



Digital laboratory and digital rock for EOR

Enhanced Oil Recovery Laboratory – LRAP

VII November Conference 2019

Nov. 13th, 2019

Prof. Paulo Couto – Petroleum Engineering/COPPE/UFRJ

LRAP Timeline

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- » Two projects funded by BG Group were approved by ANP in 2013:
 - Developing Experimental Enhanced Oil Recovery Capabilities in Brazil (Infrastructure)
 - Understanding Brazilian Pre-Salt Reservoirs: A BG Fellowship Training Programme (HR training)
- » Cooperation with Heriot-Watt University, UK
 - Expertise developed in the past 20 years of R&D
- » Shell acquires BG Group in 2016
- » One RD&I project funded by Petrobras at the end of 2016: SCAL
- » Two RD&I projects funded by Shell were approved by ANP in 2017:
 - WAGEX & CFC
- » NMR and μ CT commissioned November 2019

- » COPPE: Instituto Alberto Luiz Coimbra de Pós-Graduação e Pesquisa de Engenharia (Coordination of the Post-graduate Programmes in Engineering);
- » Created in 1963, graduates around 500 M.Sc. And Ph.D. per year;
- » 13 diferente Engineering post-graduate programmes;

OVER THE COURSE OF THE LAST FIVE DECADES IT HAS BECOME THE MOST IMPORTANT CENTER FOR ENGINEERING RESEARCH AND EDUCATION IN LATIN AMERICA.

LRAP/COPPE and NIDF

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NIDF

Núcleo Interdisciplinar
de Dinâmica dos Fluidos



RD&I from reservoir to primary separation unit (UPSTREAM)

To develop high level RD&I projects, carbonate focused, by means of human resources capacity building and utilization of high technology laboratory equipment, aiming to increase the recovery factor of Brazilian oil fields.

To be world-leading and reference in EOR techniques applied to the Brazilian pre-salt scenario, attracting new investments aiming the development of Brazilian O&G sector, focusing laboratory personnel and operational safety.

This vision is aligned with the Brazilian Petroleum Agency strategic plan.

Our Values

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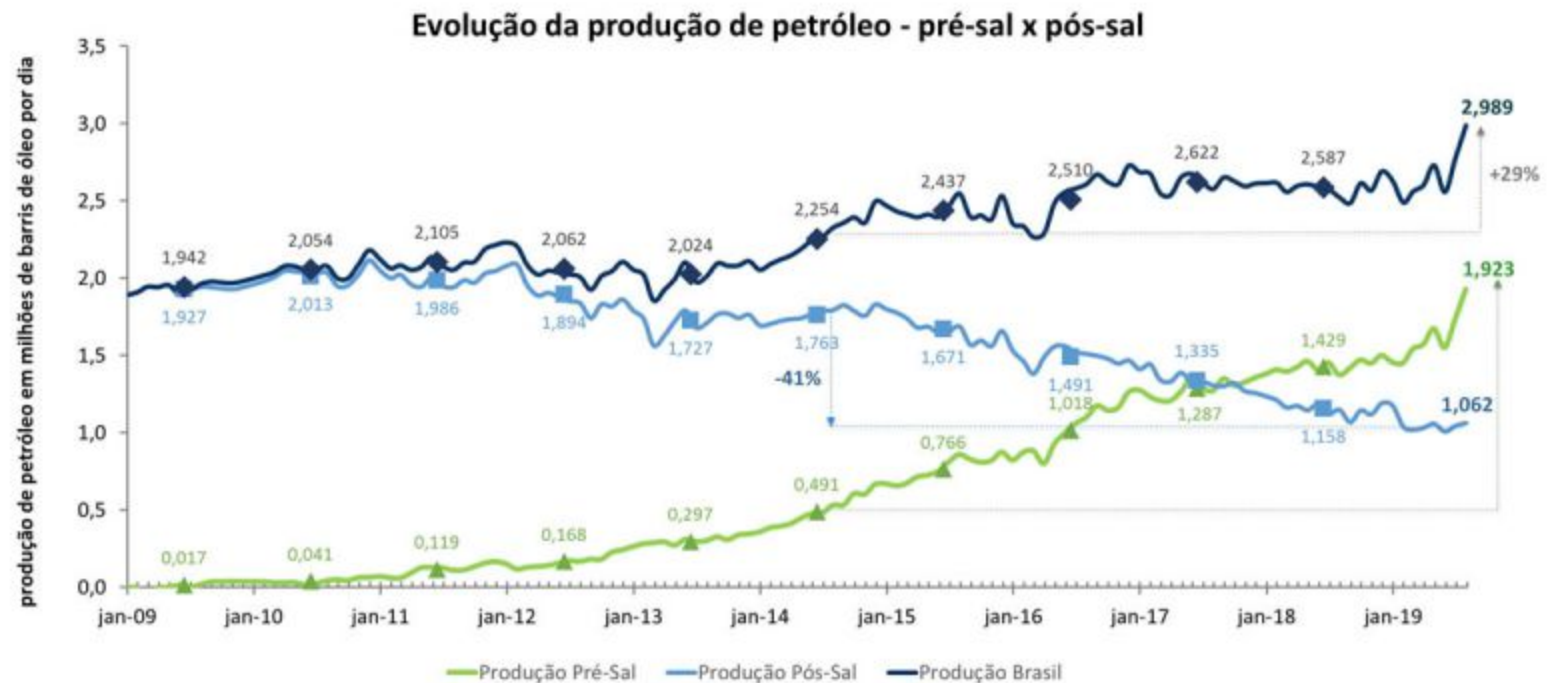
- Ethic
- Safety
- Innovation
- Quality
- Trustfulness
- Sustainability
- Cooperation
- Continuous professional growth



LRAP Impact in the Oil & Gas Sector

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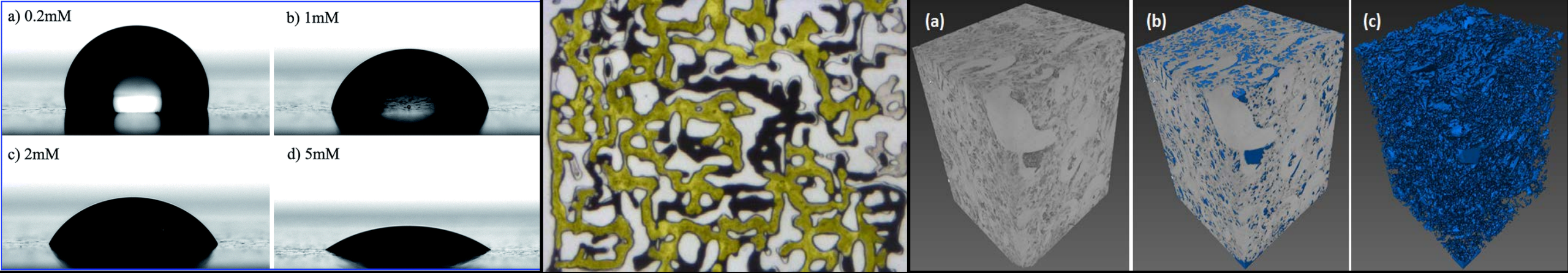
- Low recovery factor in Brazil: 21%
- Post-salt field in decline phase
- Pre-salt represents a significant part of Brazilian portfolio
- Increase in 1% on RF:
 - ▣ USD 18 Billion in new investments
 - ▣ USD 11 Billion in royalties
 - ▣ 2,2 Billion boe increase in reserves



Objectives

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- To **develop an EOR World-leading reference centre**, fostering Brazilian industry and supporting the RF growth;
- To **train Brazilian researcher and scientists** on EOR techniques for carbonate rocks;
- To **assure a QHSE focused research environment** following the industry best practices;
- To **develop high-end RD&I projects** in **collaboration** with the industry, research institutions and scientists world wide, investigating solutions and challenges for the next decades;
- To **deliver high-end experimental results** on EOR techniques, at the worldwide forefront.



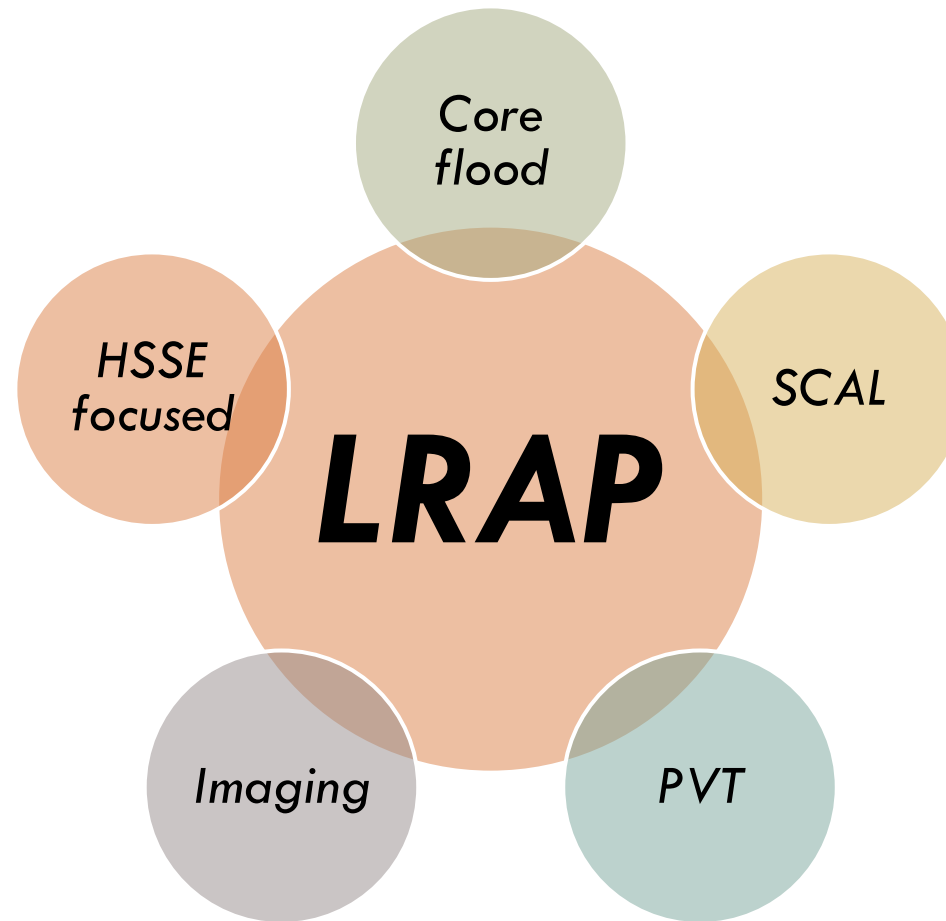
» LRAP Research: Multi-scale, pore-to-core-to-field understanding

- Conduct full field EOR reservoir simulations calibrated to core scale data and phenomenon calibrated to pore scale processes and physics
 - **Field:** Full field numerical, analytical and hybrid simulation (*comp.*)
 - **Core:** core plug theoretical modelling (*comp.*) + corefloods (*expt.*)
 - **Pore:** pore scale theoretical modelling (*comp.*) + micromodel (*expt.*)



LRAP unique equipment and integrated operations

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State-of-the-Art

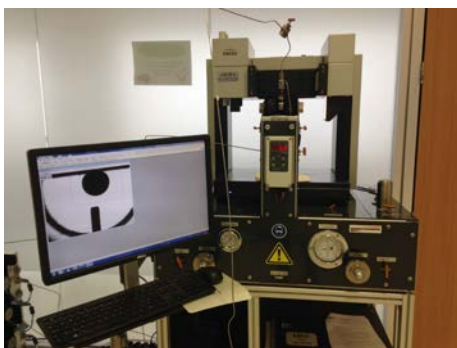
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Small coreflood rig – rock samples with 1" to 2" diameter and up to 20cm length.



Medius coreflood rig – rock samples with 1" to 2" diameter and up to 30cm length.



Drop shape analyser – Wettability studies



Large core flood rig equipped with X-Ray scanner. Designed for WAG experiments – rock samples with 1" to 2" diameter and up to 3 ft length.

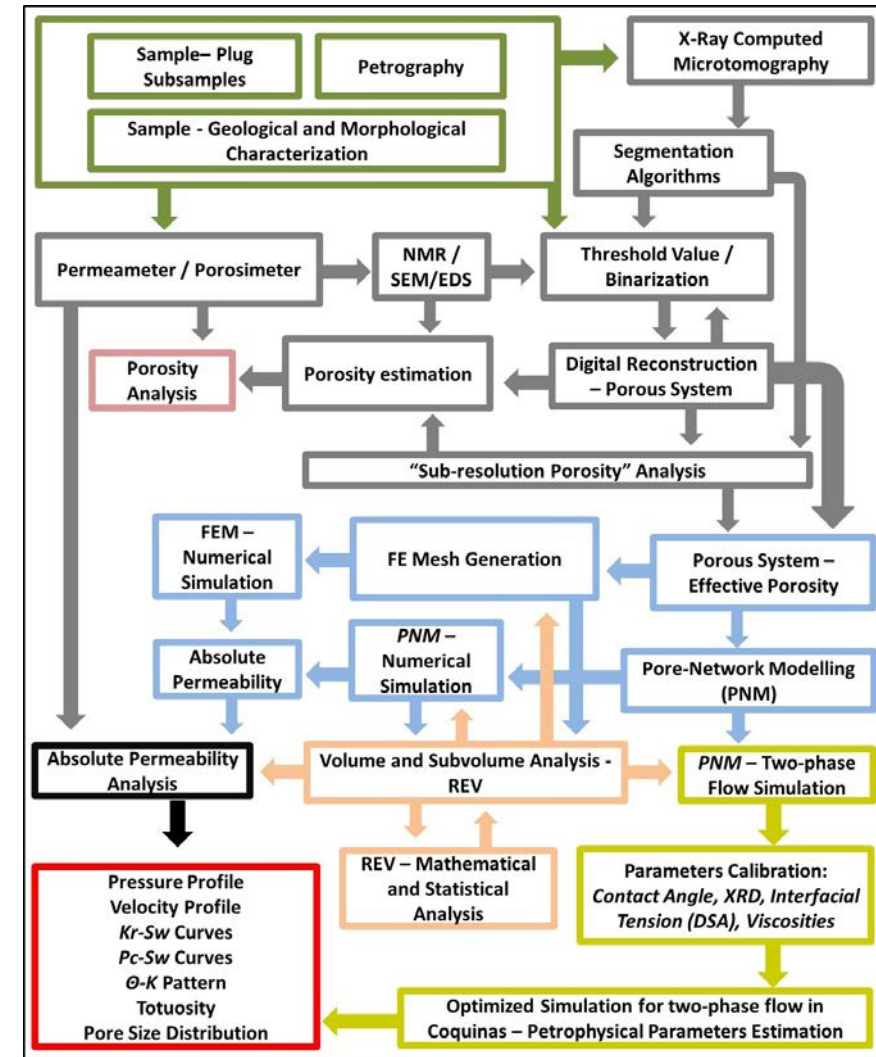
Fluid recombination cell



Evaluation of a Proposed Workflow for Digital Petrophysics Involving Experimental Data and 3D Digital Models Using PNM and FEM Numerical Simulations

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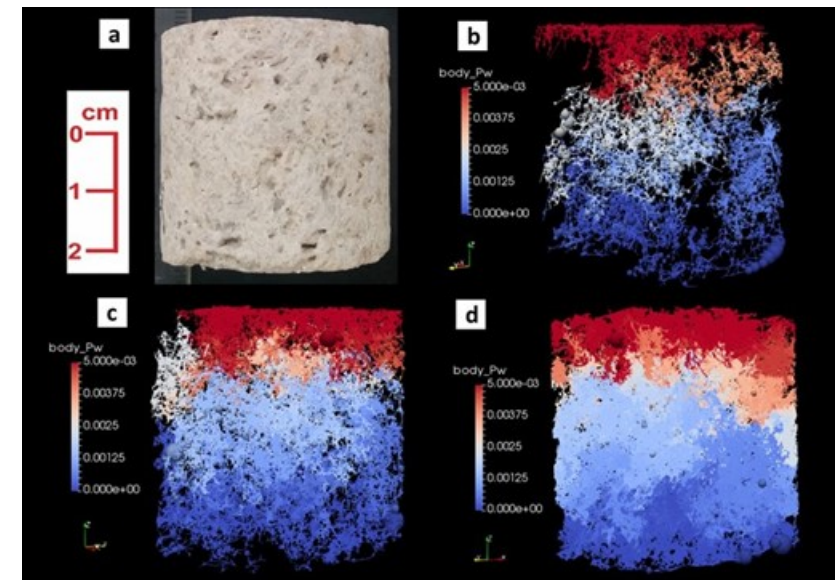
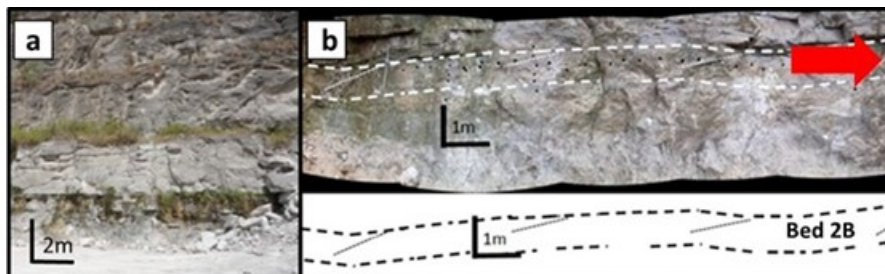
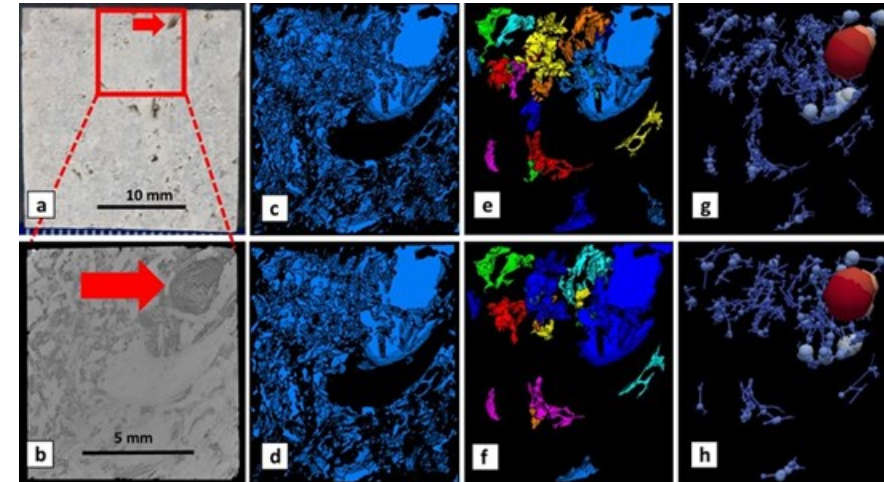
- Objective: Develop a well-defined workflow involving Basic and digital petrophysics for Brazilian pre-salt reservoir rocks evaluation, using experimental data, geological information, 3D modelling, and numerical simulation;
- Use of different techniques: permeameter/porosimeter, SEM-EDS and XRD measurements, μ CT with different pixel sizes, centrifuge method for two-phase fluid flow, and numerical simulation;
- Colaboration with Universiteit Utrecht.



Modelling of Coquina Pore Networks: A Computational and Experimental Pore-Scale Study

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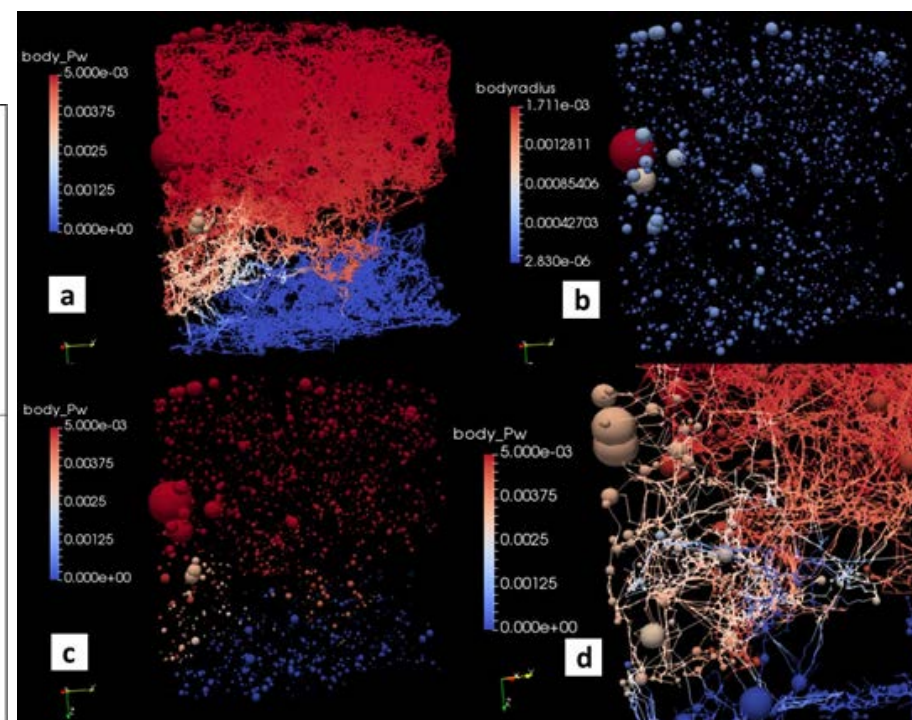
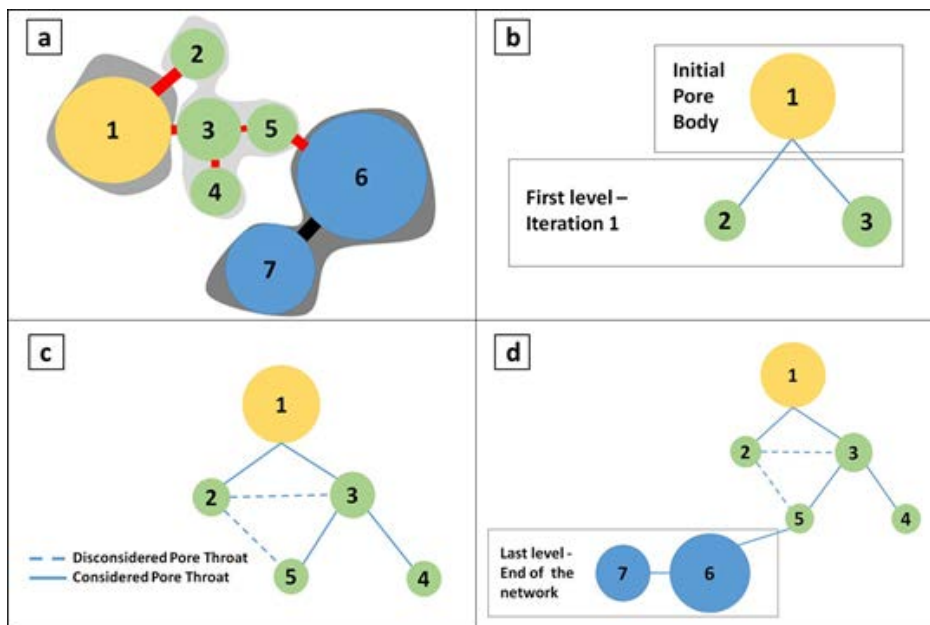
- Journal of Hydrology and Hydromechanics
- Objective: Develop a pore structure to represent a real coquina sample that is a geologically analogue to a Brazilian pre-salt reservoir rock;
- Use of different techniques: permeameter/porosimeter, SEM-EDS and XRD measurements, μ CT with different pixel sizes, and numerical simulation;
- The results gave us the carbonate rock composition and the pore systems from different scales, allowing us to reconstruct and model the porosity and absolute permeability using 3D digital reconstruction and numerical simulation based on Pore Network Models (PNM);
- Colaboration with Universiteit Utrecht.



Sub-resolution porosity Analysis using PNM and NMR

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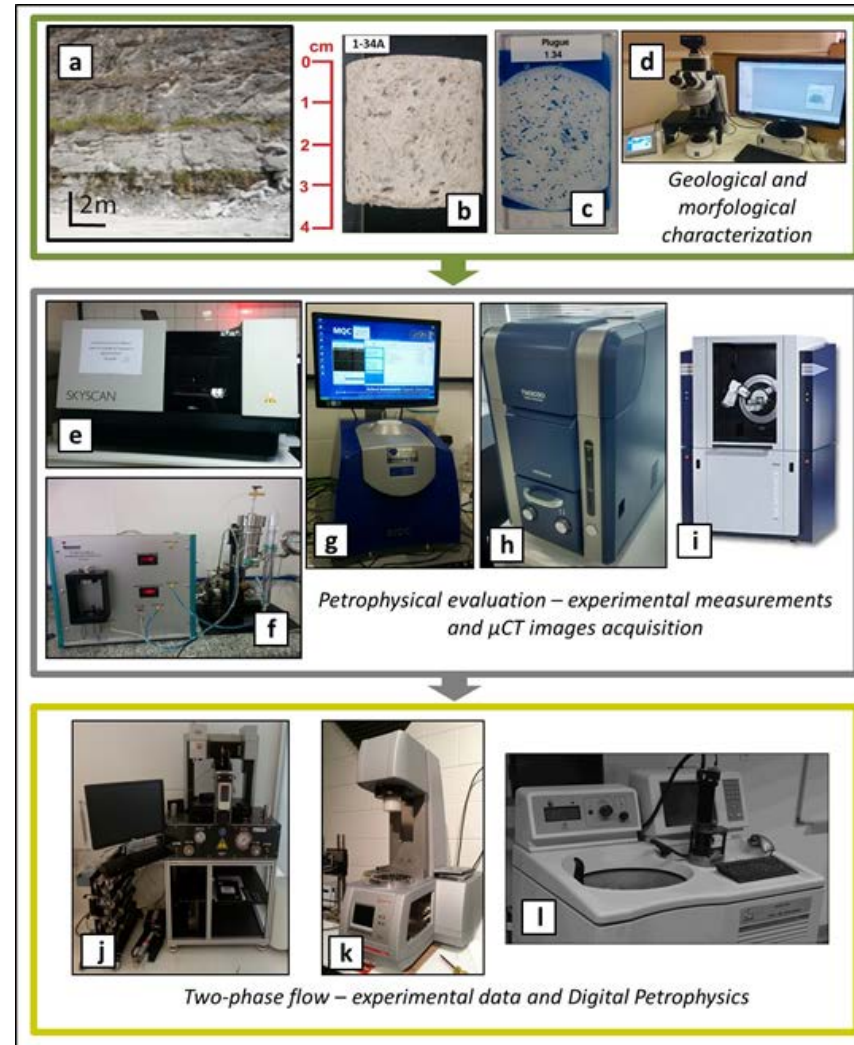
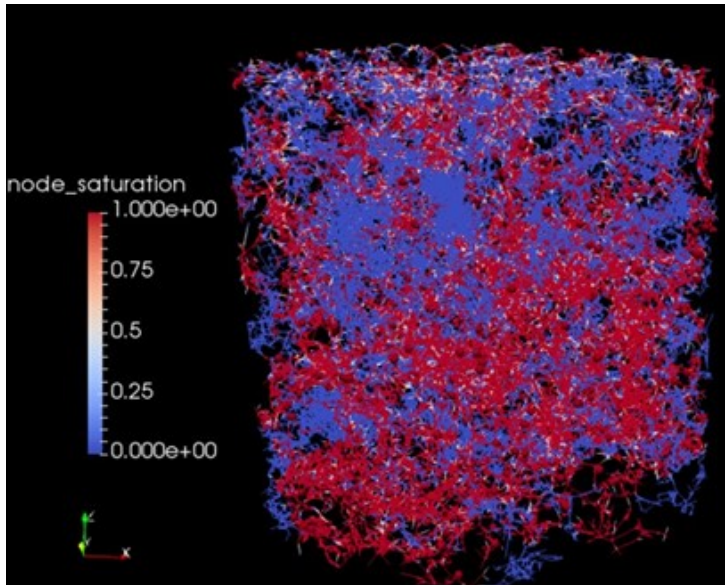
- Objective: Develop a code and test fluid flow numerical simulation in a heterogeneous carbonate rock sample with low absolute permeability value using NMR data and PNM;
- Use of different techniques: μ CT with different pixel sizes, NMR data to evaluate pore size distribution, and numerical simulation;
- Colaboration with Universiteit Utrecht.



Primary drainage – An experimental and computational study with Brazilian pre-salt analogue carbonate rocks

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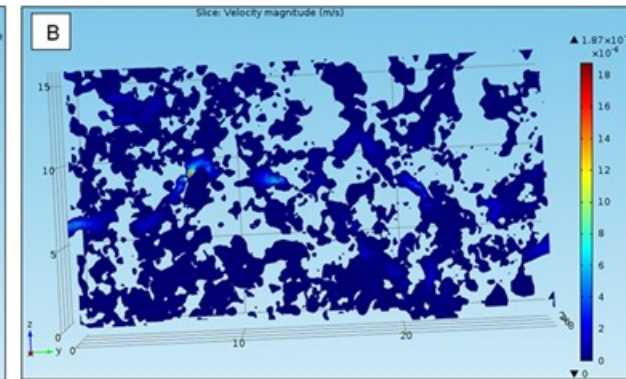
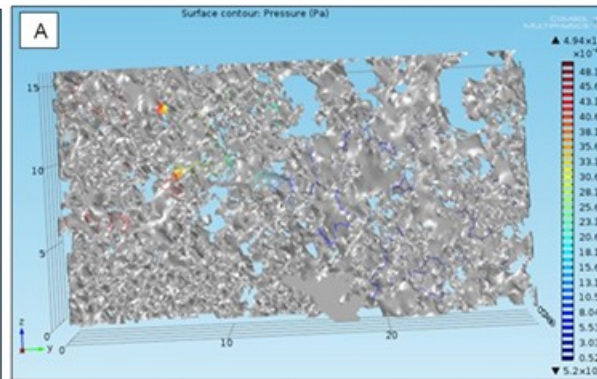
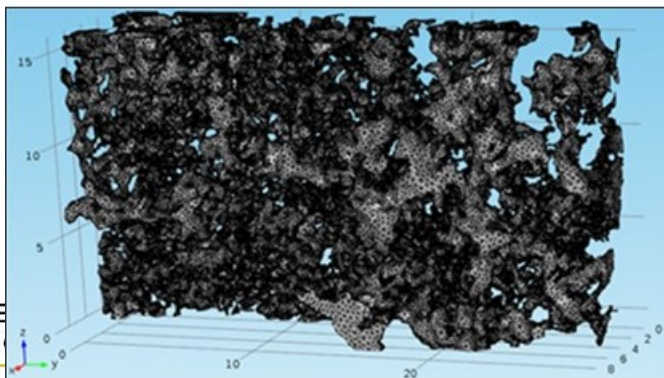
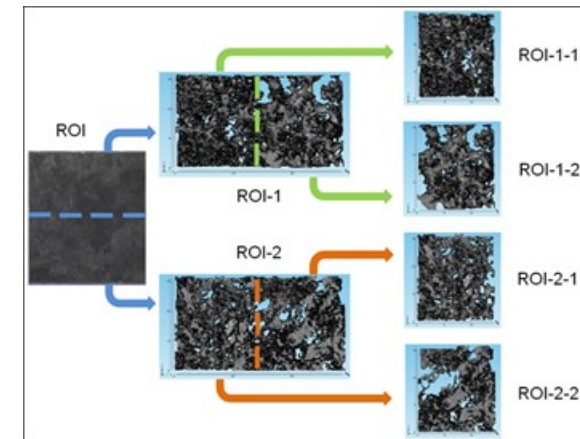
- Objective: Evaluate primary drainage simulations based on PNM and comparison with measurements from centrifuge method;
- We generated calibrated Pore Network Models (PNM) from Brazilian pre-salt analogue carbonate rocks μ CT images, using experimental techniques such as NMR, DRX, SEM/EDS and DSA to evaluate the pore and rock structures, rock-fluid and fluid-fluid interactions for two-phase flow modeling;
- Colaboration with Universiteit Utrecht.



Representative elementary volume in a region of interest of a heterogeneous carbonate rock using X-ray computed microtomography and numerical simulation

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- Brazilian Journal of Geophysics
(DOI: <http://dx.doi.org/10.22564/rbgf.v36i4.1975>)
- Objective: This study analyzes the representative elementary volume (REV) in a region of interest (ROI) of a highly heterogeneous carbonate rock sample;
- Porosity and absolute permeability are estimated in different subvolumes of the sample based on digital petrophysics;
- All necessary steps for reconstruction and segmentation of the complex pore system of the sample, as well as numerical simulations of fluid flow, are presented and discussed;
- The results are promising for reservoir evaluation because the workflow can be applied for any type of highly heterogeneous carbonate reservoir rocks.



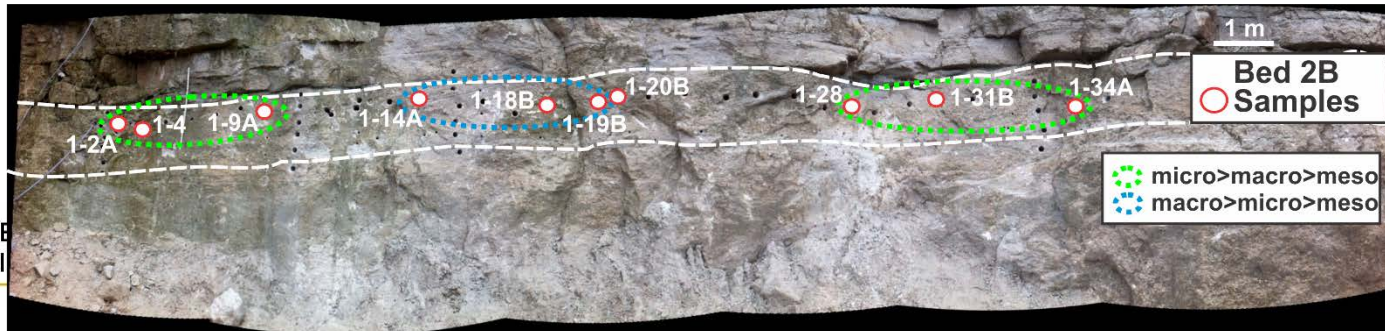
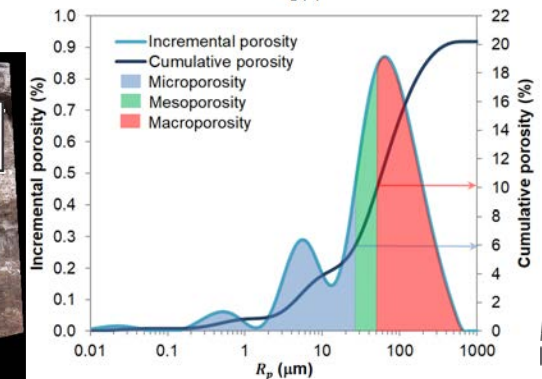
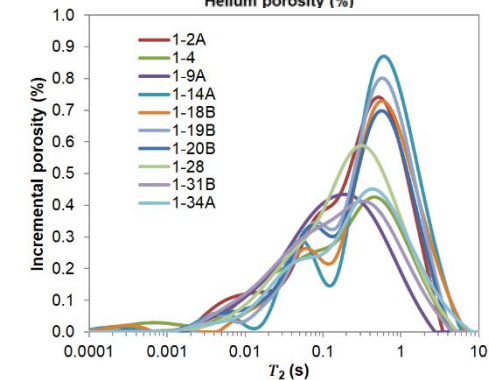
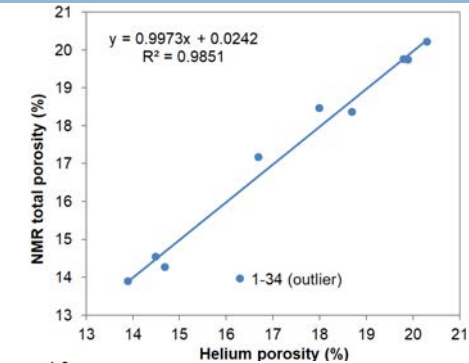
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DO RIO DE JANEIRO

RAP
COPPE/UFRJ

NMR to characterize the pore system of coquinas from Morro do Chaves Formation

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- Brazilian Journal of Geophysics
(DOI: <http://dx.doi.org/10.22564/rbgf.v36i3.1960>)
- Objective: characterize the porous system of coquinas in terms of total porosity and pore size distribution using NMR;
- Coquinas were classified and ranked according to their percentage of macro, meso and micro porosity using Lonoy (2006) pore size classification;
- NMR proved to be an efficient for total porosity measurements of coquinas from the Morro do Chaves Fm.;
- The coquinas contain macro, meso and micro pores and the rocks do not have a predominant pattern of pore size;
- There is a lateral variation in poroperm properties along the studied layer;
- The study provides some clues on lateral porosity and pore size variation in any reservoir for which this unit is an analogue.



Characterization of Carbonate Rocks

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Our studies using carbonate rock analogues of the Brazilian Pre-Salt (coquinas), taken from the Morro do Chaves Formation, involved:

- quantification and parameterization of selected properties of the coquinas and their pore systems;
- application of various techniques and their integration (i.e., μ CT, NMR, petrography, DIA and routine petrophysics);
- to determine and visualize the anisotropy, heterogeneity and connectivity of the pore systems of these rocks;
- to provide information for analysis of the potential of Pre-Salt oil reservoirs in Brazil.

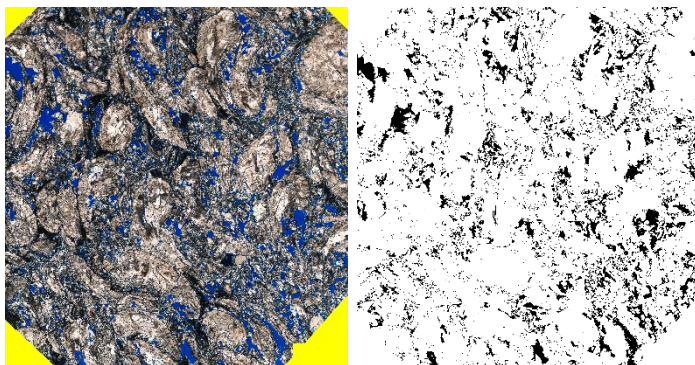
Rock formation where the samples were taken (Morro do Chaves Formation, Brazil)
(Modified from: Hoerlle *et al.*, 2018)



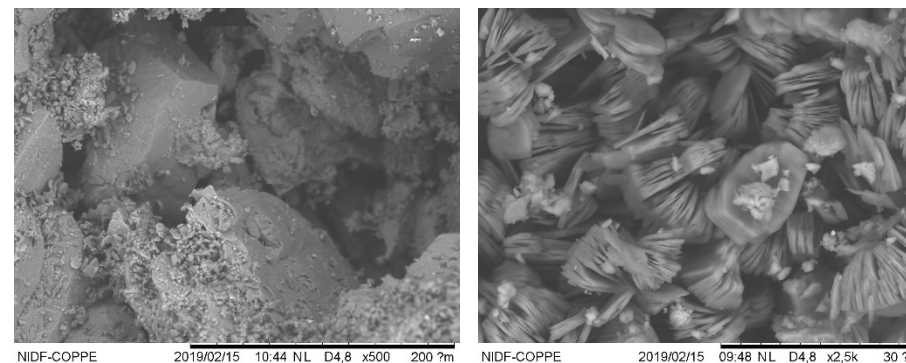
Integration of various techniques

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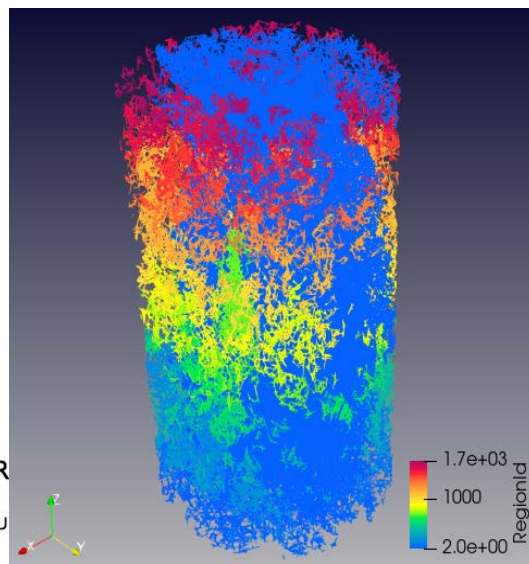
DIA – Digital Image Analysis



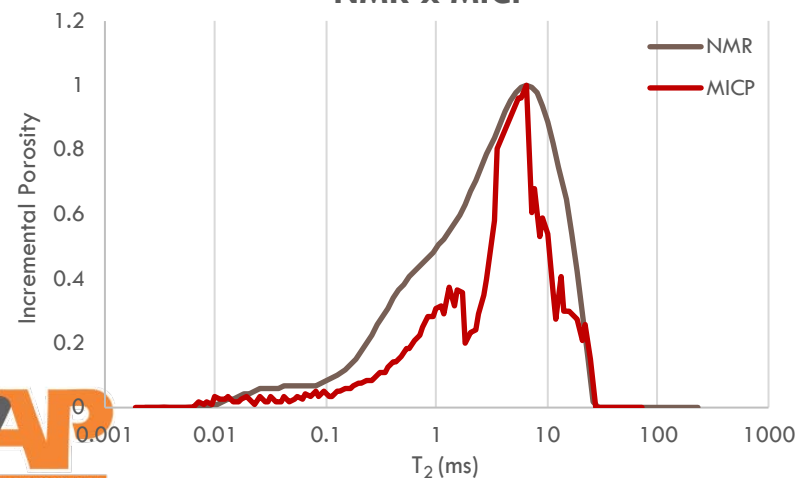
SEM



MicroCT



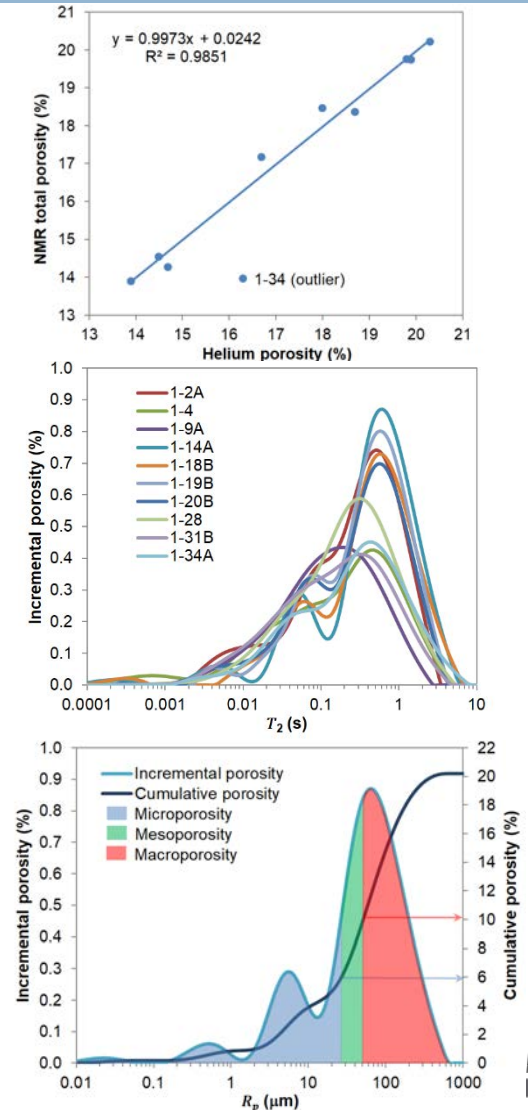
NMR x MICP



NMR to characterize the pore system of coquinas from Morro do Chaves Formation

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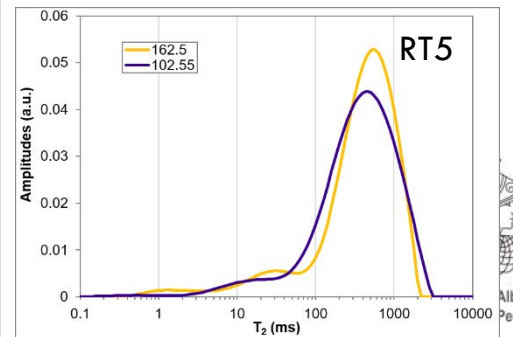
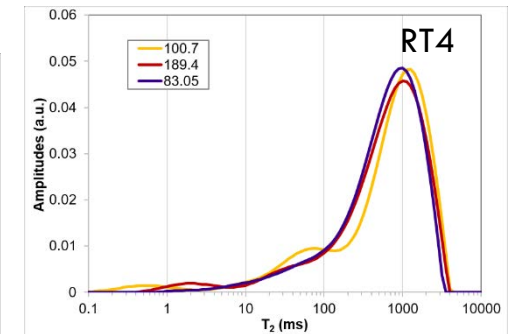
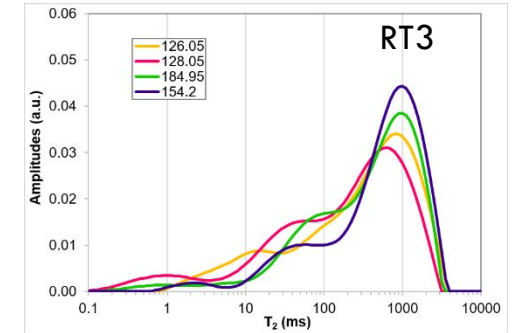
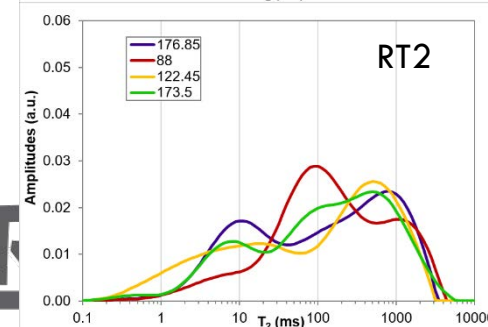
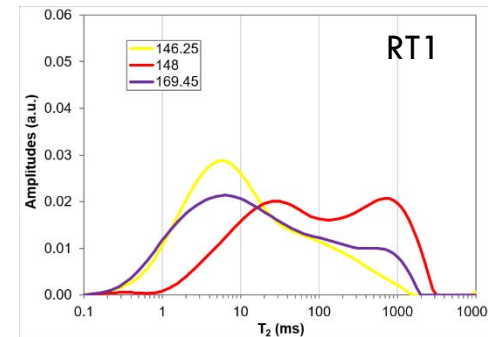
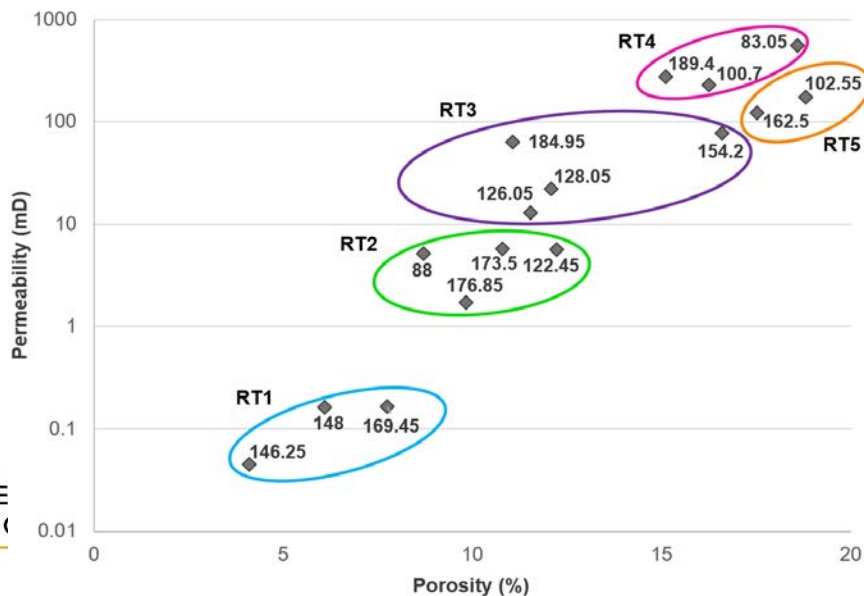
- Brazilian Journal of Geophysics
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Rock Typing of Carbonate Formations and their Influence on Permeability Predictions based on NMR

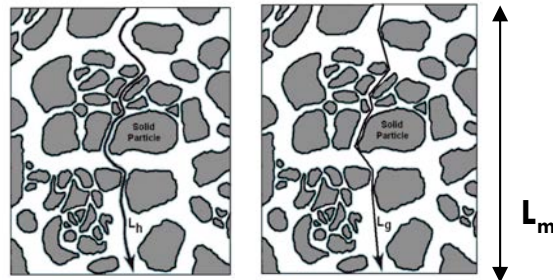
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- 16th International Congress of the Brazilian Geophysical Society;
- Rock types are based on clusters developed from permeability bands, with their similarities demonstrated using transverse relaxation times (T_2) which reflect the distributions of the pore size families;
- Since the samples showed large heterogeneities, the recognition of similarities between them became complex, being insufficient for their separation into different groups based on geological descriptions;
- Based on the assumption that logarithmic mean relaxation times are associated with mean pore size, we observed that the T_{2LM} increase is directly related to increasing permeability.



Impact of tortuous path and throat constrictions on permeability. Synthetic Rocks

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Objective: To investigate the impact of tortuosity path and constrictions in the pore throats on permeability calculations using PoreFlow PNM simulations. Results showed that the differences between geometric and hydraulic path tortuosity based permeabilities were relatively small. On the other hand, constrictions in the throats were found to have much more impact on the permeability calculations.

Synthetic rocks, based on coquinas skeletons, were constructed using a module from PoreFlow. The data needed to generate a PNM were: pore radius distribution, throat radius distribution, throat length distribution and mean coordination number. The objective of this research is to develop ways to upscale from small plug to core, using μ CT images and PNM modelling.

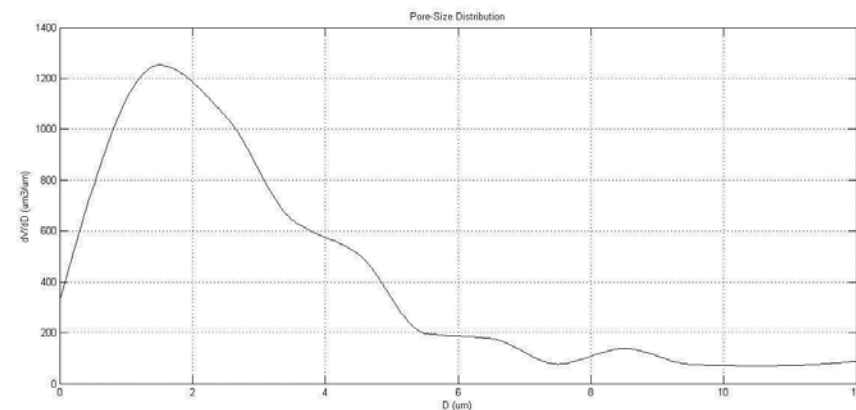
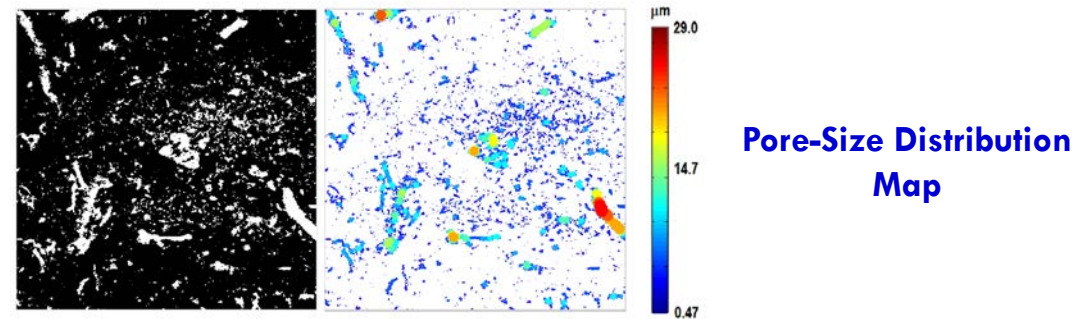
Example of a synthetic rock sample using PoreFlow

Rock sample	3D Image	Original porous network	Digital porous network
Coquina 1_34A			
	Voxel (μm): 18.17 Aver. pore radius: 86 μm Aver. throat radius: 84 μm Aver. throat length: 315 μm Volume (mm^3): 27.944	n ^o nodes: 75,609 n ^o throats: 97,501 Volume (mm^3): 27.944 porosity: 6% conectivity: 2.4 perm (mD): 582.1	n ^o nodes: 74,659 n ^o throats: 90,972 Volume (mm^3): 27.756 porosity: 5.5% conectivity: 2.3 perm (mD): 534.0

Extraction of Pore-Size Distribution (PSD) from Digital Reconstruction of Porous Media and Analysis of REV PSDs

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- The objective of this work is to create a software to estimate the PSD of porous media samples by analysing their μ CT images and then evaluate the PSD of REV samples.
- The software is in development. The pores in the images can be identified and measured;
- Currently improving results for images having resolutions that are not the same in the three directions.
- Comparison of the results with NMR pore size distributions

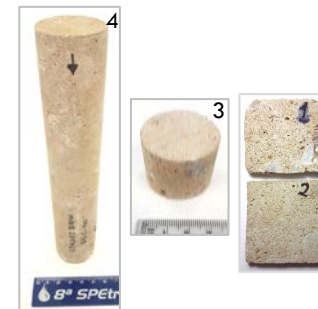


REV and Upscaling Studies of Carbonate Rock Petrophysical Properties Using μ CT Images and NMR Experiments

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- » NMR is currently been used at both the core sample scale and wellbore by logging tools
 - » μ CT images allow digital petrophysical studies at the pore scale
-
- » The objective of this work is to evaluate REV's for permeability and build synthetic PNMs using correlations between properties found in PNMs extracted from μ CT images (smaller samples) and NMR properties (larger samples)

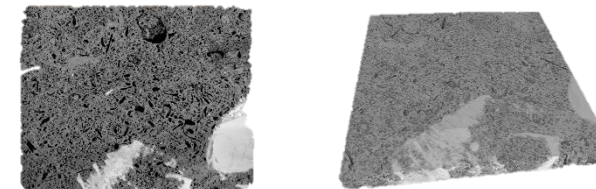
1 Routine Core Analysis



Sample	Porosity (%)	Permeability (md)
EDB-3	31.4	314.4
EDB-4	33.62	408.00

2 Micro-CT images acquisition

- Resolution: 12, 17 and 25 μ m (slabs, small plug, large plug)
- Use of coquinas images in 6, 10, 18 and 25 μ m (slab and plug)
- Acquiring more images with higher resolution than previous



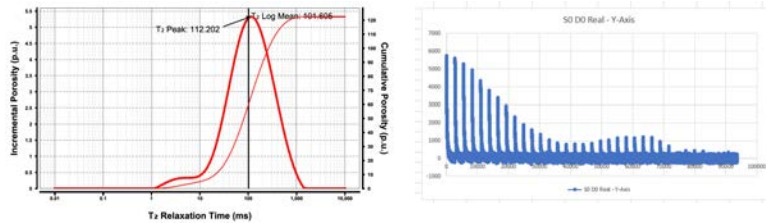
REV and Upscaling Investigation of Carbonate Rocks Petrophysical Properties Through Micro-CT Images And NMR Experiments

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NMR T_2 and DT_2

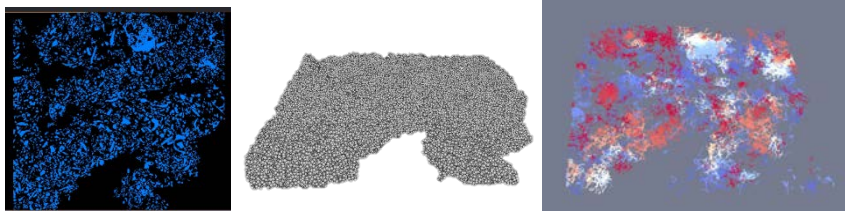
- 2 T_2 and 2 DT_2 experiments performed
- To be acquired new DT_2 due to noise in signal



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PNM: Skeletons (Avizo)

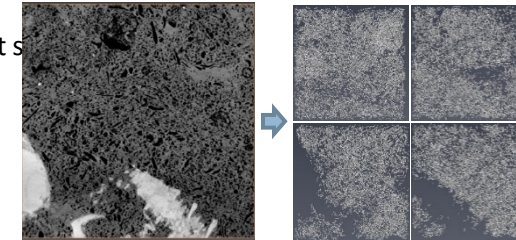
PNM and Fluid flow for permeability: Poreflow



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REV analysis

- Pore-throat radius: arithmetic, geometric and harmonic
- Threshold
- Inlet/outlet s



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Synthetic PNM generation

- Reference from Raoof and Hassanizadeh, A New Method for Generating Pore-Network Models of Porous Media (2013).

Verification

- PNM results against laboratory measurements

μ CT – Tescan CoreTOM

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Equipment was ordered to XRE/TESCAN. The CoreTOM is ideal for imaging reservoir samples and combining information from pore scale to core. The acquired version is with 4D studies (ability to perform μ CT during experiments)



Characteristics:

- a) 3D X-Ray imaging from large reservoir cores to microplugs (multi resolution image),
- b) Fast and automated acquisition workflow,
- c) Samples up to 1.5 m (\sim 5 ft) in height,
- d) Spatial resolution of 3 μ m,
- e) Superior signal to noise at short acquisition time,
- f) Intuitive volume of interest selection,
- g) Dynamic *in situ* imaging



NMR: Oxford Geospec 12+

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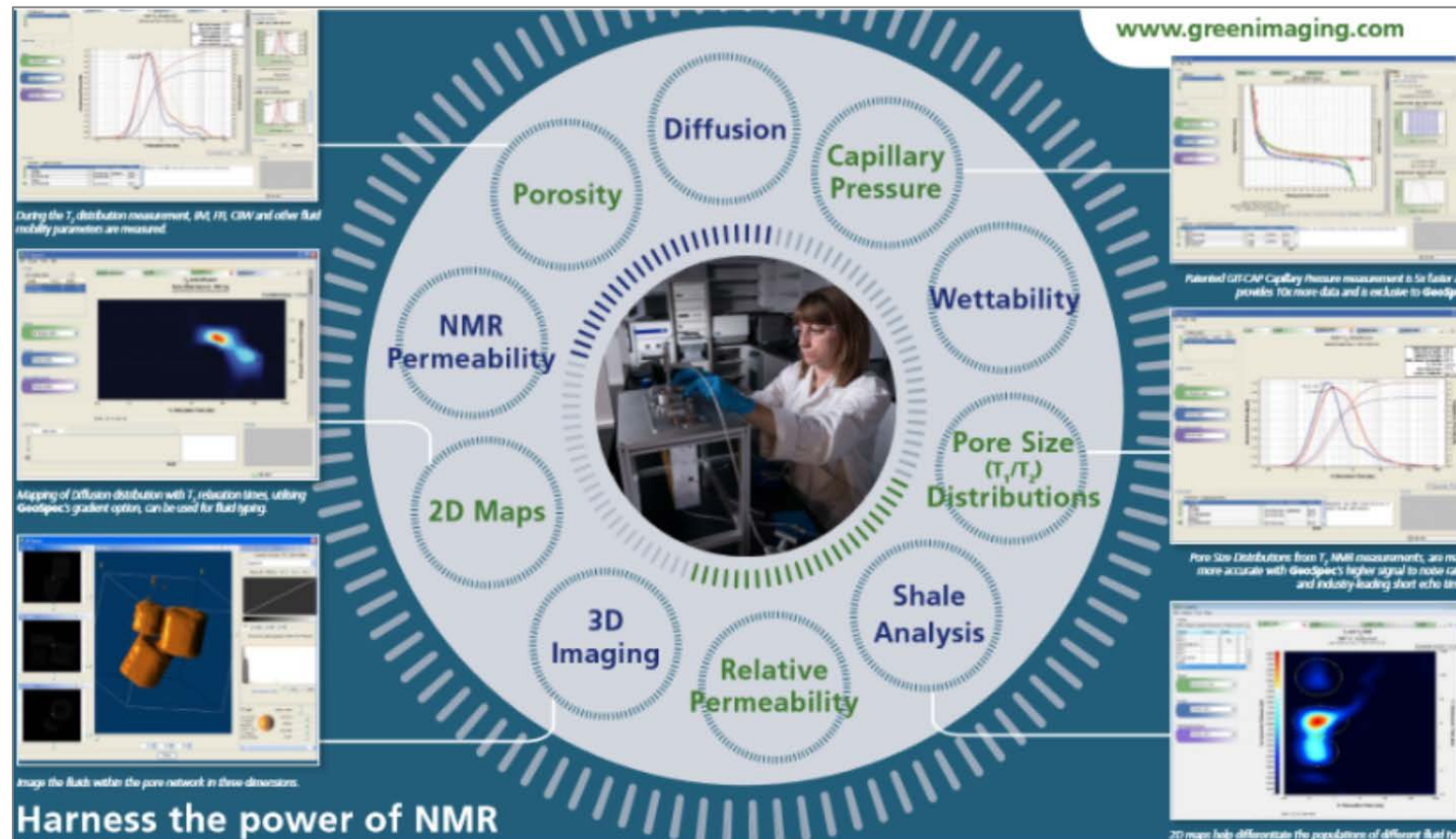
- GeoSpec 12+ is a low-field nuclear magnetic resonance (NMR) benchtop rock analyser designed by Oxford Instruments (UK) in partnership with Green Imaging Technology (Canada).



NMR: Oxford Geospec 12+

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- *Main applications to be investigated at LRAP.*

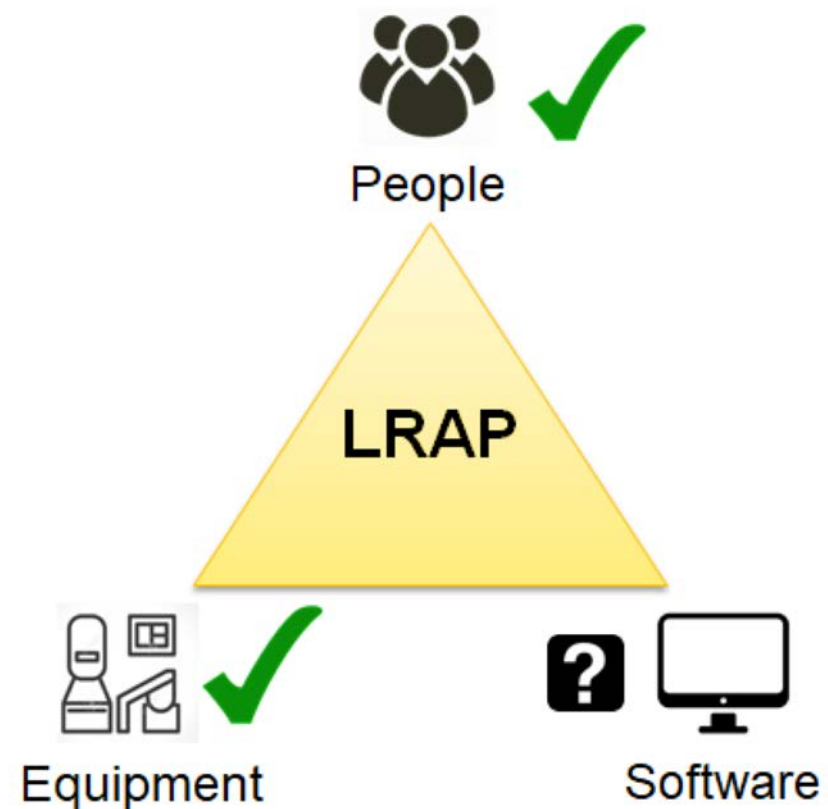


Rock & Fluid Data Analysis Platform: RF-DAP

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□ **Needs & Concerns**

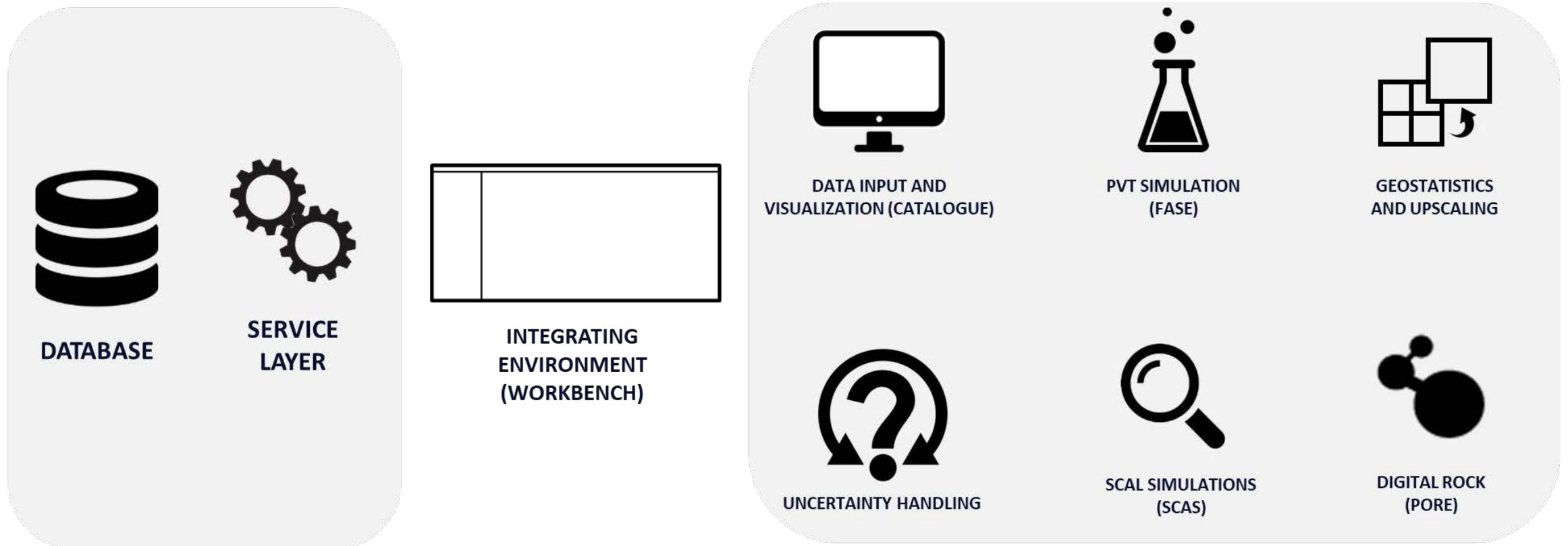
- ▣ High tech equipment (few in the world)
- ▣ People (researchers) are being trained in UFRJ & Heriot Watt
- ▣ Needs a software to manage all the knowledge and data that will be created



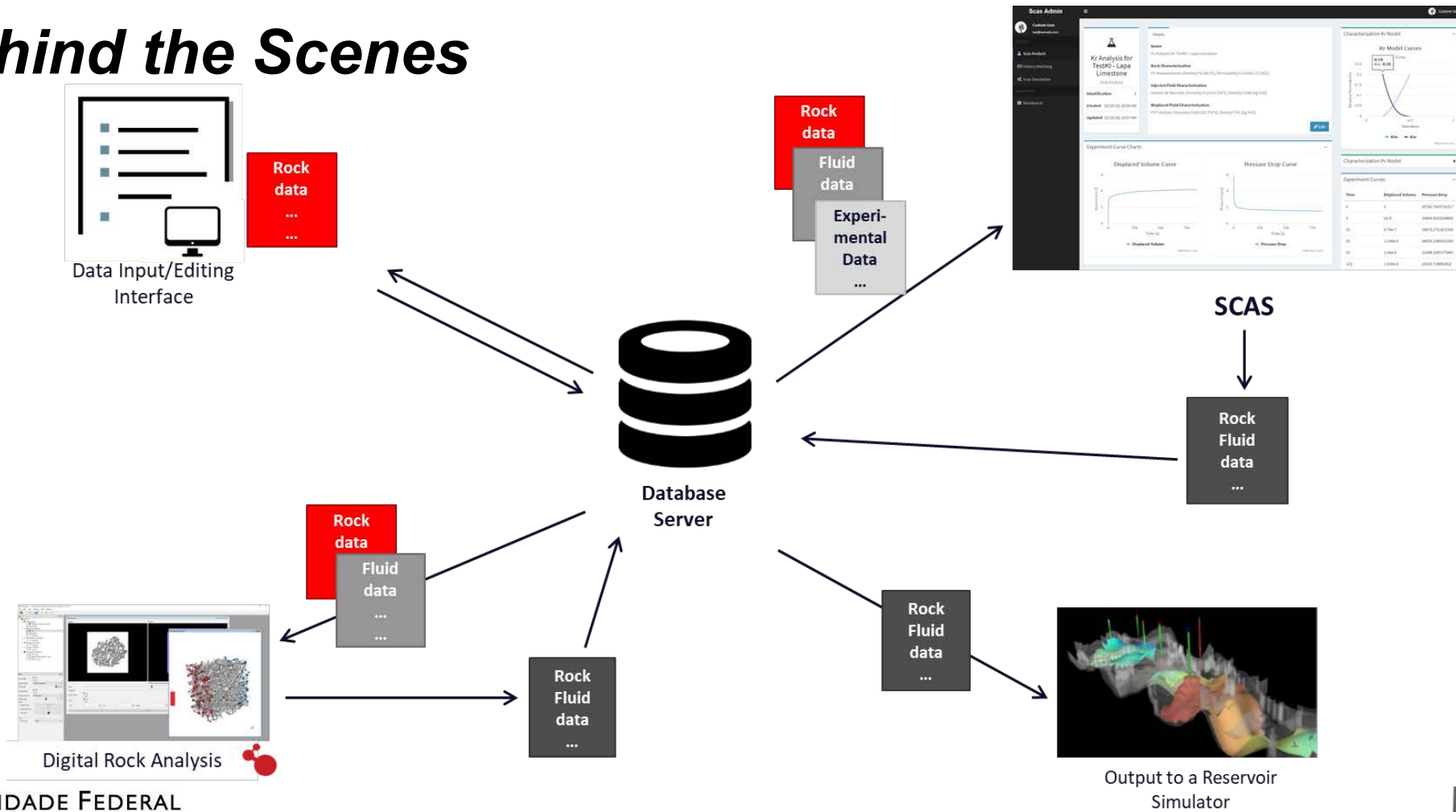
□ ***Integrated Lab Data Management***

- Did we have any pressure drop in the sample-bottle in which this live oil sample was stored?
- The maintenance of the core flooding equipment in which we did this experiment was up-to-date?
- The viscosity value for this sample is a little off. Which was the viscometer we used? When was the last time we calibrated it?

□ *Key components of Digital EOR Lab*

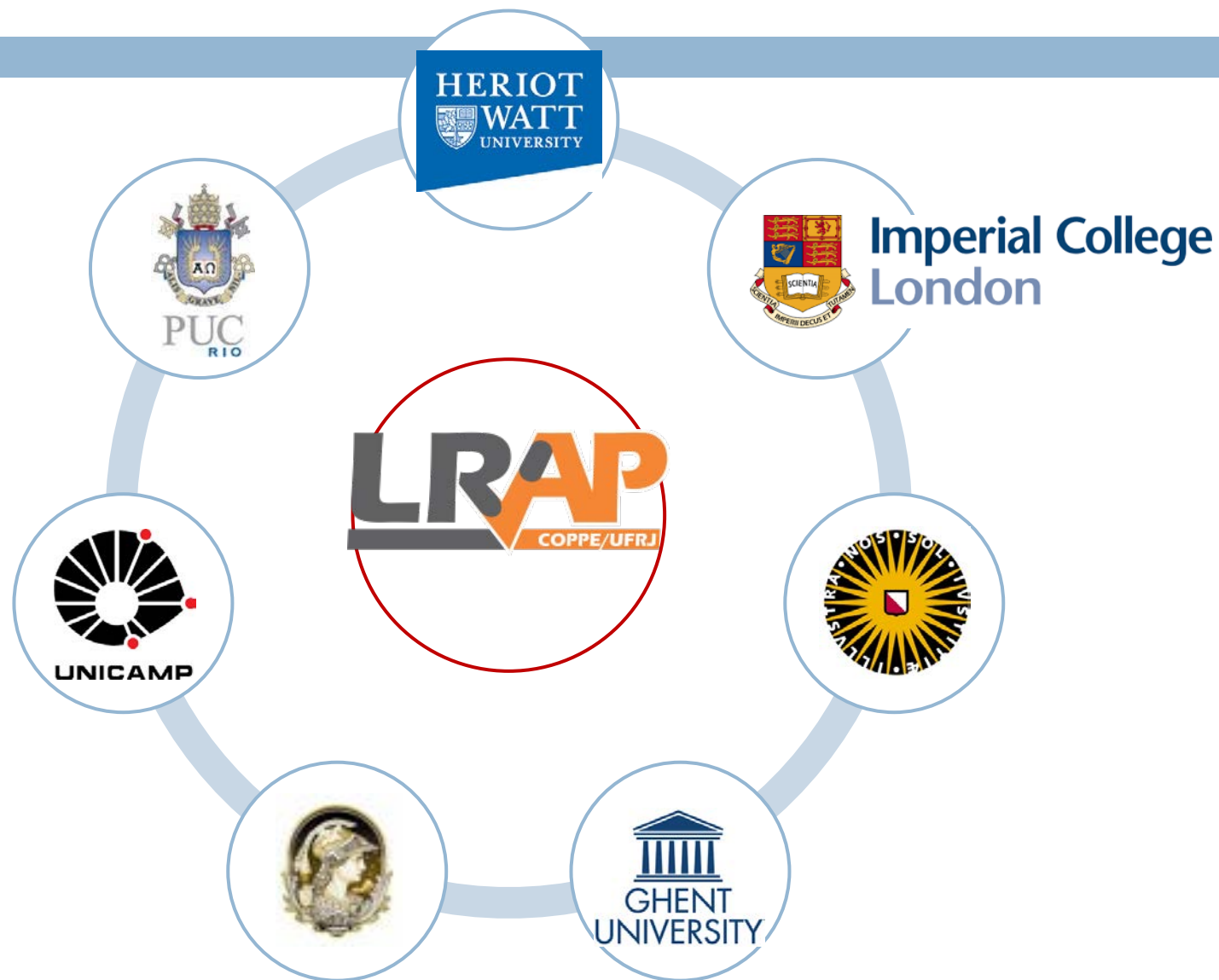


Behind the Scenes



International and National Collaboration

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Associated Projects

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- ANP 19027-2 – Desenvolvimento de Infraestrutura para Pesquisa e Desenvolvimento em Recuperação Avançada de PETRÓLEO – rap – no Brasil
- ANP 19017-3 – Fomento à Formação de Recursos Humanos visando aumentar a compreensão dos reservatórios do Pré-Sal Brasileiro
- ANP 19717-8 – avaliação da utilização de fluidos viscosificados para ensaios de permeabilidade relativa em condição de semireservatório
- ANP 18029-9 – Projeto de Correlação Petrofísica Rocha x Perfil
- ANP 20045-1 – Capacitação do Laboratório de Recuperação Avançada de Petróleo da COPPE/UFRJ para Pesquisas Experimentais Avançadas em Injeção de Água, Gás (incluindo WAG) e outros métodos de EOR.
- ANP 20163-2 – ANÁLISE EXPERIMENTAL DA RECUPERAÇÃO DE PETRÓLEO PARA OS CARBONATOS DO PRÉ-SAL DO BRASIL ATRAVÉS DE INJEÇÃO ALTERNADA DE CO2 E ÁGUA.
- ANP 20062-6 – Capacitação do Laboratório de Recuperação Avançada de Petróleo da COPPE/UFRJ para Pesquisas Experimentais Avançadas em caracterização de Fluidos Complexos em condições de reservatórios de campos brasileiros
- ANP 20352-1 – CARACTERIZAÇÃO DE FLUIDOS COMPLEXOS EM CONDIÇÕES DE RESERVATÓRIO DE CAMPOS BRASILEIROS

ACKNOWLEDGEMENTS

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