

Fluid/Rock Interactions in Porous Carbonate Rocks: An Integrated Mechanical, Ultrasonic and Microstructural Study

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Search and Discovery Article #41745 (2015)**

Posted December 28, 2015

*Adapted from oral presentation given at AAPG International Conference & Exhibition, Melbourne, Australia, September 13-15, 2015

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Abstract

The mechanical and physical properties of reservoir rocks are affected by the nature of the fluids saturating their pore space. Water flooding is a commonly adopted practice for enhanced oil recovery; however, saturating the reservoir with water can result in a reduction in rock strength (i.e., water weakening), leading to enhanced compaction which in turn can impact reservoir productivity and management. This study is concerned with the laboratory measurement of mechanical, elastic and fluid transport properties of samples of synthetic limestones with the aim of investigating the mechanisms involved in water weakening. Blocks of synthetic limestone were fabricated using the Calcite In situ Precipitation System (CIPS), a proprietary mineral cementation grouting technology (Lithic Technology Pty Ltd), and sub-samples from these were experimentally tested to assess the sensitivity of their mechanical and elastic properties to water saturation. To this end, high pressure geomechanical tests were conducted to characterize the behaviour of the samples under dry and water-saturated conditions while monitoring elastic wave velocities (compressional and shear waves) at ultrasonic frequencies. Three types of geomechanical tests were performed covering the brittle to ductile range of rock responses: i) unconfined compressive strength (UCS); ii) multistage triaxial (MTXL); and iii) hydrostatic (isotropic) compaction. The saturated hydrostatic compaction and MTXL tests were run with a pore pressure of 1MPa and maintaining the same effective stresses as used for the dry tests. The laboratory geomechanical tests were complemented by a series of petrophysical and microstructural analyses aimed at characterizing the porosity, permeability, pore and grain size distributions of the rock samples and track their evolution as functions of the applied stress. Experimental results show that, in all tested stress configurations, water-saturated CIPS-cemented samples are weaker

and more compliant than those with empty pore spaces (i.e., dry); therefore the mechanical and elastic properties of the CIPS calcite cement are affected by the presence of water. The results provide new insights into the micromechanical mechanisms leading to water weakening, strain localization and failure in high porosity carbonate rocks as well as links between their elastic wave velocities, water saturation and degree of deformation.

Selected References

Heap, M.J., P. Baud, and P.G. Meredith, 2009, Influence of temperature on brittle creep in sandstones: *Geophysical Research Letters*, v. 36, L19305, 6p. Website accessed December 7, 2015, https://eost.unistra.fr/fileadmin/upload/EOST/Mike_Heap/pdf_files/Heap_et_al_2009_GRL.pdf.

Nagel, N., 2001, Ekofisk geomechanics monitoring: International. Workshop on Geomechanics in Reservoir Simulation: IFP, Reuil-Malmaison, France.

Røyne, A., J. Bisschop, and D.K. Dysthe, 2011, Experimental investigation of surface energy and subcritical crack growth in calcite: *Journal of Geophysical Research*, v. 116/B04204, 10p. Website accessed December 7, 2015, <http://onlinelibrary.wiley.com/doi/10.1029/2010JB008033/pdf>.

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INTRO

- Mechanical properties of reservoir rocks are affected by the nature of the fluids saturating their pore space;
- Water flooding is a commonly adopted practice for enhanced oil recovery but can result in a reduction of strength → water weakening.

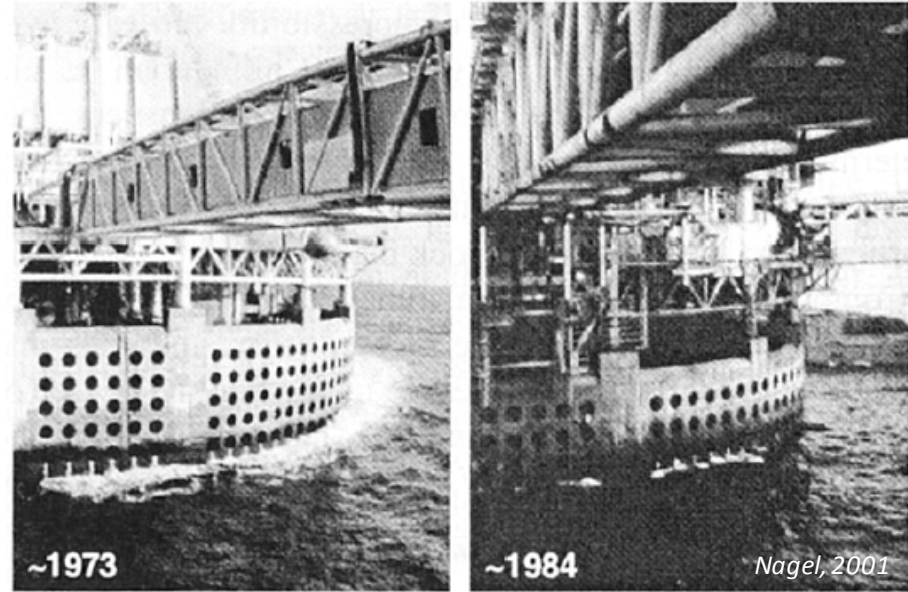
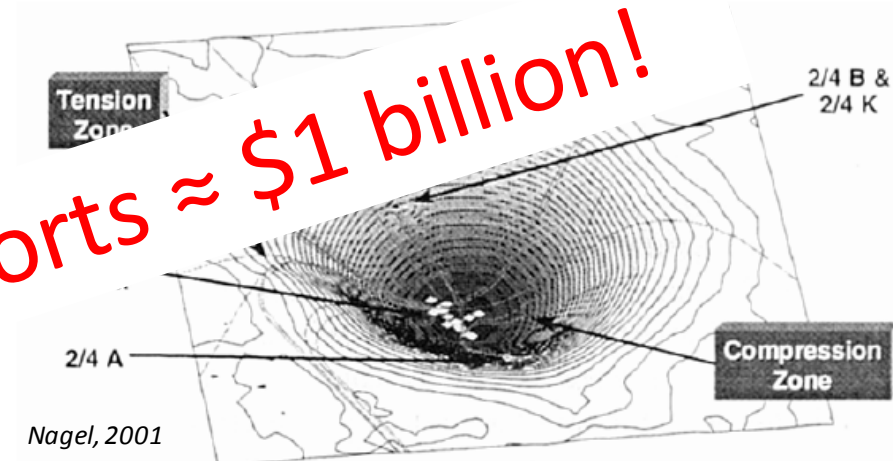


Fig. 5. Photographs of the 2/4T platform at the Ekofisk field. Subsidence was confirmed by comparison of the number of holes visible in the exterior protective wall.

Consequences of water weakening

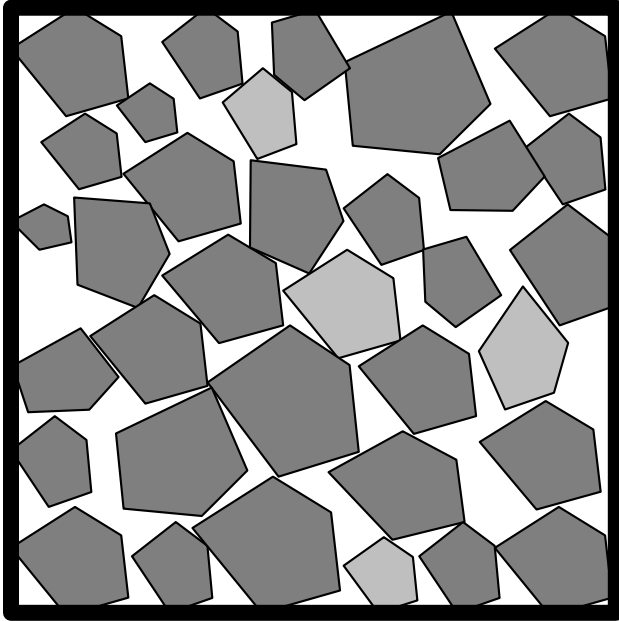
- Increase in rock compressibility;
- Reduction in matrix permeability;
- Increased reservoir compaction and sea floor subsidence.
- Reduced well bore
- Increases

Remediation efforts \approx \$1 billion!



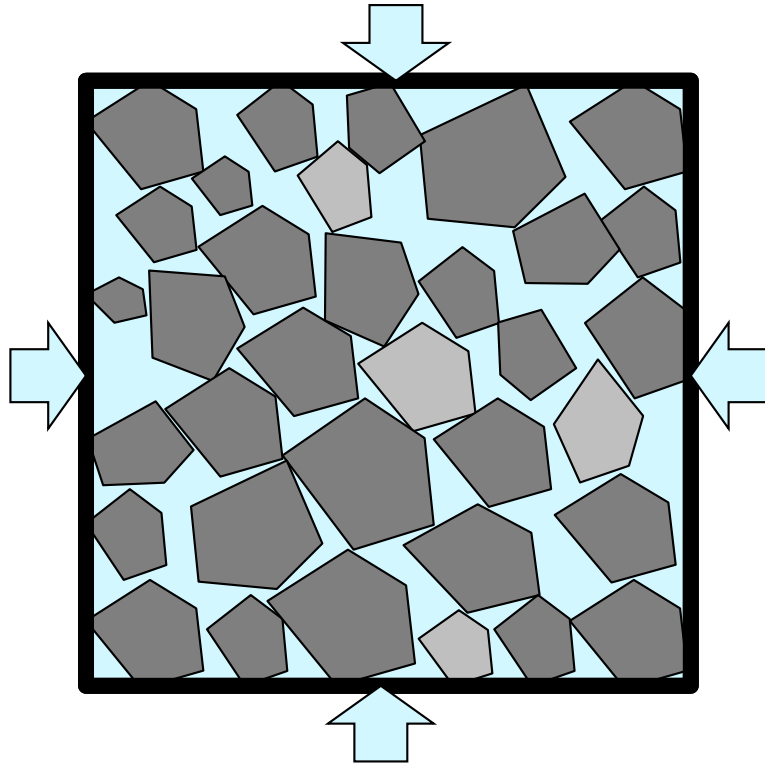
63km of new pipeline laid during Ekofisk II redevelopment to replace sections inside the subsidence bowl

CIPS (Calcite In-situ Precipitation System)



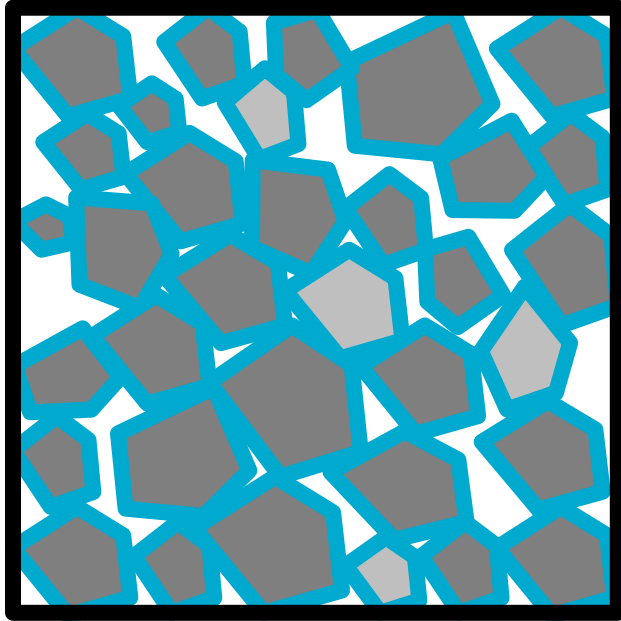
1. Dry sand pack (95% calcite and 5% quartz)

CIPS (Calcite In-situ Precipitation System)



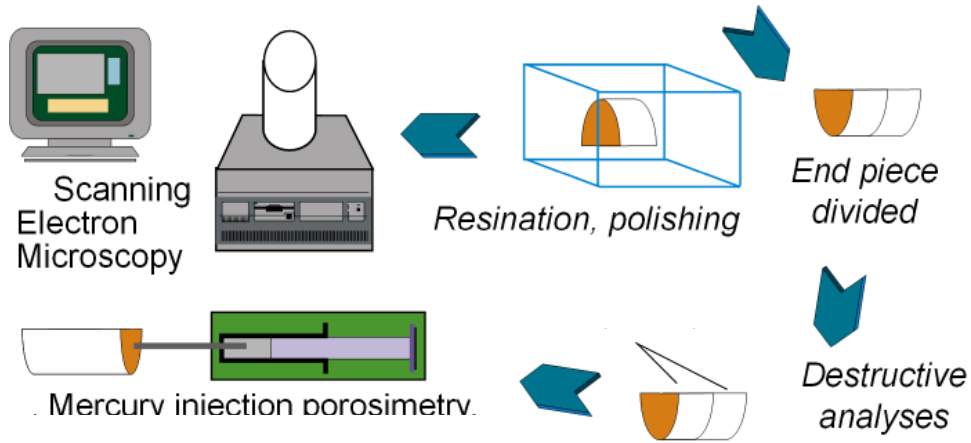
1. Dry sand pack (95% calcite and 5% quartz)
2. Flush with CIPS solution

CIPS (Calcite In-situ Precipitation System)

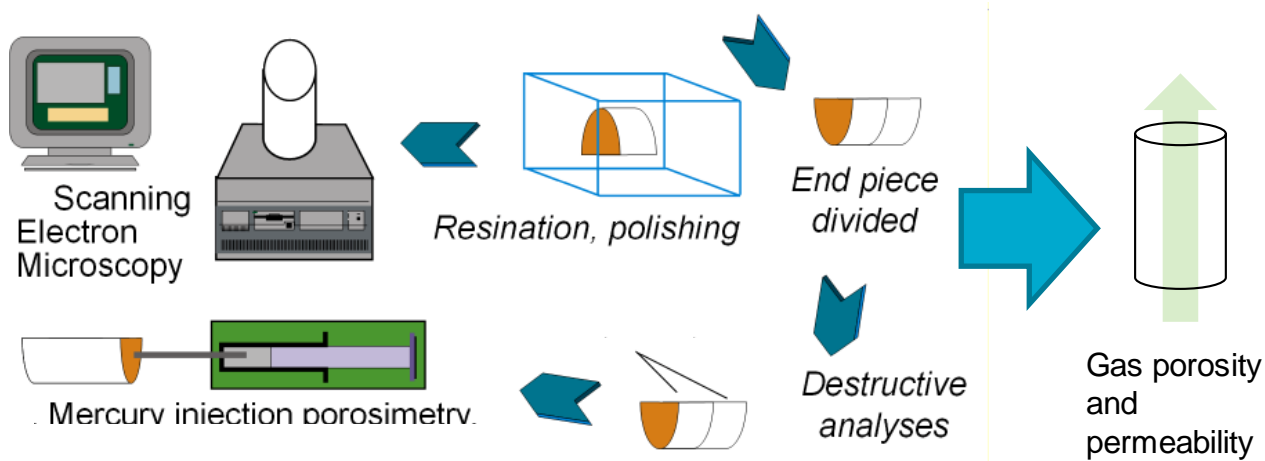


1. Dry sand pack (95% calcite and 5% quartz)
2. Flush with CIPS solution
3. Calcite cementation

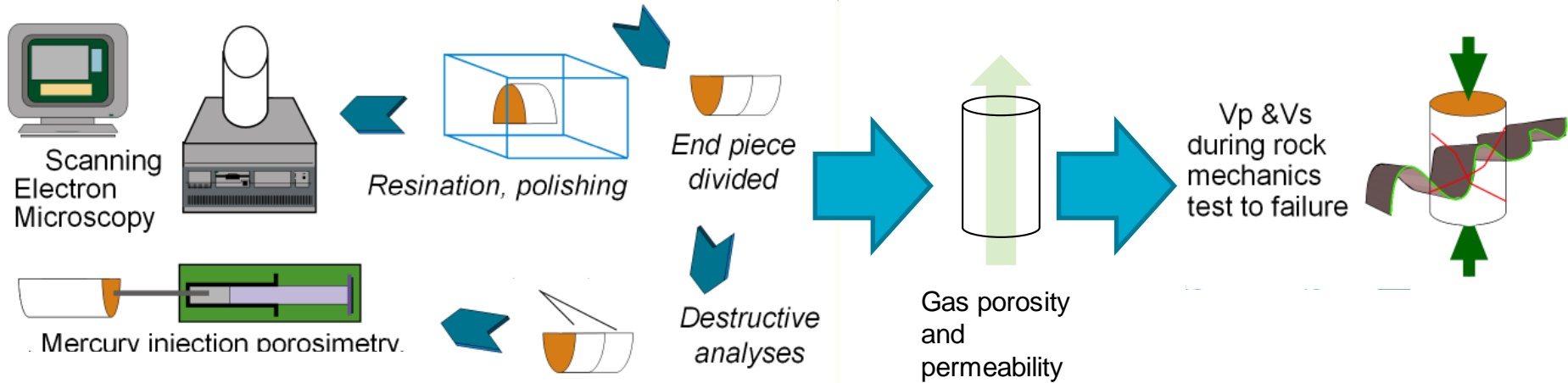
Characterisation workflow



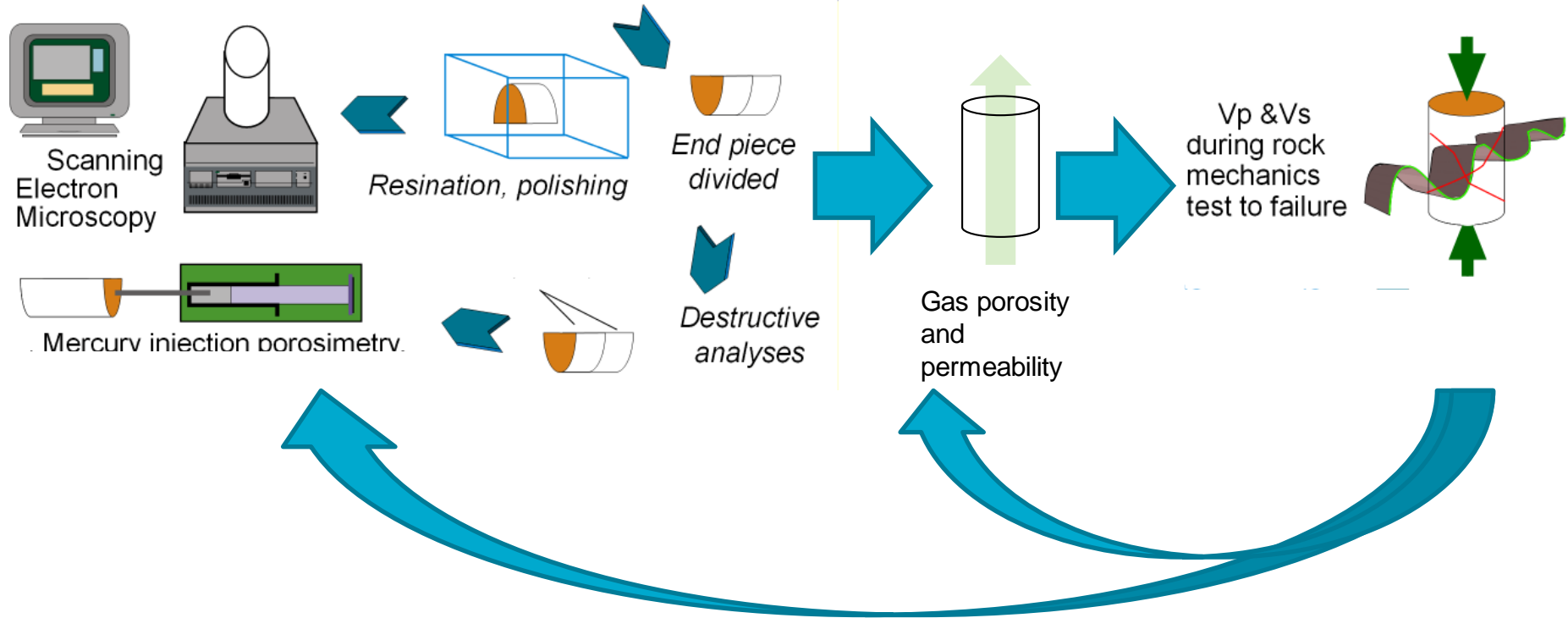
Characterisation workflow



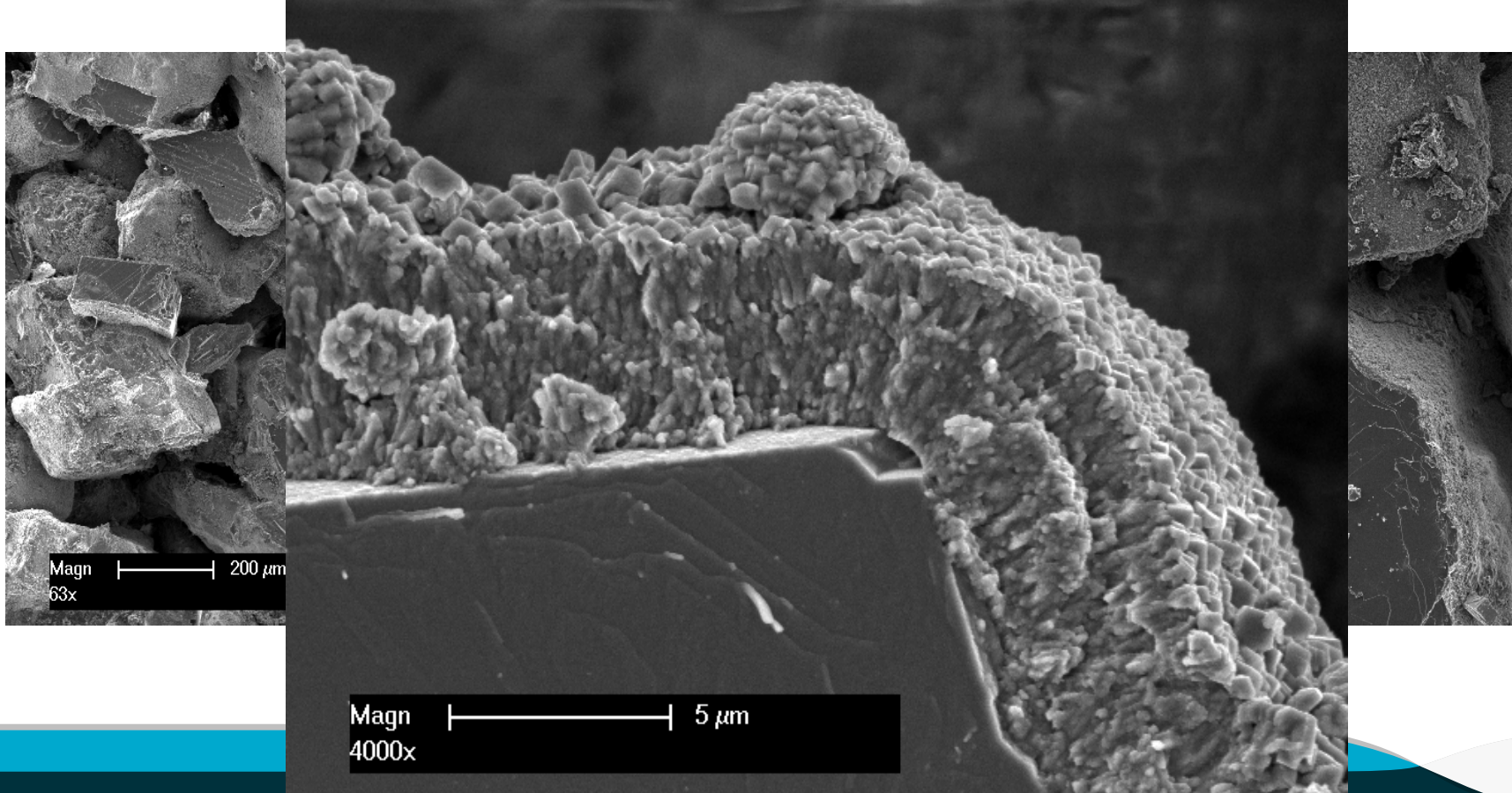
Characterisation workflow



Characterisation workflow



Starting material



CIPS porosity/permeability

Gas porosity: 26.95 % \pm 1.06

Gas permeability: 8 \pm 1.9D



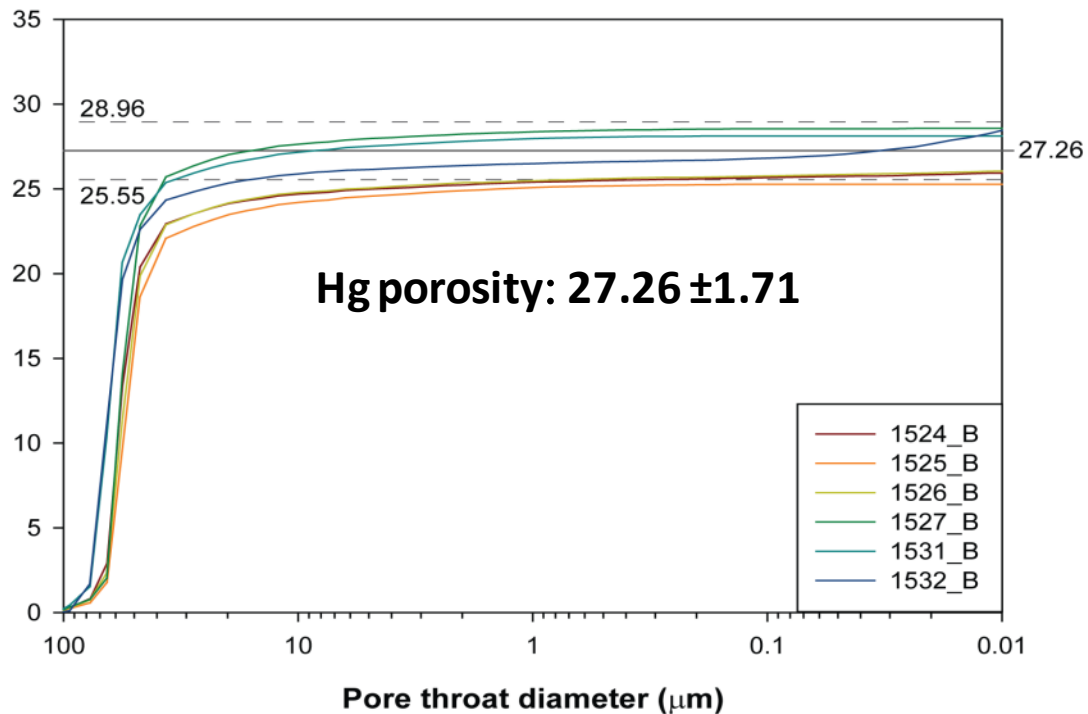
CIPS porosity/permeability

Gas porosity: $26.95 \% \pm 1.06$

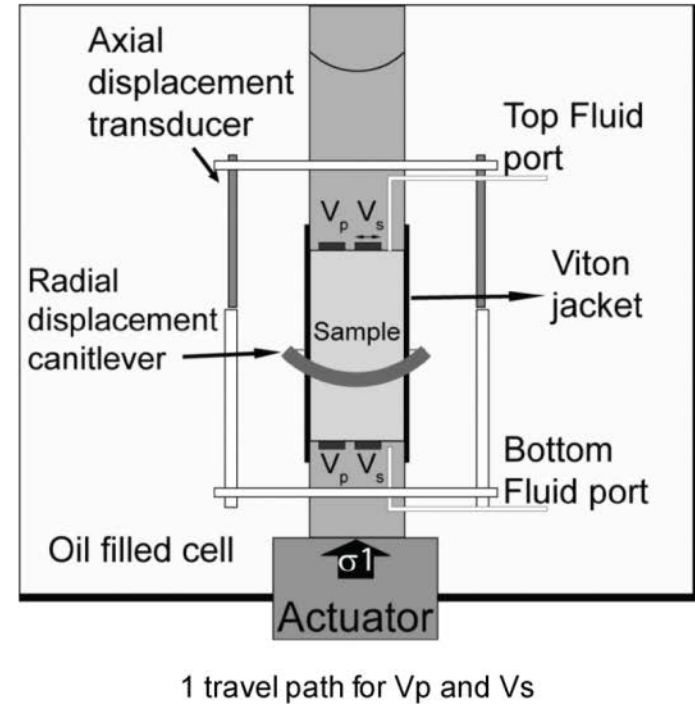
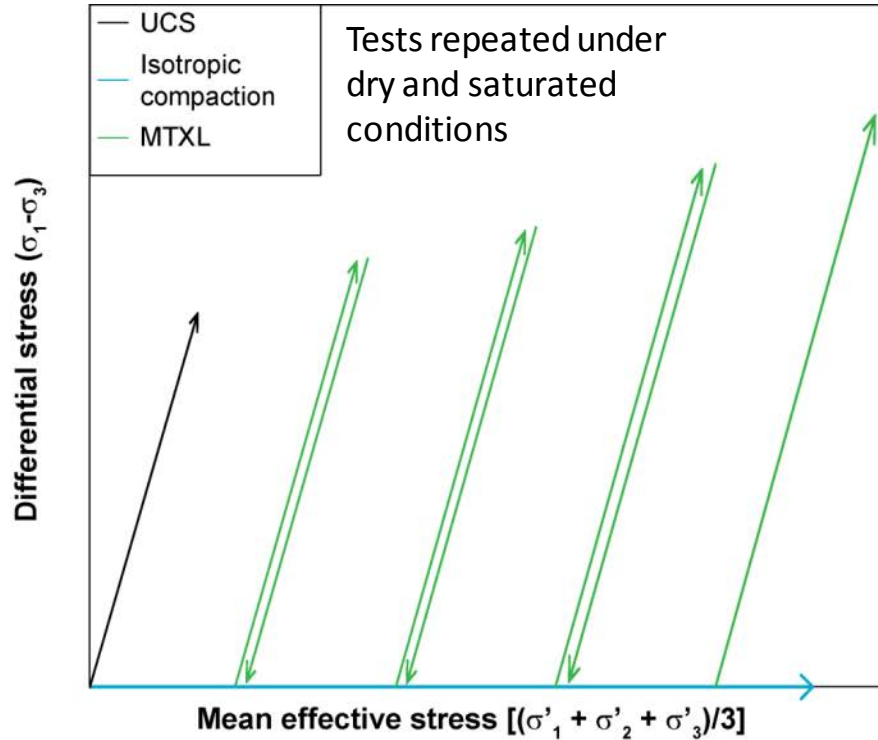
Gas permeability: $8 \pm 1.9D$



Cumulative porosity (%)



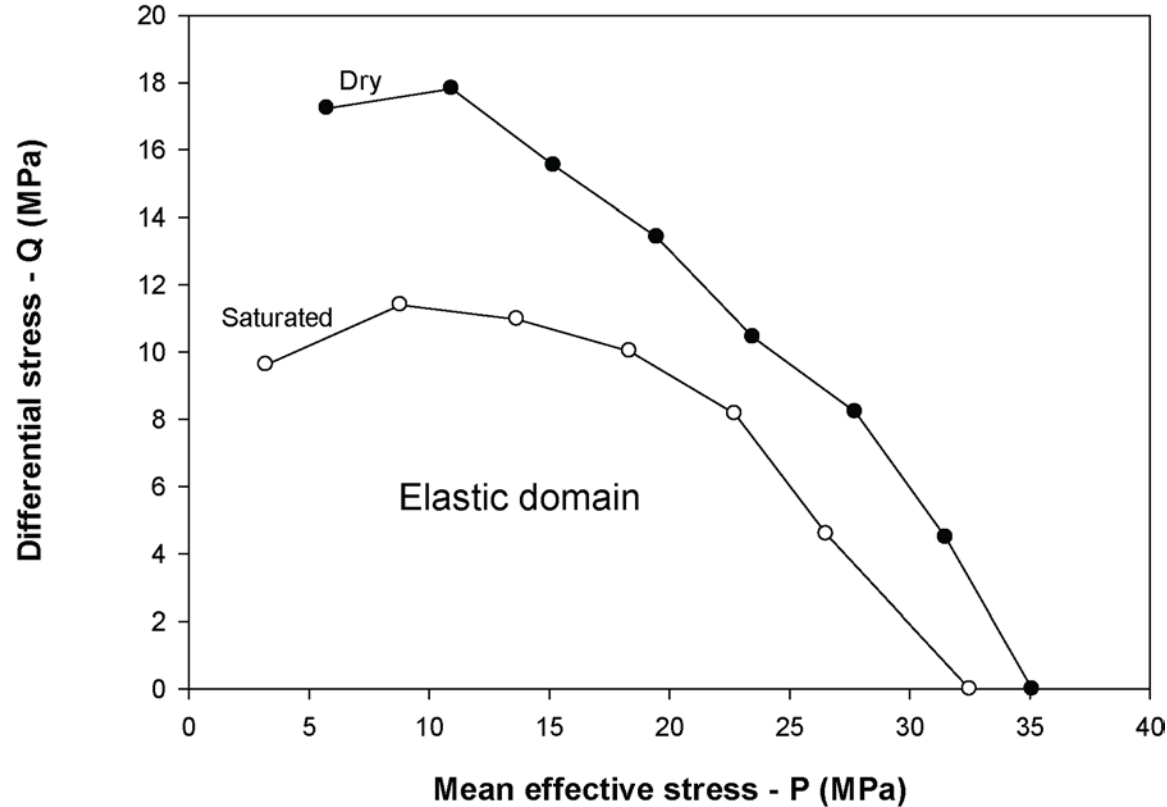
Geomechanical testing



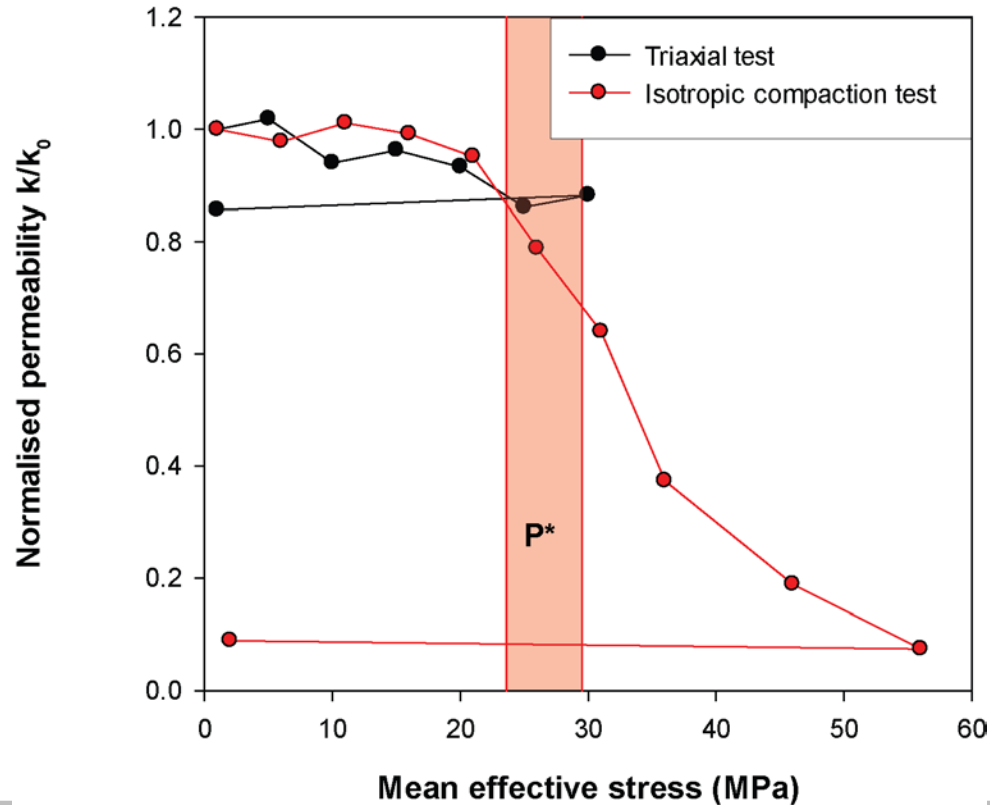
Results



CIPS mechanical characterization



Permeability evolution

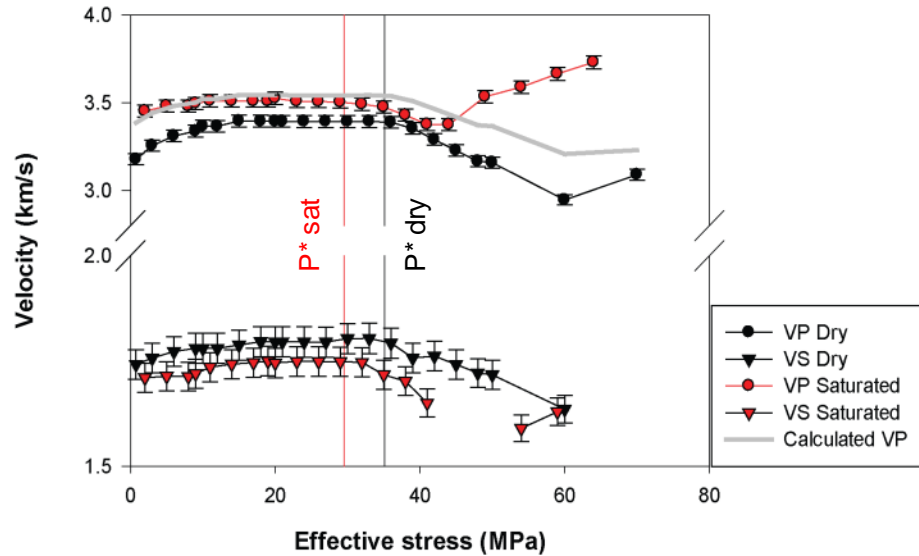


Water permeability

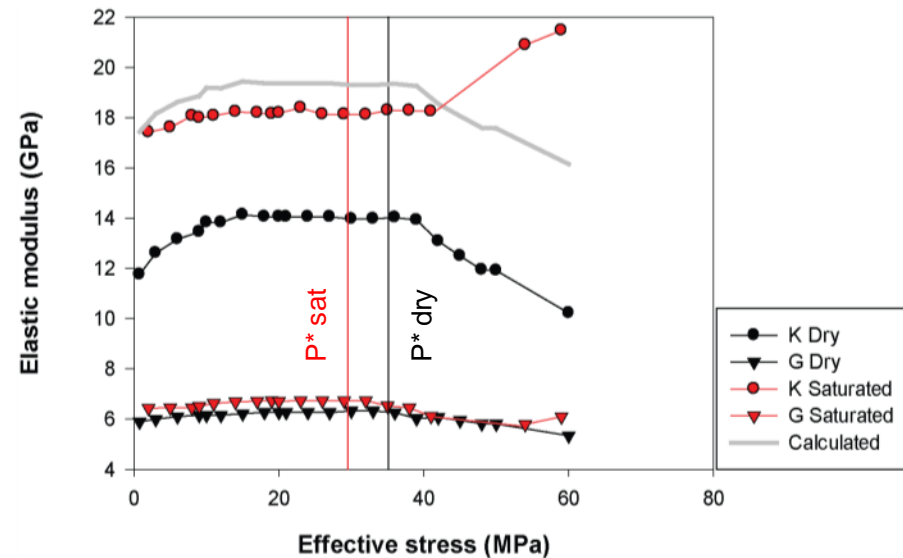
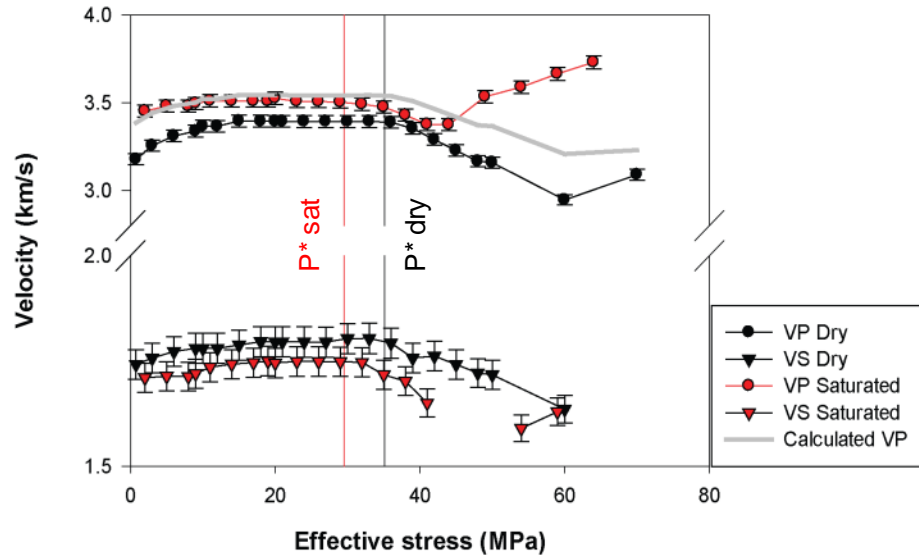
Steady state method at increasing stress levels

Note the difference in k reduction at the same stress for different stress configurations

Rock physics results



Rock physics results

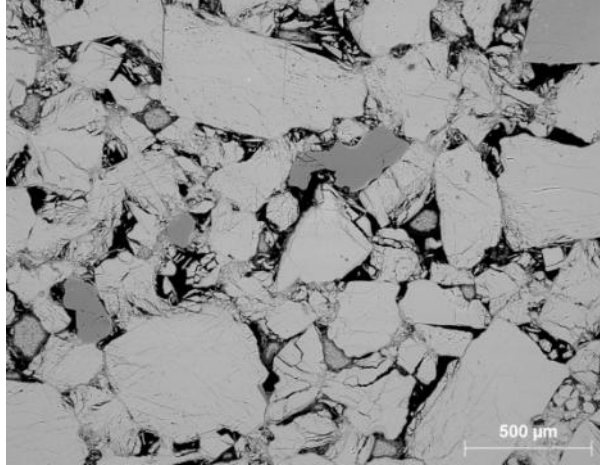


Microstructure: isotropic compaction

Porosity: 26.7 % // Gas k: 8D



Porosity: 18.6 % // Gas k: 0.17D

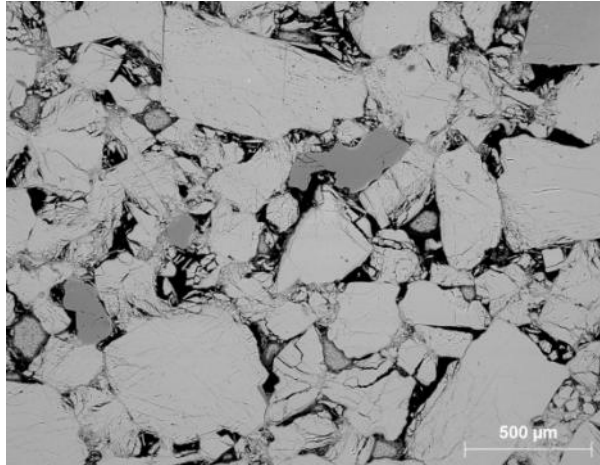


Microstructure: isotropic compaction

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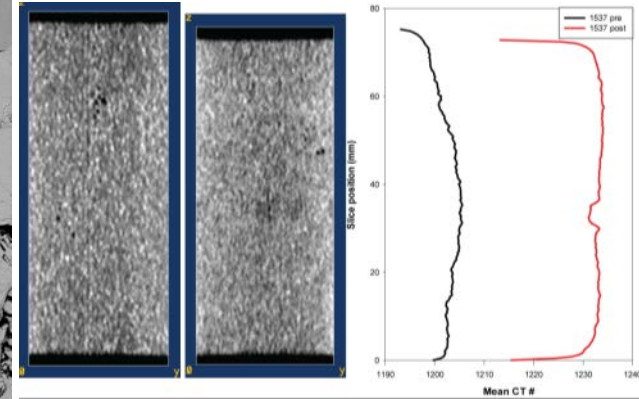


Porosity: 18.6 % // Gas k: 0.17D

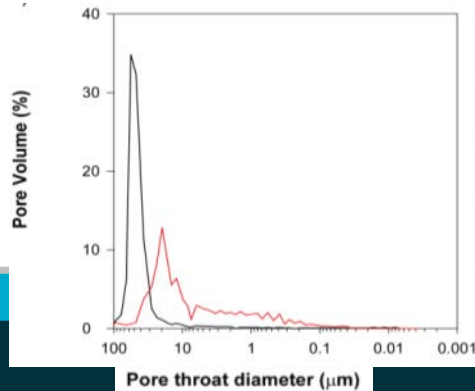


Before

After

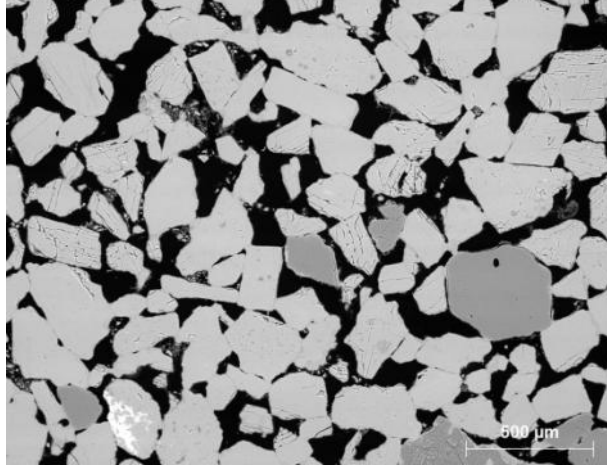


Pervasive grain crushing and pore collapse

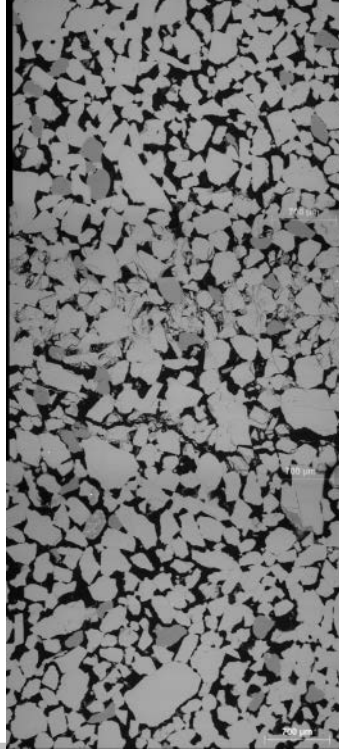


Microstructure: triaxial test

Porosity: 26.7 % // Gas k: 8D

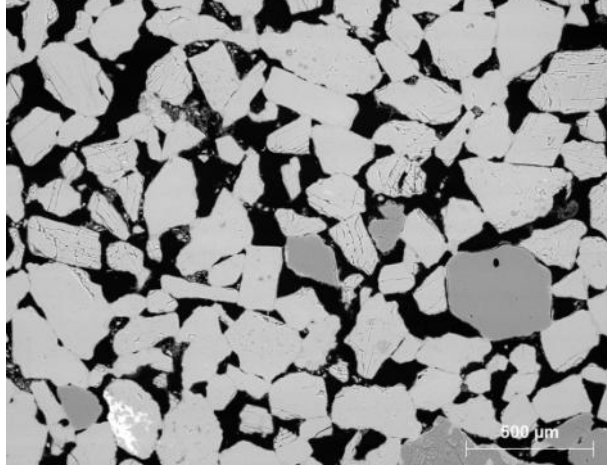


Porosity: 25 % // Gas k: 2.3D

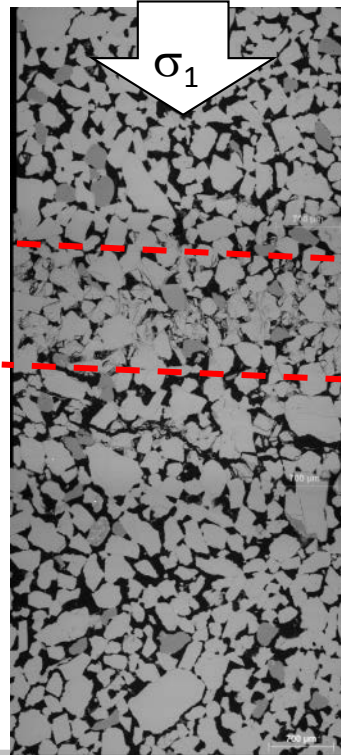


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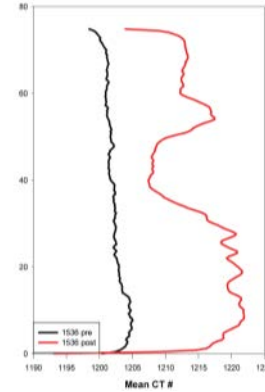
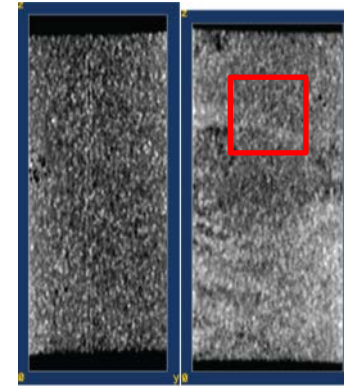


Porosity: 25 % // Gas k: 2.3D

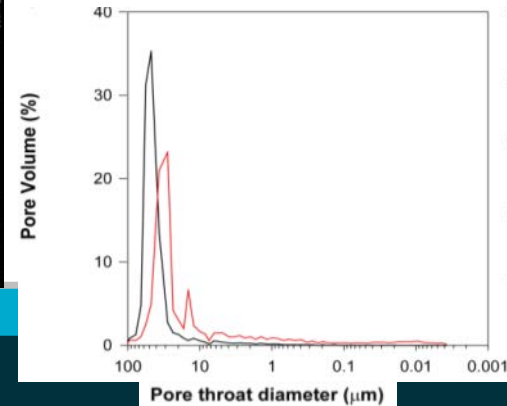


Before

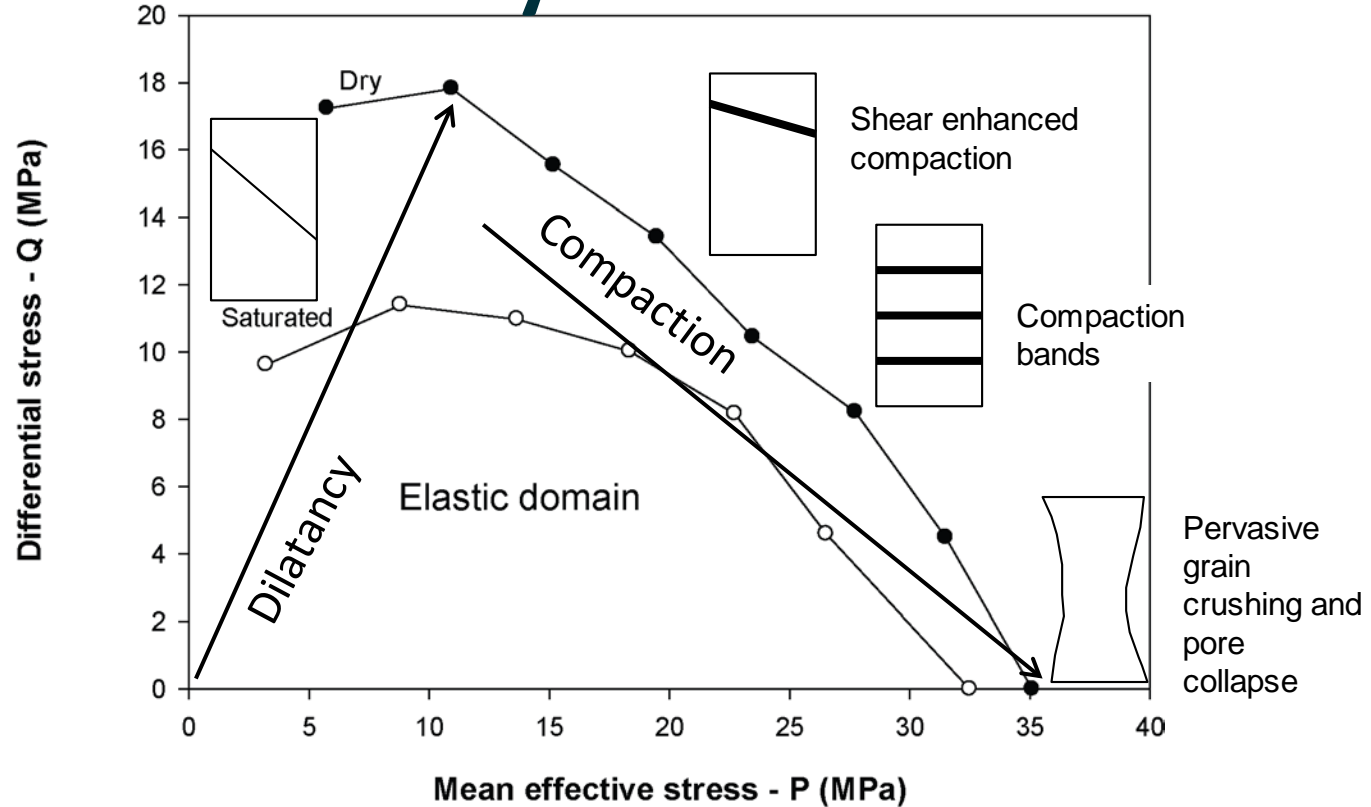
After



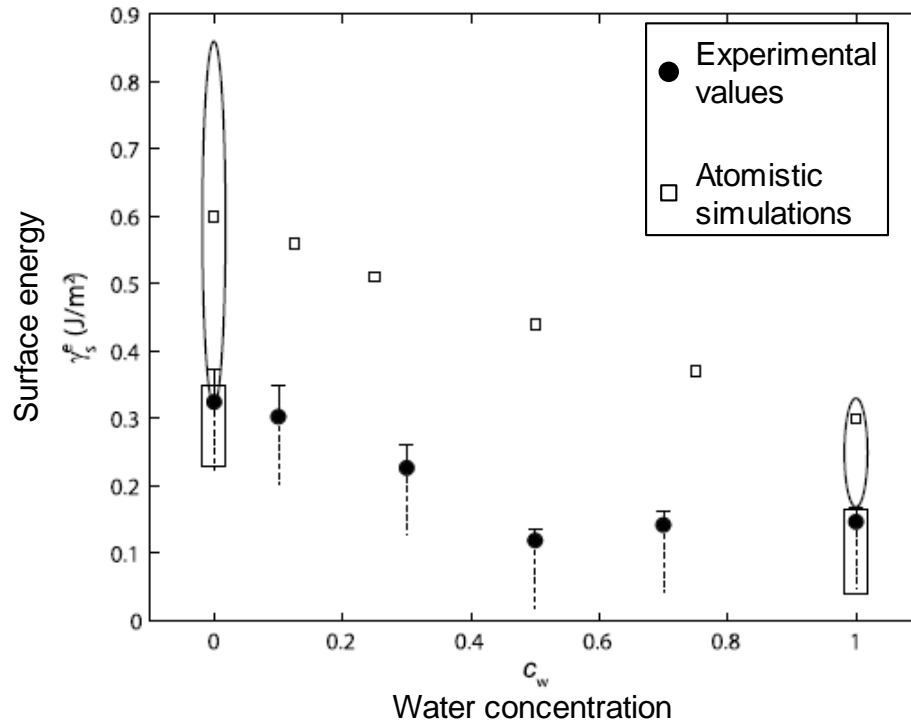
Localised compaction bands



Mechanical summary



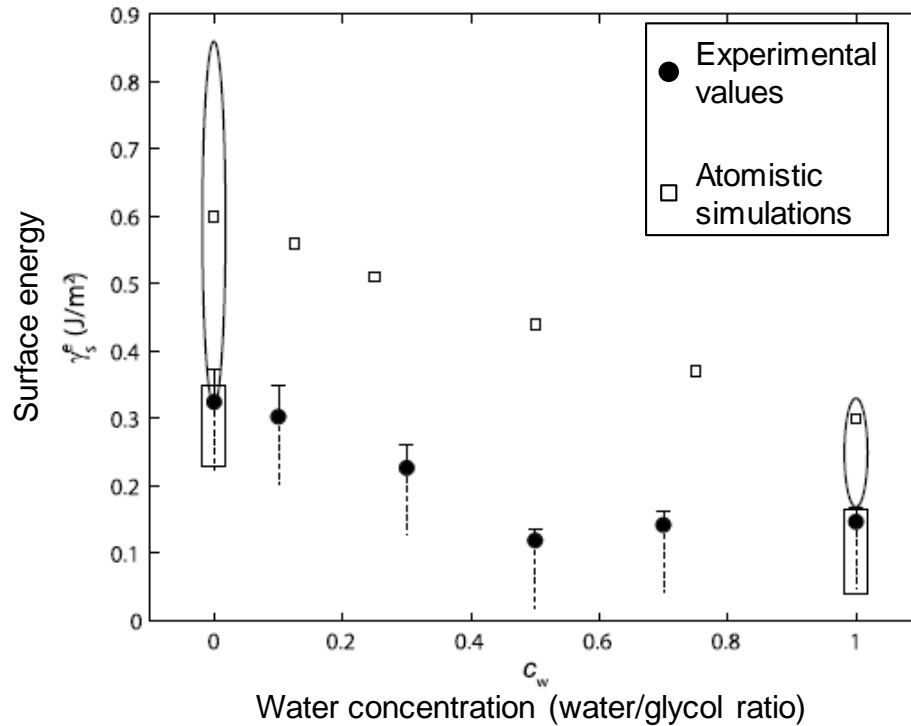
Weakening



$$\lambda = \left(\frac{\gamma'}{\gamma} \right) = \left(\frac{P_{\text{wet}}^*}{P_{\text{dry}}^*} \right)^{2/3}$$

Røyne et al. (2011)

Weakening



Røyne et al. (2011)

$$\lambda = \left(\frac{\gamma'}{\gamma} \right) = \left(\frac{P_{\text{wet}}^*}{P_{\text{dry}}^*} \right)^{2/3}$$

$\lambda = 0.8$ Majella limestone ($\phi = 30\%$)

$\lambda = 0.84$ Saint Maxim Limestone ($\phi = 36\%$)

$\lambda = 0.89$ CIPS ($\phi = 26\%$)

Baud et al., 2009

Summary and conclusions

Synthetic porous carbonate rock fabricated



Consistent microstructure and petrophysical properties

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Synthetic porous carbonate rock fabricated



Consistent microstructure and petrophysical properties

Yield cap established under dry and saturated conditions



In any stress configuration dry rock is stronger than saturated one

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Evolution is sensitive to stress and stress path

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Ultrasonic velocities measured as a function of stress and saturation



Ultrasonic velocities track the onset of pervasive cataclasis

Dynamic bulk modulus smaller than theoretical prediction

Thanks

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