Workshop on Core Preparation

AGENDA:

09.30 – 09.45 Welcome, Aksel Hiorth and Tina Puntervold

09.45– 10.15 "SCAL core preparation: methodologies and challenges" by Álvaro Muñoz Beltran, Stratum Reservoir – formerly Weatherford Laboratories

10.15 - 10.45 "Challenges in Achieving "Representative" Reservoir Wettability" by Izaskun Zubizarreta, Lloyd's Register, UK

10.45 – 11.00 Break

11.00 – 11.30 "Representative wettability conditions in lab" by Ingebret Fjelde, NORCE

11.30 – 12.00 "Core handling: from reservoir to reliable laboratory results" by Skule Strand, UiS

12.00 – 12.45 Lunch

12.45 - 13.15 "Digitizing core data – Improve reservoir understanding" by Egil Boye Petersen, AkerBP

13.15 – 13.45 "What is missing in our understanding/implementation of Core Preparation?" by Robert Orr, Equinor

13.45 – 14.15 Group discussions:
"What is missing in our understanding of core preparation?"
"When are the traditional methods not good enough?"
"Way forward - Future research?"

14.15 – 15.00 Summarize and close

SCAL CORE PREPARATION: METHODOLOGIES AND CHALLENGES

Alvaro Munoz-Beltran

SCAL Project Manager

9th May 2019

Core preparation Workshop

The National IOR Centre of Norway - UiS

2019

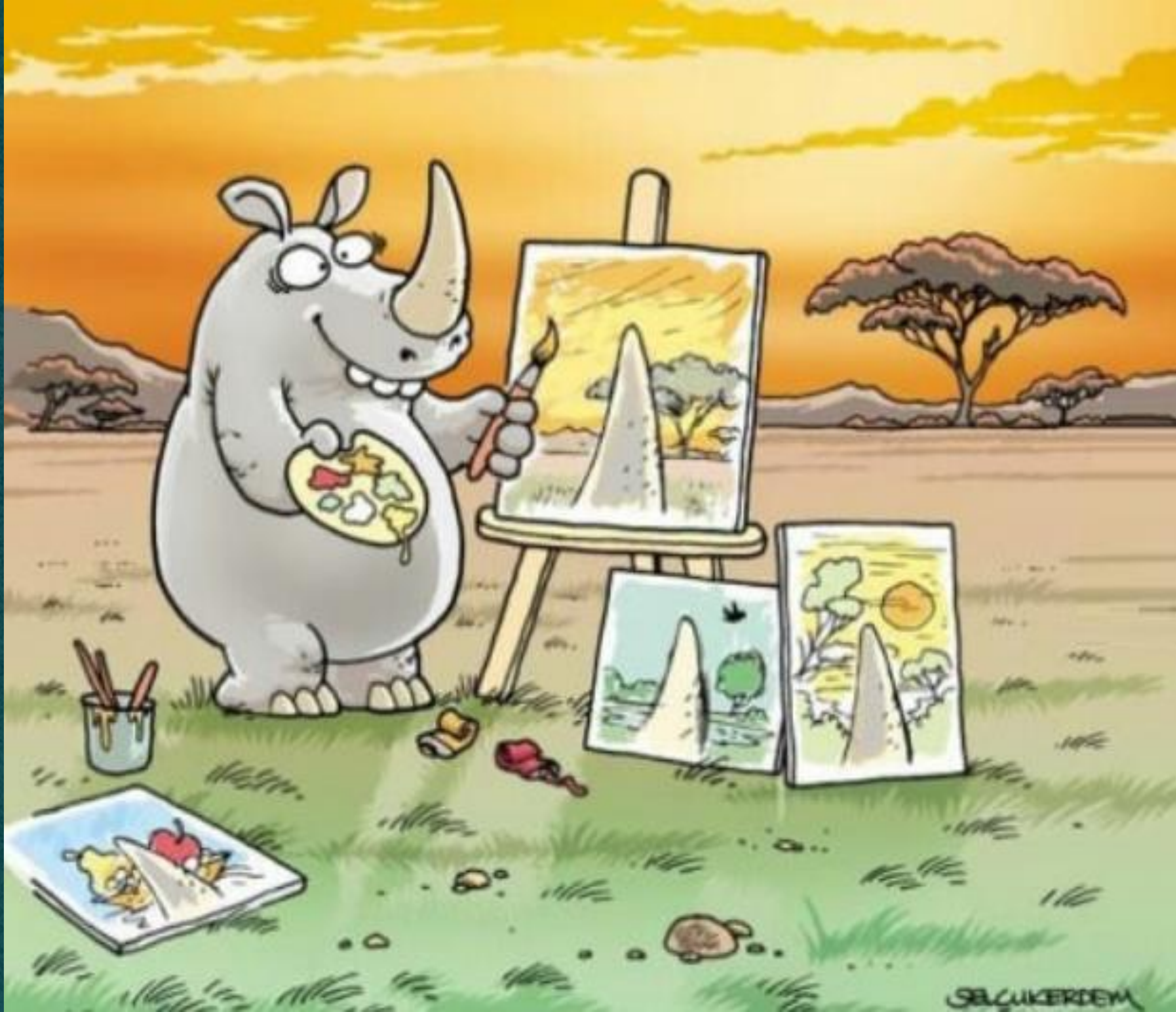
STRATUM RESERVOIR, FORMERLY Weatherofrd Laboratories, BECAME AN INDEPENDENT AND MORE DYNAMIC ORGANIZATION

STRATUM

RESERVOIR

THE POINT OF VIEW

IT'S ALL ABOUT PERSPECTIVE



OUTLINE

INTRODUCTION

CLEANING METHODS

DRYING METHODS

CHALLENGES

RECOMMENDATION

ADDITIONAL THOUGHTS

INTRODUCTION

WHAT DO WE REALLY WANT?

Representative rock of the reservoir formation.

Minimize physical and chemical alteration of the core during core handling and storage.

How was the core drilled? (mud type, coring operations, well-site work)

How the core was handled and preserved

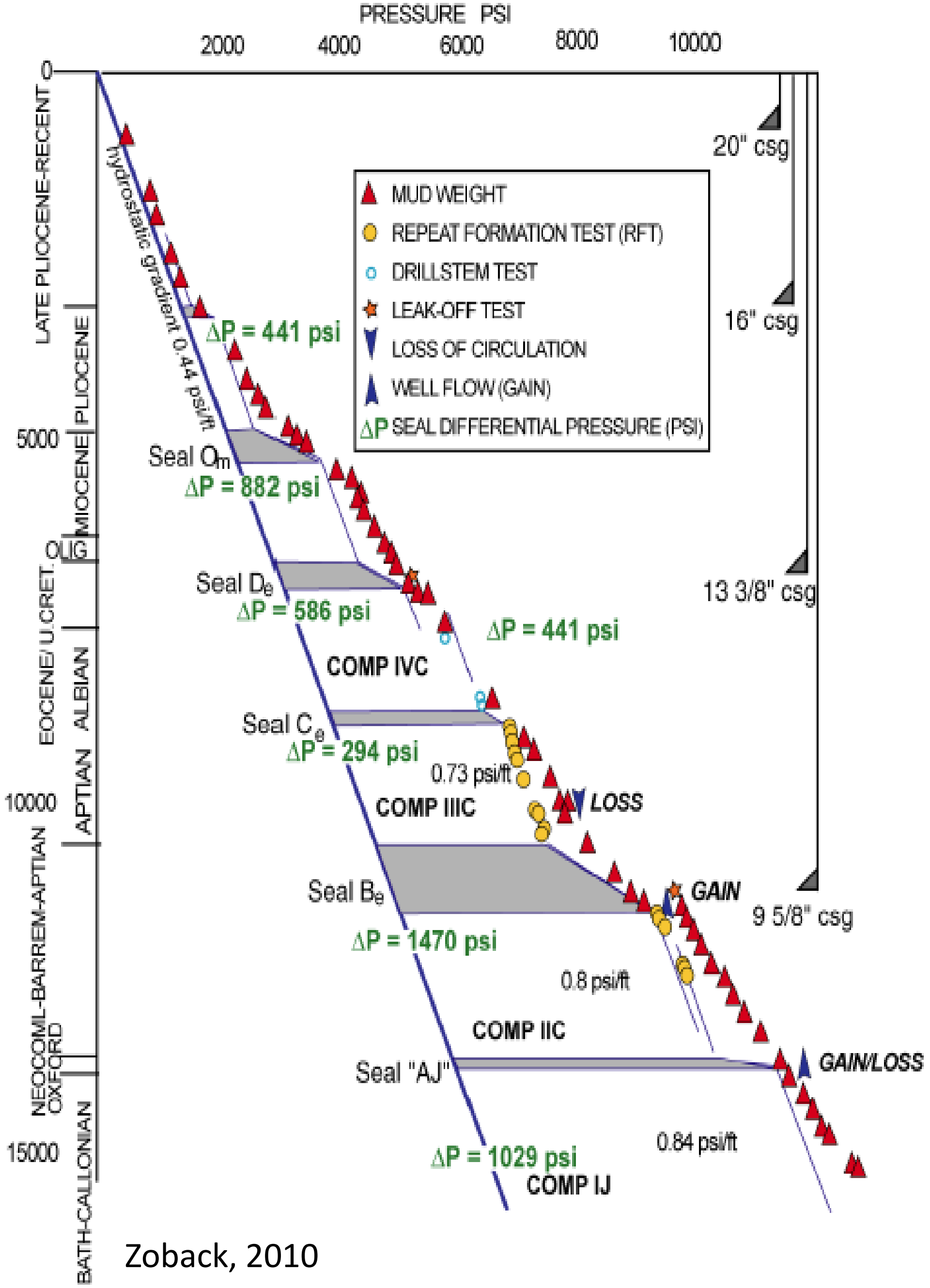
Reservoir Fluids Type (Oil or Gas Field)

INTRODUCTION

WHAT DO WE REALLY WANT?

Representative rock of the reservoir formation.

Minimize physical and chemical alteration of the core during core handling and storage.



Zoback, 2010

oring operations, well-site work)

erved

Field)

Coring Fluids

OBM / WBM

Pore pressure

Gas evolves/expands

Wettability alters

Rock structure alters

Increases heavy end components

Overburden stress

Rock relaxes

Porosity, permeability increased

Fractures can occur

Unconsolidated sands

Temperature

Wettability alters

Reduces surfactant solubility

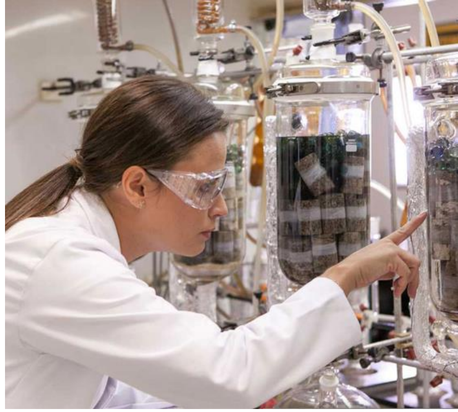
Exposure of Core to Air

Oxidation precipitates asphaltenes

Most drilling and coring processes will alter **wettability** to some extent

INTRODUCTION

PRESERVATION and PREPARATION



Core preservation

Fresh Core

Preserved Core

Pressure Retained Core

Core preparation

Native/'As receive' Core

Maintain native (unknown?) wettability.

No core sample cleaning and drying.

Re-establish original fluid saturations with no alteration of rock minerals structure and composition.

Cleaned Core

Core sample cleaning and drying, minimizing the possible alteration of rock minerals structure and composition.

Restore water-wet wettability state.

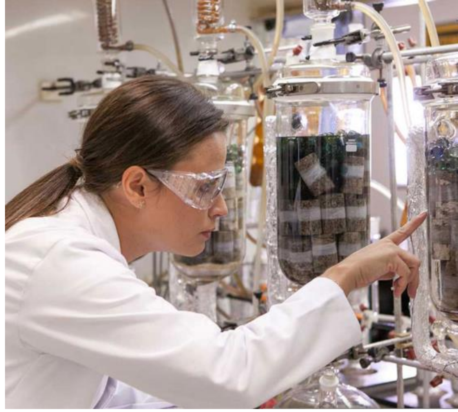
Restored State Core

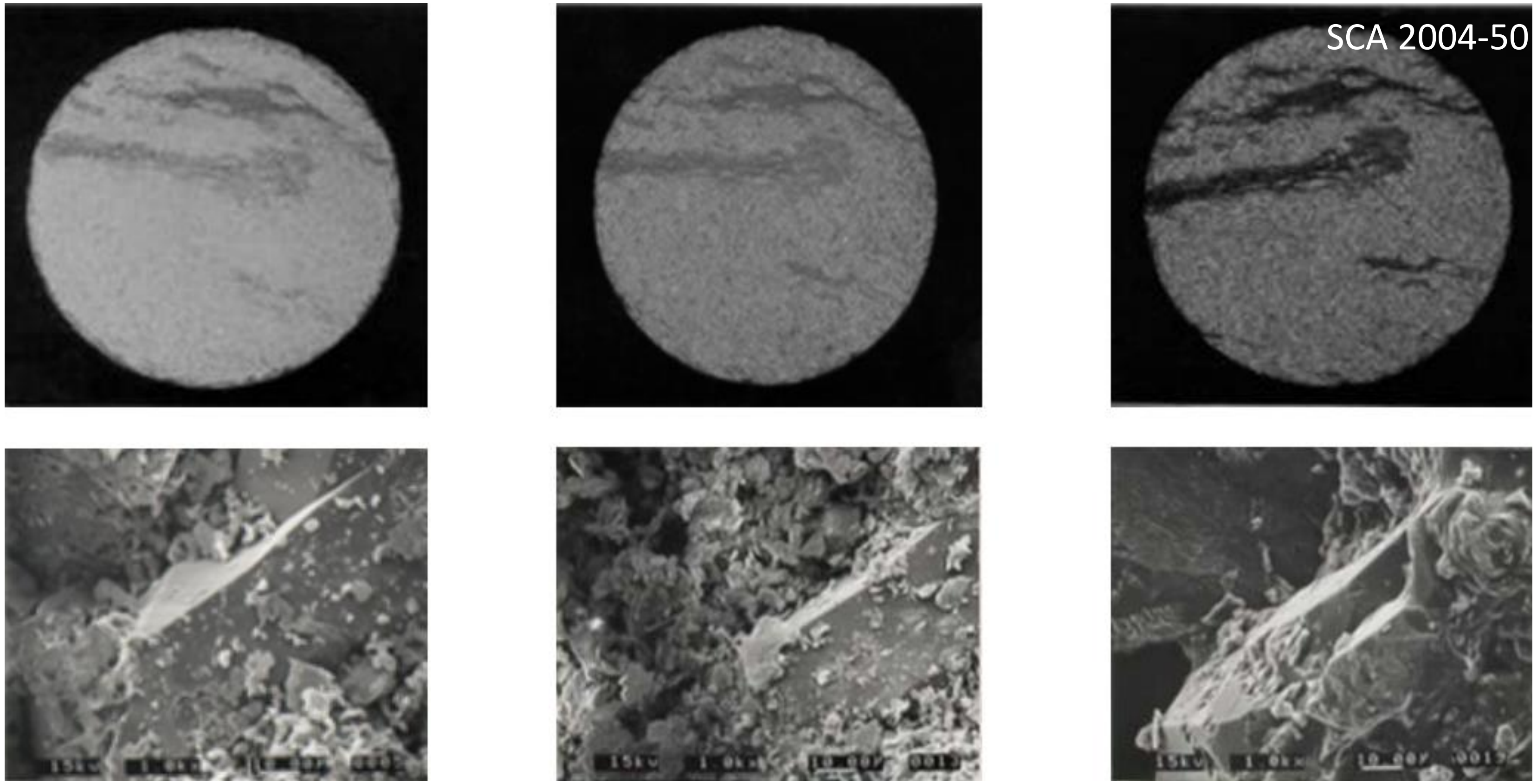
Core sample cleaning and drying, minimizing the possible alteration of rock minerals structure and composition.

Re-exposure to reservoir fluids and conditions to try to reproduce native wettability state and original fluid saturations.

INTRODUCTION

PRESERVATION and PREPARATION





INTRODUCTION

CLEANING/DRYING – WHY IS IT SO IMPORTANT?

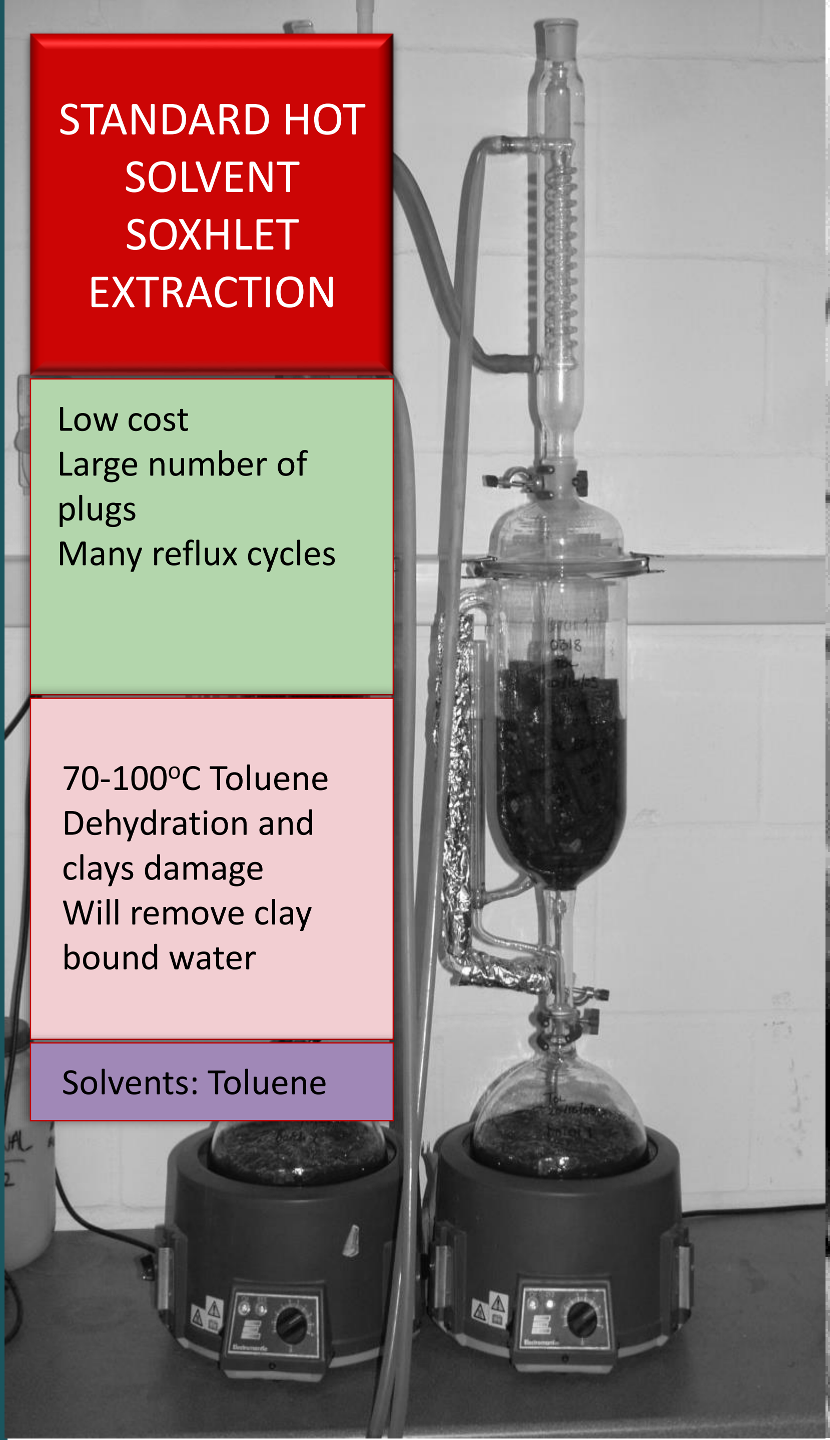
1. Cleaning and drying can cause damage to the core.
2. Some cleaning techniques are not totally effective.
3. Data based on improperly prepared core may be not reliable.
4. Choice of solvents depends on hydrocarbon type, minerals type/structure and surfaces and drilling mud contaminants present.
5. Each cleaning method has some advantage or disadvantage.
6. Different methods for different samples (Hot shot, RCA, SCAL…)

CLEANING METHODS

HARSH

versus

MILD

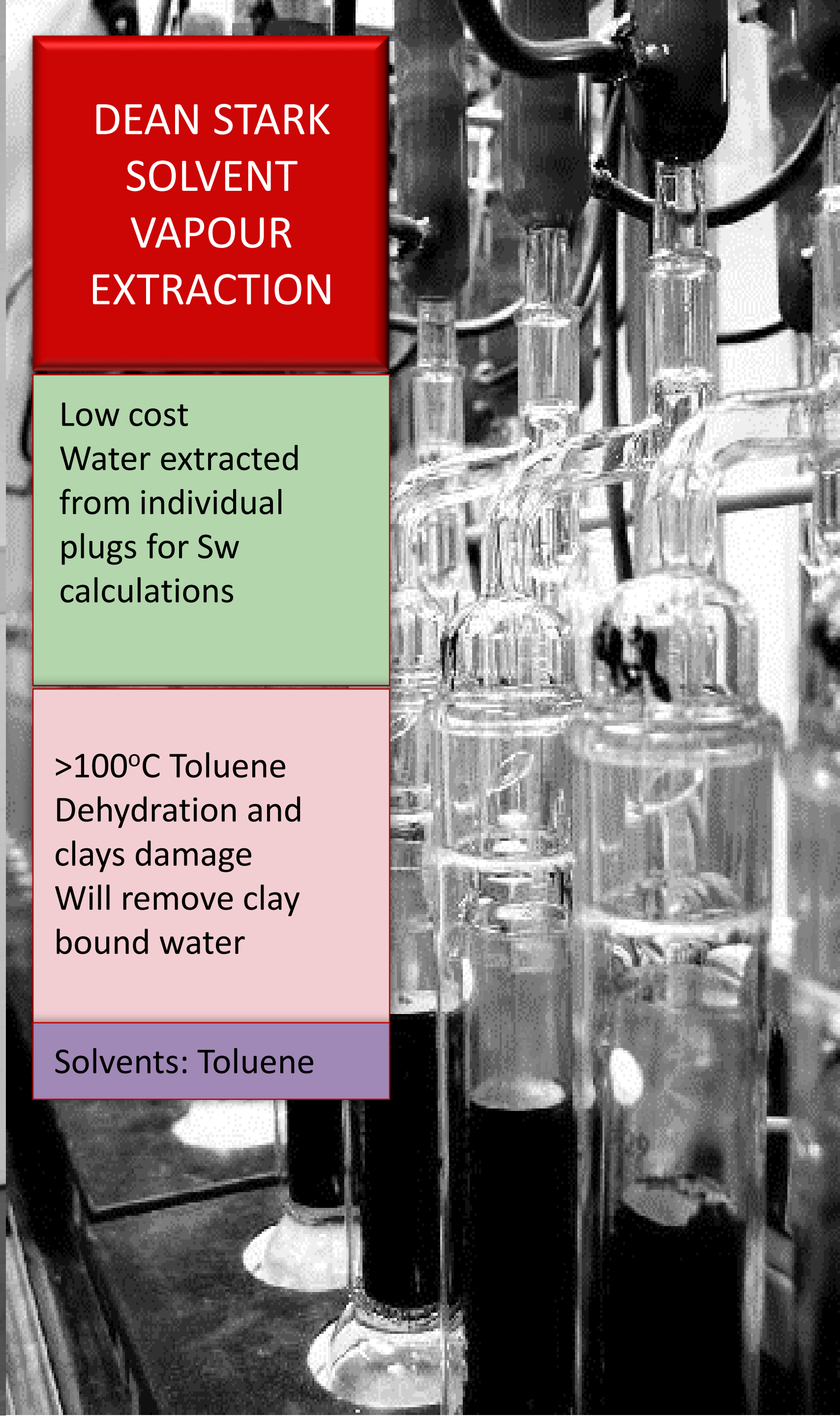


STANDARD HOT SOLVENT SOXHLET EXTRACTION

Low cost
Large number of plugs
Many reflux cycles

70-100^{o}C Toluene
Dehydration and clays damage
Will remove clay bound water

Solvents: Toluene



DEAN STARK SOLVENT VAPOUR EXTRACTION

Low cost
Water extracted from individual plugs for Sw calculations

>100^{o}C Toluene
Dehydration and clays damage
Will remove clay bound water

Solvents: Toluene

CLEANING METHODS

HARSH

versus

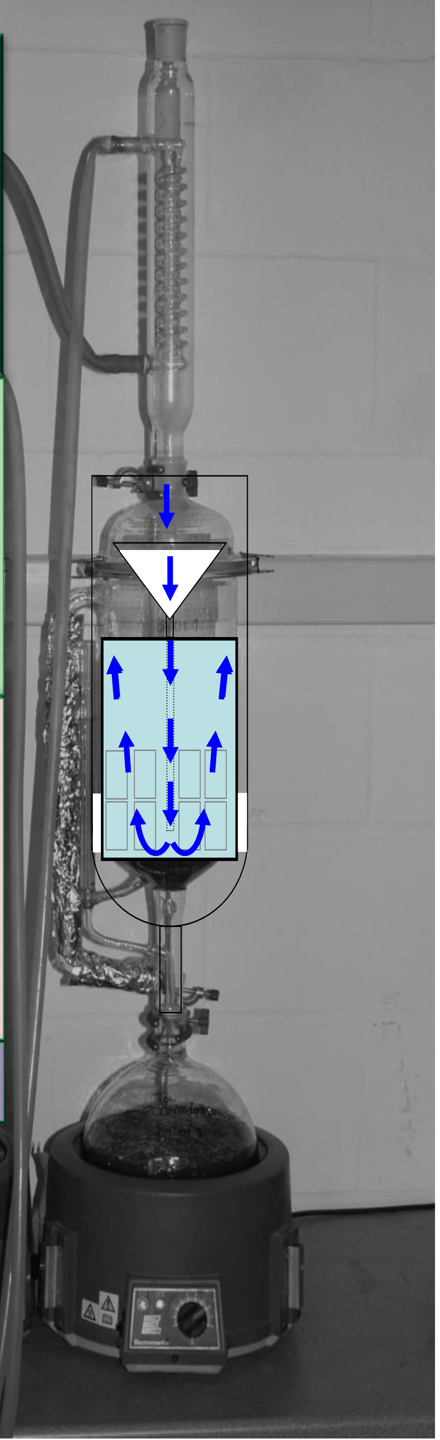
MILD

IMMERSED SOXHLET EXTRACTION

<60°C
Preserving delicate clay morphology
No flooding to create fines migration

May be inefficient for removal of asphaltenes, waxes or heavy mud contaminated cores

Solvents: Chloro. mix

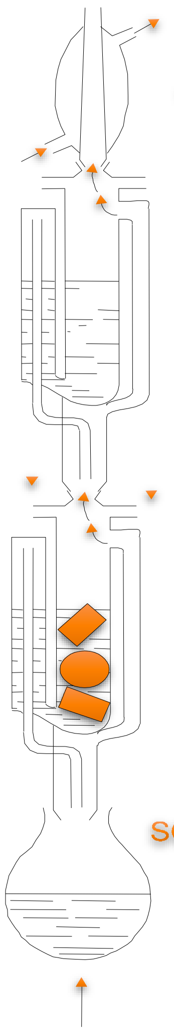


COLD SOLVENT SOXHLET EXTRACTION

<30°C
Residence time increased
Prevents core damage due to low temperature

Inefficient cleaning
Requires much longer cleaning periods
Not always suitable for SCAL

Solvents: Chloro. mix



CLEANING METHODS

HARSH

versus

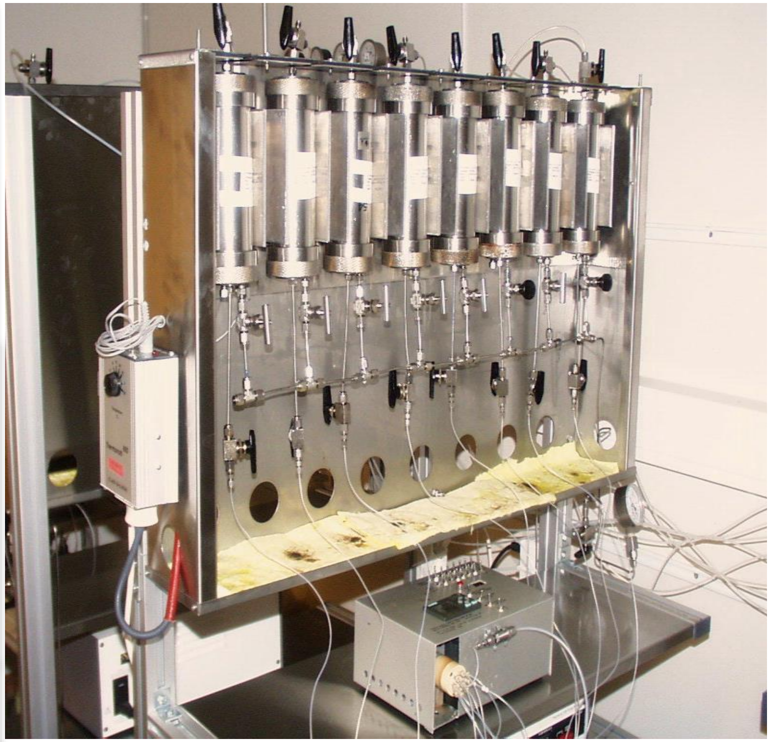
MILD

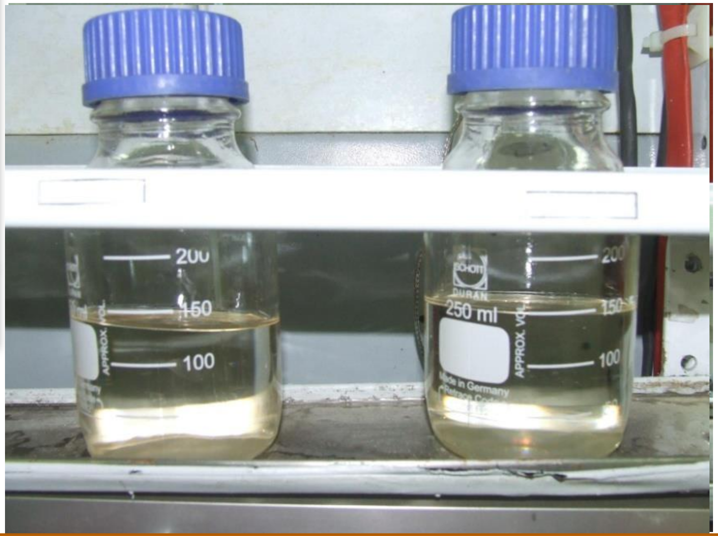
DYNAMIC FLOODING

Low rate miscible solvent flow, temperature and pressure controlled
Efficient to remove OBM contaminants

Permeability limitations
Fines migration could be an issue at high flow rates

Solvents: Several





CLEANING CARD

0	1	2	3	4	5	6	7	8	9	10	11

CLEANING METHODS

SOLVENT TYPES

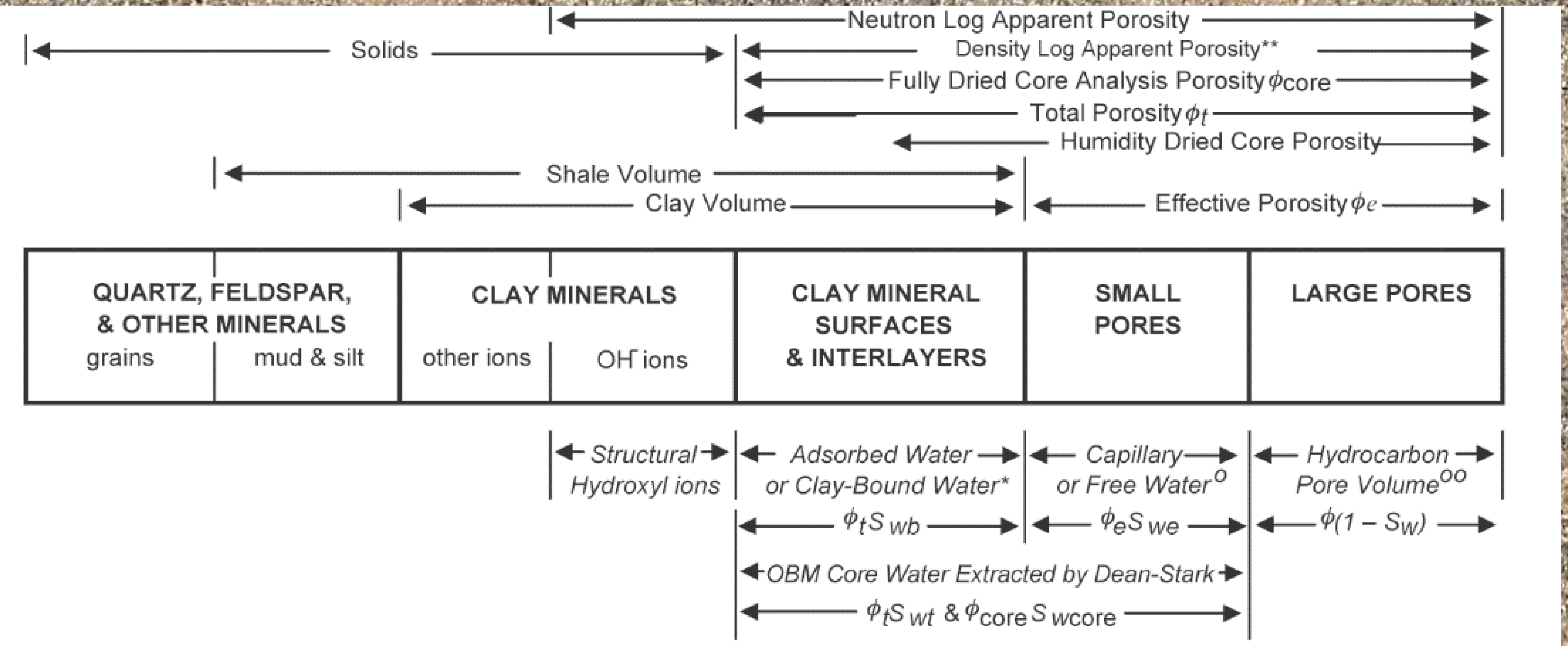
- Non-polar solvent removes oil (heavy ends)
- Polar solvent removes salts and oil (light ends)

SOLVENT TYPE	Boiling Point °C	SOLUBILITY	Polarity	Polarity Index	Solubility in Water %
Acetone	**56.5**	**oil, water, salt**	**Polar Solvent**	**5.1**	**100**
Chloroform	**61.2**	**oil**	**Moderately Polar**	**4.1**	**0.815**
Chloroform/Methanol Azeotrope (91/8)	**53.5**	**oil, water, salt**			
Toluene	**110.6**	**oil**	**Aromatic Non Polar Solvent**	**2.4**	**0.051**
Toluene/Methanol (28/72)	**63.8**	**oil, water, salt**			
Methanol	**64.7**	**water-salt**	**Polar Solvent**	**5.1**	**100**
Cyclohexane	81.4	oil	Aromatic Non Polar Solvent	0.2	0.01
Ethylene Chloride	83.5	oil, limited water		3.5	
Hexane	49.7 - 68.7	oil	Aromatic Non Polar Solvent	0.0	0.001
Methylene Chloride	40.1	oil, limited water			
Naphtha	160	oil			
Tetrachloroethylene	121	oil	Aromatic Non Polar Solvent		0.015
Tetrahydrofuran	65	oil, water, salt		4.0	100
Trichloroethylene	87	oil,limited water		1.0	0.11
Xylene	138.0 - 144.4	oil	Aromatic Non Polar Solvent	2.5	0.018
Isopropanol; 2-Propanol	82.3	water-salt , limited oil	Polar Solvent	3.9	100

DRYING METHODS

MOST COMMON TECHNIQUES

HOT DRY OVEN 95°C to 150°C
HOT OVEN DRY 60°C
HUMIDITY OVEN 60°C, 40/45% (Rel. Hum.)
VACUUM OVEN 40° - 105°C
CRITICAL POINT DRYING CO_2
TBA (T-Butyl Alcohol) FREEZE DRYING



** Density log apparent porosity using the grain density of dried core and correct invaded-zone fluid density.
* Smectite clays have a large capacity to adsorb water, whereas most other clay minerals have little or no adsorbed (or bound) water.
oo This model has no mobile water, and the model sandstone will produce water-free hydrocarbons during its initial production phase.
o As height above the hydrocarbon-water contact increases, capillary water volume decreases and hydrocarbons displace capillary water.
Humidity dried core analysis porosity is shown as including some of the clay-bound water.
Box sizes are schematic.

DRYING METHODS

MOST COMMON TECHNIQUES

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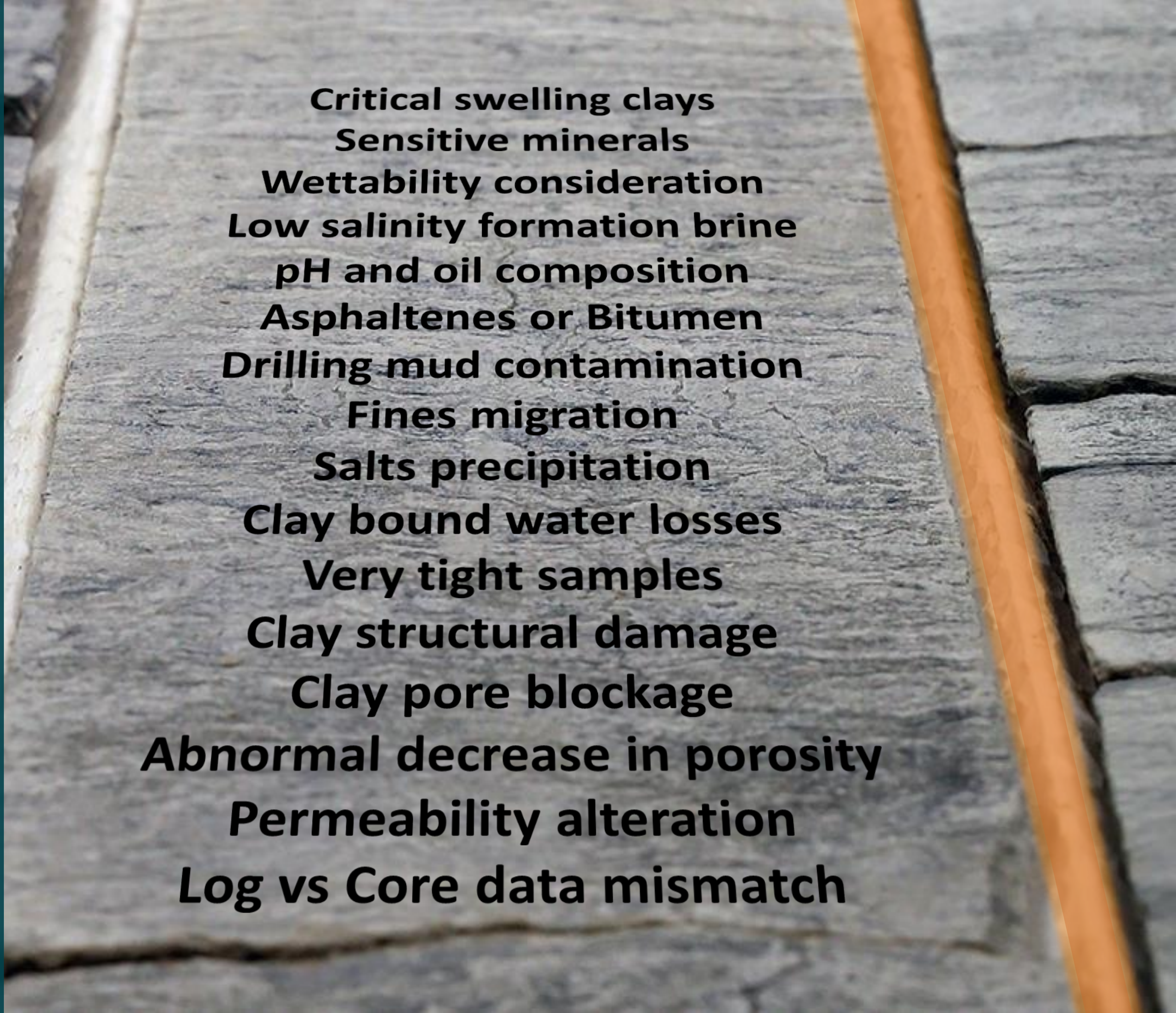
CRITICAL POINT DRYING CO_2
TBA (T-Butyl Alcohol) FREEZE DRYING

95° C Hot oven Drying (conventional)	60° C Hot Oven Drying	60° C 45% RH Humidity Drying	Vacuum Drying (20° to 95° C)	Critical Point Drying CO_2 (60° C)	Freeze Drying (low temp.)
Fast	Intermediate	Slow	Fast	Medium	Medium
Total Porosity	Not Total Porosity	"Effective" Porosity	Total Porosity?	"Effective" Porosity?	"Effective" Porosity?
Damage delicate clays, gypsum, smectite, zeolite	Preserve clay structure, CBW? Damage smectite,	Preserve clay structure, CBW? Reproducibility low, fresh water absorption issue	Damage fibrous,delicate clays structure, smectite, CBW?	Preserve clay structure, fibrous clay structure, semi-dynamic	Preserve clay structure, fibrous clay structure, static

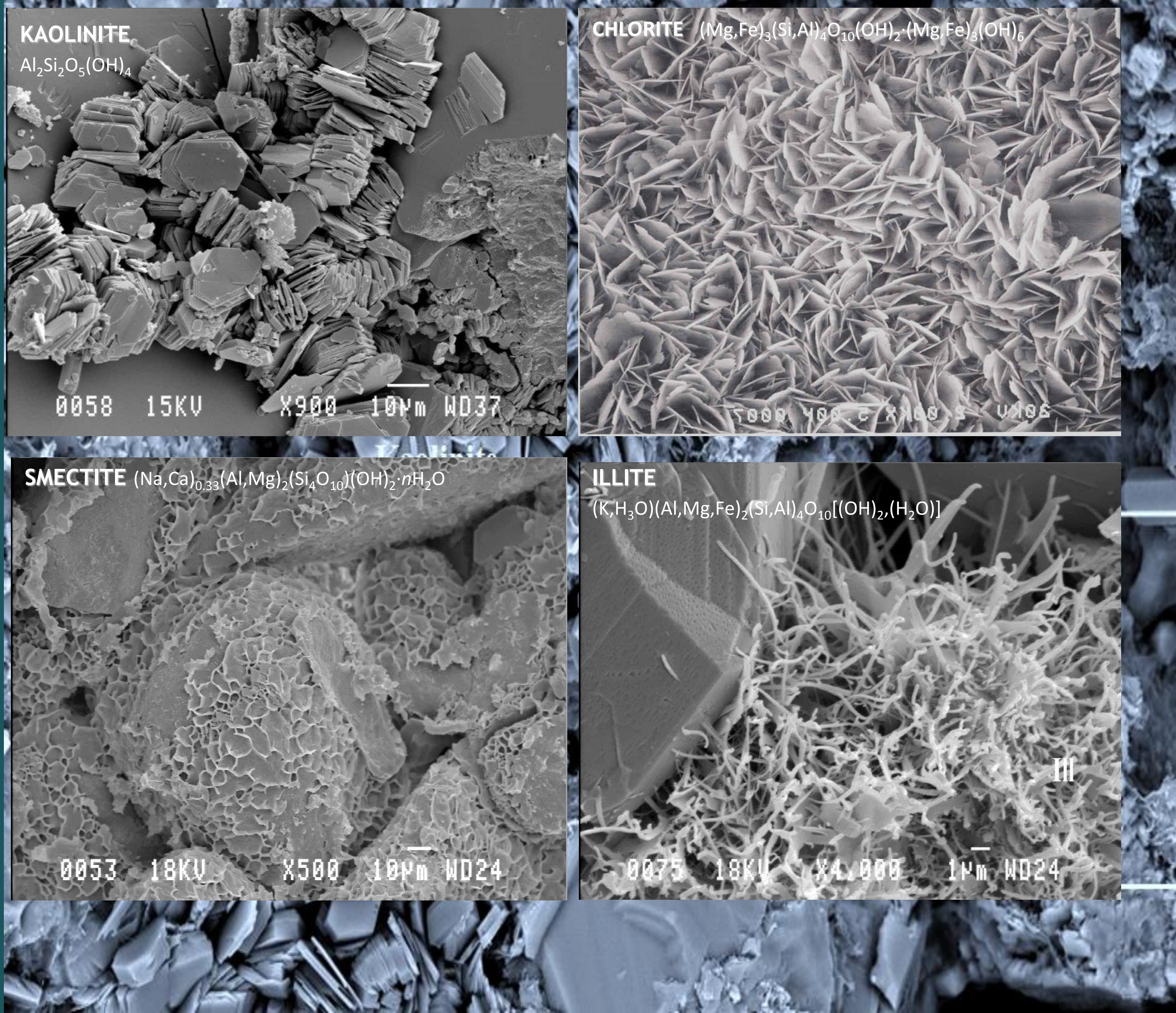
CHALLENGES

IF WE OBSERVE THIS PERHAPS IT IS TOO LATE



CHALLENGES

SEM ROCK STRUCTURE AND MINERALOGICAL OBSERVATIONS



CHALLENGES

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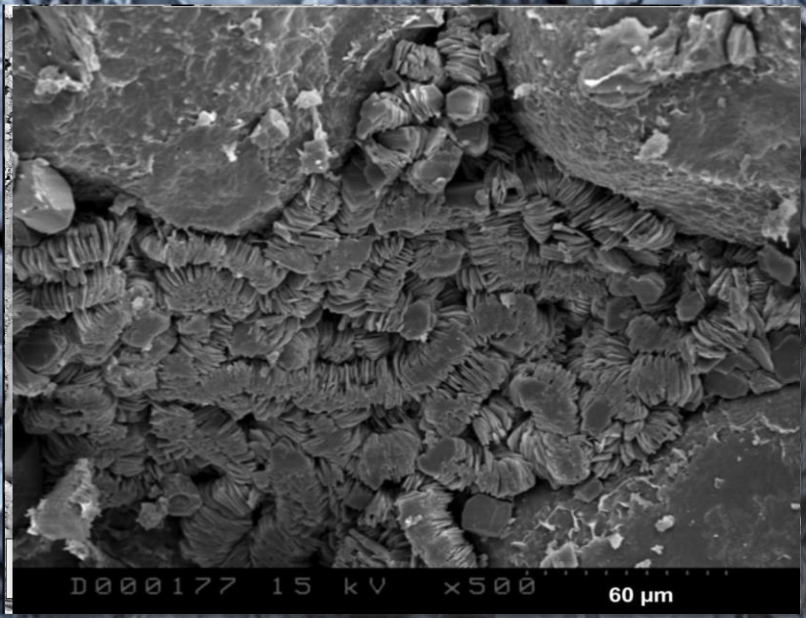
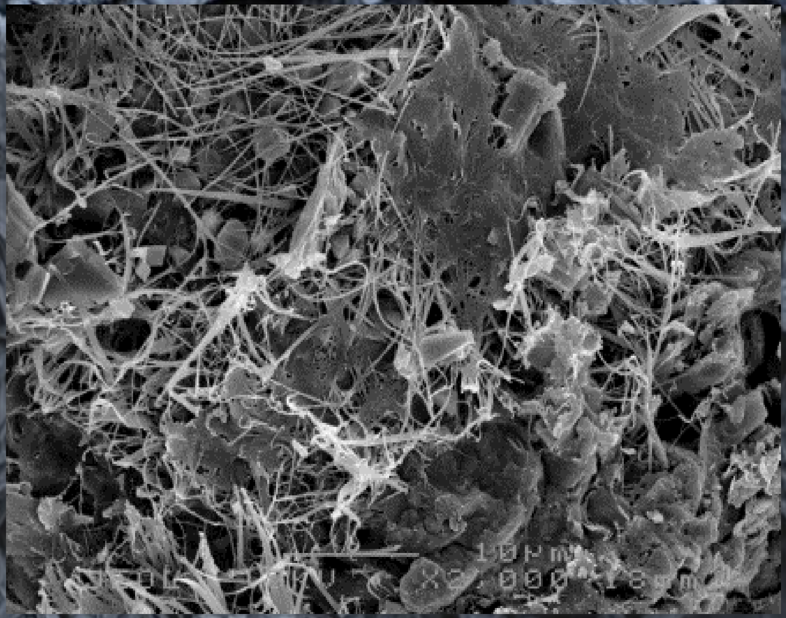
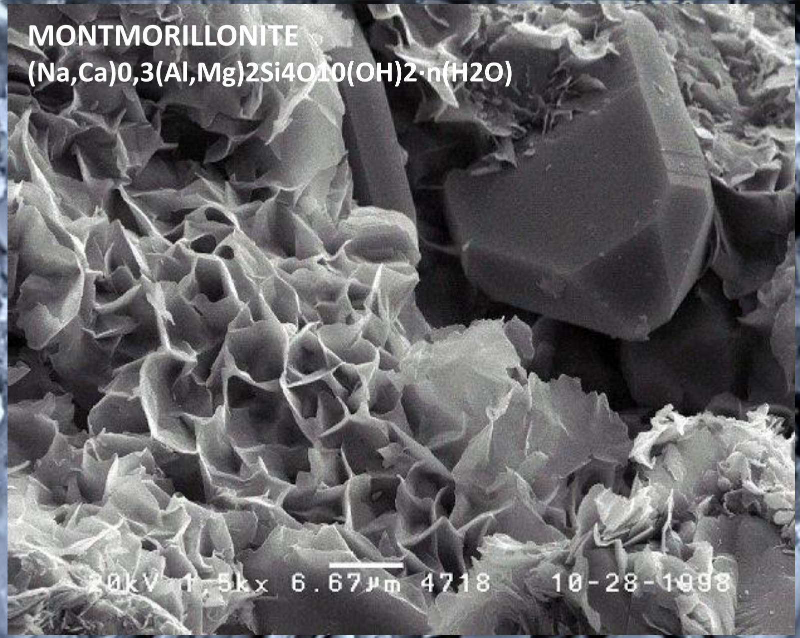
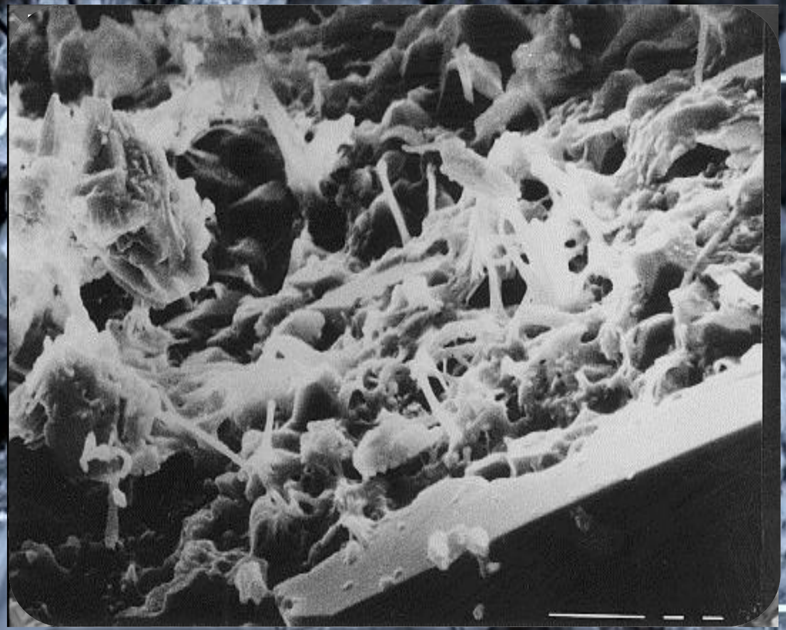




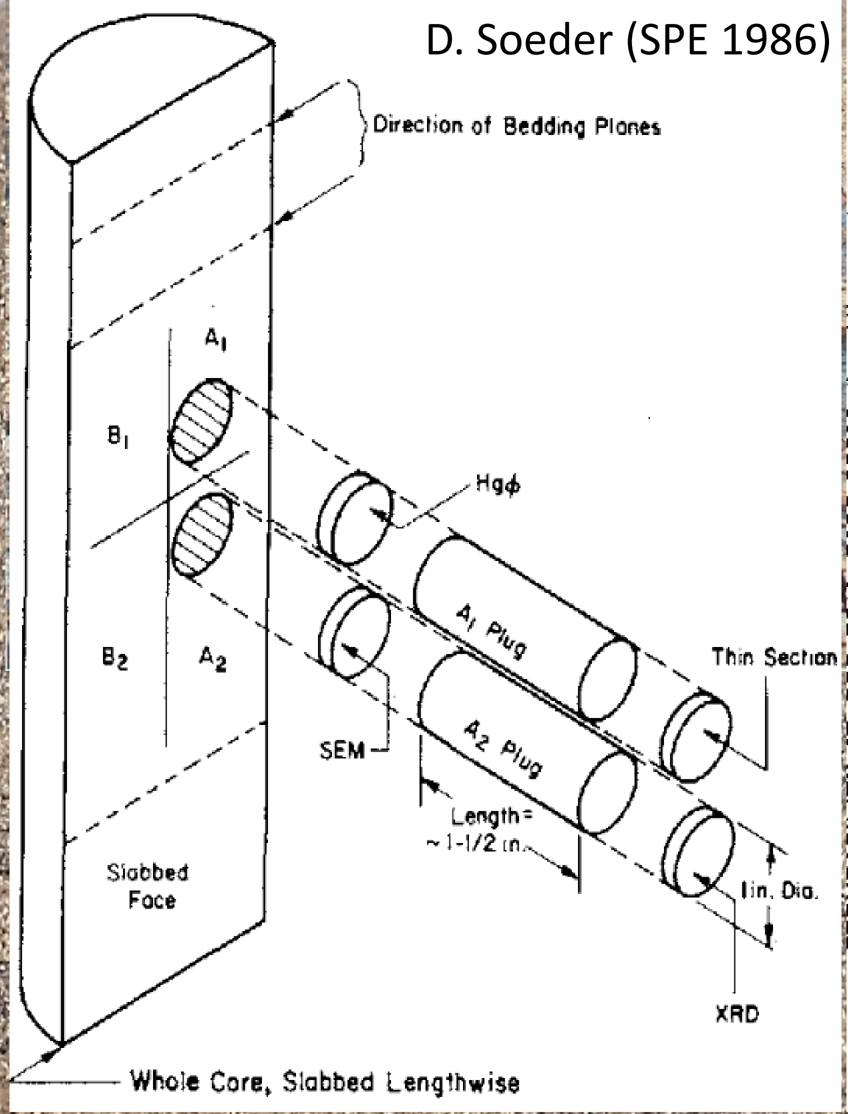


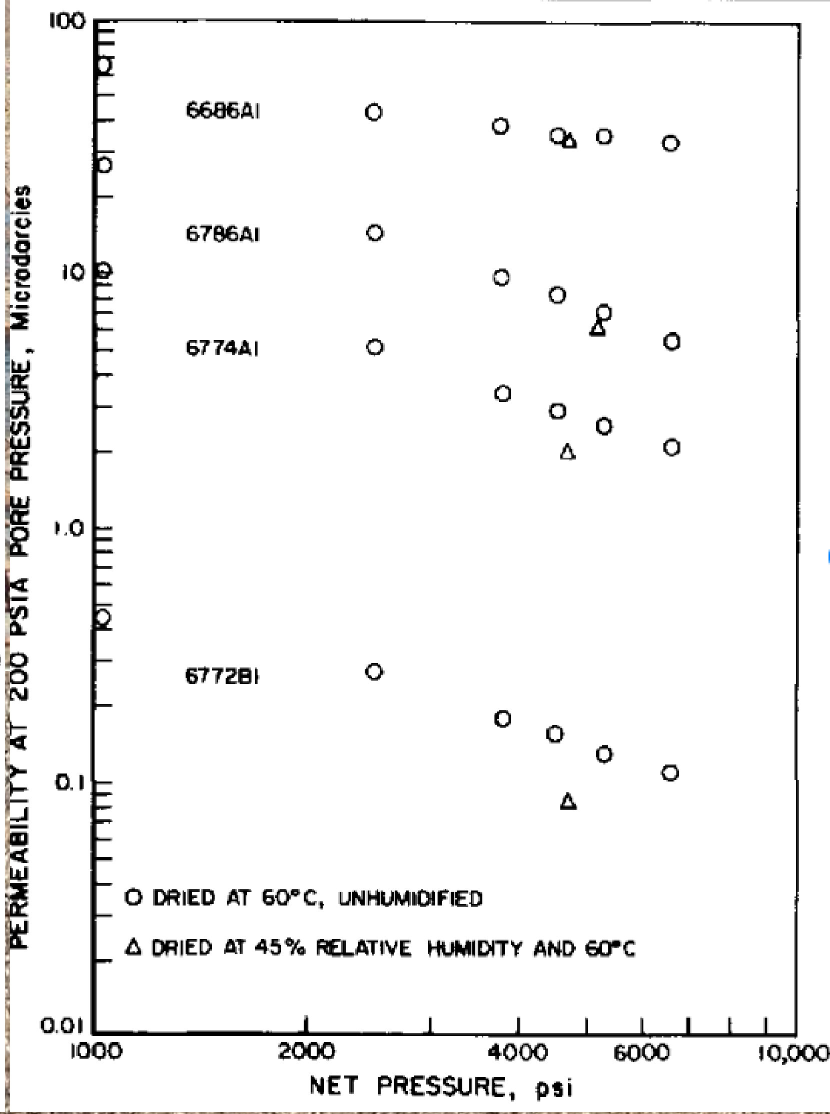


CHALLENGES

CLAY DAMAGE can happen everywhere!

D. Soeder (SPE 1986)





CHALLENGES

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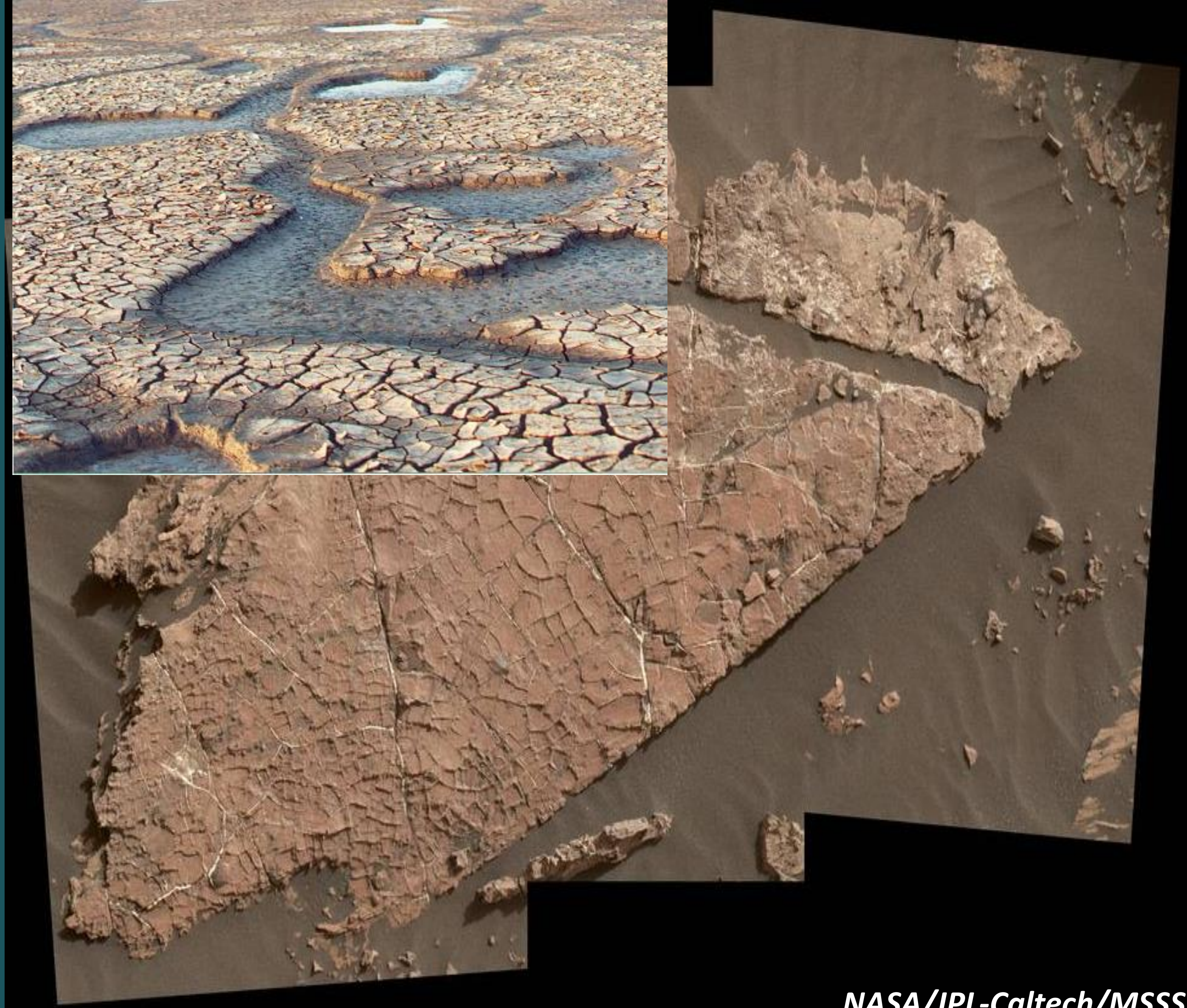
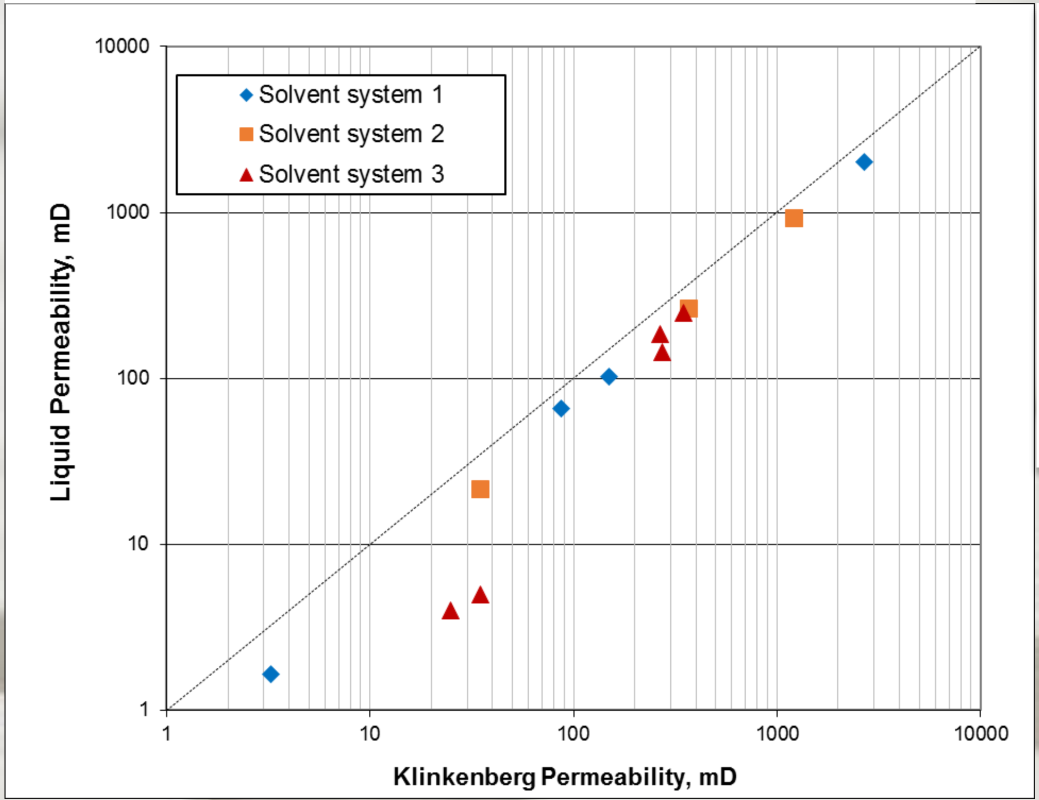


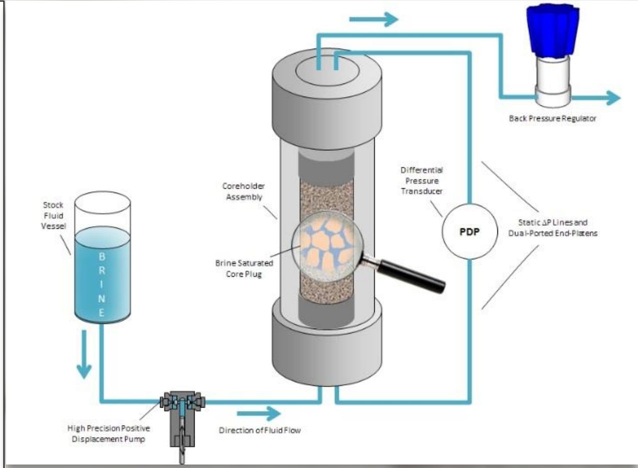
NASA/JPL-Caltech/MSSS

CHALLENGES

PERMEABILITY MEASUREMENTS vs. CLEANING METHOD or SOLVENT SYSTEM

Permeability impairment measurements and comparison

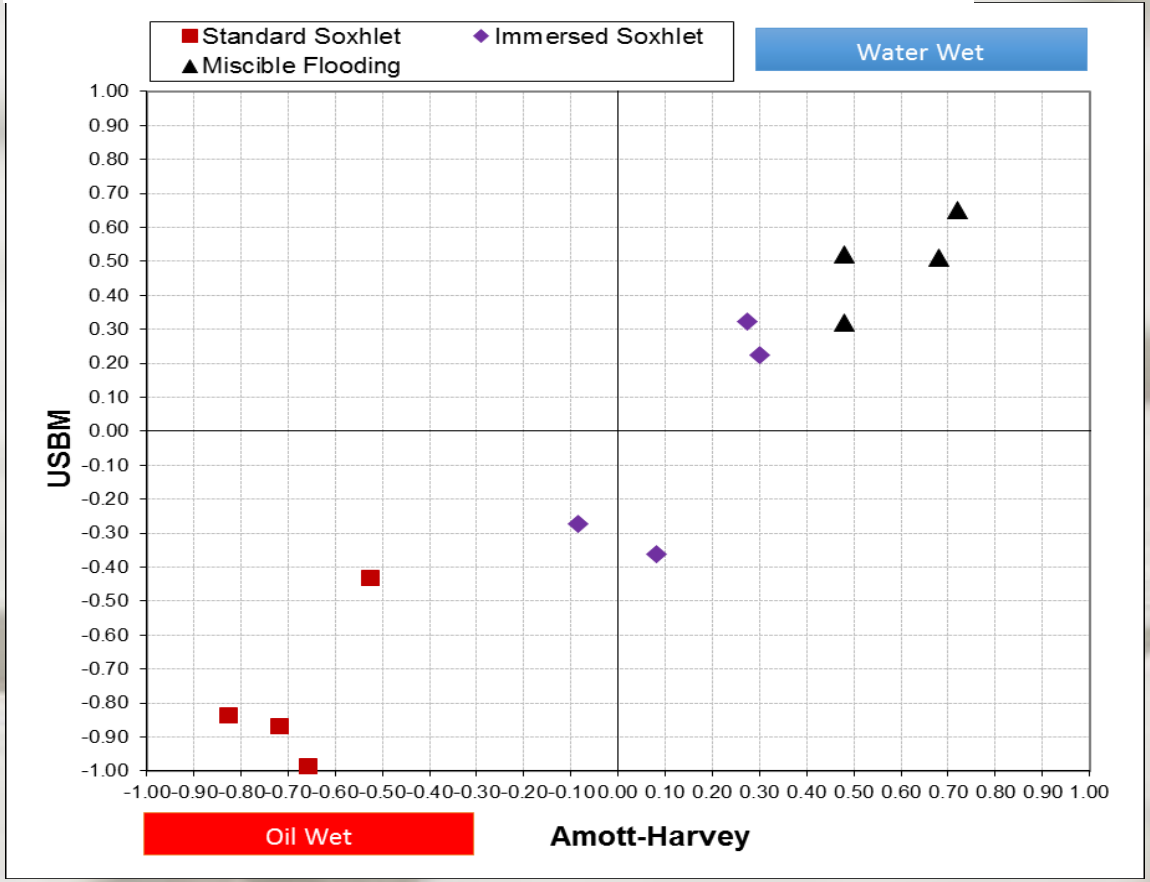




CHALLENGES

WETTABILITY BEHAVIOR vs. CLEANING METHOD

Wettability behavior observation after cleaning



RECOMMENDATION

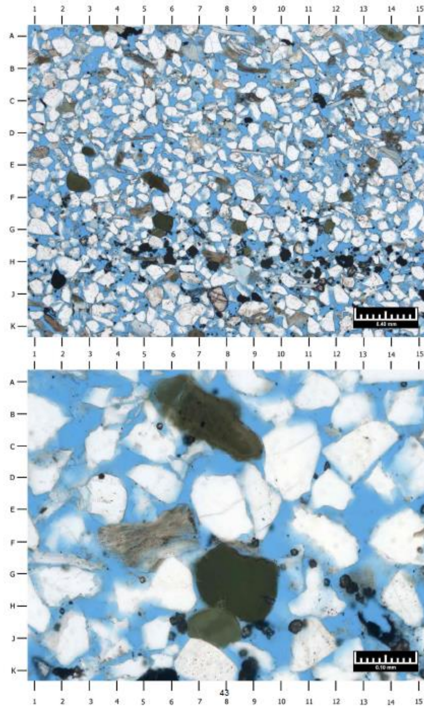
WHAT IS A PRE-STUDY?

INVESTIGATION PROGRAM TO DEFINE CLEANING AND DRYING BEST PROCEDURE

X-Ray Diffraction Mineralogy (Quantitative)

- TO IDENTIFY AND QUANTIFY MINERALOGY OF THE CORE
- REQUIRED FOR SOLVENT CLEANING SELECTION
- REQUIRED FOR TEMPERATURE DRYING LIMITS

Scanning Electronic Microscope SEM (Qualitative)



- TO IDENTIFY MINERALOGICAL STRUCTURE
- REQUIRED FOR CLEANING EFFECTIVENESS
- REQUIRED FOR SOLVENT CLEANING SELECTION
- REQUIRED FOR TEMPERATURE DRYING LIMITS
- NATIVE STATE WETTAB. AND ROCKS vs. FLUID INTERACTION

Petrography (Thin Section) and Lithological Description

- TO IDENTIFY BASIC MINERALOGY BY VOLUME
- FABRIC AND MINERAL TEXTURE
- MICROPOROSITY ASSOCIATED WITH CLAYS
- REQUIRED FOR FORMATION SENSITIVITY CONCERNS
- REQUIRED FOR DIAGENETIC HISTORY

RECOMMENDATION

WHAT IS A PRE-STUDY?

INVESTIGATION PROGRAM TO DEFINE CLEANING AND DRYING BEST PROCEDURE

Fluids Properties and Composition

- FORMATION WATER SALINITY AND Ph
- CRUDE OIL COMPOSITION, ASPHALTENES
- MUD CONTAMINATION

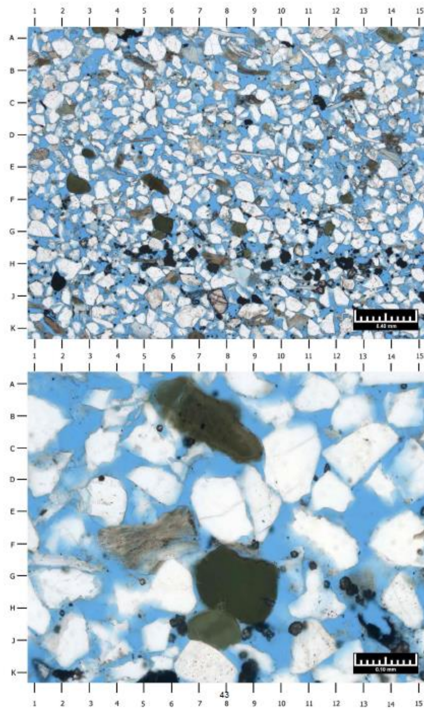
Rock and Fluids Interaction

- BRINE SENSITIVITY STUDIES
- CRITICAL VELOCITY TEST
- SALT PRECIPITATION SENSITIVITY ANALYSIS
- PERMEABILITY COMPARISON

Wettability control

- WETTABILITY AFTER CLEANING
- WETTABILITY RESTORATION
- CHEMICAL ANALYSIS ON EFFLUENTS
- AGING TESTS

Mainly for the SCAL program…but not only!



ADDITIONAL THOUGHTS

CHALLENGES

- What happen when there is no oil or water samples from the reservoir?
- What to do when the core is highly mud contaminated?
- Is there a need to include wettability in Pc and Kr?
- Wetting index meaning for further evalulations?
- Shall we always use tracers?
- What to do if there is no IFT measurements?
- How to work when the reservoir information cannot be shared?
- How to deal with data that show very strong oil wet behavior?
- Do you see an interest in core restoration with analogue oils?
- When is an old core too «old»?
- Is it possible to accomplish coring without causing core damage?
- Can we perform a SCAL study without a pre-study?
- What to do when the rock is very tight?
- How far can we clean a sample with bitumen to be representative of the reservoir?
- When timing and money is a big issue then better any results than project delays?

THANK YOU

STRATUM
RESERVOIR

Some Challenges in Achieving “Representative” Reservoir Wettability

Izaskun Zubizarreta, Core Analysis Manager

May, 2019

Lloyd's Register

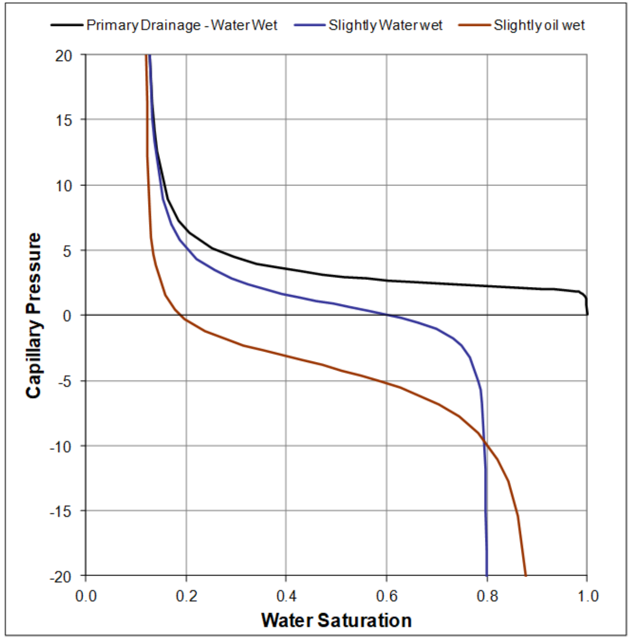
Reservoir Wettability

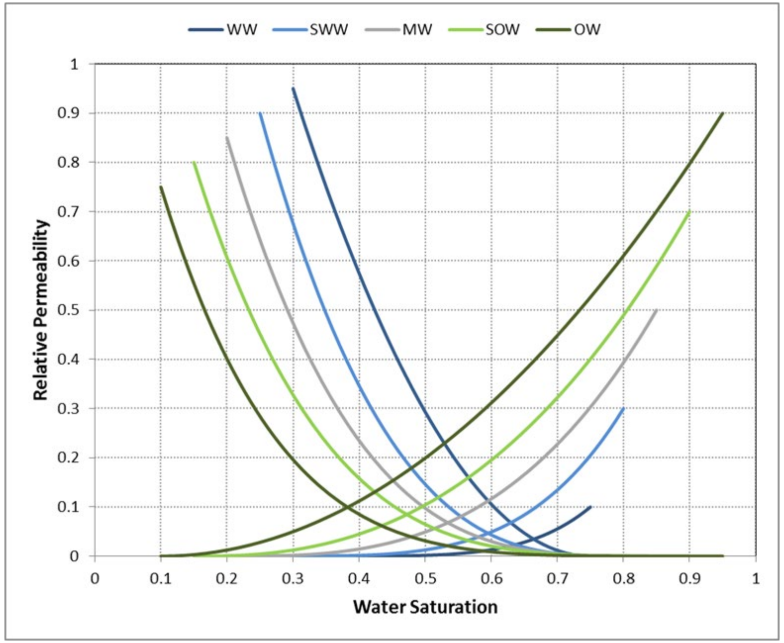
Wettability – essential.......... but meaningless

(by current measurement methods)

- Wetting index only provides qualitative indication of reservoir properties
- Wrong wettability = wrong reservoir properties

- Wrong Sw vs. H (volumetrics)
- Wrong Swi
- Wrong Kr (Pc imb. to correct capillary end effects)





- Wrong reservoir performance prediction
- Wrong hydrocarbon recovery

Coring and Core Retrieval Alteration

Journey from Reservoir to Surface

Stress Released Rapidly	Mud Filtrate Invasion	Pore Pressure Depletes	Temperature Reduces

These changes may result in

Alteration of the rock's native wettability	Alteration of the native spatial and volumetric distribution of fluids within the reservoir pore space	Alteration of the rock's pore geometry, texture and mineralogical properties
A non-representative rock surface affinity to oil/water	*Non-representative Initial Fluids Distribution*	*Non-representative Porous Media*

Mud Filtration Invasion “Native” Wettability Alteratio

- Wettability is sensitive to surfactants, brine chemistry and pH
- Components of drilling muds can alter the wettability
- The ideal mud should contain no surfactants and a minimum of additives
- Creating adequately designed CaCO3 filter cake may help to minimize mud filtrate invasion (input data for design may not be available)
- Adding tracer in the mud phases helps quantify potential filtrate invasion
- But, in reality:
    - Coring muds containing oilfield chemicals are used routinely (sometimes for good reasons)
    - Well control / HSE always takes precedence over bland coring mud requirements
    - Wettability alteration maybe severe for SBM because of chemicals use to make them work (emulsifiers for water phase and strong oil wetting agents to keep clays, barite and cuttings oil wet and in suspension)
    - In many reservoirs, contact with SBM is known to induce a strong oil-wetting tendency that can be difficult to remove

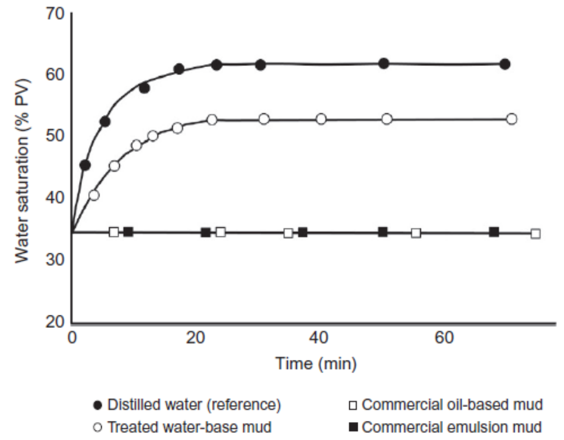


FIGURE 2.38 Effects of oil-based mud on spontaneous imbibition. *After Bobek et al. (1958).*

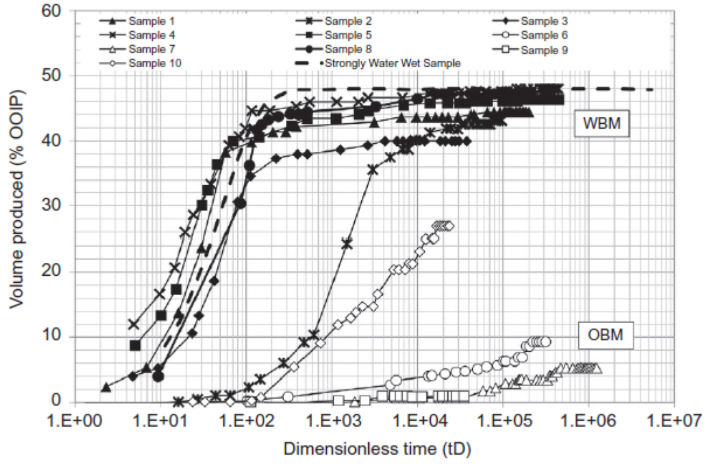
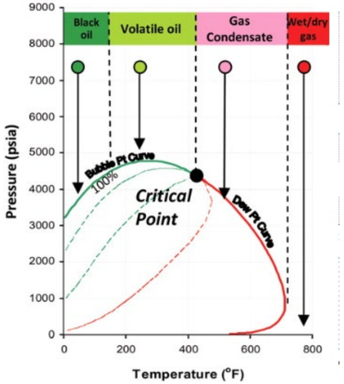


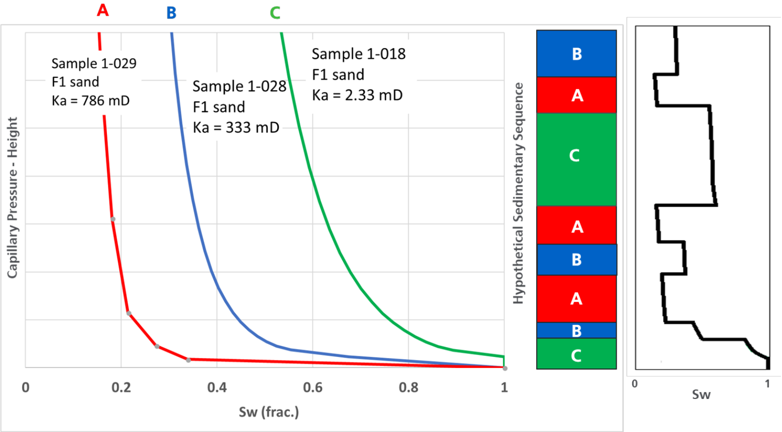
FIGURE 2.40 Imbibition curves for Berea sandstone core treated with different mud systems.

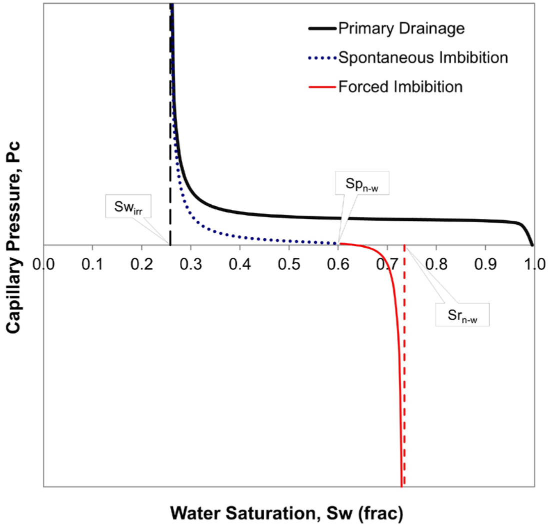
Wettability Alteration by Pressure and Temperature Reduction / Oxidat



- P and T reduction releases gas as the core is retrieved
- Relative concentration of heavier end components and surfactants increases
- These can be adsorbed onto the rock surface
- Asphaltene and wax components of the oil can precipitate
- As a consequence, rock can be made more oil wet (or less water wet)
- Solubility of surfactants in the oil is also reduced, increasing potential for adsorption
- In addition, oxidation of the crude oil, through exposure of core to air during handling at wellsite and in the laboratory can also induce a less water-wet tendency
- Correct core preservation, designed to eliminate or minimise core exposure to air, will prevent this form of wettability damage (applies also for preserved core material)

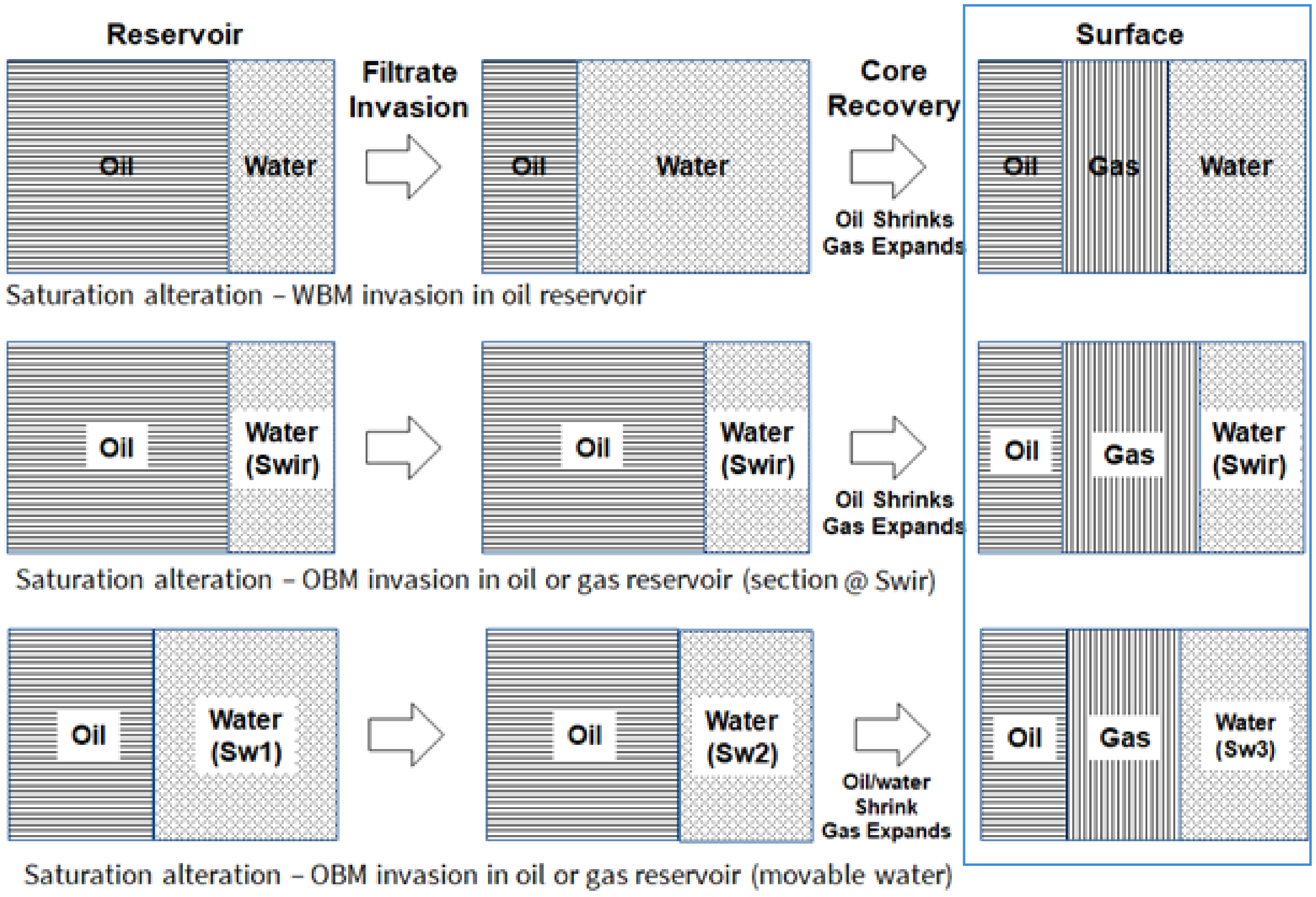
"Native" Fluid Saturation Alteration





- Fluid distribution --- controlled by capillary forces (Pc)
- During coring (OBM or WBM) mud filtrate can enter the pore system of the rock before, during and after coring, altering the initial volumetric and spatial fluid distribution
- Degree of mud-filtrate invasion depends on:
  - Coring bit design
  - Drilling parameters
  - Mud rheological propertie
  - Mud cake
  - Rock properties: porosity, Pc, wettability, Ka and Kr

“Native” Fluid Saturation Alteration Schematics



- “Fresh-State” status of samples when received in the lab
- Are they representative of the reservoir?

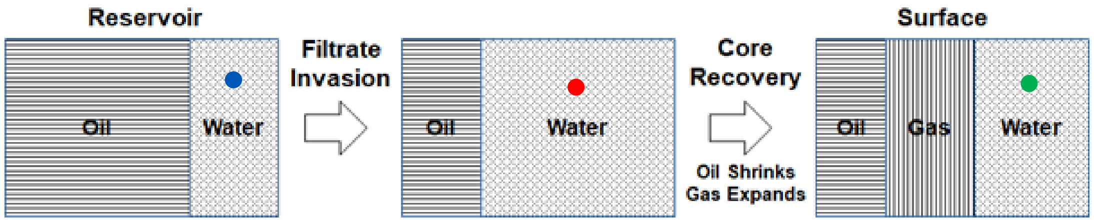
Swir trapped by capillary forces unless IFT is altered (surfactants)

Best case scenario to start a typical lab Wettability test, provided the mud has not altered Native wettability

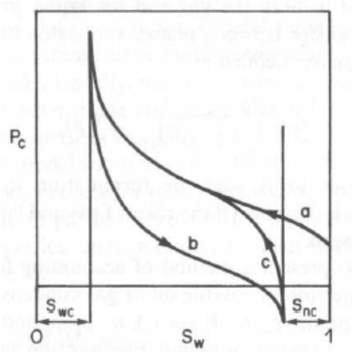
Challenge: most OBM now days contain a water phase 10 – 40 % of the total mud volume !!!! Tracers required, even in OBM

Fluid Saturation Hysteresis - Example

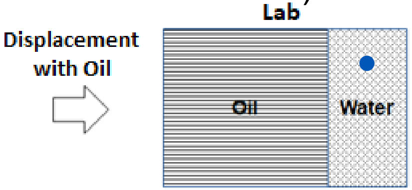
Saturation alteration – WBM invasion in oil reservoir scenario



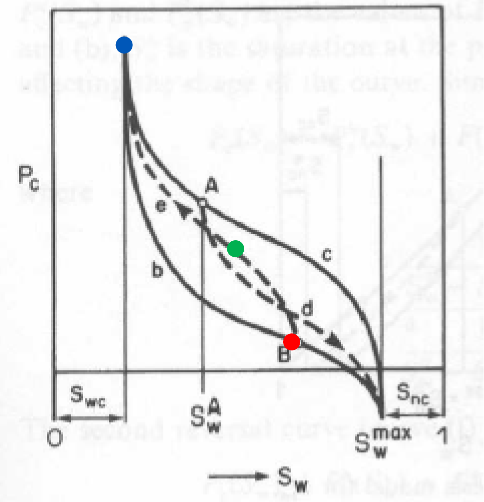
Bounding Drainage and Imbibition Pc Curves (strongly water-wet case)



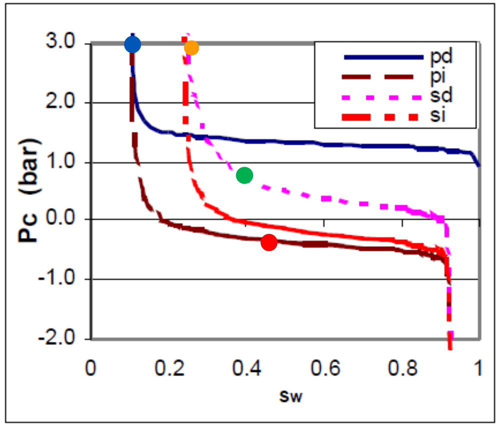
Case 1 – Strongly Water Wet System (Swir may be achieved)



Strongly Water-Wet Case*

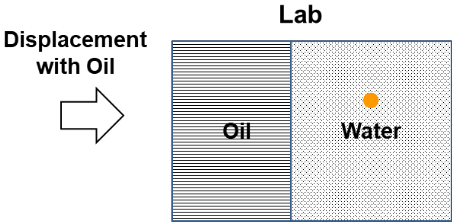


Non-water-wet Case**



Case 2 – Non-Water Wet system

Swir may not be achieved



However, most reservoirs are not strongly water-wet !!

This illustrates the uncertainty of tests run with fresh-state samples

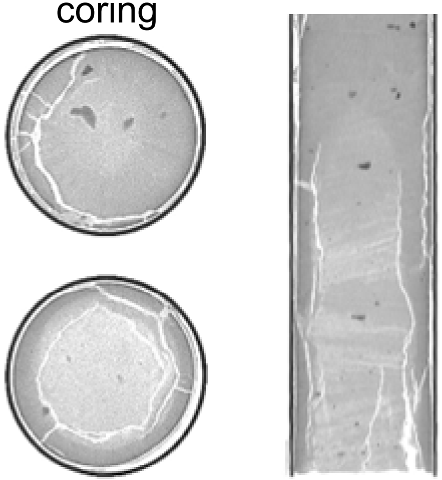
* Aziz and Settari [1979]

** SCA 2001-23. Masalmeh

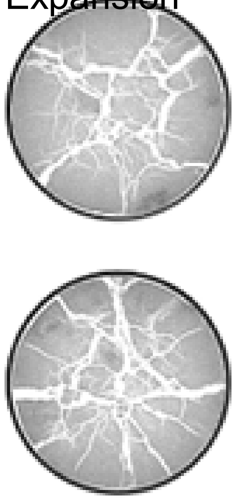
Core Physical Alteration

In addition to fluid saturation and wettability alterations, core physical disturbance can also produce material that is not representative of the reservoir in terms of its petrophysical properties. This may also lead to uncertainty on any measurement carried out in the lab, including the estimation of wettability

Shearing during coring

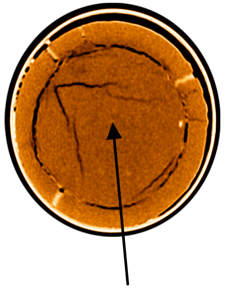


Gas Expansion



Longitudinal Fracturing

Shock Damage



Chevron fracture due to damage in transit/handling

Initial Wetting States Scenarios

- Clean state
  - Starting point to primary drainage tests - any restored state wettability conditioning
  - Reservoir wettability state prior to oil migration
  - Clean state wettability to be included in SCAL (even CCA) programme (as a QC step)
  - If water-wet state on clean samples can't be achieved ---- no further testing (Pc, Kr, etc.) should continue (questionable data)
- Fresh-State (or as received) (not to be confused with Native)
  - Samples at some "uncertain" initial fluid saturation
  - Not recommended to start any SCAL test at this condition --- uncertainty in fluid saturations / representativeness wetting state
  - Recommended to test wettability Fresh State samples (part of wettability study) -- compare against clean and restored state wettability tests
- Restored State
  - Requires fully clean samples --- aiming to achieve a water-wet state (needs checking)
  - Age under oil --- to mimic geological time hydrocarbon migration into the water filled reservoir
  - Starting point to imbibition tests (water displacing oil)
- Native State
  - Arguably no one is certain this state is actually ever achieved (with current technology)

Preparing Representative “Clean State” Samples

- Core Cleaning:
  - Objective: remove oil + water + other contaminants, preserving the rock fabric
  - Should render core samples water wet
  - Water wet condition is a pre-requisite for:
    - Wettability restoration (prior to Kr, Pc imb., wett. Tests)
    - Tests involving a primary drainage cycle
  - Solvent flush (core holder) and total immersion cleaning --- proven effective in removing contaminants, preserving clays
  - Harsh cleaning may remove clay bound water, inducing an oil-wet tendency:
    - Polar oil fractions get access to the rock surface
    - Exacerbated by low initial Sw, long term storage and exposure to air (oxidation)
  - In some cases, extremely harsh cleaning methods and solvents may be required, which balances against the need to preserve the rock’s fabric
  - In any case, the results of the cleaning procedure need to be checked by performing wettability tests in what is believed to be a “Clean-State” samples

Preserving Rock Surface Morphology during Preparation

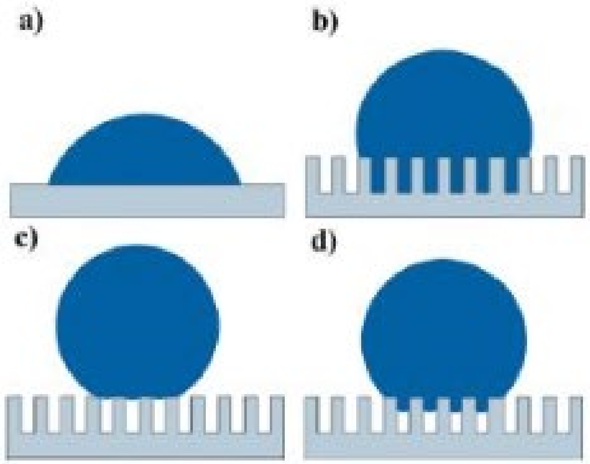


Figure 2. Effect of surface structure on the wetting behavior of solid substrates. a) A liquid drop on a flat substrate (Young's mode). b) Wetted contact between the liquid and the rough substrate (Wenzel's mode). c) Non-wetted contact between the liquid and the rough substrate (Cassie's mode). d) Intermediate state between the Wenzel and the Cassie modes.

Source: Feng et al., *Adv. Mater.*, 18 (2006), 3036-3078

- Alteration of surface roughness also affects the way fluids interact with the rock
- Surface alteration will affect the final wetting tendency and maybe irreversible
- Important to preserve the pore surface structure (clays)
- Key consideration in core preparation process

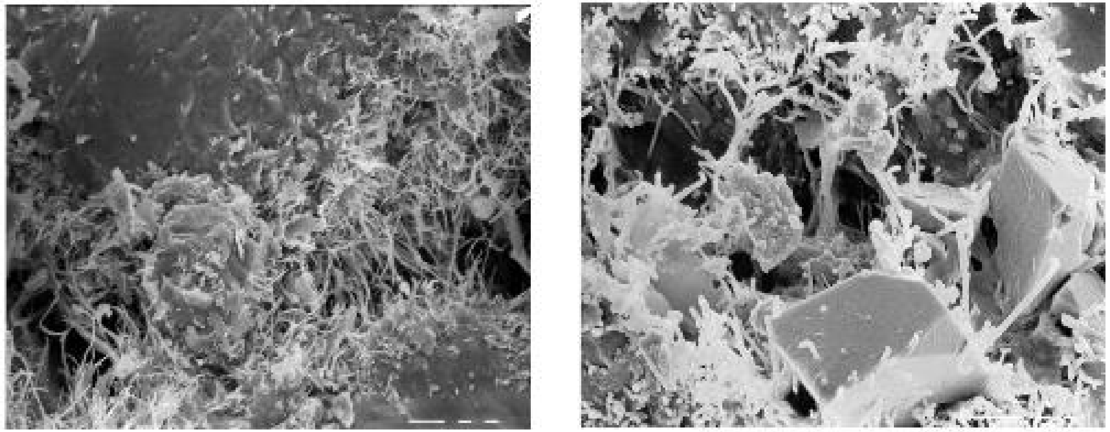


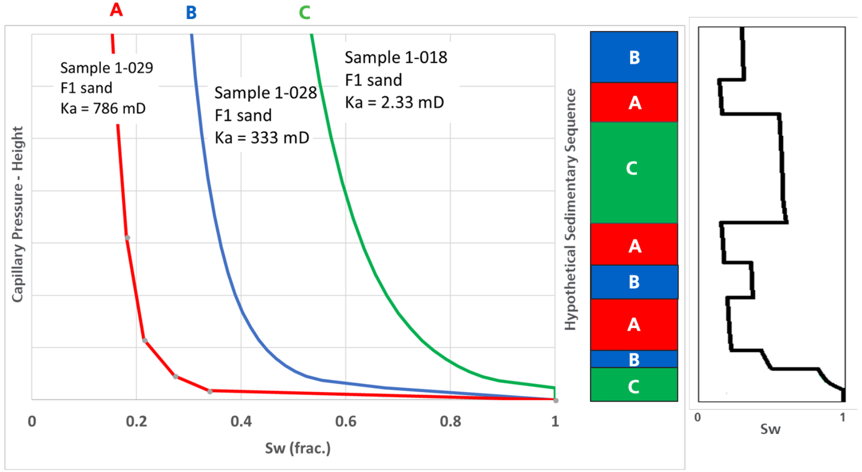
FIGURE 4.22 SEM photomicrograph indicating damage to illite on evaporative drying. *From Byrne and Patey (2004).*

Preparation for Wettability Restoration - Swi

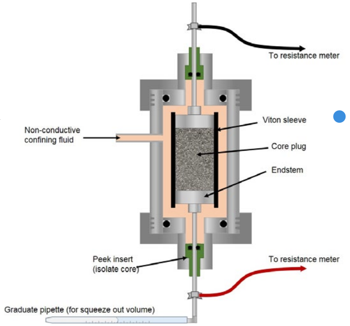
Swi pre-ageing representative of:

- Rock quality
- HAFWL

Requires early input from Sw. vs. H



- *Centrifuge*
  - May not be suitable for delicate samples (tend to fracture)
  - Relatively fast. Preferred method is sample allows (weeks)
  - Samples should be allowed for the non-uniform saturation profile to equilibrate
- *Dynamic Displacement (core holder)*
  - Forces may be too low to achieve target Swi (Sw is normally too high)
  - Applied pressure to achieve Sw is normally not reported
- *Porous plate*
  - Best method as uniform saturation can be achieved
  - Very slow compared to other options (months)



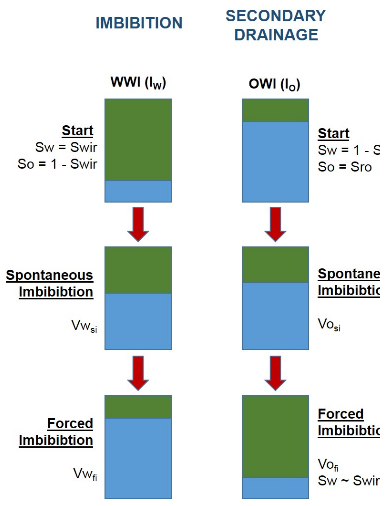
Ageing Time and Fluids for Wettability Restoration

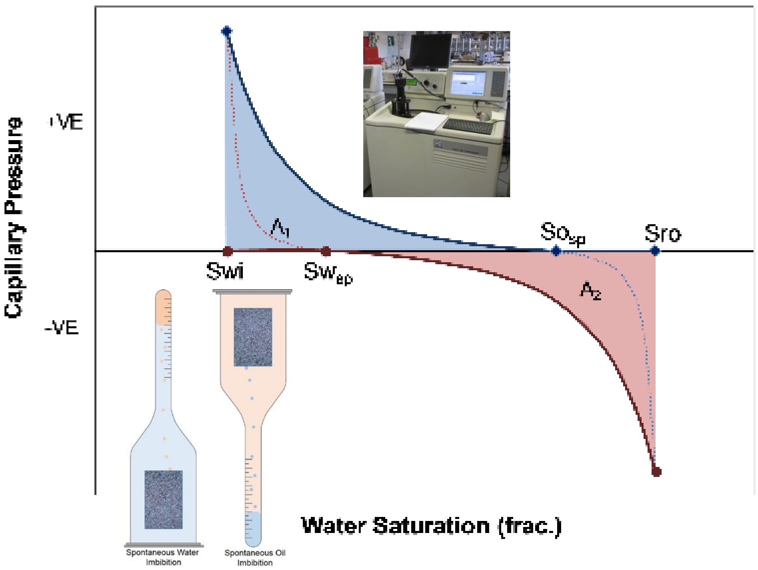
- Ageing time
  - How long?
    - 6h, 6d, 14d, 28d, 40d (1000h), more? Standard is 40 days (always debatable this is enough to mimic millions of years of oil accumulation. Changes for each reservoir)
- Ageing oil
  - Oil samples taken by wireline are often contaminated by wettability altering mud filtrate
  - No reservoir oil available (or not enough) in some cases
  - Use of analogue oils is sometimes the only alternative
- Ageing process
  - Dead or live oil ageing? Depends on the nature of the oil. GOR < 400-500 Mcf/bbl is normally regarded as not requiring life oil ageing
  - Dead ageing (most common) – batch (no injection – can't quantify production)
  - Dead ageing – injection (1 PVI STO/ week) – oscillating direction
  - Live ageing – injection (1 PVI STO/ week) – oscillating direction
    - Expensive, requires skilled lab to recombine the oil (good PVT), prompt to leaks, not all labs have the required capabilities

Wettability Tests

Combined Amott/USBM Method. Challenges:

- Estimating/achieving adequate target Swir
- Applying same energy (Pc) in all forced displacement directions, to avoid bias towards any of the fluids (oil / water)
- Accurate measurement of displaced volumes (reading pixels from centrifuge) (need check against gravimetric saturations)
- Enough stabilisation time for production during spontaneous Amott cycles
- Using average Sw values (not end-face centrifuge calculated Sw)
- Running Dean-Stark (or similar) water saturation check on completion of test recommended
- Dealing with delicate samples, not ideal for the centrifuge





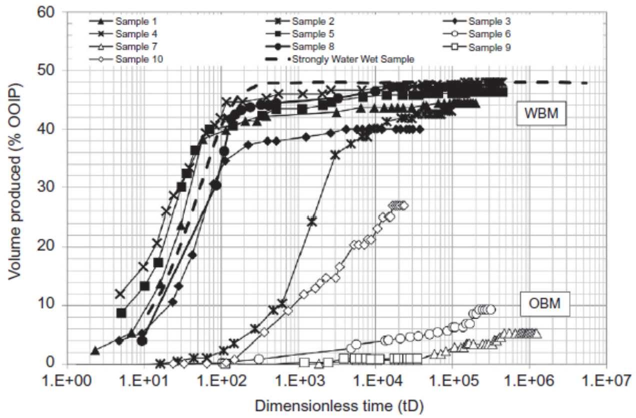


FIGURE 2.40 Imbibition curves for Berea sandstone core treated with different mud systems.

Thanks very much for your attention !!!

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Core Analysis Manager
Principal Consultant
T +44 1224 398353

Lloyd’s Register [Energy]

Kingswells Causeway, Prime Four Business Park, Kingswells

Lloyd’s Register

Working together
for a safer world

Representative conditions in lab

Core preparation workshop

University in Stavanger, 9 May 2019

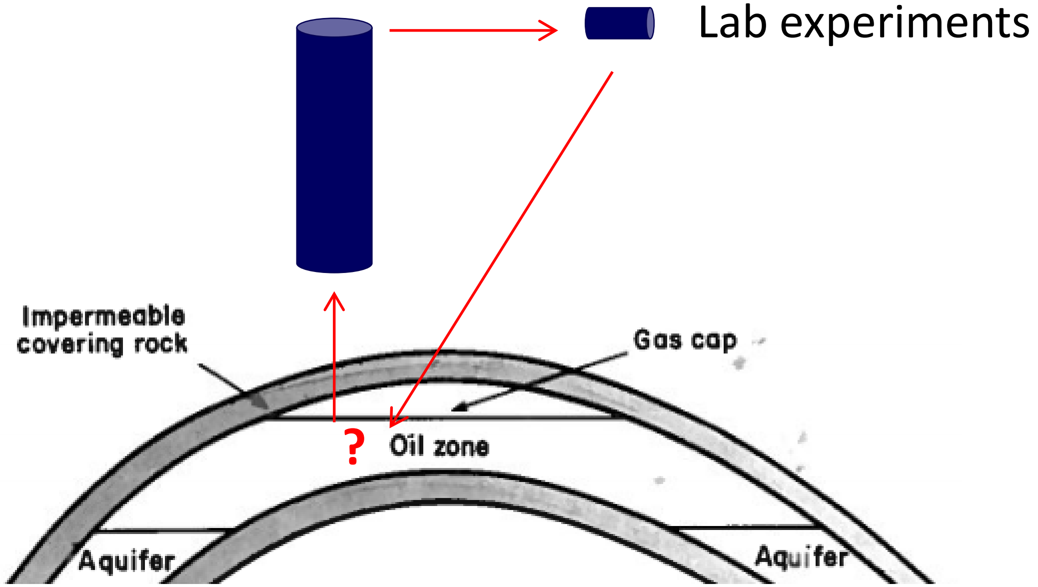
Ingebret Fjelde

Core preparation procedure

- What should be measured?
  - Should this affect the procedure for core preparation
- Which steps are most important?

Samples

- Equilibrium rock-brine-oil at reservoir conditions
- Reservoir rock
  - Change of state during sampling, mud contamination, storage and cleaning
  - Reduction in temperature and pressure, e.g. change solubility
- Crude oil sample
  - Should not be contaminated or oxidized
- Brine composition
  - Can be corrected for mud contamination by tracer

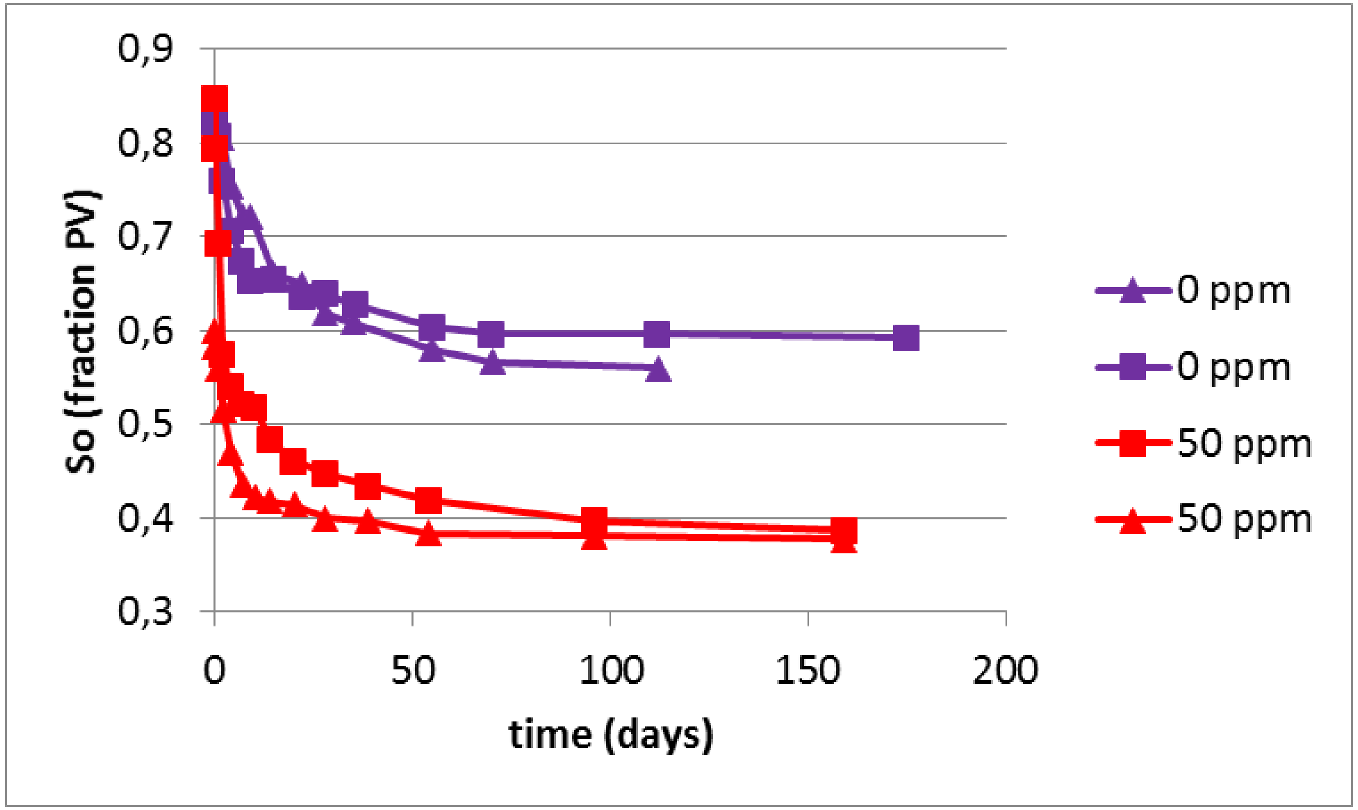


Simplifications understood?

EXAMPLES

- Ions of low concentrations not always included in synthetic formation water
  - Because some ions may cause precipitations or low concentrations assumed to not be important
- Partitioning of polar hydrocarbons of low molecular weight between oil and brine phases
  - Not always included in synthetic formation water, e.g. carboxylic acids
- Partitioning of CO_2 between oil and water phases
  - Can be important for wettability, but not always included in live oil
- Rock cleaning
  - Some of the components adsorbed on original rock may not be present in crude oil sample
- Exchange of fluids
  - E.g. synthetic oil → spacer → STO → live oil

Effect of low sulphate concentration as in real FW on spontaneous imbibition of sea water in chalk



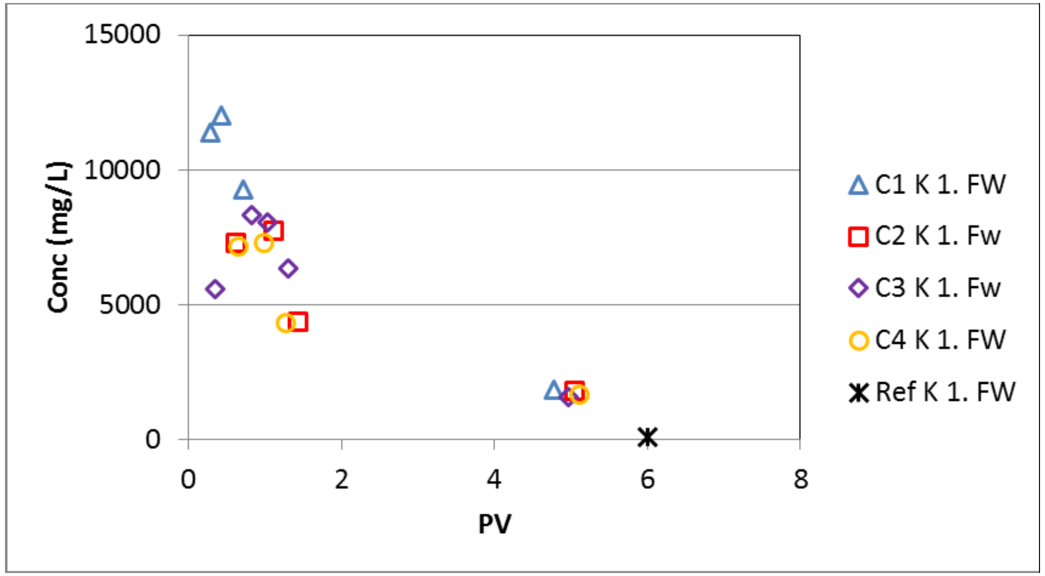
Fjelde, I., Åsen, S.M. Effect of Initial Sulfate in Reservoir Chalks on the Spontaneous Imbibition of Sea Water. 18th European Symposium on Improved Oil Recovery, Dresden, Germany, 14-16 April 2015.

How to reduce the risk for wrong results?

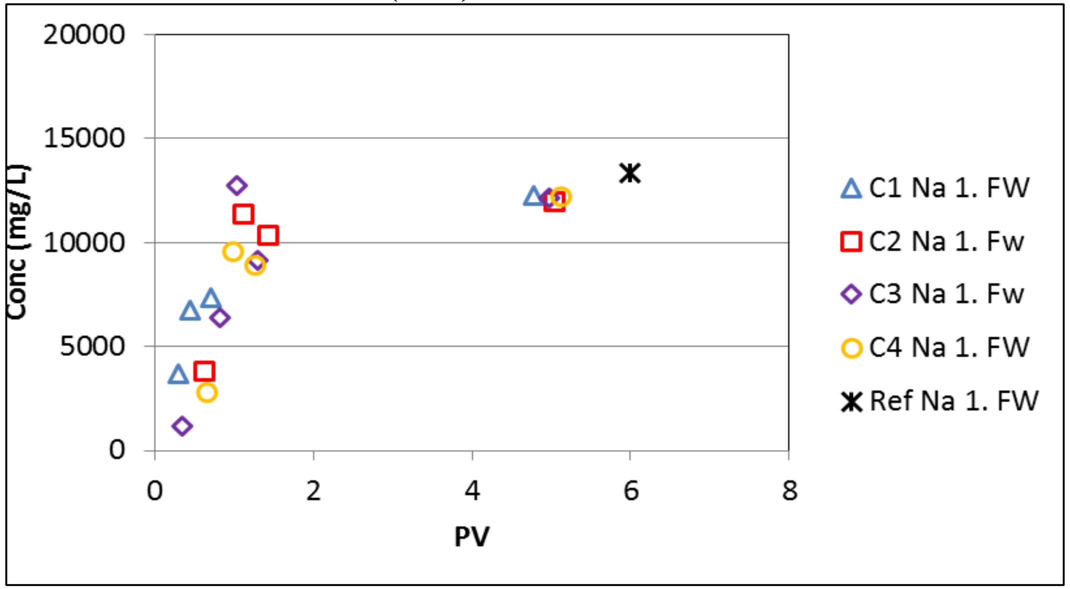
- Better to know where core preparation is started
  - Than to search for reasons after unexpected results are obtained
  - If different starting points, may this cause scattering in results?
- Information about possible contaminations
  - E.g. coring fluid compositions
- Should be determined whether samples contaminated
  - Rock, Oil and Water
  - If contaminated rock, it should ideally not be used
- Should be determined whether contaminations removed during cleaning, e.g.
  - Water-wet rock after cleaning (if not natural insoluble material on rock surfaces)
  - Inject synthetic formation water until effluent composition as injected
  - Rock-analyses (XRD, SEM), e.g. mud particles difficult to remove
  - Analyses of rock extract can prove that organic contaminations are removed

Determine whether mud contamination KCl-mud / SFW before solvent cleaning

Effluent potassium (K) concentration



Effluent sodium (Na) concentration



K first much higher than in SFW

K and S similar profiles

Na first much lower than in SFW

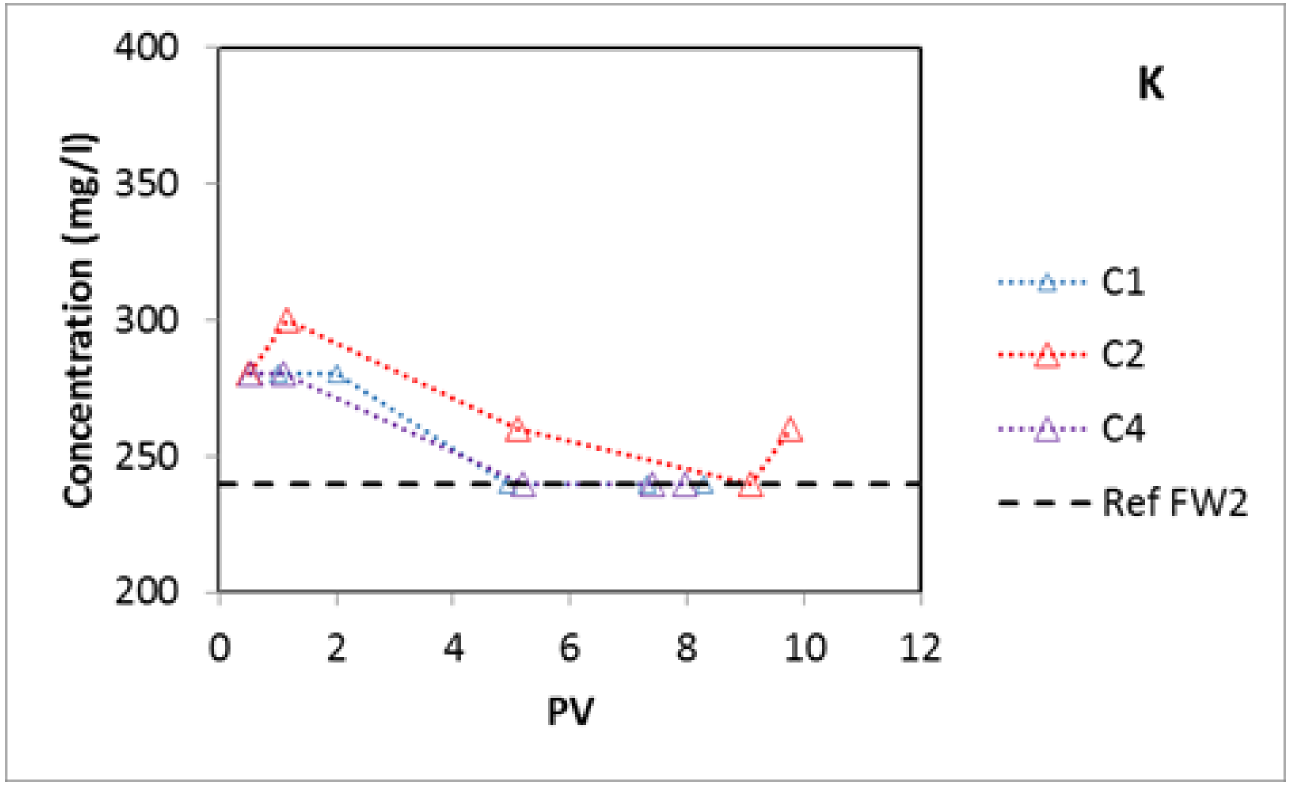
Similar profiles Ca and Mg

Core plugs contaminated by KCl-mud

Fjelde. 2017. 19th European Symposium on Improved Oil Recovery. Stavanger, Norway.

Ionic composition effluent vs SFW
SFW-injection after solvent cleaning

K effluent concentration



Confirmed K concentration became as injected FW

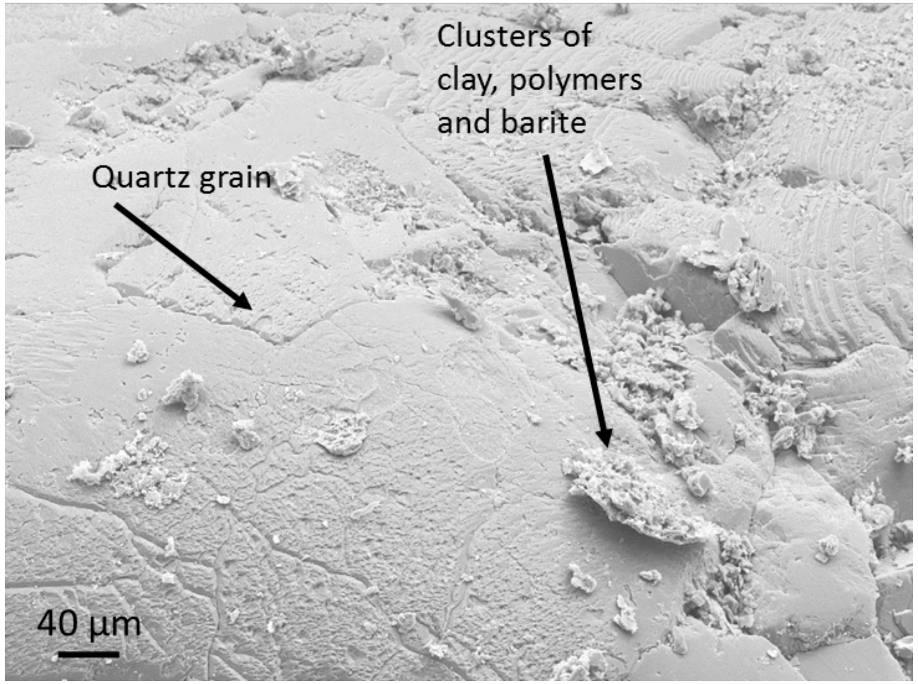
Concentration of other elements in effluent became similar as injected FW

Fjelde. 2017. 19th European Symposium on Improved Oil Recovery. Stavanger, Norway.

Mud particle invasion: Cleaned rock / SEM

NORCE

Rock crushed and freeze-dried



Element composition based on EDS-spectra

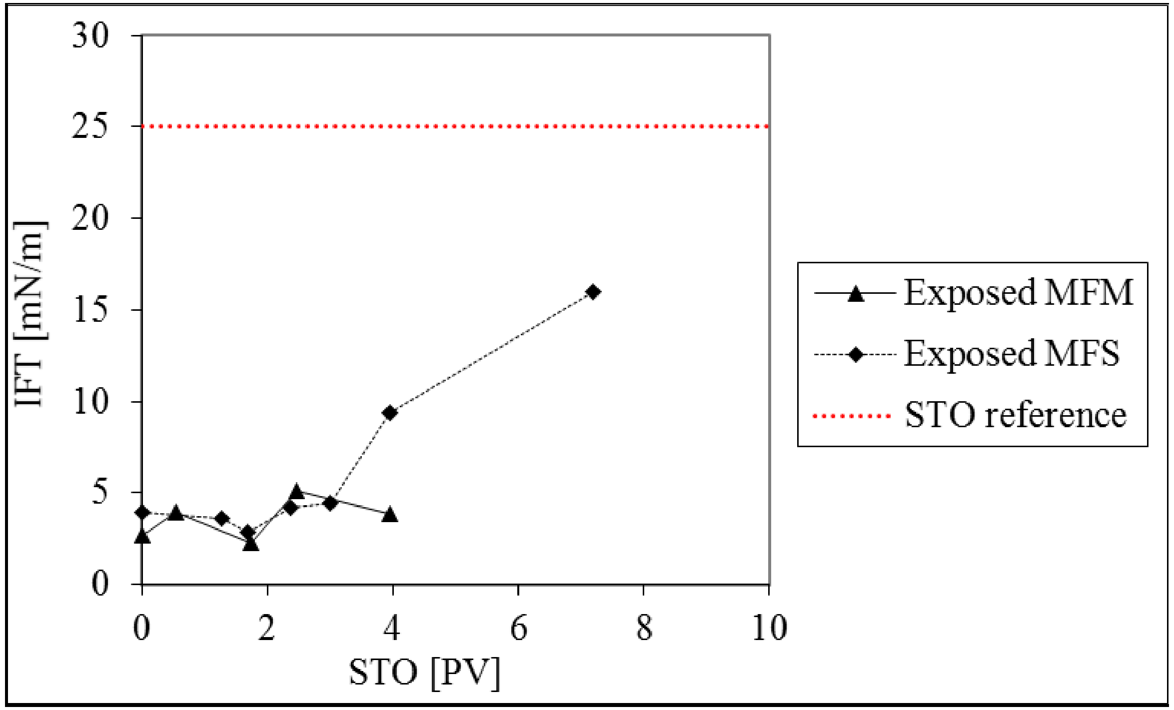
Element	Inlet	Mid	Outlet
O	36.3	37.7	38.5
Na	1.2	0.6	0.4
Mg	0.1	0.1	0.2
Al	6.9	6.6	5.4
Si	45.5	43.6	45.2
S	1.0	0.9	1.0
K	3.8	5.3	4.0
Ba	3.7	3.5	3.5
Fe	1.5	1.8	1.8

- Mud components not removed
- Invasion particles and polymers can reduce permeability
- Invasion particles, especially clay, will increase surface area and may affect established wettability

Fjelde, Omekeh and Minde. 2015. SCA2015-016. St. John's Newfoundland and Labrador, Canada.

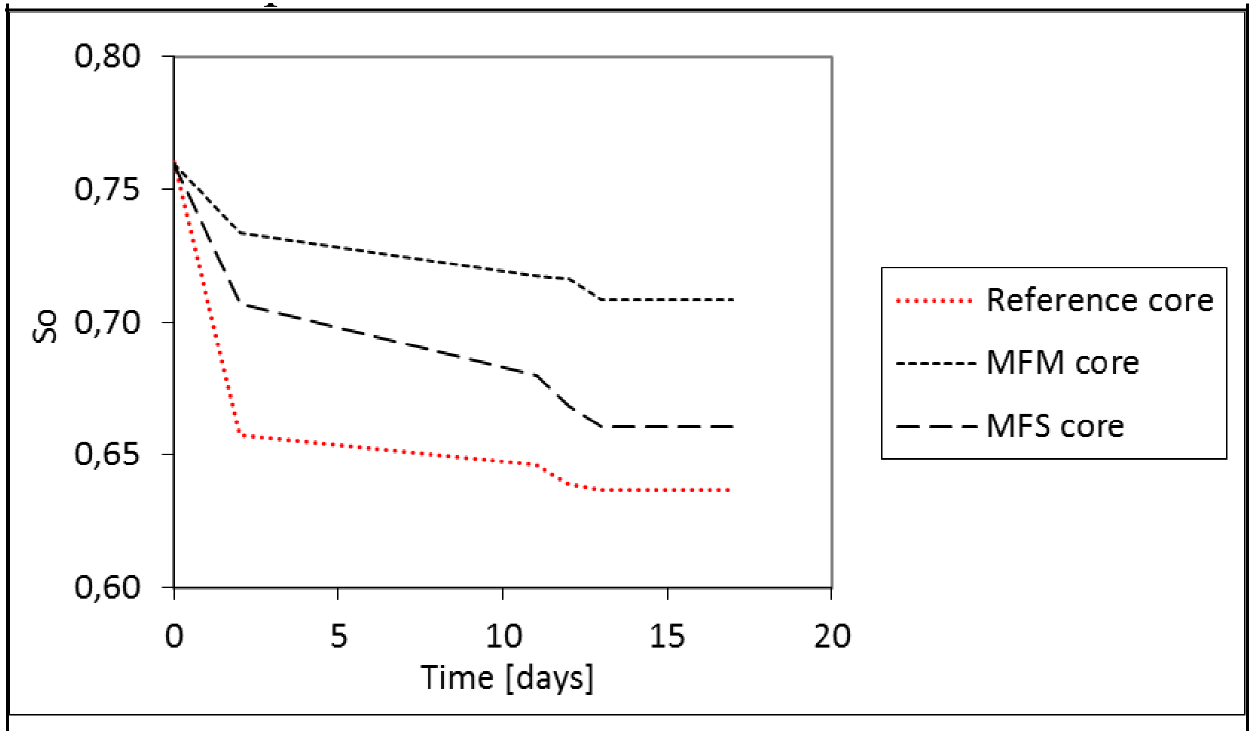
OBM STO injection / IFT

IFT between effluent samples and SFW



MFM = Mud Filtrate Mineral base oil
MFS = Mud Filtrate Synthetic base oil

Spontaneous imbibition SFW

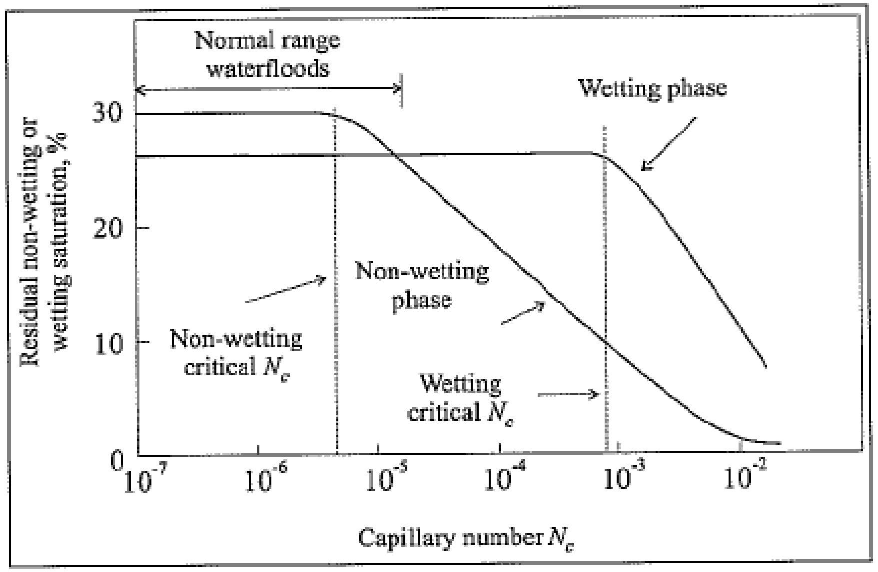


Core plugs exposed to MF less water-wet

Fjelde, Omekeh and Minde. 2015. SCA2015-016. St. John's Newfoundland and Labrador, Canada.

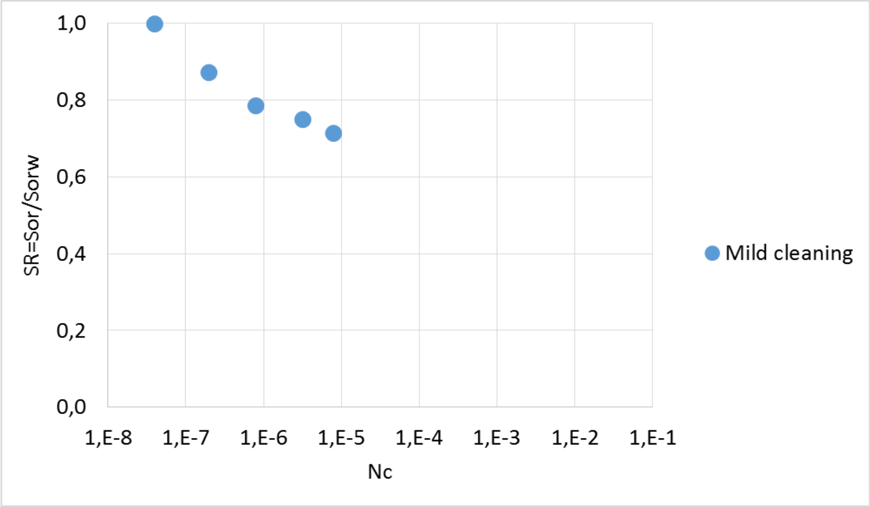
OBM / Capillary Desaturation Curve
Unexpected results are not necessarily wrong

Water-wet rock expected in project

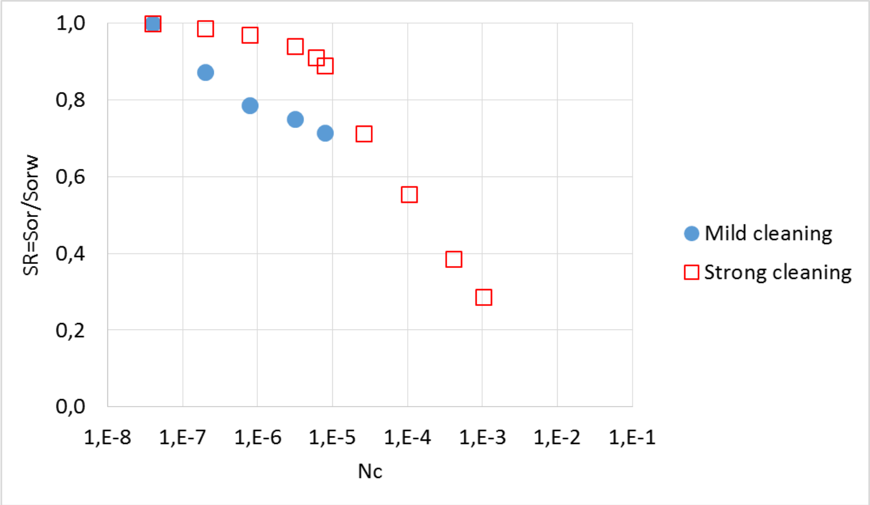


Fjelde, Omekeh and Minde. 2015. SCA2015-016.
St. John's Newfoundland and Labrador, Canada.

Mild cleaning: Unexpected CDC



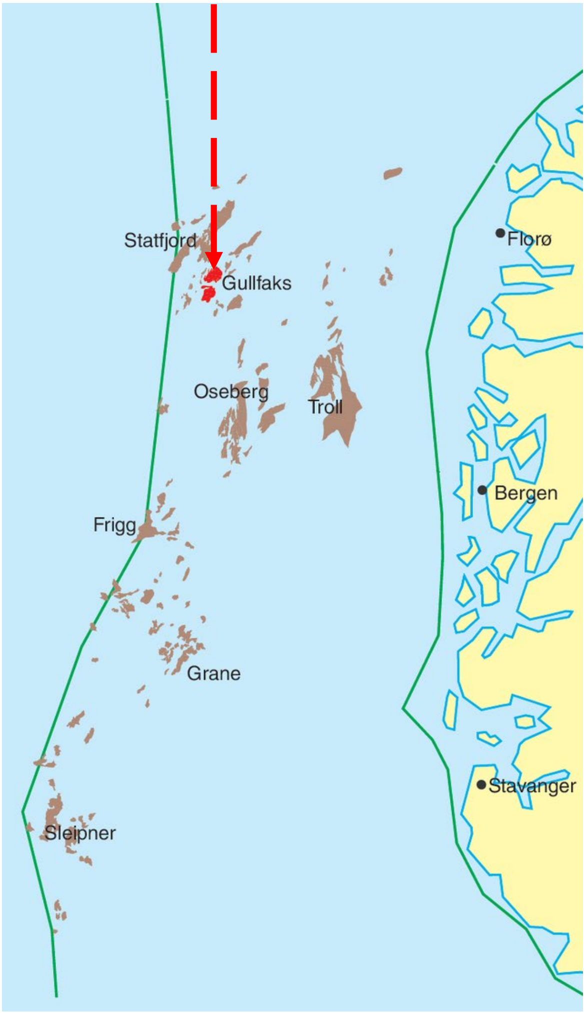
Strong cleaning including acetic acid: CDC as expected



Rock composition probably altered by acetic acid

Gullfaks – Surfactant flooding

- First
  - Remaining Oil Saturation (ROS) estimates up to 0.35 and surfactant flooding (SF) extensively studied (Maldal et al. 1998)
  - For several reasons, SF not implemented
- Later
  - ROS < 0.20 in high permeability zones of Gullfaks and Statfjord (Maldal et al. 1998)
  - Earlier too high ROS-estimates because original wettability not preserved or restored in experiments or results not correctly scaled (Maldal et al., 1999)
- Incorrect input from experiments could have led to a costly EOR project, which would not have been approved with correct data



Reasonable results?

- Unexpected results can be correct, e.g.
  - Sandstone rocks (previous slide)
  - All carbonate rocks are not oil-wet, e.g. chalk
  - Textbooks not always correct
  - Unexpected results should be confirm, i.e. not just rejected
- Compare results with other information
  - Reservoir information
  - Similar reservoirs and try to explain the differences
- Geochemical simulations, e.g.
  - Potential for adsorption of polar oil components
  - Variation in potential for adsorption with different mineral compositions/distributions
    - Example: Why should core plugs with similar mineral compositions give different results when same crude oil and formation water used?

Missing

- Standard procedures to show that representative materials are used in core preparation
  - Uncontaminated rock and oil samples
- Representative compositions of fluids
  - Importance of polar oil components of low MW and ions of low concentrations, and CO_2, not completely understood
- Reasonable results
  - Procedure
- Comparison of saturation functions for native and restored reservoir core plugs
- Effects of mud contamination on results
- Effects of mud contamination on upscaled properties

NORCE

University of Stavanger

The National IOR Centre of Norway

Thank you

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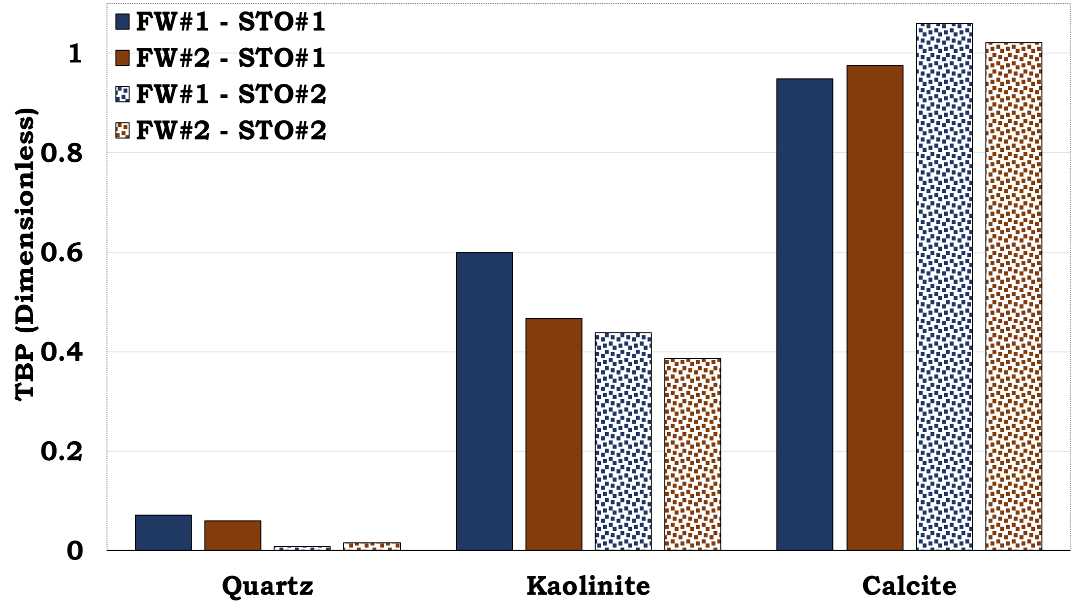
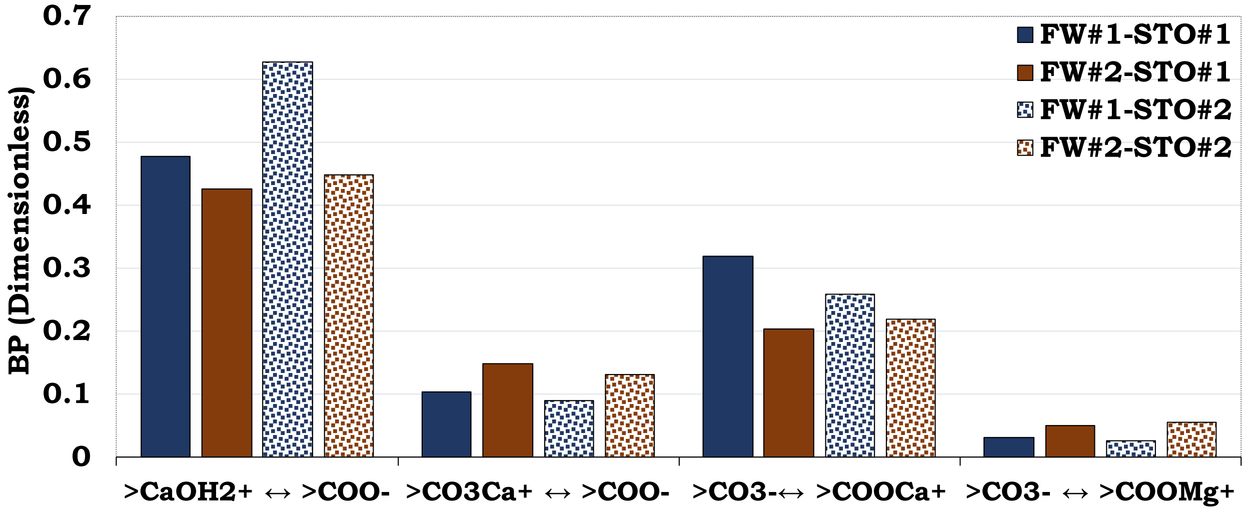
Geochemical modelling of crude oil-brine-rock (COBR) interactions

NORCE

Electrostatic interactions by Surface Complexation Modelling

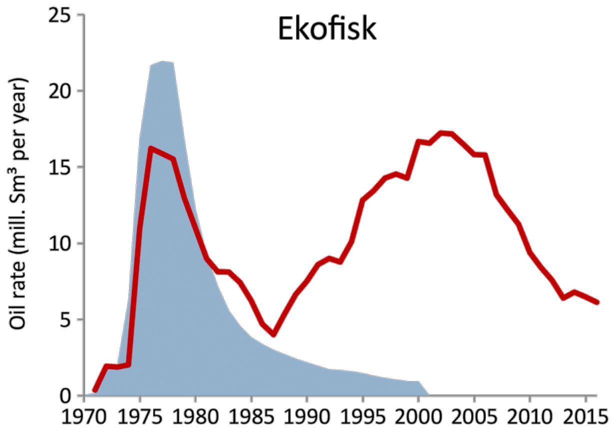


Calcite: Interaction mechanisms



Ekofisk – Water flooding (WF)

- First
  - Pressure depletion estimate 18 OOIP%
  - Based on experiments, concluded WF would not improve recovery
- Later
  - Pilots much higher recovery than estimated
  - Increased suspicion against laboratory results (Sylte et al., 1988; Sulak, 1991)
- Low sulphate concentration as in real formation water → more water-wet conditions (Fjelde and Asen, 2015)
- Current recovery estimate 50 %OOIP
- If first conclusion final, income due to WF would have been lost



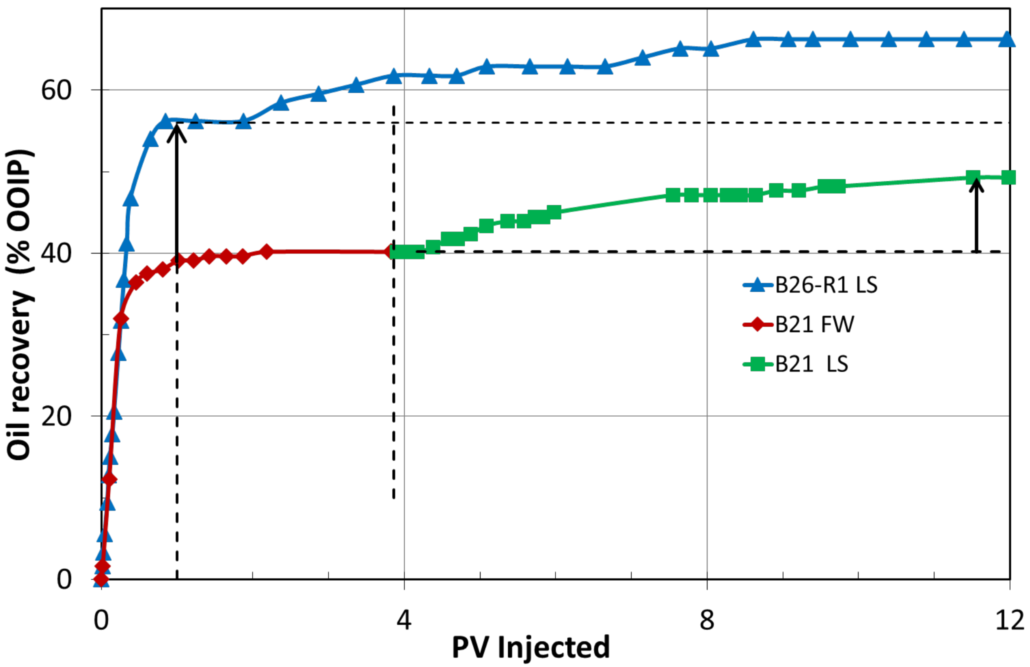
CORE HANDLING: FROM RESERVOIR TO RELIABLE LABORATORY RESULTS

Skule Strand, Tina Puntervold

Smart Water
EOR Group

Universitetet i Stavanger

«SMART WATER» INJECTION IN SANDSTONE



- Total outcrop cores B26 and B21
  - S_{wi} = 0.2 with FW
  - Exposed to T-Oil (BN = 1.9)
- Oil recovery test on core B21 at 60 °C
  - Secondary FW injection, 4 PV/D
  - Tertiary LS injection, 4 PV/D
- Oil recovery test on core B26 at 60 °C
  - Secondary LS injection, 4 PV/D

Temp (°C)	T-Oil (cP)	FW (cP)	LS (cP)	(μ_o/μ_{wFW})	(μ_o/μ_{wLS})
60	4.5	0.63	0.60	7.29	7.65

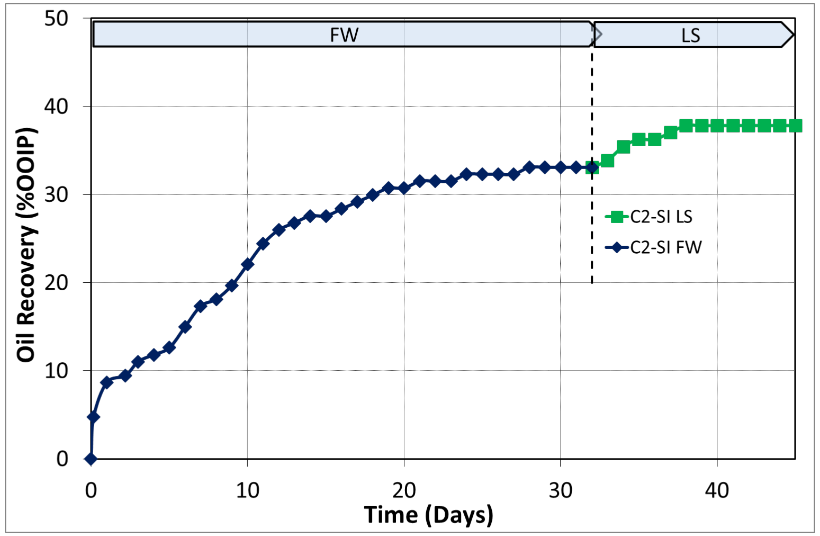
Ref.: Piñerez Torrijos et.al
E&F 30 (2016) p.4733–4739

- No chemical induced wettability alteration during FW flooding - 40 %OOIP
- Tertiary LS recovery 49 %OOIP (NB! Could not be explained by mobility ratios)
- Secondary LS Recovery; - 58% OOIP (after 1 PV) – 66 %OOIP (Recovery plateau)
  - ➢ > 50 % extra oil compared to FW

Smart Water
EOR Group

WETTABILITY AND WETTABILITY ALTERATION IN SANDSTONE

SI for core wettability evaluation



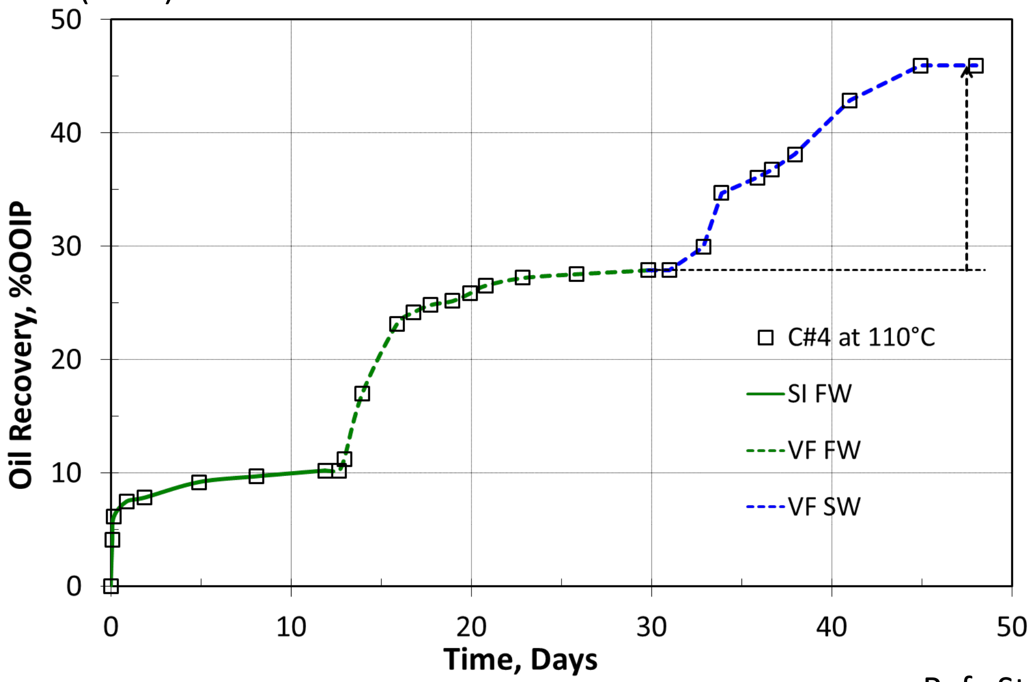
- Total outcrop core# C2
  - 10% Clay and 30 % Albite
  - S_{wi} =20% FW,
  - Sat and aged at 60°C in Crude Oil (BN =1.9)
- Spontaneous imbibition (SI) at 60 °C
  - FW – LS

- SI with FW gives 33 %OOIP (after 32 days)
  - Restored core behaves quite / slightly water wet
- SI with LS gives 38 %OOIP after 6 days (5 %OOIP Extra oil)
  - Significant (5 %OOIP Extra oil) improvement in oil recovery

➢ The SI tests confirms
- Capillary forces are important in fluid displacement
- LS brine induce wettability alteration and increases the ultimate oil recovery

Smart Water
EOR Group

Seawater (SW) as a smart water in Chalk:



- Chalk core
  - S_{wi}=0.1, Crude oil (AN=1.9 mg KOH/g.)
- SI with FW at 110°C
- Viscos flooding at 110°C (low flow rate)
  - FW
  - SW

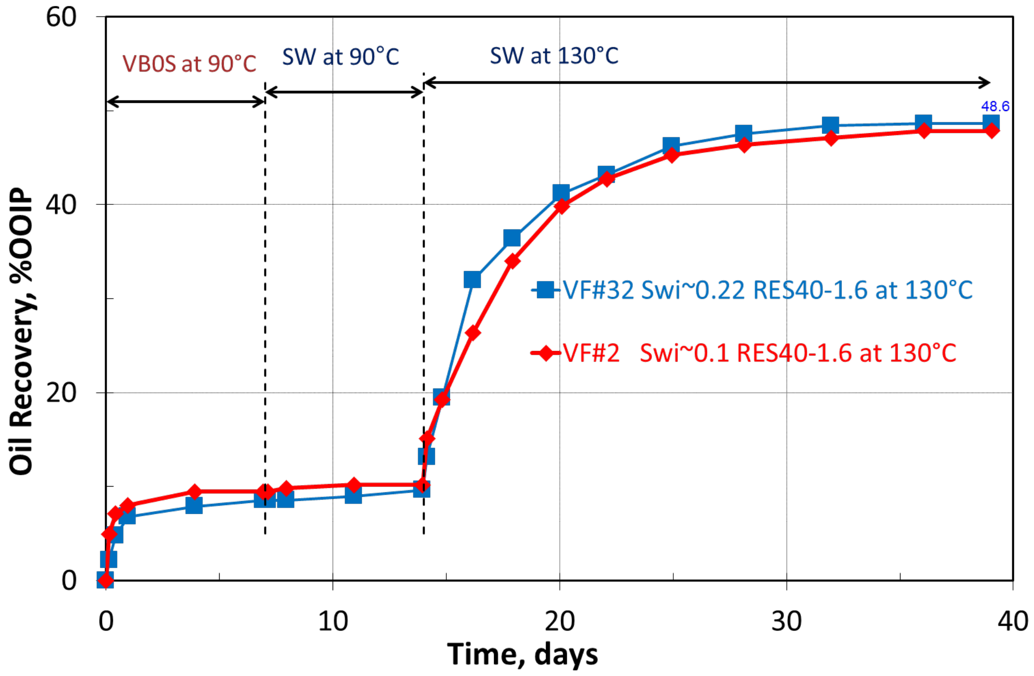
Ref.: Strand et al
E&F 22 (2008) p.3222–3225

- SI with FW
  - fractional intermediate Initial wetting
- Viscous Flooding (FI)
  - FW gave an ultimate recovery plateau of 26% OOIP
  - SW improved the displacement efficiency to 47 %OOIP

➢ SW behaves as a Smart Water and Enhance oil recovery

Smart Water
EOR Group

Seawater (SW) as a smart water in Chalk:



- 2 SK outcrop chalk cores restored
  - S_{wi}=0.1, Crude oil (AN=1.6mg KOH/g.)
  - S_{wi}=0.22, Crude oil (AN=1.6mg KOH/g.)
- SI at 90 and 130 °C
  - VB0S as FW
  - SW

Ref.: Puntervold et al
E&F 21 (2007) p 3425-3430

- SI with FW (VB0S)
  - Very good reproducibility ~10 %OOIP
  - Initial wetting – fractional (neutral to oil wet)
- SI with SW at 90 °C
  - No extra oil within 7 days
- SI with SW at 130 °C
  - SW improved the displacement efficiency to 47 %OOIP

➢ SW behaves as a Smart Water at high temperature
➢ Reproducible experimental results

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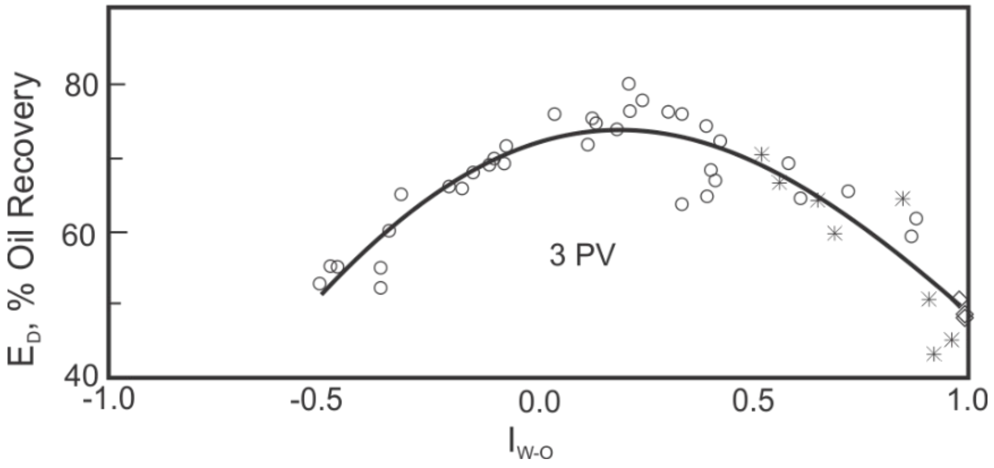
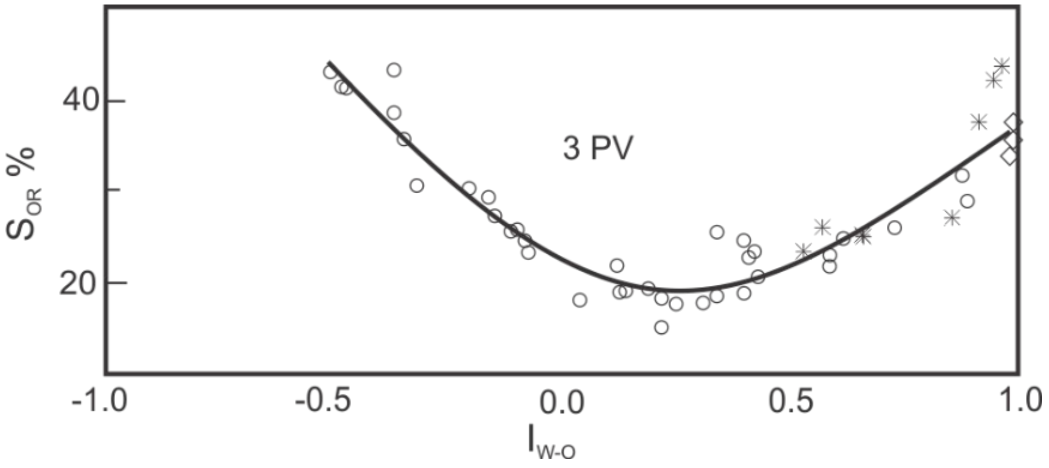
General accepted understanding of Oil recovery during water flooding:





Ref.:
Jadhunandan and Morrow
SPE-22597 (1995)

- Highest Oil recovery / Lowest S_{or} at Slightly water-wet conditions

➢ Not in line with Smart Water observations

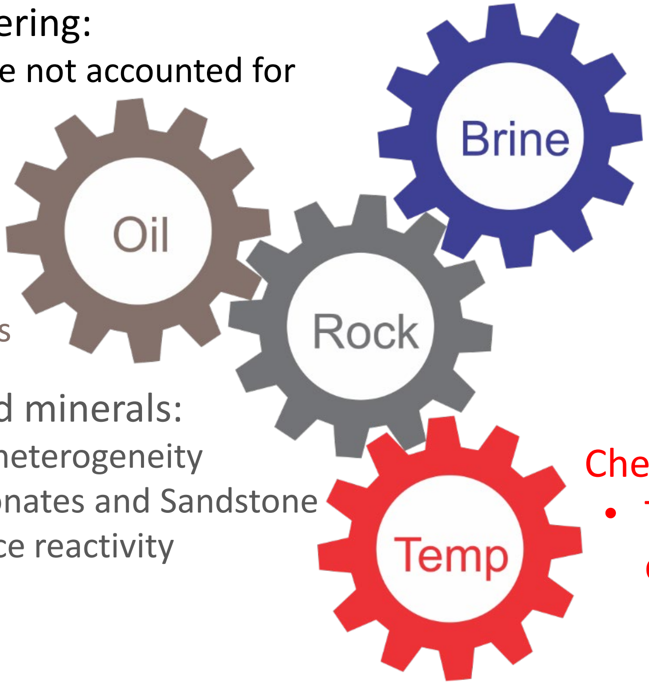
Reservoirs consist of pore systems with Mineral surfaces, Brine, and Crude Oil.

Classical reservoir engineering:

- The 3 reservoir phases are not accounted for

Crude Oil:

- Polar acids
- Polar bases
- Resins
- Asphaltenes



Formation Water and injection Brines:

- Salinity
- Ion composition

Rock and minerals:

- Pore heterogeneity
- Carbonates and Sandstone
- Surface reactivity

Chemical reactivity:

- Temperature dependent

✓ Improved understanding of Reservoir Chemistry are needed

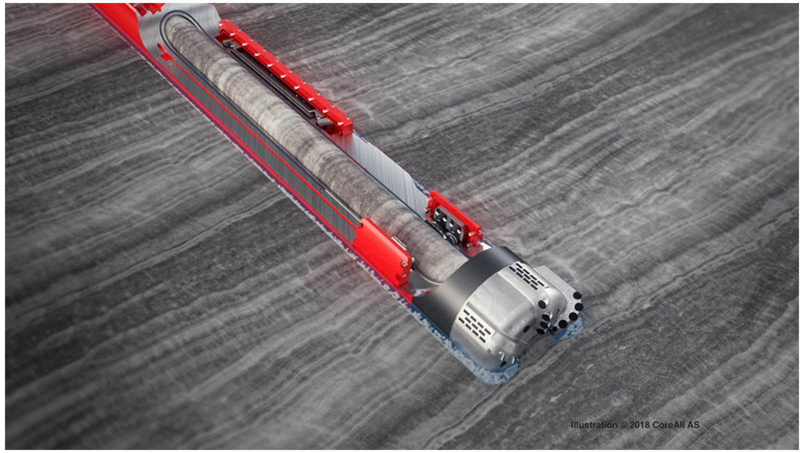
✓ Crude oil – Brine - Rock (CoBR) integrations effects:

  – pH
  – Initial Reservoir wettability
  – Fluid flow in porous media and reservoirs
  – Wettability alterations by «Smart Water»
  – Scaling

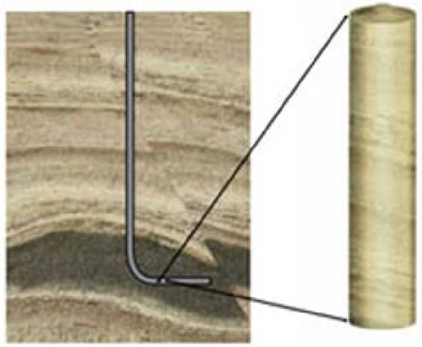
CORE HANDLING - FROM RESERVOIR TO RELIABLE EXPERIMENTAL RESULTS IN LABORATORY

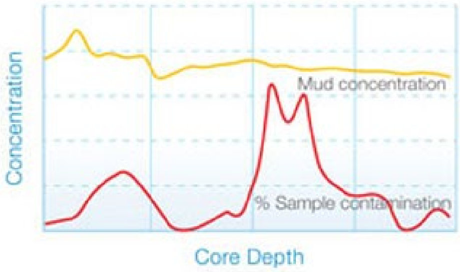
Parameters affecting core restoration of reservoir cores:

- Core sampling
  - Coring
  - Core handling
  - Preservation of reservoir cores
  - Core storage



- Laboratory core handling responsibility of the laboratories/oil companies
  - Core cleaning
  - Core restoration
    - S_{wi}
    - Exposure to Crude oil
  - Core experiments





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Laboratory core restoration :

- **Main goal**
  - Restored core wetting / conditions close to reservoir conditions

- **At least**
  - Comparable/reproducible experimental results
    - In between restorations on the same core
    - In between different / twin /sister cores

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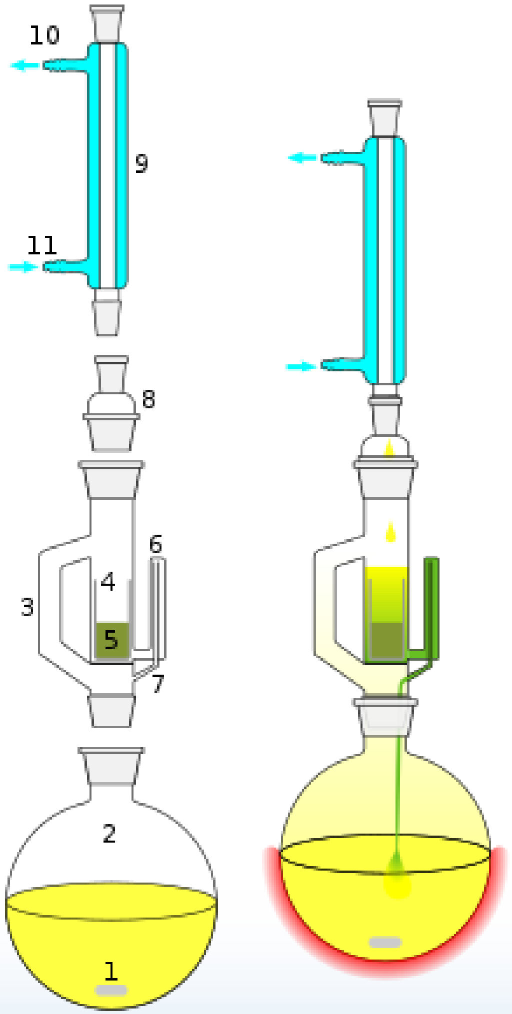
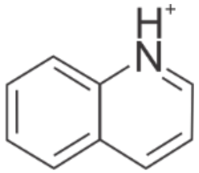
Parameters affecting properties of reservoir cores during restoration:

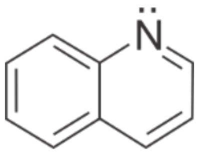
- Core cleaning :
  - Standard cleaning – Complete water wet state
    - Solvents for optimized cleaning
      - Toluene / Methanol
    - Soxhlet extraction
    - Core flooding
  - Water injection could remove easily dissolvable minerals that are part of important reservoir minerals
  - Mild core cleaning
    - Preserving reservoir wettability
    - Prevent redistribution of polar components in the pore system



Parameters affecting properties of reservoir cores during restoration:

- Core restoration:
  - Establishing initial water saturation (S_{wi})
    - Ion composition of FW
    - Crude oil flooding
    - Centrifuge
    - Porous plate
    - Desiccator
  - Introducing the Oil phase
    - Crude oil effects /controls initial core wettability
      - Fluid/Rock pH
      - Amount of crude oil
      - Aging
      - Dynamic aging
    - Displacing crude oil with mineral oil





Low pH High pH

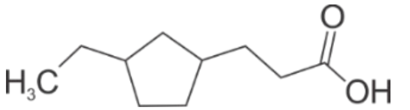
$$R_3NH^+ \rightleftarrows H^+ + R_3N:$$

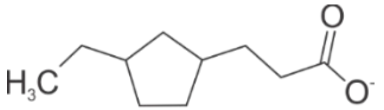
pKa ~ 4..5 – 5.5

Low pH High pH

$$RCOOH \rightleftarrows H^+ + RCOO^-$$

pK_a ~ 4.0 – 4.5





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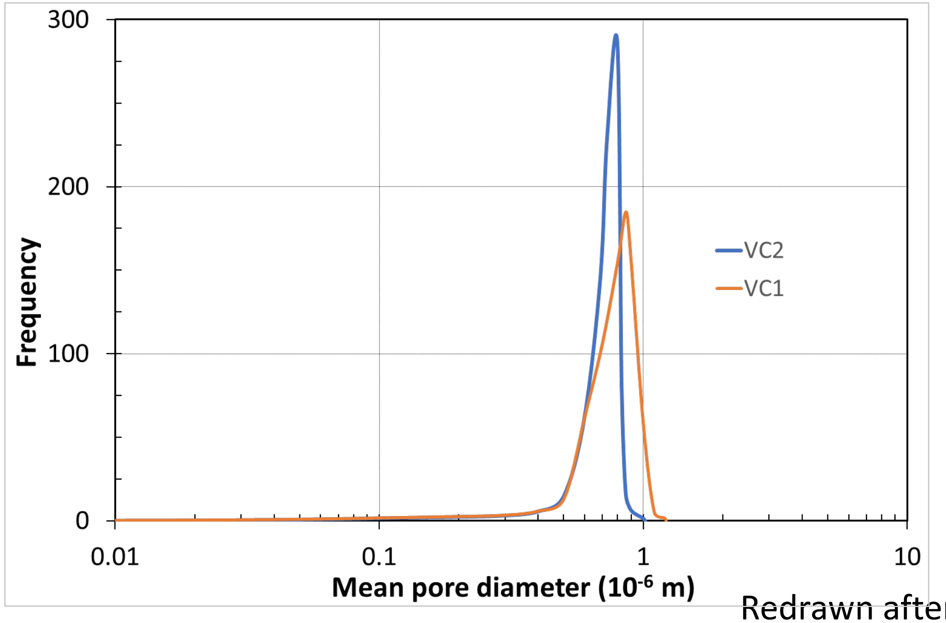
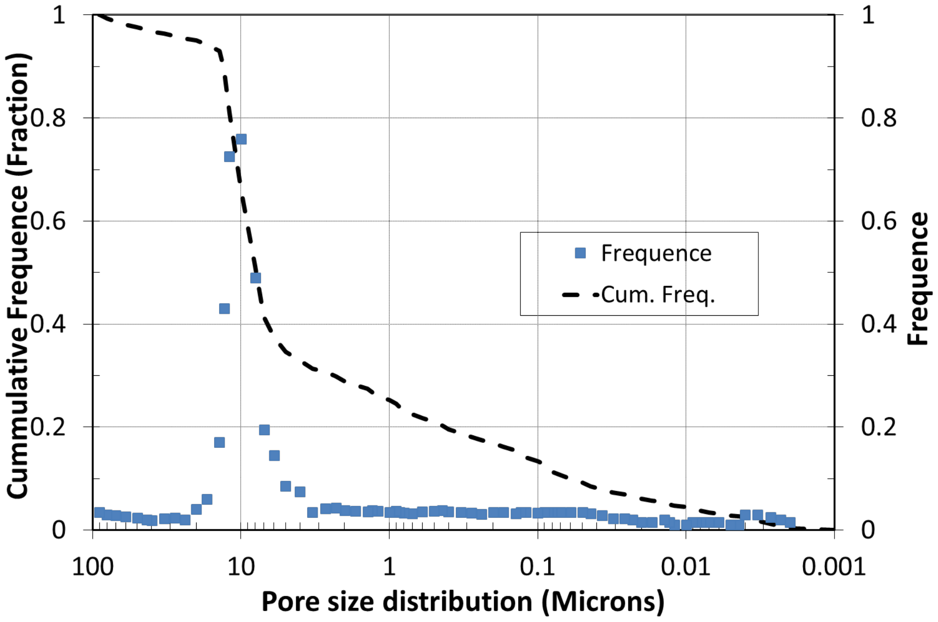
WHAT WE KNOW - PORE DISTRIBUTION

Mercury (Hg) injection rock samples:



Redrawn after Webb et al.
IPTC 10506 (2005) Doha



- Heterogeneous pore distribution in reservoir chalk
  - From 100 nm – more than 1 µm

- Heterogeneous pore distribution in sandstone
  - From less than 2 nm – 100 µm

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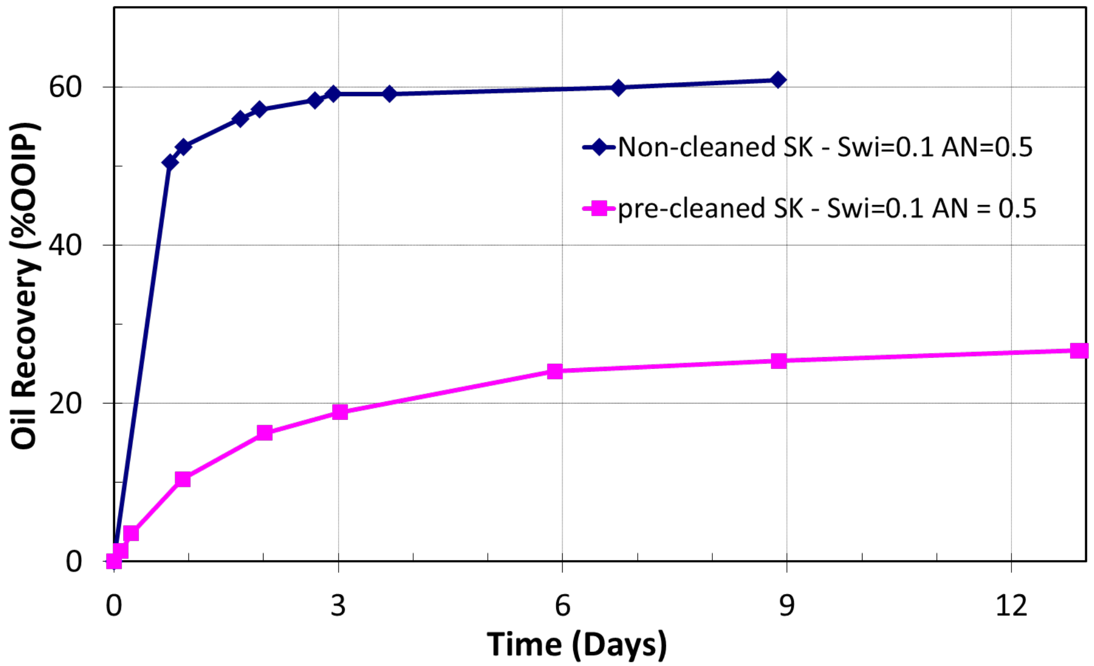
Effect of core cleaning on initial wettability:



- 2 SK cores restored
  - 1 non precleared core
  - 1 precleared core with 4 PV DI water (removal of initial salts, SO_4^{2-})
  - S_{wi} =10% using VB0S
  - Exposed (5PV) and aged in Crude Oil with AN = 0.5
- Spontaneous imbibition with FW (VB0S) at 90 °C
  - Effect of initial salt removal, especially SO_4^{2-}

Ref.: Puntervold et al
E&F 21 (2007) 6, p.3425-3430

- ➢ Non-cleaned SK cores containing SO_4^{2-} behaved very water wet
  - Ultimate recovery of 60 %OOIP after 3 days
- ➢ Large reduction in water wetness on cleaned cores
  - Ulimate recovery of 26 %OOIP after 12 days

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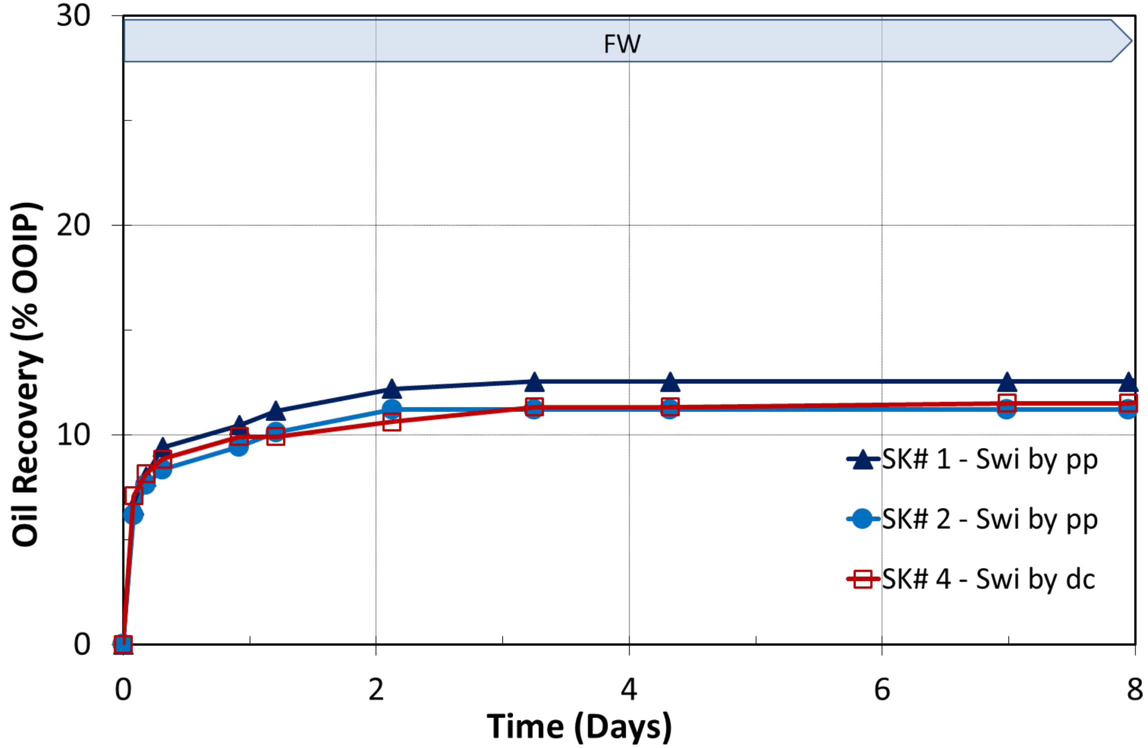
WHAT WE KNOW – ESTABLISHING S_{wi} BY POROUS PLATE AND DESICCATOR

Effect of initial water saturation (S_{wi})-techniques on initial wetting:



- 4 SK cores restored
  - S_{wi} =10% with FW (VB0S)
    - Desiccator (dc)
    - Porous plate (pp)
  - Crude Oil exposure (AN = 1.8 mgKOH/g)
    - Vacuum sat.
    - 2 PV flooded in each direction
    - Aging at 110 °C for 14 days
- Spontaneous imbibition SI at 110 °C
  - FW

➢ Reproducible initial wetting – S_{wi} established by :

- Desiccator (dc)
- Porous plate (pp)

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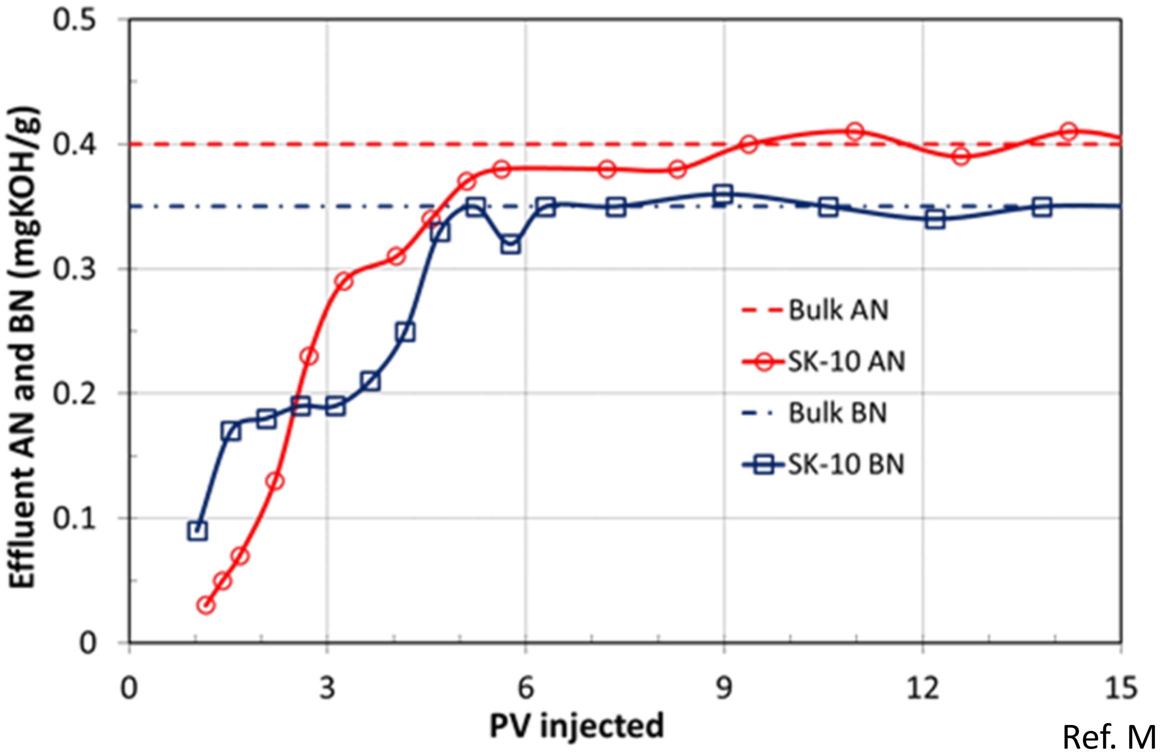
WHAT WE KNOW - ADSORPTION OF POLAR CRUDE OIL COMPONENTS IN CHALK

Adsorption of Acidic and Basic polar organic components (POC) :



- SK chalk core
  - SK-10 ; S_{wi} = 10% FW (VB0S)
- Crude oil flooded 15 PV at 50 °C
  - AN = 0.40 and BN = 0.35 mgKOH/g oil
- Produced oil samples analyzed for POC

Ref. Mjos el al.
SPE 190414 (2018)

- Immediately adsorption of polar crude oil components
- Acids effects the wetting more than bases
- Acid adsorption more important than aging
- Amount of crude oil during core restoration effects initial wetting

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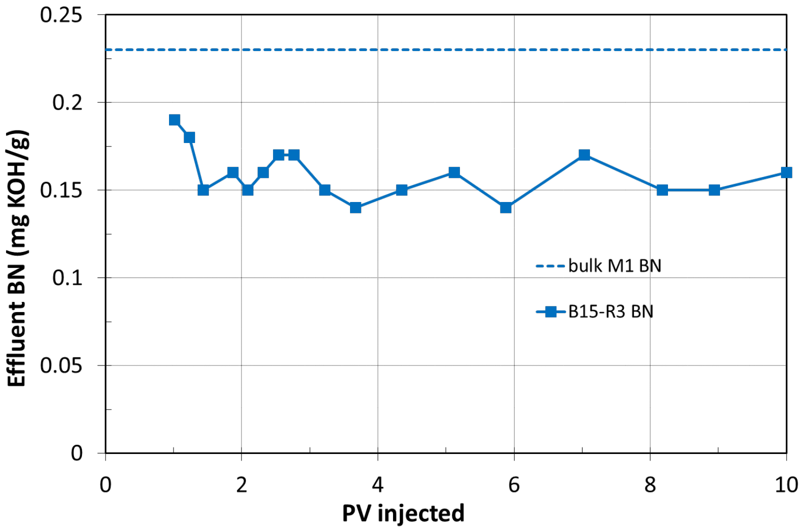
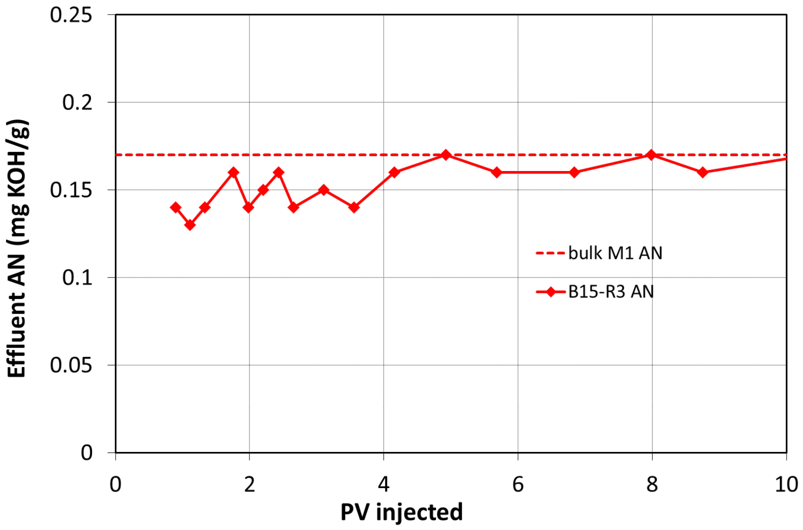
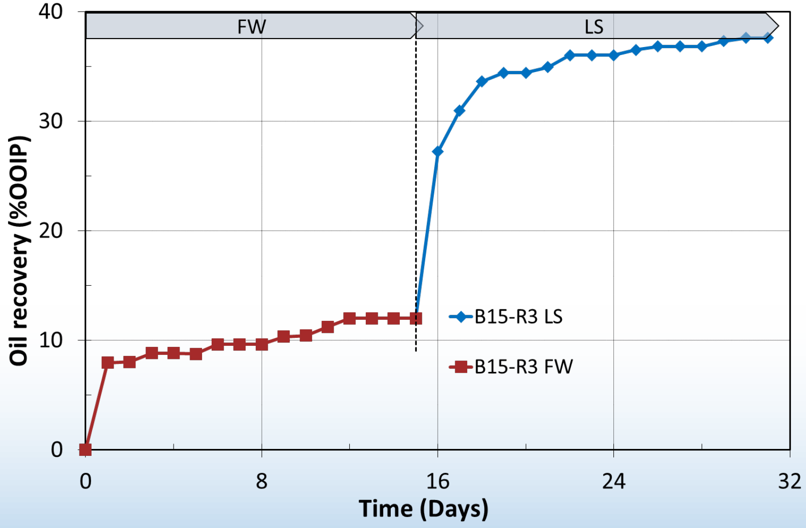
WHAT WE KNOW - ADSORPTION OF POLAR ORGANIC COMPONENTS (POC) IN SANDSTONE

Adsorption of Acidic and Basic polar crude oil components





- Total outcrop sandstone
  - Quartz, 10 wt% Illite clay, 30 wt% Ab
- Core restoration
  - Swi=20%
- Adsorption of POC, T=50˚C
  - Crude Oil flooding at 0.1 ml/min
    - BN=0.23,
    - AN =0.17,
    - low asphaltene
- Spontaneous imbibition at T=60˚C
  - FW (50 000 ppm with 20mM Ca^{2+})
  - LS (1 000 ppm NaCl)



- Bases adsorbed more/stronger than acids
- Amount of crude oil during core restoration effects initial wetting
- Oil recovery by SI
  - 12 %OOIP with FW
  - 38 %OOIP with LS

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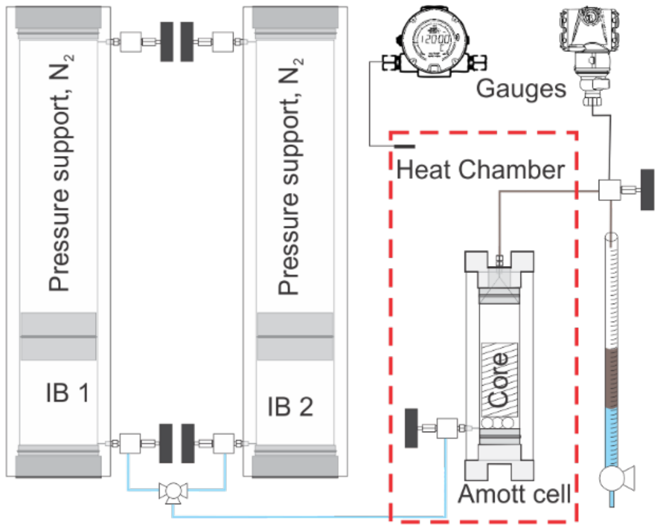
CORE HANDLING FROM RESERVOIR TO RELIABLE EXPERIMENTAL RESULTS IN LABORATORY

Parameters affecting experimental results:

- Core experiment procedures
  - Wettability measurements
  - Oil recovery tests
  - Capillary pressure measurements
  - Resistivity measurements
  - Relative permeability measurements



- Questions:
  - ➢ Reproducible results?
  - ➢ Are laboratory experiments designed to represent reservoir processes?
  - ➢ Are we doing experiments for understanding reservoirs?
  - ➢ Are we doing experiments mainly for input parameters to models and simulators?

  - ➢ Do we really understand fluid flow in porous media?

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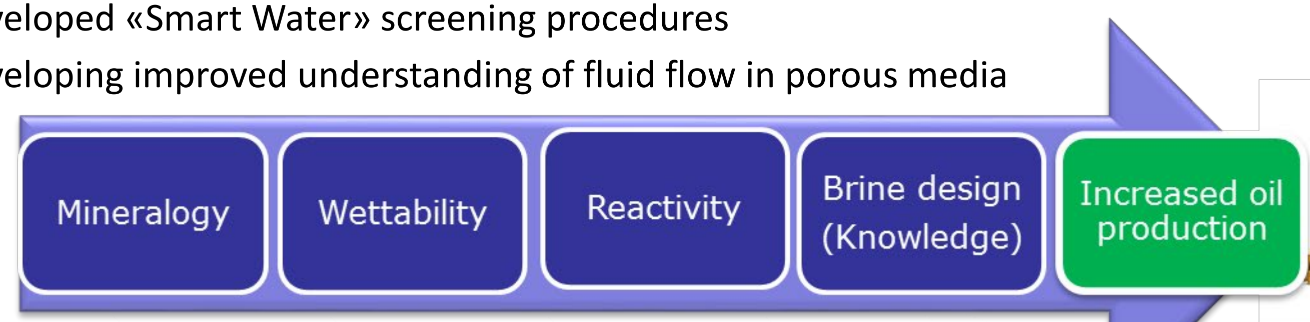
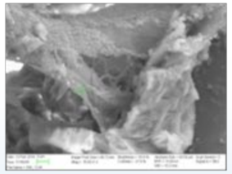
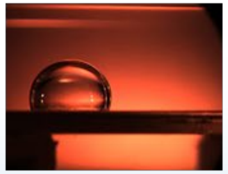
Systematically worked with the chemical understanding of «Smart Water» EOR:

- Outcrop core systems for Parametric studies :
  - Sandstone
  - Carbonate
- Fundamental understanding the effects of
  - Mineral composition
  - Crude Oil properties
  - FW composition
  - Wettability alteration by «Smart Water»
- Tested and verified on real carbonate and sandstone reservoir systems
- Developed optimized core restoration procedures
- Developed «Smart Water» screening procedures
- Developing improved understanding of fluid flow in porous media

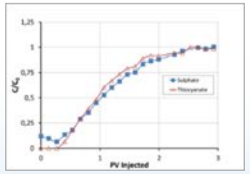




- Main mineralogy
- Trace minerals



- SI tests
- Capillary forces



- Affinity of ions
- Incr. reactivity

- "Smart Water" composition

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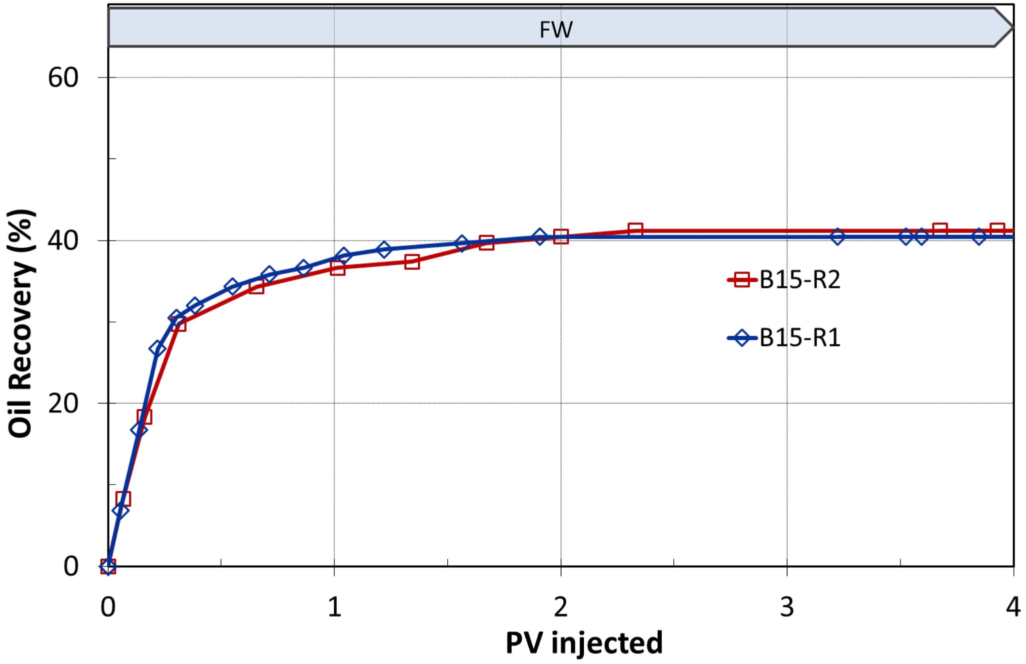
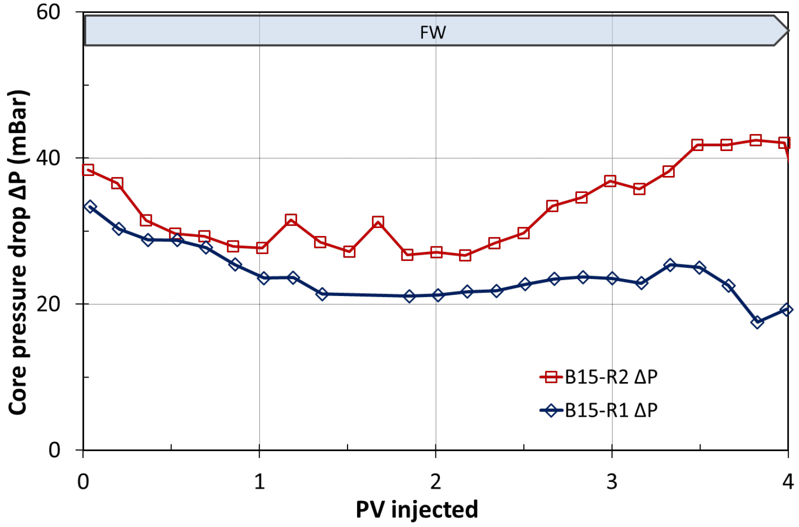
REPRODUCIBLE CORE RESTORATIONS IN LABORATORY

Reproducible core restorations on Sandstone cores:



Ref.: RezaeiDoust
PhD thesis (2011) UiS

- Total outcrop Sandstone core:
- Core restoration:
  - Mildly cleaned cores
  - S_{wi} established with desiccator
  - Cores exposed to the same amount of Crude oil
- Oil recovery experiments at 40 °C
  - FW flooding at 4 PV/D



- ➢ Reproducible Oil Recovery profiles in between experiments
- ➢ Pressure drop (ΔP) measurements are less comparable

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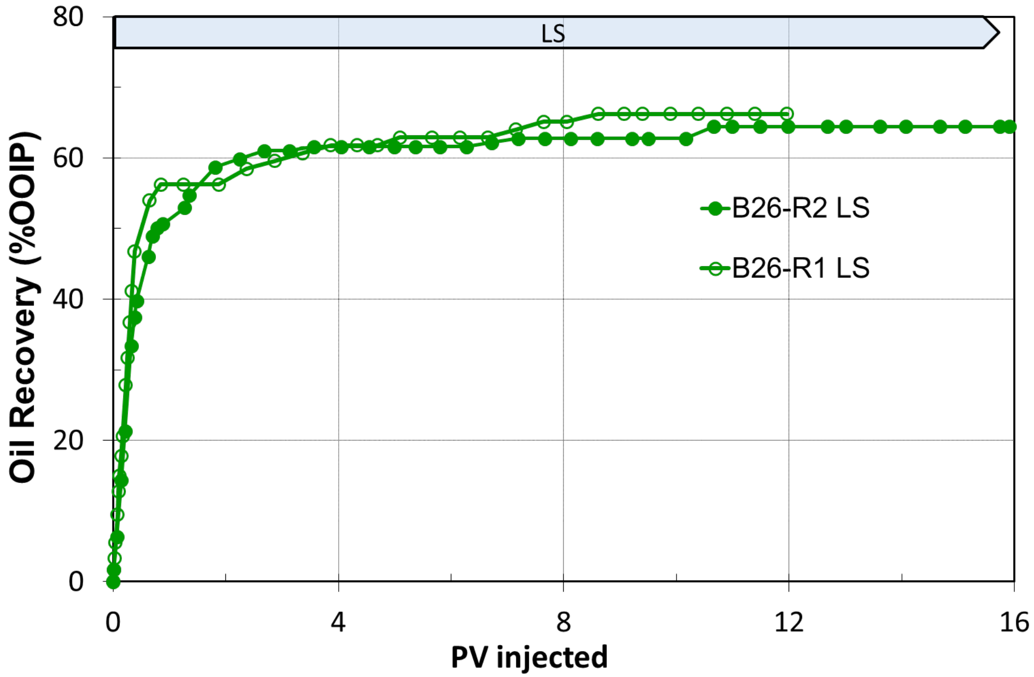
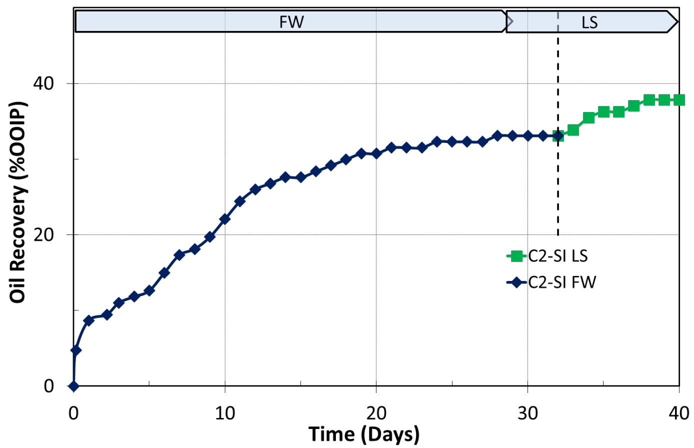
REPRODUCIBLE CORE RESTORATIONS IN LABORATORY

Reproducible core restorations on Sandstone cores:



- Total outcrop Sandstone core:
- Core restoration:
  - Mildly cleaned cores
  - S_{wi} established with desiccator
  - Cores exposed to the same amount of Crude oil
- Oil recovery experiments
  - LS flooding at 4 PV/D



Ref.: Piñerez Torrijos et.al
E&F 30 (2016) p.4733–4739

- ➢ Reproducible Oil Recovery profiles during wettability alteration in restored single core
- ➢ Significant higher recovery with Secondary LS injection compared to FW
- ➢ SI results confirms quite water wet initial conditions
- ➢ LS brine promotes wettability alteration

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RESEARCH PARTNERS

BP

Total

Wintershall

Talisman

Saudi Aramco

AkerBP

Talisman Synoptics

DNO

TaQa

Maersk

Petoro

Shell

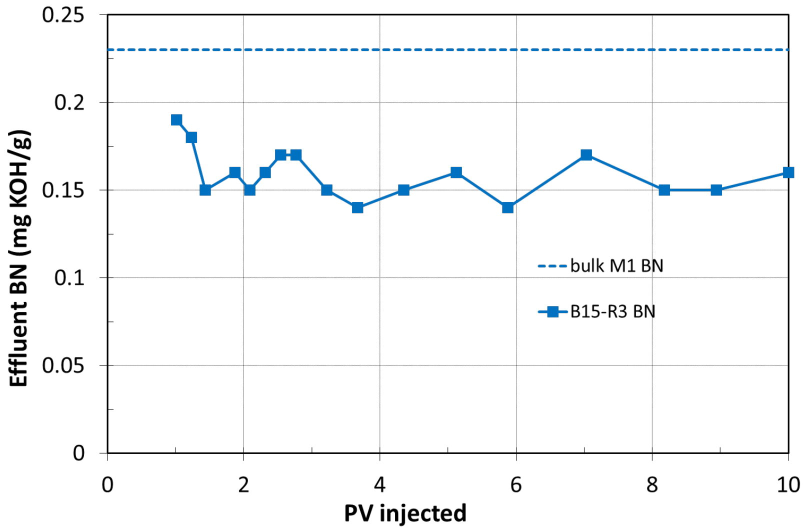
Core Specialist Services

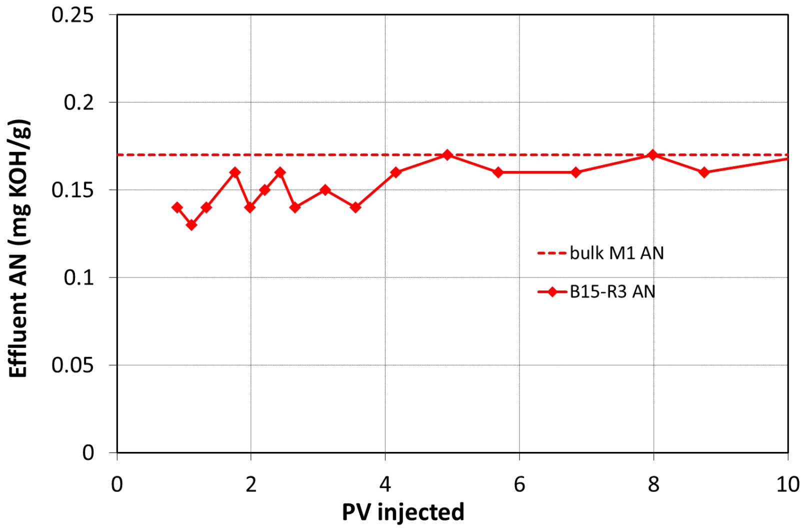
Conoco Phillips

NFR

ADSORPTION OF POLAR CRUDE OIL COMPONENTS ON SANDSTONE

Adsorption of Acidic and Basic polar crude oil components





- Total outcrop sandstone
  - Quartz, 10 wt% Illite clay, 30 wt% Ab
- Core restoration
  - Swi=20%
- Adsorption of polar components at T=50˚C
  - Crude Oil flooding at 0.1 ml/min
    - BN=0.23, AN =0.17, low asphaltene
- Spontaneous imbibition at T=60˚C, glass cell
- FW (50 000 ppm NaCl + 20mM Ca^{2+}), LS (1 000 ppm NaCl)

Bases adsorbed more than acids

Increase in oil recovery by improved capillary forces

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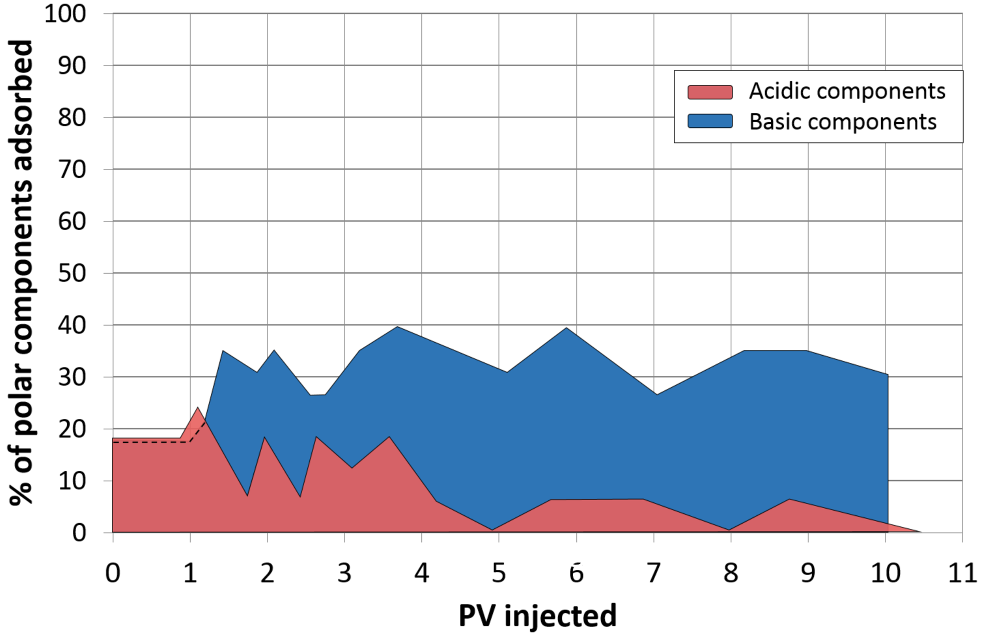
ADSORPTION OF POLAR CRUDE OIL COMPONENTS ON SANDSTONE

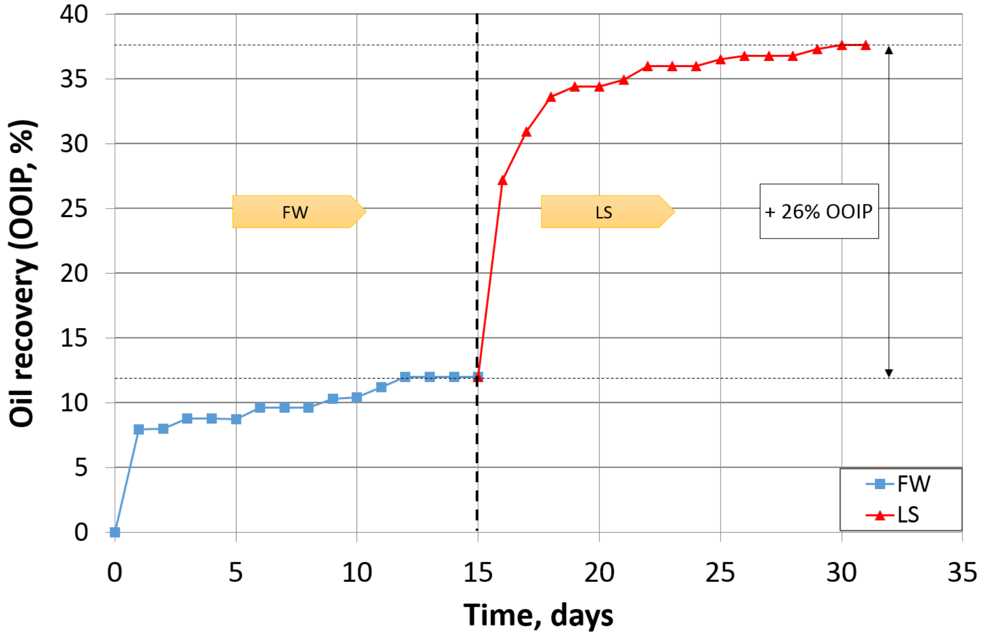
- Outcrop sandstone core (Quartz, 10 wt% Illite clay, 30 wt% Na-feldspar)
- Crude oil (AN=BN=0.22, low asphaltenic content), Swi=20%
- Oil flooding at T=50˚C, injection rate = 0.1 ml/min

- Spontaneous imbibition at T=60˚C, glass cell
- FW (50 000 ppm NaCl + 20mM Ca^{2+}), LS (1 000 ppm NaCl)

BET≈2 m^2/g



Bases adsorbed more than acids



Increase in oil recovery by improved capillary forces

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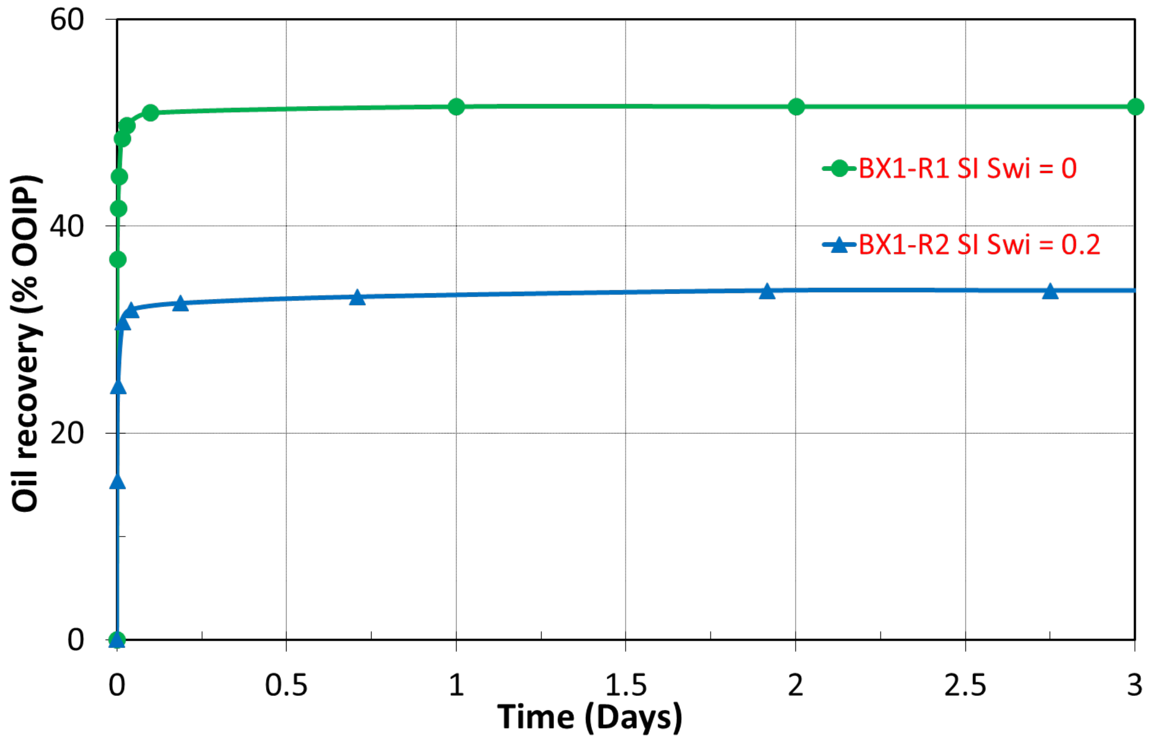
TOTAL OUTCROP SANDSTONE

SI to evaluate initial wettability of Total Outcrop Sandstone cores



- Total Outcrop Sandstone core X1 restored
  - X1-R1
    - $S_{wi} = 0$
    - C_7 sat.
  - X1-R2
    - $S_{wi} = 0.2$ with LS
    - C_7 sat.
- SI recovery test with LS brine at 50 °C
  - X1-R1
  - X1-R2

- High speed of recovery confirms strong positive capillary forces
- $S_{wi} = 0$ gave a recovery plateau of 52 %OOIP
- $S_{wi} = 0.2$ gave a recovery plateau of 34 %OOIP
- ➢ Strongly water wet core

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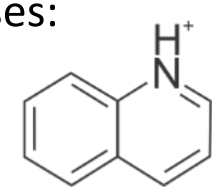
Crude oil not a homogeneous phase

- Dictates the reservoir wetting
  - Asphaltenic material
  - Individual Polar Organic species in Crude Oil
  - contribute as anchor molecules towards rock surface

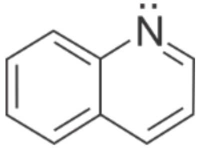
- Organic Bases:



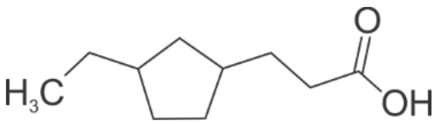
Low pH High pH

$$R_3NH^+ \rightleftarrows H^+ + R_3N:$$

pK_a ~ 4..5 – 5.5



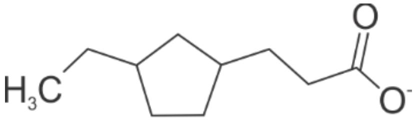
- Carboxylic Acids :



Low pH High pH

$$RCOOH \rightleftarrows H^+ + RCOO^-$$

pK_a ~ 4.0 – 4.5



➢ Protonated Bases and Acidic have the same variation with pH

➢ At alkaline conditions

  ➢ Naphthenic acids / carboxylic acids are charged: $RCOO^-$

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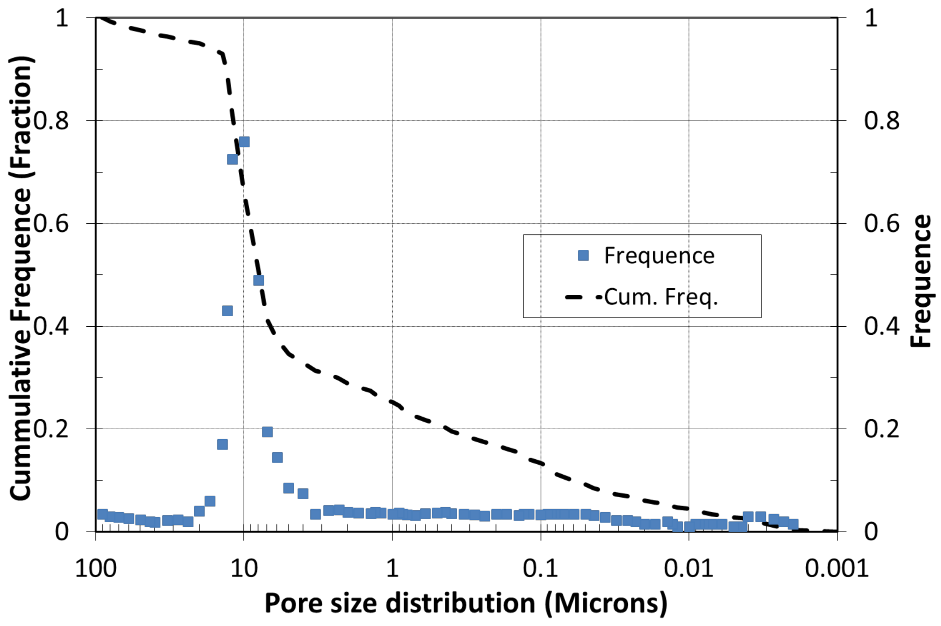
Pore size distribution in Total Outcrop Sandstone



- Total Outcrop Sandstone Cores
  - Mercury (Hg) injection (data from Total E&P)

➢ Heterogeneous pore distribution
- Smallest pores 2 nm
- 14 % less than 100 nm
- 26 % less 1 micron
- 75 % less than 10 microns
- 100% less than 90 microns

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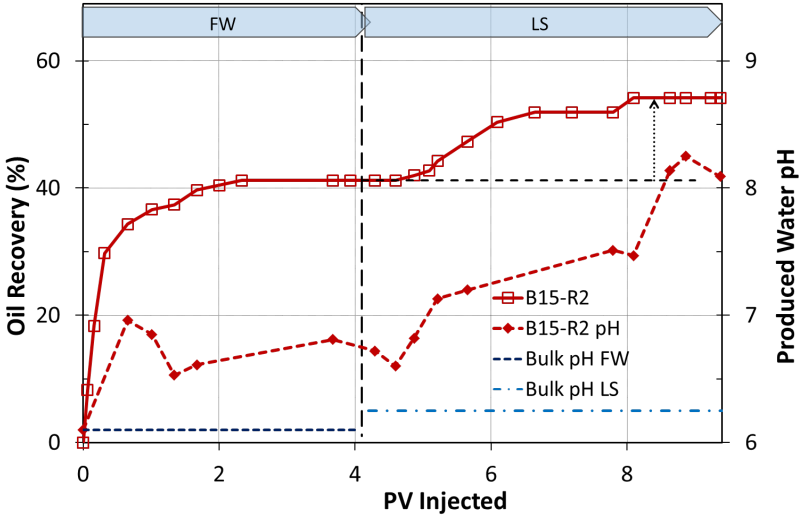
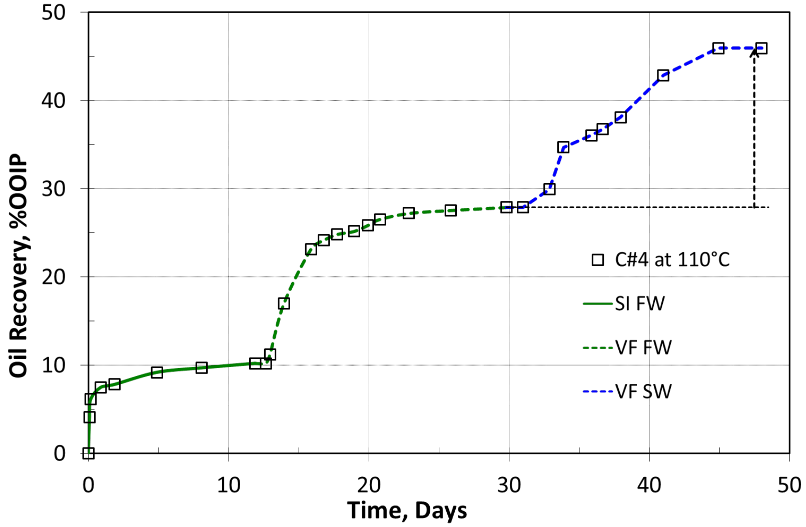
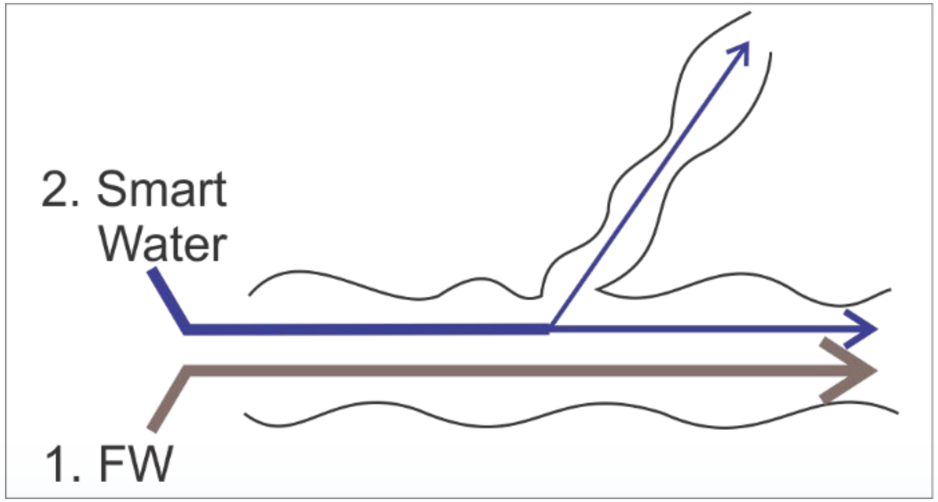
HOW DOES «SMART WATER» WORK?



- ✓ Minor changes in IFT
- ✓ Same pore distribution (FW and LS)
- ✓ Unfavorable mobility ratio with LS
  - ✓ LS viscosity lower than HS
- ➢ Wettability alteration
- ➢ Increased Microscopic Sweep





$$P_c = \frac{2\,\sigma\,\cos\theta}{r}$$

Wettability alteration toward more water-wet
Increased capillary forces promote
increased microscopic sweep efficiency

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RESERVOIR CHEMISTRY

Reservoirs consist of pore systems with mineral surfaces, brine, and Crude Oil.

- Improved understanding of Reservoir Chemistry are needed

Crude oil	Brine	Rock
• Polar organic acids • Polar organic bases • Asphaltenes	• Salinity and Ion composition • Formation water (FW) • Injection Brines	• Minerals • Surface reactivity • Carbonate rock • Sandstone rock

- Chemical reactivity are temperature dependent
- Reservoir Chemistry effects:
  - Fluid flow in porous media and reservoirs
  - Initial Reservoir wettability
  - Wettability alterations by «Smart Water»
  - Scaling

WATER FLOODING OF OIL RESERVOIRS

Water flooding has been performed for a century with the purpose of:

- Pressure support
- Oil displacement

Question:

- Do we know the secret of water flooding of oil reservoirs??
- If **YES**,
  then we must be able to explain why «Smart Water» sometimes increases oil recovery and sometimes not.

This is the CORE of research activities in «Smart Water» EOR group

- Increased competence and knowledge needed
  - Pore surface mineralogy
  - FW composition
  - Crude oil properties
- Initial wettability
- How to induce wettability alteration - Smart Water EOR processes
  - chemical mechanism
  - Optimized injected water composition for oil recovery.
- Injection strategies,
- Combined Smart Water EOR with other EOR techniques

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BRINE COMPOSITIONS – FW AND SW

Formation Water ≠ Injection Water

Ca^{2+}/Mg^{2+} and SO_4^{2-} in SW
affects surface wetting of Chalk

↓

Increased SI and FI
with Seawater

↓

Enhanced oil recovery

Ions	FW mM	SW mM
Na^+	996	450
K^+	5	10
Ca^{2+}	**29**	**13**
Mg^{2+}	**8**	**45**
SO_4^{2-}	**-**	**24**
Cl^-	1066	525
HCO_3^-	9	2
Ionic strength	1.112	0.657
TDS (g/l)	62.8	33.39

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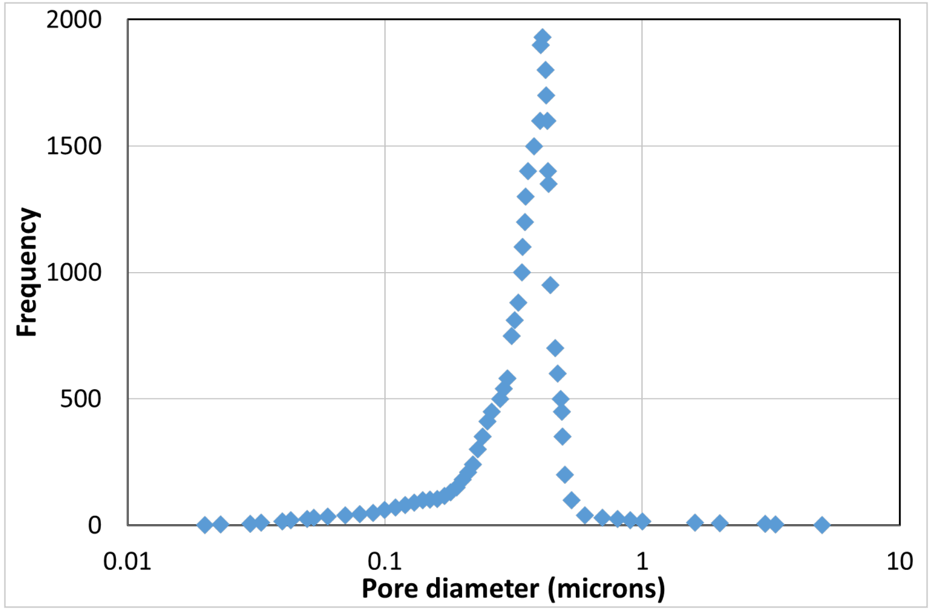
PORE SIZE DISTRIBUTION IN SK CHALK

Mercury injection into Outcrop SK Chalk



Pore size distribution in Stevns Klint chalk determined by mercury injection capillary pressure curve

Redrawn after J.Milter (1996) PhD thesis UiB

- Pore size distribution in outcrop SK Chalk
  - ✓ Smallest pores less that 100 nm
  - ✓ Largest pores close 1000 nm (1 µm)
  - ✓ SK Chalk have a heterogenous pore distribution
- ➢ Main pore diameter close to ~ 800nm

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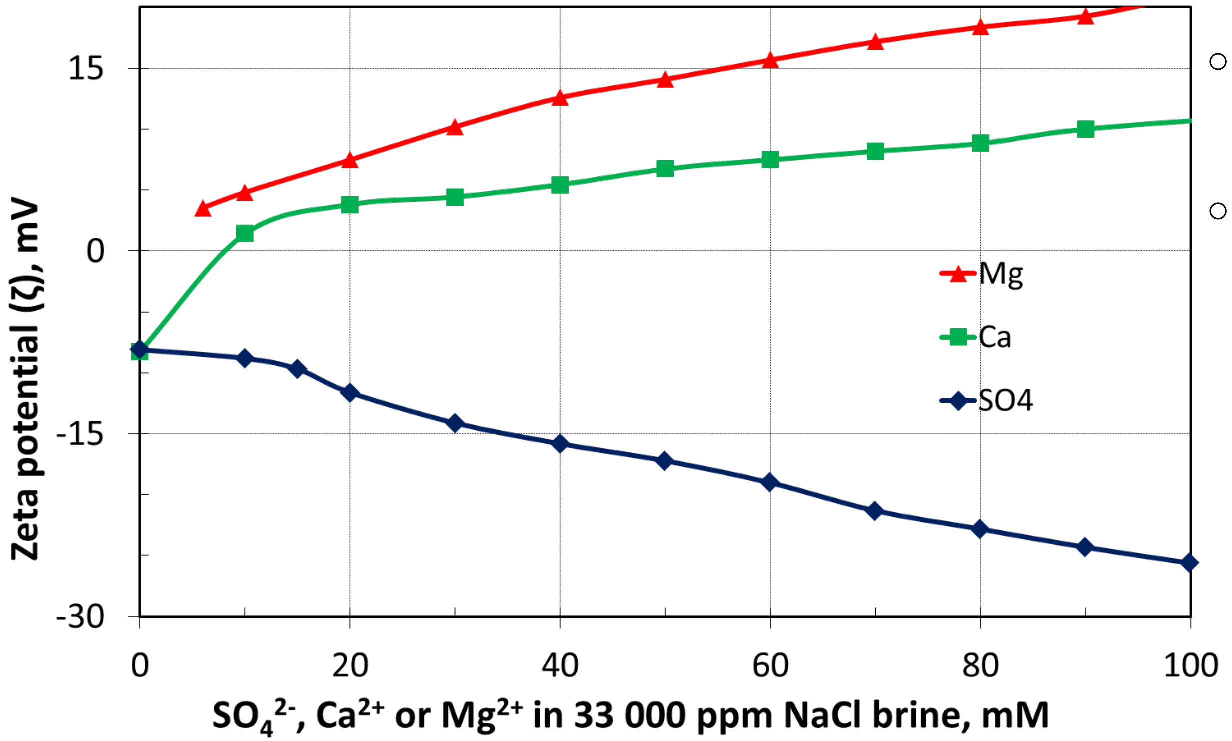
Impact of divalent ions on surface charge

- (a) Outcrop SK chalk , pH=8.4, T=25°C



- 4 wt% milled SK Chalk
  - non-cleaned
  - 33000 ppm NaCl ("SW-salinity")
- Adding divalent ions at pH=8.4, T=25°C
  - SO_4^{2-} conc.
  - Ca^{2+} conc.
  - Mg^{2+} conc.

Ref.: Korsnes et al EUROCK (2006)

- Pure NaCl – Zeta slightly negative
- Zeta potential more negative with increased SO_4^{2-} conc.
- Zeta potential more positive with increased Ca^{2+} conc.
- Zeta potential more positive with increased Mg^{2+} conc.

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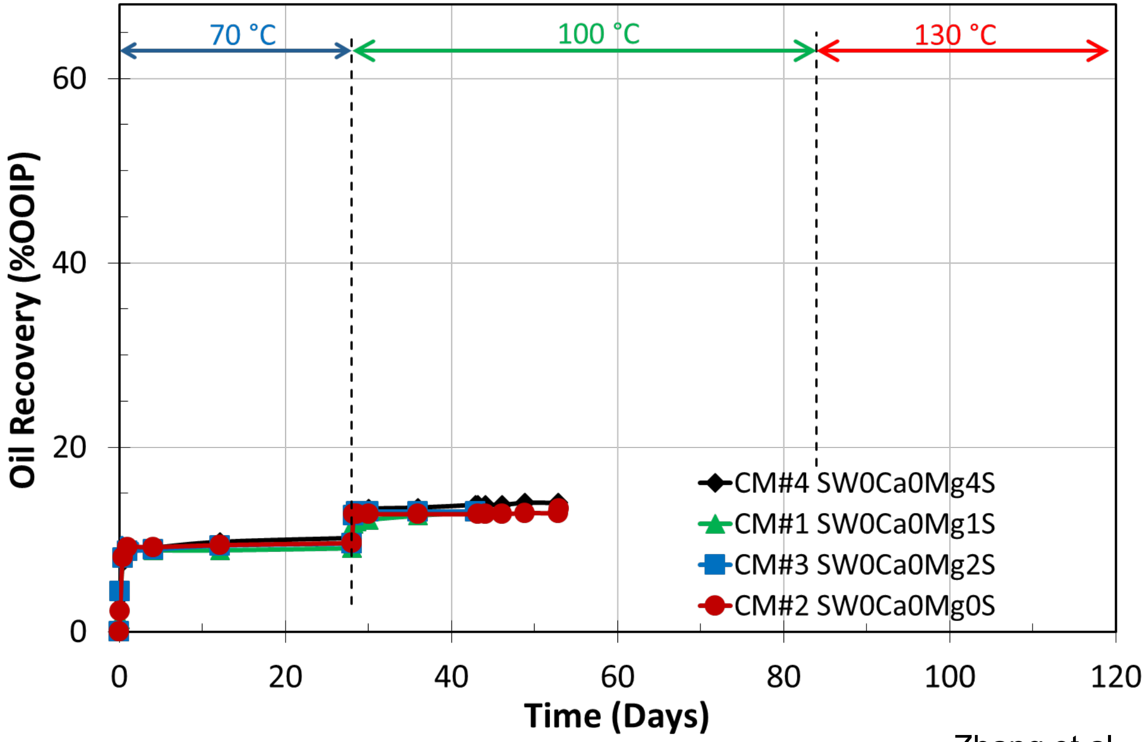
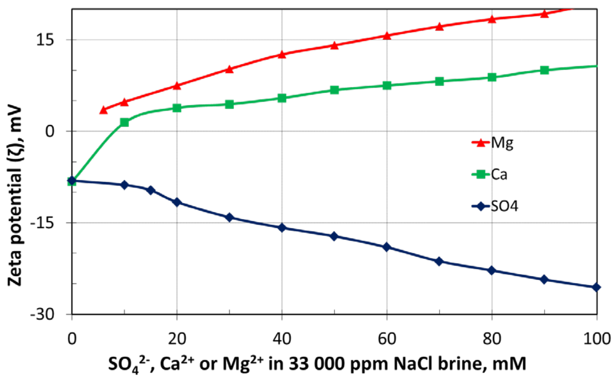
EFFECT OF POTENTIAL DETERMINING IONS AS SMART WATER IONS

Effect of SO_4^{2-} ions and temperature on spontaneous imbibition:



- 4 SK Chalk cores equally restored
  - S_{wi} ~ 22%, NaCl- brine (84 g/l)
  - Sat., flooded and aged in Crude Oil, AN = 2.07 mg KOH/g oil
- Spontaneous imbibition tests.
  - Temperatures 70, 100 and 130°C
  - Modified SW was initially used as imbibing fluids
    - Without and with increasing SO_4^{2-} conc.
    - without Ca^{2+} and/or Mg^{2+}

Zhang et al
C&S A 301 (2007) p.199–208



- Zeta potential /surface charge more negative with increased SO_4^{2-} conc.
- Increasing SO_4^{2-} conc. gives no wettability alteration and extra Oil
- ➢ Surface charge could not explain the Smart Water EOR effect

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RESEARCH PARTNERS

BP

Total

Wintershall

Talisman

Saudi Aramco

Talisman Synoptics

DNO

TaQa

Maersk

Petoro

Shell

Core Specialist Services

Conoco Phillips

NFR

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What is missing in our understanding/implementation of Core Preparation?

Equinor

What we don't understand

- Is the effect of different muds on core flood behaviour documented?
  - Effect of muds on oil properties
  - Effect of muds on actual cores
  - What does the damage; particles or surfactants
- Can the effect of muds be removed?
  - Which cleaning procedures are recommended?
  - Hard cleaning – gentle cleaning – what is the evidence?
    - Wrt muds?

- Cleaning / preparation – sandstone vs carbonates?

- How should one establish rest oil saturation before?
  - Arguments – porous plate vs (low connate water) vs centrifuge etc.

- Oxidation – recognised as important?

MINUTES OF MEETING

Workshop: Core Preparation 9th May 2019
University of Stavanger, 09:30-15:00

Place: University of Stavanger, Kjølv Egelands hus
Meeting room: E-101

Participants:

Egil Boye Petersen, AkerBP

Edvard Omdal, ConocoPhillips

Erik Rauge Andersen, ConocoPhillips

Robert Moe, ConocoPhillips

Christian Burmester, DEA Norge

Dag Chun Standnes, Equinor

Omid Karoussi, Equinor

Robert Orr, Equinor

Amare Mebratu, Halliburton

Iselin Klungland Gilje, Halliburton

Kristian Eide-Engdahl, Lundin

Jan Øystein Haavig Bakke, Schlumberger

Jarle Haukås, Schlumberger

Heine Madsen, Vår Energi

Andrey Kovalev, Wintershall

Gunnar Oeltzschner, Wintershall

Norbert Schleifer, Wintershall

Sissel Opsahl Viig, IFE

Arne Stavland, Norce

Ingebret Fjelde, Norce

Jan Ludvig Vinningland, Norce

John C. Zuta, Norce

Ketil Djurhuus, Norce

Reza Askarinezhad, Norce

Jan Erik Iversen, Norce

Aksel Hiorth, UiS

Aleksandr Mamonov, UiS

Ida Lykke Fabricius, UiS

Iren Lobekk, UiS

Ivan Dario Piñerez Torrijos, UiS

Kjersti Riiber, UiS

Merete Vadla Madland, UiS

Mona Wetrhus Minde, UiS

Panagiotis Aslanidis, UiS

Pål Østebø Andersen, UiS

Reidar Inge Korsnes, UiS

Skule Strand, UiS

Tina Puntervold, UiS

Alvaro Muñoz-Beltran, Stratum Reservoir (formerly Weatherford Laboratories)

Izaskun Zubizarreta, Lloyd's Register

The workshop was also available as streaming on the UiS website – 24 participants in addition to the ones above followed the streaming.

Program

AGENDA:

09.30 – 09.45	Welcome, Aksel Hiorth and Tina Puntervold
09.45 – 10.15	"SCAL core preparation: methodologies and challenges" by Álvaro Muñoz Beltran, Stratum Reservoir
10.15 – 10.45	"Challenges in Achieving "Representative" Reservoir Wettability" by Izaskun Zubizarreta, Lloyd's Register, UK
10.45 – 11.00	Break
11.00 – 11.30	"Representative wettability conditions in lab" by Ingebret Fjelde, NORCE
11.30 – 12.00	"Core handling: from reservoir to reliable laboratory results" by Skule Strand, UiS
12.00 – 12.45	Lunch
12.45 – 13.15	"Digitizing core data – Improve reservoir understanding" by Egil Boye Petersen, AkerBP
13.15 – 13.45	"What is missing in our understanding/implementation of Core Preparation?" by Robert Orr, Equinor
13.45 – 14.30	Group discussions: • "When are the traditional methods not good enough?" • "What is missing in our understanding of core preparation?" • "Way forward - Future research?"
14.30 – 15.00	Summarize and close

First a couple of overall points from the workshop as a whole:

- There is a lack of standardization of core scale preparation procedures in the industry
- The major unknown is reservoir wettability, it is extremely hard to know if the right wettability is reproduced in the lab
- Mud invasion and mud effect on cores are a big challenge, and more research is needed

Below is a brief summary of the main points in the presentations, all the presentations are available as pdf.

"SCAL core preparation: methodologies and challenges" by Álvaro Muñoz-Beltran, Stratum

Álvaro presented the service industry view and challenges regarding core preparation. He highlighted the lack of standardization in the industry, and that cores should be prepared depending on what one really want to investigate. It is important to have a representative rock of the reservoir formation, and to minimize the physical and chemical alteration of the core during handling and storage. He also expressed a frustration that the service industry has a lack of information about the cores. This makes it hard to suggest the optimal core preparation procedures and also to check the quality of the core restoration. Álvaro went into detail about the different cleaning procedures (Harsh, and Mild cleaning methods – see the presentation). One of the main challenges in the cleaning procedures is to prevent clay damage. He highlighted that the cores has to be restored to a water-wet state before reestablishing the wetting state. Microscale investigations, like SEM and XRD, is always helpful and should always be done in order to choose the appropriate core preparation procedure.

“Challenges in Achieving “Representative” Reservoir Wettability” by Izaskun Zubizarreta, Lloyd’s Register, UK

Izaskun started off with a provoking statement “Wettability – essential … but meaningless”, arguing that nowhere in the reservoir simulator the wettability is explicitly entered. However, it is crucial to prepare cores with the correct wettability when measuring effective flow properties (rel perm and Pc), because the rel perm and Pc curves are used in the reservoir simulator to estimate field recovery potential. Izaskun described in detail the journey of the core from the reservoir to the lab. She emphasized that it was almost impossible to keep a core in the “native” state, because of rapid stress release, mud invasion, pressure depletion leading to saturation alterations inside the pore space, alteration of the geometric pore space and mineralogical alterations.
Recommendations:

- Core cleaning:
  - Remove oil + water + other contaminants, preserve the rock fabric
  - Should render core sample **water wet - because one cannot distinguish organic components from the original reservoir oil and mud**
  - Water wet cores a pre requisite for:
    - Wettability restoration
    - Tests involving a primary drainage cycle
  - Harsh cleaning may remove clay bound water, inducing oil wet tendency
- Establishing of Swi
  - Centrifuge – too hard for delicate samples
  - Dynamic displacement – forces may be too low to achieve target Swi
  - Porous plate – best, but slow
- Ageing
  - Tme:
    - How long? Standard is 40 days
  - Oil:
    - Oil samples taken by wireline are often contaminated
    - No reservoir oil available
    - Use analog
  - Process:
    - Dead or live oil? Depends, GOR < 400-500 Mcf/bbl is not required live oil ageing
    - Dead oil ageing (most common)
    - Dead oil ageing – injection 1PVI STO/week – oscillating direction
    - Live ageing injection 1PVI STO/week – oscillating direction
- Wettability Test:
  - USBM/Amott – need to use the same energy to obtain Swi and Sro

"Representative wettability conditions in lab" by Ingebret Fjelde, NORCE

Ingebret highlighted the fact that what we want to measure should impact the choice of cleaning method. He also warned against doing lab simplifications, several examples were mentioned were the simplifications affected the final results. In one example he showed that the removal of sulphate from the formation brine (to avoid scaling issues) affected the wettability of the rock samples. On the other hand he also mentioned examples were the lab results were correct, but it did not match the expectation of the customers. Thus, it is really important to understand the unexpected results, store them and try to get as much learning out of them as possible. Ingebret also pointed out the importance of using simulation tools, like geochemistry calculations.
What is missing?

- Standard procedure to show that representative materials are used in core preparation
- Representative composition of fluids
  - The importance of polar components of low Mw, and ions of low concentration, and CO_2, not understood

- Effect of mud contaminants

<u>“Core handling: from reservoir to reliable laboratory results” by Skule Strand, UiS</u>

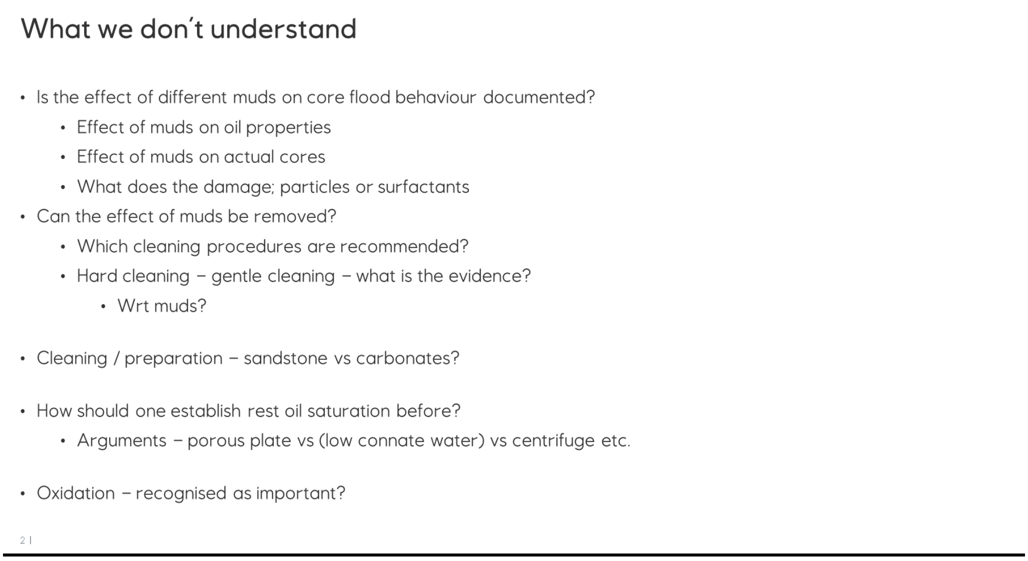
Skule highlighted that the only good measure for wettability of core samples was spontaneous imbibition experiments. He also claimed that the “smiley” curve of Morrow that shows that max recovery is for intermediate wettability, did not match his data. All phases, crude oil, brine, and rock and temperature needs to be taken into account when establishing the initial wettability. Skule argued strongly for a mild cleaning procedure, not to remove all the organic compounds in the rock and porous plate or desiccator to reach Swi. For carbonates the acidic oil components are the most important, and for sandstone rocks the basic components are the most important for oil adsorption and hence rock wettability. This fits with the general notion that carbonate tends to have a positive surface charge and sandstones a negative charge.

<u>“Digitizing core data – Improve reservoir understanding” by Egil Boye Petersen, AkerBP</u>

Egil gave a presentation about how AkerBP is working to digitalize the core data. They need SCAL data for reservoir characterizing and reserve forecast. There are challenges related to the data format, and he describe a general procedure: (i) Collect SCAL data, (ii) Quality assure the data, (iii) Store the data in databases (iv) parameter based SCAL-analysis (v) parametrize the data using correlations (LET) (vi) use data in reservoir simulation model. He showed some interesting correlations from the SCAL, in particular how the Sor (after water flooding) varied as a function of Swi, there was a maximum value around Swi=0.3. The relperm and Pc curves are parametrized using the LET correlations, a pessimistic, a base case, and an optimistic case is defined to investigate the field recovery in each of the cases.

<u>“What is missing in our understanding/implementation of Core Preparation?” by Robert Orr, Equinor</u>

Robert gave a different type of presentation (one slide – see below) highlighting that we need data to make good decisions, and that there are still a lot missing in our understanding on core preparation:



After the break the participants split into four groups, a summary is given below for all the groups:

<u>Group 1:</u>

1. What is missing in our understanding of core preparation?
   - **a.** collection of data/common database
   - **b.** data history
   - **c.** data knowledge & sharing
2. When are the traditional methods not good enough?
   - **a.** unconventional reservoirs (tight/vuggy)
3. Way forward – Future research:
   - **a.** digital rock physics
   - **b.** close collaboration operators, service operators and researchers

   c. sharing info/data

Group 2:

1. What is missing in our understanding of core preparation?
   - **a.** actual reservoir wettability
   - **b.** implication of core preparation procedure
   - **c.** fine migration, too high rate can affect measurements
   - **d.** mud effect, cleaning
   - **e.** mixed wettability due to core mineralogy
   - **f.** multidisciplinary understanding
2. When are the traditional methods not good enough?
   - **a.** rel perm measurements
3. Way forward – Future research:
   - **a.** NMR for wettability, can be used in field
   - **b.** Further development of digital rock
   - **c.** Dual energy CT to identify mud invasion
   - **d.** Digitalization of core data

Group 3:

1. What is missing in our understanding of core preparation?
   - **a.** drilling mud – coring
   - **b.** SCAL data and potential for EOR
   - **c.** formation brine and organic compounds present
2. When are the traditional methods not good enough?
   - **a.** investigating the potential for EOR
3. Way forward – Future research:
   - **a.** interaction with drilling mud
   - **b.** new technology, e.g. digital rock physics

Group 4:

1. What is missing in our understanding of core preparation?
   - **a.** a certainty that we are doing things right
   - **b.** do we know when we are right?
   - **c.** all data should be reported in reports together with the procedures used
   - **d.** main issue is that we do not know the reservoir wettability
   - **e.** mud composition used to acquire each core
2. When are the traditional methods not good enough?
   - **a.** they are uncertain by nature (because we do not know the true answer)
   - **b.** labs should be better at reporting when they are uncertain about the data that are being reported

   c. sometimes we do not understand why we are using the traditional methods

3. Way forward – Future research:
   a. Mud infiltration research: expose different cores to mud, measure the effect on displacement properties, clean cores and measure if the mud was removed