EVOLVING PETROPHYSICS OF THE OVERBURDEN: A SPECTROSCOPY APPROACH

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ConocoPhillips Norway

Schlumberger

NFES - Norwegian Formation Evaluation Society

The Greater Ekofisk Area (GEA)

- *Discovered in 1969*
- *Largest producing field on the Norwegian continental shelf*
- *Naturally fractured chalk reservoirs*
- *Evaluation: Integrating logs with GEA Legacy Database*
- *Core / cuttings: XRD, XRF, SEM+EDS, TOC, Petrography*

Problem Overview

Challenges (GEA overburden shales)

- Compaction & Subsidence
- Fault reactivation
- Wellbore instability
- Narrow drilling windows
- Fluid containment

G&G model

- Volume fractions of minerals and organic matter
- Porosity
- Gas saturation
- Clay types & volumes

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G&G model *← high resolution petrophysical inputs*

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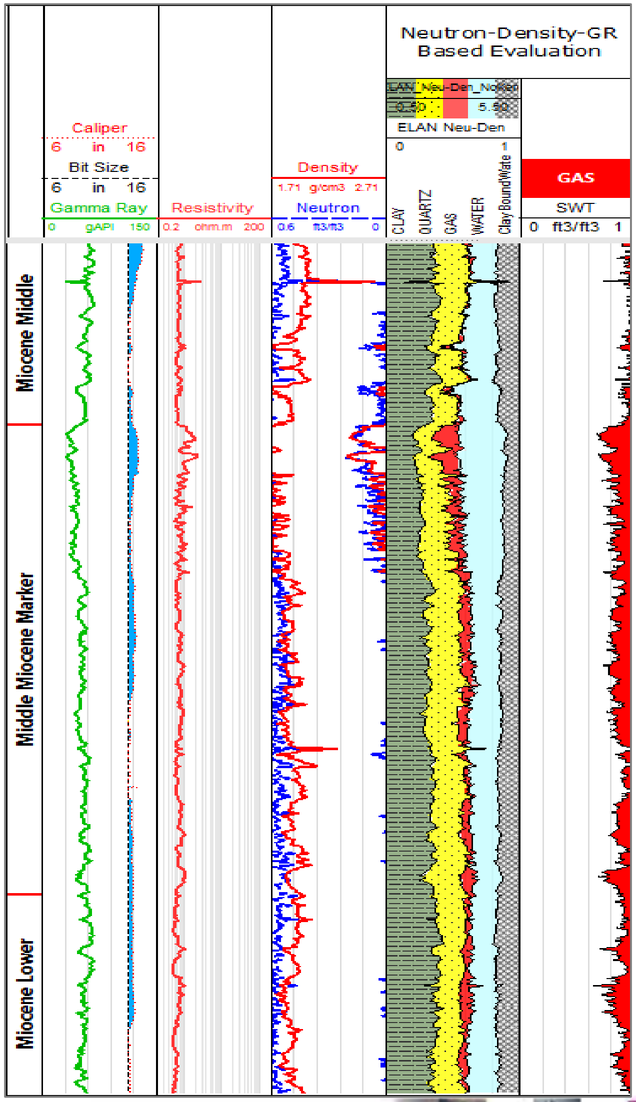
Previous Evaluation <u>Known Challenges</u>

Model 1: Conventional logs

- Conventional logs
- Solving only single mixed clay, quartz, water, gas
- Highly subjective
- Inconsistencies* across the field
- Couldn't solve important minerals (calcite, dolomite, pyrite...)

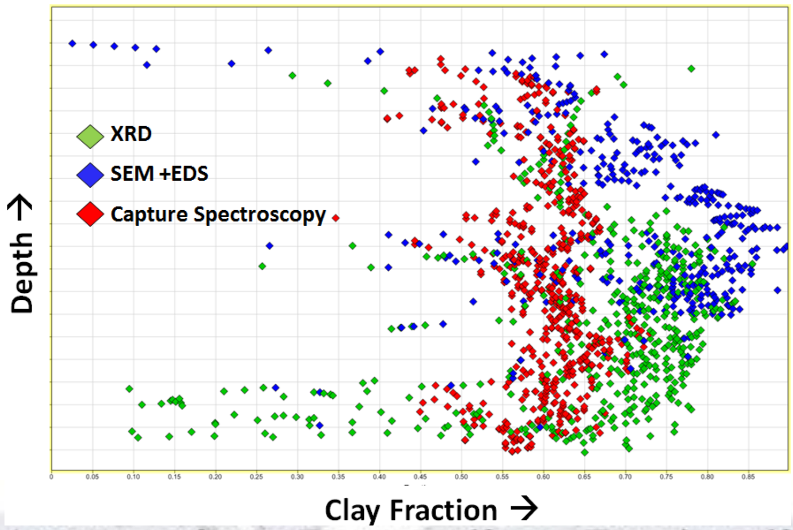
Outputs >> Input measurements



Previous Evaluation <u>Known Challenges</u>

Model 2: Adding capture only spectroscopy

- Mineralogy fixed to spectroscopy (Spectrolith*)
- Clay typing difficult
- Better total clay control than Model 1 (variation vertically and laterally)
- Similar observations from XRD, SEM+EDS
- Are these variations real?
- Computed porosities too high – no correction for organic matter

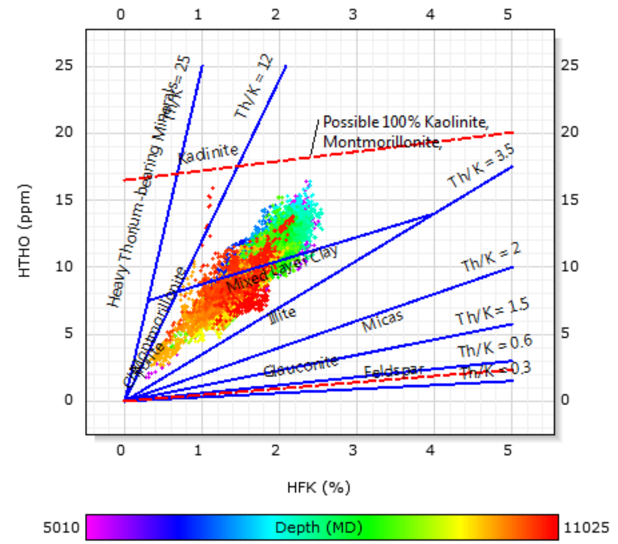


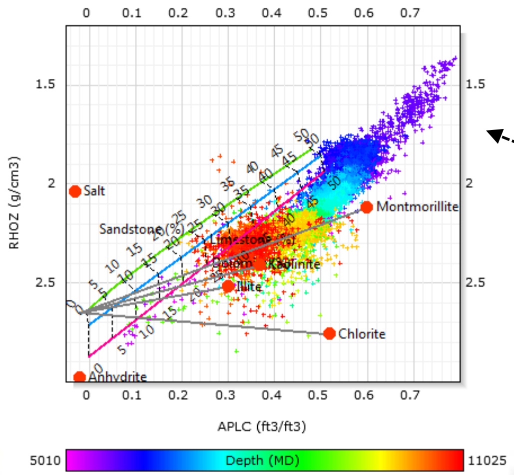
Outputs > Input measurements

Previous Evaluation Challenges

Clay diagenesis

- Various authors (Bjørlykke, 1997; Thyberg et al, 2000; and Marcussen et al., 2009)
- Not seen on Th-K crossplot
- Observed on neutron-density crossplot
- Transition with depth, validated by literature
- Attempted zoning: single mixed clay
- High interpreter subjectivity

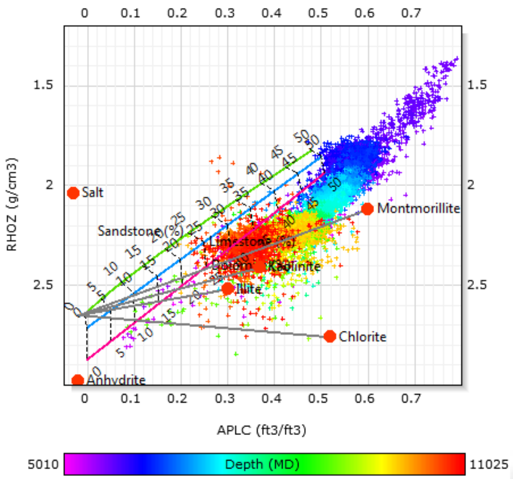




Organic matter (diatomite)

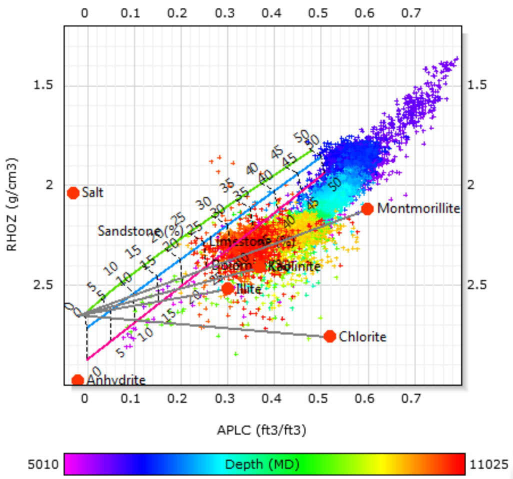
- Very low density
- Very high neutron porosity
- Excessive porosities (needs inclusion of organic matter)
- Log measurement to solve (organic carbon - TOC)

Previous Evaluation Challenges



Previous Evaluation Challenges

Gas and light hydrocarbons



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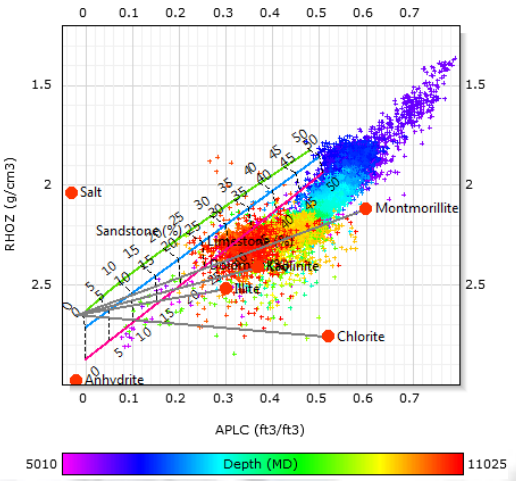
- Migrated from reservoir over geologic time



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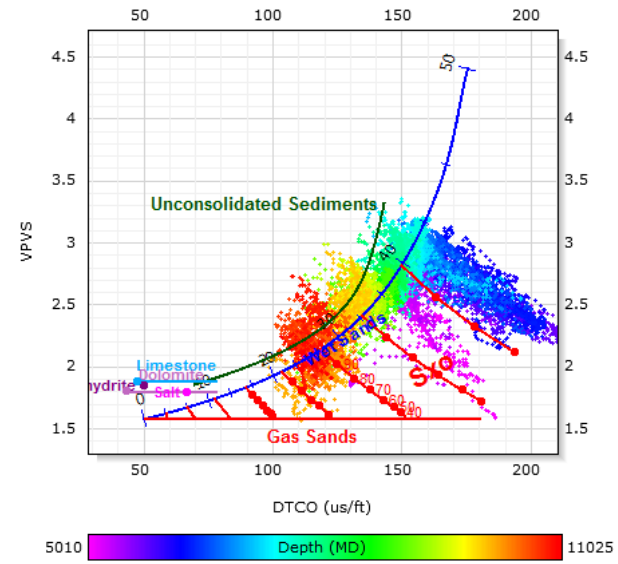

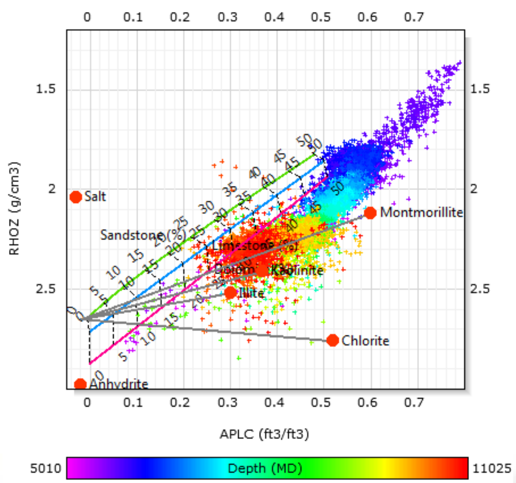

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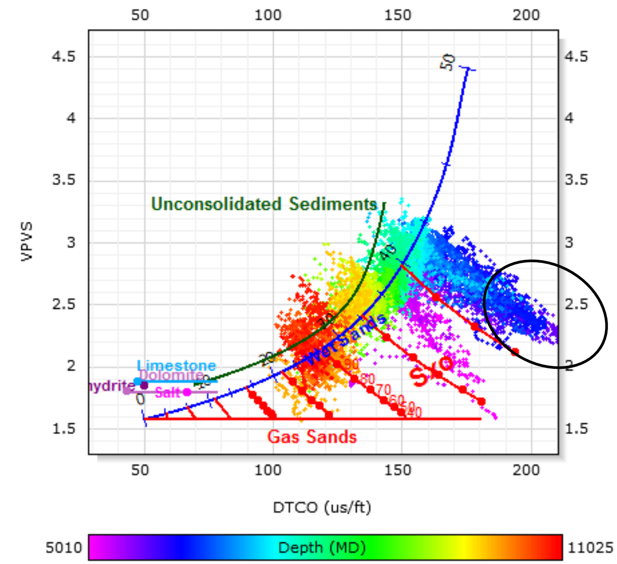

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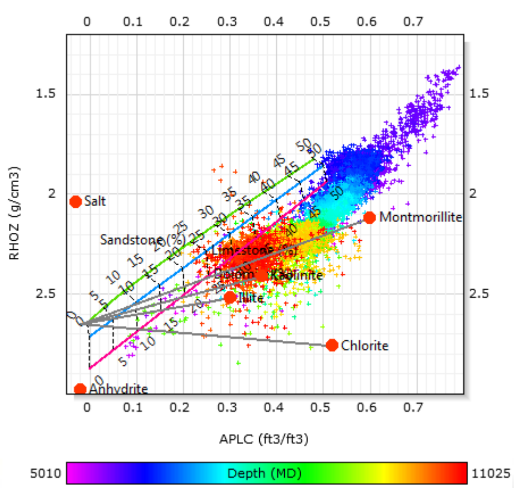

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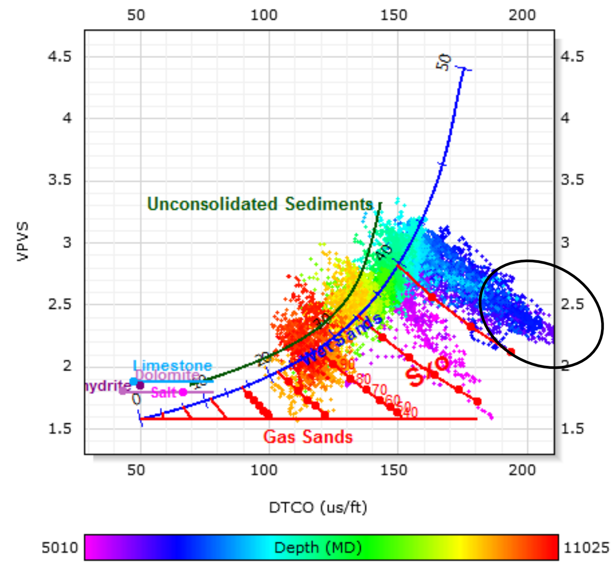

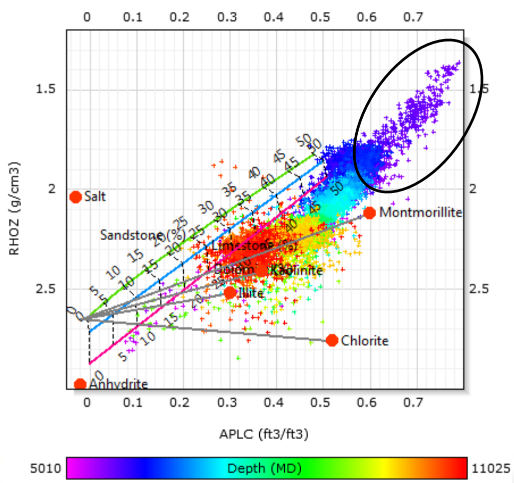

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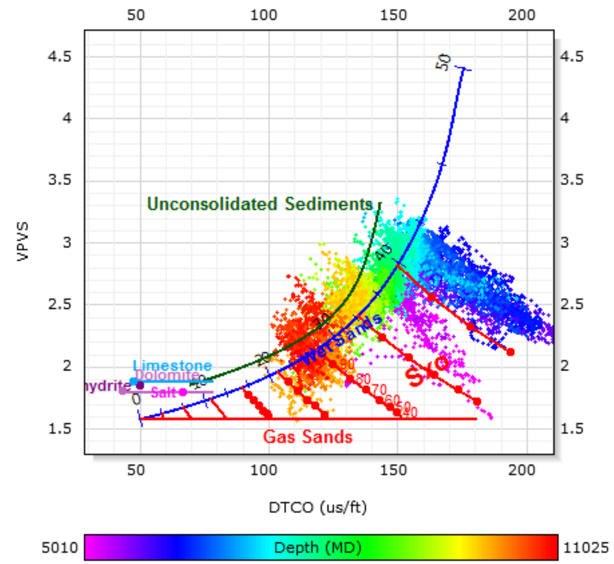
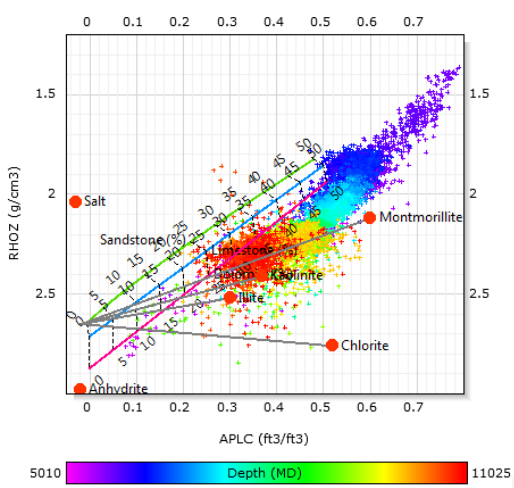


Carbonate stringers



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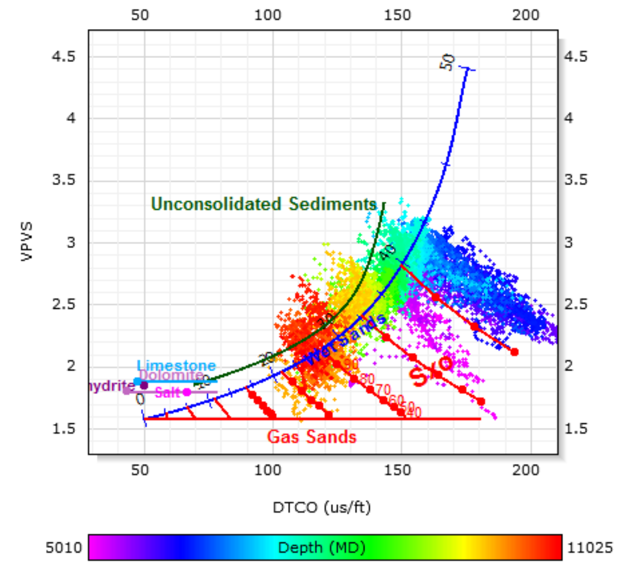

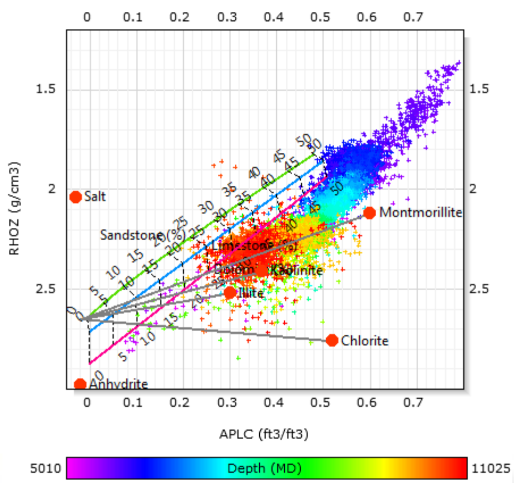

Carbonate stringers

- Hard to drill
- Associated gas below some stringers
- Laterally extensive
- Both calcite and dolomite
- Log measurements to solve (Ca, Mg, Mn)

Methodology

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Two step interpretation

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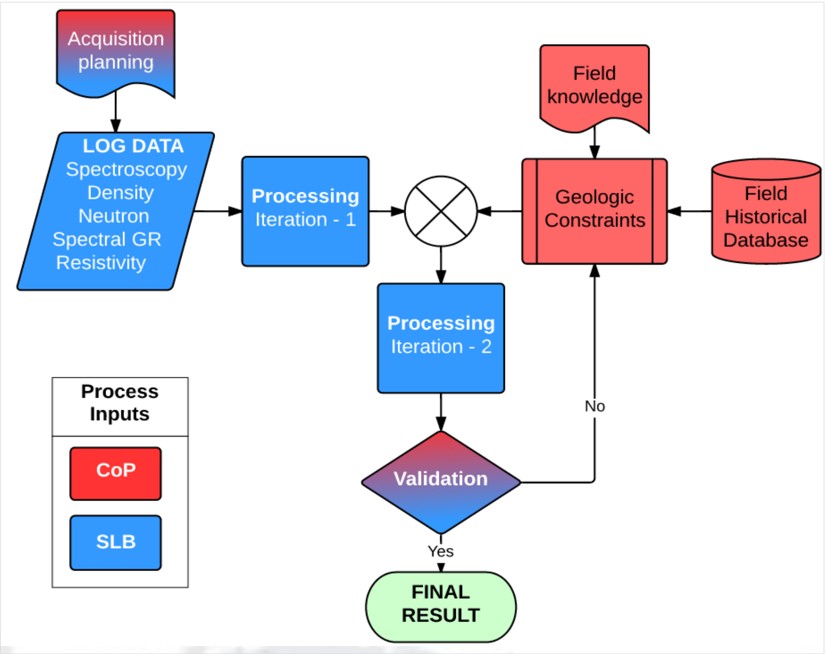

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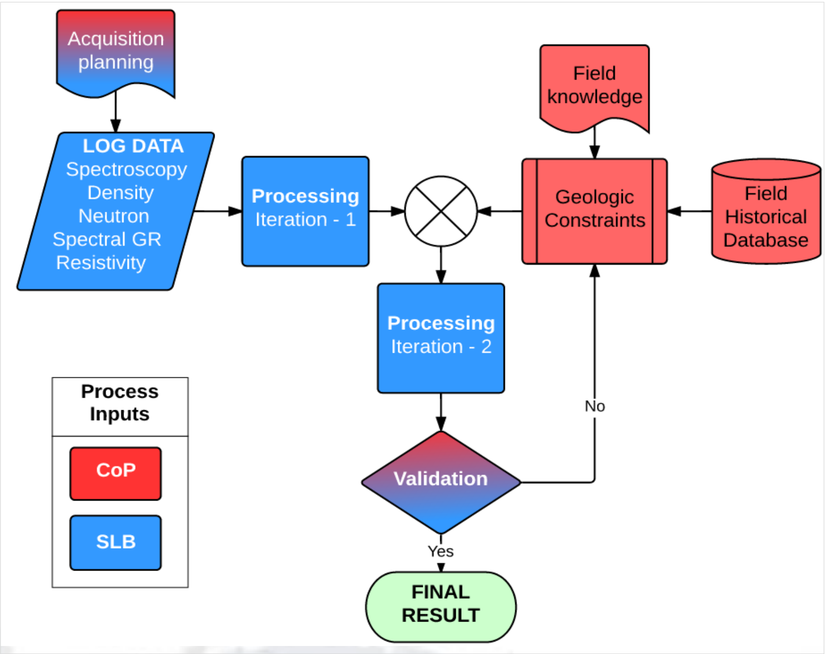

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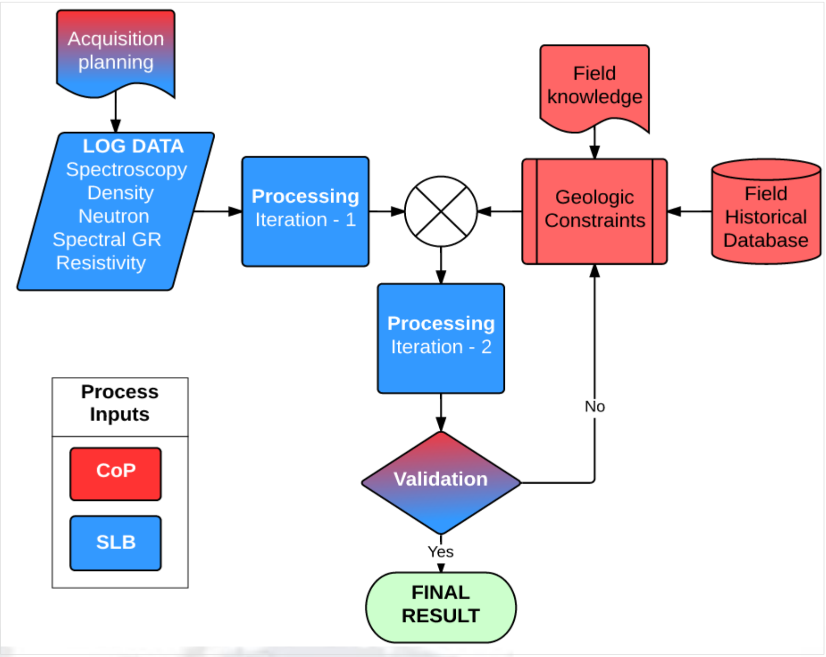

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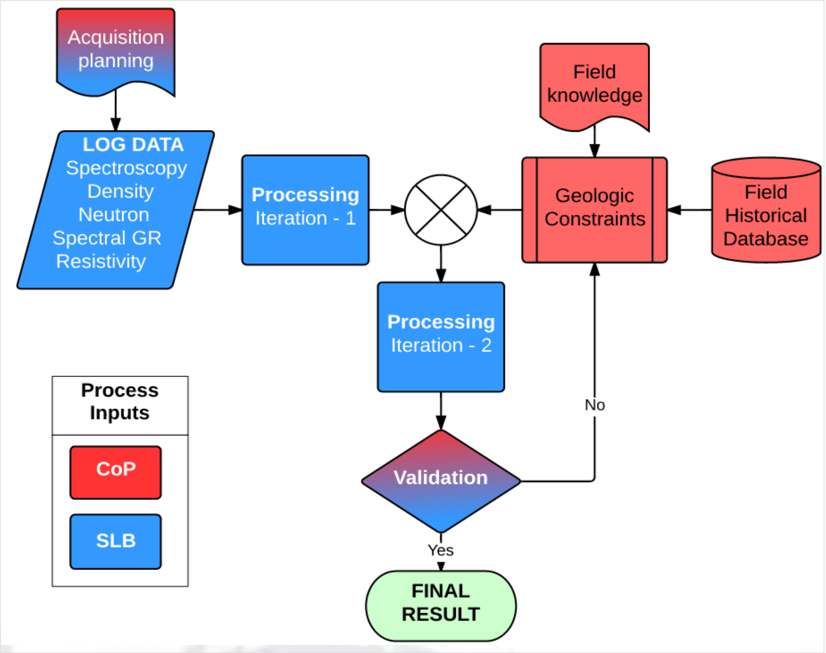

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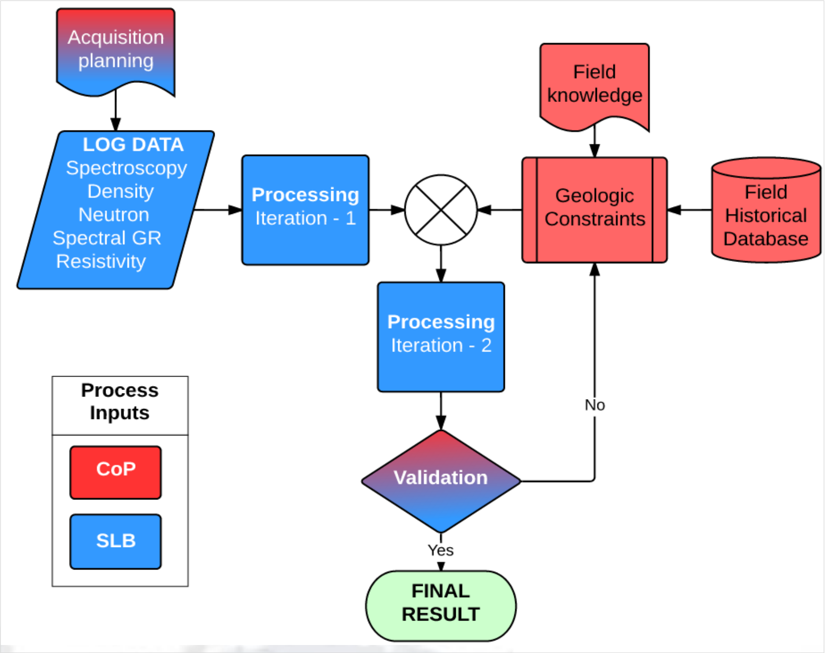
- Iteration 2: integration with GEA database



Spectroscopy Principles

Radtke et. al, 2012

Spectroscopy Principles

Spectral Acquisition
- Capture
- Inelastic

Spectral Analysis
- Elemental Yields

Closure
- Elemental Weight Fractions

Interpretation
- Petrophysical answers

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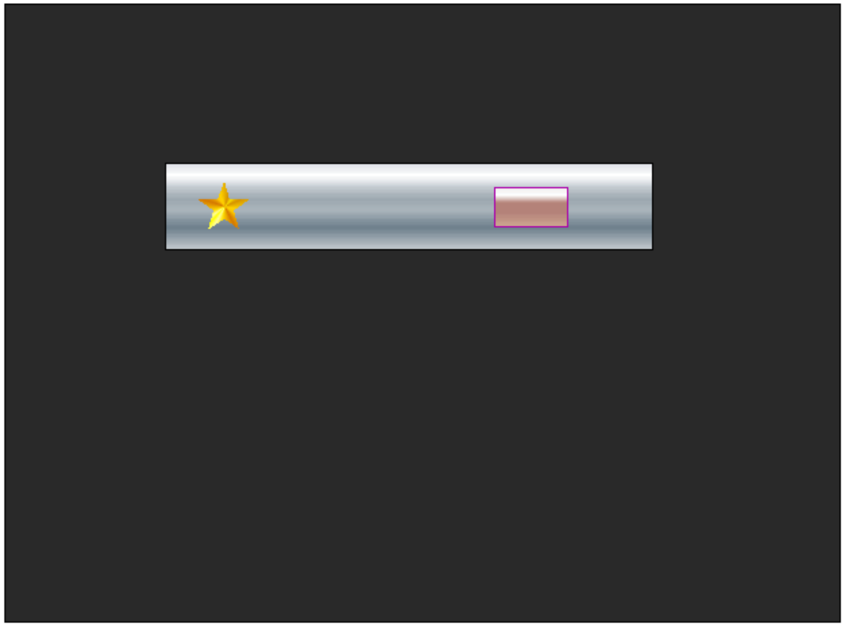

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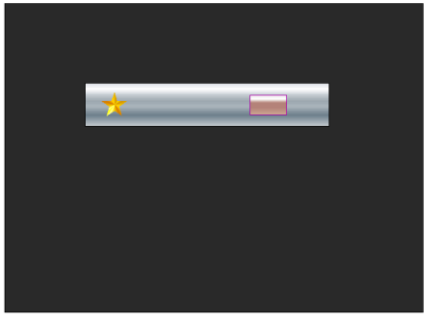

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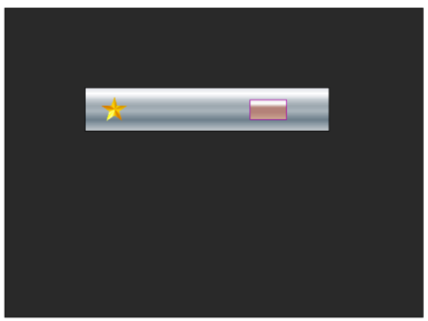

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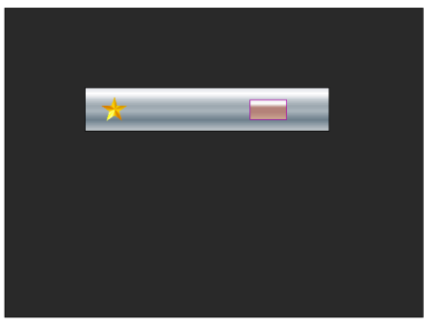

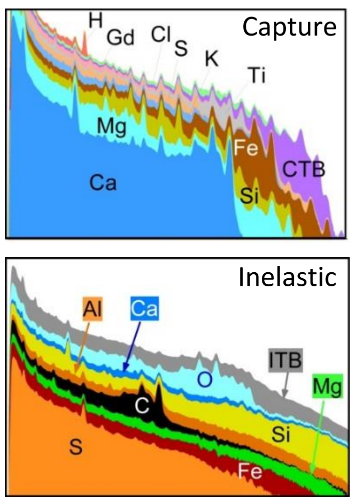

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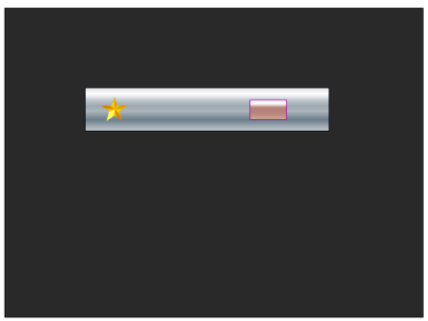

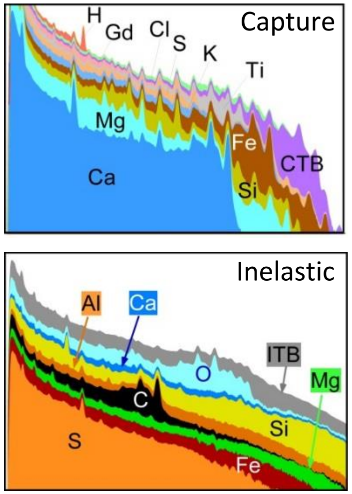

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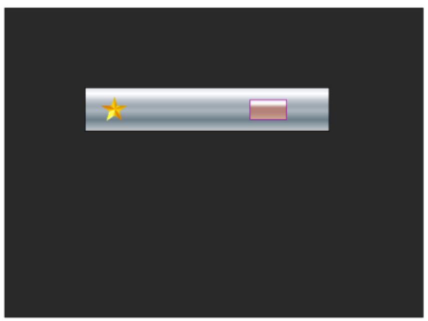

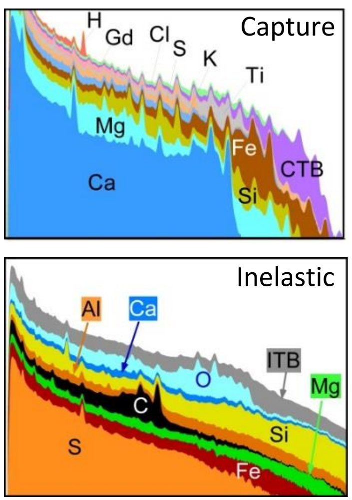

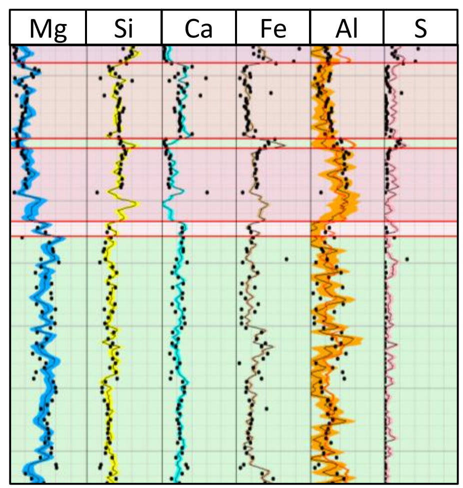

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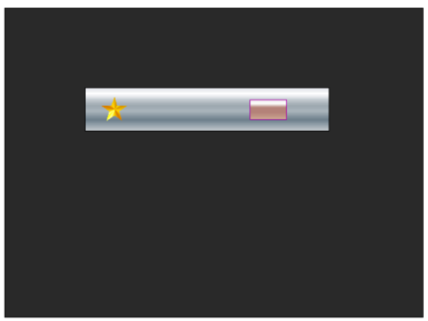

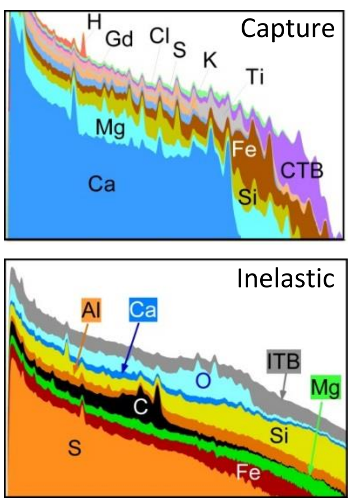

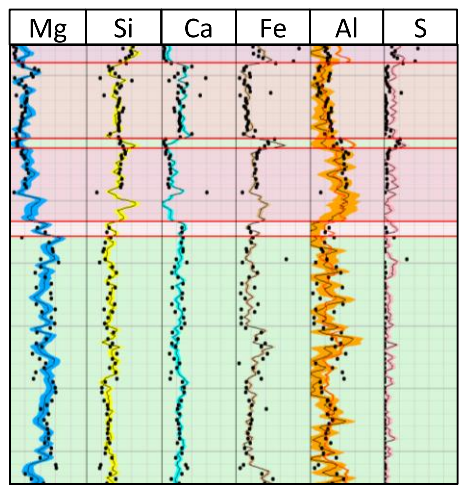

Radtke et. al, 2012

Spectroscopy Principles

Spectroscopy directly
- Minerals (limited)
- Matrix Properties
- TOC
- Sigma

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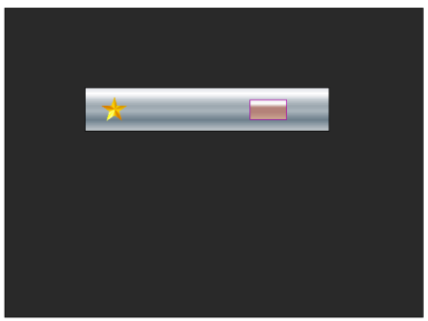

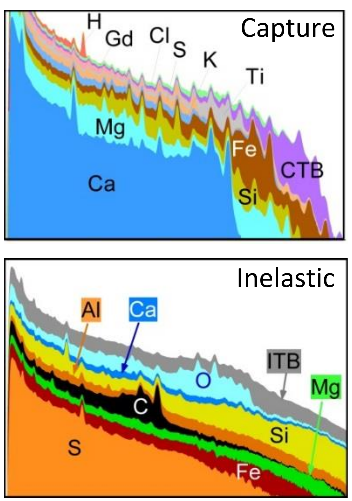

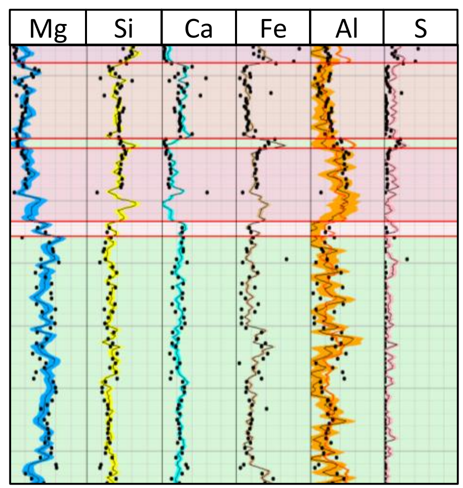

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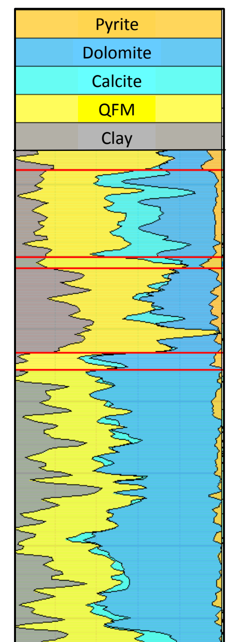

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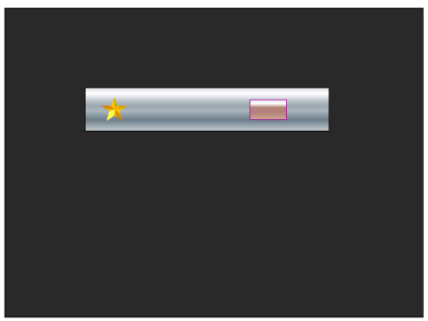
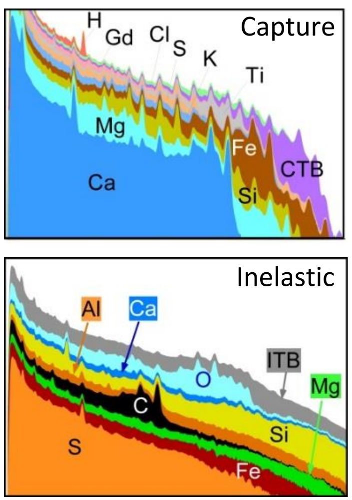
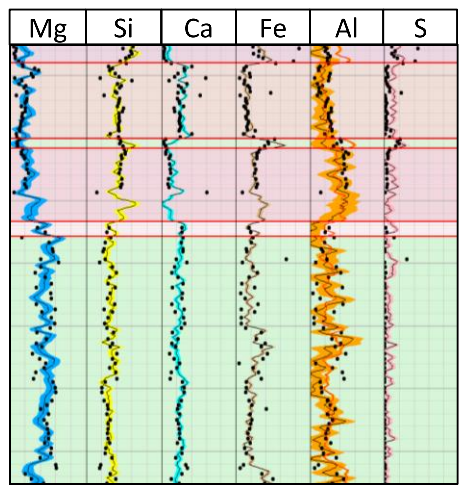
Multimineral Analysis
- Minerals (full)
- Organic matter
- Clay Typing
- Porosity
- Saturation







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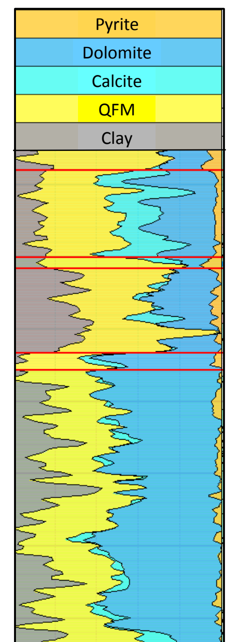

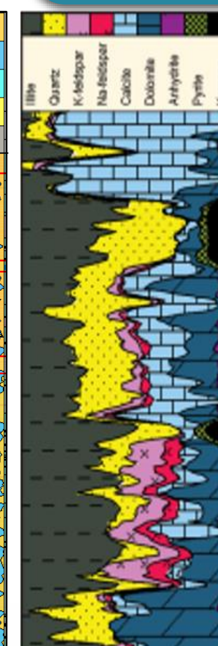

Mineralogical solution

Using direct spectroscopy outputs

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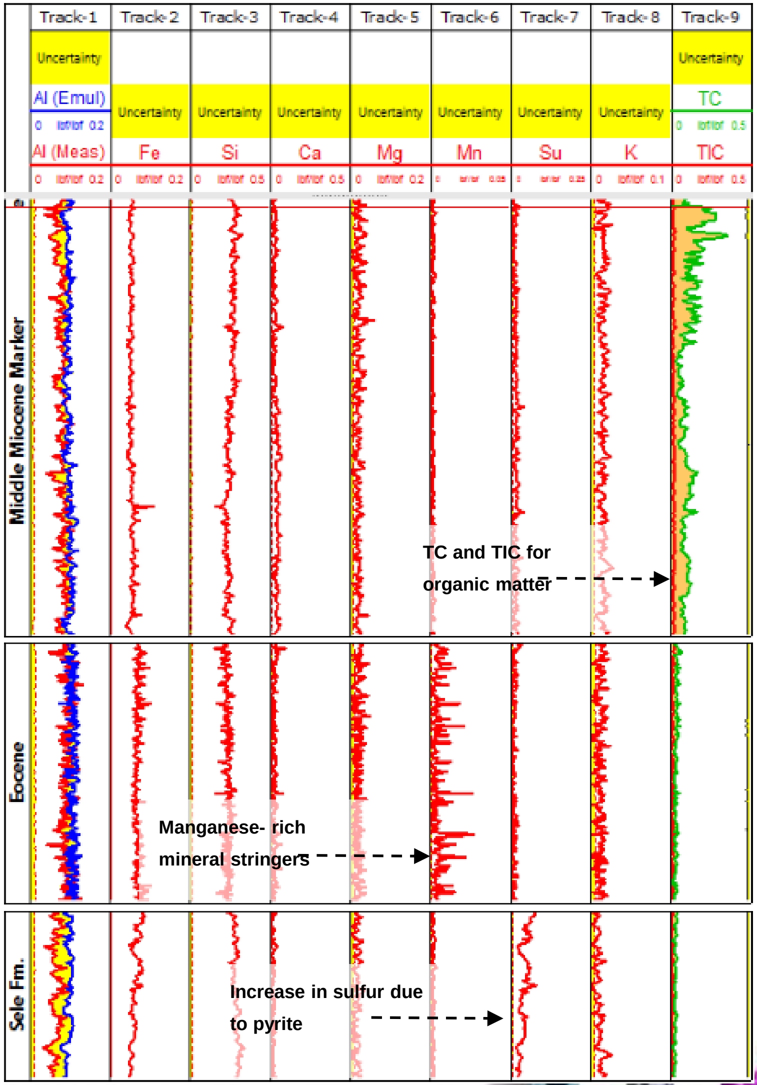
- Elemental dry weights and uncertainties
- TOC = TC – TIC → organic content



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- Magnesium → calcite vs. dolomite
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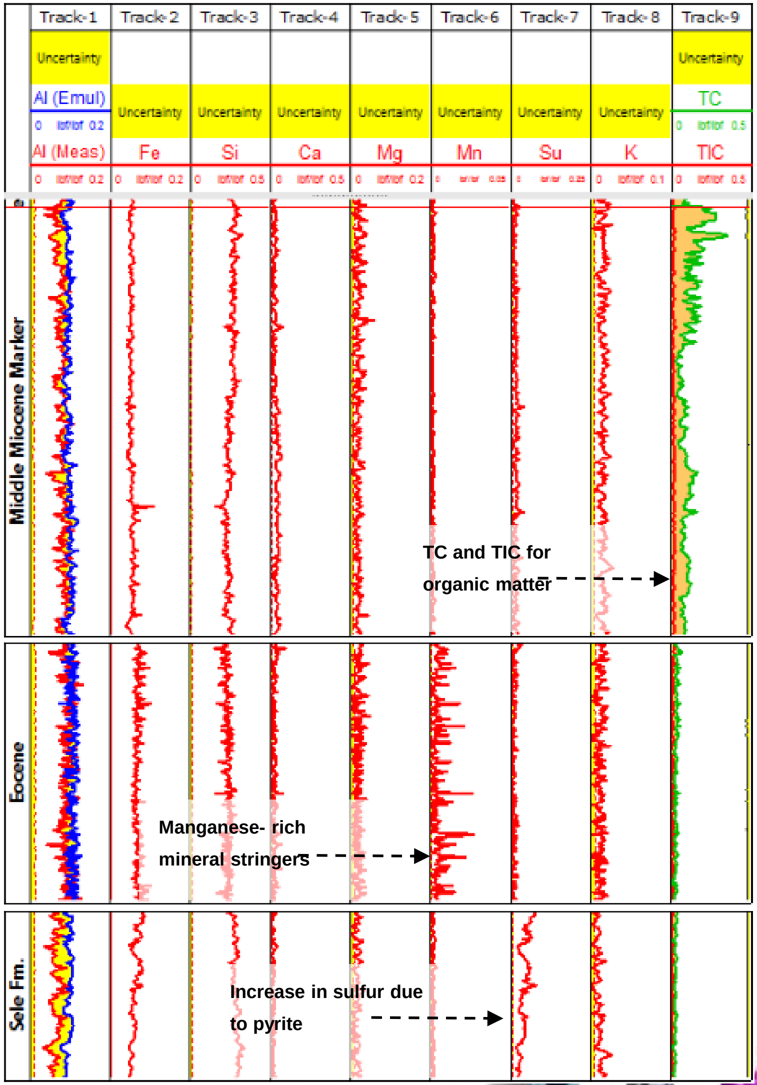

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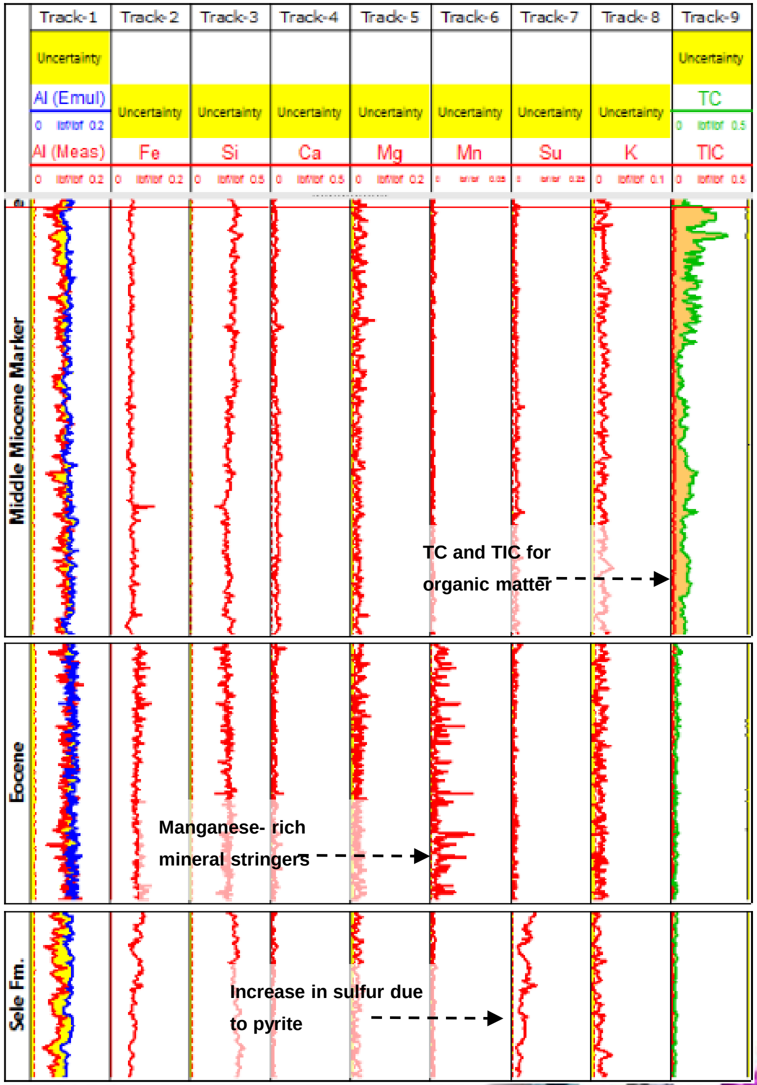

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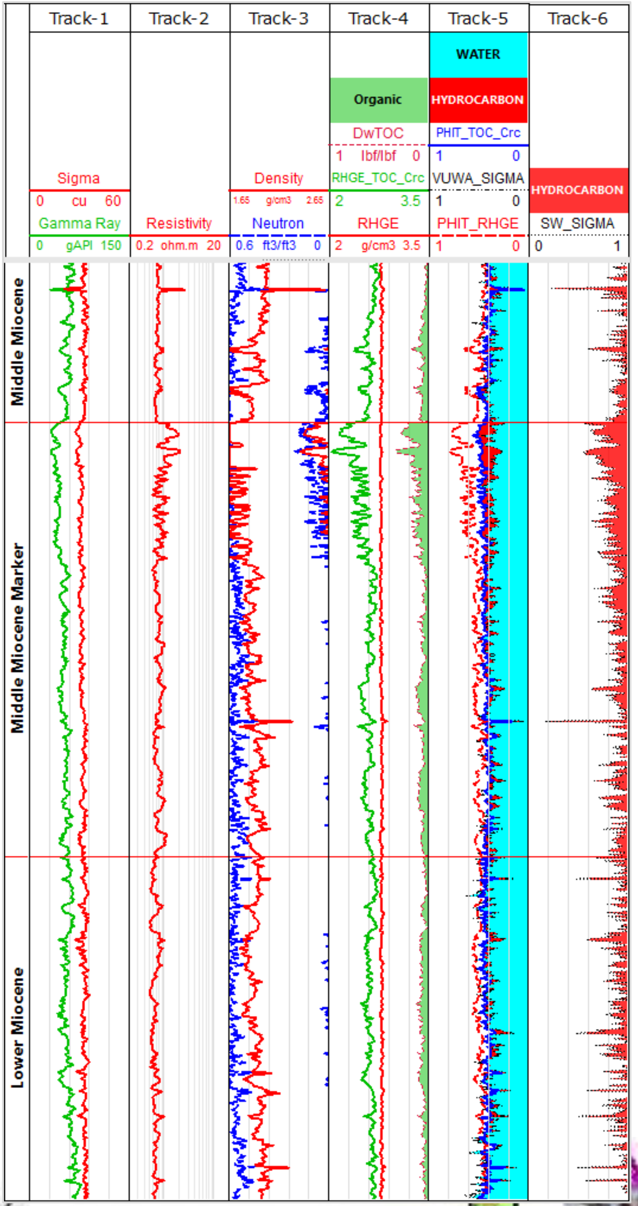
- Sigma →water saturation



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- Mineral volumes: Clay types (4), Carbonates (2), quartz, feldspars, mica (4), iron minerals (2), rhodochrosite (1)
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Iterative inversion technique: ELANPlus*

Ground rules:

- Retain default end points (unless specific justification)
- Constraints & zoning based on GEA database

Linking Minerals to Elements

Minerals

Elements

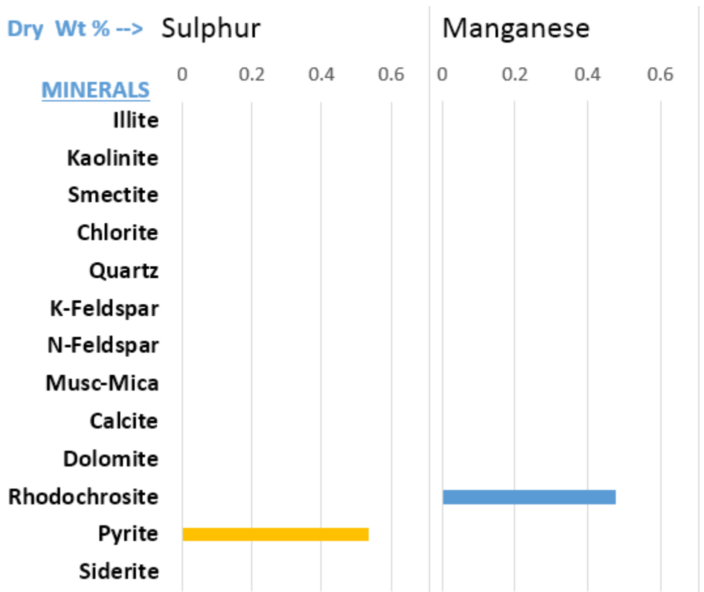
Linking Minerals to Elements

Minerals → Elements

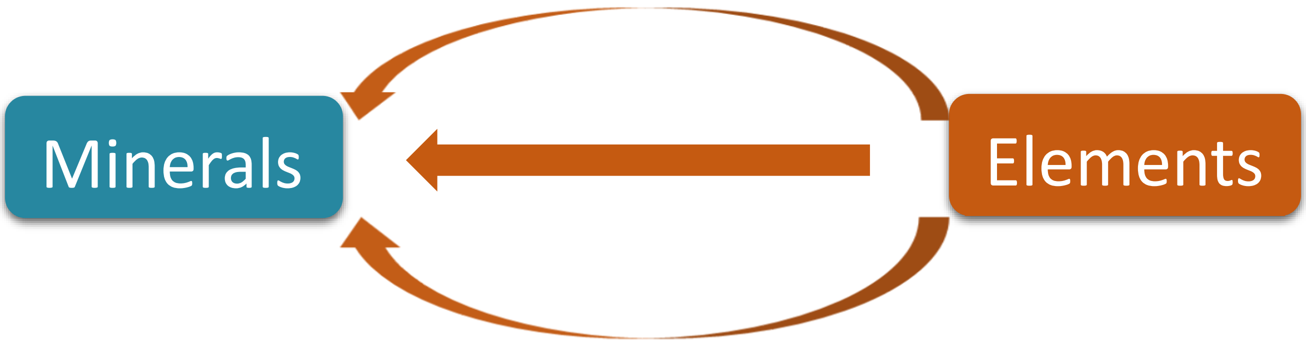
Linking Minerals to Elements

Elements to minerals is not always a unique mapping

- Some elements can be mapped uniquely (with assumptions), others not

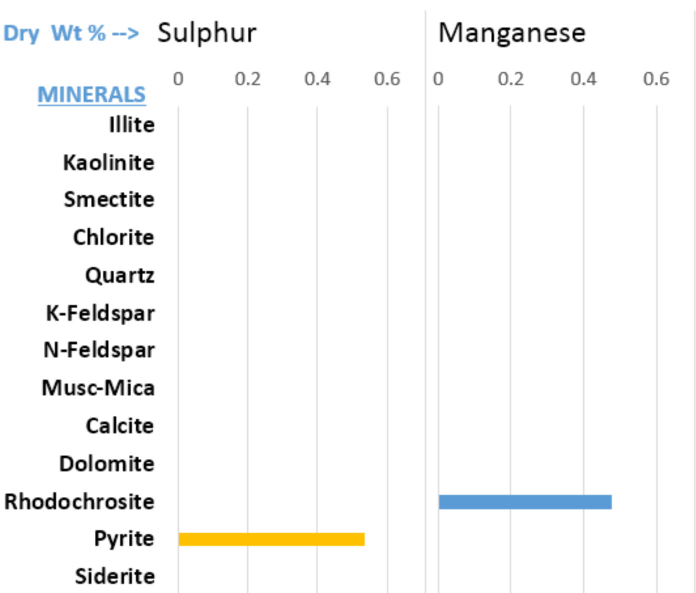


Linking Minerals to Elements



Elements to minerals is not always a unique mapping

- Some elements can be mapped uniquely (with assumptions), others not



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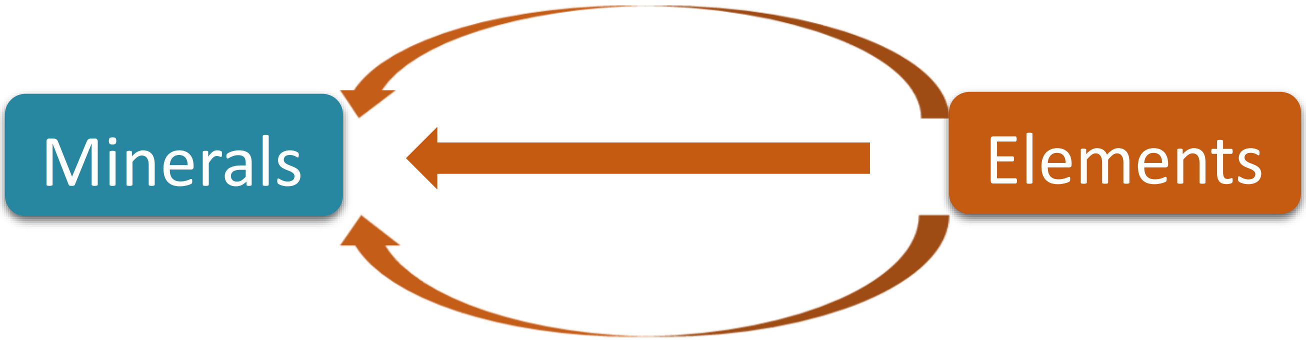

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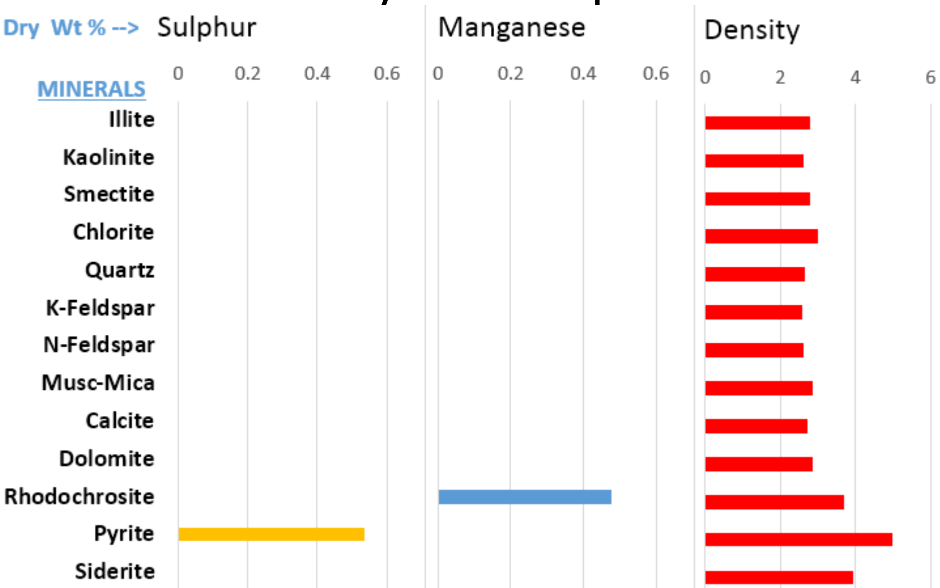

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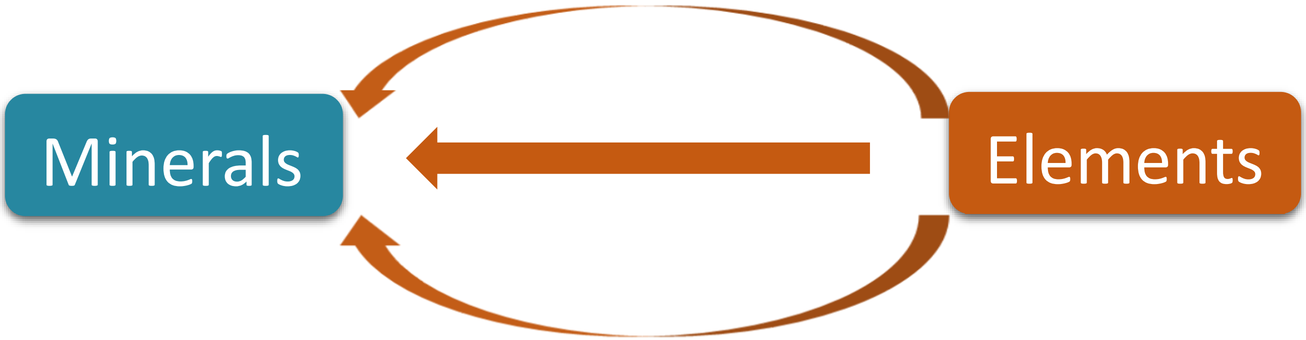

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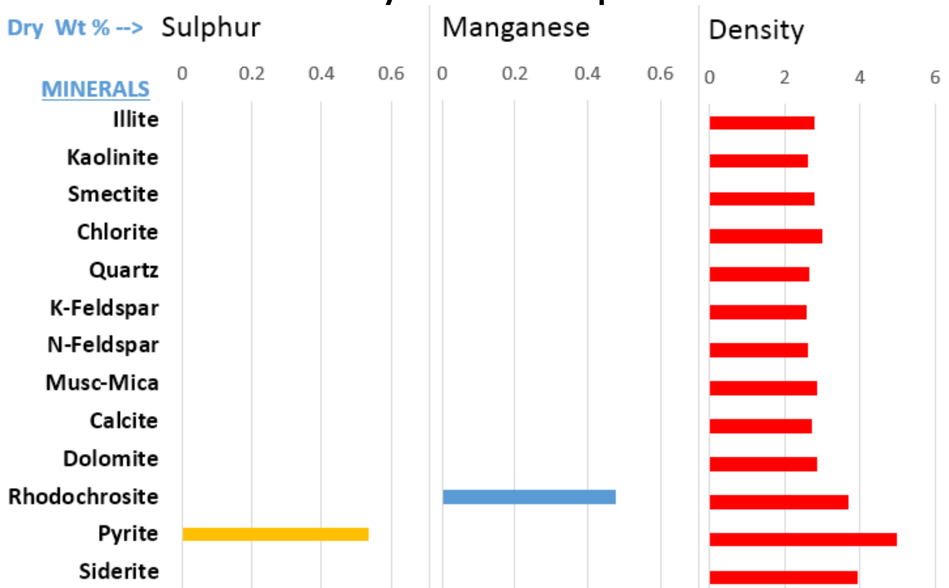

- Poor discriminator between rock minerals
- Strong driver for porosity

Linking Minerals to Elements

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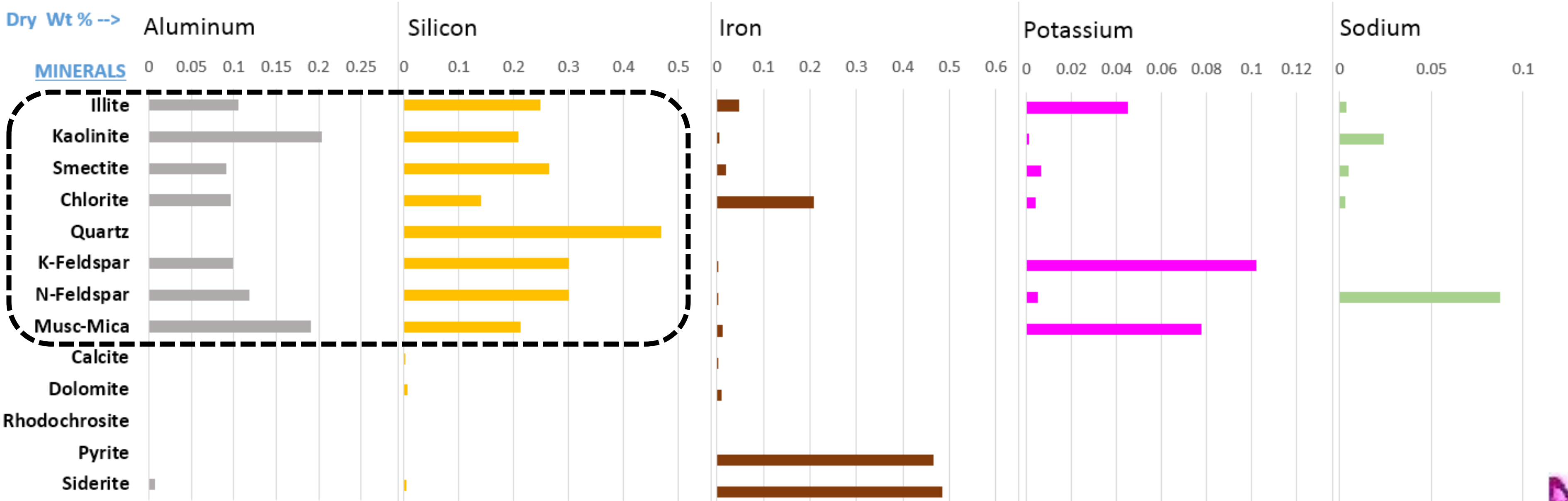

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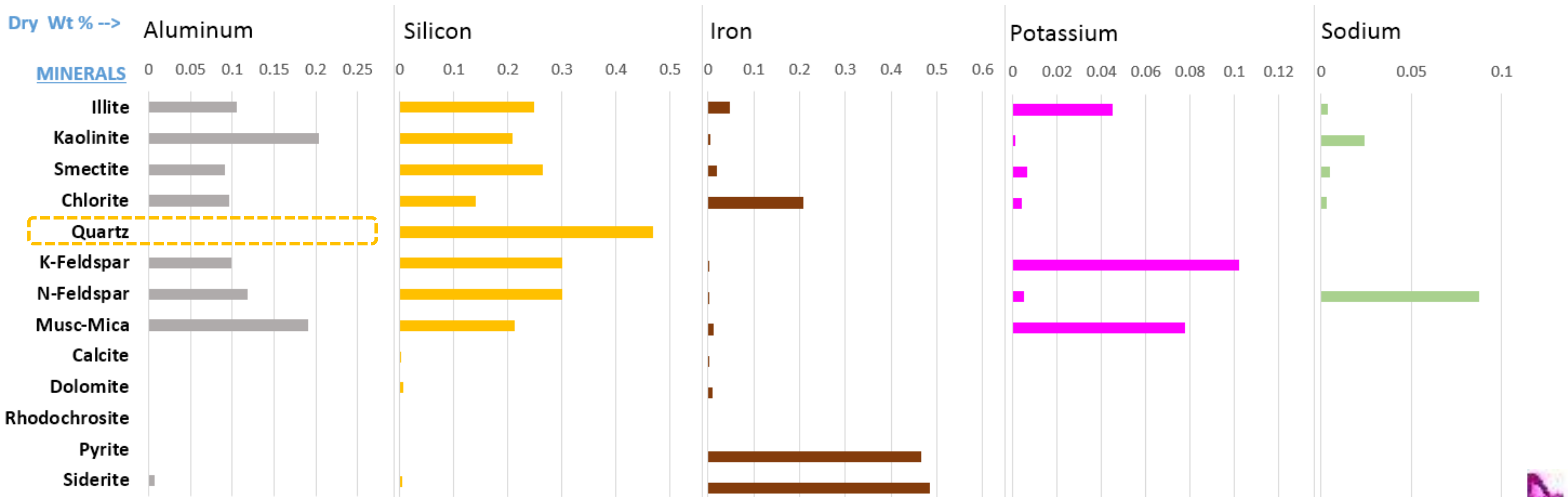

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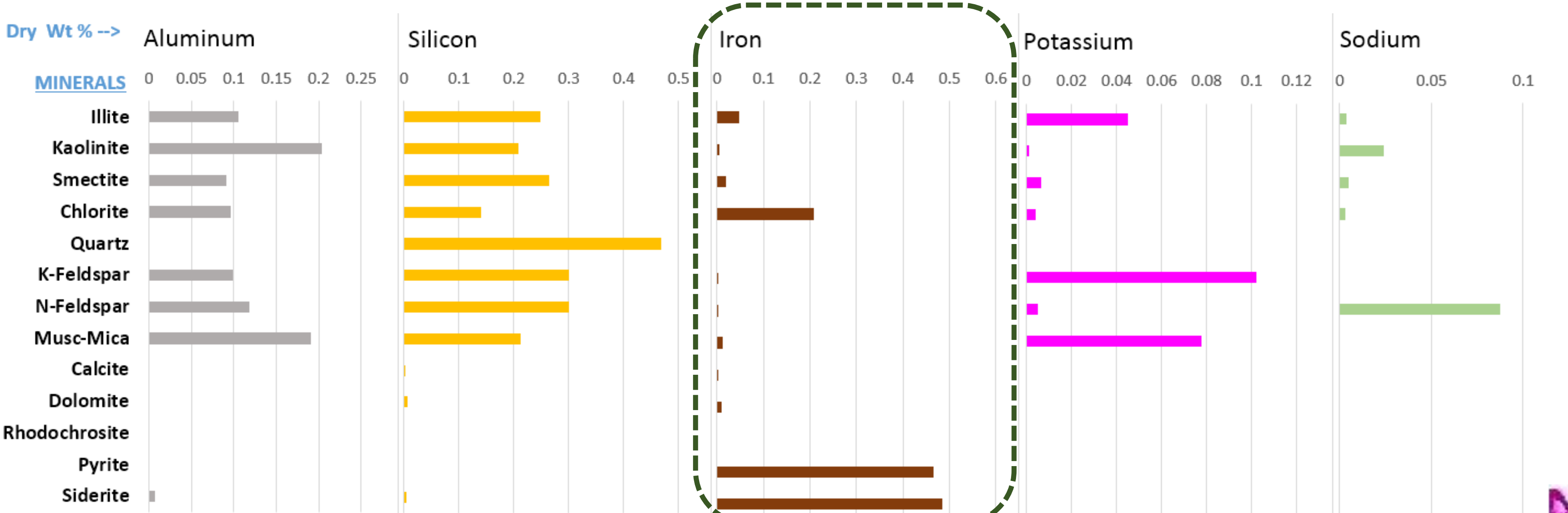

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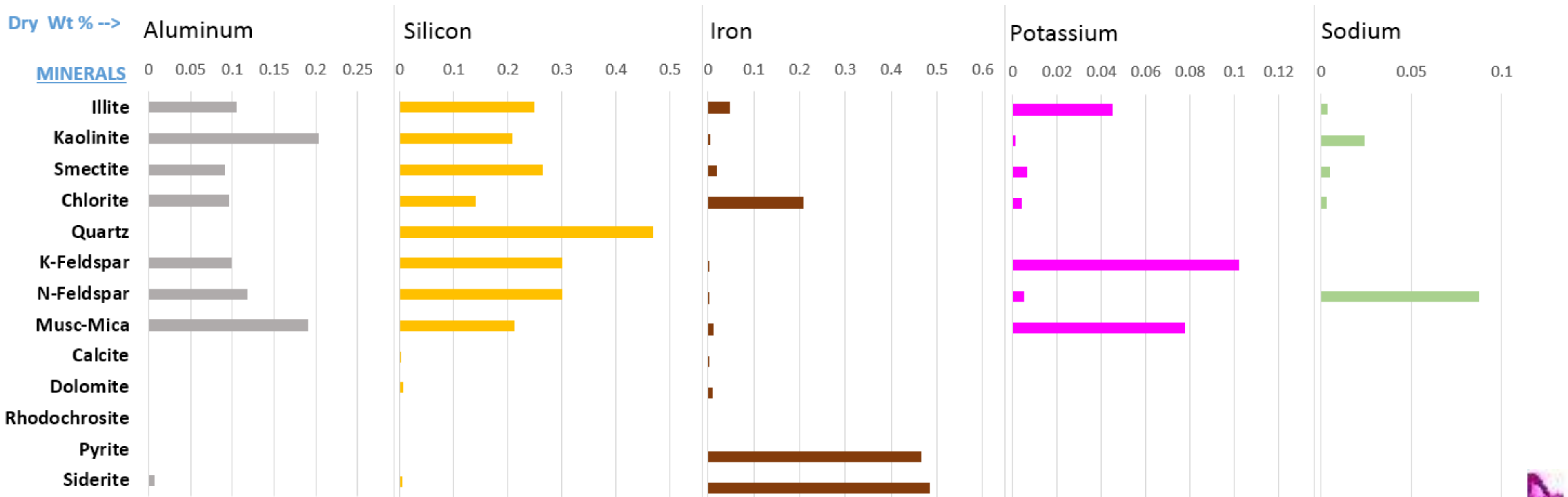

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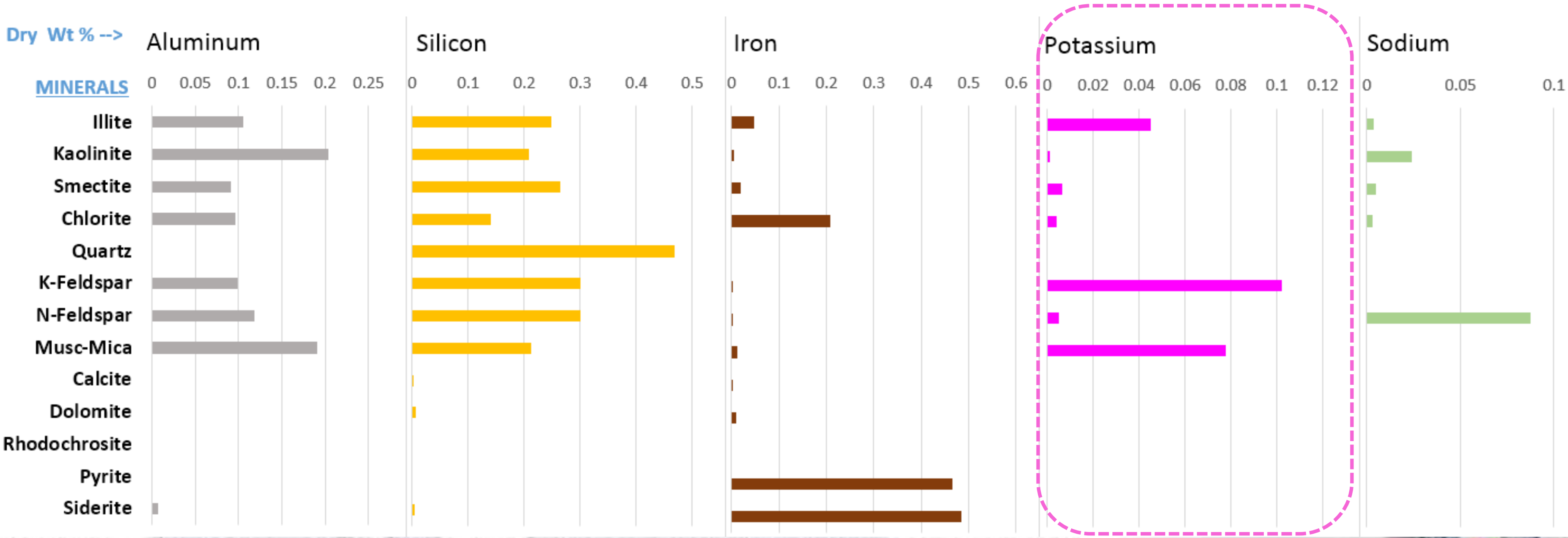

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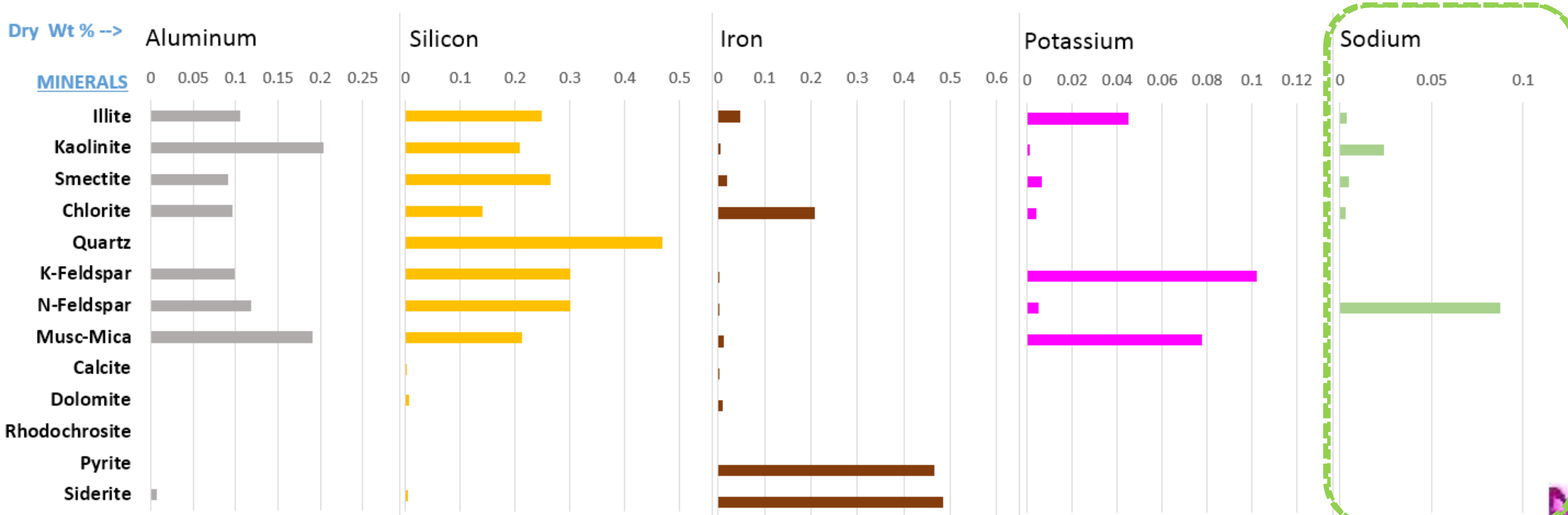

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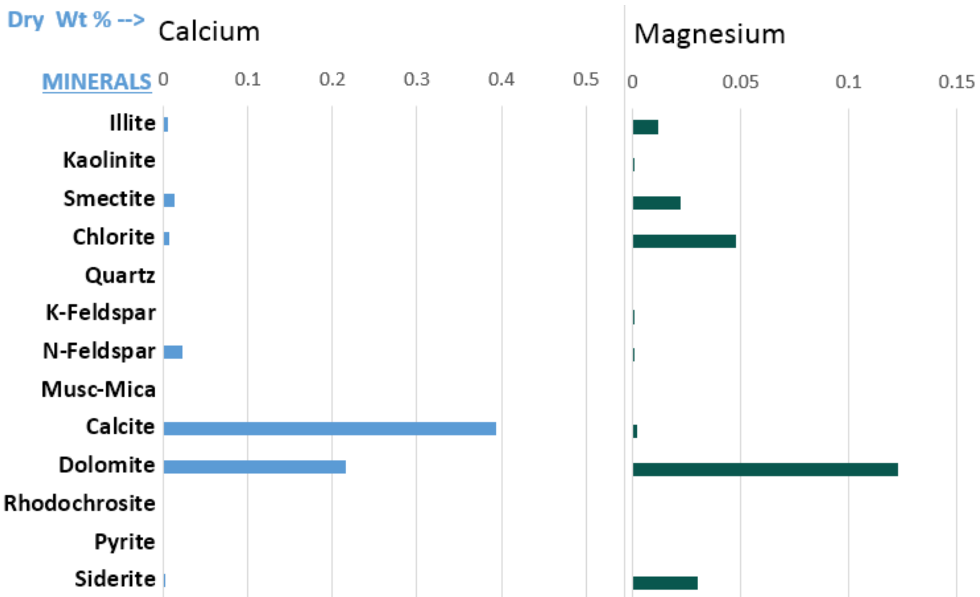
- Calcium + Magnesium mostly sufficient to solve main carbonate minerals.



Building the Petrophysical model

Integrating log with local knowledge & geologic information

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- Many minerals can be solved via spectroscopy

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GEA legacy database
Literature survey in Area

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Mineral constraints ← GEA legacy database / Literature survey in Area

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Multimineral solver ← Mineral constraints ← GEA legacy database / Literature survey in Area

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Multimineral solver ← Mineral constraints ← GEA legacy database / Literature survey in Area

ERA	PERIOD	EPOCH	GROUP	Formation/ Section
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		PLIOCENE		
		MIOCENE		Upper Miocene
				Upper Miocene Marker
			HORDALAND	Middle Miocene Marker
				Lower Miocene
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			ROGALAND	Balder
		PALEOCENE		Sele
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CENOZOIC	PALEOGENE	PALEOCENE	ROGALAND	Sele
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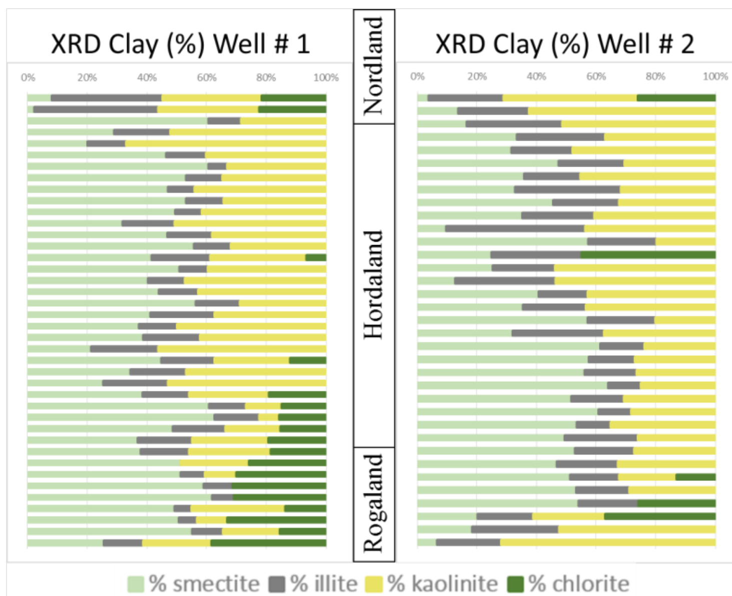

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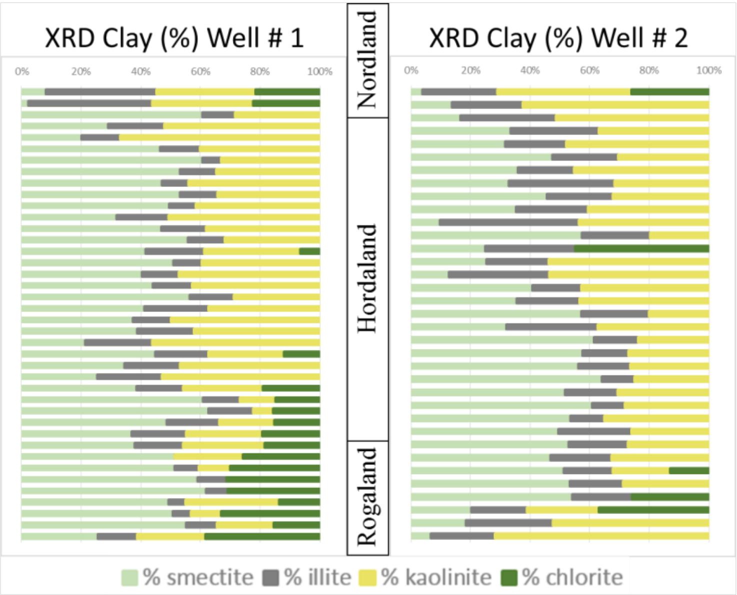

Dominantly smectite
Variable kaolinite
Little chlorite

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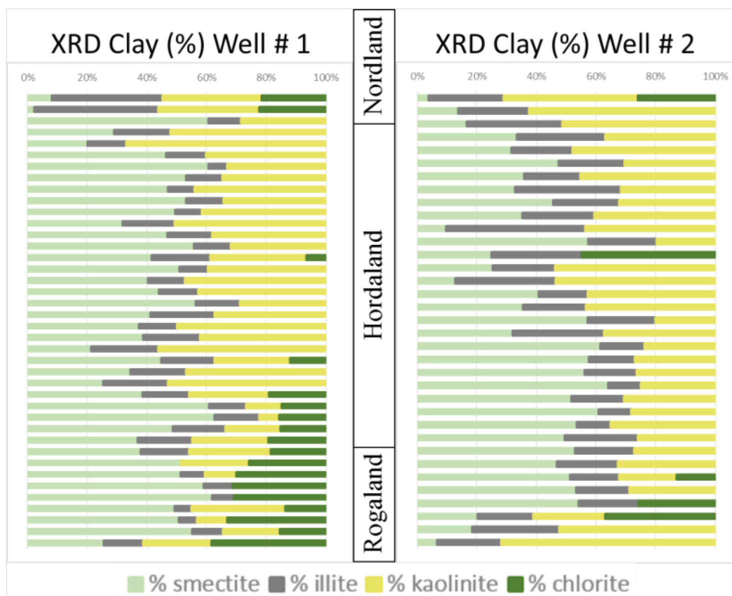

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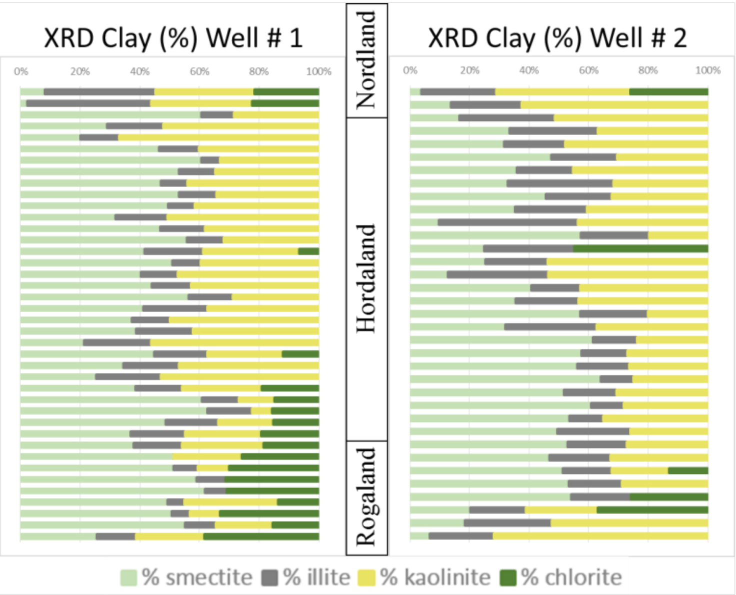

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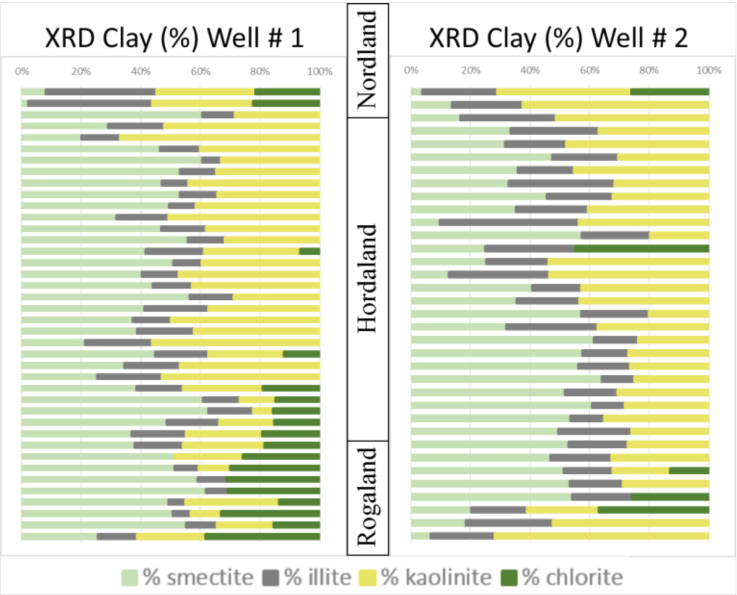

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- ***Clay mineral constraints based on GEA legacy database & elemental reconstructions***

Building the Petrophysical model

- ***Selection of minerals made for each formation***
  - Calcite, pyrite, siderite, and quartz were solved everywhere
  - Dolomite was not solved for in the Upper Miocene and Våle formations
  - Rhodochrosite solved in the Oligocene and lower formations

Multimineral solver ← Mineral constraints ← GEA legacy database / Literature survey in Area

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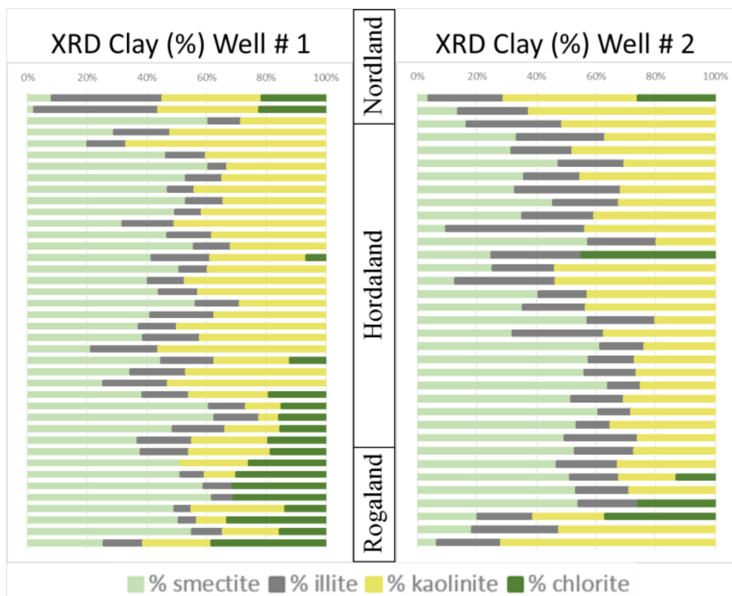
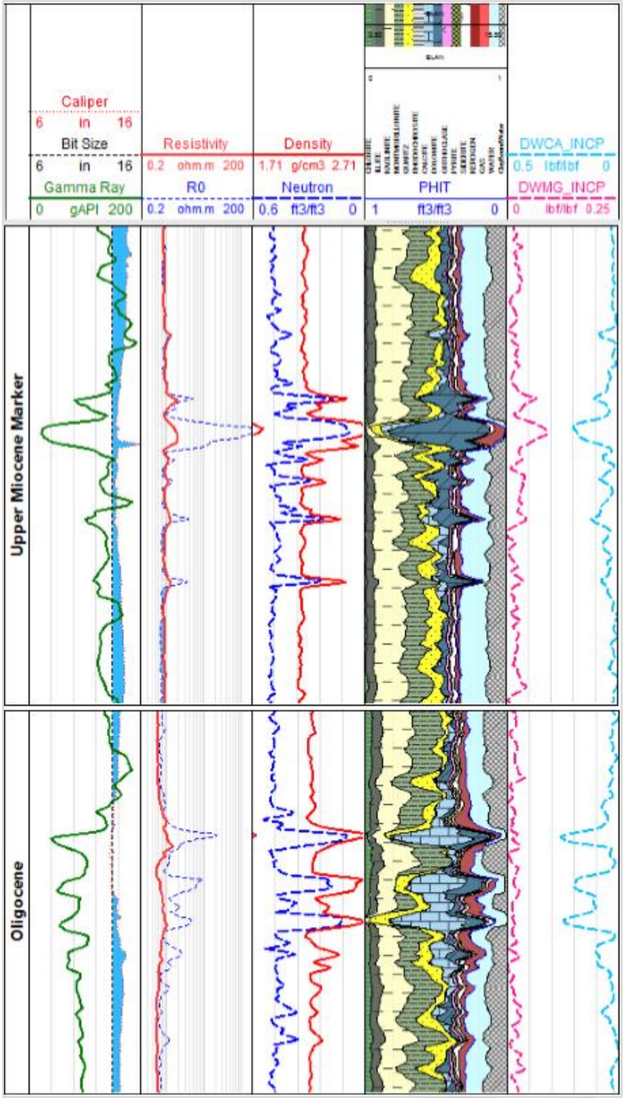


- ***Clay mineral constraints based on GEA legacy database & elemental reconstructions***

Mineral Model Results

- *Calcite dolomite stringers*



Mineral Model Results

- *Calcite dolomite stringers*
- *TOC*

Mineral Model Results

- *Calcite dolomite stringers*
- *TOC*

↓

- *Organic matter (part of matrix)*

Mineral Model Results

- *Calcite dolomite stringers*
- *TOC*

↓

- *Organic matter (part of matrix)*

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- *Matrix grain density (TOC corrected)*

Mineral Model Results

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- *Porosity (accounting for organic matter on log responses)*

Mineral Model Results

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↓

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↓

- *Gas saturation (Resistivity ←------→ Sigma, Sonic crossplot)*

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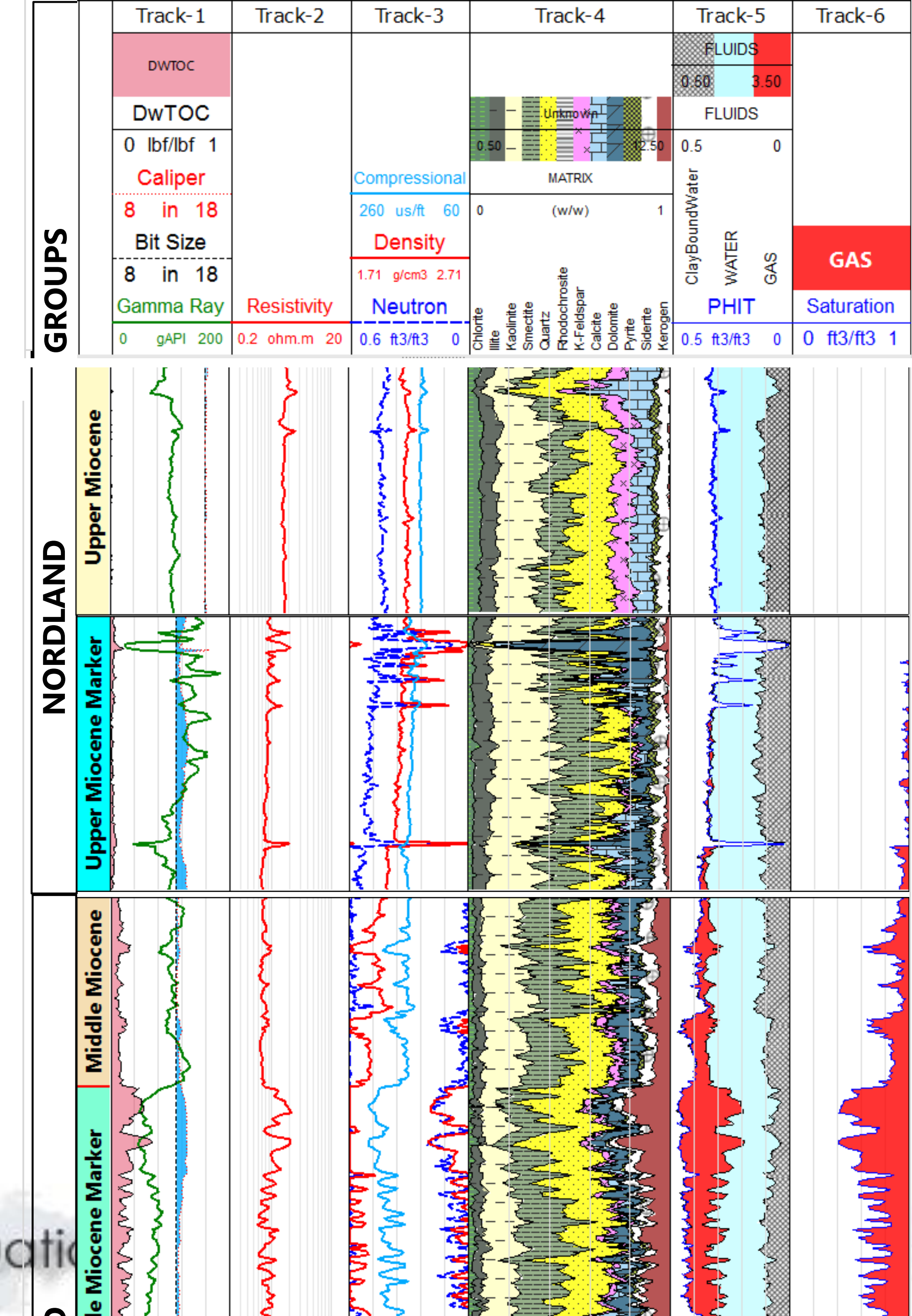

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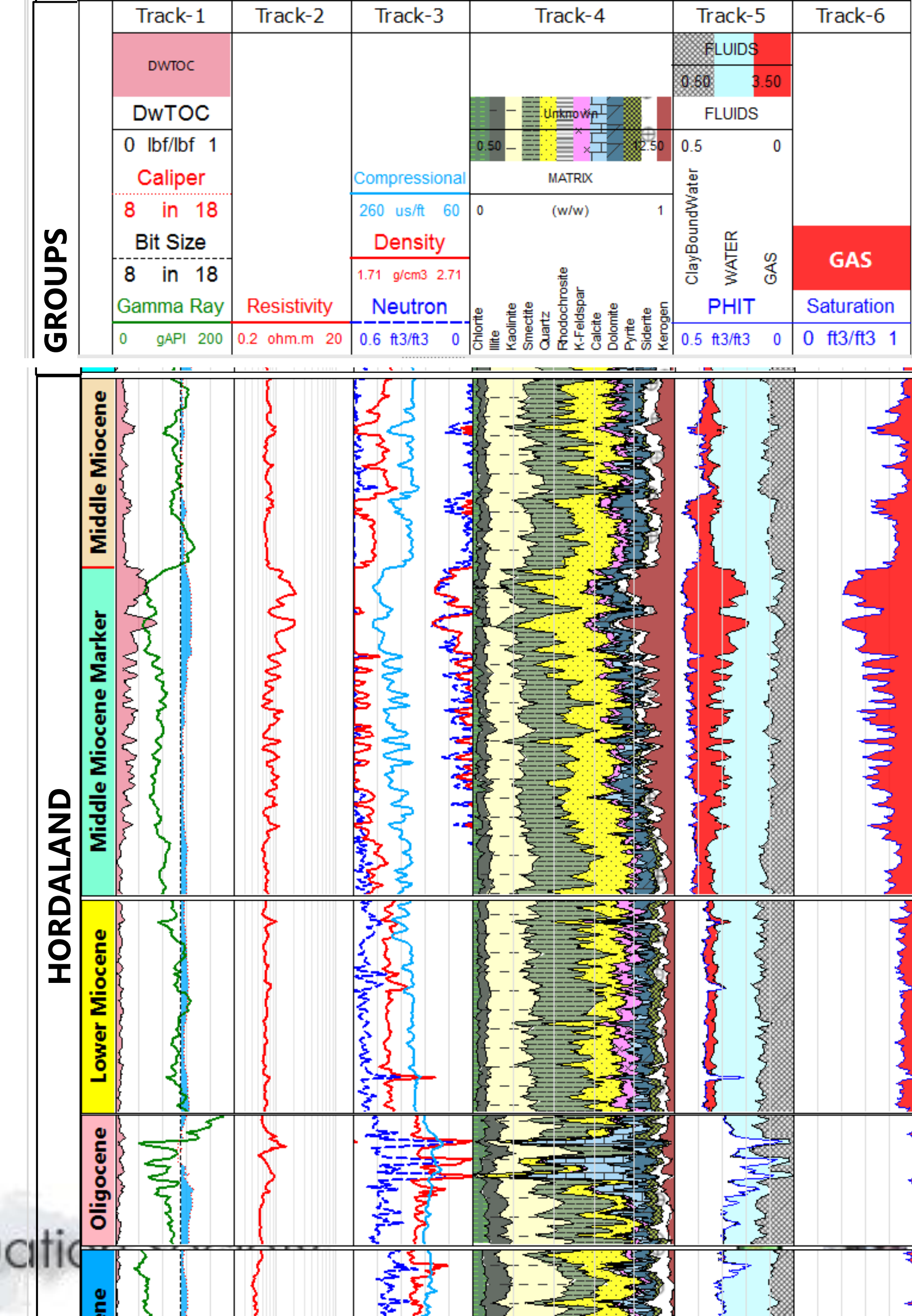
GROUPS
Track-1
Track-2
Track-3
Track-4
Track-5
Track-6
DWTOC
DwTOC
0 lbf/lbf 1
Caliper
8 in 18
Bit Size
8 in 18
Gamma Ray
0 gAPI 200
Resistivity
0.2 ohm.m 20
Compressional
260 us/ft 60
Density
1.71 g/cm3 2.71
Neutron
0.6 ft3/ft3 0
Unknown
0.50
2.50
MATRIX
0 (w/w) 1
Chlorite
Illite
Kaolinite
Smectite
Quartz
Rhodochrosite
K-Feldspar
Calcite
Dolomite
Pyrite
Siderite
Kerogen
FLUIDS
0.50
3.50
FLUIDS
0.5 0
ClayBoundWater
WATER
GAS
PHIT
0.5 ft3/ft3 0
GAS
Saturation
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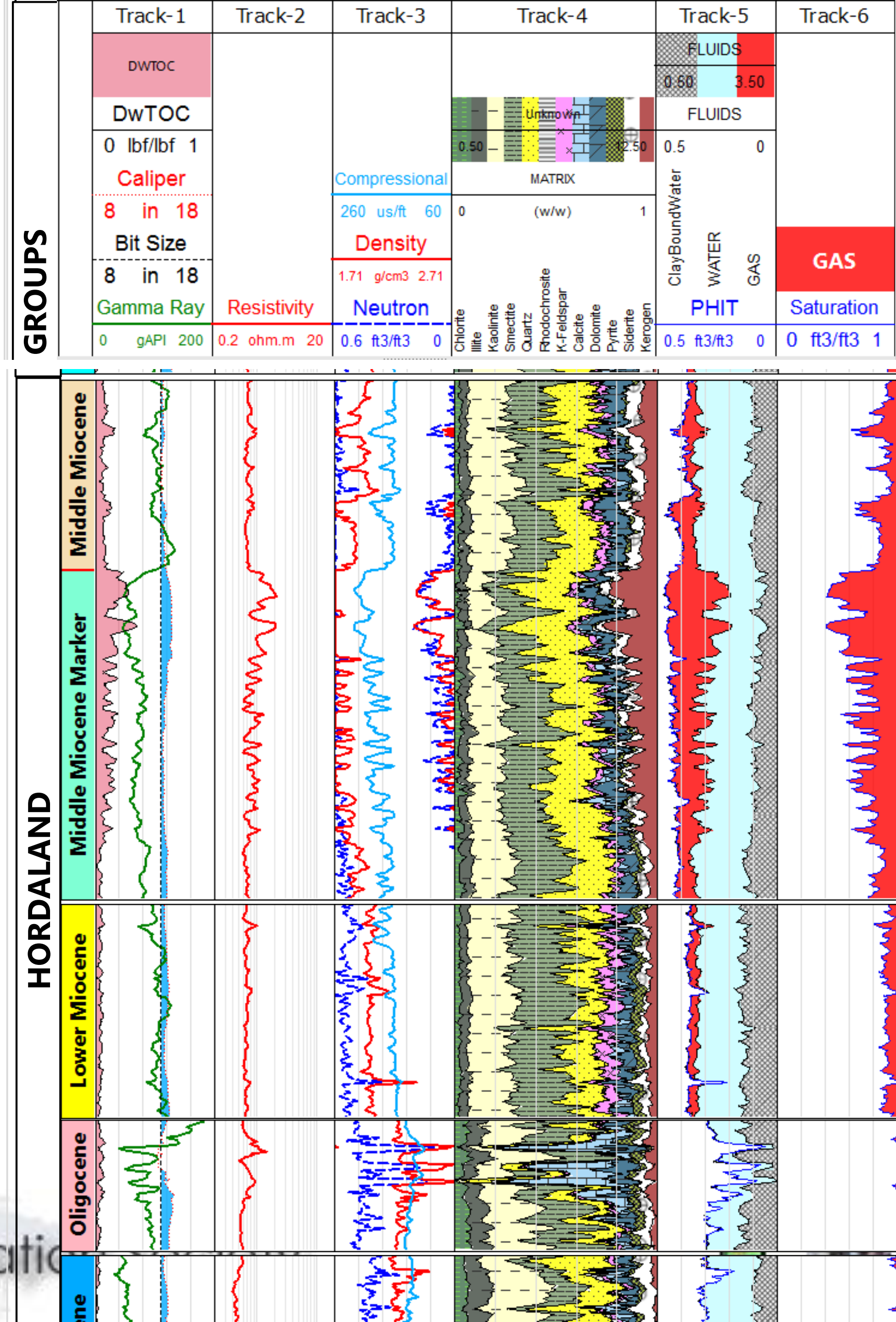
HORDALAND
Middle Miocene
Middle Miocene Marker
Lower Miocene
Oligocene

Results

Hordaland



Results

Hordaland

- Very high levels of TOC
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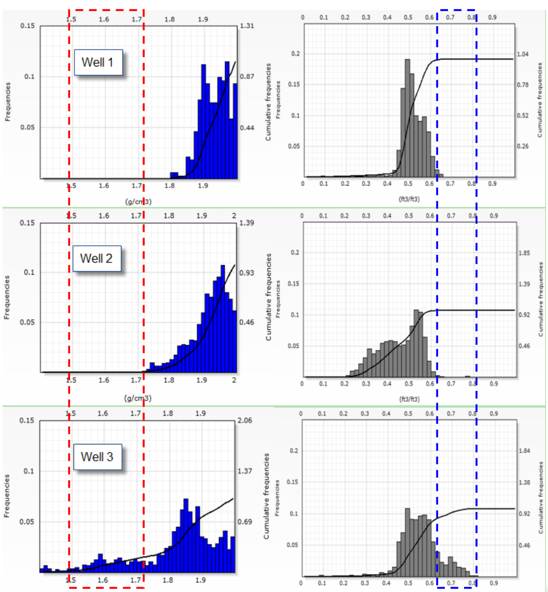

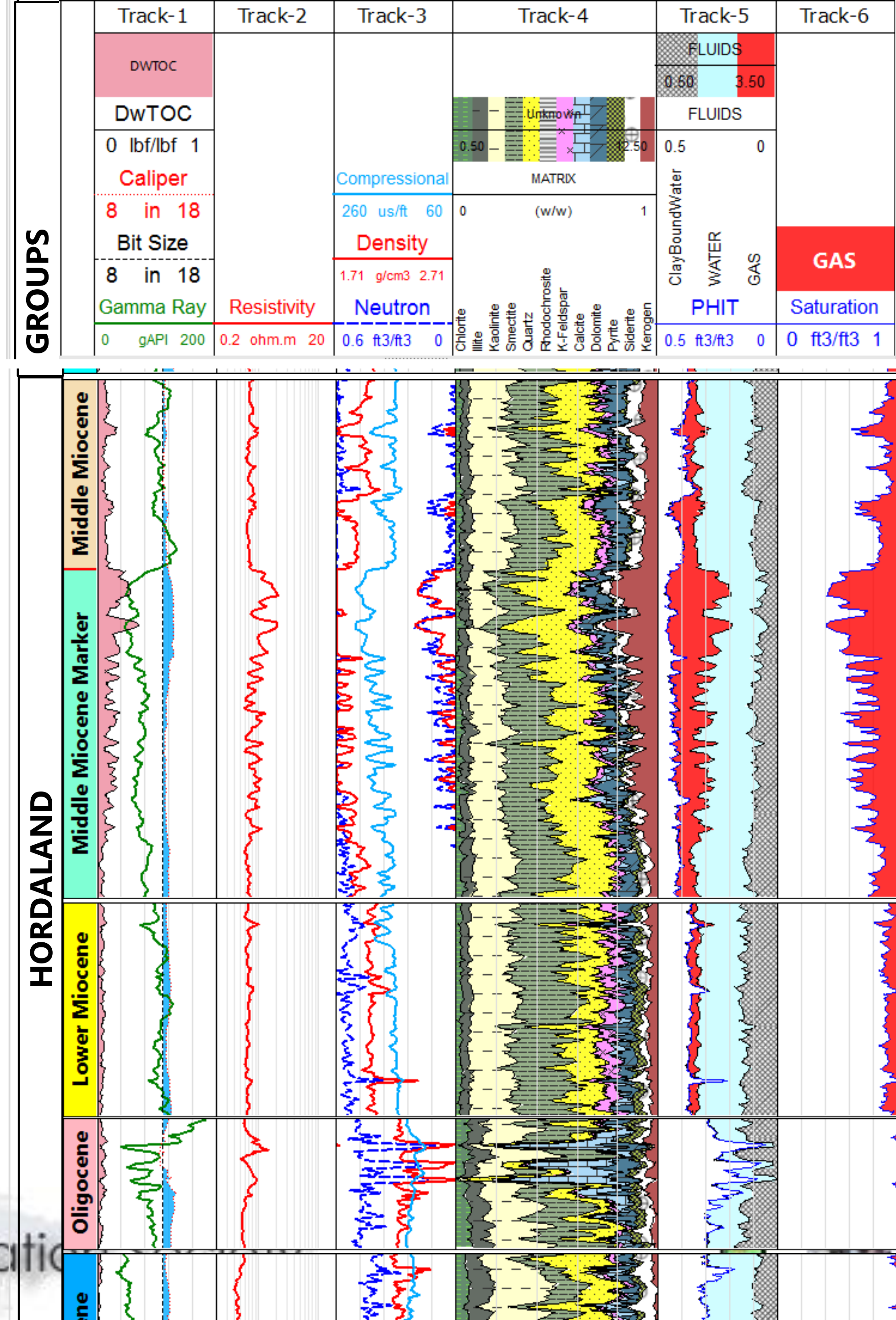

Results

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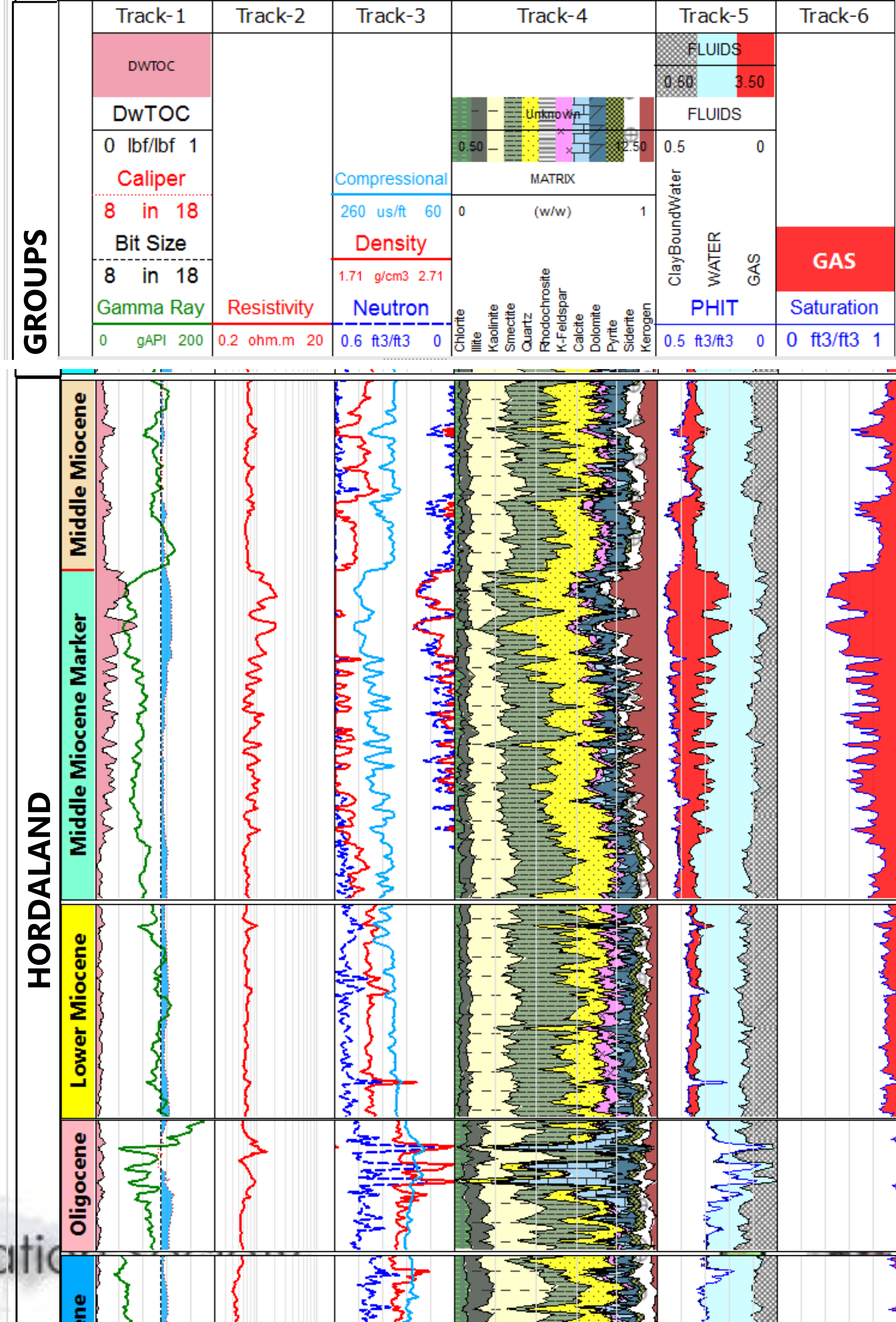
- Matrix grain density
  - ***~ 2.75 g/cm³ → 2.25 – 2.55 g/cm³***



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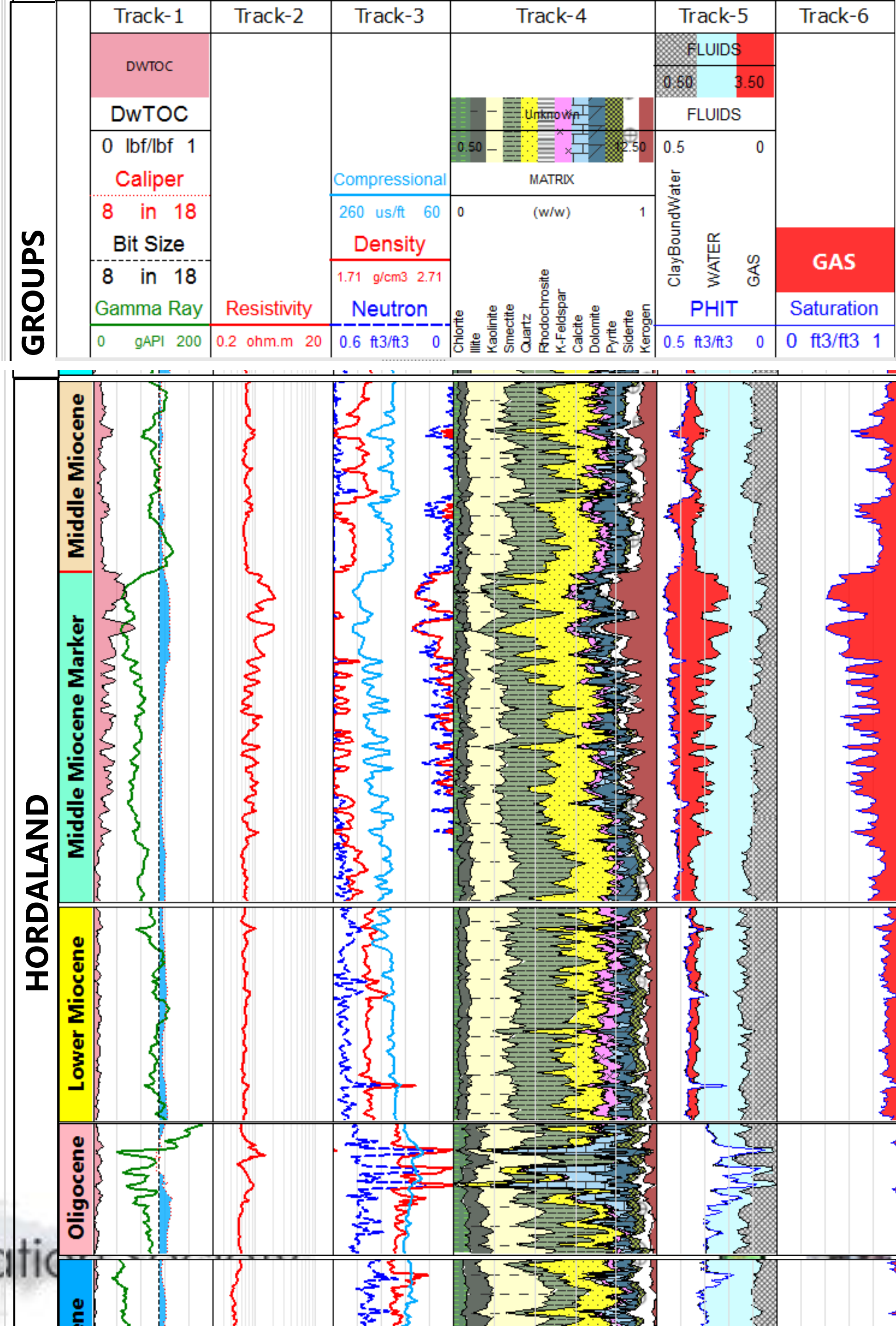
  - *~ as high as 45 pu*



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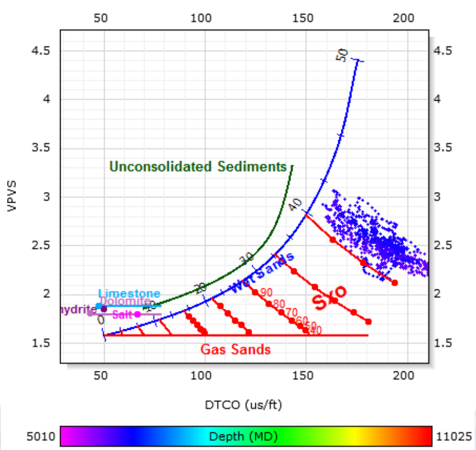

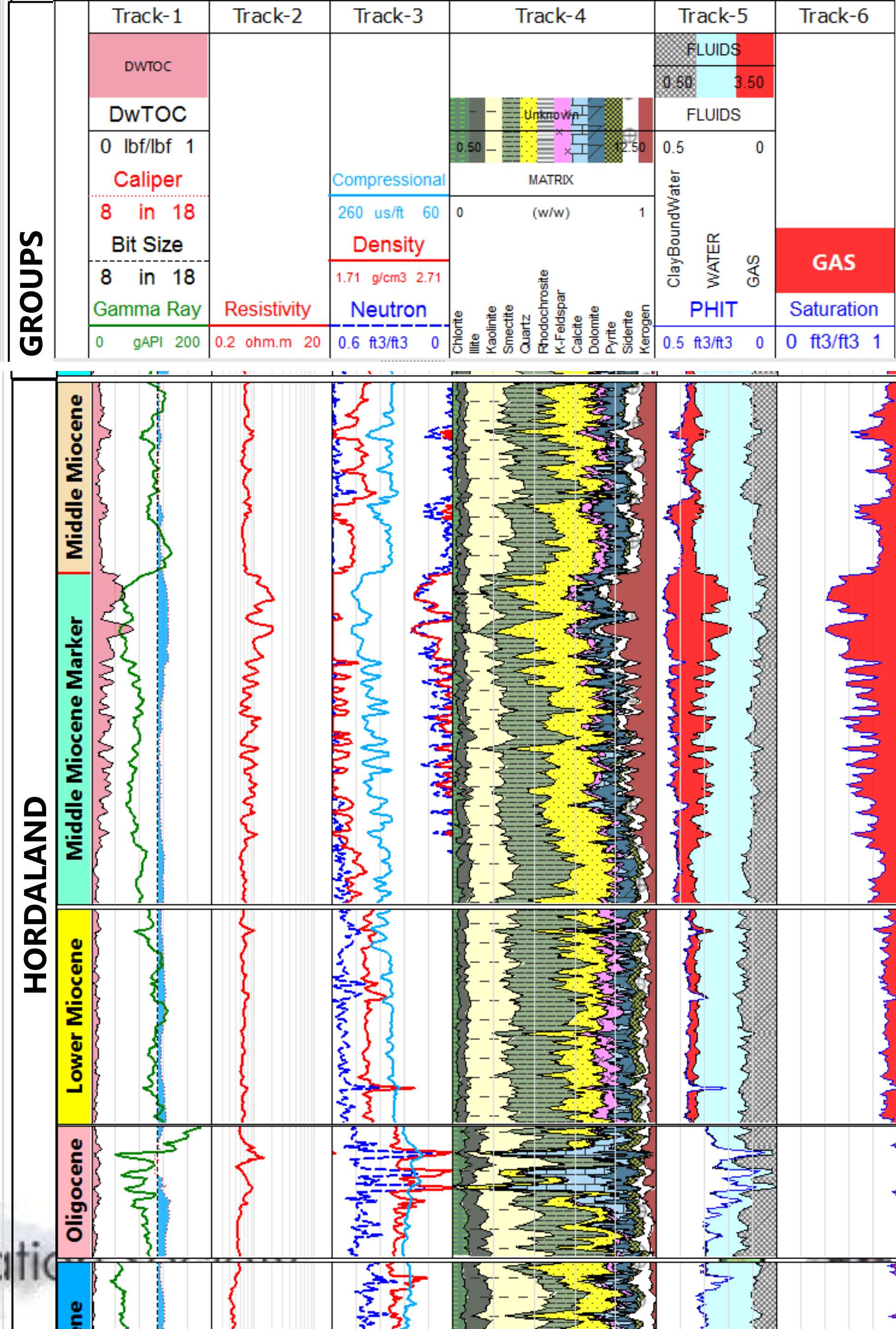

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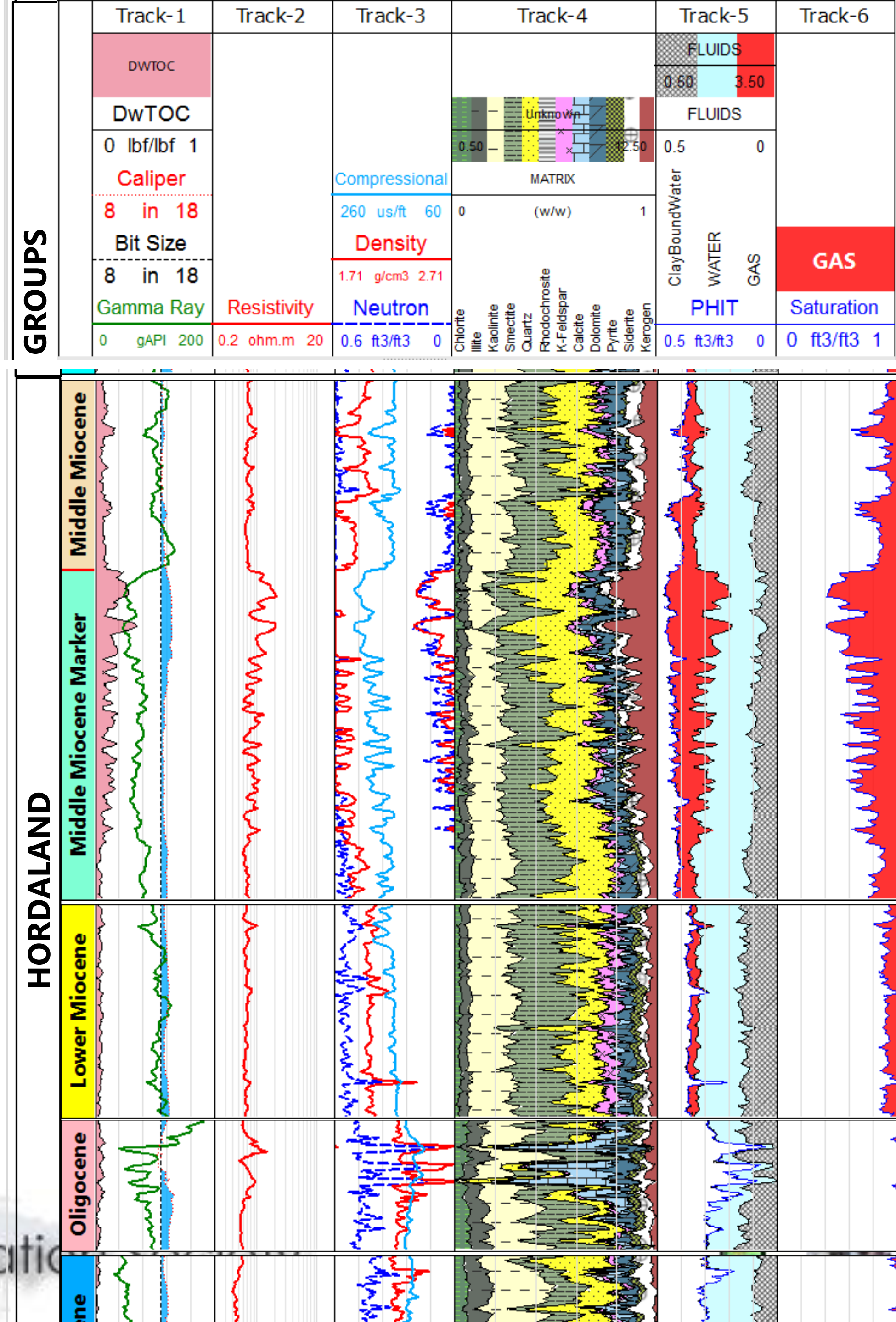
- Gas highest in Middle Miocene



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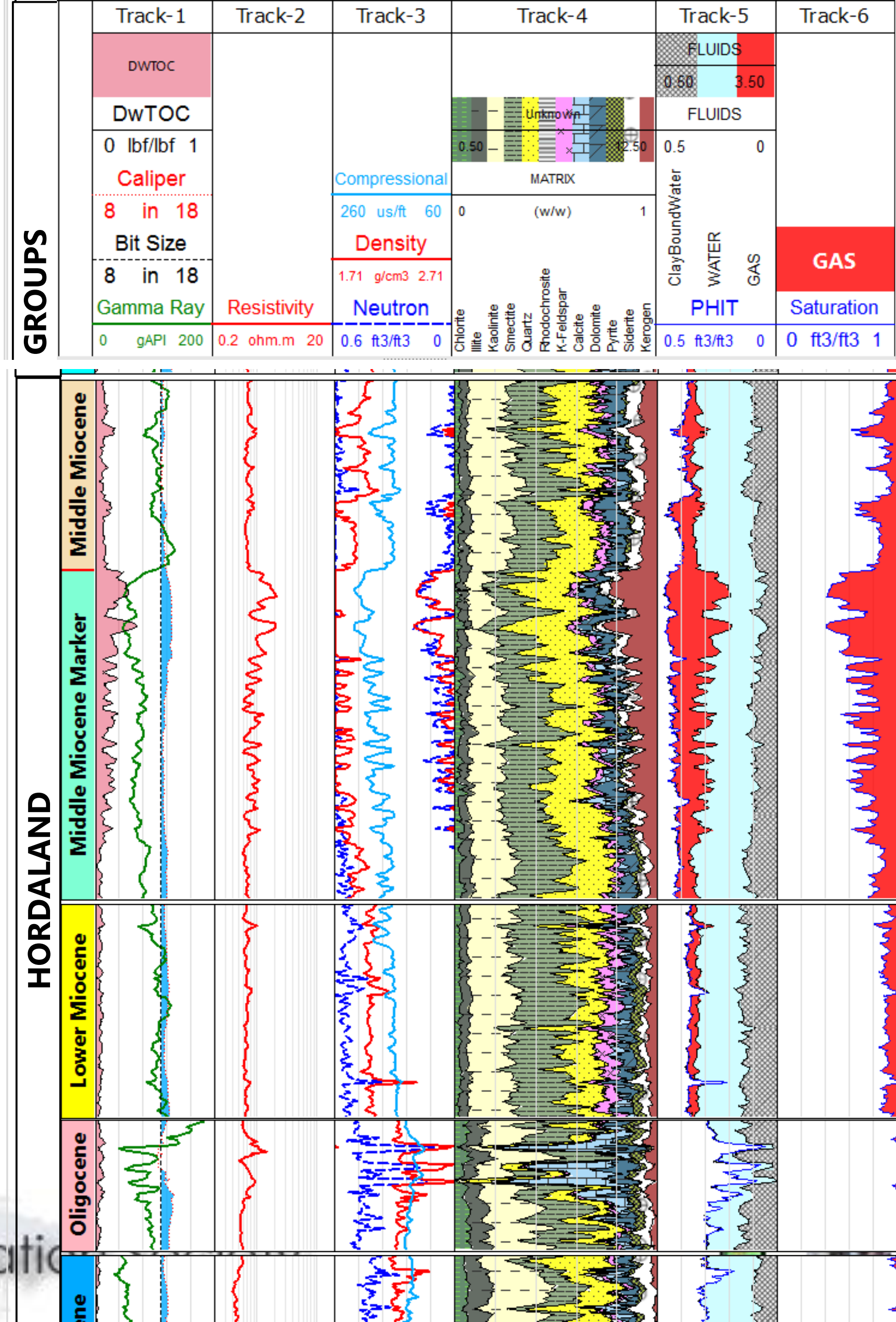
- No gas in Oligocene, Eocene



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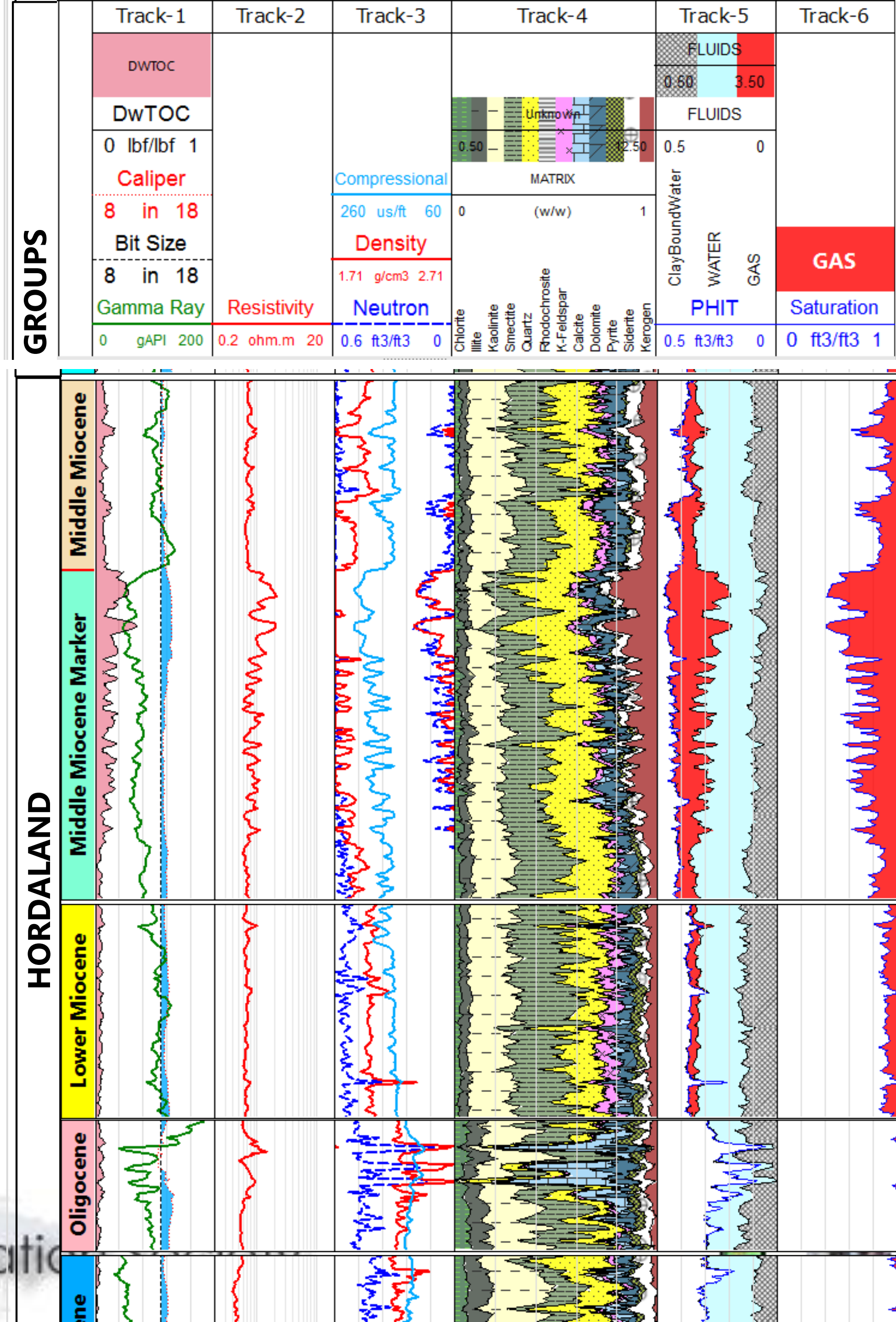

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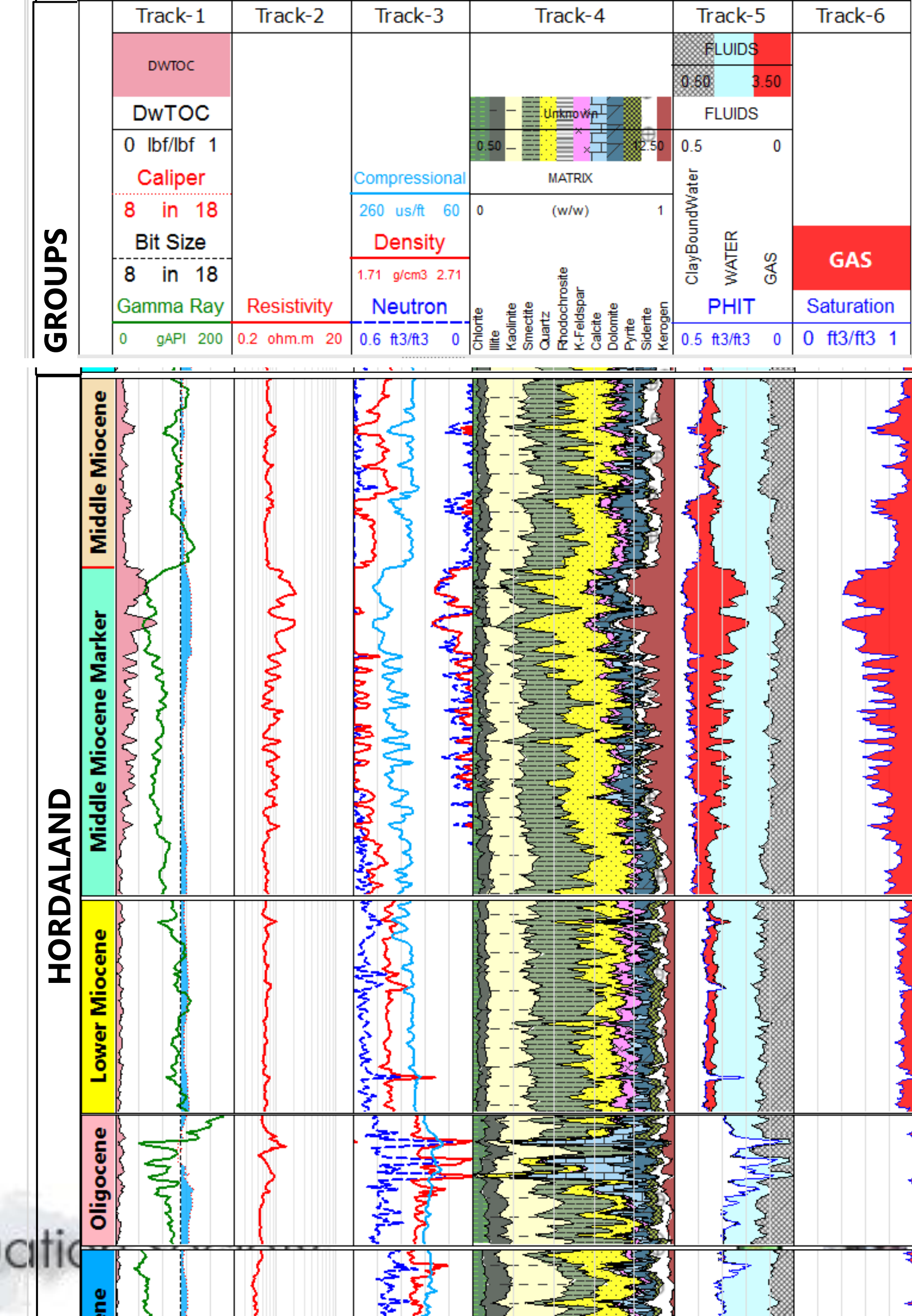
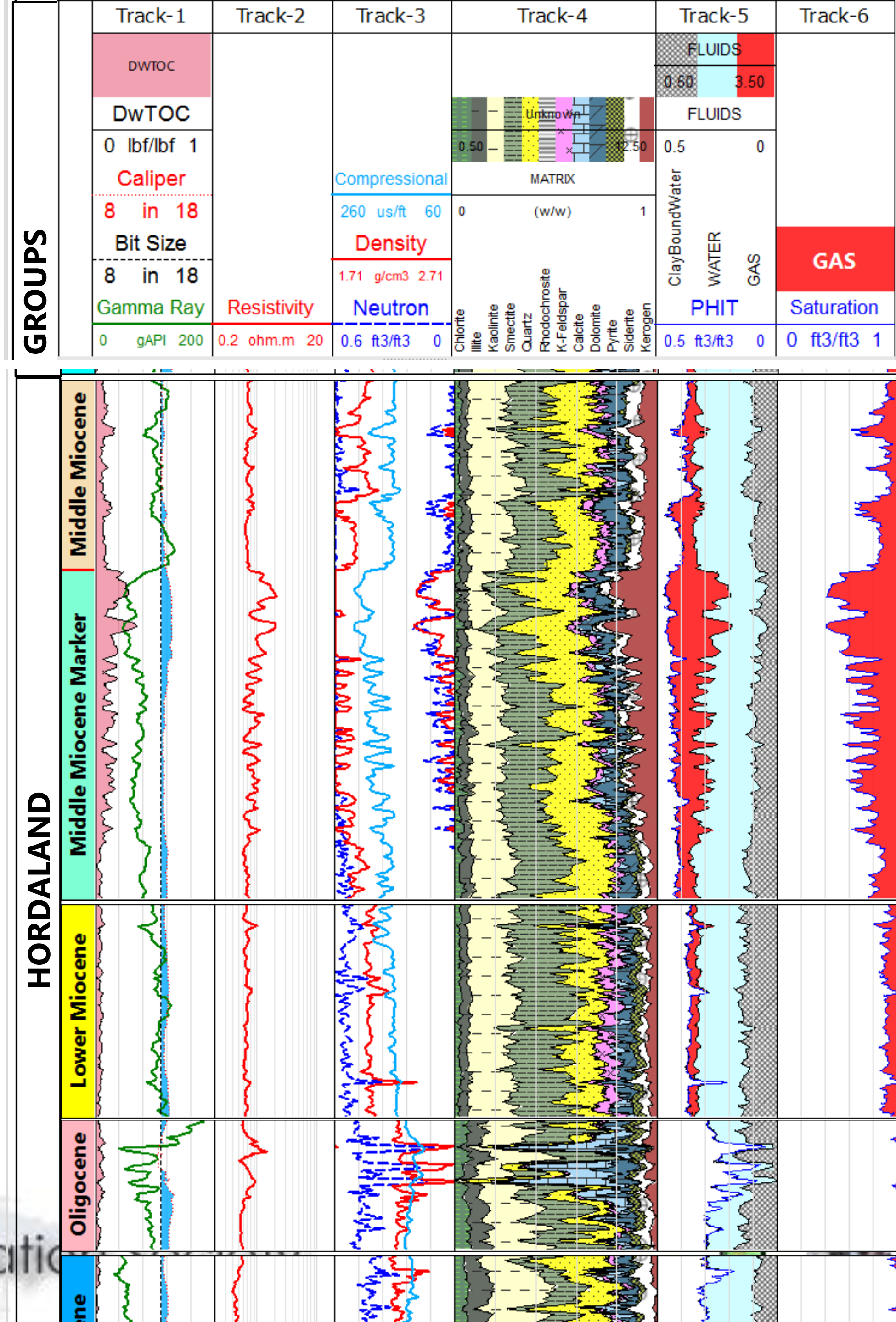
- No gas in Oligocene, Eocene
- Main clays: smectite, kaolinite
- Minor amounts of quartz



Results

Hordaland

- Very high levels of TOC
  - *~ highest in study well (# 3)*
- Matrix grain density
  - *~ 2.75 g/cm³ → 2.25 – 2.55 g/cm³*
- High porosity
  - *~ as high as 45 pu*
- Gas saturation highest
  - *~ as high as 60%*
- Gas highest in Middle Miocene
- No gas in Oligocene, Eocene
- Main clays: smectite, kaolinite
- Minor amounts of quartz
- Carbonate stringers present



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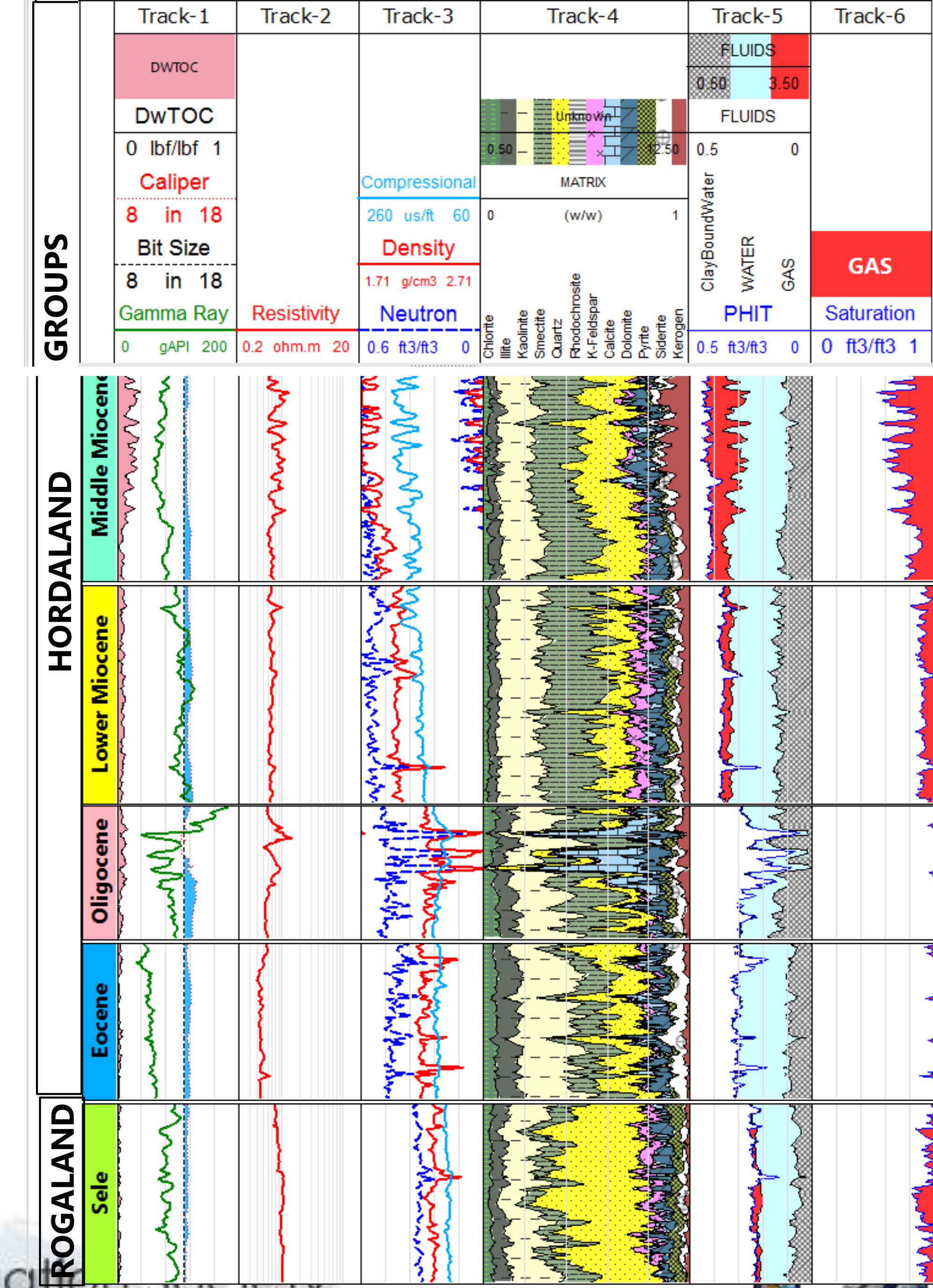
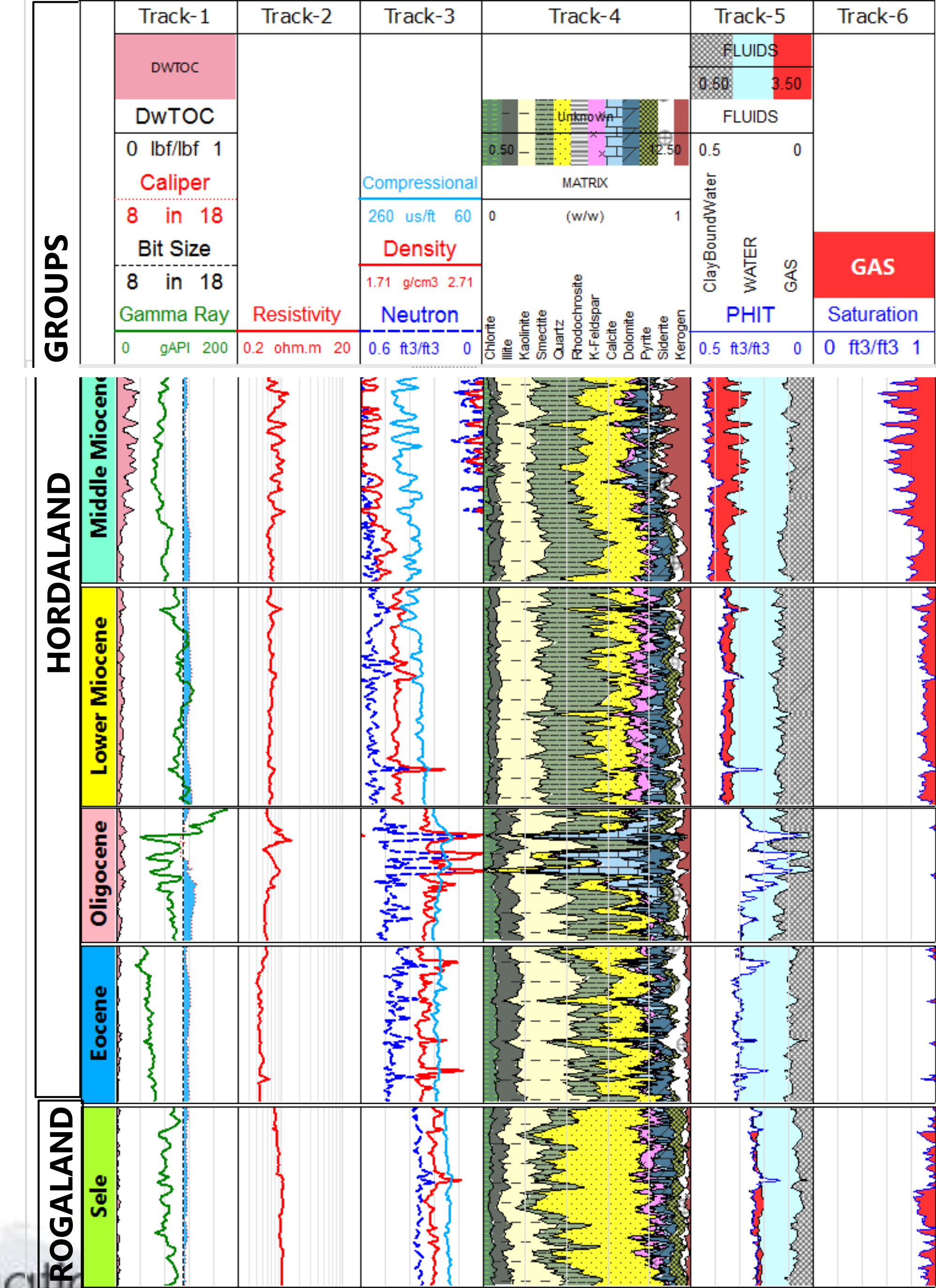


Results

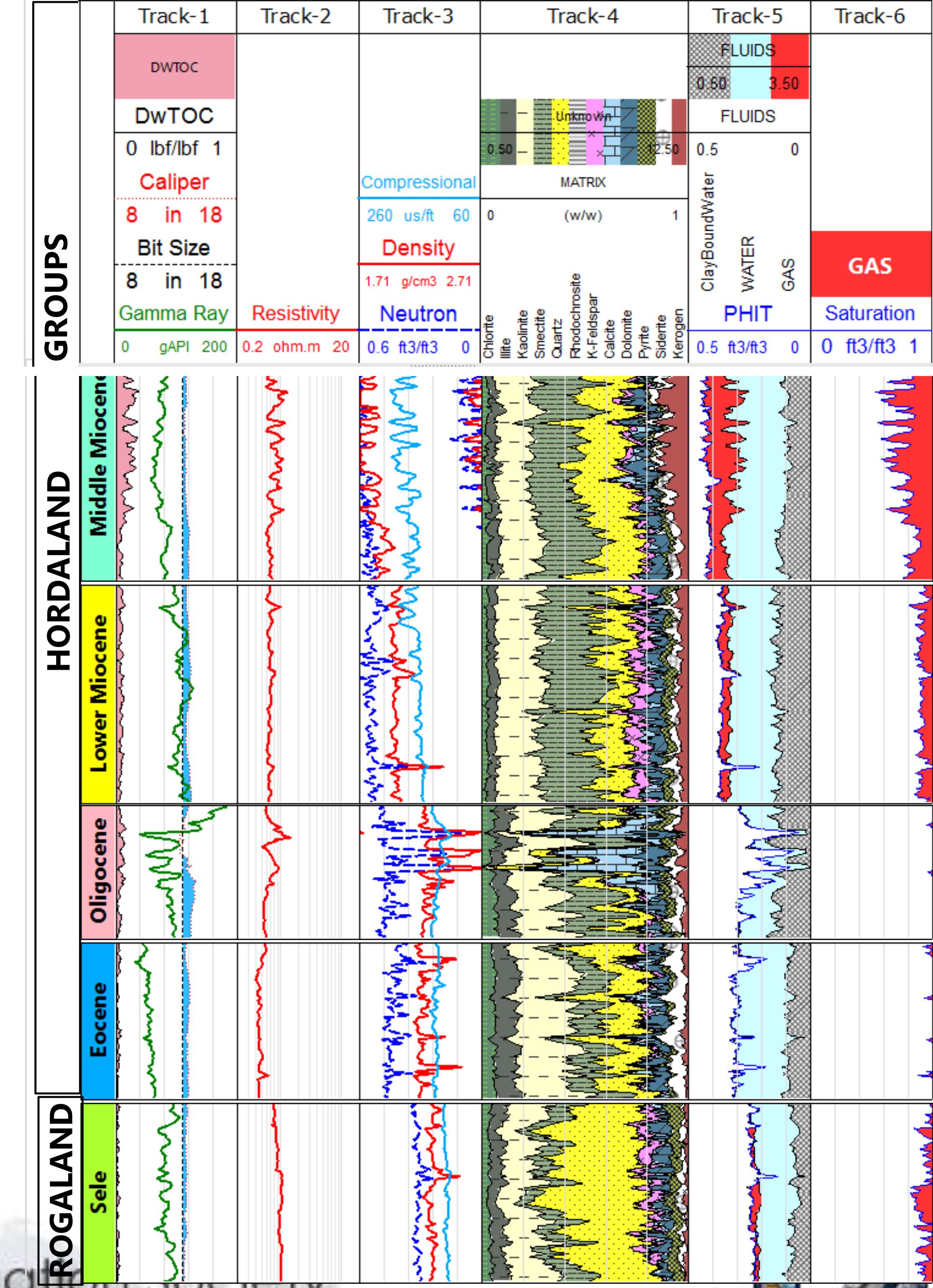
Rogaland



Results

Rogaland

- Low levels of TOC

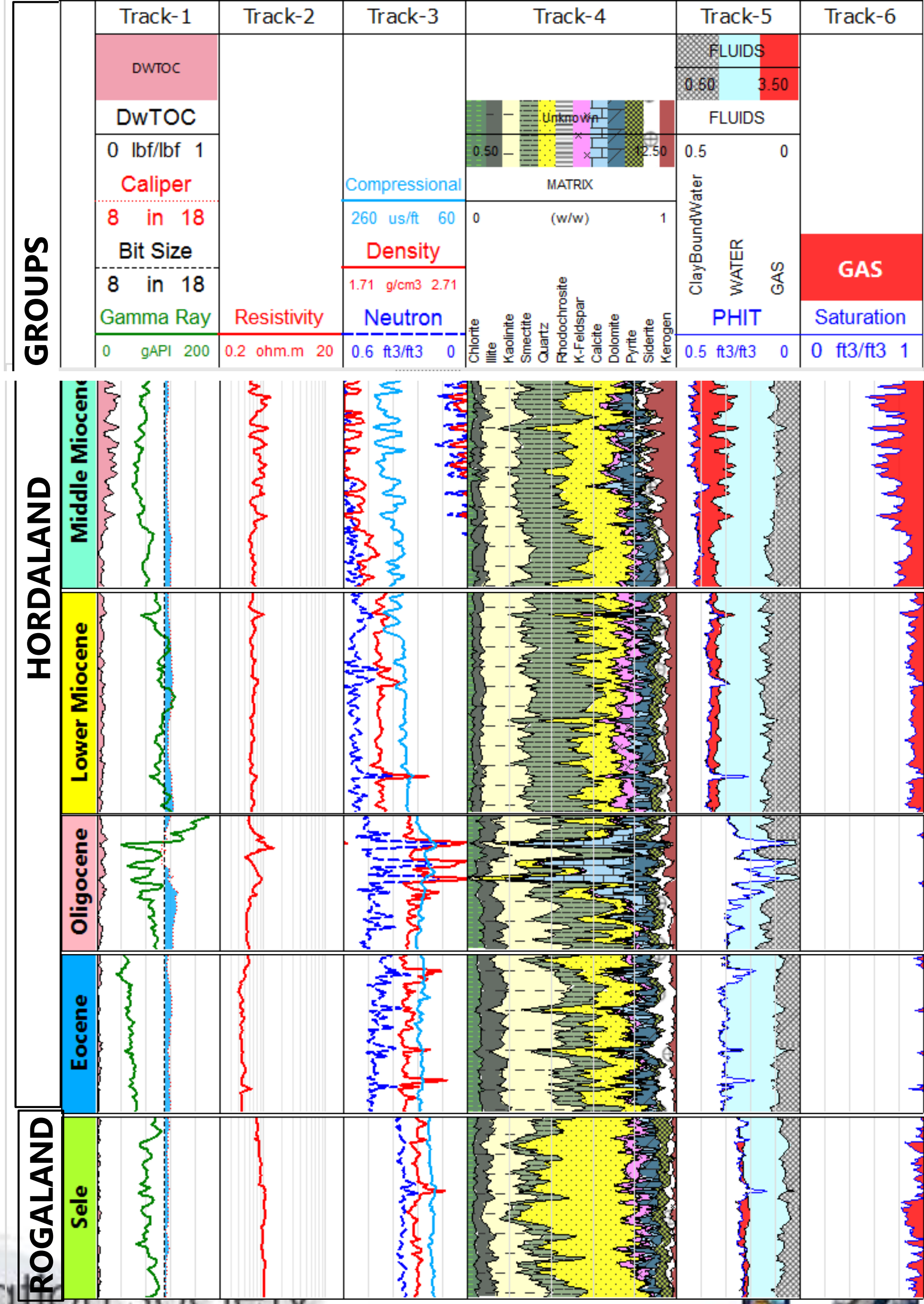


Results

Rogaland

- Low levels of TOC

- Decreased porosity
  ~ 20 pu



Results

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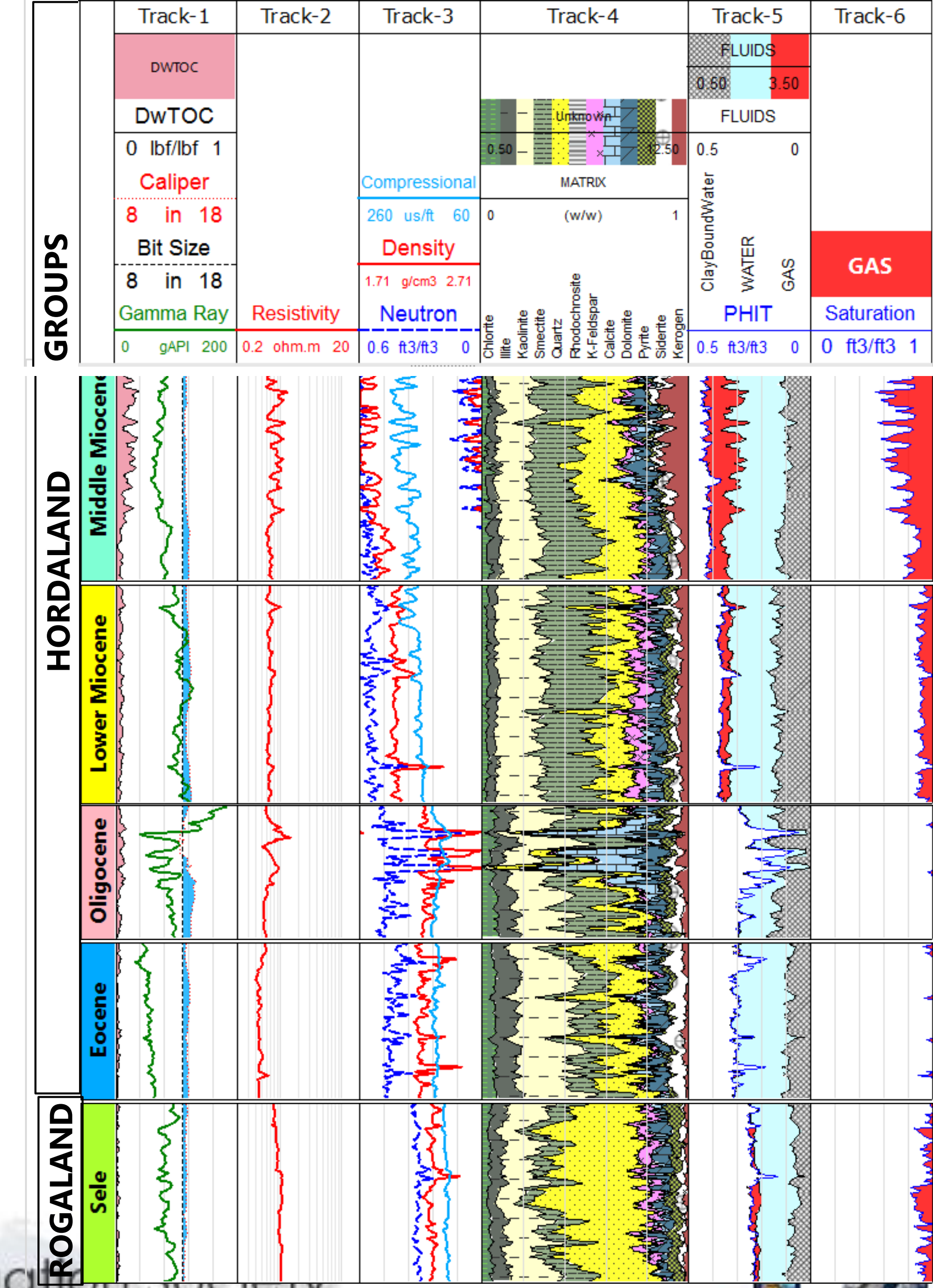
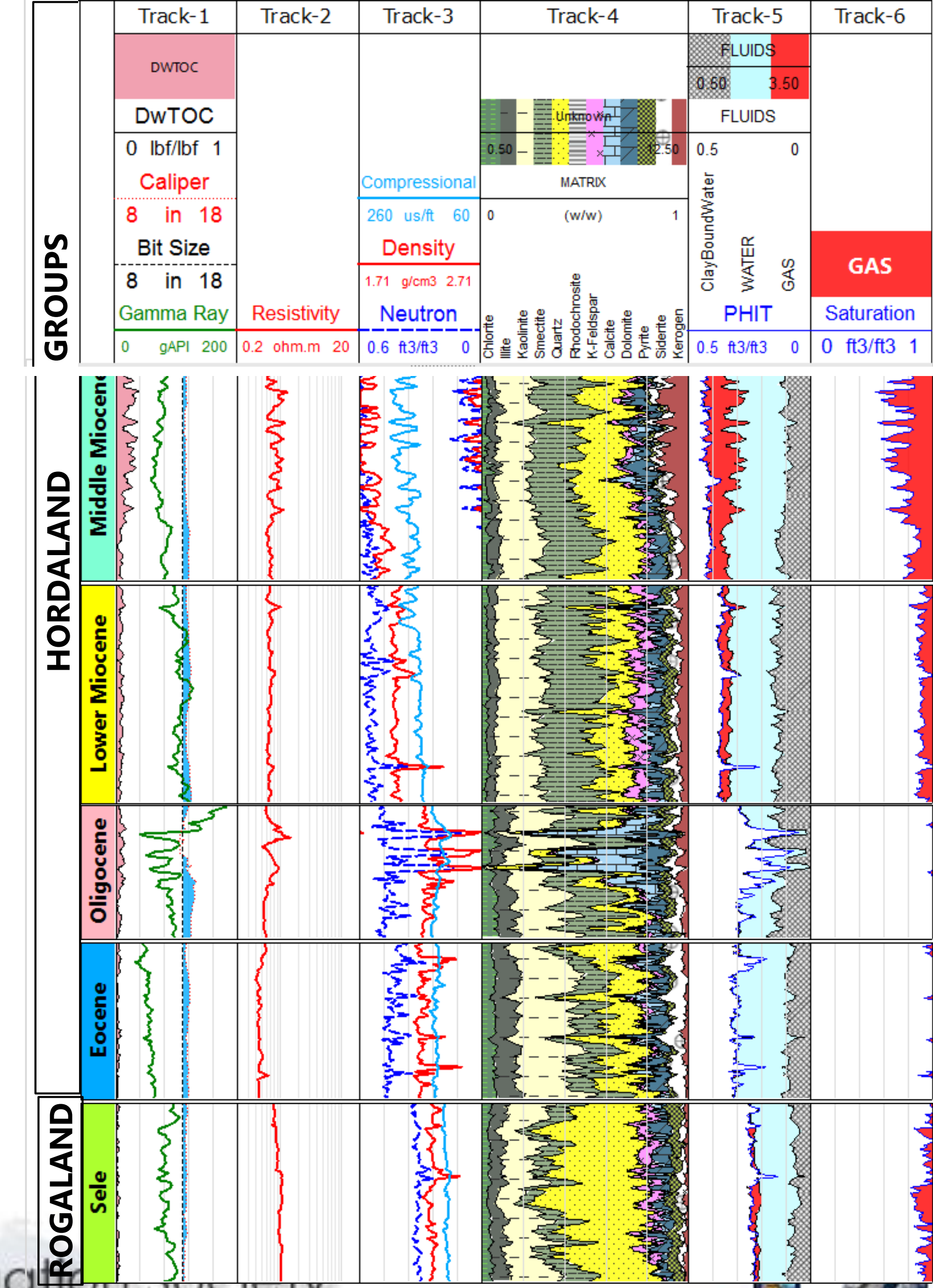
- Decreased porosity
  ~ 20 pu
- Slight gas saturation



Results

Rogaland

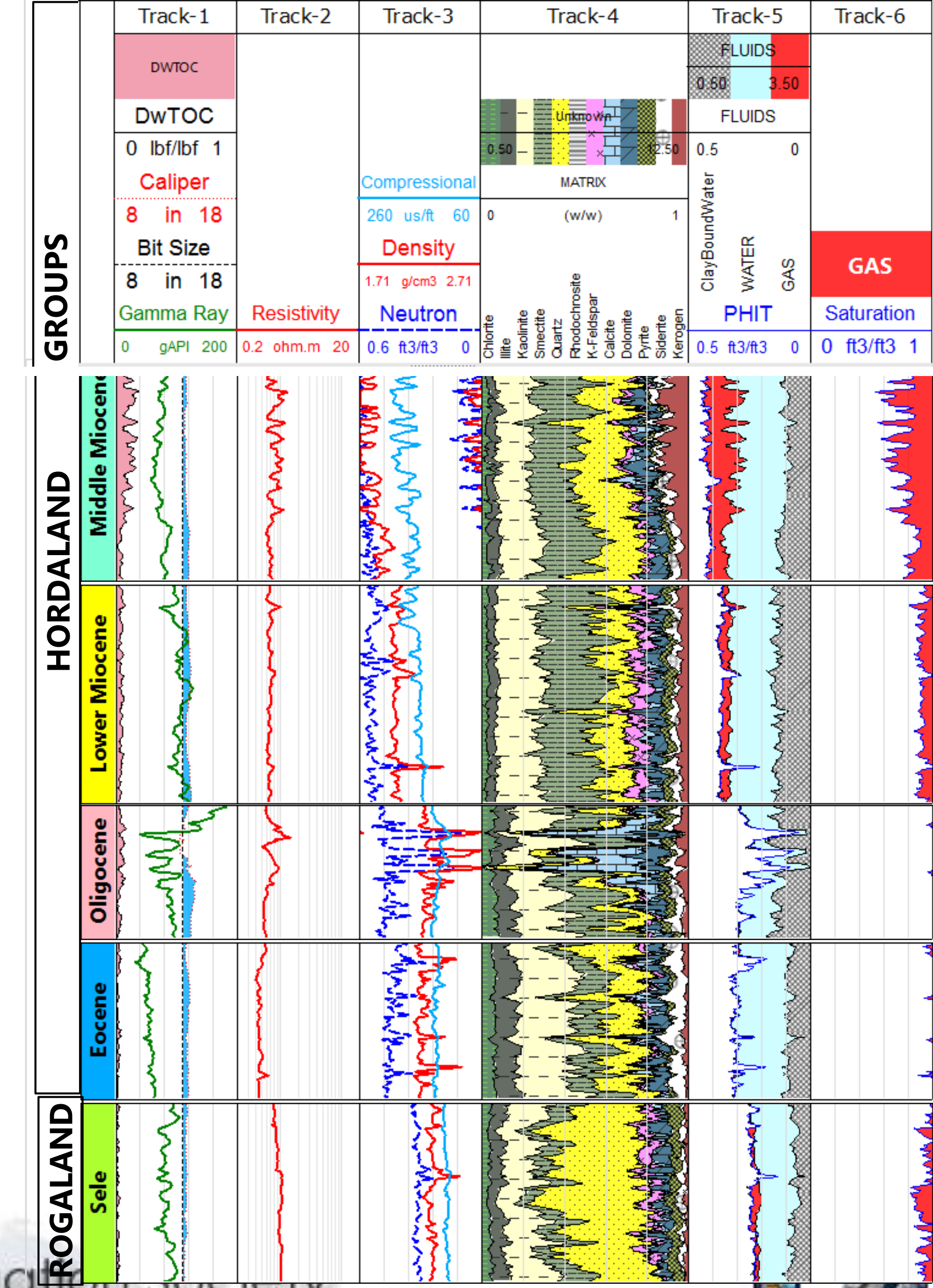
- Low levels of TOC
- Decreased porosity
  ~ 20 pu
- Slight gas saturation
- Lower amounts of smectite



Results

Rogaland

- Low levels of TOC
- Decreased porosity
  ~ 20 pu
- Slight gas saturation
- Lower amounts of smectite
- Increased amounts of quartz



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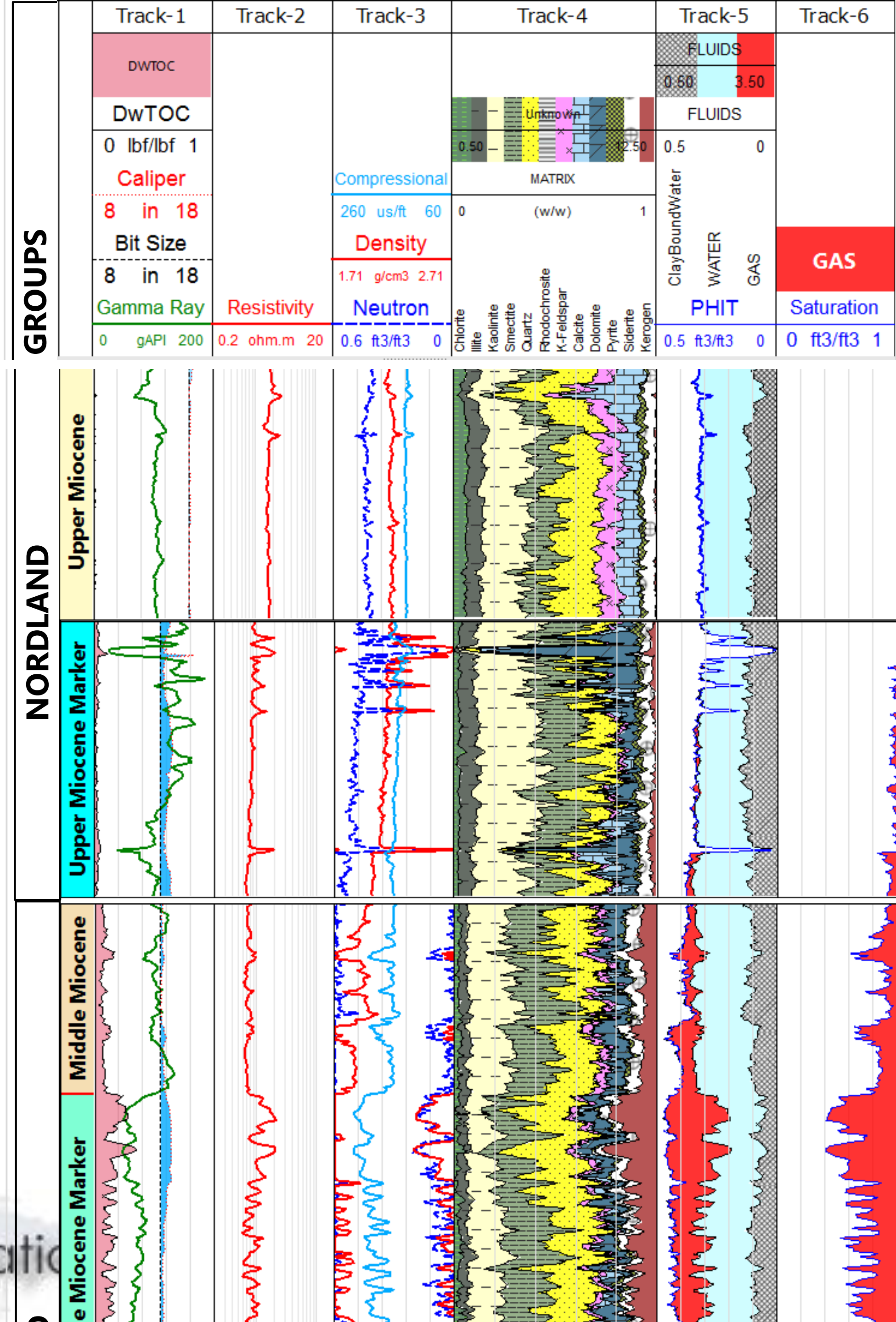
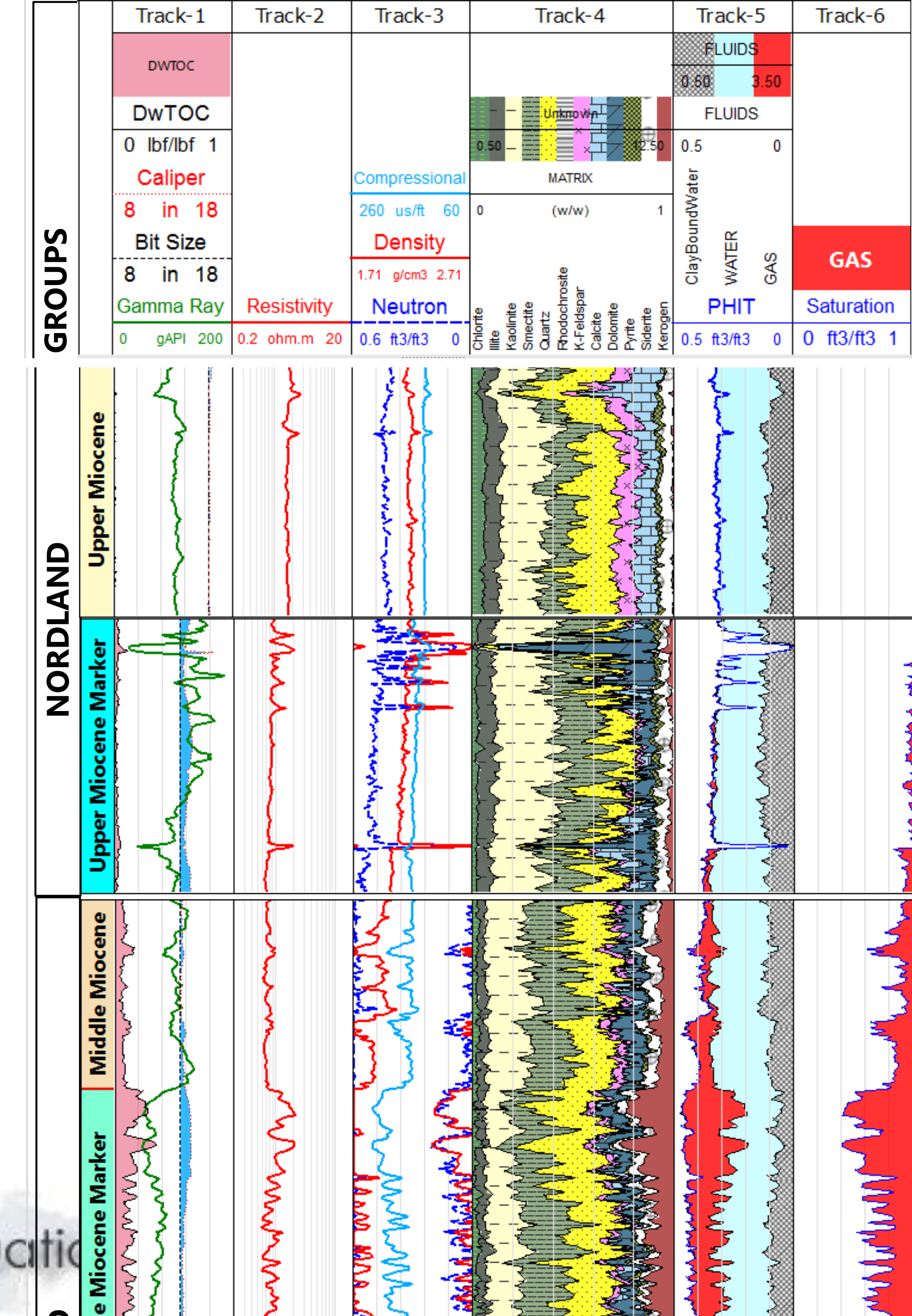


GROUPS
Track-1
Track-2
Track-3
Track-4
Track-5
Track-6
DWTOC
DwTOC
0 lbf/lbf 1
Caliper
8 in 18
Bit Size
8 in 18
Gamma Ray
0 gAPI 200
Resistivity
0.2 ohm.m 20
Compressional
260 us/ft 60
Density
1.71 g/cm3 2.71
Neutron
0.6 ft3/ft3 0
Unknown
0.50
2.50
MATRIX
0 (w/w) 1
Chlorite
Illite
Kaolinite
Smectite
Quartz
Rhodochrosite
K-Feldspar
Calcite
Dolomite
Pyrite
Siderite
Kerogen
FLUIDS
0.50
3.50
FLUIDS
0.5 0
ClayBoundWater
WATER
GAS
PHIT
0.5 ft3/ft3 0
GAS
Saturation
0 ft3/ft3 1
NORDLAND
Upper Miocene
Upper Miocene Marker
Middle Miocene
e Miocene Marker

Results

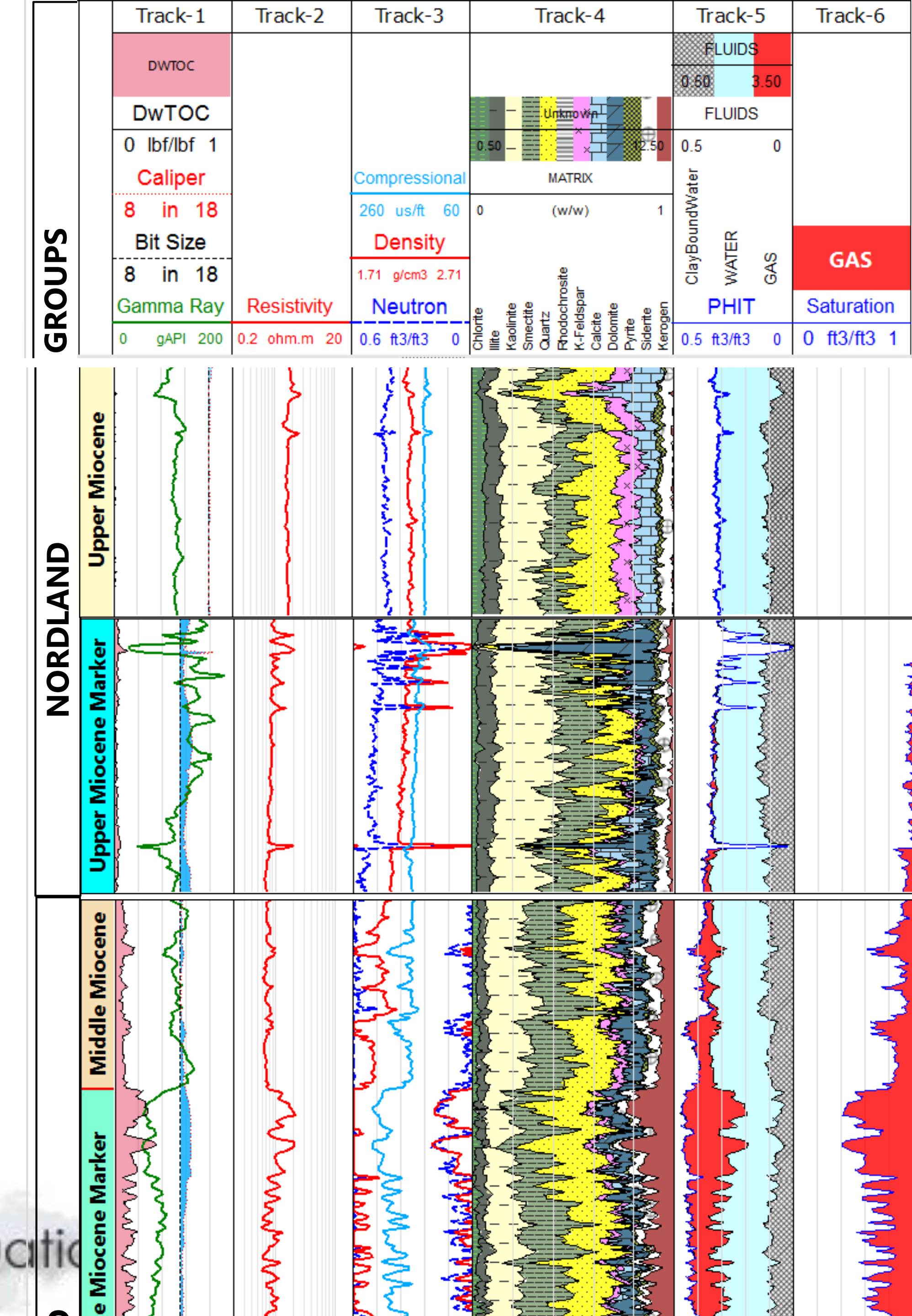
Nordland



Results

Nordland

- Low levels of TOC

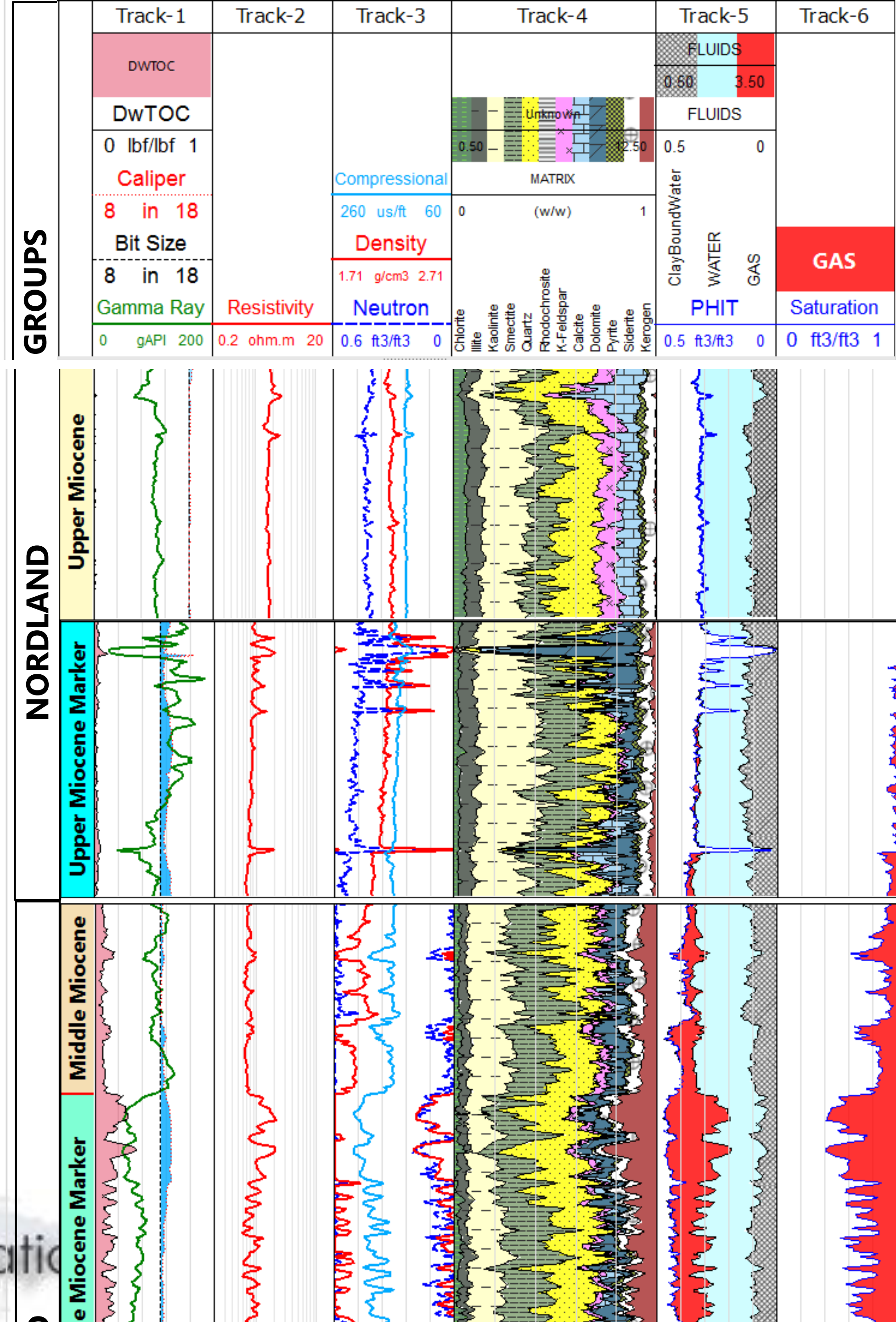


Results

Nordland

- Low levels of TOC

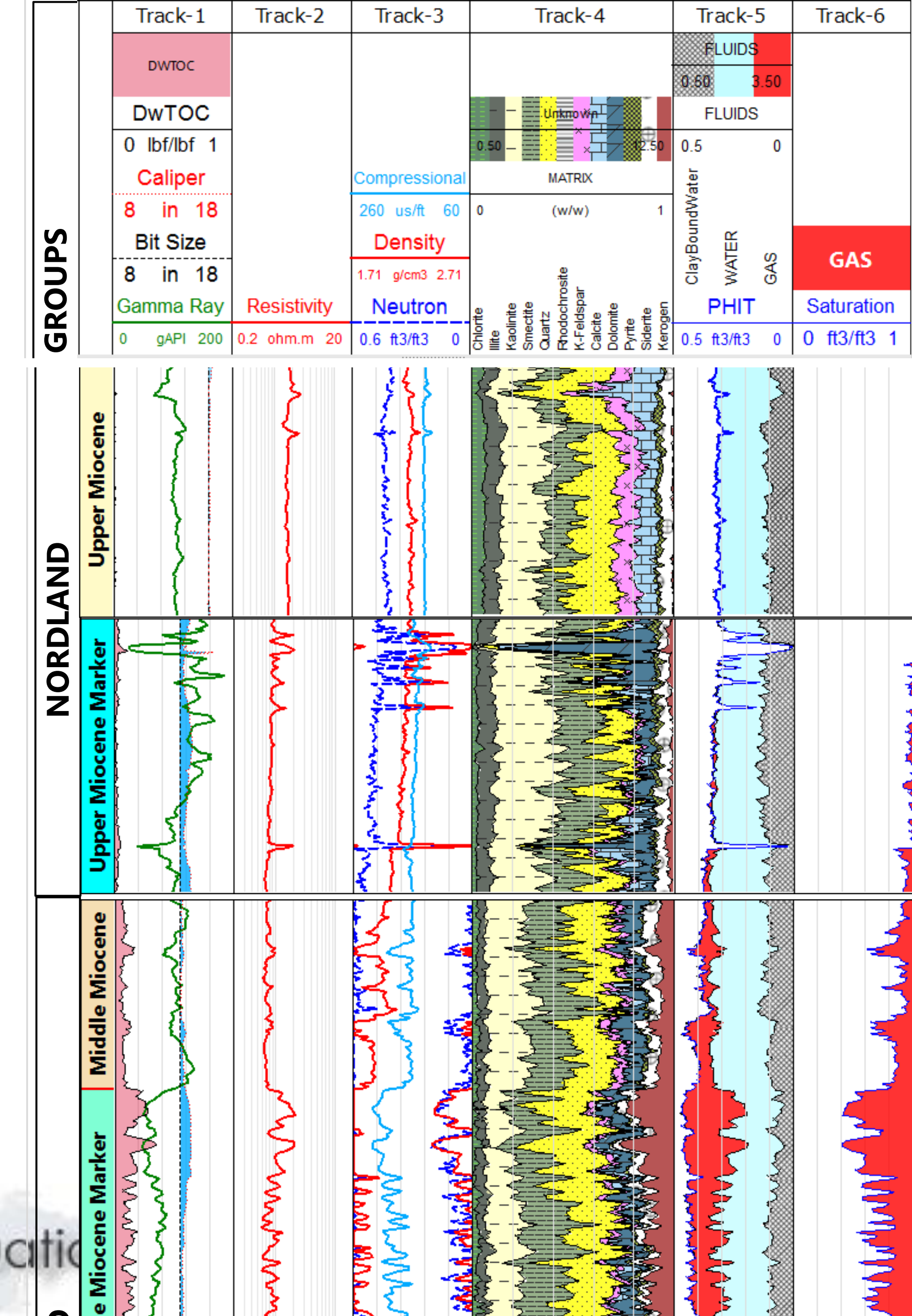
- Reduced porosity
  ~ 35 pu



Results

Nordland

- Low levels of TOC
- Reduced porosity
  ~ 35 pu
- Gas saturation – negligible to none



Results

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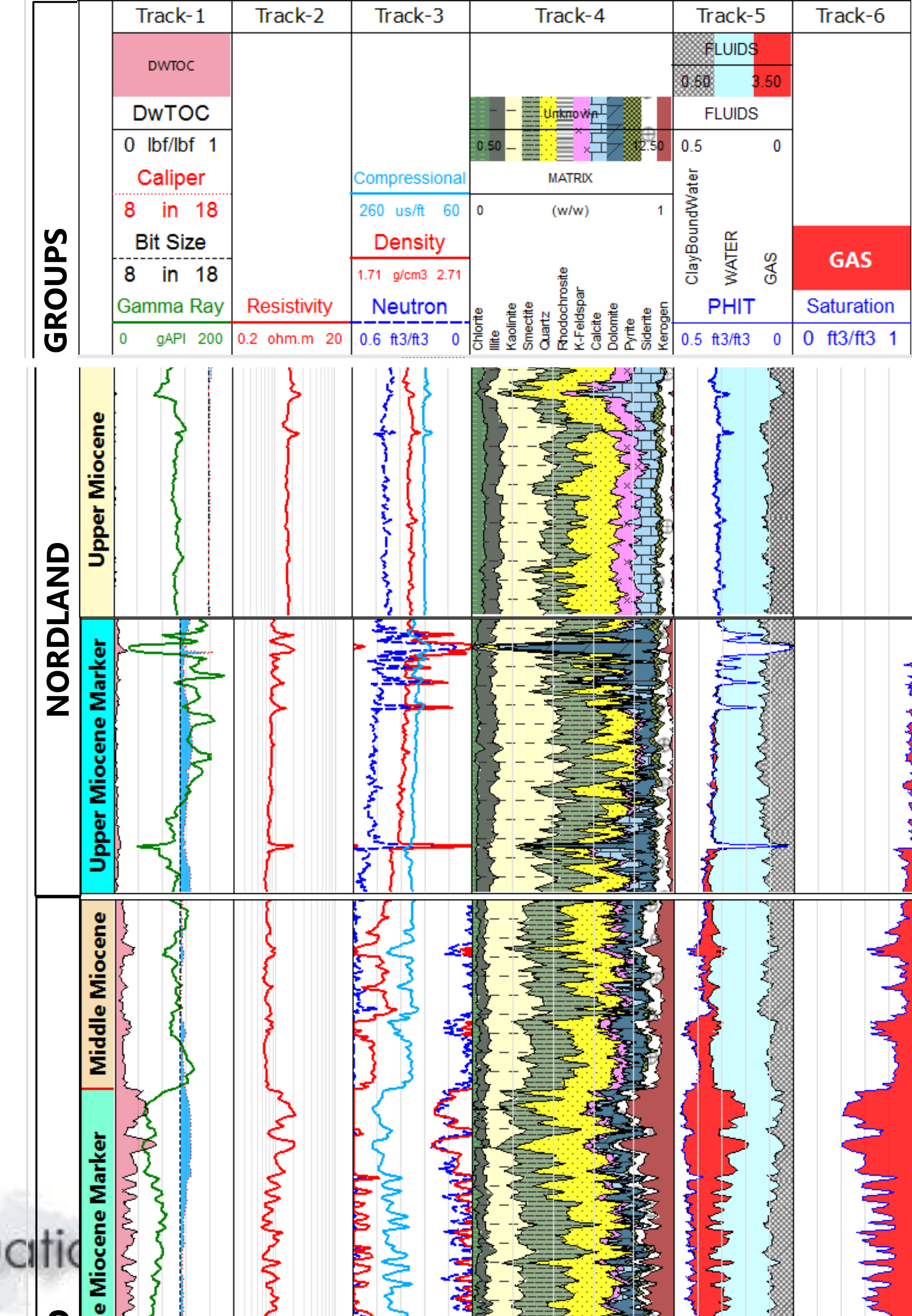
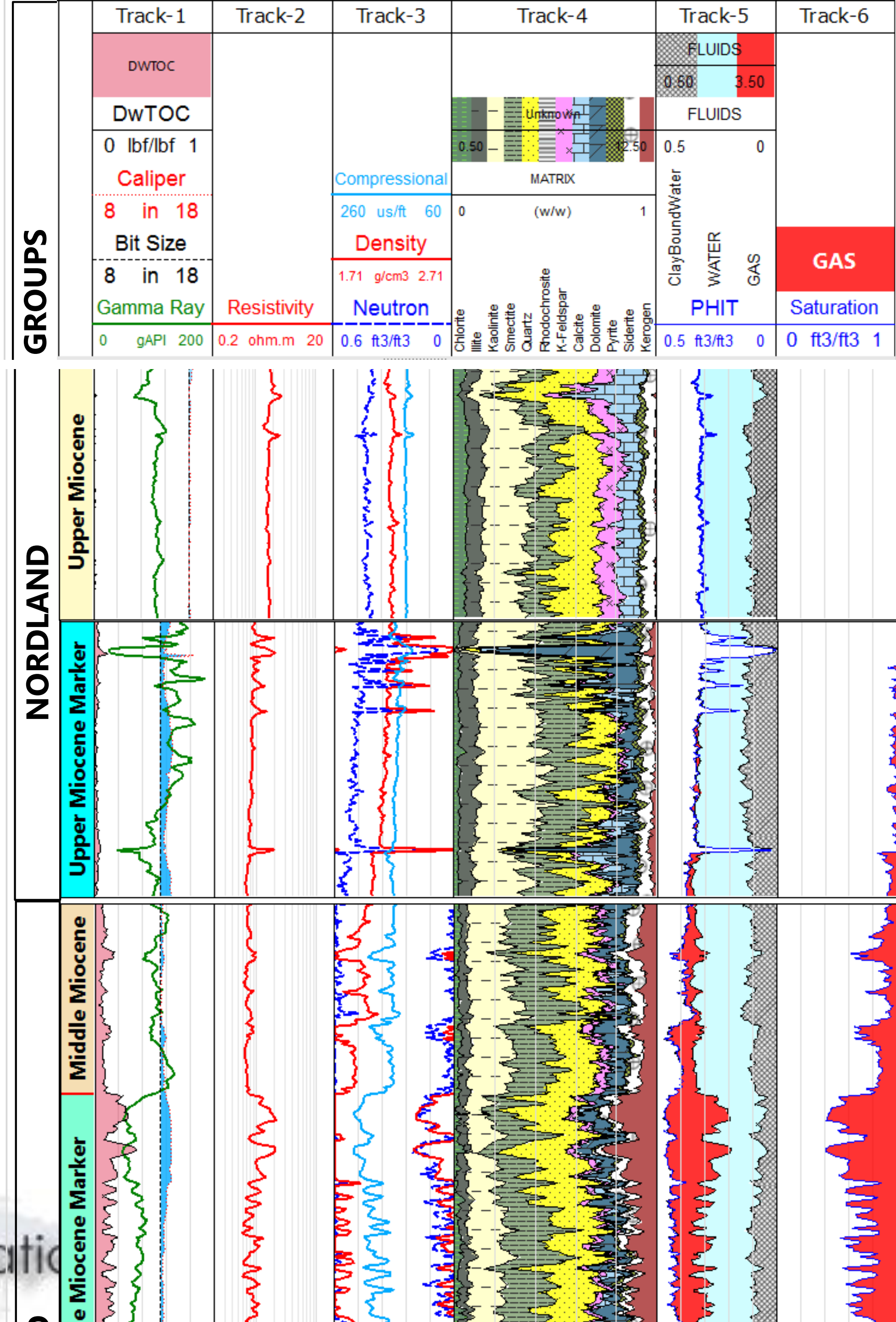
- Low levels of TOC
- Reduced porosity
  ~ 35 pu
- Gas saturation – negligible to none
- Lower amounts of smectite



Results

Nordland

- Low levels of TOC
- Reduced porosity
  ~ 35 pu
- Gas saturation – negligible to none
- Lower amounts of smectite
- higher amounts of chlorite



Conclusions & Lessons Learnt

Overburden

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Key to answering complex mineralogy challenges:

Integration of logs and advanced spectroscopy with local knowledge, petrological data, and geological information

Acknowledgements

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ConocoPhillips Eni Norge petoro Statoil TOTAL