Shale Diagenesis and Permeability: Examples from the Barnett Shale and the Marcellus Formation*

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Abstract

Diagenetic style often exerts a controlling influence upon permeability. At deposition, the size and interconnectivity of the pore network is a function of the size, shape and packing of the constituent clasts. As the sediment is progressively buried, it dewaters and compacts, reducing the size of the pores, their interconnections, and the permeability. Cementation furthers this process. While shale permeability is poorly understood and difficult to measure, we can assume that diagenesis exerts similar controls upon the pore network in shales. The following reports the results of an analysis of pore size and permeability in 43 core plugs from the Barnett Shale and the Marcellus Formation. The results clearly illustrate the effect of diagenetic style, an effect that accounts for a variation in permeability ranging over four orders of magnitude.

The Barnett Shale is a Mississippian argillaceous shale formation located in north-central Texas. It is described as a spent-oil source rock that has surpassed the thermal transition from liquid to gas generation. With this transition, maturation-induced microfractures developed, enhancing both the porosity and permeability. The Marcellus Formation is a highly fissile, black, argillaceous shale of Devonian age found throughout most of the Appalachian Basin. Unlike the Barnett, much of the Marcellus formation has not matured through liquid to dry-gas generation, and the formation contains varying amounts of interbedded limestones and calcite cement, both in the form of vein filling and matrix cements. In short, diagenesis within the Barnett shale served to expand the pore network, making it more efficient, while that within the Marcellus served to reduce the pore network, making it less efficient.

Permeability and throat-size information were obtained from Hg capillary pressure testing while pore-size information was obtained from NMR T2 spectra. A clear relationship between pore size and permeability was evident in each group of samples. However, given a specific

pore size, the samples from the Barnett Shale will have permeabilities that are in micro-, not nanoDarcies.. When compared with similar results from high-permeability sandstones, the results suggest that the efficiency of the pore network in the Barnet Shale approximates that found in sands, while that of the Marcellus samples is lower than that found in tight gas sands.

Reference

Prince, C.M., 2009, Permeability estimation in tight gas sands using NMR — A new interpretive methodology (abstract): Search and Discovery Article #90100 (2009) (http://www.searchanddiscovery.net/abstracts/html/2009/intl/abstracts/prince.htm).

Shale Diagenesis and Permeability:

Examples from the Barnett Shale and the Marcellus Formation.

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It is difficult to accurately measure permeability in impermeable samples!

- Steady State
- Unsteady State

- Fractured Plugs
  - Pressure Release
  - Microfractures from Liquid Nitrogen coolant.
  - Microfractures from Drying/Desiccation
- Bypass around seals

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Notes by Presenter: It is difficult, if not impossible, to reliably measure permeabilities in impermeable samples.

The commonly applied methodologies: Steady State, or unsteady state, suffers from the same disadvantages:

1) Fracturing. It can be very difficult to drill an unfractured plug in shale. If it is a fissile shale like the Marcellus, just getting a competent plug can be a challenge. Fracturing can also arise from pressure release, turning a competent plug into a stack of poker chips overnight.

Even if a competent plug is obtained our research suggests that microfractures are generated around the periphery of the plug both from contact with the liquid nitrogen coolant and desiccation of the surface; both are more than enough to cause leakage.

2) The microfracturing and the roughness of the plug surface combine to bring about leakage around the seals.

Non-Flow Estimation Techniques

- Mercury Injection Capillary Pressure
    - Small sample size
    - Destructive test
    - Hazardous waste

- Modal NMR Technique (2009 AAPG ICE)
    - Full Size Plugs
    - Fragments
    - Cuttings

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Notes by Presenter: That leaves us dependent upon methodologies that do not involve measuring the rate of fluid movement through the sample.

1) MICP can also be used to determine permeability (we use the Swanson method). The advantage it that MICP results do not depend upon the shape of the plug, or the competence of the plug. The disadvantages lie in the small sample size (sample support – the sample may not be large enough to be representative); it is a destructive test; (these days) the hazardous waste generated by the technique.
2) Modal NMR technique – presented at last year's ICE in Rio. The advantages - full size samples: we have also tested the technique on fragments and cuttings, and both produce results that are consistent with plugs.

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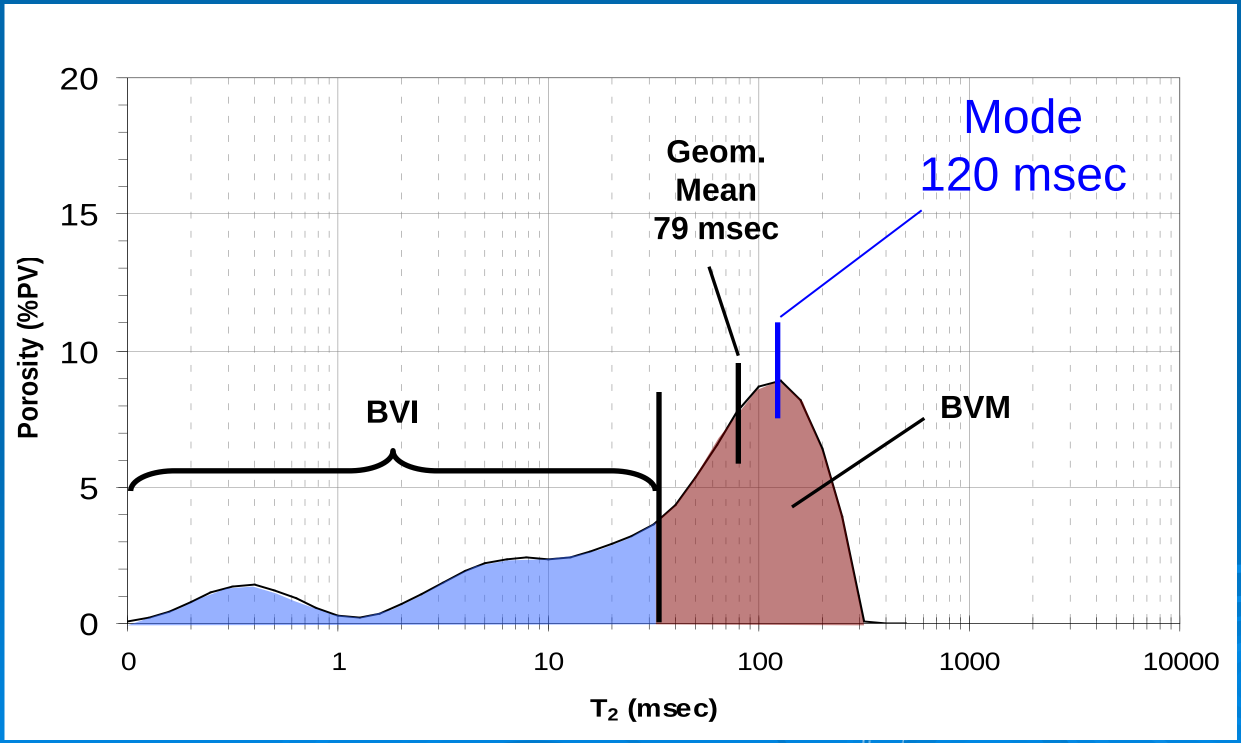
T_2 Spectrum:

- Reservoir-Quality Sand: K_{air} = 299 mD



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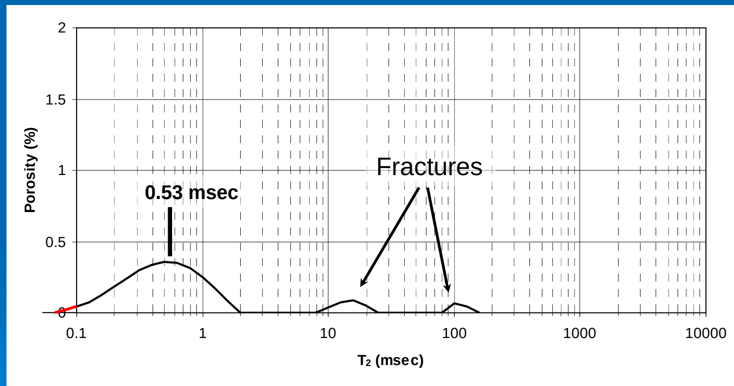
Notes by Presenter: A T2 spectrum from a sandstone has a general form like this. The commonly measured variables are BVI, BVM, and the Geometric mean. Note that the mode is a much better indicator of the dominant pore size than the geometric mean. Variables are derived from the entire T2 distribution, and it is assumed that the entire distribution is determined.

The Mode is far more stable than any of the other variables, and is recoverable, even when the entire distribution is not.

Modal T_2

K_{Klink}: 3.26 mD



Notes by Presenter: Representative spectra from sample of tight gas sand with fractures. Should we lump these fractures with BVM? Note that the mode is approximately 0.55msec, and at this point the 'good' part of the spectrum is incomplete and is missing a tail…..(How do we get BVI from this?).

Barnett Shale and Marcellus Formation:

- Argillaceous shales with varying amounts of calcite
- Spent oil source rocks.

Best Case:

9 samples from Barnett
- low Calcite
- high thermal maturity

Worst Case:

30 samples from Marcellus
- high calcite
- low thermal maturity

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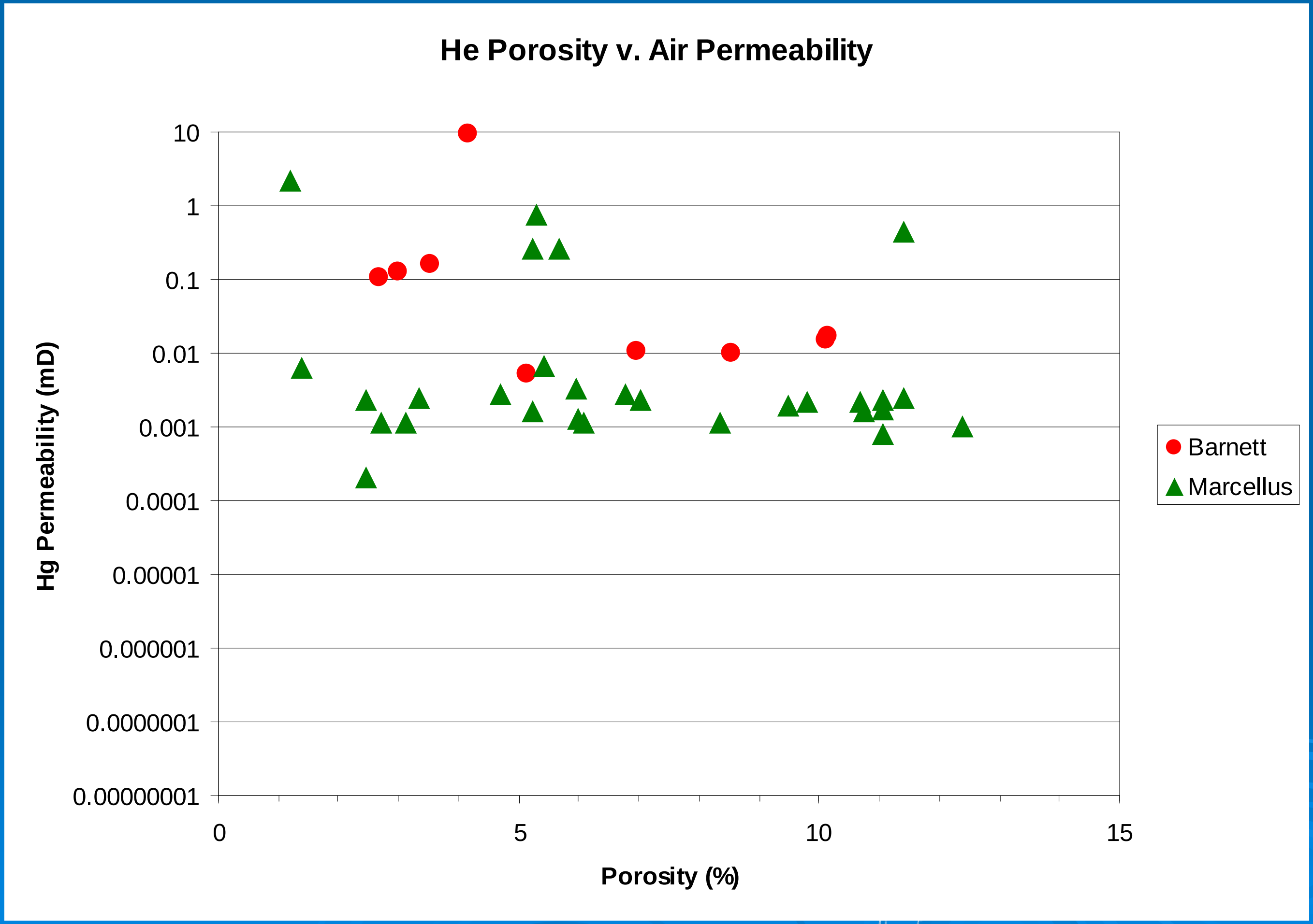
Notes by Presenter: For this presentation we wanted to test the extremes of this technique.

Diagenetic style often exerts a controlling influence upon permeability. At deposition, the size and interconnectivity of the pore network is a function of the size, shape, and packing of the constituent clasts. As the sediment is progressively buried, it dewaters and compacts, reducing the size of the pores, their interconnections, and the permeability. Cementation furthers this process. While shale permeability is poorly understood and difficult to measure, we can assume that diagenesis exerts similar controls upon the pore network in shales.

We selected a series of ‘best case’ samples from the Barnett shale, and a series of ‘worst case’ samples from the Marcellus

He Porosity vs. Air Permeability



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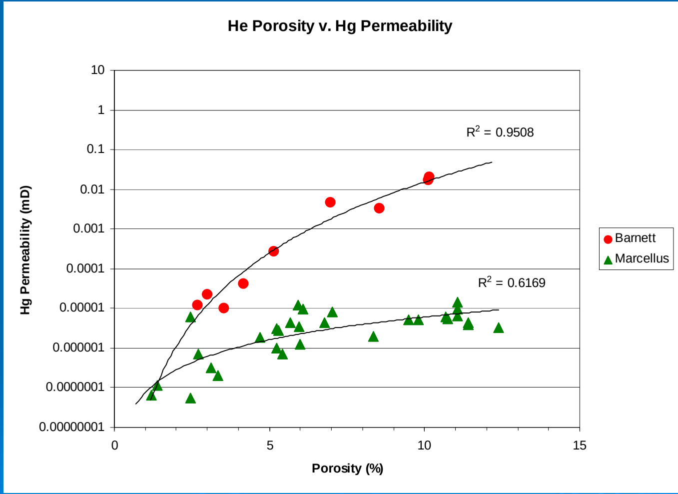
Notes by Presenter: A short review:

Here is an example of standard routine core analysis on two shales (Barnett and Marcellus), as well as a tight gas sand. You can see that there is no rhyme or reason to this data: Low permeability values do not extend below a microDarcy (the limit of the equipment).

1) The highest permeability values are associated with the lowest porosities.

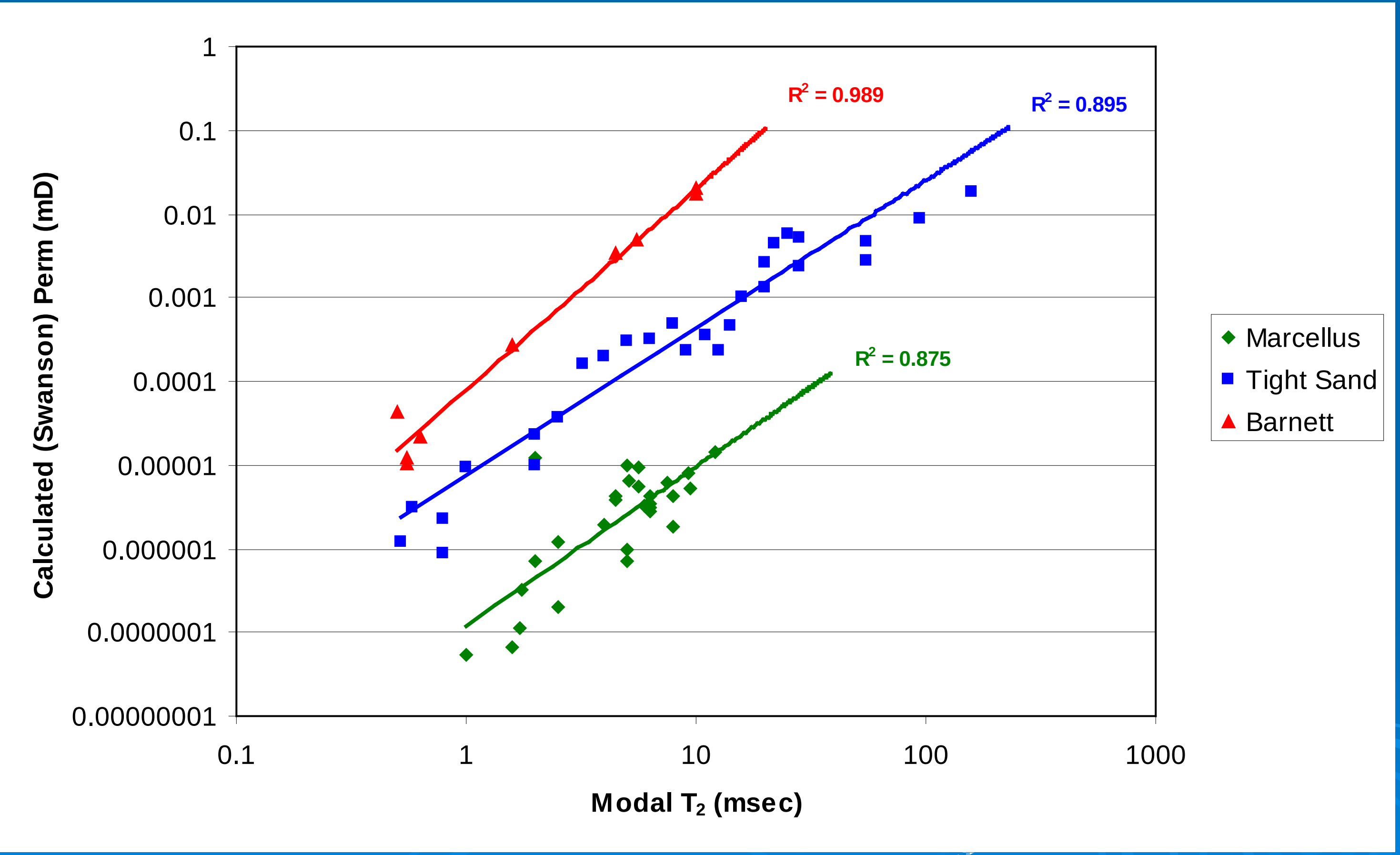
This leads us to NMR techniques….

He Porosity vs Hg Permeability



Notes by Presenter: We can tighten up this relationship if we use MICP derived perms that are only minimally affected by fracturing.

Modal T_2 is intrinsically related to Permeability



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Notes by Presenter: The title of this slide says it all…

Note that there are strong differences associated with lithology and diagenesis. Yet the slope of the best fit line is approximately equal for both of the shales. Note that the Barnett has permeabilities that are, on average, three orders of magnitude greater than the Marcellus. This may be due to lithology in that the Marcellus is coeval with adjacent limestones and is a calcareous shale.

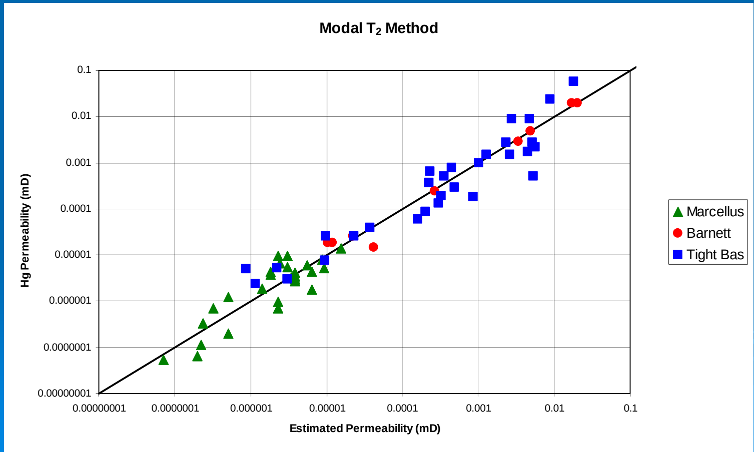
However, it may also be associated with diagenesis. The Barnett Shale is described as a spent-oil source rock that has surpassed the thermal transition from liquid to gas generation. With this transition, maturation-induced microfractures developed, enhancing both the porosity and permeability. Unlike the Barnett, much of the Marcellus Formation has not matured through liquid to dry-gas generation, and the formation contains varying amounts of interbedded limestones and calcite cement, both in the form of vein filling and matrix cements. In short, diagenesis within the Barnett Shale served to expand the pore network, making it more efficient, while that within the Marcellus served to reduce the pore network, making it less efficient

Modal T_2 Method: $log(K_{Brine}) = m * log(\text{Modal } T_2) + b$

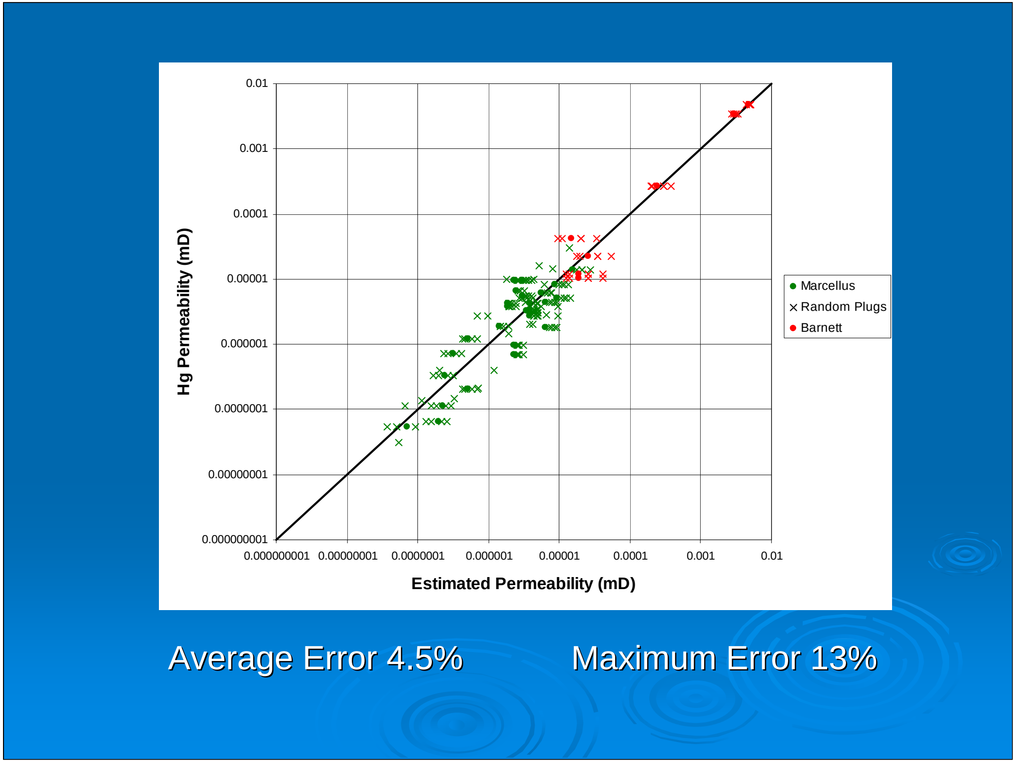
Sand: $m = 4.65$
$b = -9.84$

Barnett : $m = 2.40$
$b = -4.10$

Marcellus: m = 2.17
b = -7.15

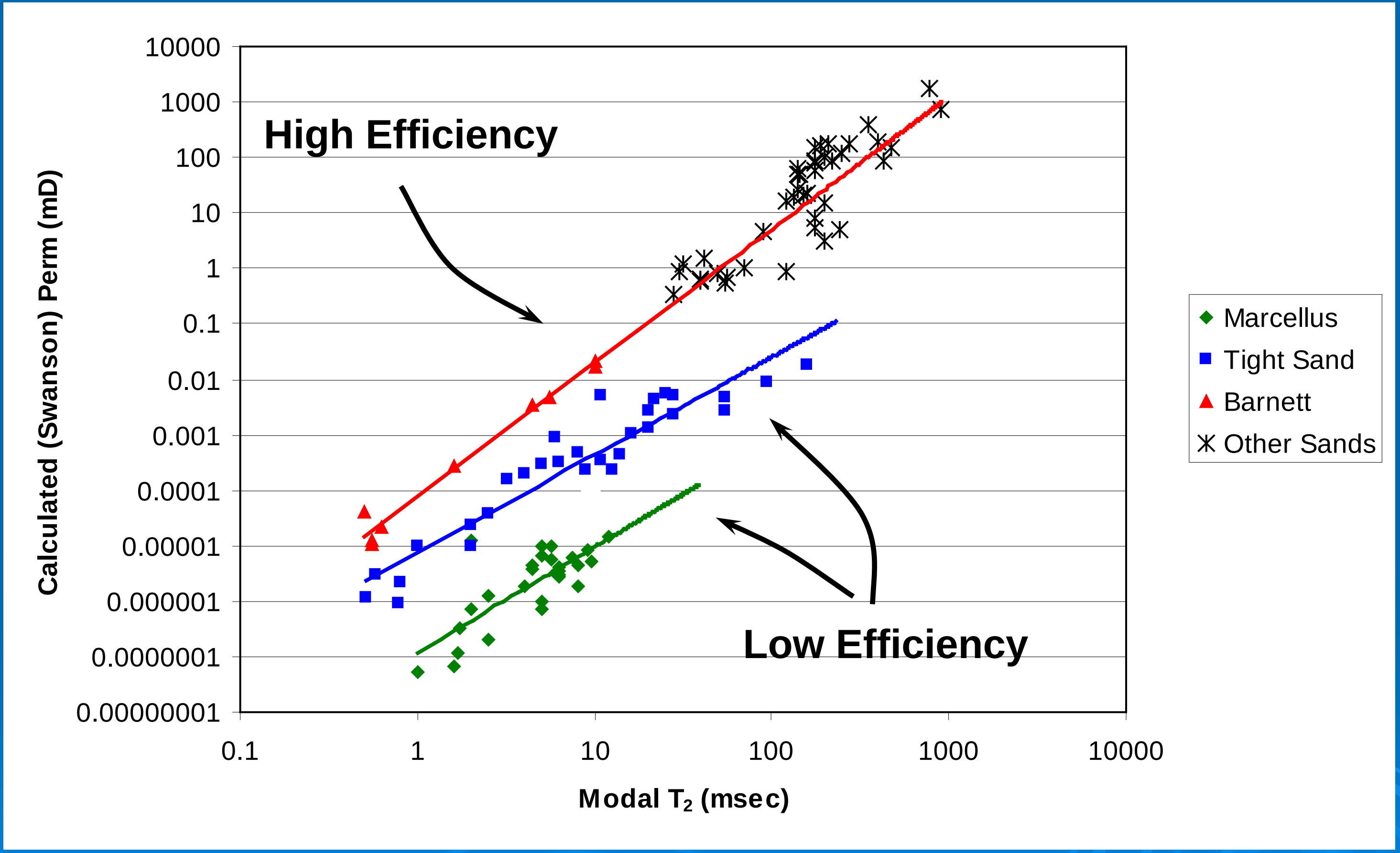


Notes by Presenter: Finally, let's look at the results obtained using the Modal T2 time. Using MICP data to seed the regression, we can derive the parameters for each rock type and obtain results that have very little deviation from the measured values. Note that the small amount of deviation that is present is symmetrically distributed around the 1:1 line.



Notes by Presenter: Now, let's look again at the results obtained using the Modal T2 time. To repeat: Using MICP data to seed the regression, we can derive the parameters for each rock type and obtain results that have very little deviation from the measured values. Note that the small amount of deviation that is present is symmetrically distributed around the 1:1 line.

Comparison with high-K Sandstones



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Notes by Presenter: If we compare the Barnett with reservoir sands, we see that, in terms of pore size and permeability, the Barnett shale has a pore network that is just as efficient as that of many reservoir sandstones. This suggests that the dry-gas generation phase creates enough pressure either to re-open pathways that were closed during compaction, or to generate microfractures which substitute for these pathways.

The tight gas sands and Marcellus samples are far less efficient. In the case of the Marcellus samples the low efficiency may be associated with the thermal diagenesis and the absence of the dry-gas generation phase, or it may be solely due to the calcite--or it may be a mixture of both.

It would be nice to confirm these conclusions. So, if any of you have access to some samples of the Marcellus from eastern WV, or western PA, areas where the formation has passed through the dry-gas generation zone, we would like to analyze them.

Summary

- The Modal NMR technique worked well with both the best case and worst case samples.
- The results demonstrate the impact of diagenesis on the evolution of the pore network.
- While it is not possible to completely define the effects of thermal maturity and calcite content based upon the current sample set, the Barnett samples surprisingly demonstrated that the pore network in mudrocks can, in some cases, be just as efficient as that found in sandstones.