The Relevance of Mineralogy to the Life Cycle of a Petroleum Field

P Joseph Hamilton
Lithicon and Applied Maths, Research School Physics and Engineering, ANU
OUTLINE

1. Introduction

2. Overview of Digital Rock Technology
   - Importance of mineralogy

3. Methods of Mineral Analysis

4. Applications
Lithicon – World leader in Digital Rock Technology

- Lithicon is the integration between Digitalcore of Australia and Numerical Rocks of Norway.
- Digitalcore: a leader in rock imaging and image processing
- Numerical Rocks: a leader in rock modelling + simulation
The Life Cycle of a Petroleum Field
Exploration..development..production..CO₂ sequestration

The Petroleum System = concept for exploration

Suitable rocks, in suitable places, at suitable times → Petroleum

(Magoon and Dow, 1994. AAPG, Memoir 60, 655 p.)
What is Digital Rock Analysis

The analysis is based on high resolution 3D imaging of rock microstructure, mineralogy, texture and calculation of pore scale distribution of fluids.

3D X-ray images of rock microstructure + integrate 2D images from EM techniques

compute rock + flow properties from images

in-house built micro-CT imaging technology down to 1 micron

Porosity, Permeability NMR relaxation, Formation Factor Pc, Rel. Permeability
Key technology: Image Registration

Enables:

- A process of capturing the large scale AND honouring the smaller scale
- 4D time series/dynamic studies
- Combining multiple imaging modes
Why Are Minerals Important?

Reservoir porosity, permeability, fluid saturations

Provenance and Correlation

Affect log measurements

Formation damage

Geomechanical properties; fault seal; fracing strategies

CO\textsubscript{2} Geosequestration
Key technology under development
Mapping mineralogy of pore surfaces at μm scale

Kaolinite cemented
Illite cemented

Poroperm, logs, wettability, formation damage

Selley, 1998

(Photos: Ray Frost, Sample "K"; M. Roe, Macaulay Inst. Sample 'Ill-34': Macaulay Collection)
Chlorite Porosity Preservation

- Chlorite coatings are efficient in preventing the growth of quartz cements by sealing the reactive surface.
- Coatings have a high microporosity.
Fe-Rich Chlorite and NMR

paramagnetic chlorite
chlorite content increases, relaxation times decrease $T_2$ cutoffs decrease.

important input parameter for log based permeability estimates

Adapted from MD Hürlimann et al., Application of NMR diffusion editing as chlorite indicator. SCA2003-26.
APPLICATIONS: Fe-Rich Chlorite + grain density

Fe-rich chlorite $\rho = 3.3$

Grain density increases with chlorite content important for reliable $\Phi$ determination from density logs.

Adapted from MD Hürlimann et al., Application of NMR diffusion editing as chlorite indicator. SCA2003-26.
# The Size of Clays and Petrophysics

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Typical Particle Thickness nm</th>
<th>Specific surface m²/g</th>
<th>C.E.C meq/100g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaolinite</td>
<td>50-2000</td>
<td>10-20</td>
<td>3-10</td>
</tr>
<tr>
<td>Illite</td>
<td>30</td>
<td>80-100</td>
<td>20-30</td>
</tr>
<tr>
<td>Montmorillonite</td>
<td>3</td>
<td>800</td>
<td>80-120</td>
</tr>
<tr>
<td>Chlorite</td>
<td>30</td>
<td>80</td>
<td>20-30</td>
</tr>
</tbody>
</table>
Methods of Mineral Analysis

SEM/EDS – commercialized – QEMSCAN + ROQSCAN; rapid, automated; textures allow cuttings lithotyping;

  calibration to formation mineralogy may be required; clay mineral id and quantification difficult in fine grained clay rich +/- or OM rich rocks

XRD – rapid, automated; minimal sample prep for bulk analysis; calibration to formation not required;

  no texture; mineral id software requires knowledge; clay analysis – more time + space; poorly crystalline clay underestimated
### Mineral Analysis Methods

**SEMEDS Automated Mapping**

<table>
<thead>
<tr>
<th>Mineral Name</th>
<th>Area%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>46.79</td>
</tr>
<tr>
<td>Alkali Feldspar</td>
<td>9.74</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>5.41</td>
</tr>
<tr>
<td>Illite/Muscovite</td>
<td>0.66</td>
</tr>
<tr>
<td>Biotite</td>
<td>2.59</td>
</tr>
<tr>
<td>Chlorite</td>
<td>0.18</td>
</tr>
<tr>
<td>Calcite</td>
<td>10.78</td>
</tr>
<tr>
<td>Dolomite</td>
<td>16.97</td>
</tr>
<tr>
<td>Pyrite</td>
<td>0.08</td>
</tr>
<tr>
<td>Apatite</td>
<td>0.03</td>
</tr>
<tr>
<td>Rutile</td>
<td>0.18</td>
</tr>
<tr>
<td>Zircon</td>
<td>0.04</td>
</tr>
<tr>
<td>Unclassified</td>
<td>6.55</td>
</tr>
</tbody>
</table>

MINERAL ANALYSIS METHODS

SEMEDS Automated Mapping

![Image of mineral analysis](image.png)

- **Background** 1.77
- **Quartz** 46.79
- **Alkali Feldspar** 9.74
- **Plagioclase** 5.41
- **Illite/Muscovite** 0.66
- **Biotite** 2.59
- **Chlorite** 0.18
- **Calcite** 10.78
- **Dolomite** 16.97
- **Pyrite** 0.08
- **Apatite** 0.03
- **Rutile** 0.18
- **Zircon** 0.04
- **Unclassified** 6.55

**MINERAL ANALYSIS METHODS**

**SEMEDS Automated Mapping**

![Image of mineral analysis](image.png)
Hyperspectral Scanning imaging narrow spectral bands over a continuous spectral range within Vis to TIR

Full core scanned images of mineral distribution at mm resolution

Advantages
• Distinguish clay polymorphs
• % illite in mixed layer illite/smectite
• ID organic compounds

Mineral mapping potential with IR microscope, but ~10μm resolution
Methods of Mineral Analysis

**Infrared Spectrometry**

Involves absorption of specific wavelengths by bonds between atoms and groups of atoms
- minimal sample prep, rapid analysis
- best method for clay mineral id

Scanners to produce low resolution images or
Spectrometers for mineral id and quantification


After P G Nahin
Allophane

Si = ☜ Purple ☜ Al = ☜ Gray ☜ O = ☜ Red ☜

Nanoball allophane

φ 3.5–5.0 nm

Absorbance

Wavenumber, cm⁻¹

http://minerals.gps.caltech.edu/files/attr/myweb5/images/clay%20standards/allophane.gif
Raman Microscopy

Advantages

- Robust mineral ID
- ID organic compounds
- Mineral mapping potential with sub micron resolution

Laser Raman microscope images of section of marine gastropod (*Nerita undata*), showing aragonite in two different crystallographic orientations (black and blue), calcite (red) and organic compounds (polyenes, green)
Objective

Use Cuttings Mineralogy to define U/L Talang Akar Fm in an unfossiliferous compartmentalised reservoir
Correlation

Albite = A Mineral Marker for the U/L Talang Akar Fm.

Occurs as phenocrysts in particles of dacite
high $\Phi$ sst with low-clay content
abundant cataclastic grainsize reduction
abundant quartz cement healing fractures
only minor crystal plasticity processes like DMT

low $\Phi$, diagenetic clay-rich sst
crystal plasticity dominates
minor intragranular fracturing

Clay content affects the microstructures involved in deformation
Wettability and Minerals

Haematite, Fe Chlorite - oil wet
Smectites – oil wet.
Illite - water wet
Kaolinite - different crystallographic surfaces
- different wettabilities

At the nanoscale more crystal lattice disorder (eg detrital vs overgrowth surface, crystal face edges) more mixed wettability.
ESEM image - water drops on kaolinite and quartz in sandstone contrasting their wetting characteristics.

Fig. 8. Effect of kaolinite morphology on its wettability state. (a) Booklet of kaolinite showing the crystal faces exposed. (b) Cross section through kaolinite (viewed facing the 110 crystal face) showing the greater density of hydrophilic hydroxyl groups on the 001 face as compared with the 010 face.
Standard wettability (pore scale)

- Salathiel (1973) proposed that asphaltenes and resins of the crude oil can rupture the thin brine films lining larger pore walls to deposit on these surfaces and render them oil-wet, while the smaller pores remain shielded by residual brine and retain their water-wetness.
- Is this behaviour universal?
Simple carbonate: Dolomite rich rock

• Imaging (via FESEM) distinguishes oil-wet from water-wet, can map wettability in rocks.

Salathiel, 1973 picture correct
Outcrop Limestone: Aged in reservoir crude

Salathiel, 1973 picture incorrect
Reservoir carbonate 1
After cleaning, drainage of brine by crude oil and aging

Wettability alteration again favors curved, rougher subareas, and especially facet edges.
Wettability Experiment – The Model

- Oil
- Brine
- Calcite
- Oil advancing
- Asphaltene deposit
- Deposit around rim
- Water on euhedral face
Applications and Developments:

- Organic Carbon in a dolostone reservoir

<table>
<thead>
<tr>
<th>Mineral Name</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>0.15</td>
</tr>
<tr>
<td>Bitumen 1</td>
<td>0.46</td>
</tr>
<tr>
<td>Bitumen 2</td>
<td>1.89</td>
</tr>
<tr>
<td>Bitumen 3</td>
<td>19.51</td>
</tr>
<tr>
<td>Quartz</td>
<td>0.47</td>
</tr>
<tr>
<td>Dolomite</td>
<td>77.68</td>
</tr>
</tbody>
</table>

separate bitumen phases?
Stylolite Mineralogy – Automated SEM-EDAX

[Image of mineralogy map with various mineral distributions marked by colors: Background, Quartz, Kaolinite, Muscovite/illite, Anatase/Rutile, Zircon, organic C, etc., with a scale bar of 1mm.]

- Background: 0.814454532285141
- Quartz: 58.9453656476675
- Kaolinite: 15.7290466375109
- Muscovite/illite: 1.38860615792768
- Anatase/Rutile: 0.0140602764524928
- Zircon: 0.00104150195944391
- Organic C: 0.398137794496514
- Tremolite: 0
- Quartz (Charging): 2.03329587082346
- Calcite: 0
- Ankerite: 0
- Muscovite: 13.9080751434196
- Albite: 0.00582294277325461
- Albite (Charging): 0.0128767514985793
- Alkali-Feldspar: 1.2697329115566
- Plagioclase-Feldspar: 0.000236704990782708
- Chamosite: 0.414139051873425
- Illmenite: 0
- Goethite: 4.73409981565415E-05
- Anatase: 0.542385815879496
- Zircon: 0.0643364164947399
- Barite: 0
- Halite: 0.000426068983408874
- Sphalerite: 0
- Kaolinite (High S): 0.00265109589676633
- Smectite: 0.00222502691335745
- Anhydrite: 0
- Zn Oxide: 0
- Al Oxide: 0.00132554794838316
- Apatite: 0.00061543297603504
- Anatase-BNDY: 0.0209720621833479
- Chamosite-BNDY: 0.114186487553578
- Calcite-Silicate BNDY: 0.000804796968661206
- Calcite-BNDY: 0
- Pyrite: 0.0971437282172232
- Illmenite-BNDY: 0
- Anatase-BNDY: 0.0118825905372919
- KCl: 0
- Glauconite: 0.000284045988939249
- Smectite-Calcite BNDY: 0.00118352495391354
- (Na,Mg) Alumino Silicate: 0.00506548680274994
- Sphene: 0
- Quartz-BNDY: 4.97828468414559
- Kaolinite-BNDY: 0
- Ankerite-BNDY: 0
- Undefined: 0.0357424536081889
Stylolite Mineralogy – residual from qz solution
Automated Mineral Analysis – SEM-EDAX

Thin section mineral map

Stylolites (S) offset by and entrained by fault (F)
Observe pyrite mineralisation in stylolites and fault: Infer fluid flow connectivity
SUMMARY I

Stylolites

develop on muscovite / illite rich laminae

Rutile needles residual to quartz dissolution
= Ti source for anatase precipitation

Zircon + Rutile residual to pressure solution removal of large quartz volumes

Displaced by +/- or entrained into fault rock
CO₂ Geosequestration - Offshore Gippsland Basin

- significant CO₂ emissions
  - coal-fired power stations, more planned
- close proximity to emission sources
- Productive oil and gas province
  - some large fields nearing end of production
  - potential for large scale storage projects
- hydrocarbon fluids contained ~ 10Ma
Regional top seal = Lakes Entrance Formation

‘Seals in’ the hydrocarbon accumulations at the top of the Latrobe Group

What will contain CO$_2$?
Thick enough?  
Wide enough?  
Reactive enough?  

Slows migration.  
Storage also by dissolution in pore water and reaction to form new carbonates

= reactive minerals to form carbonates trapping CO₂ and sealing Φ

After Gibson-Poole et al 2006
Compare with optical and CL microscopy for carbonate rocks

- Background 1.47
- Kaolinite 5.16
- Siderite 0.05
- Low Mg Calcite 60.24
- High Mg Calcite 26.82
- Ankerite 0.04
- Dolomite 7.37
- Minor phases 0.31
SUMMARY

Mineralogy is very important