A Coupled Geomechanical, Acoustic, Transport and Sorption Study of Caprock Integrity in Carbon Dioxide (CO2) Sequestration

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Presentation Outline

- Objectives and motivation
- Experimental Updates

1. Mineralogy Control on CO2 Accessibility on Micropores of Shales for CCUS Application
2. Acoustic Measurements with CO2 saturation
3. *NMR studies of CO2-saturated brine*
4. *Direct-shear experiments on shale permeability*

- Accomplishments to date
- (Near-) Future work

Objectives

- Determine the behavior of intact and fractured caprocks when exposed to supercritical CO_2 at elevated pressures
- **Quantify adsorption and acoustic properties of shales with sorbed CO_2**
- Provide framework for monitoring, verification and accounting (MVA) efforts of CO_2 sequestration and its effect on caprock

(1) CO_2 Accessibility in Shale Micropores

- Gas adsorption to characterize nanopores
- Samples Used
- Analysis methods and Results
- Application to CO_2 storage

Motivation

Storage capacity estimates:

– Economically feasible CO_2 capacity of Utica + Marcellus + Antrim + Devonian Ohio ≈ 50 Gt

(Godec et al, 2014)

– Theoretical CO2 capacity of Utica = 10 Gt

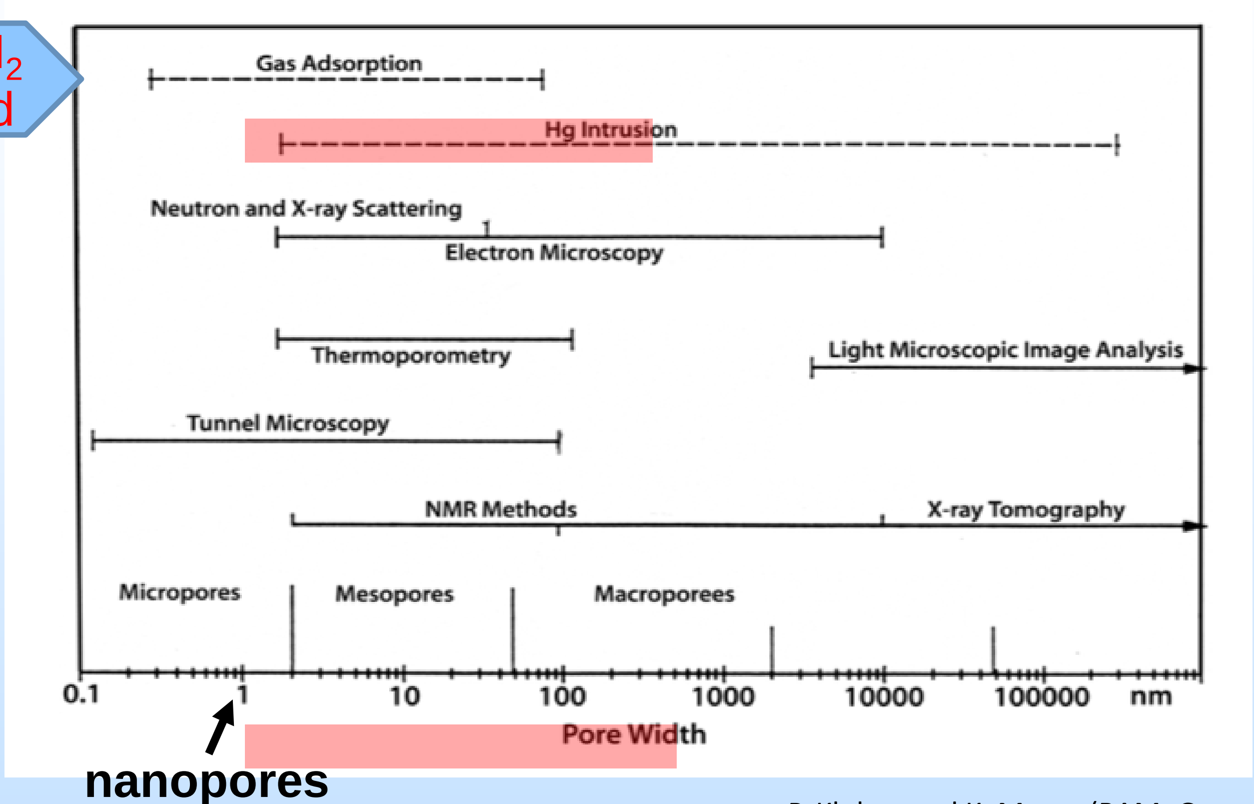
(Godec et al, 2014)

– 80% storage capacity by sorption

(Ambrose et al, 2012)

Pore characterization methods

Typically, N_2 gas is used



P. Klobes and K. Meyer (BAM, Germany)

Kinetic diameters: CO_2 (0.33 nm) < N_2 (0.36 nm).

We use CO_2 to access smaller micropores than those accessible to N_2

Joewondo and Prasad, 2018

Previous studies

- Recommended practice (IUPAC 1985 & IUPAC 2015)
- Adapted N_2 adsorption to characterize shales, also compared to WIP (Kuila, 2013)
- Limited accessibility for N_2 in immature oil window samples due to blockage by bitumen (Saidian, 2015)
- Limited pore accessibility dependent on mineralogy and gas type; preferential CO_2 uptake in OM (Kumar, 2016)
- In presence of water, preferential uptake of CO_2 only in OM not in clay minerals (Kumar, 2016)
- **N_2 - and CO_2- derived PSD on shales with 2-21% TOC**

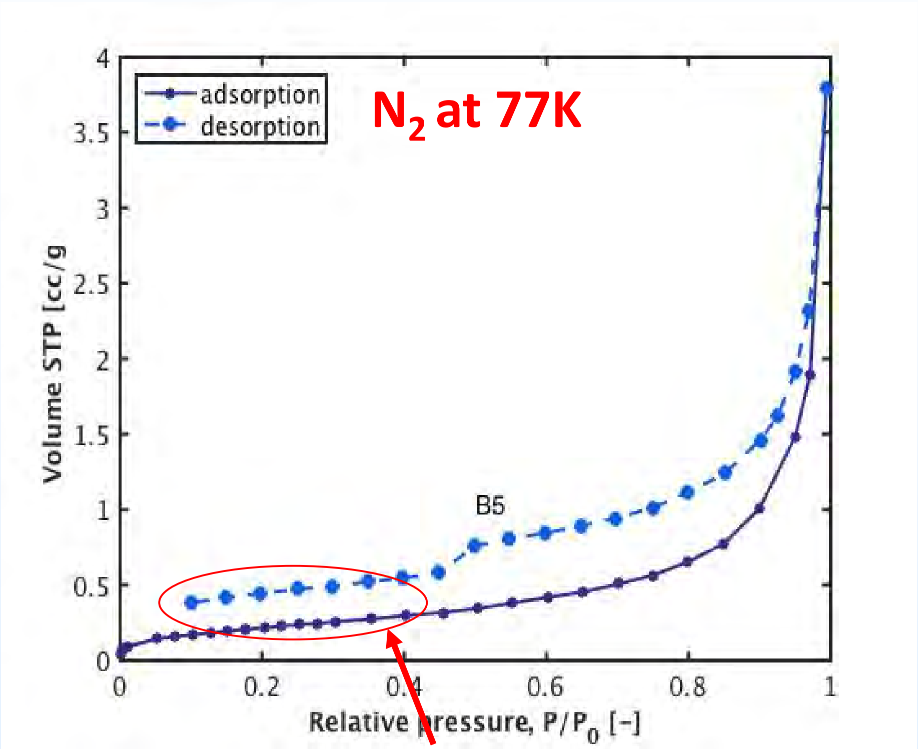
Joewondo and Prasad, 2018

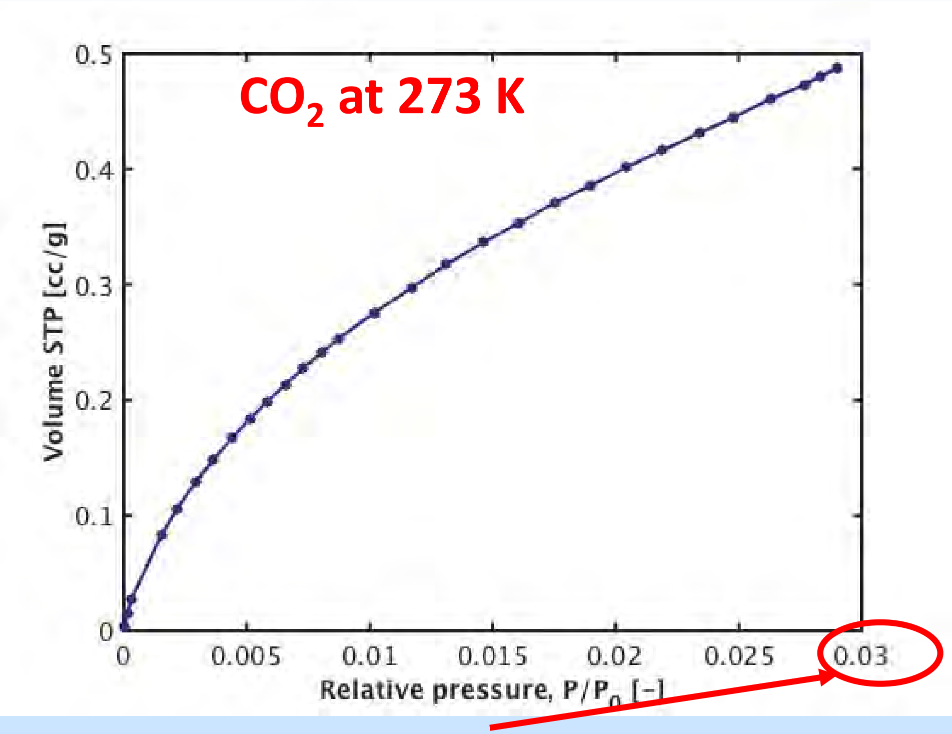
Samples Used

- Standard clay samples – benchmarking
  - Illite, Illite-smectite, Na-rich montmorillonite
- Producing shales in North America
  - Bakken (7-21% TOC), Utica (2% TOC) and Niobrara (3-5% TOC)
- Analog to caprock of CO_2 storage site in the Norwegian North Sea
  - Agardhfjellet (12% TOC), Rurikfjellet (2% TOC)
  - CCS candidates

Joewondo and Prasad, 2018

Measured adsorption isotherm



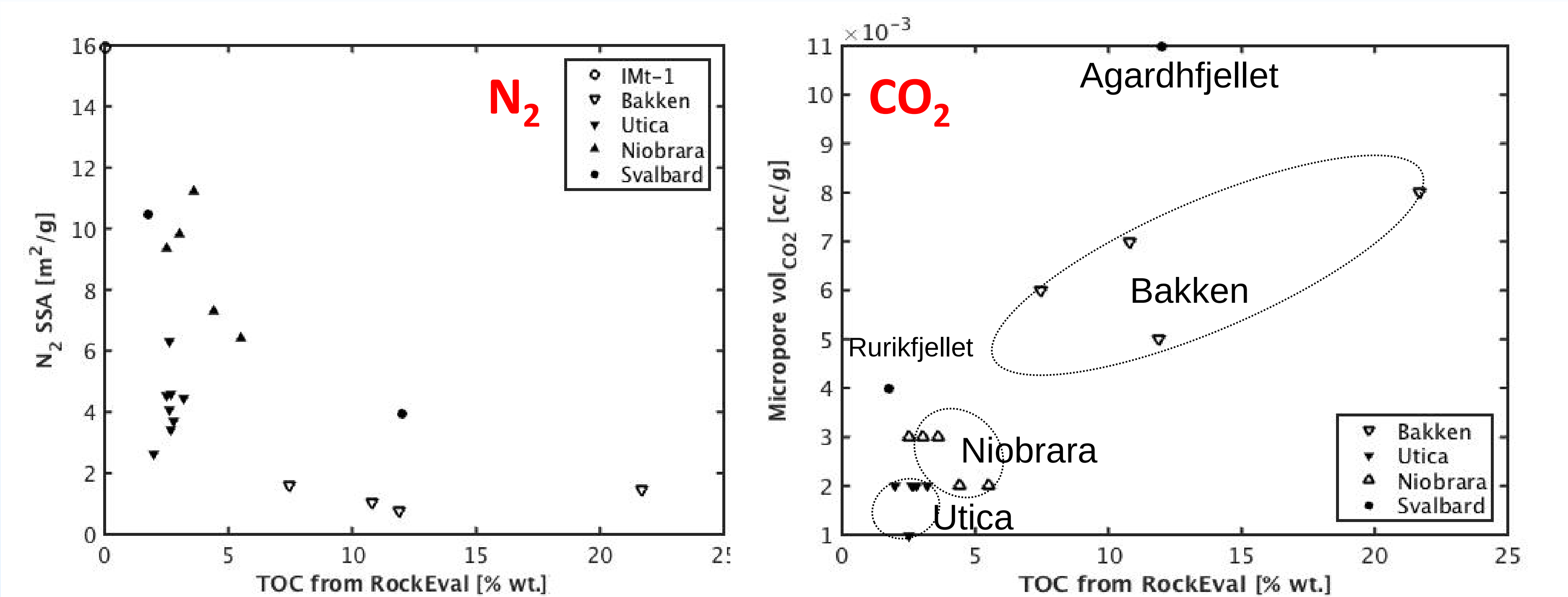


- **Diffusional limitations of N_2** molecules in narrow pores
  - Underestimate micropores

- Require high pressure setup to measure full isotherm
  - P0 > 1 atm

Joewondo and Prasad, 2018

TOC controls on micropore volume



Note: Opposite trend of N_2- and CO_2- derived pore structures; Mudrocks with high TOC have higher CO_2 storage potential

Joewondo and Prasad, 2018

Implications for Storage Capacity

Micropore volume measured in this work

Utica = 2E-3 cc/g   Agardhfjellet = 11E-3 cc/g

Assume micropores are filled with CO_2

CO_2 density 0.6 g/cc (30 C, 8 Mpa) (van der Meer 2005)

Shale density 2.4 g/cc

Calculated CO_2 storage capacity in 1 m^3 of shales from this work

Utica (2% TOC): 2.8 kg_{CO2} Agardhfjellet (12 % TOC): 15.8 kg_{CO2}

Compare with Godec et al. (2014) for the same area:

Average thickness of 150 ft or 45.7 m (Refayee et al. 2016)

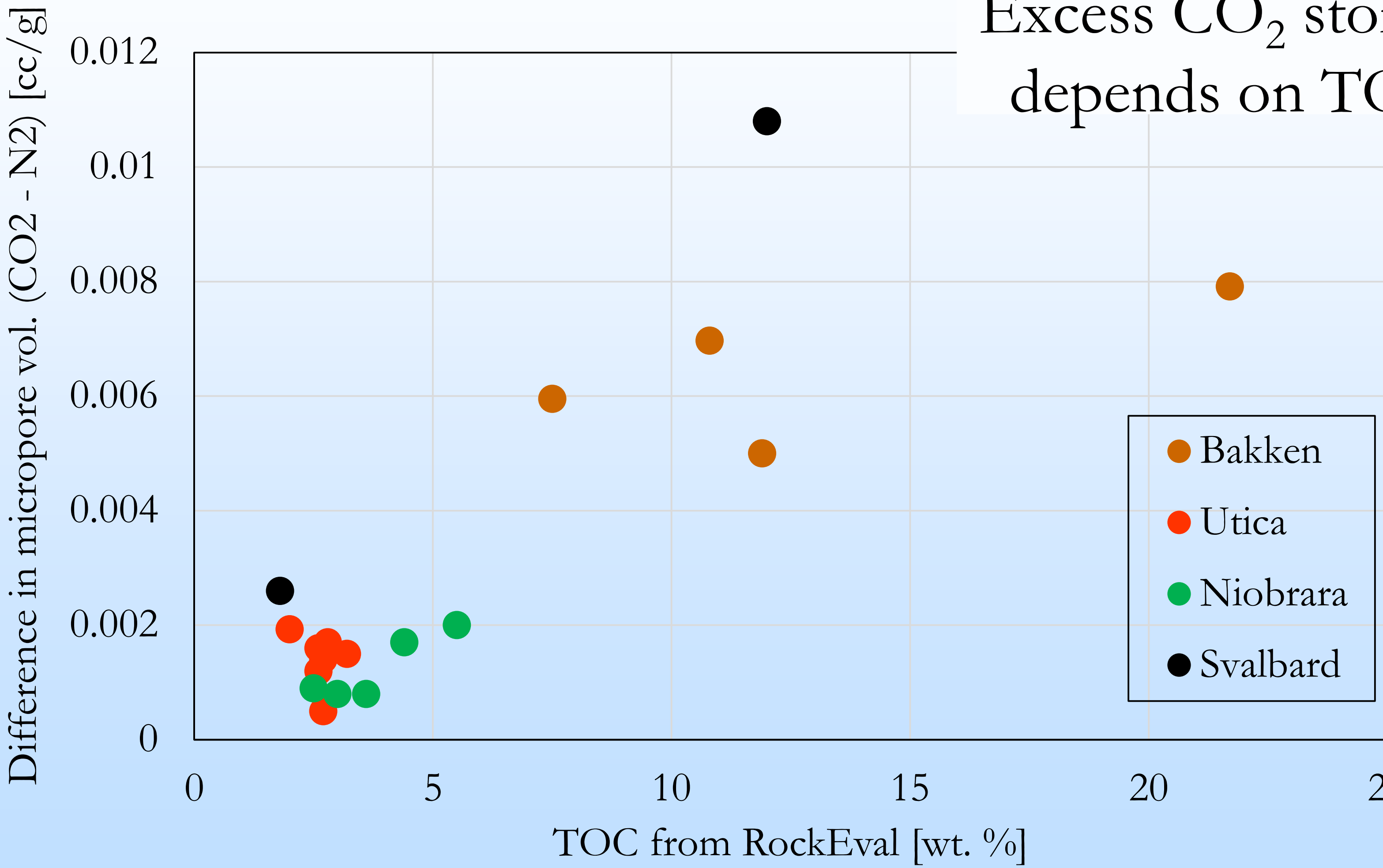
Theoretical CO_2 capacity of Utica formation

19.7 Gt_{CO2} (this work) and 10 Gt_{CO2} (Godec et al. 2014)

Joewondo and Prasad, 2018

Comparing CO_2 and N_2- accessible volumes

Excess CO_2 storage depends on TOC



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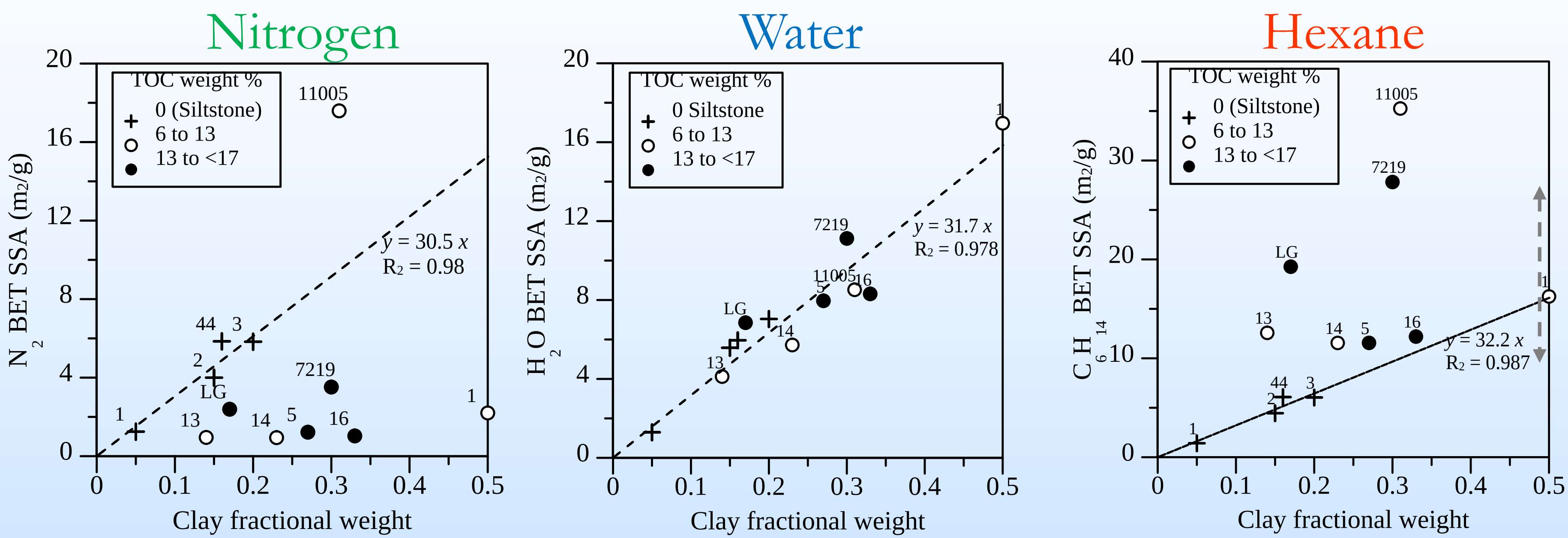
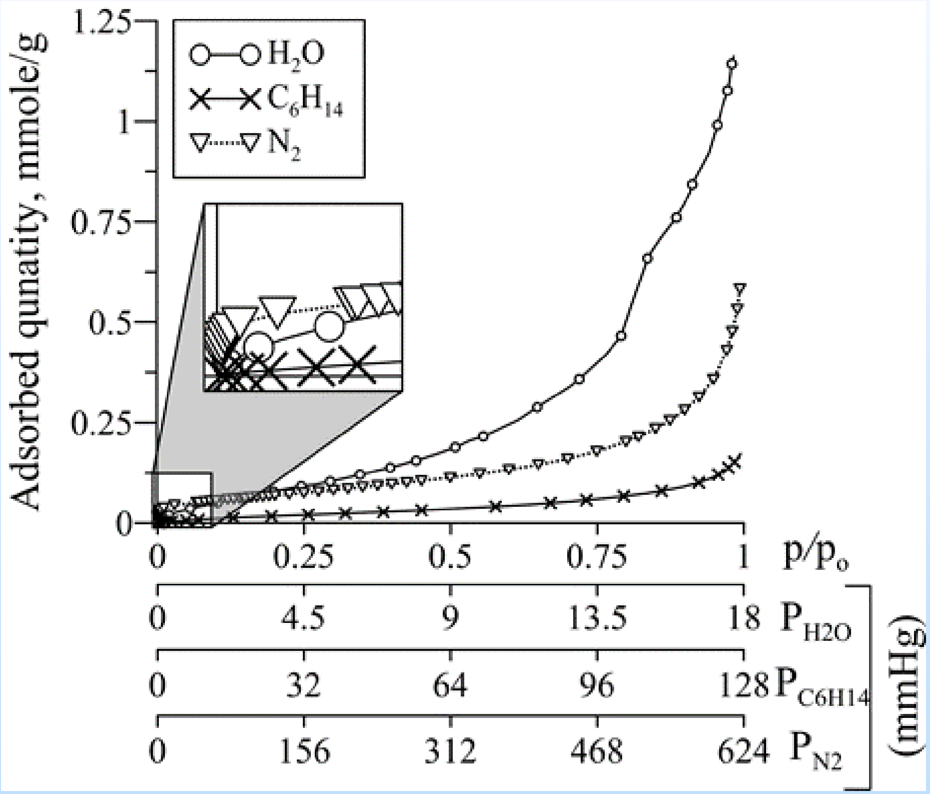
Surface Area and Clay Content

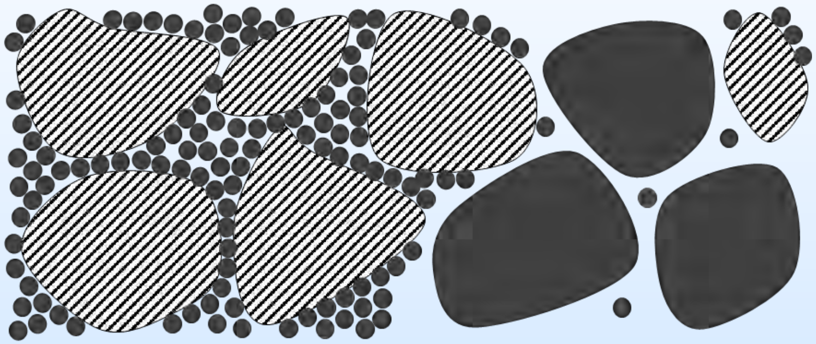


- OM pores are hydrophobic
- OM pore development starts at the onset of oil window
- Presence of **bitumen free OM pores**
- Cryogenic N_2 blocked by nano-sized pores in organic matter

Preferential sorption of fluids

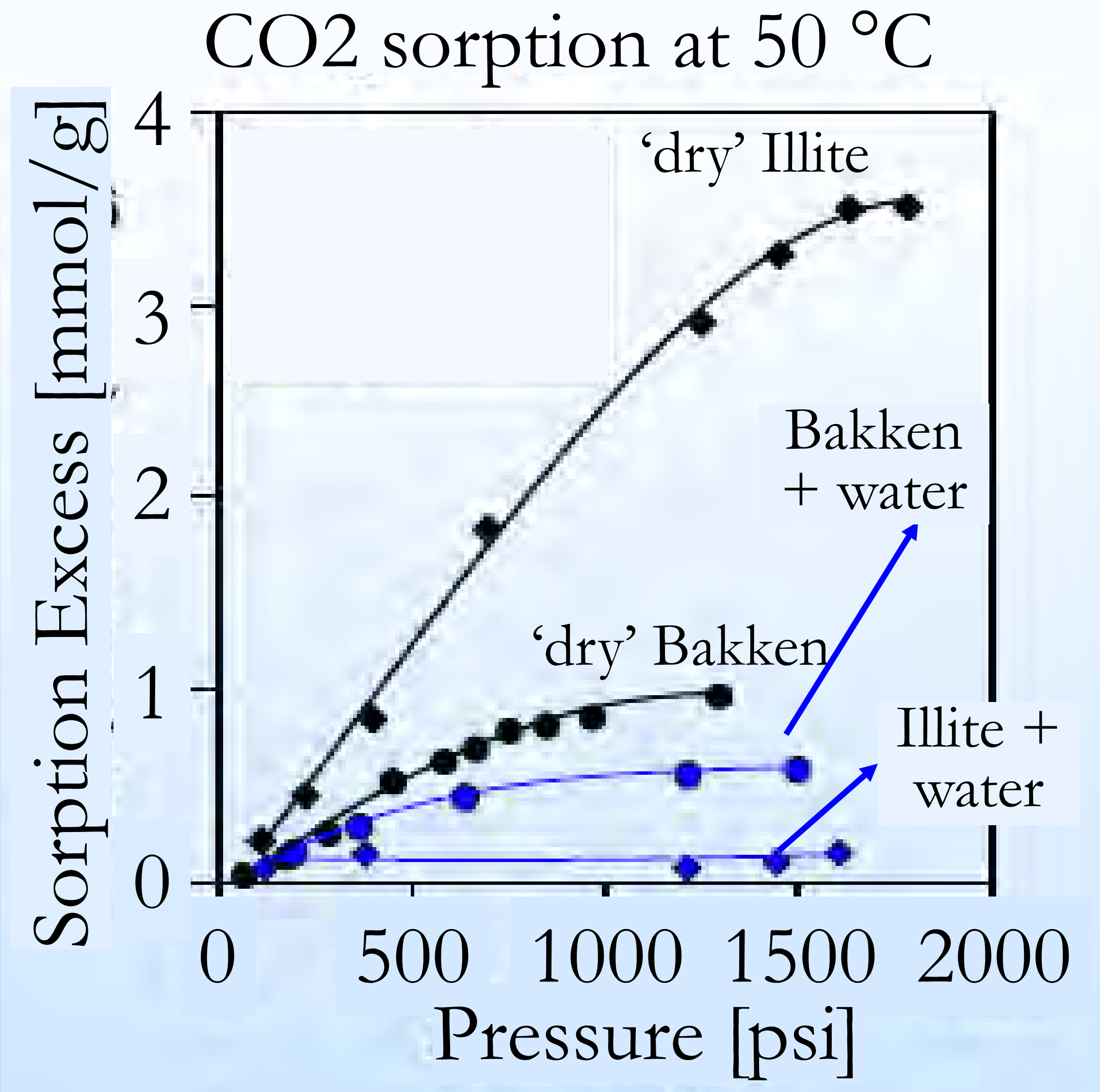
Preferential sorption of fluids depends on polarity of surfaces





Quantification of hydrophilic and hydrophobic pores of shales

Sorption in shales with water

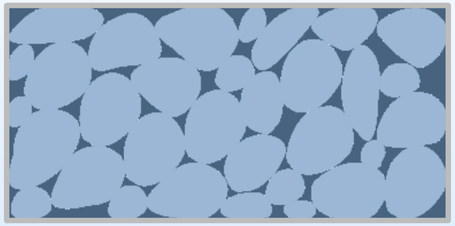


Kumar, 2016

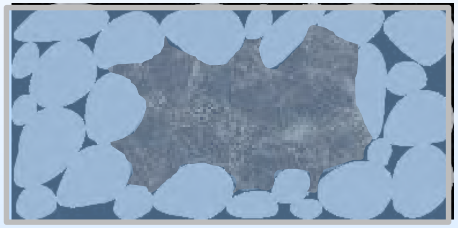
Sorption in shales with water

In presence of water: Illite pores take up water; CO_2 fills OM pores

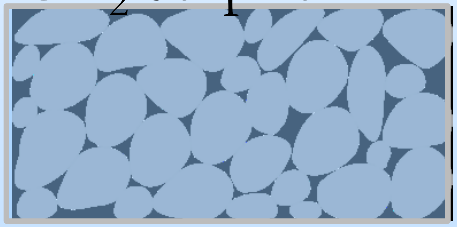
Illite: Water Imbibed



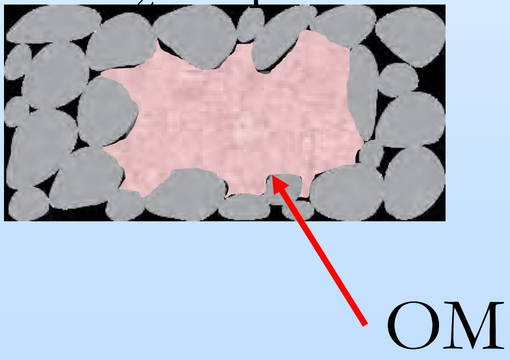
Bakken: Water Imbibed



CO_2 sorption



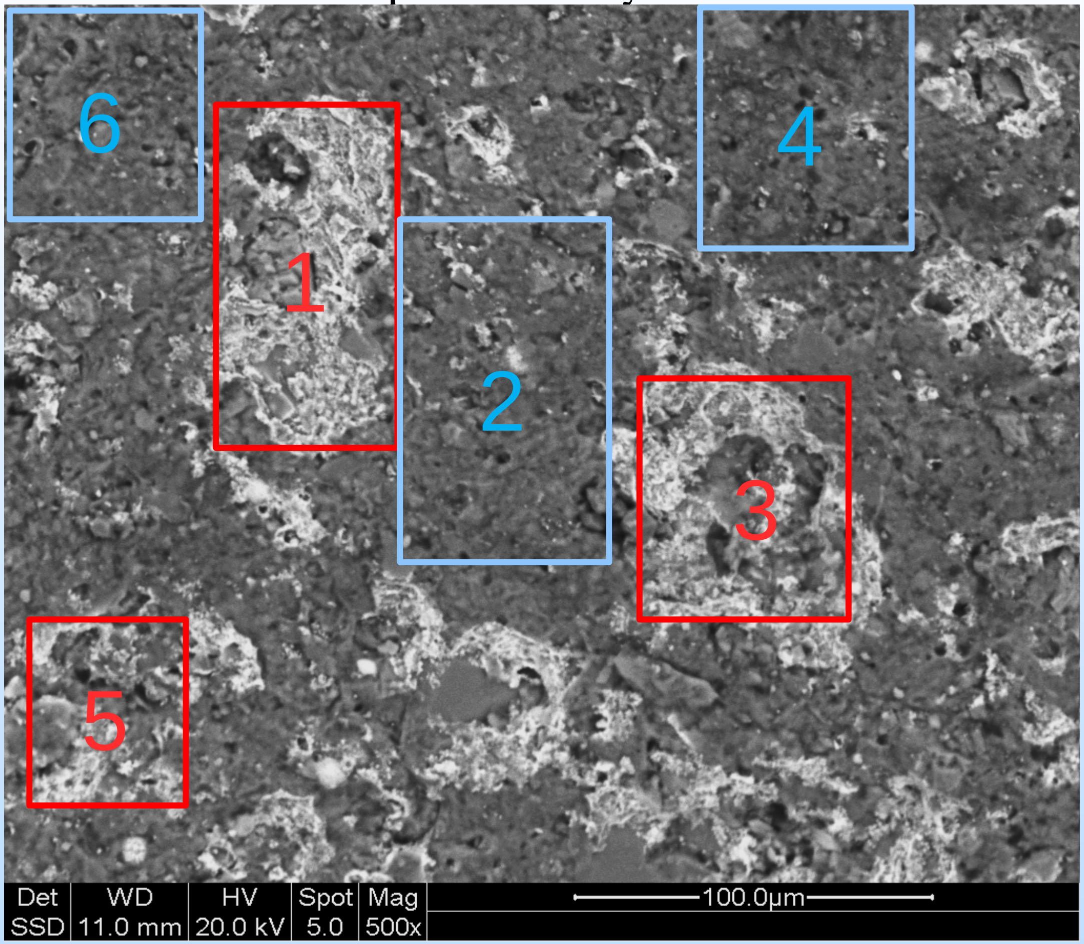
CO_2 sorption



Environmental Scanning Electron Spectroscopy (ESEM)

Agardhfjellet from Svalbard

Spot Analysis

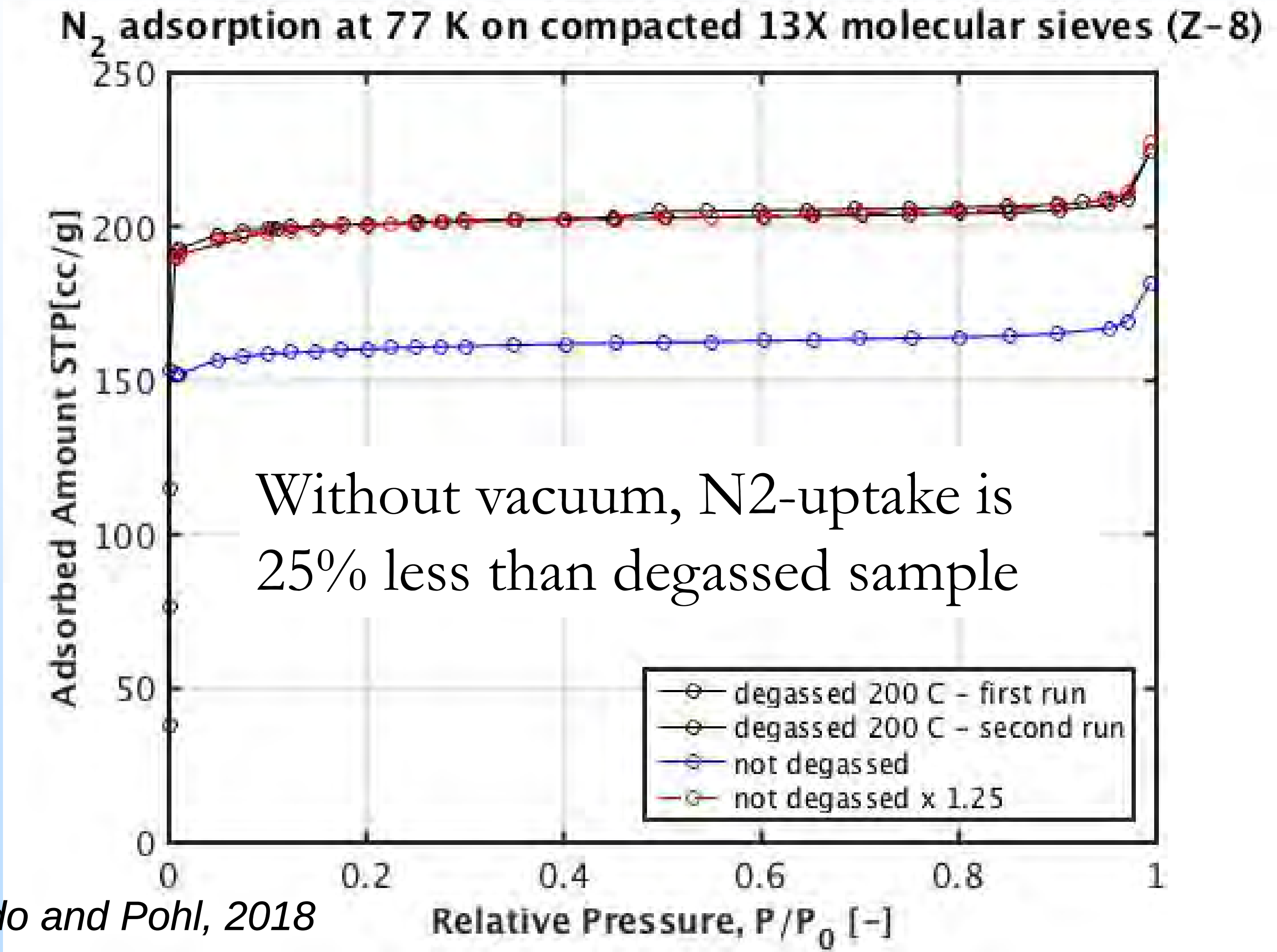


Lighter areas: silt- rich

Darker areas: clay- and OM-rich

Murugesu, 2018

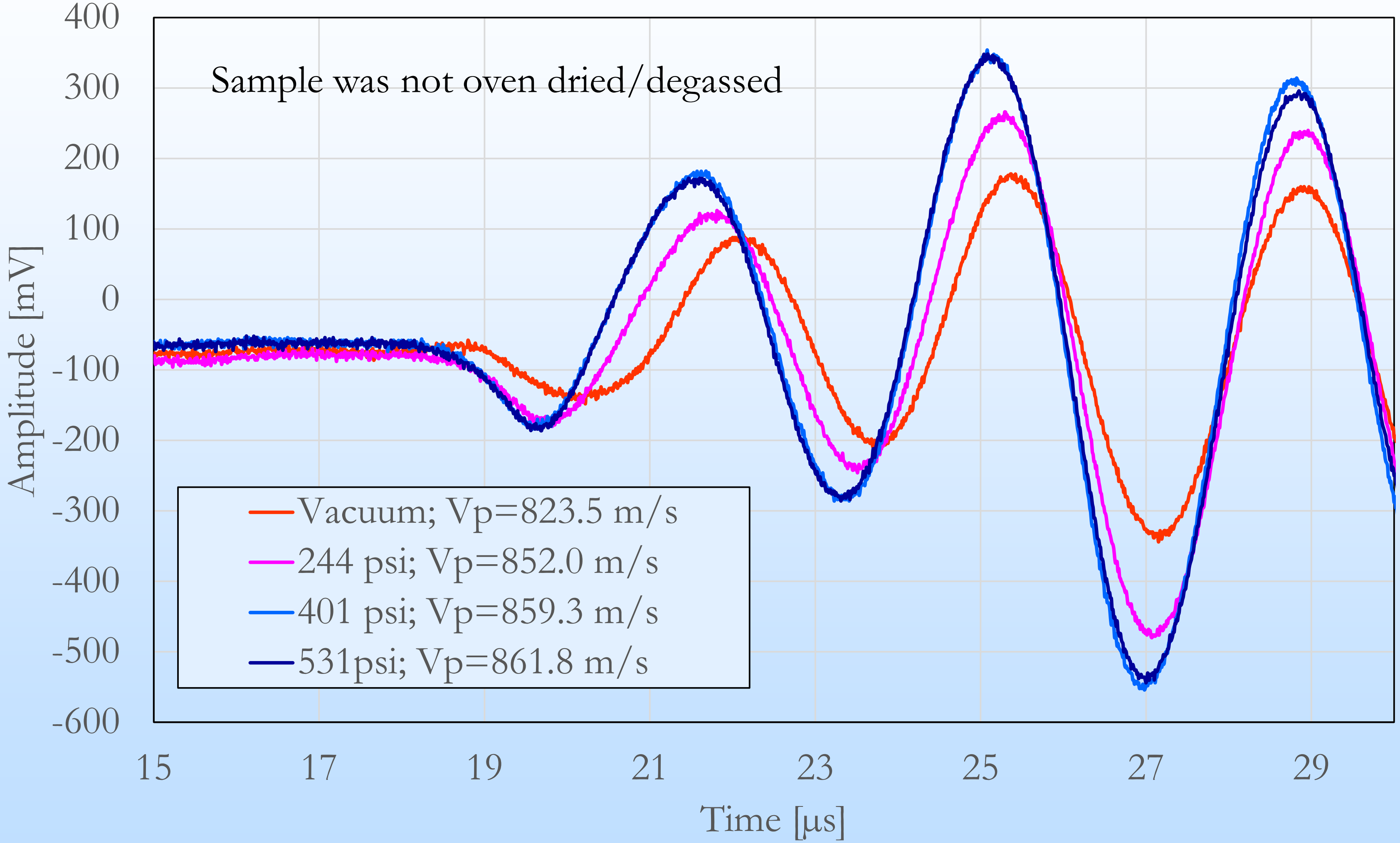
Sorption in Zeolite



Without vacuum, N2-uptake is 25% less than degassed sample

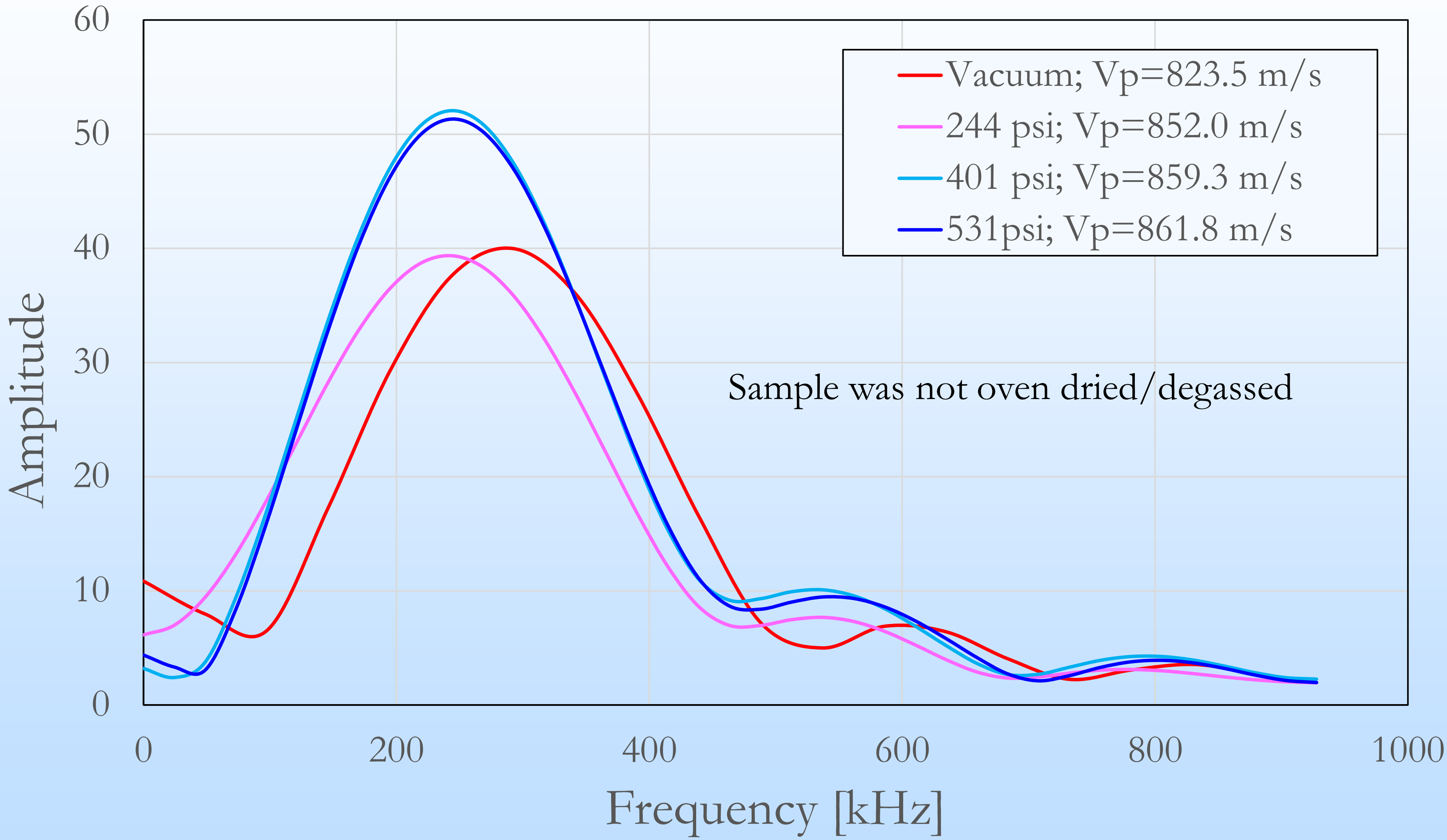
Joewondo and Pohl, 2018

Waveforms and Velocities with CO_2



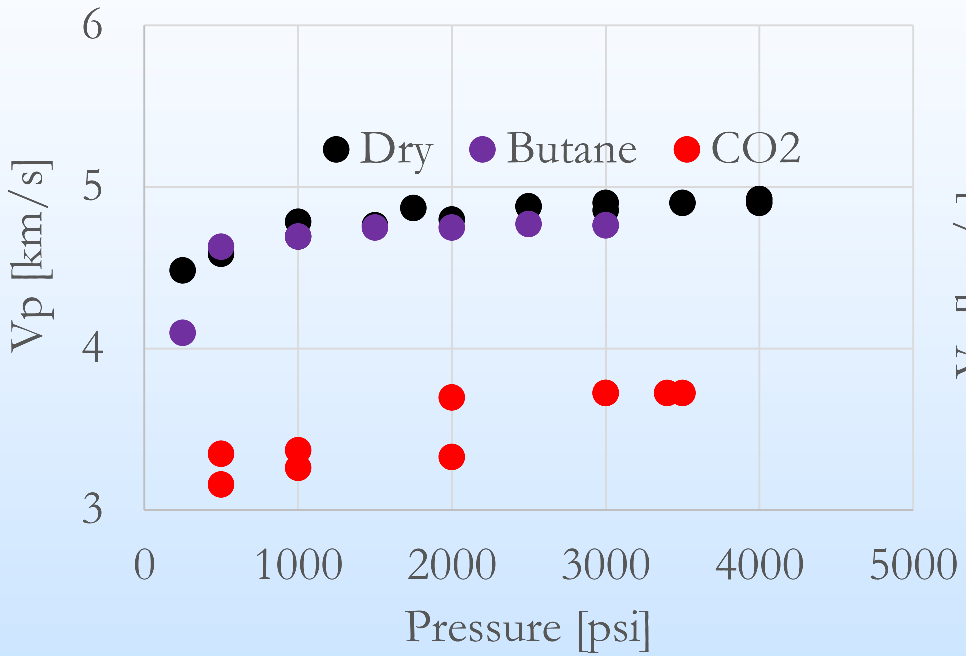
Pohl and Joewondo, 2018

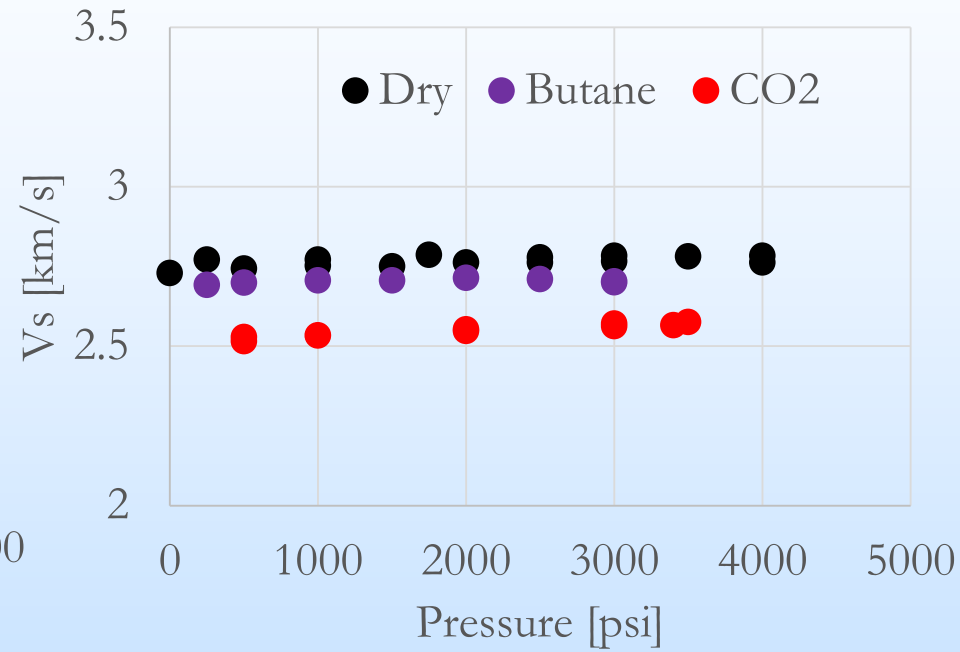
Frequency and Velocities with CO_2



Pohl and Joewondo, 2018

Ultrasonic Velocities

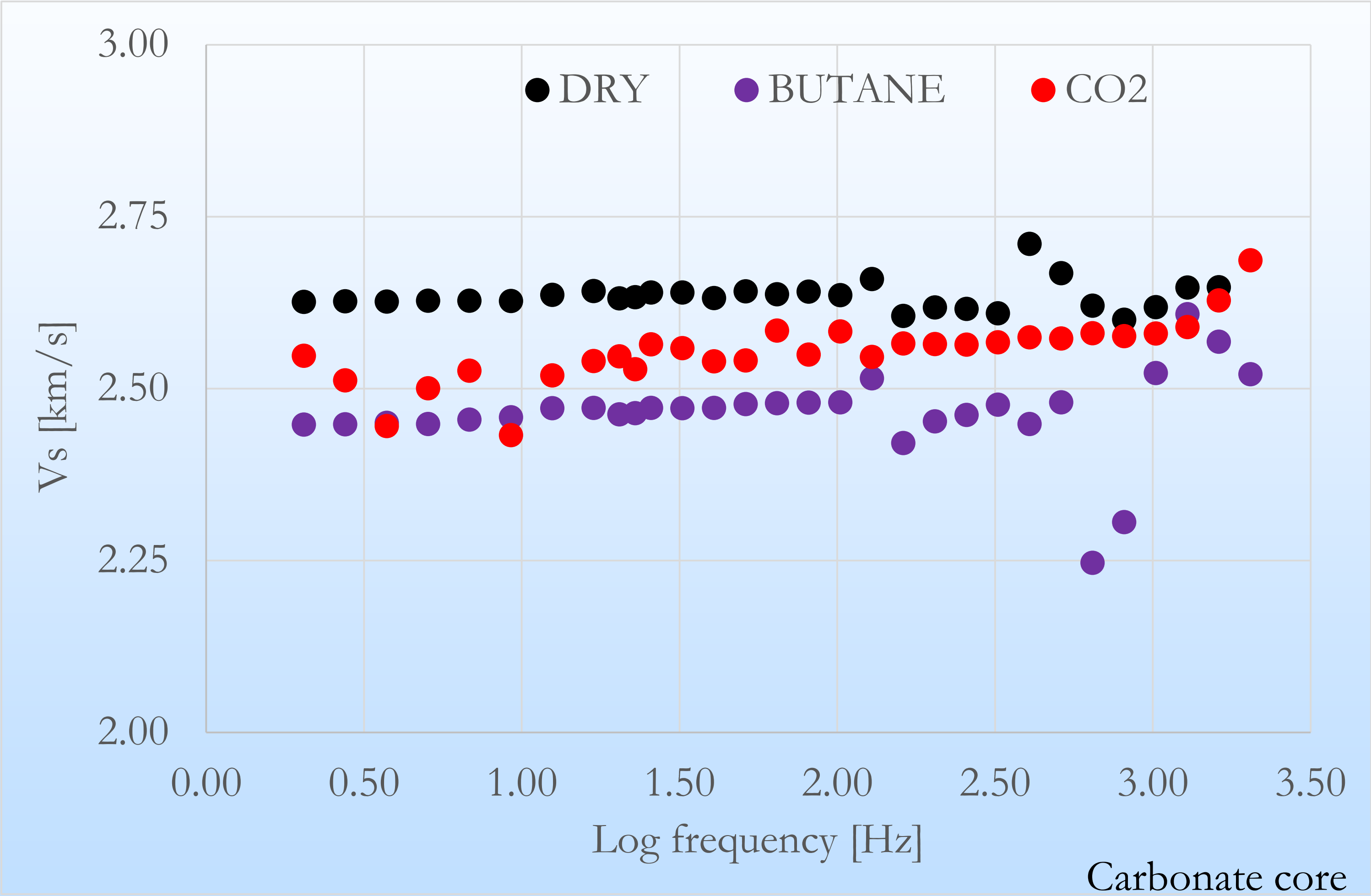




Carbonate core

Sharma, 2016

Seismic Velocities



Conclusions

- CO_2-accessible micropore volume depends on TOC
  - Need to complement N_2 measurements with CO_2 for CO_2 storage capacity
  - **CO_2 storage capacity increases with TOC**
  - **CO_2 storage capacity decreases in presence of water (clay effect)**
- Frequency content (seismic attenuation) is sensitive to gas content
- Fluid in micropores depends on mineralogy – should be accounted for in seismic inversion

Synergy Opportunities

- Calibrate rock physics models with partial saturation due to mineralogy – dependent pore volumes and preferential fluid sorptions. Relevance: 4D seismic operations
- Investigate well log NMR signals for changes in fluid signatures versus changes in the rock due to rock –fluid interactions. Relevance: CCUS and Oil & Gas operations
- Joint acoustic –permeability changes with CO_2 before and after shearing. Relevance: caprock changes with stress changes
- Imaging CO2 migration – student intern with SINTEF