# Workshop Outline

- **Finding gas hydrate in nature**

- **Characterizing gas hydrate occurrences**

- **Can methane be extracted for profit?**

- **Gas hydrate formation & breakdown**
  (Geologic time)

Physical property measurements: answering the question "Is collecting methane (CH_4) in this location worth the cost?"

Physical property measurements: answering the question "Is collecting methane (CH_4) in this location worth the cost?"
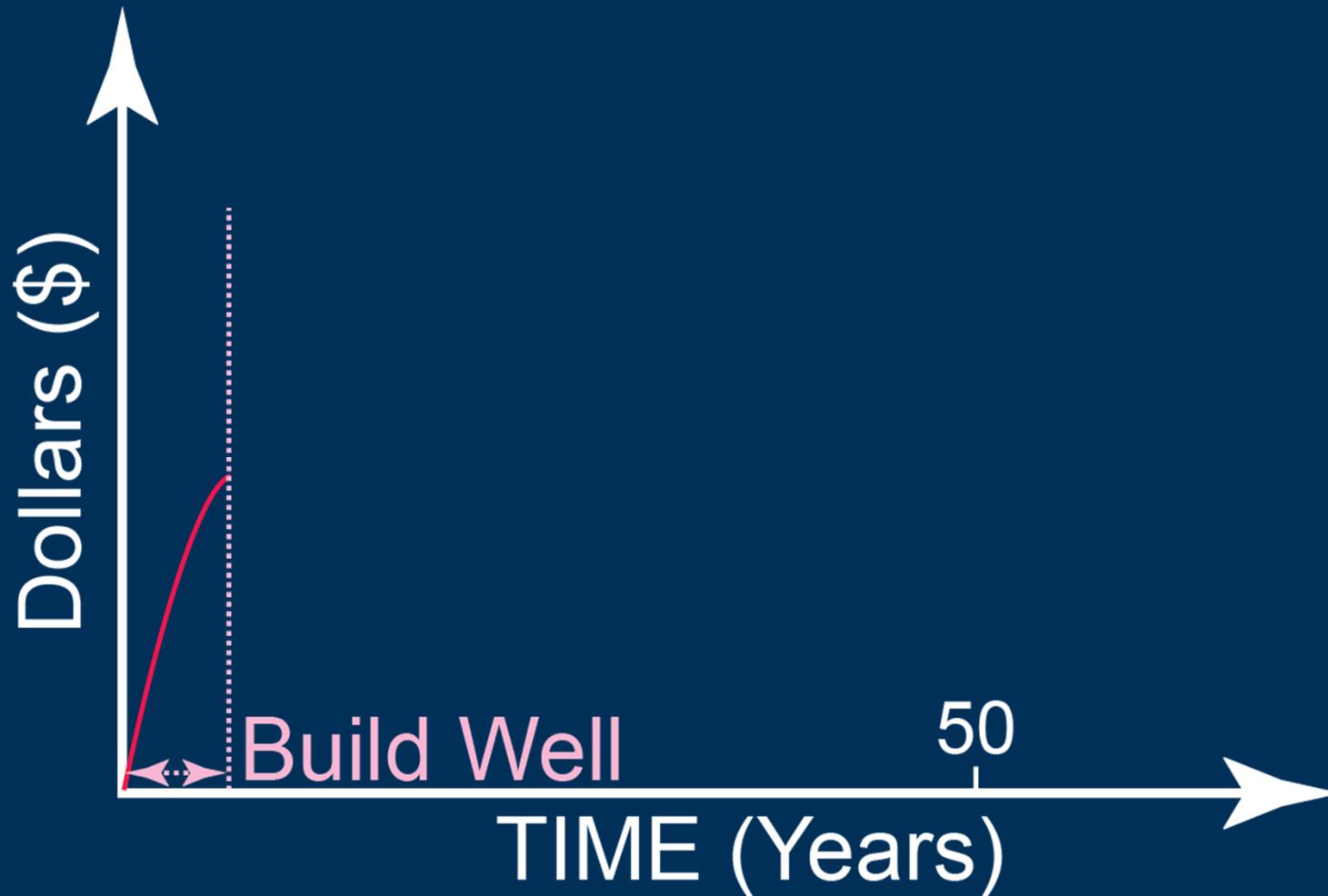
Physical property measurements: answering the question "Is collecting methane (CH$_4$) in this location worth the cost?"
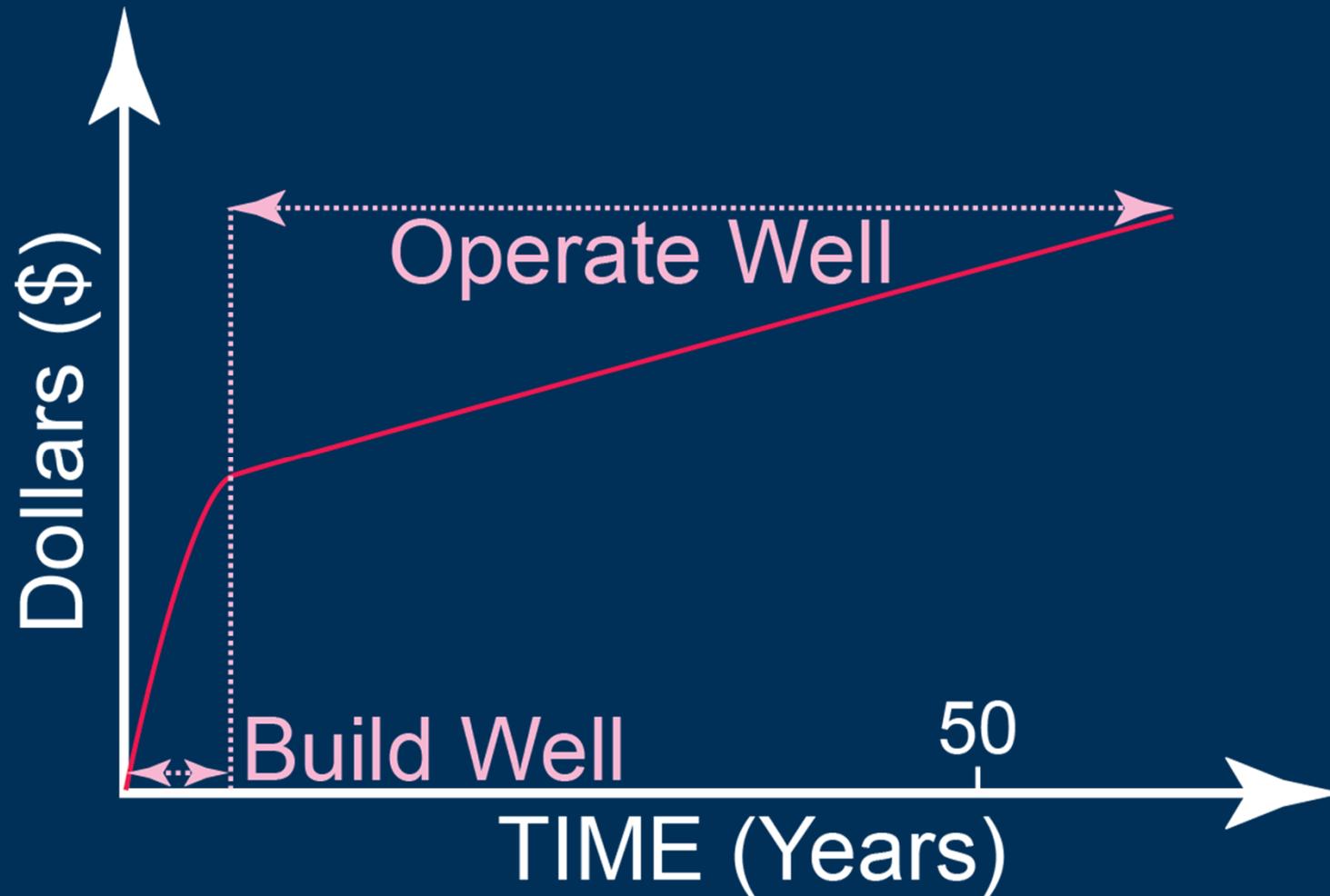
Physical property measurements: answering the question "Is collecting methane (CH_4) in this location worth the cost?"
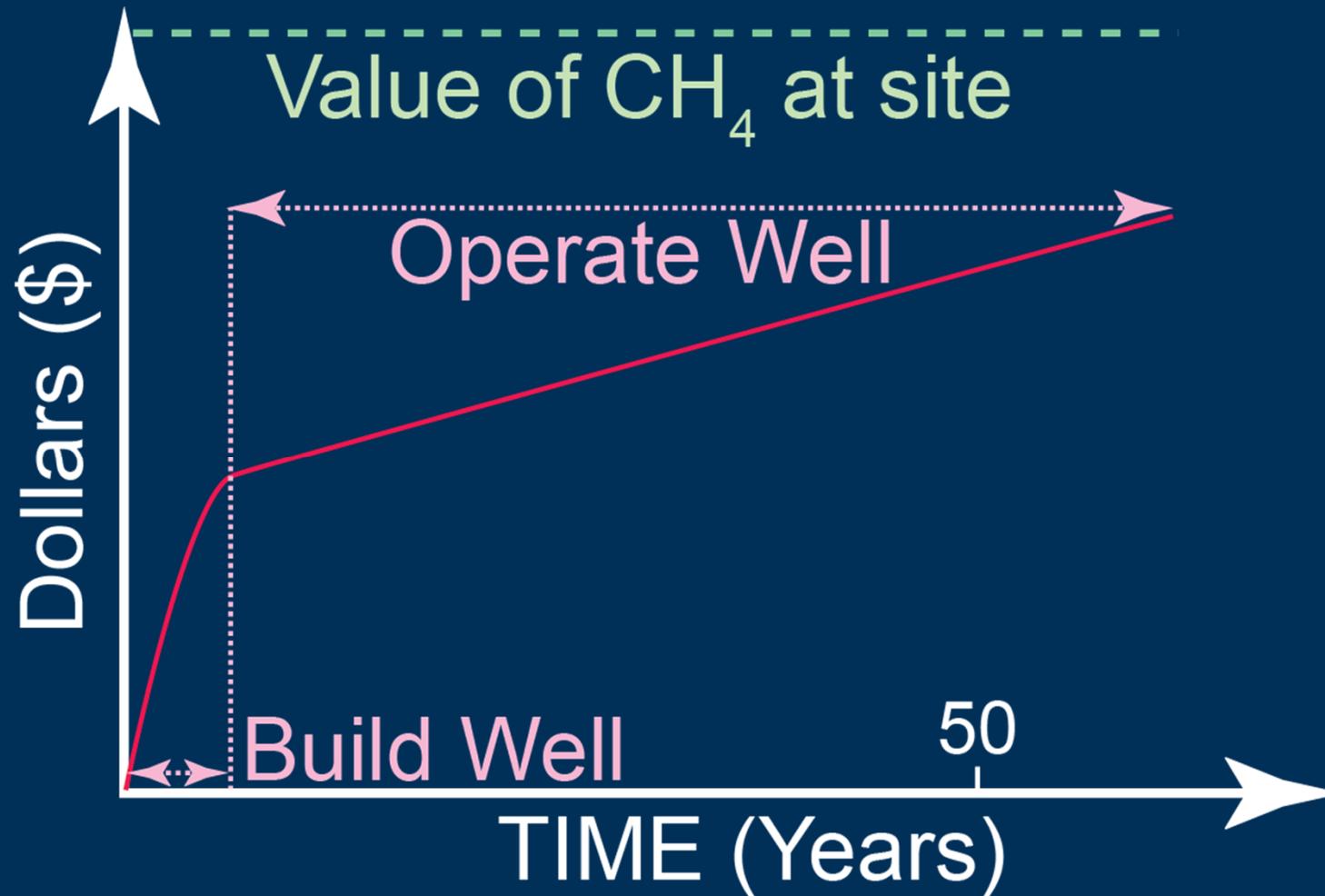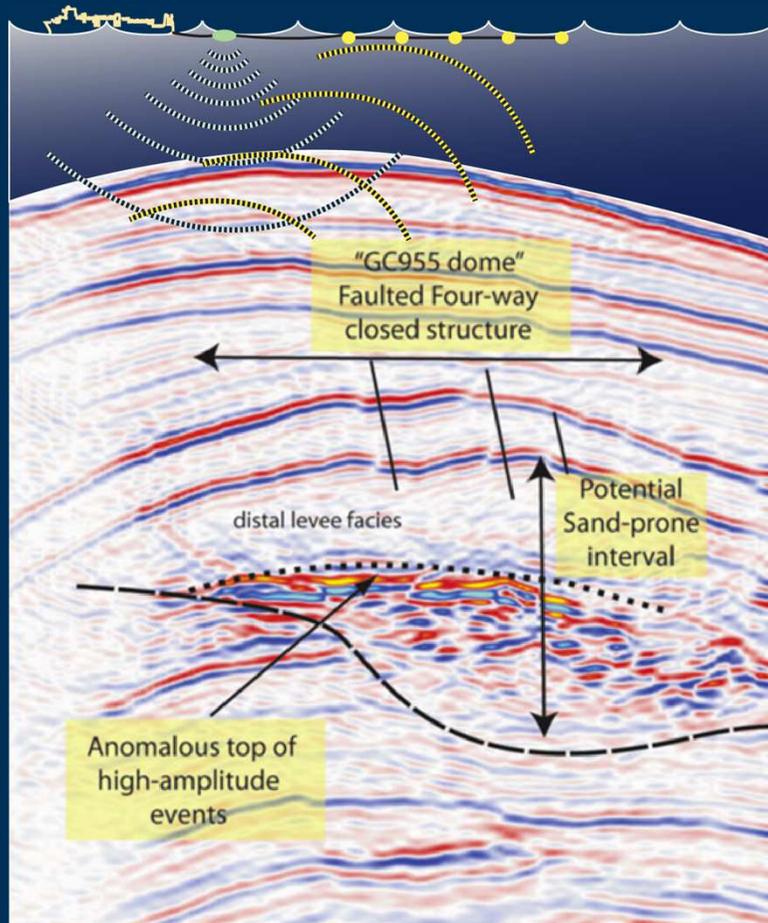
1) Is there enough methane?

Remote sensing data: answering the question "How much methane is there?"
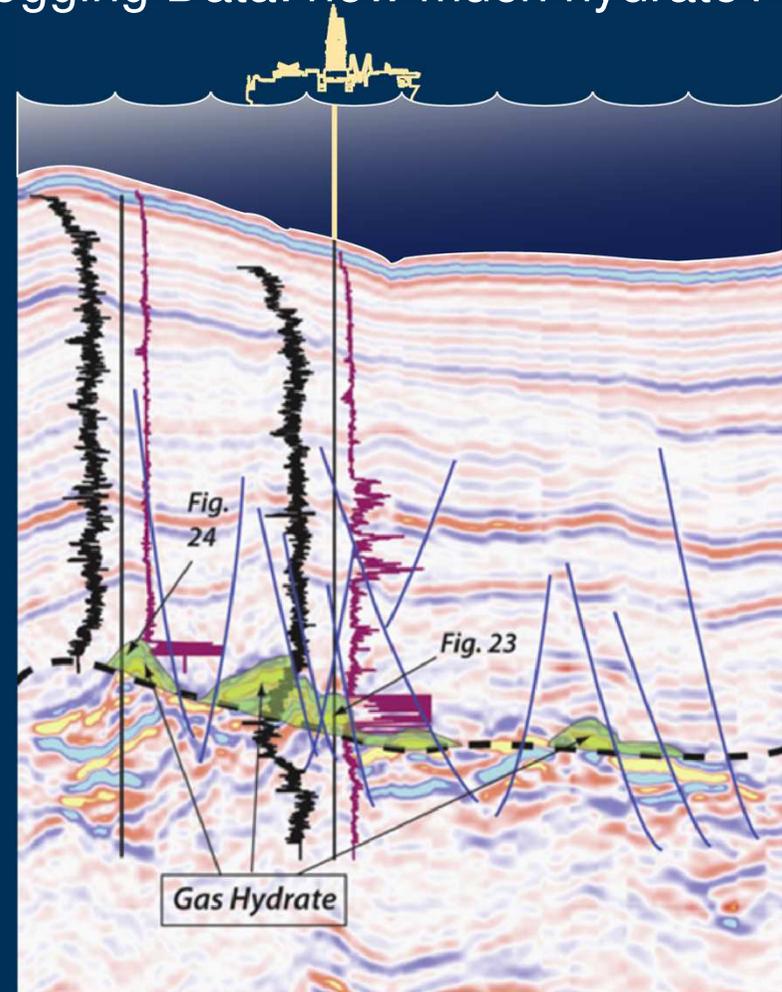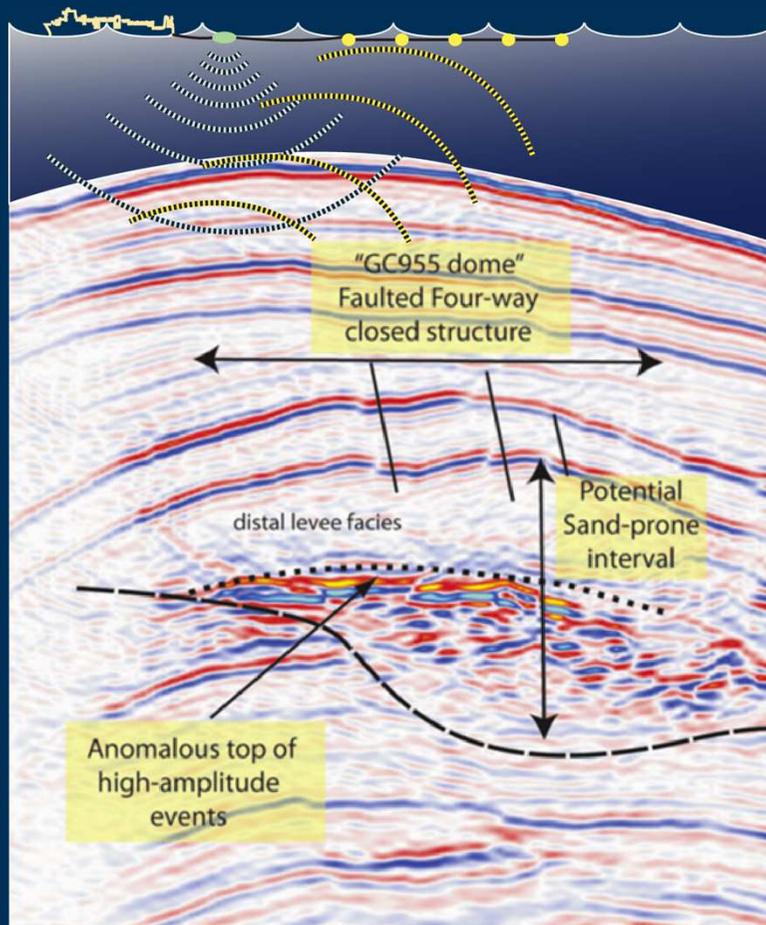
Seismic Data: where is the hydrate?

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

Remote sensing data: answering the question "How much methane is there?"

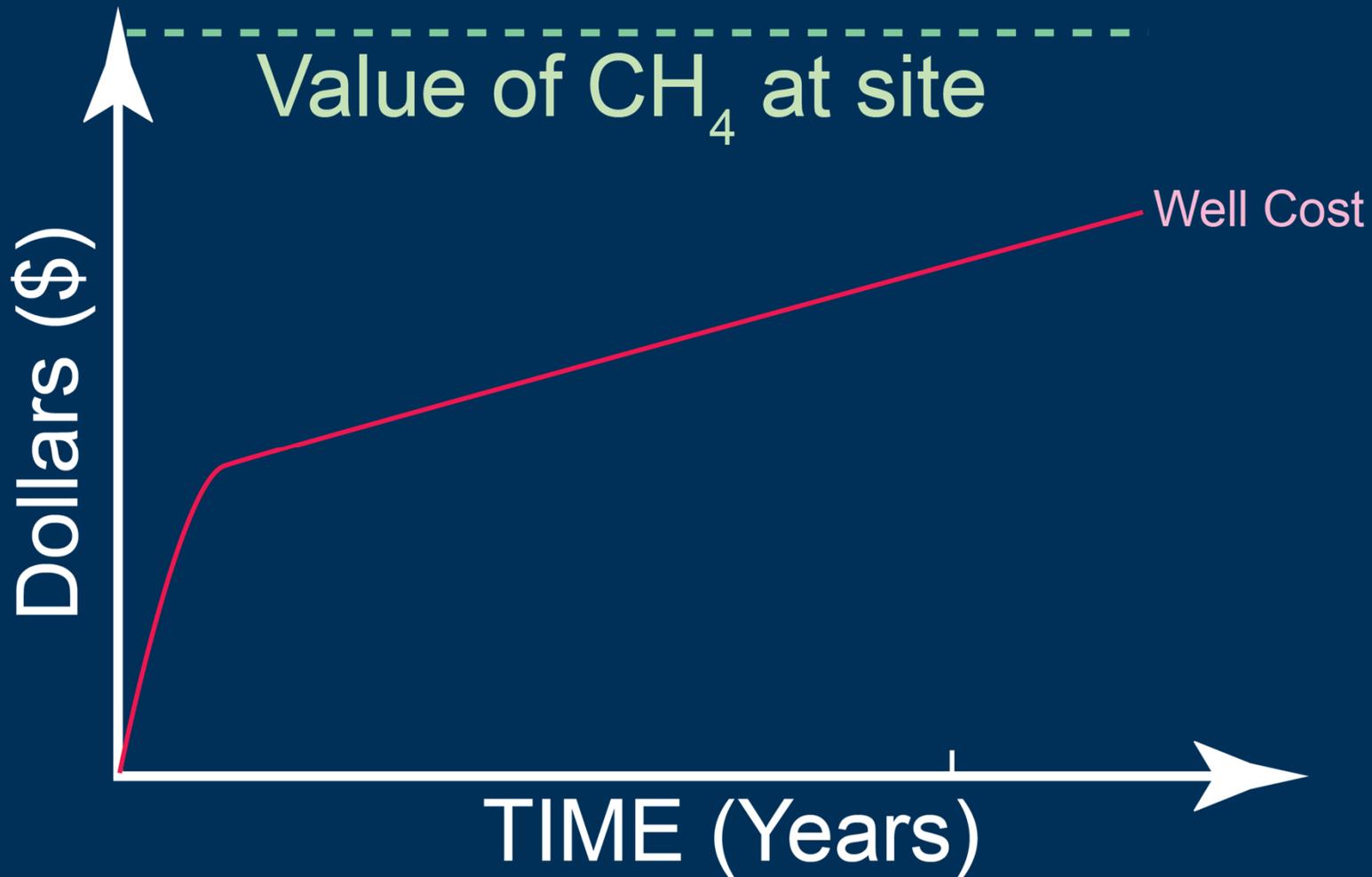## Seismic Data: where is the hydrate?

Logging Data: how much hydrate?

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

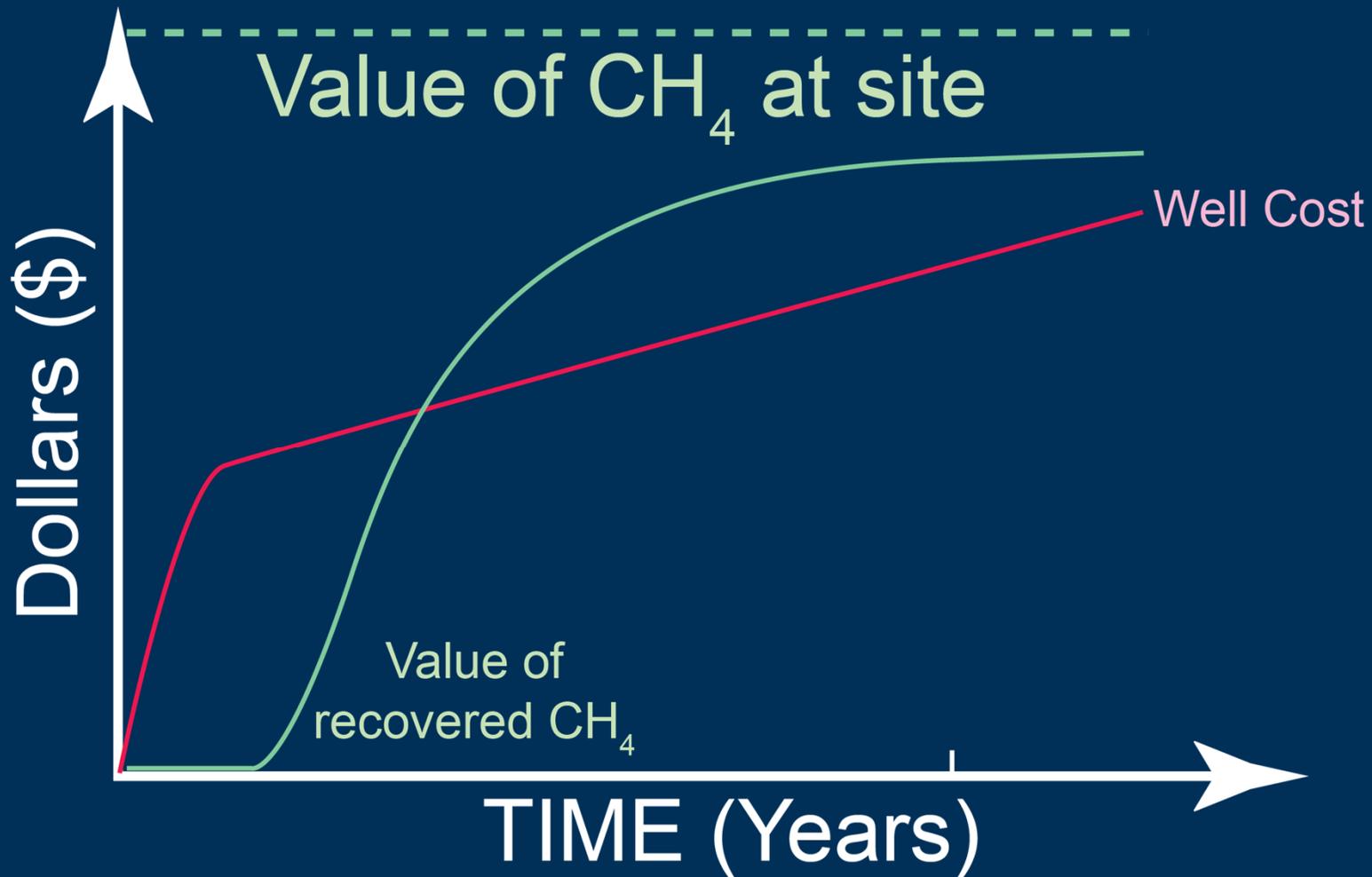Physical property measurements: answering the question "Is collecting methane (CH$_4$) in this location worth the cost?"

2) Can enough methane be collected?

Value of CH$_4$ at site

Dollars ($)

Well Cost

Value of recovered CH$_4$

TIME (Years)

Physical property measurements: answering the question "Is collecting methane (CH_4) in this location worth the cost?"

2) Can enough methane be collected?
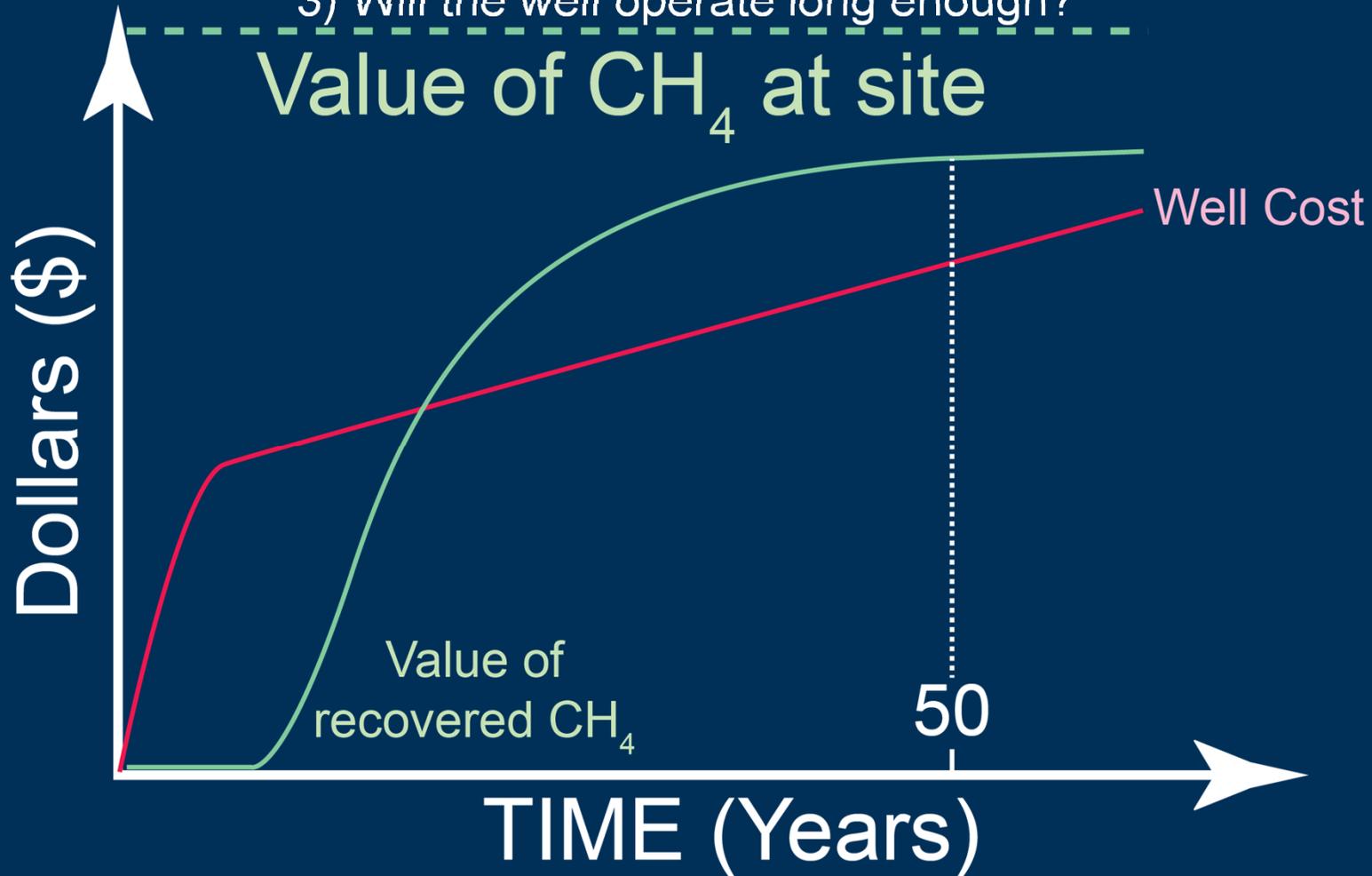
3) Will the well operate long enough?
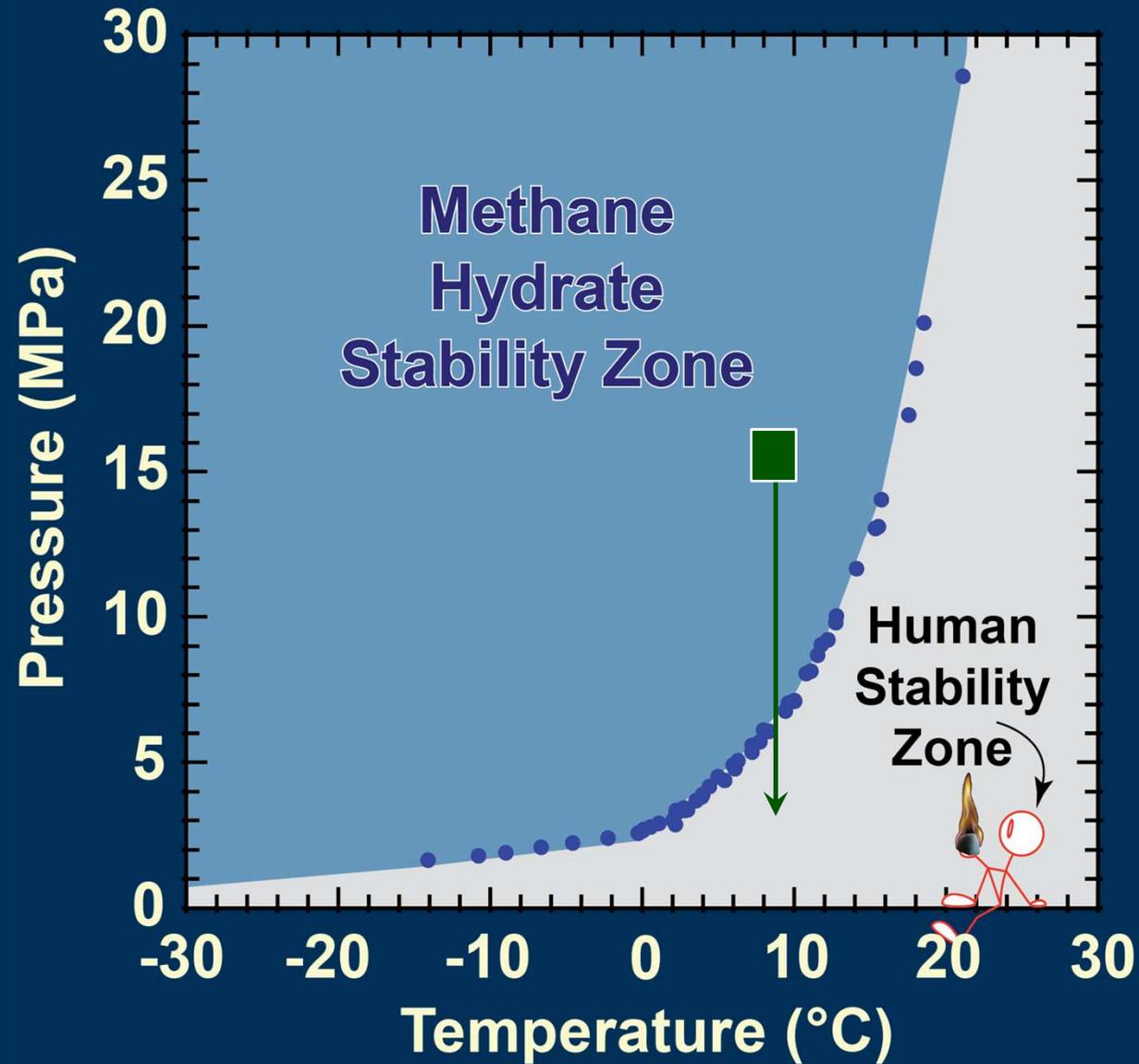
Value of CH_4 at site

Well Cost

Dollars ($)

Value of recovered CH_4

50

TIME (Years)

Extracting methane from gas hydrate: depressurization

Extracting methane from gas hydrate: depressurization

Seafloor

Hydrate-Rich Sediment

Extracting methane from gas hydrate: depressurization

Seafloor

Hydrate-Rich Sediment

Extracting methane from gas hydrate: depressurization

Seafloor

Hydrate-Rich Sediment
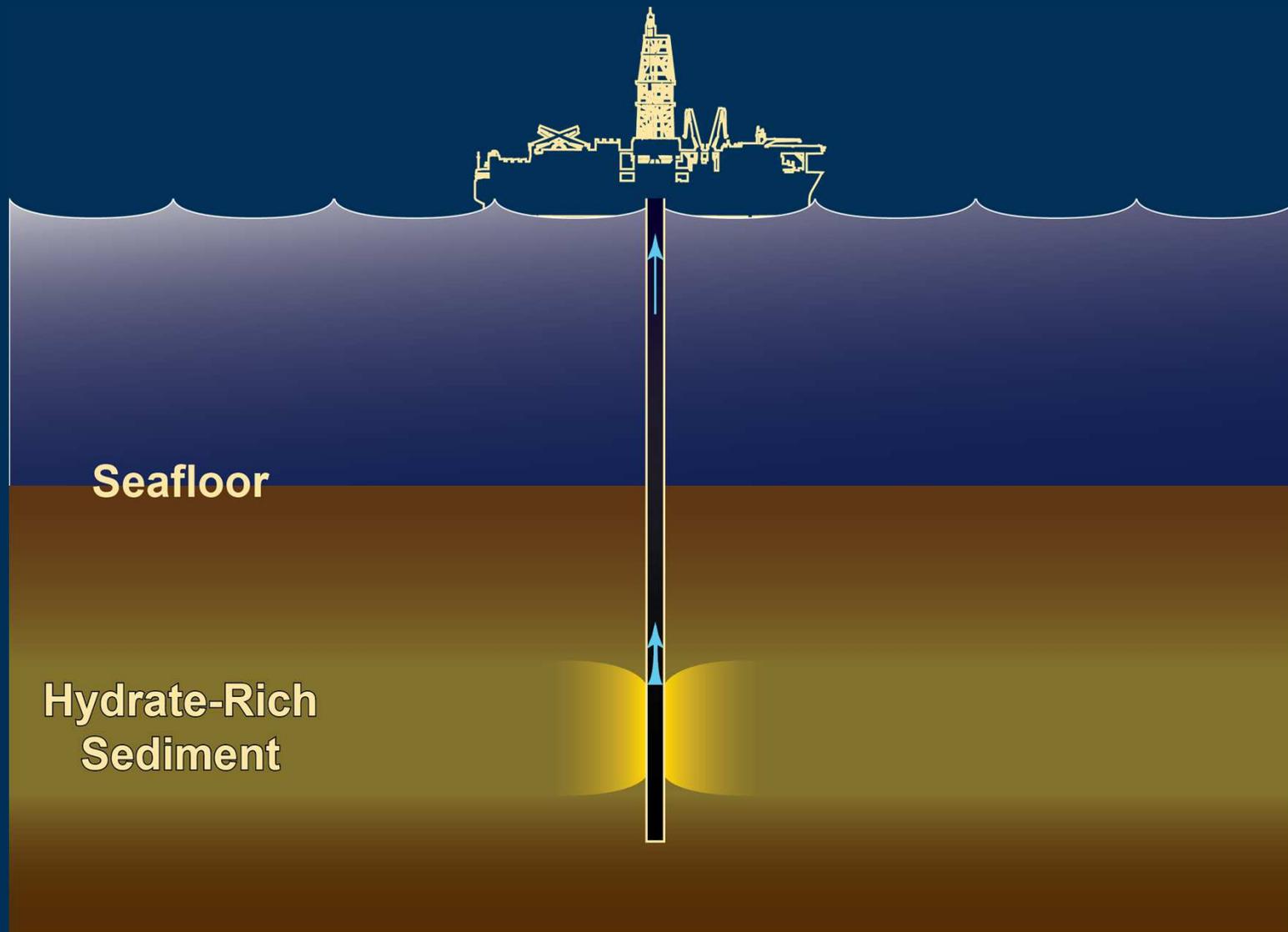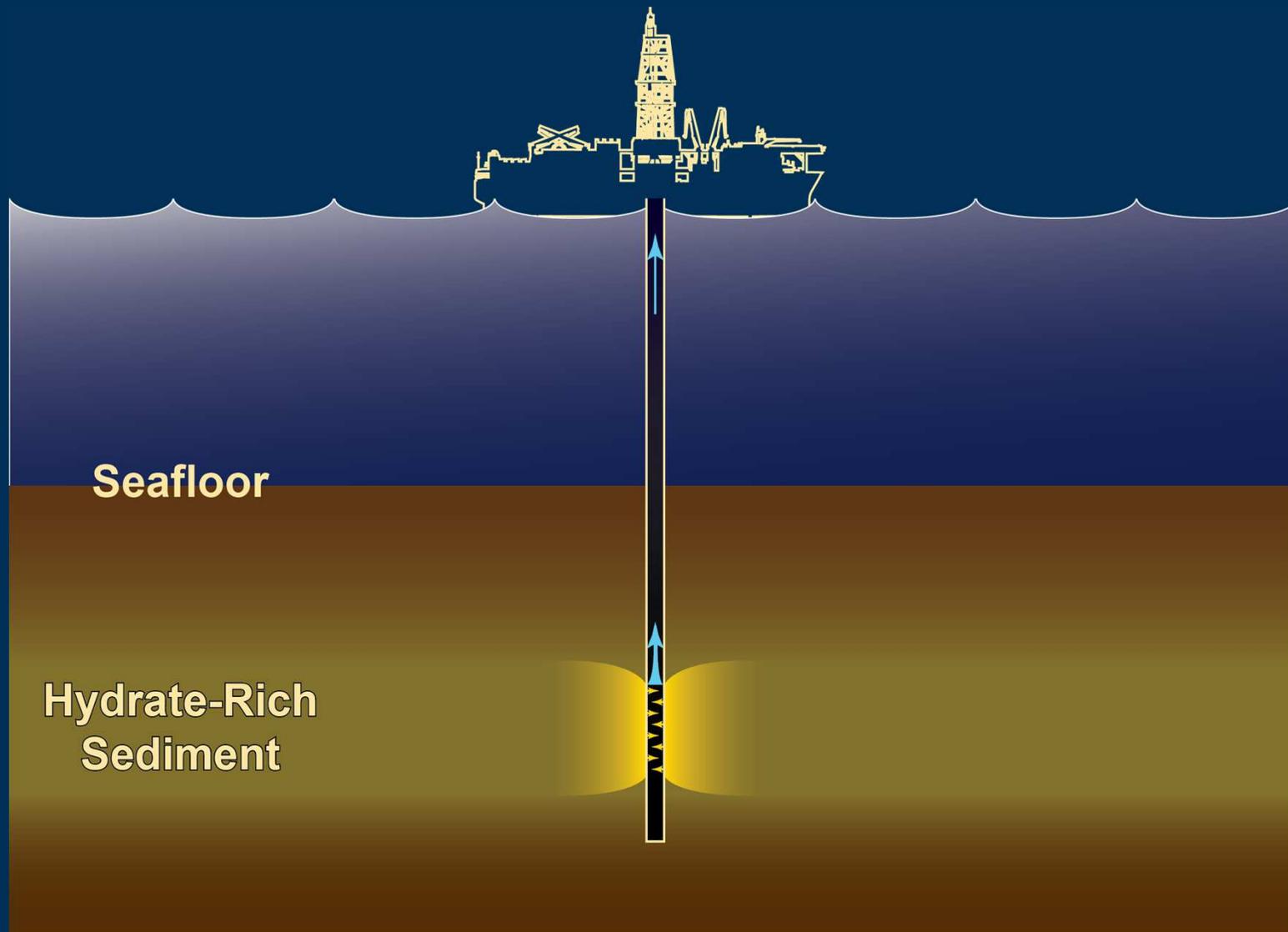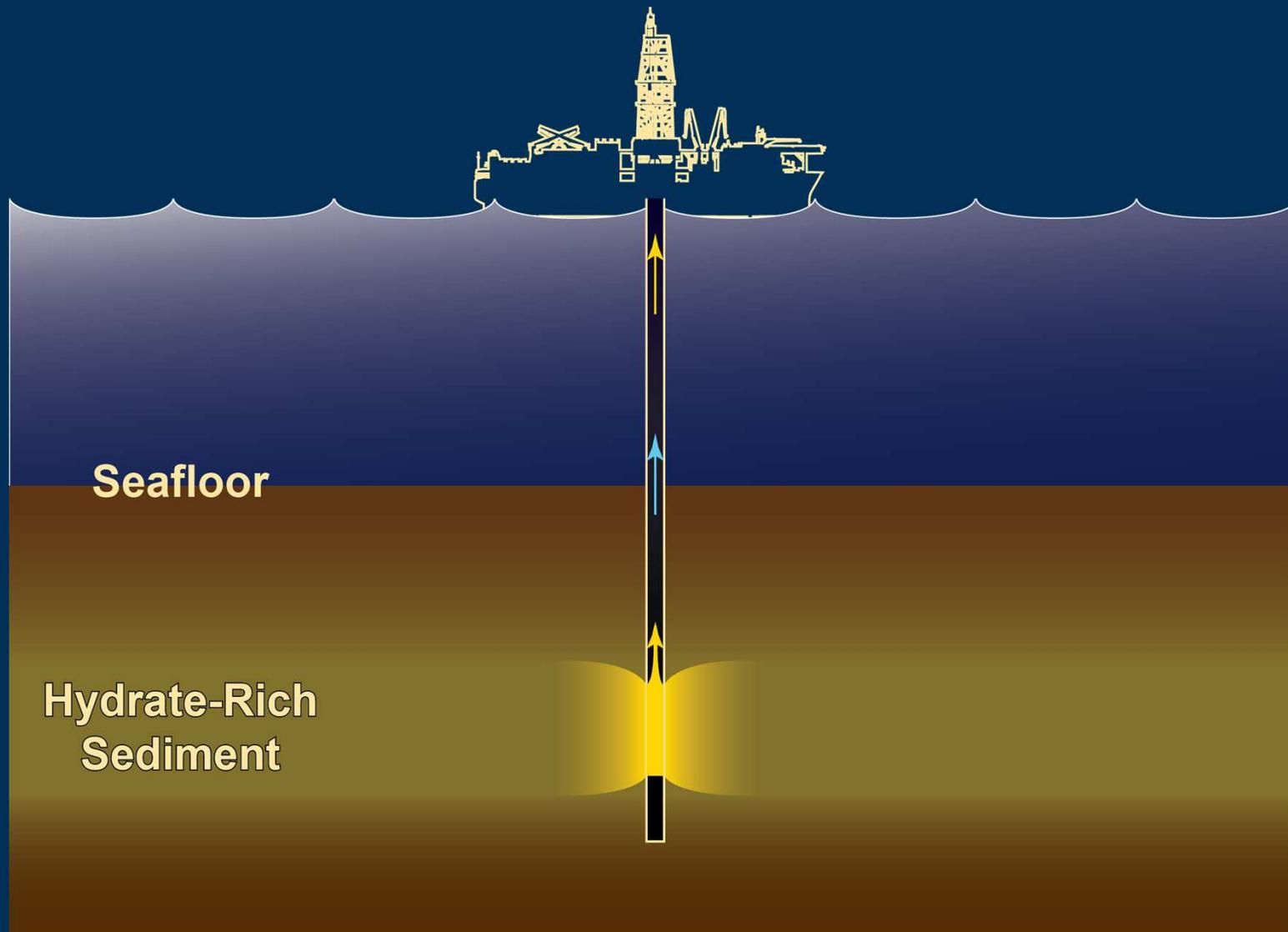
Permeability: a critical control on gas extraction rate

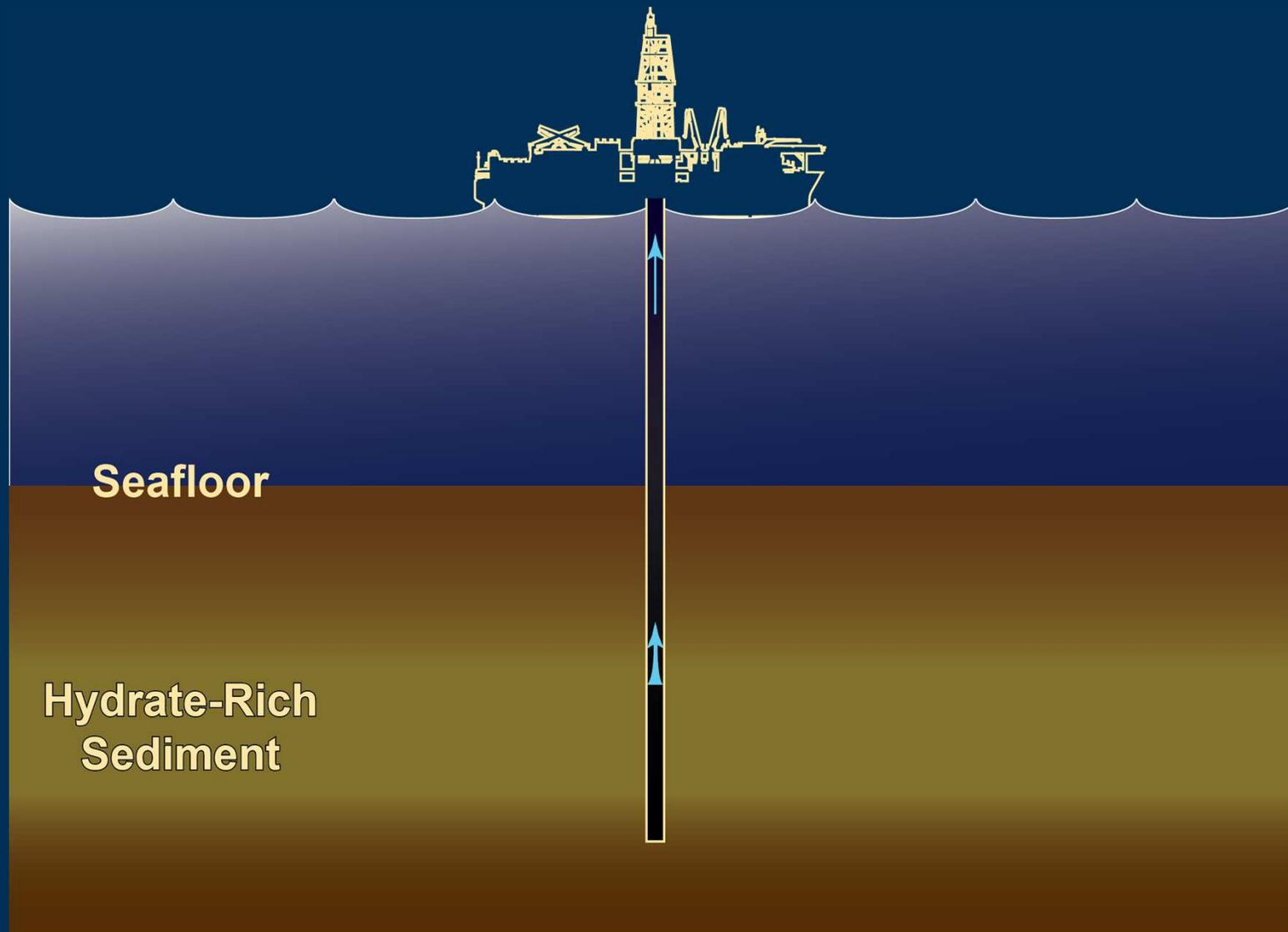# Permeability: a critical control on gas extraction rate
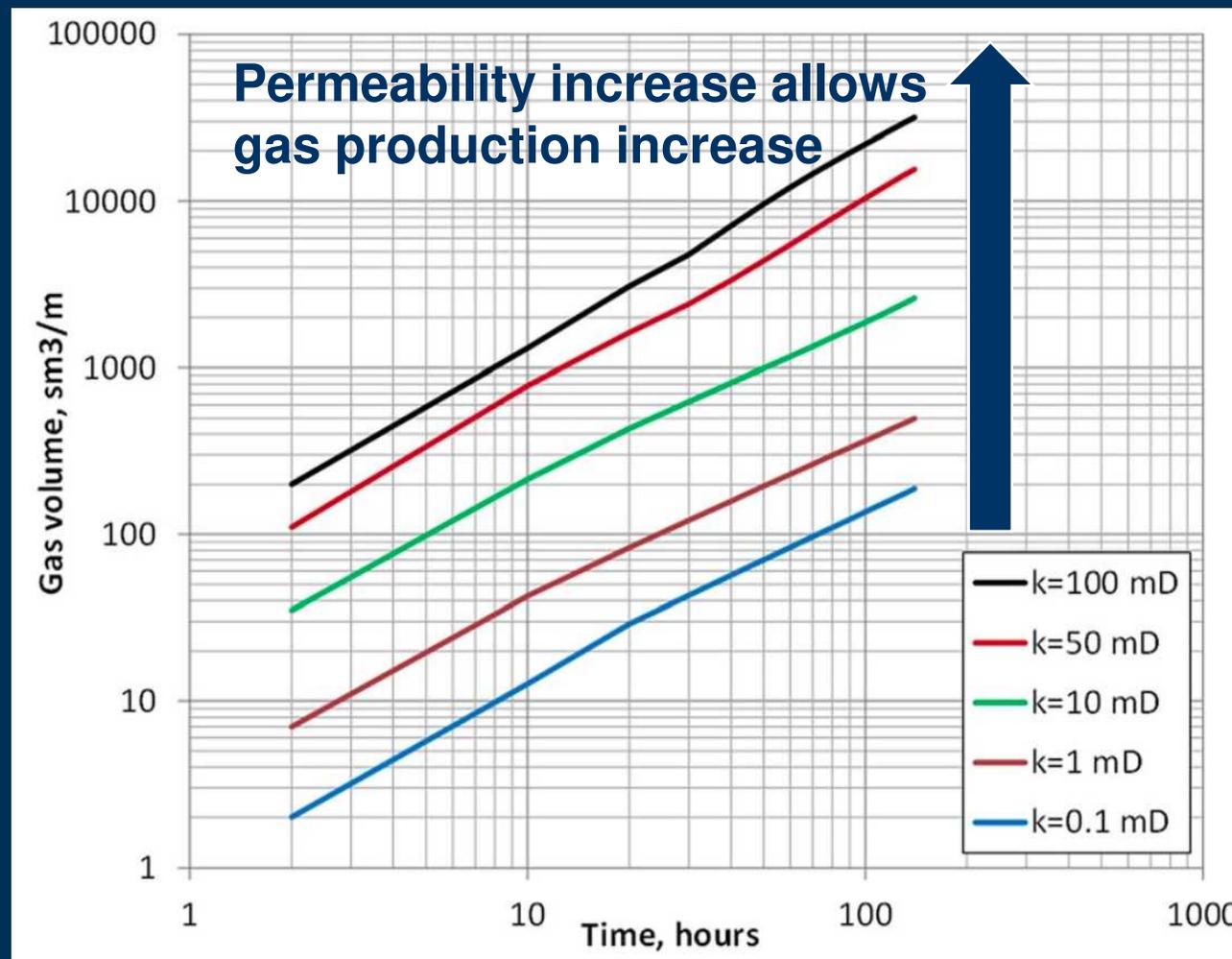
Yamamoto et al. (2017), Roy. Soc. Chemistry

Extracting methane from gas hydrate: depressurization
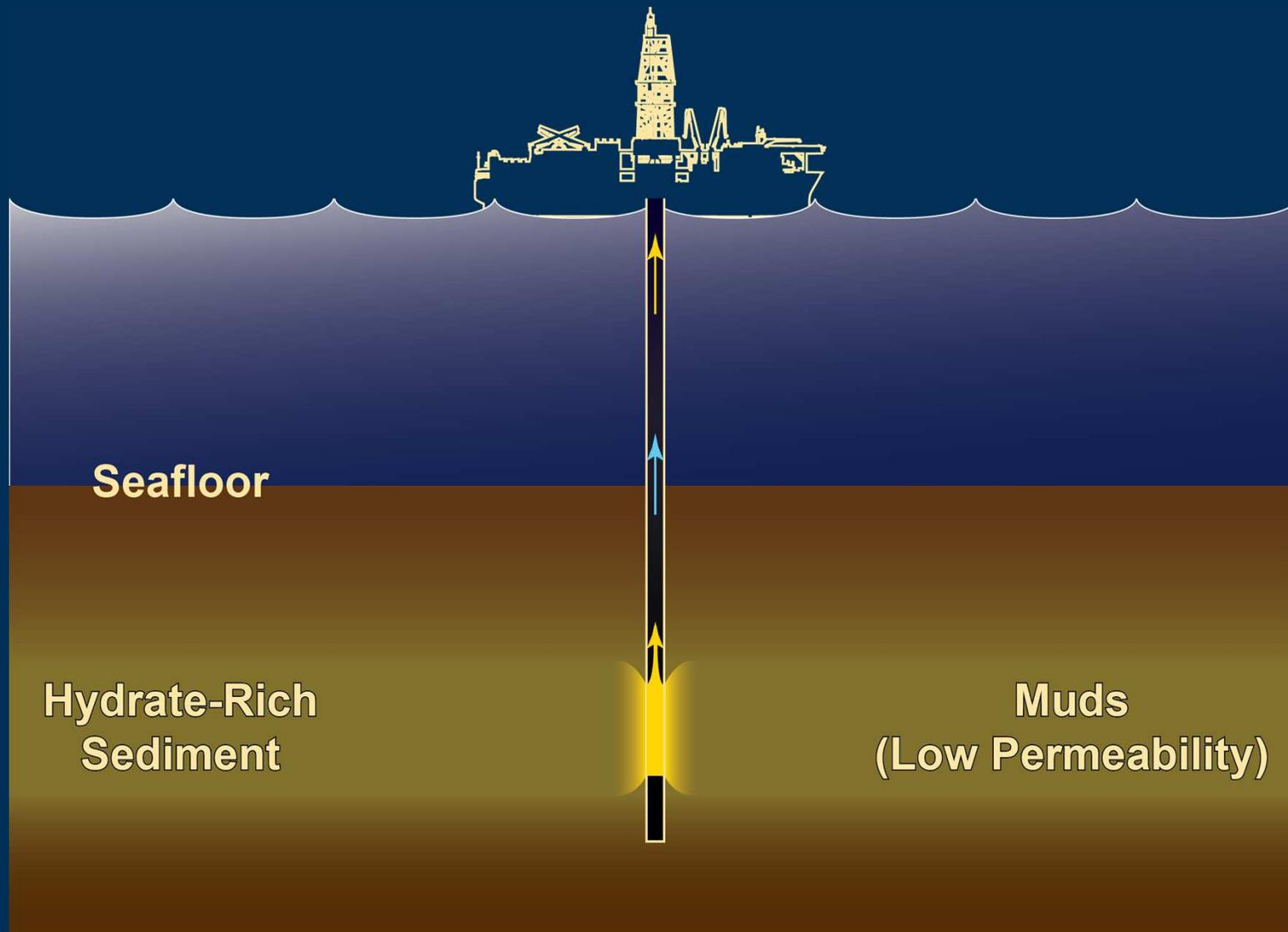
Extracting methane from gas hydrate: depressurization
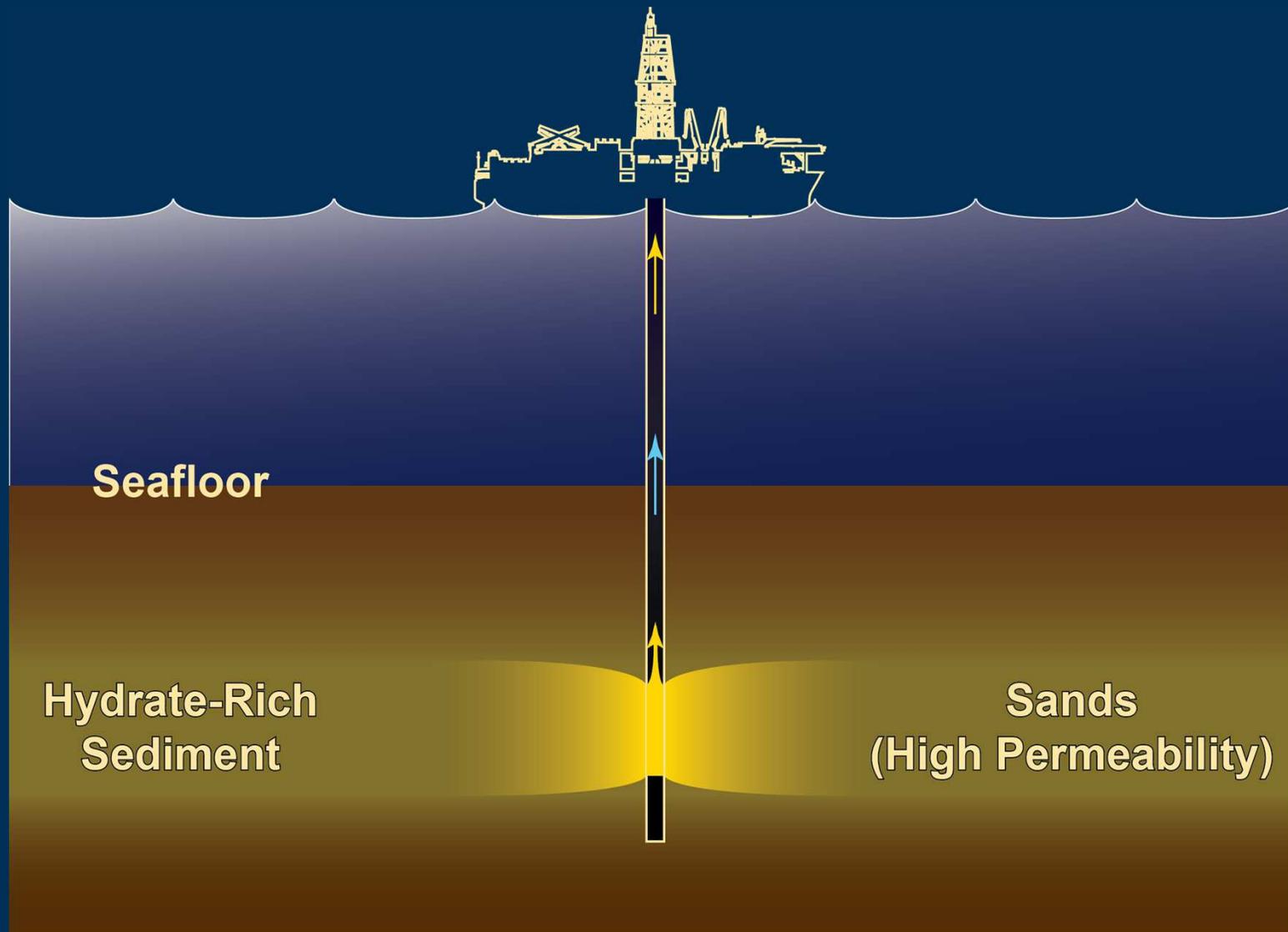
Glossary of permeability terms

Absolute permeabilities: measured in Darcies or milliDarcies

1 Darcy (D) = 0.9869x10^{-12} m^2 = 1000 milliDarcies (mD)

- $k_{intrinsic}$ (Intrinsic or absolute permeability): describes water flow through hydrate-*free* sediment.

- k_{eff} (Effective permeability): describes water flow through hydrate-*bearing* sediment.

Glossary of permeability terms

Absolute permeabilities: measured in Darcies or milliDarcies
1 Darcy (D) = 0.9869×10^{-12} m^2 = 1000 milliDarcies (mD)

- k_{vert} (Vertical permeability): describes water flow in the vertical direction, generally perpendicular to the sedimentary layers.

- k_{horiz} (Horizontal permeability): describes water flow in the horizontal direction, generally within a sedimentary layer.

Farrell et al. (2017), J. Structural Geology
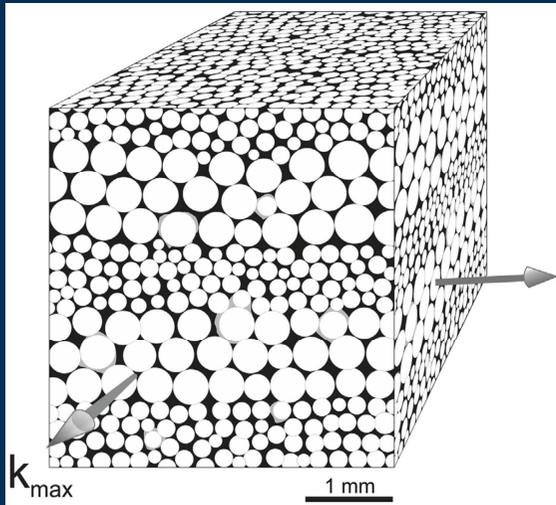
Glossary of permeability terms

Absolute permeabilities: measured in Darcies or milliDarcies
   1 Darcy (D) = 0.9869×10^{-12} m^2 = 1000 milliDarcies (mD)

- k_{vert} (Vertical permeability): describes water flow in the vertical direction, generally perpendicular to the sedimentary layers.

- k_{horiz} (Horizontal permeability): describes water flow in the horizontal direction, generally within a sedimentary layer.

$k_{horiz} / k_{vert} = 2$ to 20

Weeks et al. (1969), Water Resources Res.

Glossary of permeability terms

Absolute permeabilities: measured in Darcies or milliDarcies
1 Darcy (D) = 0.9869×10^{-12} m^2 = 1000 milliDarcies (mD)
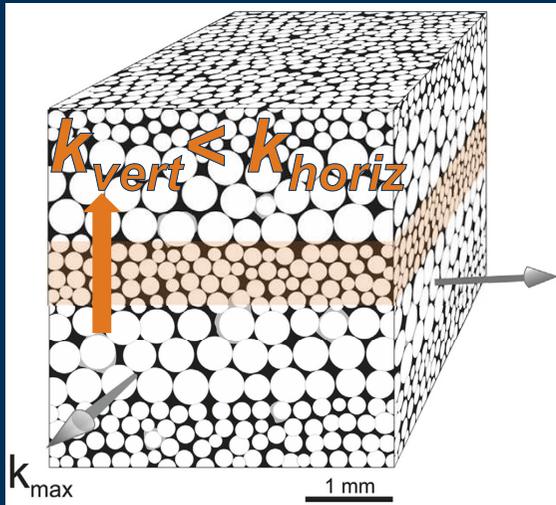
- k_{vert} (Vertical permeability): describes water flow in the vertical direction, generally perpendicular to the sedimentary layers.

- k_{horiz} (Horizontal permeability): describes water flow in the horizontal direction, generally within a sedimentary layer.
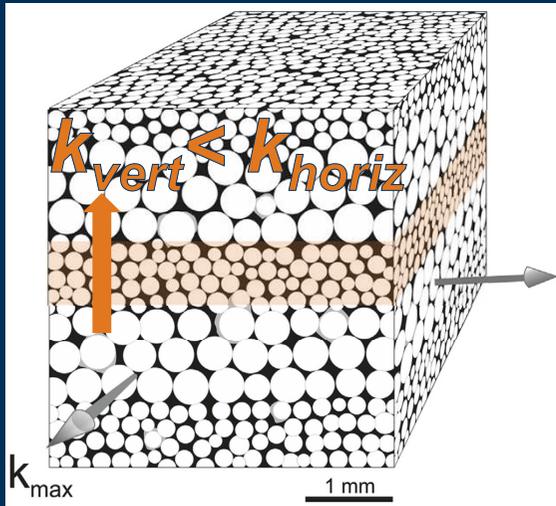

k_{horiz} / k_{vert} = 2 to 20

Has often assumed to be ~10 in hydrate modeling

Within a single clean sand layer,
k_{horiz} / k_{vert} = 1 to 5 may be more appropriate

Mitchell and Soga (2005), Fundamentals of soil behavior; Chapuis et al. (1989), CGJ

Glossary of permeability terms

Relative permeabilities: unitless ratios of a measured permeability to the intrinsic permeability, $k_{intrinsic}$

- k_{rh} (relative hydrate permeability, also known as the permeability reduction factor): ratio of the permeability of water through gas-free, hydrate-bearing sediment, k_{eff}, to the intrinsic permeability for water, $k_{intrinsic}$:

$$k_{rh} = k_{eff} / k_{intrinsic}.$$

- k_{rw} (relative permeability for water): ratio of the measured water permeability through sediment in the presence of gas, k_{water}, to the intrinsic permeability for water, $k_{intrinsic}$:

$$k_{rw} = k_{water} / k_{intrinsic}.$$
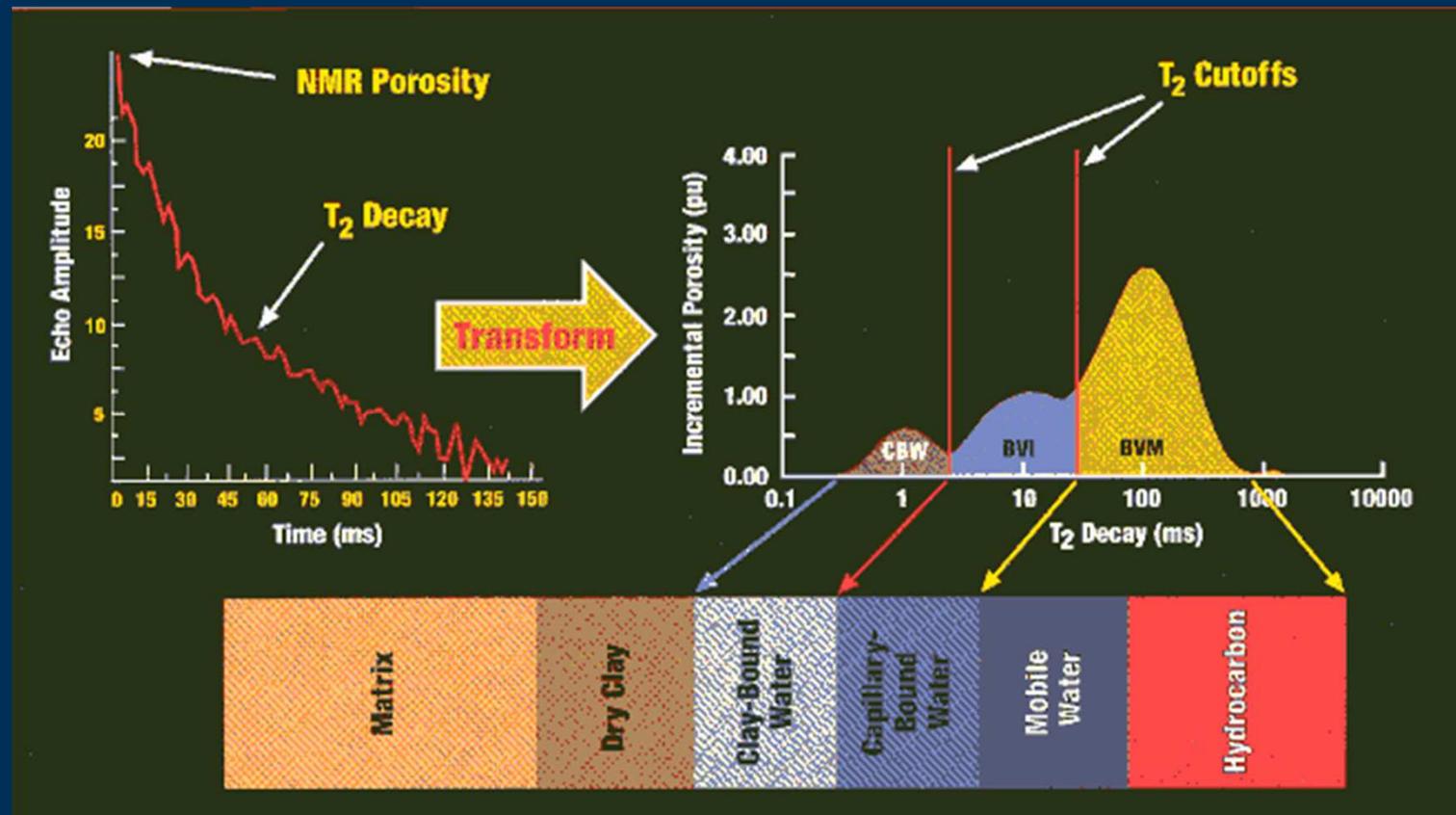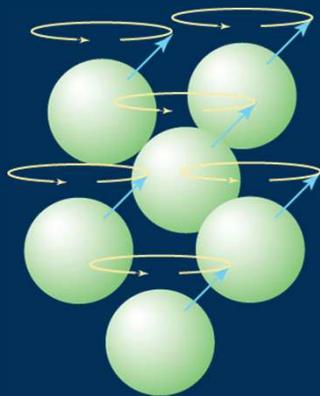
- k_{rg} (relative permeability for gas): ratio of the measured gas permeability through sediment in the presence of water, k_{gas}, to the intrinsic permeability for water, $k_{intrinsic}$:
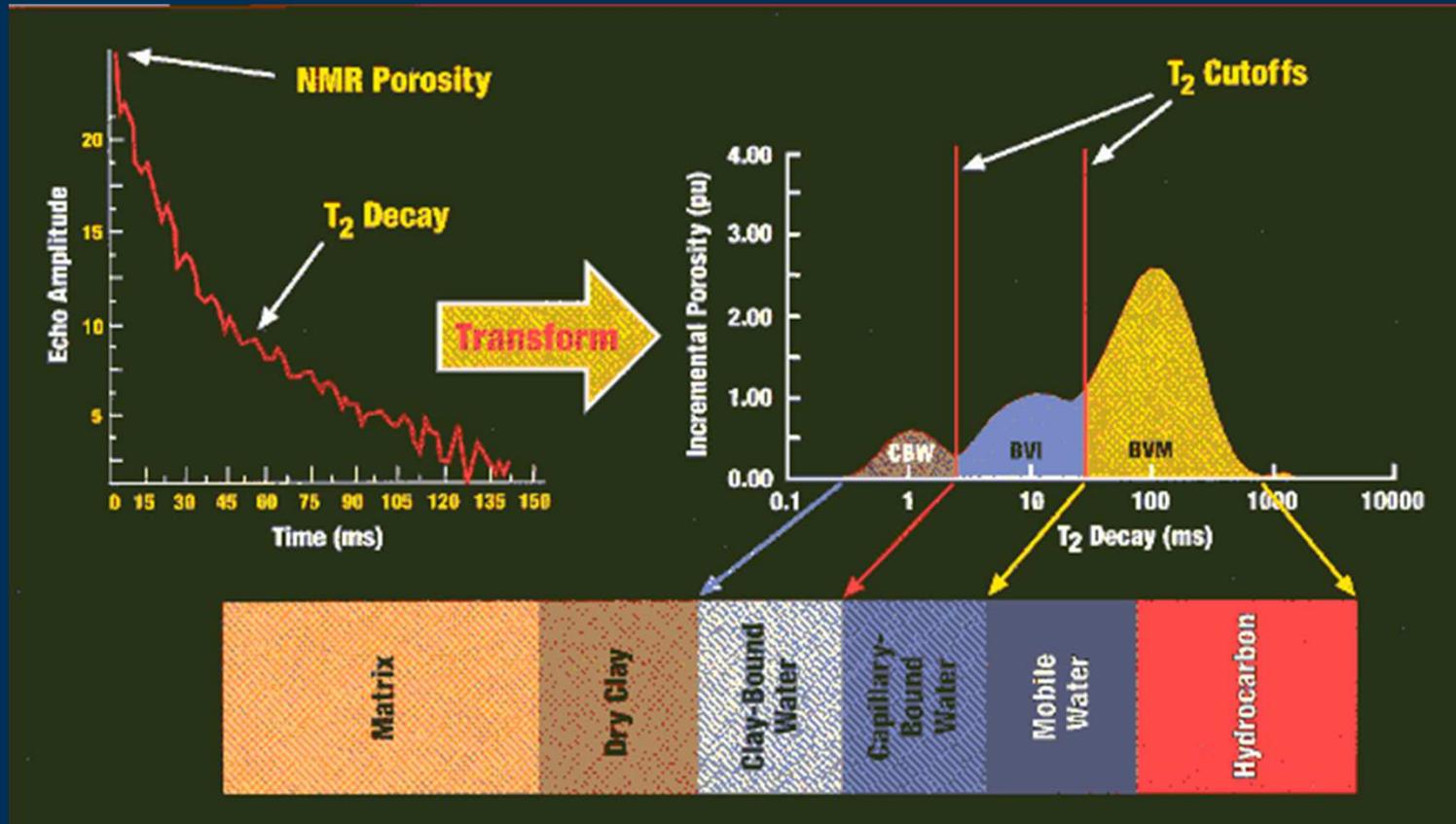
$$k_{rg} = k_{gas} / k_{intrinsic}.$$

Permeability: a critical control on gas extraction rate

Downhole measurement options for permeability in sands

- Nuclear Magnetic Resonance (SDR or Timur-Coates)

T_2 distribution has pore size information

Characterizing the T_2 distribution by the logarithmic mean, T_{2LM}:

$$T_{2LM} = 10^{\left(\frac{1}{\phi_{NMR}} \sum_i A(T_{2i}) \log_{10} T_{2i}\right)}$$

Kleinberg et al. (2003), JGR

NMR permeability: SDR
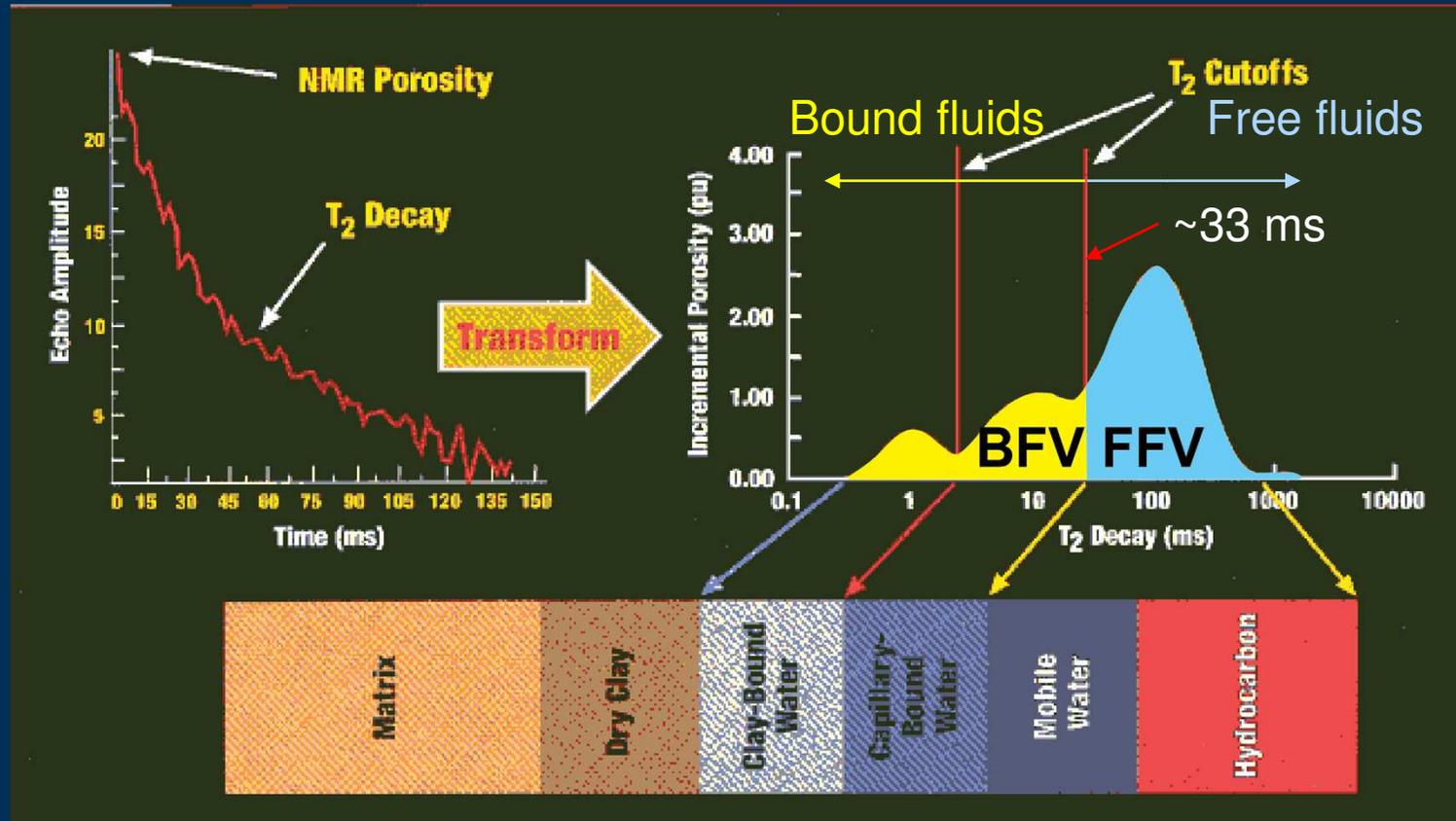
Schlumberger Doll Research (SDR) permeability, k_{SDR}:

$$k_{SDR} = C \cdot T_{2LM}^2 \cdot \phi_{NMR}^4$$

k_{SDR} [mD]; T_{2LM} [ms]; ϕ_{NMR} []

C = empirical constant $\approx$ 4 [mD/(ms)^2]

Kleinberg et al. (2003), JGR

NMR permeability: Timur Coates:

Fujii et al. (2015), Marine and Petroleum Geology
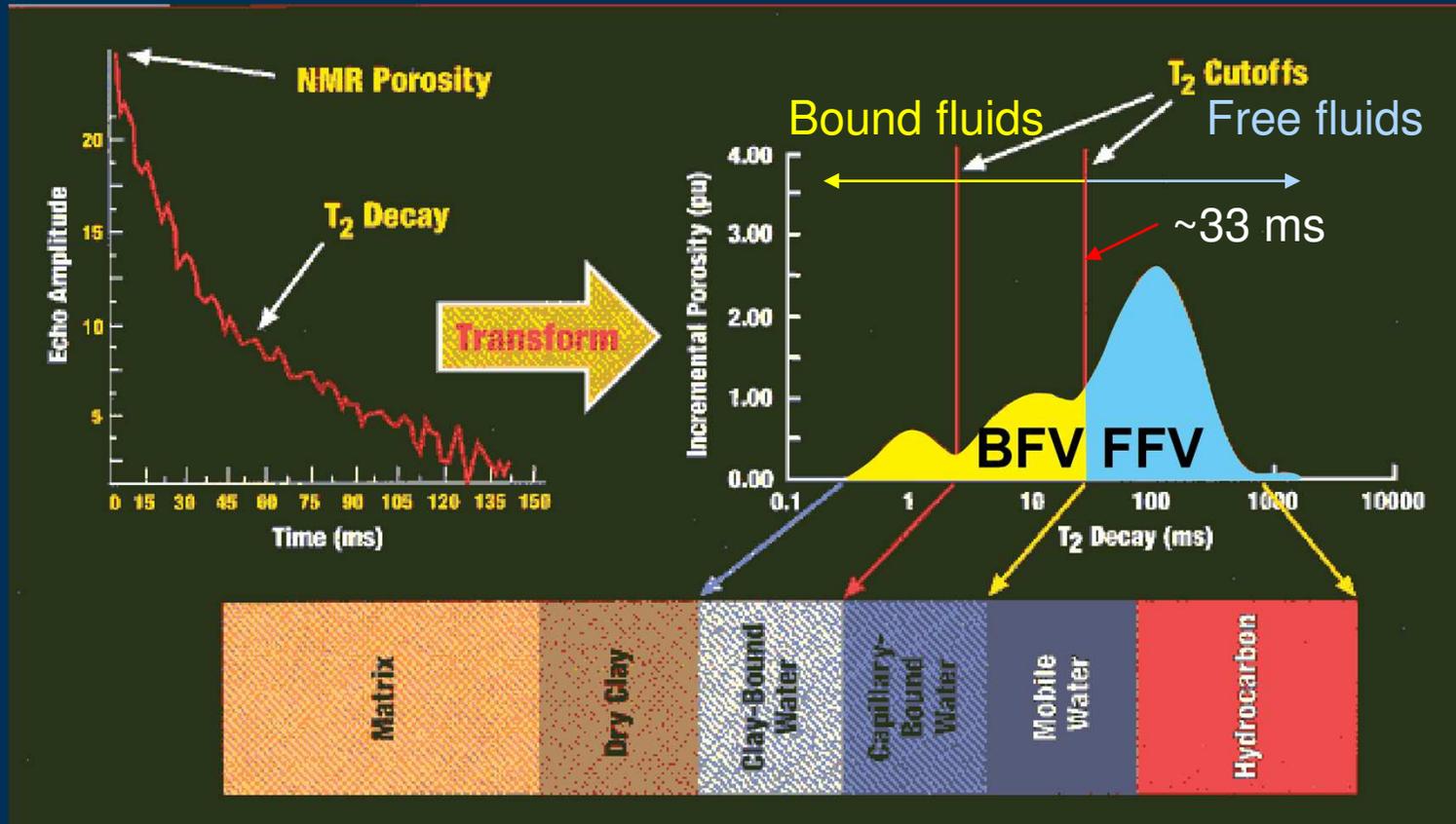
NMR permeability: Timur Coates:

Characterizing the T_2 distribution by bound and free fluids:

$$k_{T-C} = a \cdot \phi_{NMR}^4 \cdot \left(\frac{FFV}{BFV}\right) ; \quad a = 10{,}000 \, mD ; \quad FFV + BFV = \phi_{NMR}$$

Fujii et al. (2015), Marine and Petroleum Geology
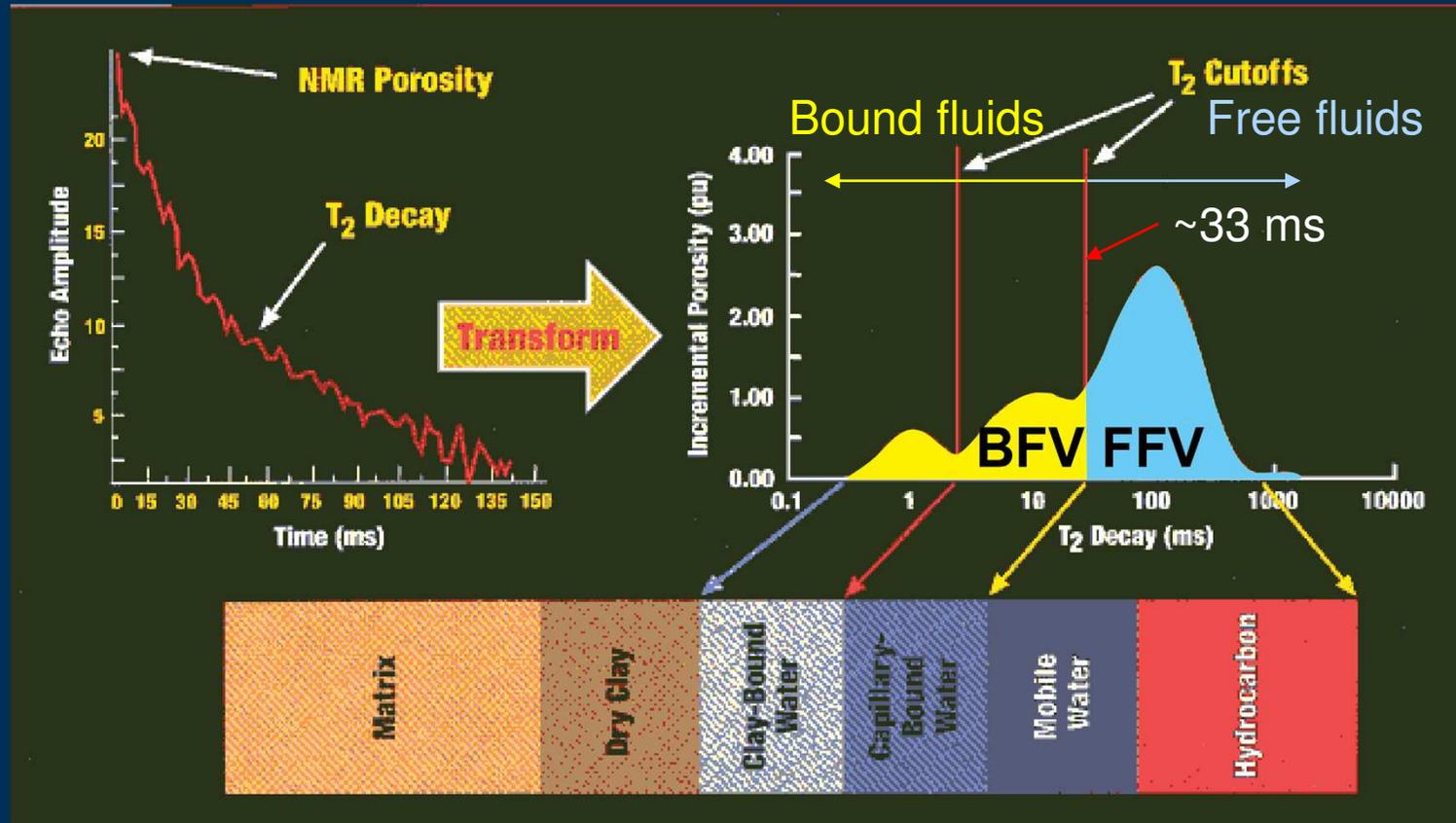
NMR permeability: Timur Coates:

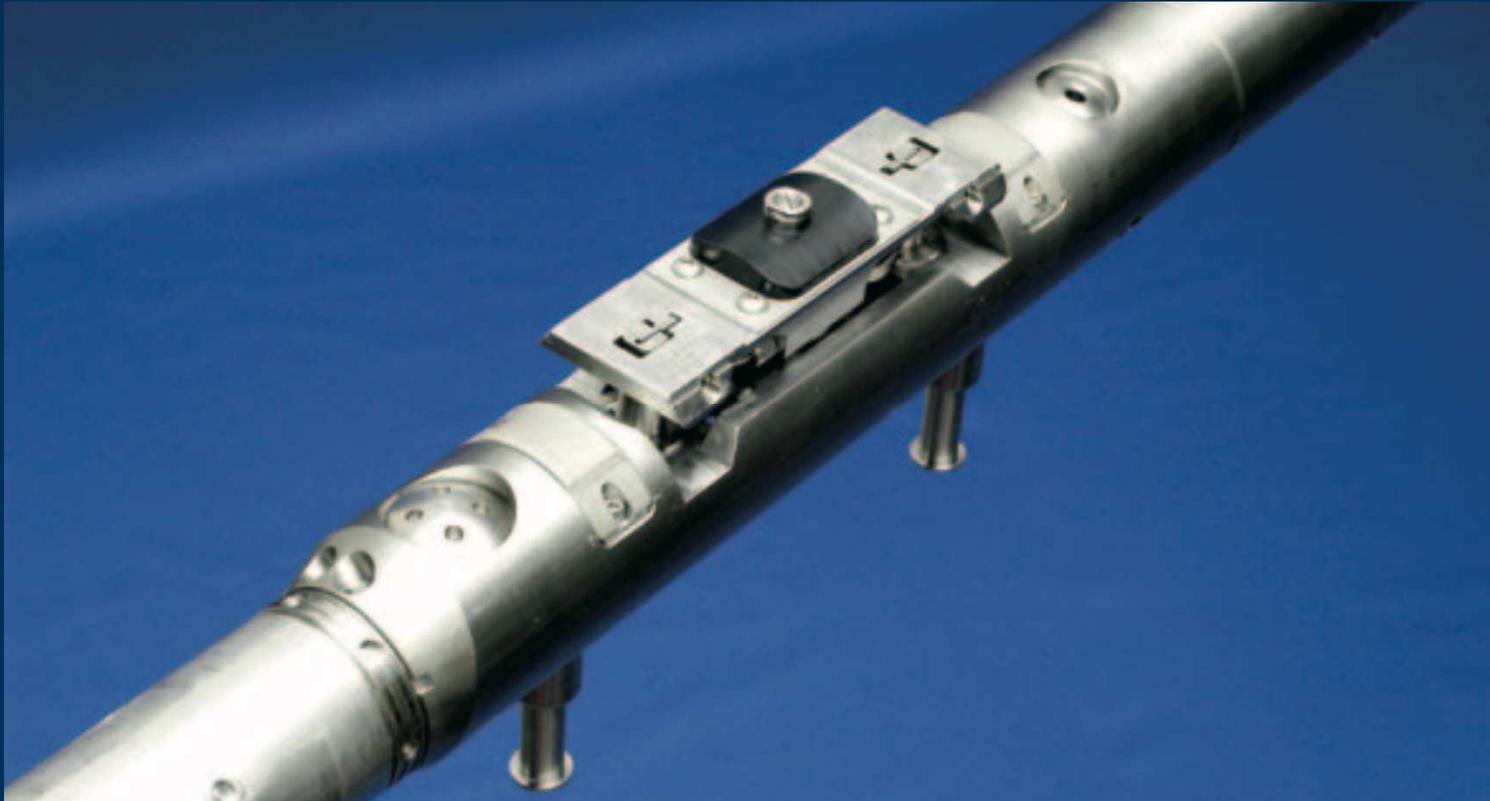Characterizing the T_2 distribution by bound and free fluids:

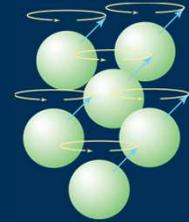$$k_{T-C} = a \cdot \phi_{NMR}^4 \cdot \left(\frac{FFV}{BFV}\right); \quad a = 10{,}000\,mD; \quad FFV + BFV = \phi_{NMR}$$

See Daigle and Dugan (2009), JMPG
for NMR in fine-grained sediment

Permeability: a critical control on gas extraction rate

Downhole measurement options for permeability

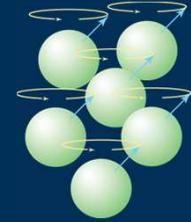- Nuclear Magnetic Resonance (SDR or Timur-Coates)

- Pressure Express (XPT)

Schlumberger (2006), PressureXpress

Permeability: a critical control on gas extraction rate

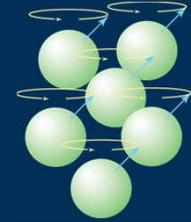## Downhole measurement options for permeability

- Nuclear Magnetic Resonance (SDR or Timur-Coates)

- Pressure Express (XPT)

- Modular Formation Dynamics Tester (MDT)

Schlumberger (2002), MDT Modular Formation Dynamics Tester

Permeability: a critical control on gas extraction rate

Downhole measurement options for permeability

- Nuclear Magnetic Resonance (SDR or Timur-Coates)

- Pressure Express (XPT)

- Modular Formation Dynamics Tester (MDT)

Vertical permeability probe

Horizontal permeability probe

Sink probe

Schlumberger (2002), MDT Modular Formation Dynamics Tester

Permeability: a critical control on gas extraction rate
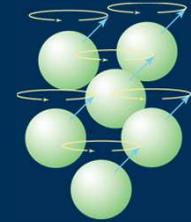
Downhole measurement options for permeability

- Nuclear Magnetic Resonance (SDR or Timur-Coates)
  Empirical relation between pore size and permeability,
  No specific flow direction

- Pressure Express (XPT)
  Measured flow and
  pressure change, primarily horizontal.

- Modular Formation Dynamics Tester (MDT)
  Measured flow and pressure change,
  horizontal or vertical.

Permeability: a critical control on gas extraction rate

Core-based measurement options for permeability

- Effective Stress Cell (Georgia Institute of Technology)
  Direct measure of vertical flow and pressure change.
  Known specimen shape.

Santamarina et al. (2015), Marine and Petroleum Geology

Permeability: a critical control on gas extraction rate

Core-based measurement options for permeability

- Effective Stress Cell (Georgia Institute of Technology)
  Direct measure of vertical flow and pressure change.
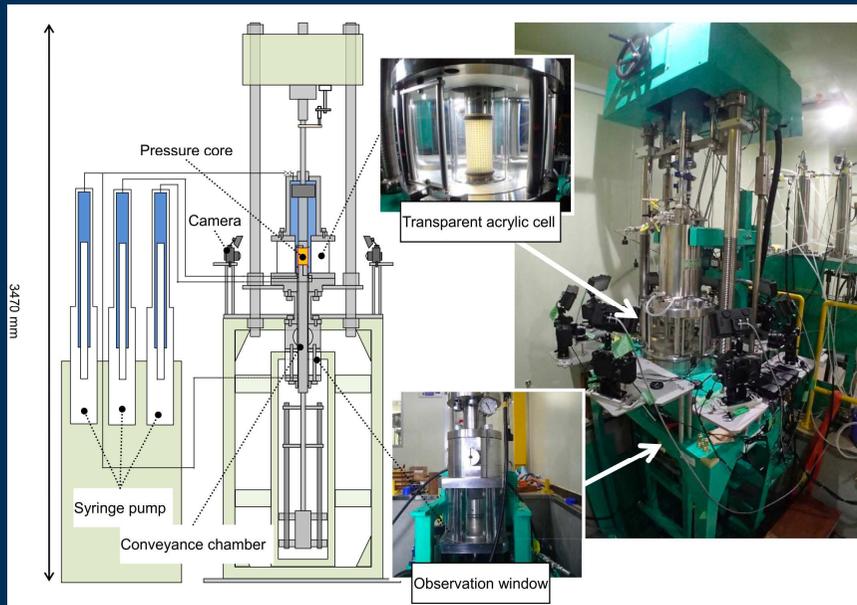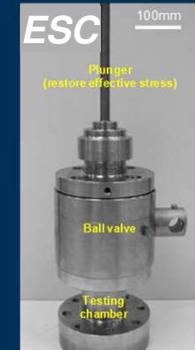 Known specimen shape.

- Triaxial Acrylic Testing Chamber (AIST)

Yoneda et al. (2015), Marine and Petroleum Geology

Permeability: a critical control on gas extraction rate

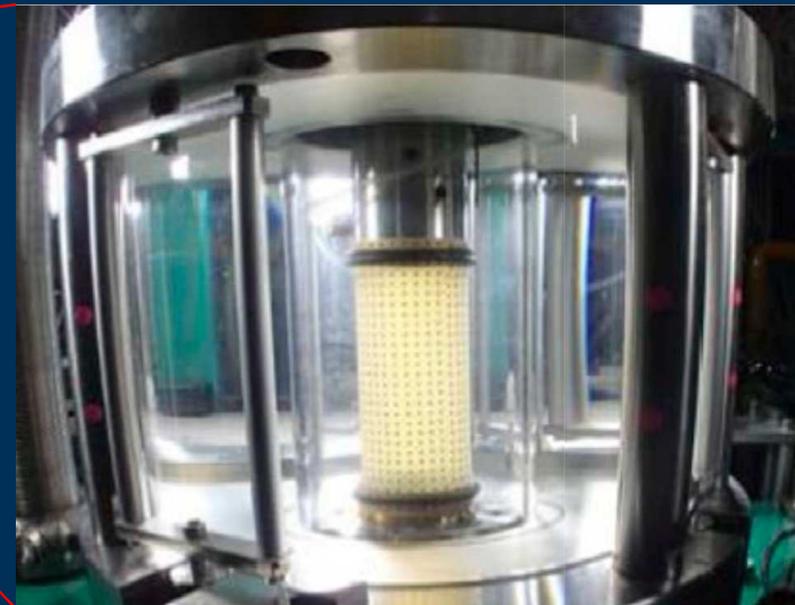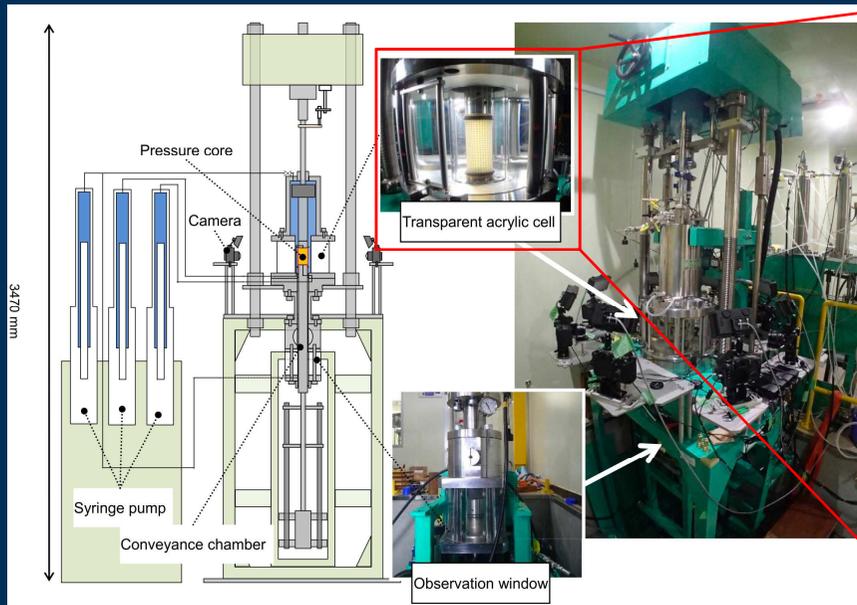## Core-based measurement options for permeability

- Effective Stress Cell (Georgia Institute of Technology)
  Direct measure of vertical flow and pressure change.
  Known specimen shape.

- Triaxial Acrylic Testing Chamber (AIST)

Yoneda et al. (2015), Marine and Petroleum Geology

Permeability: a critical control on gas extraction rate

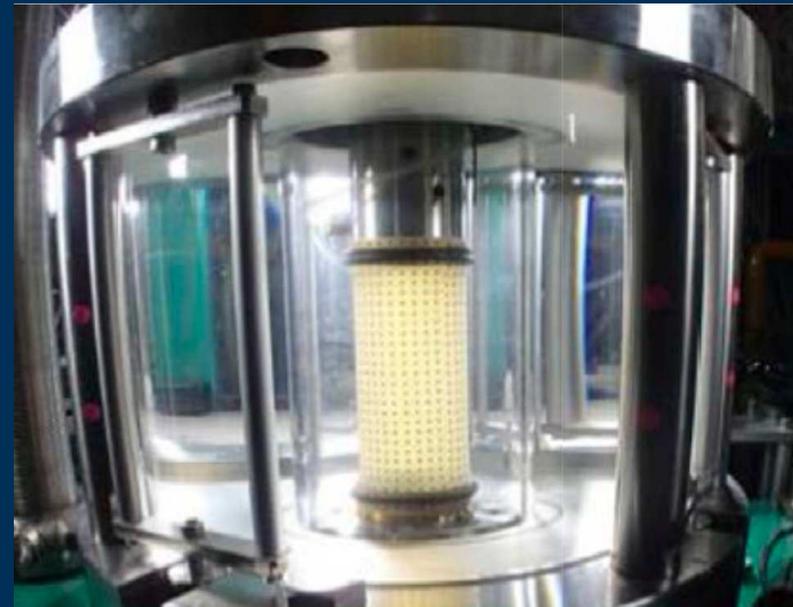## Core-based measurement options for permeability

- Effective Stress Cell (Georgia Institute of Technology)
  Direct measure of vertical flow and pressure change.
  Known specimen shape.

- Triaxial Acrylic Testing Chamber (AIST)
  Direct measure of vertical and
  horizontal flow and pressure
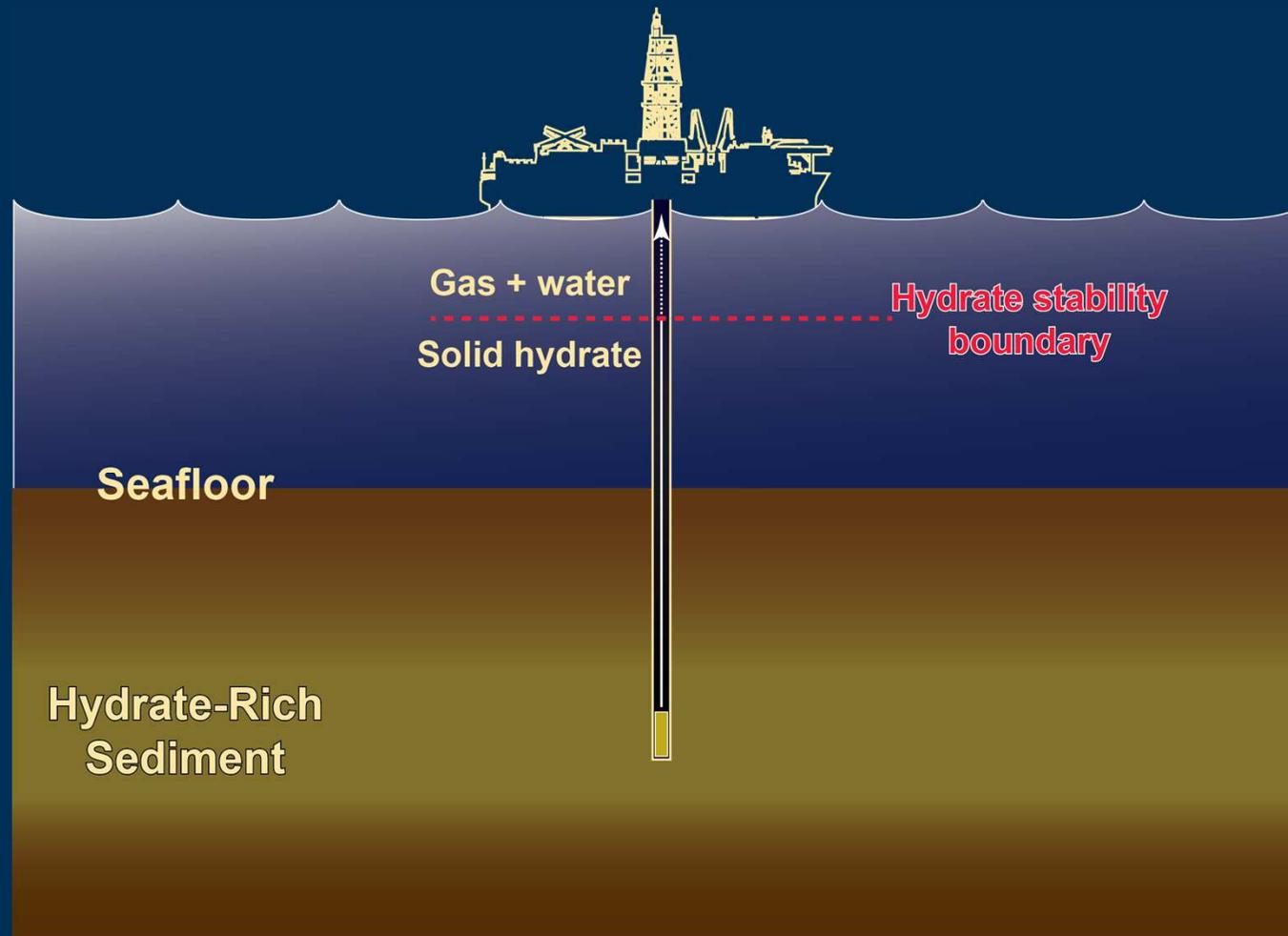 change. Known and imaged
  specimen shape.

Yoneda et al. (2015), Marine and Petroleum Geology

Permeability: a critical control on gas extraction rate

Core-based measurement options for permeability

- PCATS Triax (Geotek)
  Direct measure of vertical flow
  and pressure change.
  Known specimen shape.

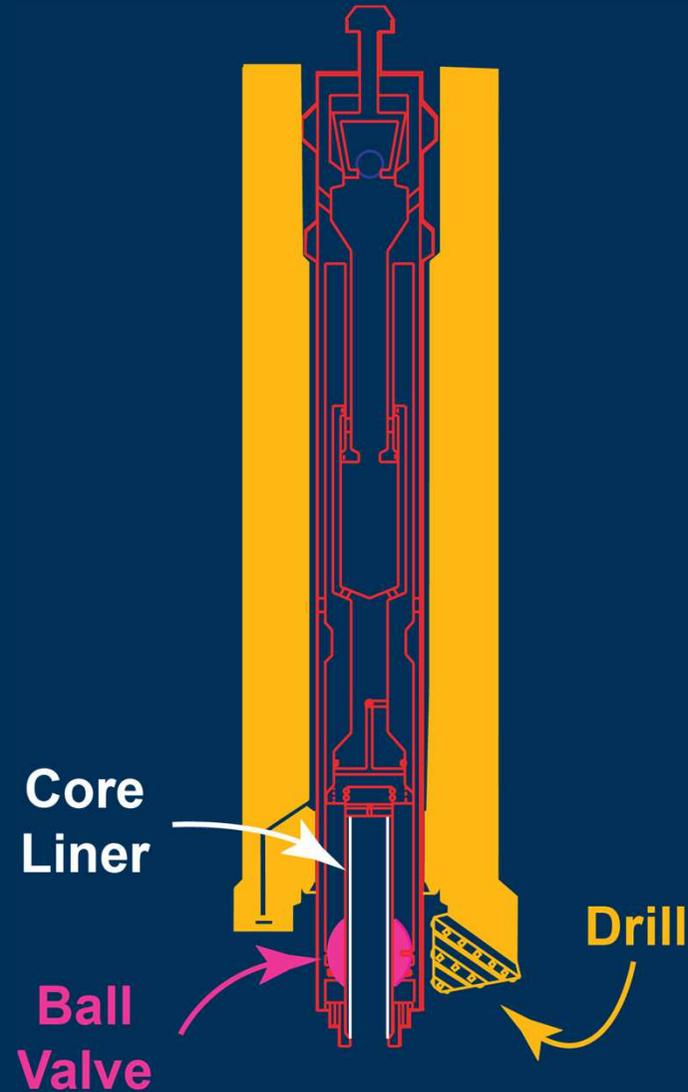Priest et al., (2015), Marine and Petroleum Geology; Liang et al., (2017), ICGH9
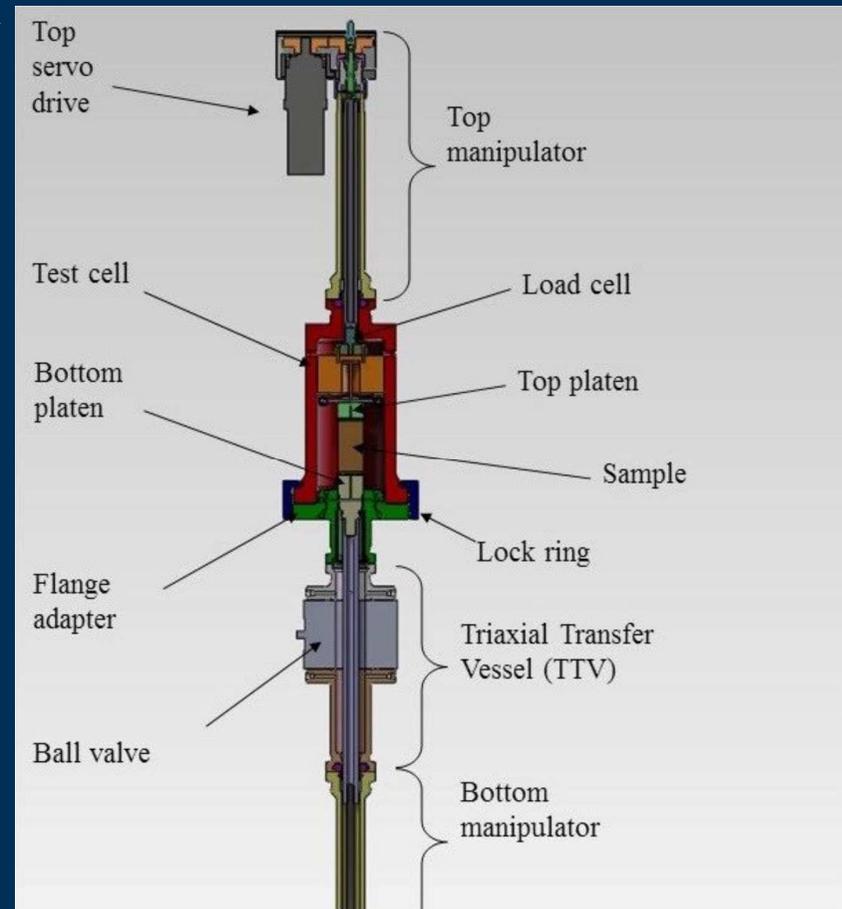
How do these chambers get hydrate-bearing sediment?

How do these chambers get hydrate-bearing sediment?

Preserve hydrate during recovery by keeping core at in situ pressure

Core Liner

Ball Valve

Drill

Pressure Corer operated by Geotek Ltd.

How do these chambers get hydrate-bearing sediment?

Preserve hydrate during recovery by keeping core at in situ pressure

Core Liner

Ball Valve

Drill

Pressure Corer operated by Geotek Ltd.

How do these chambers get hydrate-bearing sediment?

Preserve hydrate during recovery by keeping core at in situ pressure

Core Liner

Ball Valve

Drill

Pressure Corer operated by Geotek Ltd.

How do these chambers get hydrate-bearing sediment?

Preserve hydrate during recovery by keeping core at in situ pressure

Core Liner

Ball Valve

Drill

Pressure Corer operated by Geotek Ltd.

How do these chambers get hydrate-bearing sediment?

Pressure and temperature always in hydrate stability field

Geotek Coring, Offshore India

How do these chambers get hydrate-bearing sediment?
Pressure and temperature always in hydrate stability field

Geotek Coring, Offshore India

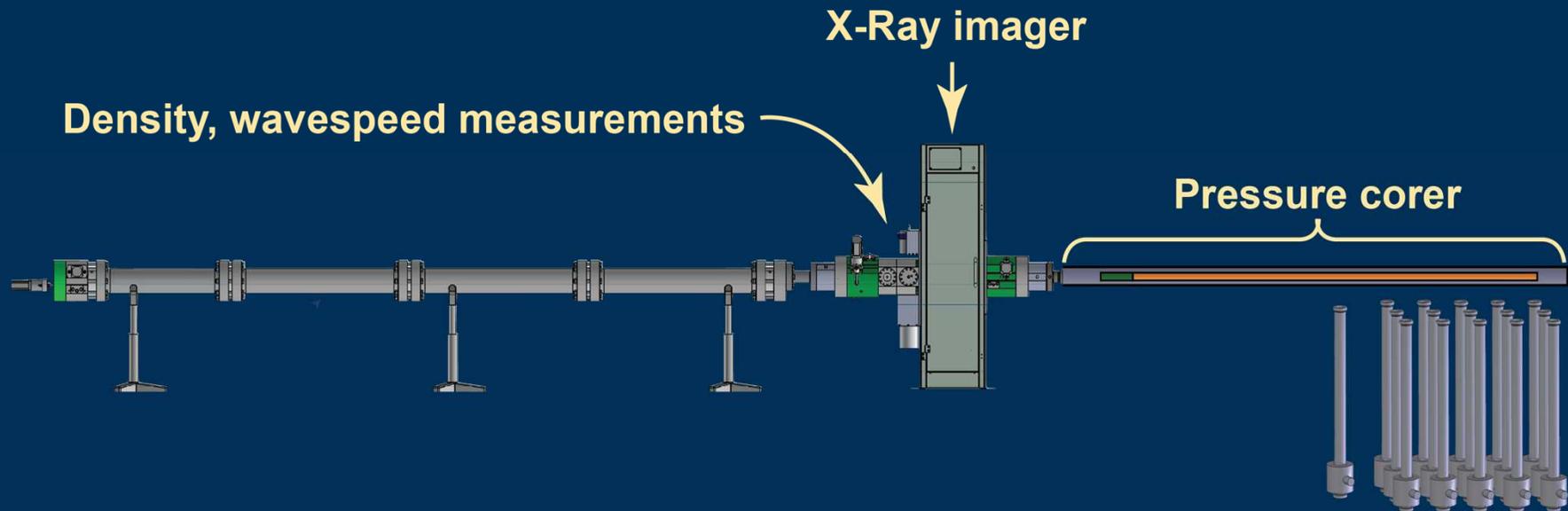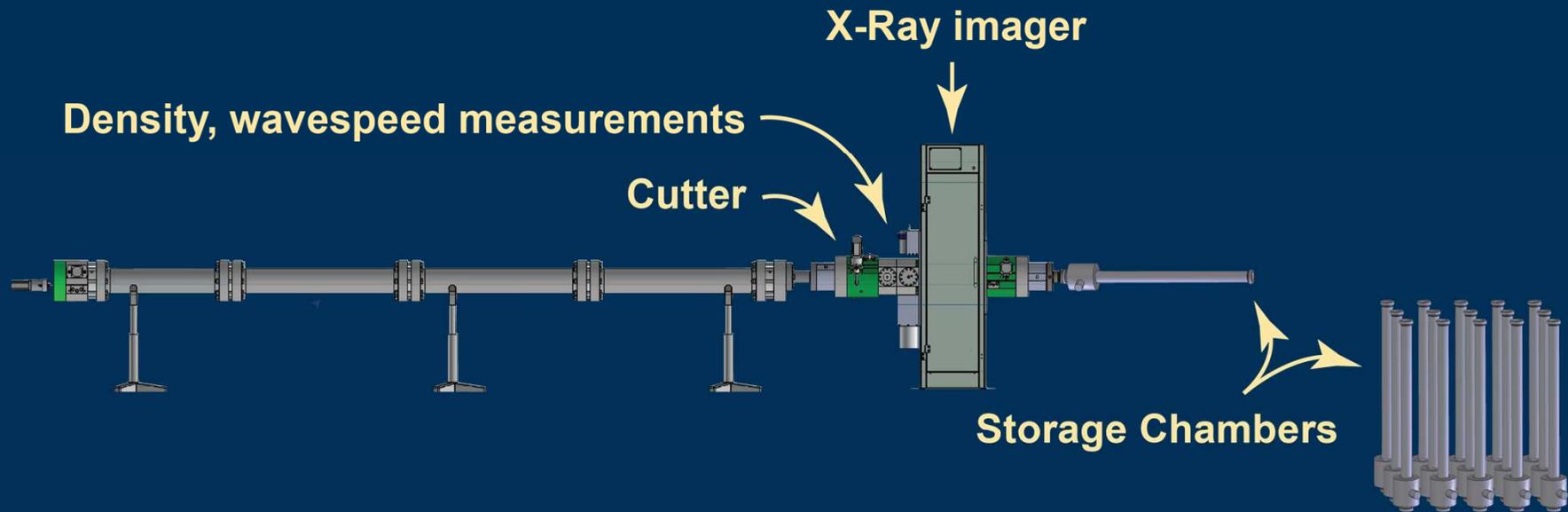# How do these chambers get hydrate-bearing sediment?

Pressure and temperature always in hydrate stability field

X-Ray imager

Density, wavespeed measurements

Pressure corer

Geotek Coring, PCATs System

How do these chambers get hydrate-bearing sediment?
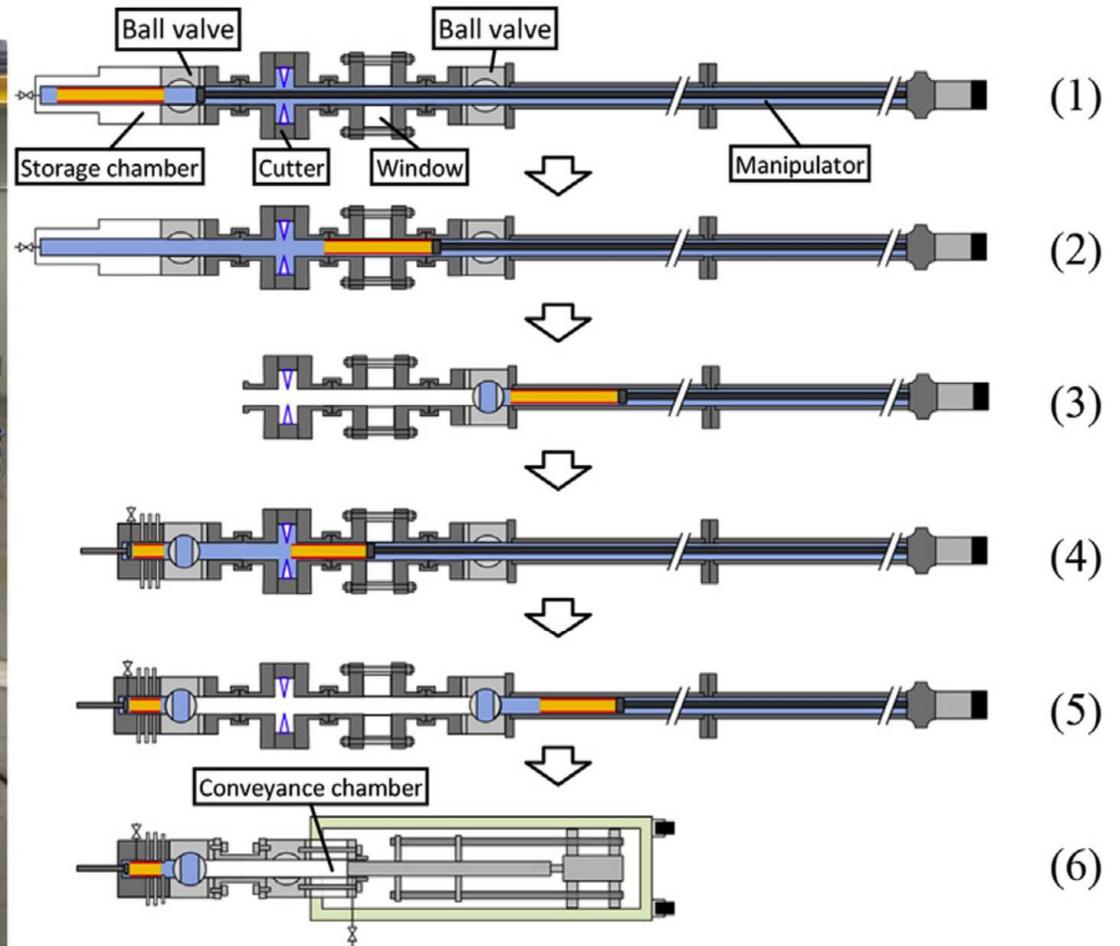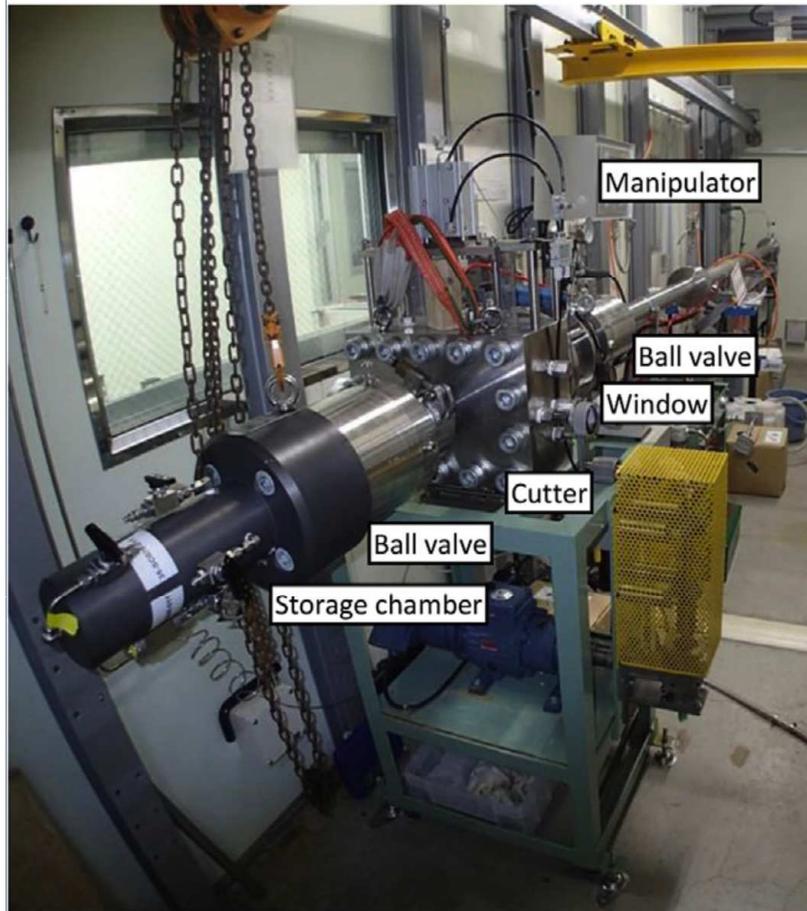
Pressure and temperature always in hydrate stability field

Cores transferred to USGS, Woods Hole

How do these chambers get hydrate-bearing sediment?
Pressure and temperature always in hydrate stability field
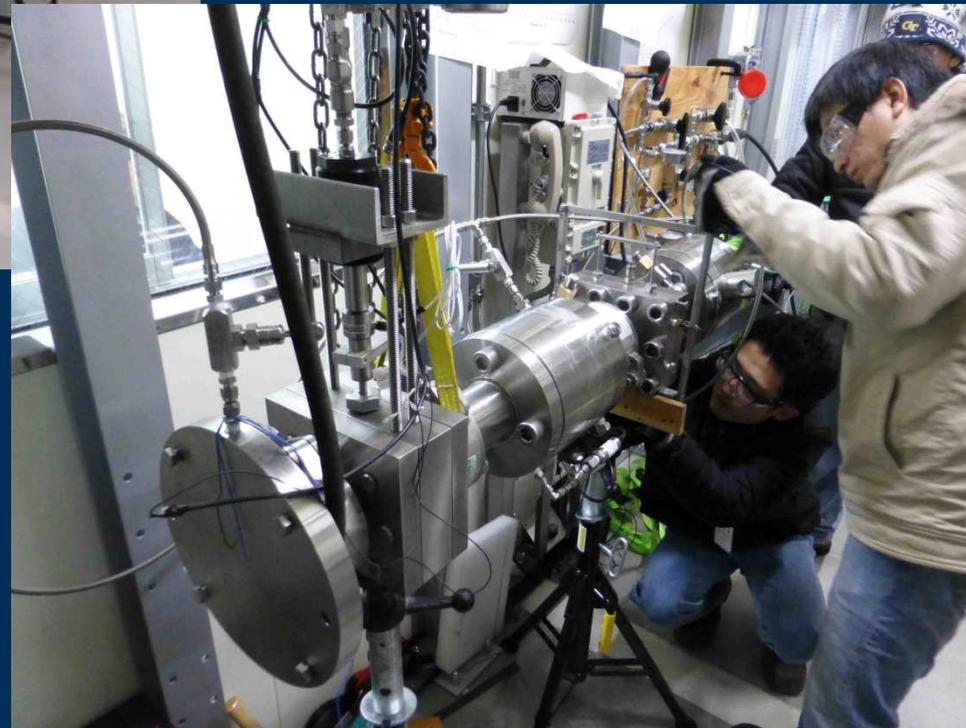
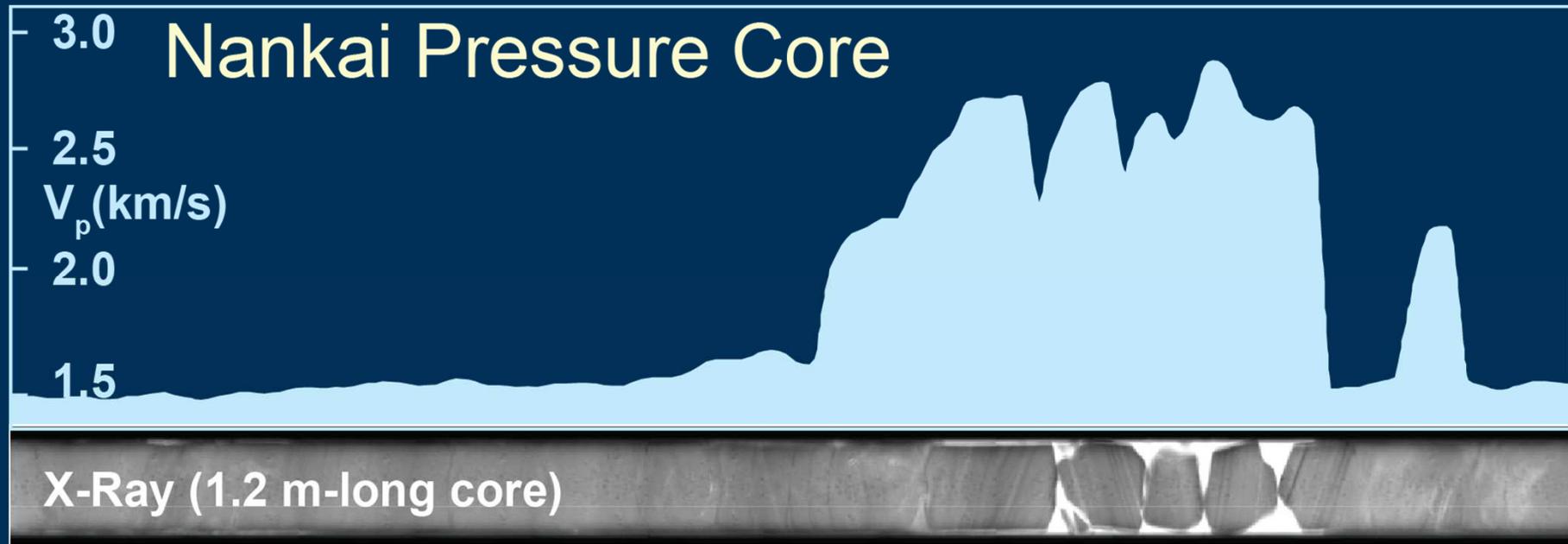Yoneda et al. (2017), Marine and Petroleum Geology

How do these chambers get hydrate-bearing sediment?
Pressure and temperature always in hydrate stability field

Identification of hydrate-bearing sediment using V_p

Nankai Pressure Core

V_p(km/s)

3.0
2.5
2.0
1.5

X-Ray (1.2 m-long core)

Santamarina et al. (2015), Marine and Petroleum Geology

Identification of hydrate-bearing sediment using V_p
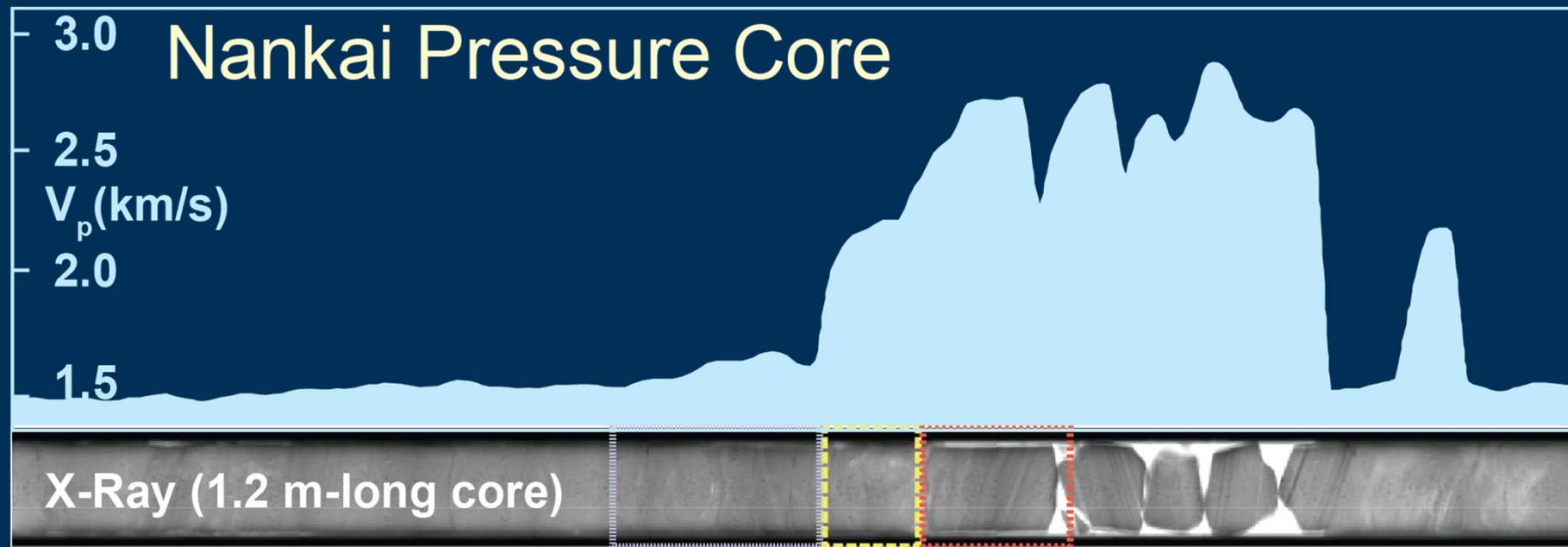
Locations chosen for three types of testing

Santamarina et al. (2015), Marine and Petroleum Geology

What are the measured permeability results?

Effective Permeability
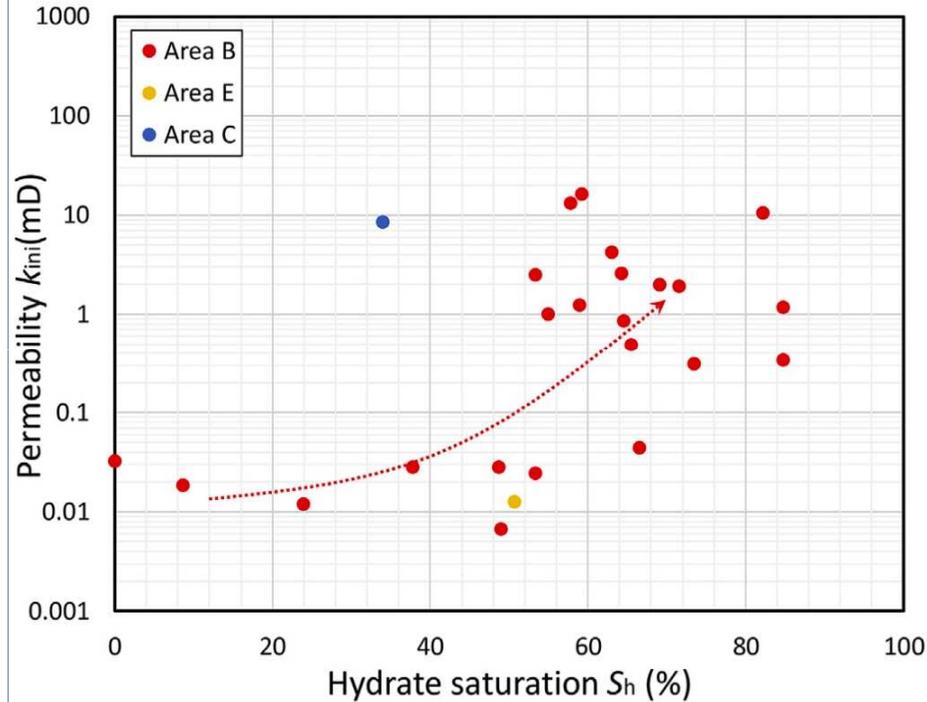
Intrinsic Permeability
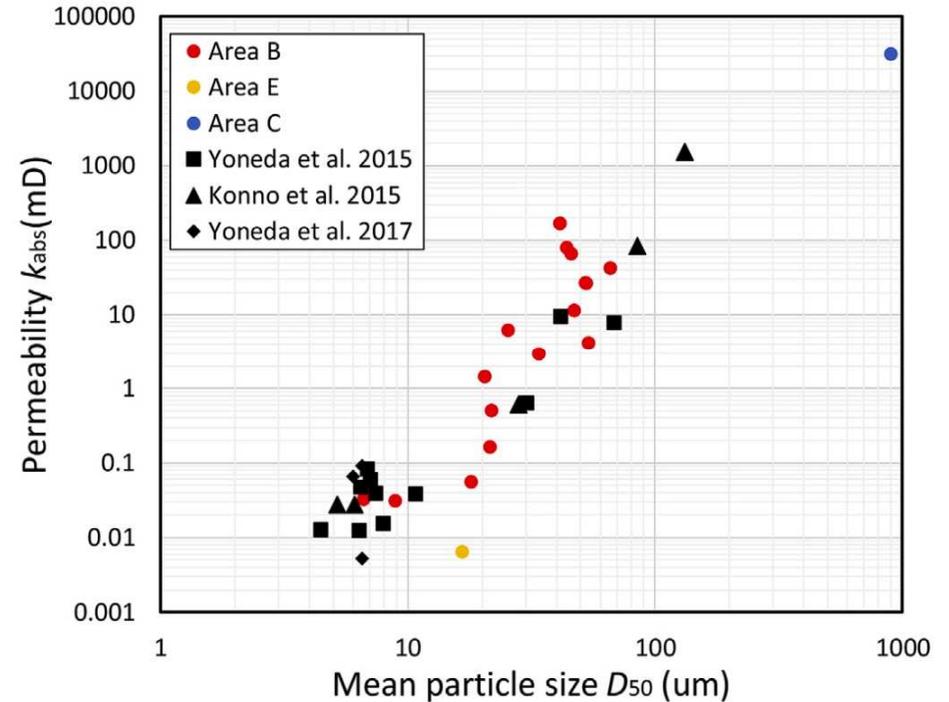
Pressure core results:
0.1 – 10 mD effective permeability in the reservoir sands

Yoneda et al. (2018), JMPG

What are the measured permeability results?

Pressure Core k_{eff}

**Pressure core results:
0.1 – 100 mD effective permeability in the reservoir sands**

Boswell et al. (2018), JMPG
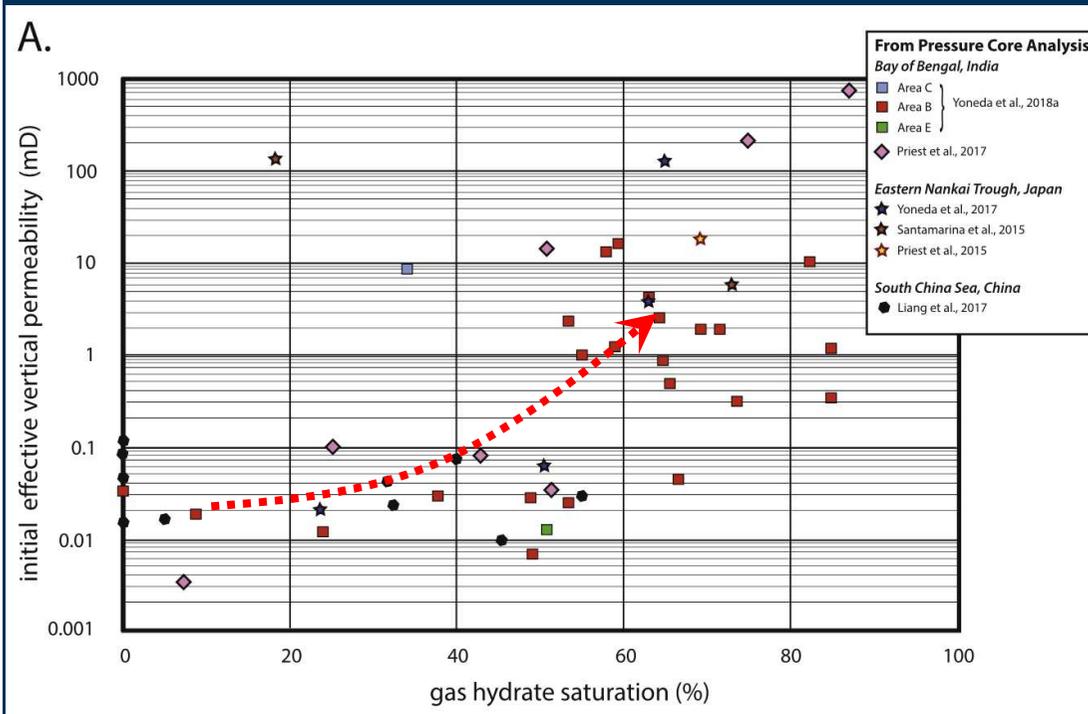
What are the measured permeability results?

Pressure Core k_{eff}

Well Log k_{eff}
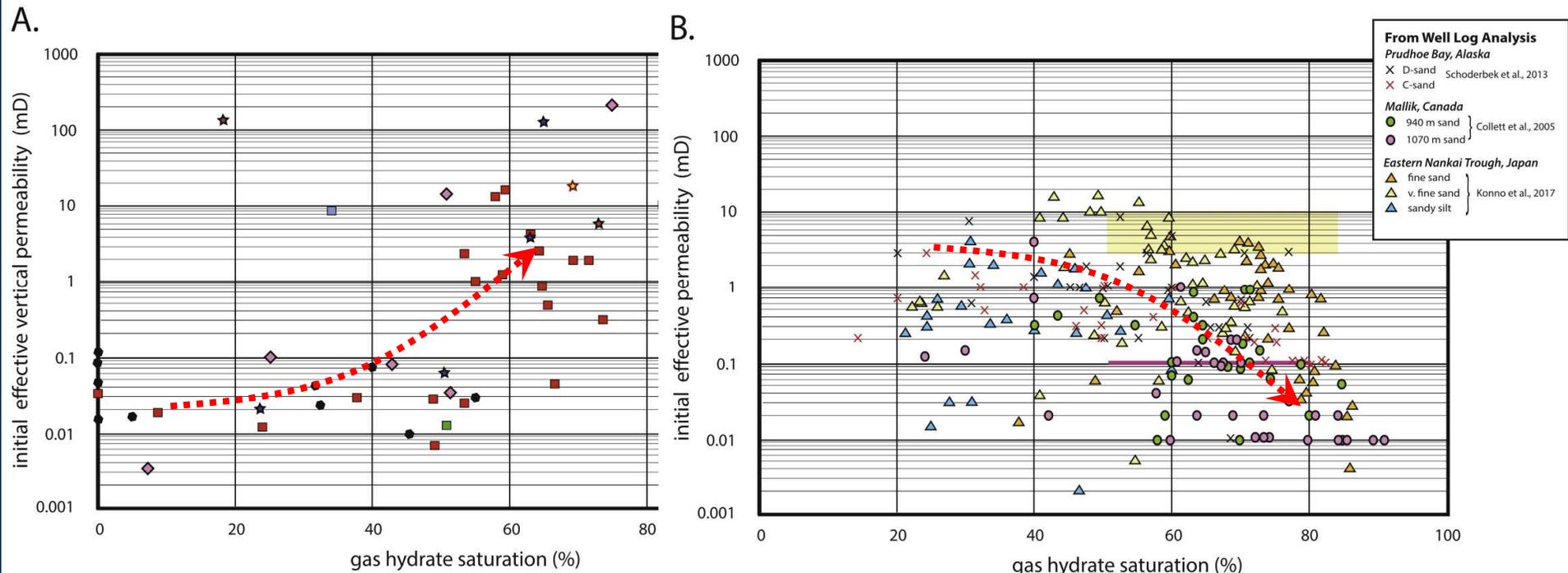
Pressure core results:
0.1 – 100 mD effective permeability in the reservoir sands

Well log results:
0.01 – 10 mD effective permeability in the reservoir sands

Boswell et al. (2018), JMPG

Measurement resolution and thin sand beds

Boswell et al. (2012), JMPG
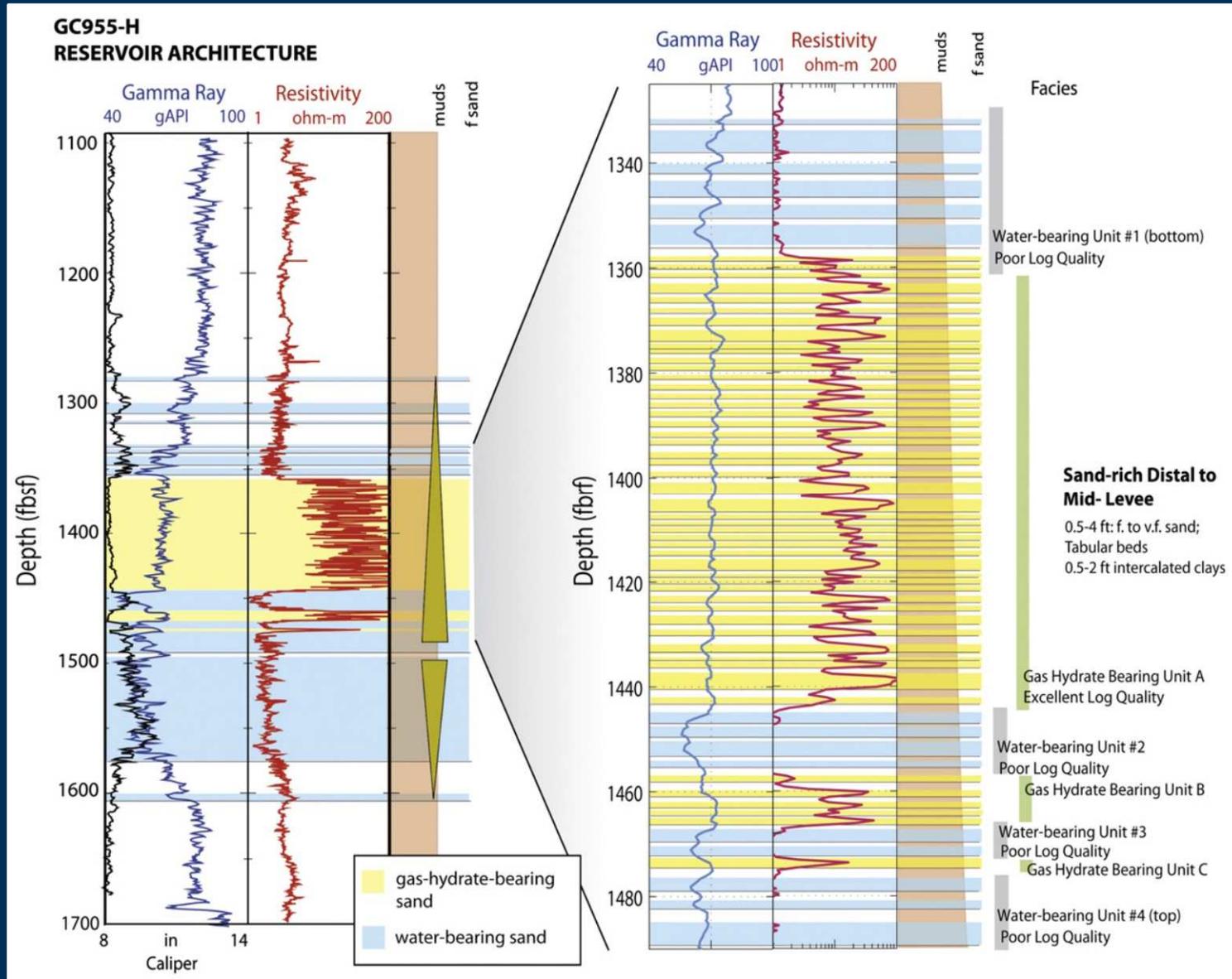
Measurement resolution and thin sand beds

Measurement resolution and thin sand beds

Fujii et al. (2015), JMPG

Measurement resolution and thin sand beds

Fujii et al. (2015), JMPG
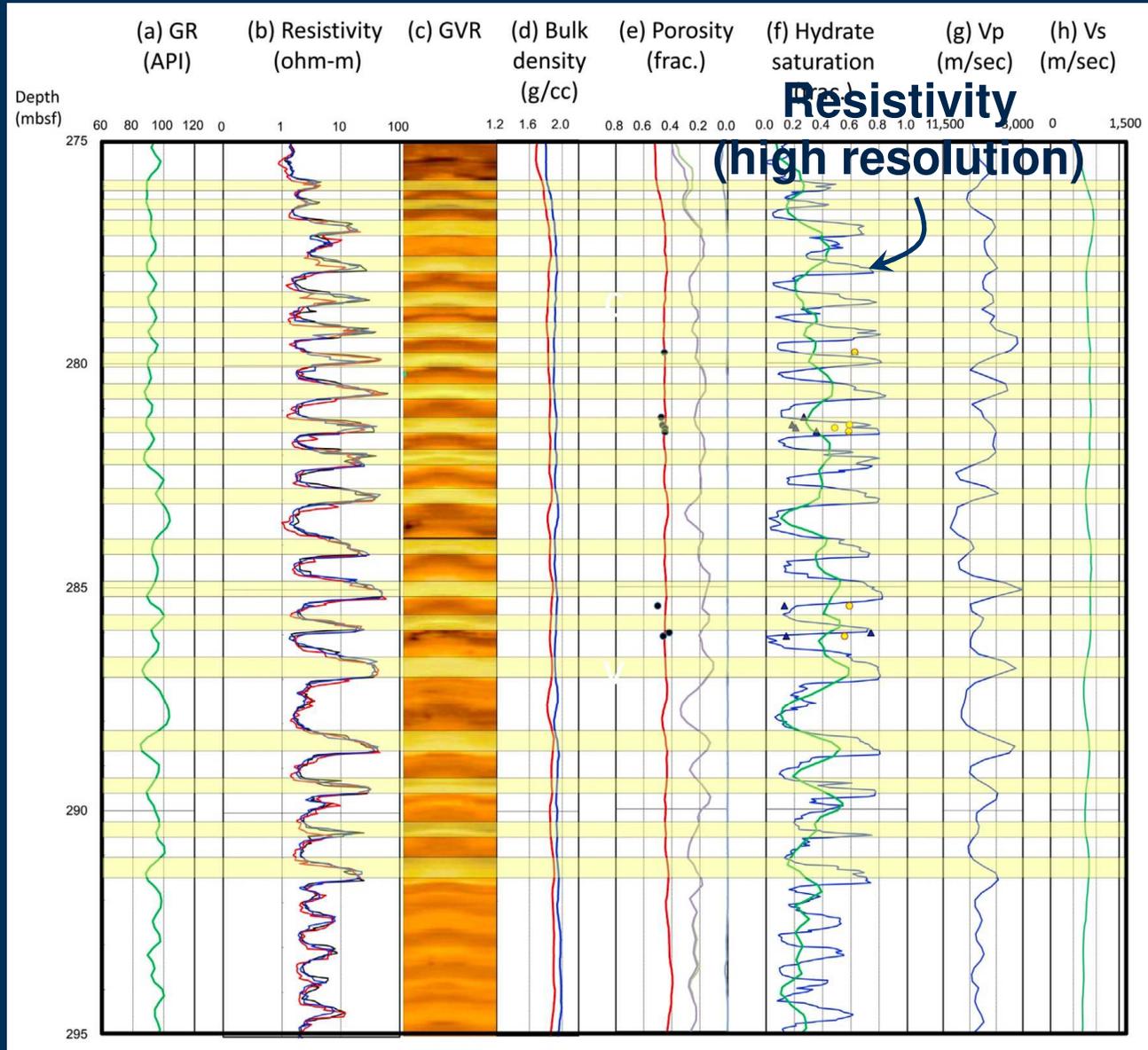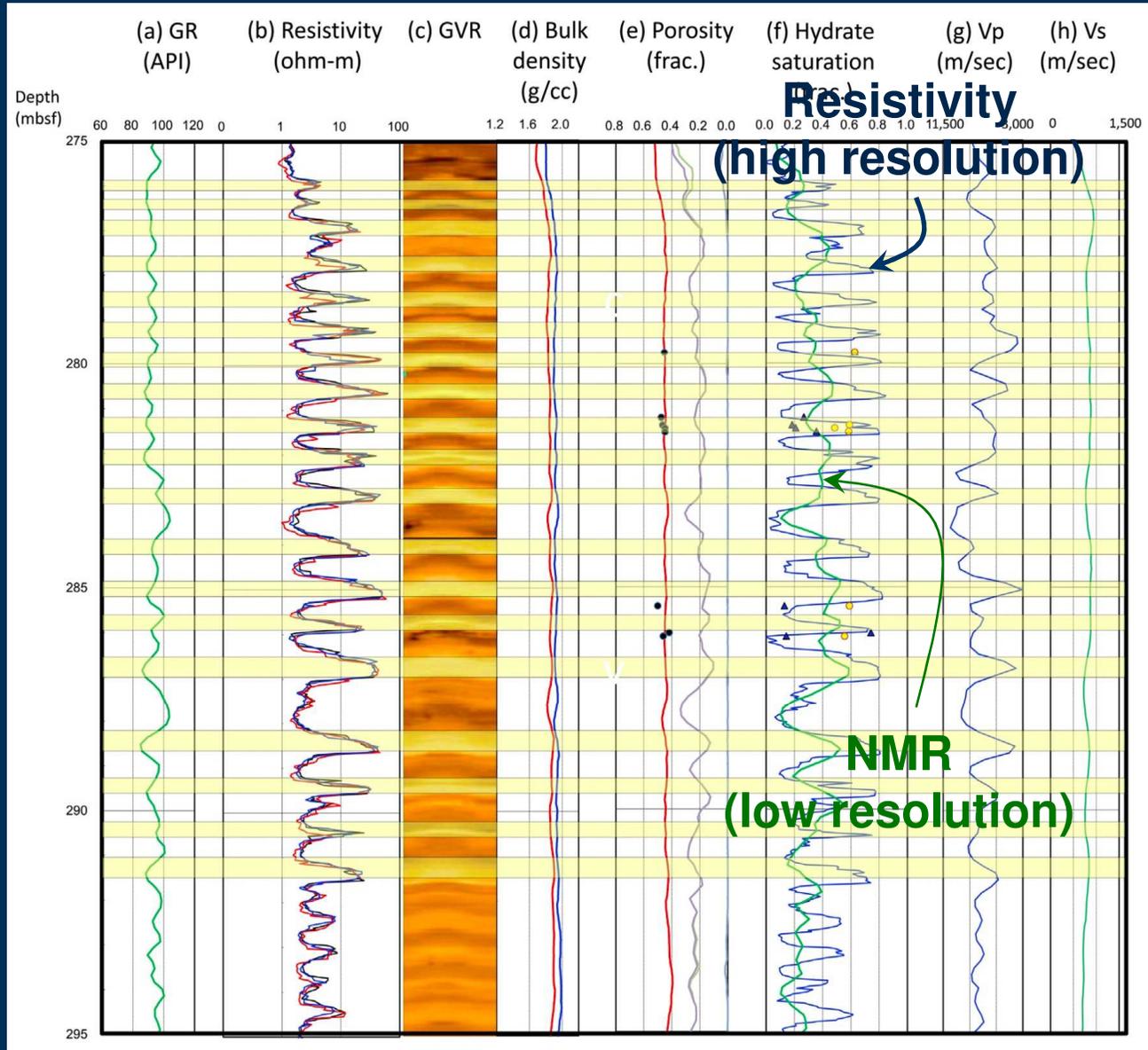
Permeability results depend on measurement type
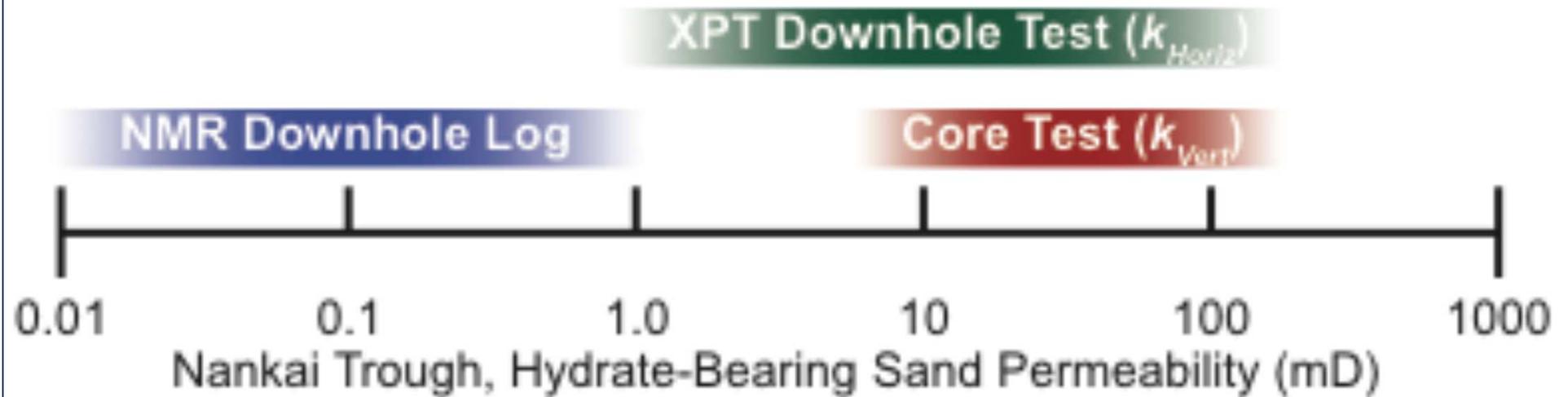
XPT Downhole Test (k_{Horiz})

NMR Downhole Log

Core Test (k_{Vert})

0.01   0.1   1.0   10   100   1000

Nankai Trough, Hydrate-Bearing Sand Permeability (mD)

Dai et al. (2017), ICGH9

What does permeability suggest about morphology?

Like velocity, k_{rh} depends on how hydrate is distributed

Santamarina et al. (2015), JMPG; Mahabadi et al. (2019), JPSE
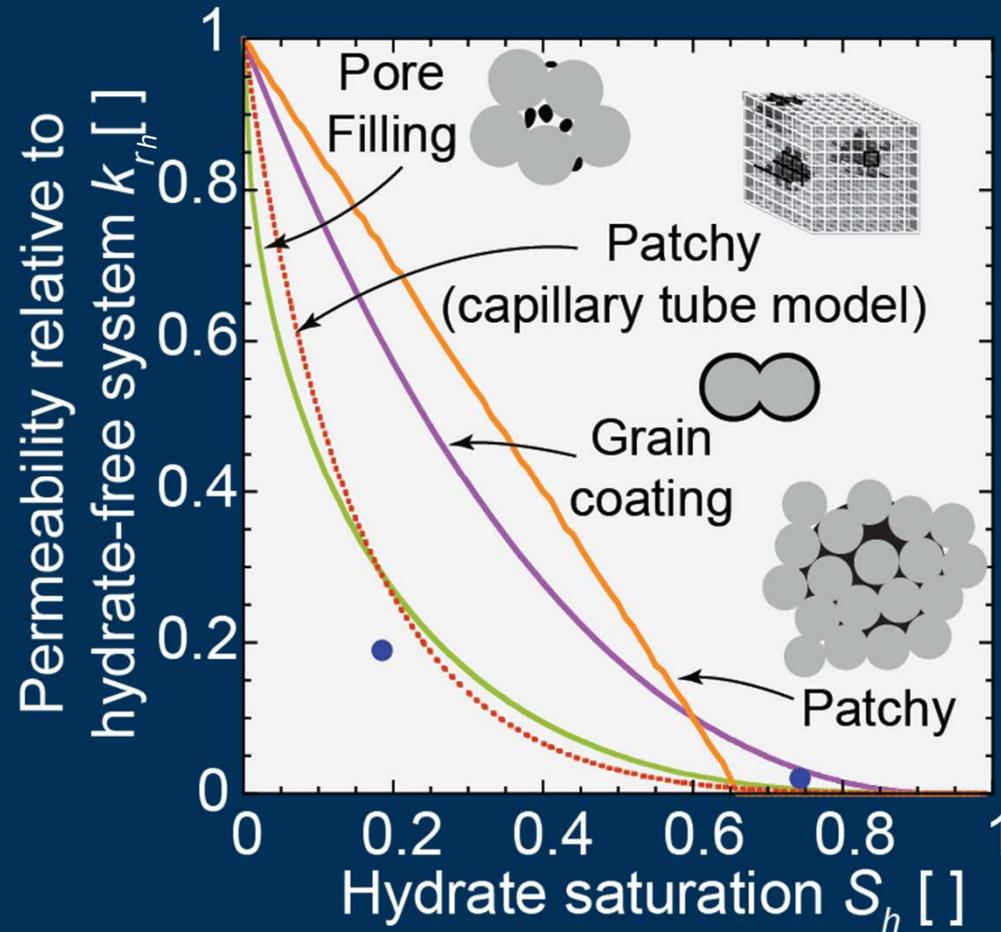
What does permeability suggest about morphology?

Like velocity, k_{rh} depends on how hydrate is distributed
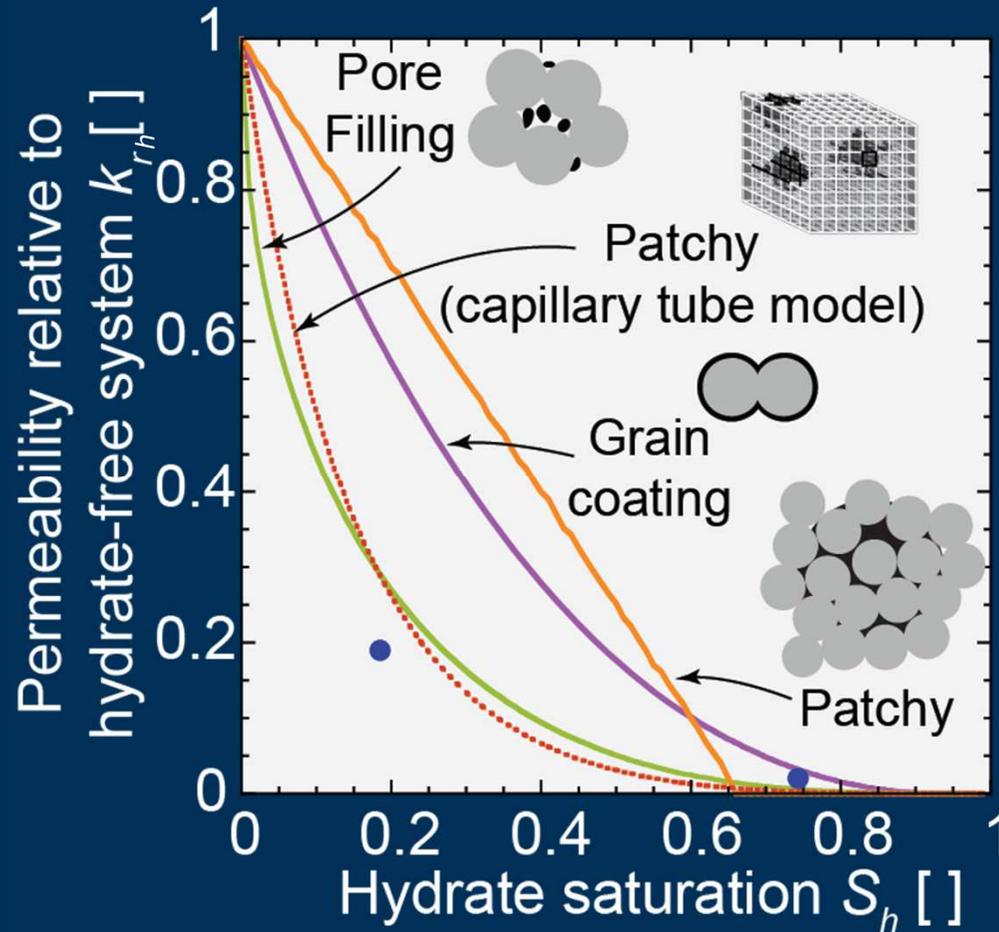
$k_{rh} = k_{eff} / k_{intrinsic}$ *agrees with velocity:*
hydrate in pores, not cementing

Santamarina et al. (2015), JMPG; Mahabadi et al. (2019), JPSE

What is the effect of generating gas during dissociation?

Santamarina et al. (2015), Marine and Petroleum Geology

What is the effect of generating gas during dissociation?

Santamarina et al. (2015), Marine and Petroleum Geology
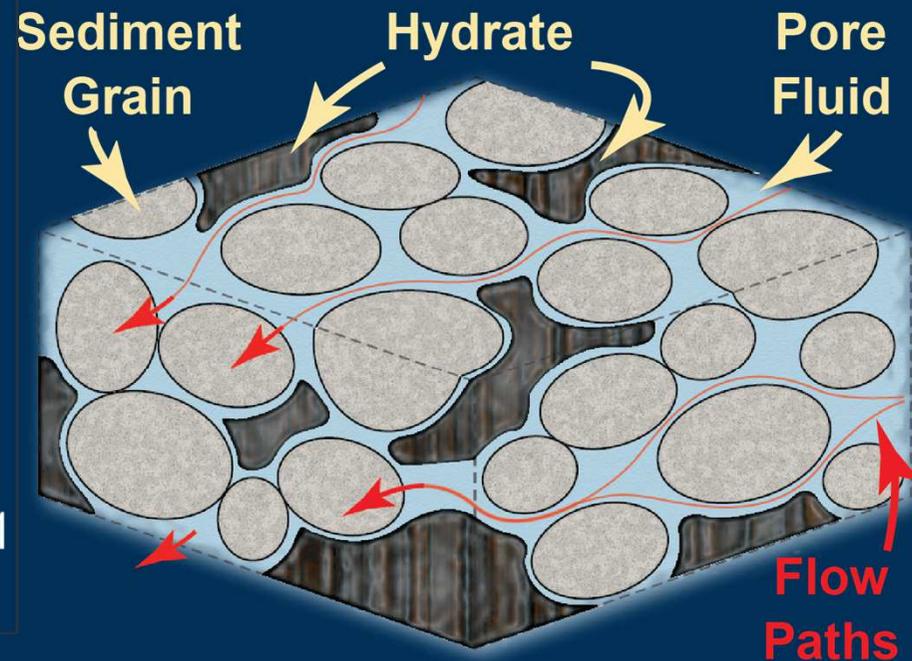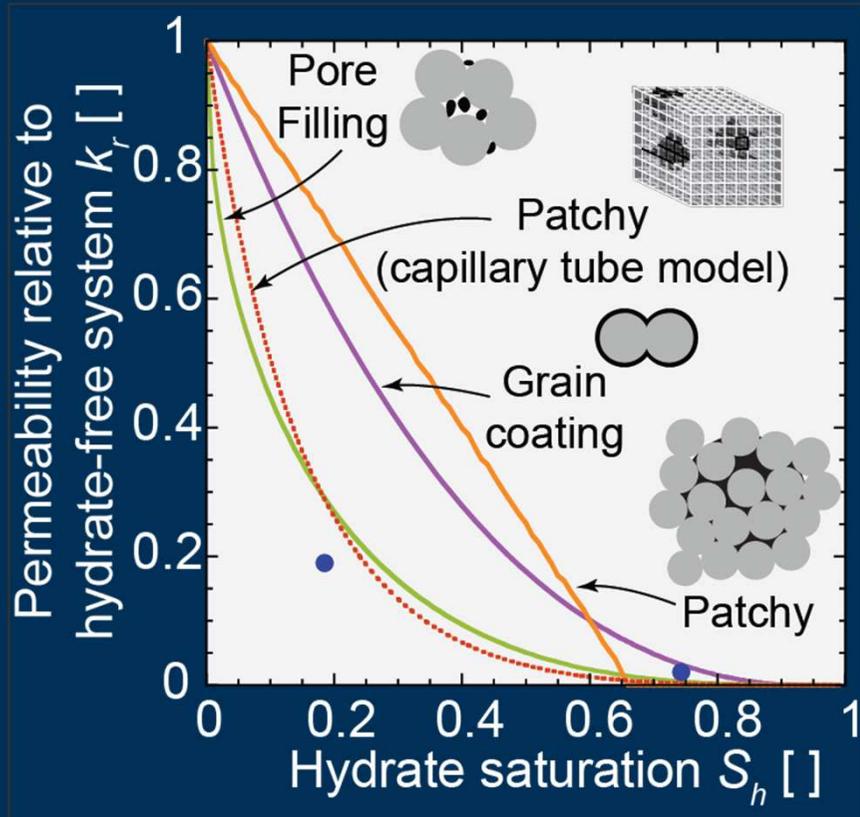
What is the effect of generating gas during dissociation?

What is the effect of generating gas during dissociation?

The presence of gas makes flow more difficult for water (low k_{rw})

Santamarina et al. (2015), Marine and Petroleum Geology

What is the effect of generating gas during dissociation?

The presence of gas makes flow more difficult for water (low k_{rw})

Santamarina et al. (2015), Marine and Petroleum Geology

Permeability: a critical control on gas extraction rate

Yamamoto et al. (2017), Roy. Soc. Chemistry

What about the permeability of the adjacent sediment?

Sea floor

Fine-grained sediment

Coarse-grained sediment

Depth

Jang et al. (2019), OTC

What about the permeability of the adjacent sediment?

Jang et al. (2019), OTC

What about the permeability of the adjacent sediment?

Poor seal: inefficient depressurization

Good seal: efficient depressurization

Sea floor

Produced gas and water

Depth

Production Interval

Production Well
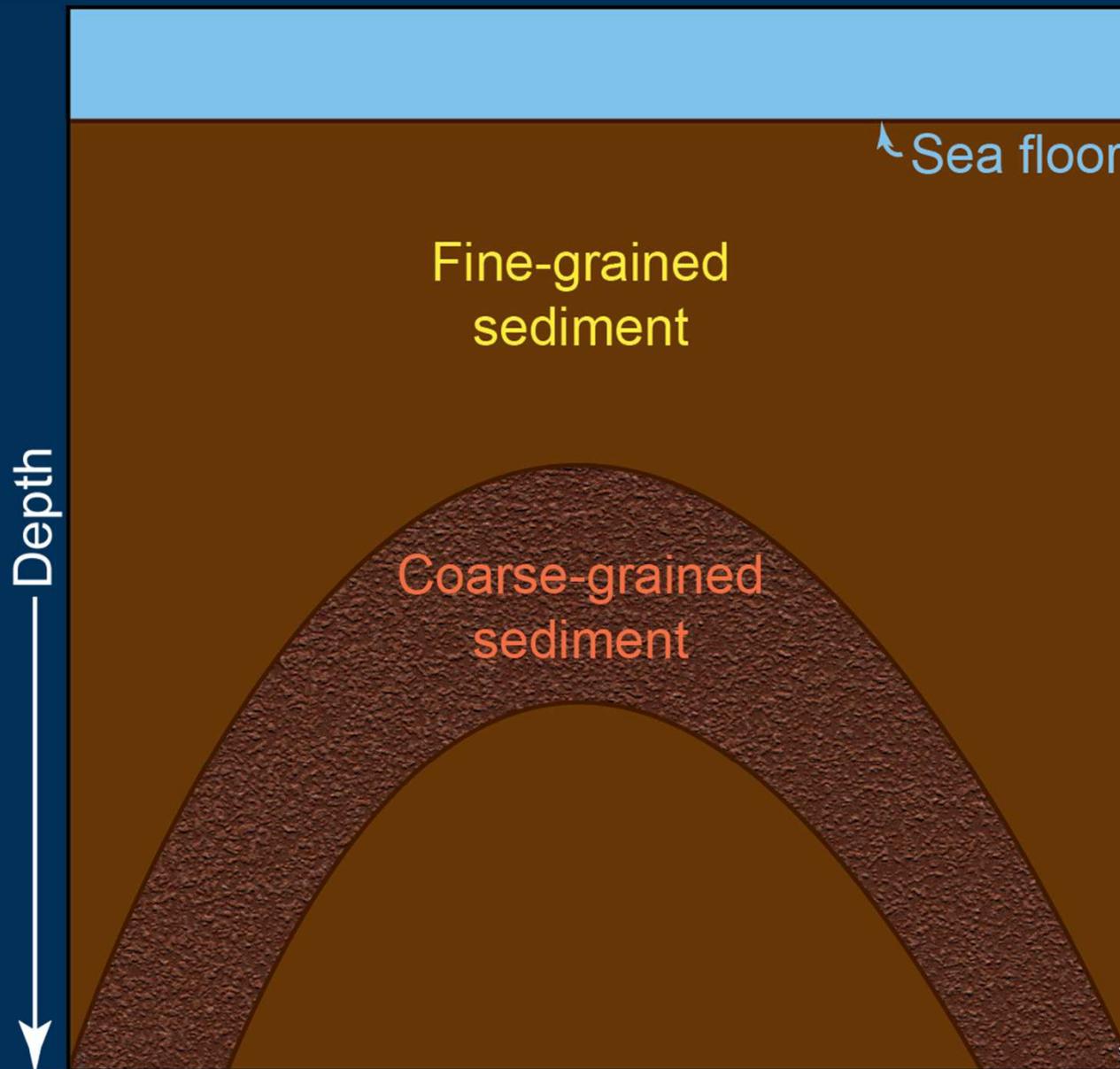
Jang et al. (2019), OTC

What about the permeability of the adjacent sediment?

Jang et al. (2019), OTC

What about the permeability of the adjacent sediment?

Jang et al. (2019), OTC

What about the permeability of the adjacent sediment?

Offshore India
NGHP-02-16
$0.01 \rightarrow 0.1$ mD
25% recovery rate
decrease
(Konno et al., 2018, JMPG)

Jang et al. (2019), OTC

What about the permeability of the adjacent sediment?
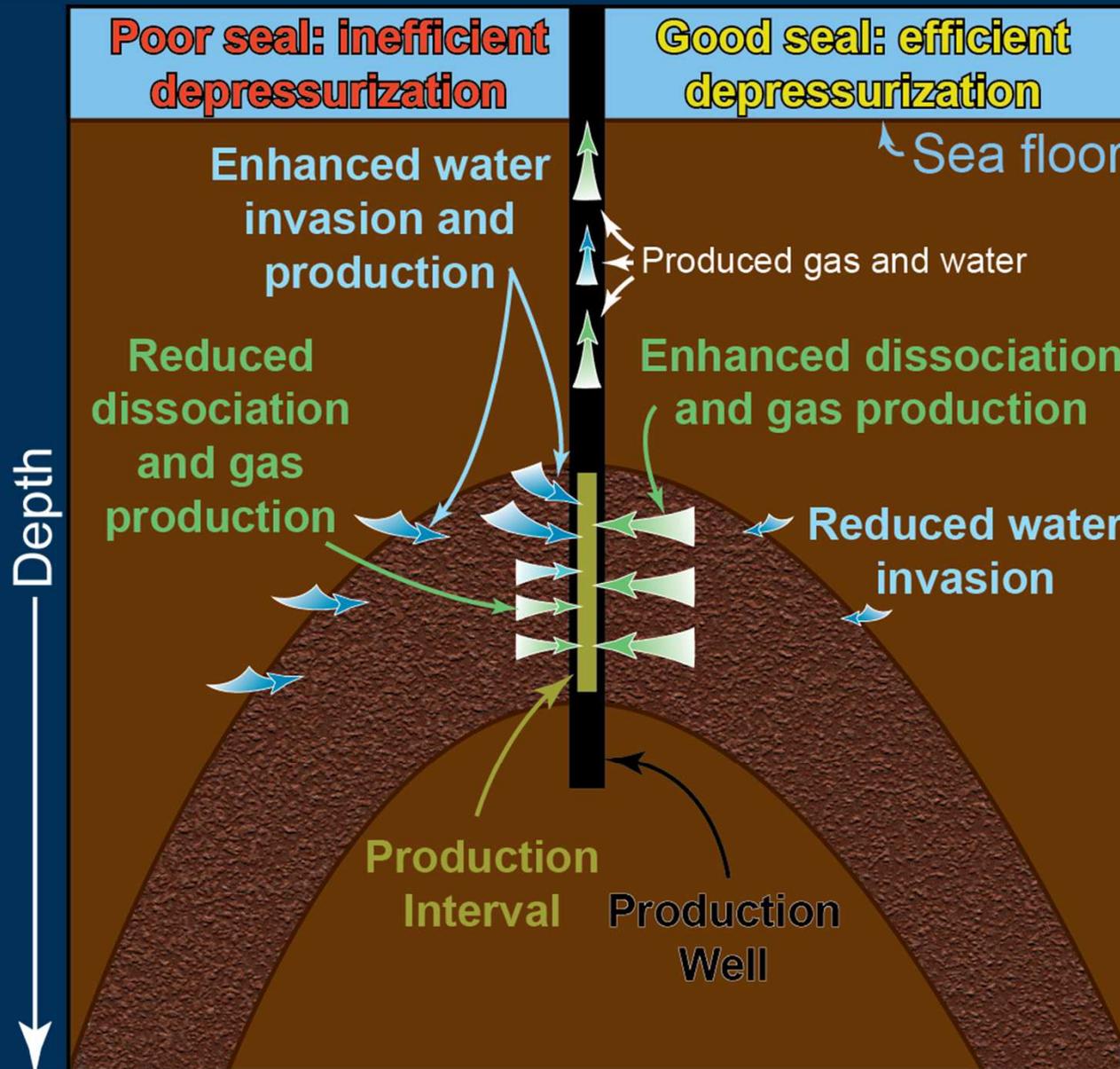
Offshore India
NGHP-02-16
0.01→0.1 mD
25% recovery rate
decrease
(Konno et al., 2018, JMPG)

Permafrost Alaska
Ignik Sikumi
0.1→1 mD
50% recovery rate
decrease
(Ajayi et al., 2018, JNGSE)

Jang et al. (2019), OTC

Thermal properties: the flow of heat

Hydrate dissociation is endothermic, absorbing energy:

The energy absorbed is heat from the surroundings. Hydrate dissociation cools the surroundings like ice melting in a glass.

If there is enough ice, the phase boundary temperature can be measured.

Thermal properties: the flow of heat

Like ice, if there is enough hydrate, dissociation will cool the environment down to the hydrate stability temperature, then warm up after dissociation.

Santamarina et al. (2015), Marine and Petroleum Geology

Thermal properties: the flow of heat

Like ice, if there is enough hydrate, dissociation will cool the environment down to the hydrate stability temperature, then warm up after dissociation.

Santamarina et al. (2015), Marine and Petroleum Geology
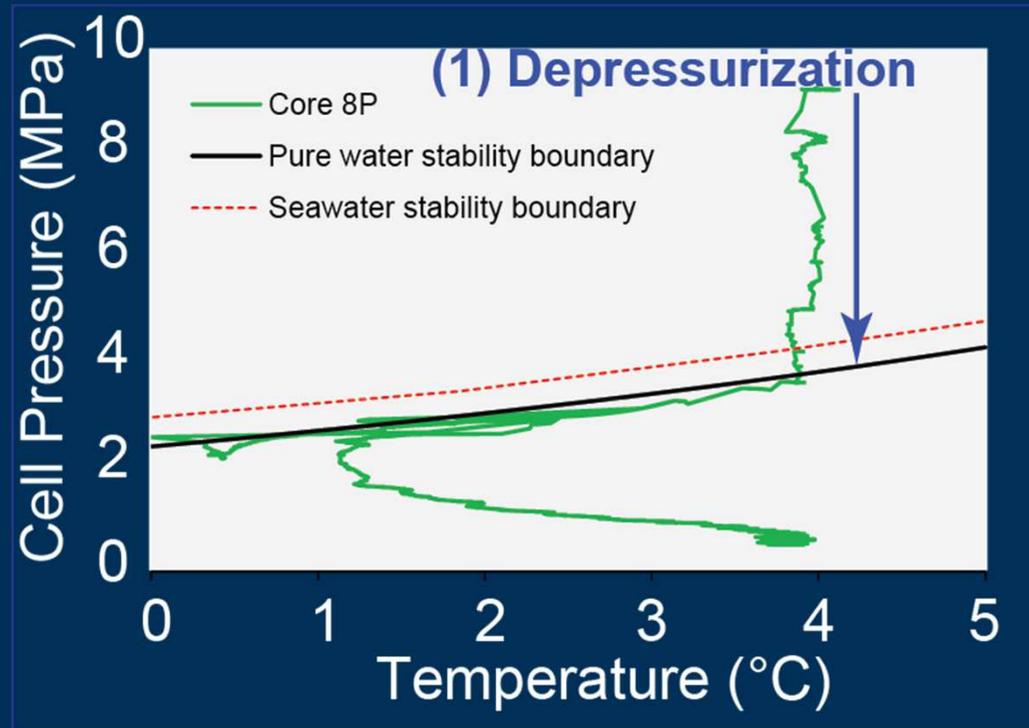
Thermal properties: the flow of heat

Like ice, if there is enough hydrate, dissociation will cool the environment down to the hydrate stability temperature, then warm up after dissociation.

With no added heat, the system would stop dissociating and equilibrate at the temperature appropriate for the applied pressure.

Santamarina et al. (2015), Marine and Petroleum Geology

Thermal properties: the flow of heat

Like ice, if there is enough hydrate, dissociation will cool the environment down to the hydrate stability temperature, then warm up after dissociation.

Heat must be supplied to the dissociation front to maintain dissociation:

Required heat: 54.2 – 54.4 kJ/mol; 436.6 – 436.8 kJ/kg

Handa (1986), J. Chem. Thermodynam; Gupta et al. (2008), Chem. Eng. Sci.
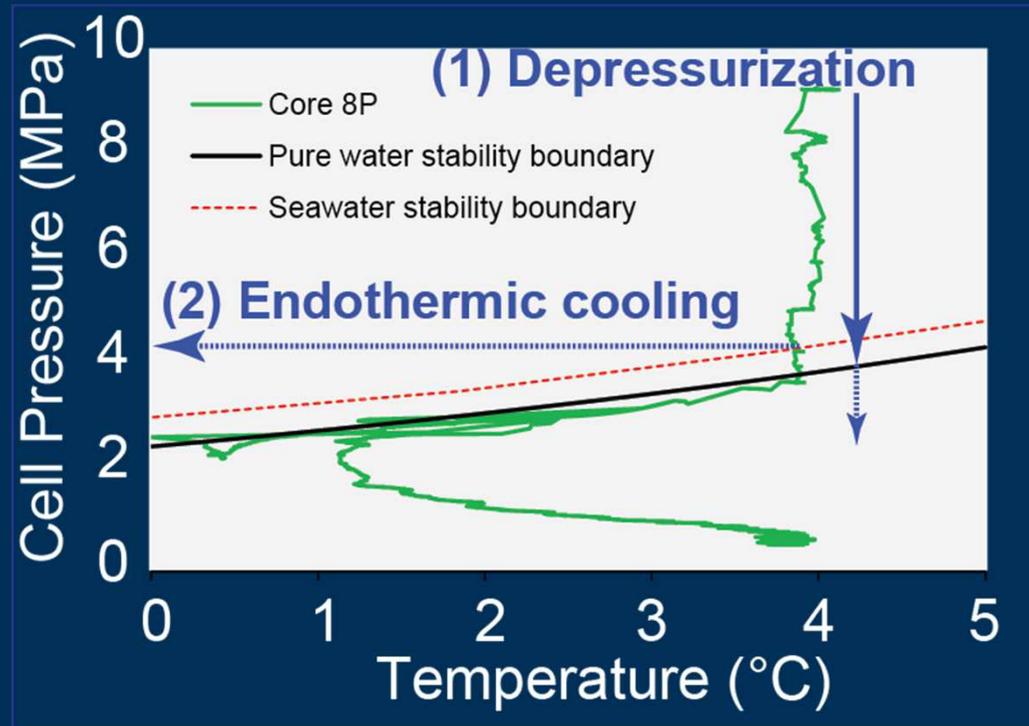
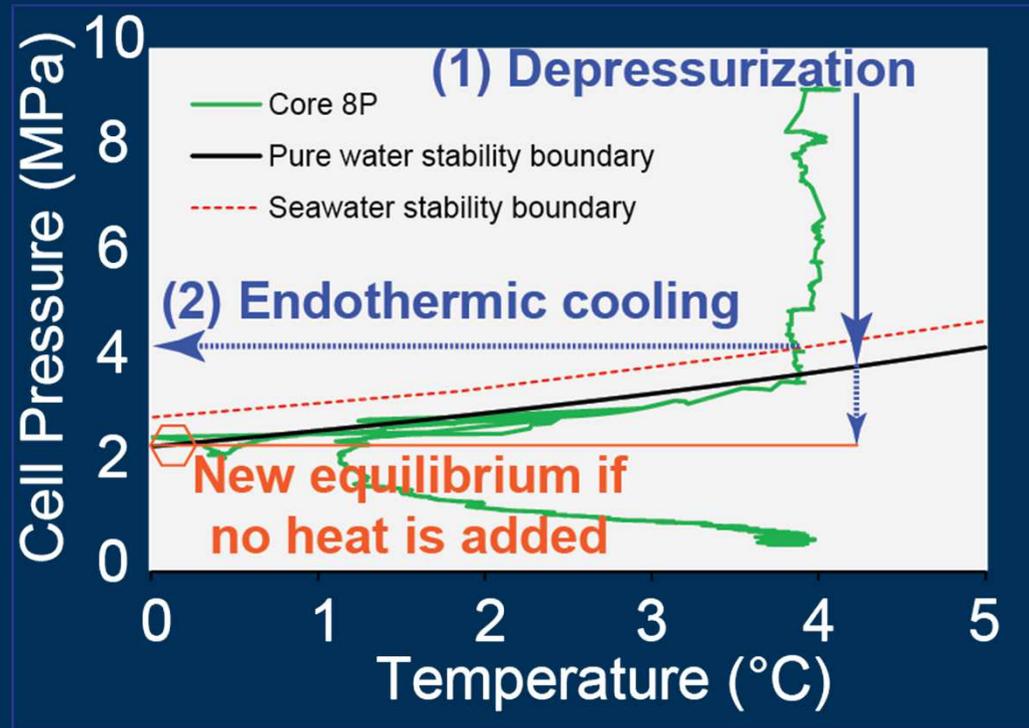# Thermal properties: the flow of heat

Like ice, if there is enough hydrate, dissociation will cool the environment down to the hydrate stability temperature, then warm up after dissociation.

Heat must be supplied to the dissociation front to maintain dissociation:

Required heat: 54.2 – 54.4 kJ/mol; 436.6 – 436.8 kJ/kg

Handa (1986), J. Chem. Thermodynam; Gupta et al. (2008), Chem. Eng. Sci.

Where does the required heat come from?

Canadian Arctic (Photo from USGS)

For a "typical" case:

~5% can come from the gas hydrate itself

~33% can come from the sediment and pore water

Yamamoto et al. (2017), Roy. Soc. Chemistry

Where does the required heat come from?

Canadian Arctic (Photo from USGS)

For a "typical" case:

~5% can come from the gas hydrate itself

~33% can come from the sediment and pore water

Remaining ~62% must come from conduction and from convection of warm fluids through the system. Tracking the flow of heat requires the thermal properties of gas, hydrate, water and sediment.

Yamamoto et al. (2017), Roy. Soc. Chemistry

Glossary of thermal terms

- c_p (Specific heat, J/(kg·K)): energy required to change the material's temperature by 1 degree K (or °C).

- λ (Thermal conductivity, W/(m·K)): describes how easily heat flows through a material (higher means easier heat flow).

- κ (Thermal diffusivity, m²/s): describes how rapidly a material can change temperature.

Thermal properties are related via the density of the material, ρ:

$$\lambda = \rho \cdot c_p \cdot \kappa$$
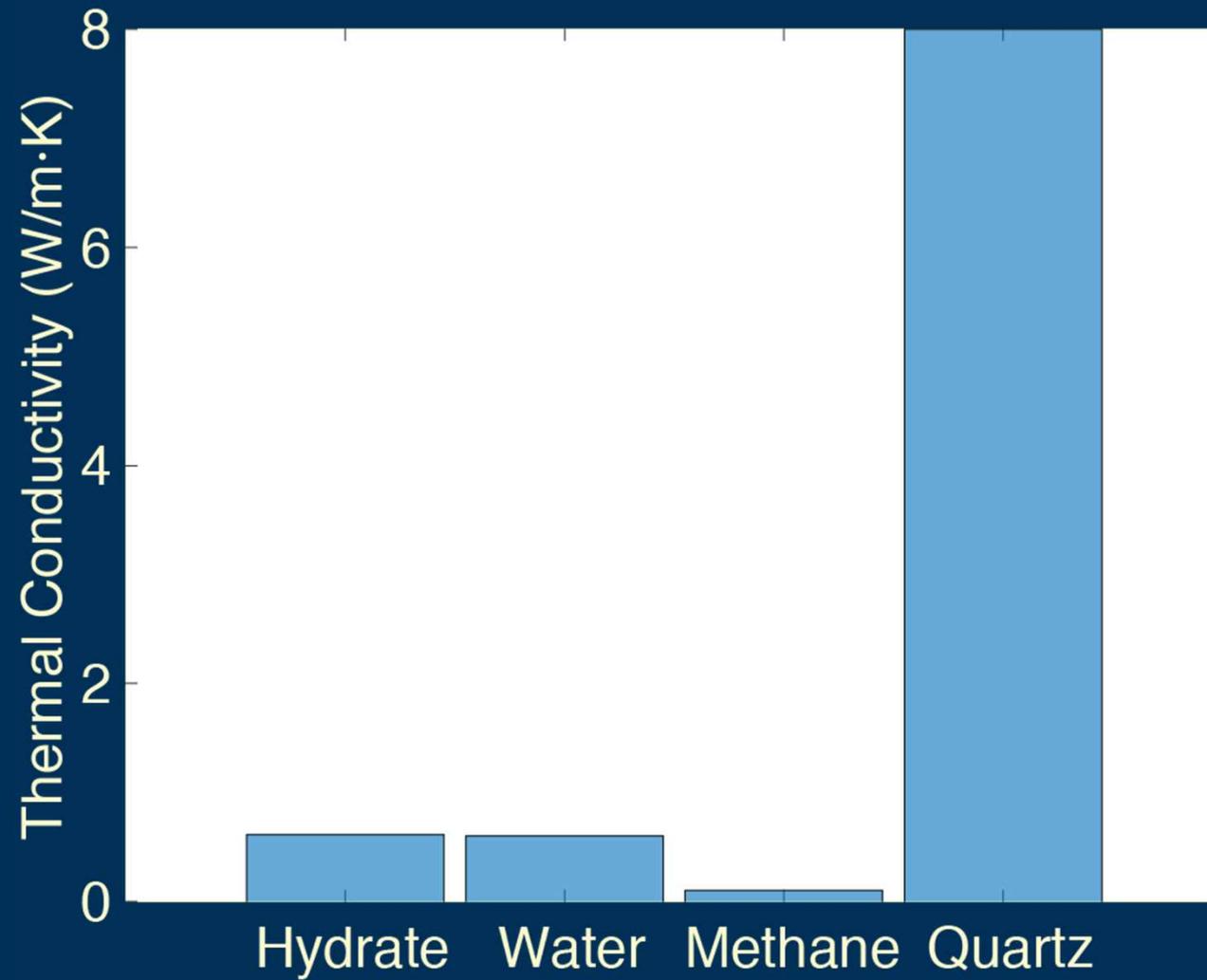
Thermal Conductivity, λ (W/(m·K))
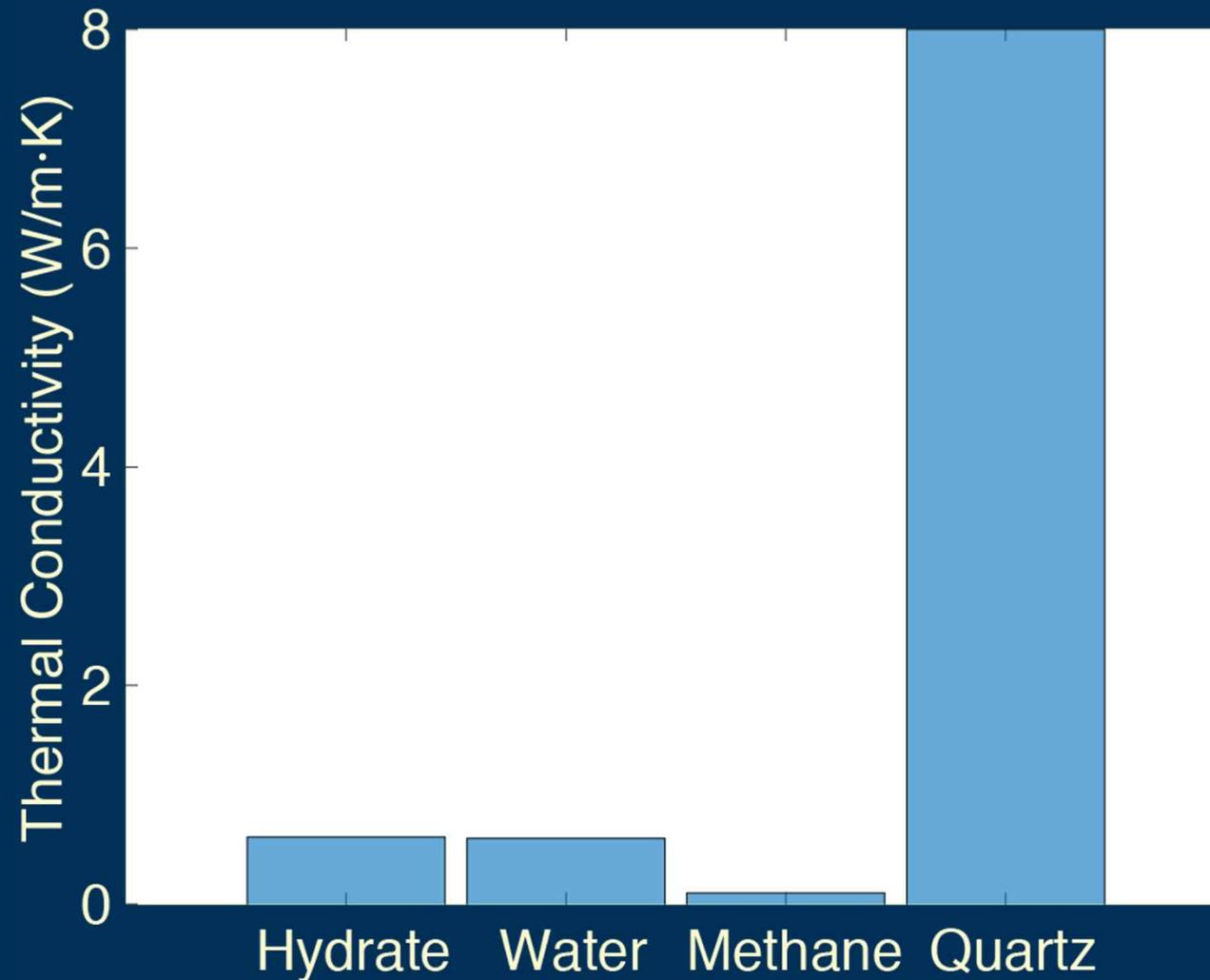
Thermal conductivity depends mostly on porosity (how much high λ sediment is present) and on gas saturation.
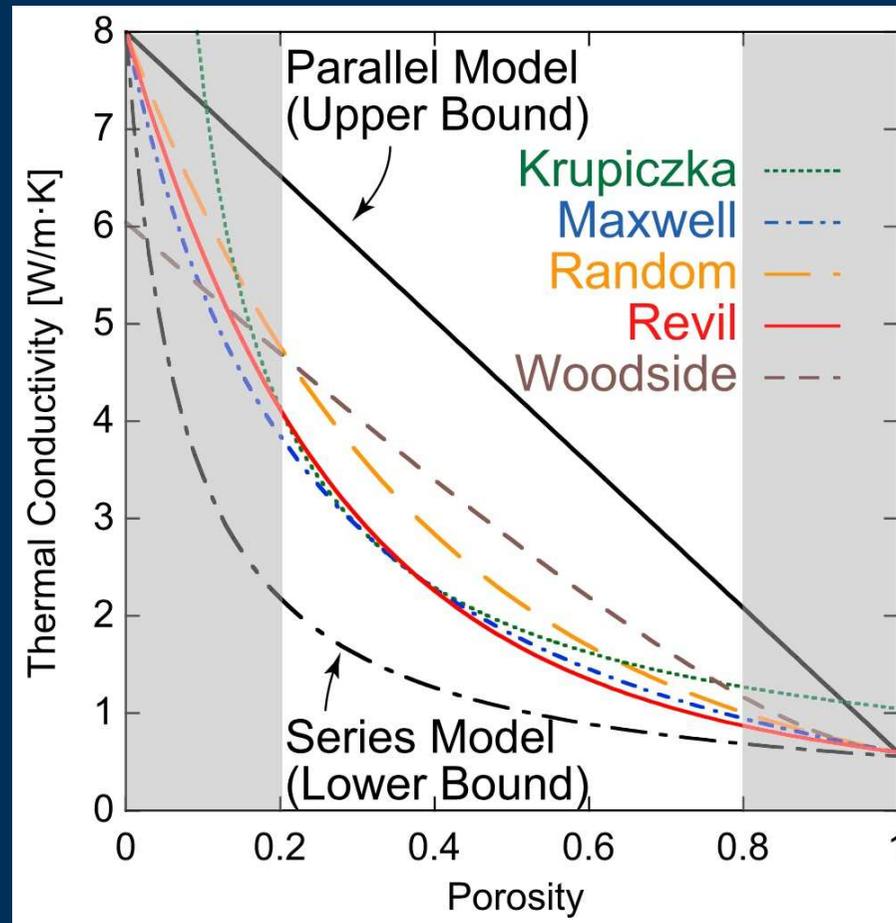
Thermal conductivity mixing models (no gas)

Mixing models use different ideas about
how particles and fluid are arranged.

Thermal conductivity mixing models (no gas)

Parallel heat flow

Parallel Model (Upper Bound)

Krupiczka
Maxwell
Random
Revil
Woodside

Thermal Conductivity [W/m·K]

Series Model (Lower Bound)

Porosity

High λ
Low λ

Mixing models use different ideas about
how particles and fluid are arranged.

Thermal conductivity mixing models (no gas)

Parallel heat flow

Series heat flow

- High λ
- Low λ

Mixing models use different ideas about
how particles and fluid are arranged.

Thermal conductivity mixing models (no gas)

Parallel heat flow

Series heat flow

Parallel Model (Upper Bound)

Krupiczka
Maxwell
Random
Revil
Woodside

Series Model (Lower Bound)

Thermal Conductivity [W/m·K]

Porosity

High λ
Low λ

Typical values

Mixing models use different ideas about
how particles and fluid are arranged.

Waite et al. (2009), Rev. of Geophys.

Thermal conductivity mixing models (no gas)

| Model	Equation for the Estimation of $\lambda_{\text{effective}}$
Parallel (upper bound) [*Huang and Fan*, 2005]	$\phi\,\lambda_f + (1-\phi)\lambda_s$
Series (lower bound) [*Huang and Fan*, 2005]	$\dfrac{\lambda_s\lambda_f}{\phi\,\lambda_s + (1-\phi)\,\lambda_f}$
Krupiczka [1967]	$\lambda_f\left(\dfrac{\lambda_s}{\lambda_f}\right)^{A+B\log_{10}\left(\frac{\lambda_s}{\lambda_f}\right)}$, $A = 0.280 - 0.757\log_{10}(\phi)$, $B = -0.057$
Maxwell [1954]	$\lambda_f\dfrac{2\phi\lambda_f + (3-2\phi)\lambda_s}{(3-\phi)\lambda_f + \phi\lambda_s}$
Random [*Huang and Fan*, 2005]	$\lambda_f^{\phi}\lambda_s^{(1-\phi)}$
Revil [2000]	$\dfrac{\lambda_f}{\xi}\left[\xi\,\Theta + \tfrac{1}{2}(1-\Theta)\left(1 - \Theta + \sqrt{(1-\Theta)^2 + 4\xi\,\Theta}\right)\right]$, $\Theta = \dfrac{\lambda_s}{\lambda_f}$, $\xi = \phi^{\left(\frac{m}{1-m}\right)}$
Woodside and Messmer [1961]	$A\lambda_f + \dfrac{B\lambda_s\lambda_f}{\lambda_s(1-C) + C\lambda_f}$, $A = \phi - 0.03$, $B = 1 - A$, $C = (1-\phi)/B$

Mixing models are all based on how much of each type of material is present. Equations differ based on assumed distribution of materials.

Models collected in: Waite et al. (2009), Rev. of Geophys.

Measured thermal conductivity in hydrate-bearing sediment

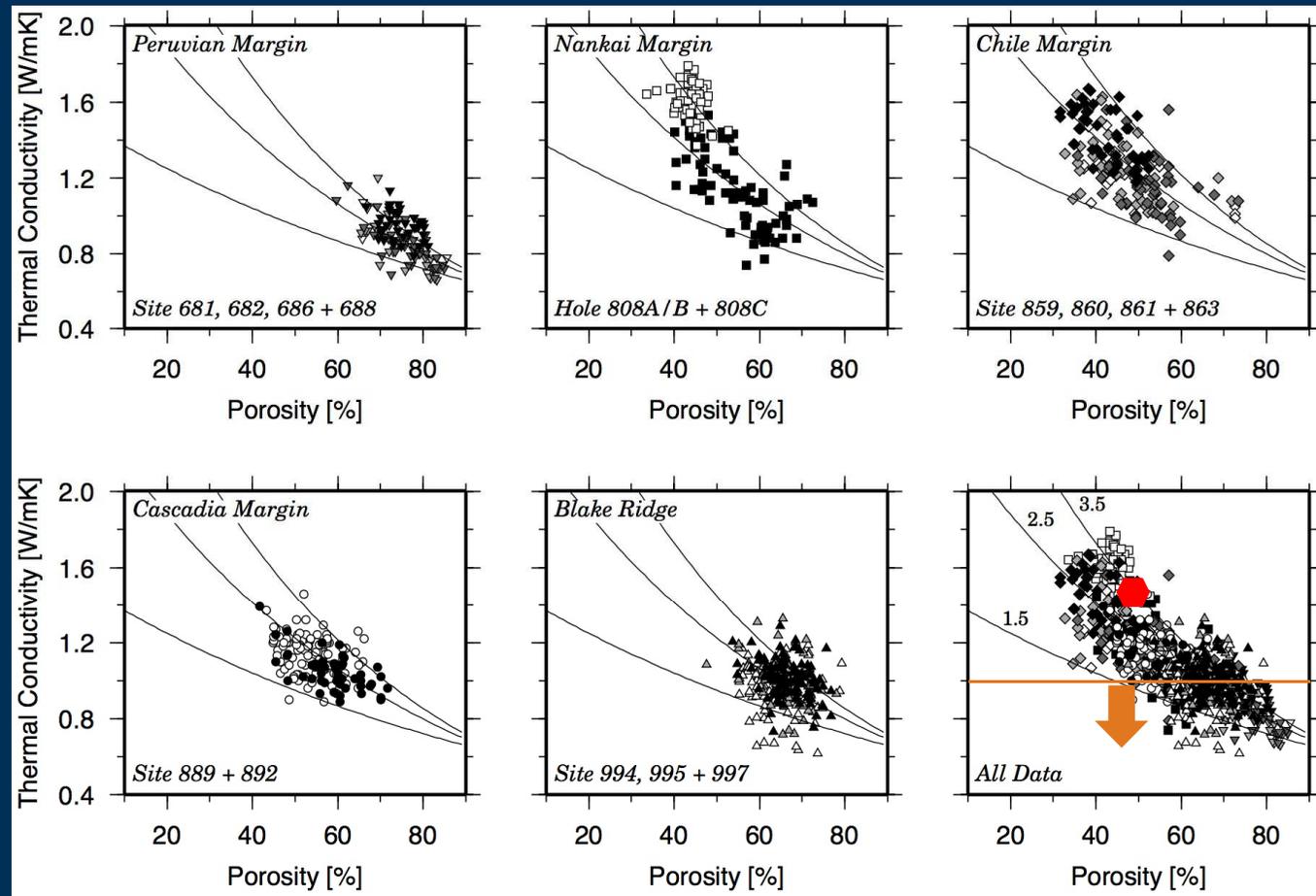Grevemeyer and Villinger (2001), GJI
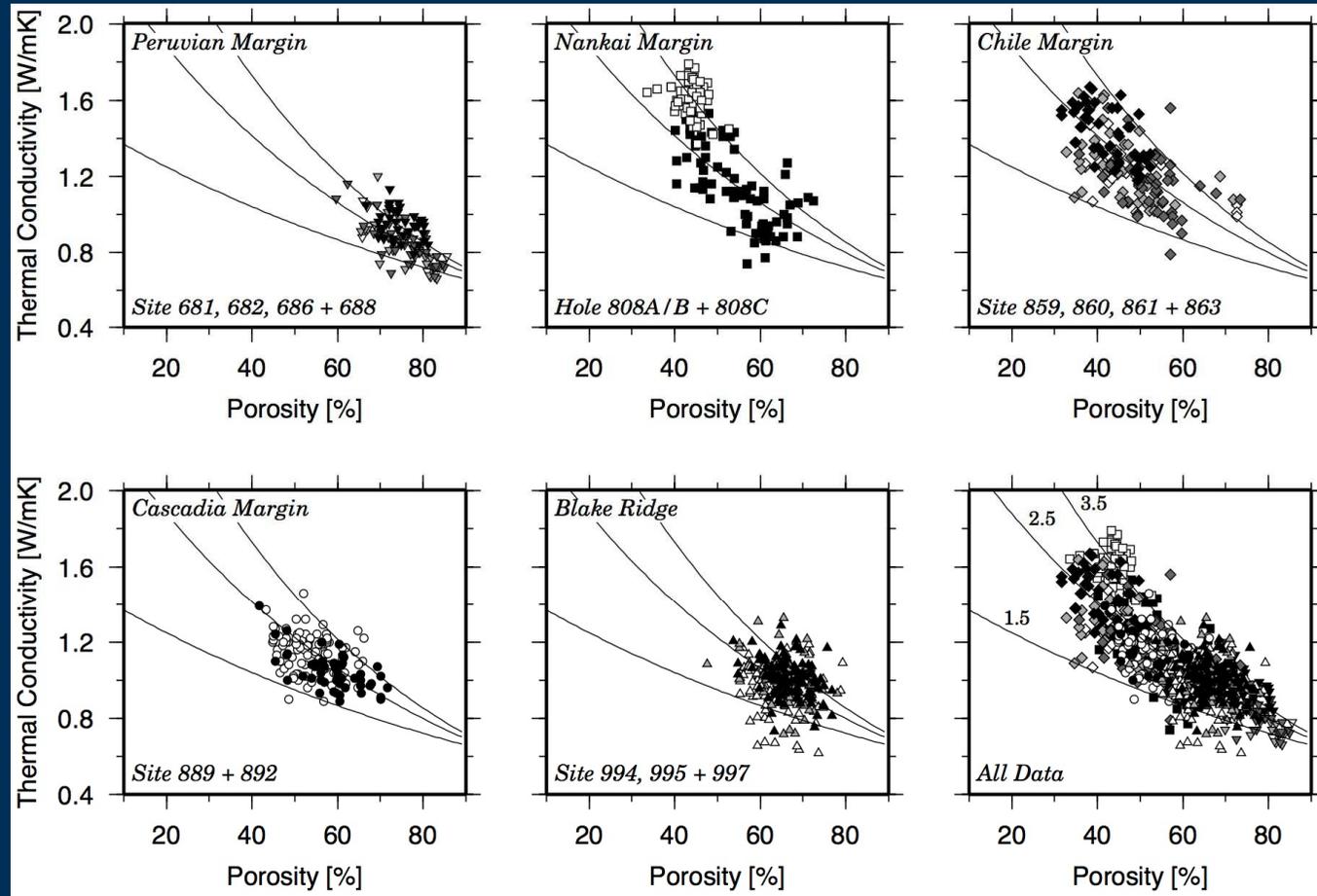
Measured thermal conductivity in hydrate-bearing sediment
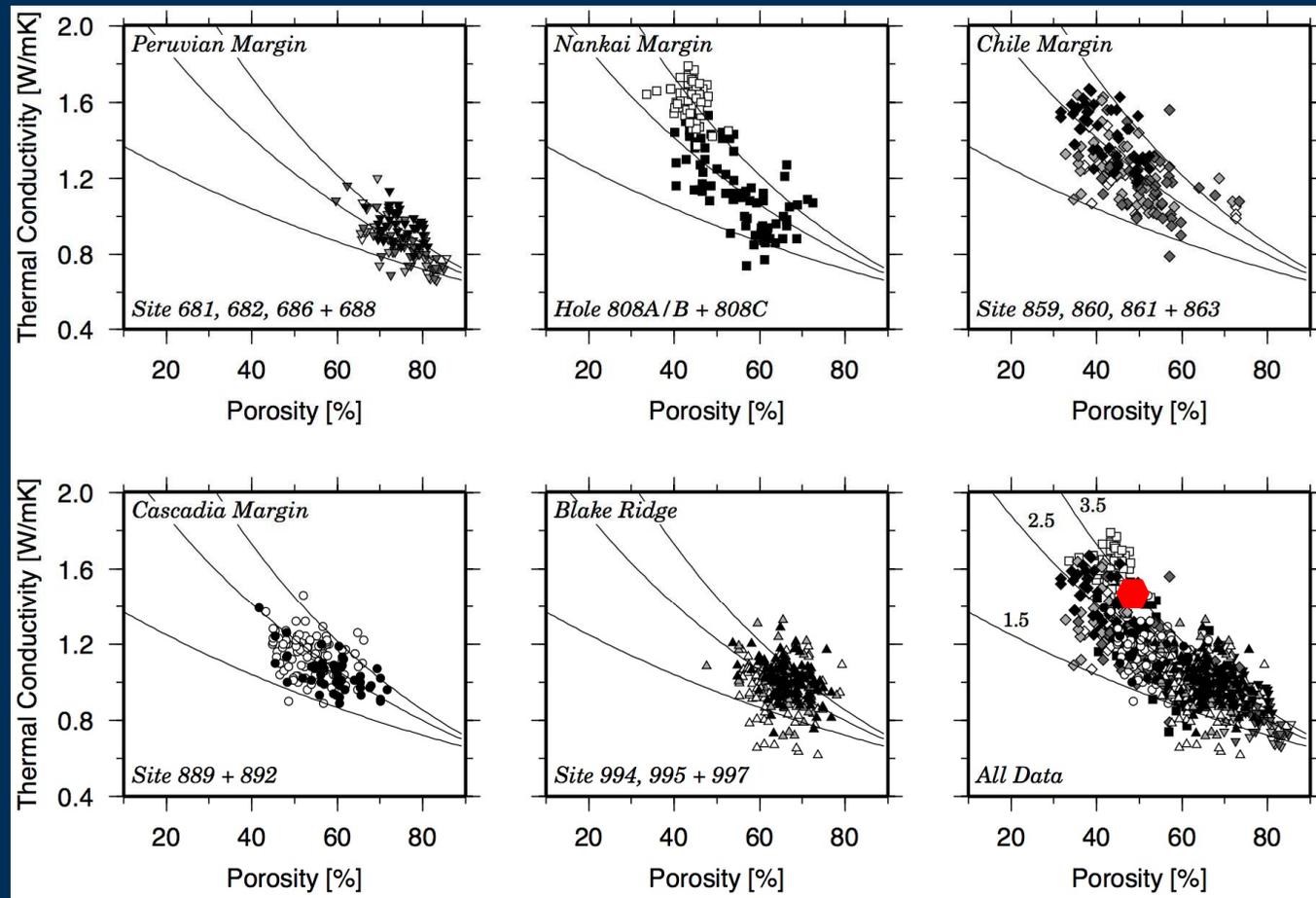
Measurements of thermal conductivity from UBGH2 (offshore Korea) also fall within this trend.

Kim and Yun, (2013), MPG

Measured thermal conductivity in hydrate-bearing sediment

Caution: thermal conductivity values below ~1W/(m·K) are likely due to very high porosity, or cracks or gas in the specimen.

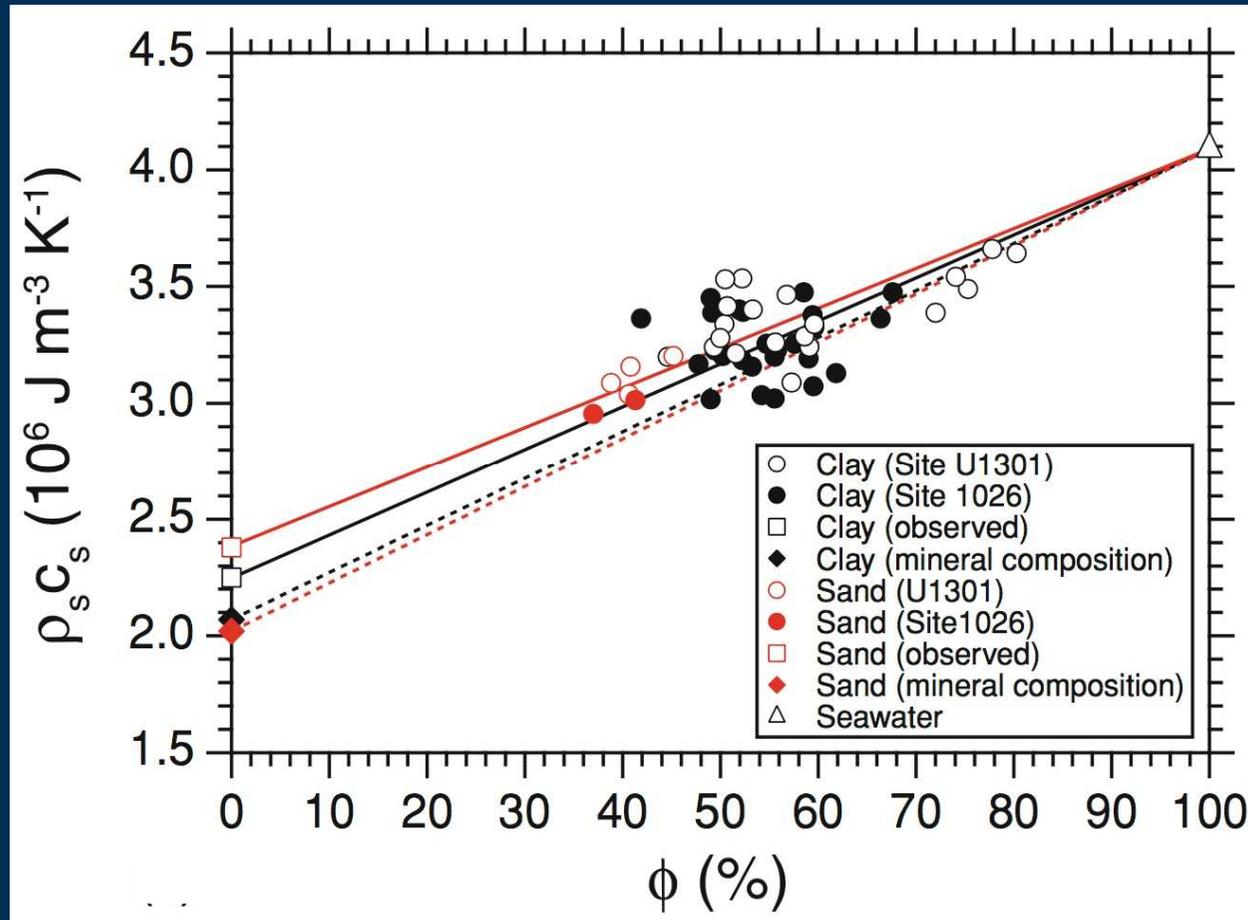Specific Heat, c_p (J/(kg·K))
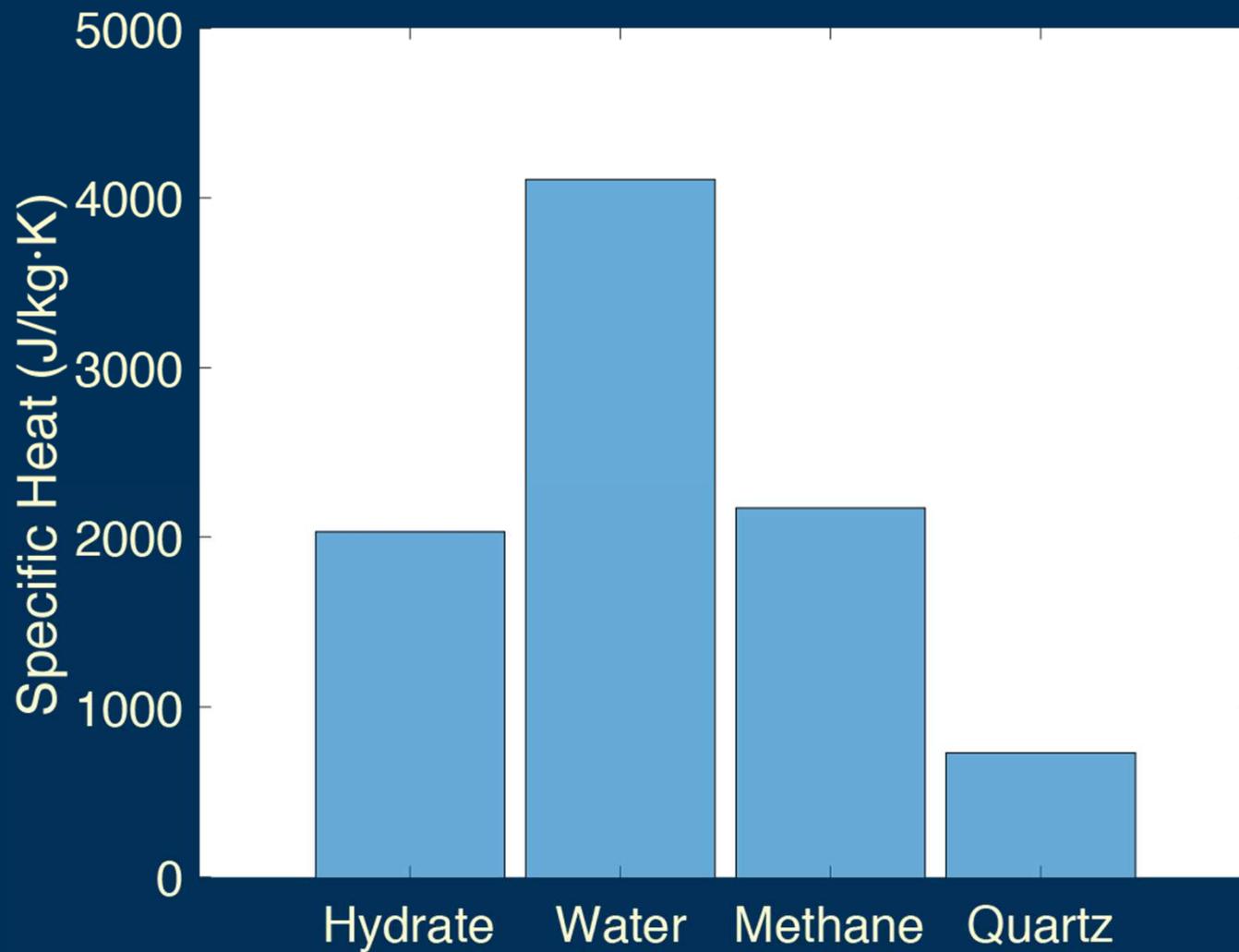
Specific Heat, c_p (J/(kg·K))
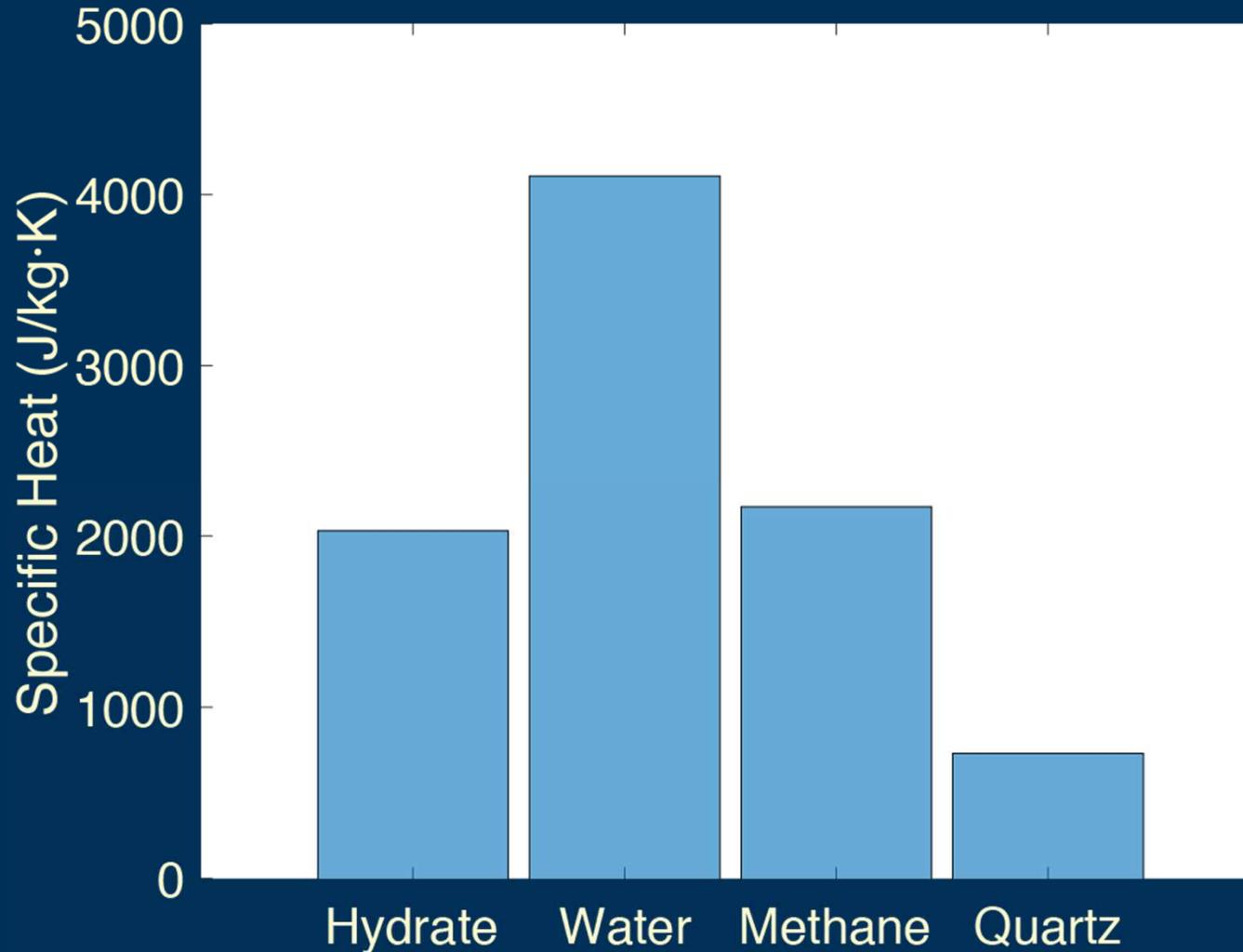
Water is effective for heat storage, but the low value for quartz indicates external heat is required for hydrate dissociation

Heat Capacity = Density·Specific Heat: ρc_p (J/(m³·K))

Juan de Fuca Ridge (offshore North America)

Increase with porosity shows the low specific heat of quartz.

Heat Capacity = Density·Specific Heat: ρc_p (J/(m³·K))
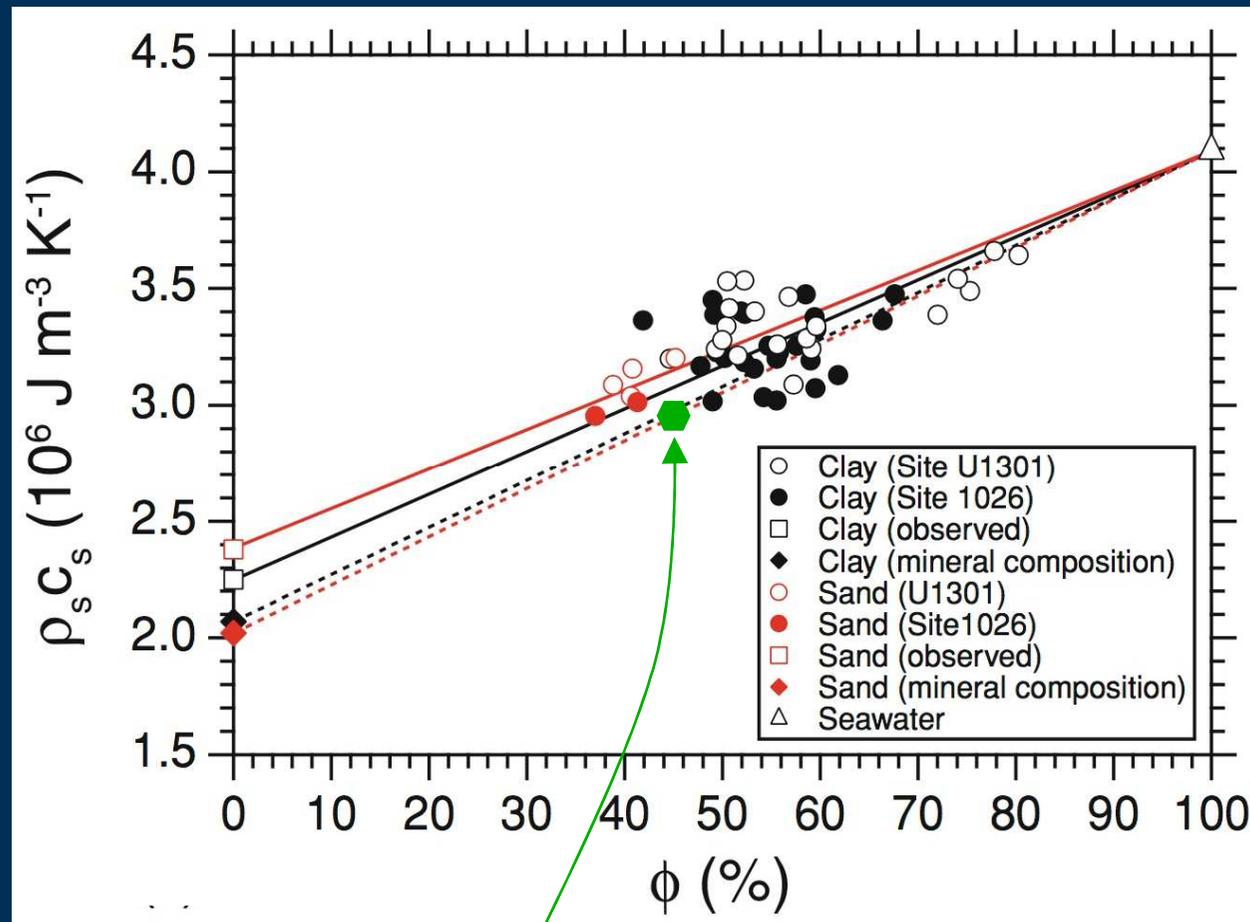
Juan de Fuca Ridge (offshore North America)

Measurements from the 2004 Nankai Trough hydrate research well (offshore Japan) agree with non-hydrate sediment results.

Muraoka et al. (2014), JGR

Thermal Diffusivity, κ (m²/s)

Thermal Diffusivity, κ (m²/s)

Temperature can change most rapidly in the quartz

Thermal Diffusivity, κ (m²/s)

Juan de Fuca Ridge (offshore North America)

Decrease with porosity shows the high diffusivity of quartz.
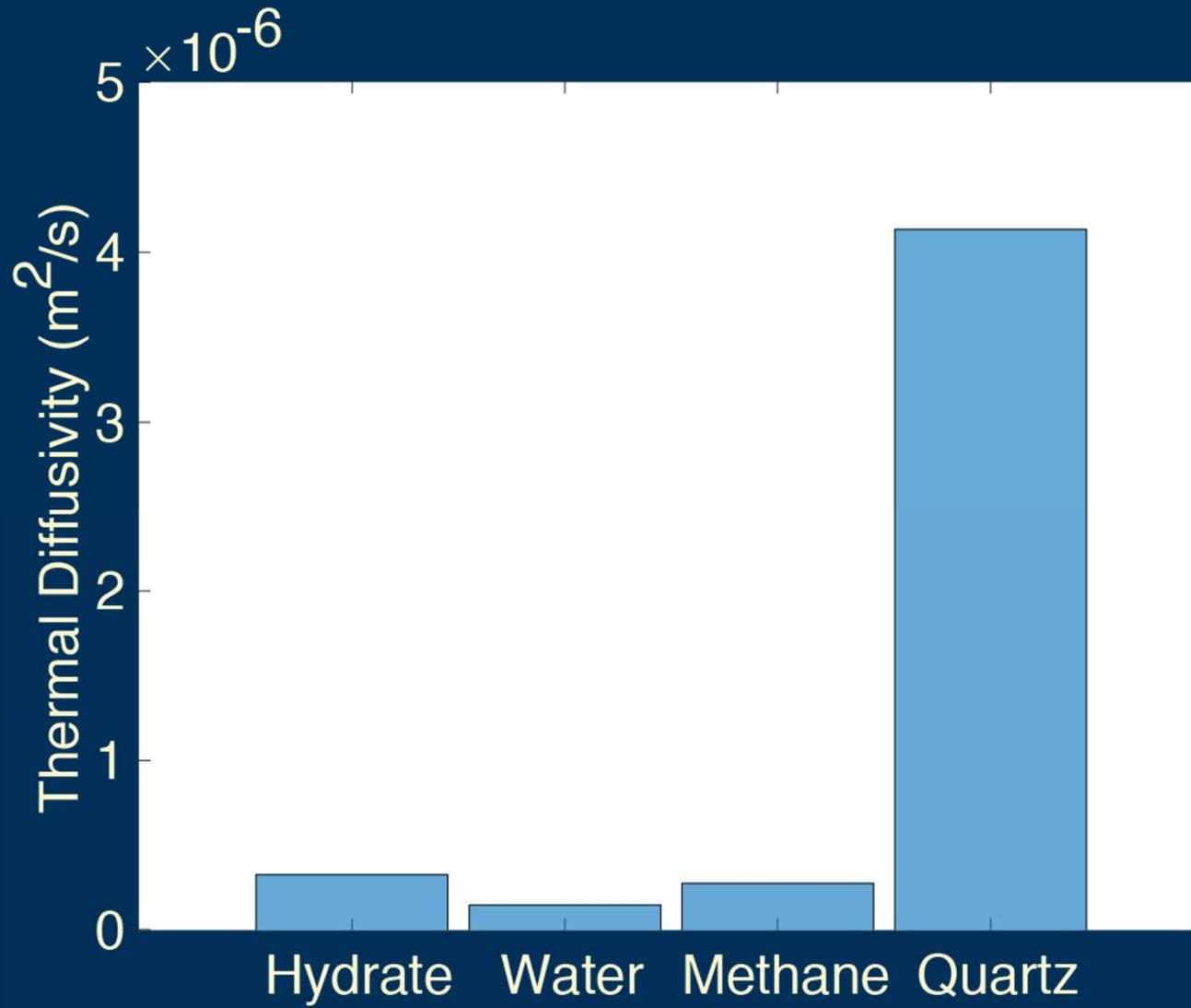
Thermal Diffusivity, κ (m²/s)
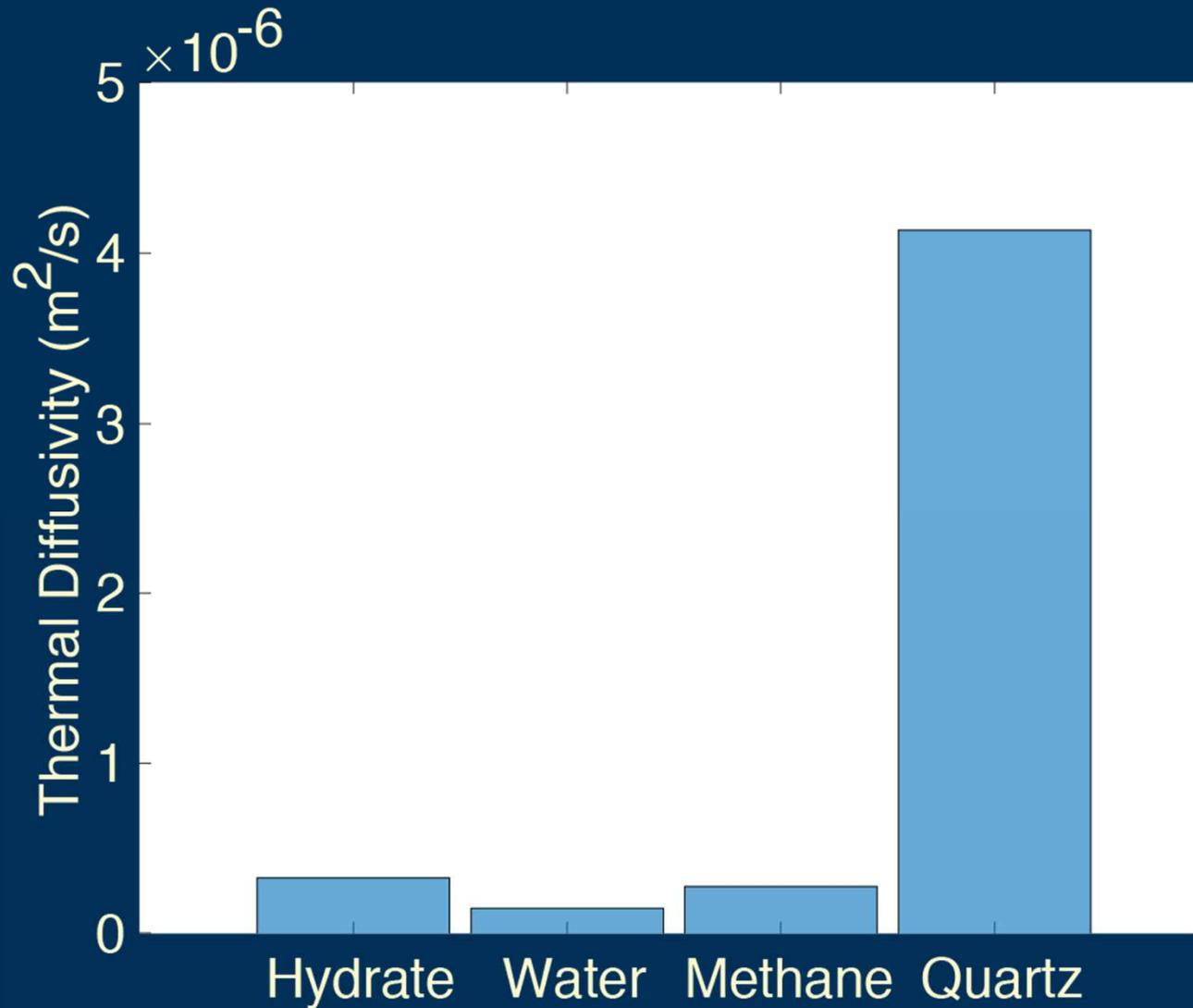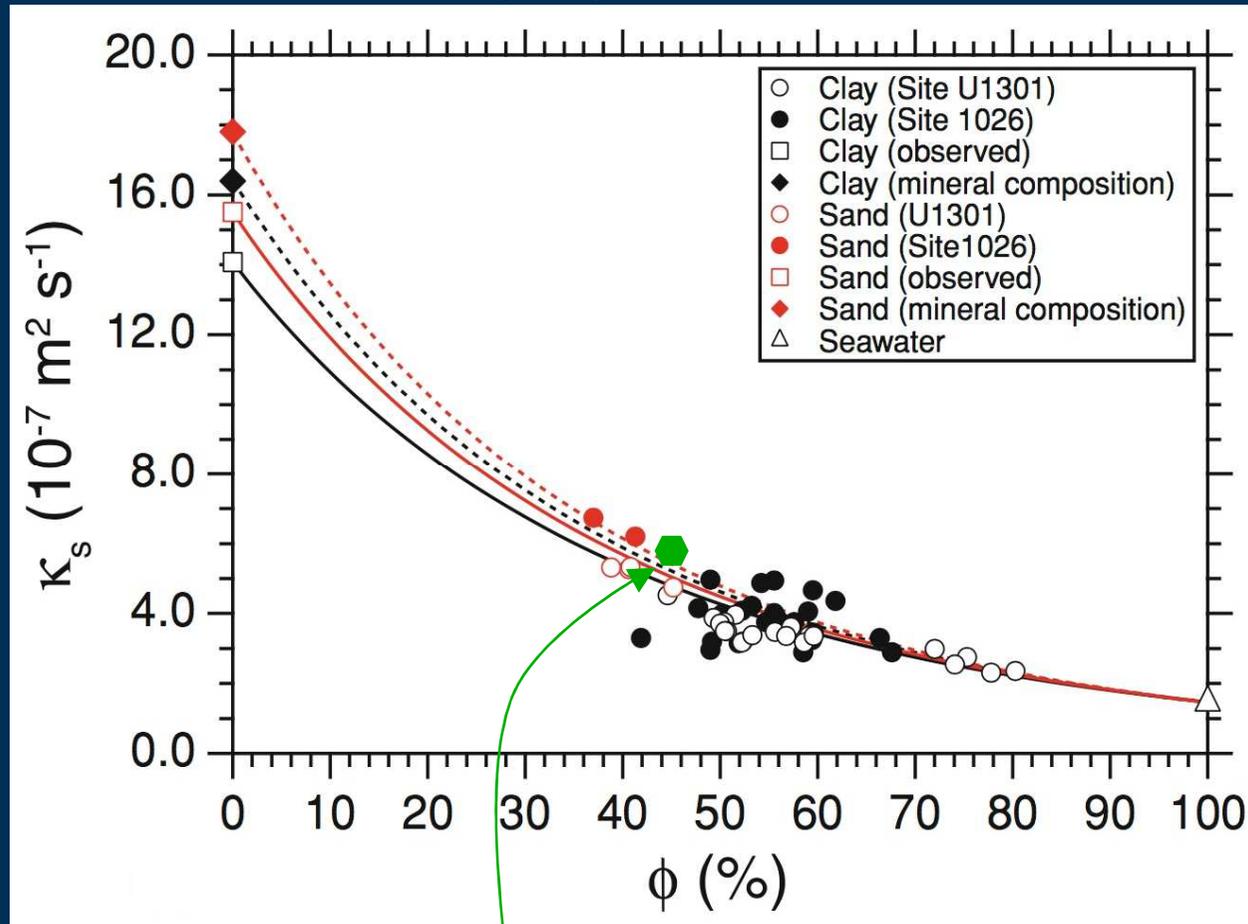
Juan de Fuca Ridge (offshore North America)

Measurements from the 2004 Nankai Trough hydrate research well (offshore Japan) agree with non-hydrate sediment results.

Muraoka et al. (2014), JGR

Thermal Summary – Tracking heat flow
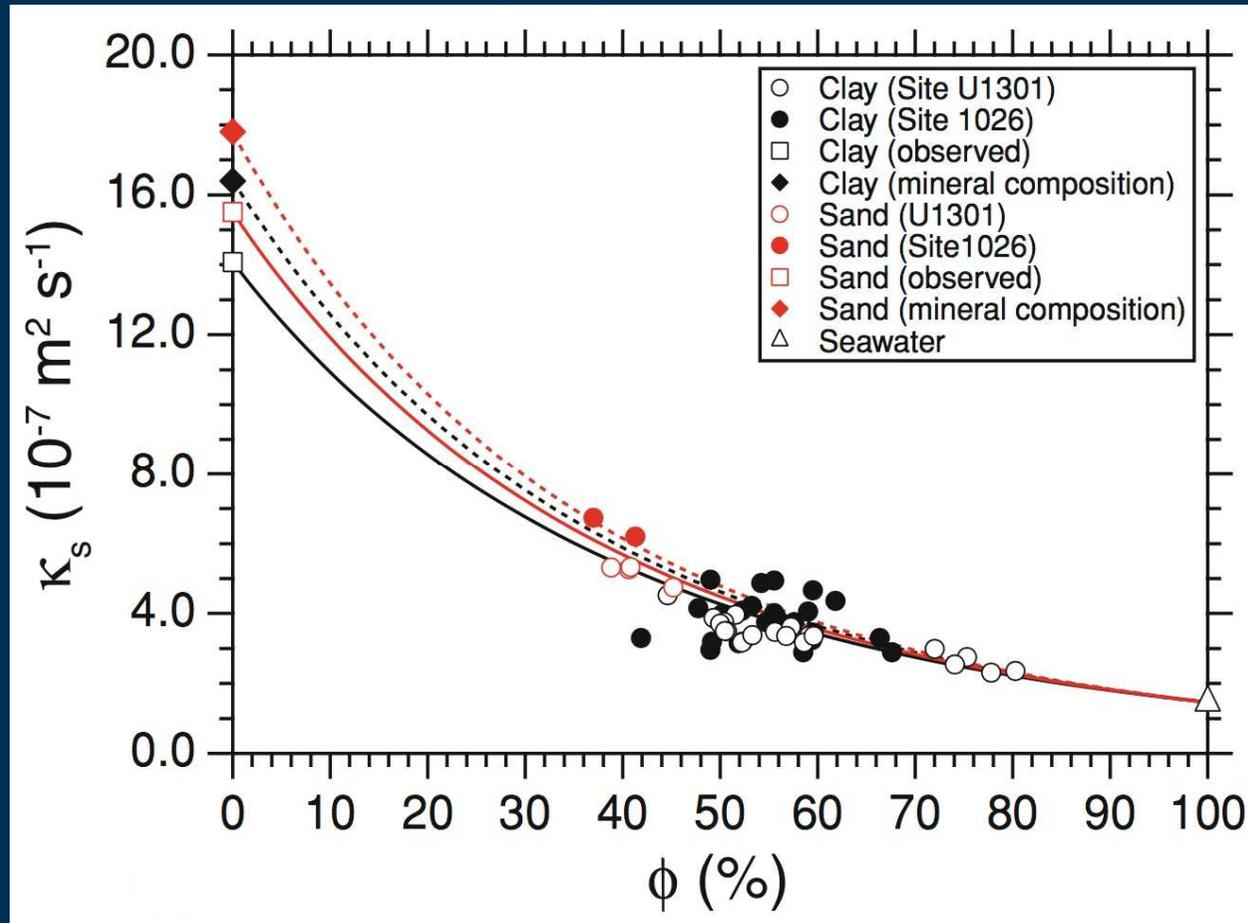
Heat will move to where gas hydrate is dissociating.

More heat means faster dissociation.

Thermal Summary – Tracking heat flow

Heat will move to where gas hydrate is dissociating.

More heat means faster dissociation.

Heat supplied from:
- Warm fluid drawn in by depressurization.

Yamamoto et al. (2015), Marine Petroleum Geology
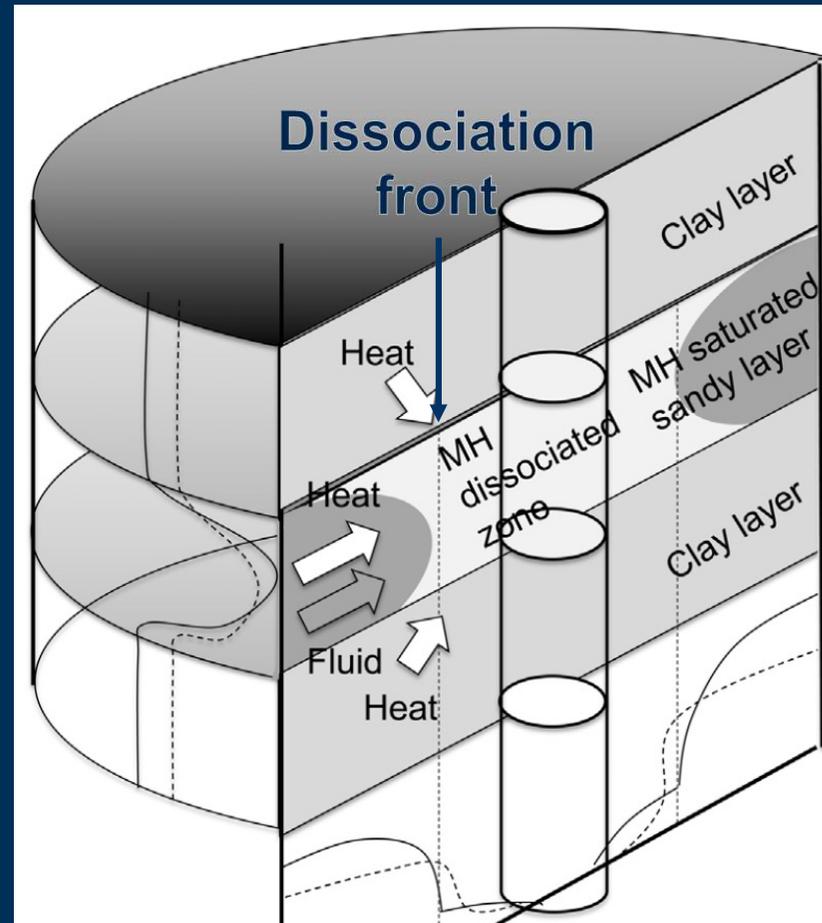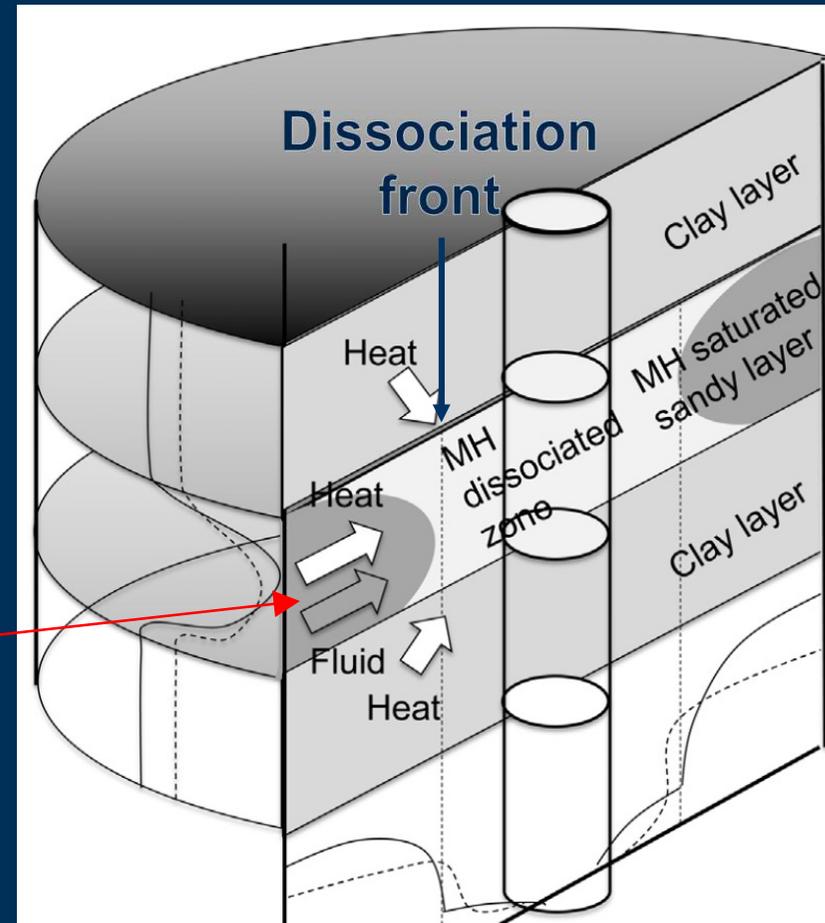
Thermal Summary – Tracking heat flow

Heat will move to where gas hydrate is dissociating.

More heat means faster dissociation.

Heat supplied from:
- Warm fluid drawn in by depressurization.

- Heat supplied from neighboring sediment. Is there a perfect hydrate layer thickness for gathering heat?

Yamamoto et al. (2015), Marine Petroleum Geology
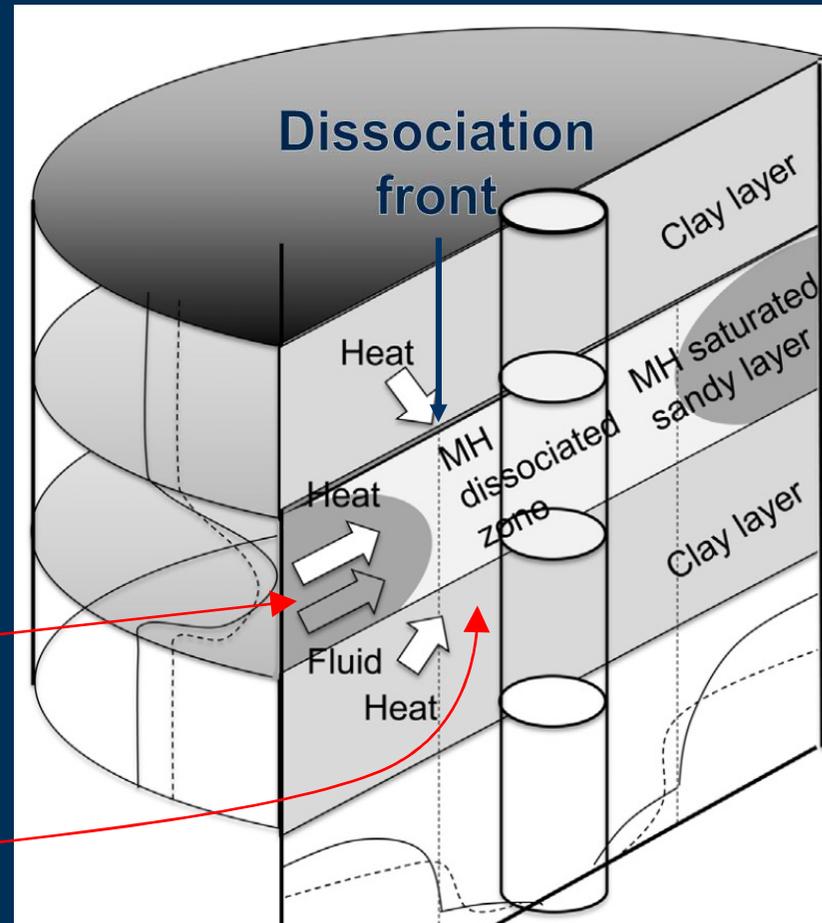
Interbeds may be a source of heat for dissociation
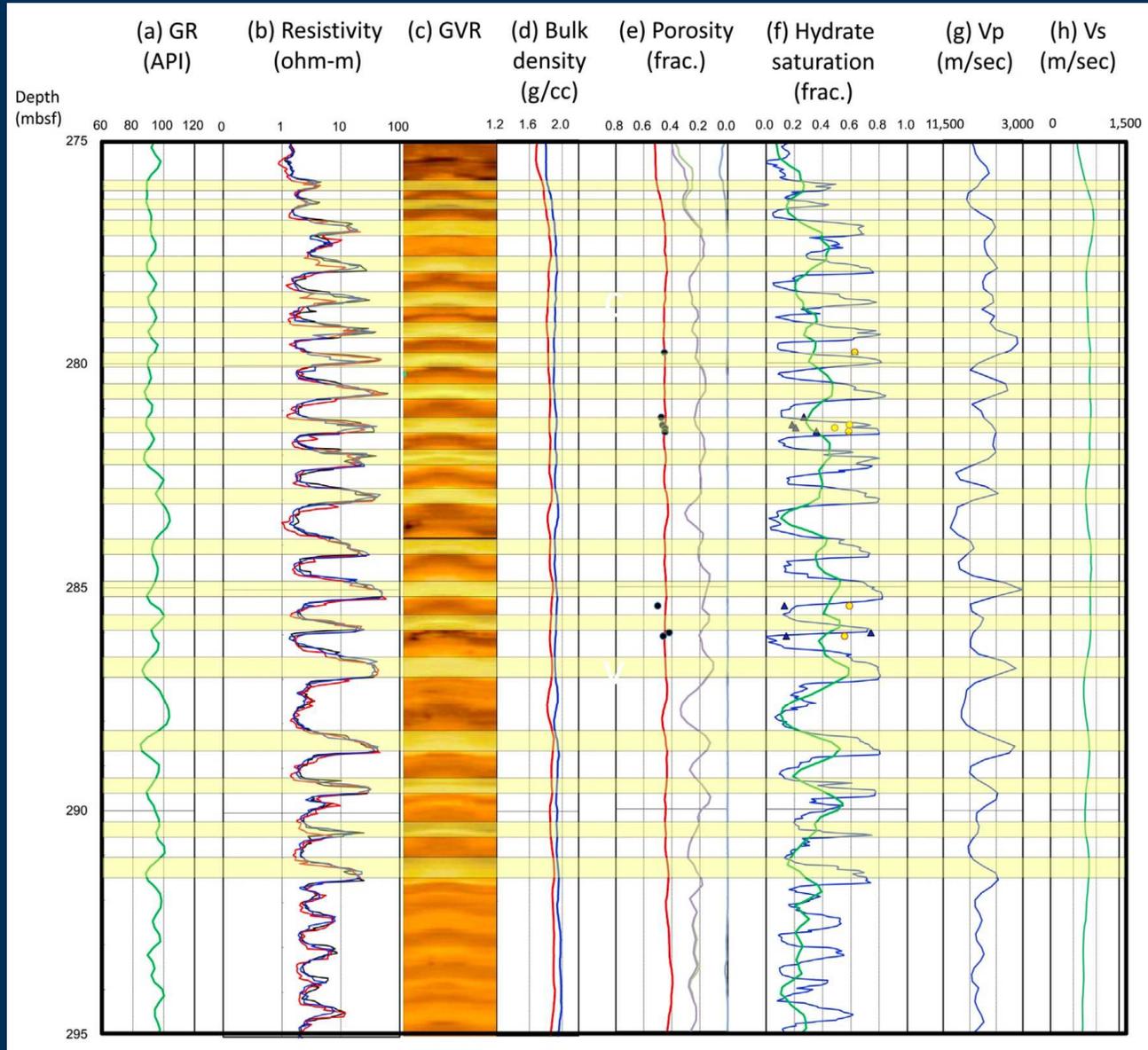
Interbeds may be a source of heat for dissociation
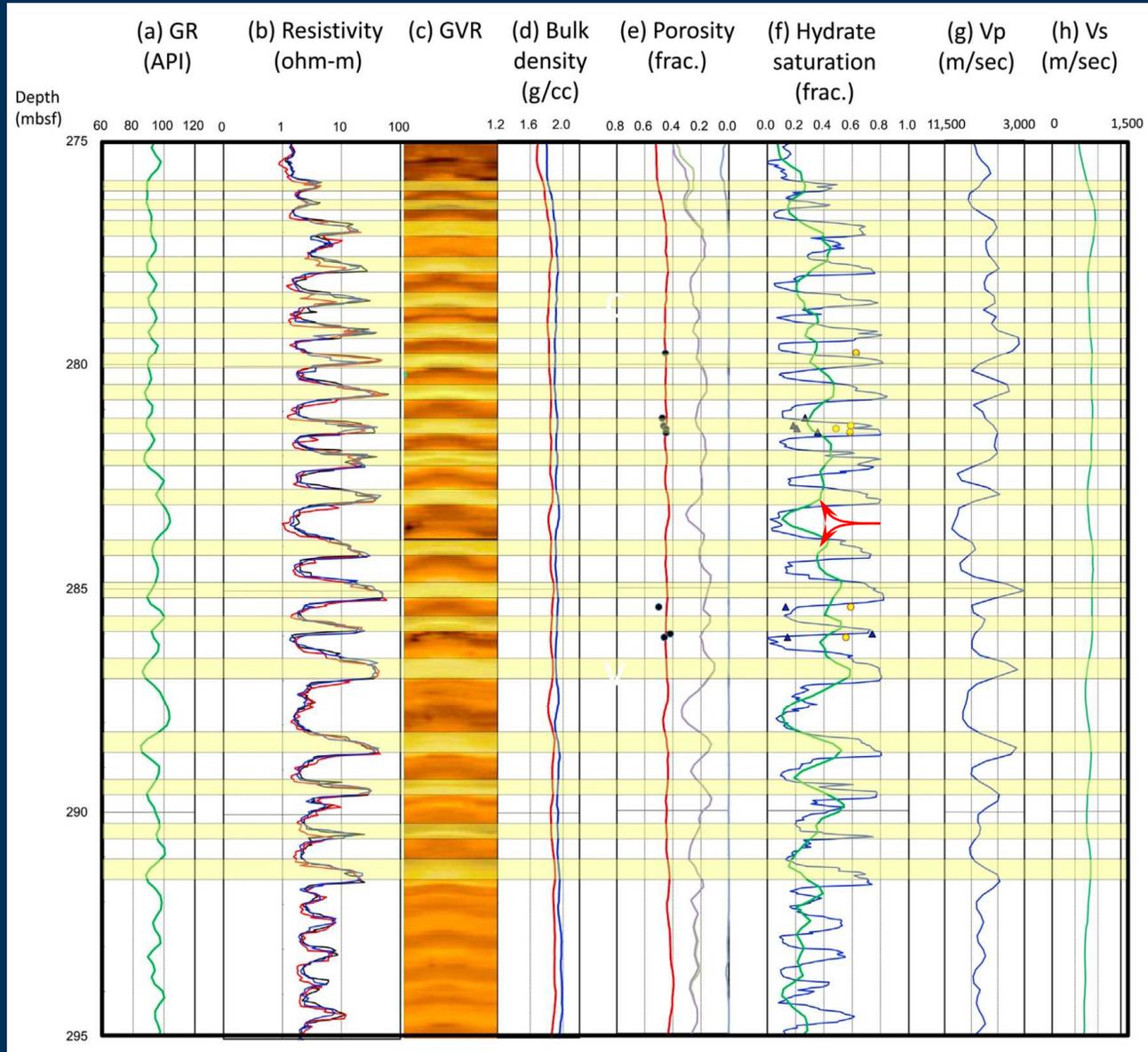
In addition to heat and fluid… sediment also moves

In addition to heat and fluid… sediment also moves

Production via depressurization reduces pressure in the sediment pore space. This *increases* the effective stress on the sediment grains because the water pressure helped support the weight of the overlying water and sediment.

How much depressurization is required?
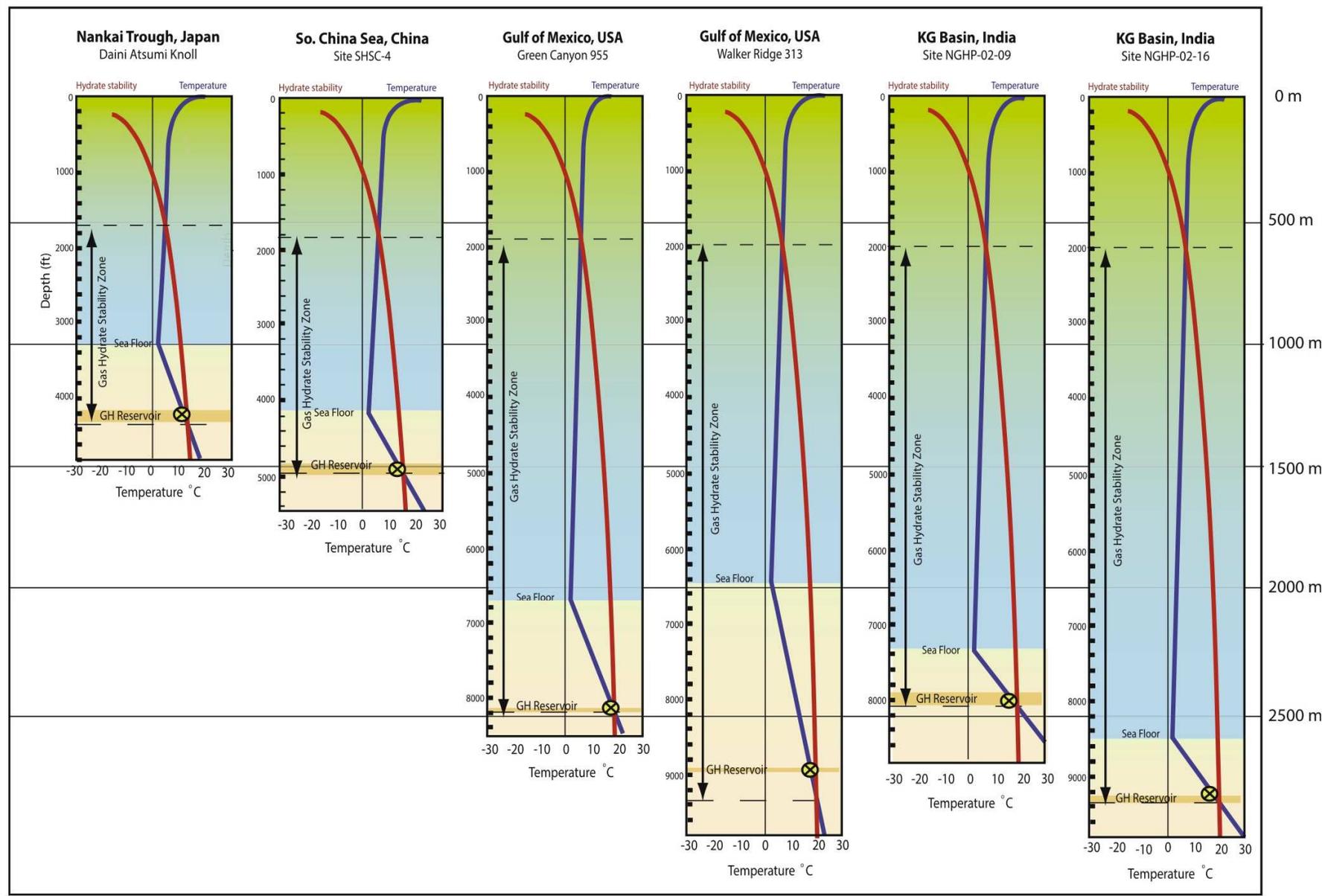
How much depressurization is required?
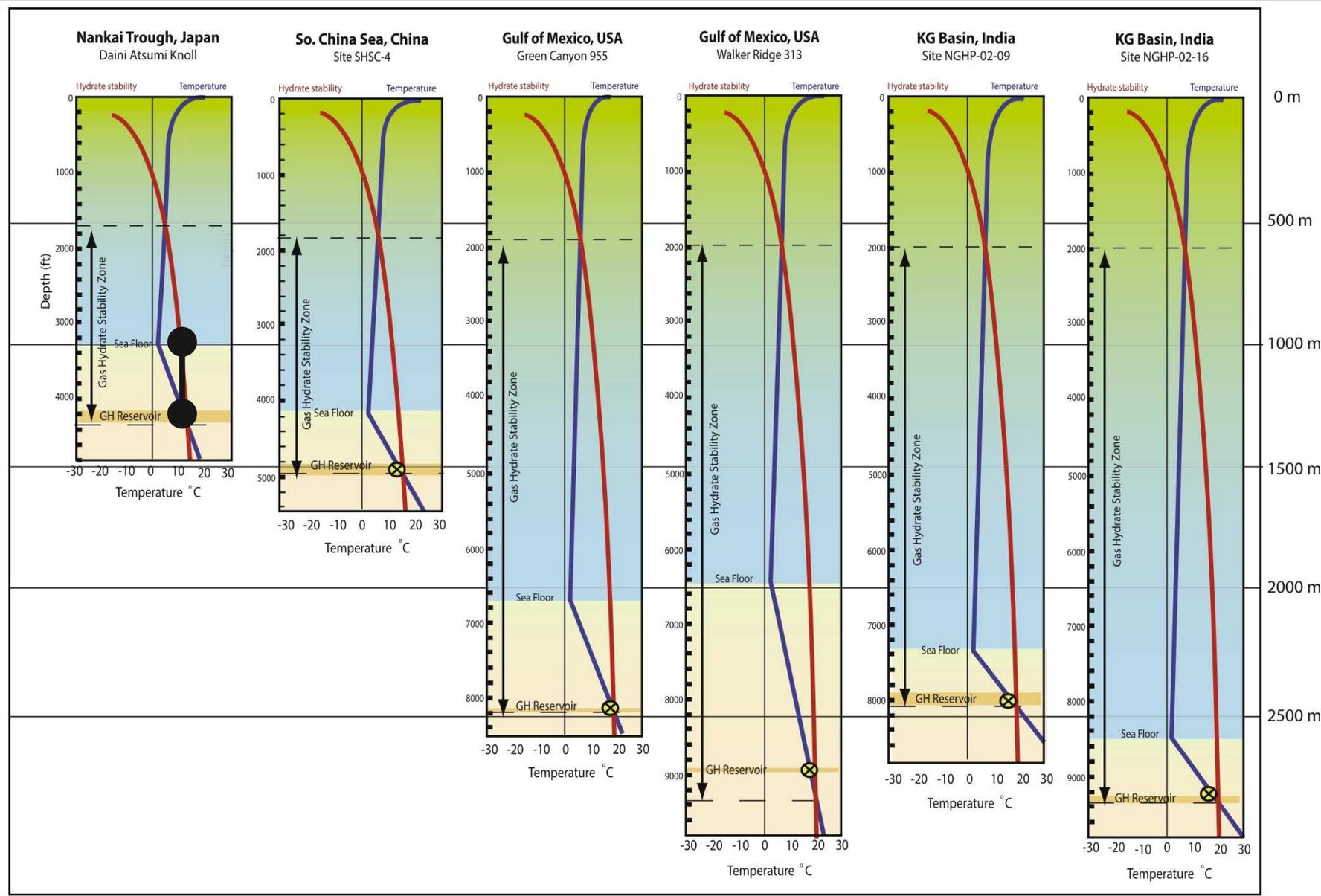
How much depressurization is required?

How much depressurization is required?

Deeper systems can require *large* depressurizations

Boswell et al. (2018), JMPG

How will the depressurization effect the sediment?

Production via depressurization reduces pressure in the sediment pore space. This _increases_ the effective stress on the sediment grains because the water pressure helped support the weight of the overlying water and sediment.

- _Shear strength_: will stress changes during methane production cause the sediment to fail and potentially collapse into the borehole?

How will the depressurization effect the sediment?

Production via depressurization reduces pressure in the sediment pore space. This _increases_ the effective stress on the sediment grains because the water pressure helped support the weight of the overlying water and sediment.
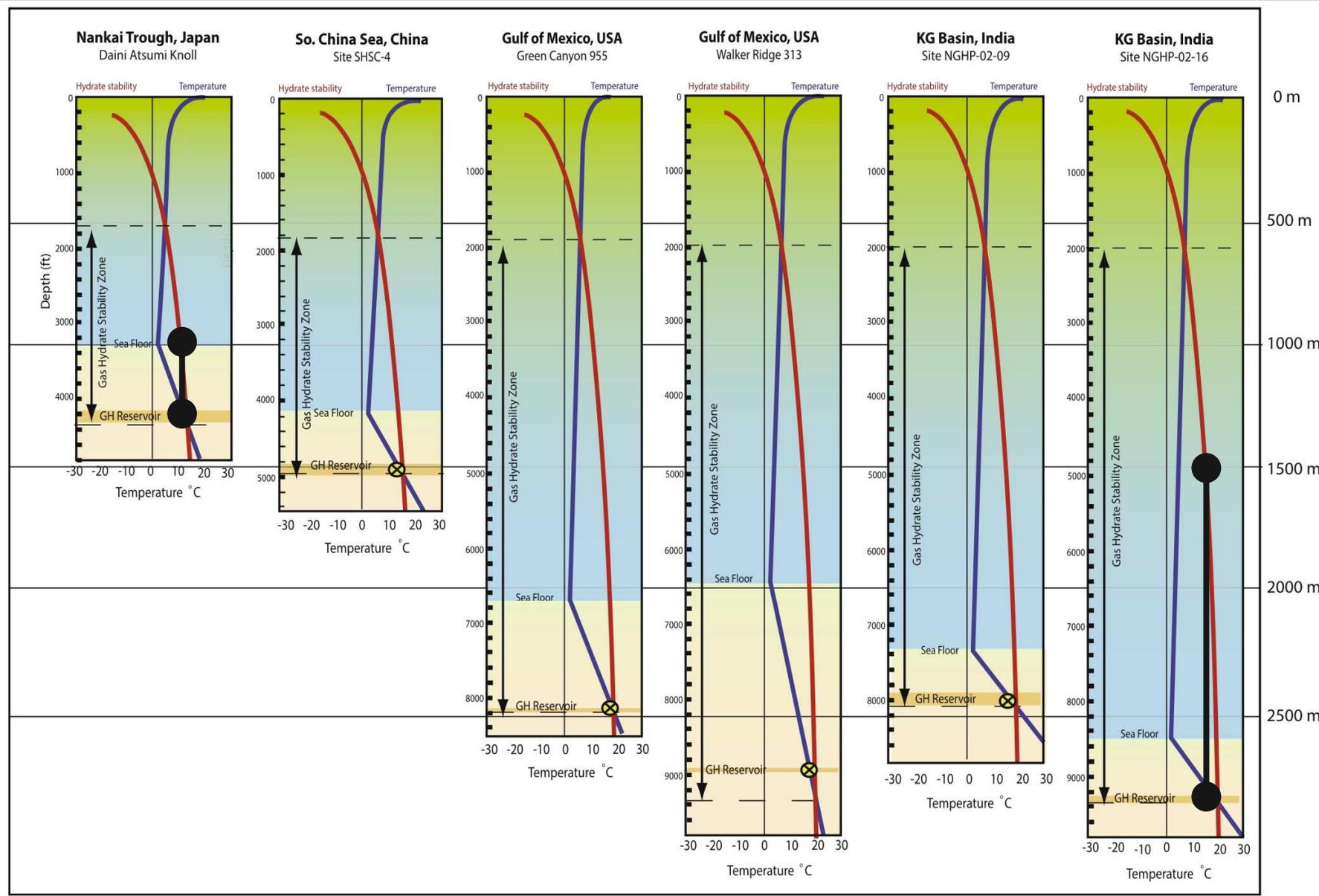
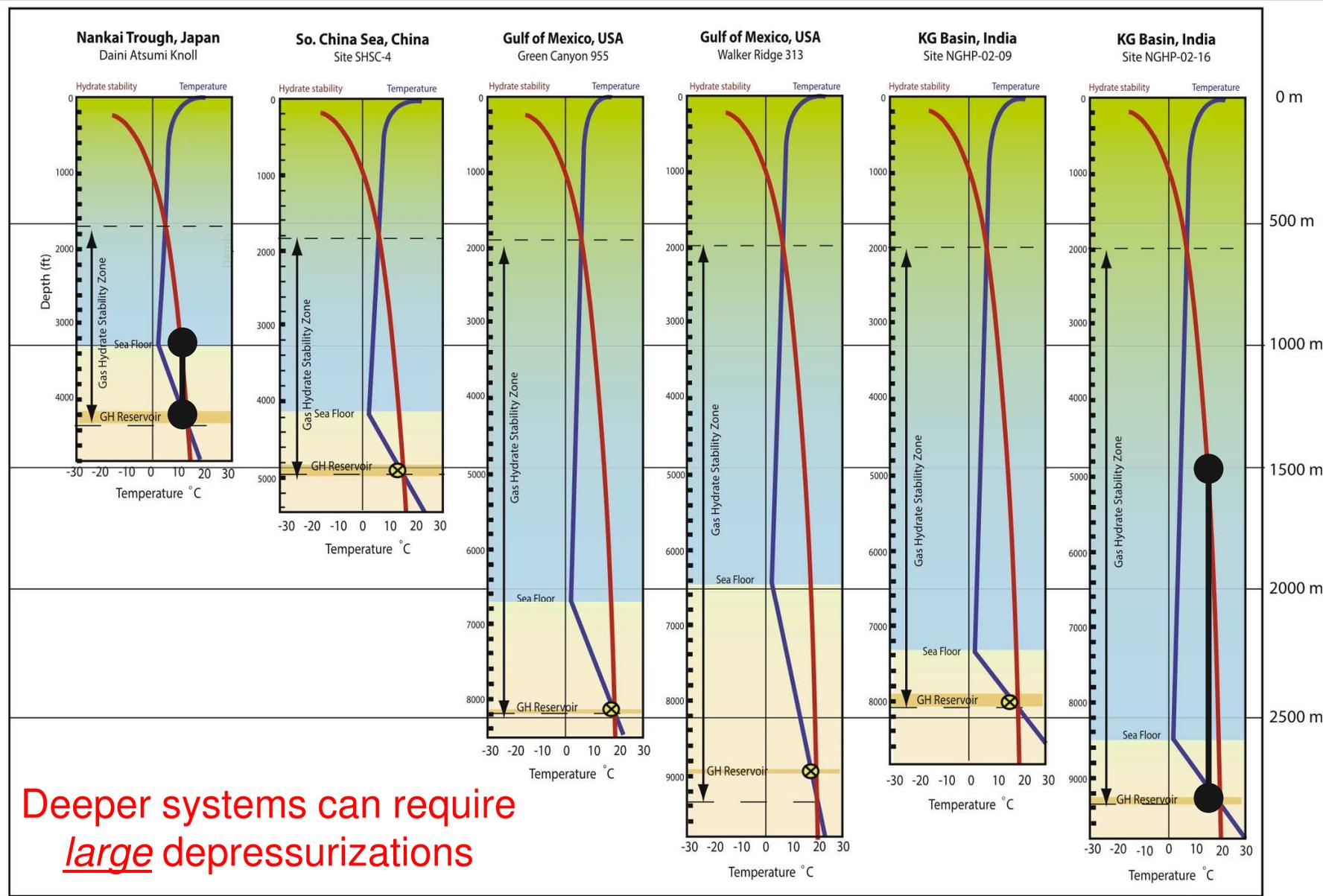- _Shear strength_: will stress changes during methane production cause the sediment to fail and potentially collapse into the borehole?

- _Consolidation_: how much will stress changes during production cause the sediment to settle, taking up less volume by reducing porosity? A porosity decrease can reduce permeability and flow efficiency.

Shear strength: will the sediment fail?

Sediment does not generally feel a vertical stress that is the same as the horizontal stress. If the two stresses differ by enough, the sediment will deform, or fail.

Vertical stress

Radial Stress

Digital image p

Yoneda et al. (2017), Marine and Petroleum Geology
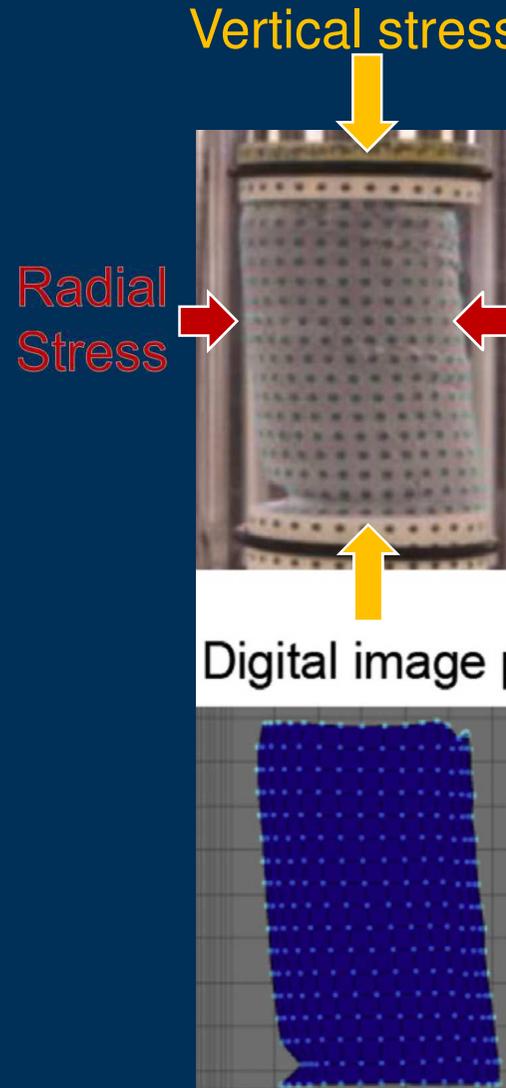
Shear strength: will the sediment fail?

Sediment does not generally feel a vertical stress that is the same as the horizontal stress. If the two stresses differ by enough, the sediment will deform, or fail.

Sediment failure can be a hazard – failed sediment is more likely to move into the production well [Uchida et al., (2018), JMPG]

Vertical stress

Radial Stress

Shear

Digital image processing

Yoneda et al. (2017), Marine and Petroleum Geology
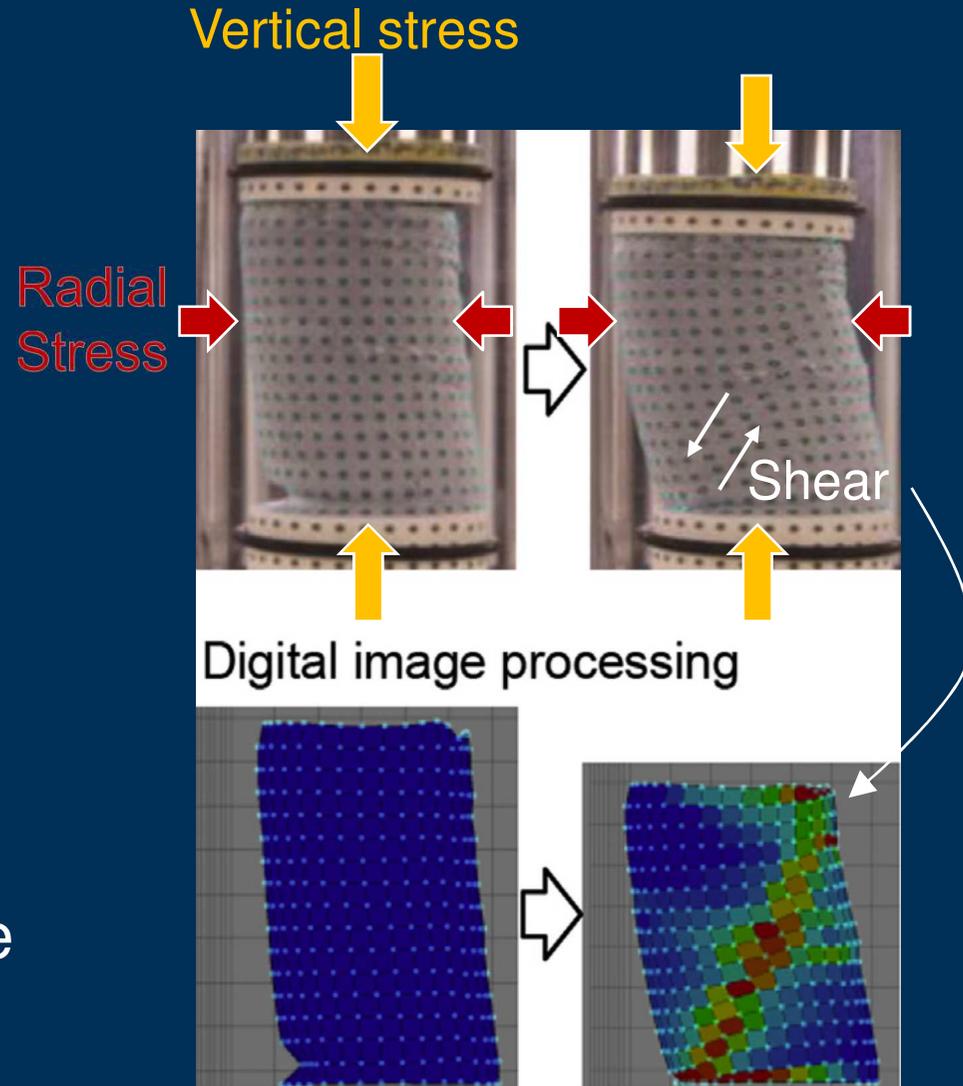
Shear strength: will the sediment fail?

Sediment does not generally feel a vertical stress that is the same as the horizontal stress. If the two stresses differ by enough, the sediment will deform, or fail.

Mohr-Coulomb Failure Criteria

τ = Cohesion + $\sigma_n \cdot$ tan(Friction Angle)

Vertical stress

Radial Stress

Shear

Digital image processing

Normal Stress, σ_n

Shear stress, τ

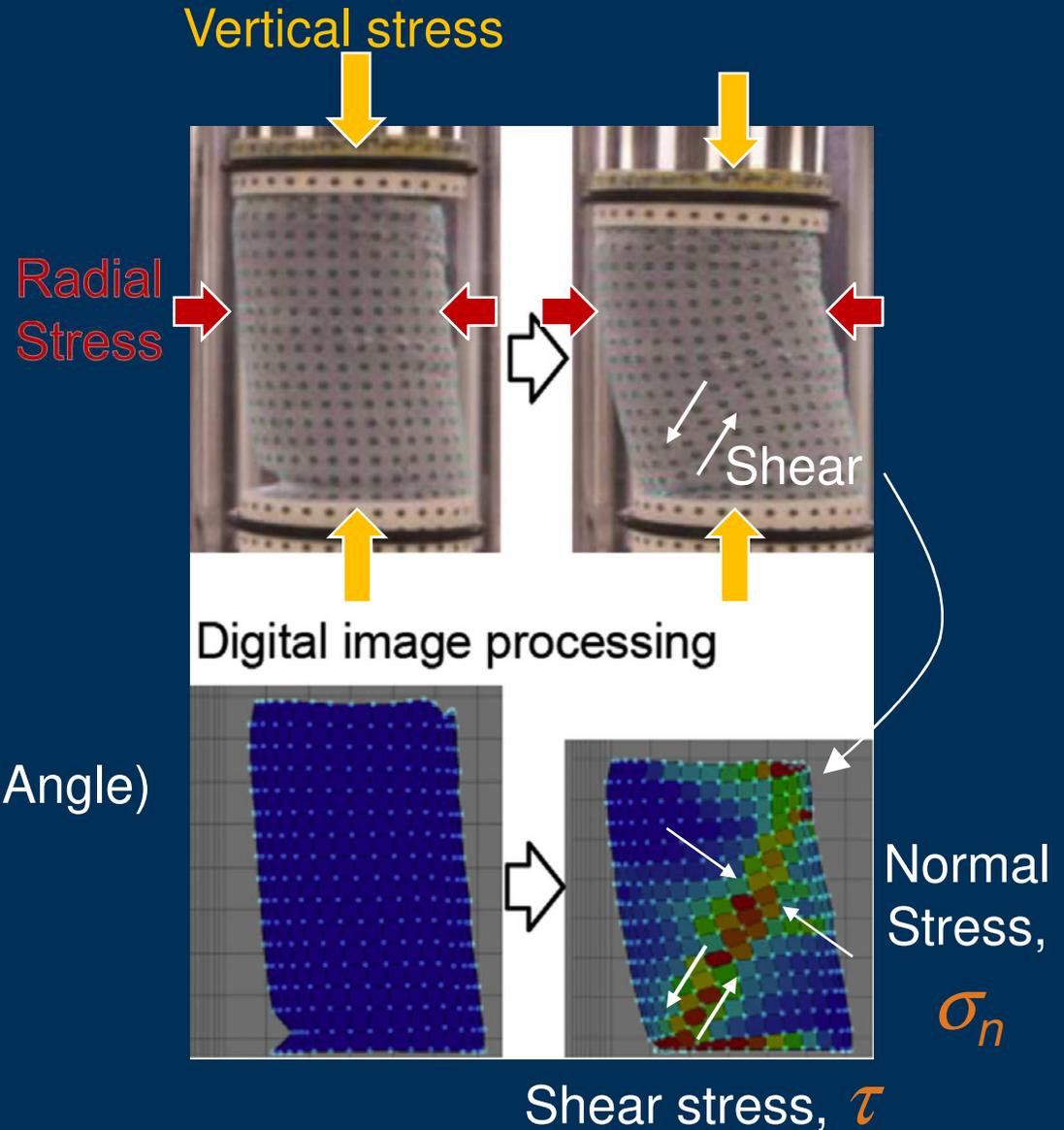Yoneda et al. (2017), Marine and Petroleum Geology
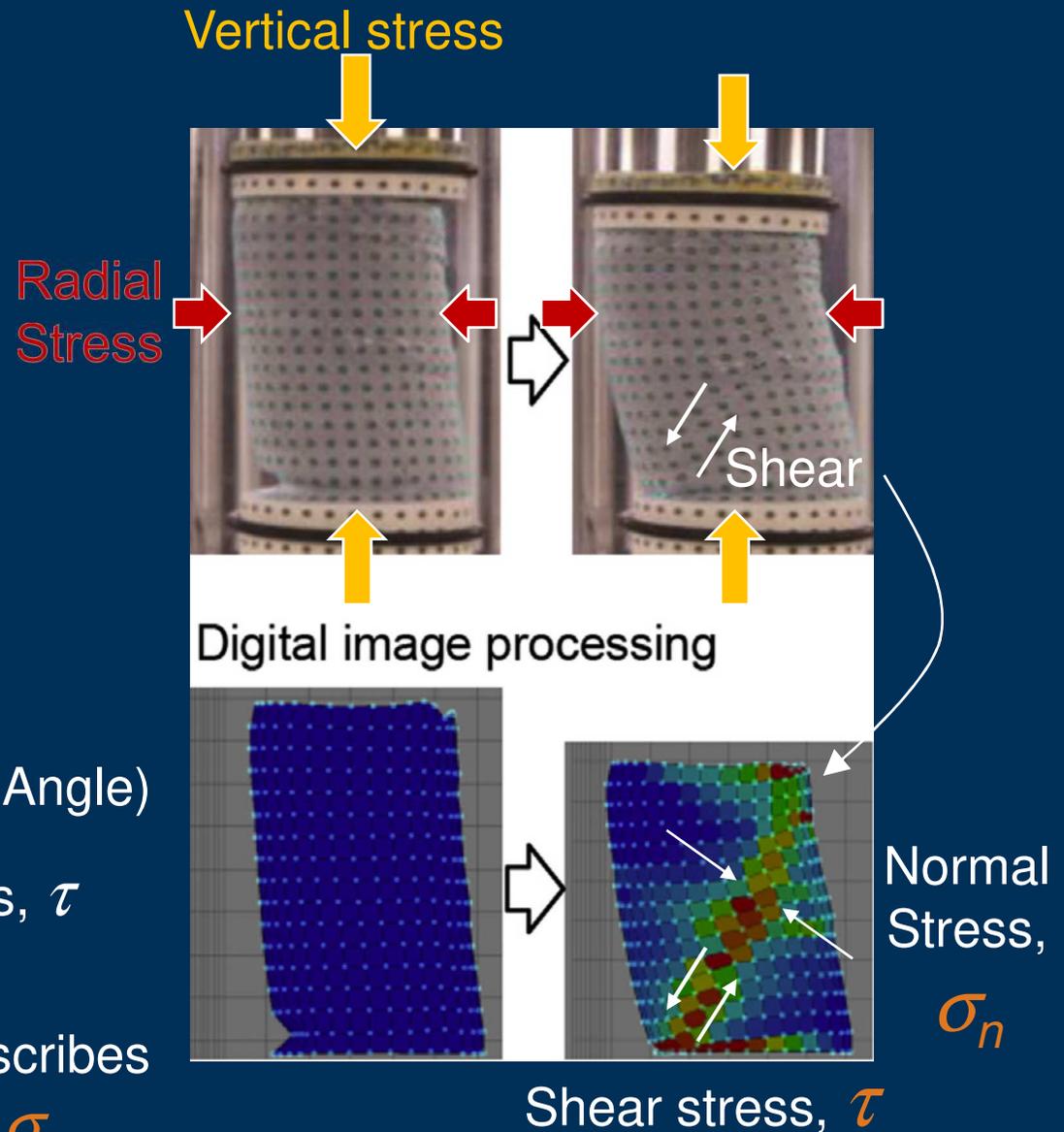
Shear strength: will the sediment fail?

Sediment does not generally feel a vertical stress that is the same as the horizontal stress. If the two stresses differ by enough, the sediment will deform, or fail.

Mohr-Coulomb Failure Criteria

τ = Cohesion + $\sigma_n \cdot$ tan(Friction Angle)

Cohesion: maximum shear stress, τ with no confining stress

Tangent of the Friction angle: describes how τ increases with increasing σ_n.

Vertical stress

Radial Stress

Shear

Digital image processing

Normal Stress, σ_n

Shear stress, τ

Yoneda et al. (2017), Marine and Petroleum Geology

Hydrate provides cohesion?

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

Yoneda et al. (2018), JMPG
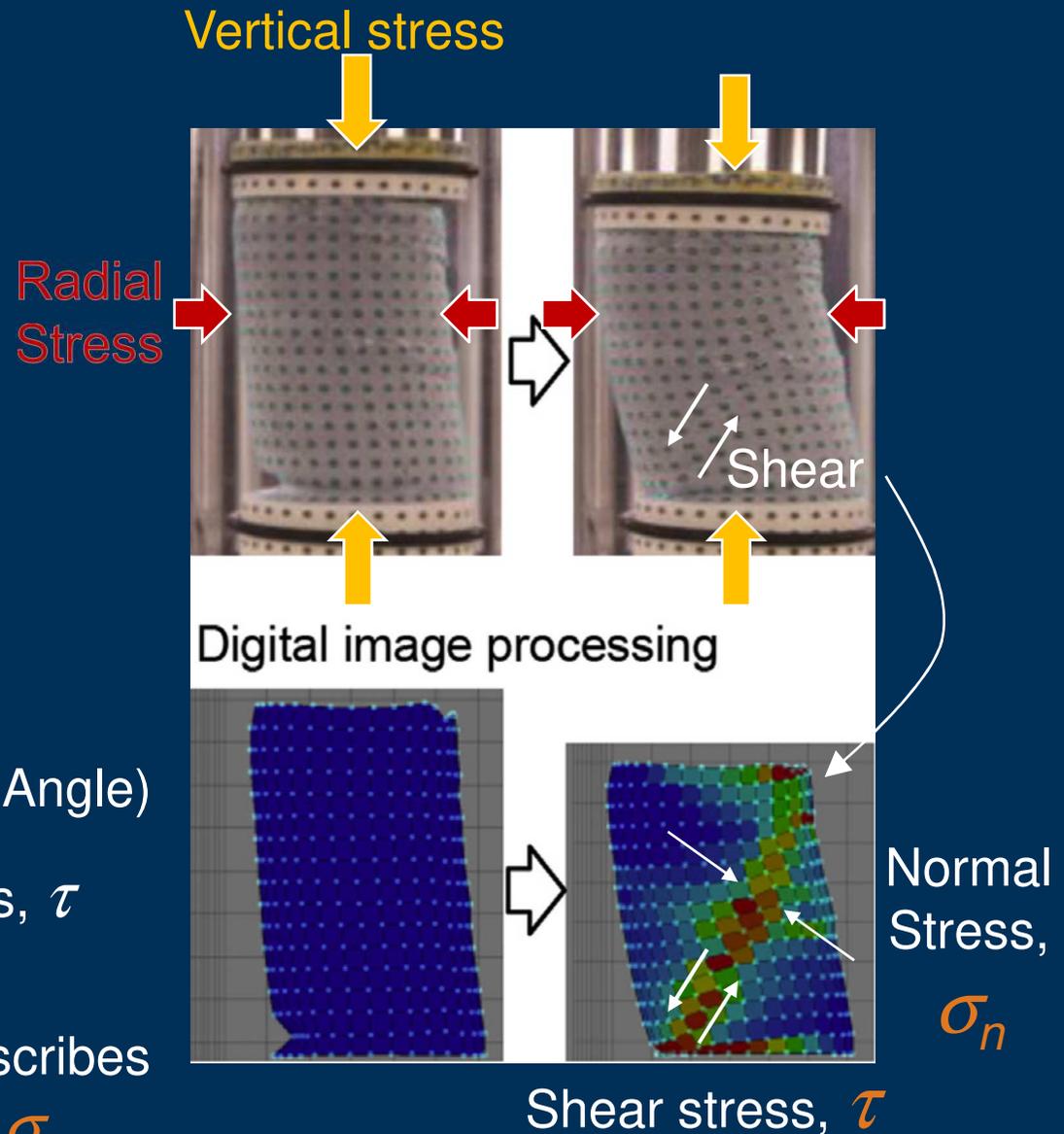
Shear strength: will the sediment fail?

Sediment does not generally feel a vertical stress that is the same as the horizontal stress. If the two stresses differ by enough, the sediment will deform, or fail.
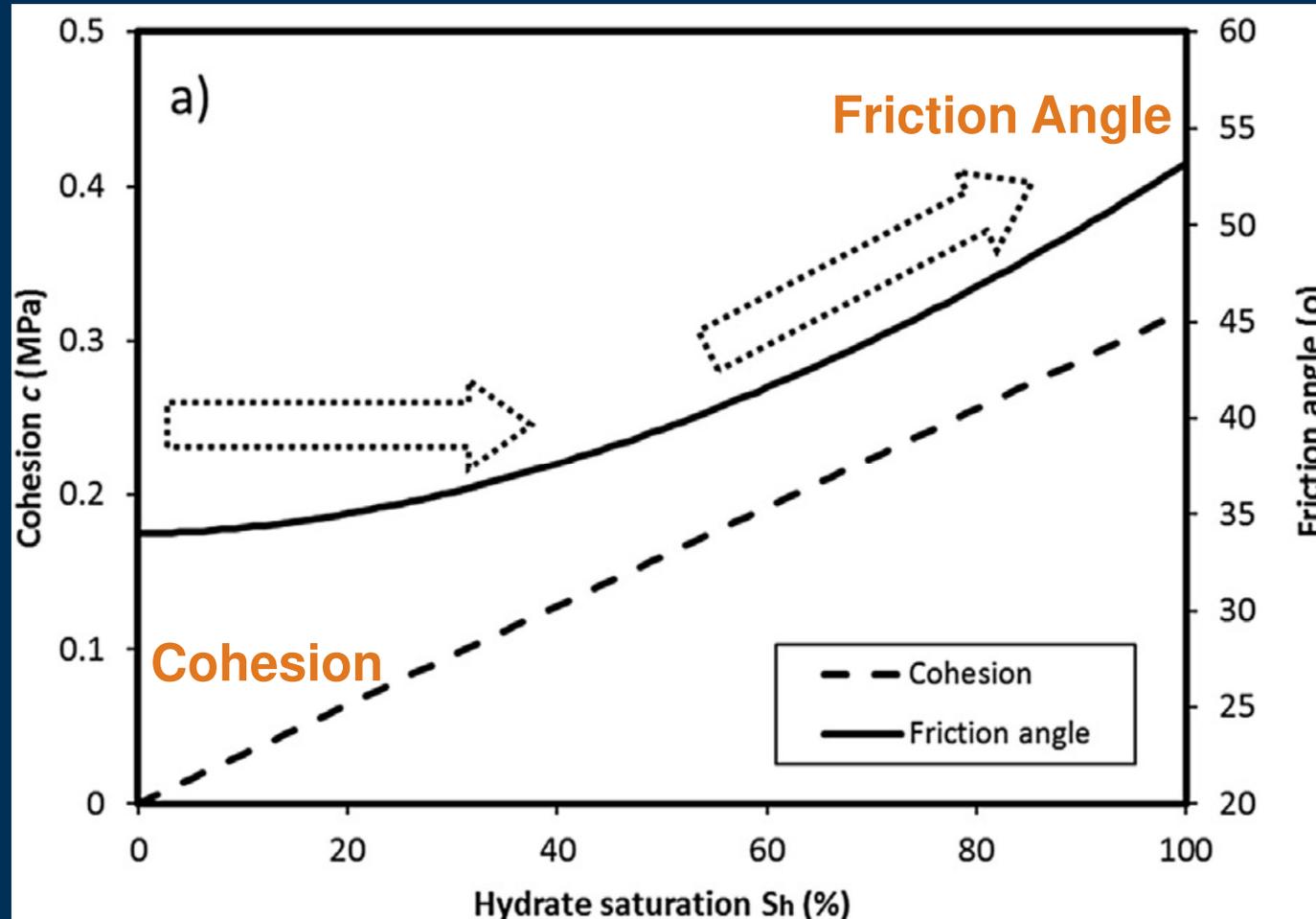
Mohr-Coulomb Failure Criteria

τ = Cohesion + $\sigma_n \cdot$ tan(Friction Angle)

Cohesion: maximum shear stress, τ with no confining stress

Tangent of the Friction angle: describes how τ increases with increasing σ_n.

Vertical stress

Radial Stress

Shear

Digital image processing

Normal Stress, σ_n

Shear stress, τ

Yoneda et al. (2017), Marine and Petroleum Geology

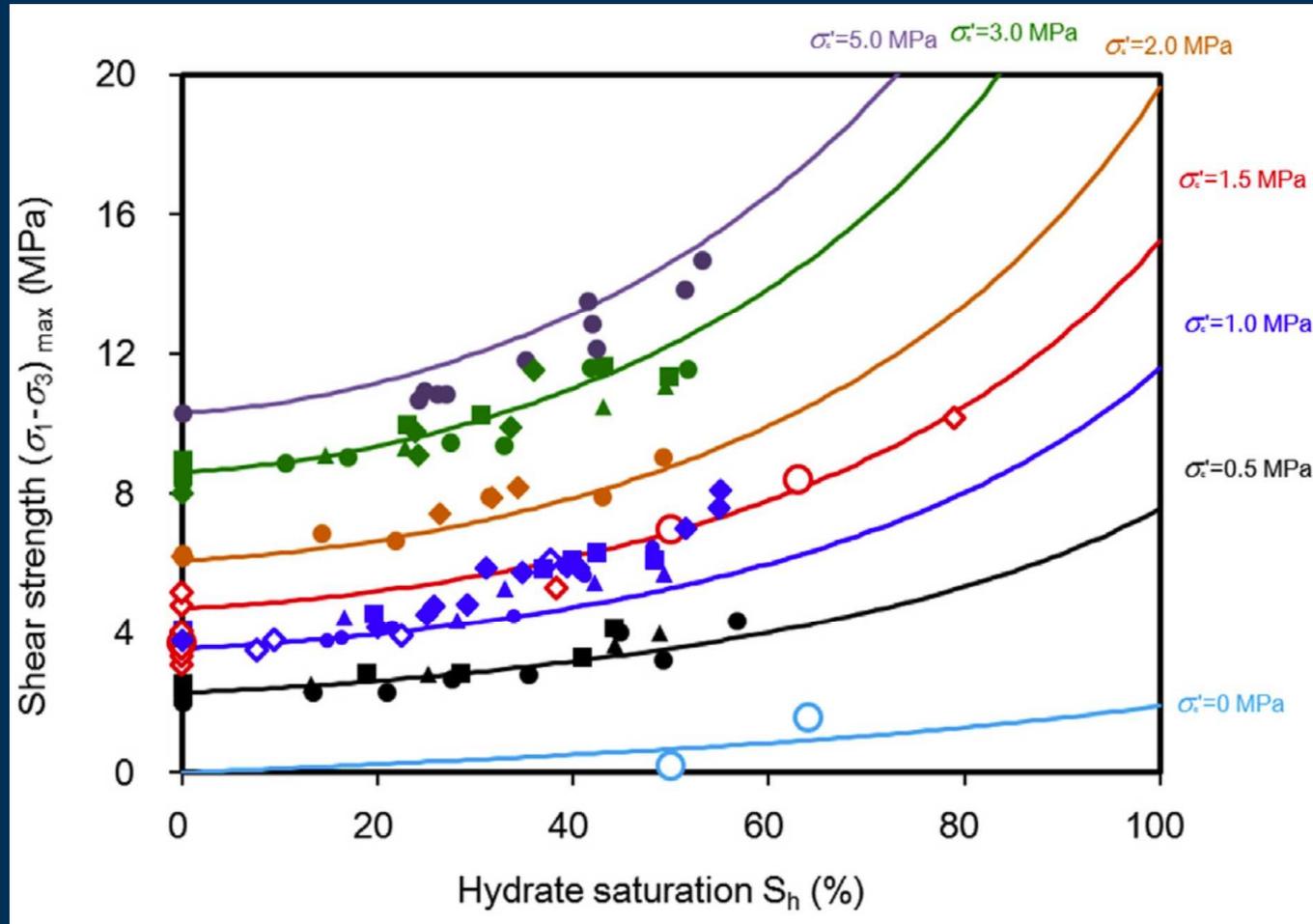# Cohesion and Friction Angle dependence on hydrate saturation

Mohr-Coulomb Failure Criteria

$$\tau = \text{Cohesion} + \sigma_n \cdot \tan(\text{Friction Angle})$$

Yoneda et al. (2017), Marine and Petroleum Geology

Shear strength dependence on effective stress

Mohr-Coulomb Failure Criteria

$$\tau = \text{Cohesion} + \sigma_n \cdot \tan(\text{Friction Angle})$$

Yoneda et al. (2017), Marine and Petroleum Geology
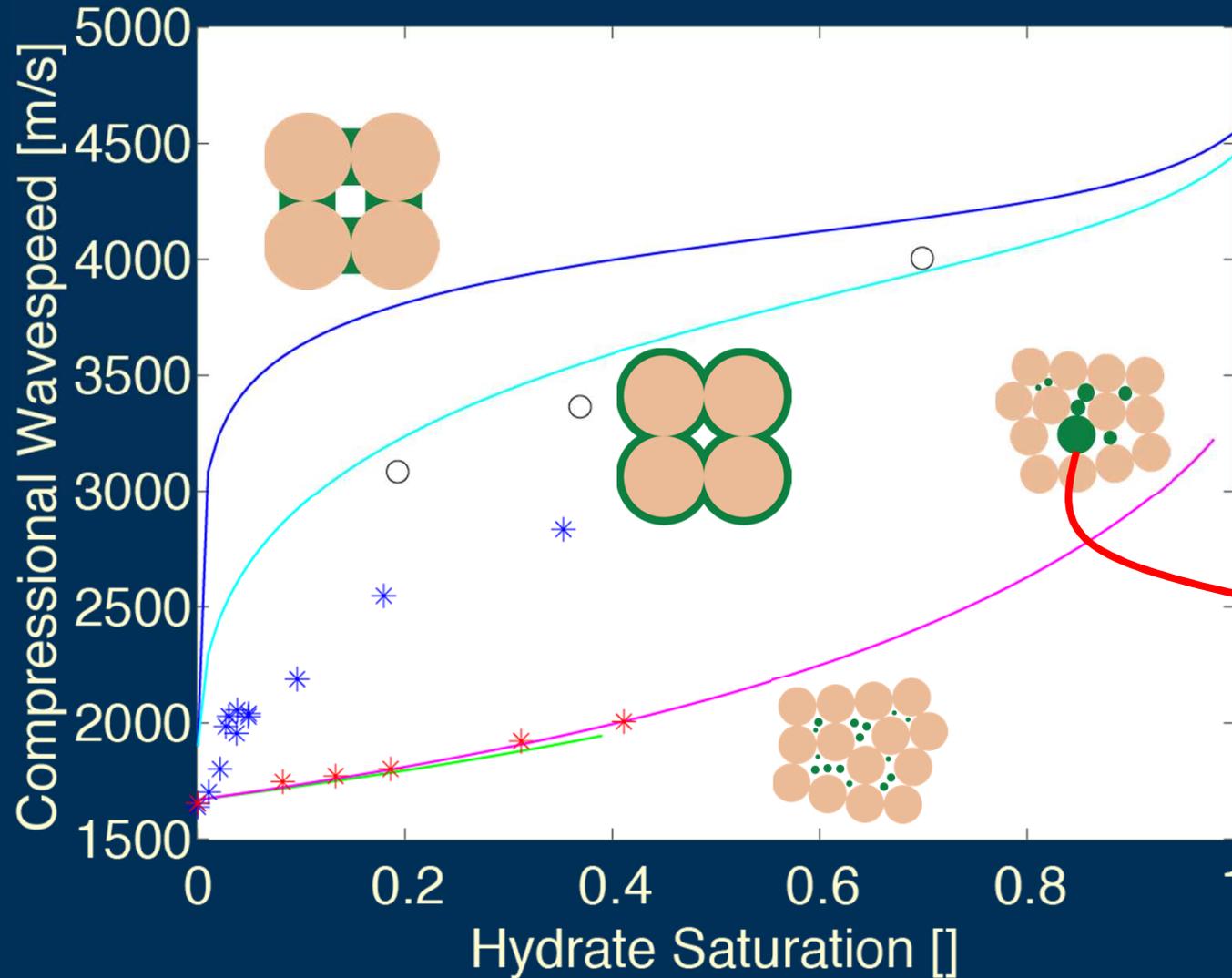
How does the hydrate provide cohesion?

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

Yoneda et al. (2018), JMPG

What is "load-bearing" gas hydrate?

What is "load-bearing" gas hydrate?

"Load bearing" hydrate restricts grain motion
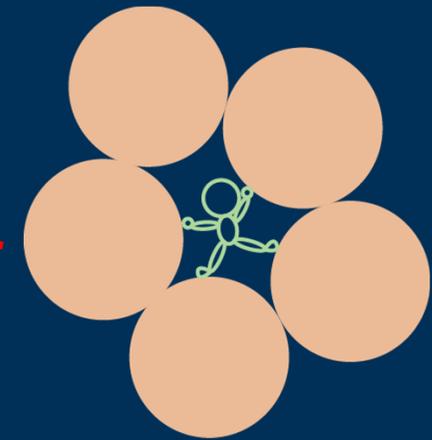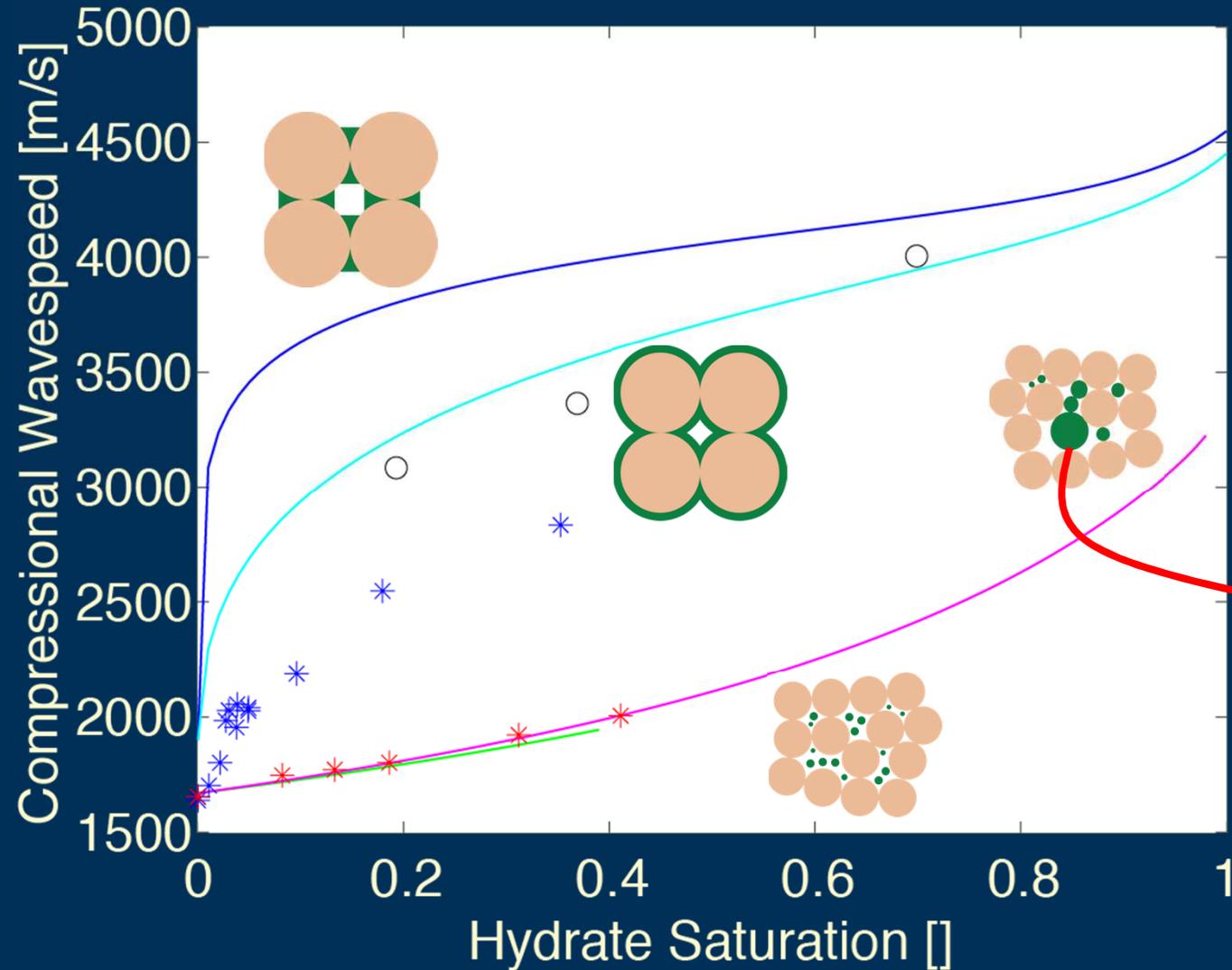
Dvorkin et al. (2000), Natural Gas Hydrates in Oceanic and Permafrost Environments

What is "load-bearing" gas hydrate?

"Load bearing" hydrate restricts grain motion

Dvorkin et al. (2000), Natural Gas Hydrates in Oceanic and Permafrost Environments
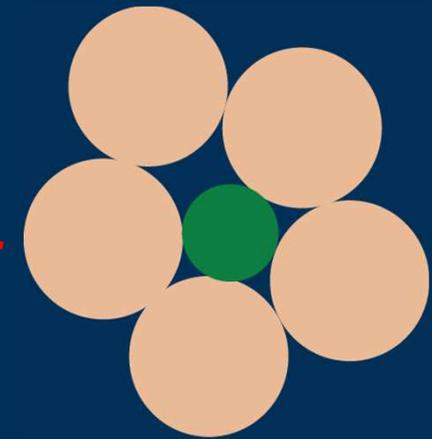
What is "load-bearing" gas hydrate?

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

What is "load-bearing" gas hydrate?

"Load bearing" hydrate restricts grain motion

Restricted grains = stiffer sediment

$V_P \, \alpha \, \sqrt{\text{stiffness}}$

Dvorkin et al. (2000), Natural Gas Hydrates in Oceanic and Permafrost Environments
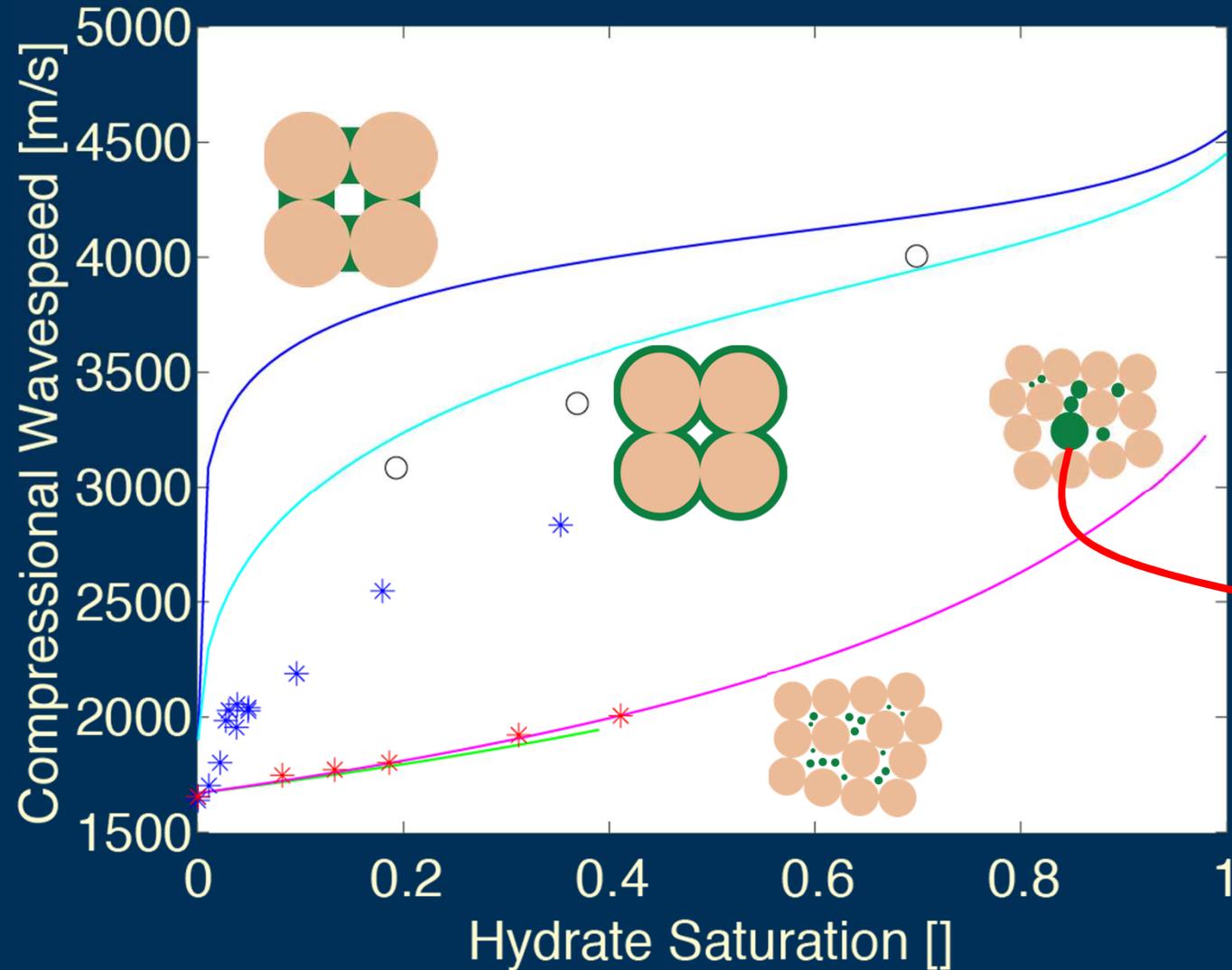
What is "load-bearing" gas hydrate?

"Load bearing" hydrate restricts grain motion
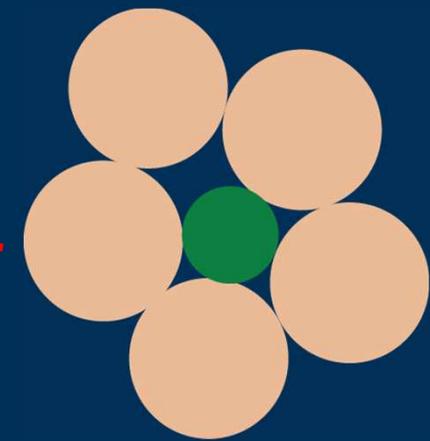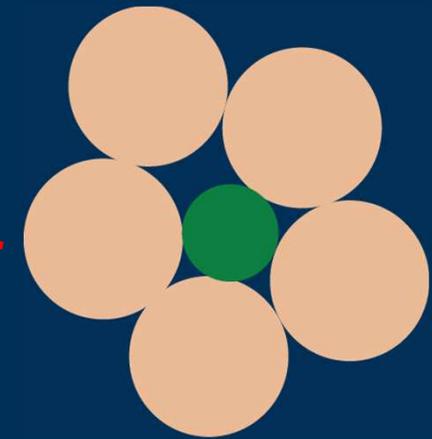
Dvorkin et al. (2000), Natural Gas Hydrates in Oceanic and Permafrost Environments
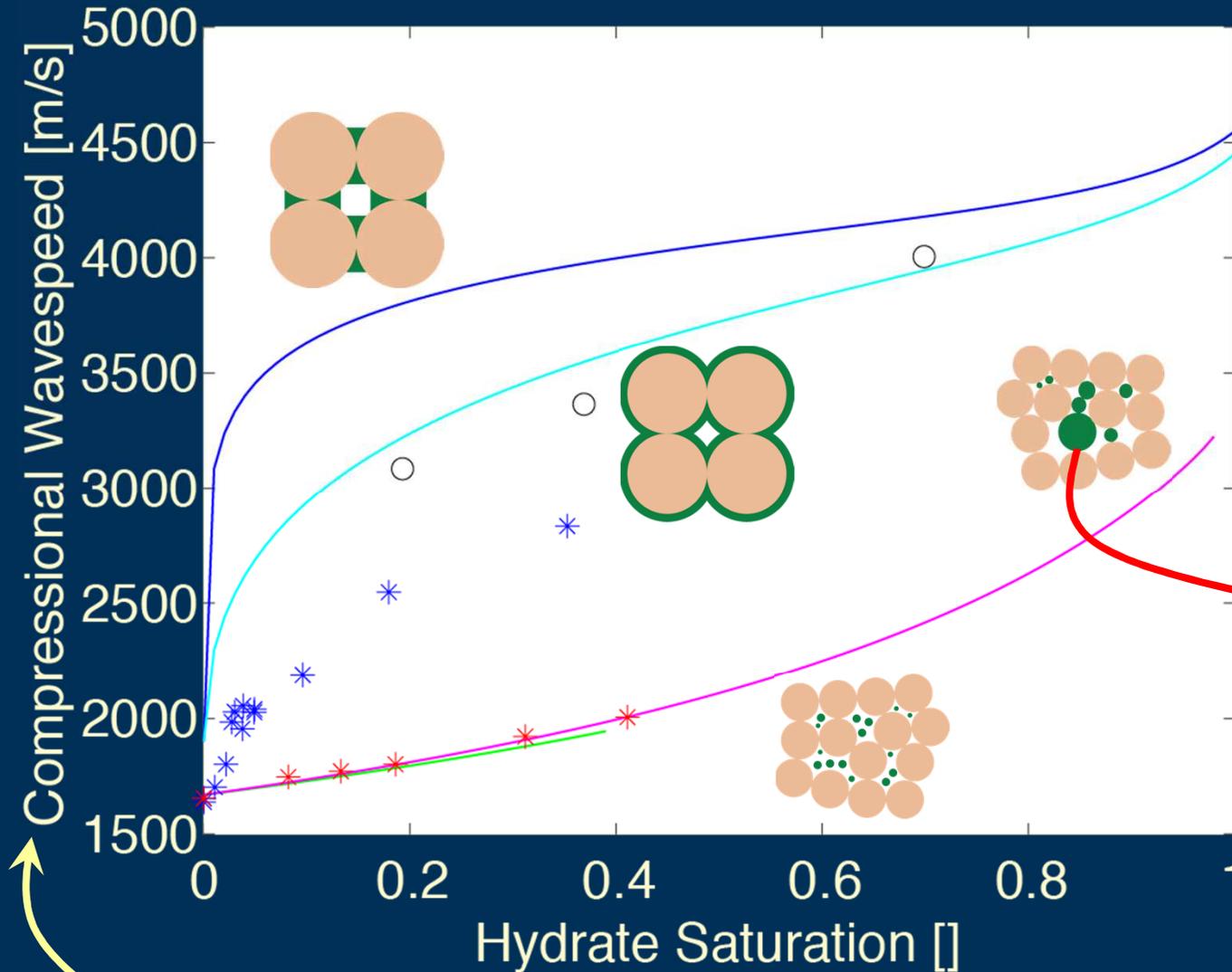
What is "load-bearing" gas hydrate?
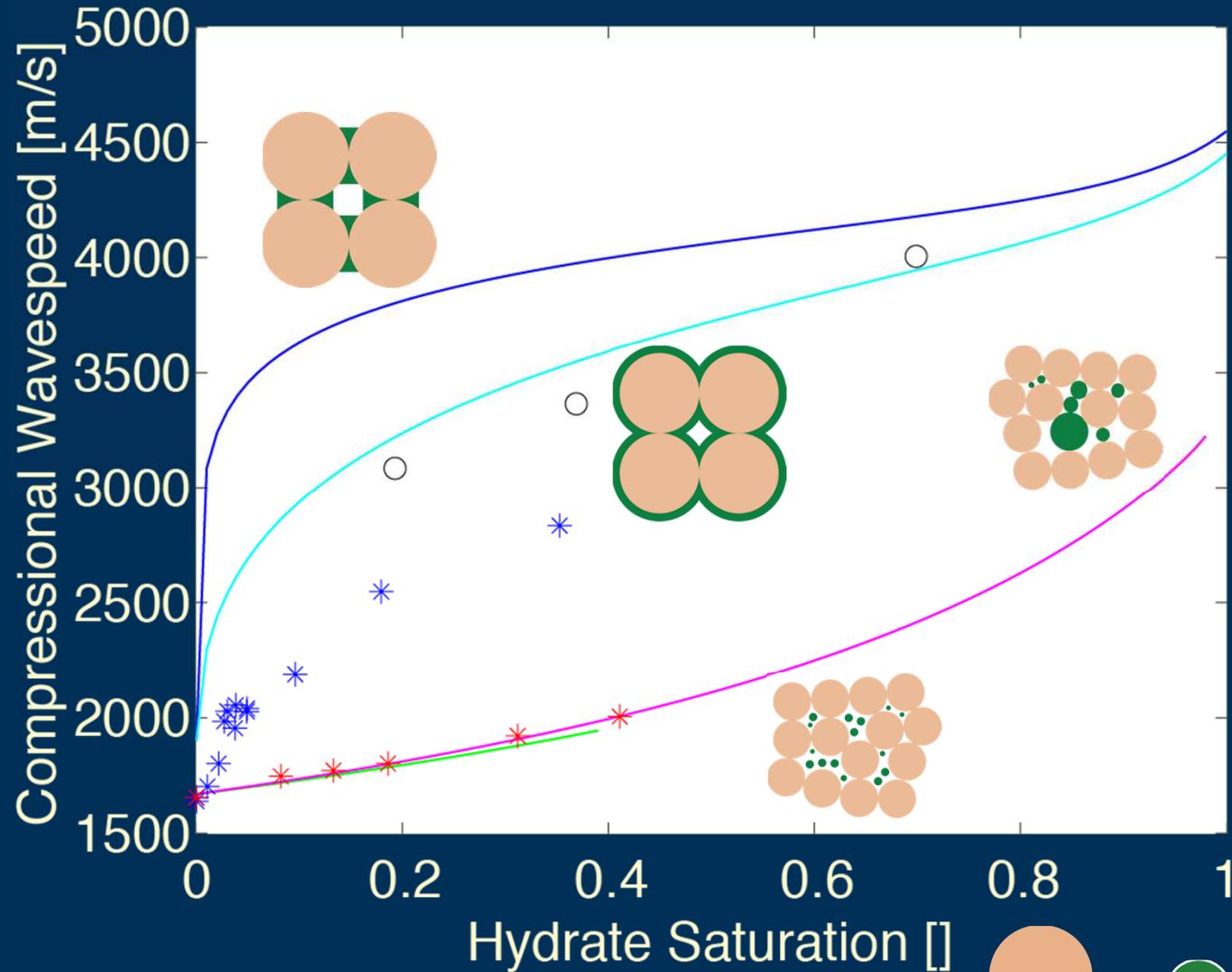
"Load bearing" hydrate restricts grain motion
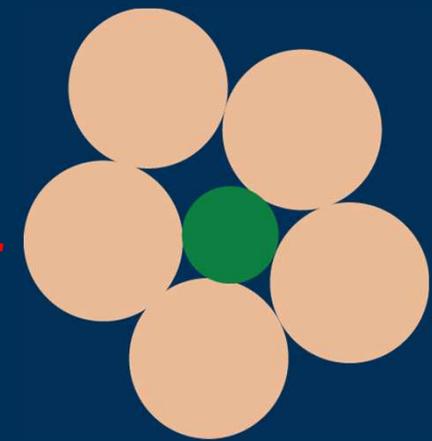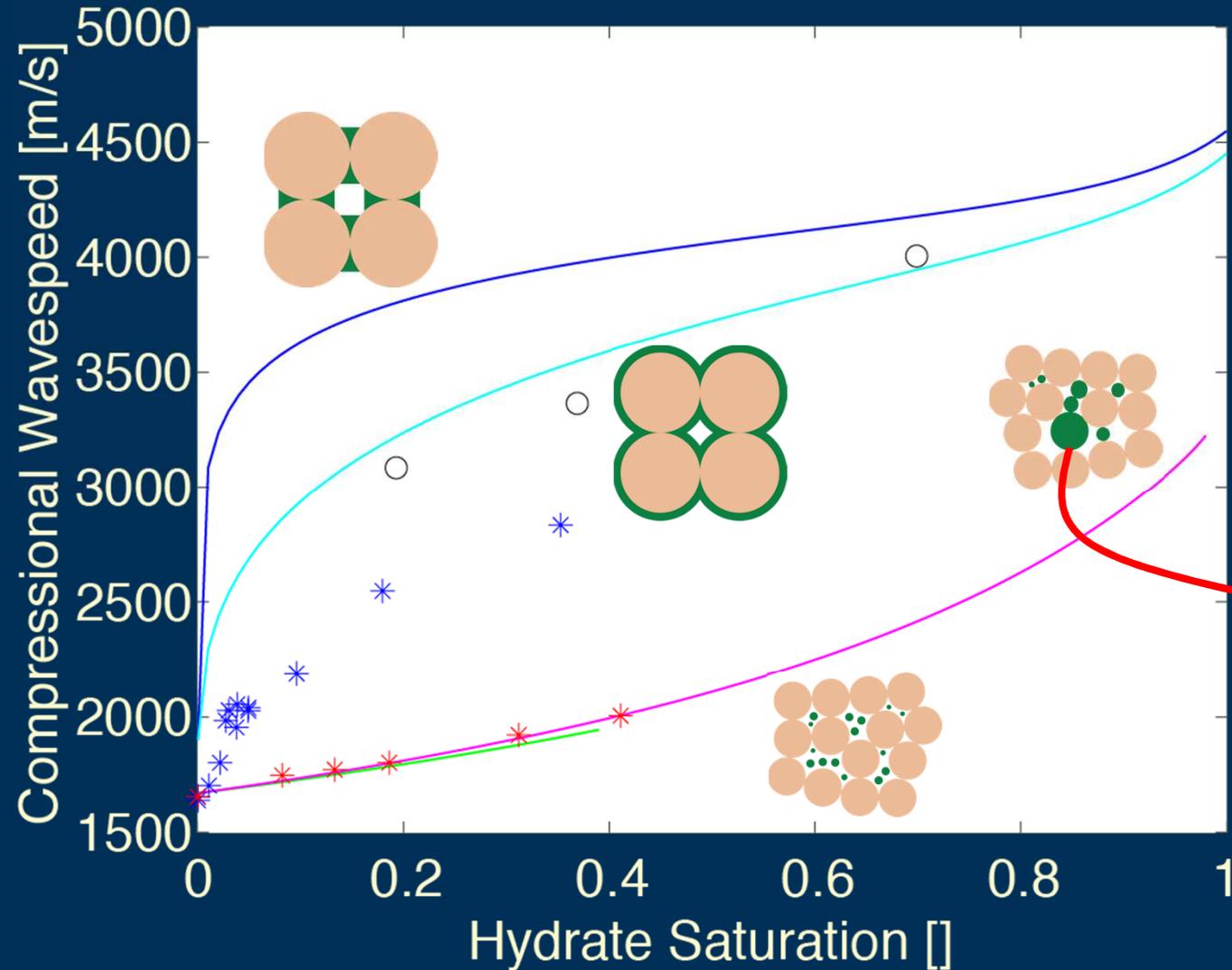
But there is no cohesion

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

How does the hydrate provide cohesion?

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

Yoneda et al. (2018), JMPG

How does the hydrate provide cohesion… without touching sand

Water

Grain

105.9°

105.5°

140.3°

Hydrate

(a)

Kerkar et al. (2014), GCubed

How does the hydrate provide cohesion… without touching sand

Water

Grain
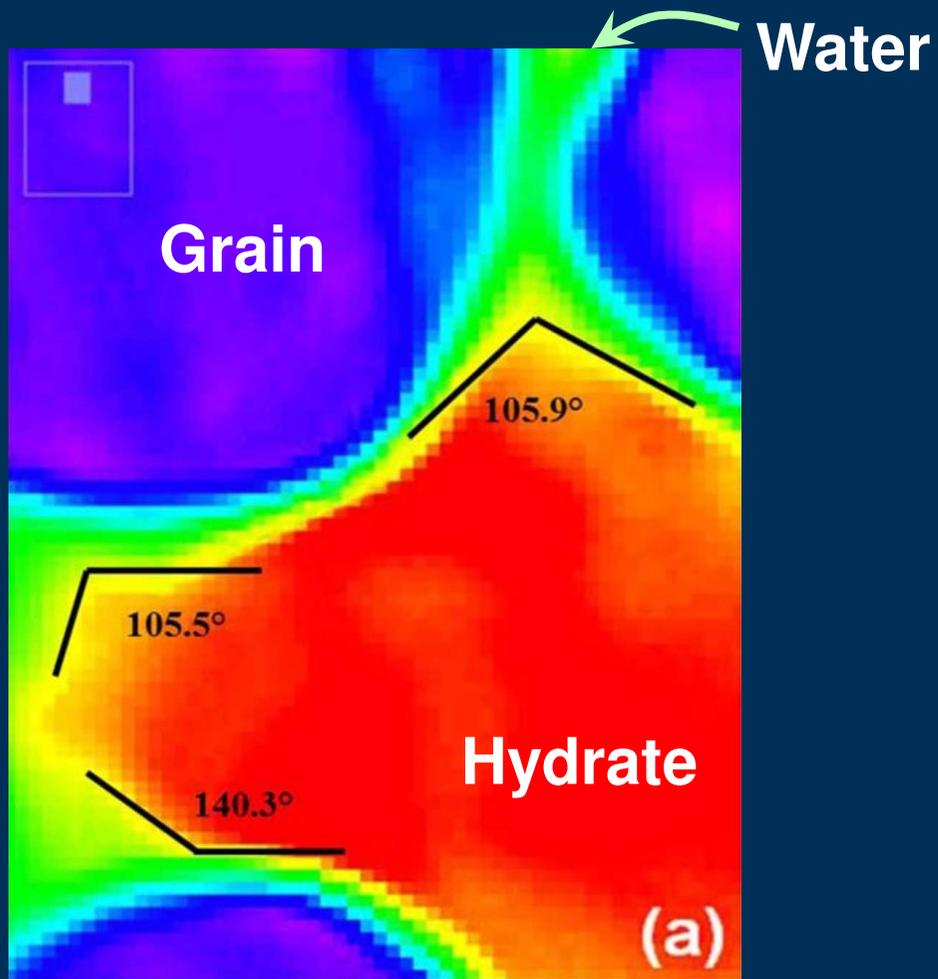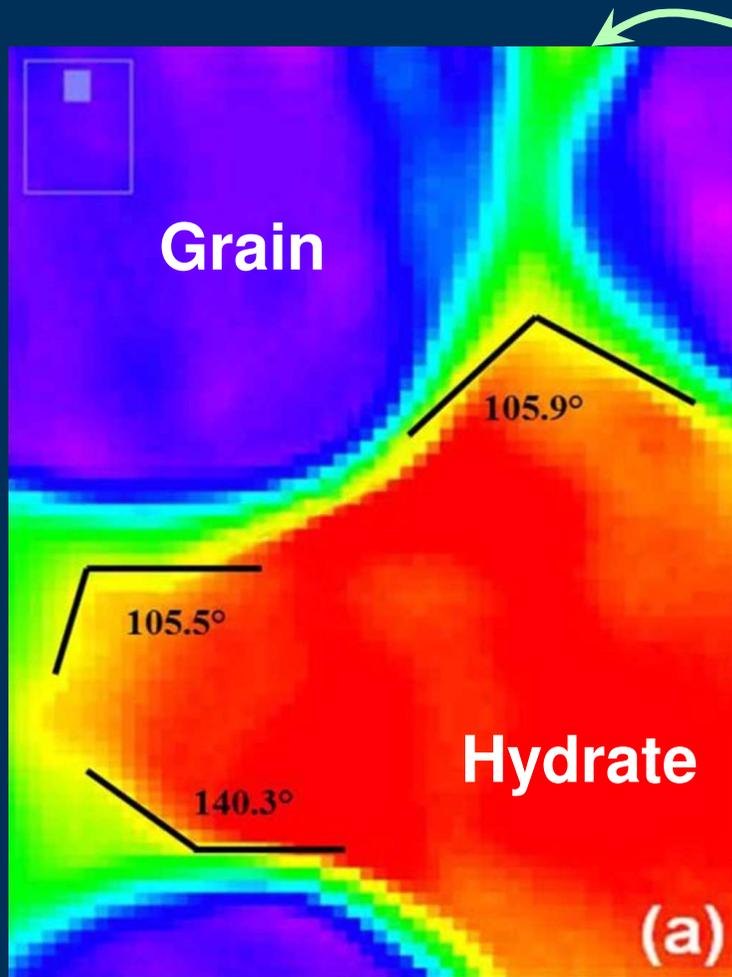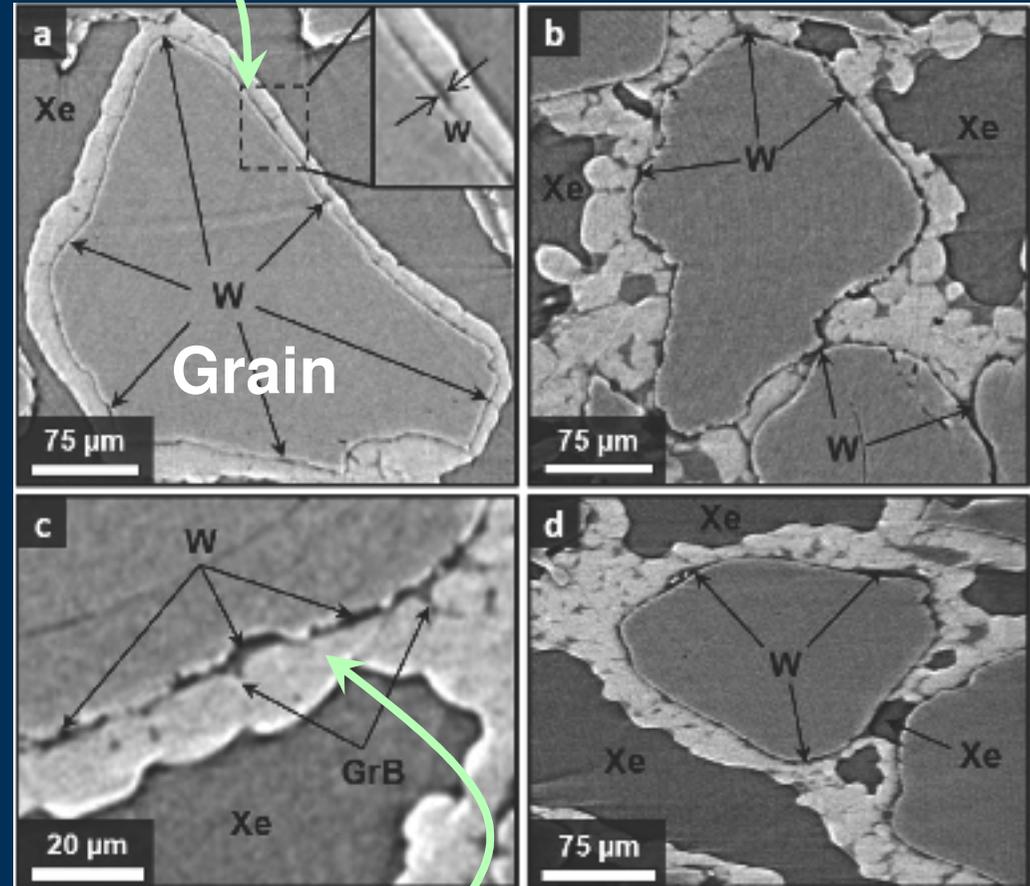
Hydrate

Kerkar et al. (2014), GCubed

Hydrate

Chaouachi et al. (2015), GCubed

How does the hydrate provide cohesion… without touching sand
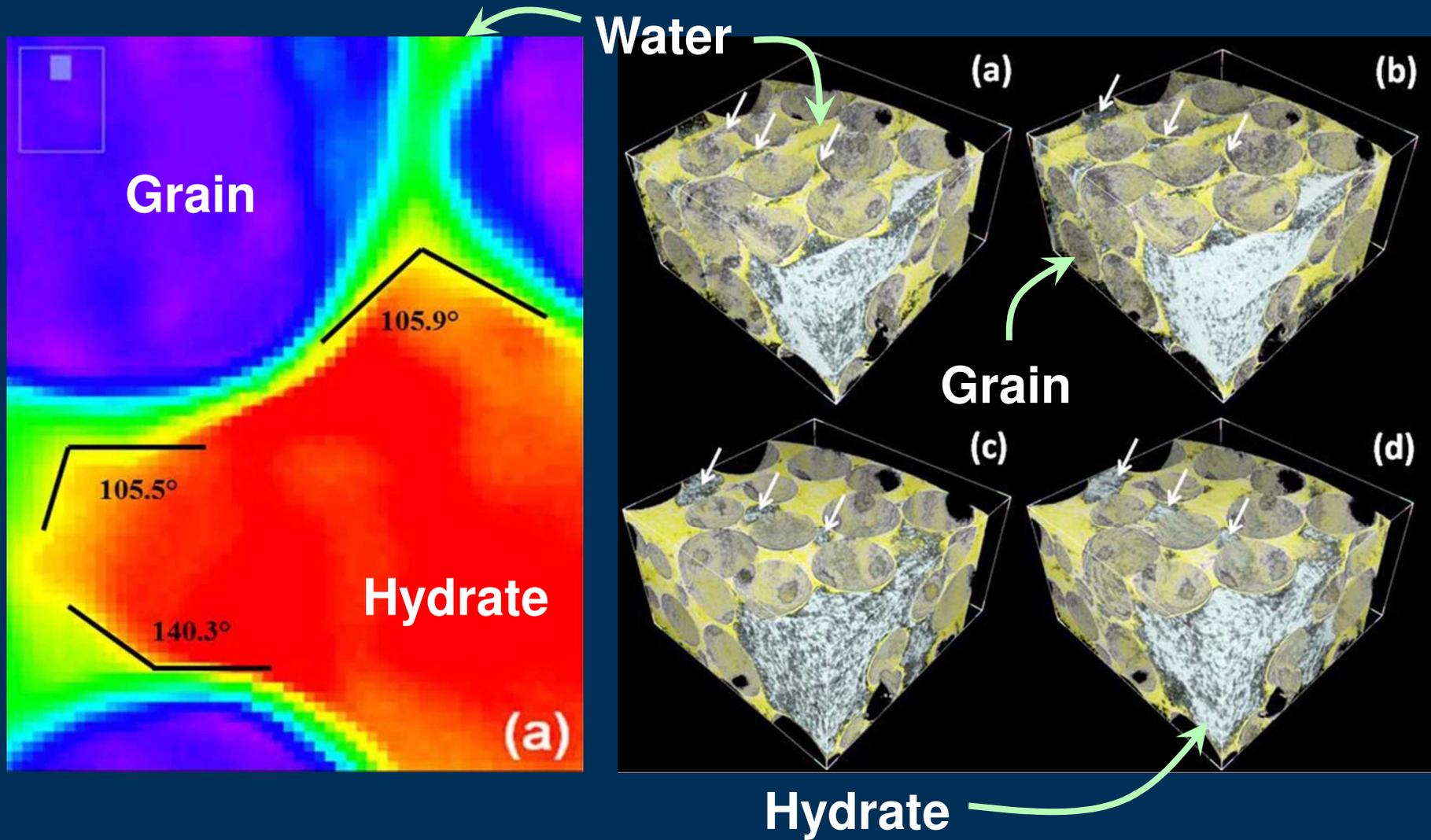
Water

Grain

Hydrate

105.9°

105.5°

140.3°

(a)

(a) (b) (c) (d)

Grain

Hydrate

Kerkar et al. (2014), GCubed

How does the hydrate provide cohesion… without touching sand

Water

Grain

Hydrate

105.9°

105.5°

140.3°

(a)

Grain

(a) (b)

(c) (d)

Hydrate

Gas hydrate forms an _interconnected network_ in the pore space

Kerkar et al. (2014), GCubed

How does the hydrate provide cohesion… without touching sand

Water

Gas

Grain
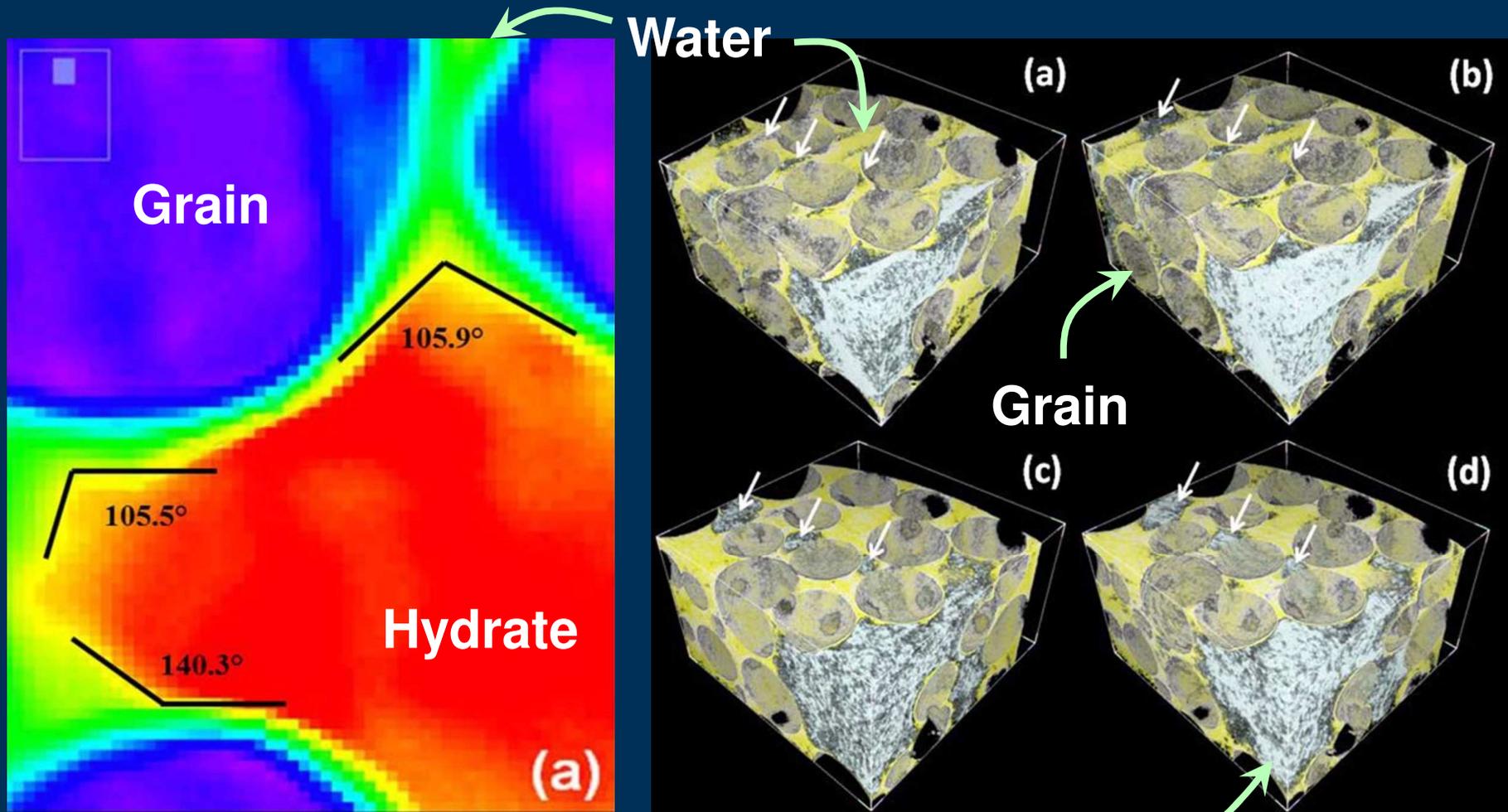
Interconnected network forms even when hydrate grows from gas in excess water.
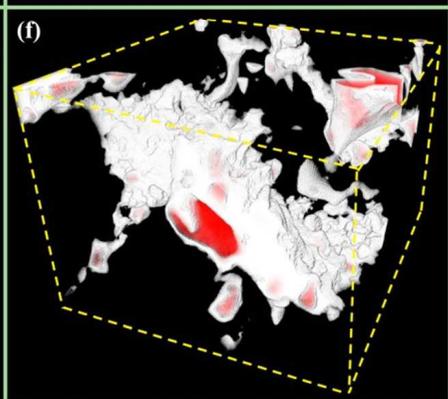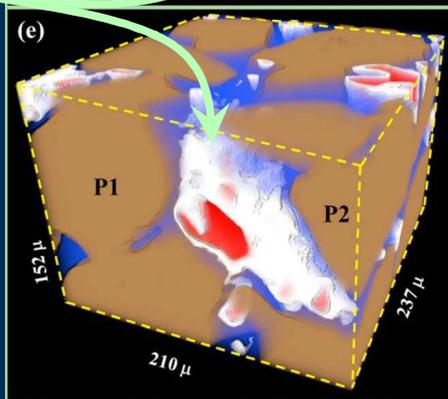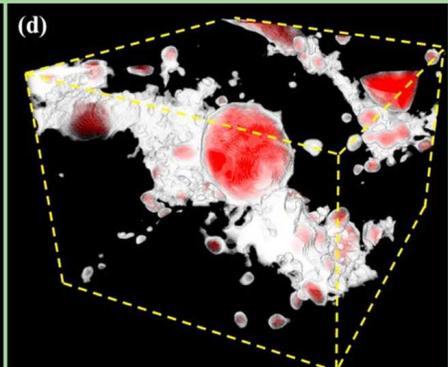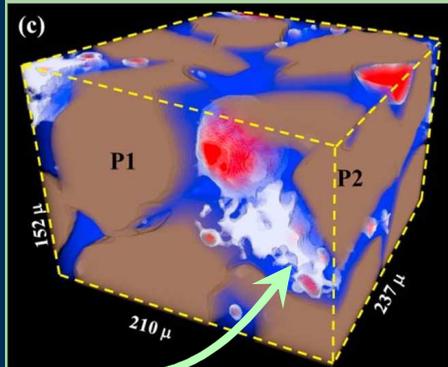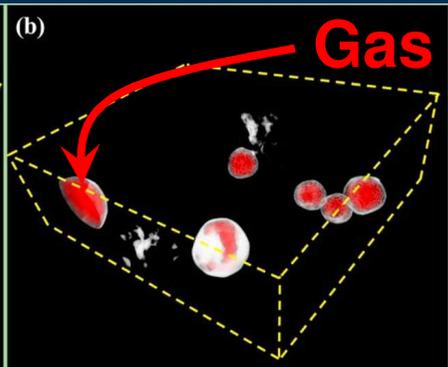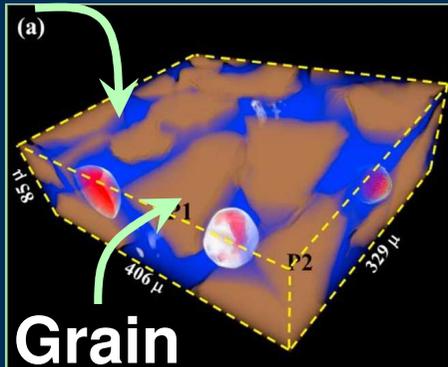
Hydrate

Gas hydrate forms an _interconnected network_ in the pore space

Sahoo et al. (2018), GCubed

Morphology: network versus load bearing

A. Sediment grains restricted by naturally-occurring, interconnected hydrate

B. Sediment grains restricted by hydrate idealized as load-bearing grains.

Sediment grains

Interconnected hydrate

Hydrate idealized as grains

Sediment grains

For *small strains* (e.g. velocity measurements), the "interconnected network" can be modelled as "additional load-bearing grains" (e.g. Dvorkin et al., 2000).

Cook and Waite (2018), JGR

Morphology: network versus load bearing

A. Sediment grains restricted by naturally-occurring, interconnected hydrate

B. Sediment grains restricted by hydrate idealized as load-bearing grains.

Sediment grains

Interconnected hydrate

Sediment grains

Hydrate idealized as grains

Good for velocity versus hydrate saturation.

Cook and Waite (2018), JGR

Morphology: network versus load bearing

A. Sediment grains restricted by naturally-occurring, interconnected hydrate

B. Sediment grains restricted by hydrate idealized as load-bearing grains.

Interconnected hydrate   Sediment grains

Hydrate idealized as grains   Sediment grains

Good for everything else.

Good for velocity versus hydrate saturation.

Cook and Waite (2018), JGR

Assumed morphology for Archie's Law
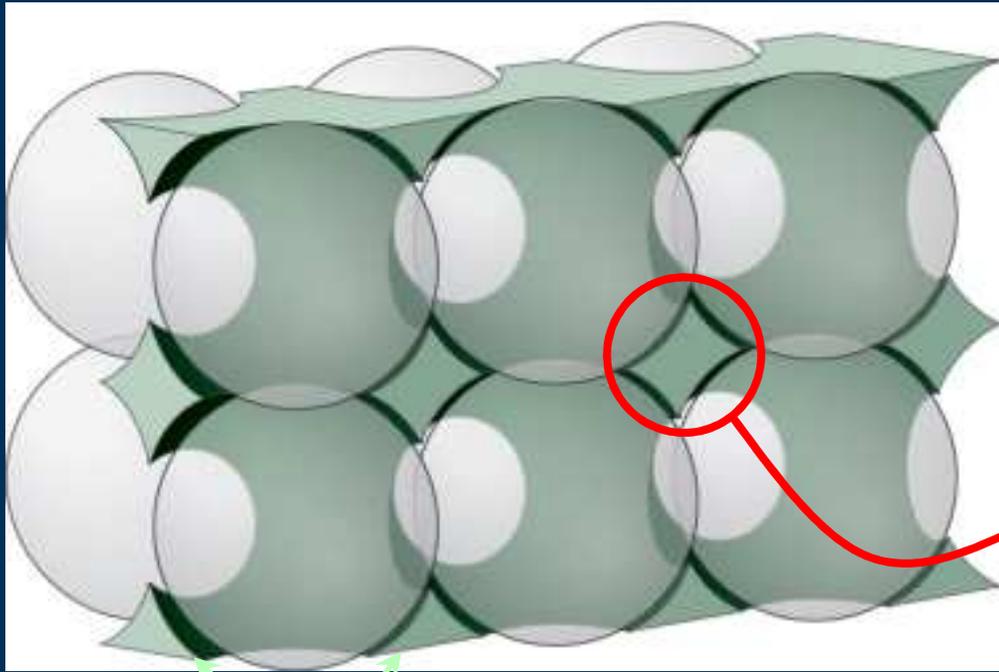
Interconnected hydrate

Morphology fits the permeability correlation

Interconnected hydrate

Hydrate Saturation []
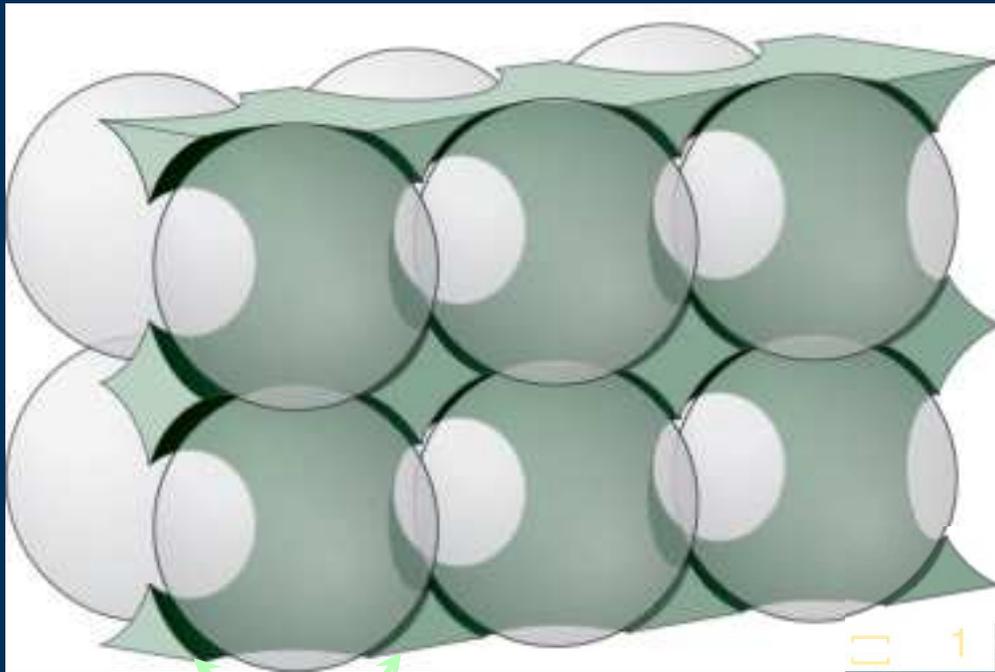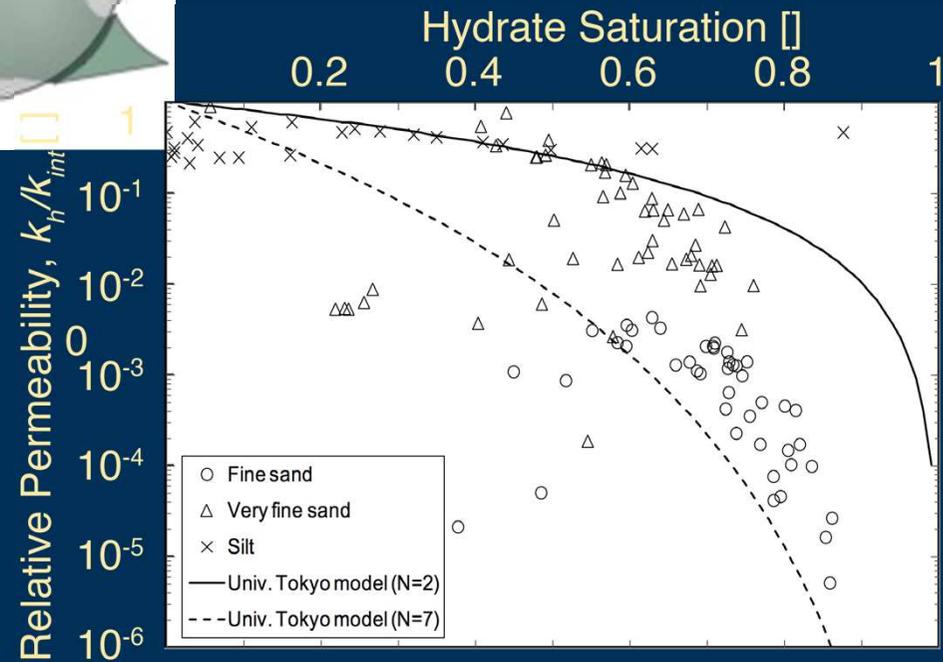
Konno et al. (2017), Energy&Fuels

Morphology fits the capillary permeability model

Grain-coating hydrate

Interconnected hydrate

Hydrate Saturation []

Relative Permeability, k_h/k_{int} []

- ○ Fine sand
- △ Very fine sand
- × Silt
- —— Univ. Tokyo model (N=2)
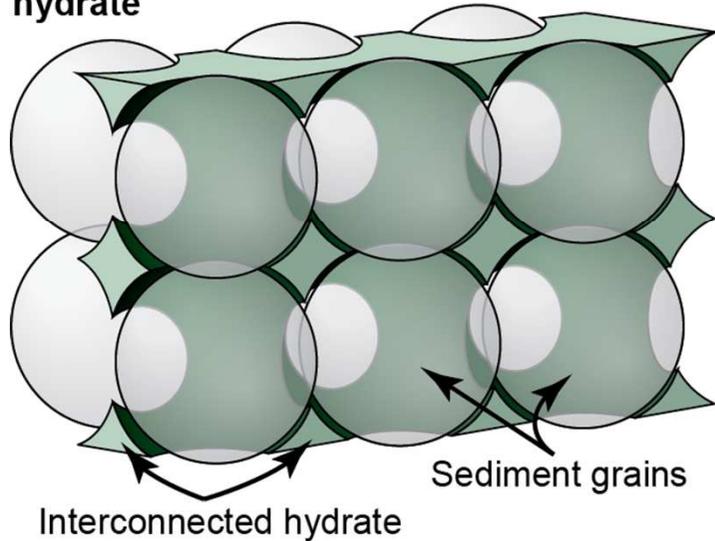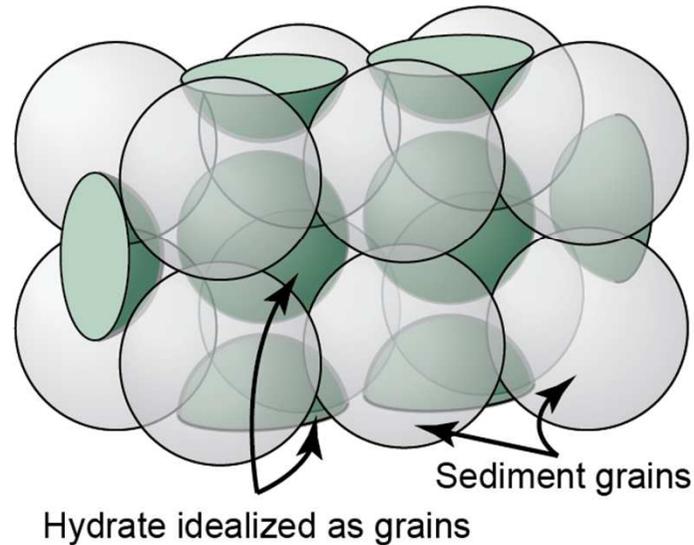- ---- Univ. Tokyo model (N=7)

Konno et al. (2017), Energy&Fuels

Morphology: network versus load bearing

A. Sediment grains restricted by naturally-occurring, interconnected hydrate

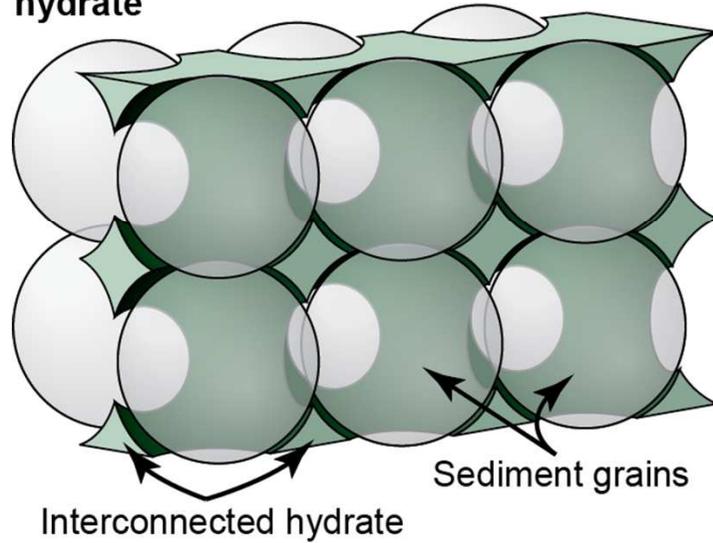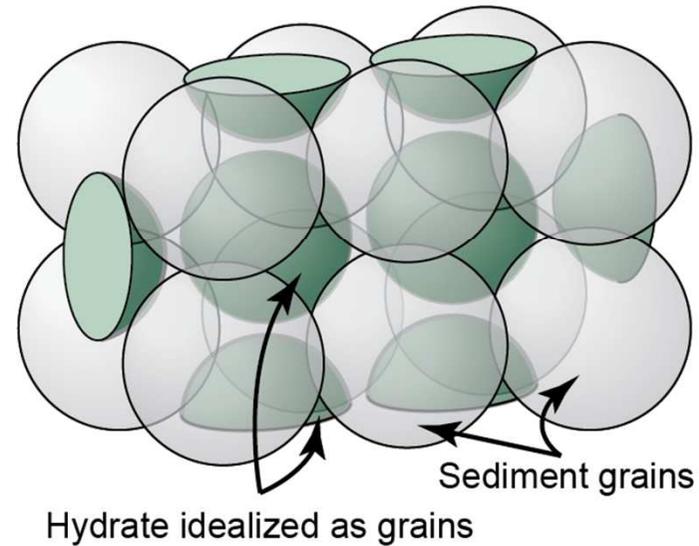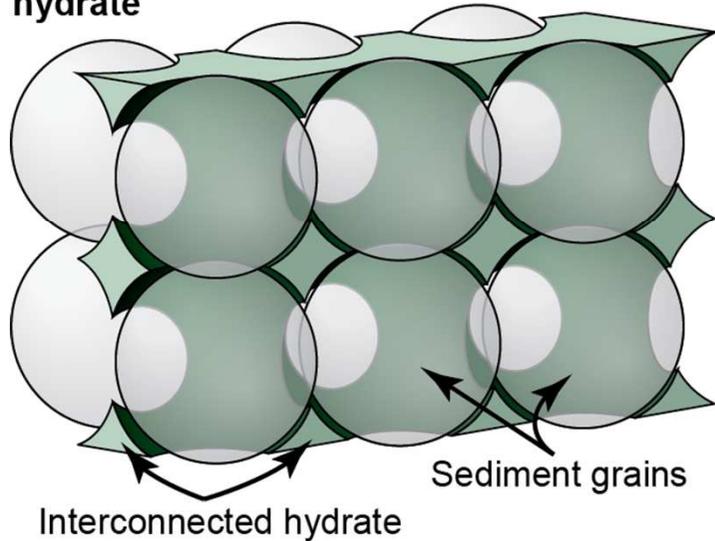B. Sediment grains restricted by hydrate idealized as load-bearing grains.

Sediment grains

Sediment grains

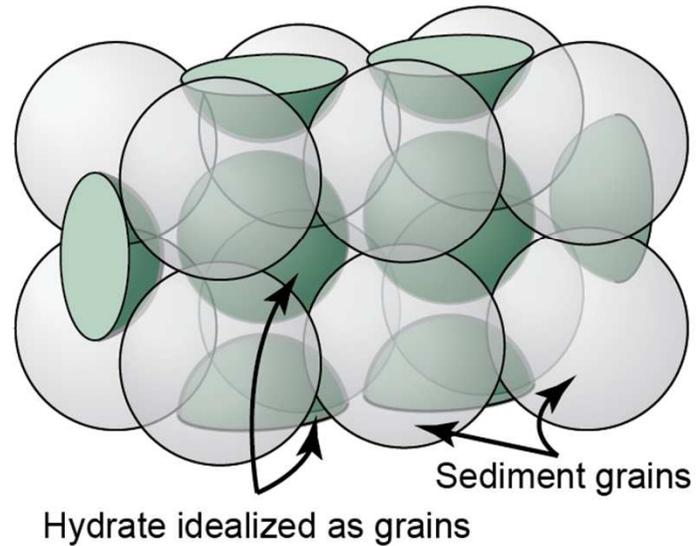Interconnected hydrate

Hydrate idealized as grains

Good for everything else.
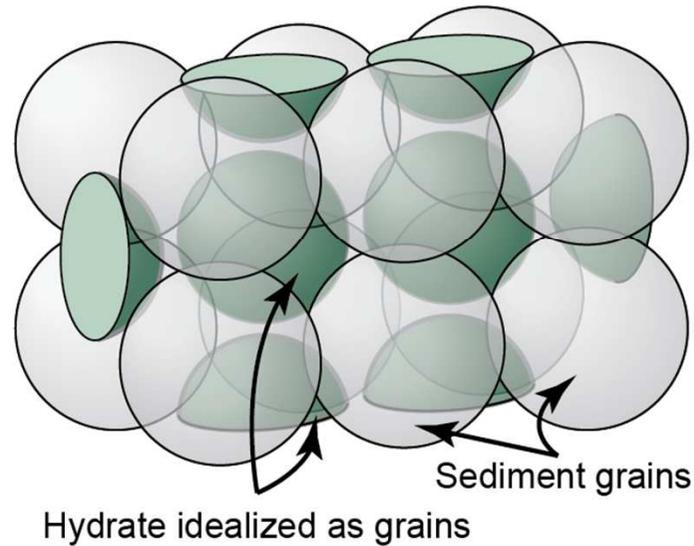
Good for velocity versus hydrate saturation.

Failure of low-cohesion sands
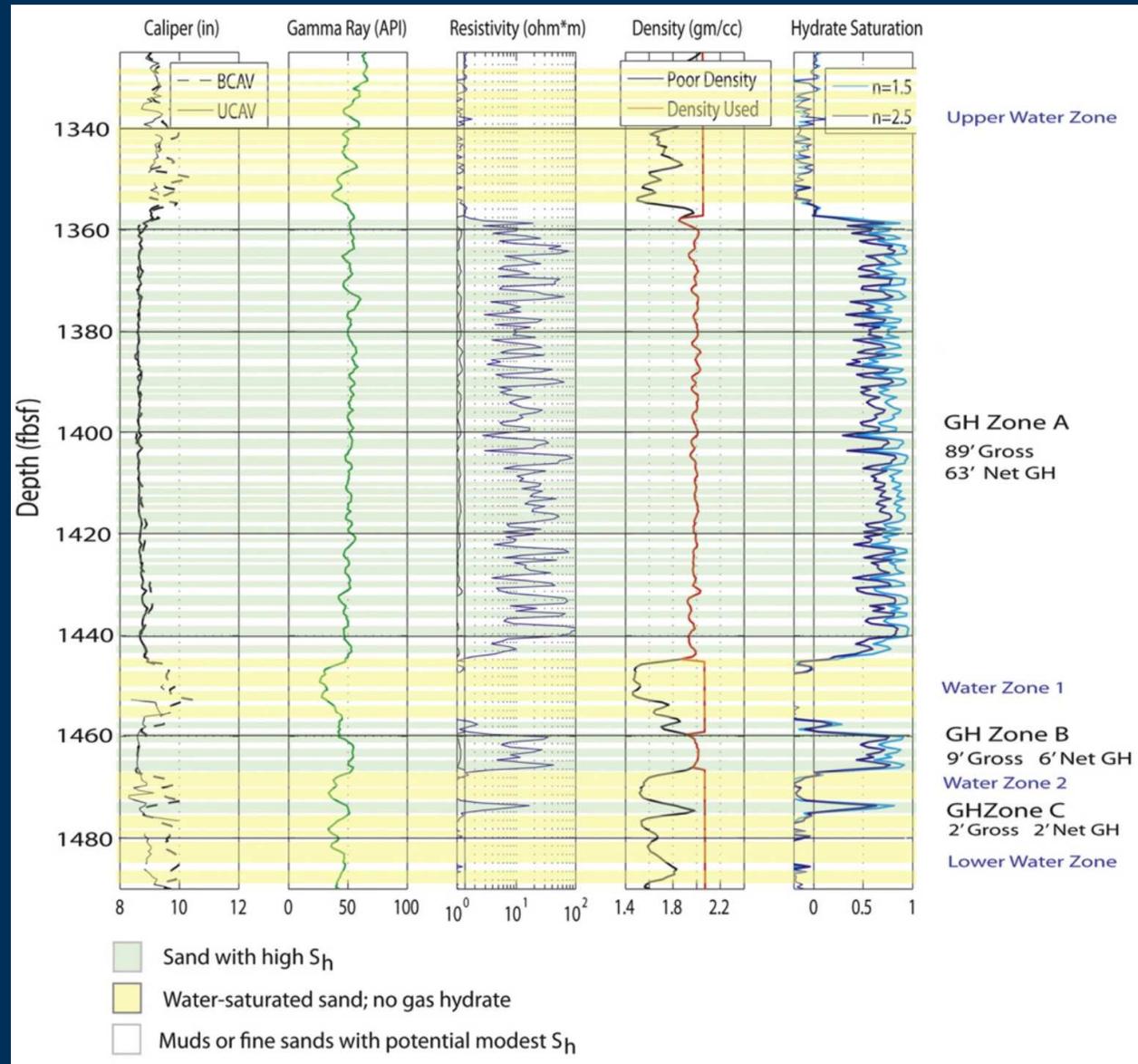
Gulf of Mexico
(Offshore USA)

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

Failure of low-cohesion sands

Sands with no hydrate: collapse dumps sediment into the borehole, leaving the hole wider (washout).

Washout

Washout

Gulf of Mexico (Offshore USA)
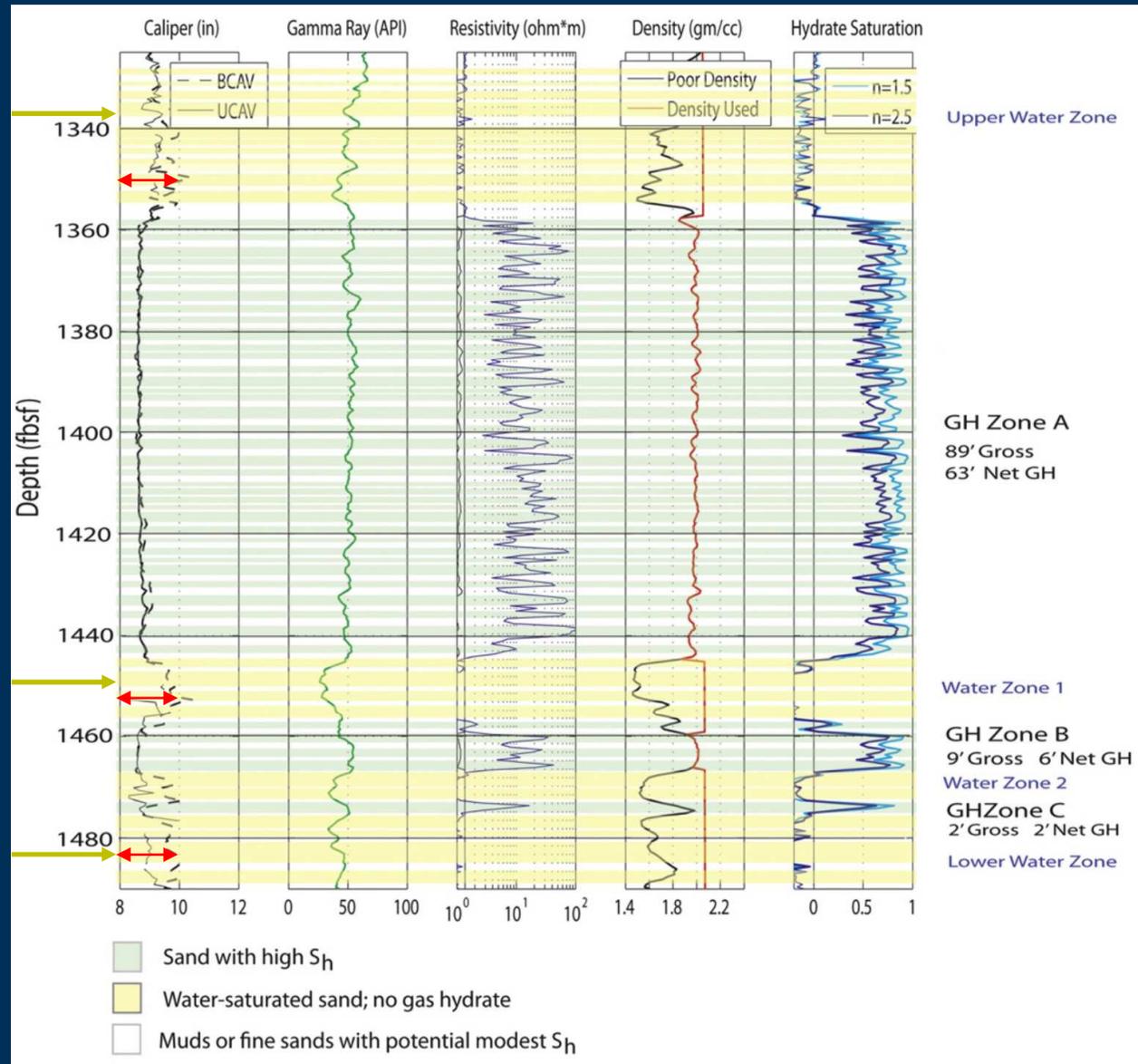
Boswell et al. (2012), Marine and Petroleum Geology

Failure of low-cohesion sands

Sands with no hydrate: collapse dumps sediment into the borehole, leaving the hole wider (washout).

Sands with hydrate: Cohesive enough to retain borehole diameter.

Washout

No washout

Washout

Gulf of Mexico (Offshore USA)
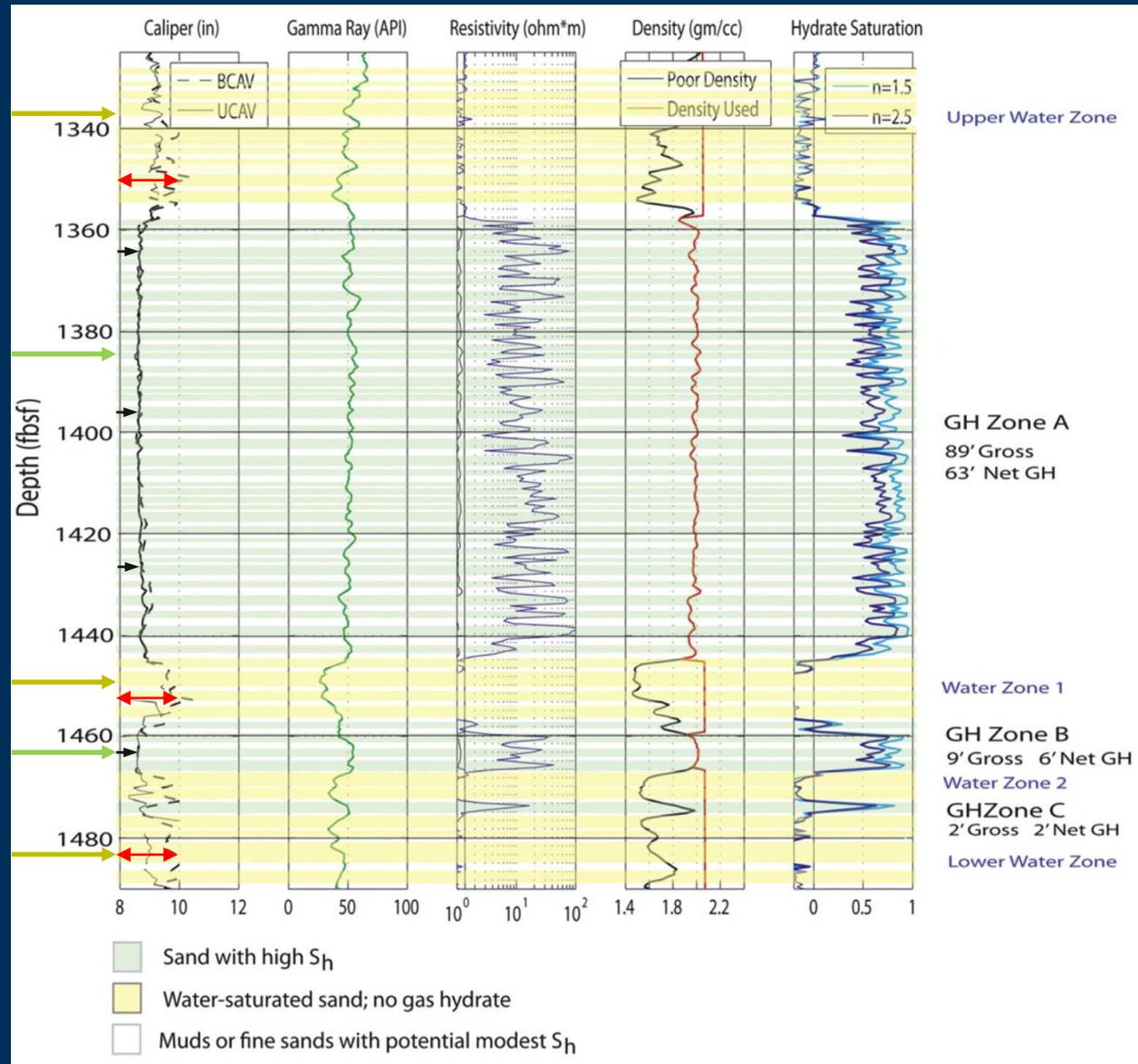
Boswell et al. (2012), Marine and Petroleum Geology

In addition to heat and fluid… sediment also moves

Production via depressurization reduces pressure in the sediment pore space. This _increases_ the effective stress on the sediment grains because the water pressure helped support the weight of the overlying water and sediment.

- _Shear strength_: will stress changes during methane production cause the sediment to fail and potentially collapse into the borehole?

- _Consolidation_: how much will stress changes during production cause the sediment to settle, taking up less volume by reducing porosity? A porosity decrease can reduce permeability and flow efficiency.

Consolidation: volume loss with increasing stress

$$e = \frac{\phi}{1-\phi}$$
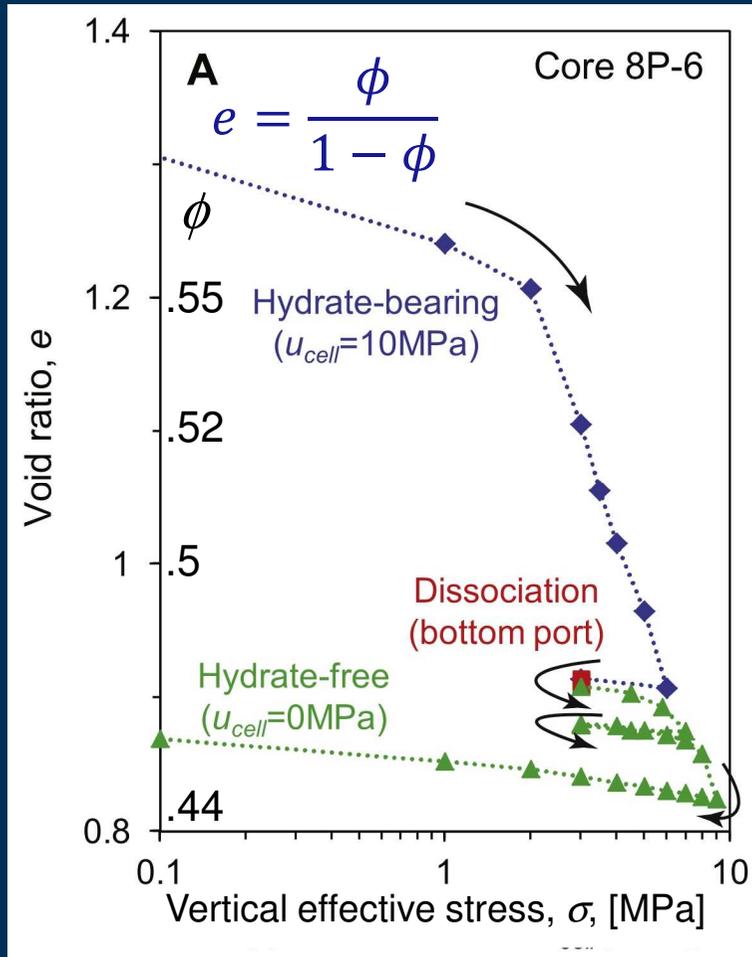
Sandy silt from Nankai Trough
(offshore Japan)

Effective Stress Cell for
pressure core analysis
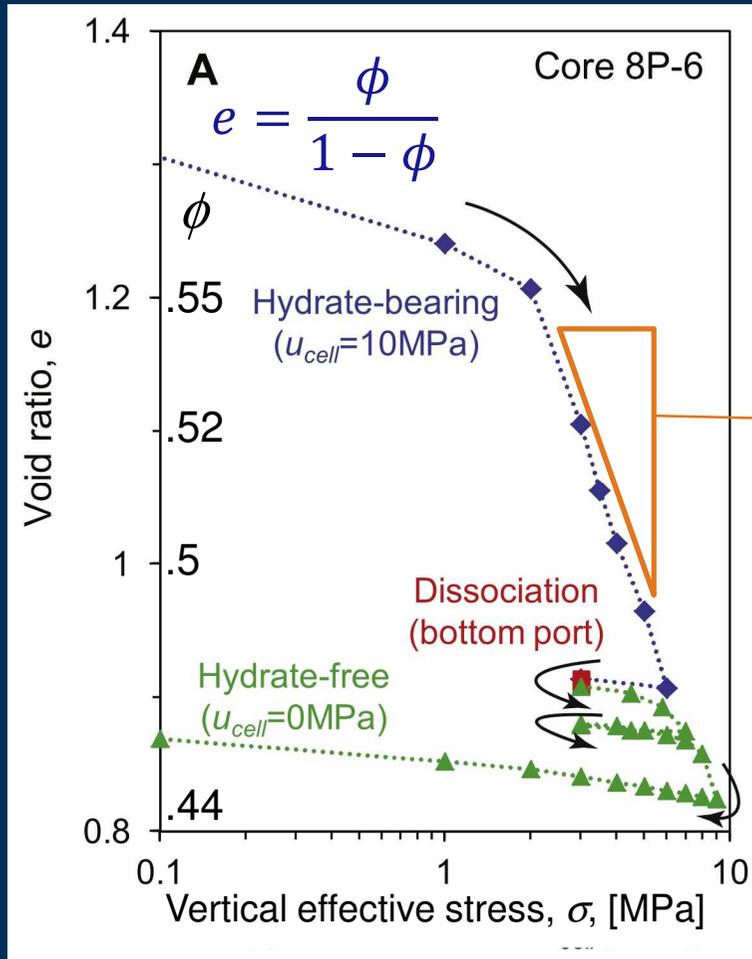
Santamarina et al. (2015), Marine and Petroleum Geology

Consolidation: volume loss with increasing stress

Core 8P-6

$$e = \frac{\phi}{1 - \phi}$$

Hydrate-bearing (u_{cell}=10MPa)

Dissociation (bottom port)

Hydrate-free (u_{cell}=0MPa)

Void ratio, e

Vertical effective stress, σ, [MPa]

Coefficient of compressibility, C_c:

$$C_c = \frac{e_1 - e_2}{log\left(\frac{\sigma_1}{\sigma_2}\right)}$$

C_c = .608, sediment with hydrate, lower stress

Porosity drops 5%, from 55% to 50%, between 2 and ~4 MPa

Sandy silt from Nankai Trough (offshore Japan)

Consolidation: volume loss with increasing stress
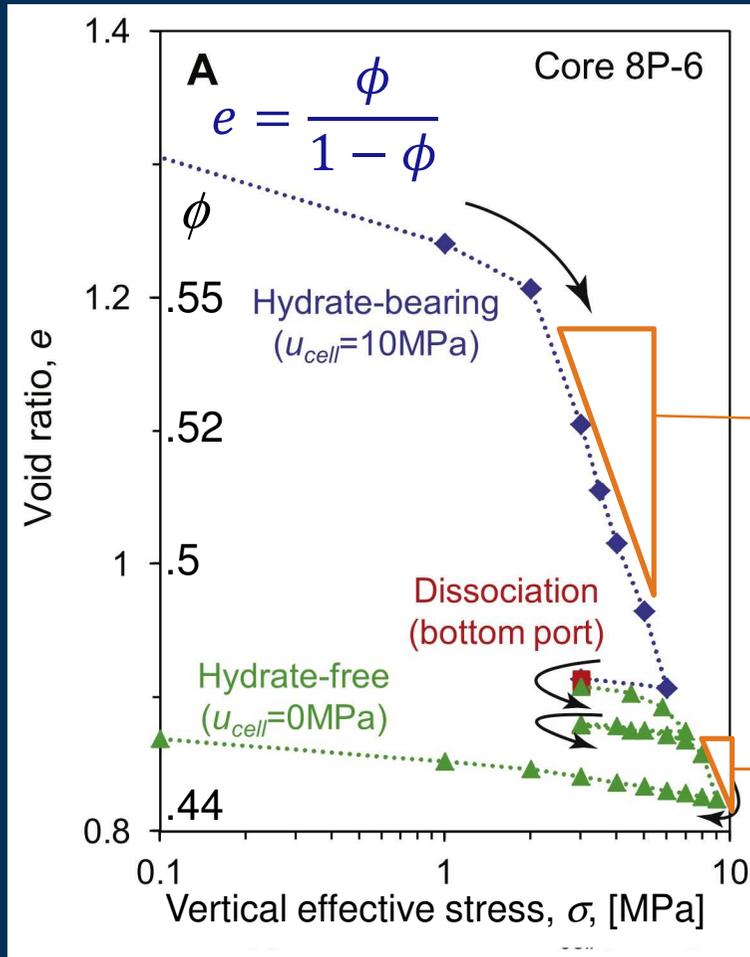
Sandy silt from Nankai Trough
(offshore Japan)

Coefficient of compressibility, C_c:

$$C_c = \frac{e_1 - e_2}{log\left(\frac{\sigma_1}{\sigma_2}\right)}$$

C_c = .608, sediment with hydrate, lower stress

Porosity drops 5%, from 55% to 50%, between 2 and ~4 MPa

C_c = .250, no hydrate, higher stress

Porosity drops 0.8%, from 46.5% to 45.7% between 8 and 9 MPa

Santamarina et al. (2015), Marine and Petroleum Geology

Testing hydrate-free sediment is important

(b) Hydrate saturation profile (interbedded)

As the models indicate, after some time, the sediment near the borehole becomes hydrate-free…

Uchida et al. (2018), JMPG

Testing hydrate-free sediment is important

(b) Hydrate saturation profile (interbedded)

$r = 0$ m   4.5 m

Mud(0.1m)
Sand (1 m)
Mud(0.1m)

Borehole Wall

$t = 5$ days $t = 10$ days $t = 30$ days

S_h (%)
80 70 60 50 40 30 20 10 0
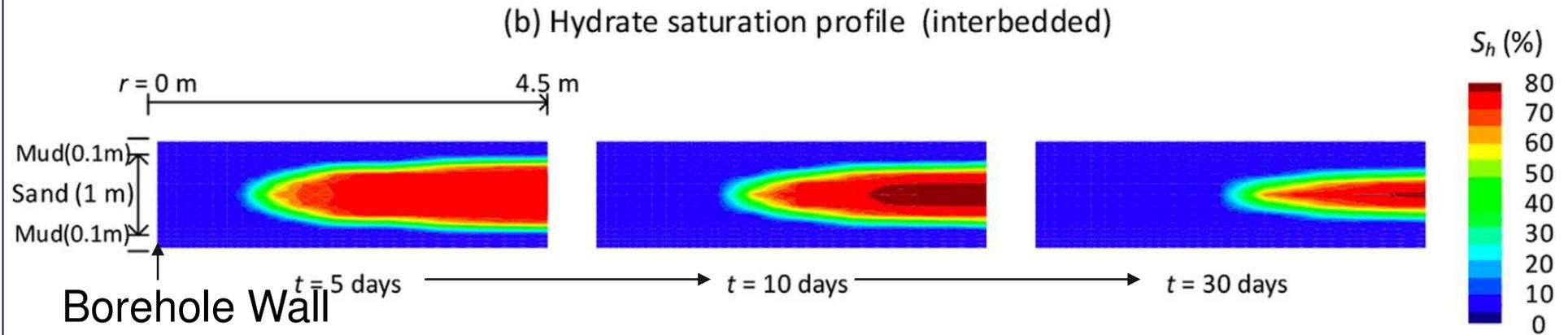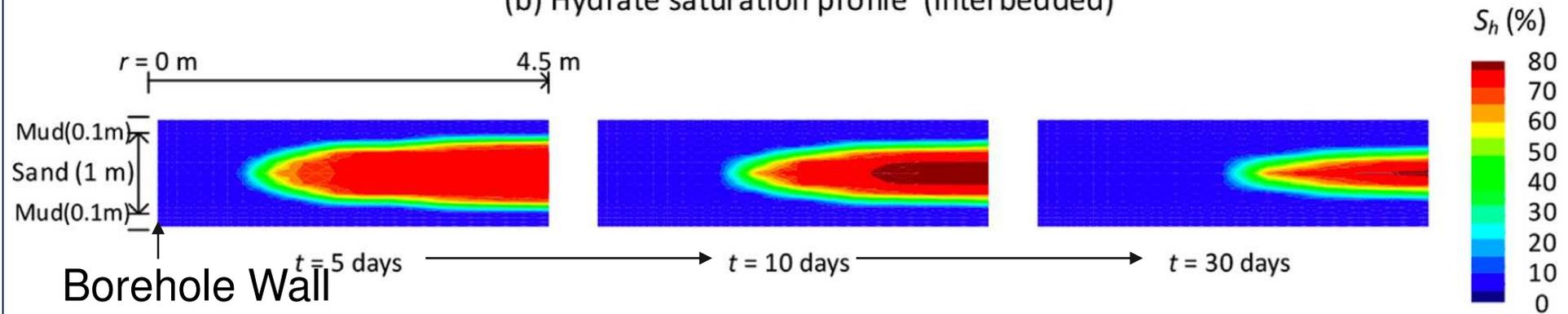
(b) Detached sand volume profile (interbedded)
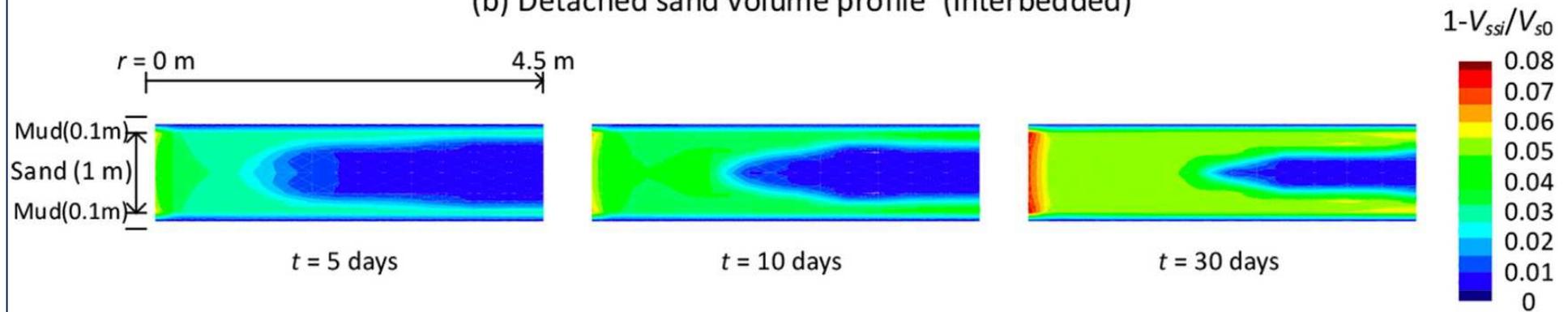
$r = 0$ m   4.5 m

Mud(0.1m)
Sand (1 m)
Mud(0.1m)

$t = 5$ days $t = 10$ days $t = 30$ days

$1 - V_{ssi}/V_{s0}$
0.08 0.07 0.06 0.05 0.04 0.03 0.02 0.01 0

As the models indicate, after some time, the sediment near the borehole becomes hydrate-free…

That sediment can flow into the production well if it fails.

Uchida et al. (2018), JMPG

Testing hydrate-free sediment is important

(b) Hydrate saturation profile (interbedded)

$r = 0$ m   4.5 m
Mud(0.1m)
Sand (1 m)
Mud(0.1m)
Borehole Wall
$t = 5$ days $t = 10$ days $t = 30$ days
S_h (%)
80 70 60 50 40 30 20 10 0

(d) Volumetric strain profile (interbedded)
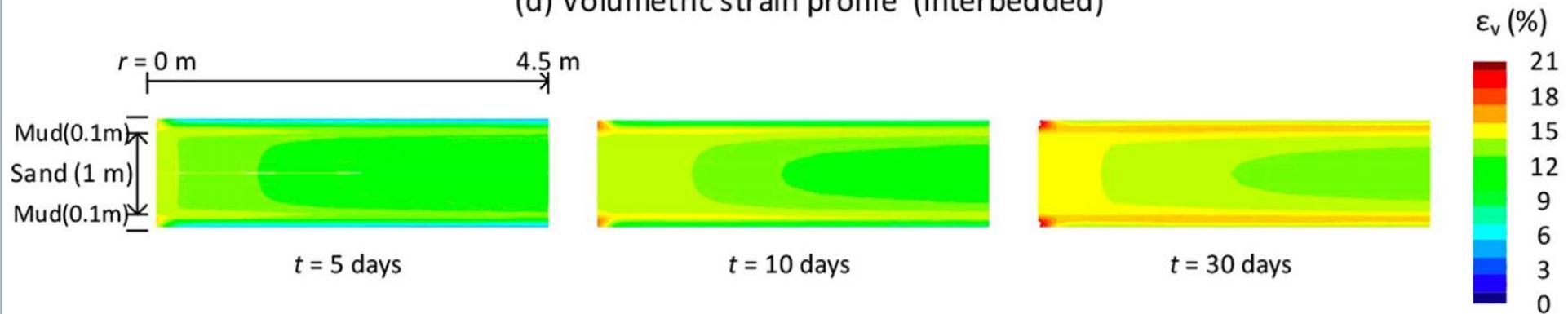
$r = 0$ m   4.5 m
Mud(0.1m)
Sand (1 m)
Mud(0.1m)
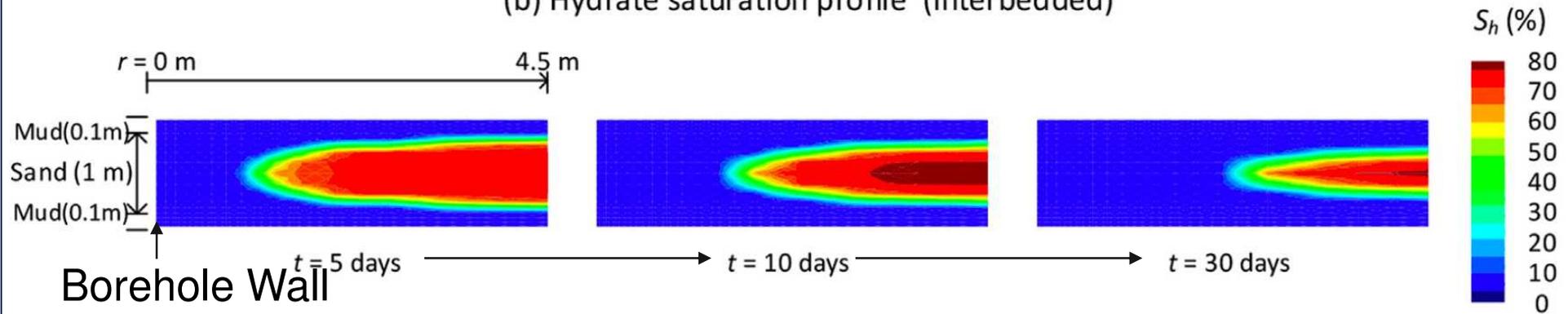$t = 5$ days $t = 10$ days $t = 30$ days
ε_v (%)
21 18 15 12 9 6 3 0

As the models indicate, after some time, the sediment near the borehole becomes hydrate-free…

That sediment can also consolidate, reducing pore space and permeability

Uchida et al. (2018), JMPG

Coping with sediment motion – NGHP-02 (Offshore India)
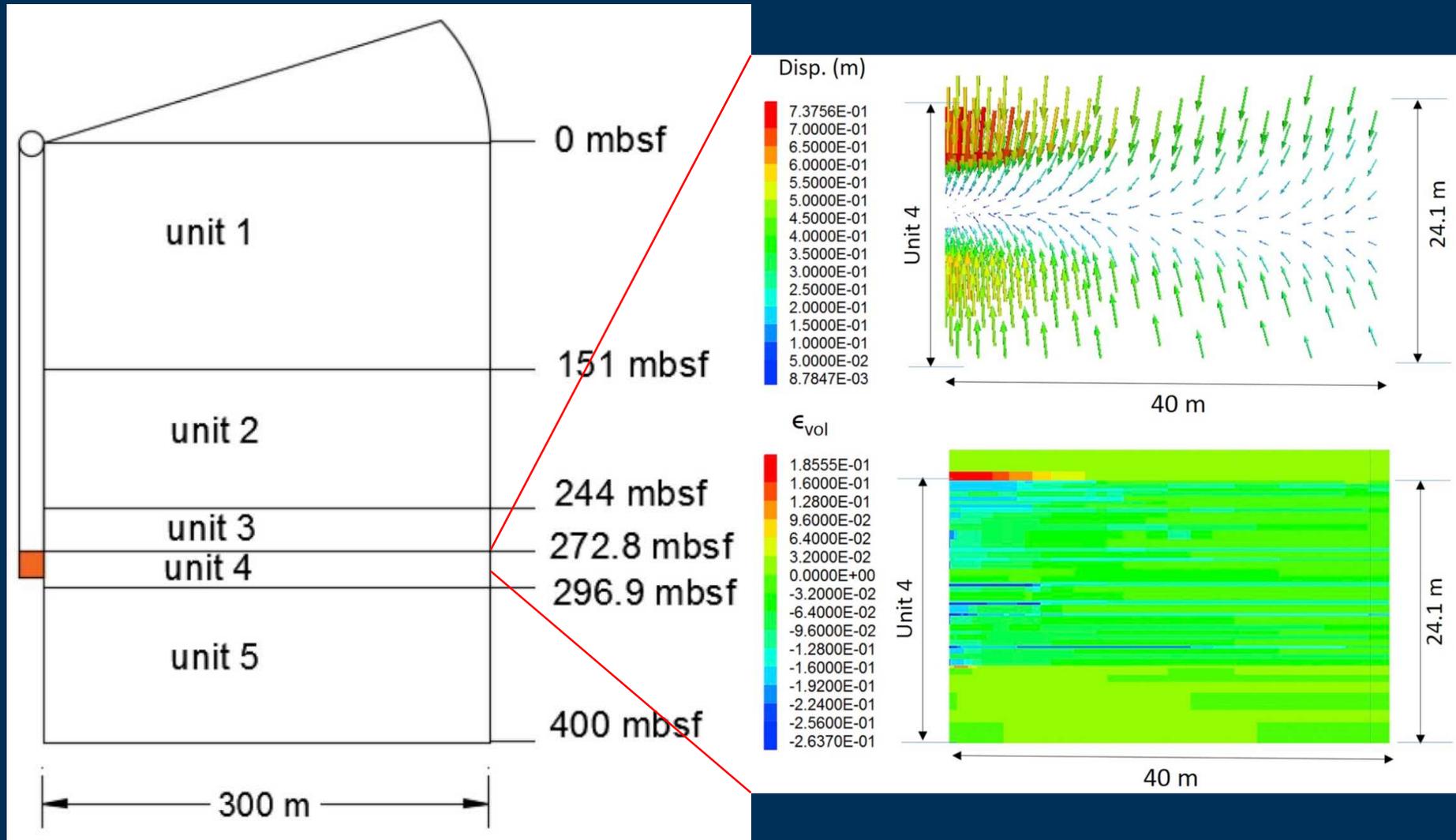
The well has to be built to handle sediment motion along the well.

Lin et al. (2018), JMPG

Consequence of sediment compressibility: permeability loss

$$e = \frac{\phi}{1 - \phi}$$

Core 8P-6

Hydrate-bearing (u_{cell}=10MPa)

Dissociation (bottom port)

Hydrate-free (u_{cell}=0MPa)

Void ratio, e

Vertical effective stress, σ, [MPa]

Sandy silt from Nankai Trough (offshore Japan)

Coefficient of compressibility, C_c:

$$C_c = \frac{e_1 - e_2}{log\left(\frac{\sigma_1}{\sigma_2}\right)}$$

C_c = .608, sediment with hydrate, lower stress

Porosity drops 5%, from 55% to 50%, between 2 and ~4 MPa ($\phi_0 = 0.55$, $\phi_1 = 0.5$)

Kozeny-Carmen estimate of permeability reduction:

$$k \propto \frac{\phi^3}{(1 - \phi)^2}$$

Consequence of sediment compressibility: permeability loss

A — Core 8P-6

$$e = \frac{\phi}{1-\phi}$$

Void ratio, e (axis: 0.8, 1, 1.2, 1.4)

ϕ (axis: .44, .5, .52, .55)

Hydrate-bearing (u_{cell}=10MPa)

Dissociation (bottom port)

Hydrate-free (u_{cell}=0MPa)

Vertical effective stress, σ, [MPa] (axis: 0.1, 1, 10)

Sandy silt from Nankai Trough (offshore Japan)

Coefficient of compressibility, C_c:

$$C_c = \frac{e_1 - e_2}{log\left(\frac{\sigma_1}{\sigma_2}\right)}$$
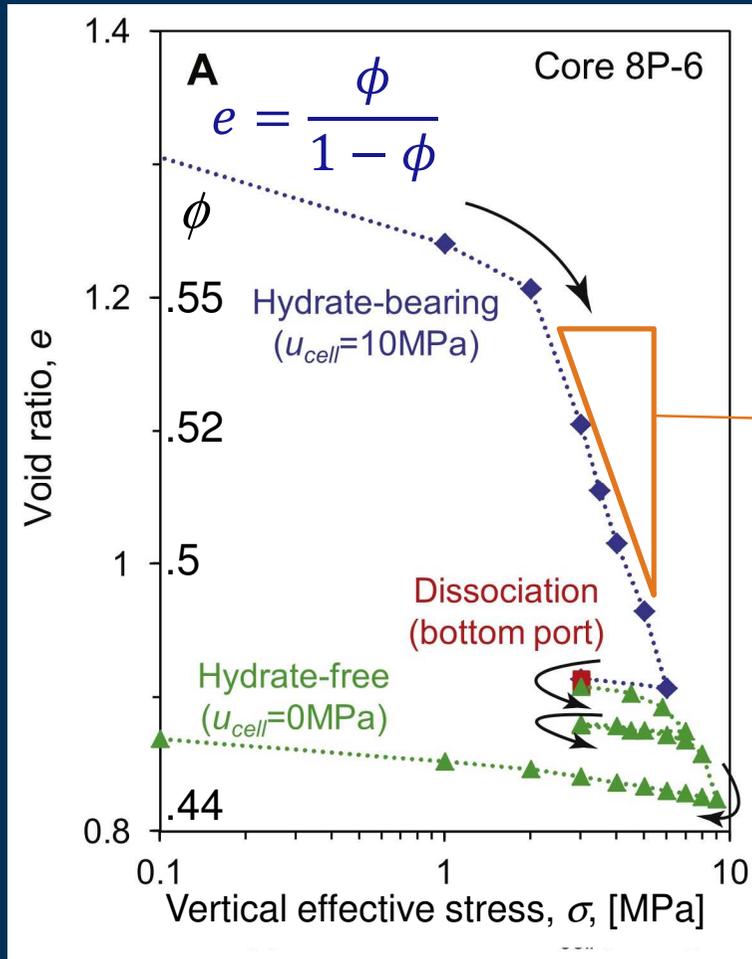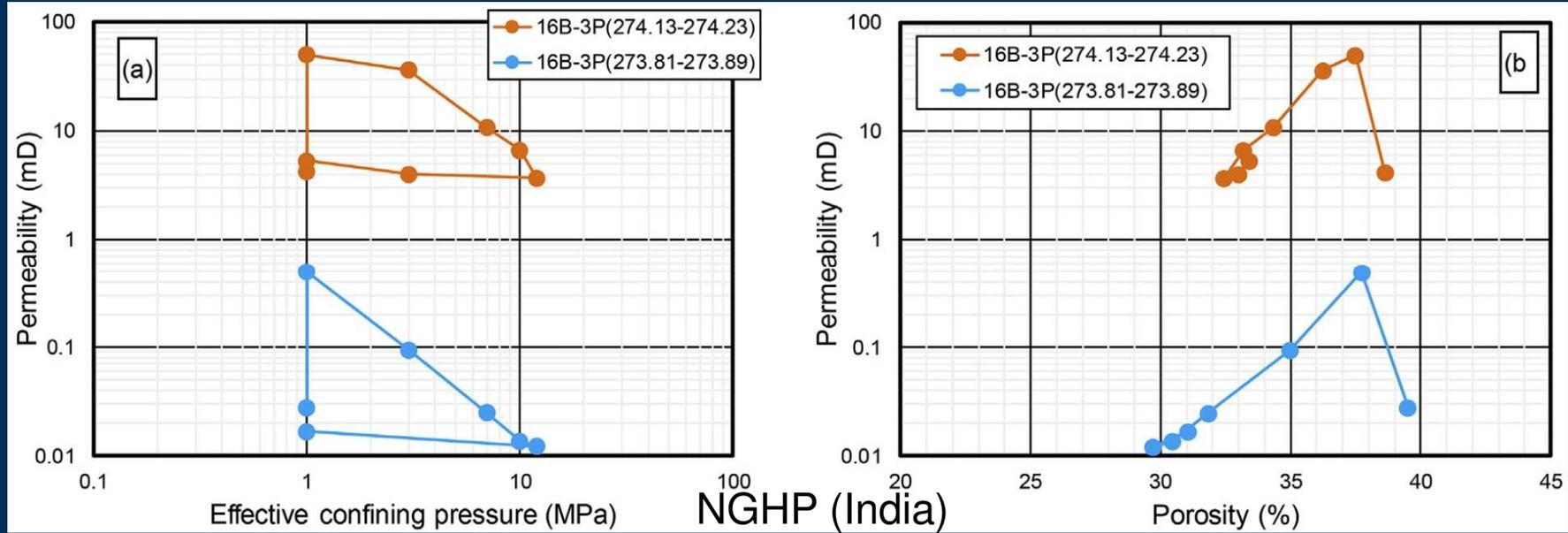
C_c = .608, sediment with hydrate, lower stress

Porosity drops 5%, from 55% to 50%, between 2 and ~4 MPa ($\phi_0 = 0.55$, $\phi_1 = 0.5$)

Kozeny-Carmen estimate of permeability reduction:
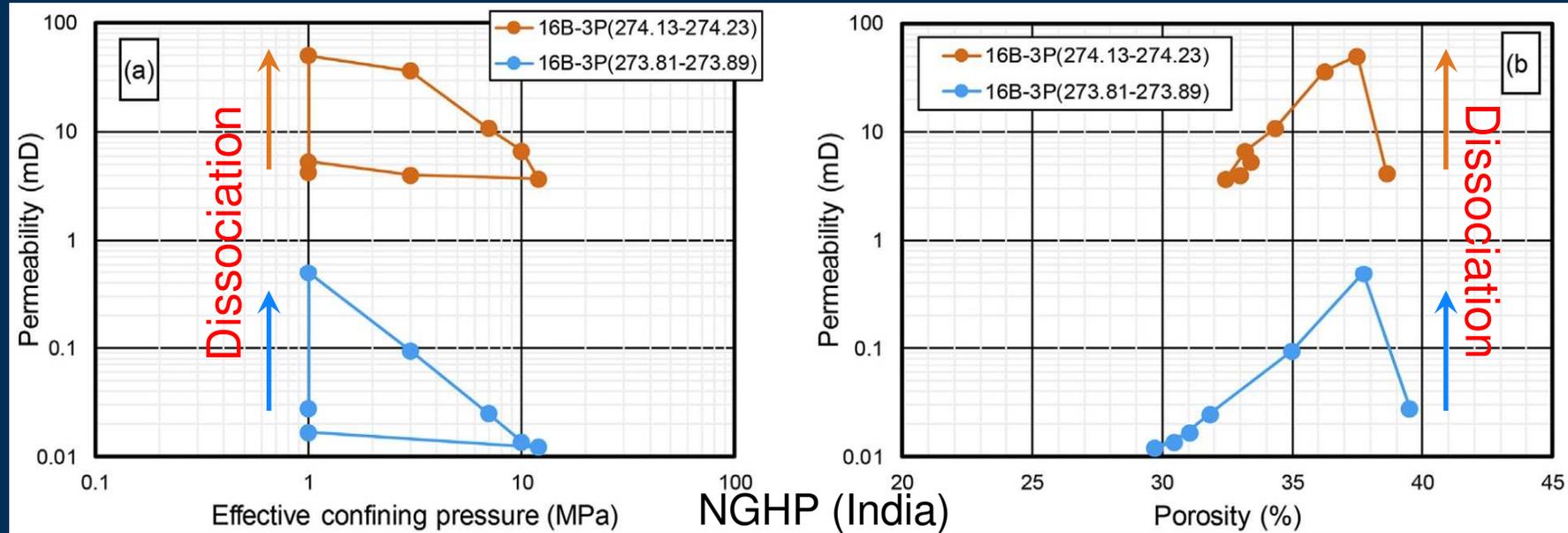
$$k \propto \frac{\phi^3}{(1-\phi)^2}$$

$$\frac{k_1}{k_0} = \frac{\phi_1^3}{\phi_0^3} \cdot \frac{(1-\phi_0)^2}{(1-\phi_1)^2} \approx 0.64 \text{ in this case}$$

Porosity does not have to drop much to significantly impact permeability.

Santamarina et al. (2015), Marine and Petroleum Geology

Consequence of sediment compressibility: permeability loss

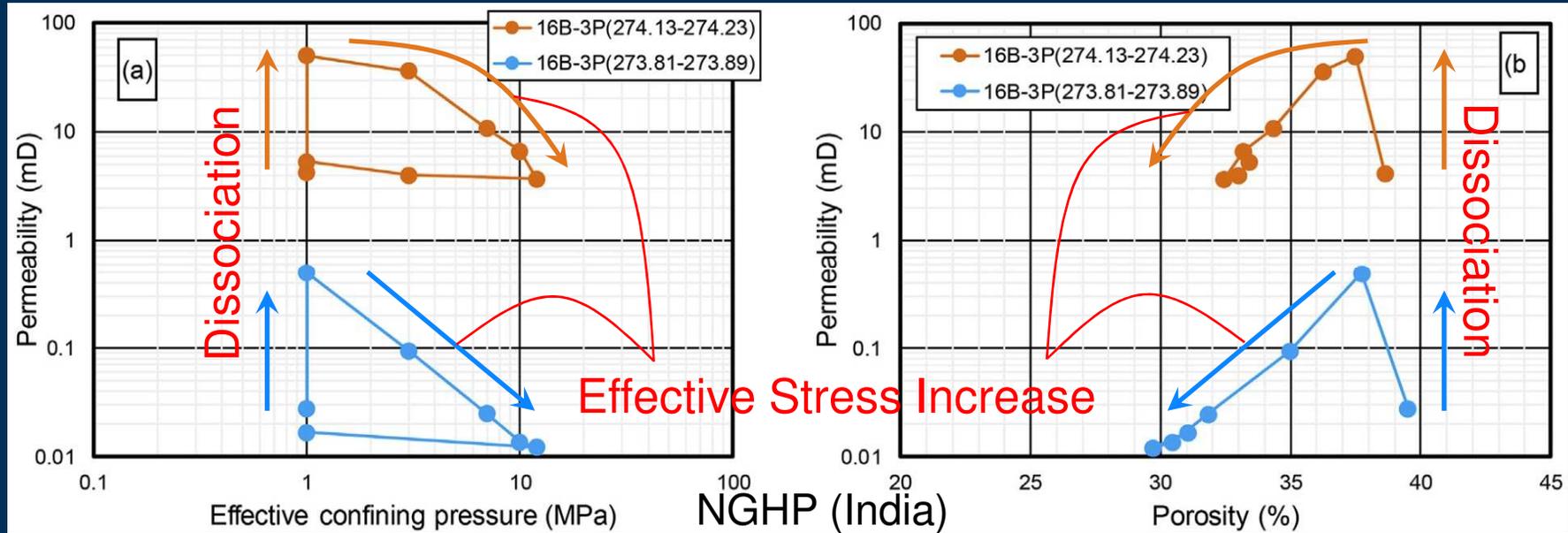NGHP (India)

Yoneda et al. (2018), JMPG

Consequence of sediment compressibility: permeability loss

Dissociation at low effective stress:
  Single-phase permeability increases due to loss of gas hydrate

Yoneda et al. (2018), JMPG

Consequence of sediment compressibility: permeability loss
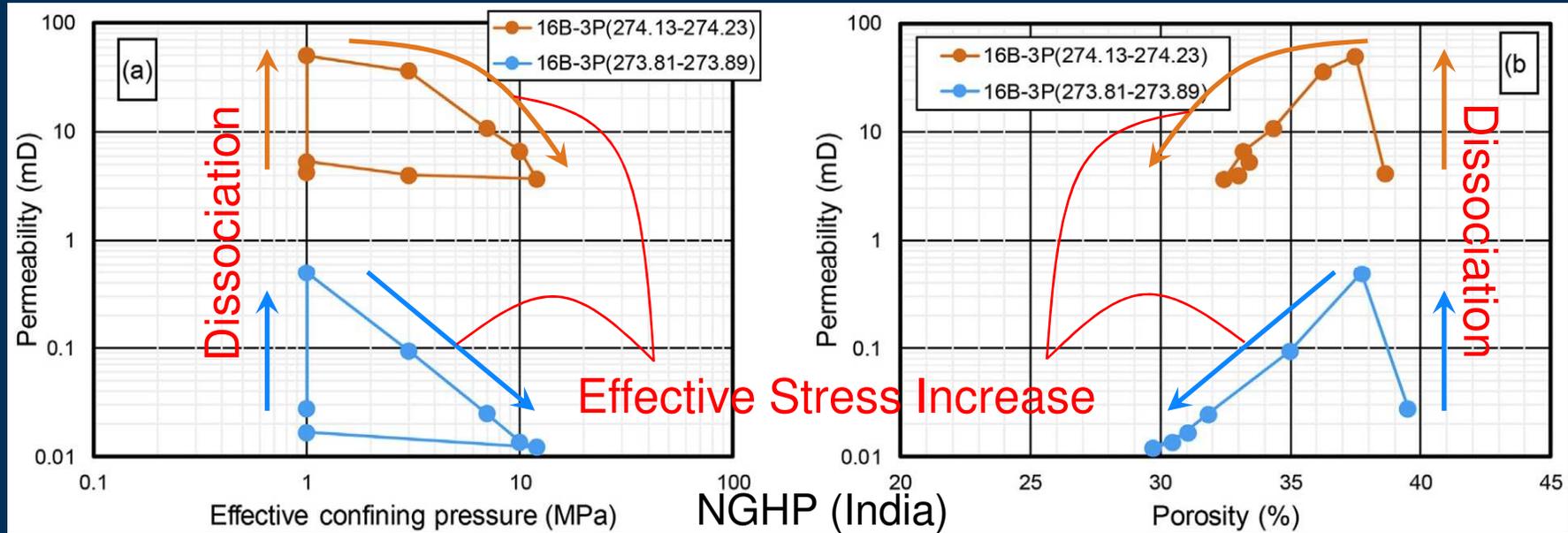

NGHP (India)

Dissociation at low effective stress:
   Single-phase permeability increases due to loss of gas hydrate

Additional effective stress increase:
   Porosity decreases, which decreases permeability

Yoneda et al. (2018), JMPG

Consequence of sediment compressibility: permeability loss
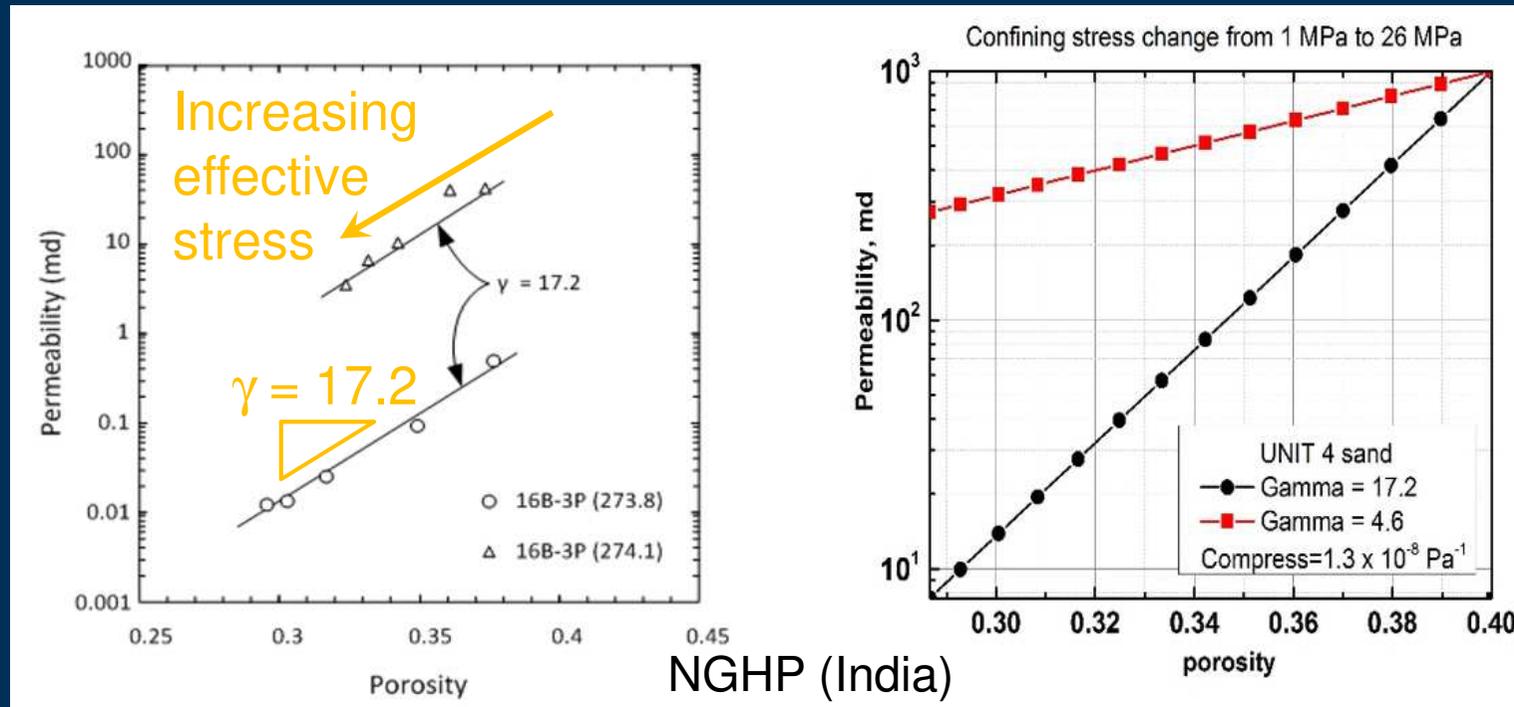

Dissociation at low effective stress:
   Single-phase permeability increases due to loss of gas hydrate

Additional effective stress increase:
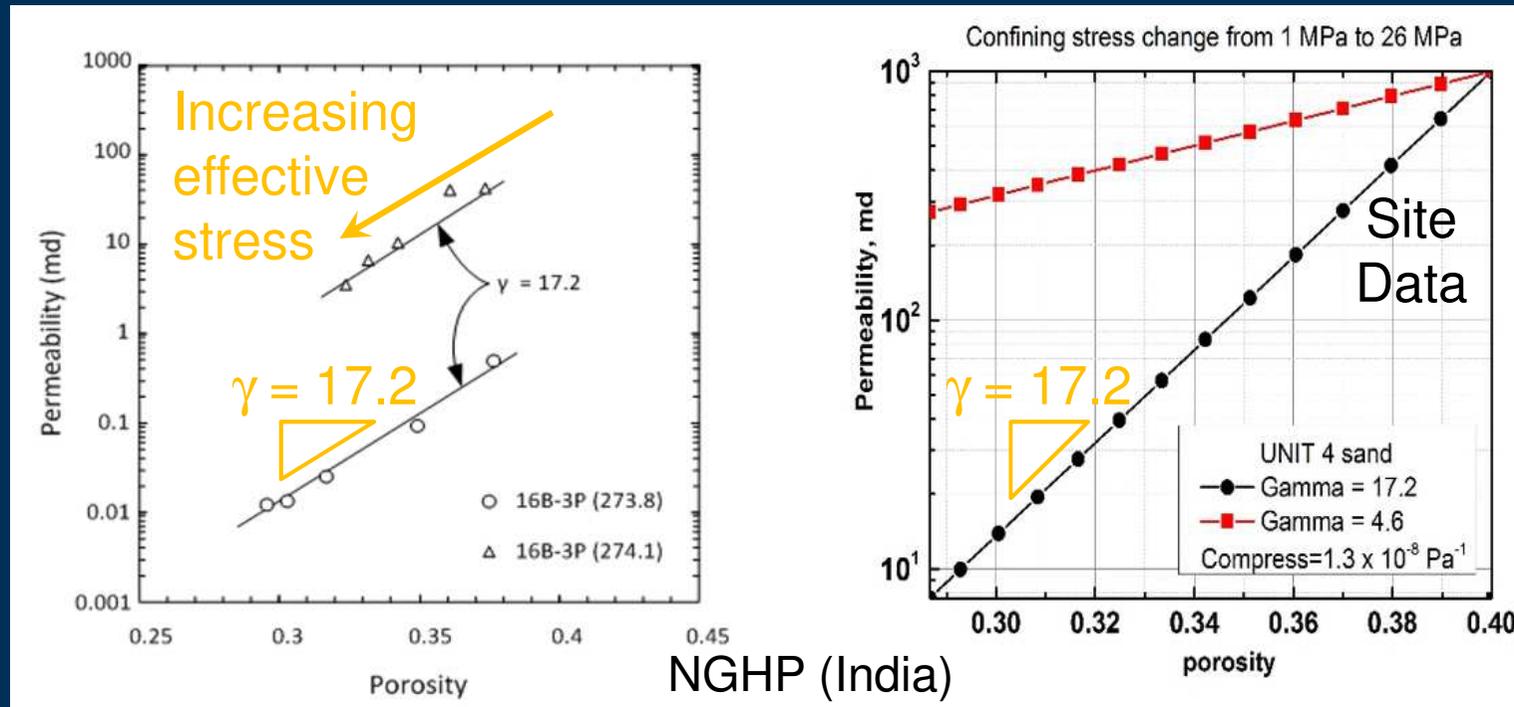   Porosity decreases, which decreases permeability

**Large pressure drawdowns can cause permeability
to _decrease_ during dissociation**

Yoneda et al. (2018), JMPG

Consequence of sediment compressibility: permeability loss

NGHP (India)
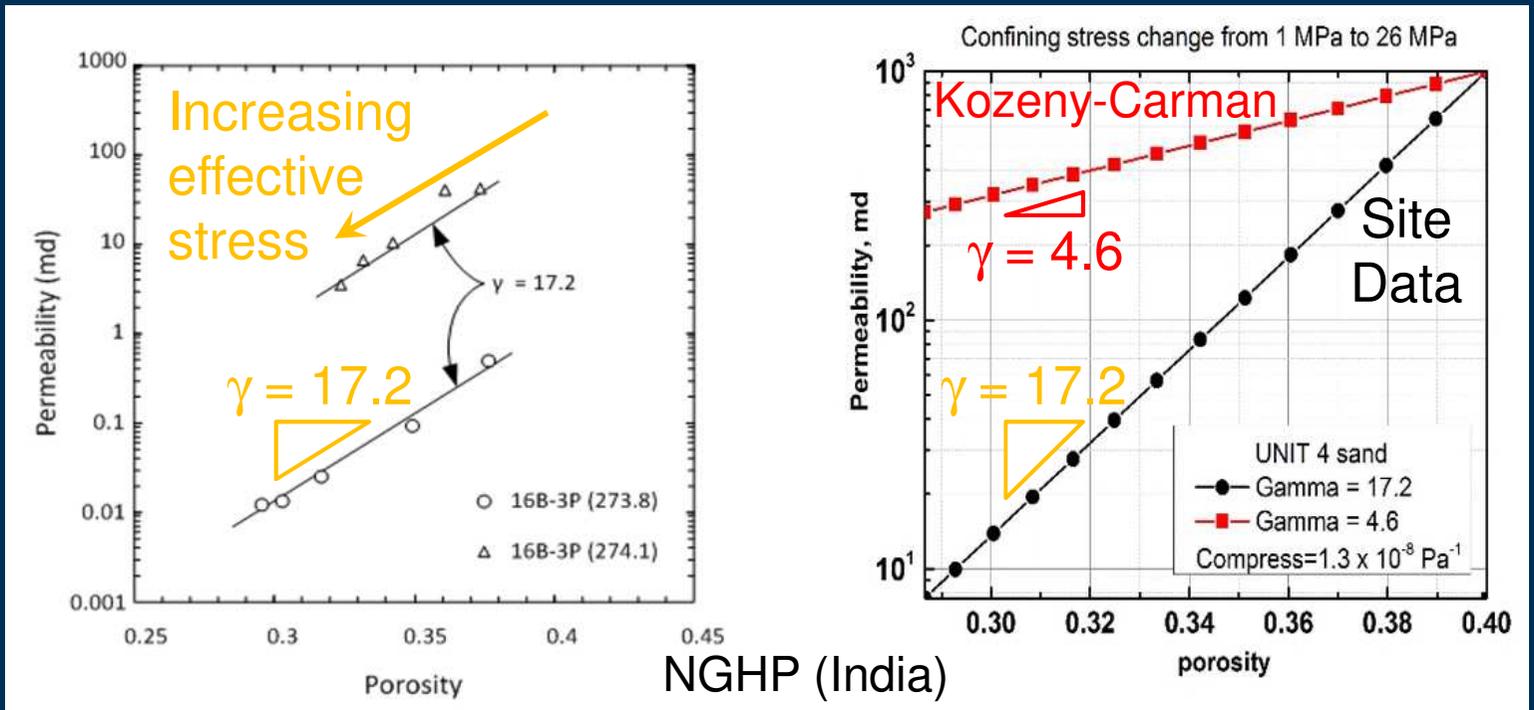
Correlation depends on sediment compressibility…
which itself depends on relationships between fine- and
coarse-grained sediment grains.

Yoneda et al. (2018), JMPG; Myshakin et al. (2018), JMPG
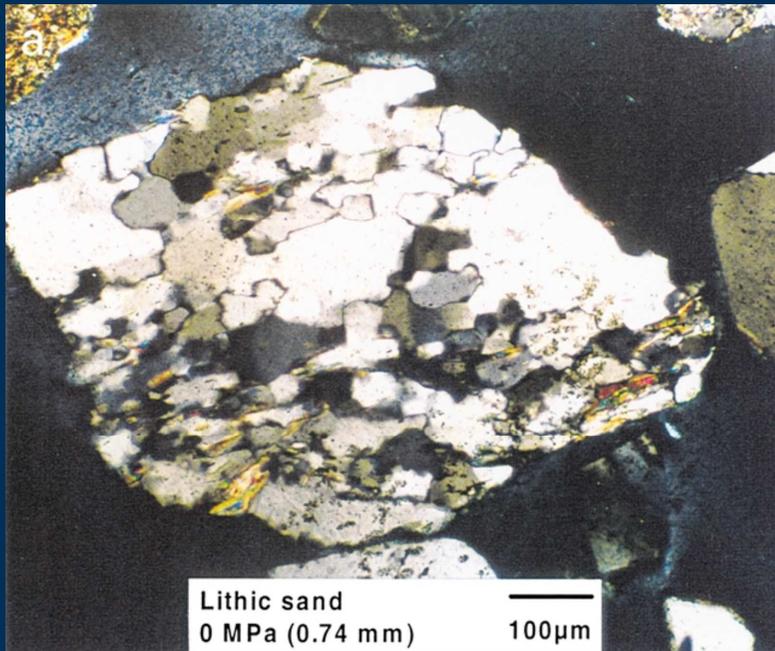
Consequence of sediment compressibility: permeability loss

Correlation depends on sediment compressibility…
which itself depends on relationships between fine- and
coarse-grained sediment grains.

Yoneda et al. (2018), JMPG; Myshakin et al. (2018), JMPG
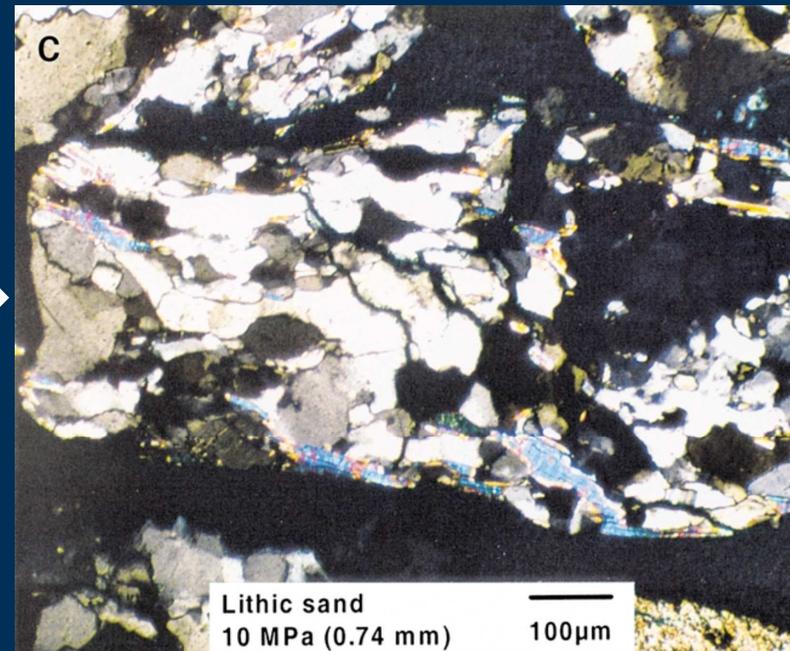
Consequence of sediment compressibility: permeability loss

Correlation depends on sediment compressibility…
which itself depends on relationships between fine- and
coarse-grained sediment grains.
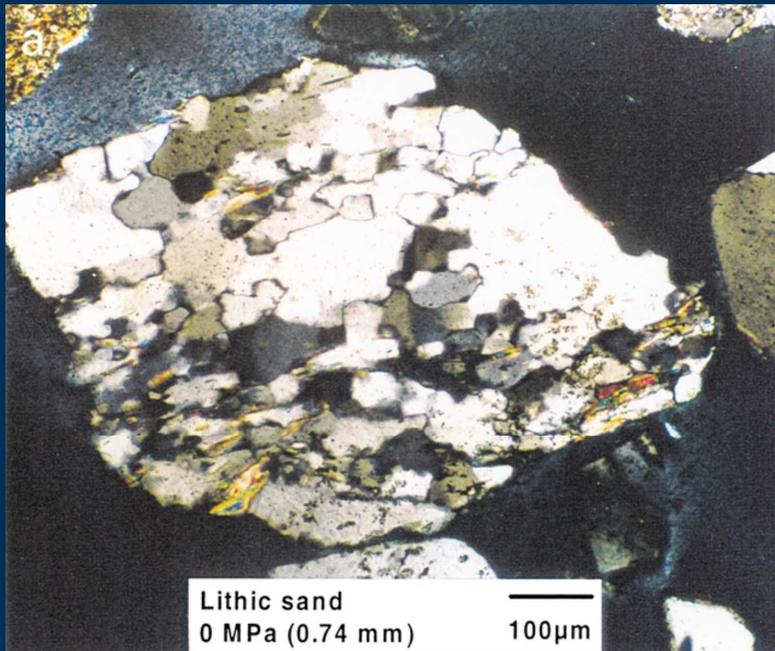
Yoneda et al. (2018), JMPG; Myshakin et al. (2018), JMPG

Consequence of sediment compressibility: grain crushing

Apply

10MPa

Lithic sand
0 MPa (0.74 mm)   100μm
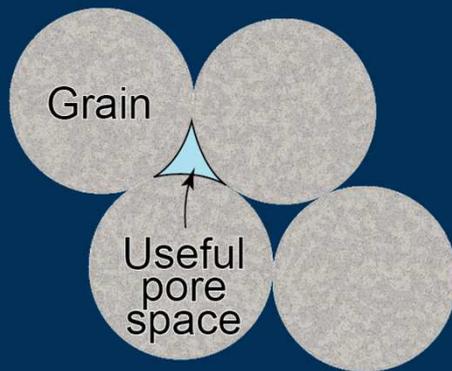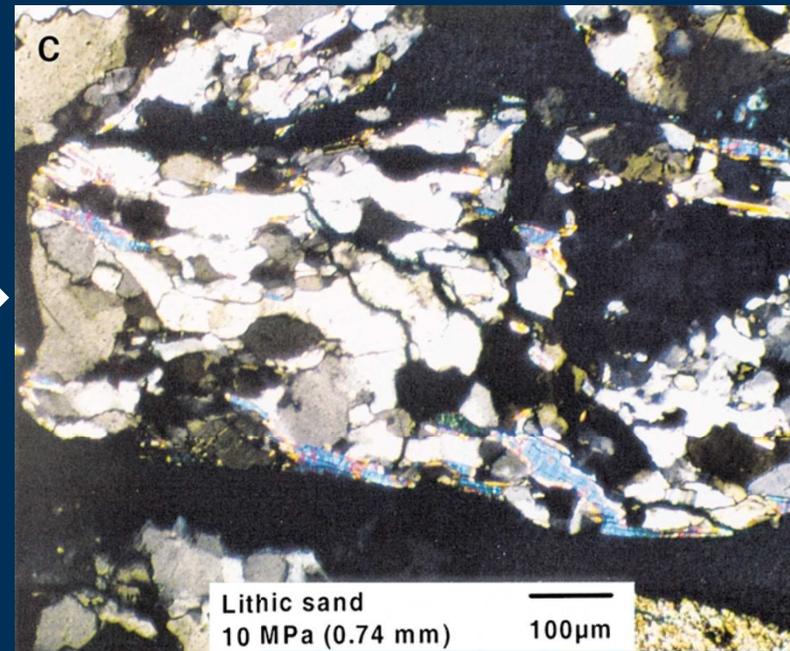
Lithic sand
10 MPa (0.74 mm)   100μm
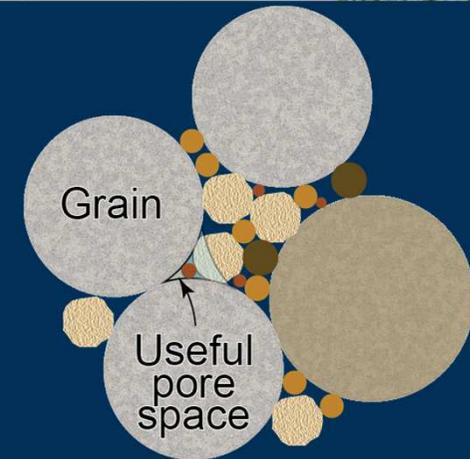
Chuhan et al. (2002), JMPG

Consequence of sediment compressibility: grain crushing

Apply

10MPa

Lithic sand
0 MPa (0.74 mm)   100µm

Lithic sand
10 MPa (0.74 mm)   100µm

Grain

Useful
pore
space

Grain crushing creates small
particles *and* allows grains to
rearrange. Result:
permeability reduction due to
smaller useful pore spaces
and less porosity overall.

Grain

Useful
pore
space

Chuhan et al. (2002), JMPG

Consequence of sediment compressibility: grain crushing
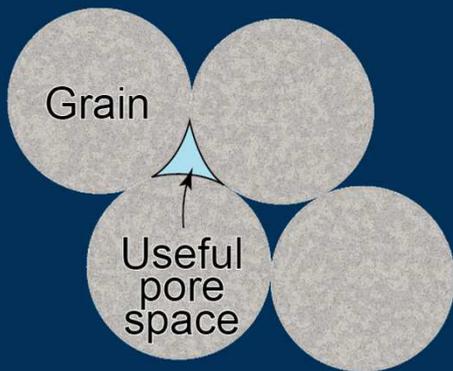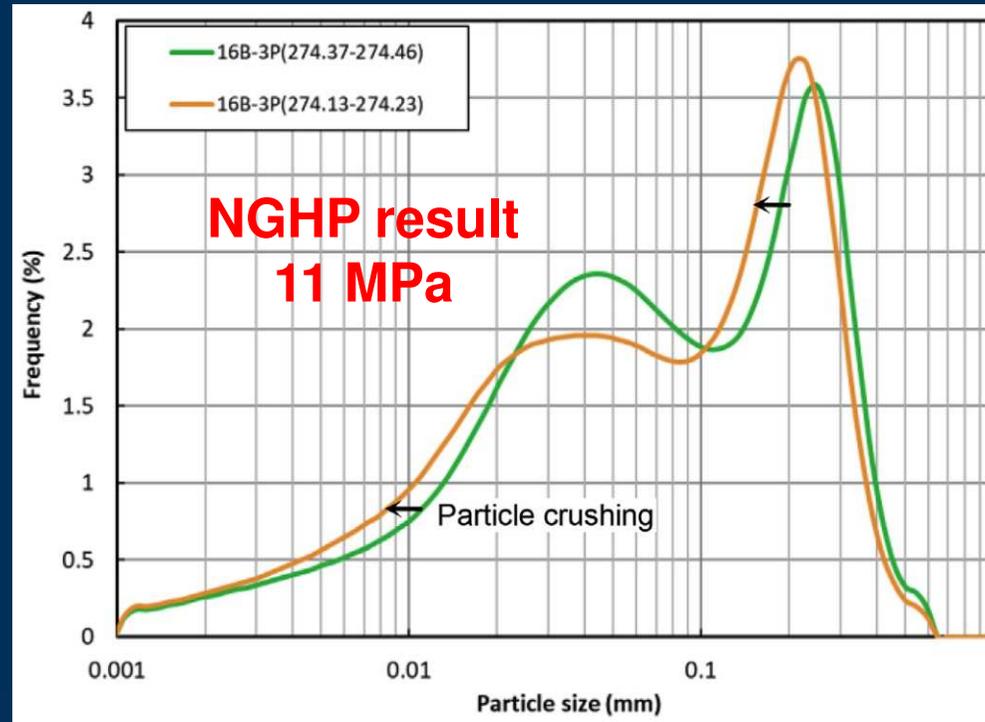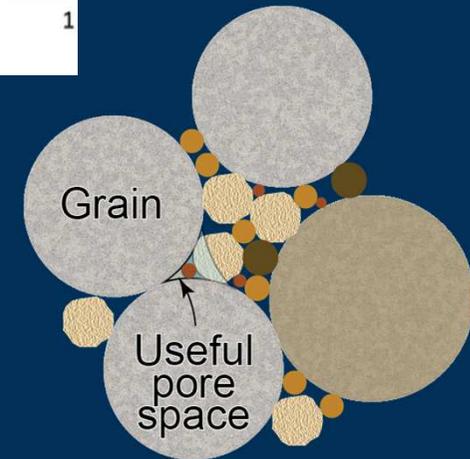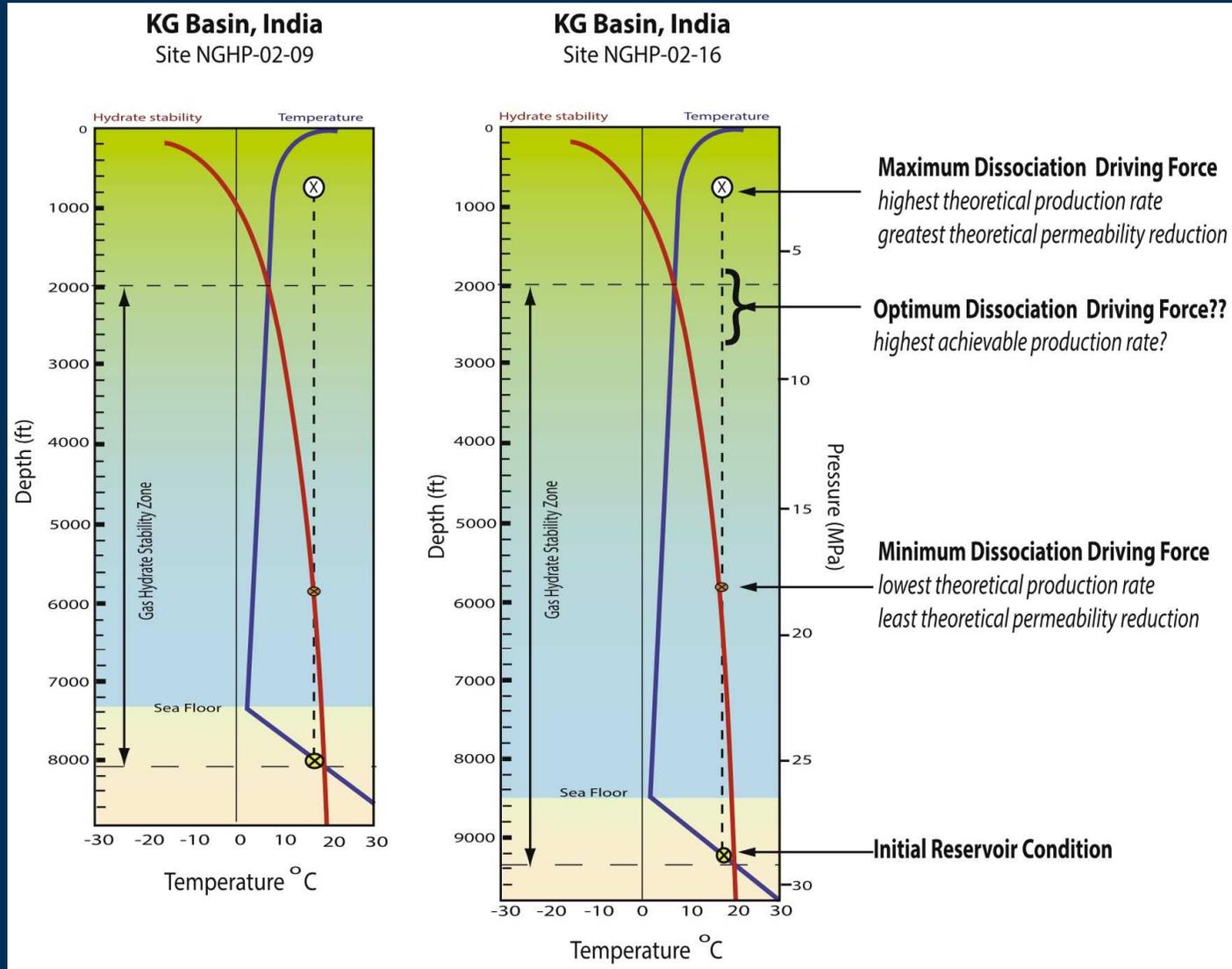

Grain crushing creates small particles *and* allows grains to rearrange. Result: *permeability reduction* due to smaller useful pore spaces and less porosity overall.

Yoneda et al. (2018), JMPG

How much should you depressurize?

KG Basin, India
Site NGHP-02-09

KG Basin, India
Site NGHP-02-16

Maximum Dissociation Driving Force
highest theoretical production rate
greatest theoretical permeability reduction

Optimum Dissociation Driving Force??
highest achievable production rate?

Minimum Dissociation Driving Force
lowest theoretical production rate
least theoretical permeability reduction

Initial Reservoir Condition

Maximum driving force for dissociation may not maximize the overall production rate
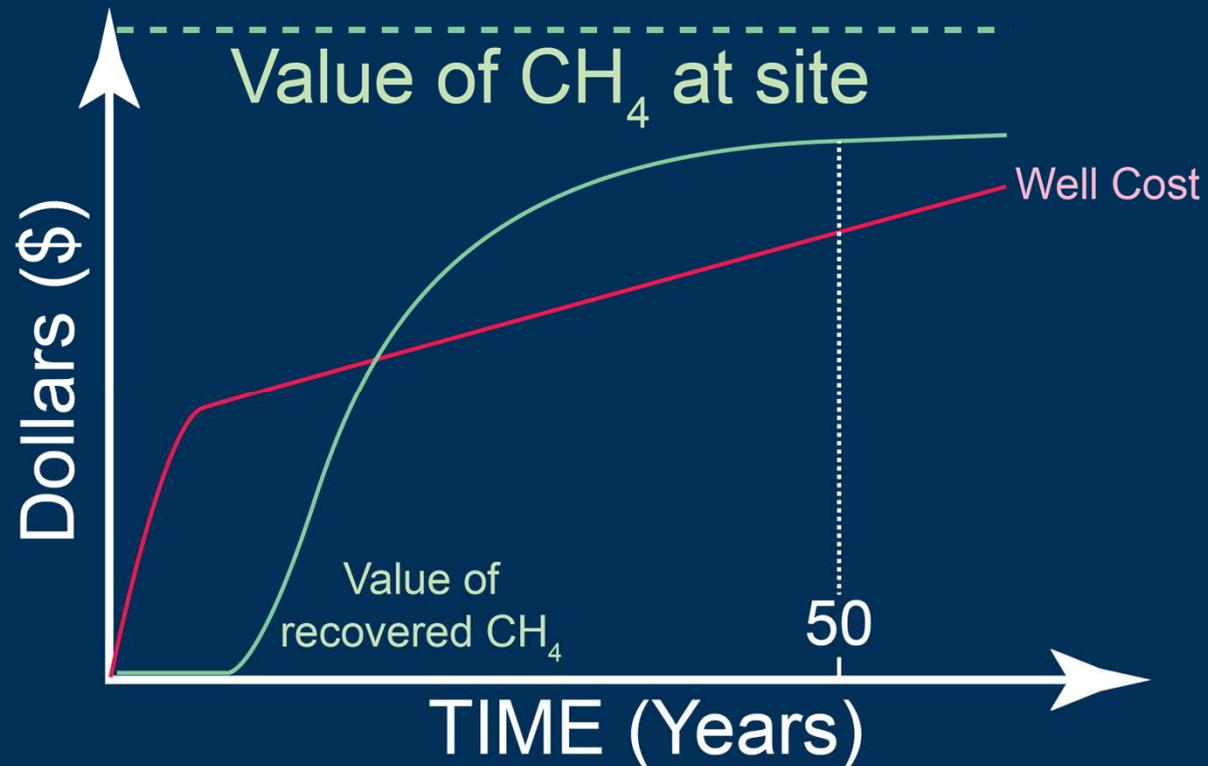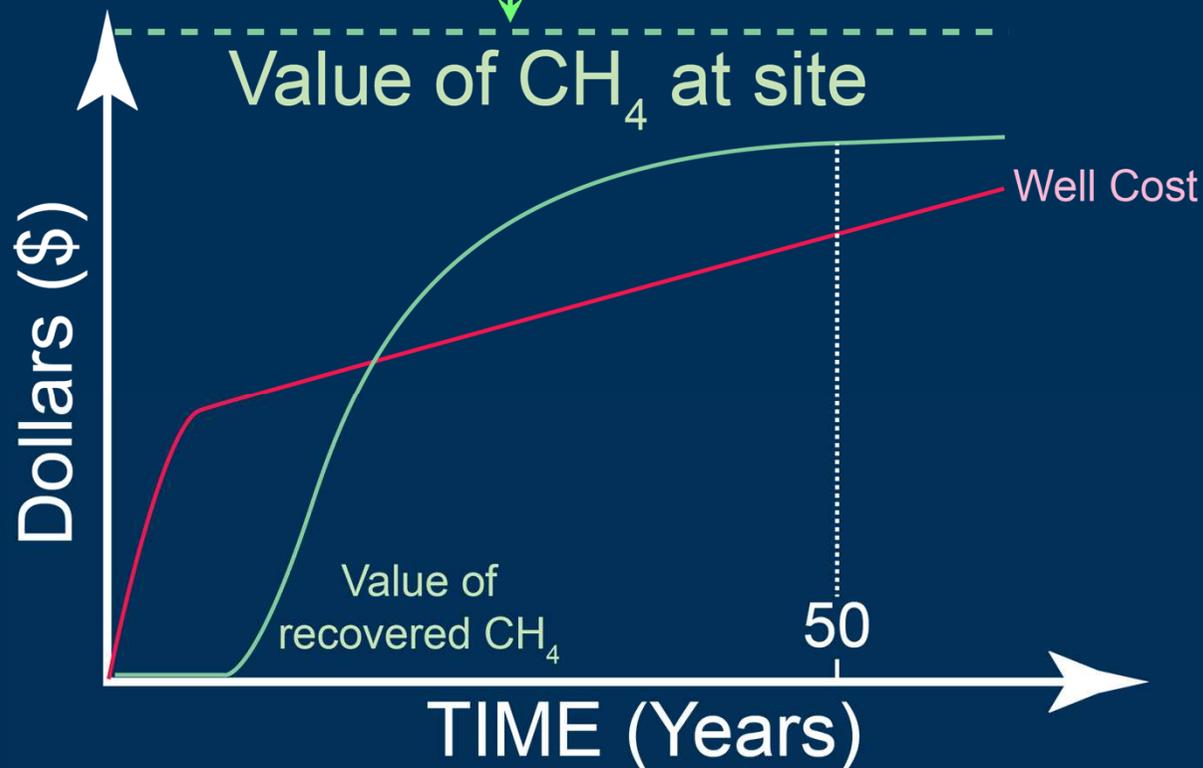
Boswell et al. (2018), JPMG

Summary: Questions physical property measurements answer

Summary: Questions physical property measurements answer

Remote sensing

1) Where is the hydrate?

2) How much hydrate is there?
   - Seismic Data
   - Logging Data

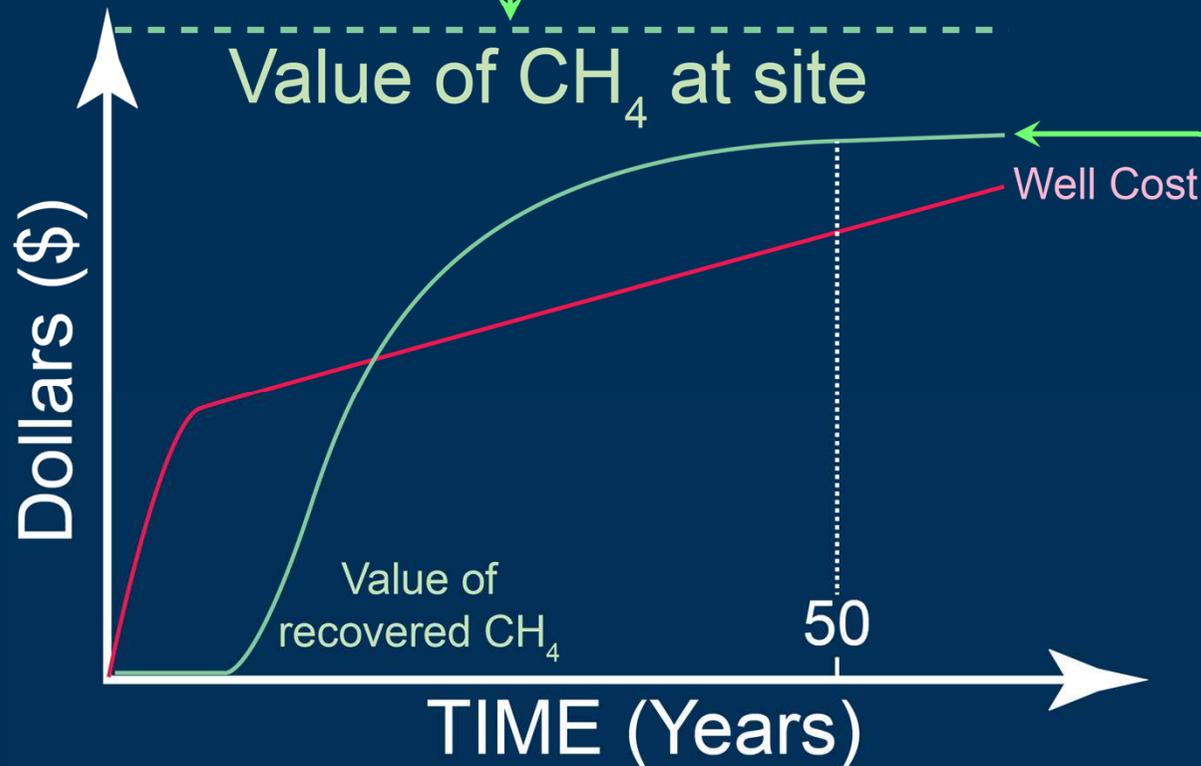# Summary: Questions physical property measurements answer

Remote sensing

1) Where is the hydrate?

2) How much hydrate is there?
   - Seismic Data
   - Logging Data

Sediment measurements

1) How much CH_4 can be collected?

Value of CH_4 at site

Dollars ($)

Well Cost
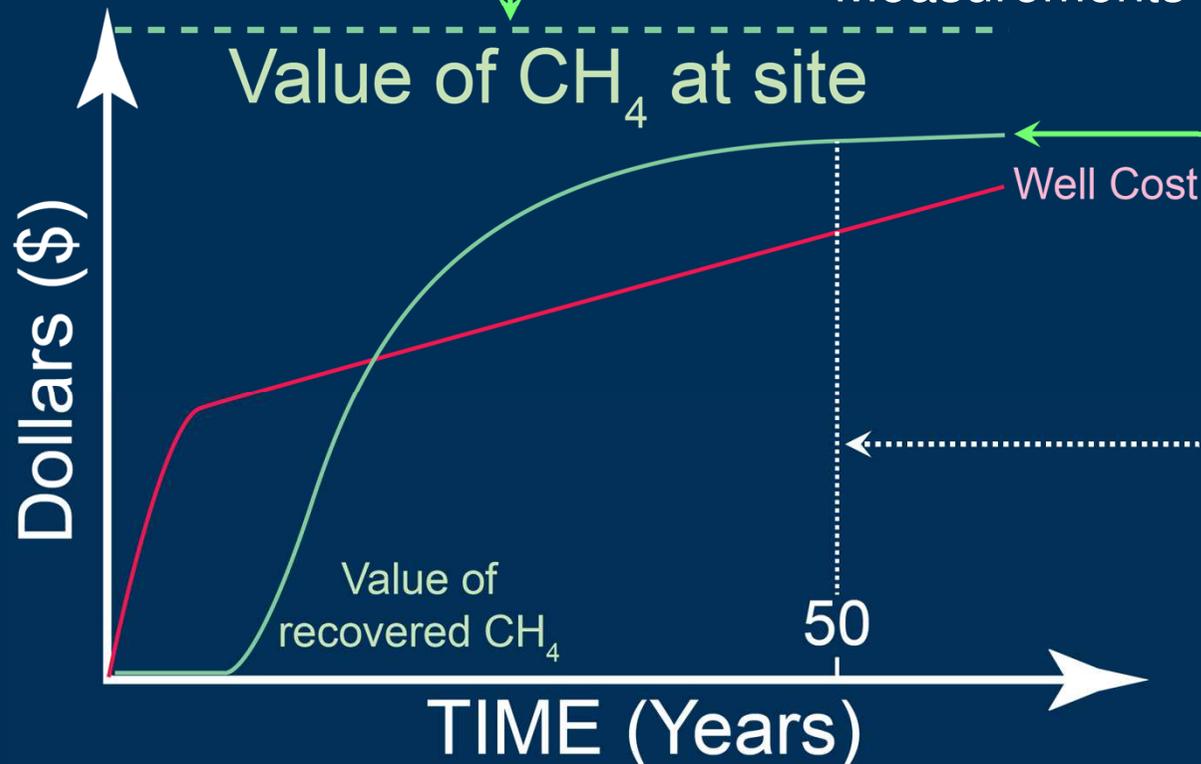
Value of recovered CH_4

50

TIME (Years)

Summary: Questions physical property measurements answer
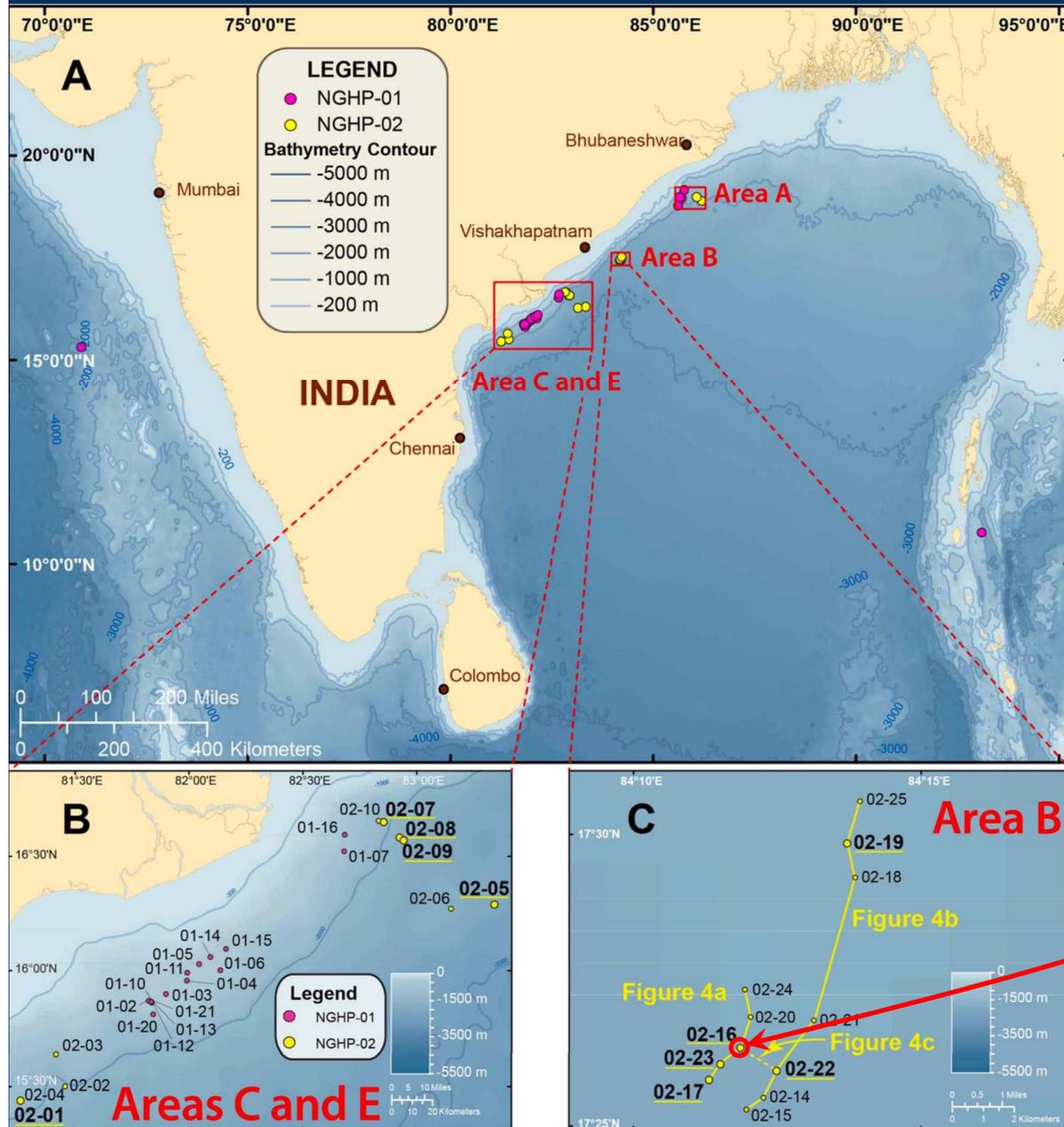
Remote sensing

1) Where is the hydrate?

2) How much hydrate is there?
   - Seismic Data
   - Logging Data

Sediment measurements

1) How much CH_4 can be collected?

2) Will the well operate long enough?
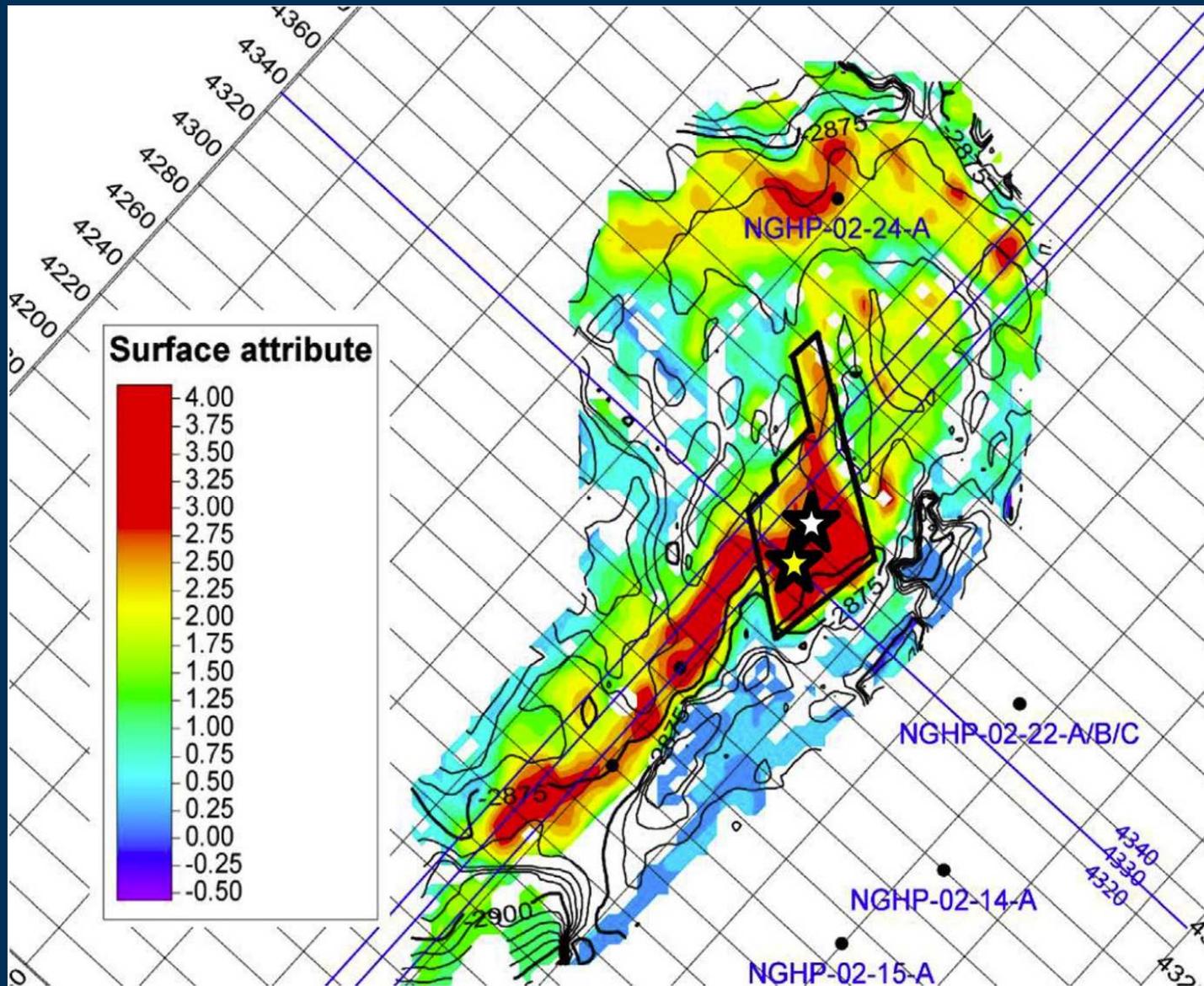   - Pressure Core Measurements
   - Hydrate-Free Sediment Measurements

Value of CH_4 at site

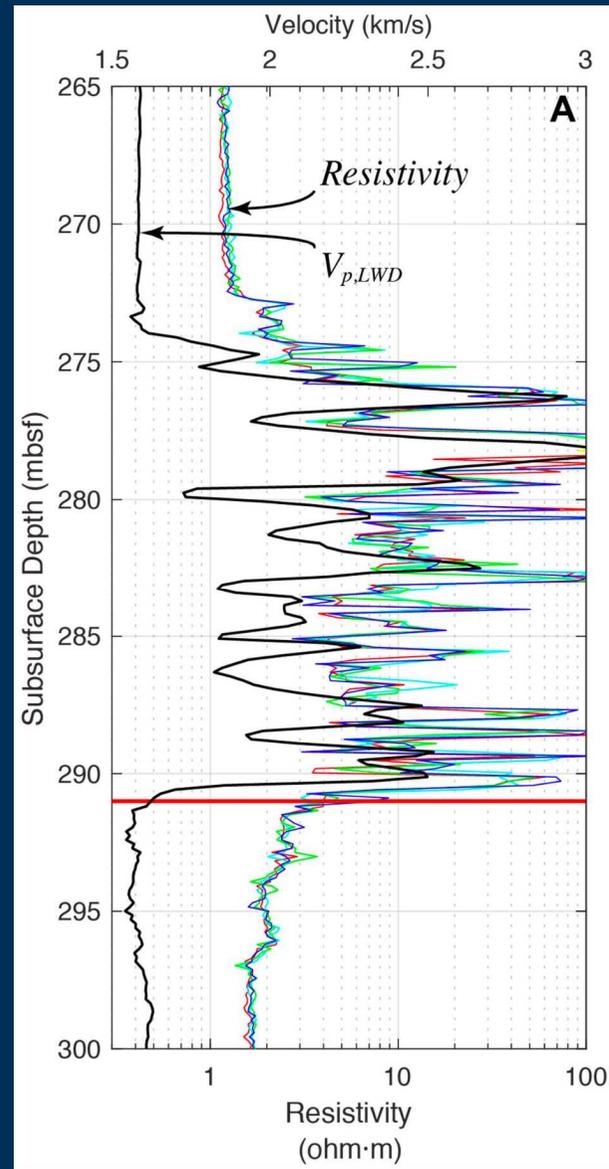Dollars ($)

Well Cost

Value of recovered CH_4

50

TIME (Years)

Sample economic forecast: NGHP-02-16

Waite et al. (2018), JMPG

Sample economic forecast: NGHP-02-16

Sample economic forecast: NGHP-02-16

Waite et al. (2018), JMPG

Sample economic forecast: NGHP-02-16
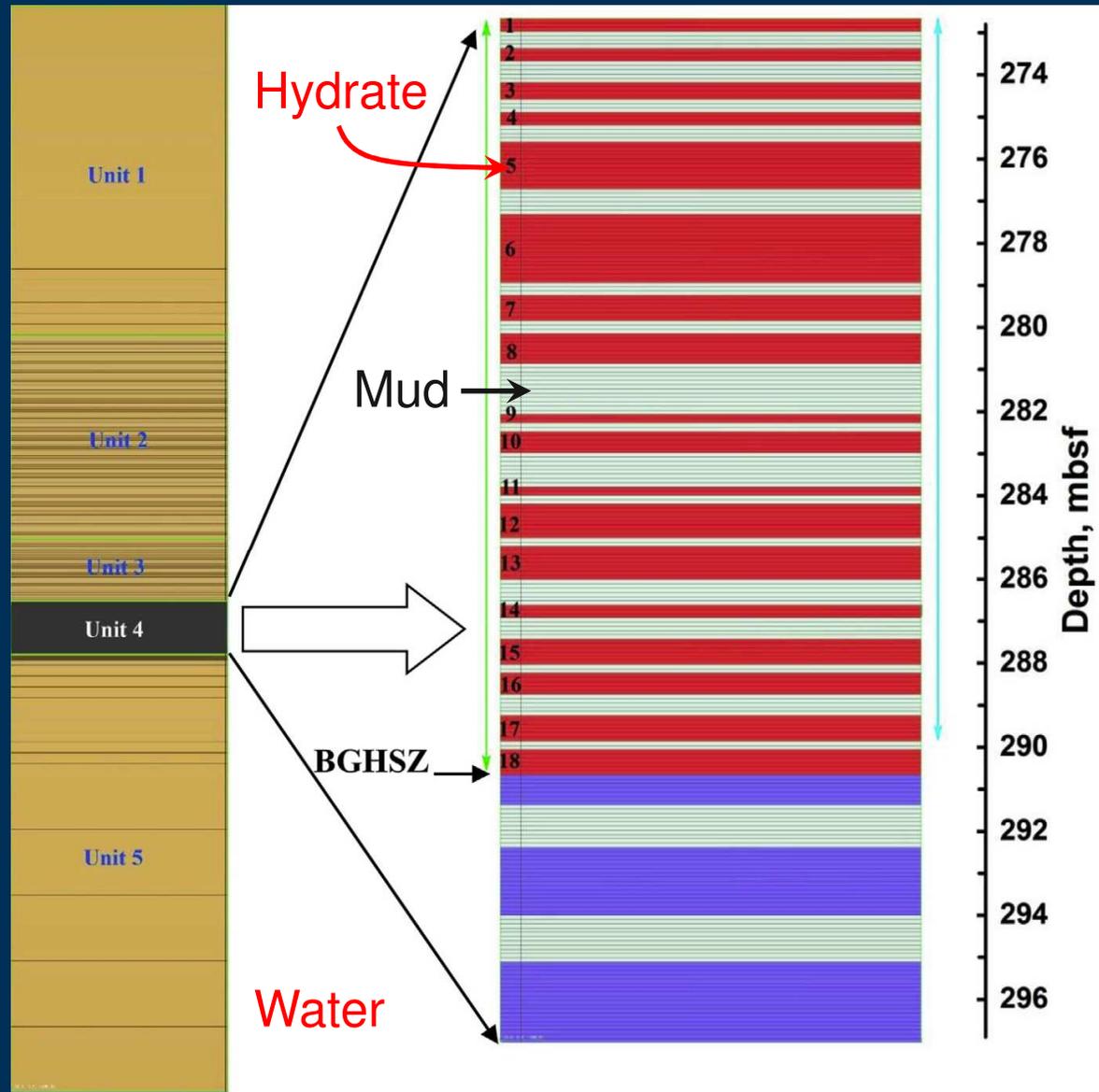
Sample economic forecast: NGHP-02-16

- 120 wells, each drawing from 0.5 km²

- Total gas to produce: 2.03 TCF

- Initial cost: $6.182 Billion

Deepak et al. (2018), JMPG

Sample economic forecast: NGHP-02-16

Gas price: $7.67/MMBTU

	Upside Case	**Base Case**	**Downside Case**
Time			
Production Rate			
Operating Cost			
Gas cost			

Deepak et al. (2018), JMPG

Sample economic forecast: NGHP-02-16

Gas price: $7.67/MMBTU

	Upside Case	Base Case	Downside Case
Time	10 years		
Production Rate	18 MMSCMD		
Operating Cost	$2.3 Billion		
Gas cost	$4.74/MMBTU		

Deepak et al. (2018), JMPG

Sample economic forecast: NGHP-02-16

Gas price: $7.67/MMBTU

	Upside Case	Base Case	Downside Case
Time	10 years	16 years	
Production Rate	18 MMSCMD	12 MMSCMD	
Operating Cost	$2.3 Billion	$2.88 Billion	
Gas cost	$4.74/MMBTU	$5.80/MMBTU	

Deepak et al. (2018), JMPG

Sample economic forecast: NGHP-02-16

Gas price: $7.67/MMBTU

	Upside Case	**Base Case**	**Downside Case**
Time	10 years	16 years	30 years
Production Rate	18 MMSCMD	12 MMSCMD	6 MMSCFD
Operating Cost	$2.3 Billion	$2.88 Billion	$5.55 Billion
Gas cost	$4.74/MMBTU	$5.80/MMBTU	$9.00/MMBTU

Deepak et al. (2018), JMPG

Big Ideas: is production worth the cost?

Big Ideas: is production worth the cost?
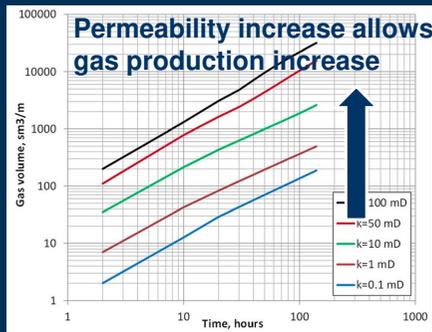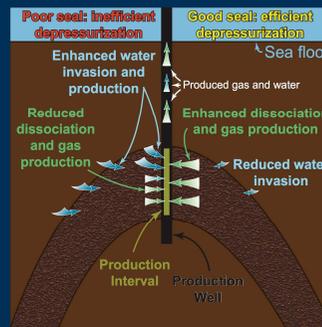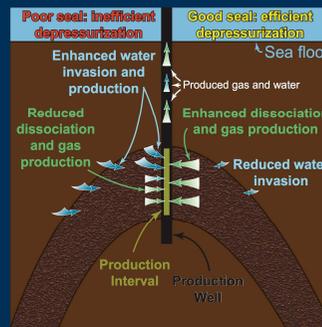

Reservoir permeability

Seal permeability

- Permeability is a critical control... and many things control permeability

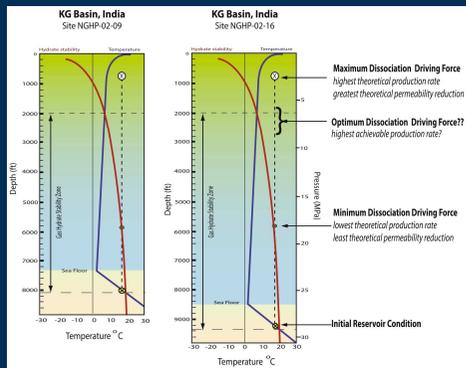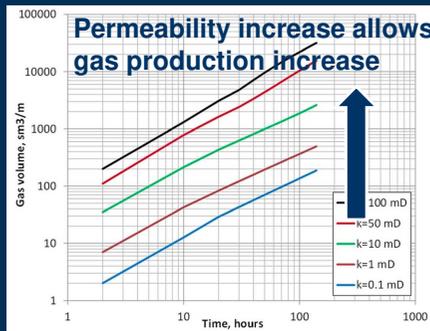# Big Ideas: is production worth the cost?
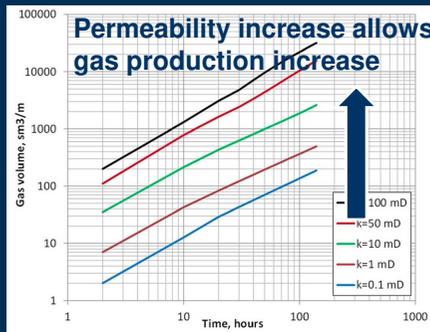
Reservoir permeability

Seal permeability

- Permeability is a critical control... and many things control permeability
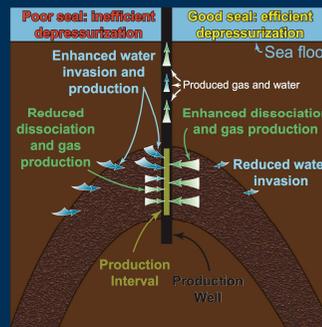
- Depressurization: maximize *production* rate, not *dissociation* rate

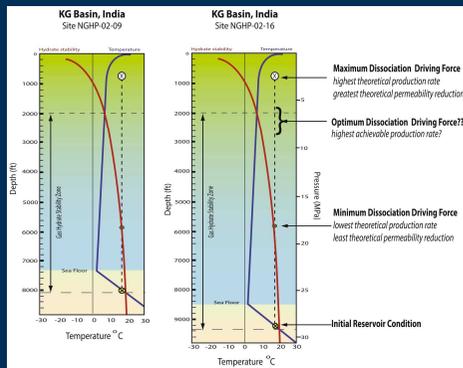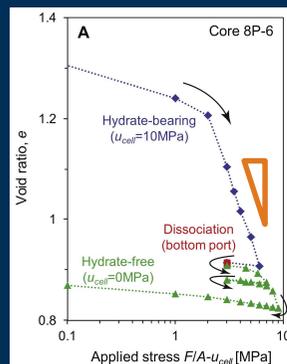# Big Ideas: is production worth the cost?

Reservoir permeability

Seal permeability

- Permeability is a critical control... and many things control permeability

- Depressurization: maximize *production* rate, not *dissociation* rate

- Mechanical and index properties are critical even for hydrate-free sediment