

Workshop Outline

- Finding gas hydrate in nature
- **Characterizing gas hydrate occurrences**
- Can methane be extracted for profit?
- Gas hydrate formation & breakdown
(Geologic time)

What is down there, and how much is gas hydrate?

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Remote sensing (broad areas)

General rules:

- Density: ↓ (gas)
- Velocity: ↓ (gas) ↑ (hydrate)
- Resistivity: ↑ (gas or hydrate)

What is down there, and how much is gas hydrate?

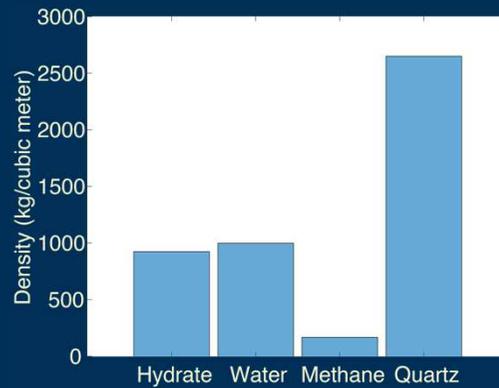
Remote sensing (broad areas)

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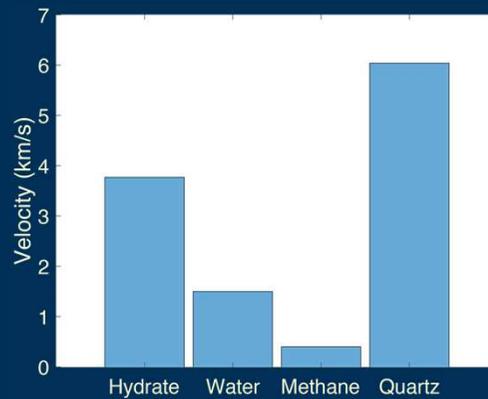
- Density: ↓ (gas)
- Velocity: ↓ (gas) ↑ (hydrate)
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**This assumes it's either gas or hydrate
that replaces water in the pores...**

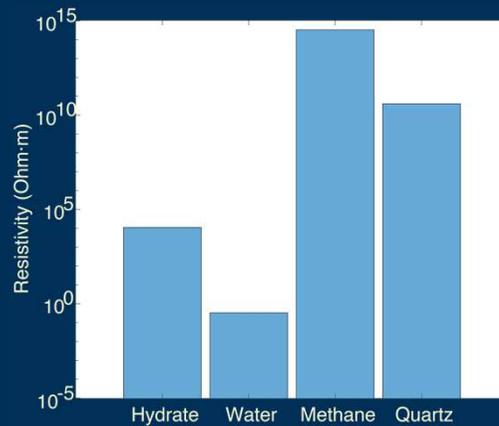
What happens if pore water is replaced by sediment?



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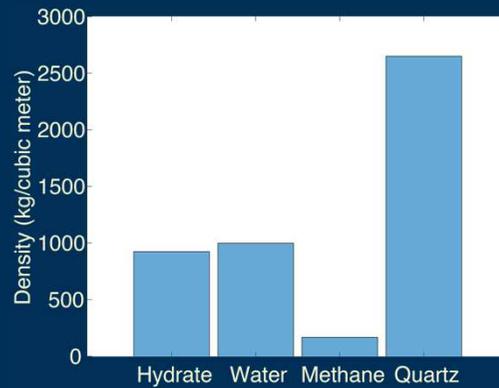


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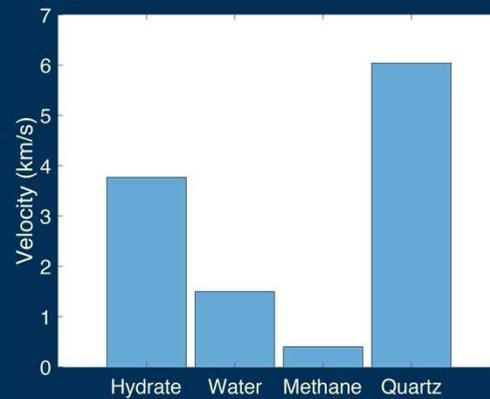


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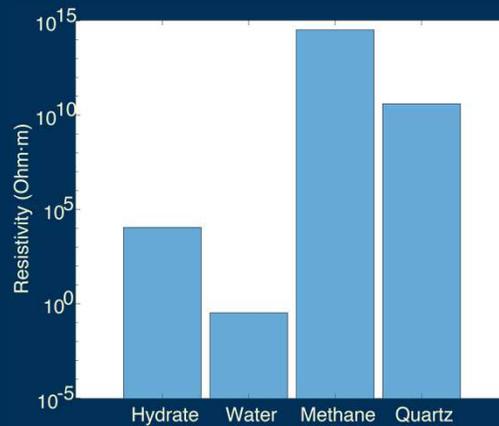
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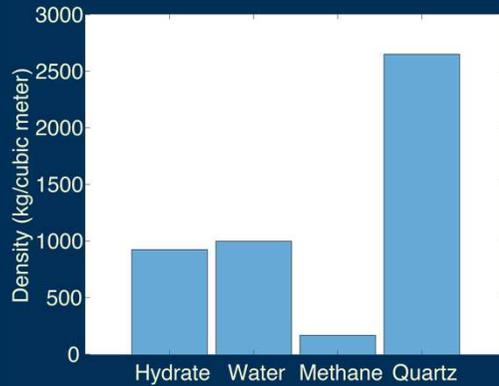
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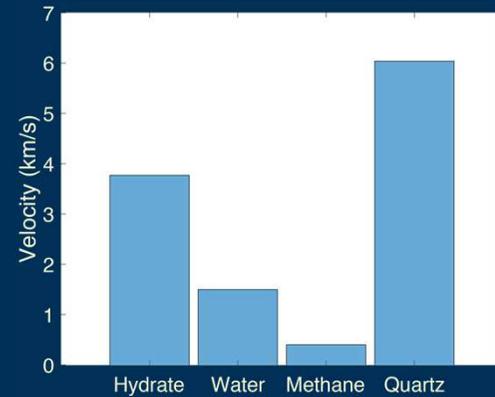
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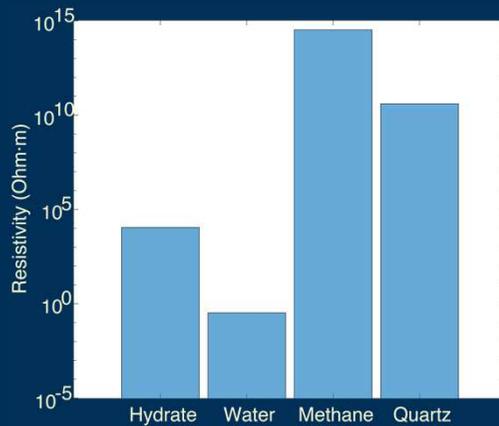
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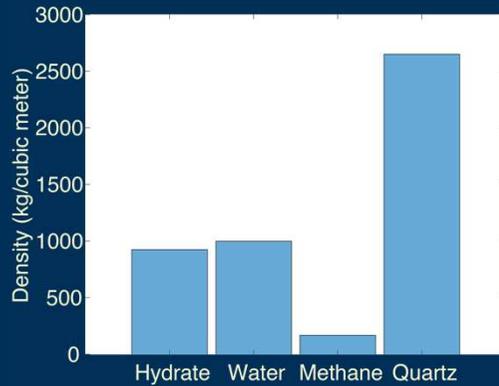
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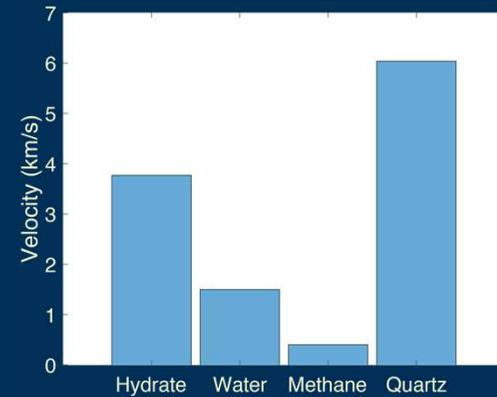
Density * Velocity =

Impedance

What happens if pore water is replaced by sediment?



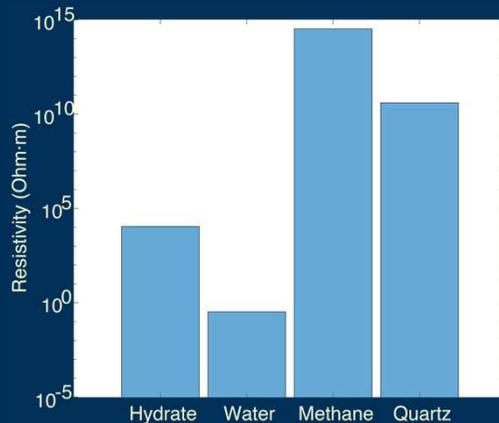
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- Velocity:



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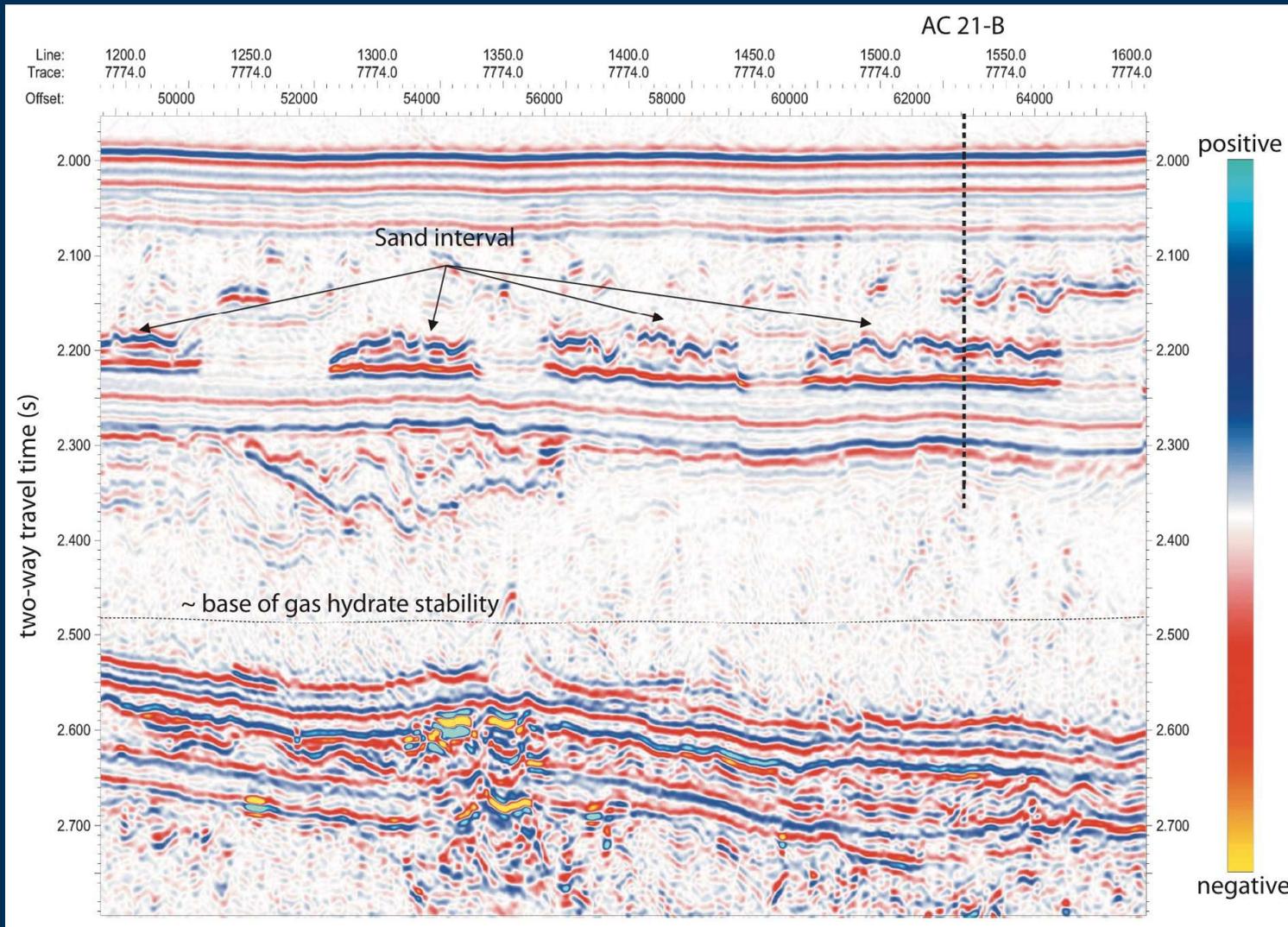


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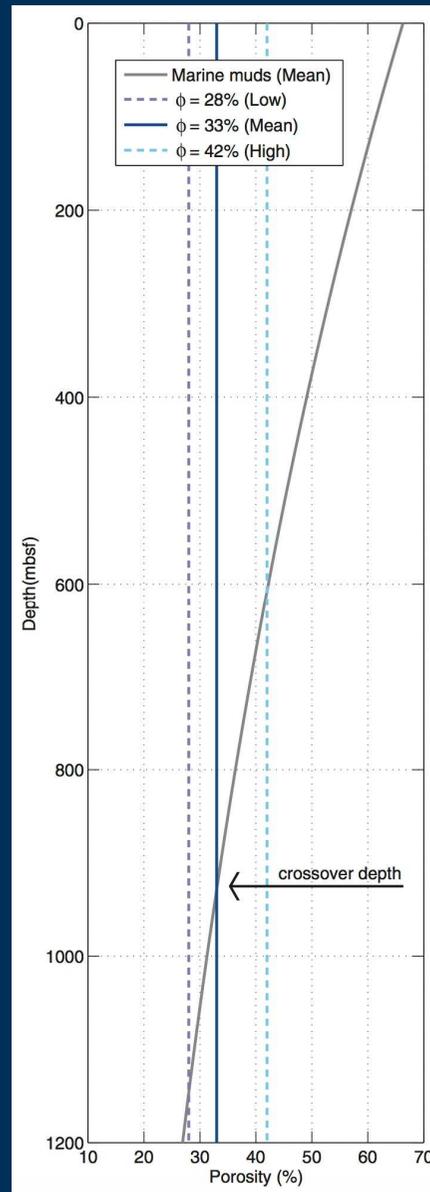


**Porosity
reduction can
look like gas
hydrate**

What happens if pore water is replaced by sediment?

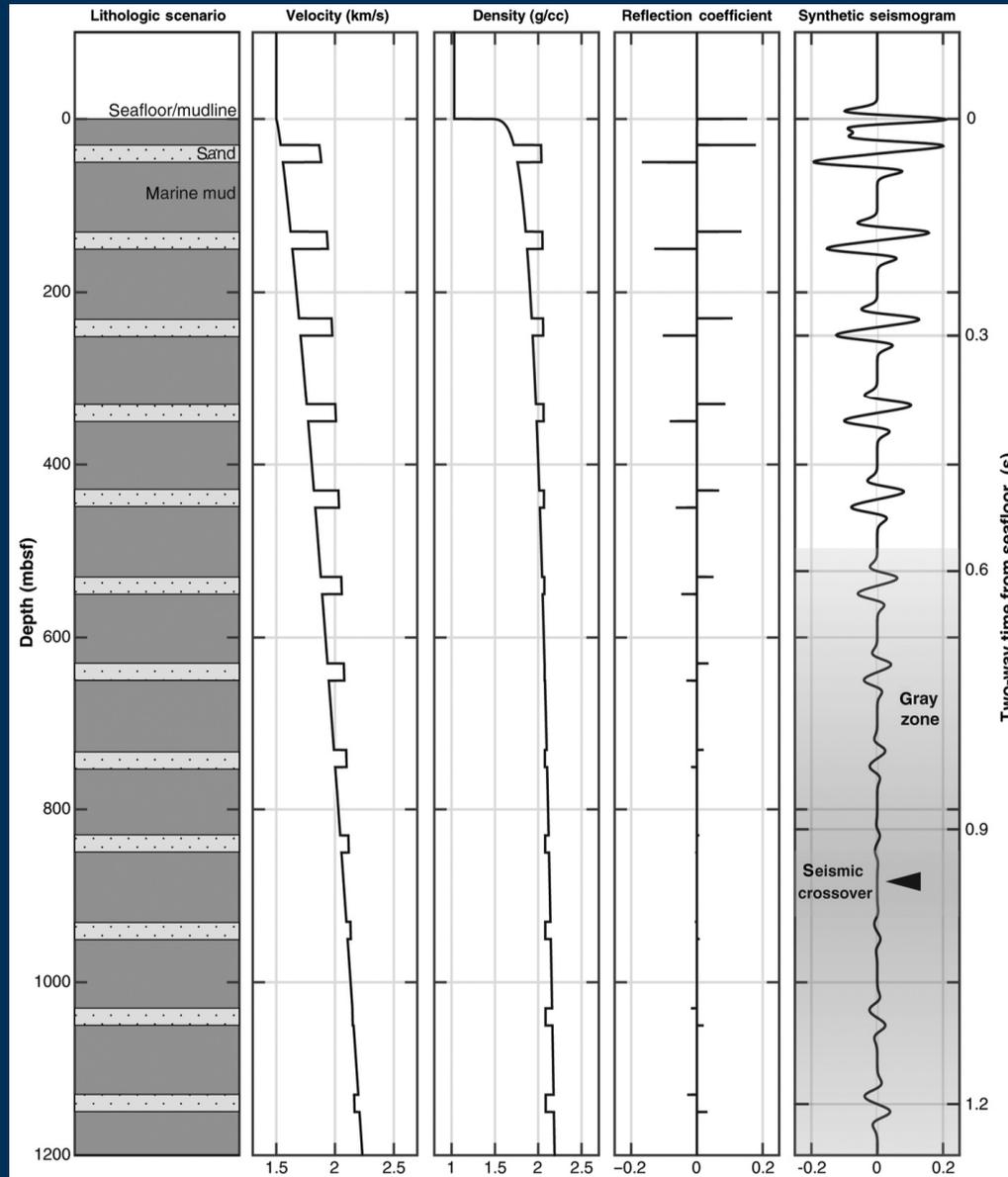


Porosity change with depth: sands versus mud



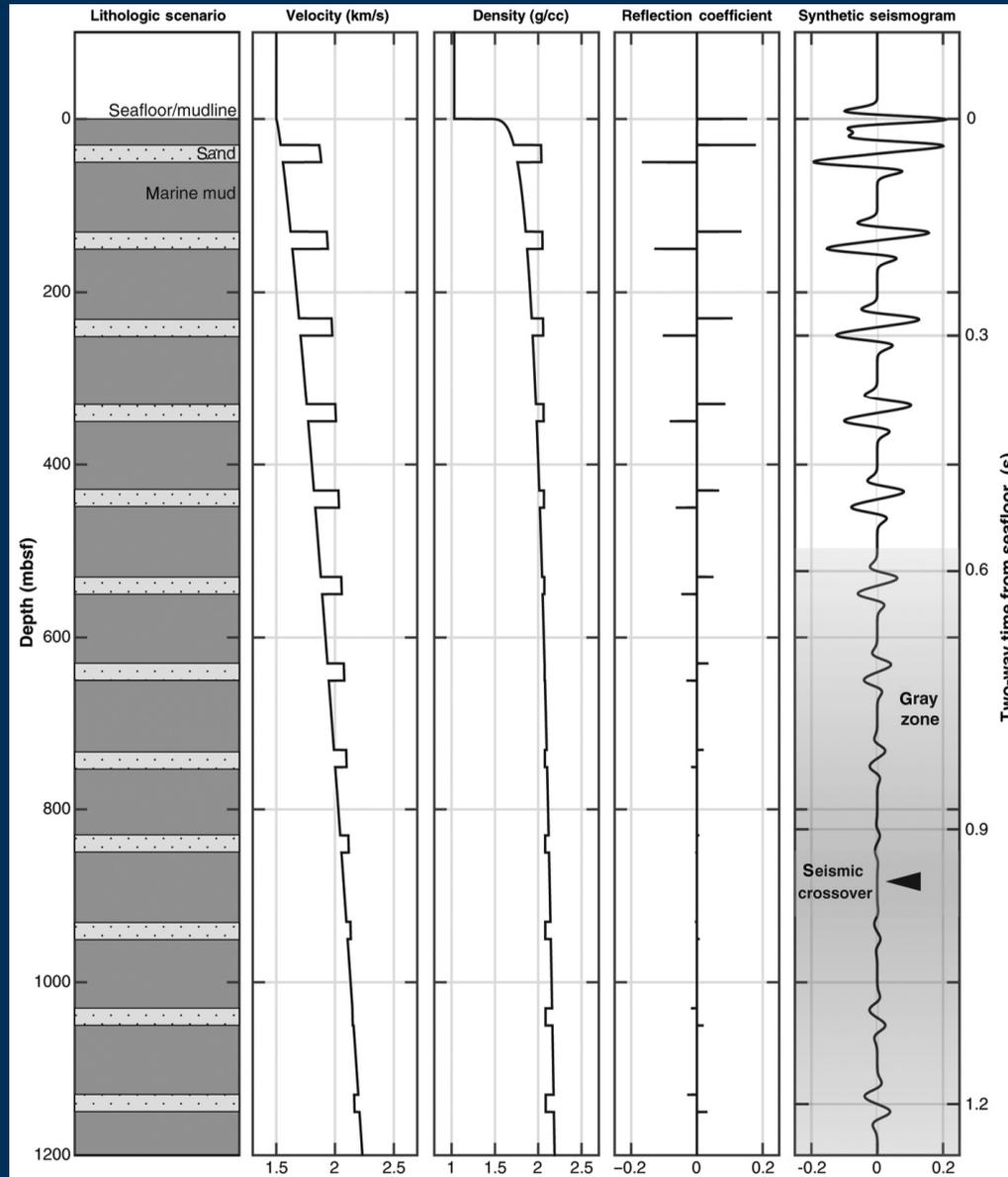
Cook and Tost (2014), JGR

Impedance contrast changes with depth



Cook and Sawyer (2015), Geophysics

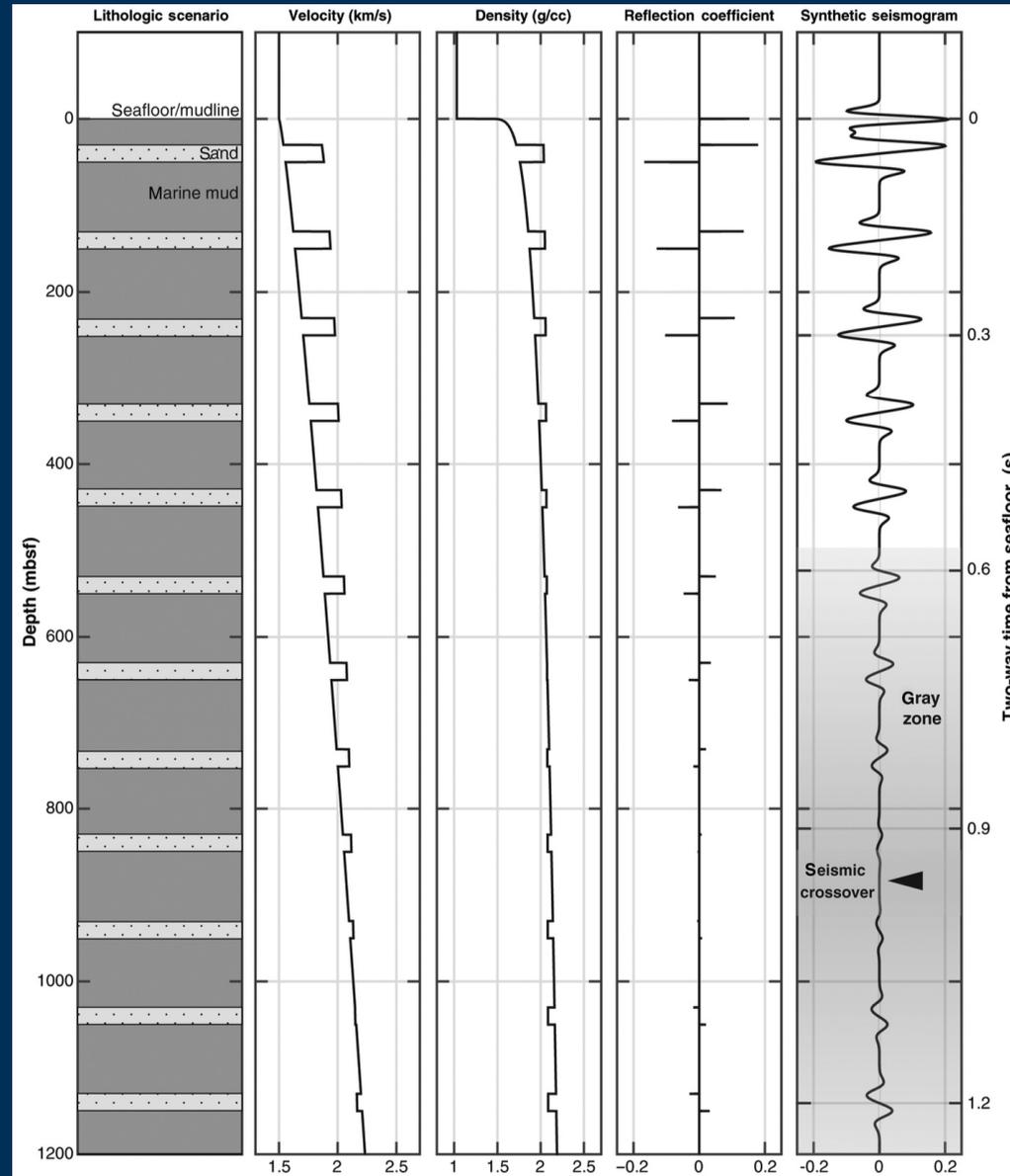
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Sand
looks like
it has
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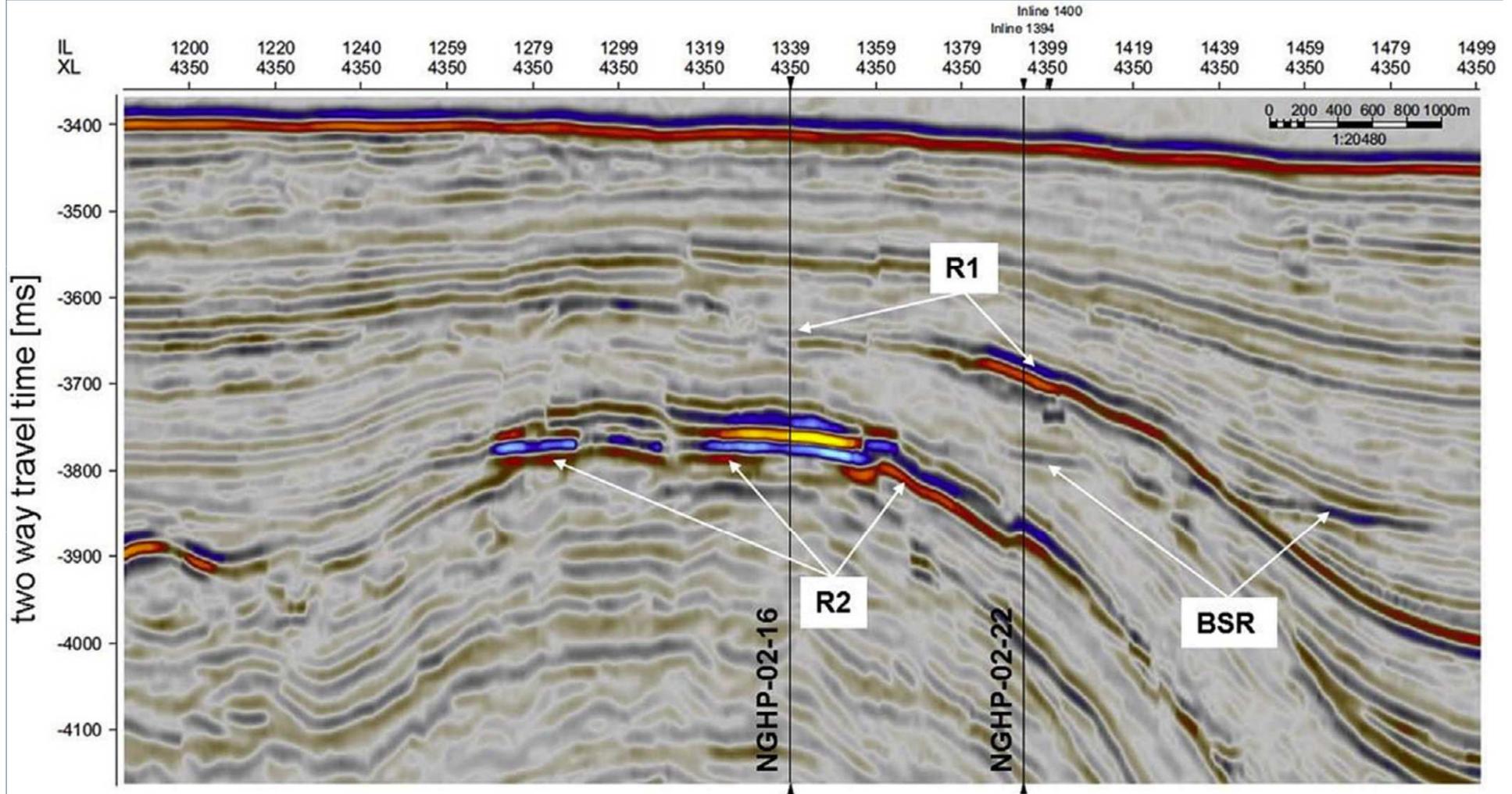
Impedance contrast changes with depth



Sand looks like it has hydrate

Sand looks like it has gas

Impedance contrast clues for sand and for hydrate



Water or hydrate? What is the sand holding?

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To find things, use properties that are very different from what you are not looking for.

Water or hydrate? What is the sand holding?

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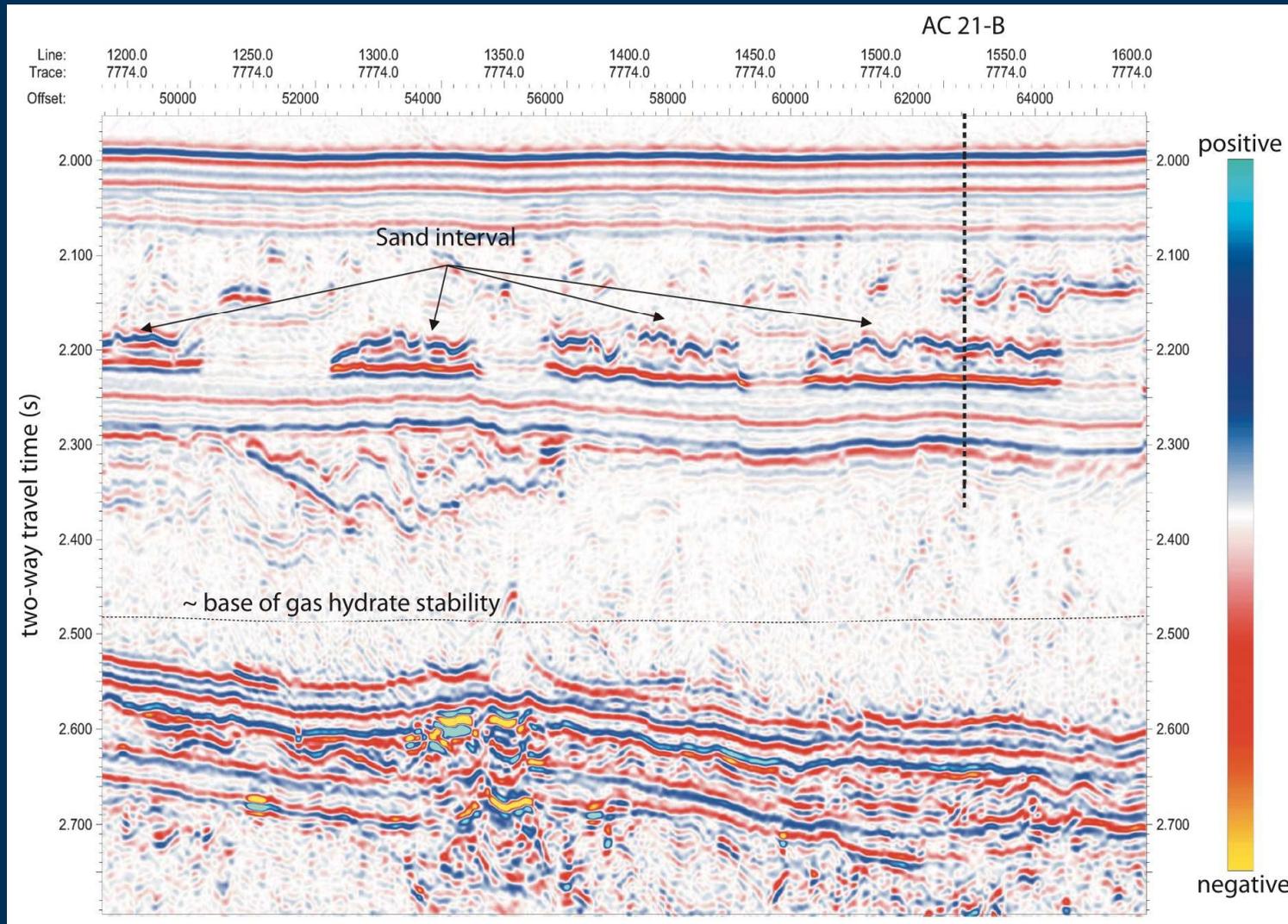


9B-35P(236.88-236.96), $S_h=75.6\%$

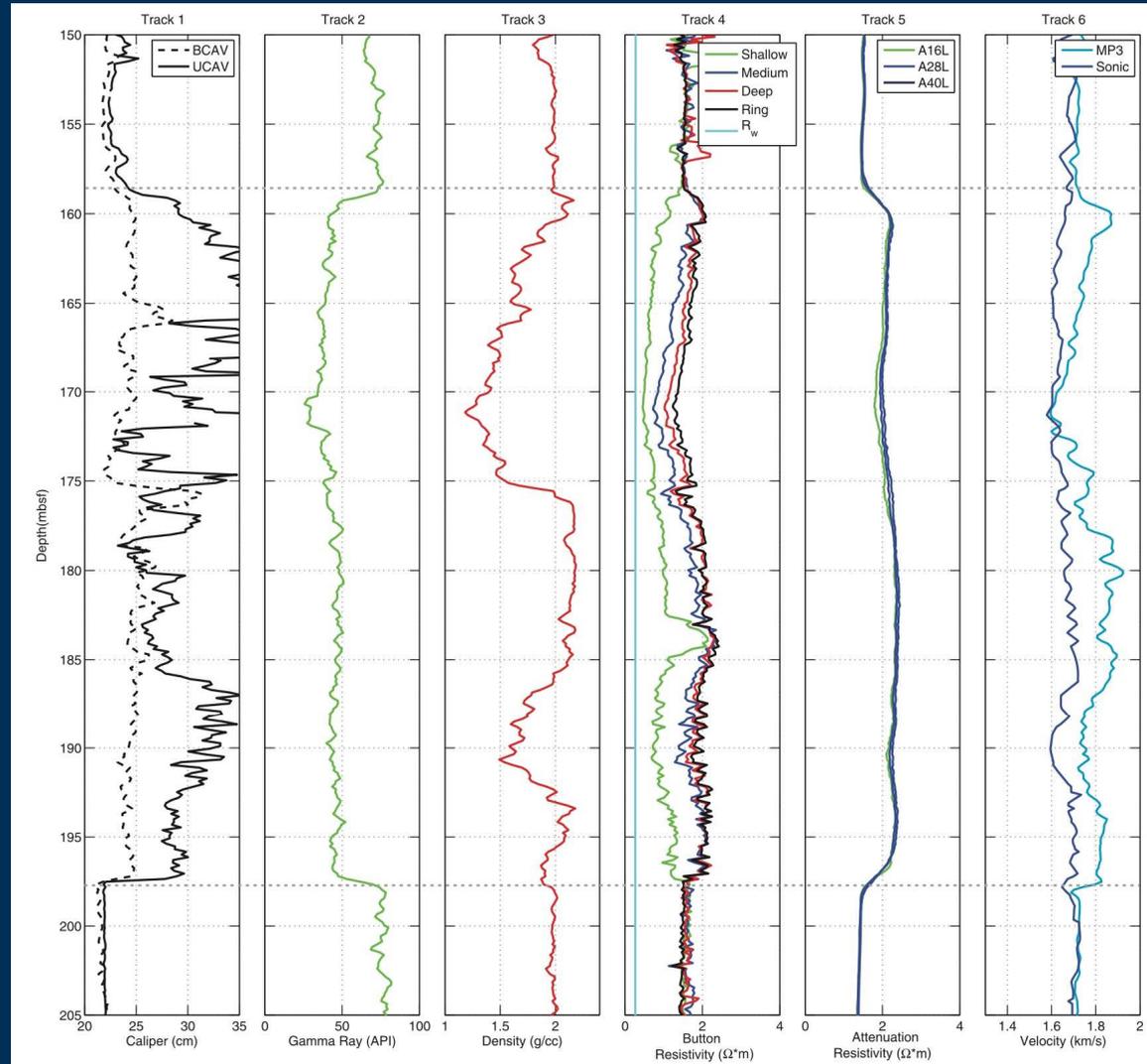
Sand with gas hydrate can hold itself together (cohesion).

Sand with only water can *not* hold itself together

To get more information, drill a borehole!



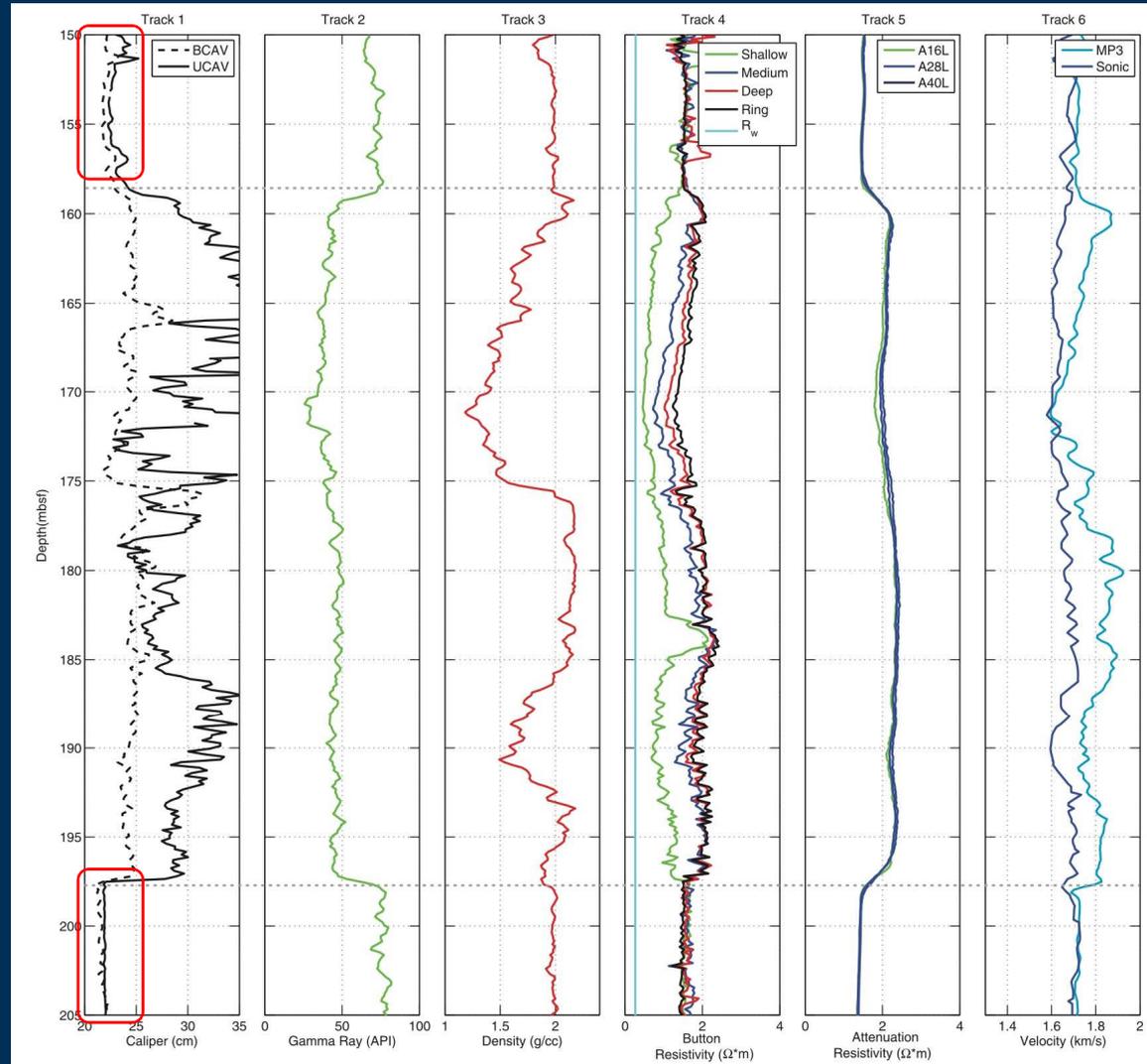
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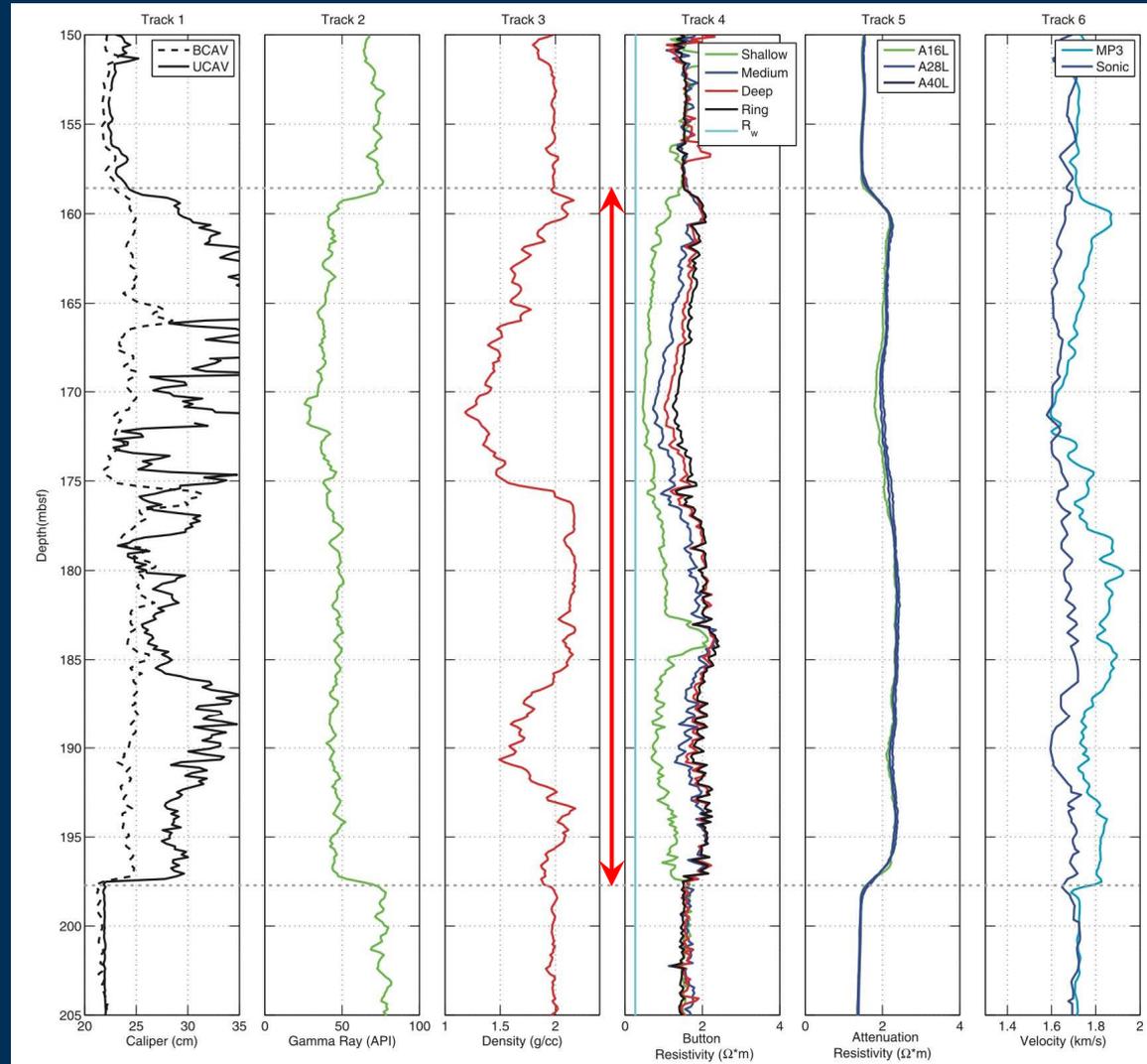
Borehole has the original, small diameter from the cutting bit in the mud layers.



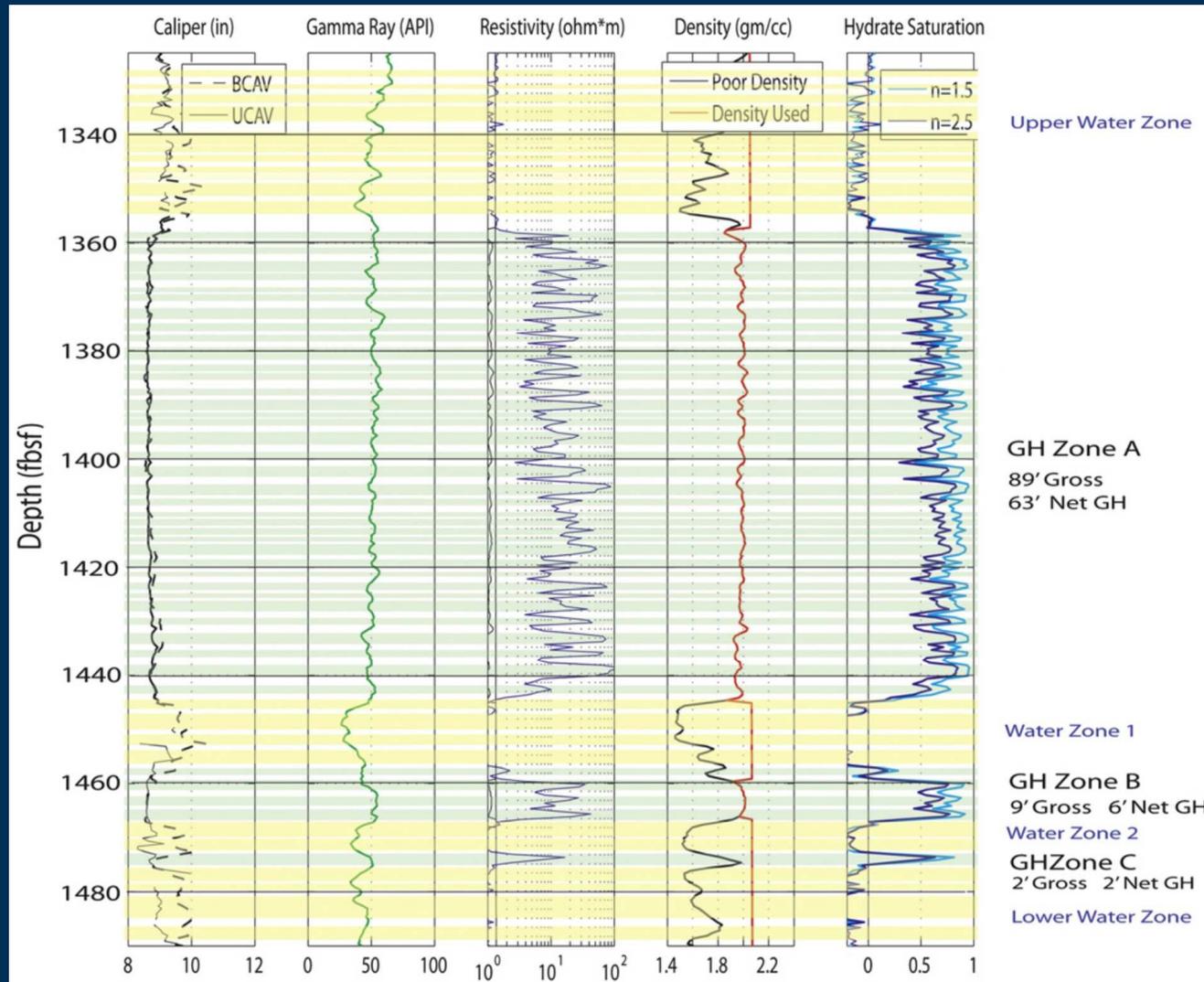
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Borehole has
“washed out” in the
sand interval

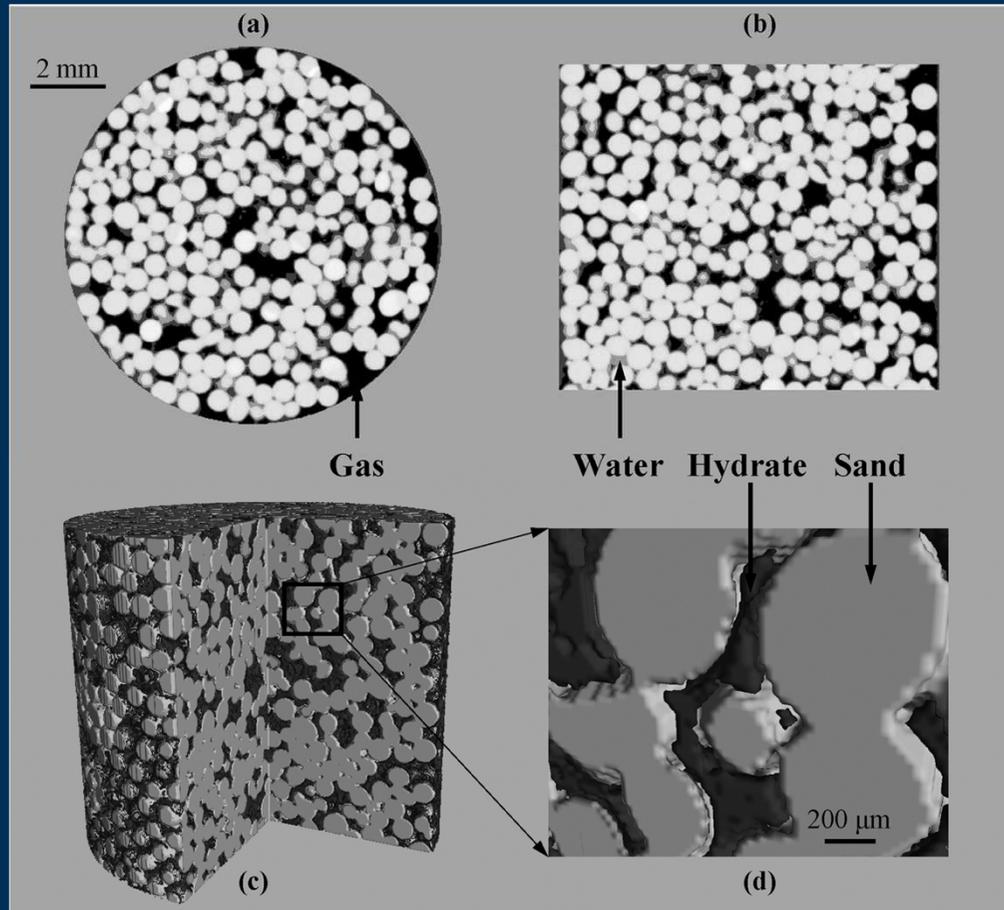
(weak sediment has
been washed away)



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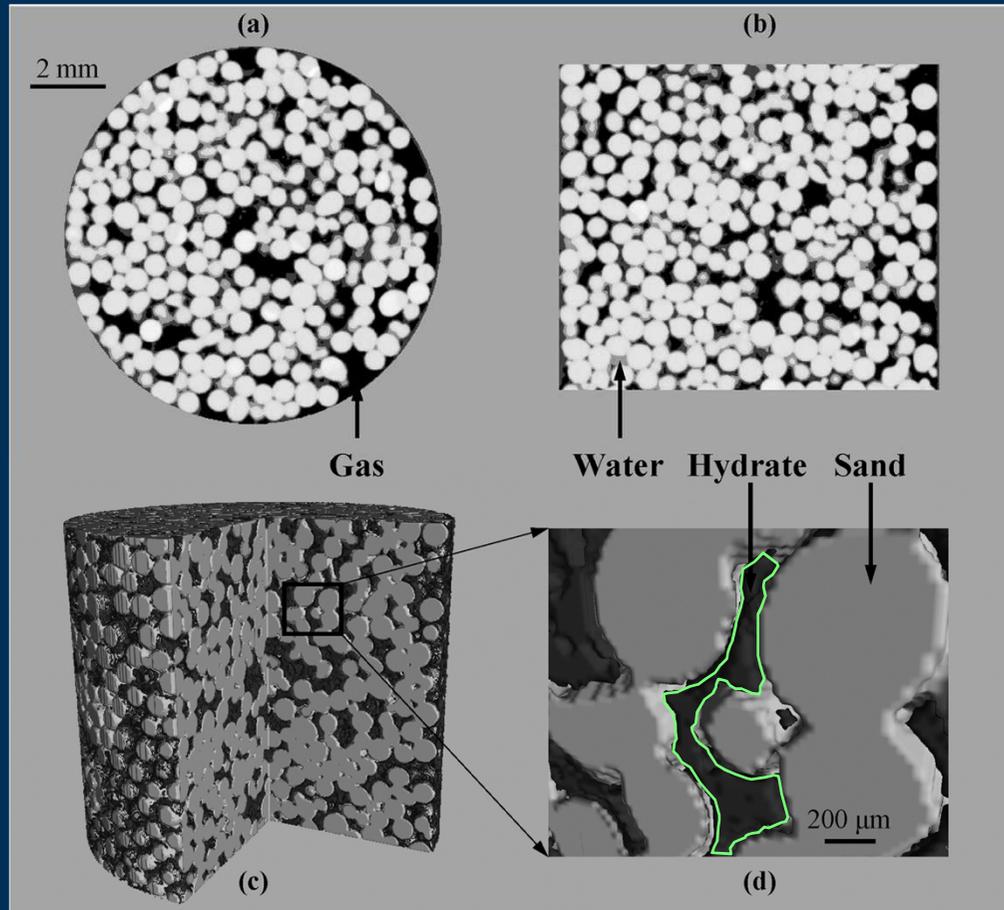


What is “gas hydrate saturation”?



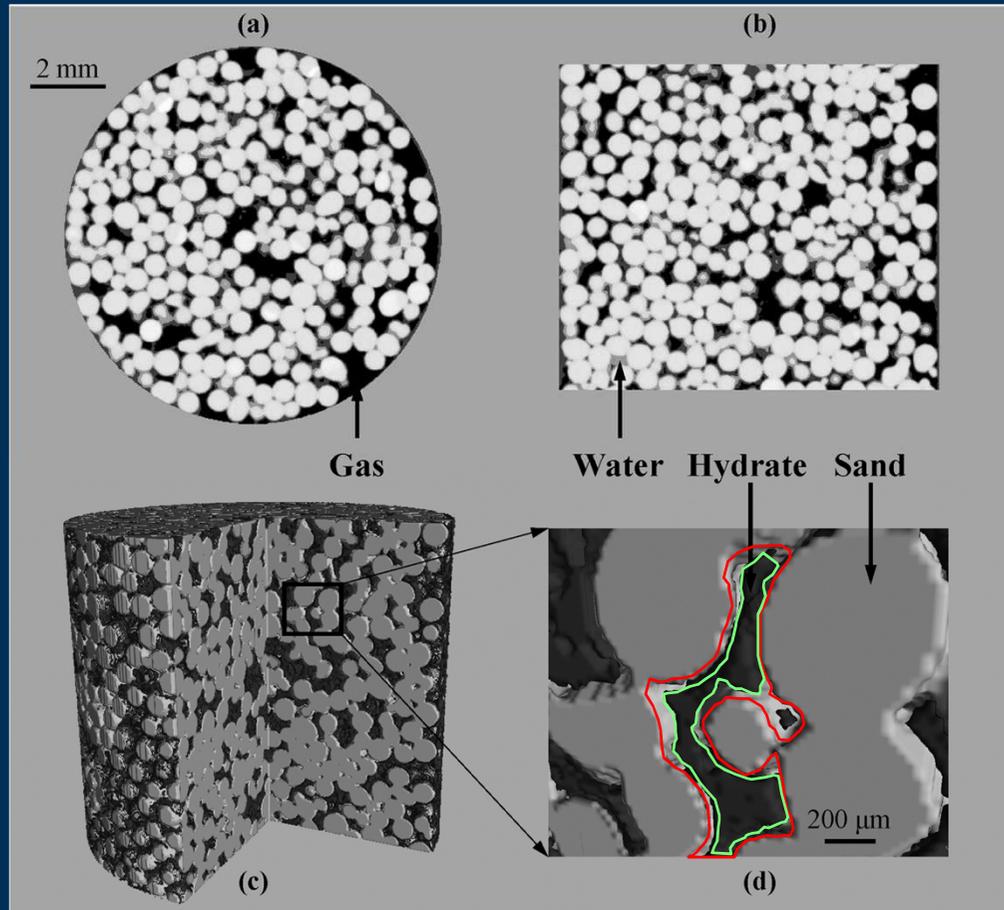
Zhao et al. (2015), J. Chem. Chem. Phys.

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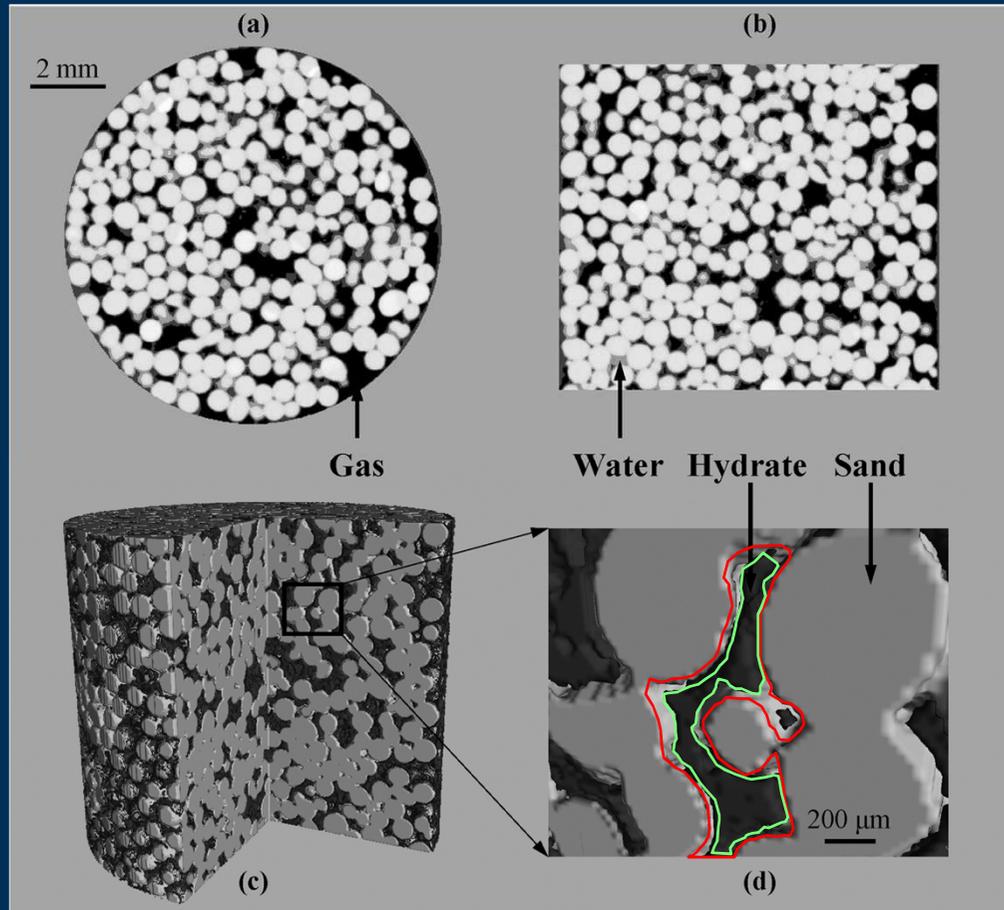
Volume of gas hydrate

What is “gas hydrate saturation”?



$$\frac{\text{Volume of gas hydrate}}{\text{Volume of the pore}}$$

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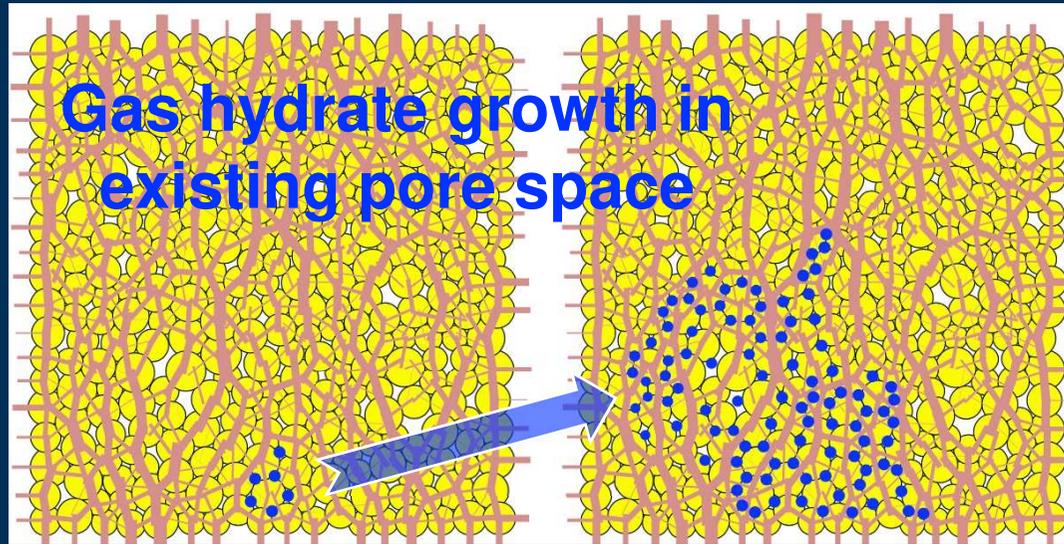


Gas hydrate
saturation, S_h :

$$\frac{\text{Volume of gas hydrate}}{\text{Volume of the pore}} = S_h$$

What is “gas hydrate saturation”?

Coarse-grained
sediment



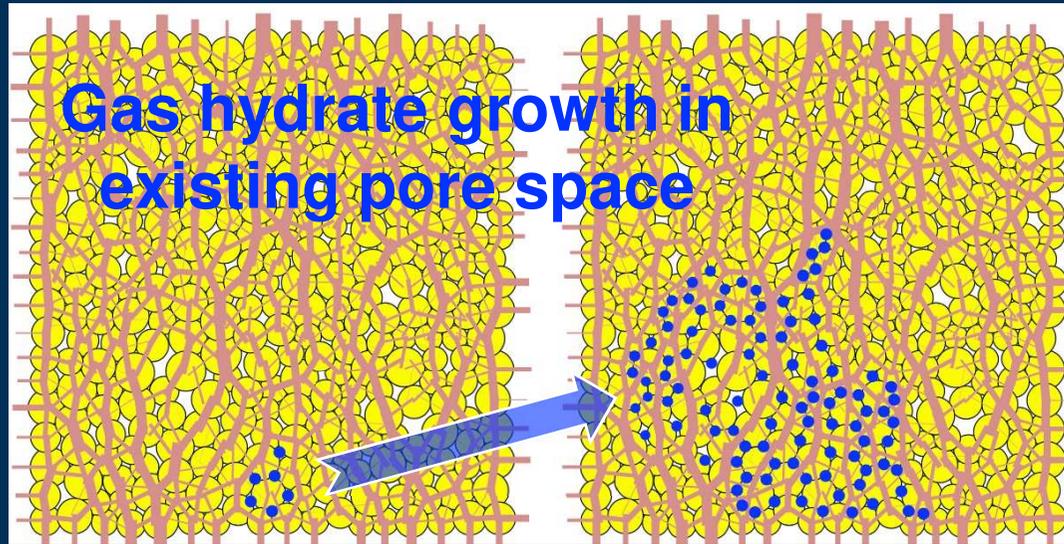
Gas hydrate
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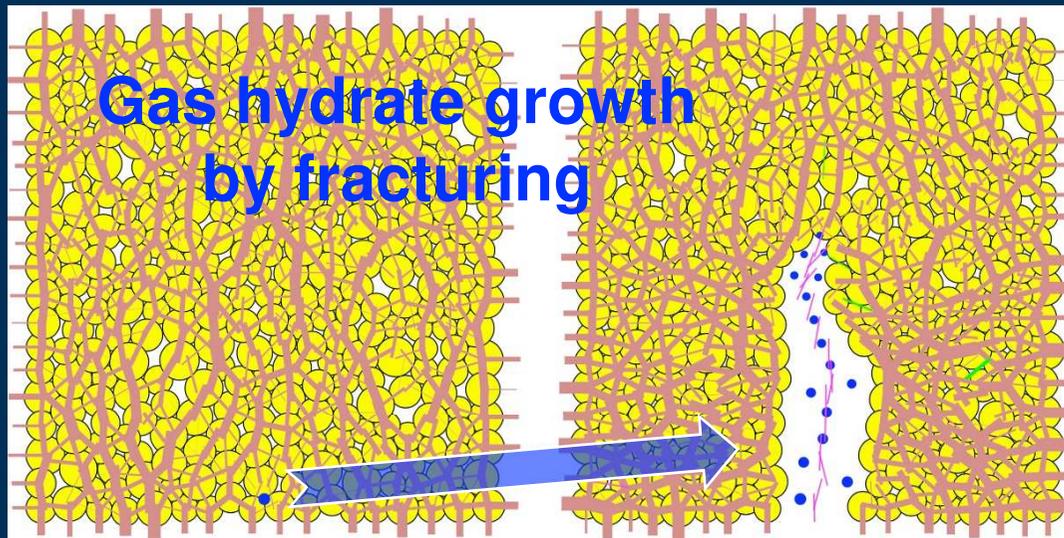
Volume of the pore

What is “gas hydrate saturation”?

Coarse-grained
sediment



Fine-grained
sediment



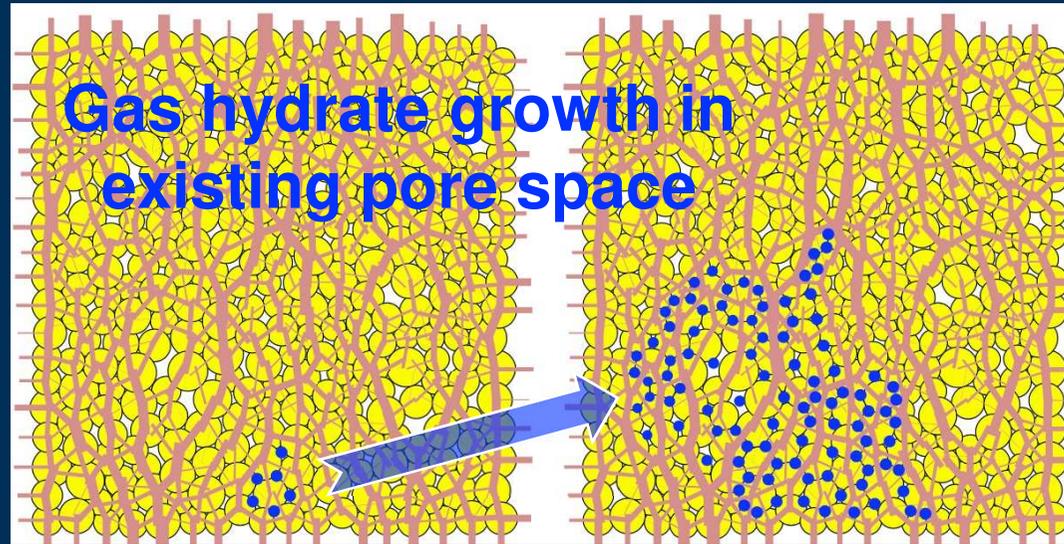
Gas hydrate
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Volume of gas hydrate

Volume of the pore

What is “gas hydrate saturation”?

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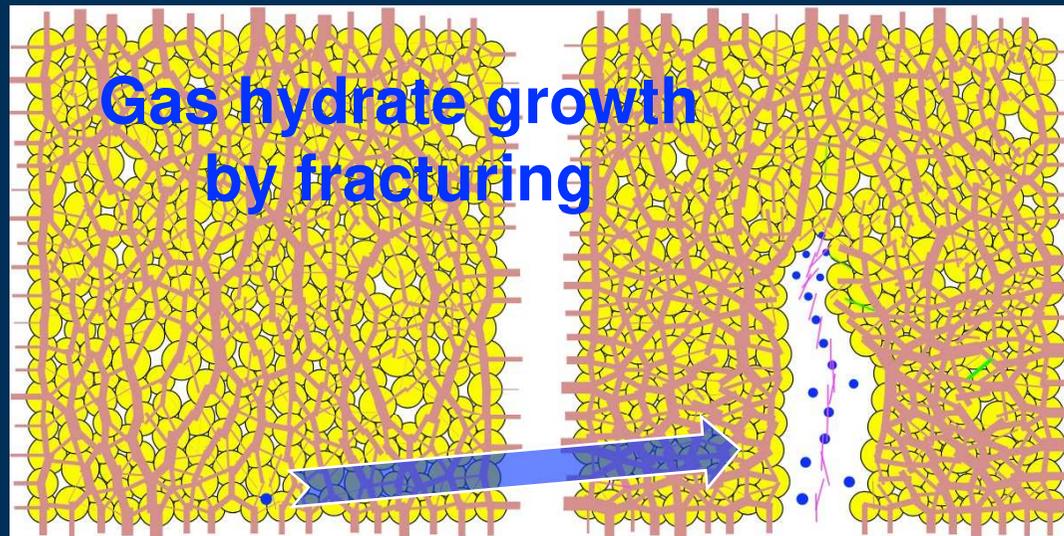


Gas hydrate
saturation, S_h :

Volume of gas hydrate

Volume of the pore

Fine-grained
sediment



Gas hydrate
saturation, S_h :

Volume of gas hydrate

Entire Volume

“Gas hydrate saturation” depends on morphology



Conglomerate (Arctic Canada)



Sand (Offshore Japan)



Fine sediment (Offshore China)



Massive layer (Offshore India)



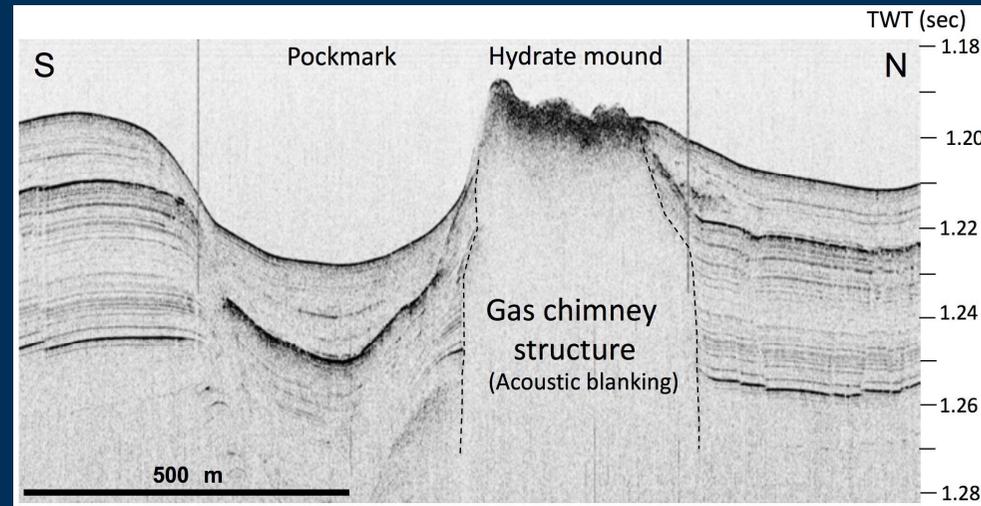
Veins (Offshore Korea)



Nodule (Offshore India)

Compiled in Beaudoin et al. (2014), U.N. Environmental Programme

“Gas hydrate saturation” depends on morphology



Gas Chimney (Offshore Japan)



Essentially pure hydrate from 17-22 mbsf

Matsumoto et al. (2017), FITI

Which morphology do we want to seek out?



Conglomerate (Arctic Canada)



Sand (Offshore Japan)



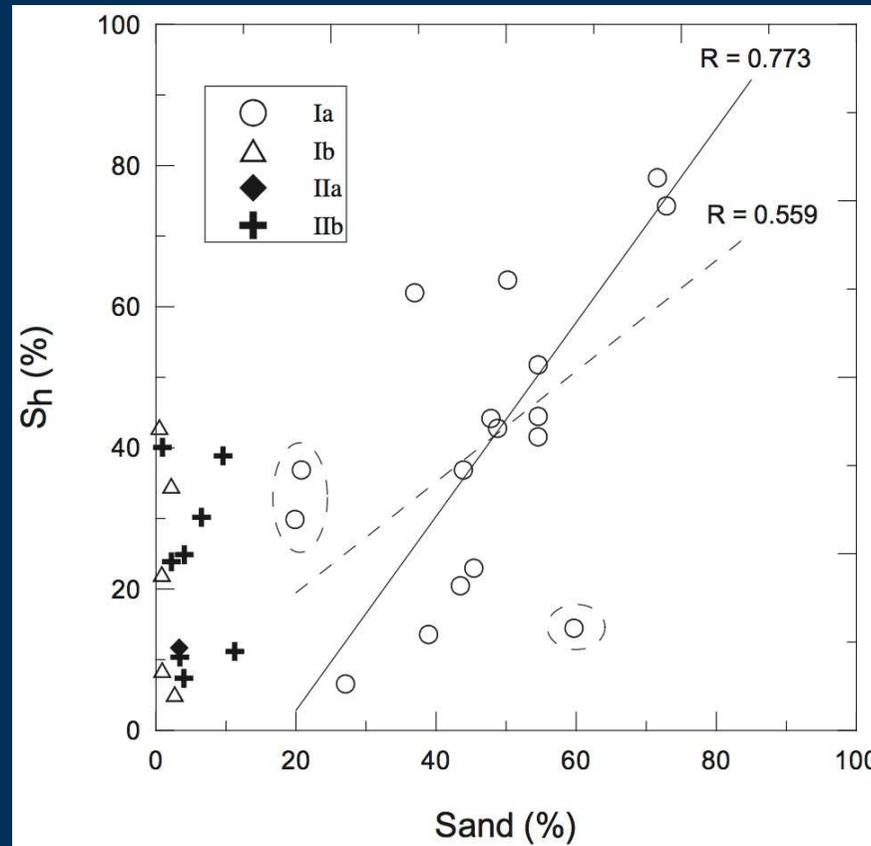
Fine sediment (Offshore China)

Gas hydrate in existing sediment pore space
is the main energy resource target

Compiled in Beaudoin et al. (2014), U.N. Environmental Programme

Coarser sediments: primary targets for energy applications

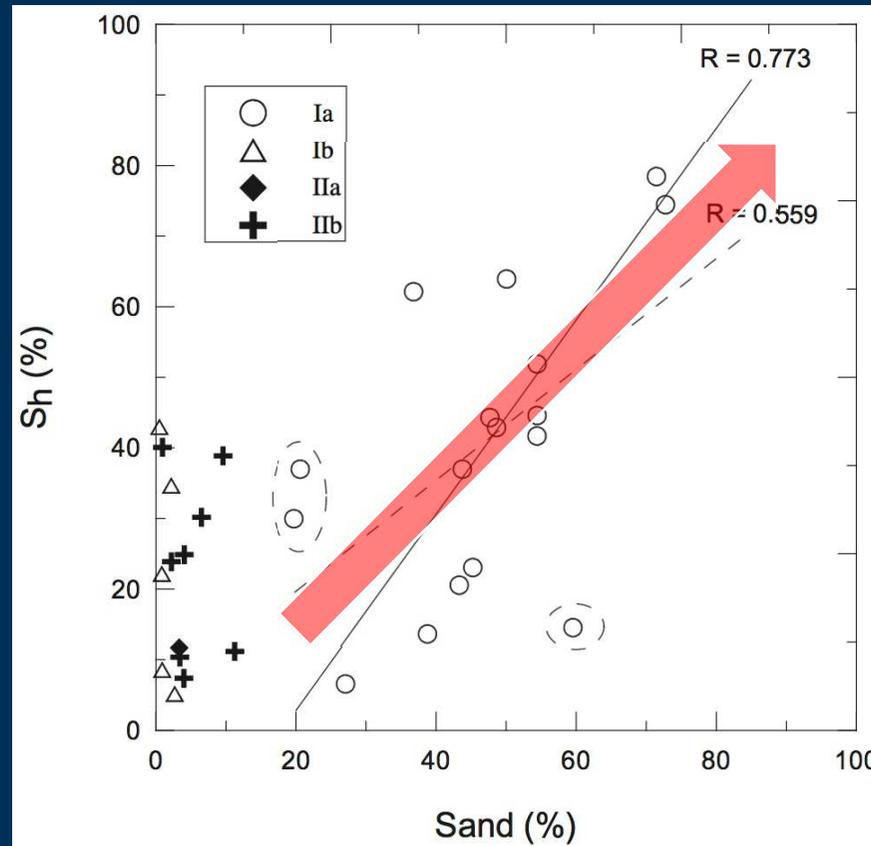
Ulleung Basin (offshore Korea)



Bahk et al. (2013), Marine and Petroleum Geology

Coarser sediments: primary targets for energy applications

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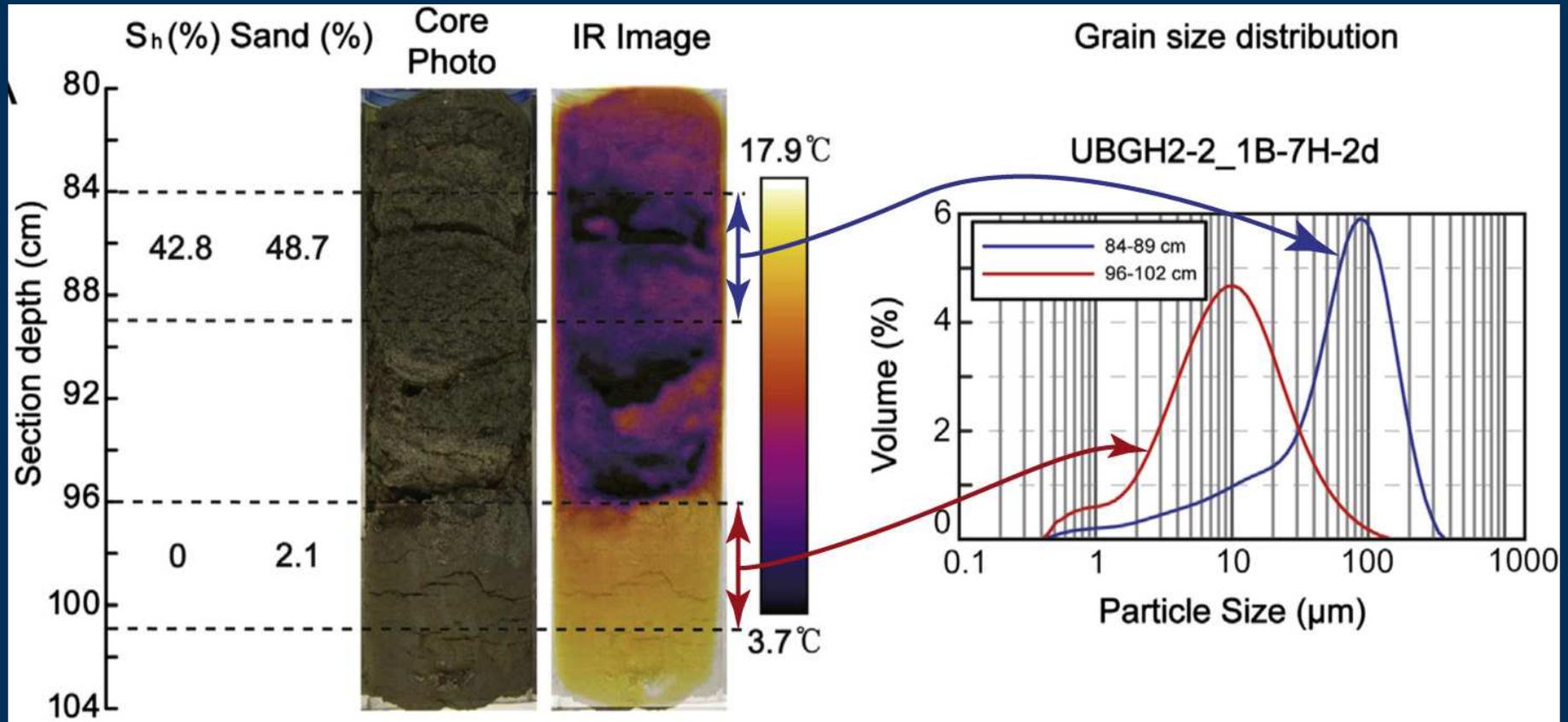


More sand
=
more hydrate

Bahk et al. (2013), Marine and Petroleum Geology

Coarser sediments can host higher gas hydrate saturations...

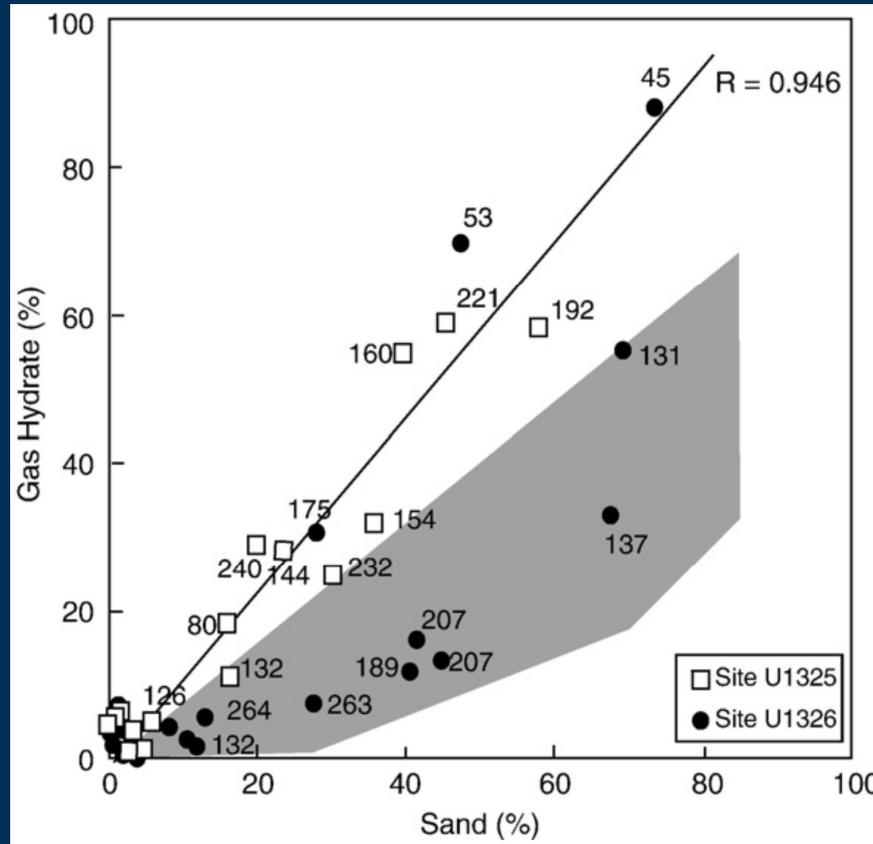
Ulleung Basin (offshore Korea)



Bahk et al. (2013), Marine and Petroleum Geology

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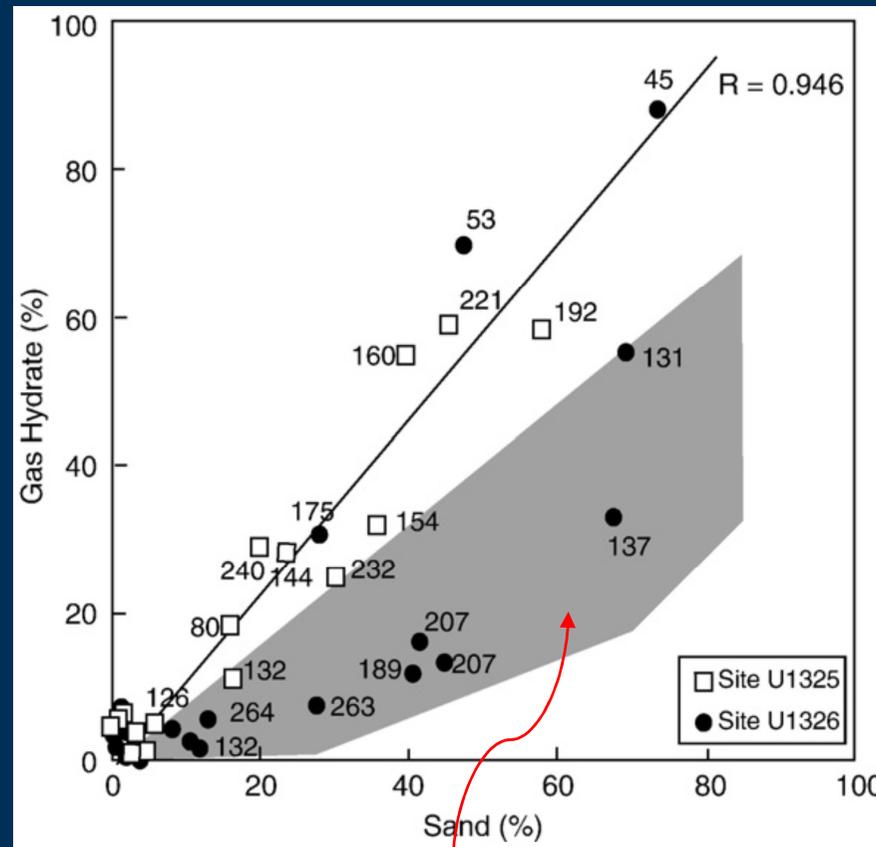
Cascadia Margin (offshore Canada)



Torres et al. (2008), EPSL

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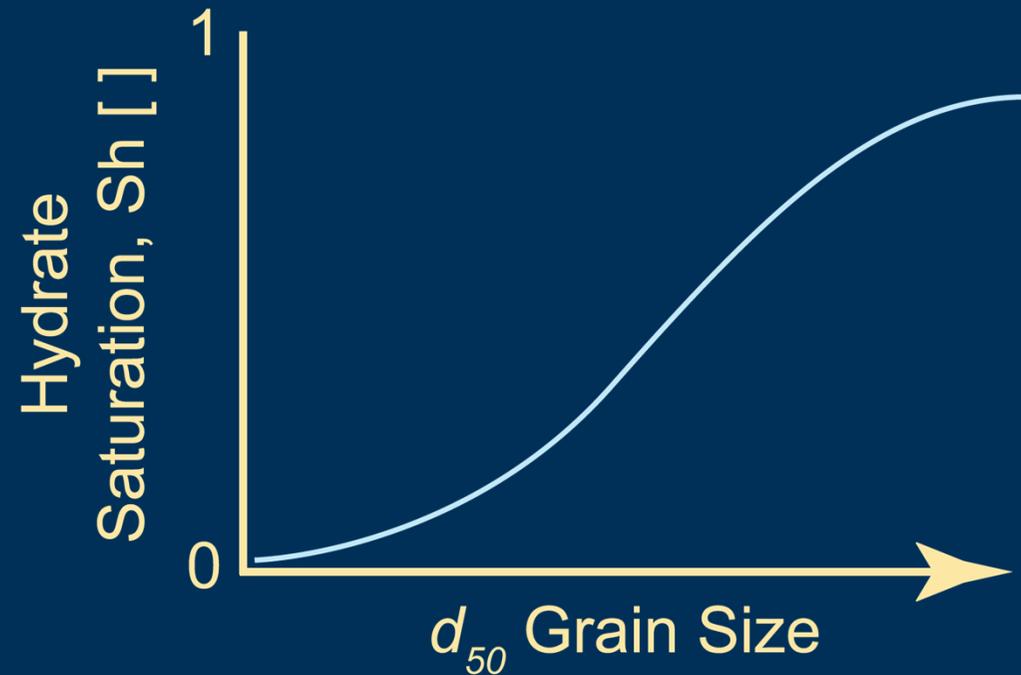
Cascadia Margin (offshore Canada)



Low hydrate saturations due to lack of methane

Torres et al. (2008), EPSL

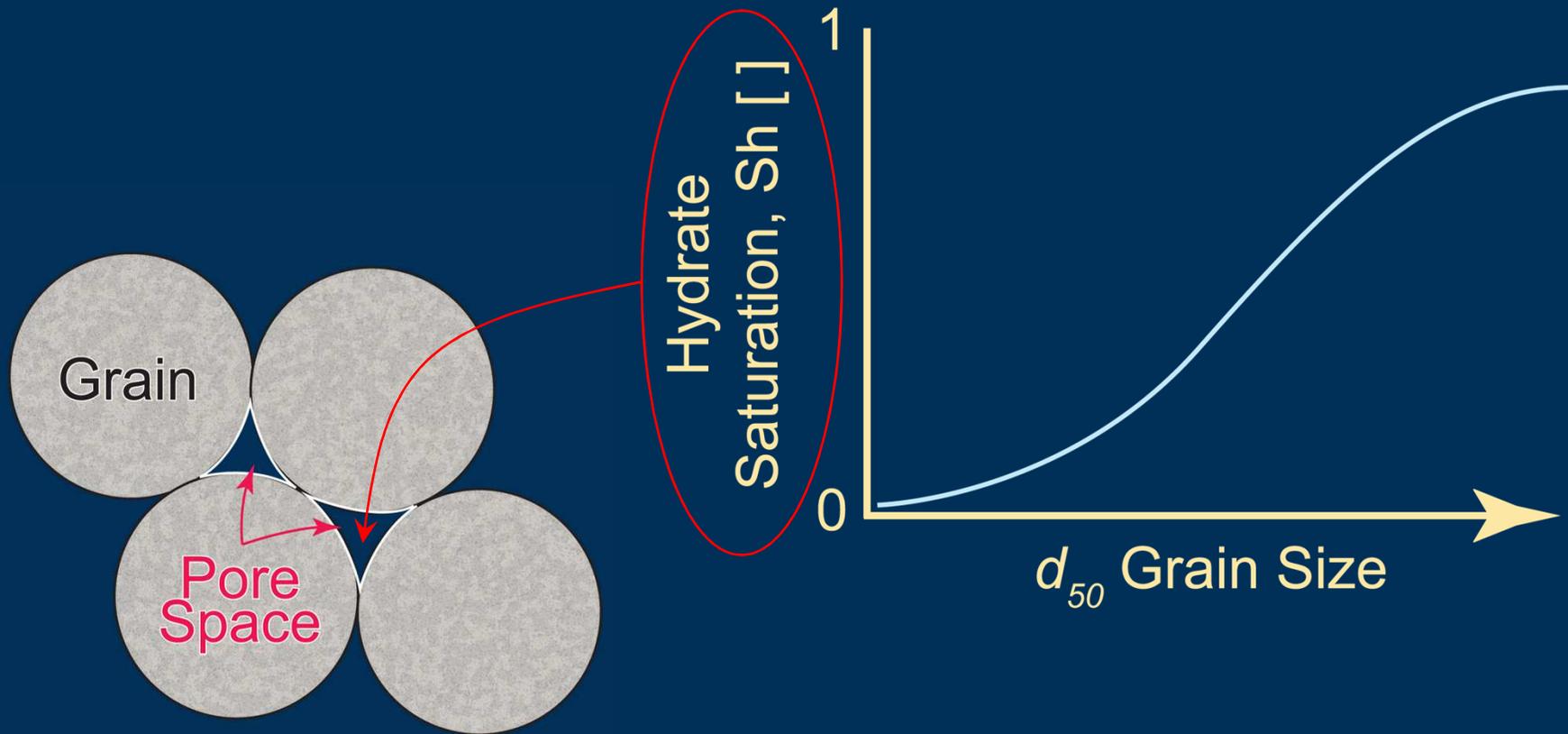
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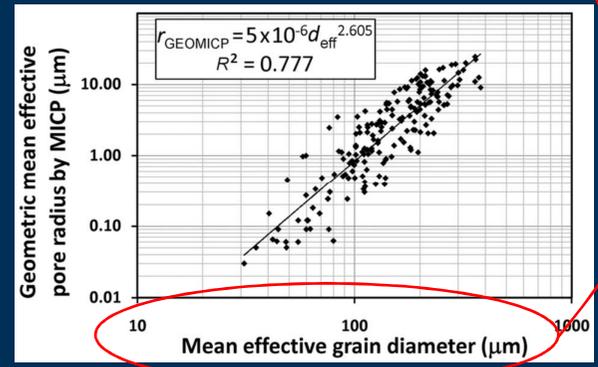
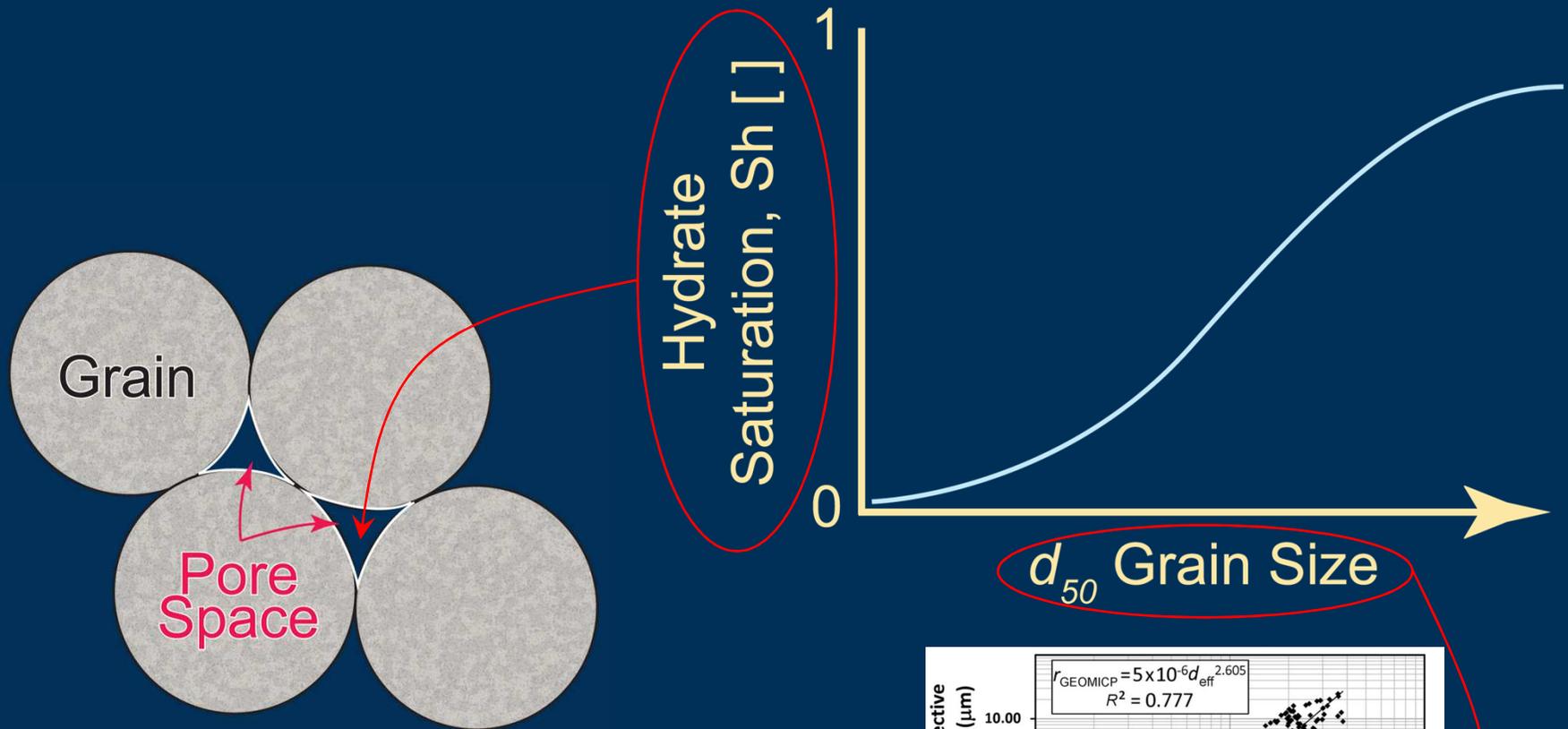
“...distribution of porous and coarser grained host sandy sediment is one of the most important factors controlling the occurrence of gas hydrate”

Uchida et al. (2009), AAPG Memoir

Coarser sediments can host higher gas hydrate saturations...

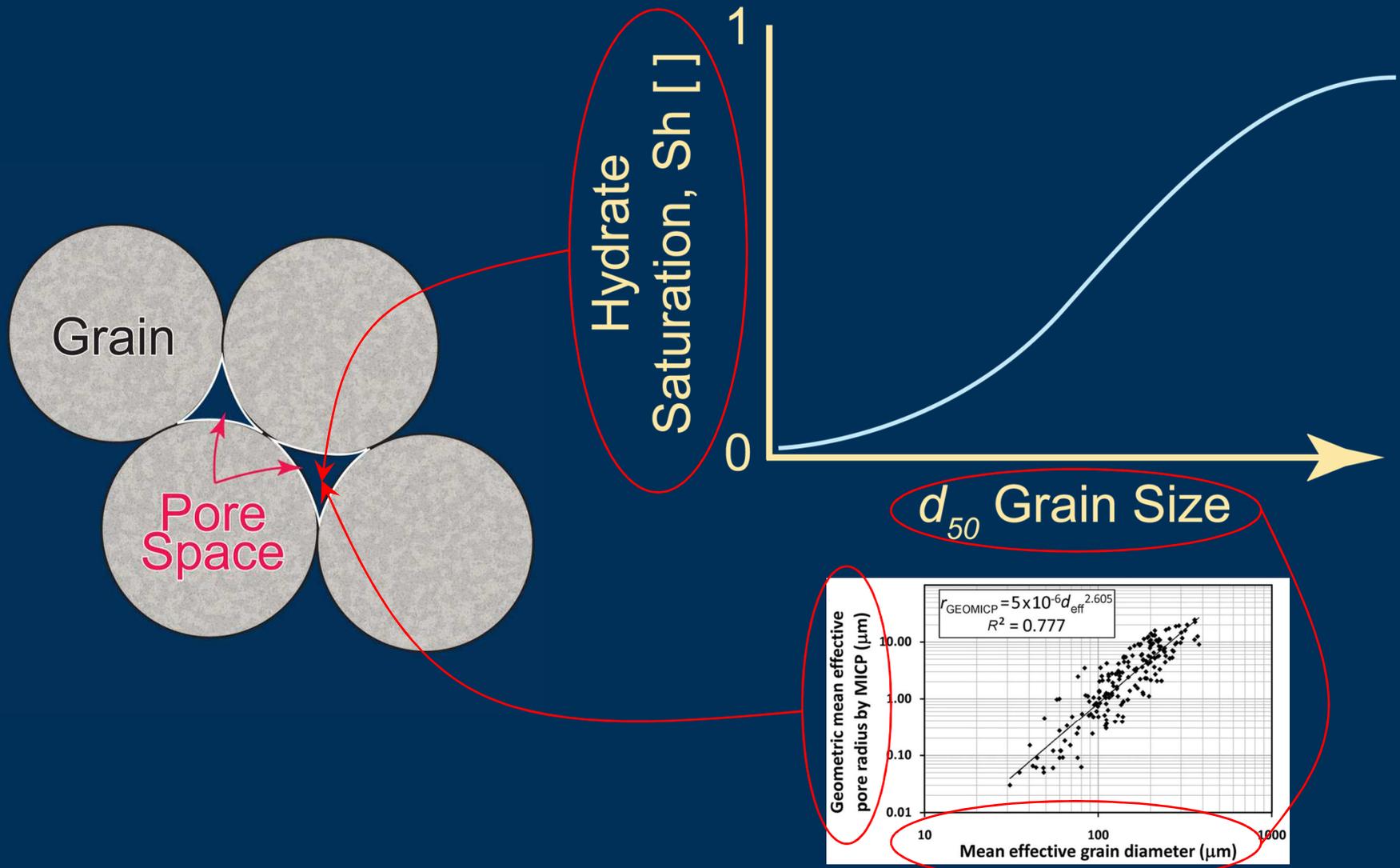


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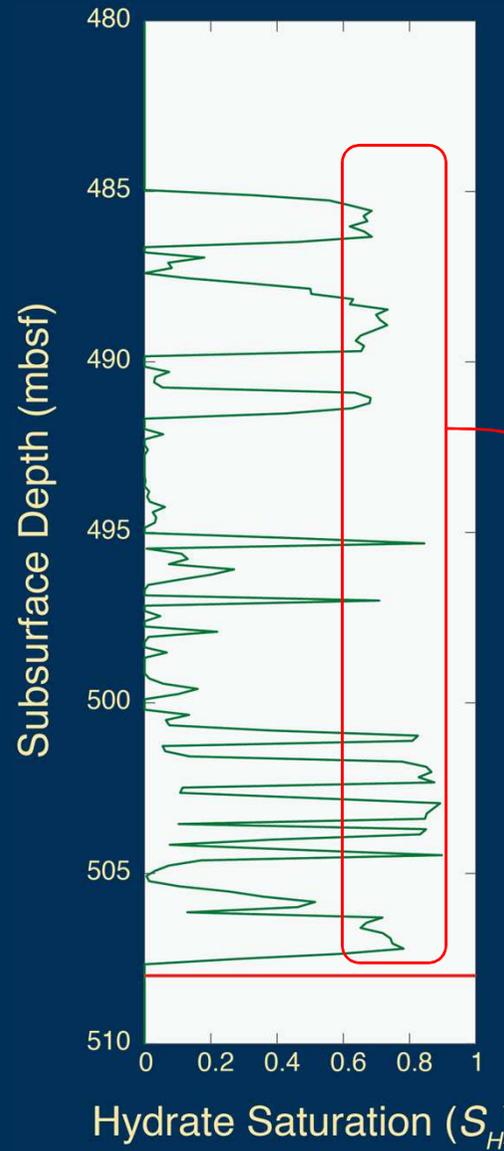
Glover and Walker (2009), Geophysics

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Gas hydrate saturation versus grain size



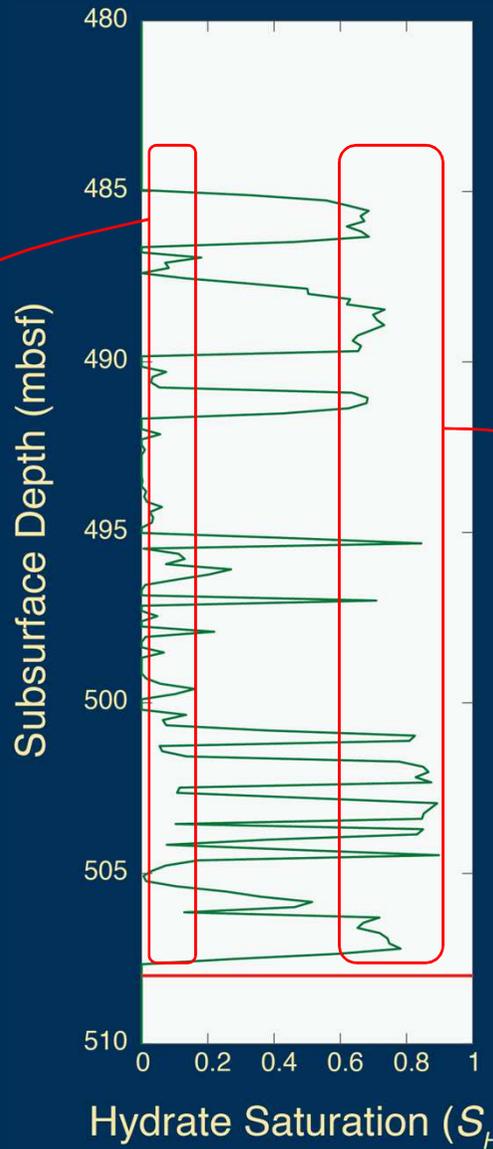
**Coarse-grained
“reservoir” sediment**

NGHP-02, Site 05

Waite et al. (2018), JMPG

Gas hydrate saturation versus grain size

**Fine-grained
“interbed” sediment**



**Coarse-grained
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**Fining upward
deposition**

**Coarse-grained
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**Fine-grained
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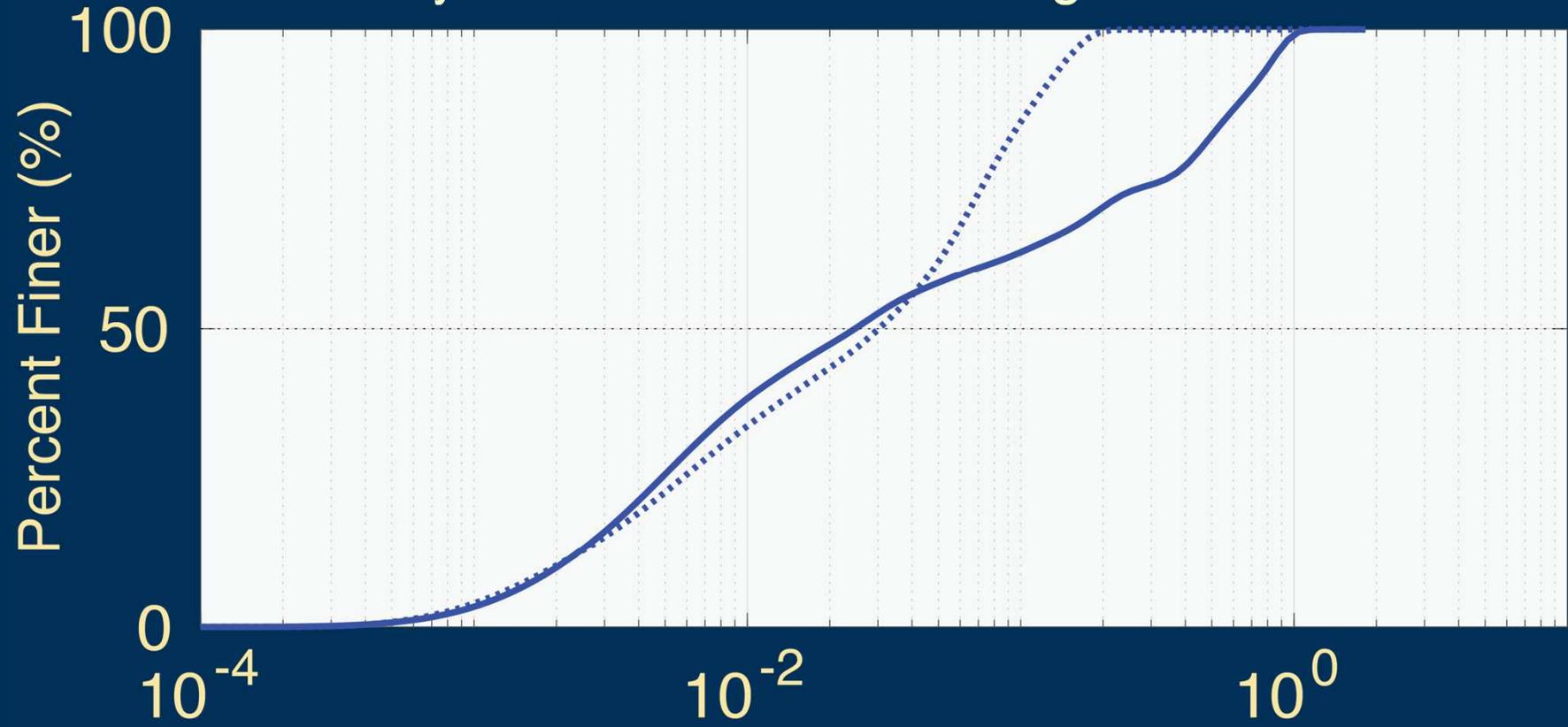
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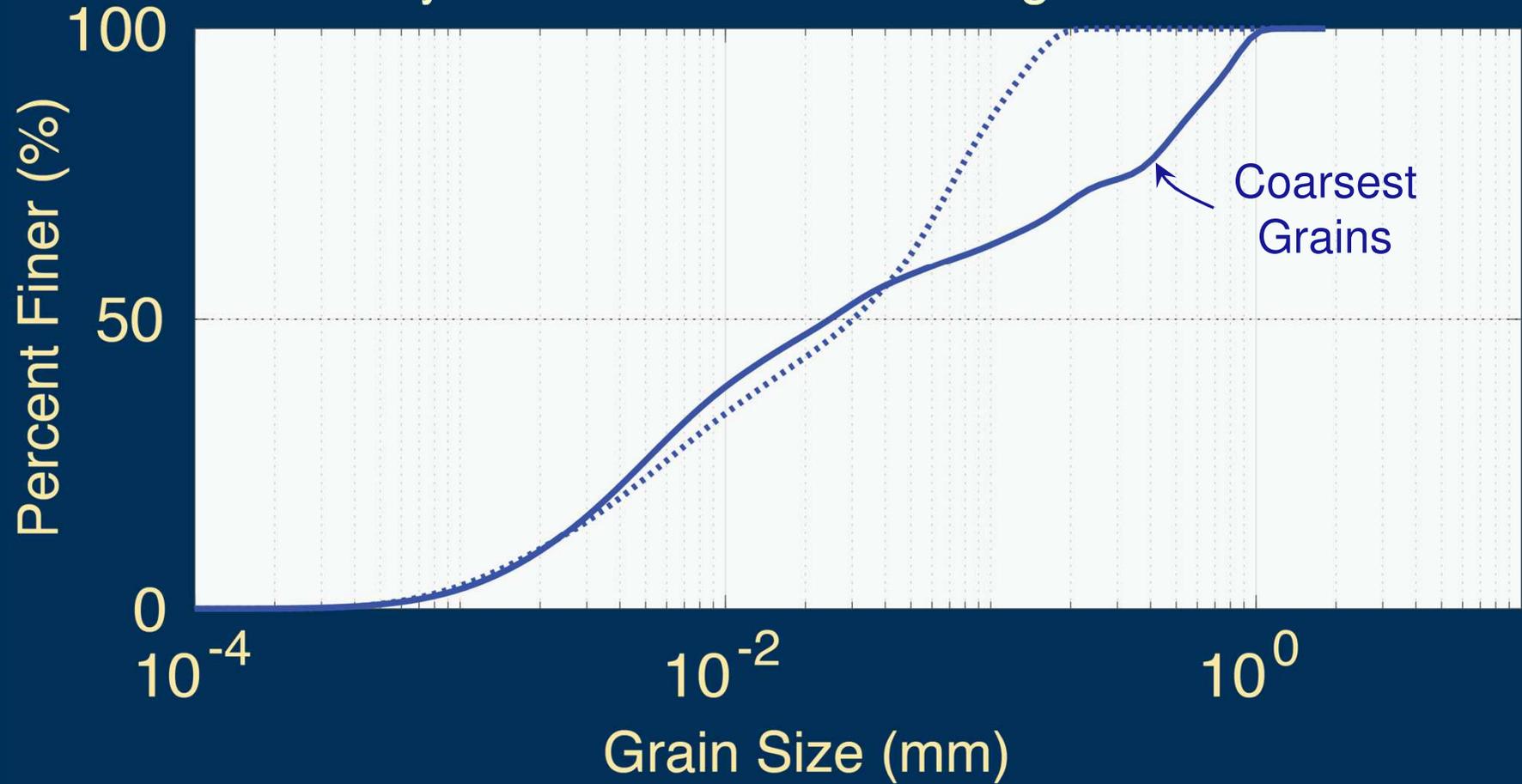


Grain Size (mm)

NGHP-02, Site 05

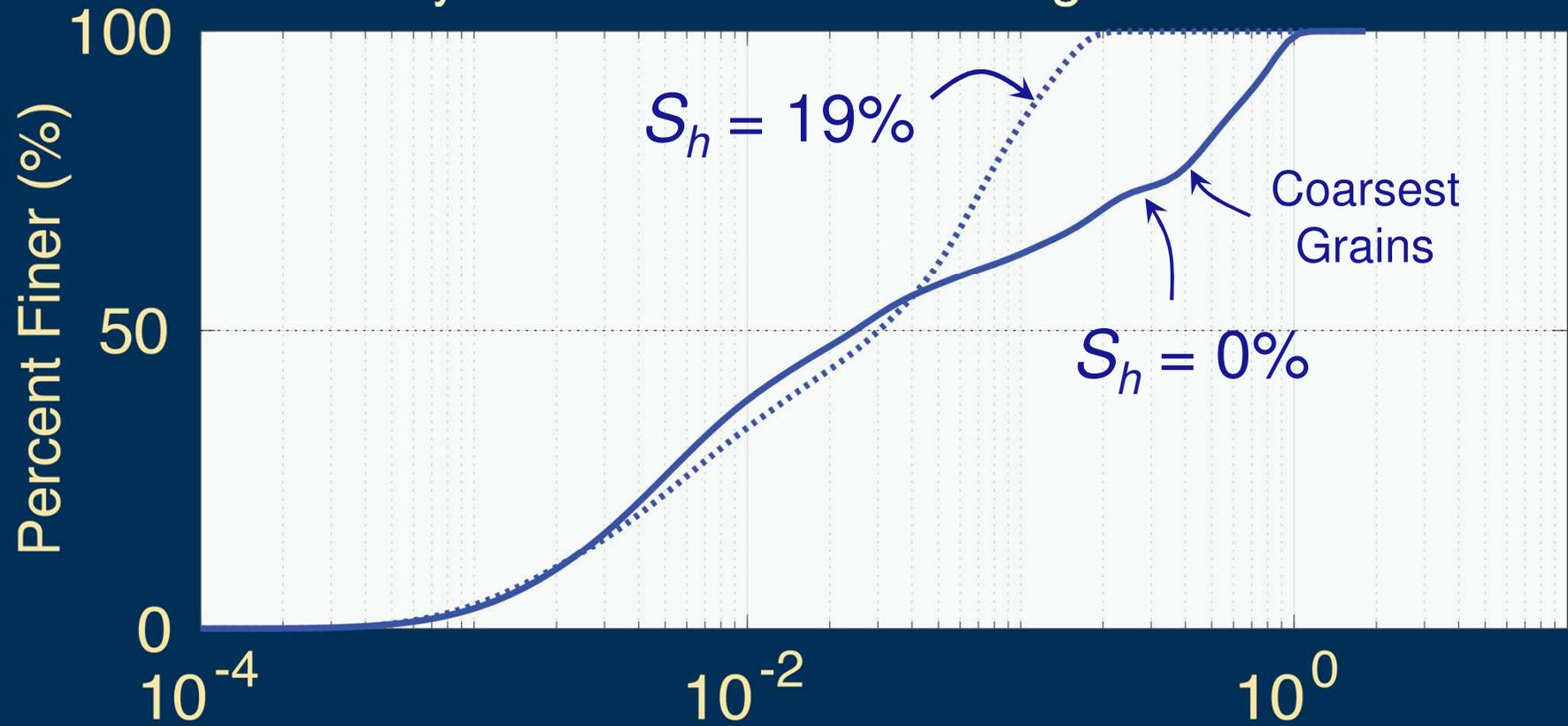
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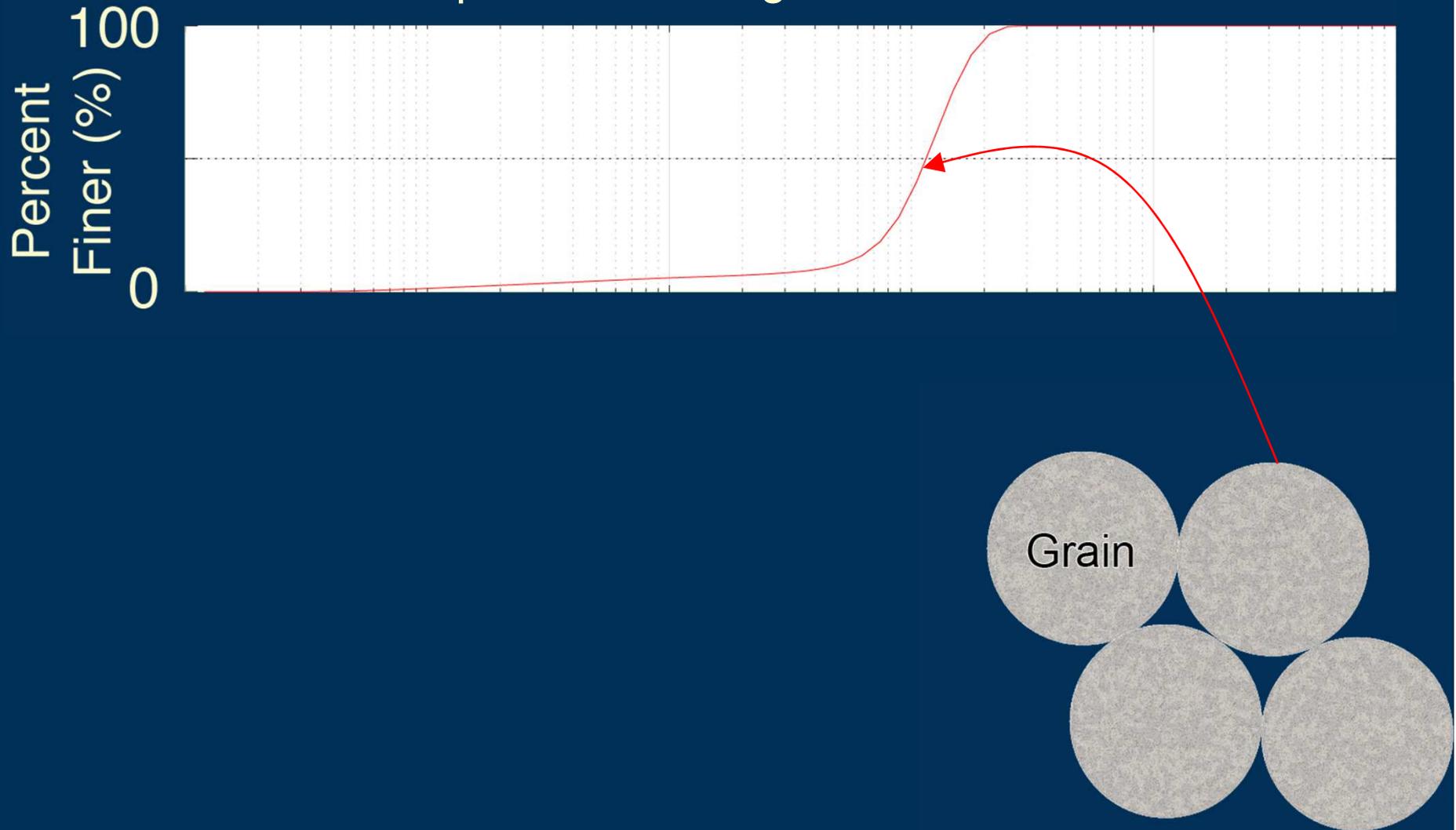
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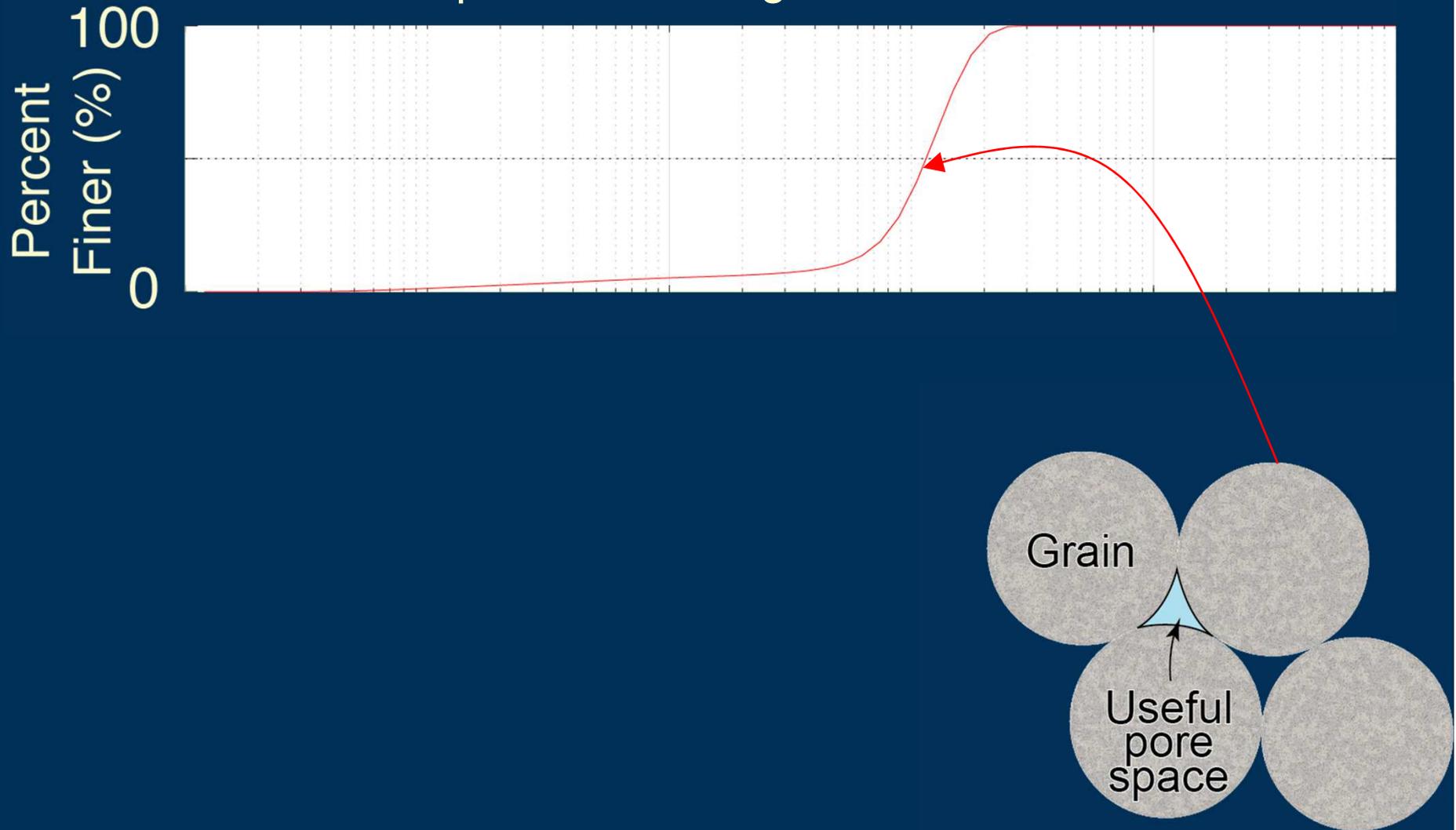
Pore size dependence on grain size distribution



Pore size is more important than grain size, so higher gas hydrate saturations tend to occur for narrower grain distributions

Uchida (2009), AAPG Memoir

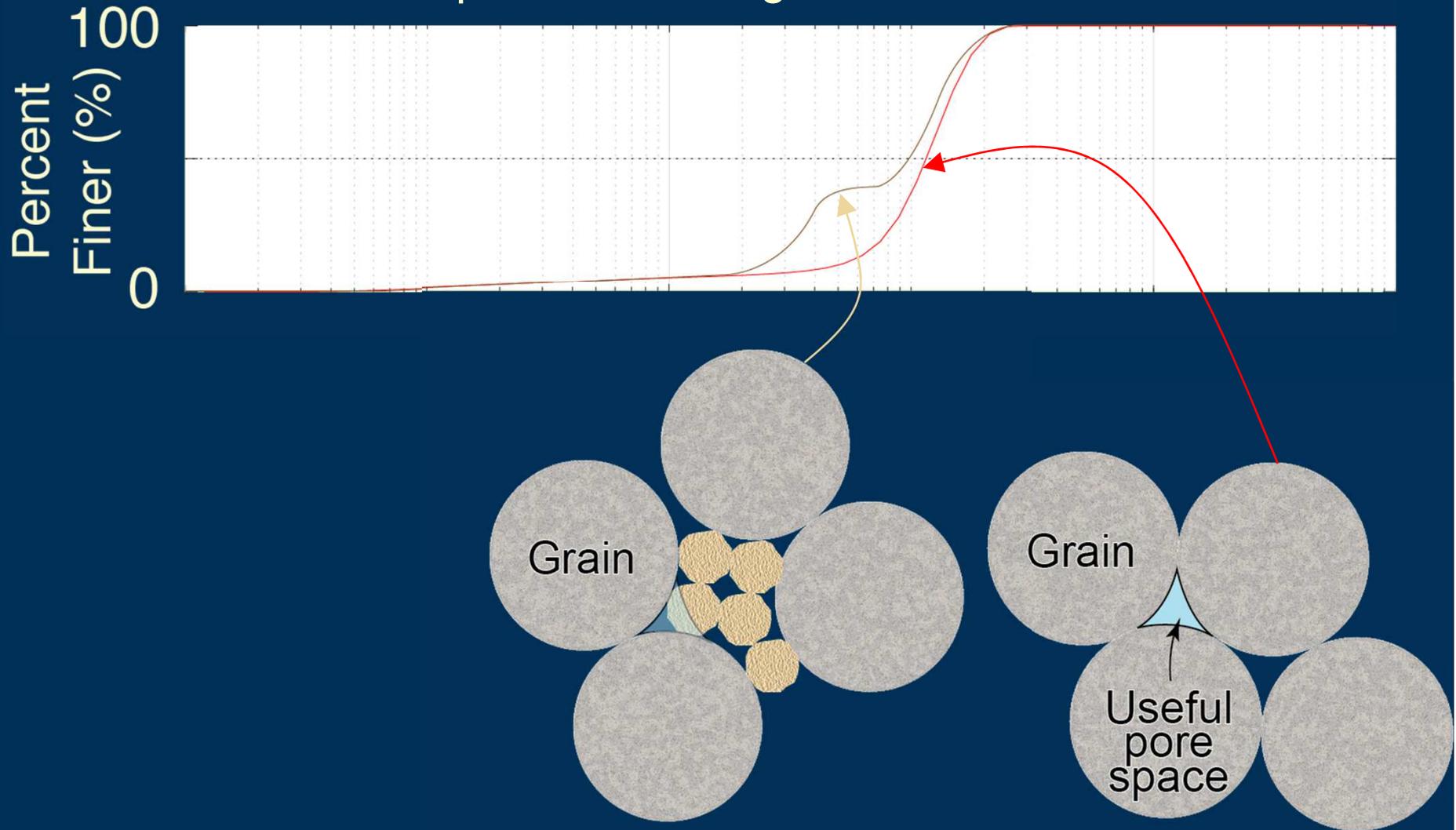
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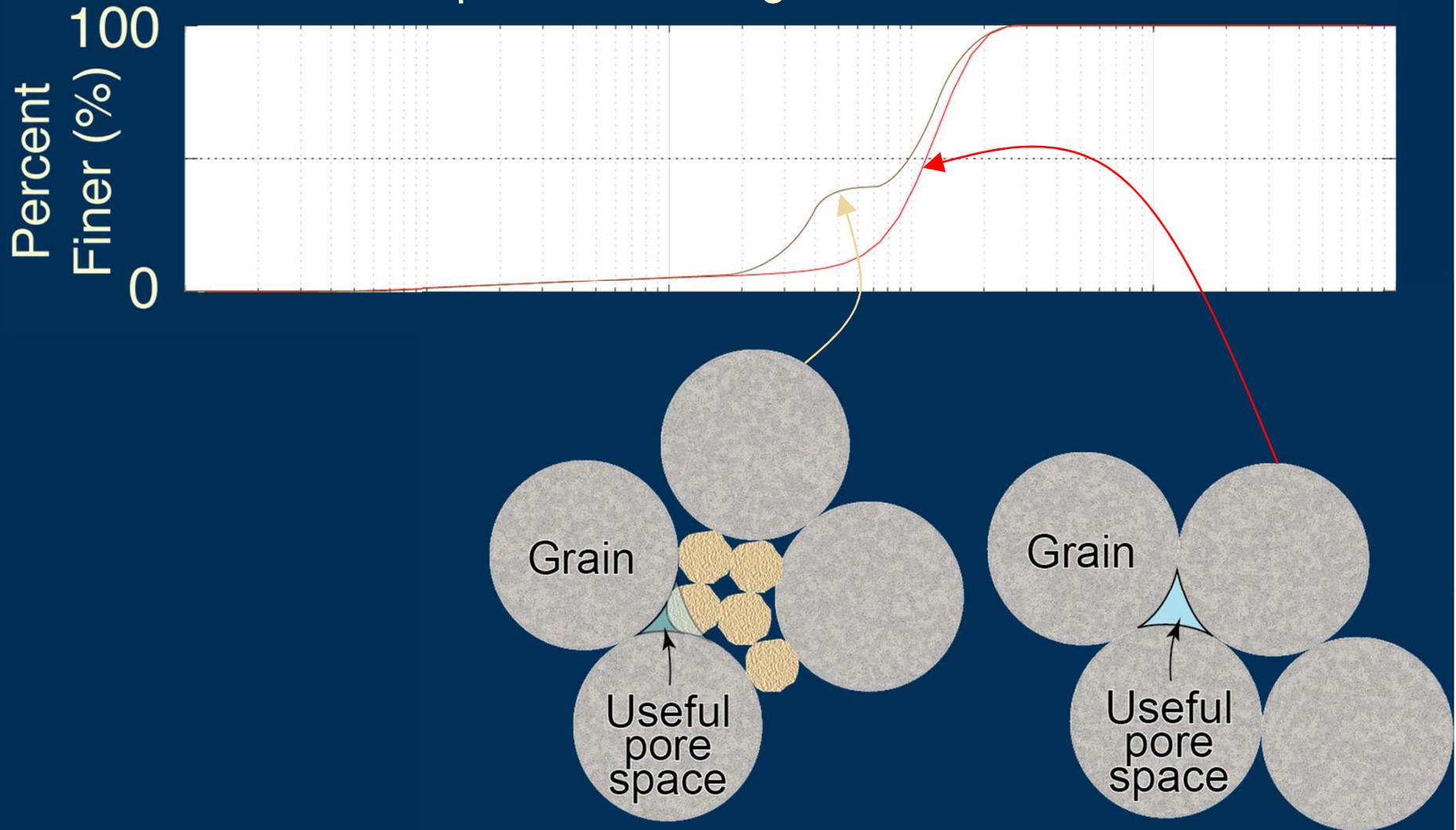
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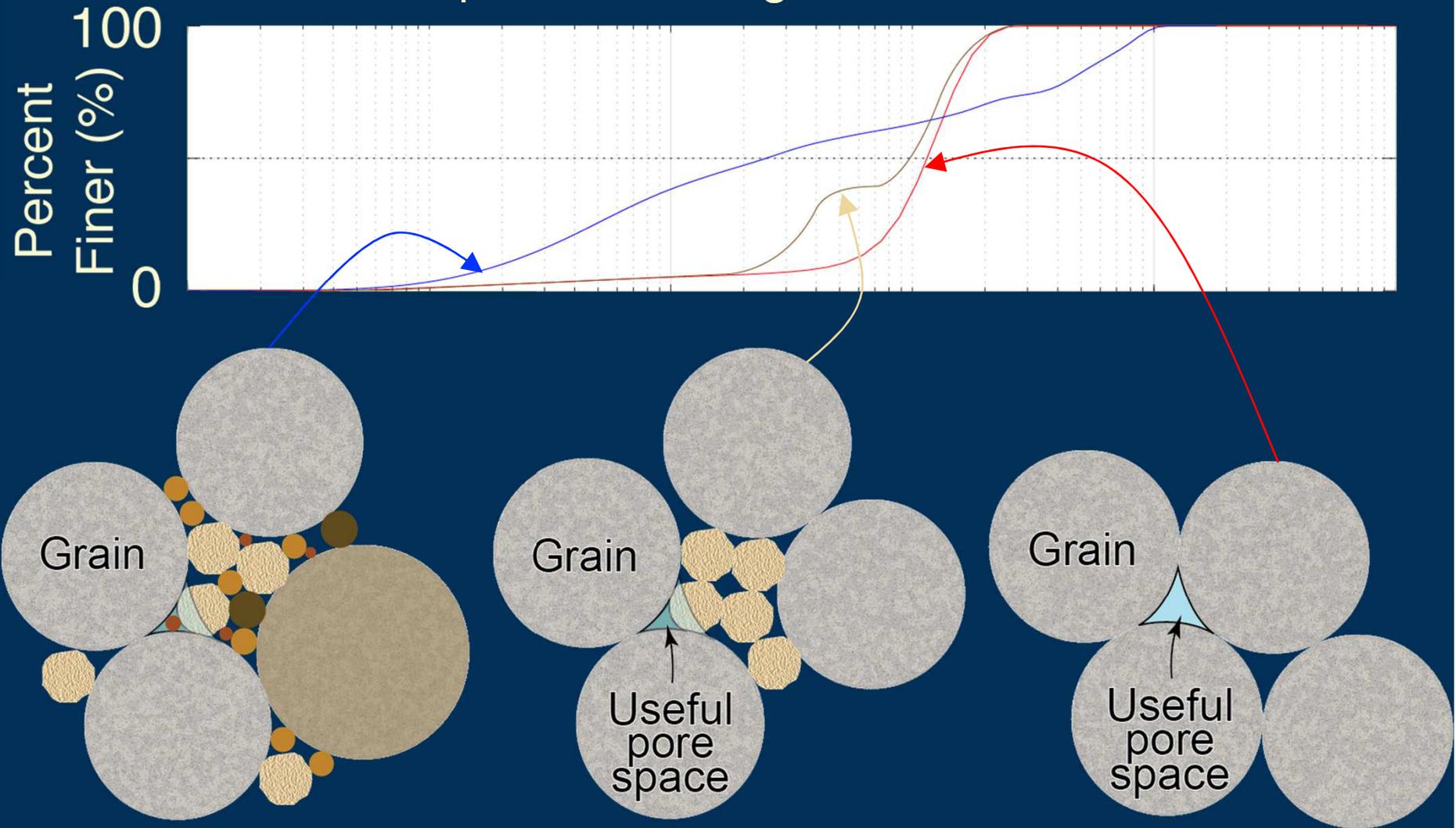
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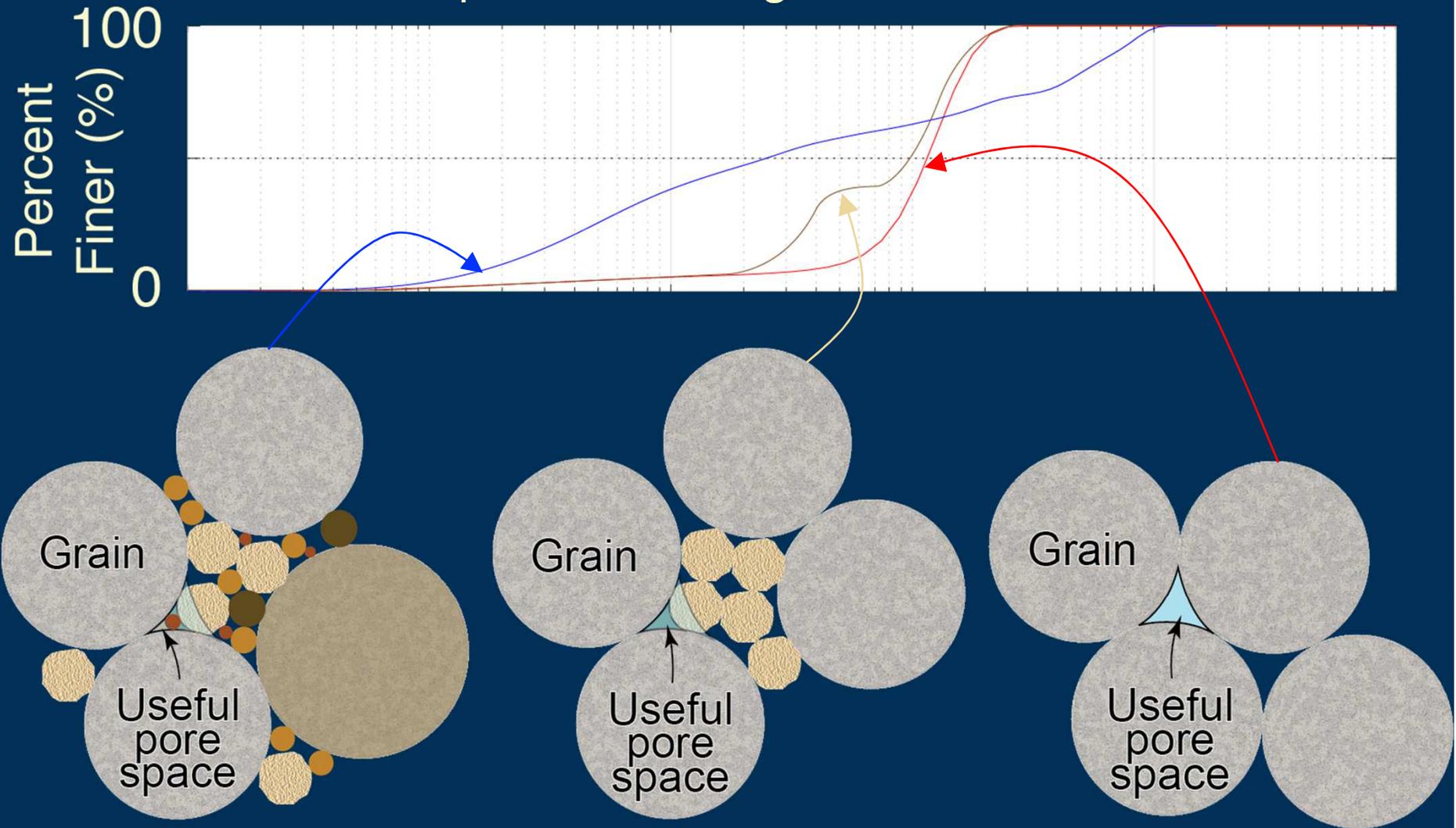
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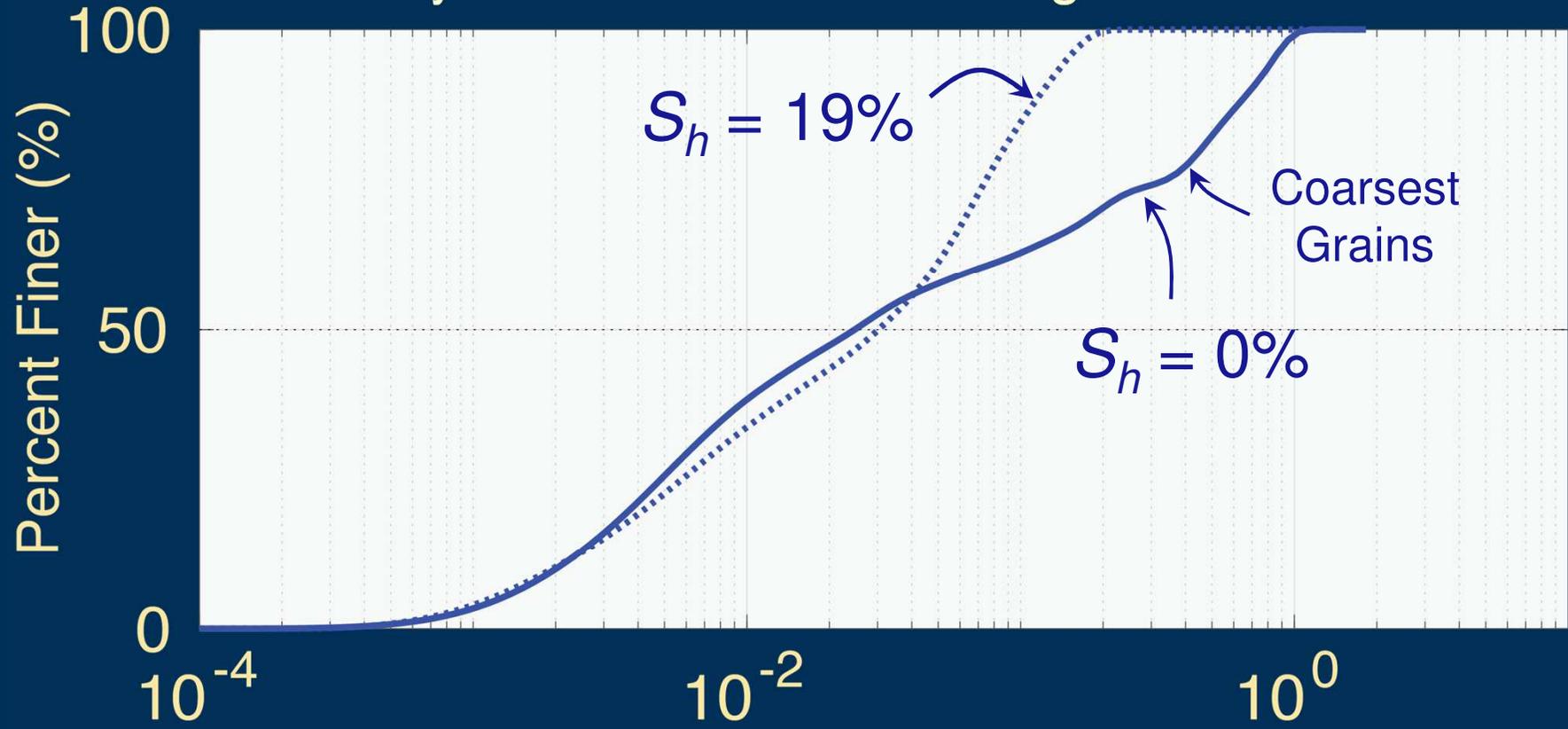
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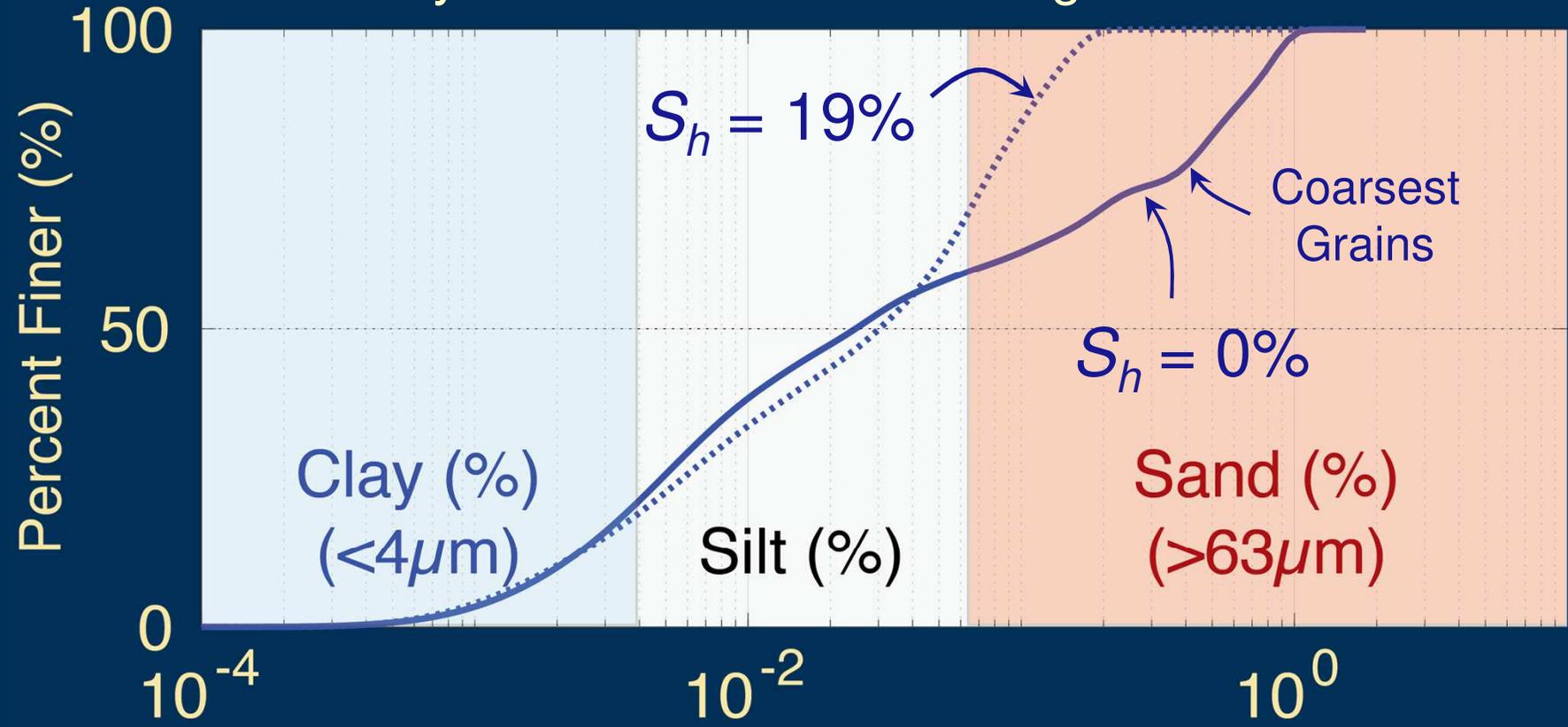
Gas hydrate saturation versus grain size



Grain Size (mm)

NGHP-02, Site 05

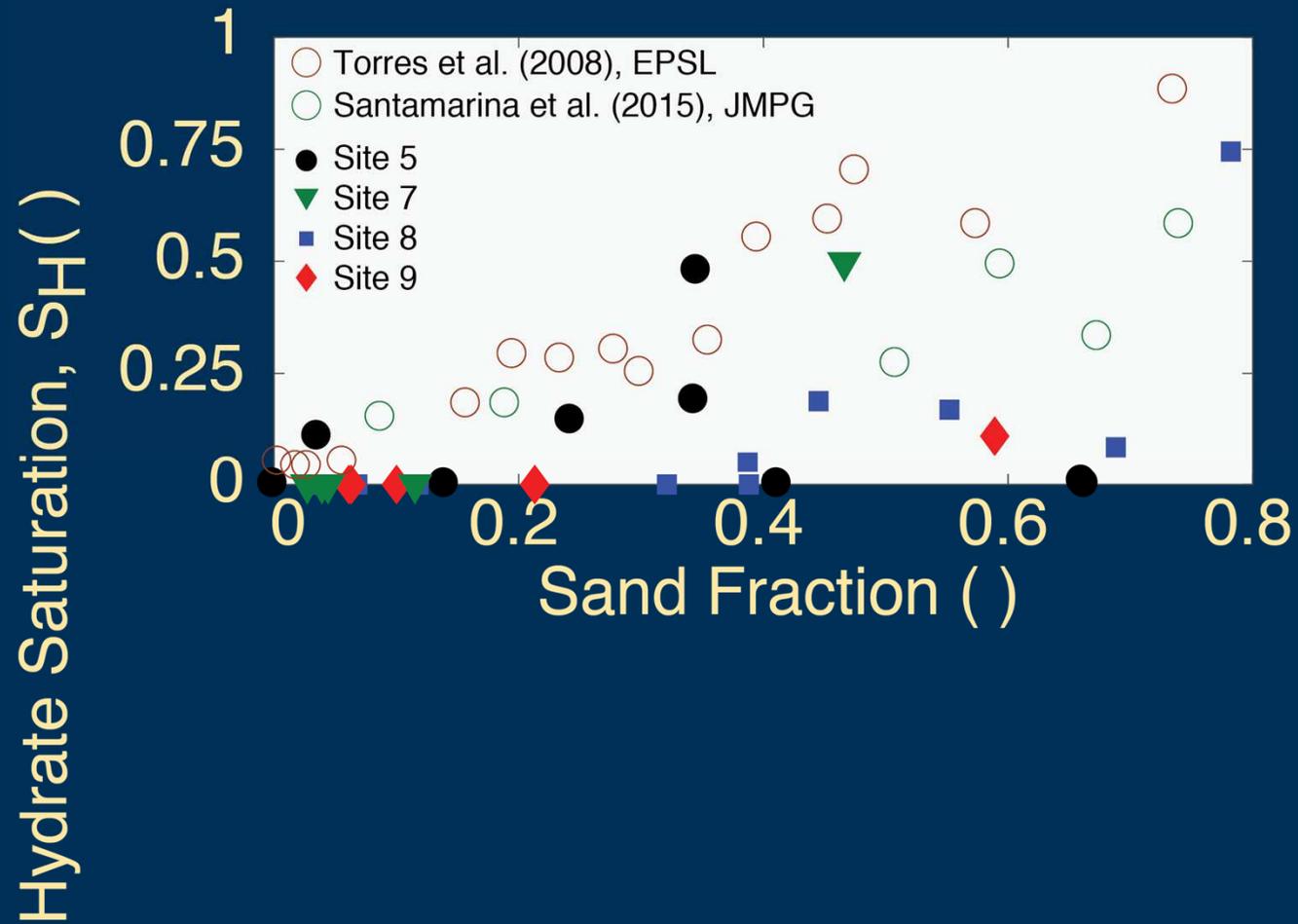
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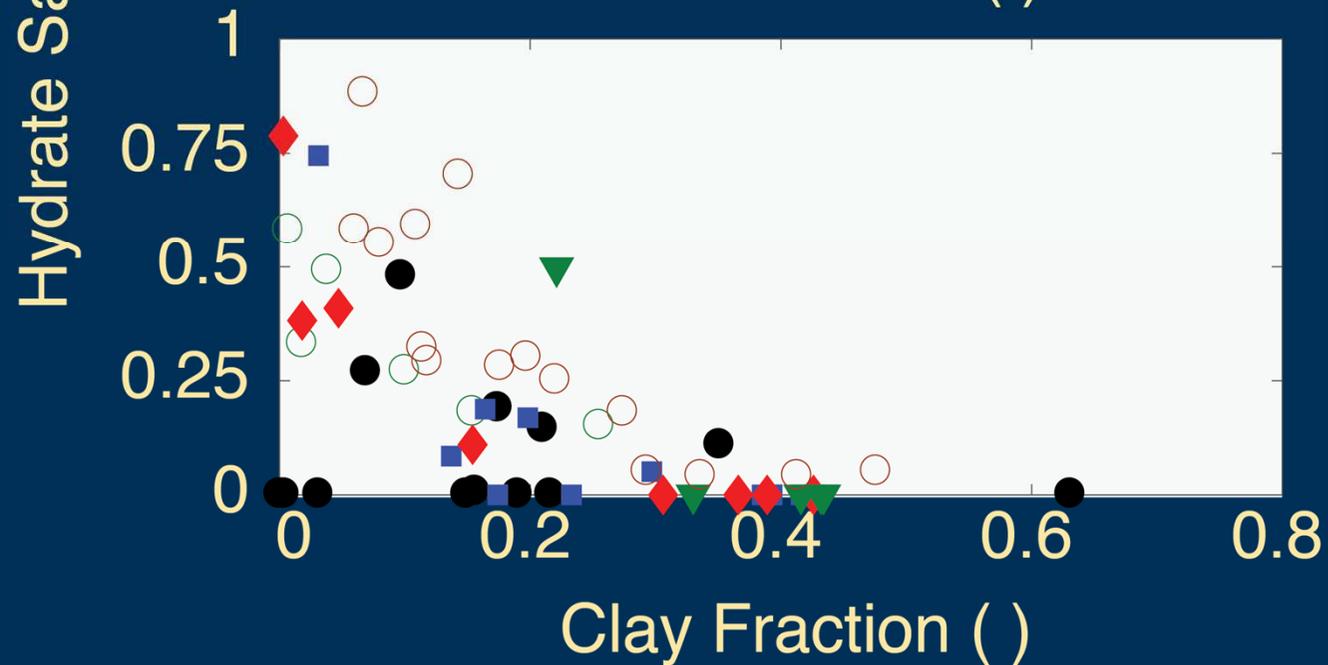
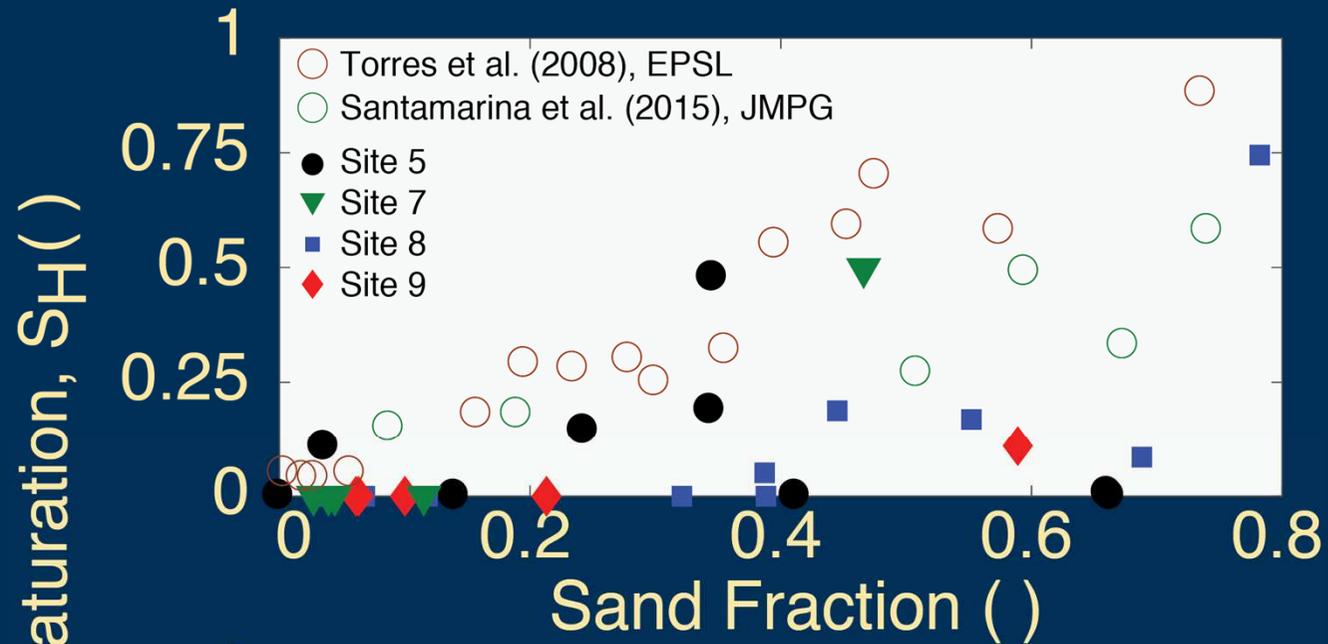
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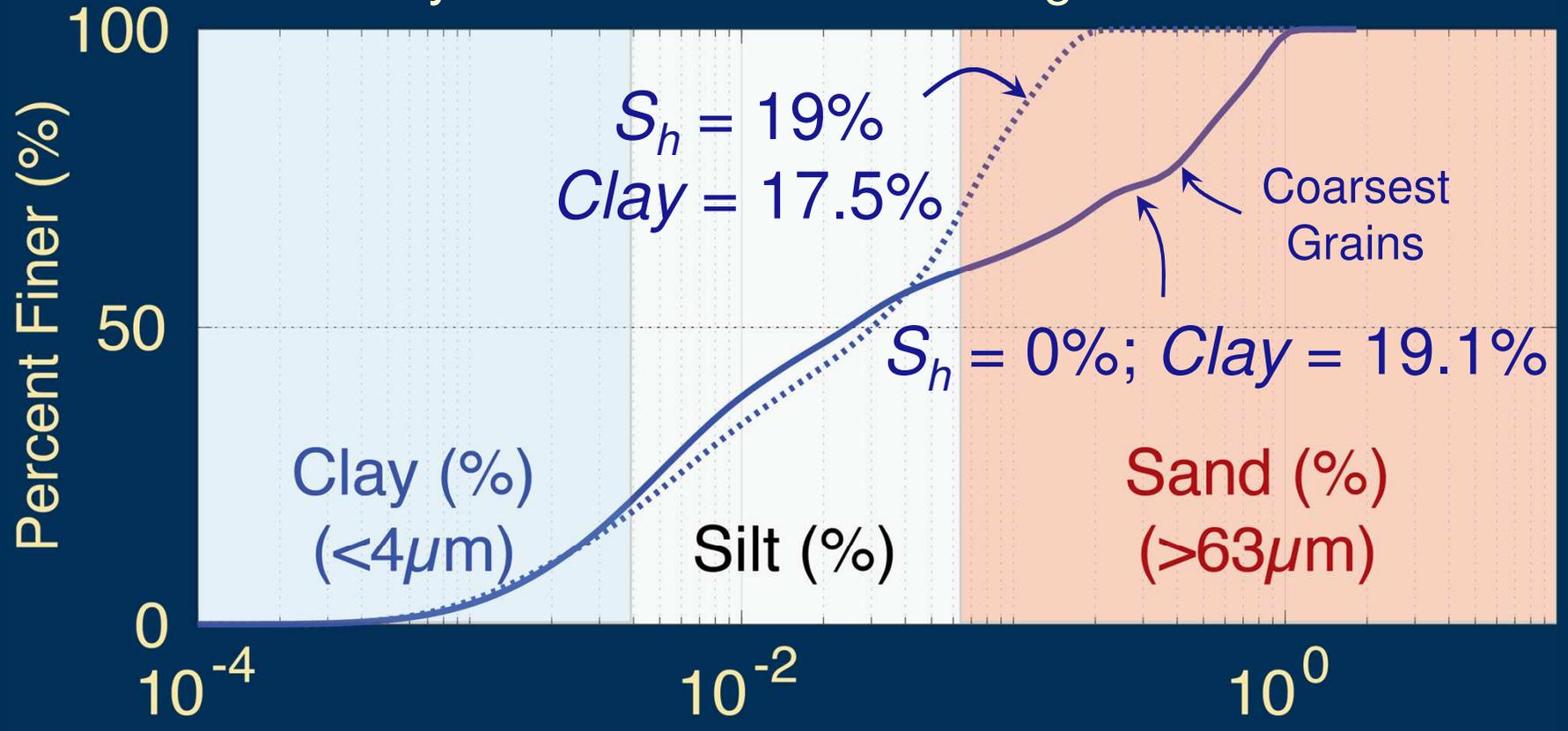
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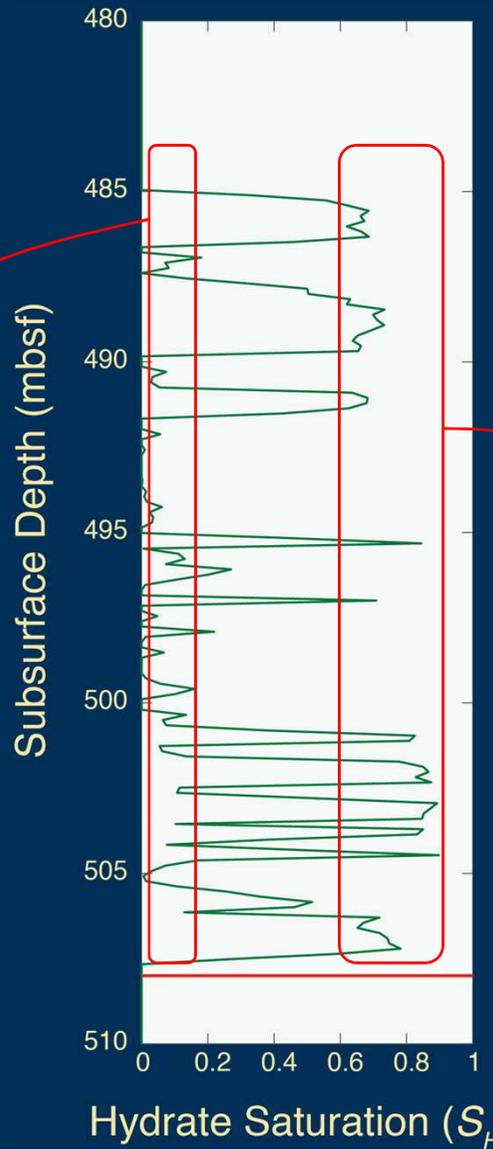
Gas hydrate saturation versus grain size



NGHP-02, Site 05

Gas hydrate saturation versus grain size

**Fine-grained
“interbed” sediment**



**Coarse-grained
“reservoir” sediment**

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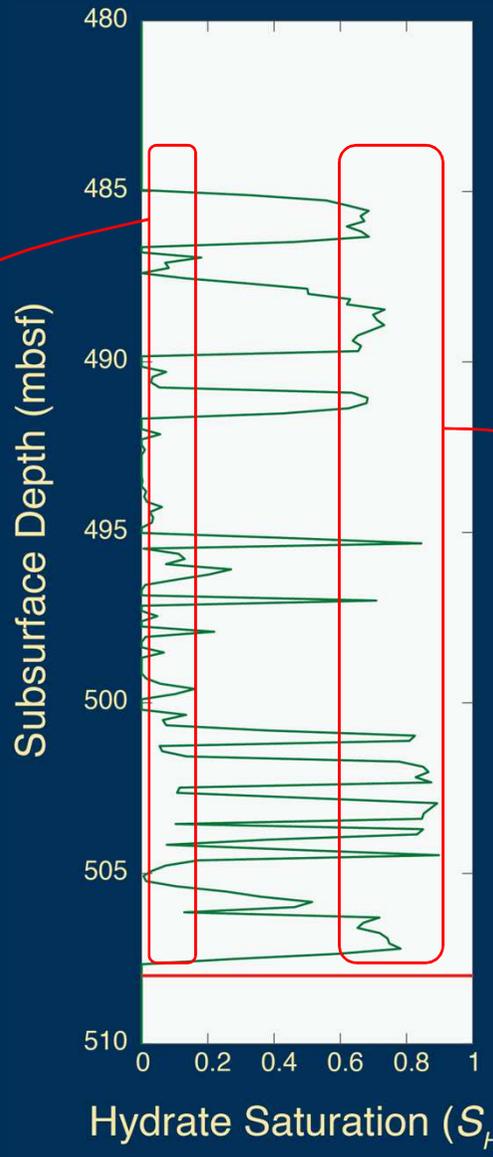
Waite et al. (2018), JMPG

Gas hydrate saturation versus ~~grain size~~

clay content

**Fine-grained
“interbed” sediment**

**Coarse-grained
“reservoir” sediment**

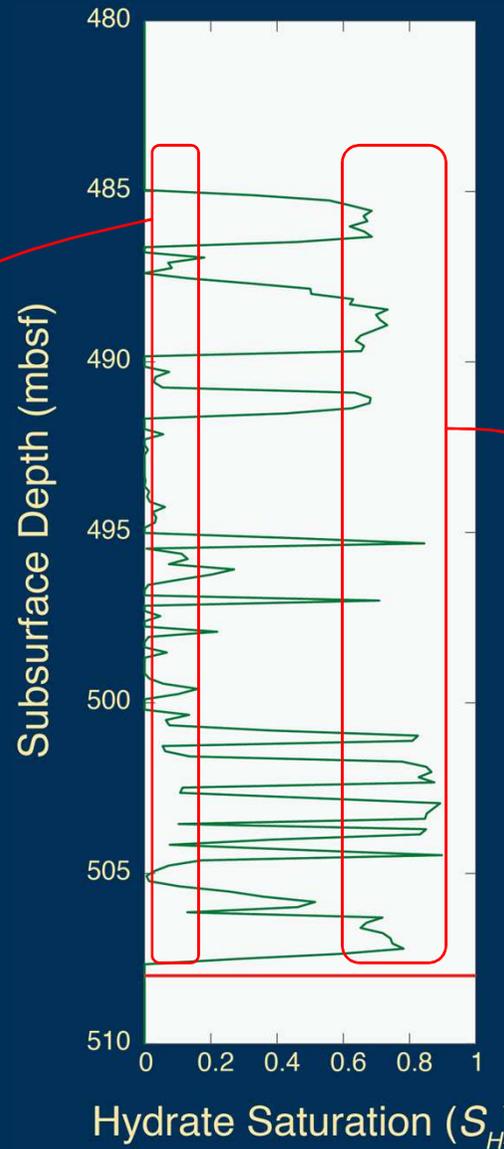


NGHP-02, Site 05

Waite et al. (2018), JMPG

Gas hydrate saturation versus ~~grain size~~

**Fine-grained
“interbed” sediment**



clay content

**Coarse-grained
“reservoir” sediment**

Low clay content
“Clean” sediment
($<10\%$ clay)

NGHP-02, Site 05

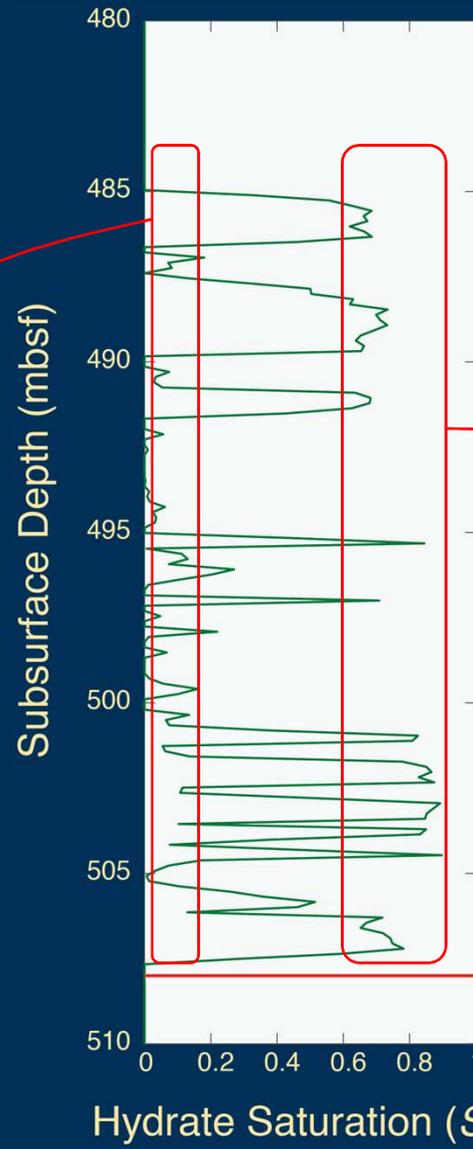
Waite et al. (2018), JMPG

Gas hydrate saturation versus ~~grain size~~

clay content

**Fine-grained
“interbed” sediment**

Medium to high
clay content
(>20-30% clay)



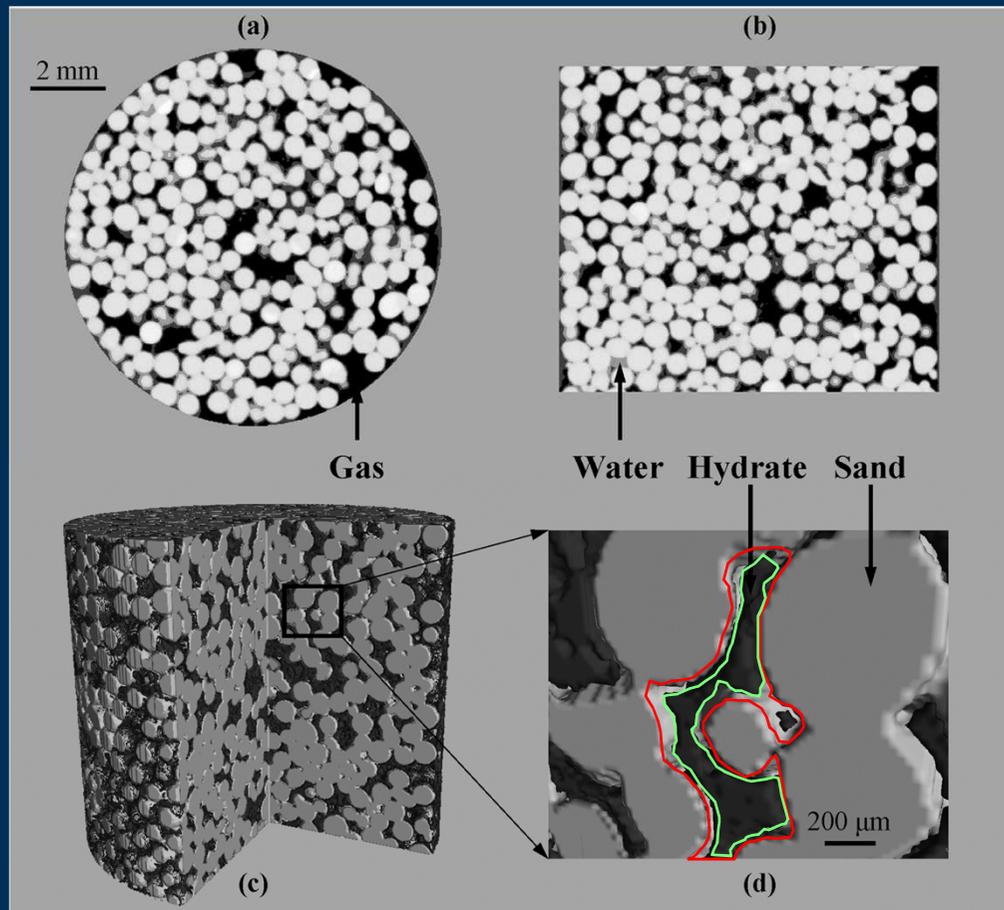
**Coarse-grained
“reservoir” sediment**

Low clay content
“Clean” sediment
(<10% clay)

NGHP-02, Site 05

Waite et al. (2018), JMPG

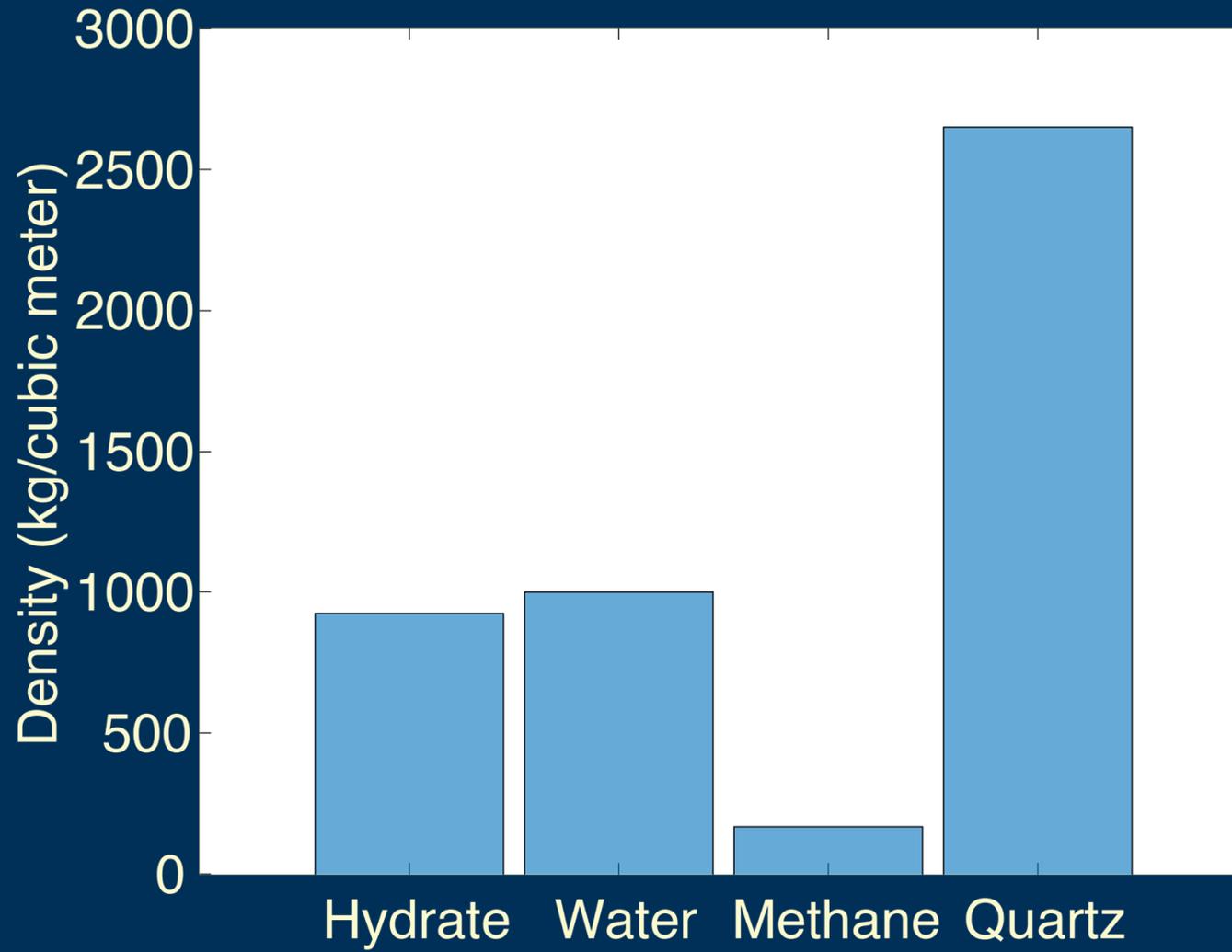
How do you measure gas hydrate saturation?



Gas hydrate
saturation, S_h :

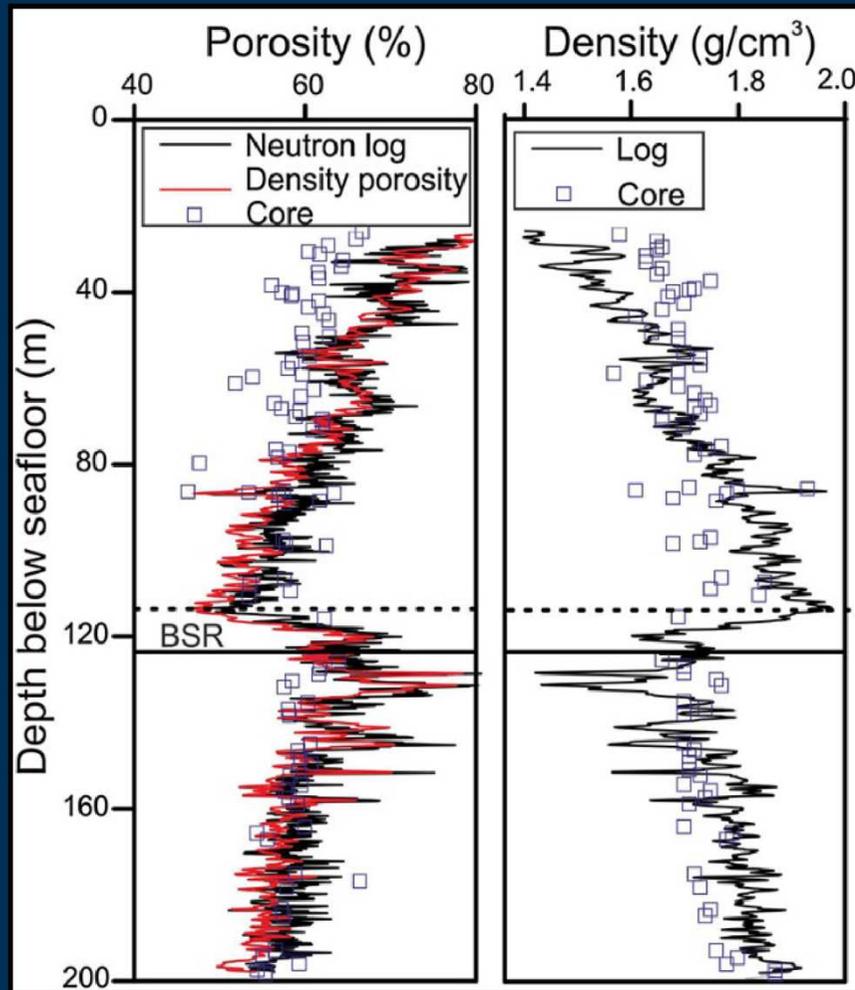
$$\frac{\text{Volume of gas hydrate}}{\text{Volume of the pore}} = S_h$$

Density, ρ



Using ρ in the field: a way to estimate porosity

NGHP-01-05, Krishna-Godavari Basin (offshore India)



Density porosity, ϕ_D

$$\phi_D = \frac{\rho_{grain} - \rho_b}{\rho_{grain} - \rho_f}$$

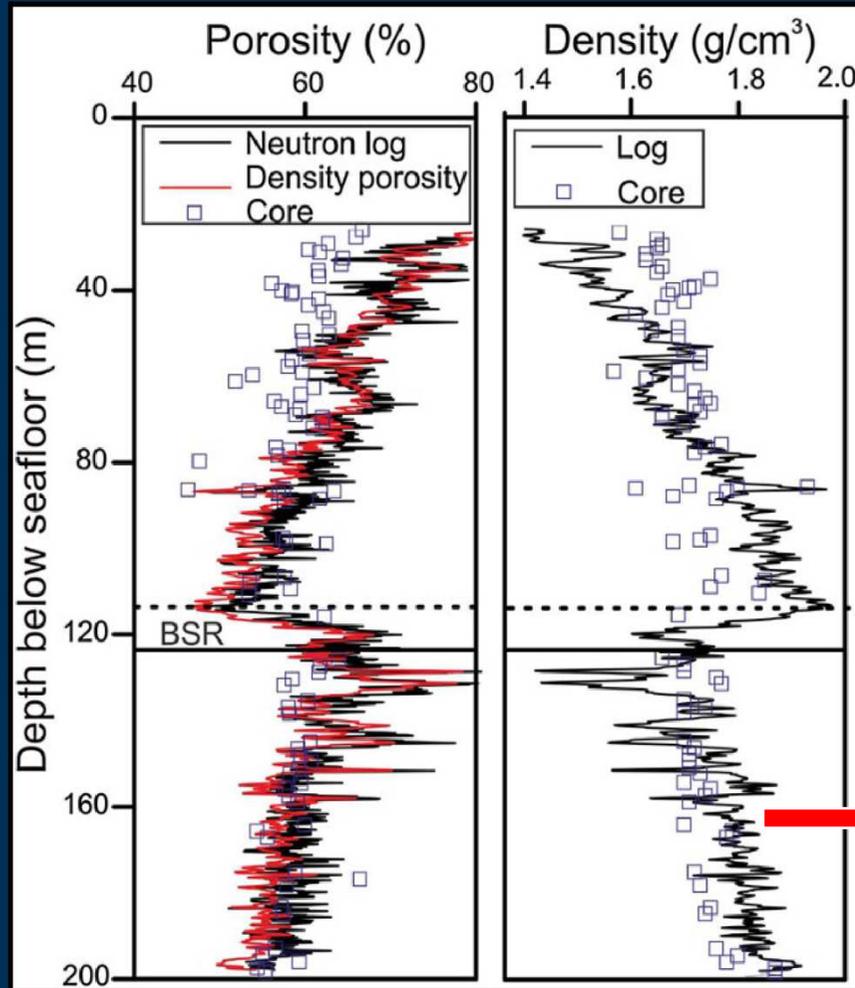
ρ_{grain} = sediment grain density

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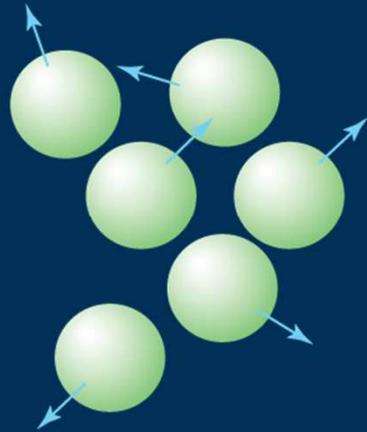
Nuclear Magnetic Resonance: a tool for many measurements

- Primary measurement
 - Porosity
 - Pore size

Nuclear Magnetic Resonance: a tool for many measurements

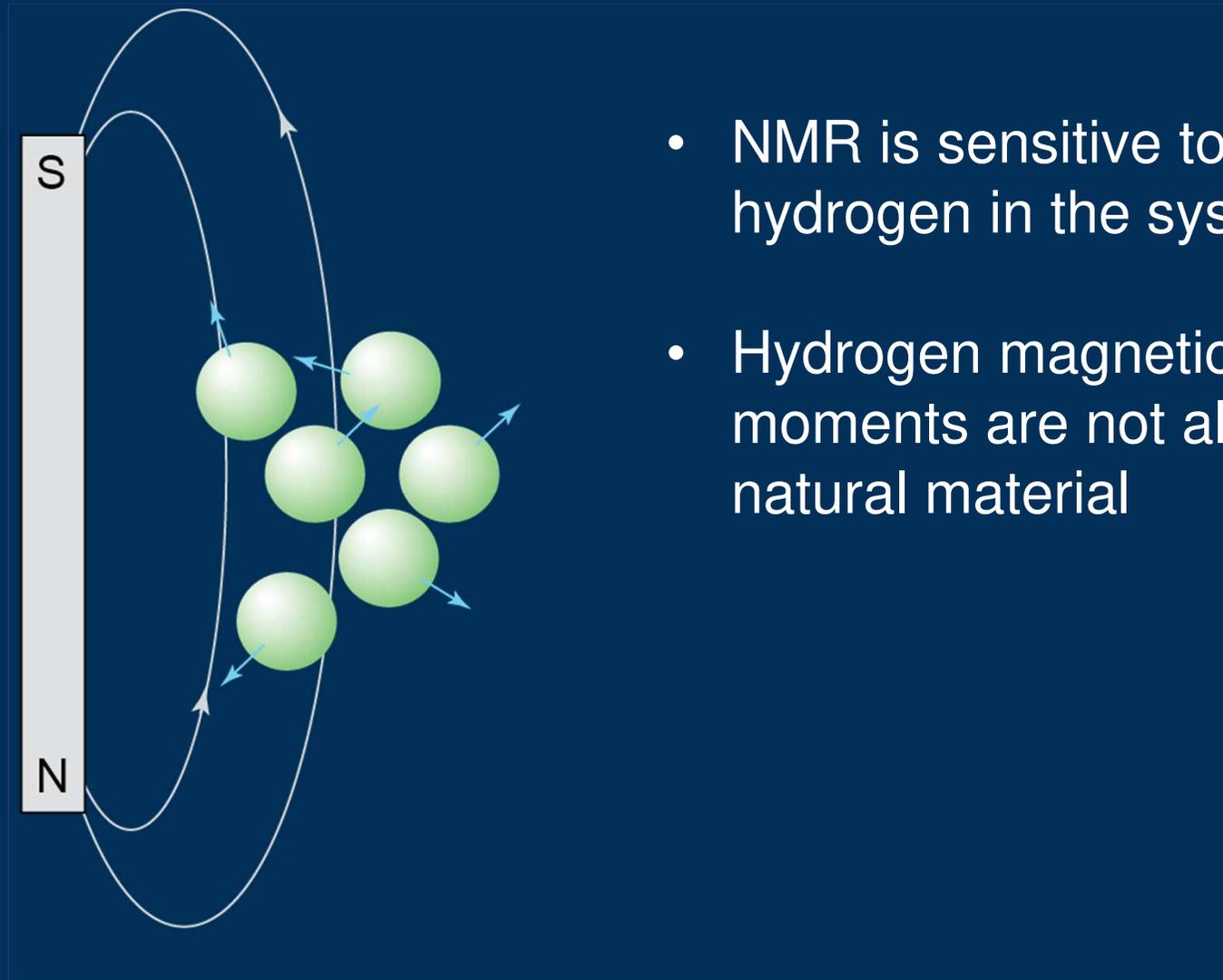
- Primary measurement
 - Porosity
 - Pore size
- Derived estimates:
 - Hydrate saturation
 - Permeability

Nuclear Magnetic Resonance: a tool for many measurements



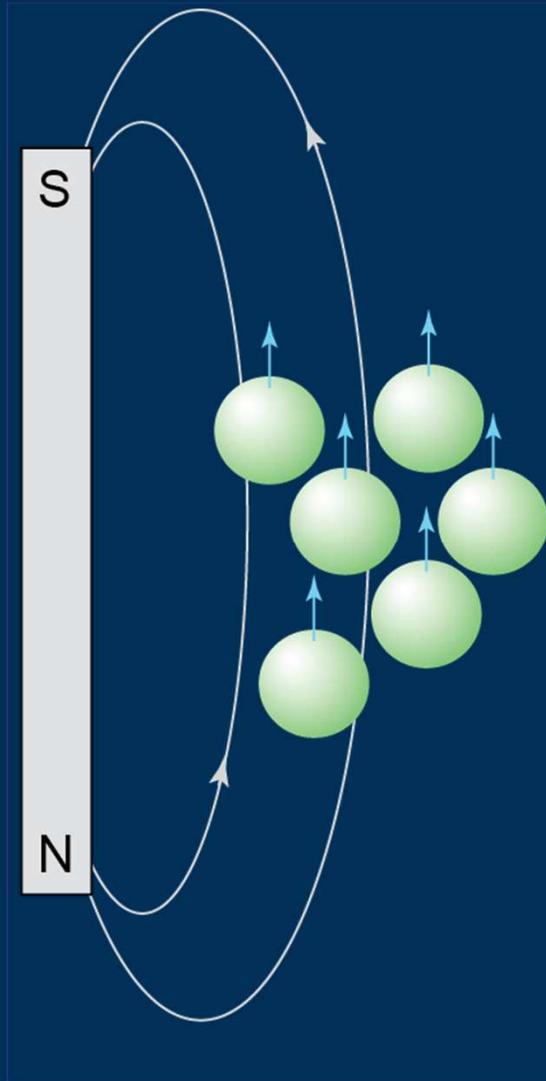
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- Hydrogen magnetic moments are not aligned in natural material

Nuclear Magnetic Resonance: a tool for many measurements



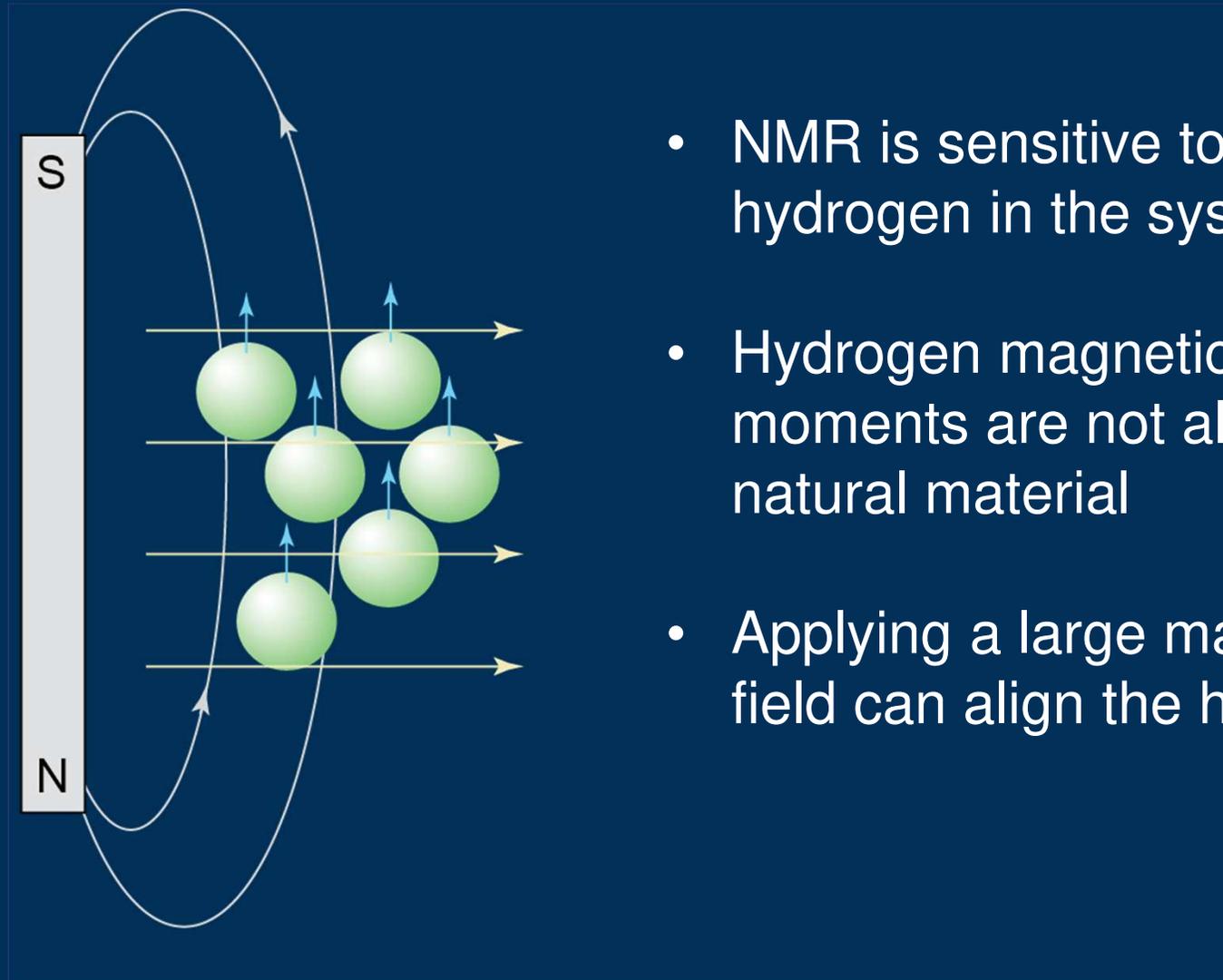
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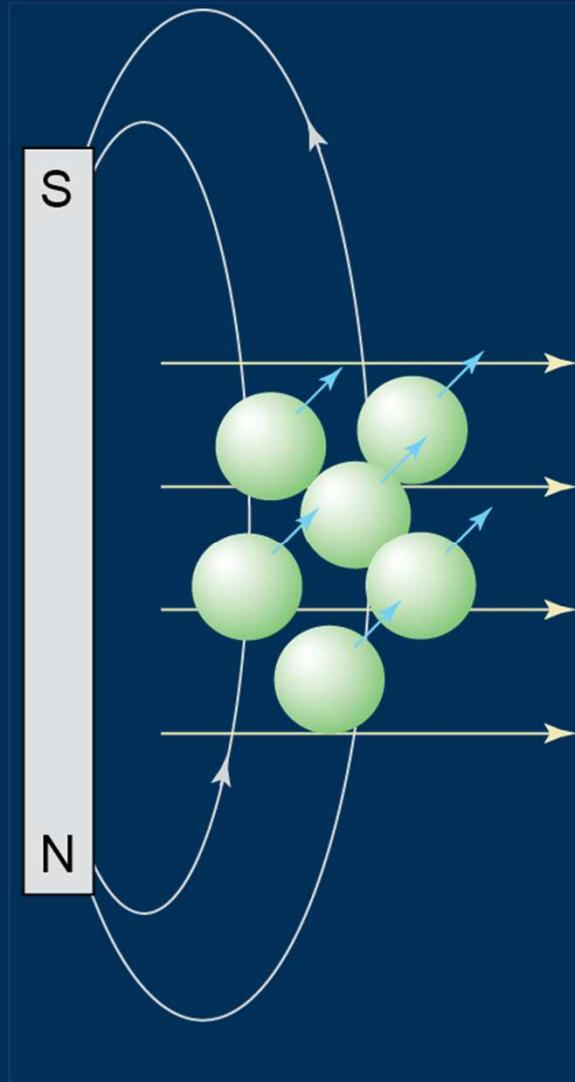
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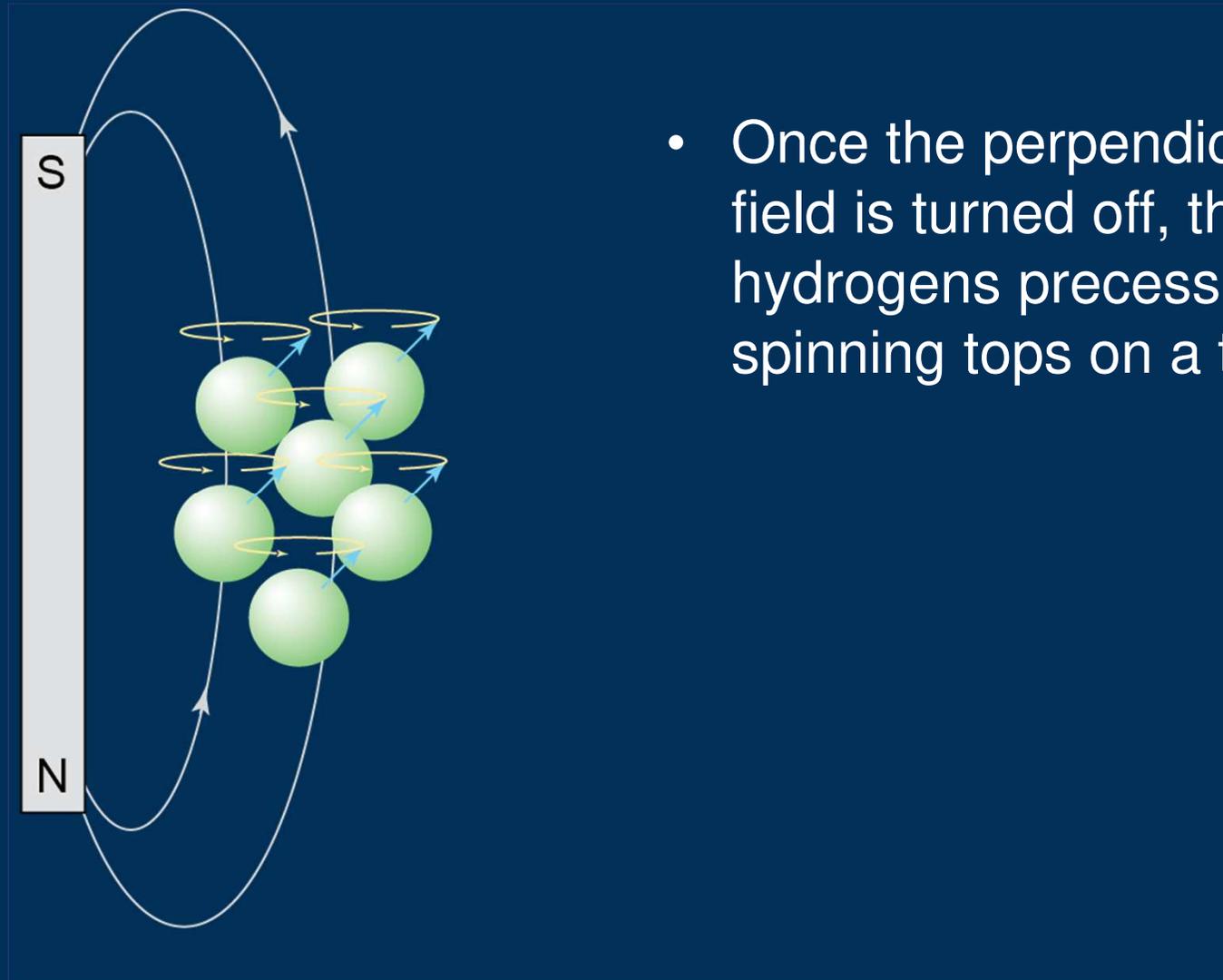
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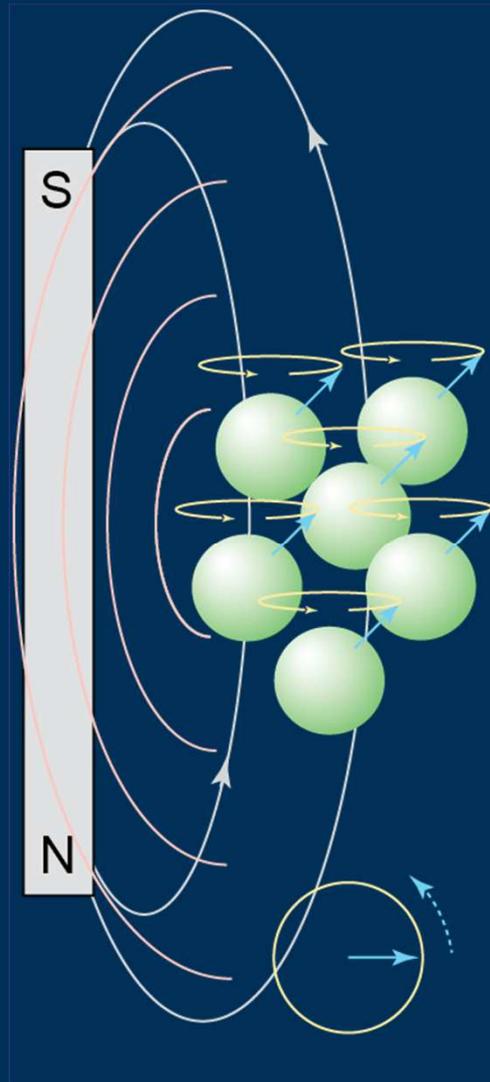
- NMR is sensitive to hydrogen in the system
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- Applying a large magnetic field can align the hydrogen
- Applying a perpendicular magnetic field will tip the aligned hydrogen

Nuclear Magnetic Resonance: a tool for many measurements



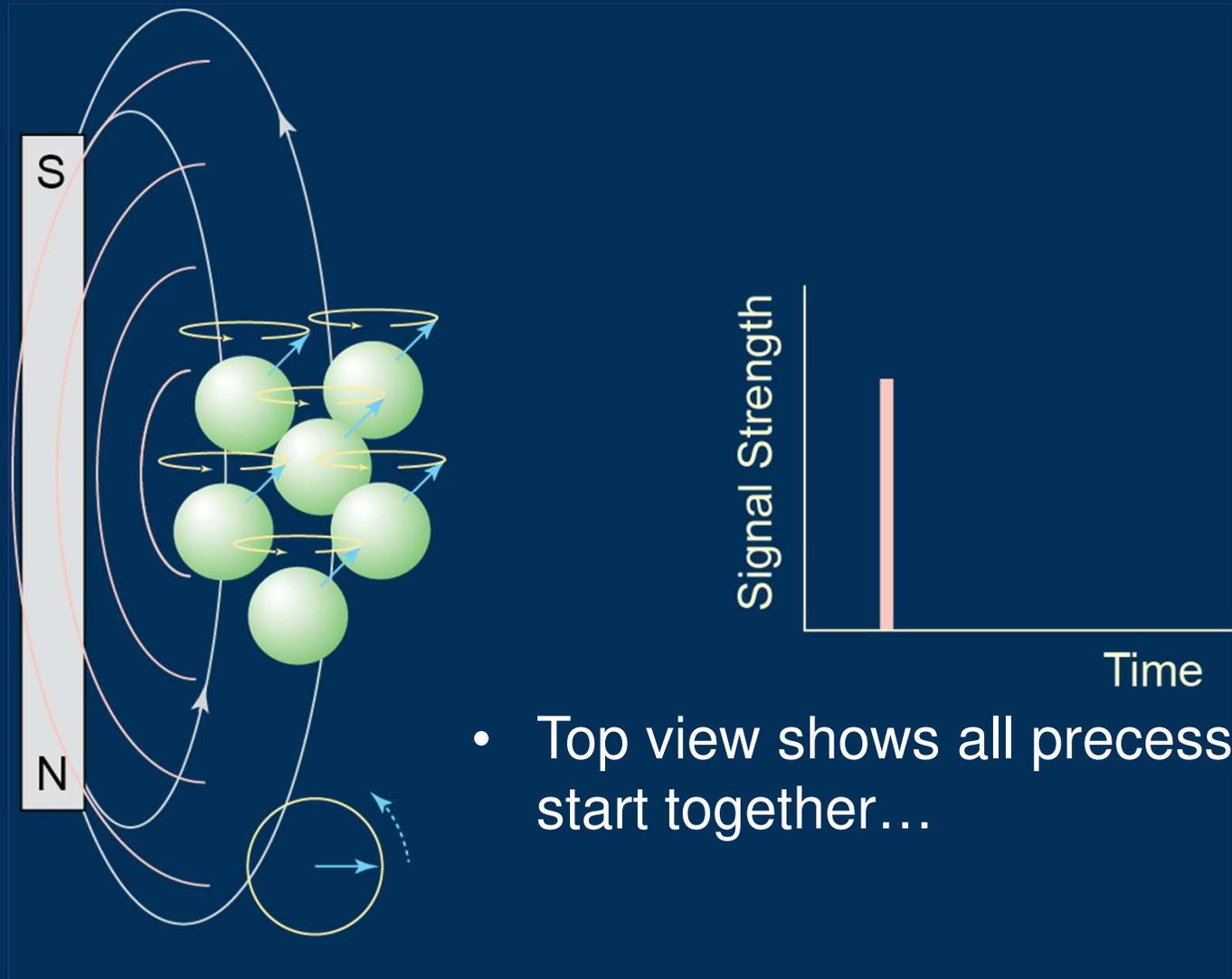
- Once the perpendicular field is turned off, the hydrogens precess like spinning tops on a table

Nuclear Magnetic Resonance: a tool for many measurements



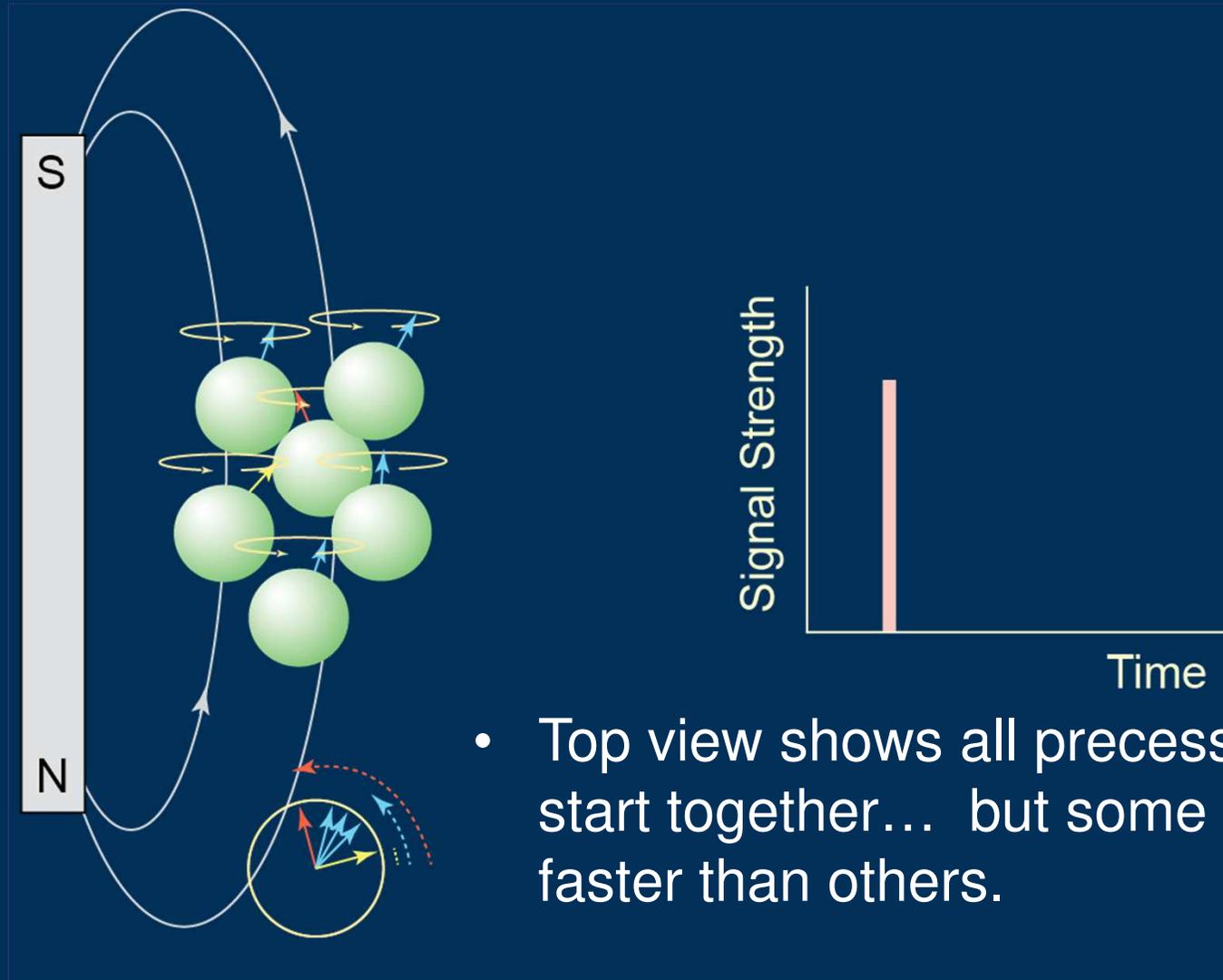
- Once the perpendicular field is turned off, the hydrogens precess like spinning tops on a table
- Precessing together, the hydrogen produce a radio frequency signal the NMR tool can detect.

Nuclear Magnetic Resonance: a tool for many measurements



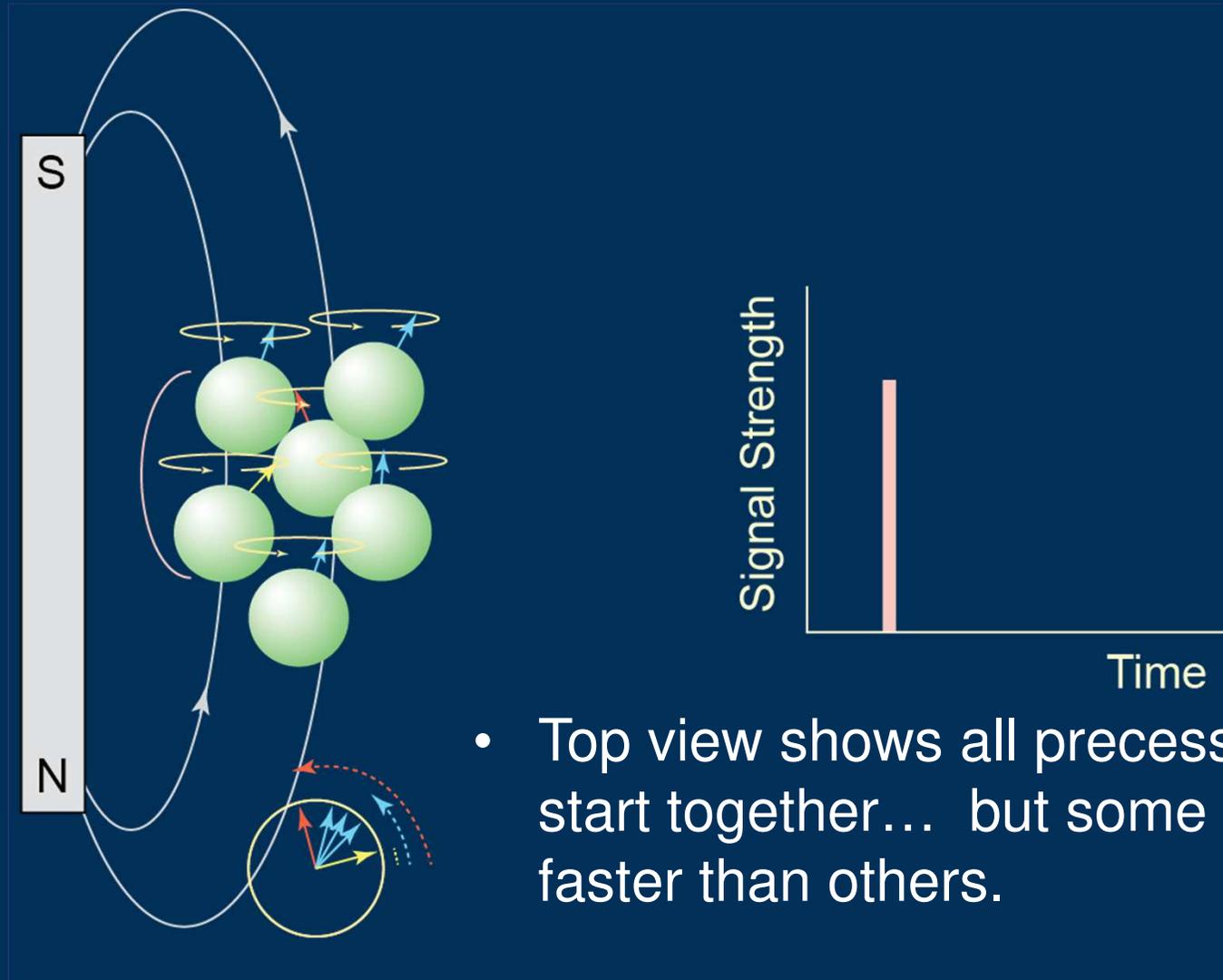
- Top view shows all precessions start together...

Nuclear Magnetic Resonance: a tool for many measurements



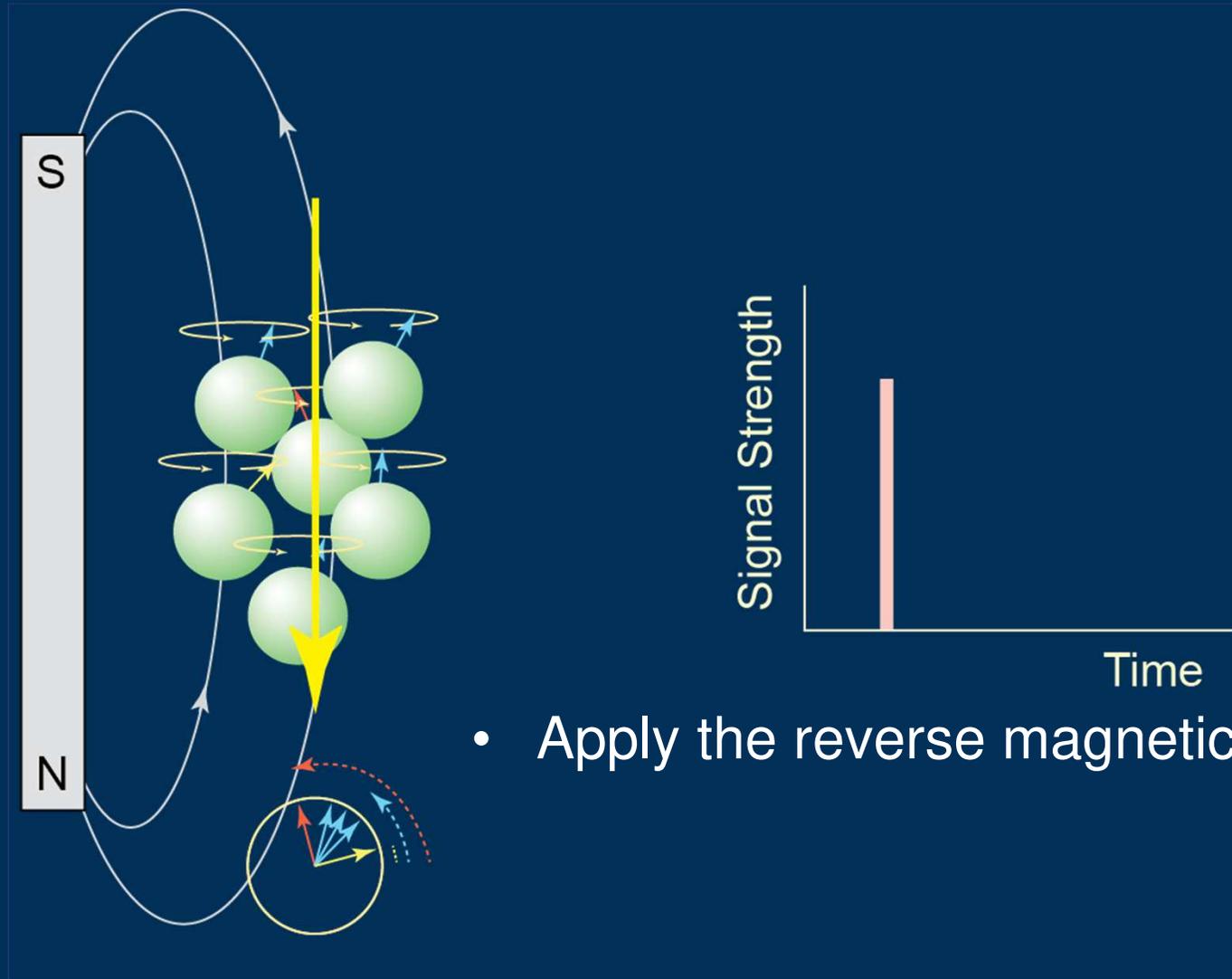
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Nuclear Magnetic Resonance: a tool for many measurements



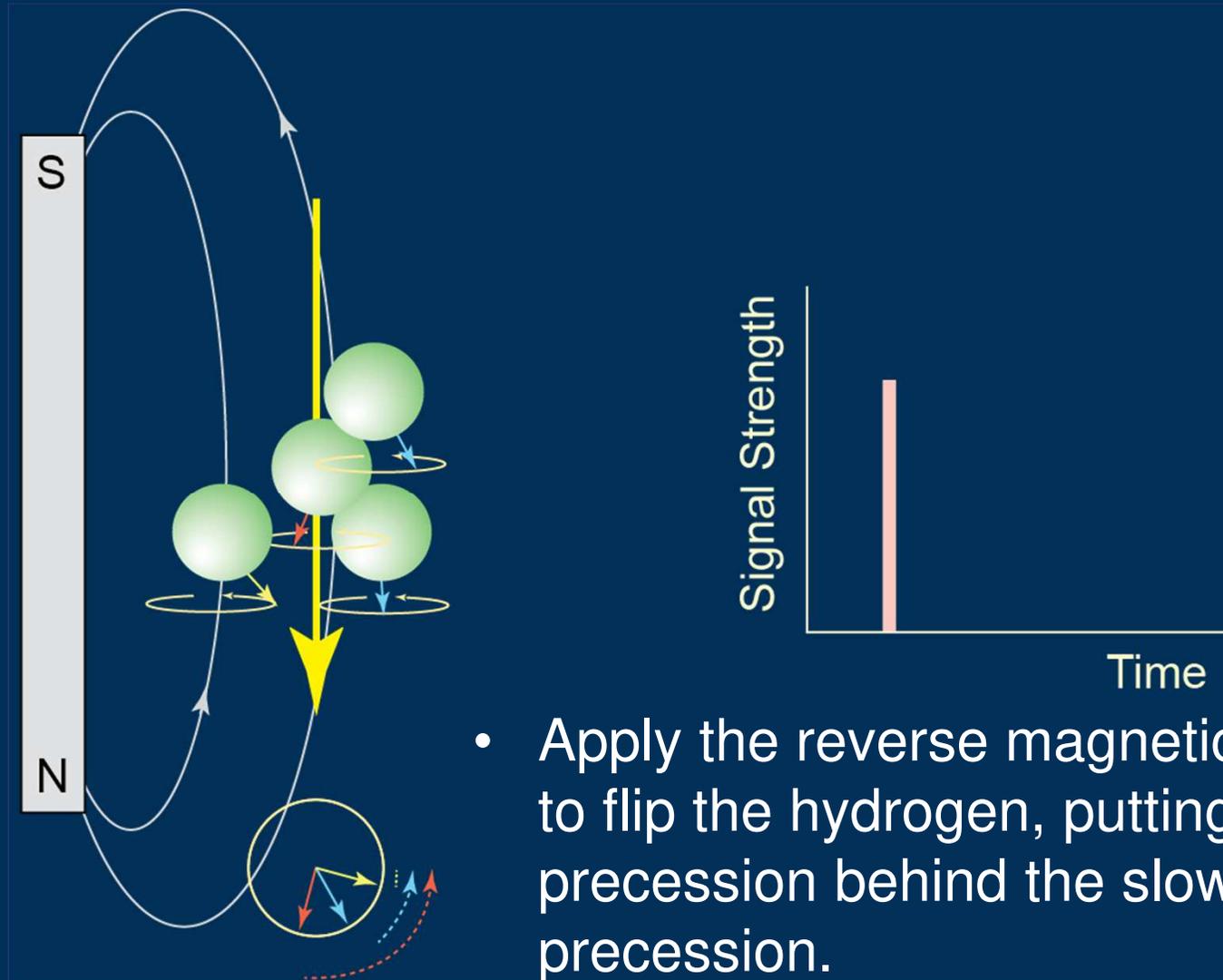
- Top view shows all precessions start together... but some are faster than others.
- Signal is weak when precessions are not together

Nuclear Magnetic Resonance: a tool for many measurements

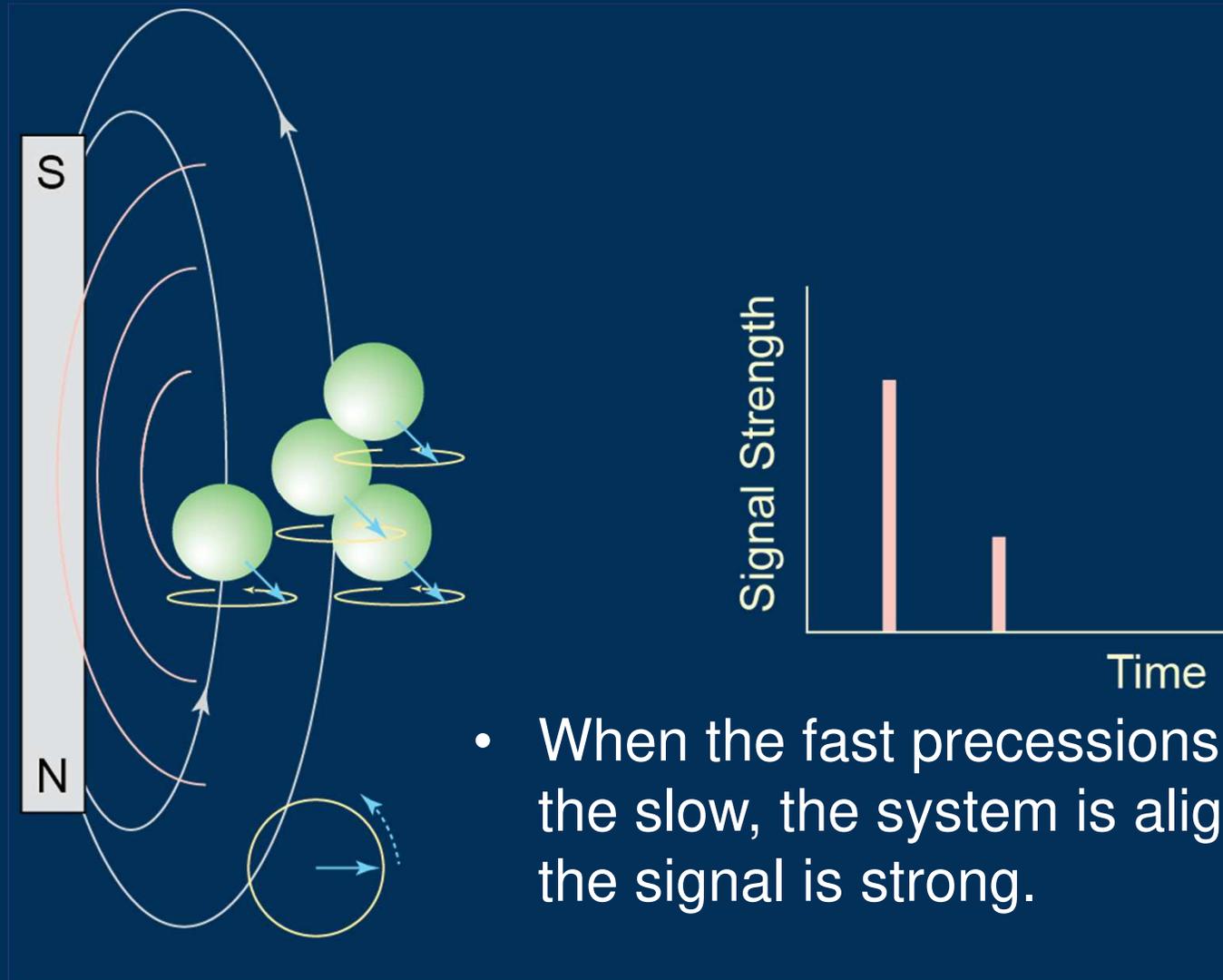


- Apply the reverse magnetic field...

Nuclear Magnetic Resonance: a tool for many measurements

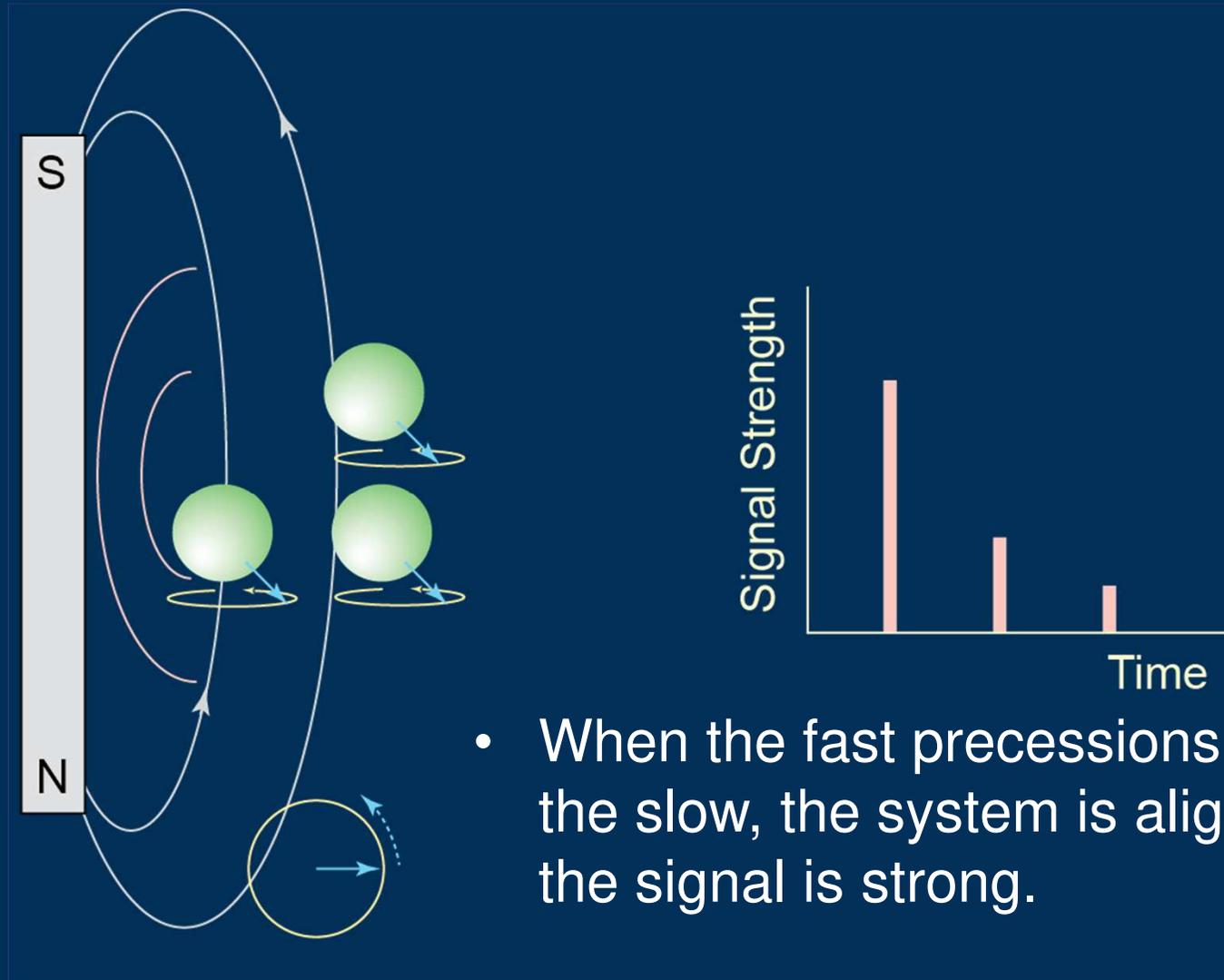


Nuclear Magnetic Resonance: a tool for many measurements



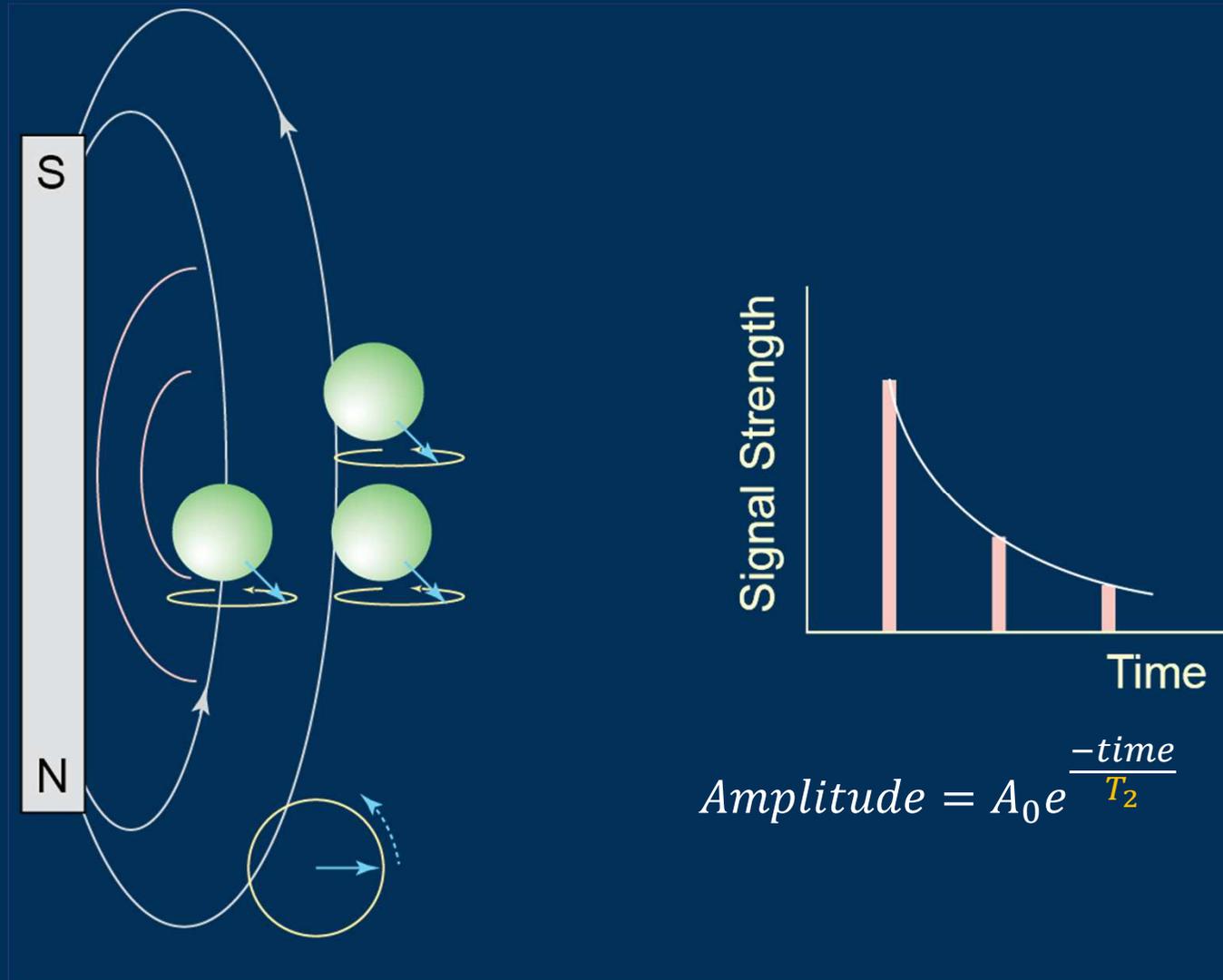
- When the fast precessions catch the slow, the system is aligned and the signal is strong.
- Some hydrogens cannot be realigned, so signal is weaker

Nuclear Magnetic Resonance: a tool for many measurements

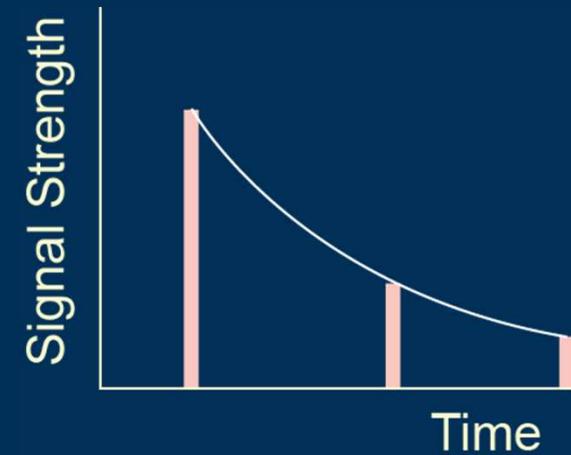


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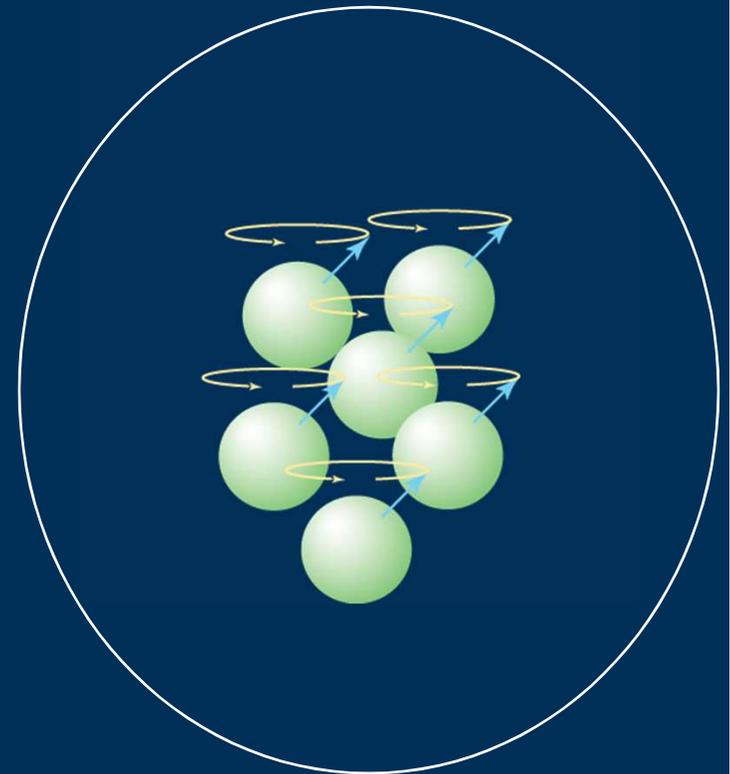
Nuclear Magnetic Resonance: a tool for many measurements



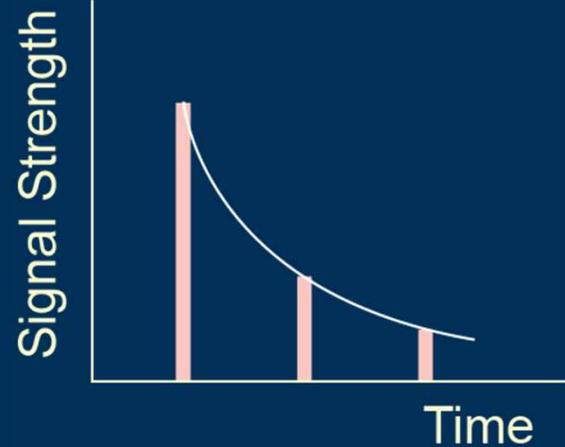
Dependence of T_2 time on environment



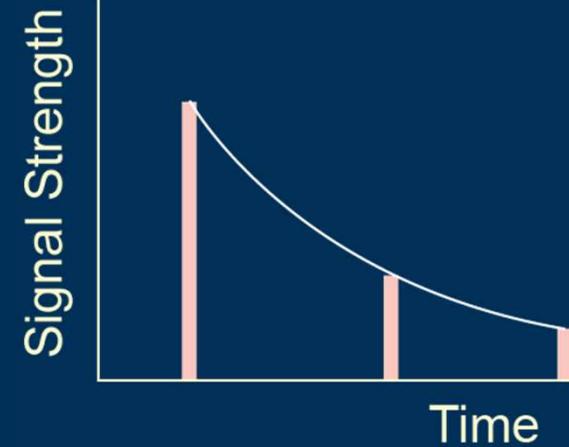
Large Pore: Long T_2 Time



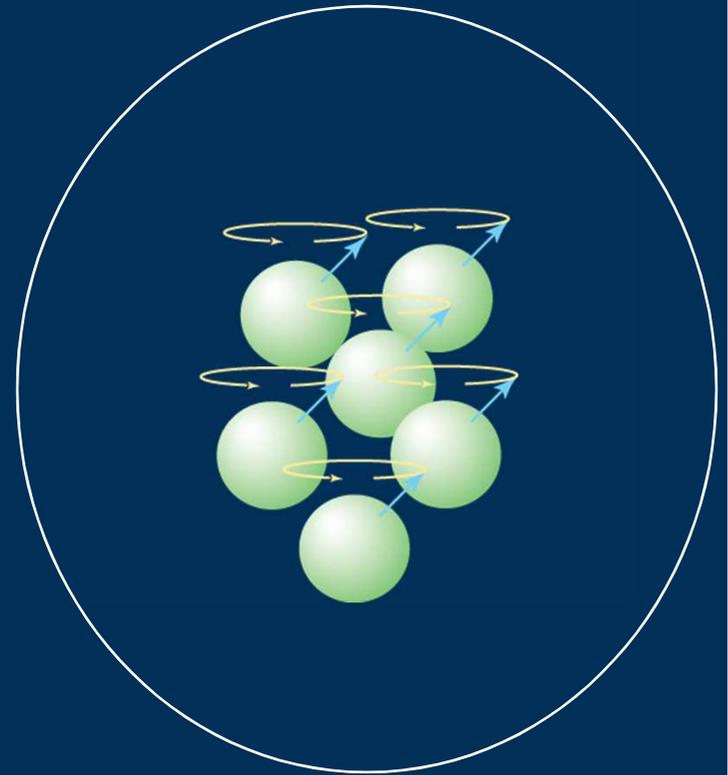
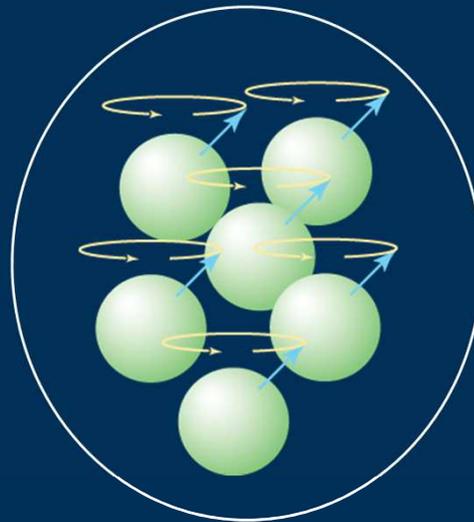
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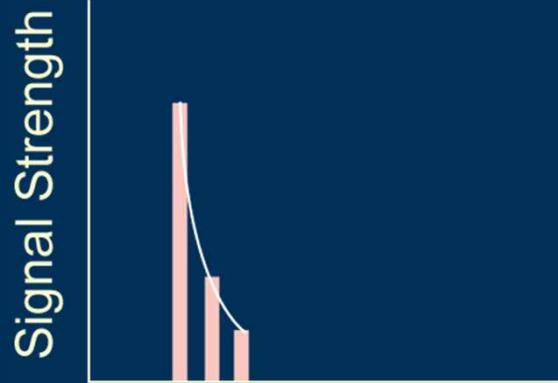
Small Pore: Shorter T_2 Time



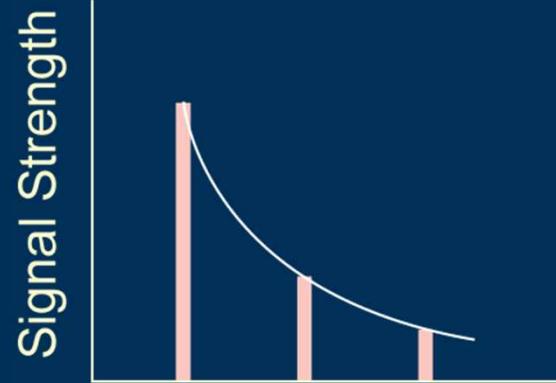
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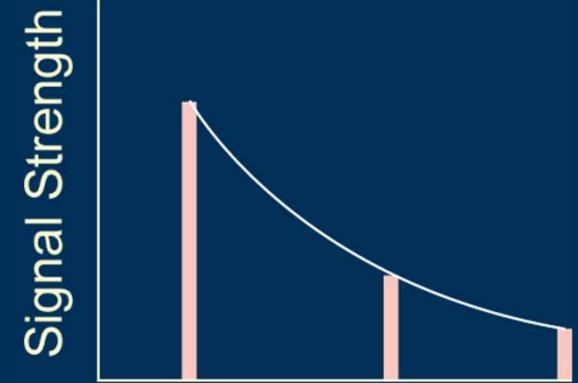
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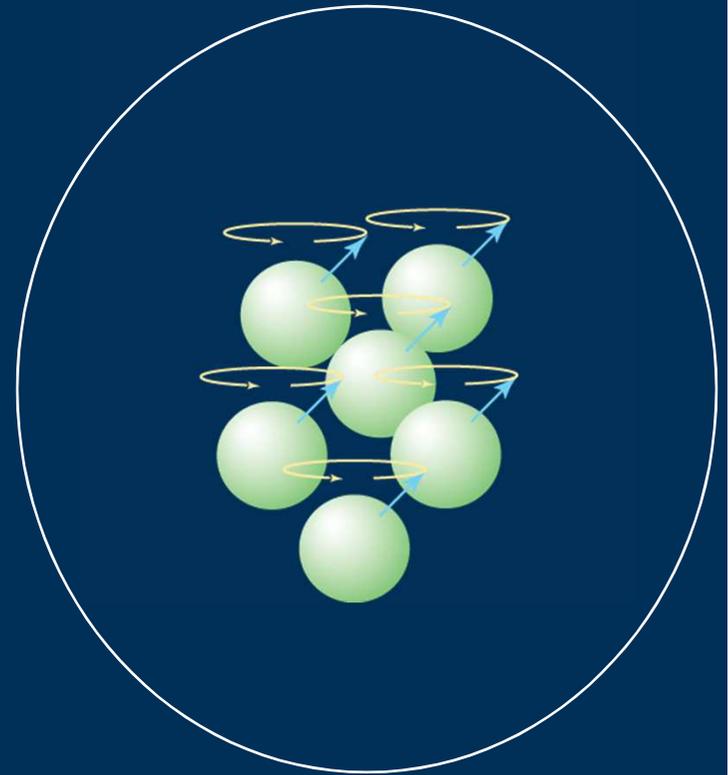
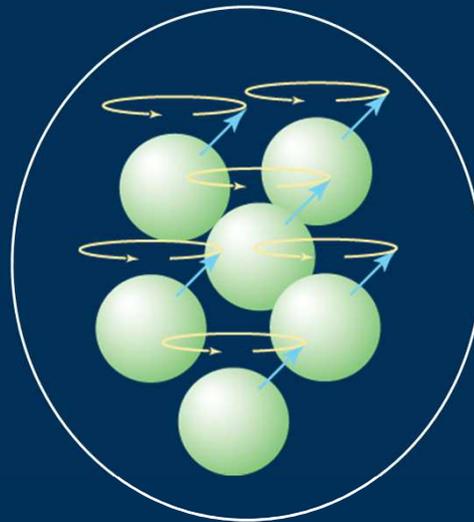
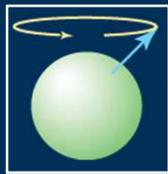
Solid: Shortest T_2 Time



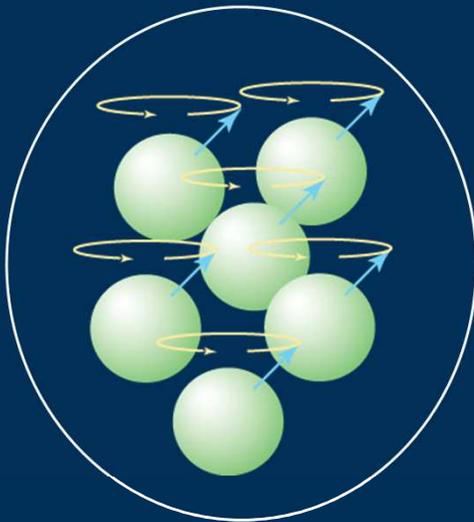
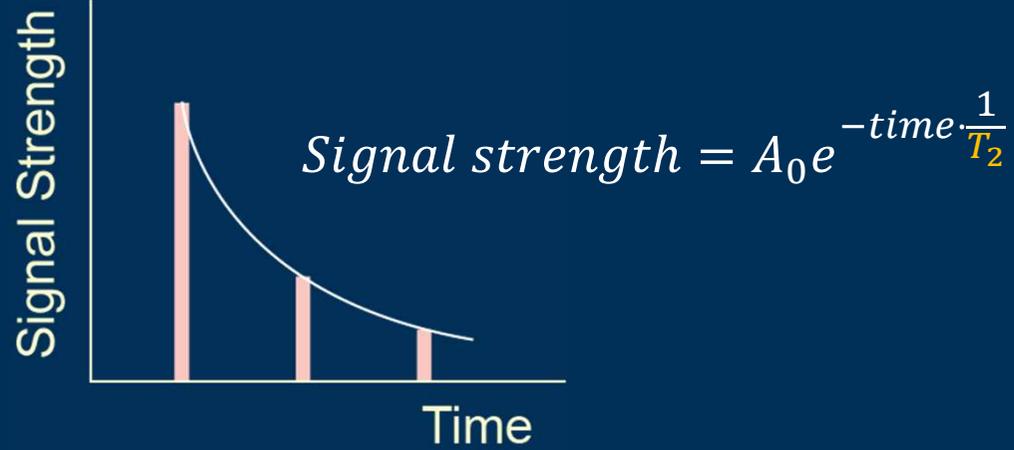
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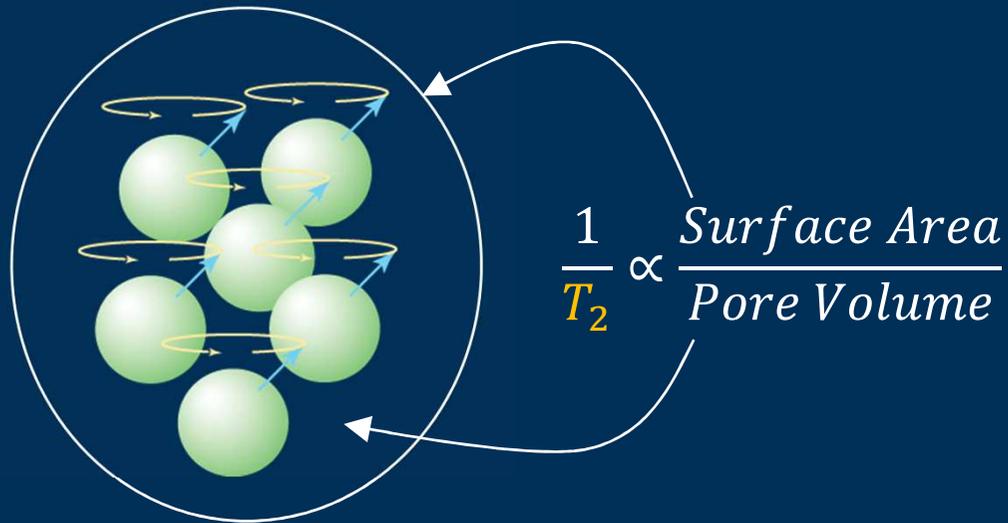
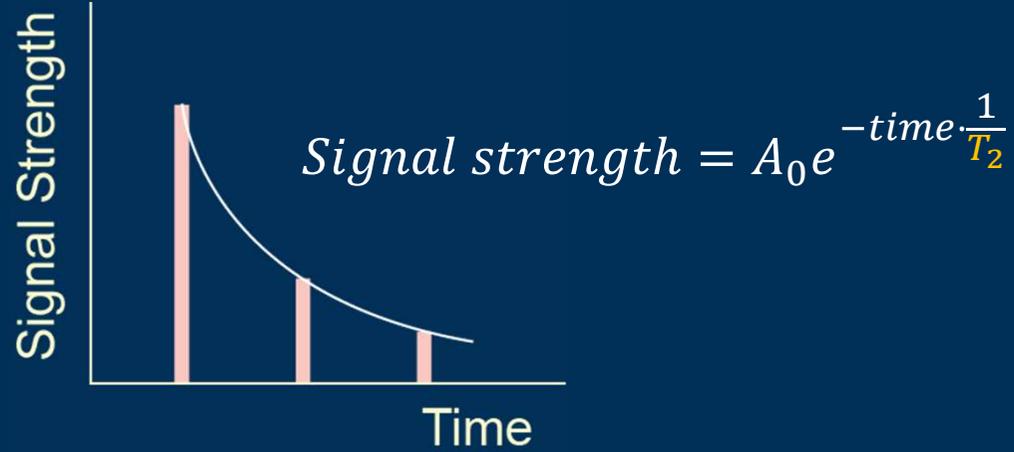
Large Pore: Long T_2 Time



What controls the T_2 time?

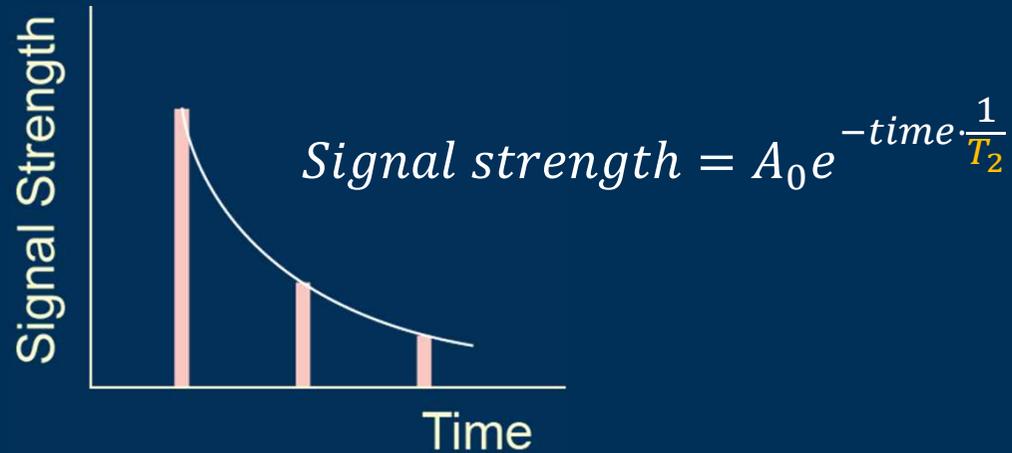


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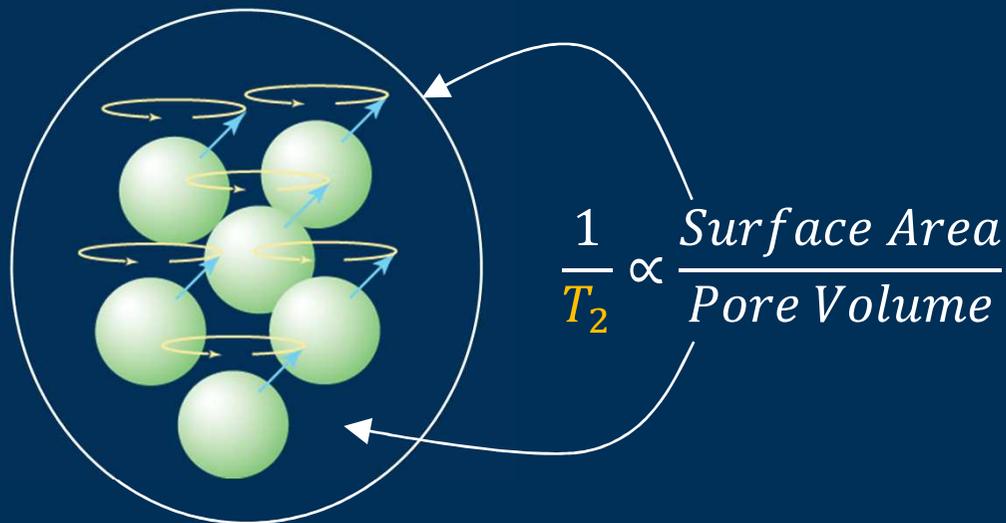
$$\frac{1}{T_2} \propto \frac{Surface\ Area}{Pore\ Volume}$$

What controls the T_2 time?

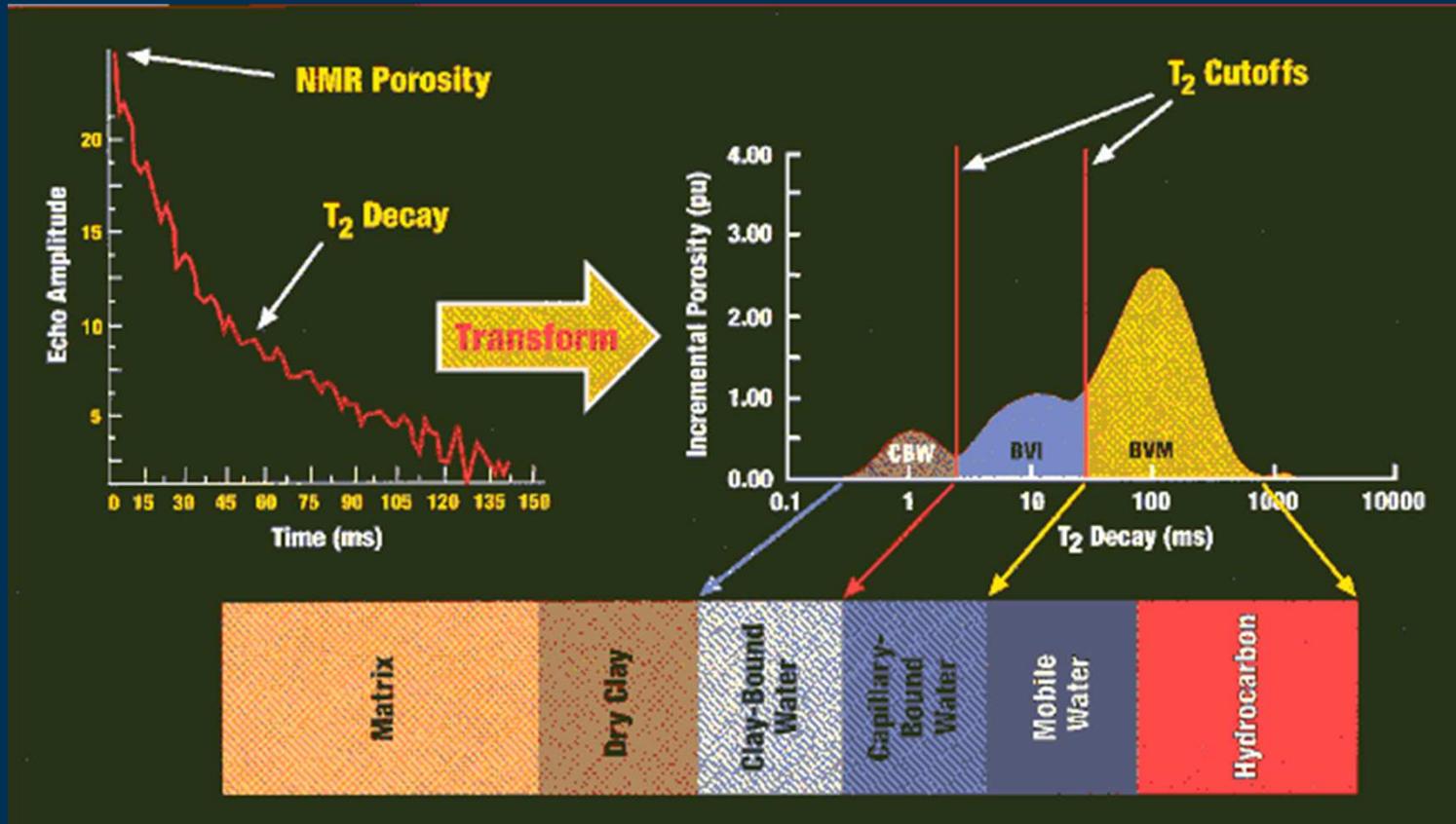


A single pore has a single T_2 .

Sediment has many pores of different sizes, so an NMR scan in the field gives a distribution of T_2 values



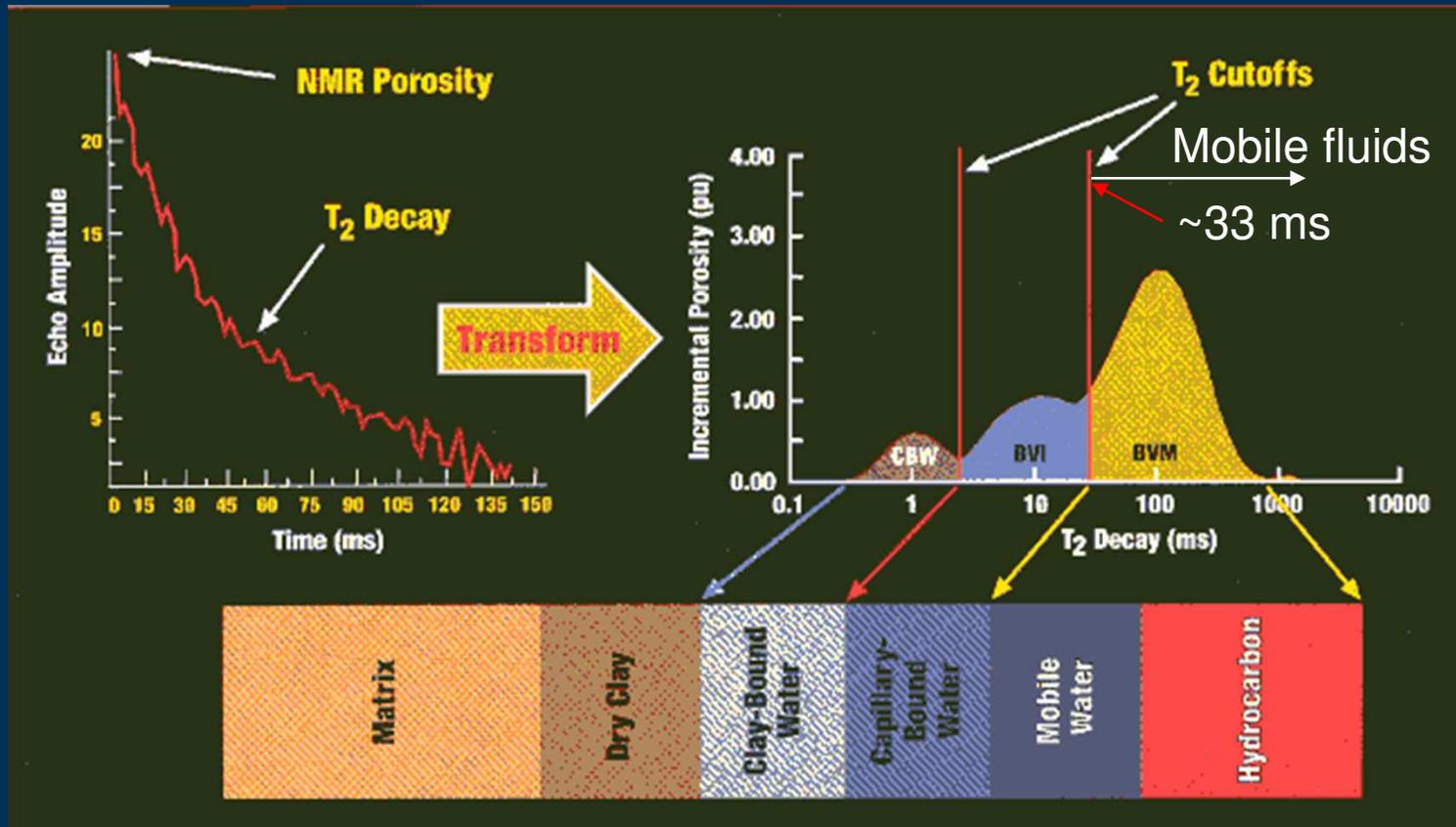
What does the T_2 distribution tell us?



T_2 distribution can be broken down into zones

Crain's Petrophysical Handbook (2018), <https://www.spec2000.net/12-phinmr.htm>

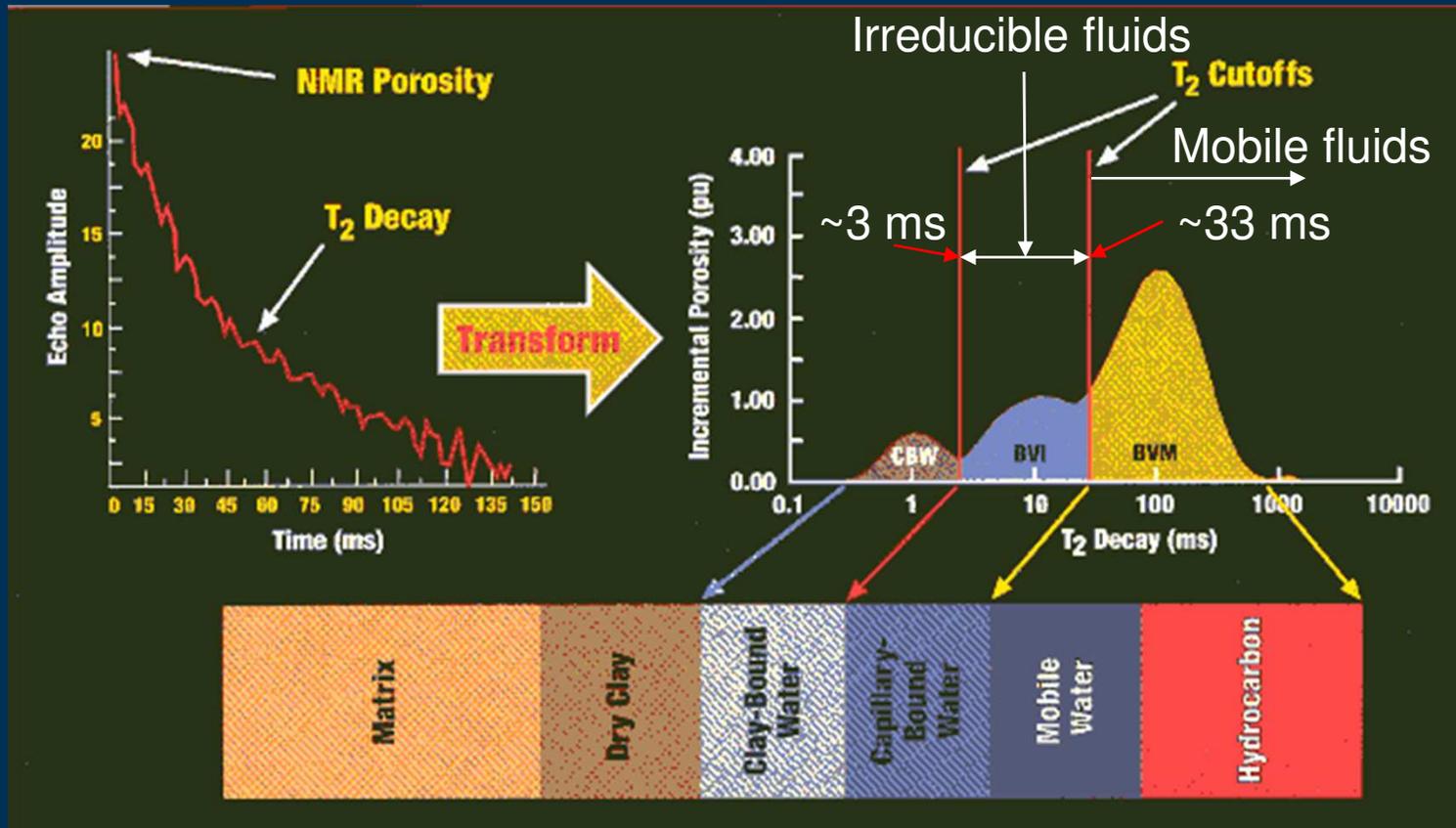
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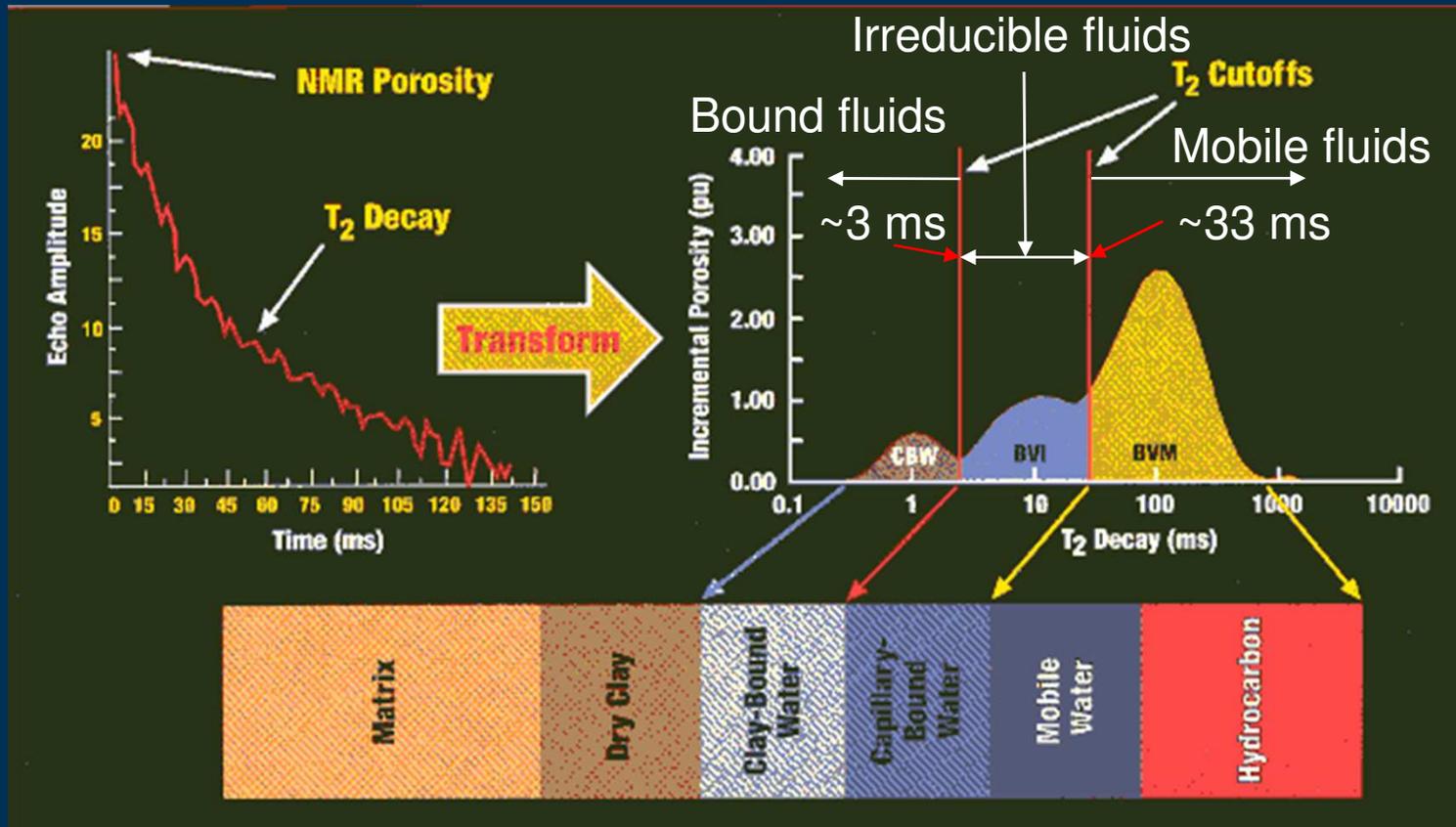
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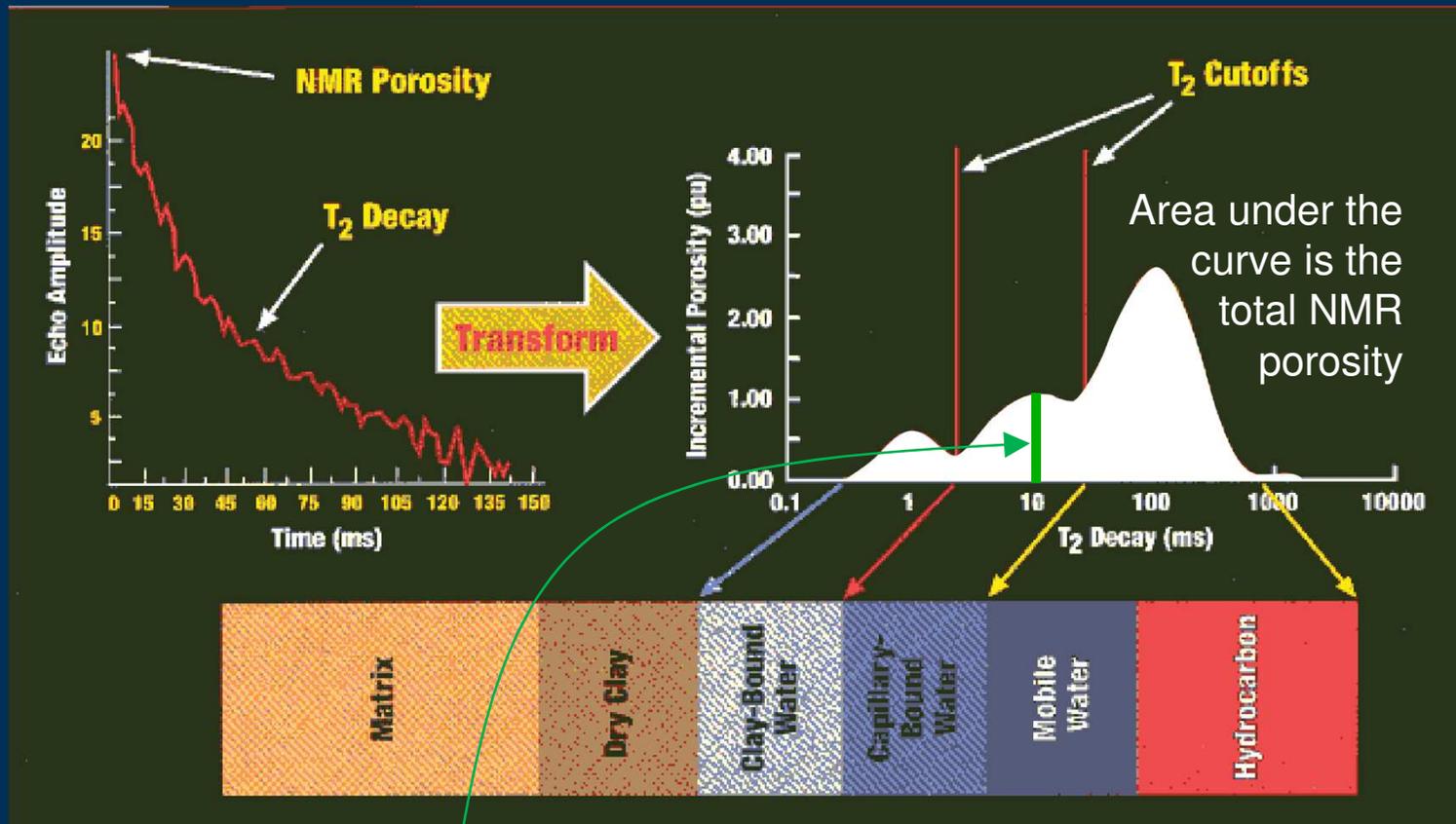


T_2 distribution can be broken down into zones

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Using T_2 to get NMR porosity

The NMR porosity is the sum of each T_2 amplitude

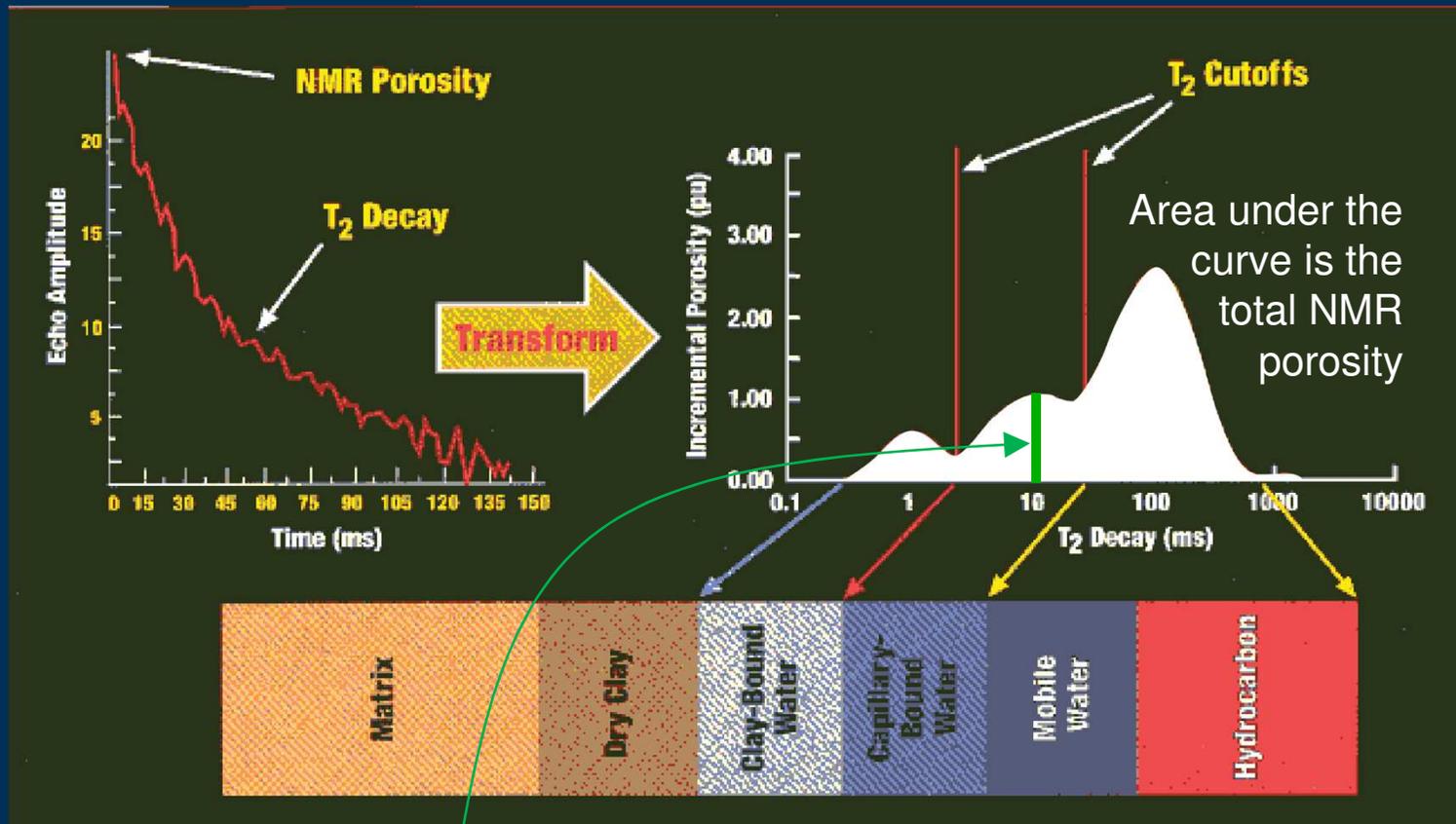


$$\text{Signal strength} = A_i e^{-\text{time} \cdot \frac{1}{T_{2i}}}$$

Kleinberg (2006), New techniques in sediment core analysis

Using T_2 to get NMR porosity

The NMR porosity is the sum of each T_2 amplitude



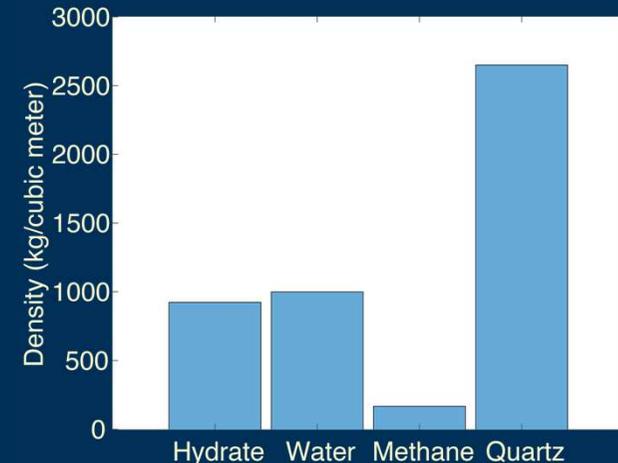
$$\text{Signal strength} = A_i e^{-\text{time} \cdot \frac{1}{T_{2i}}} \longrightarrow \phi_{NMR} \approx \sum_i A_i$$

Kleinberg (2006), New techniques in sediment core analysis

Why find ϕ_{NMR} if $\phi_{\text{density porosity}}$ is known?

The two measures of porosity see the formation differently:

- $\phi_{\text{density porosity}}$: sees the “total porosity,” (the volume that is *not* sediment)

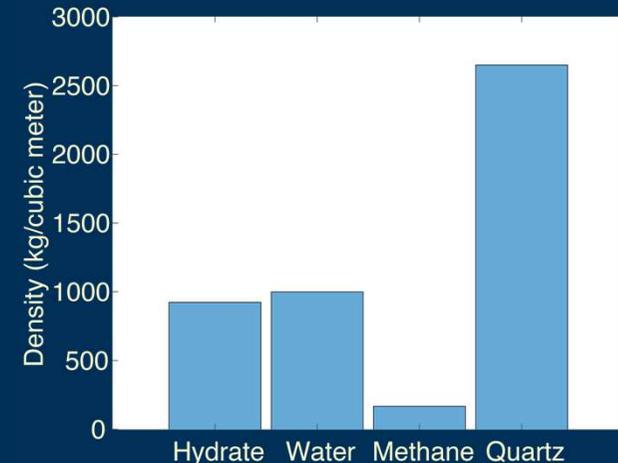


- ϕ_{NMR} : only sees the water volume, solids (including hydrate) are invisible.

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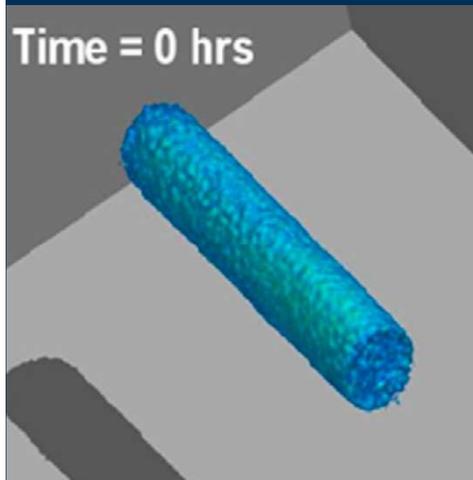
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- ϕ_{NMR} : only sees the water volume, solids (including hydrate) are invisible.
- $\phi_{\text{density porosity}} = \phi_{\text{NMR}}$ only if water saturation is 100%.
- In general, $\phi_{\text{NMR}} = S_{\text{water}} \cdot \phi_{\text{density porosity}}$

Hydrate is invisible to NMR

Hydrate formation in a sandstone cylinder

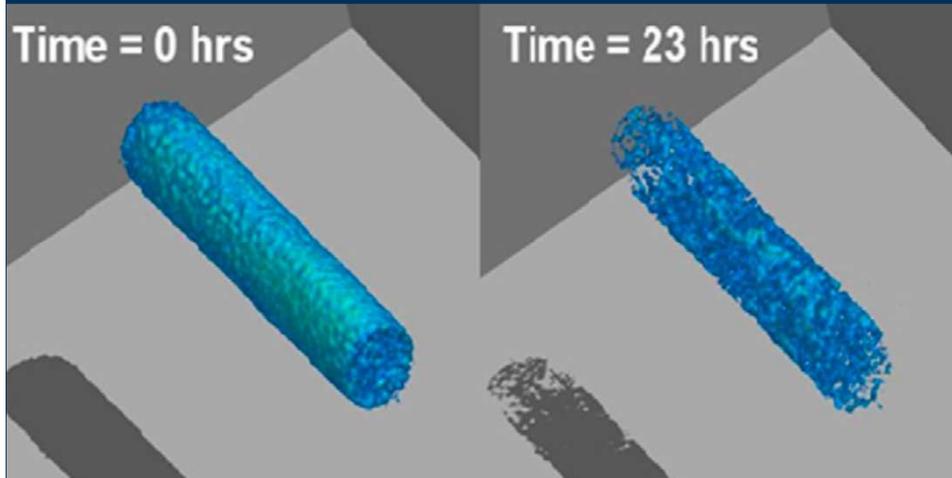


Sandstone cylinder:
pore space has
some methane,
mostly water

Erslund et al. (2010), Chemical Eng. J.

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Hydrate formation in a sandstone cylinder



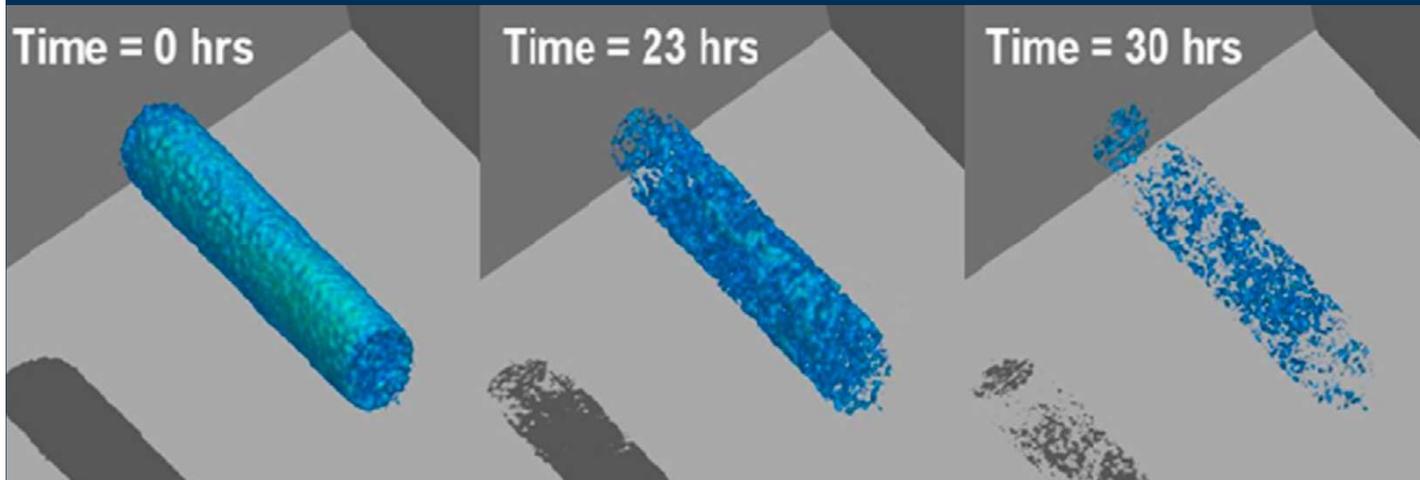
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Cooling into hydrate
stability zone.
Water being used to
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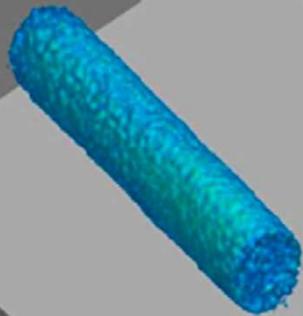
Cooling into hydrate
stability zone.
Water being used to
form hydrate

Hydrate formation
continuing to
consume water

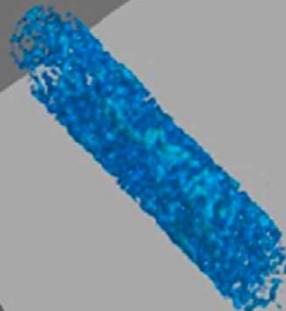
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Hydrate formation in a sandstone cylinder

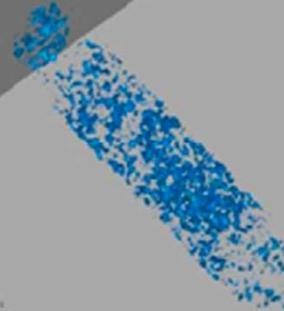
Time = 0 hrs



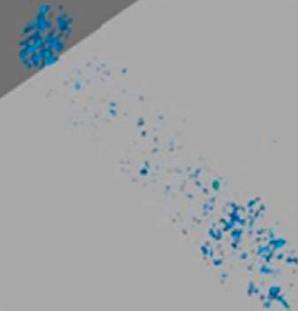
Time = 23 hrs



Time = 30 hrs



Time = 36 hrs



Sandstone cylinder:
pore space has
some methane,
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Cooling into hydrate
stability zone.
Water being used to
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Hydrate formation
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consume water

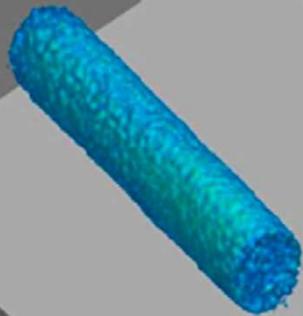
Hydrate formation
complete, nearly all
water consumed.

Erslund et al. (2010), Chemical Eng. J.

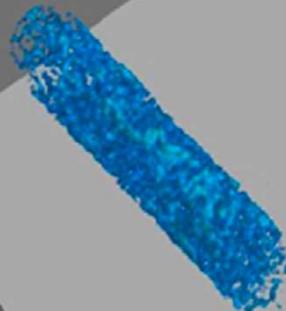
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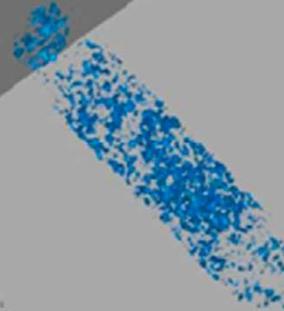
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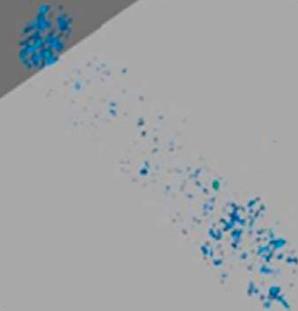
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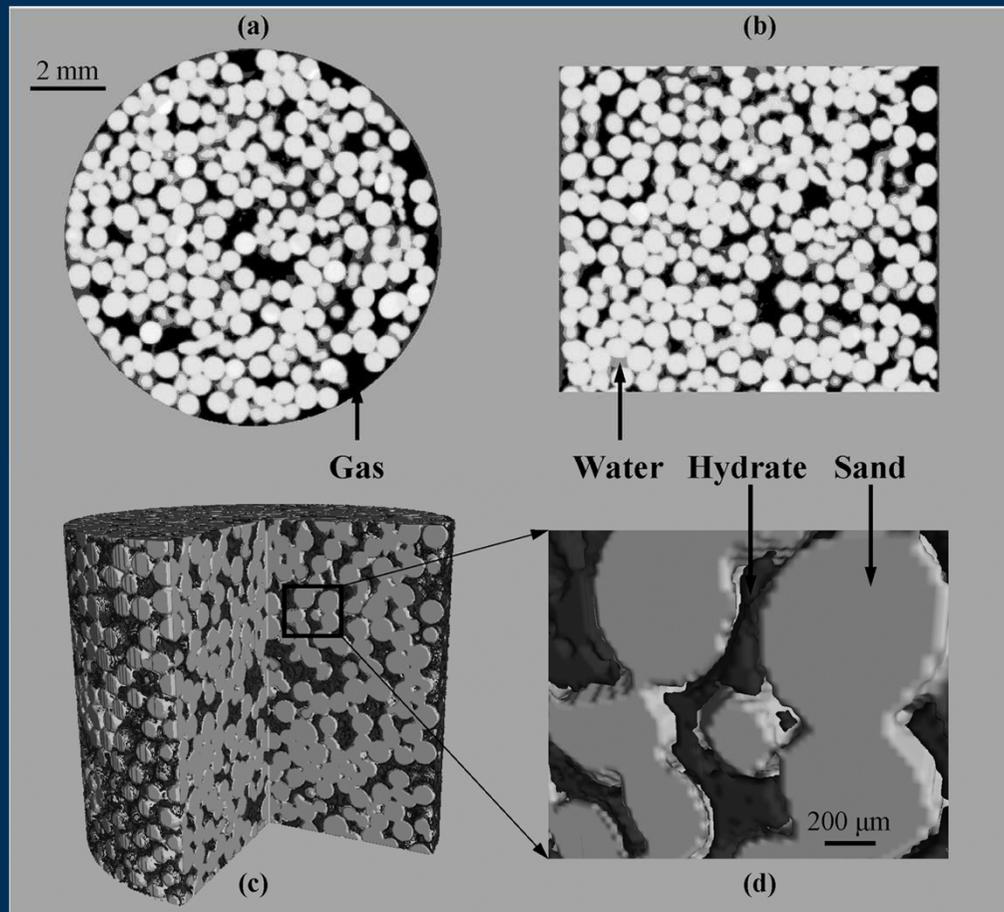
Hydrate formation
continuing to
consume water

Hydrate formation
complete, nearly all
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Sensitivity of ϕ_{NMR} to hydrate means ϕ_{NMR} can be used with $\phi_{\text{density porosity}}$ to estimate hydrate saturation, S_h .

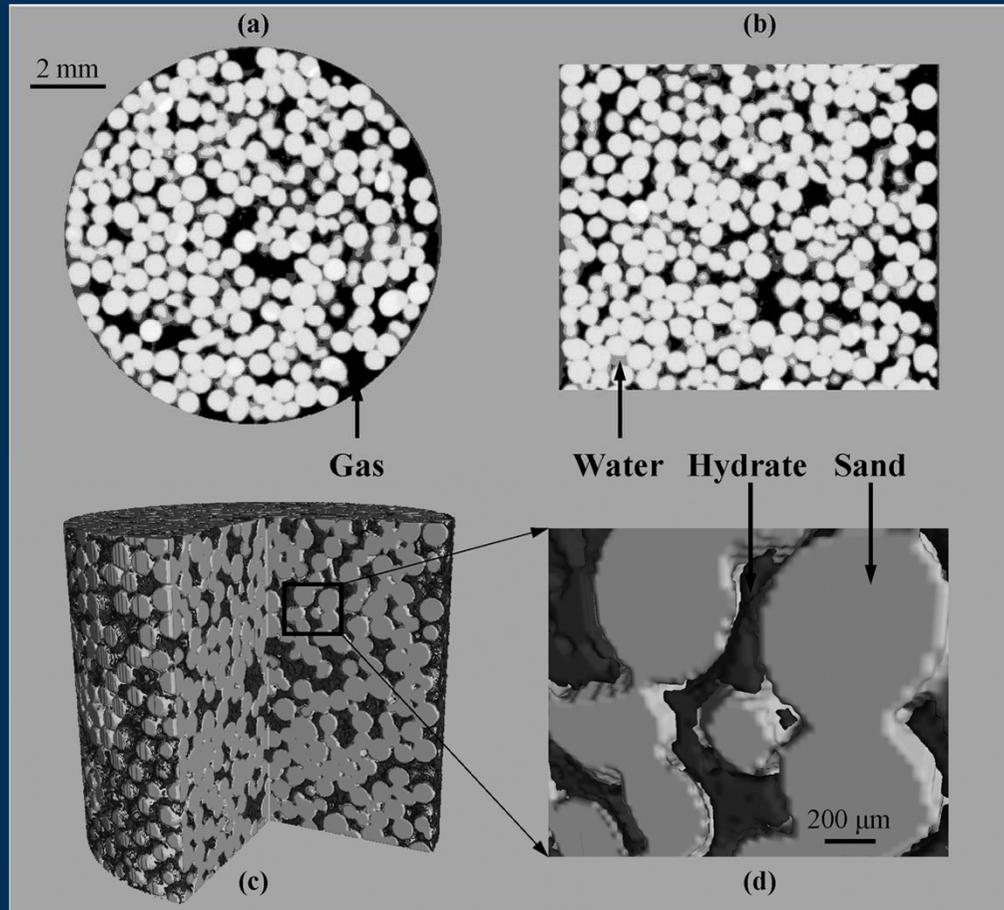
Erslund et al. (2010), Chemical Eng. J.

Estimate hydrate saturation, S_h , from ϕ_{NMR} and $\phi_{\text{density porosity}}$



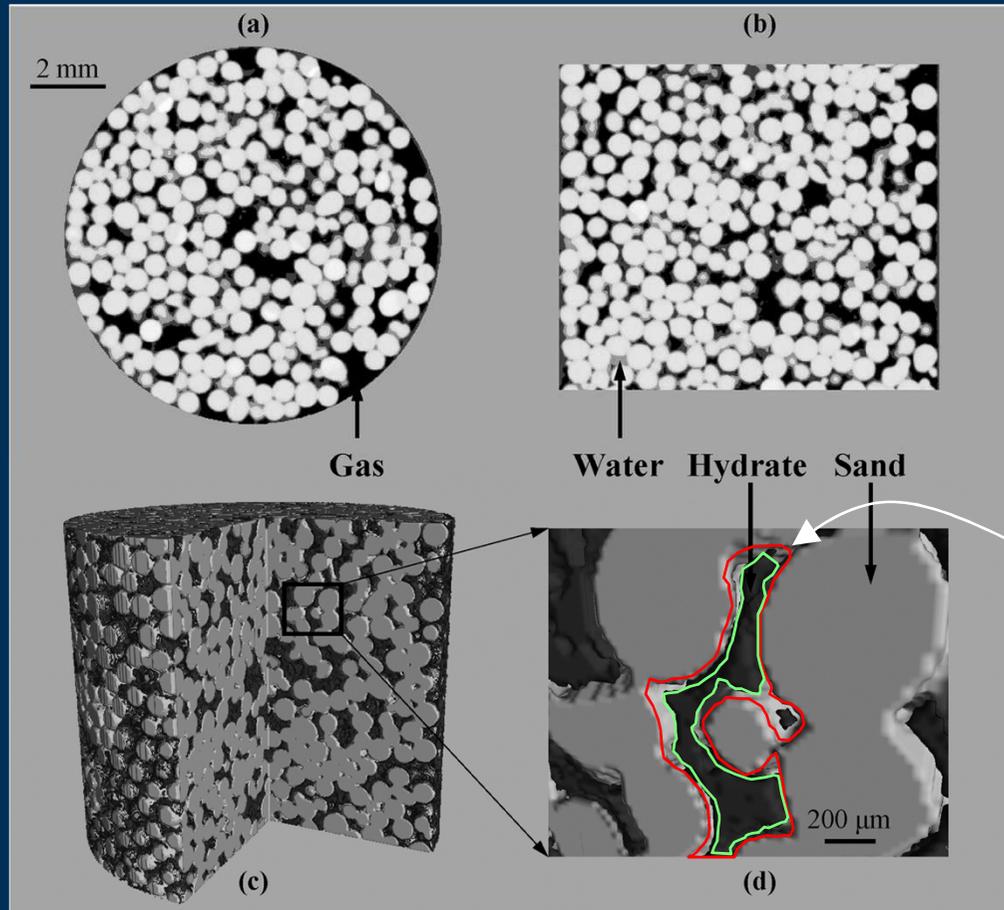
Zhao et al. (2015), J. Chem. Chem. Phys.

Estimate hydrate saturation, S_h , from ϕ_{NMR} and $\phi_{\text{density porosity}}$



$$\phi_{\text{NMR}} = S_{\text{water}} \cdot \phi_{\text{density porosity}}$$

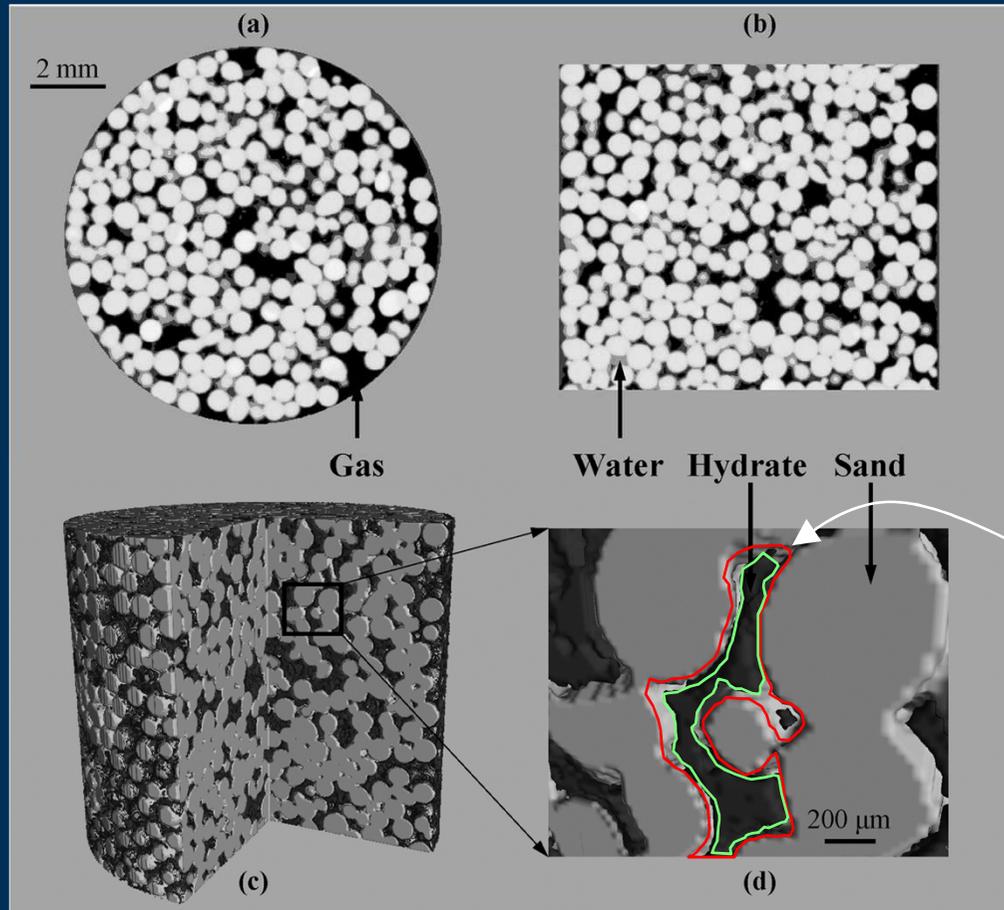
Estimate hydrate saturation, S_h , from ϕ_{NMR} and $\phi_{\text{density porosity}}$



$$\phi_{\text{NMR}} = S_{\text{water}} \cdot \phi_{\text{density porosity}}$$

$$S_{\text{water}} + S_h = 1$$

Estimate hydrate saturation, S_h , from ϕ_{NMR} and $\phi_{\text{density porosity}}$

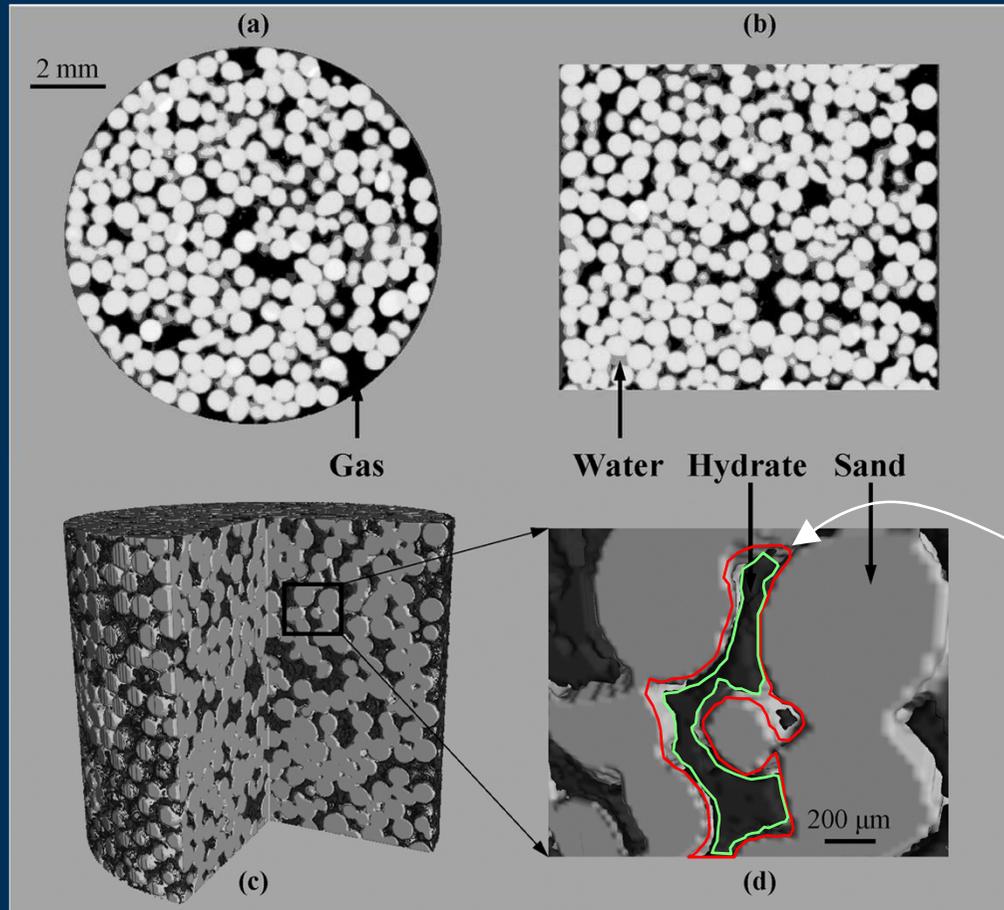


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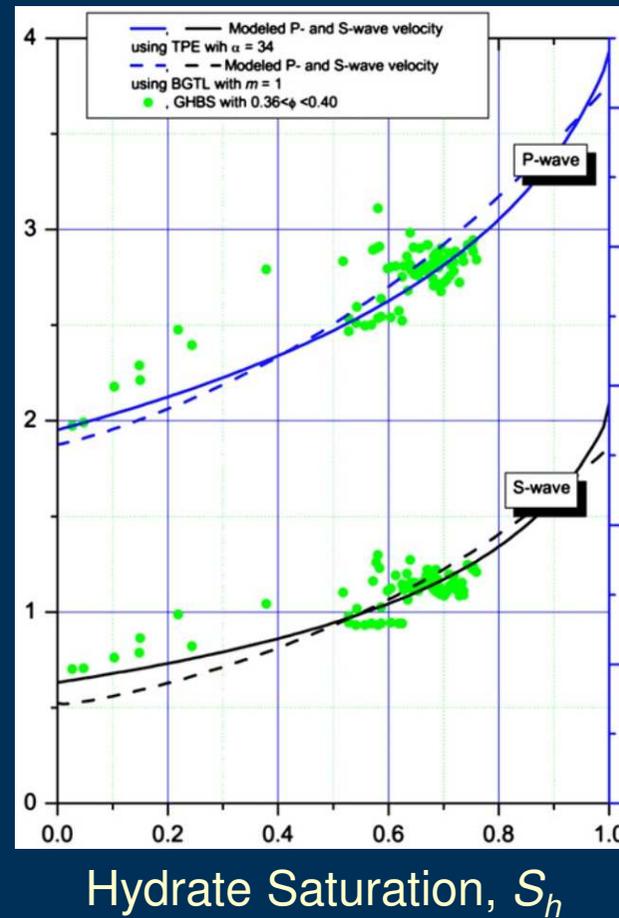
$$S_h = 1 - (\phi_{\text{NMR}} / \phi_{\text{density porosity}})$$

Kleinberg (2006), New techniques in sediment core analysis

Velocity is related to hydrate saturation

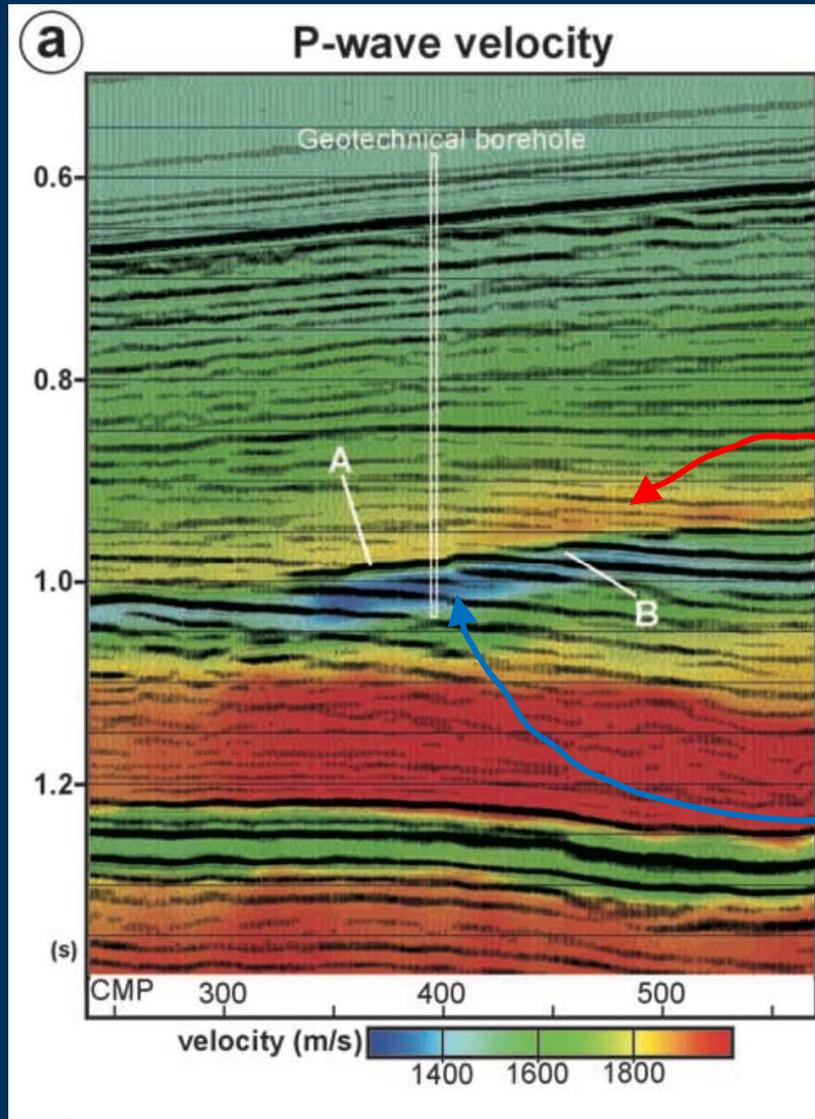
Mt. Elbert (Arctic USA)

Velocity (Compression, V_p and Shear, V_s)



Lee and Collett (2011), Marine and Petroleum Geology

Using V_p in the field: Finding regions of high V_p

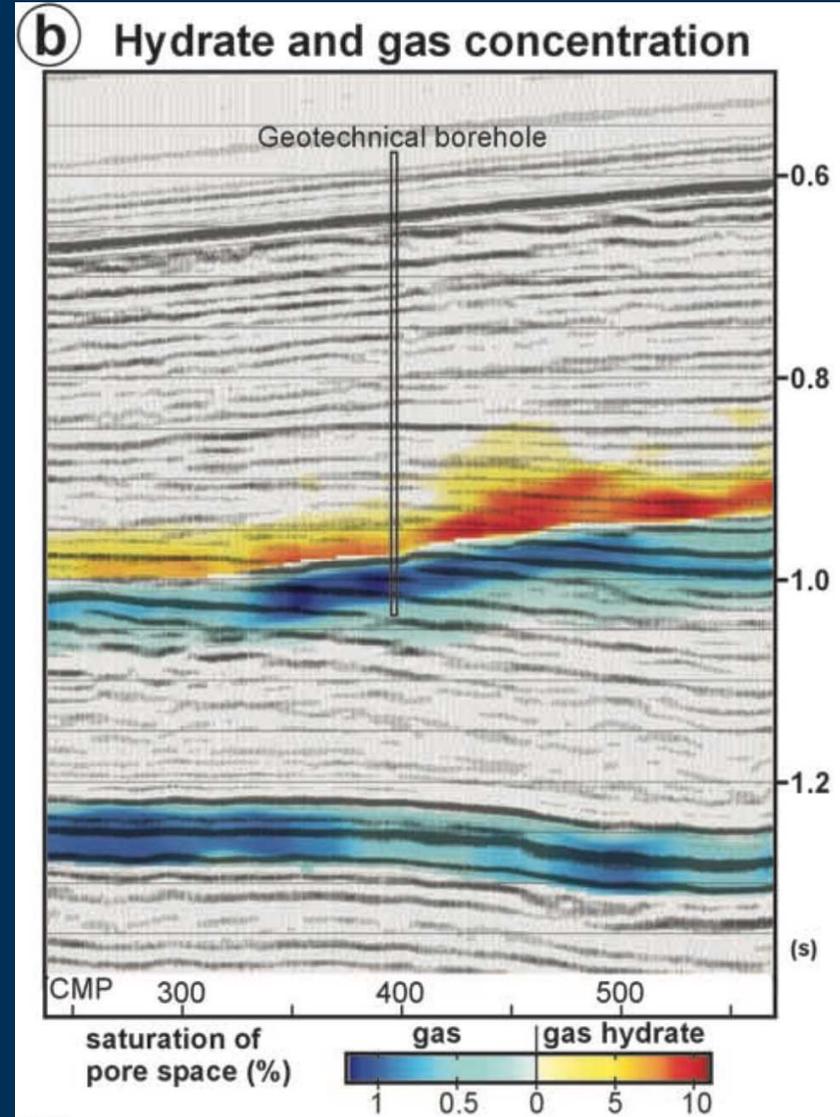
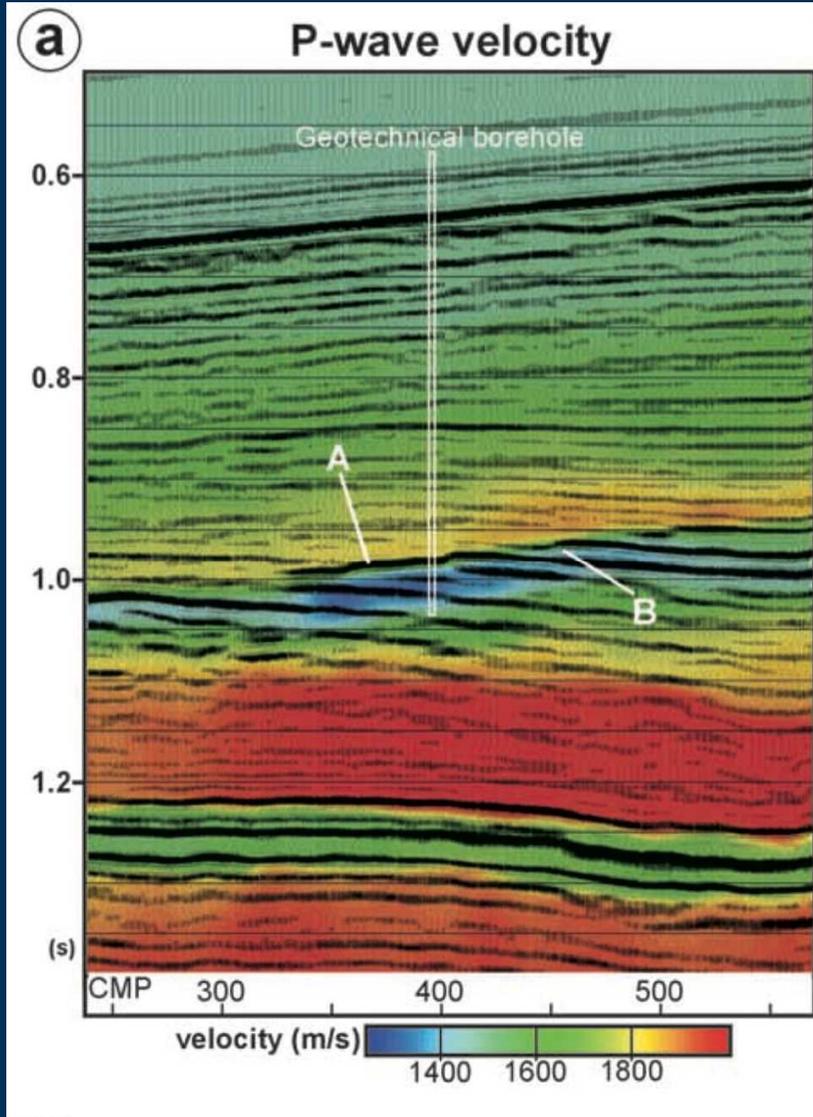


Storegga slide
(offshore
Norway)

Higher V_p
above BSR is
due to gas
hydrate

BSR on top of
the low V_p
section that
contains gas

Using V_p in the field: Mapping hydrate and gas saturations

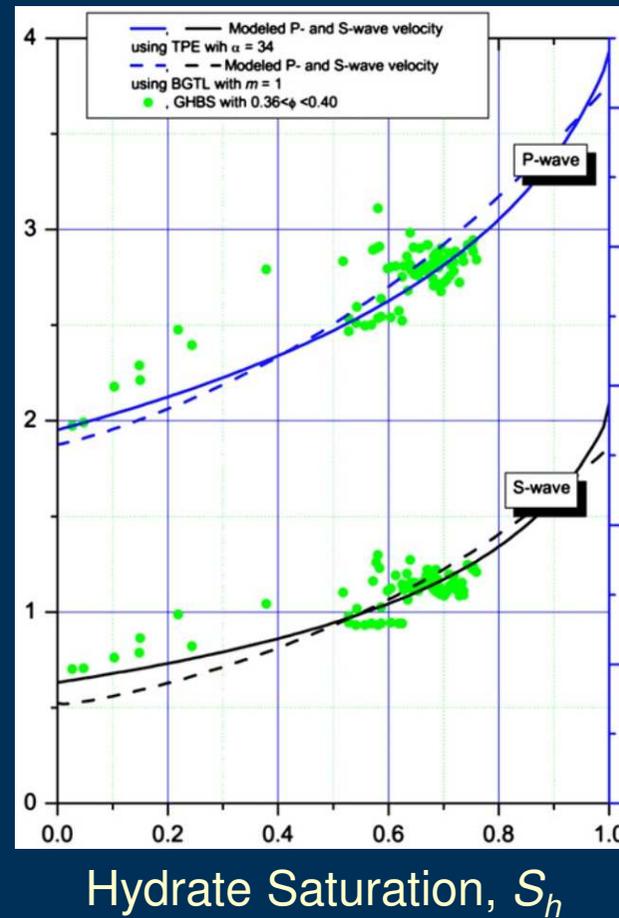


Bunz and Mienert (2004), JGR

What IS the velocity connection to hydrate saturation?

Mt. Elbert (Arctic USA)

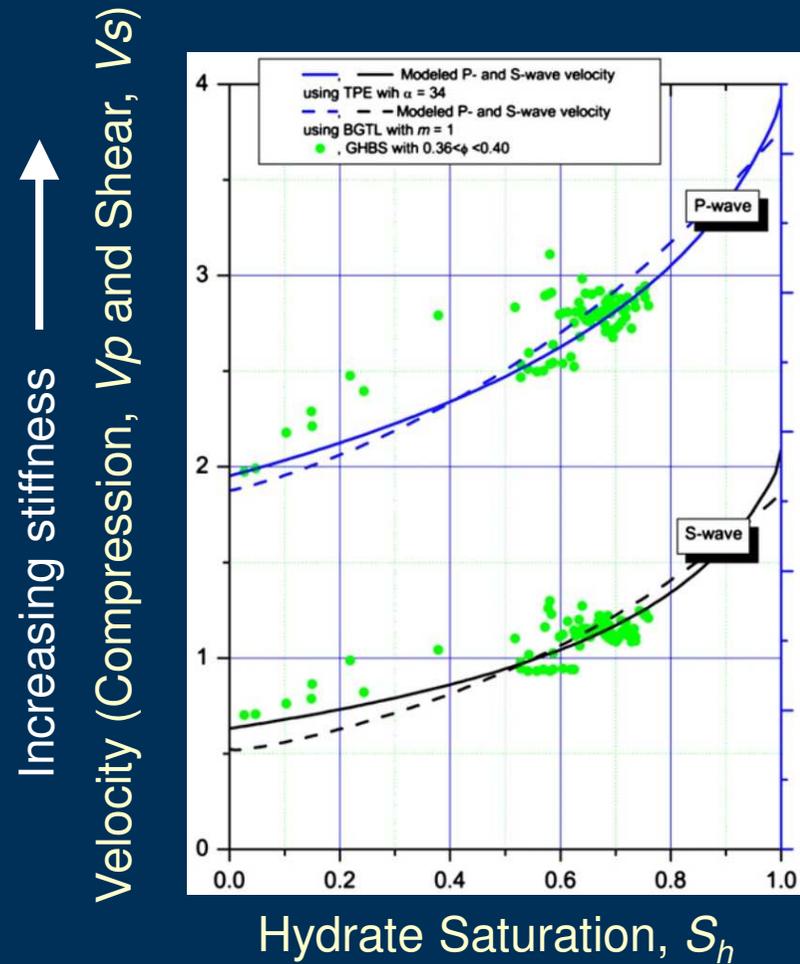
Velocity (Compression, V_p and Shear, V_s)



Lee and Collett (2011), Marine and Petroleum Geology

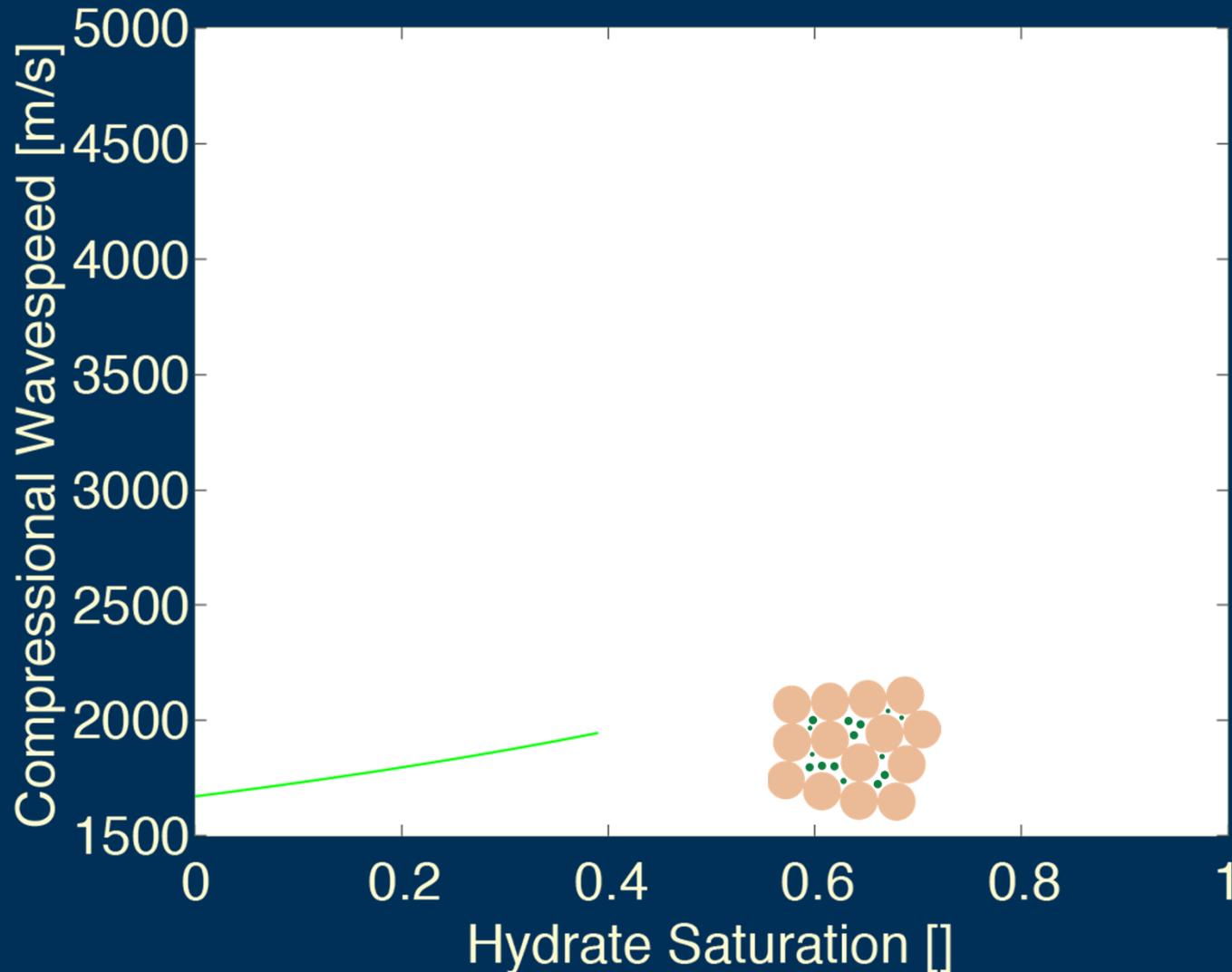
What IS the velocity connection to hydrate saturation?

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Lee and Collett (2011), Marine and Petroleum Geology

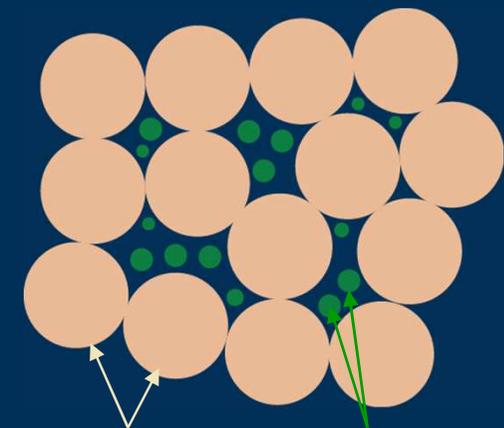
Hydrate location determines V_p dependence on S_h



Pore Filling

Hydrate:

*Very little
stiffening*

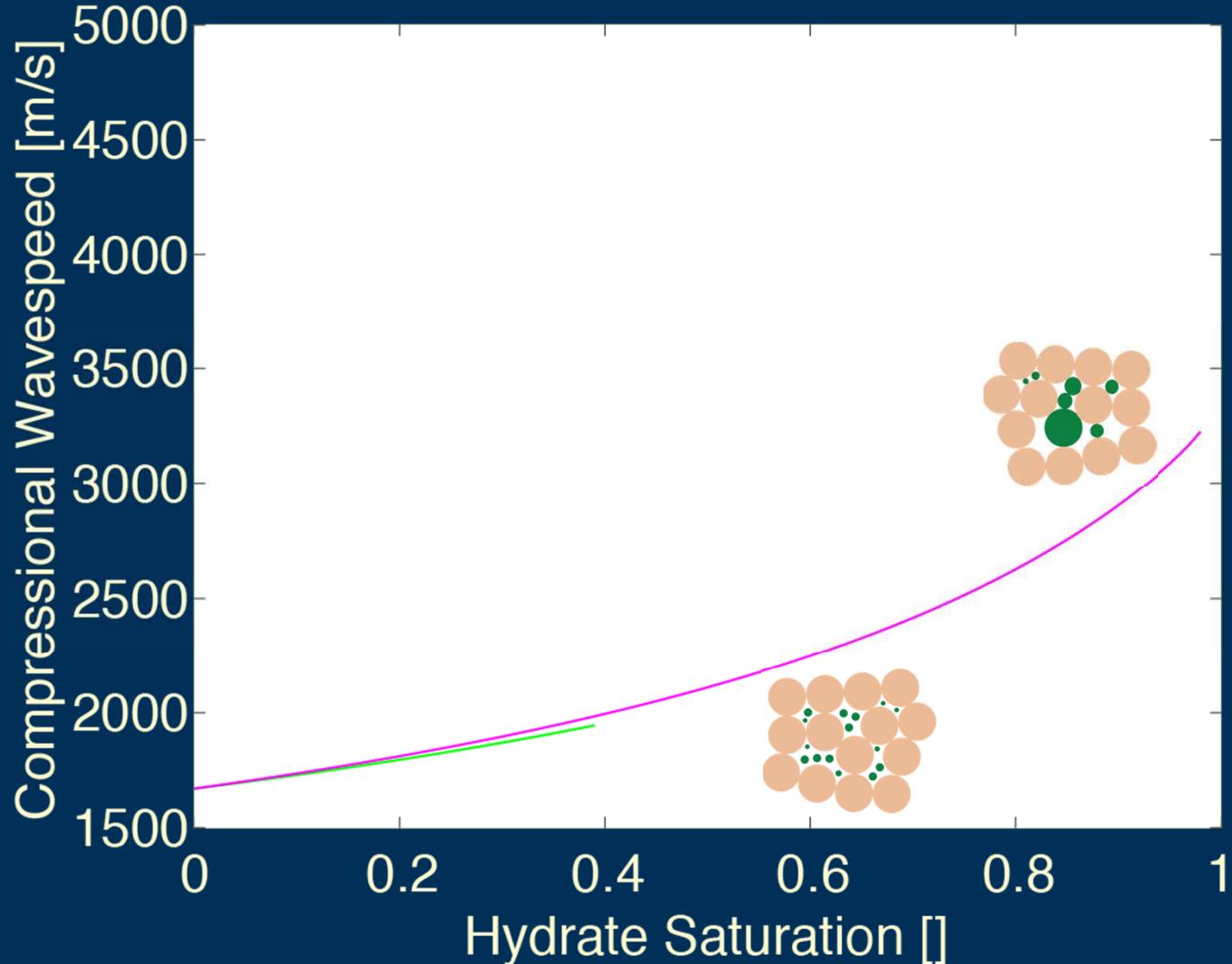


Sediment
Grains

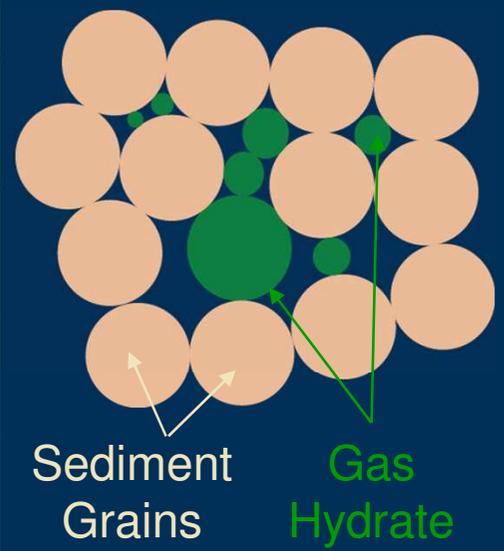
Gas
Hydrate

Dvorkin et al. (2000), Natural Gas Hydrates in Oceanic
and Permafrost Environments

Hydrate location determines V_p dependence on S_h

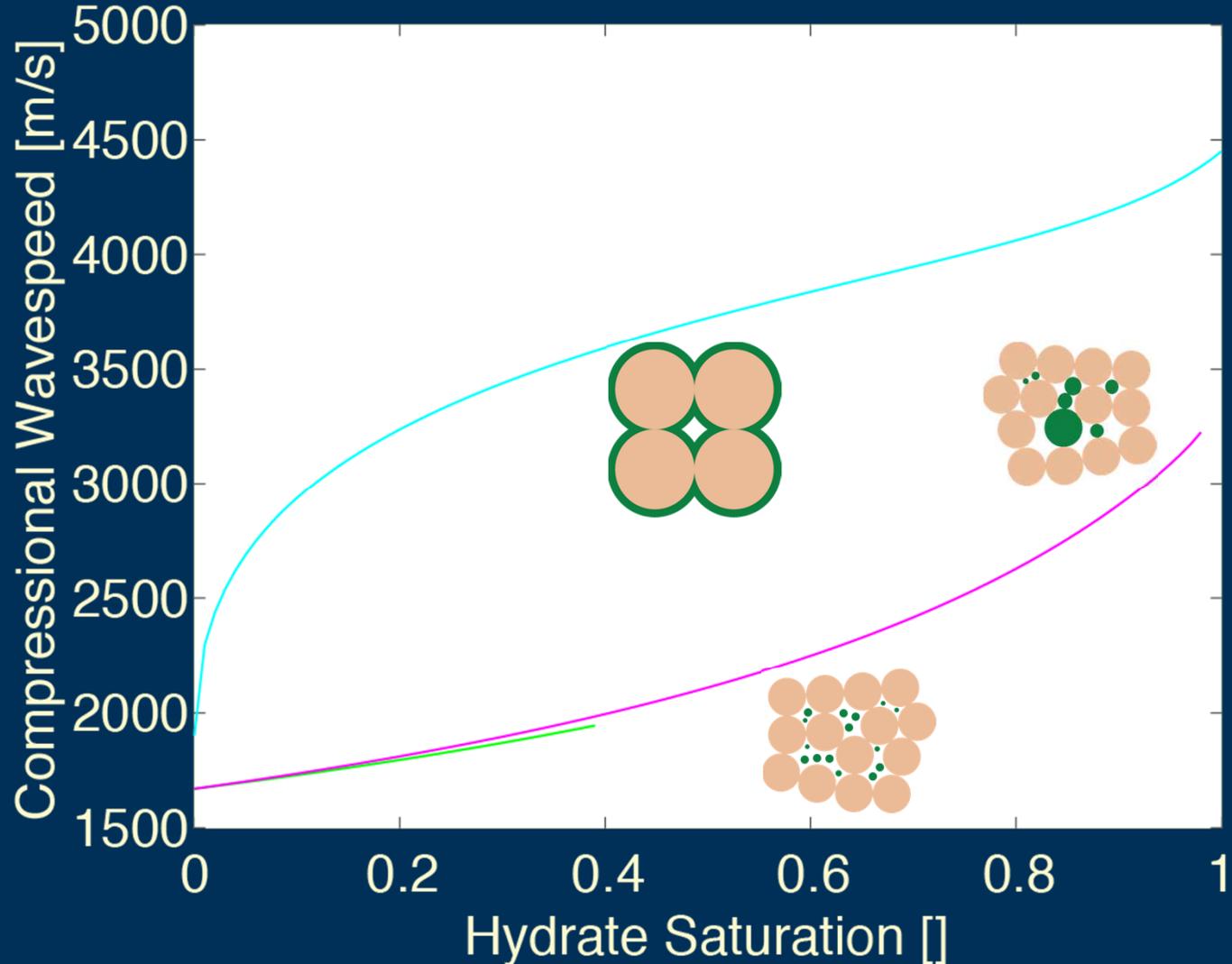


Load Bearing Hydrate:
Moderate stiffening

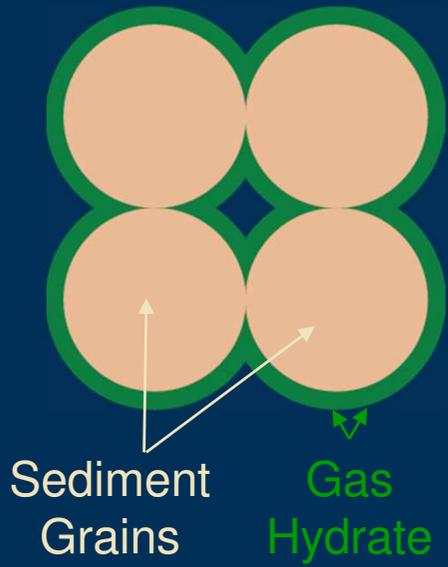


Dvorkin et al. (2000), Natural Gas Hydrates in Oceanic and Permafrost Environments

Hydrate location determines V_p dependence on S_h

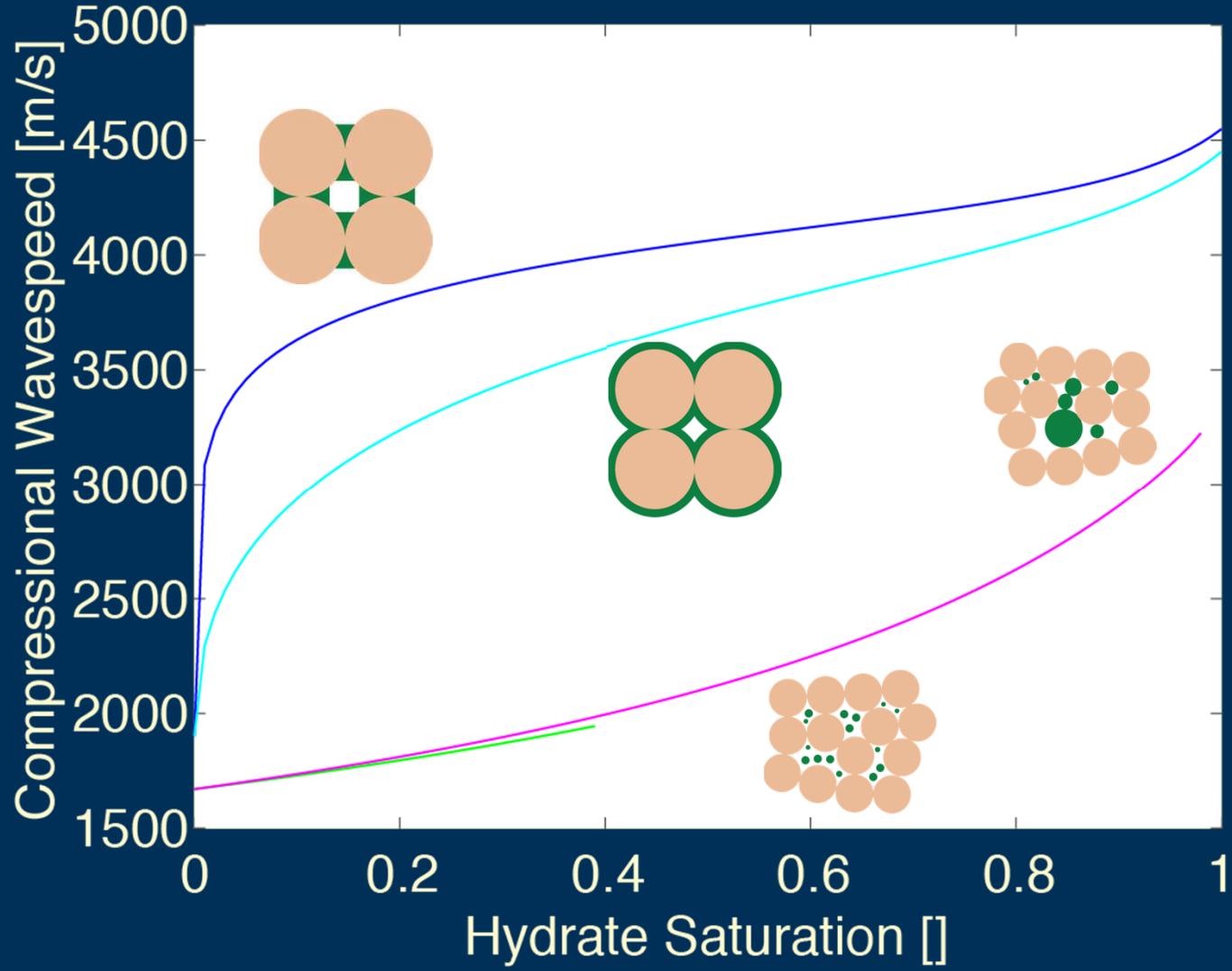


Surround & Cement Hydrate:
High stiffening

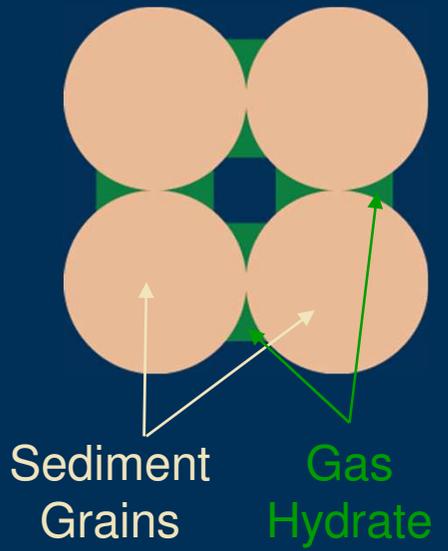


Dvorkin et al. (2000), Natural Gas Hydrates in Oceanic and Permafrost Environments

Hydrate location determines V_p dependence on S_h

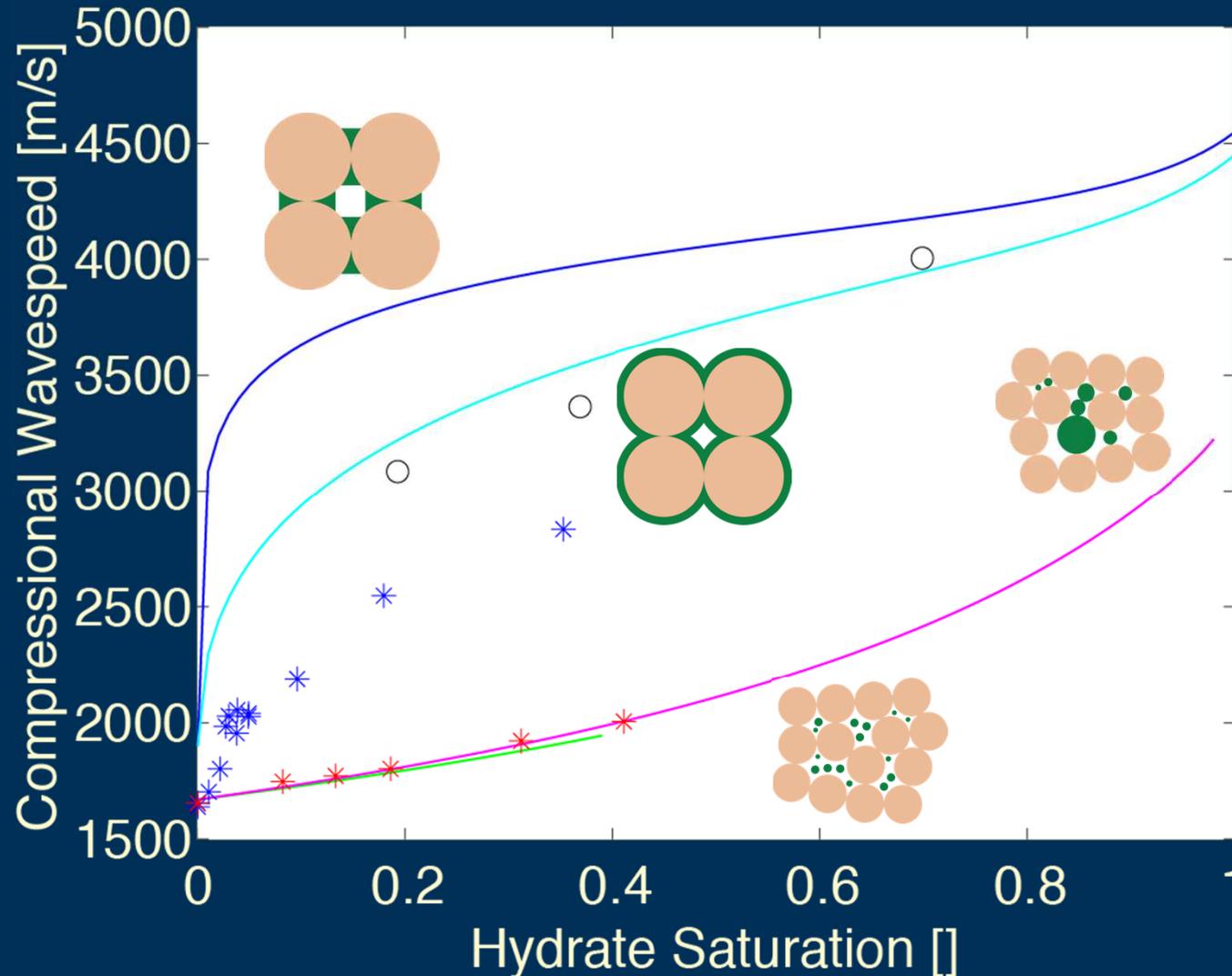


Contact Cement Hydrate: *VERY high stiffening*



Dvorkin et al. (2000), Natural Gas Hydrates in Oceanic and Permafrost Environments

How hydrate forms determines hydrate location



Cementing systems form from *excess gas*

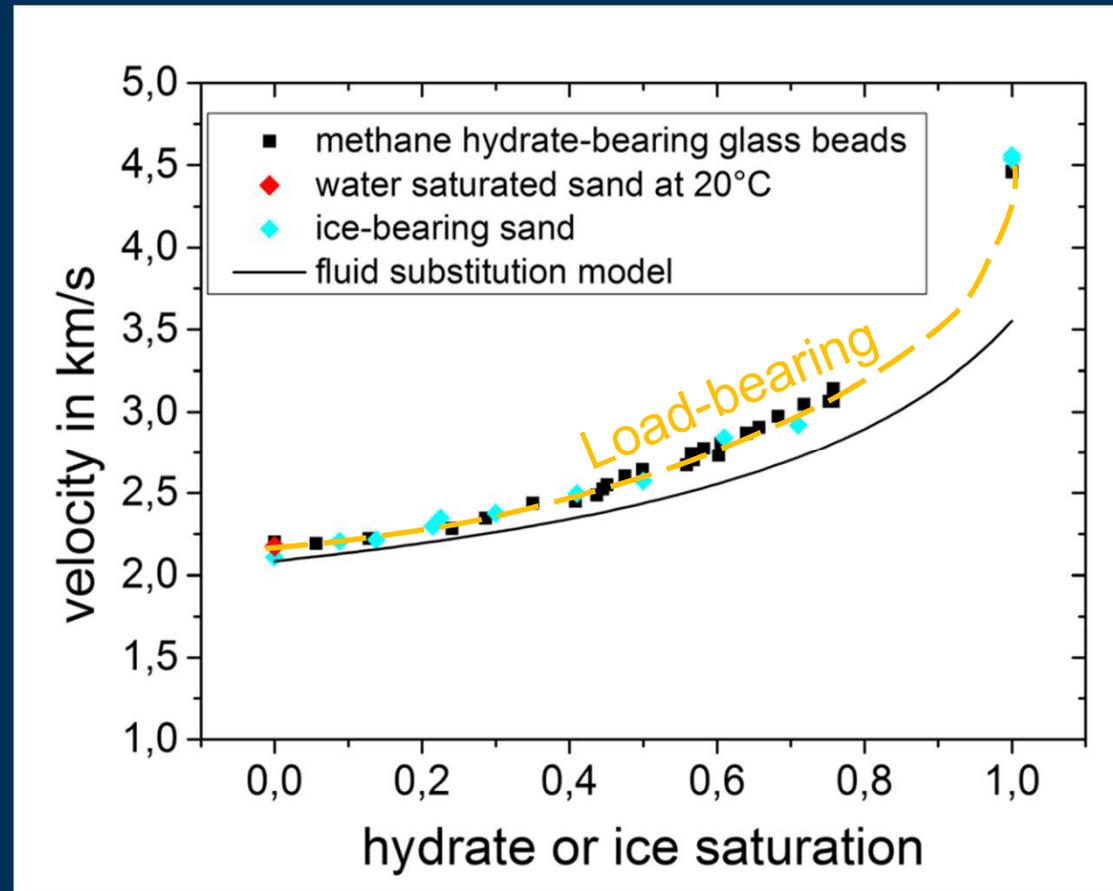
Priest et al., (2005), JGR
Waite et al., (2004), Am Min

Load bearing systems form from *excess water*

Priest et al., (2009), JGR

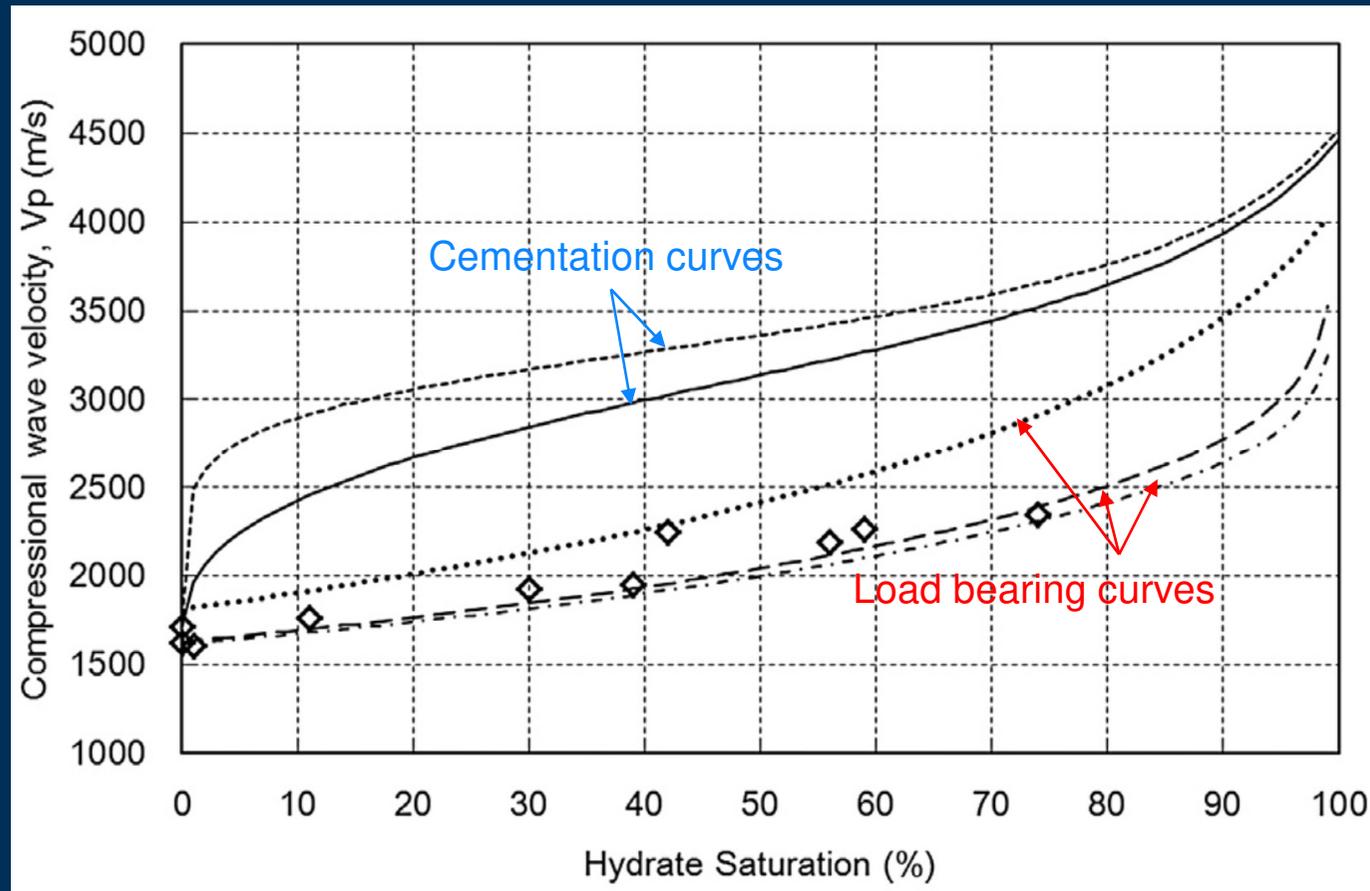
Dvorkin et al. (2000), Natural Gas Hydrates in Oceanic and Permafrost Environments

Hydrates in lab are load-bearing when made with excess water



Spangenberg et al. (2018), JGR

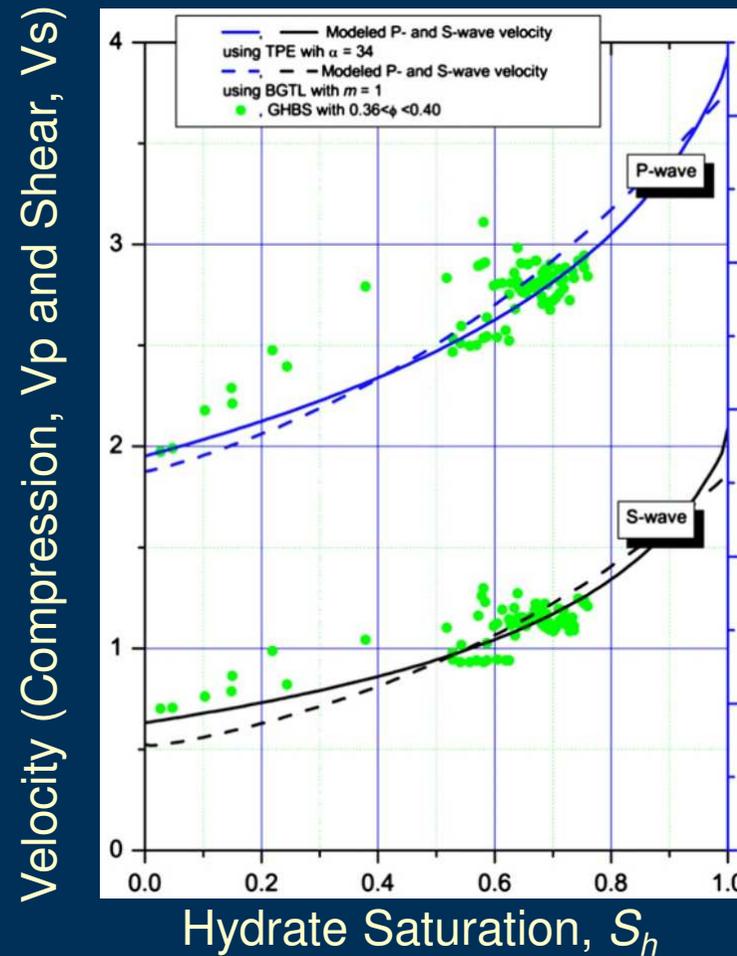
Hydrates in nature are predominantly load-bearing



Nankai Trough (offshore Japan)

Konno et al. (2015), Marine Petroleum Geology

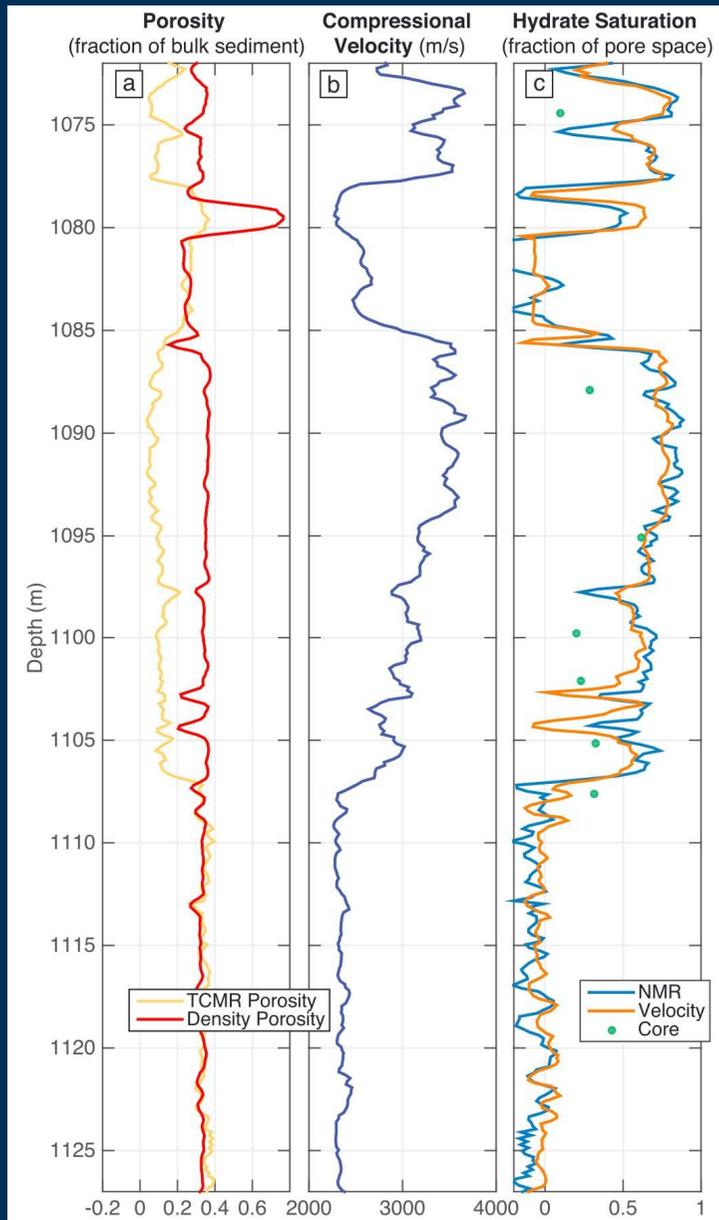
Hydrates in nature are predominantly load-bearing



Mt. Elbert (Arctic USA)

Lee and Collett (2011), Marine and Petroleum Geology

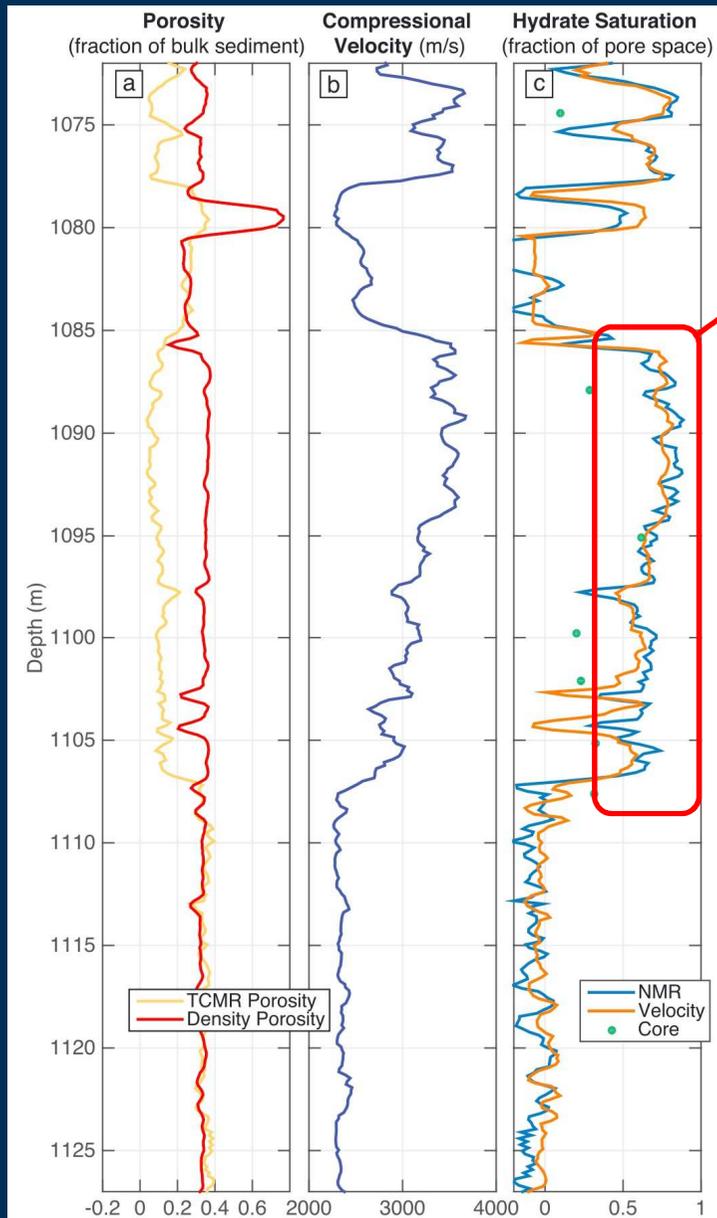
Agreement between V_p and NMR estimates of S_h



Mallik 5L-38
(Arctic Canada)

Cook and Waite (2018), JGR

Agreement between V_p and NMR estimates of S_h

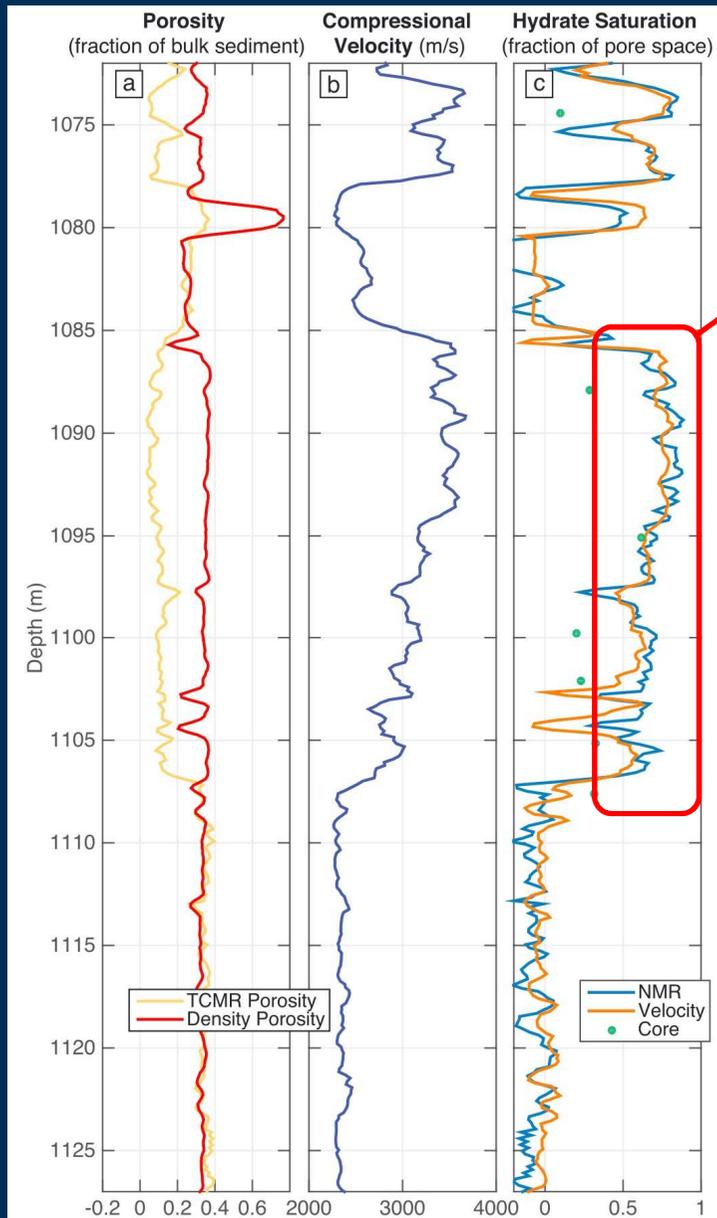


Mallik 5L-38
(Arctic Canada)

Two estimates utilize very different physical properties:

Cook and Waite (2018), JGR

Agreement between V_p and NMR estimates of S_h



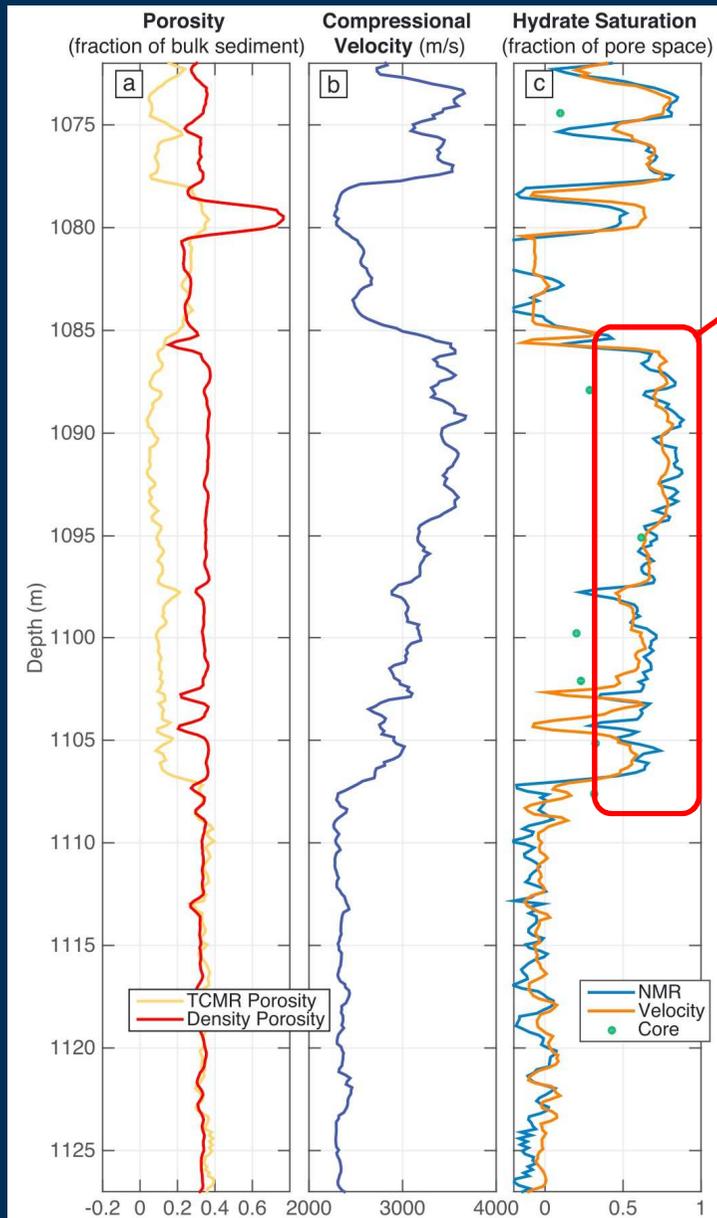
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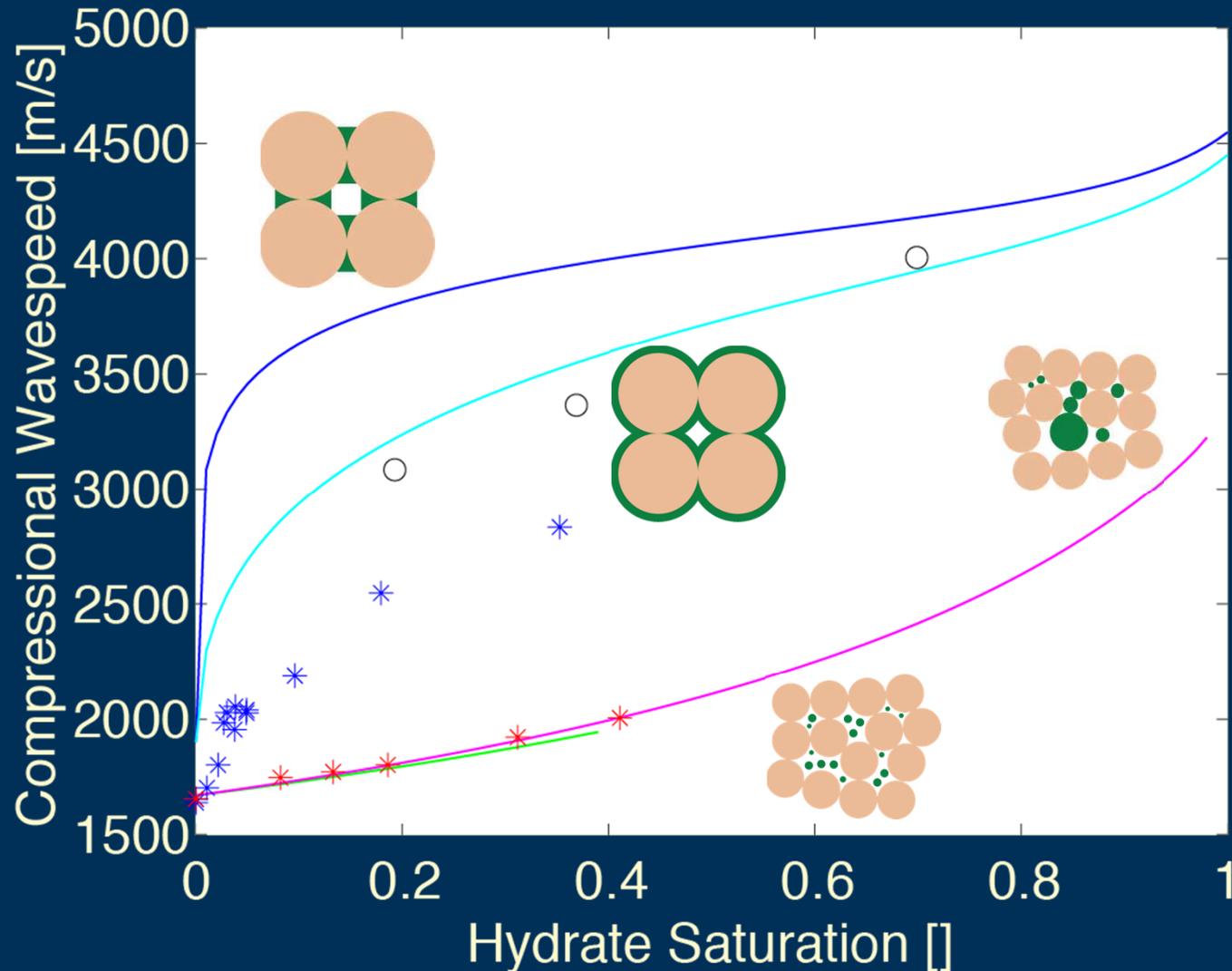
Mallik 5L-38 (Arctic Canada)

Two estimates utilize very different physical properties:

- NMR: water and pore-space volumes only
- V_p : hydrate morphology and the system's mechanical stiffness

Cook and Waite (2018), JGR

How hydrate forms determines hydrate location



Cementing systems form from *excess gas*

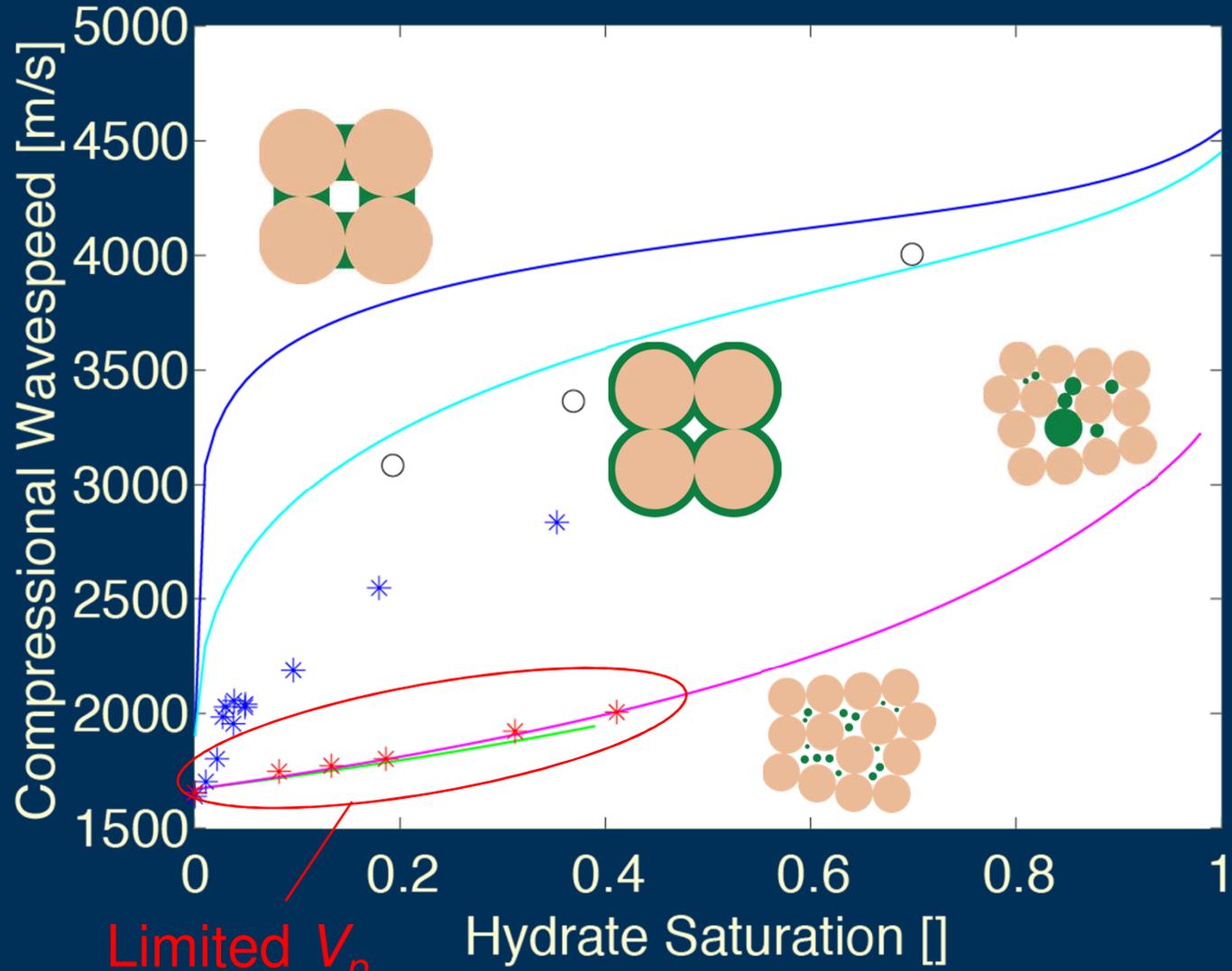
Priest et al., (2005), JGR
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Dvorkin et al. (2000), Natural Gas Hydrates in Oceanic and Permafrost Environments

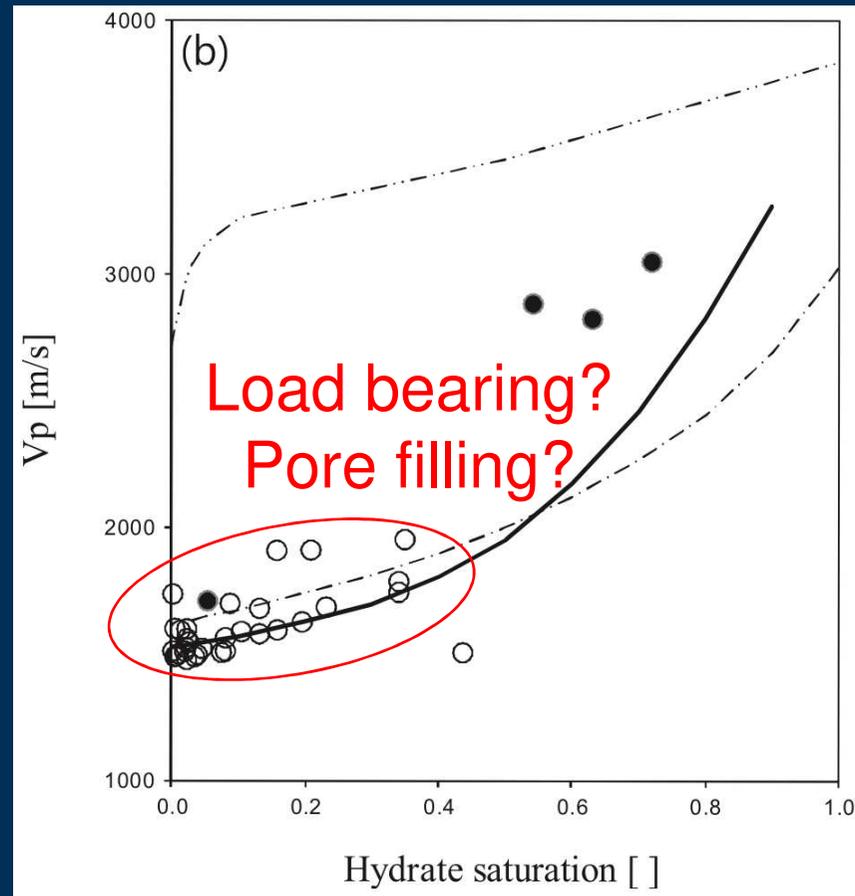
What do we do when $S_h < 0.4$?



Limited V_p
sensitivity to S_h

Dvorkin et al. (2000), Natural Gas Hydrates in Oceanic and Permafrost Environments

Lack of sensitivity at low S_h can be a problem

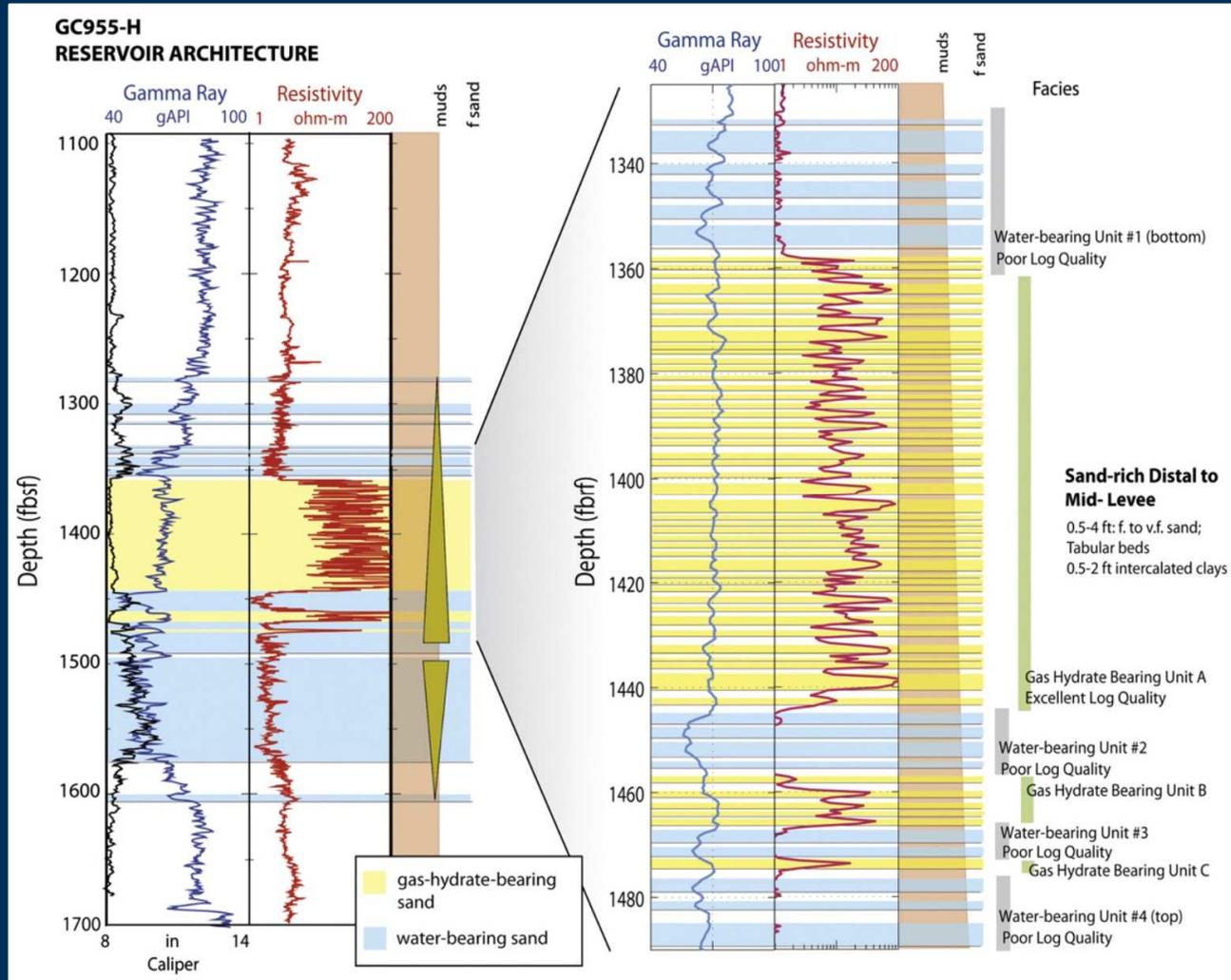


Ulleung Basin (offshore Korea)

Lee et al. (2013), Marine and Petroleum Geology

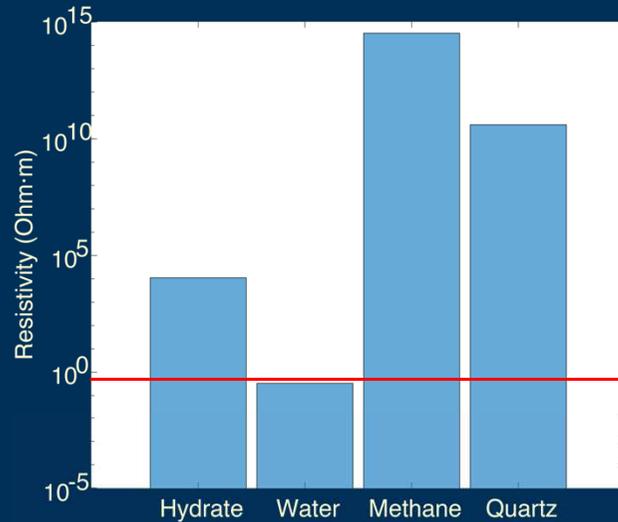
Electrical resistivity: another connection with hydrate saturation

Gulf of Mexico (offshore USA)

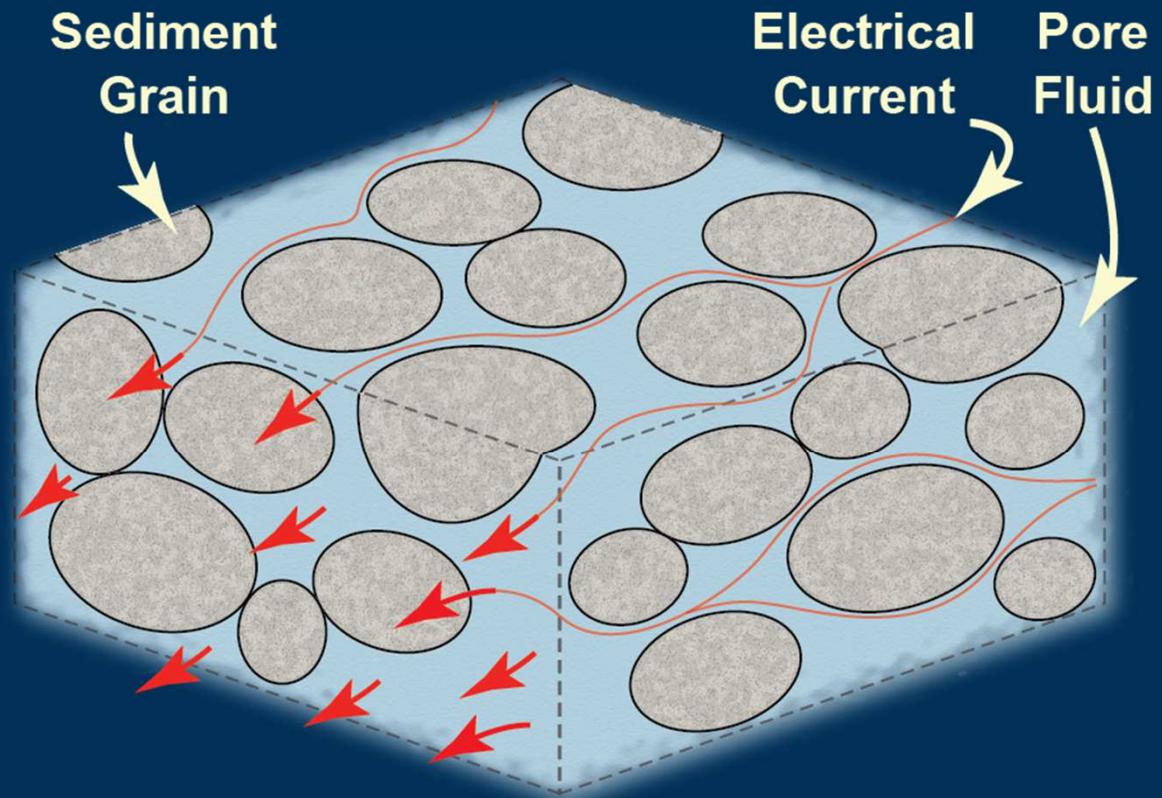


Boswell et al. (2012) Marine and Petroleum Geology

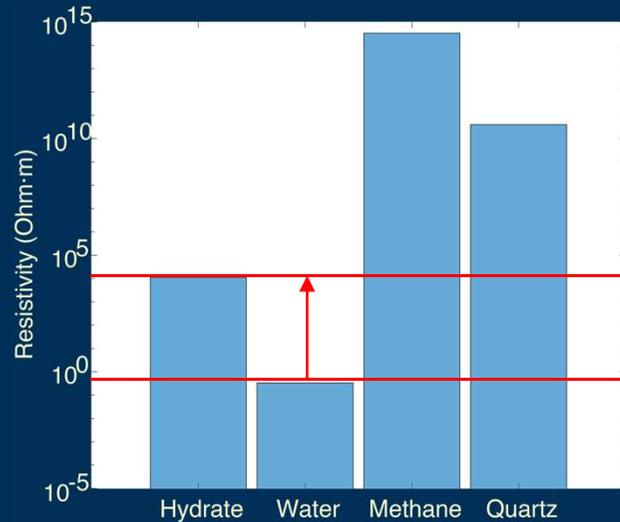
Electrical resistivity: what is happening physically?



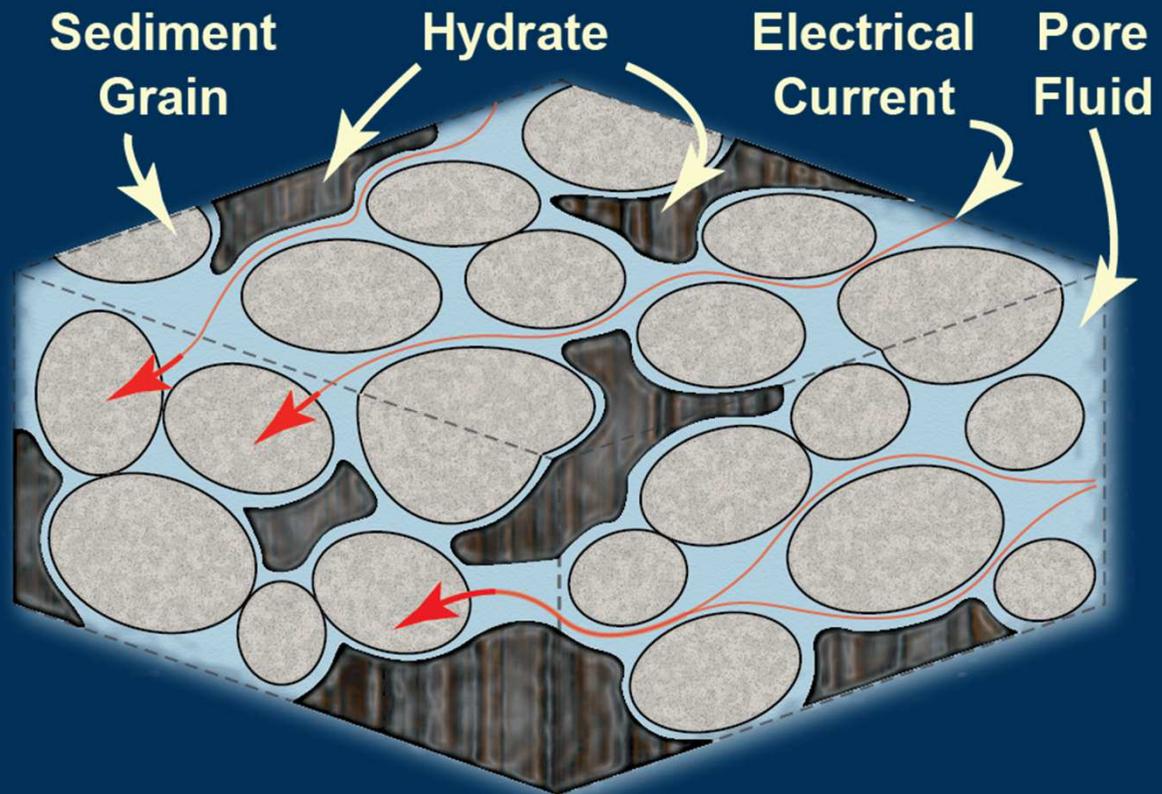
Electrical current can easily move through salty pore water (*low resistivity*)



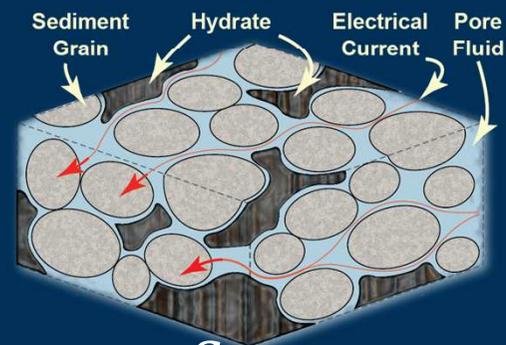
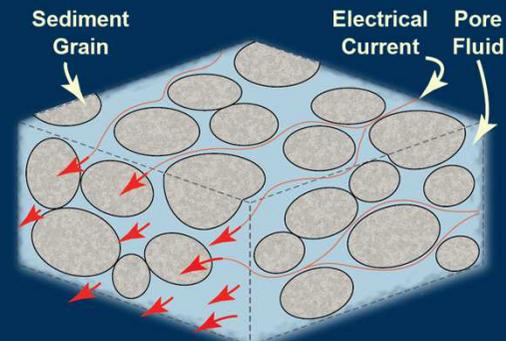
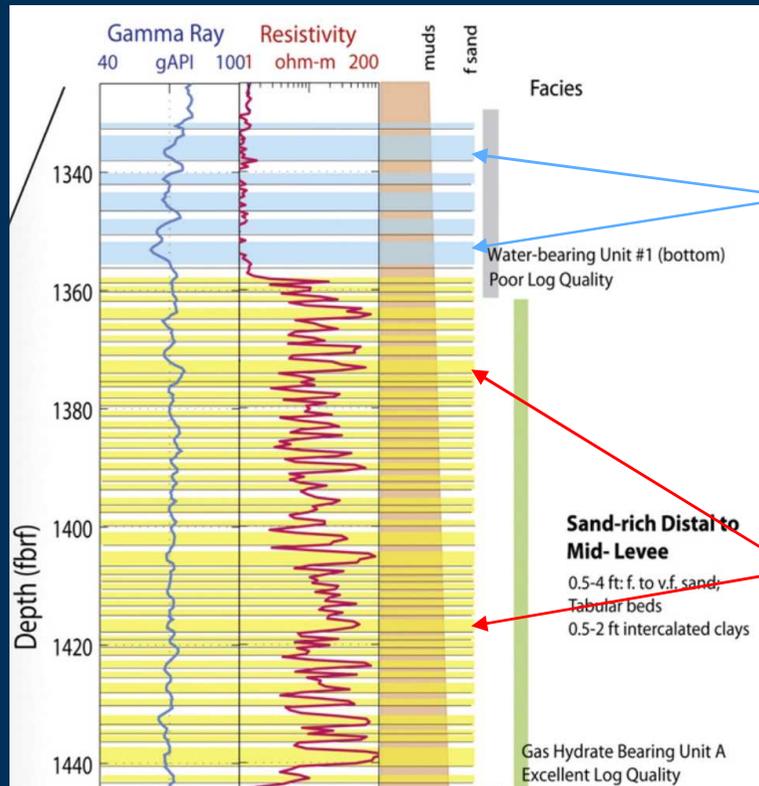
Electrical resistivity: what is happening physically?



Electrical current is restricted by hydrate
(*high resistivity*)



Archie's Law: Connecting electrical resistivity to S_h



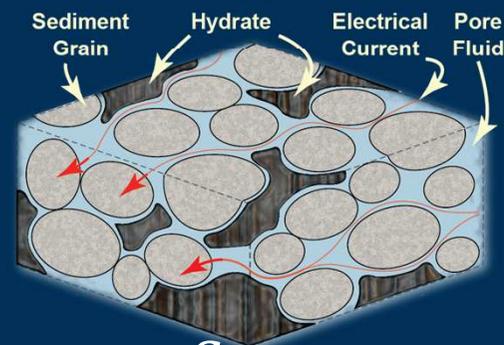
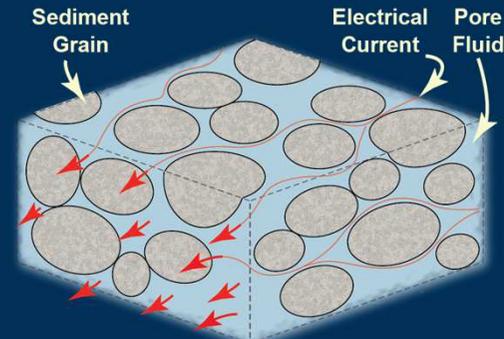
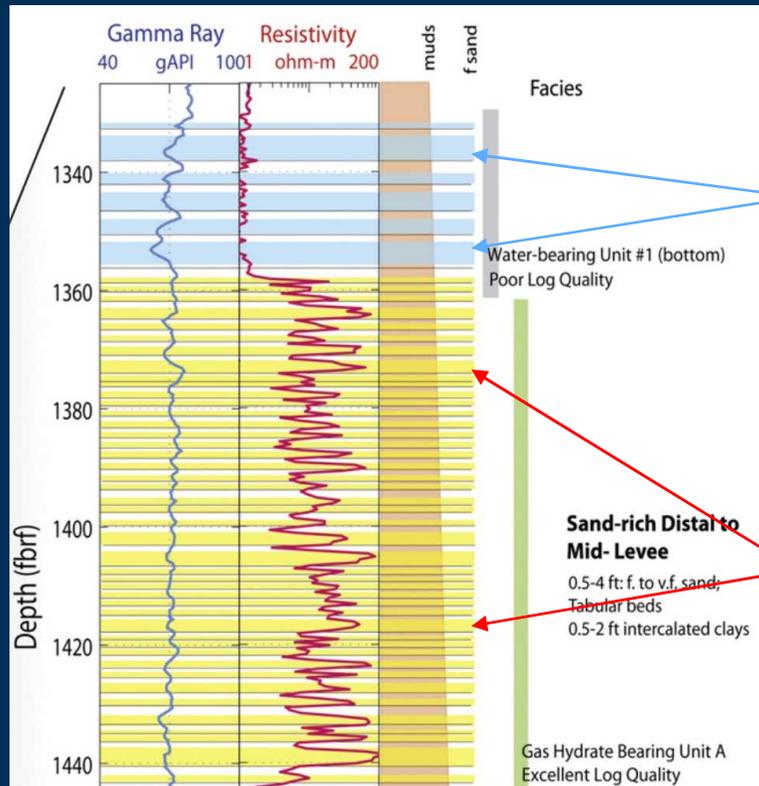
S_h

Boswell et al., (2012b) Marine and Petroleum Geology

$$= 1 - \left\{ \frac{a \cdot R_{pore\ water}}{R_{aw} [Archie, \phi^m]} \right\}^{\frac{1}{n}}$$

Archie's Law [Archie, (1942)]

Archie's Law: Connecting electrical resistivity to S_h



S_h

Boswell et al., (2012b) Marine and Petroleum Geology

$$S_h = 1 - \left\{ \frac{a \cdot R_{pore\ water}}{R_{sw} \phi^m} \right\}^{\frac{1}{n}}$$

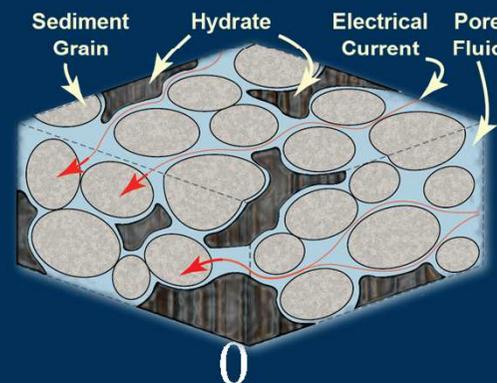
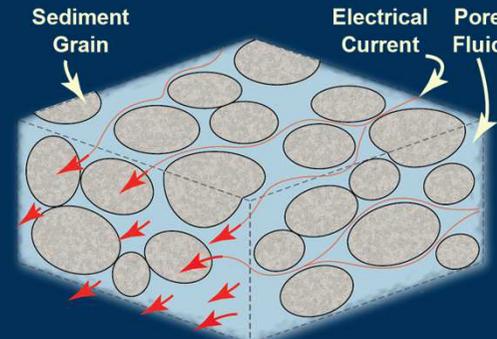
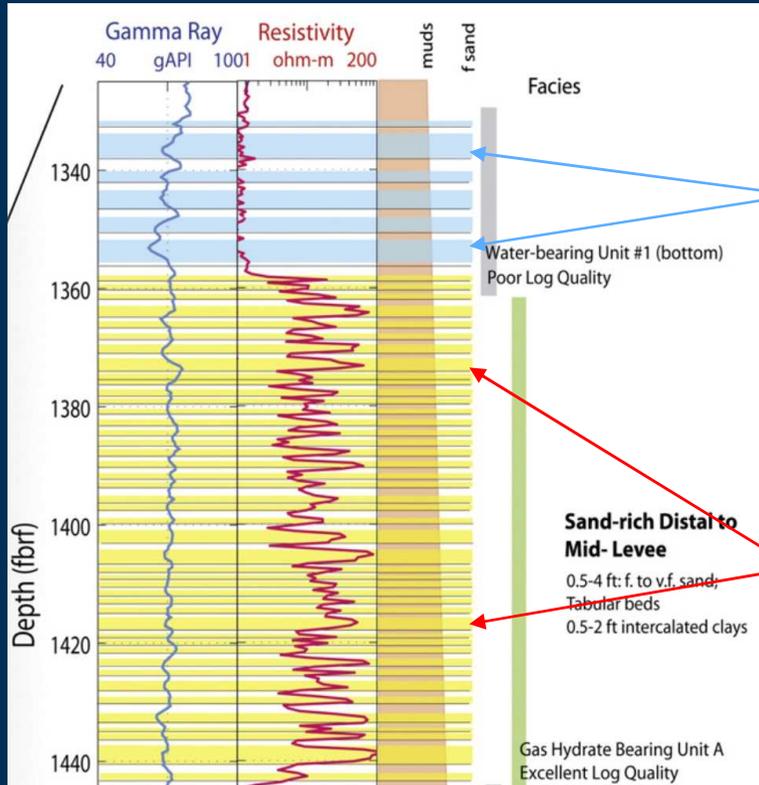
Archie's Law [Archie, (1942)]

Empirical constants:

$a = 0.62$; $m = 2.15$ [Humble Equation, Winsauer et al. (1952)]

$n = 2$ Lee and Collett (2011), MPG; 2.42 Malinverno et al. (2010), EPSL

Archie's Law: Connecting electrical resistivity to S_h



Boswell et al., (2012b) Marine and Petroleum Geology

$$= 1 - \left\{ \frac{a \cdot R_{pore\ water}}{R_{sw} \phi^m} \right\}^{\frac{1}{n}}$$

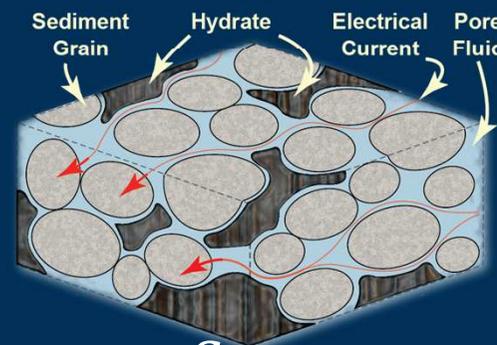
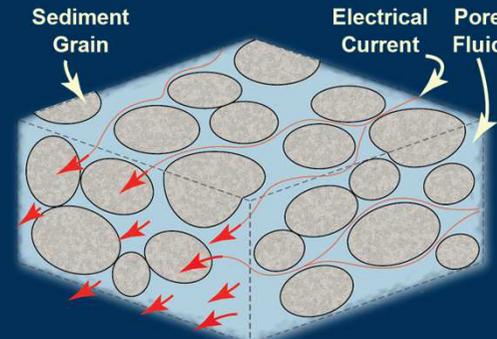
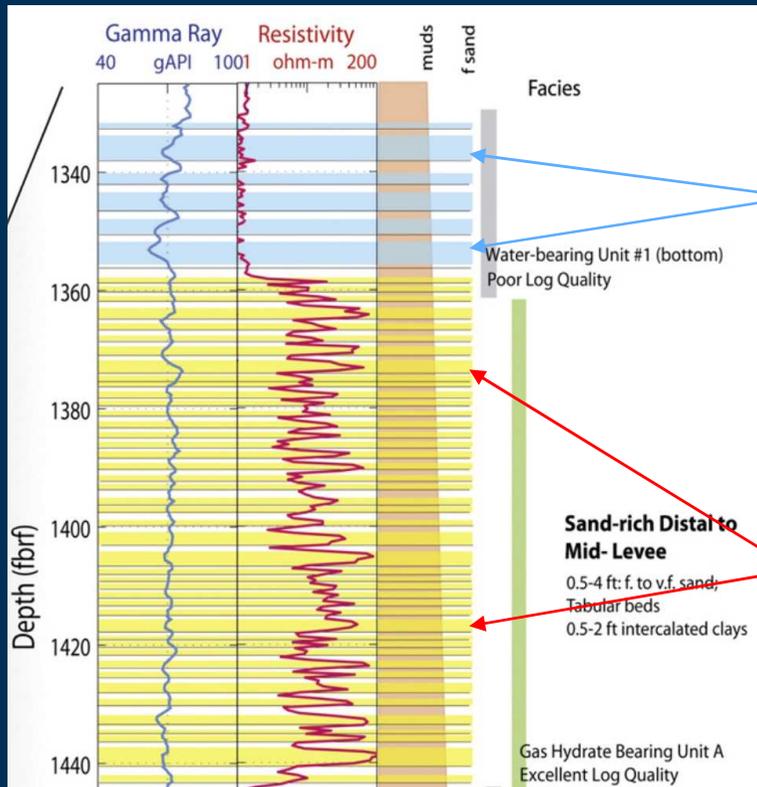
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Archie's Law: Connecting electrical resistivity to S_h



S_h

Boswell et al., (2012b) Marine and Petroleum Geology

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Archie's Law [Archie, (1942)]

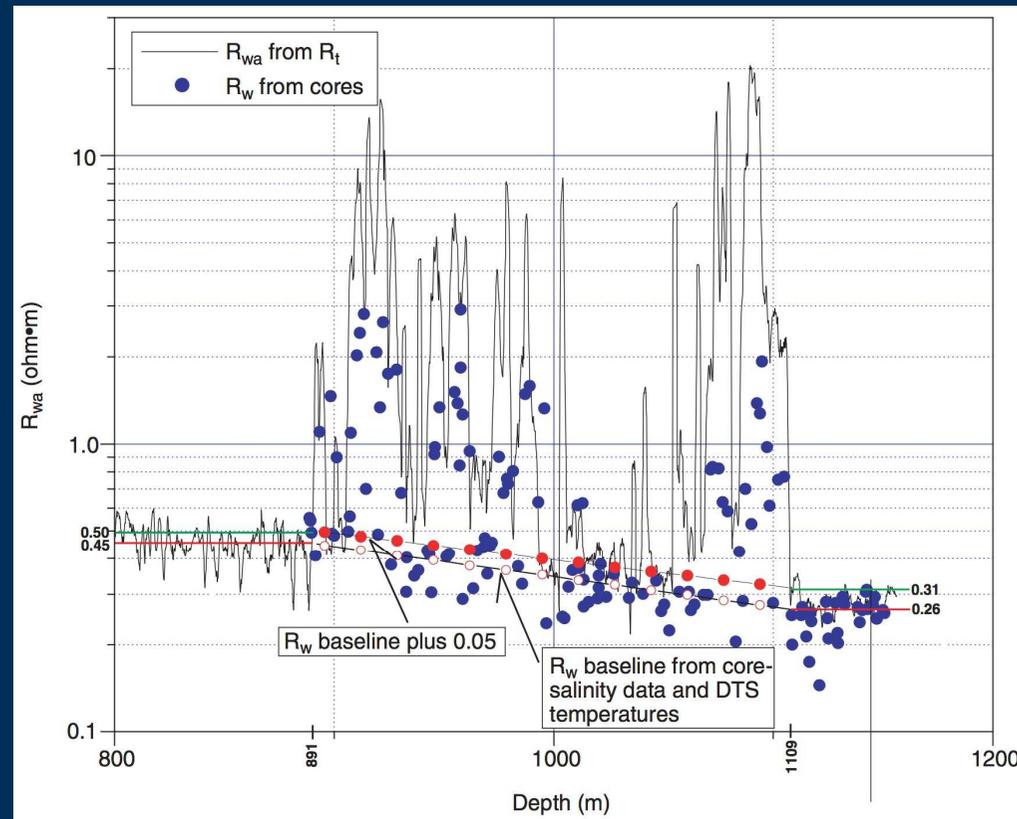
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Pore water estimates: from neighboring hydrate-free sediment

Mallik (Canadian Arctic)



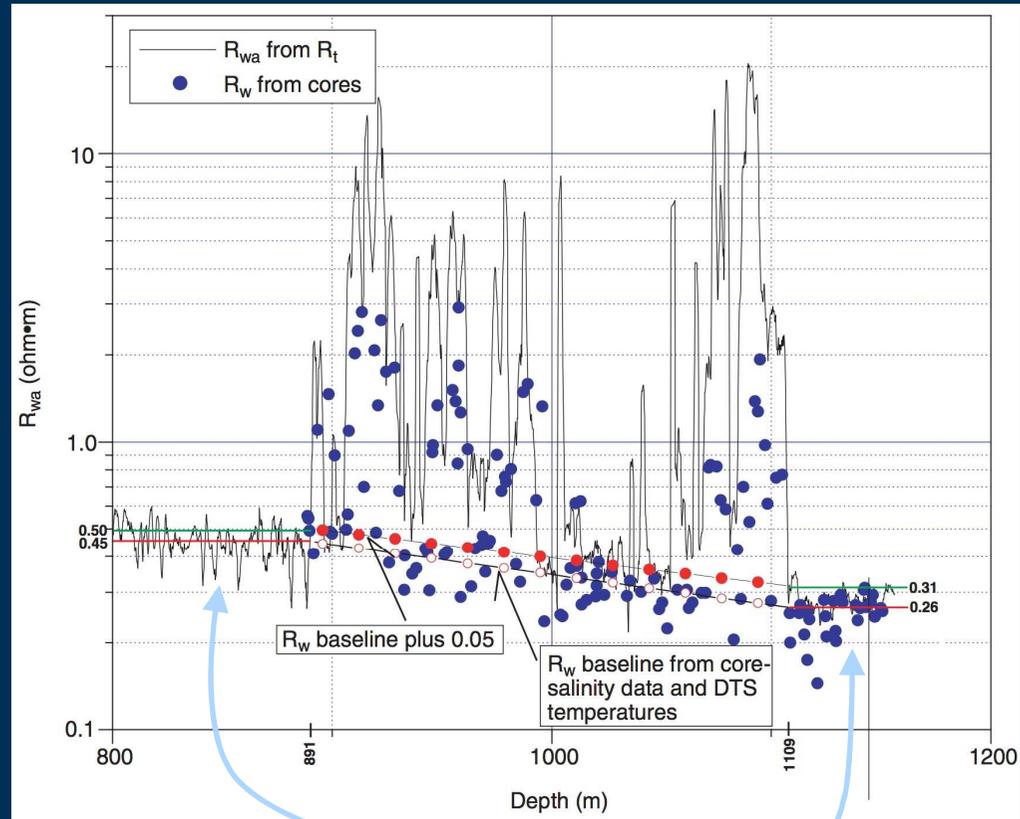
$$S_h$$

$$= 1 - \left\{ \frac{a \cdot R_{pore\ water}}{R_{measured} \cdot \phi^m} \right\}^{\frac{1}{n}}$$

Collett and Lee (2005), GSC Bulletin

Pore water estimates: from neighboring hydrate-free sediment

Mallik (Canadian Arctic)

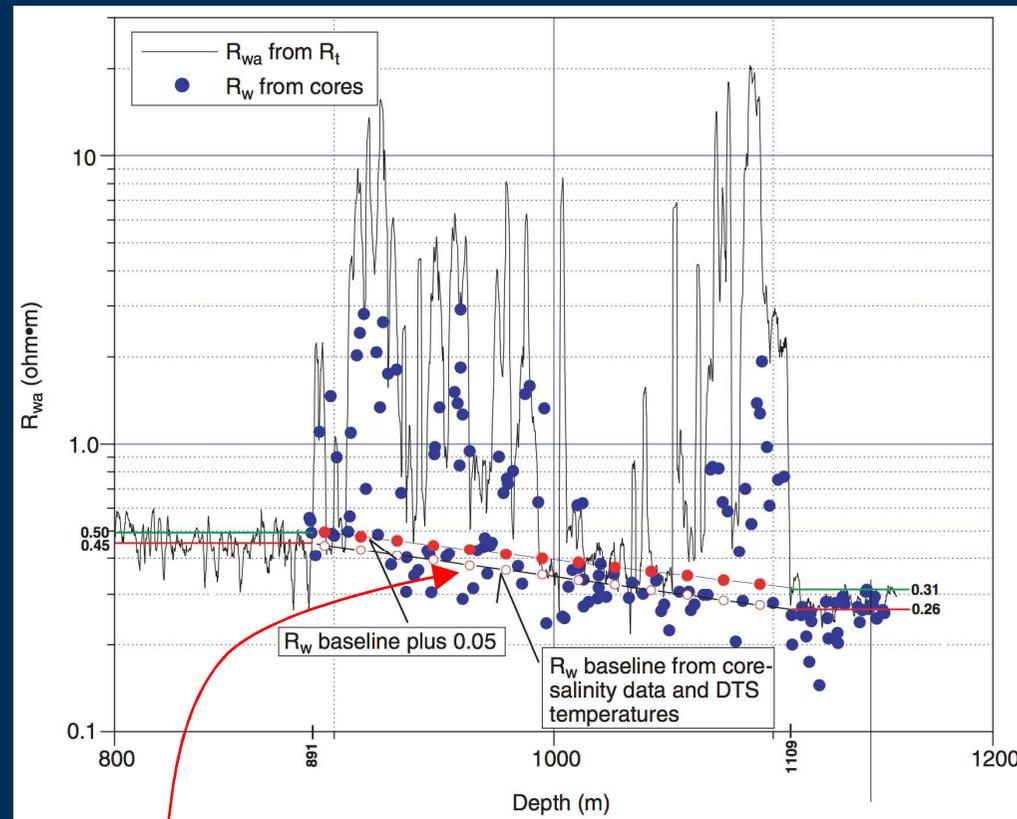


$$0 = 1 - \left\{ \frac{a \cdot R_{\text{pore water}}}{R_{\text{measured}} \cdot \phi^m} \right\}^{\frac{1}{n}}$$

Collett and Lee (2005), GSC Bulletin

Hydrate saturation estimates: assume only S_h and ϕ change

Mallik (Canadian Arctic)



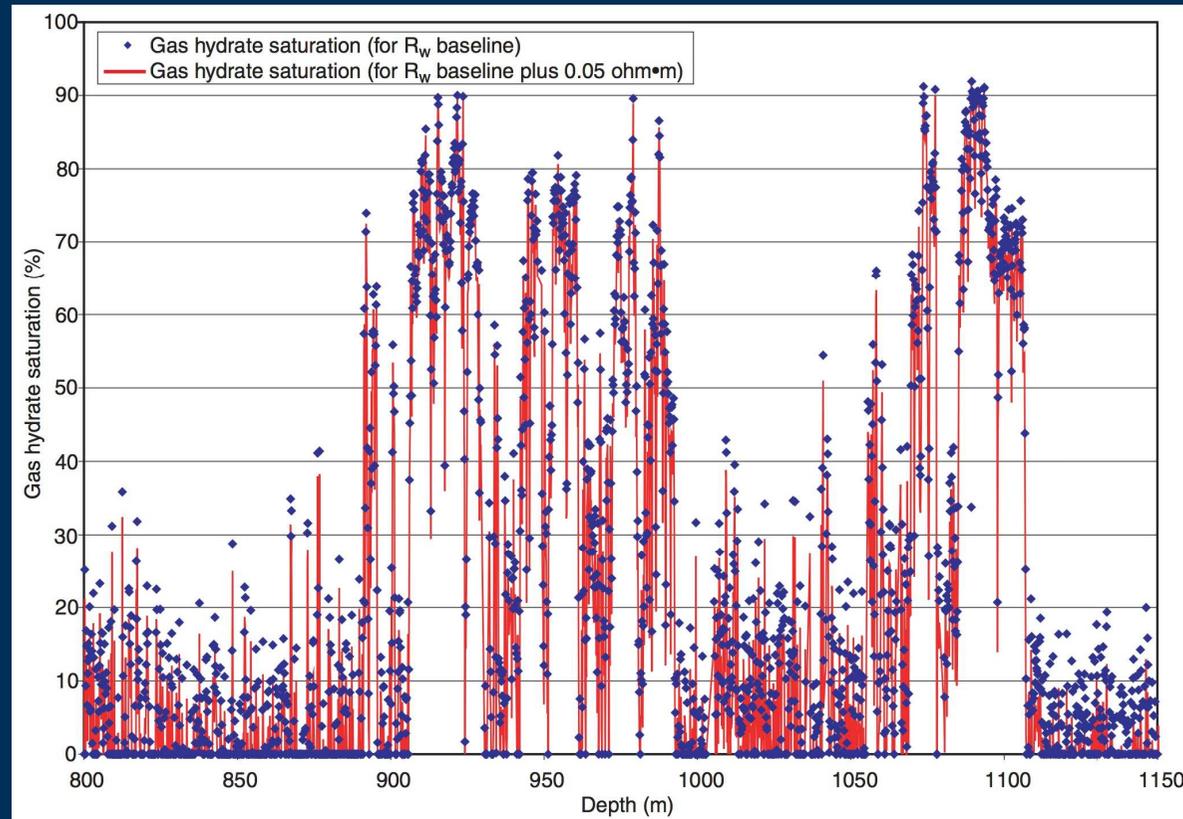
S_h

$$= 1 - \left\{ \frac{a \cdot R_{pore\ water}}{R_{measured} \cdot \phi^m} \right\}^{\frac{1}{n}}$$

Collett and Lee (2005), GSC Bulletin

Complete downhole S_h estimates from resistivity

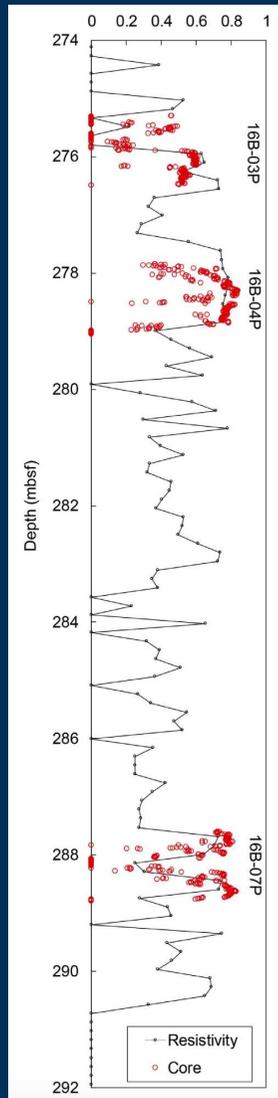
Mallik (Canadian Arctic)


$$S_h$$

$$= 1 - \left\{ \frac{a \cdot R_{\text{pore water}}}{R_{\text{measured}} \cdot \phi^m} \right\}^{\frac{1}{n}}$$

Collett and Lee (2005), GSC Bulletin

Complete downhole S_h estimates from resistivity NGHP-02 (Offshore India)



No water-bearing sands?

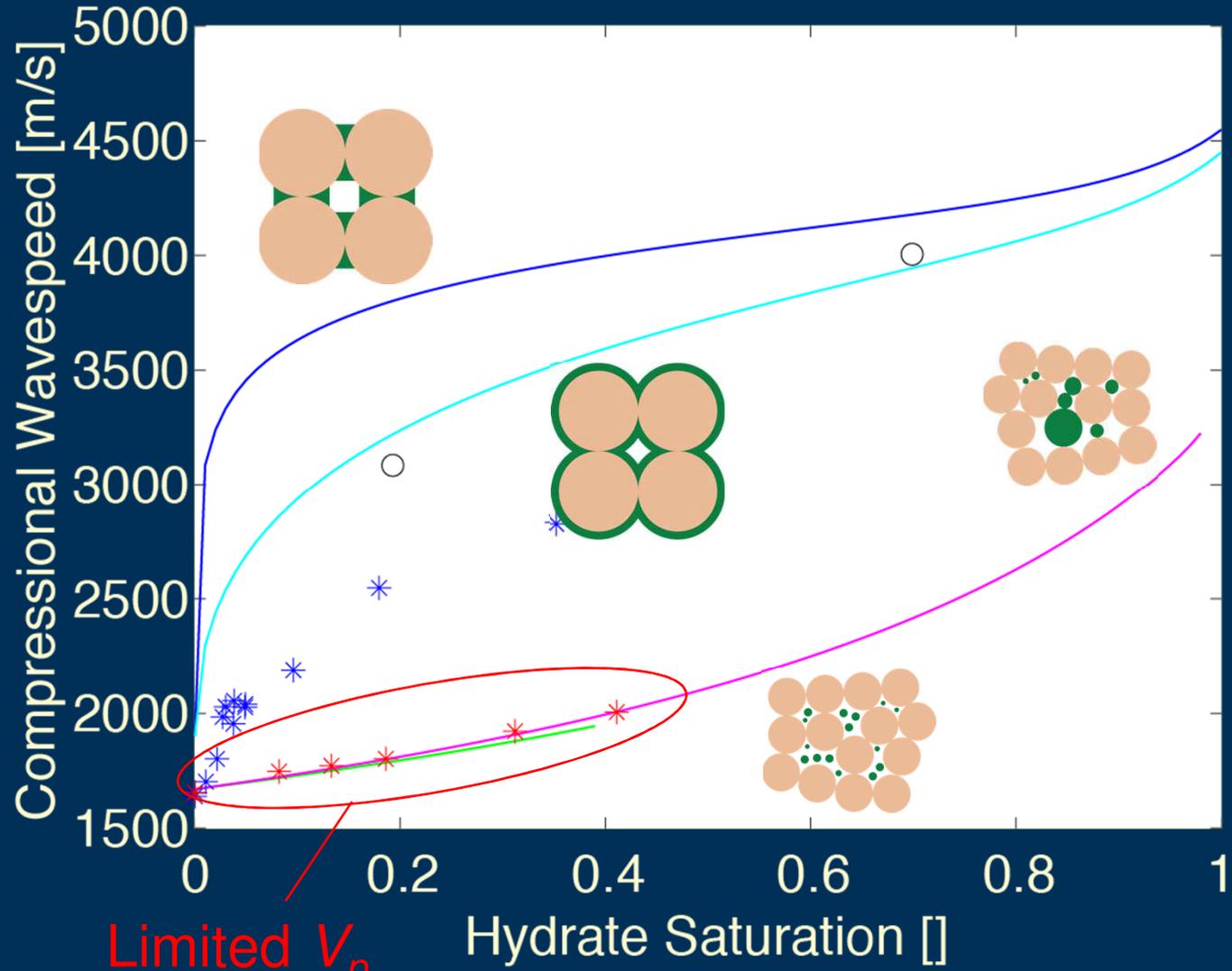
a , m and n can be found with fits to other estimates of S_h .

(Pressure cores were used in this study)

$$S_h = 1 - \left\{ \frac{a \cdot R_{pore\ water}}{R_{measured} \cdot \phi^m} \right\}^{\frac{1}{n}}$$

Konno et al. (2018), JMPG

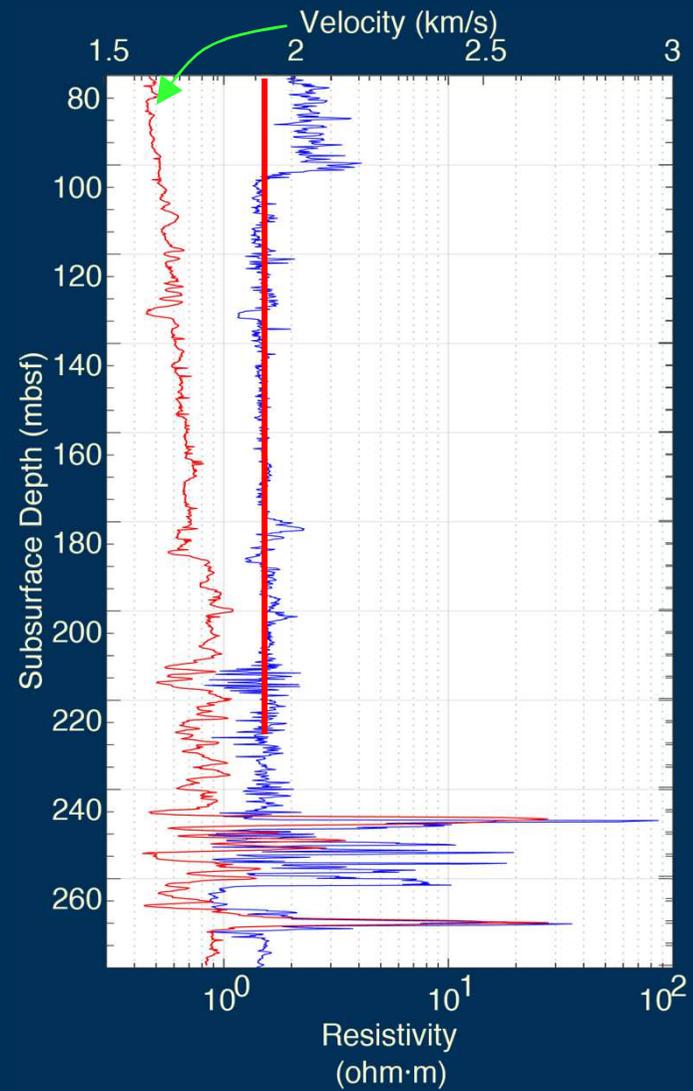
What do we do when $S_h < 0.4$?



Limited V_p
sensitivity to S_h

Dvorkin et al. (2000), Natural Gas Hydrates in Oceanic and Permafrost Environments

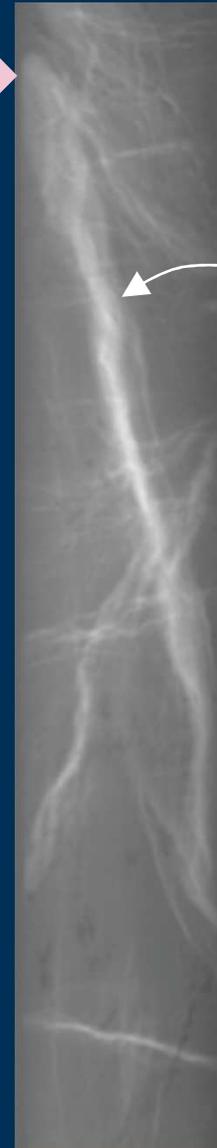
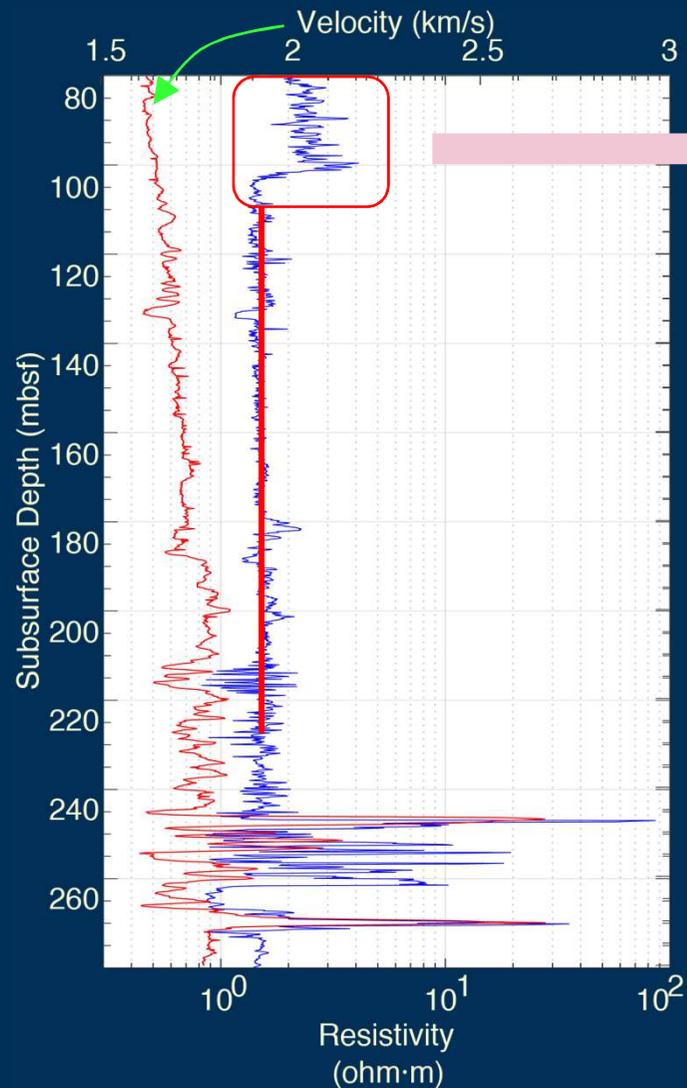
What do we do when $S_h < 0.4$? Resistivity can help!



K-G Basin (offshore India)

Waite et al. (2018), JMPG

What do we do when $S_h < 0.4$? Resistivity can help!



Hydrate veins:
Too little to change V_p ,
($S_h < .4$)

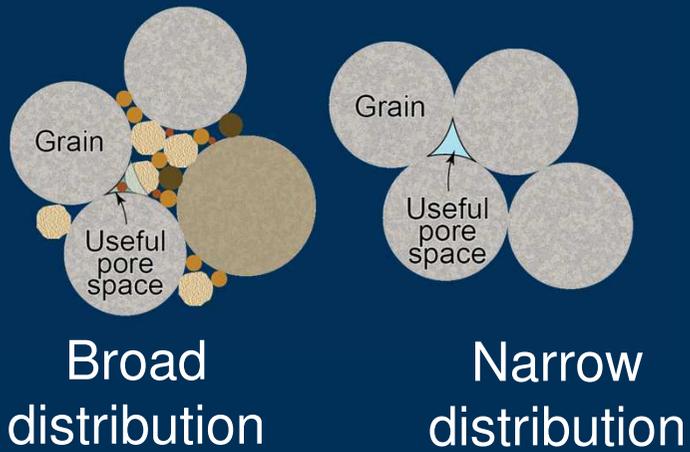
But very difficult to pass
current through
(*high resistivity*).

K-G Basin (offshore India)

Waite et al. (2018), JMPG

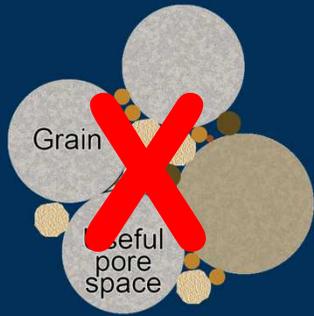
Holland et al. (2008), ICGH 6

Big Ideas: calculating the gas hydrate saturation

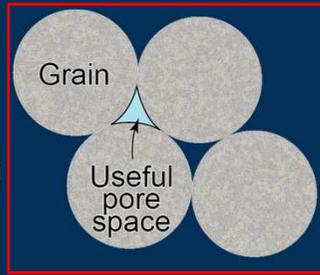


- Know your porosity! A few large pores are better than many small pores.

Big Ideas: calculating the gas hydrate saturation



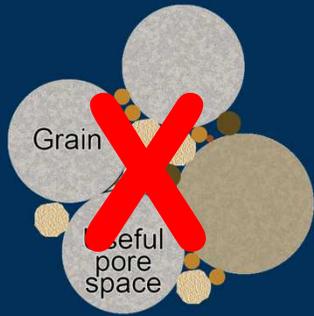
Broad
distribution



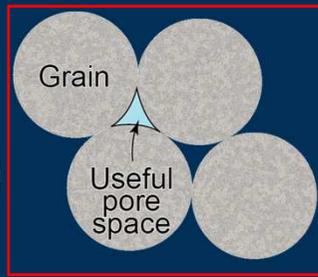
Narrow
distribution

- Know your porosity! A few large pores are better than many small pores.

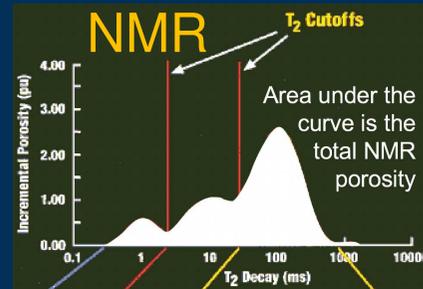
Big Ideas: calculating the gas hydrate saturation



Broad
distribution

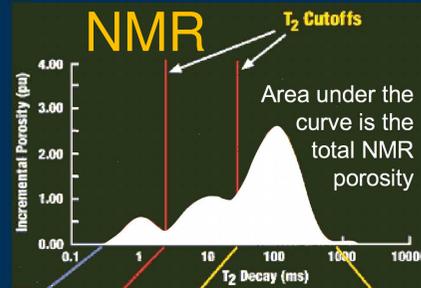
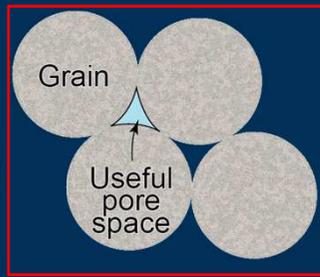
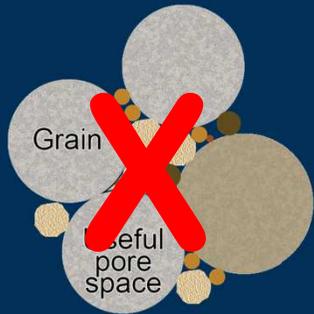


Narrow
distribution



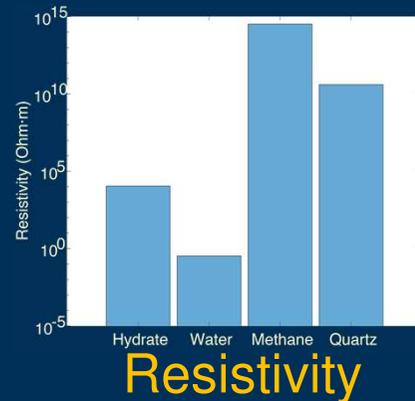
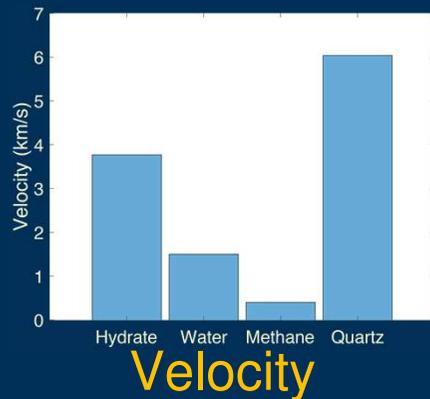
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Big Ideas: calculating the gas hydrate saturation



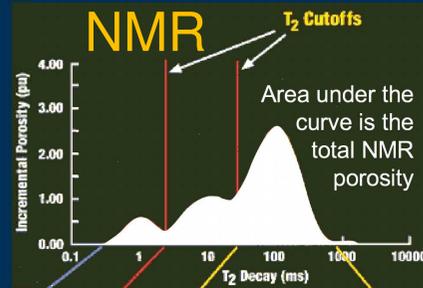
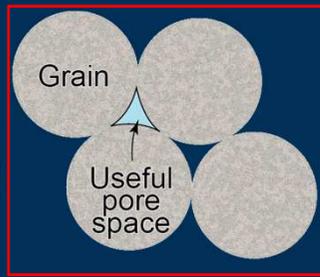
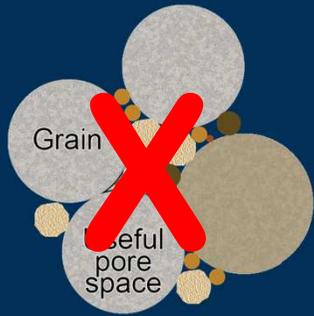
Broad distribution

Narrow distribution



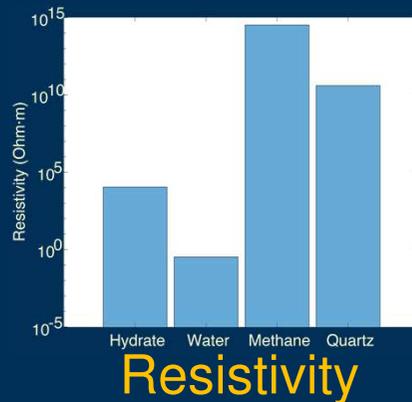
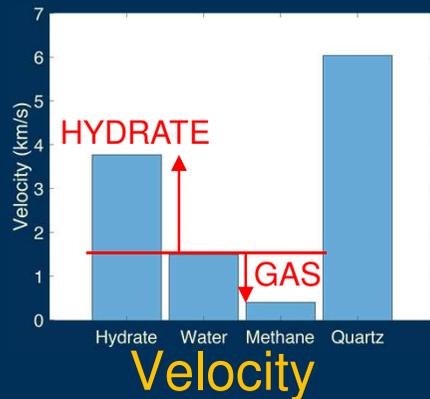
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- Effective characterizations requires physical properties that can distinguish between sediment and the pore-space constituents: water, hydrate and/or gas.

Big Ideas: calculating the gas hydrate saturation



Broad distribution

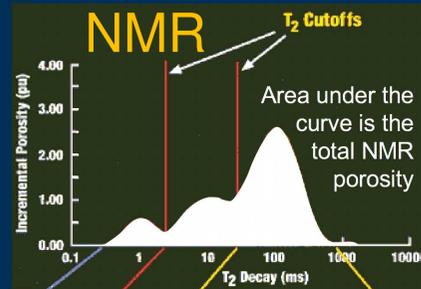
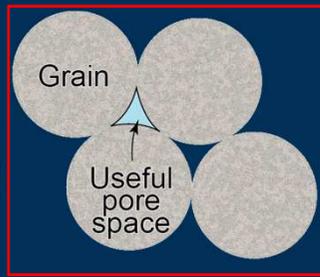
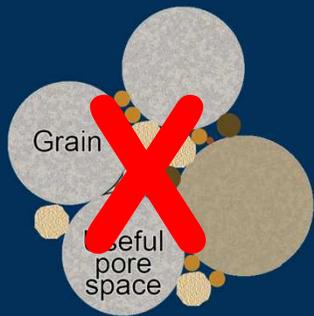
Narrow distribution



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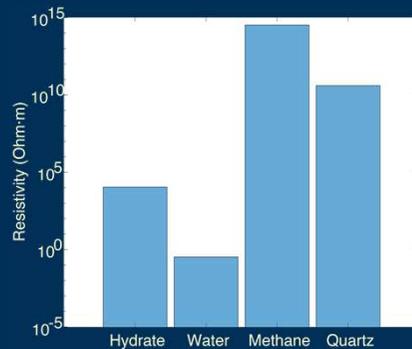
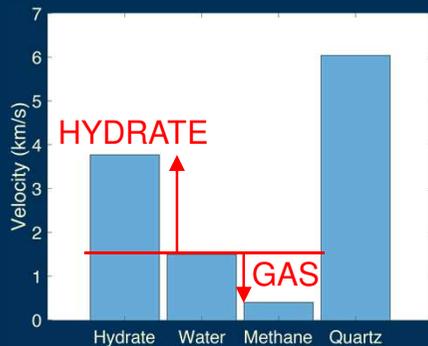
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Big Ideas: calculating the gas hydrate saturation



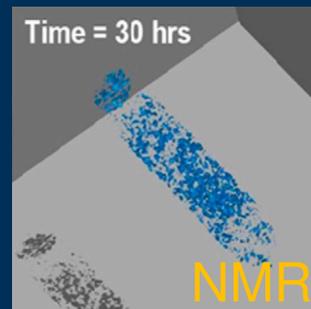
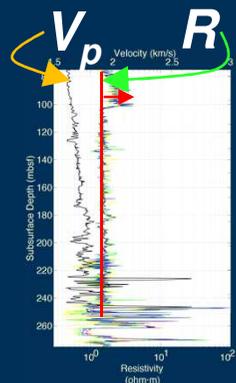
Broad distribution

Narrow distribution



Velocity

Resistivity



- Know your porosity! A few large pores are better than many small pores.

- Effective characterizations requires physical properties that can distinguish between sediment and the pore-space constituents: water, hydrate and/or gas.

- Complimentary measurements can account for drawbacks in any individual measurement and provide additional confidence in conclusions drawn from the combined results.