

# **Multiphysics Characterization of an Albian Post-Salt Carbonate Reservoir, Brazil\***

**Michael B. Clennell<sup>1</sup>, Tobias Mueller<sup>2</sup>, Valeriya Shulakova<sup>2</sup>, Jie Liu<sup>3</sup>, Lionel Esteban<sup>2</sup>, Joel Sarout<sup>2</sup>, Maxim Lebedev<sup>4</sup>, Boris Gurevich<sup>4</sup>, Vassili Mikhaltsevitch<sup>4</sup>, Sofia Correia-Lopes<sup>4</sup>, Qiaomu Qi<sup>4</sup>, Sherry Mayo<sup>2</sup>, Iko Burgar<sup>5</sup>, Gerald Pereira<sup>2</sup>, Flavia Falcao<sup>6</sup>, Marcos Grochau<sup>6</sup>, Matthew Josh<sup>2</sup>, Reem Freij-Ayoub<sup>2</sup>, Marina Pervukhina<sup>2</sup>, Shakil Ahmed<sup>2</sup>, Claudio Delle Piane<sup>2</sup>, Leigh Kiewiet<sup>2</sup>, Bruce Maney<sup>2</sup>, Jeremie Dautriat<sup>4</sup>, and Antoine Dillinger<sup>7</sup>**

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## **Abstract**

We describe a workflow that combines petrographic, petrophysical, geomechanical, and rock physics data to predict the 4D seismic response of a carbonate reservoir. Fifty standard 38 mm diameter x 60 mm long core plugs were provided from eight lithofacies in an Albian age carbonate reservoir in offshore Brazil. A disc 6–8 mm thick was cut from each plug end, polished on both sides and used for imaging and electrical-dielectric measurements. A mini-core from selected discs was used for x-ray micro-CT. Electron microscopy, helium porosity/permeability, and nuclear magnetic resonance (NMR) were used to identify the lithotypes and textural characteristics of grains and pores in the rock. Medical x-ray CT was used to assess the degree of heterogeneity of each plug, screen for vugs, fractures or core damage that could affect rock properties. Eight peloidal packstone samples from the top reservoir were used for mechanical studies, and subjected to UCS, isotropic compaction, single stage triaxial tests or zero later strain stress-path tests to define the Mohr-Coulomb failure envelope and pore collapse pressure for this lithofacies both brine saturated and dry. Samples representative of the peloidal packstones, grainstones, and oncolitic floatstones

were subjected to a range of stress-path rock physics measurements, again either dry or brine saturated to define the stress sensitivity. Saturation sensitivity of  $V_p$  for 5 samples was assessed during brine flooding experiments monitored by x-ray CT. Low frequency seismic response (1–100 Hz) was measured on 5 samples under dry and brine saturated conditions. Mechanical and rock physics data show that the majority of lithofacies are strongly water weakening and seismic velocities reduced substantially in the presence of brine to values much below that predicted by Gassmann substitution. In 4 of the low frequency samples, the shear modulus became indeterminate after brine saturation. Digital rock models were useful to assess permeability and mechanical upscaling laws, but estimates of velocities from digital rock models, even when calibrated with nano-indentation, were inaccurate owing to unresolved microstructure, and water weakening. Complex pore structures led to poor discrimination of pore size distributions from NMR, but dielectric models based on the Hanai-Bruggeman theory could be used to assess pore aspect ratio. High frequency electrical measurements correlate strongly with both porosity and with seismic velocities.

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*Coulter Cays, Bahamaspress.com*

# Multiphysics Characterization of an Albian Post-Salt Carbonate Reservoir, Brazil

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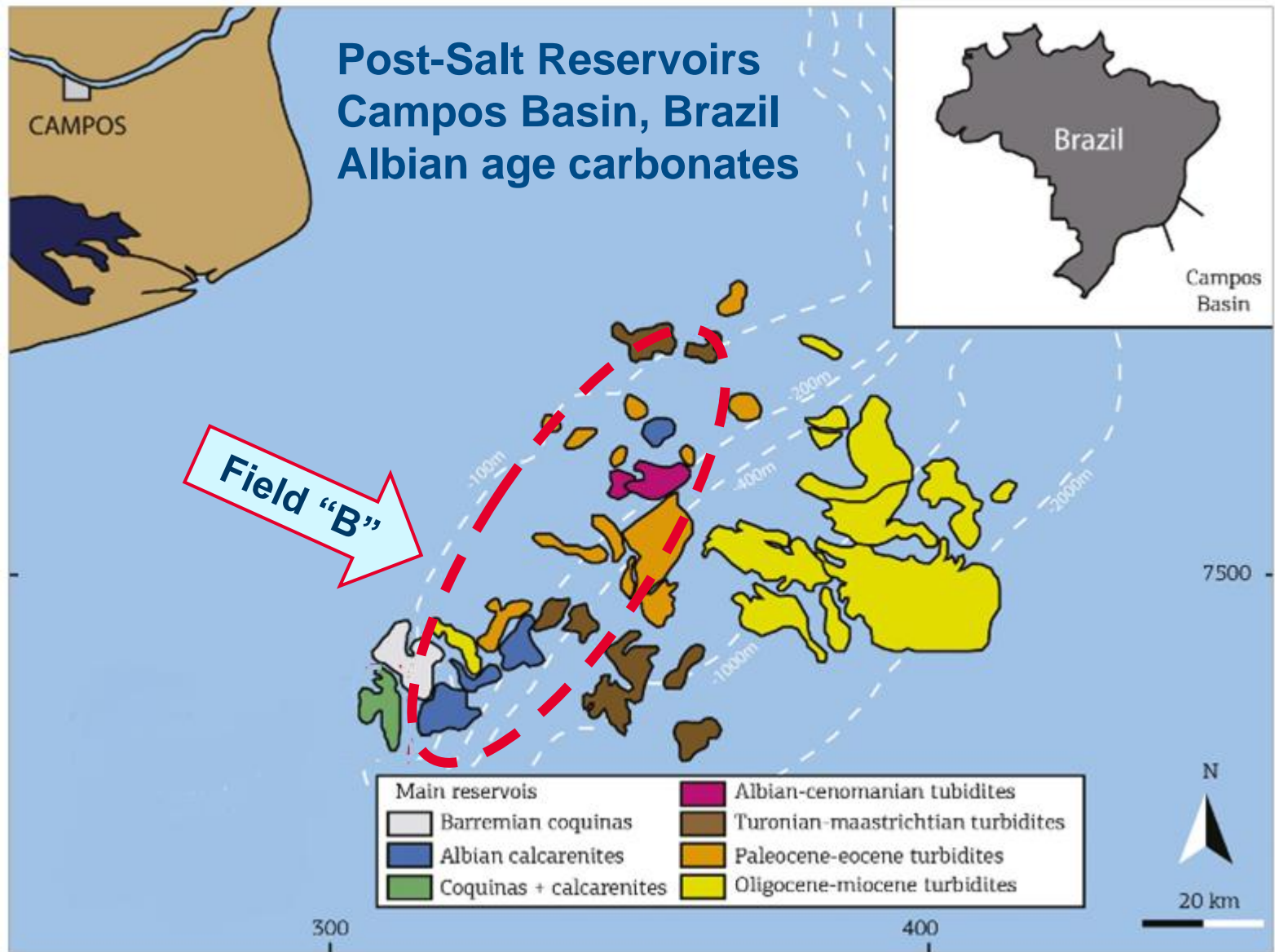
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[www.csiro.au](http://www.csiro.au)



**Curtin University**

<sup>1</sup>CSIRO; <sup>2</sup>Sun-Yat Sen University, China, formerly UWA, <sup>3</sup>Curtin University,  
<sup>4</sup>RMIT University, formerly CSIRO, <sup>6</sup>Formerly CSIRO now UWA, <sup>5</sup>Petrobras







# Problem addressed: Likely 4D seismic responses

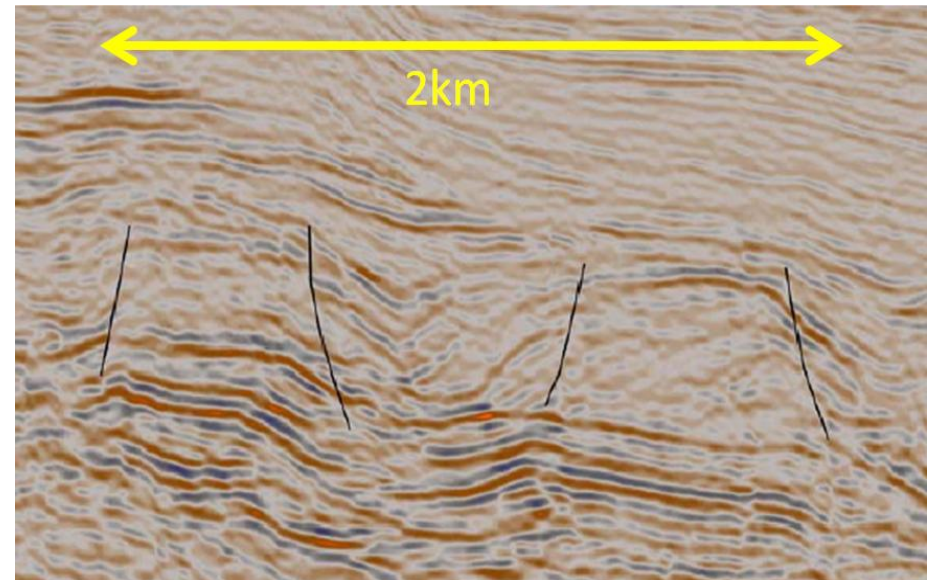
**Field B ~2500m deep, < 200m of water**

Tropical shelf carbonate cf. Bahamas

- 10 lithofacies dominated by peloidal and oncoidal packstones and grainstones
- Clay free >95% calcite ( +dolo + qtz )
- Relatively high porosity & permeability upper reservoir section
- Fine grained, less permeable, but high porosity mid reservoir section
- Less porous and permeable lower reservoir section (not part of this study)

Discovered in late 1970s, water injection from mid 1980s; mature field

**Selected for rejuvenation, a candidate for 4D (time lapse) seismic monitoring**



Seismic section of Albian post-salt carbonate reservoirs in the Campos Basin (Pires et al. 2011.)

SPE 143819

**Planning the Combined Revitalization of Two Carbonate Reservoirs in The Campos Basin**

P. Pires, R. Furuie, J. Sarturi, P. Benac, J. Pereira, Petrobras

Thanks to Marcos Grouchau, Petrobras

# 4D seismic

## Stress change

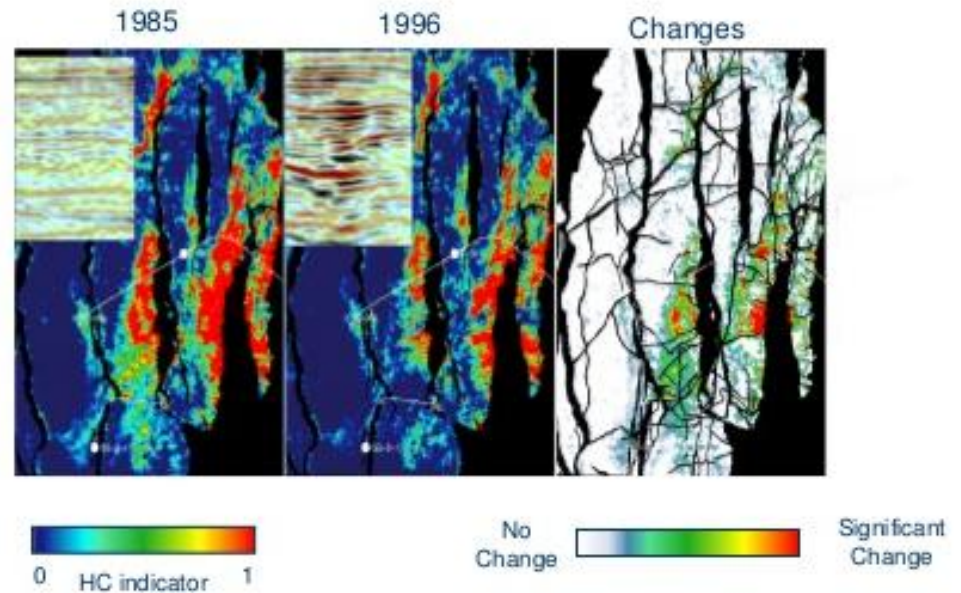
- Depletion-effective stress increases

## Saturation change

- Fluid substitution of water for oil

## Volume changes

- Interval time change
- Differential subsidence
- Lateral load transfer



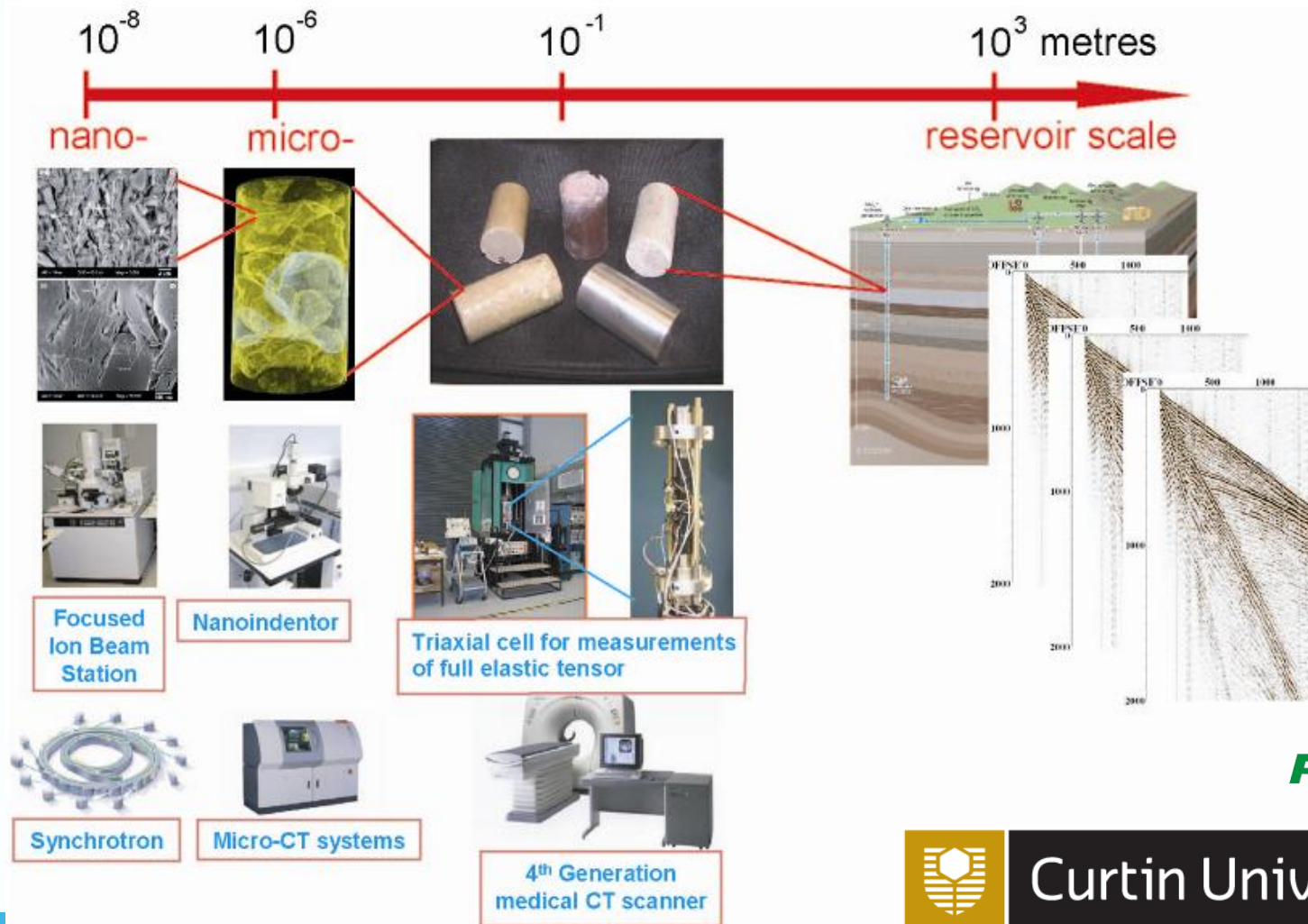
**Q: Can we predict the seismic responses?**

**A1: Rock physics measurements & models**

**A2: Mechanical, petrophysical & textural characterization to define these models**

# IGEM-4D Project:

*Integrated Geomechanics and Multiphysics for 4D Seismic Responses*



**PETROBRAS**

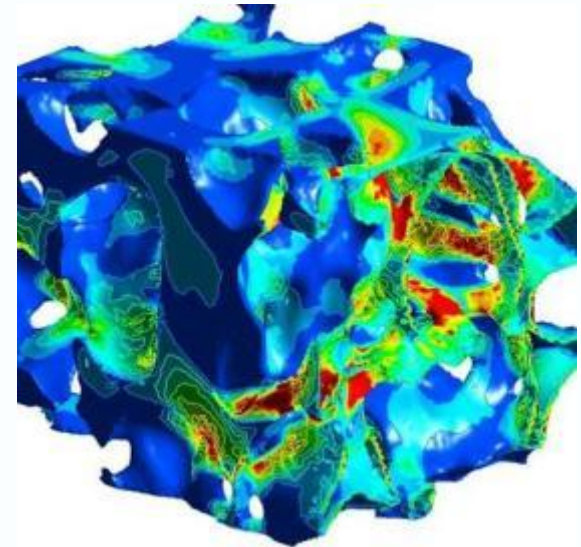
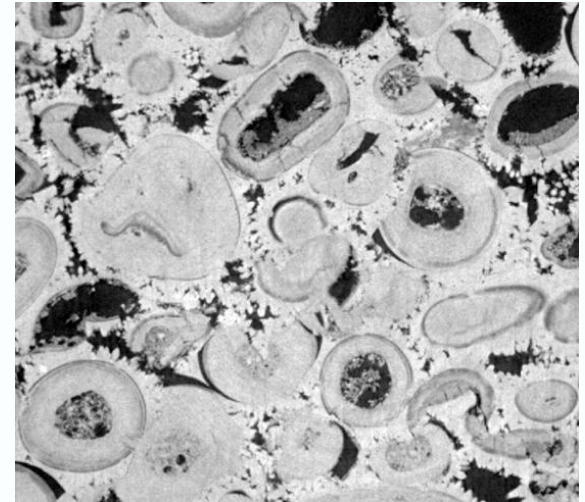


**Curtin University**

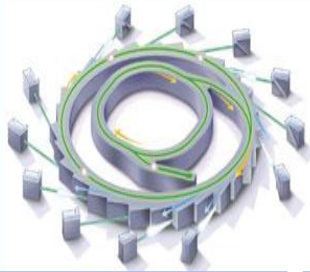


# Key technology: Digital Rocks

1. Does it work for this problem?
2. Insert digital rocks into the multiphysics measurement & modelling framework
3. What can we learn about how these particular rocks behave
4. Anything unexpected?
5. Future improvements to the multiphysics approach
  - R&D that delivers solutions and long term value



# Digital rock workflow: data acquisition, reconstruction, visualization, quantification, meshing and numerical simulation



Synchrotron



Micro-CT systems

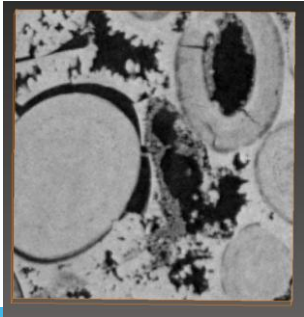
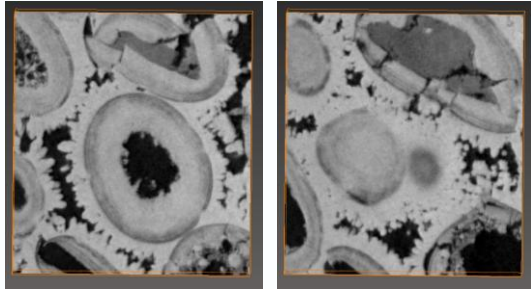
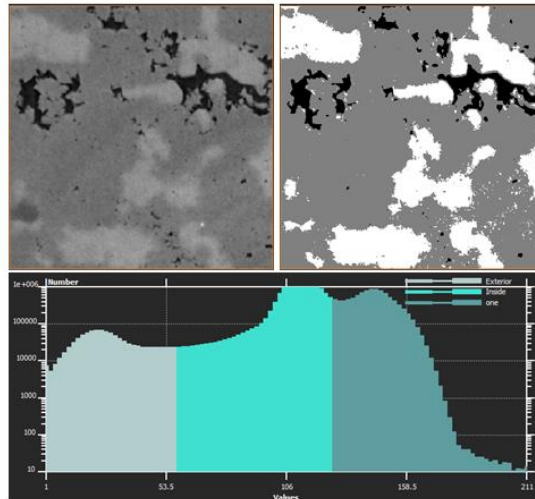
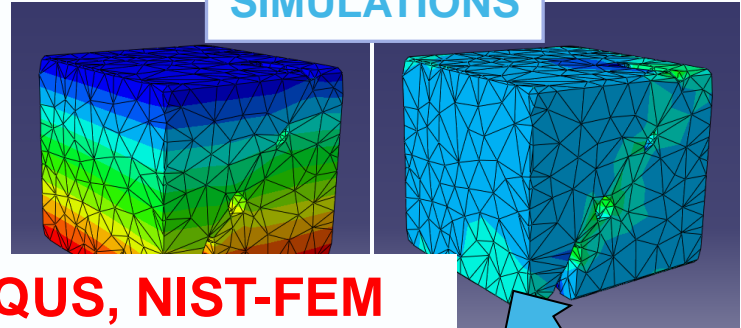


IMAGE  
PROCESSING

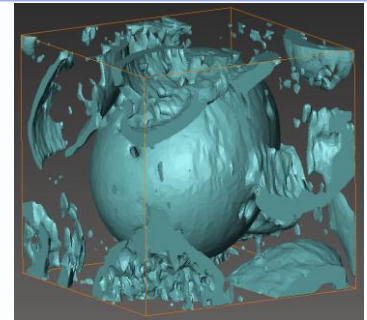


SIMULATIONS

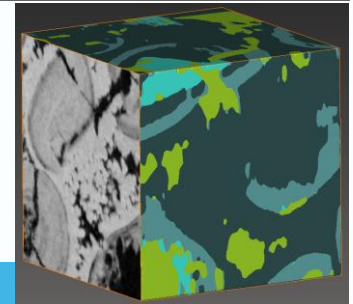


ABAQUS, NIST-FEM

SEGMENTATION

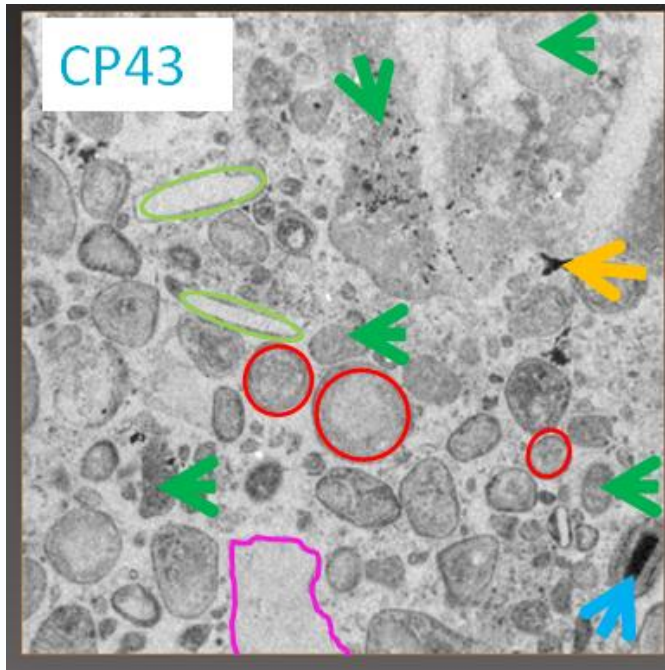


AVIZO



# Field B carbonates: complex pores & grains

many structures unresolved, i.e. “grey voxels”



## Grain Types:

- Round,
- Elliptical,
- Irregular shapes,
- Fossils



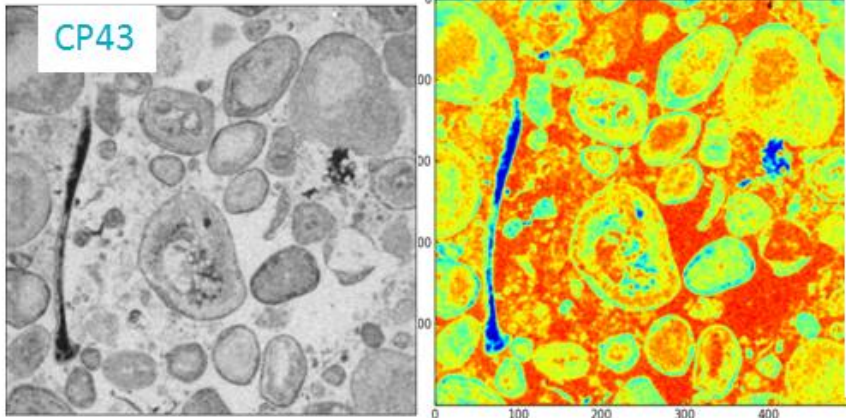
## Pores:

- Micropores-variable grey levels,
- Cracks-black,
- Macropores-black
  - Intragranular Voids,
  - Internal Voids

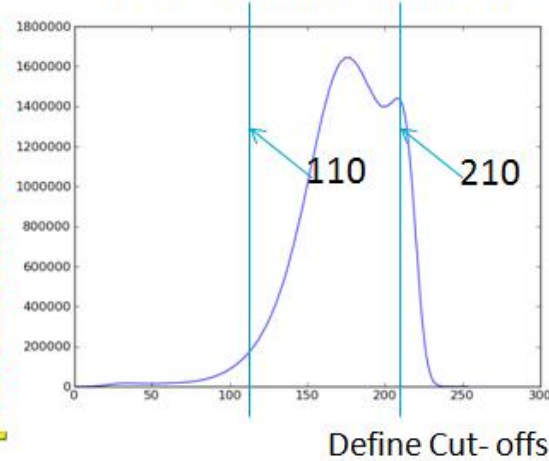


# New digital rock physics workflow

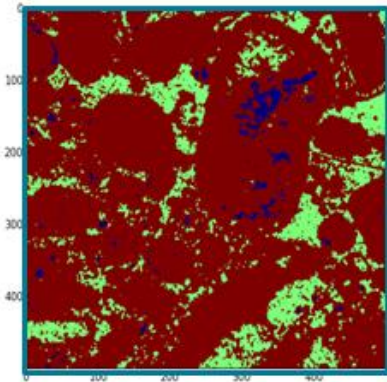
1. Raw data input and ranging to 256 levels



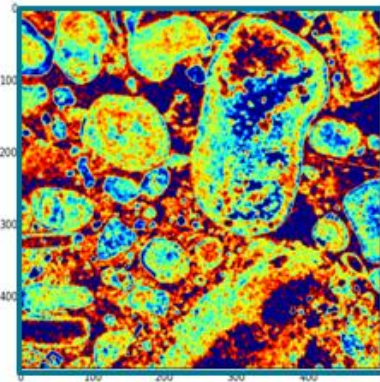
2. Calculate image histogram



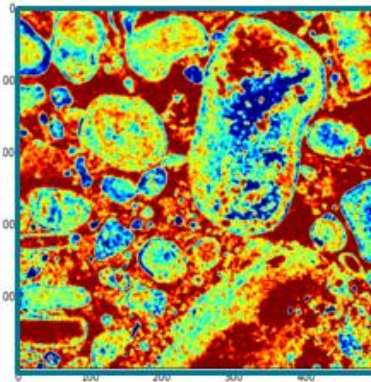
3. segment- three phases



4. Linear rescale micro phase between 1 and 101



5. Join micro & macro phases



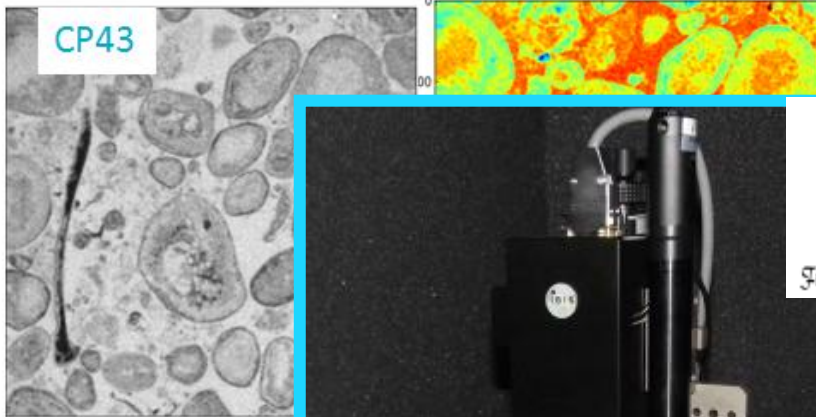
6. Compute elastic moduli in FEM

Initial Bulk, GPa	70
Initial Shear, GPa	30
Total Porosity, %	34/ <b>26.1</b>
K <sub>eff</sub> , GPa	11.9
G <sub>eff</sub> , GPa	6.9

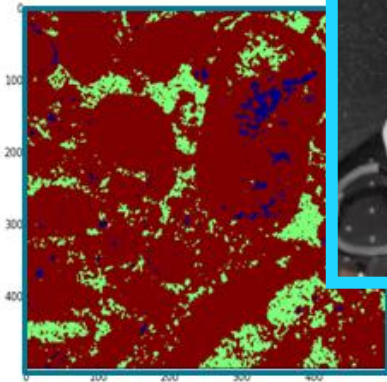
*Different effective medium rules were used to give a range of values  
To predict  $V_p$  and  $V_s$  from complex carbonate microstructures*

# New digital rock physics workflow

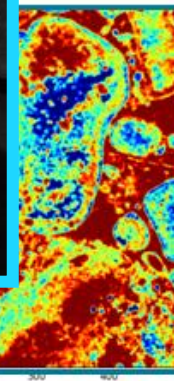
1. Raw data input and ranging to 256 levels



3. segment- three p



6. Compute elastic moduli in FEM



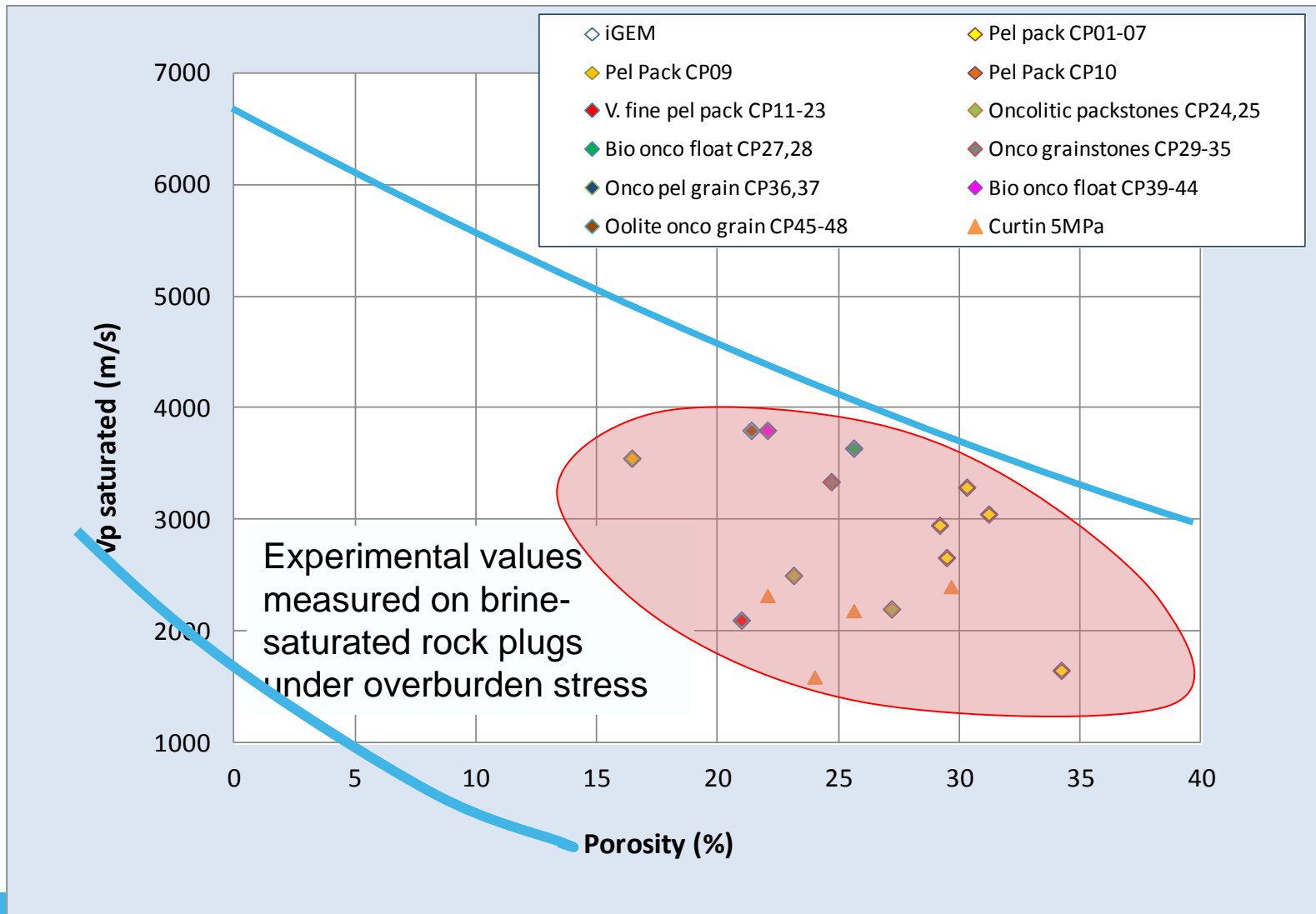
Initial Bulk, GPa	70
Initial Shear, GPa	30
Total Porosity, %	34/ <b>26.1</b>
Keff, GPa	11.9
Geff, GPa	6.9

*Different effective medium rules were used to give a range of values  
To predict  $V_p$  and  $V_s$  from complex carbonate microstructures*

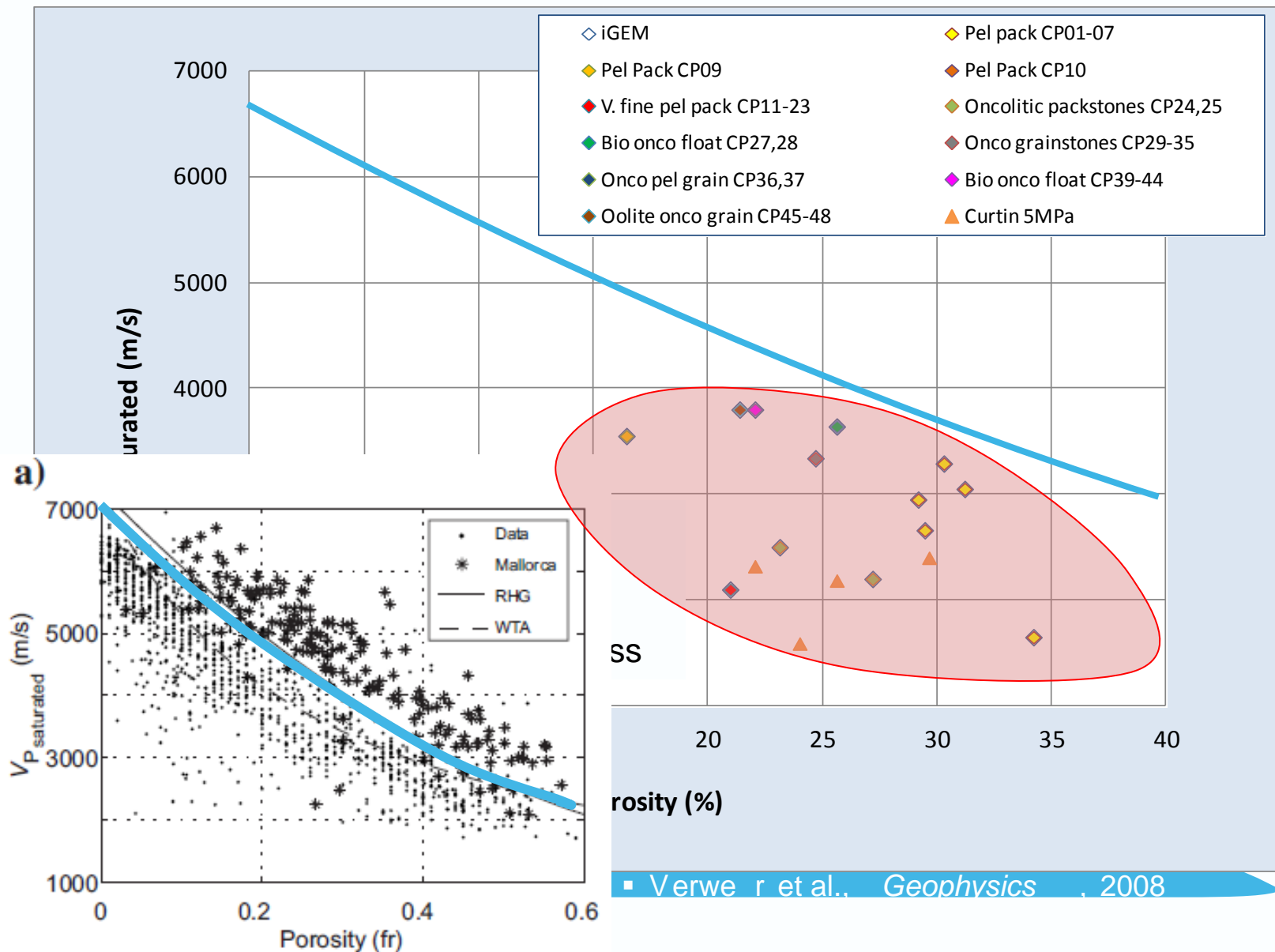




# Global misfit: rocks are “too compliant”

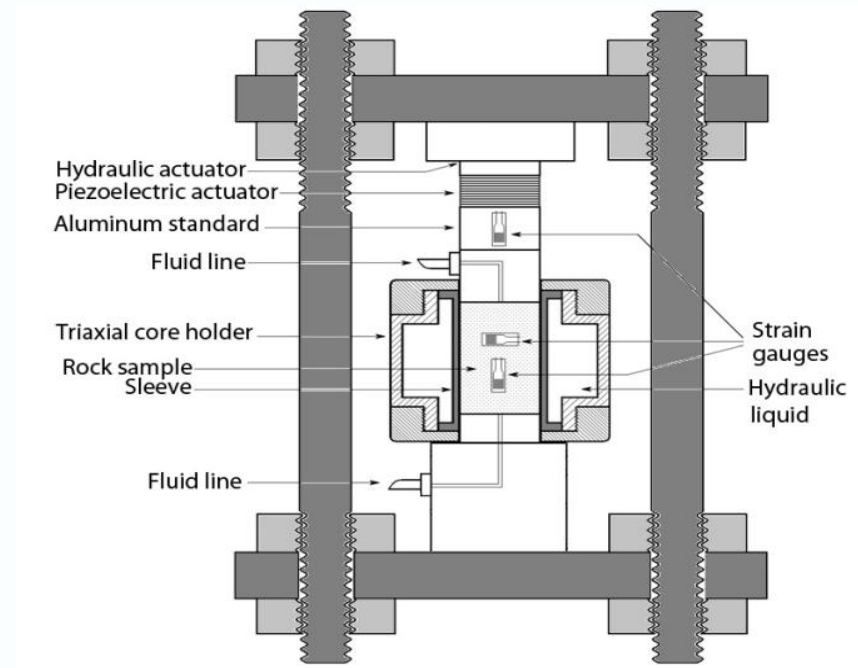
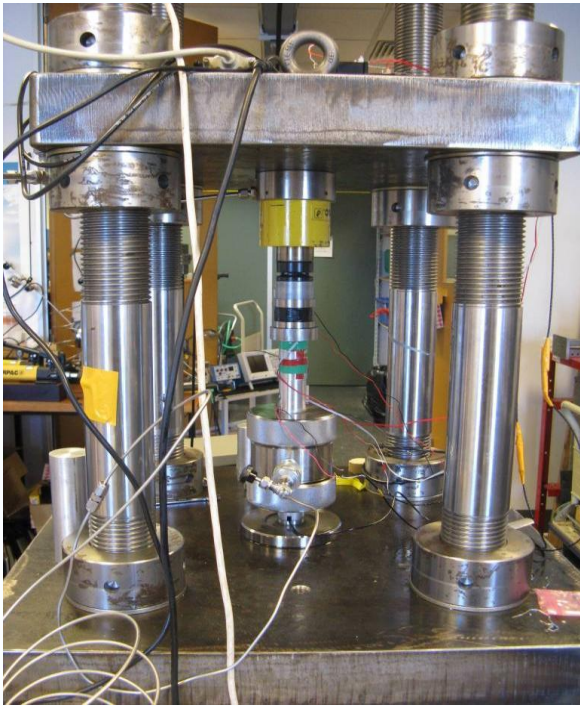


# Global misfit: rocks are “too compliant”



# Low frequency rock physics apparatus

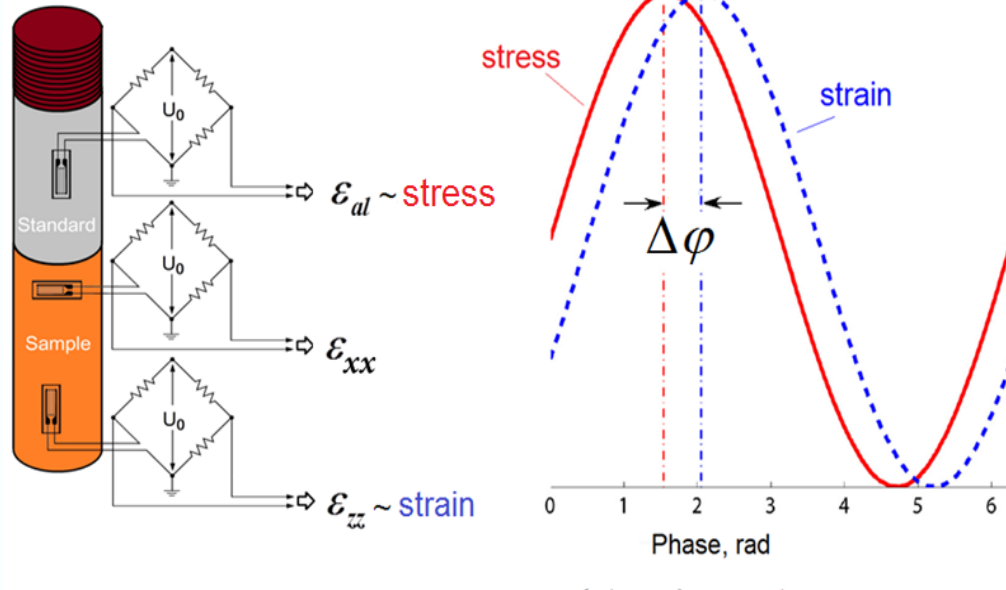
## Mechanical assembly (similar to ultrasonic measurements)



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# Extraction of complex Young's modulus

and Poisson's ratio



Young's modulus

$$E = \frac{\sigma_{zz}}{\epsilon_{zz}}$$

Poisson's ratio

$$\nu = -\frac{\epsilon_{xx}}{\epsilon_{zz}}$$

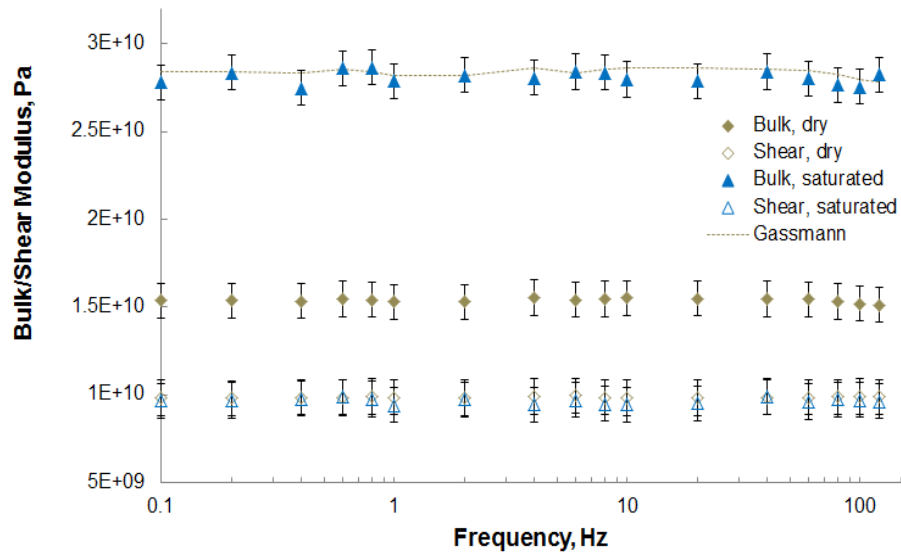
Attenuation of  
extensional wave

$$Q_E^{-1} = \tan(\Delta\phi) \approx \Delta\phi$$

- Note strains are actually *smaller* (1e-6) than those in ultrasonic measurements

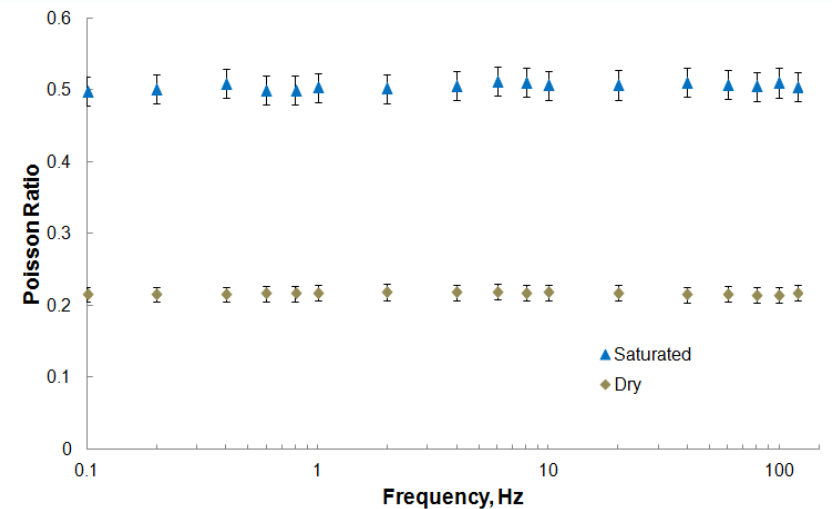
# Low frequency results

## Sample CP21: cemented packstone



**One** of five samples exhibited “Gassman Compliant” behaviour. Therefore fluid substitution **can predict 4D seismic response**.

## Sample CP32: oncolitic grainstone

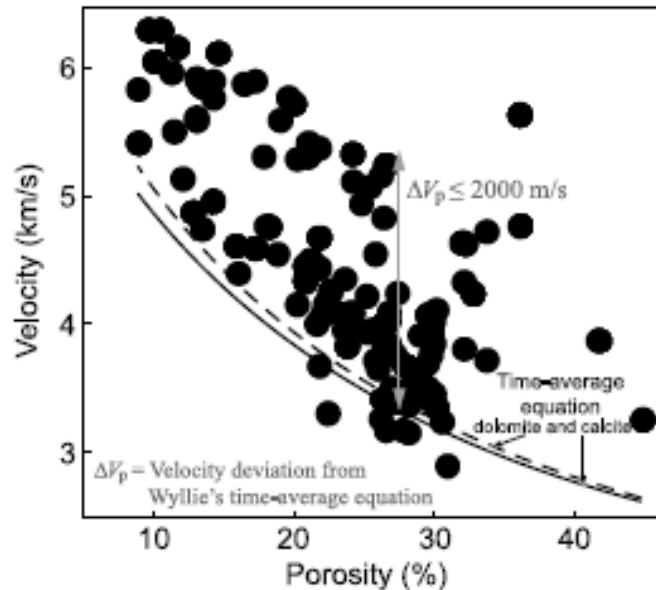


**Four** of five samples lost shear rigidity after saturation with brine...  
*Vp decreases*

*Mechanical strength also decreased on exposure to brine= **water weakening***  
{as presented by Delle Piane et al., this meeting for analogue carbonate rocks}

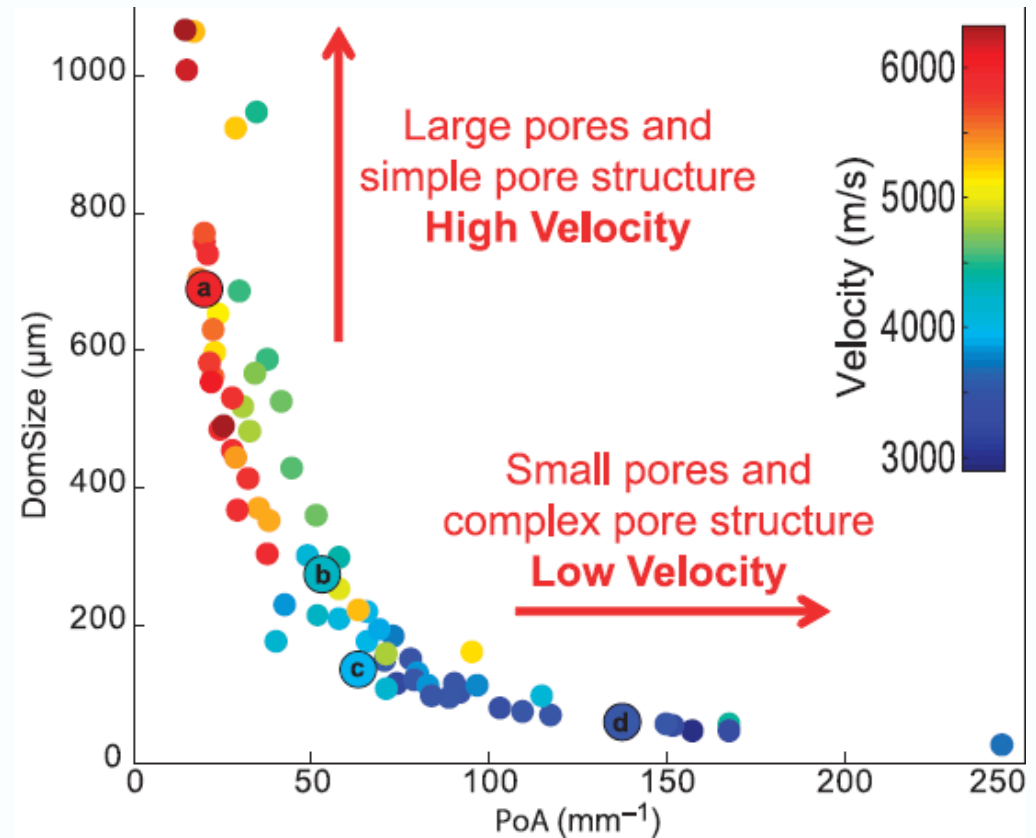


# Carbonate rock physics models: pore shape

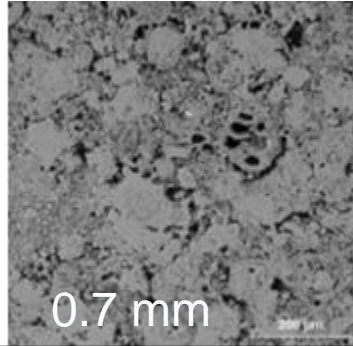
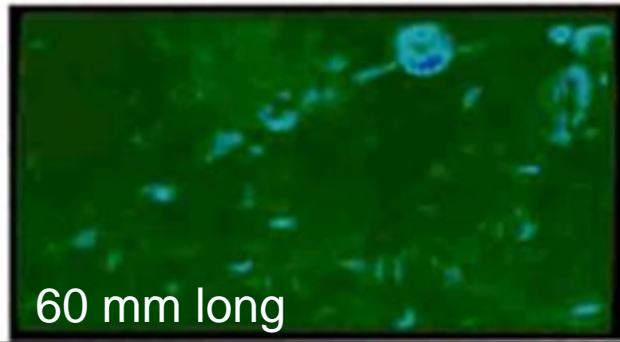


Compare: Eberli et al., 2003, Verwer et al. 2008, Xu and Payne, 2009, Zhao et al. 2013...active area of R&D

Weger et al., AAPG Bull, 2011

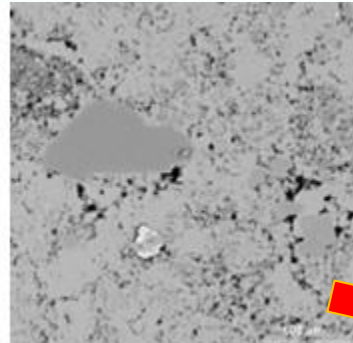
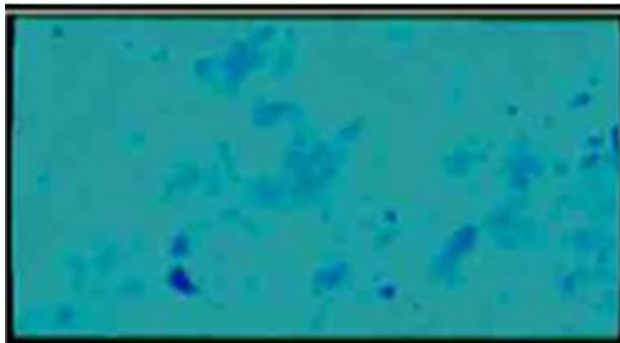
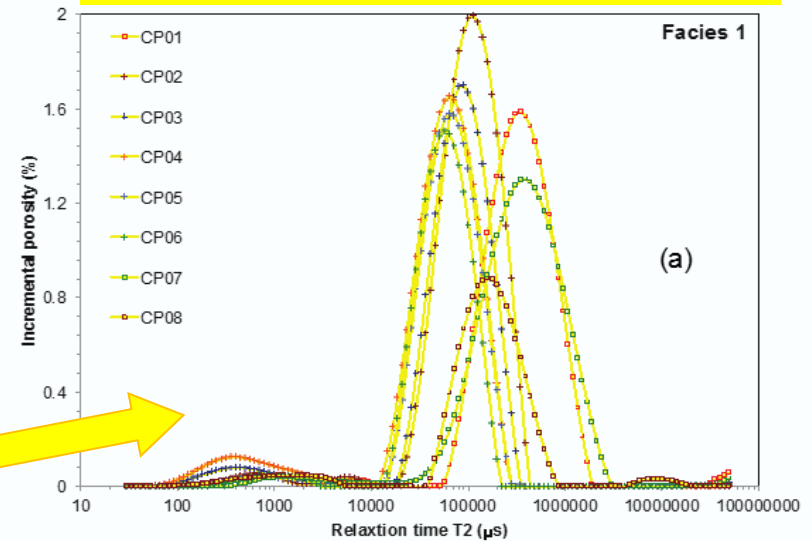


# Complex carbonate NMR

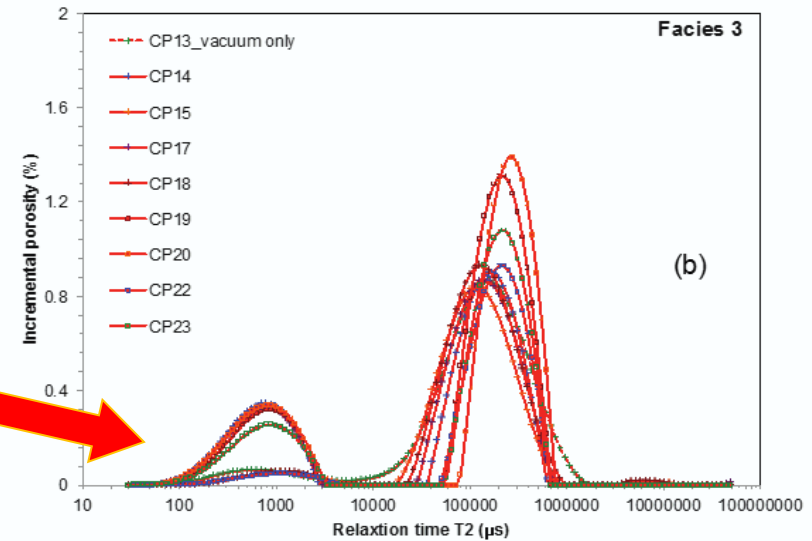


Facies 1.  $k = 10 - 37$  mD;  $\phi = 29 - 34\%$

Packstones, complex pore shapes

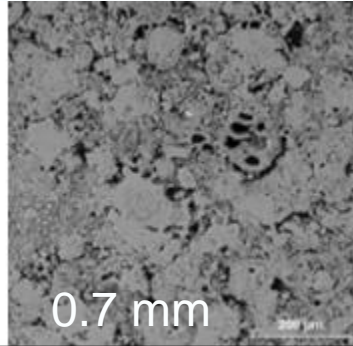
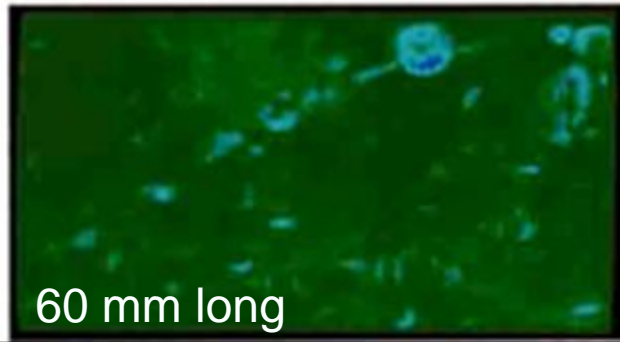


Facies 3.  $k = 0.8$  mD- 6 mD;  $\phi = 18 - 25\%$



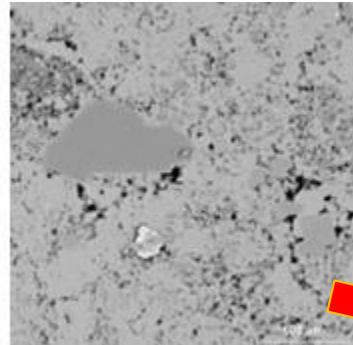
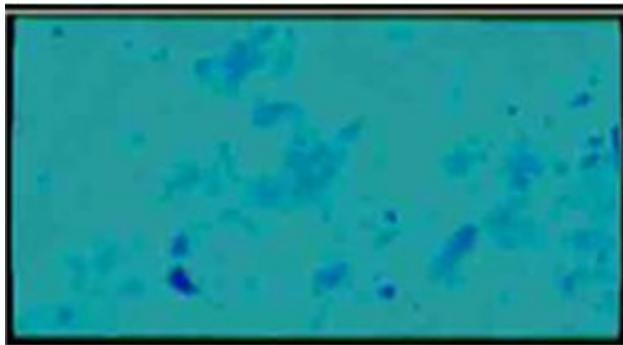
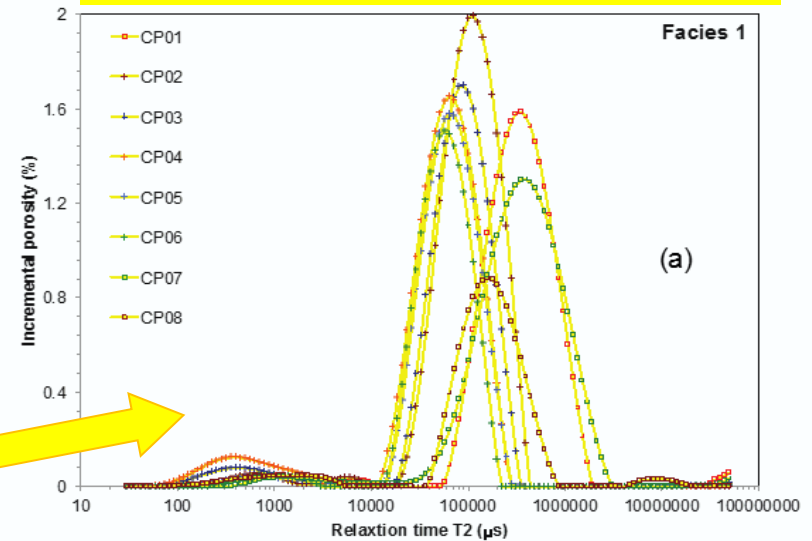
Peloidal packstones with fine matrix

# Complex carbonate NMR

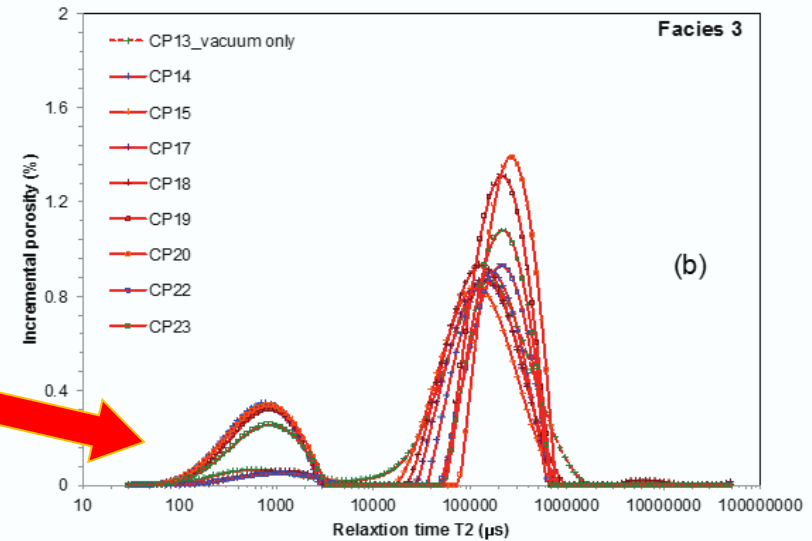


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Packstones, complex pore shapes

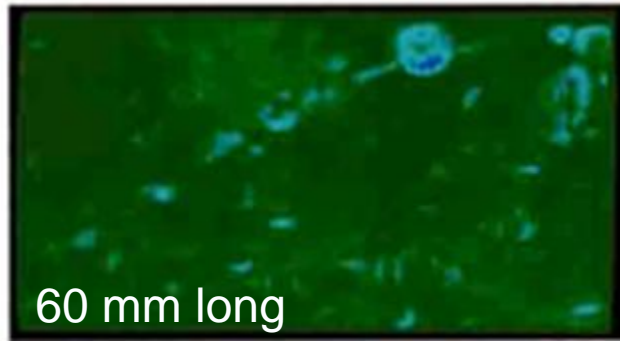


Facies 3.  $k = 0.8$  mD- 6 mD;  $\phi = 18 - 25\%$

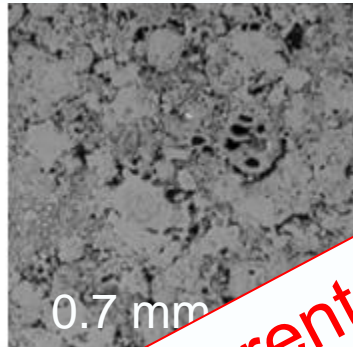


Peloidal packstones with fine matrix

# Complex carbonate NMR

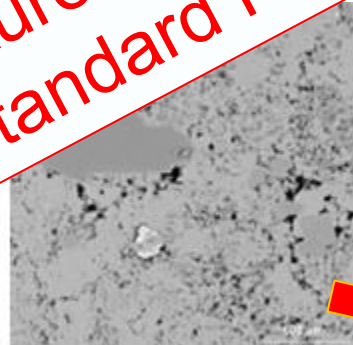
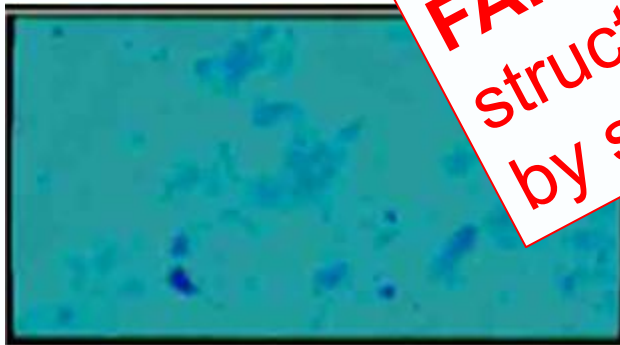


60 mm long



0.7 mm

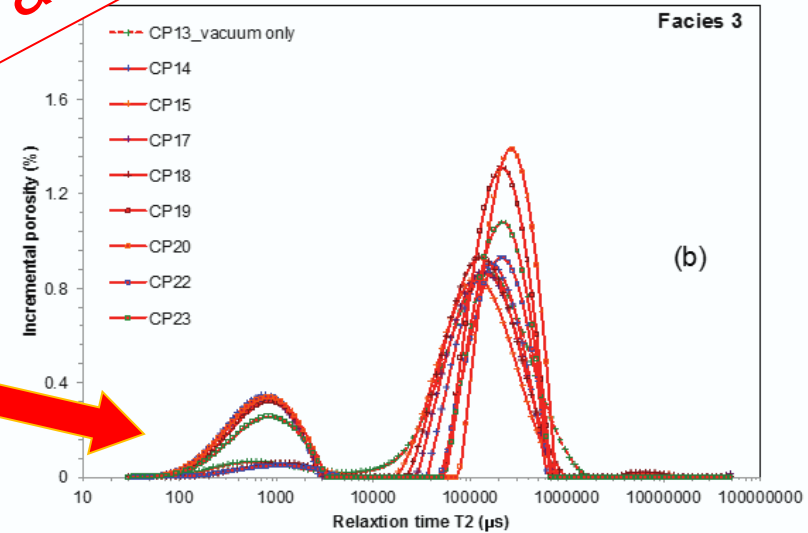
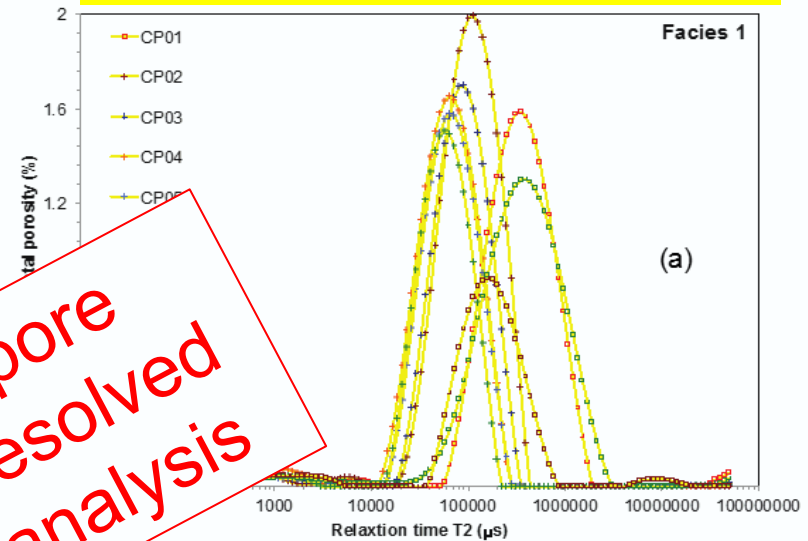
Facies 1.  $k = 10-37$  mD;  $\phi = 2-10\%$



Facies 3.  $k = 0.8$  mD- 6 mD;  $\phi = 18-25\%$

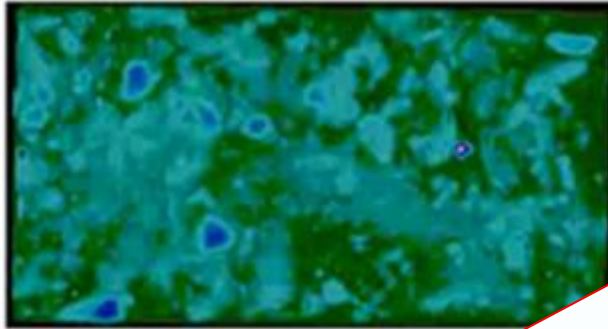
**FAIL!** The different pore structures are not resolved by standard NMR analysis

## Packstones, complex pore shapes

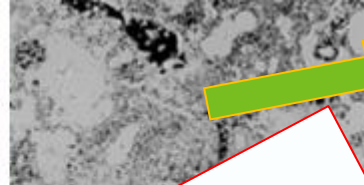


Peloidal packstones with fine matrix

# Complex carbonate dielectric spectra



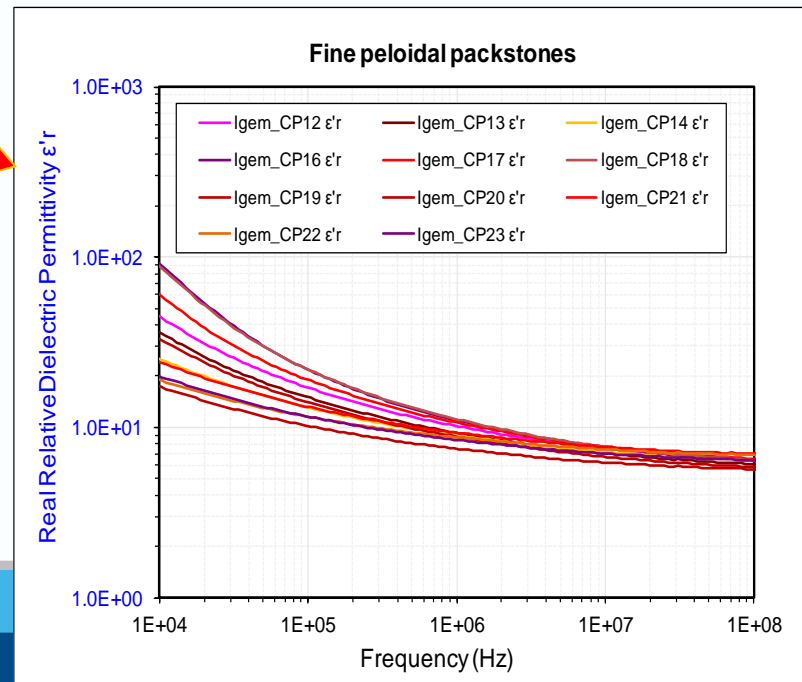
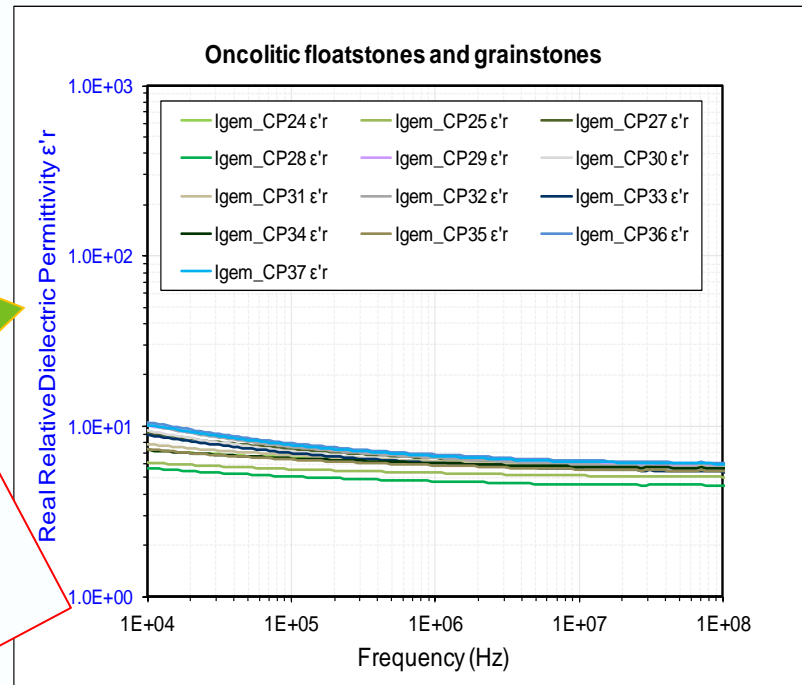
Facies 5.  $k = 37 - 7$



Similar spectral shapes  
but... very different degrees  
of dispersion



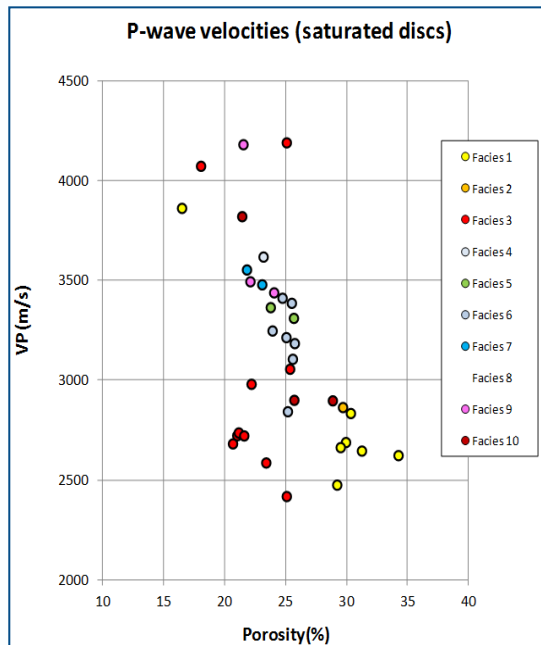
Facies 3.  $k = 0.8 - 6$  mD;  $\phi = 18-25\%$



DIELECTRIC RESPONSES OF CARBONATES FROM AN ALBIAN POST-SALT RESERVOIR, CAMPOS BASIN, BRAZIL

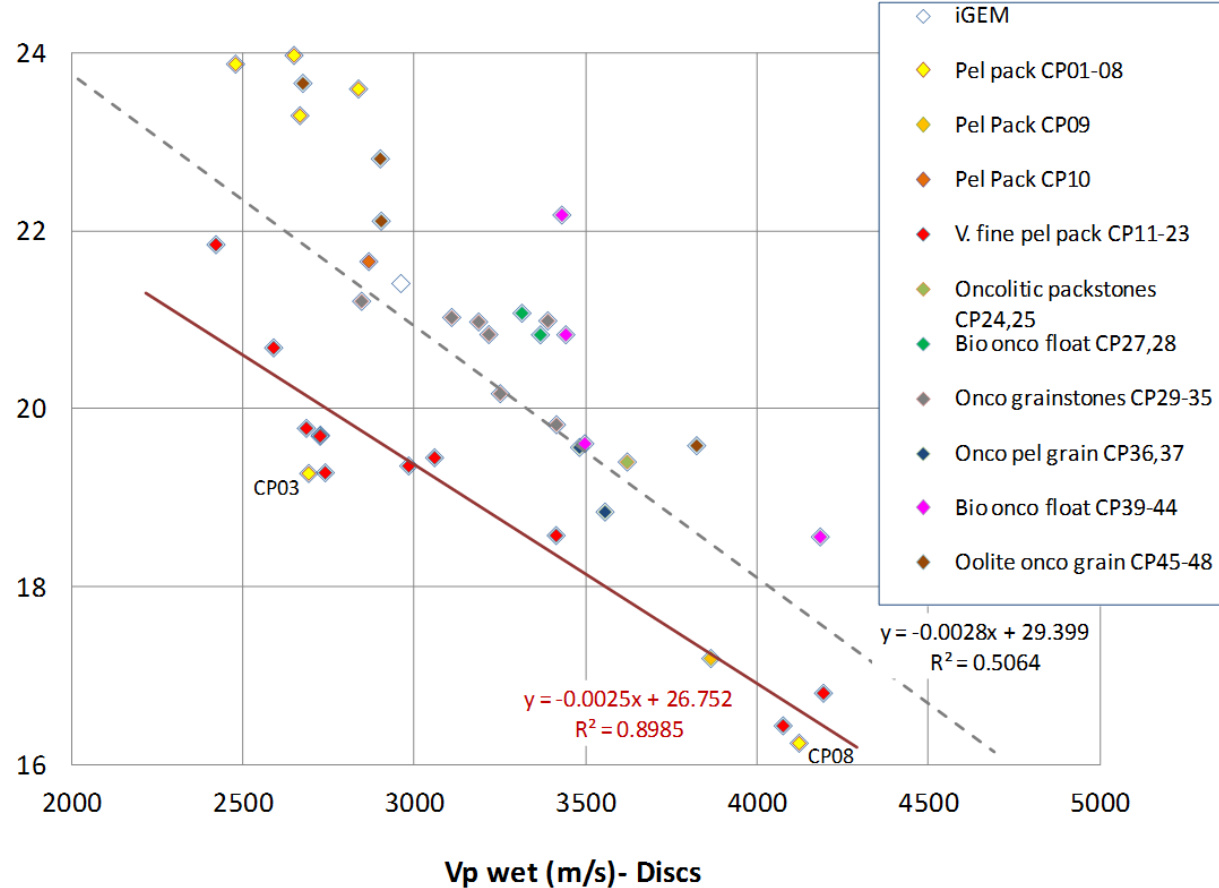


# Dielectric Spectroscopy: Correlation with Sonic Velocities



*Velocity is very poorly predicted by porosity: complex pore shapes*

Permittivity  $\epsilon_r$  @100MHz



Permittivity at 100 MHz decreases as rock rigidity, and seismic velocity increases

- A very good correlation for the fine grained **lithofacies 3** (n=10)

# Key findings and outcomes from petrophysical diagnostics

1. Standard NMR works poorly in complex carbonates: pore coupling
  - NMR can still be of significant value in the post-salt reservoirs if appropriate methods for decoupling are used.
2. Dielectric permittivity provides interesting correlations with velocity
  - Dielectric logs could possibly fill-in where  $V_p$ ,  $V_s$  logs are absent.
  - Might be a first order pore-shape control, as proposed by Weger et al. 2011
  - But the permittivity curves are all rather similar looking so certainly cannot be used to categorize microfacies



# Key findings and outcomes

## Elastic, geomechanical and flow properties scaling & prediction

1. Sub-resolution structure is an issue in any digital rock study, except for very chunky, rock types
  - A novel scheme was devised in IGEM-4D to compute effective elastic constants in more complex carbonates where voxels were not resolved.
  - Two upscaling schemes were developed and applied to the IGEM-4D data Percolation based (for flow) and Thermodynamic (for mechanical properties)
2. Mechanical and rock physics prognoses failed for 80% of samples because of a chemical effect, **water weakening**, **that was unforeseen**

(a black Swan)



The **water weakening** tendency affects the lithofacies whose load bearing grains are **micritized**: recemented upper reservoir and the lower reservoir rocks are unaffected and obey the Gassmann fluid substitution relationship.

# Something else unforeseen

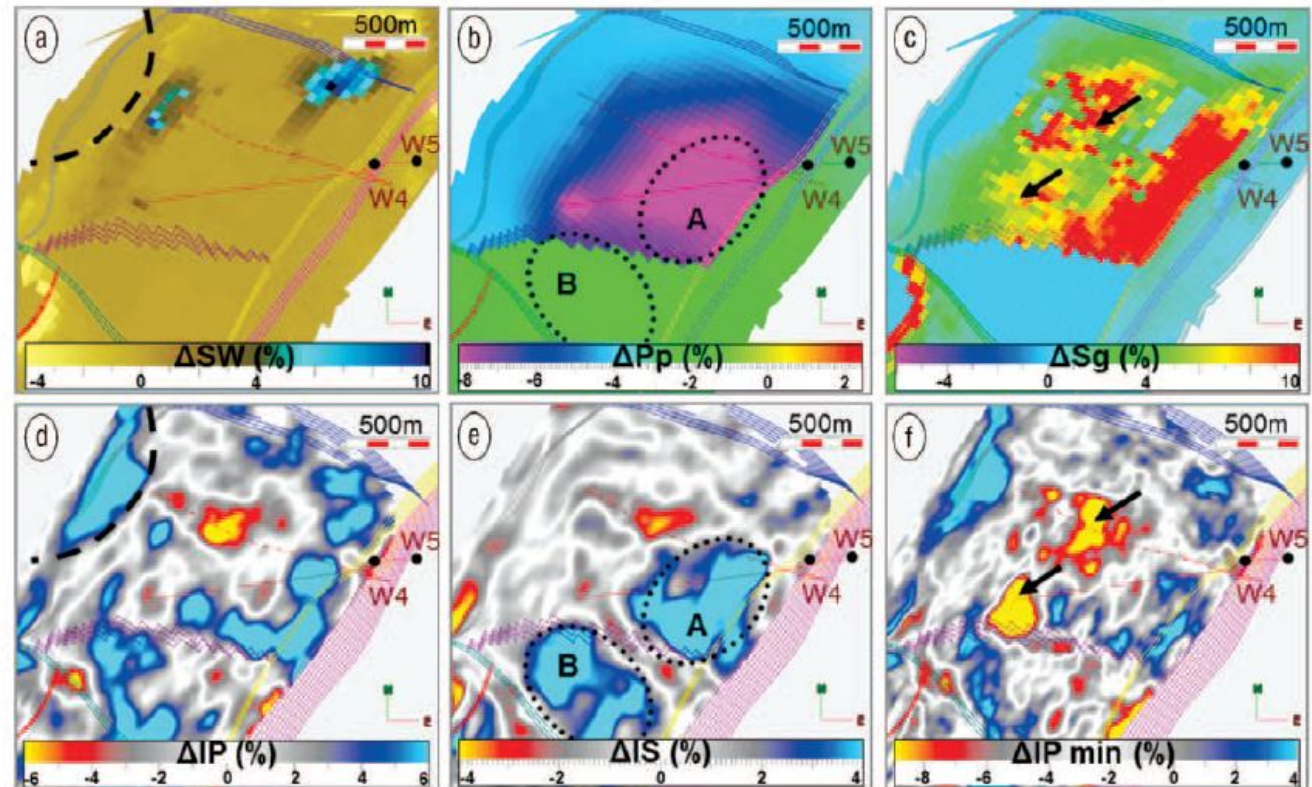
## Brazilian carbonate reservoir: A successful seismic time-lapse monitoring study

THE LEADING EDGE

FEBRUARY 2014

MARCOS HEXSEL GROCHAU, PEDRO MONTEIRO BENAC, LEONARDO DE MAGALHÃES ALVIM, RUI CESAR SANSONOWSKI, and PAULO ROBERTO DA MOTTA PIRES, Petrobras  
FLORINE VILLAUDY, Beicip-Franlab

- Large 4D effects seen in *Field B*
- Stress changes and water-to-oil fluid substitution contribute to signals
- **Gas cap expansion is the largest 4D signal**





# Something else unforeseen

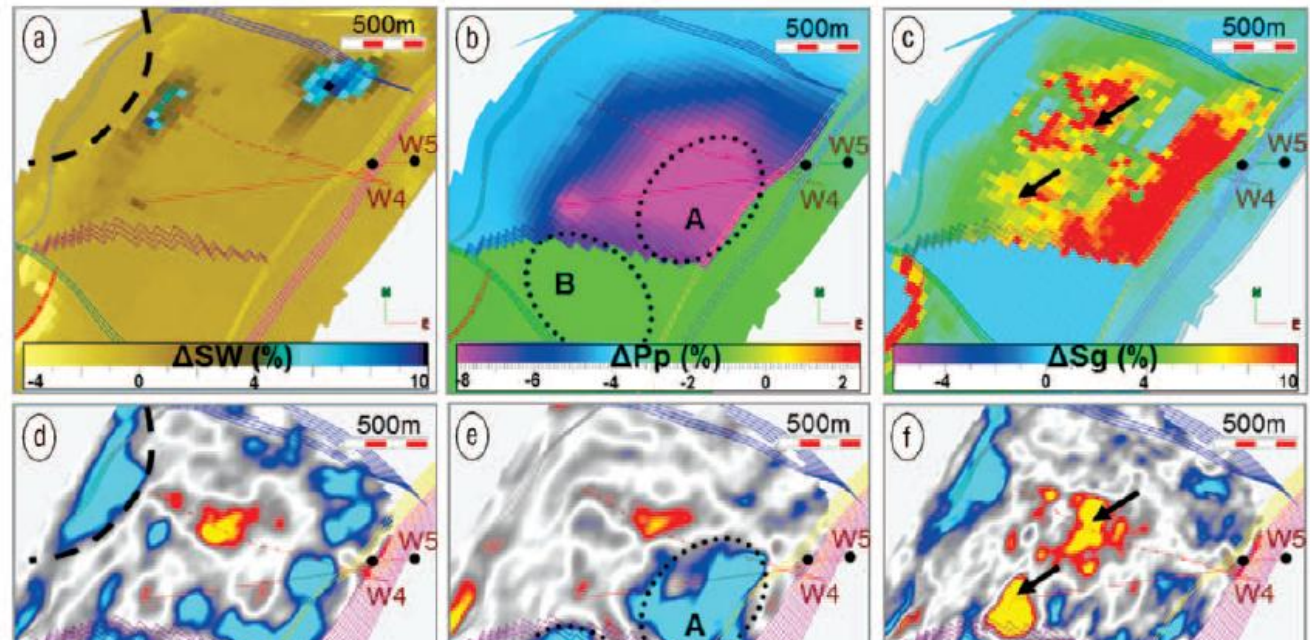
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- Large 4D effects seen in *Field B*
- Stress changes and water-to-oil fluid substitution contribute to signals
- **Gas cap expansion is the largest 4D signal**



The IGEM-4D results came too late to “predict” time lapse seismic responses...but still add value through:

- Understanding 4D responses that were observed
- Improved field management options
- Possibly avoiding pore collapse from water weakening

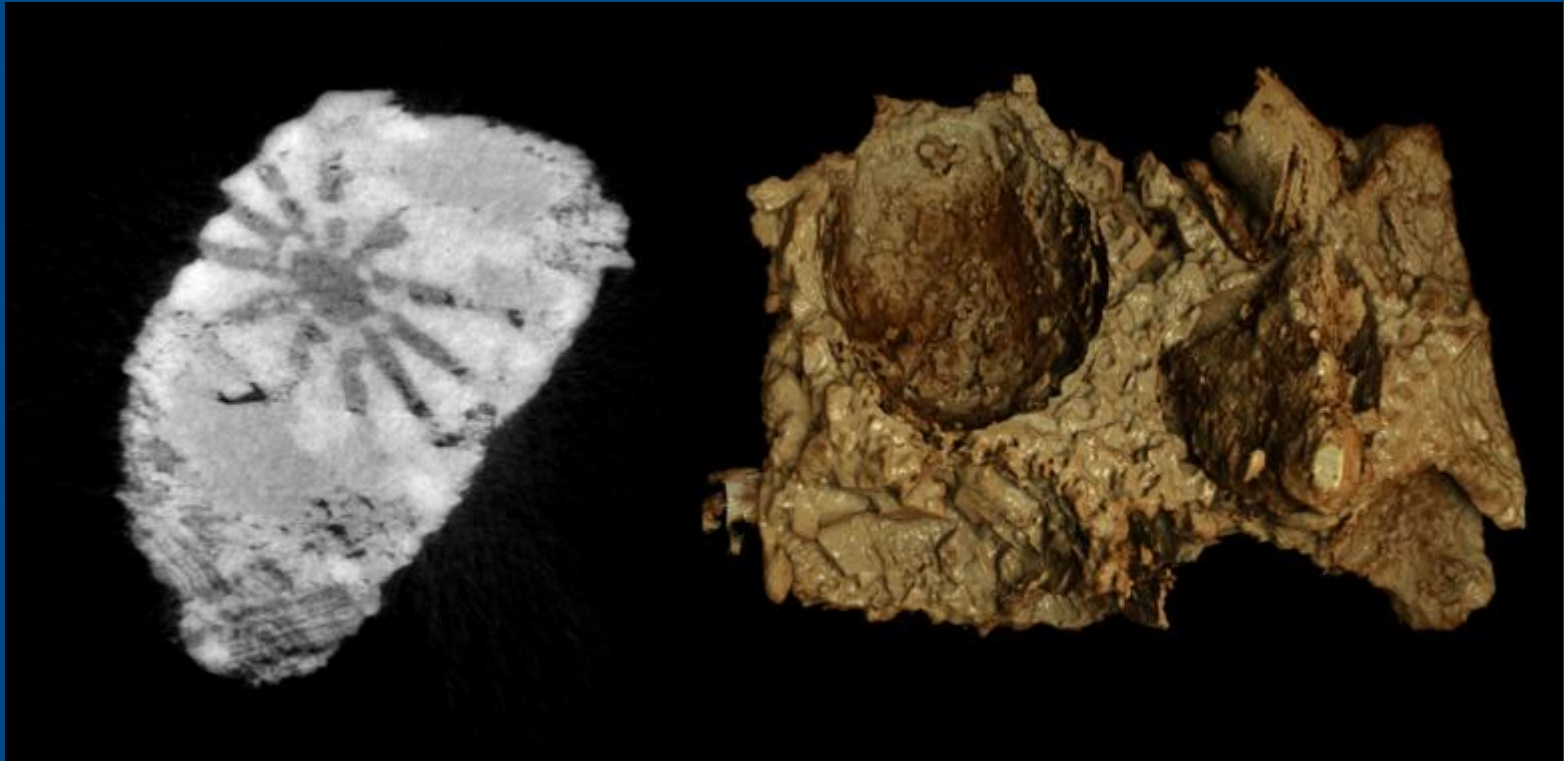


# Take away messages

1. Some new methods were developed in the iGEM-4D project
  - Some were in the plan, e.g. upscaling methods, dielectrics
  - Others were developed on the fly, e.g. subvoxel modelling
2. In complex carbonates: expect the unexpected !
3. In a multidisciplinary R&D project: prepare for the unexpected !
4. Learn from the **unexpected outcomes** to create lasting value



# Thank you



**Ben Clennell** | Research Group Leader, Exploration Geosciences, CSIRO Energy