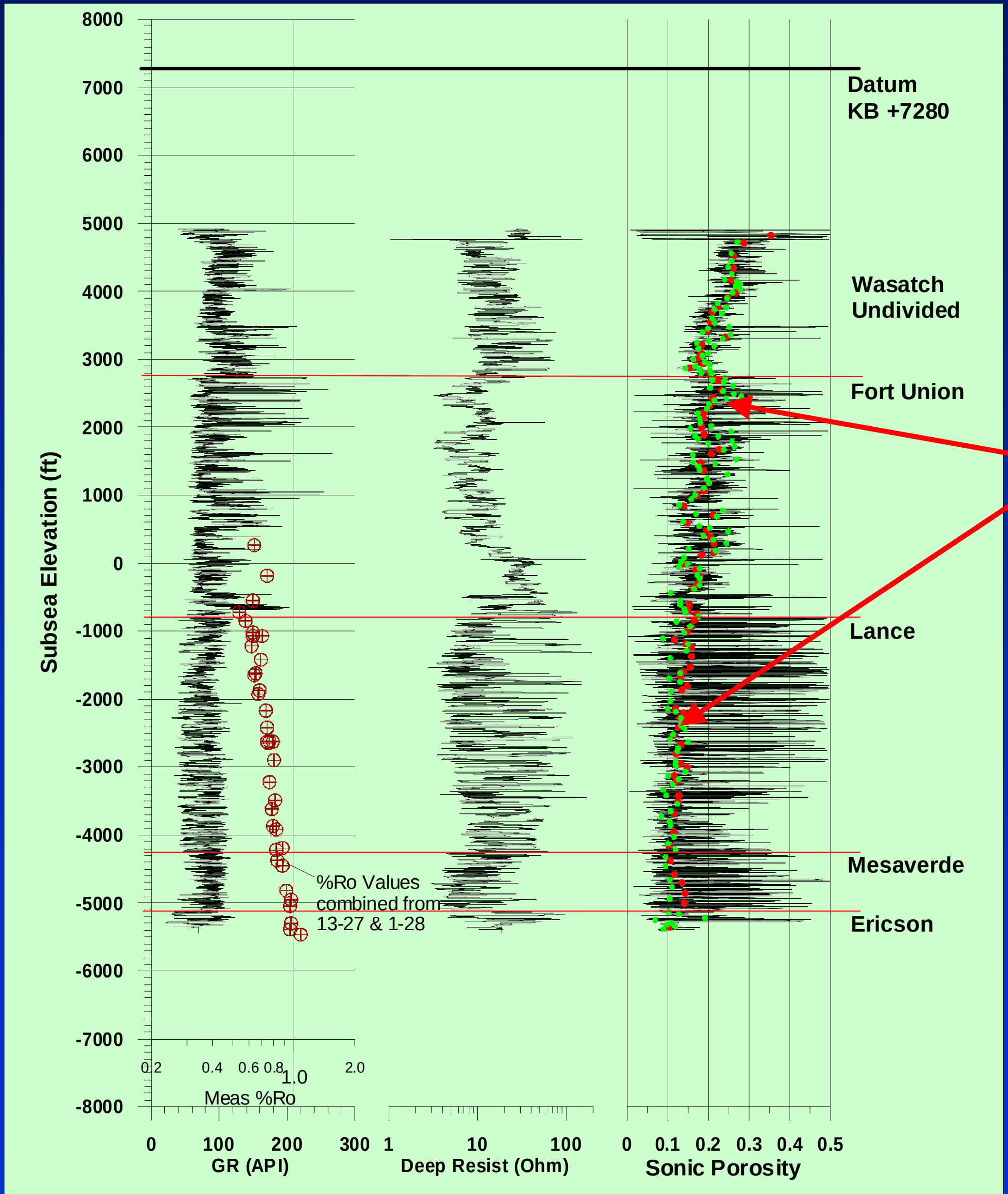
50Ma → 8 Ma

Coskey, 2004

2. Relentless loss of reservoir quality with additional burial depth, time, & temperature

- Compaction models predict ϕ was much higher when sands received their gas charge than it is today
  - perhaps 50 to 100% better! (12-24% vs. 8-12%)
- At these ϕ levels, reservoir permeability was probably in 10's of mD at time of migration and charge
- After 20 or 30 Ma additional diagenesis, perm drops by 3 to 5 orders of magnitude

Porosity Calibration Data



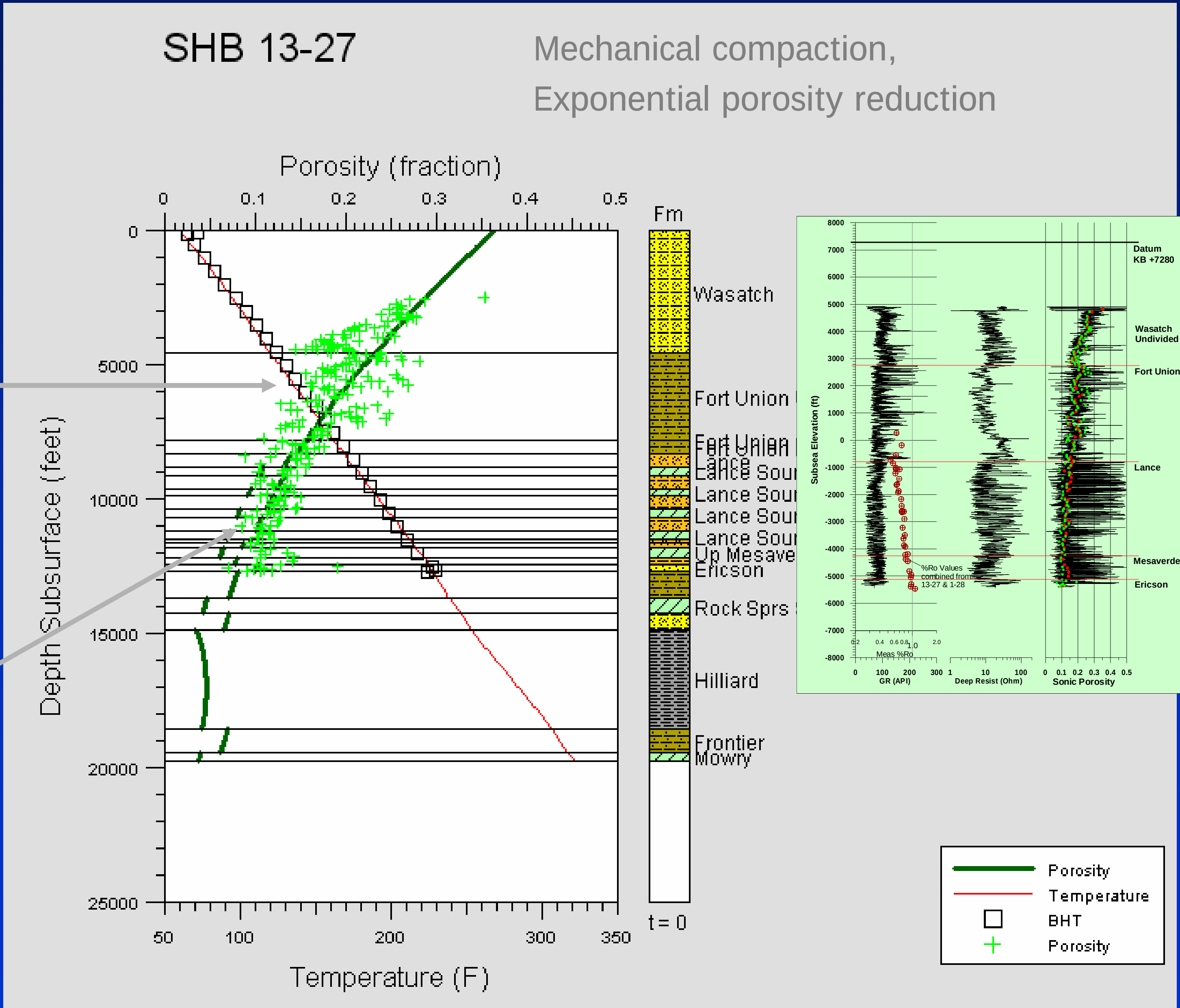
Porosity calibration data from SHB 13-27 well.

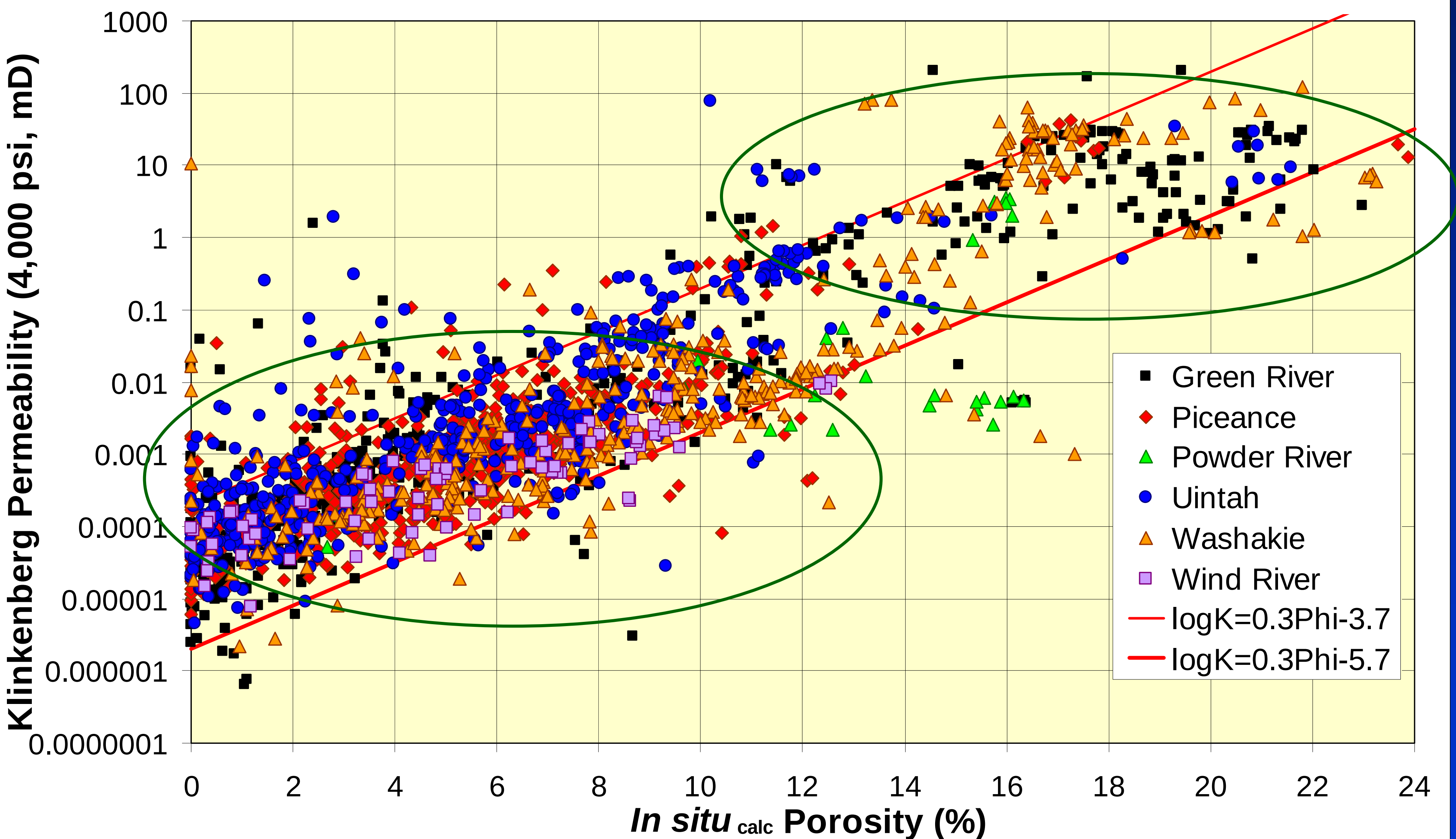
Green and red points are selected porosity data used for modeling

Porosity vs depth

18-22% ϕ
at 6K ft

8-12% ϕ
at 12K ft -
FAR
LOWER
PERM




Klinkenberg Permeability (4,000 psi, mD)
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0.0000001
0
2
4
6
8
10
12
14
16
18
20
22
24
In situ calc Porosity (%)
Green River
Piceance
Powder River
Uintah
Washakie
Wind River
logK=0.3Phi-3.7
logK=0.3Phi-5.7

BTW,

- It is a common fallacy that hydrocarbon charge stops further diagenesis. NOT TRUE. It just slows down.
  - These are water wet systems, there is plenty of water for minerals to dissolve and cements precipitate nearby.

3. Permeability jail arrives

- Absolute permeabilities deteriorate with diagenesis
- Relative perm curves shift, creating the jail cell which locks the gas in place.
- Gas columns try to expand upon uplift,
  - if they can gas contacts move downdip into tighter, progressively wetter rocks,
  - in other places the expansion pops the seals.
- Gas is unable to push water out of very tight, high Sw intervals, so reservoir sands pressure up (it's a poroelastic effect).

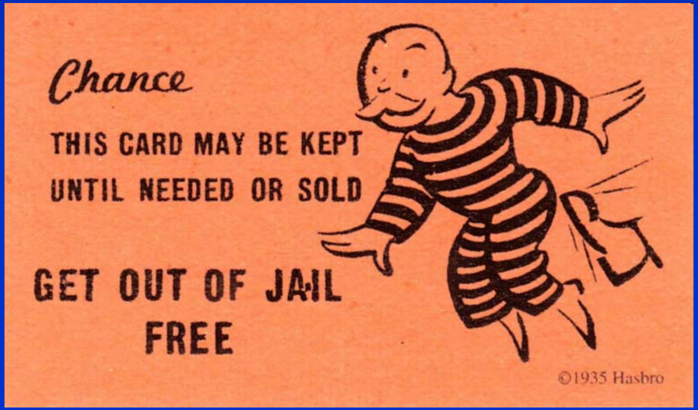
4. The end result is.....

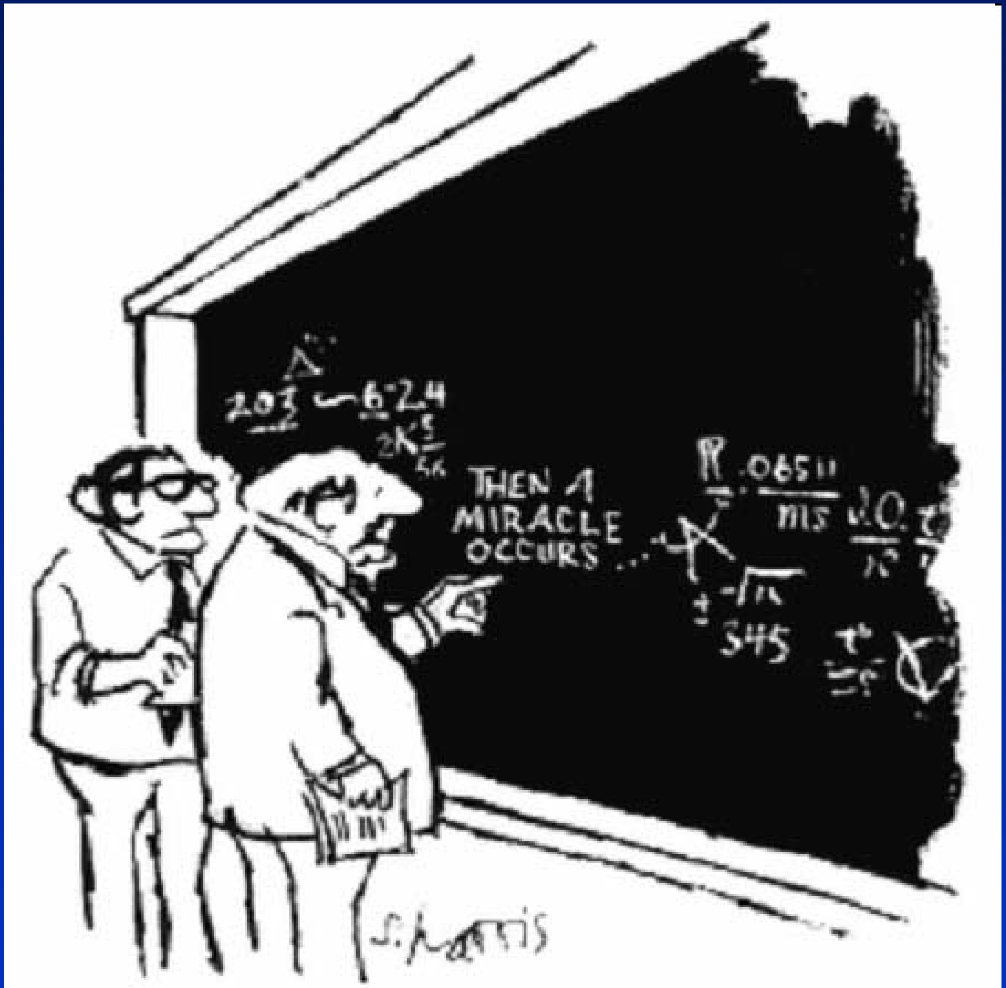
- Tight rocks, most of which are in jail and won’t produce much gas or water
- Best rocks make the gas, especially high in paleotraps (“sweetspots”)
- Overpressured sandstone lenses
- Leaky seals, top and bottom, including regional extensive wet sandstones
- “Basin centered gas”

Got a get out of jail free card?

- Since Keg*h controls productivity, the only solution is to increase h:
  - better, longer fracs
  - horizontal wells
- avoid aqueous completion fluids that might compound the problem (“water block”)
- Ultimately, however, you can’t fight City Hall.
  - Serve your sentence.
  - Keep clean and stay out of jail in the first place.

Questions?





"I think you should be more explicit here in step two."