Integrated Reservoir Characterization for Enhanced Oil Recovery, Tar Springs Formation, Illinois Basin

Tim Henderson
Dr. Ken Ridgway
Dr. Cliff Johnston
Bryan Clayton

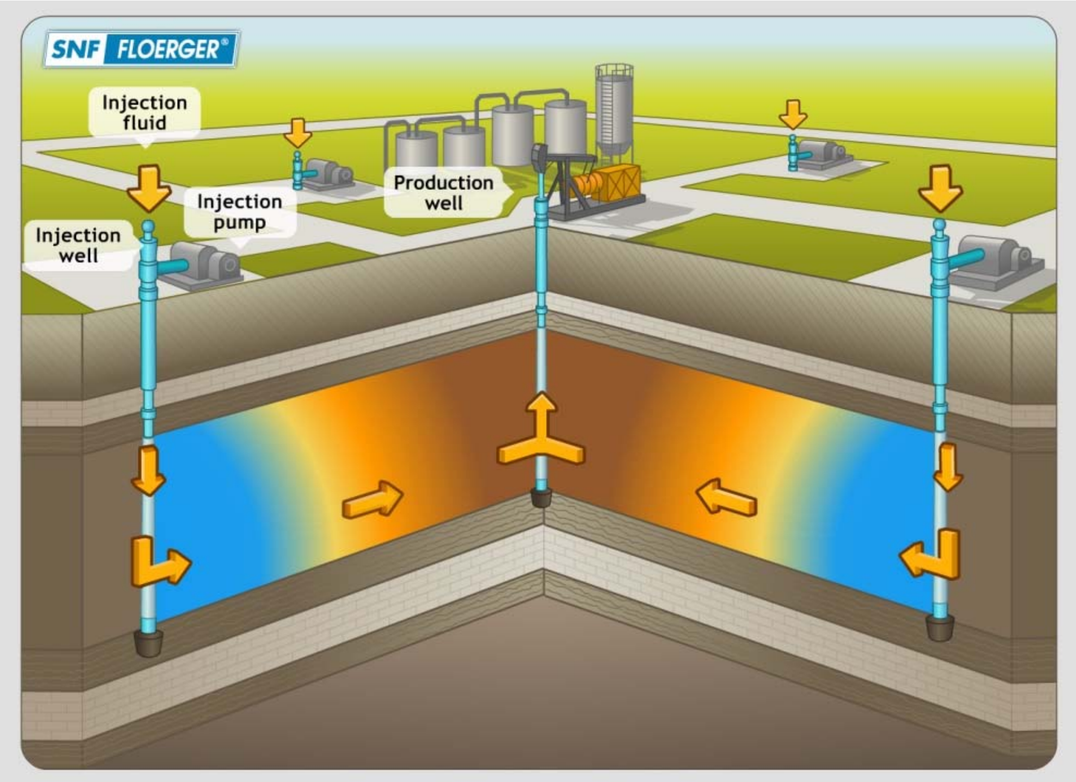
PURDUE UNIVERSITY
PURDUE UNIVERSITY Discovery Park
PIONEER Oil Company
Chevron

Outline

- 1. Introduction
- 2. Outcrops – building reservoir architecture
- 3. Cores – sedimentary properties of cores
- 4. Geochemical techniques – mineralogy, rock-fluid interactions
- 5. Ongoing work

What is Enhanced Oil Recovery?

- **E**nhanced **o**il **r**ecovery (**EOR**) – oil recovery by injection of gases or chemicals and/or thermal energy into the reservoir
- **C**hemical **e**nhanced **o**il **r**ecovery (**CEOR**) utilizes a surfactant/polymer combination to liberate and sweep oil

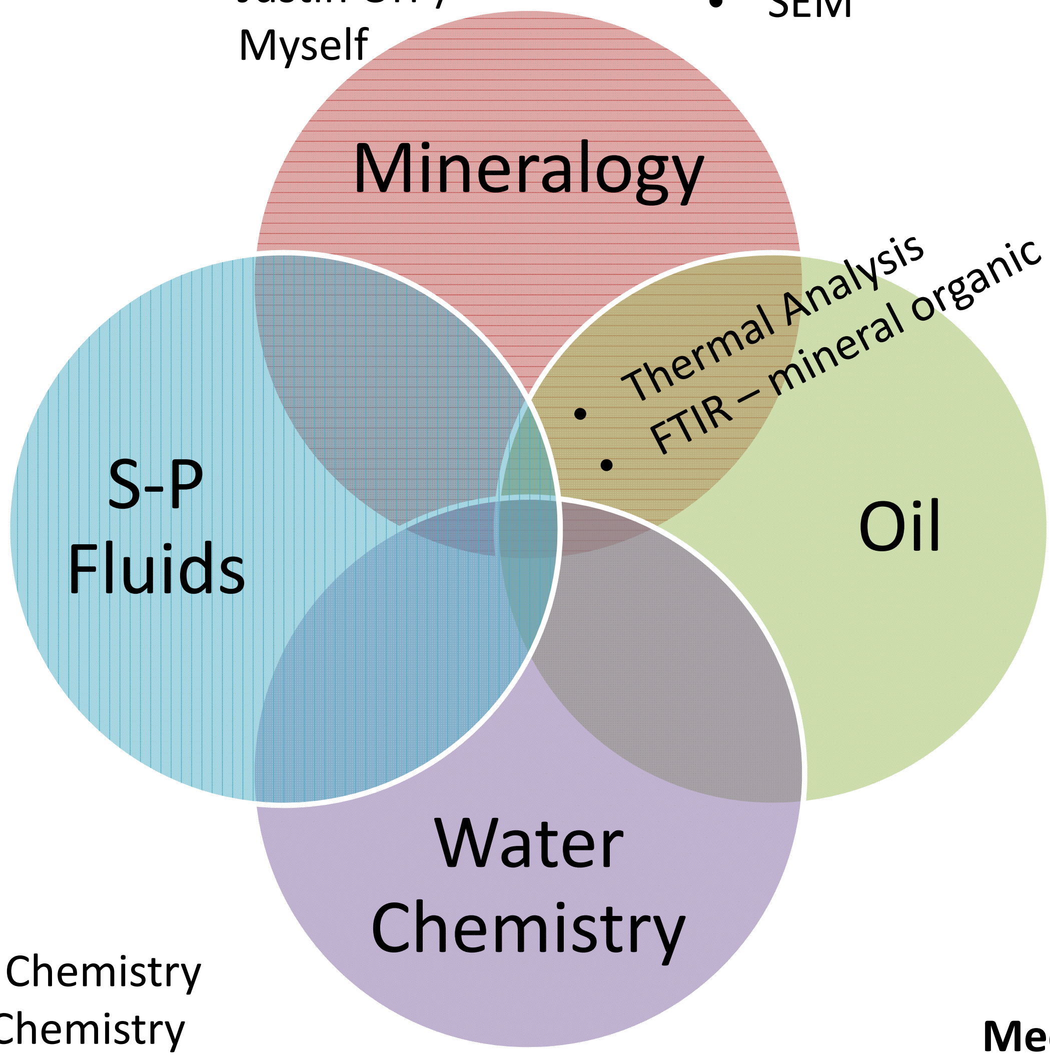


Energy.gov

Purdue EOR Lab Integrated Team

EAPS / Agronomy
Ken Ridgway / Cliff Johnston / Justin Orr / Myself

- Quantitative mineralogy (XRD)
- Particle size distribution
- Hydrophobic / hydrophilic character
- SEM



Chemical Engineering
Bryan Boudoris / Elias Franses

Chemistry
Hilkka Kenttamaa

Elemental Analysis
Oil Chemistry

Connate Water Chemistry
Process Water Chemistry
Water Reuse

Chemistry
Kenttamaa / Johnston

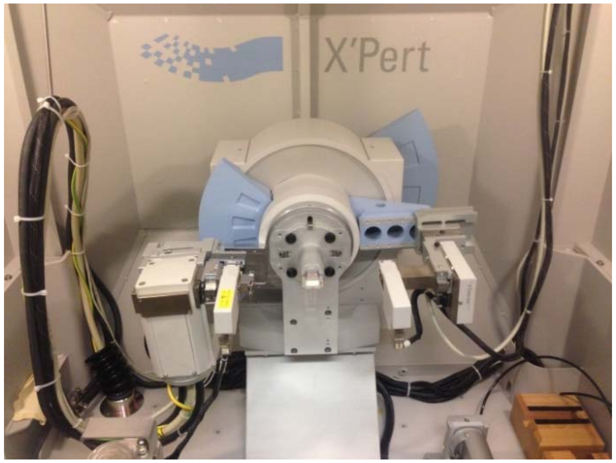
Mechanical Engineering
Pavlos Vlachos
Arezoo Ardekani

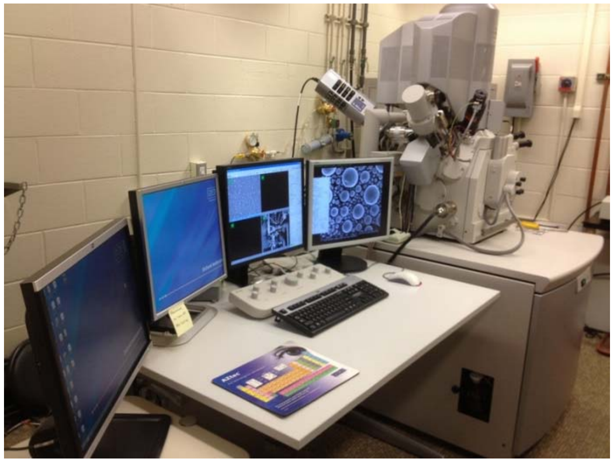
Masters Thesis Objective

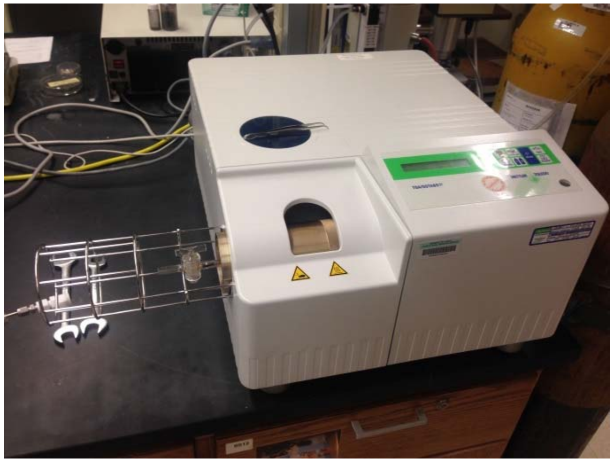
- Goal: Reservoir characterization
  - Provide an accurate and quantitative model for reservoir architecture, connectivity, and flow properties such as porosity, permeability, and fluid saturations as it relates to the mineralogy and chemistry of the reservoir.

My Research Tools

- Sedimentology / Petrography
- Quantitative powder X-ray diffraction (QPXRD)
- Fourier transform infrared analysis (FTIR)
- Thermal analysis (TGA) / Evolved gas analysis (EGA)
- Scanning electron microscopy (SEM) combined with energy dispersive X-ray spectroscopy (EDX)

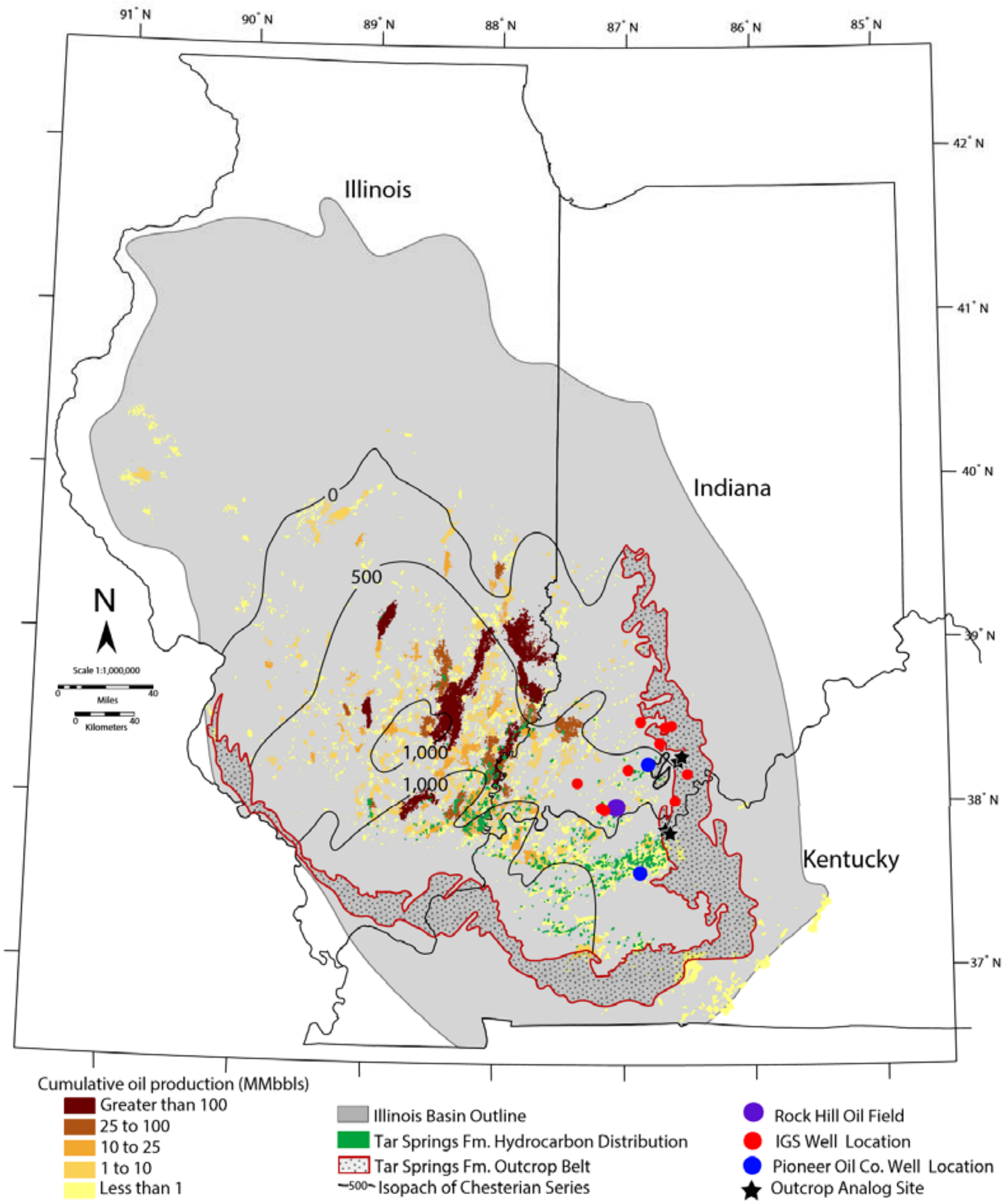




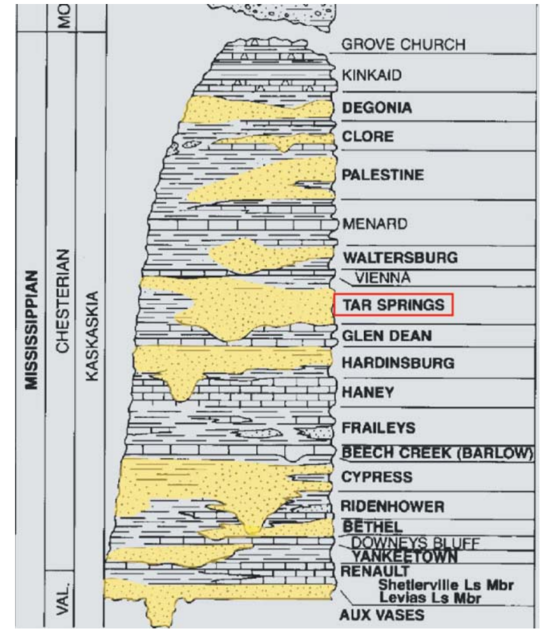


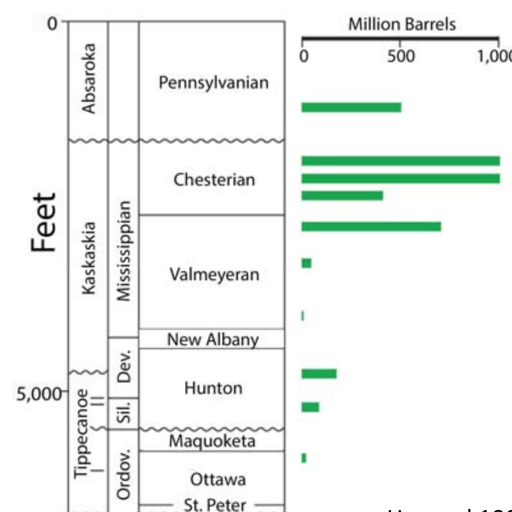
Research Area

Midwest Geological Sequestration Consortium 2005



Illinois Geological Survey





Howard 1990

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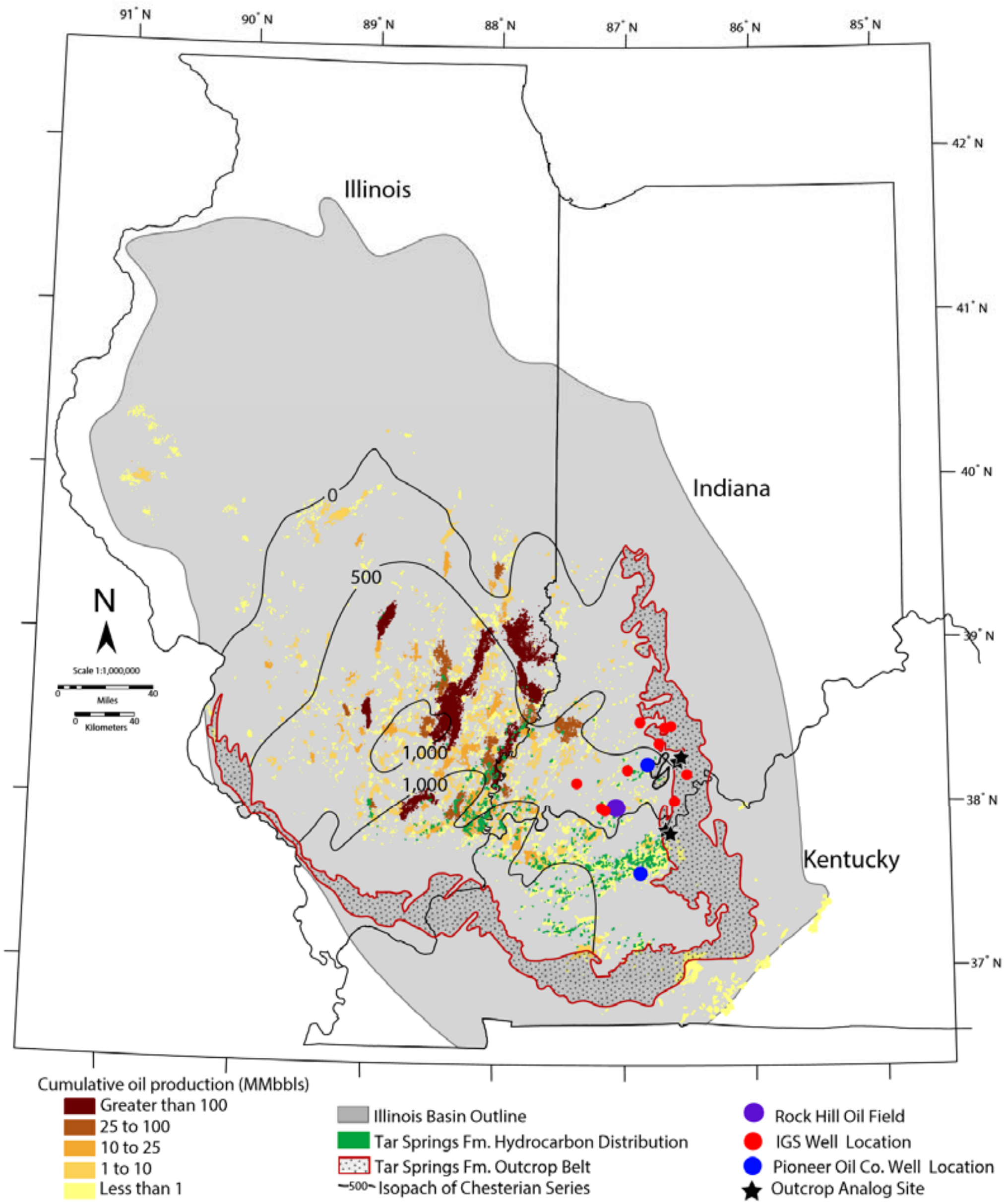
Core Sedimentology/Petrography



- Detailed analyses of Tar Springs Formation reservoir cores from Rock Hill reservoir and surrounding reservoirs
- 8 new cores (BLUE) accounting >300 ft!

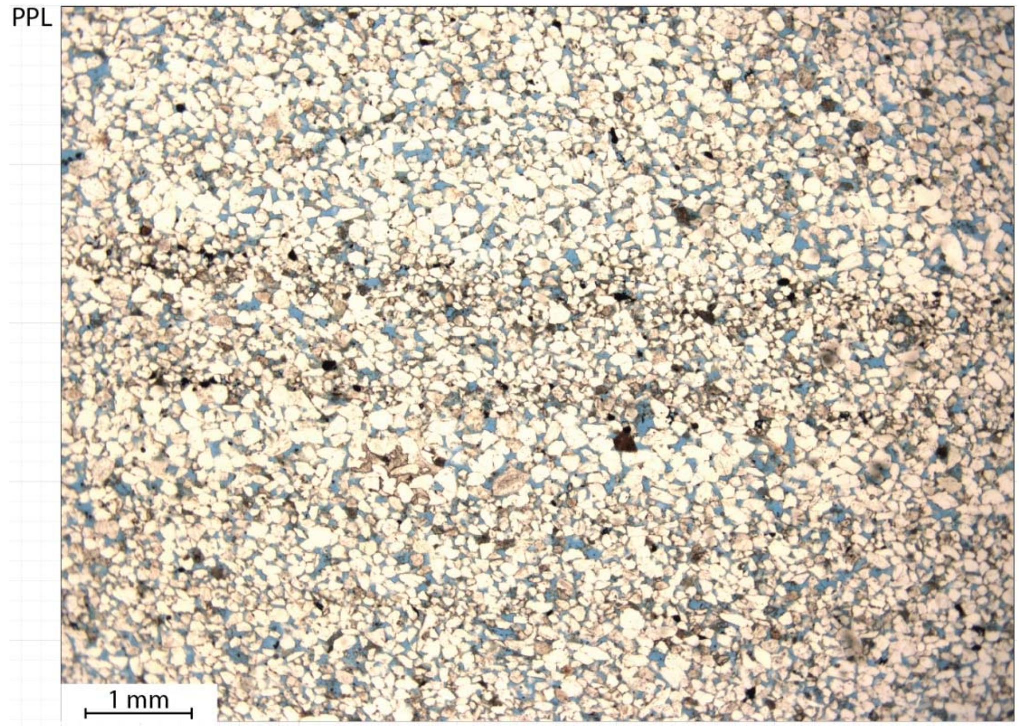
Midwest Geological Sequestration Consortium 2005

Core Sedimentology/Petrography

Core Sedimentology/Petrography

- 11 reservoir cores of the Tar Springs Formation were provided by Pioneer Oil Company (~405 feet total)
- Cores can be broken down into 5 distinct lithofacies with unique physical/chemical properties:
  - F1: fine- to medium-grained, horizontally-stratified sandstone with consistent porosity but large permeability variations
  - F2: very fine to fine-grained, flaser-bedded sandstone with consistent porosity and permeability
  - F3: very fine-grained, wavy-bedded sandstone with reduced porosity and low permeability
  - F4: very fine-grained sandy mudstone with low porosity and permeability
  - F5: fine-grained sandstone with calcite cement that occludes all porosity

F1: Horizontally-stratified sandstone



- Porosity: 20.5%; Permeability: 751 mD

Core Sedimentology/Petrography

- Rock Hill reservoir cores can be broken down into 5 distinct lithofacies with unique physical/chemical properties:
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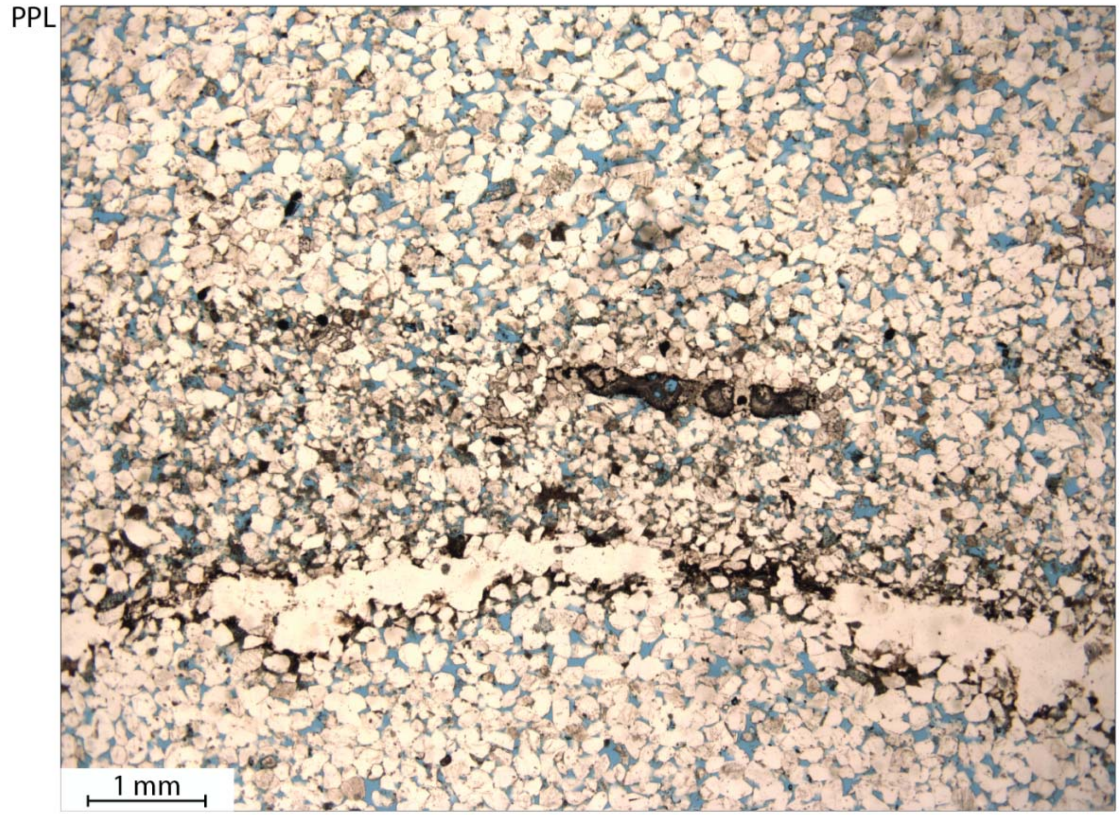
  - F2: very fine to fine-grained, flaser-bedded sandstone with consistent porosity and permeability
  - F3: very fine-grained, wavy-bedded sandstone with reduced porosity and low permeability
  - F4: very fine-grained sandy mudstone with low porosity and permeability
  - F5: fine-grained sandstone with calcite cement that occludes all porosity

F2 – Flaser-bedded sandstone



- Porosity: 16.6%; Permeability: 201 mD

Core Sedimentology/Petrography

- Rock Hill reservoir cores can be broken down into 5 distinct lithofacies with unique physical/chemical properties:
  - F1: fine- to medium-grained, horizontally-stratified sandstone with large porosity and permeability variations
  - F2: very fine to fine-grained, flaser-bedded sandstone with consistent porosity and permeability
  - F3: very fine-grained, wavy-bedded sandstone with reduced porosity and low permeability
  - F4: very fine-grained sandy mudstone with low porosity and permeability
  - F5: fine-grained sandstone with calcite cement that occludes all porosity

F3 – Wavy-bedded sandstone

- Porosity: 10.9%; Permeability: 33 mD

Core Sedimentology/Petrography

- Rock Hill reservoir cores can be broken down into 5 distinct lithofacies with unique physical/chemical properties:
  - F1: fine- to medium-grained, horizontally-stratified sandstone with large porosity and permeability variations
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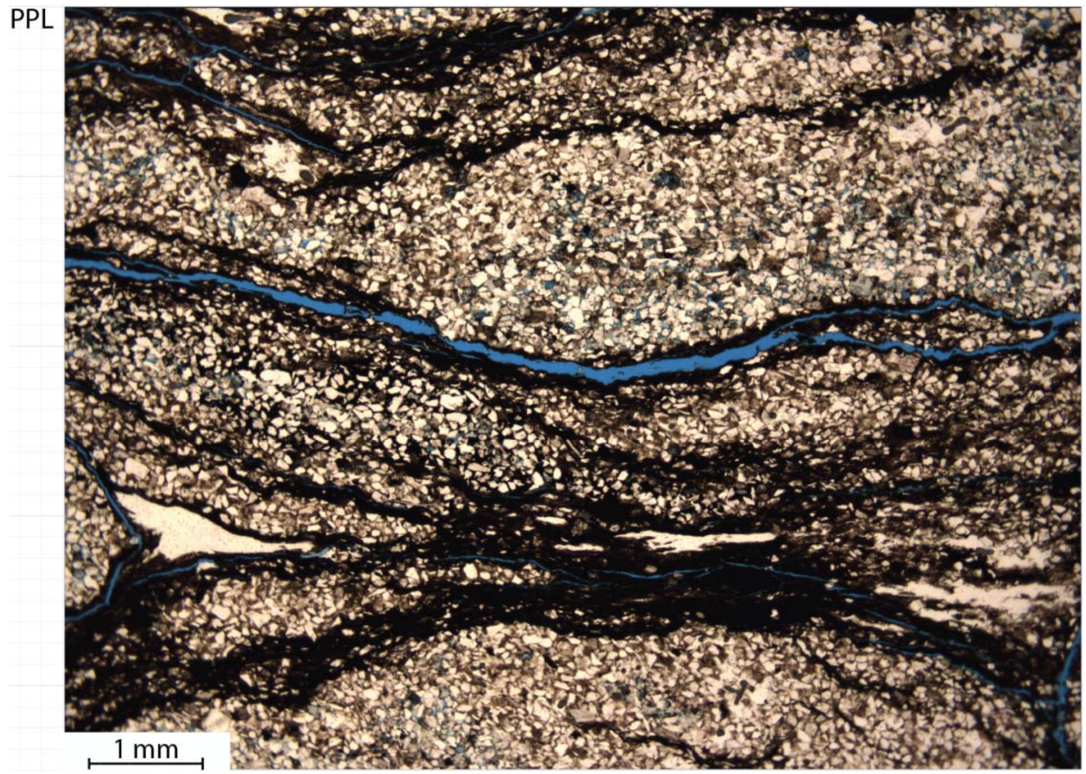
  - F4: very fine-grained sandy mudstone with low porosity and permeability
  - F5: fine-grained sandstone with calcite cement that occludes all porosity

F4 – Sandy mudstone



- Porosity: 12.1%; Permeability: 30 mD

Core Sedimentology/Petrography

- Rock Hill reservoir cores can be broken down into 5 distinct lithofacies with unique physical/chemical properties:
  - F1: fine- to medium-grained, horizontally-stratified sandstone with large porosity and permeability variations
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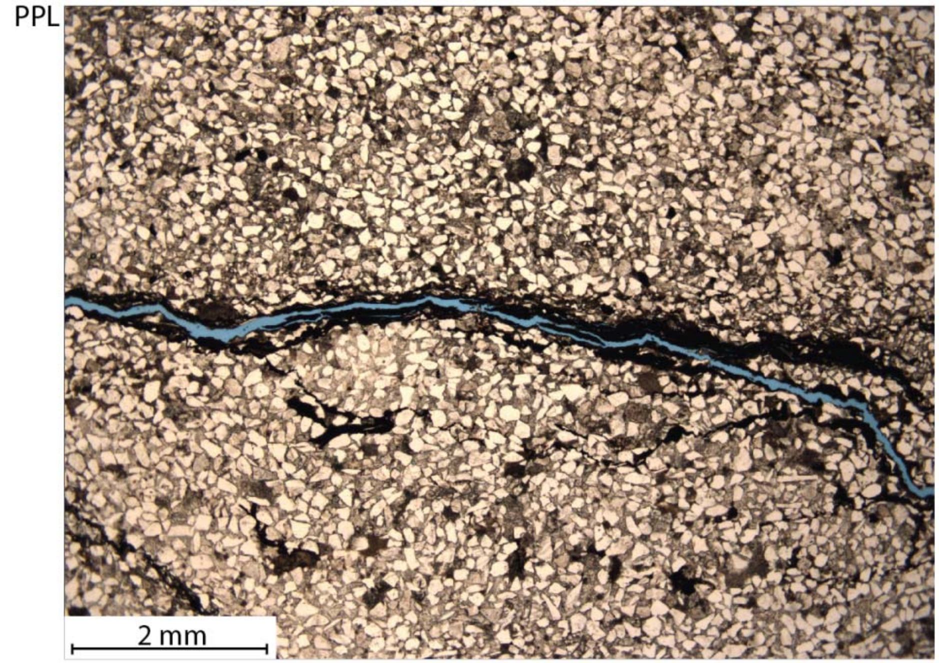
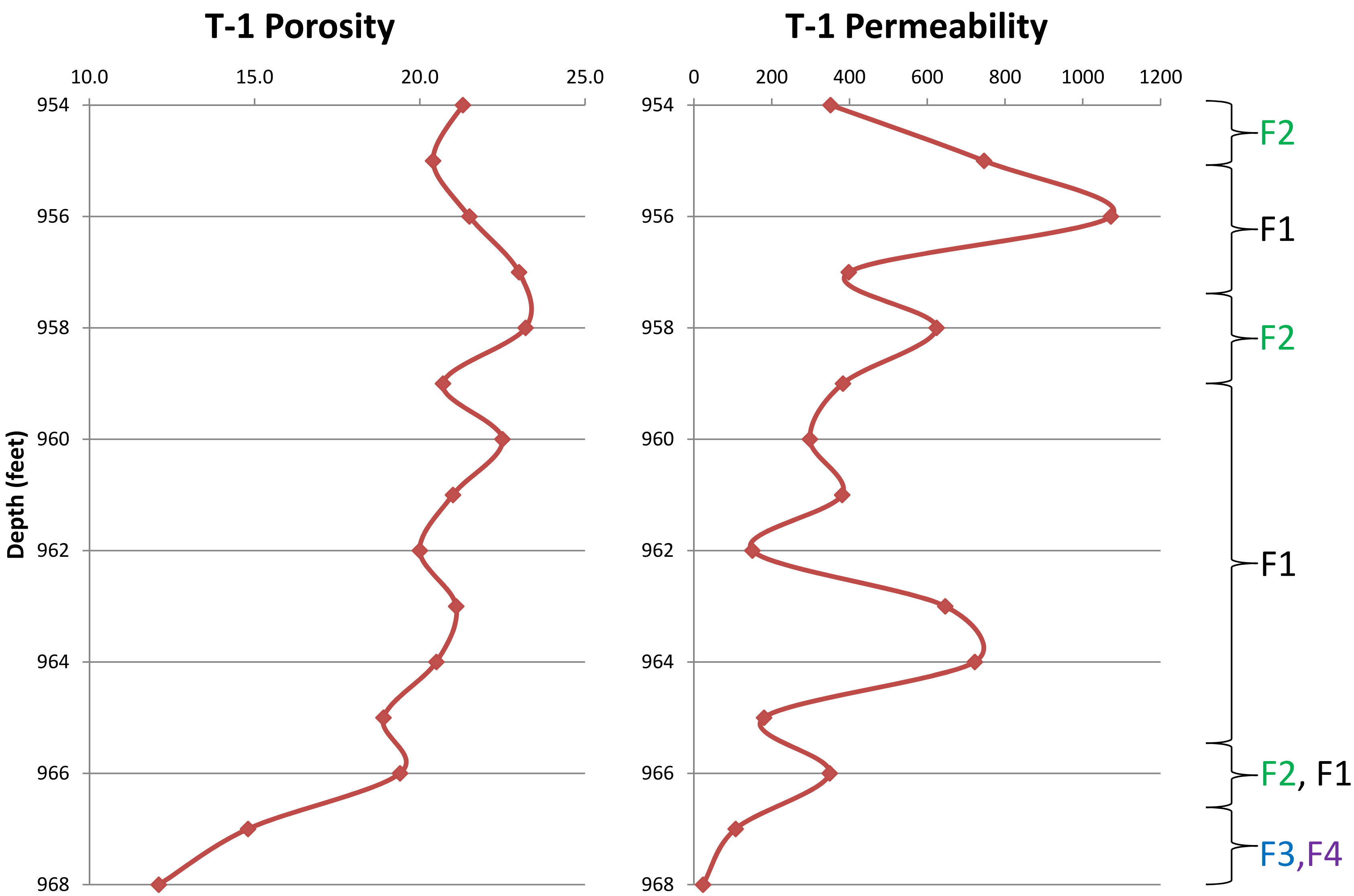
  - F4: very fine-grained sandy mudstone with low porosity and permeability
  - F5: fine-grained sandstone with calcite cement that occludes all porosity

F5 – Calcite-cemented sandstone

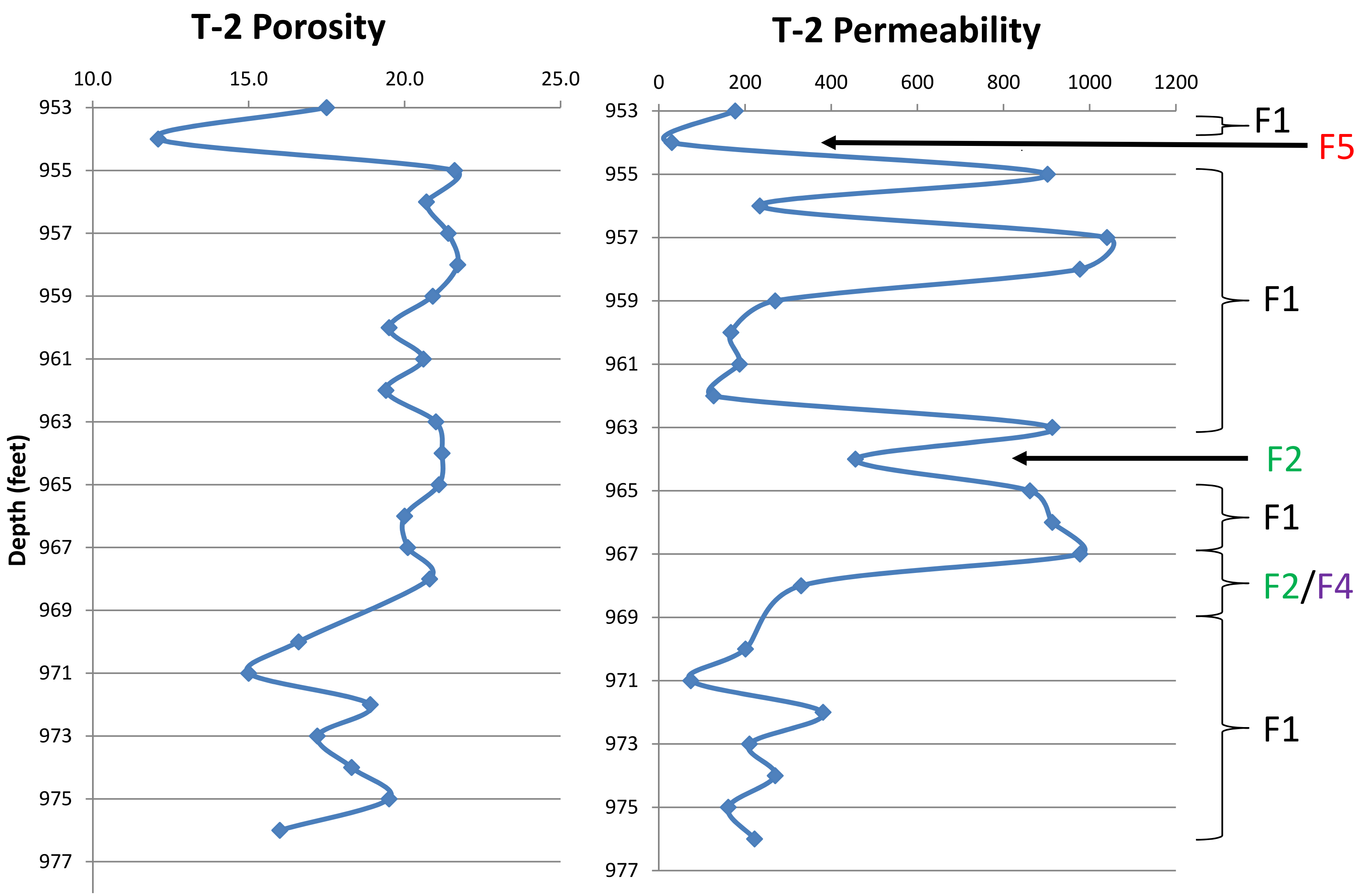


- Porosity: 12.1%; Permeability: 39.5 mD

T-1 Porosity/Permeability



T-2 Porosity/Permeability



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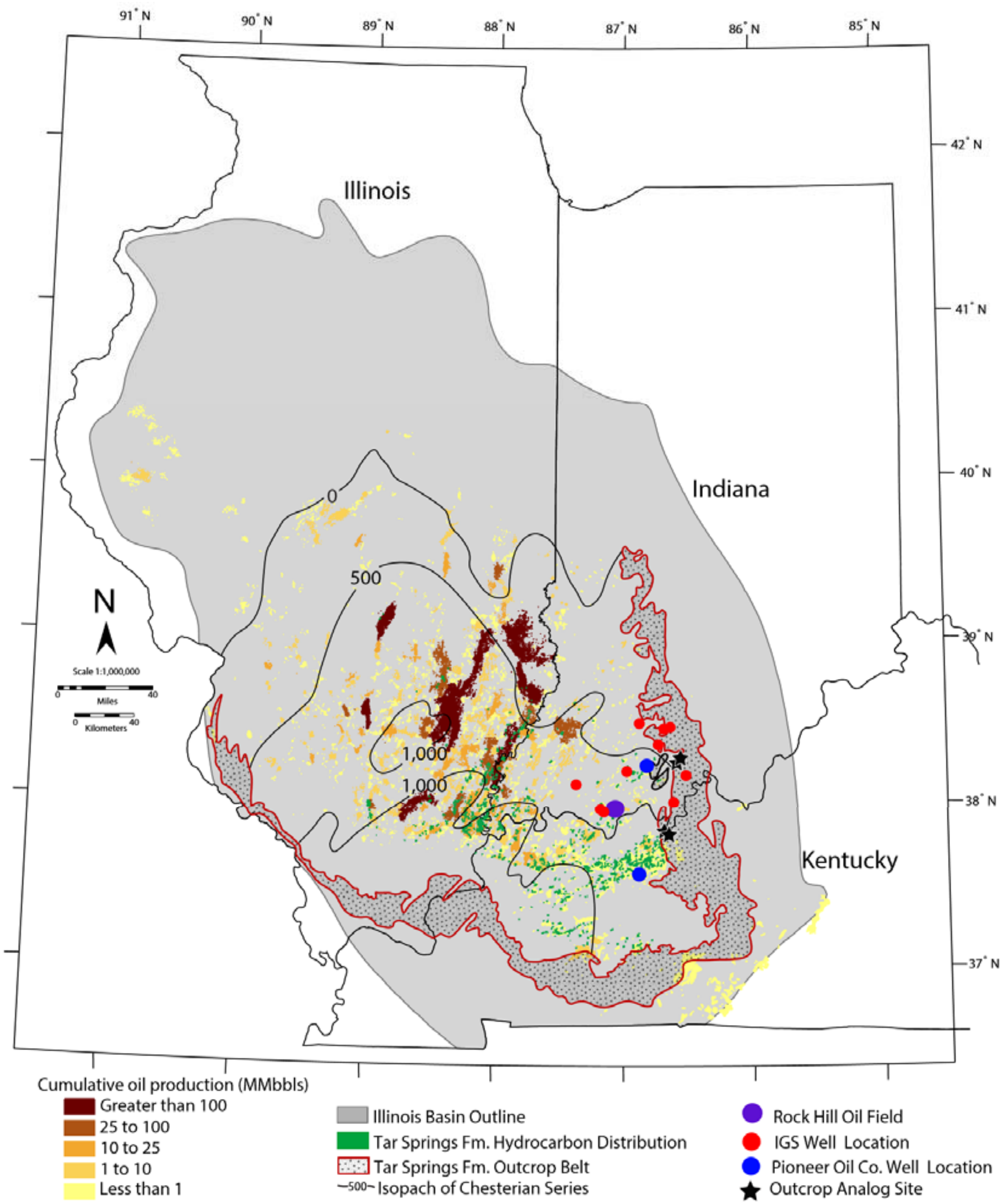
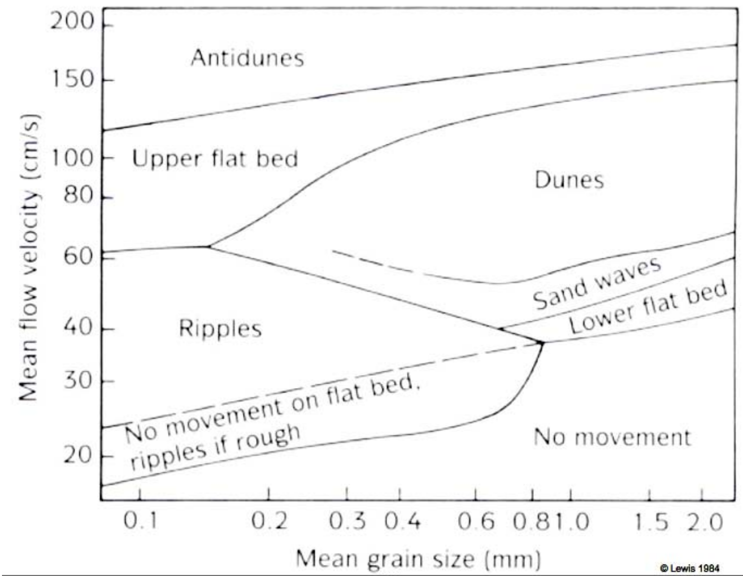
Field Work

- 4 outcrop locations in southern Indiana and northern Kentucky
- Builds 3D framework that ties into reservoir cores

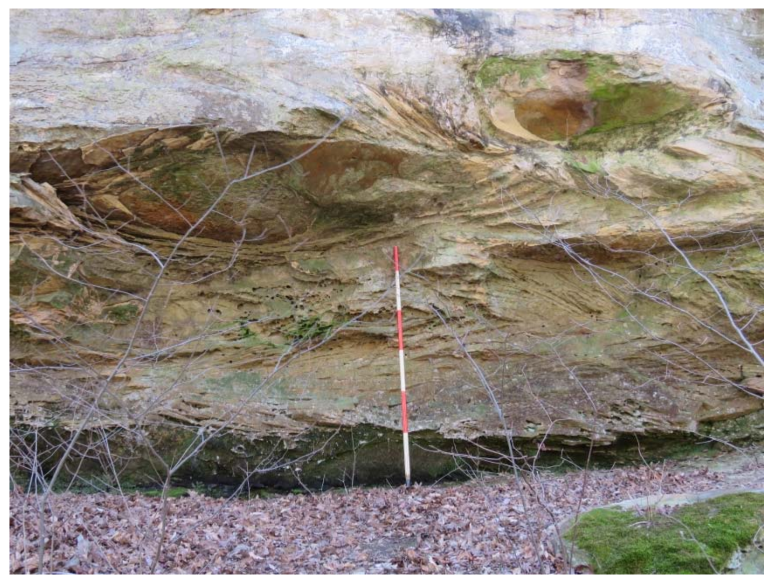


Midwest Geological Sequestration Consortium 2005

Field Work


Antidunes
Upper flat bed
Dunes
Sand waves
Lower flat bed
Ripples
No movement on flat bed, ripples if rough
No movement
Mean flow velocity (cm/s)
200
150
100
80
60
40
30
20
0.1
0.2
0.3
0.4
0.6
0.8
1.0
1.5
2.0
Mean grain size (mm)
© Lewis 1984

Field Work



Field Work

- Helps construct a 3D geological framework (lateral continuity, flow barriers) which can be utilized for reservoir models

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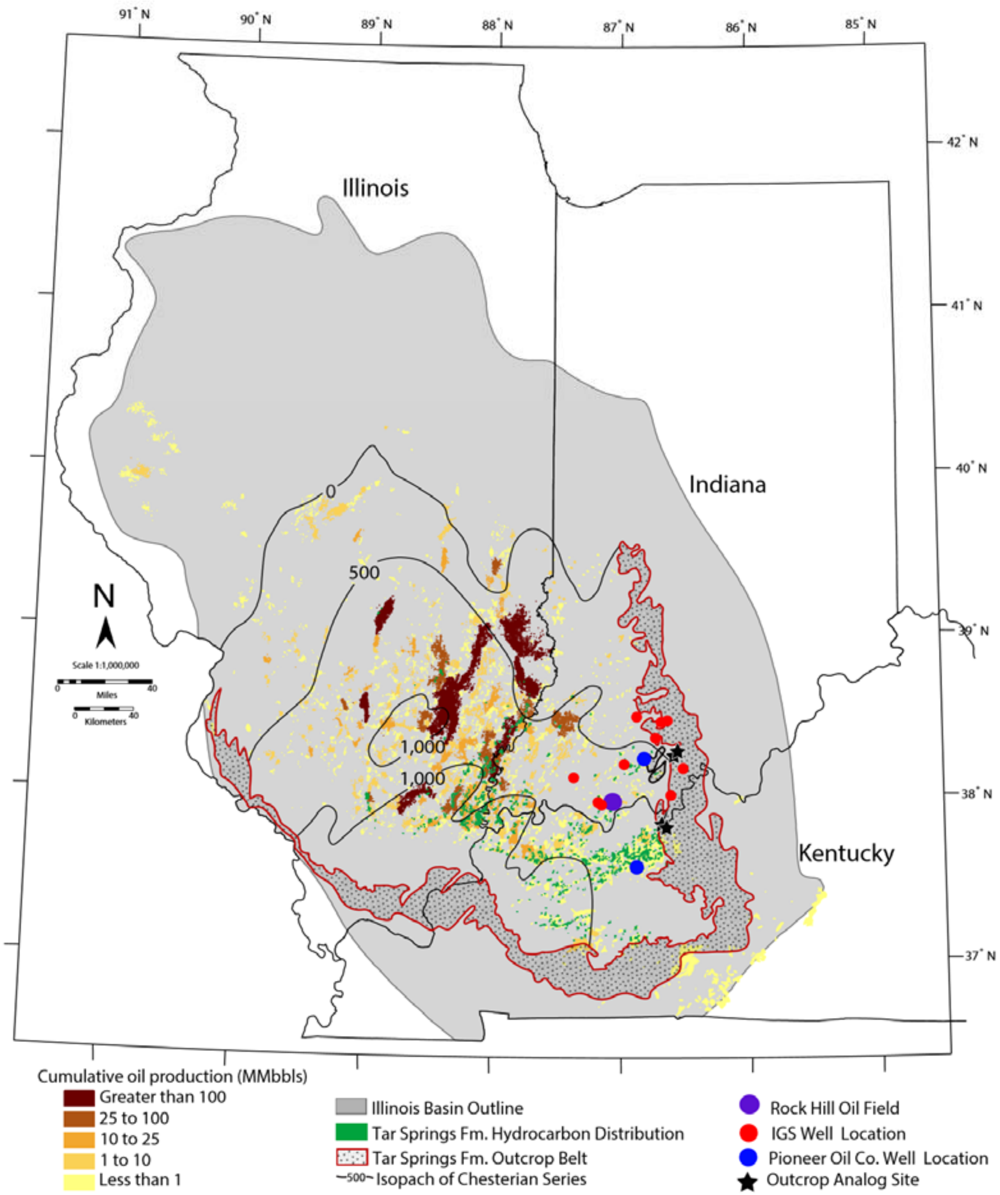
New Tar Springs Reservoir Cores



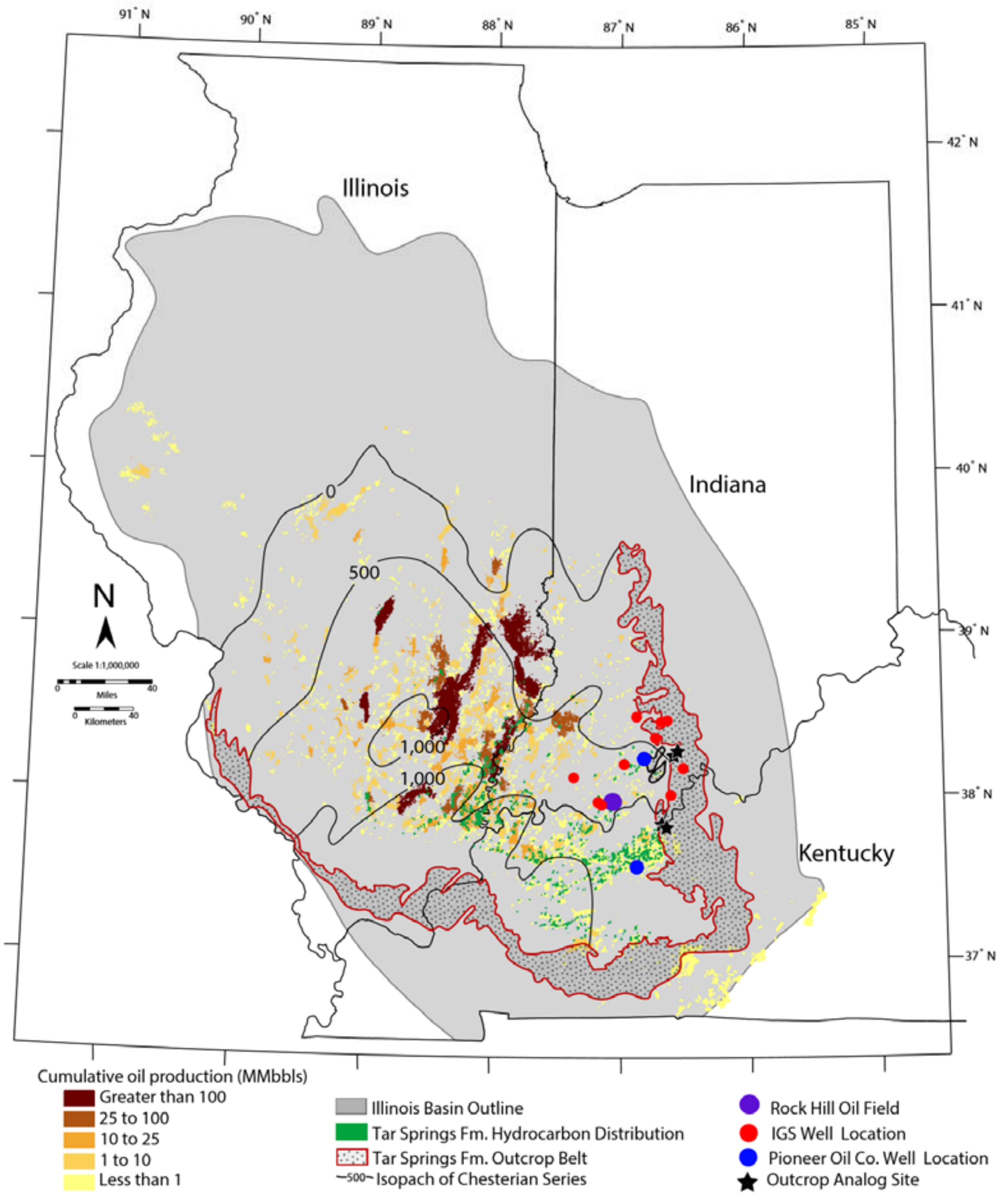
- Located in both Indiana and Kentucky (>300 ft of core material)

Midwest Geological Sequestration Consortium 2005

New Tar Springs Reservoir Cores

- Located in both Indiana and Kentucky (>300 ft of core material)

Indiana Geological Survey Cores



- 10 supplemental cores from the IGS core repository (RED) were described to aid in facies identification on a regional scale (~237 feet total)

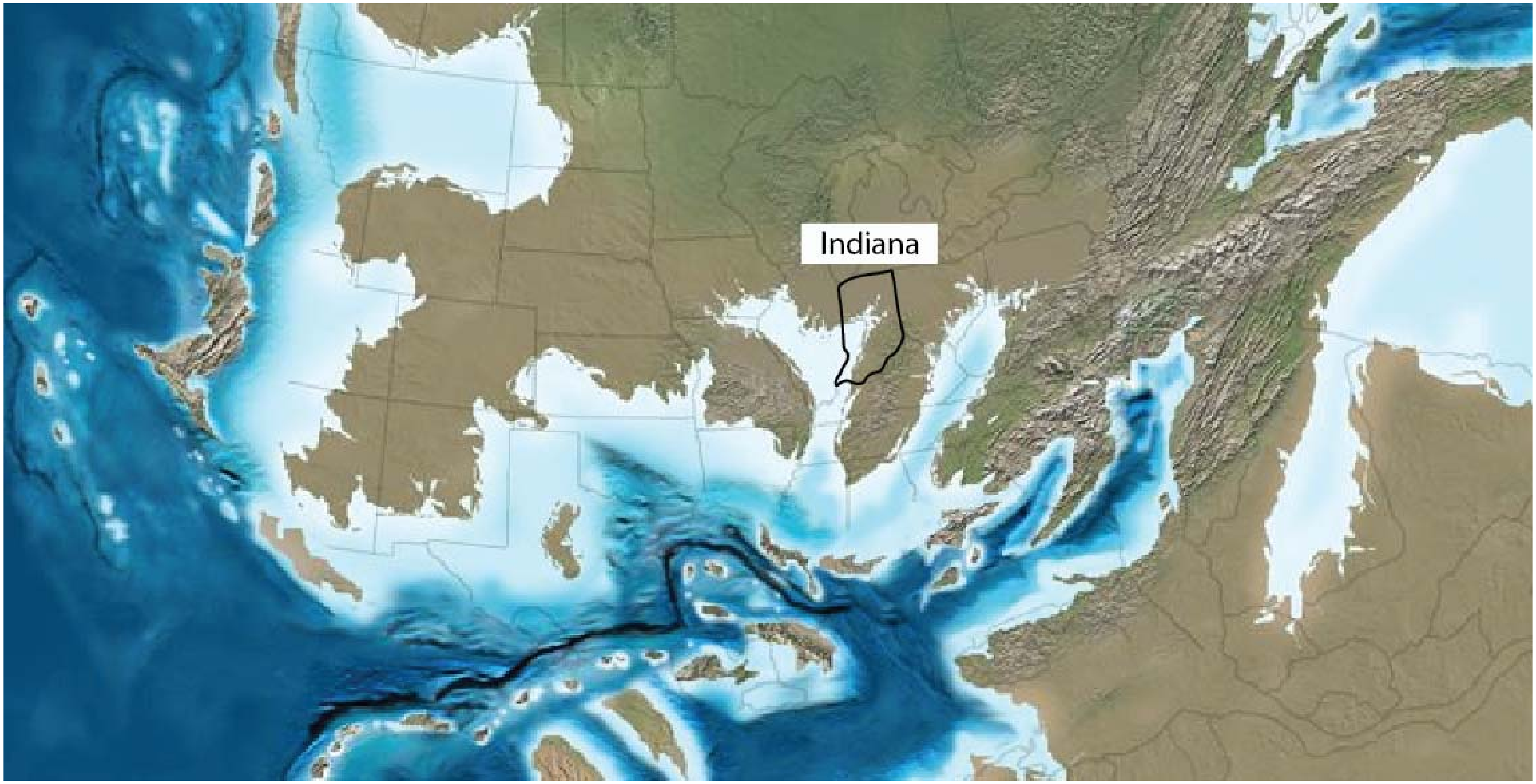
Midwest Geological Sequestration Consortium 2005

Indiana Geological Survey Cores

- All express the exact lithofacies as the reservoir cores, with additional presence of clay-rich paleosol horizons and better preserved bioturbation



L. Mississippian Paleogeography



Blakey 2011

Modern Analog: Cook Inlet, AK

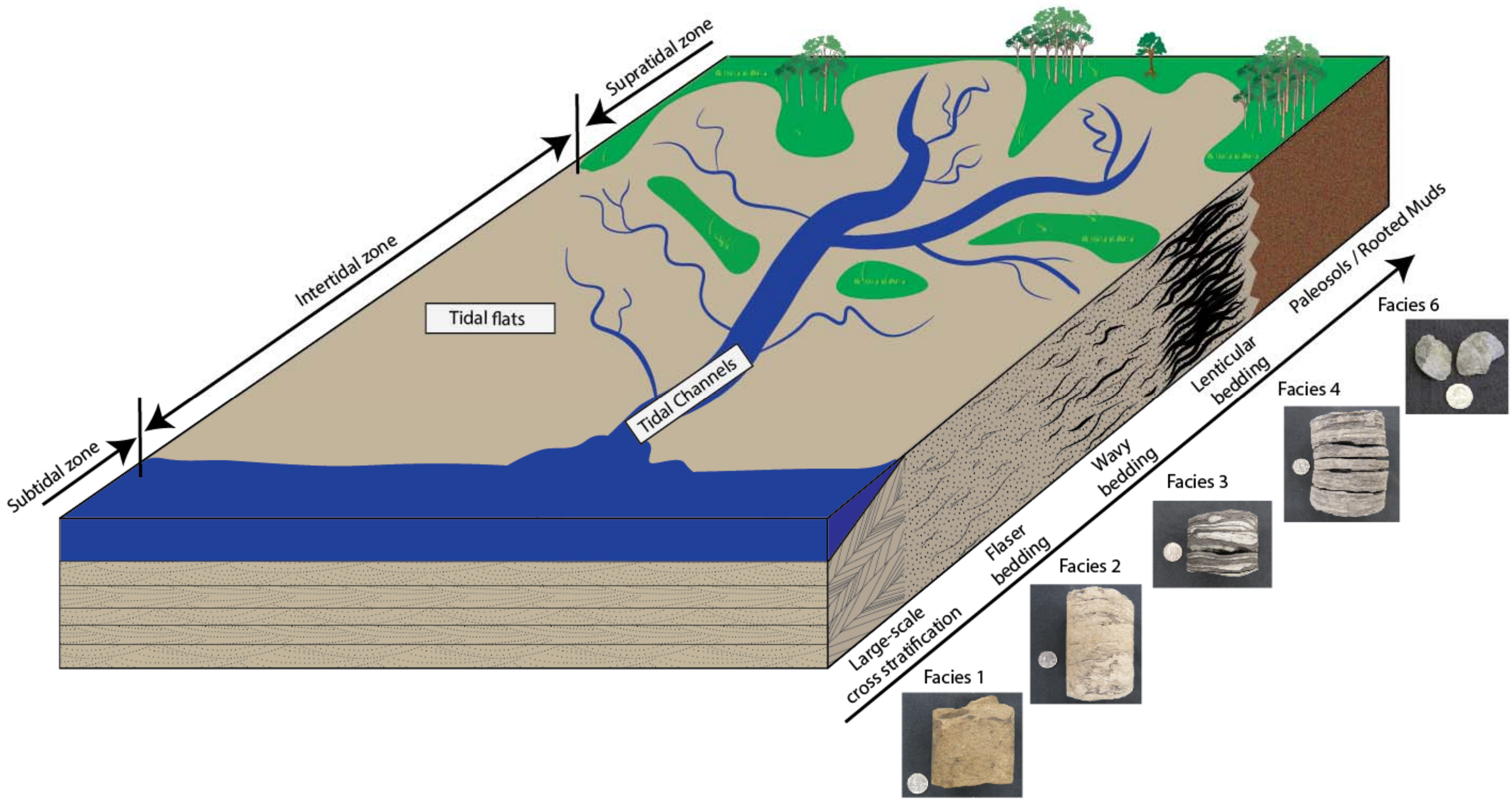
AirPhoto

GoogleEarth

Tidal Bore Energies

Federacion de Surf de Costa Rica

Tar Springs Formation Depositional Model



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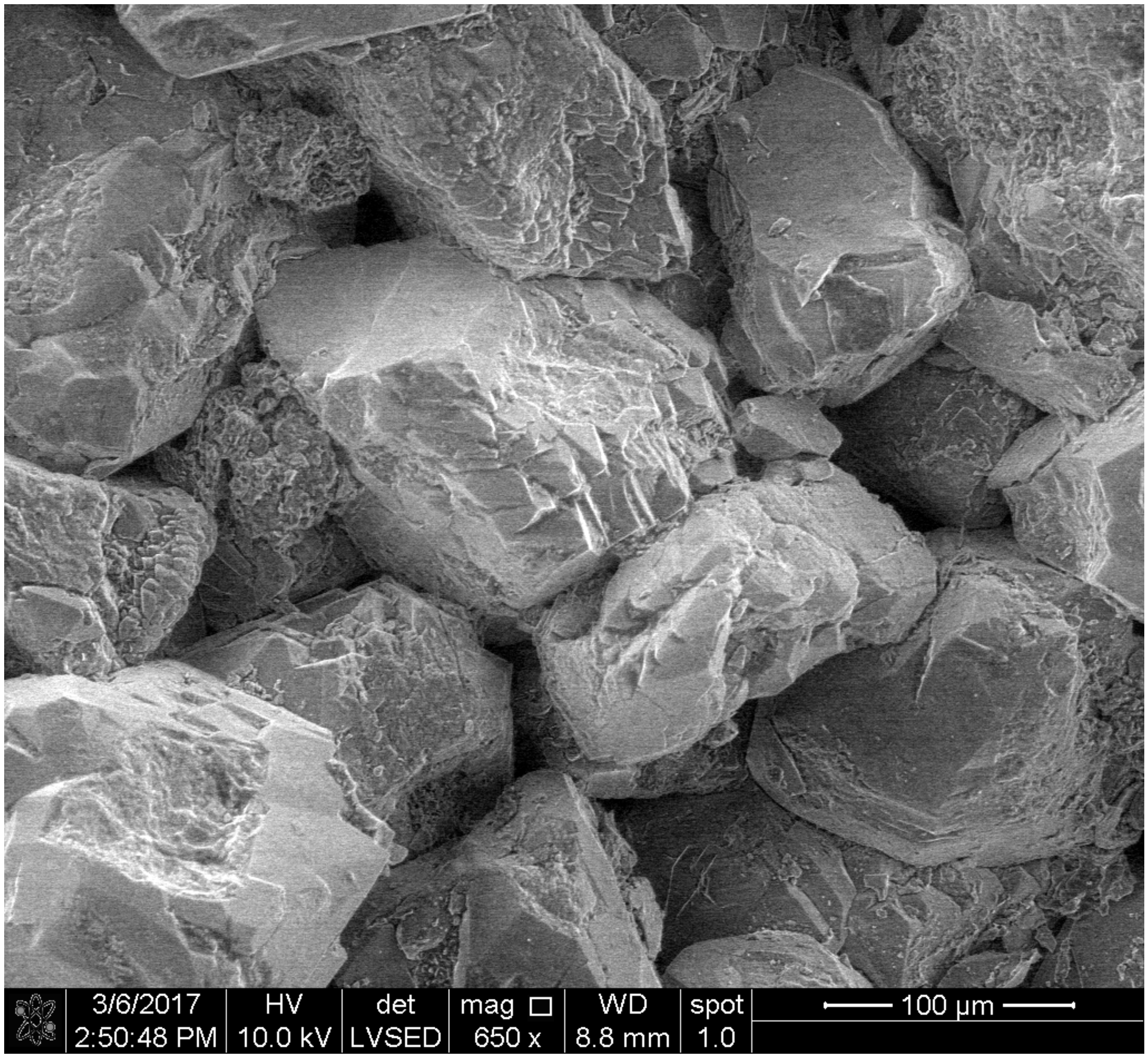
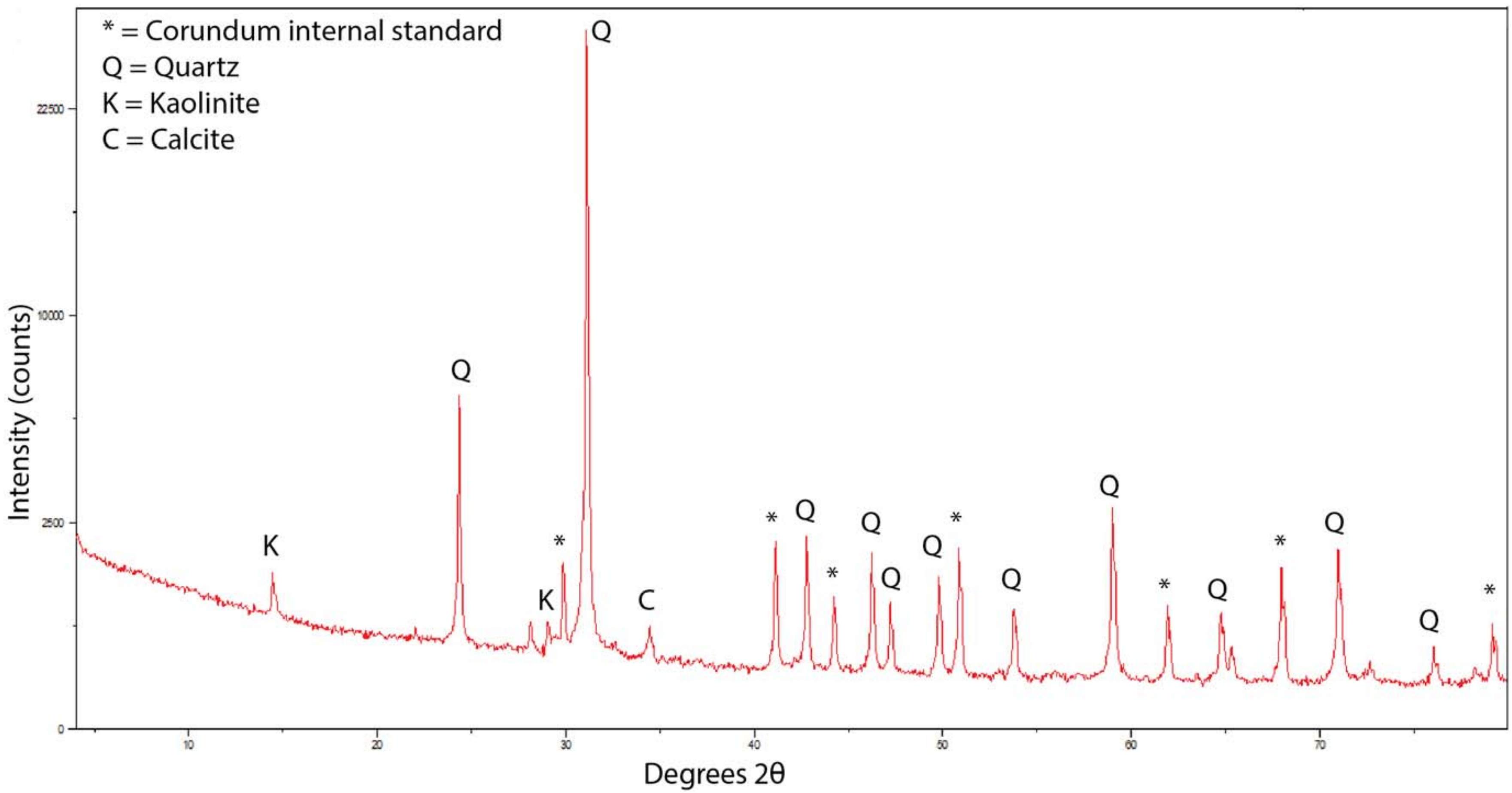
SEM:
Fine-scale Pore Mineralogy



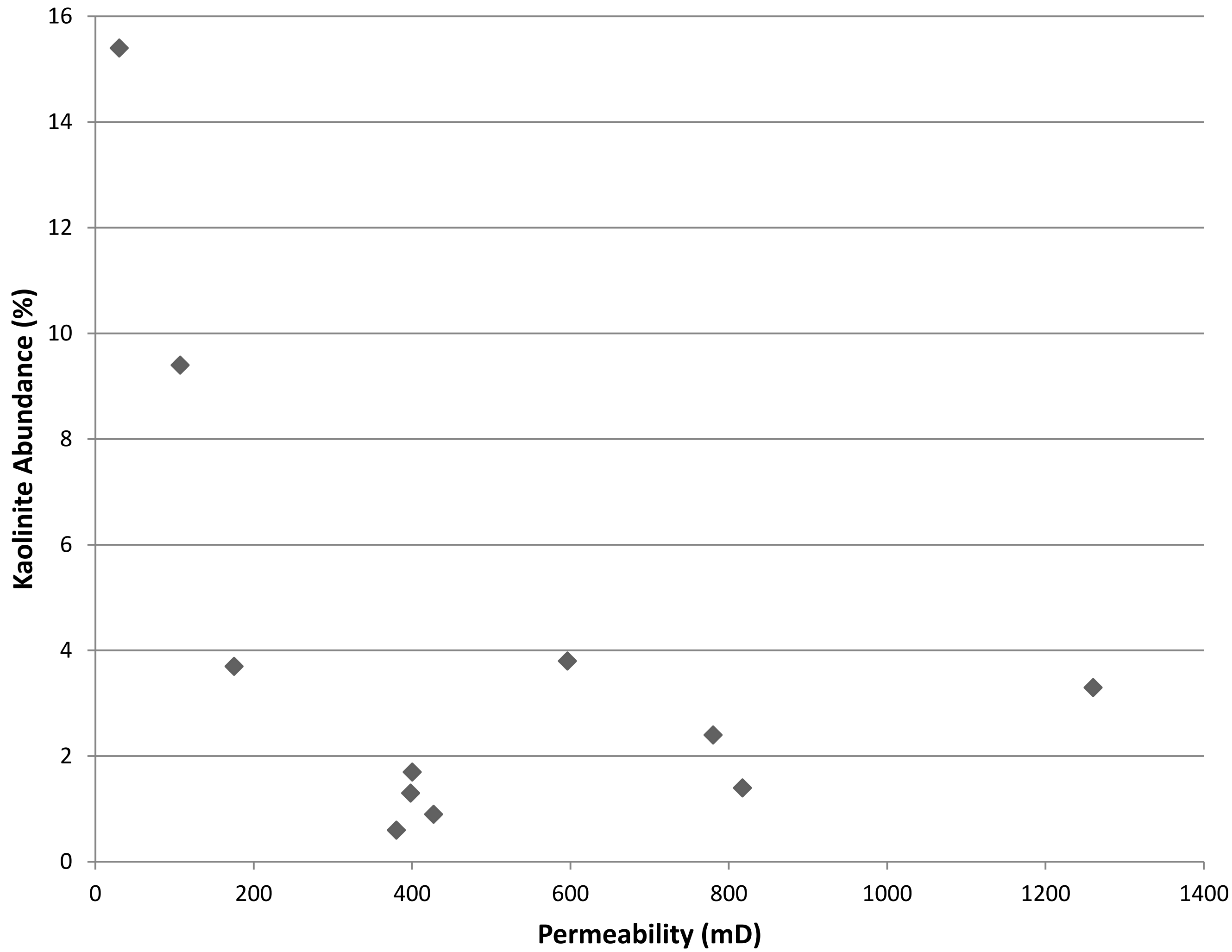
XRD

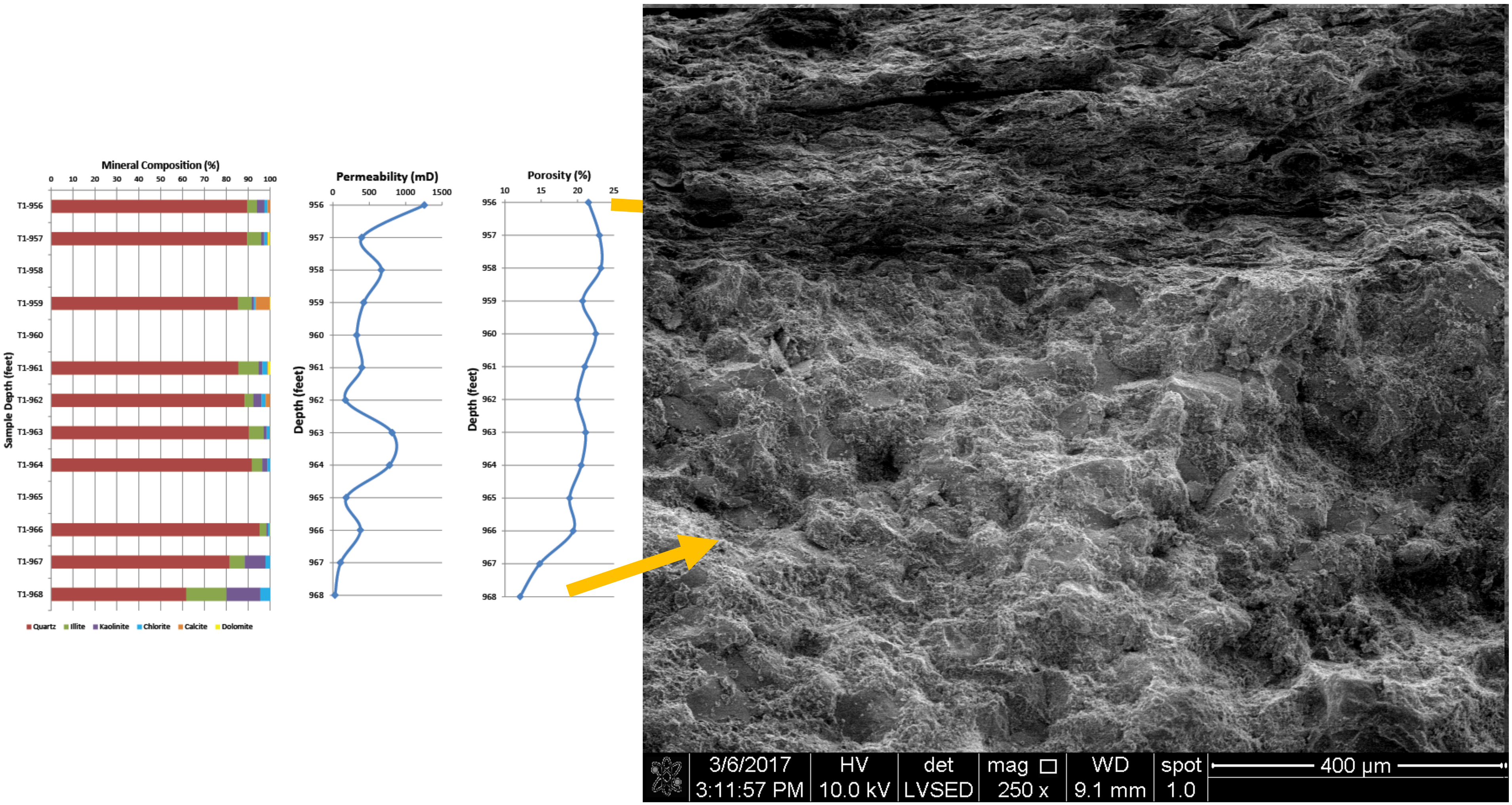
- Used for mineral identification
- Samples and mineral standards spiked with corundum for quantification



XRD of Core T-1

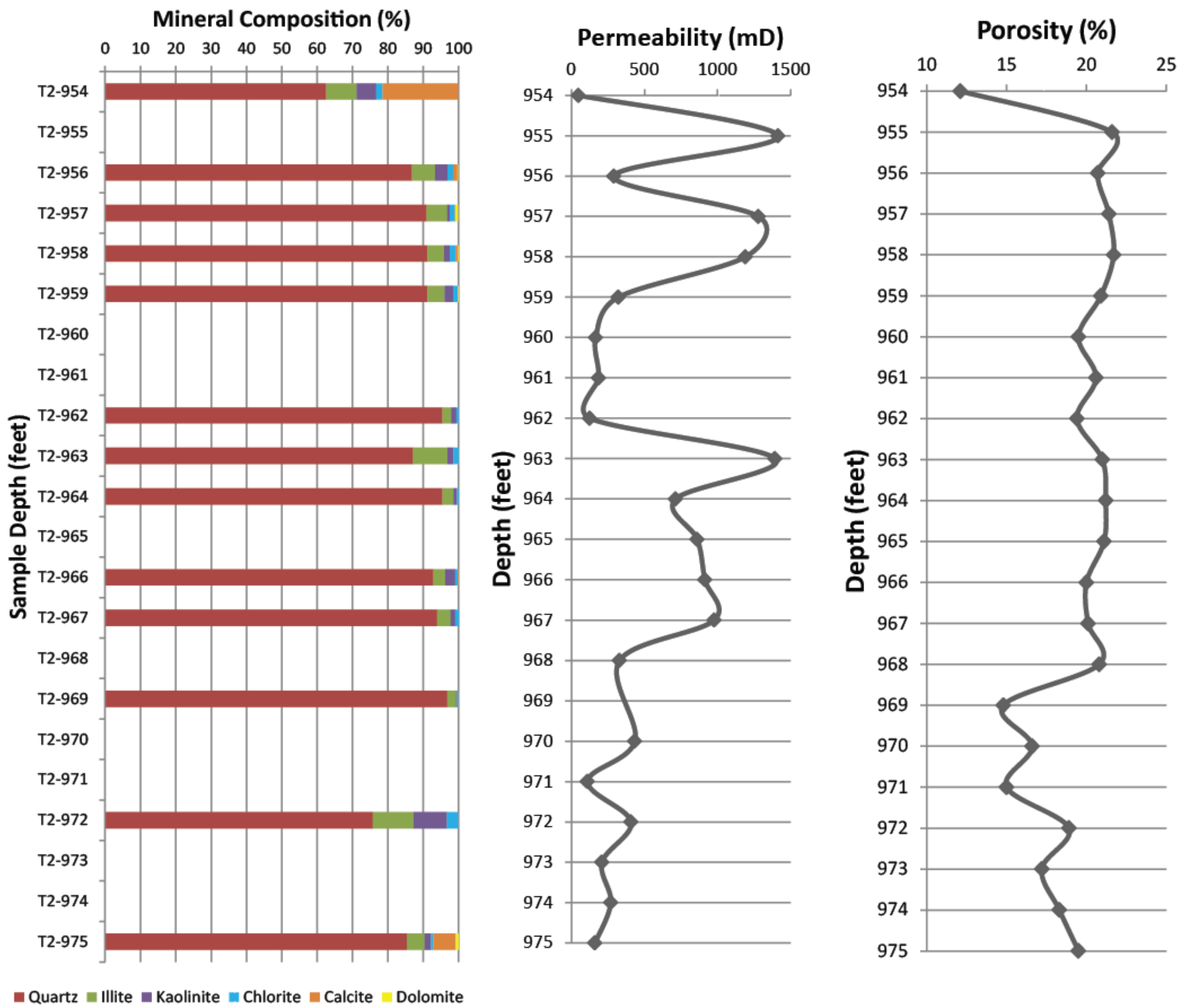
- Kaolinite appears to have primary impact on porosity and permeability degradation (carbonate cement = secondary impact)

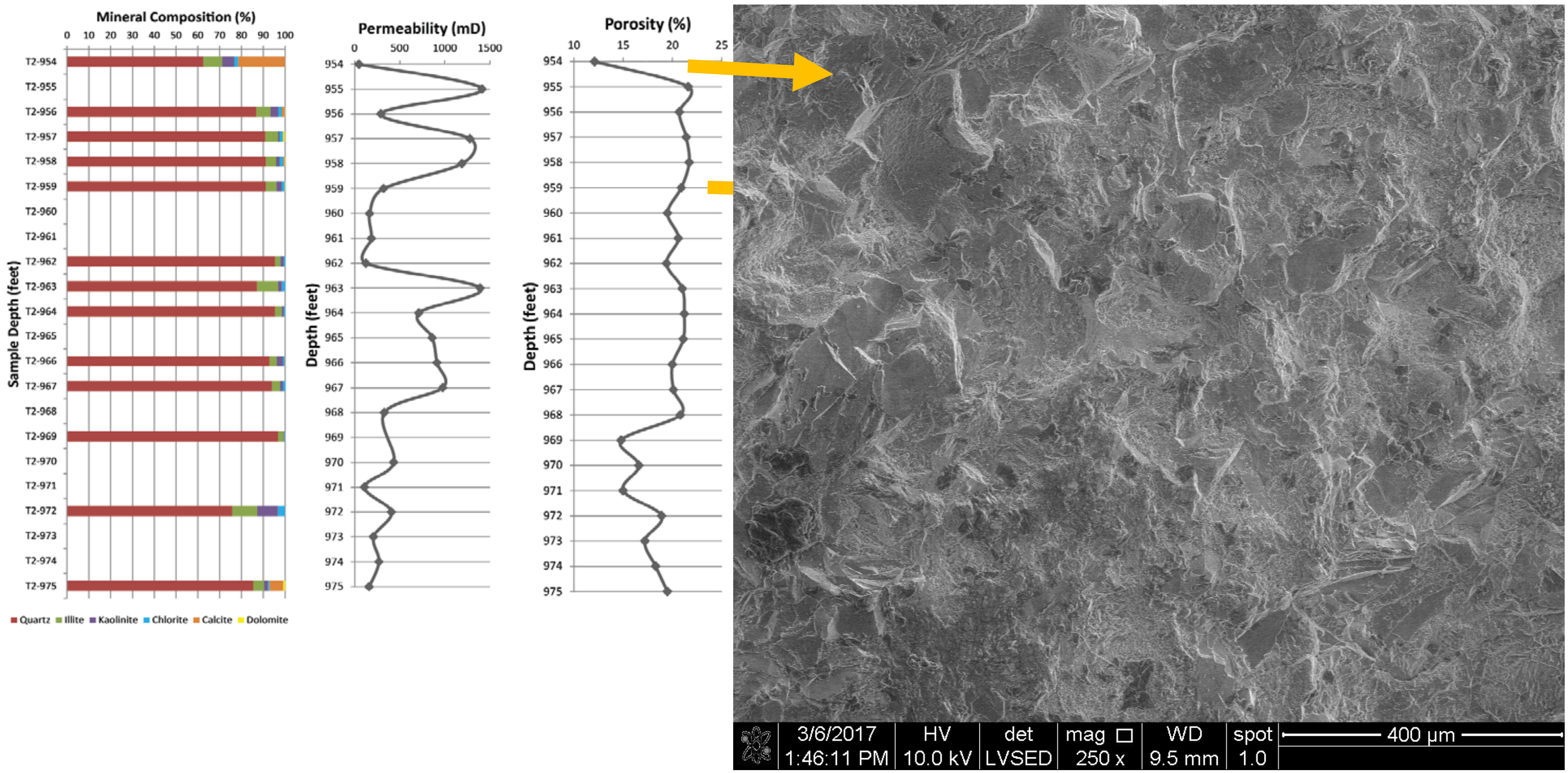



Mineral Composition (%)
0 10 20 30 40 50 60 70 80 90 100
T1-956
T1-957
T1-958
T1-959
T1-960
T1-961
T1-962
T1-963
T1-964
T1-965
T1-966
T1-967
T1-968
Sample Depth (feet)
Quartz Illite Kaolinite Chlorite Calcite Dolomite
Permeability (mD)
0 500 1000 1500
956 957 958 959 960 961 962 963 964 965 966 967 968
Depth (feet)
Porosity (%)
10 15 20 25
956 957 958 959 960 961 962 963 964 965 966 967 968
Depth (feet)
3/6/2017
3:11:57 PM
HV
10.0 kV
det
LVSED
mag
250 x
WD
9.1 mm
spot
1.0
400 µm

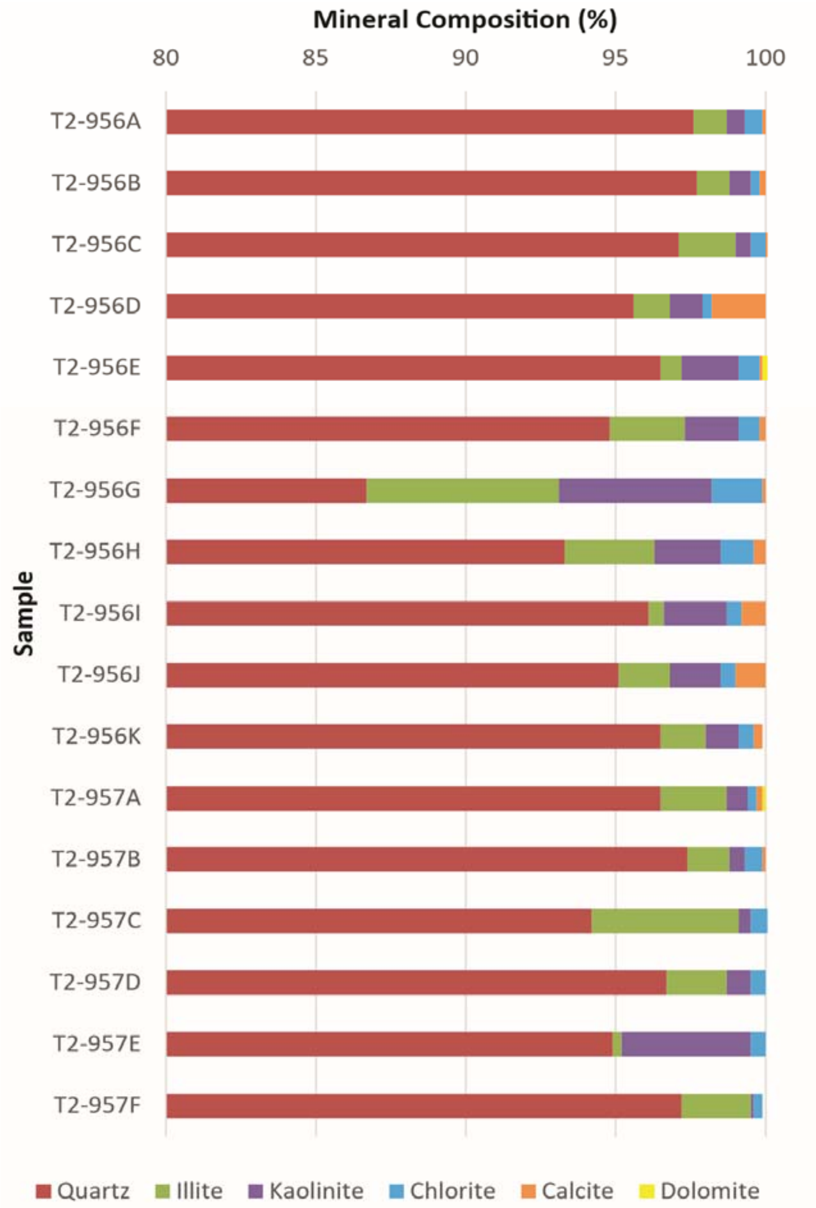
XRD of Core T-2

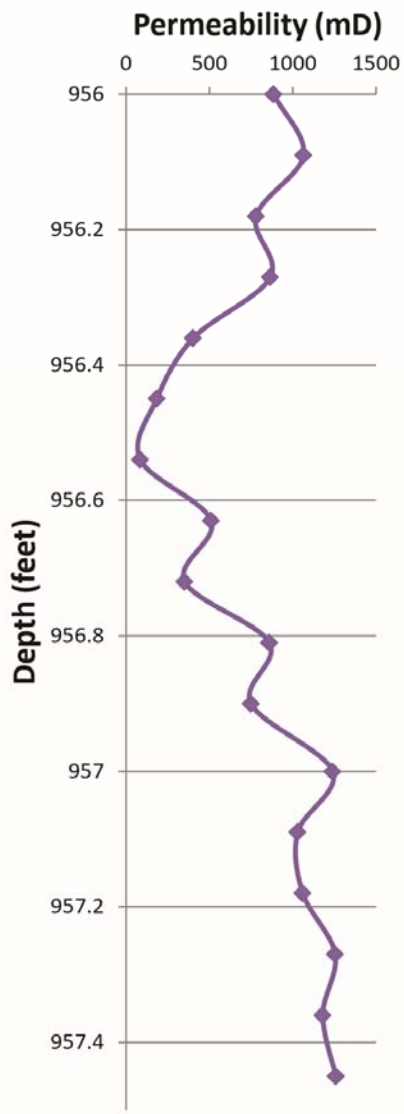
- Kaolinite/carbonate have detrimental impact on porosity and permeability

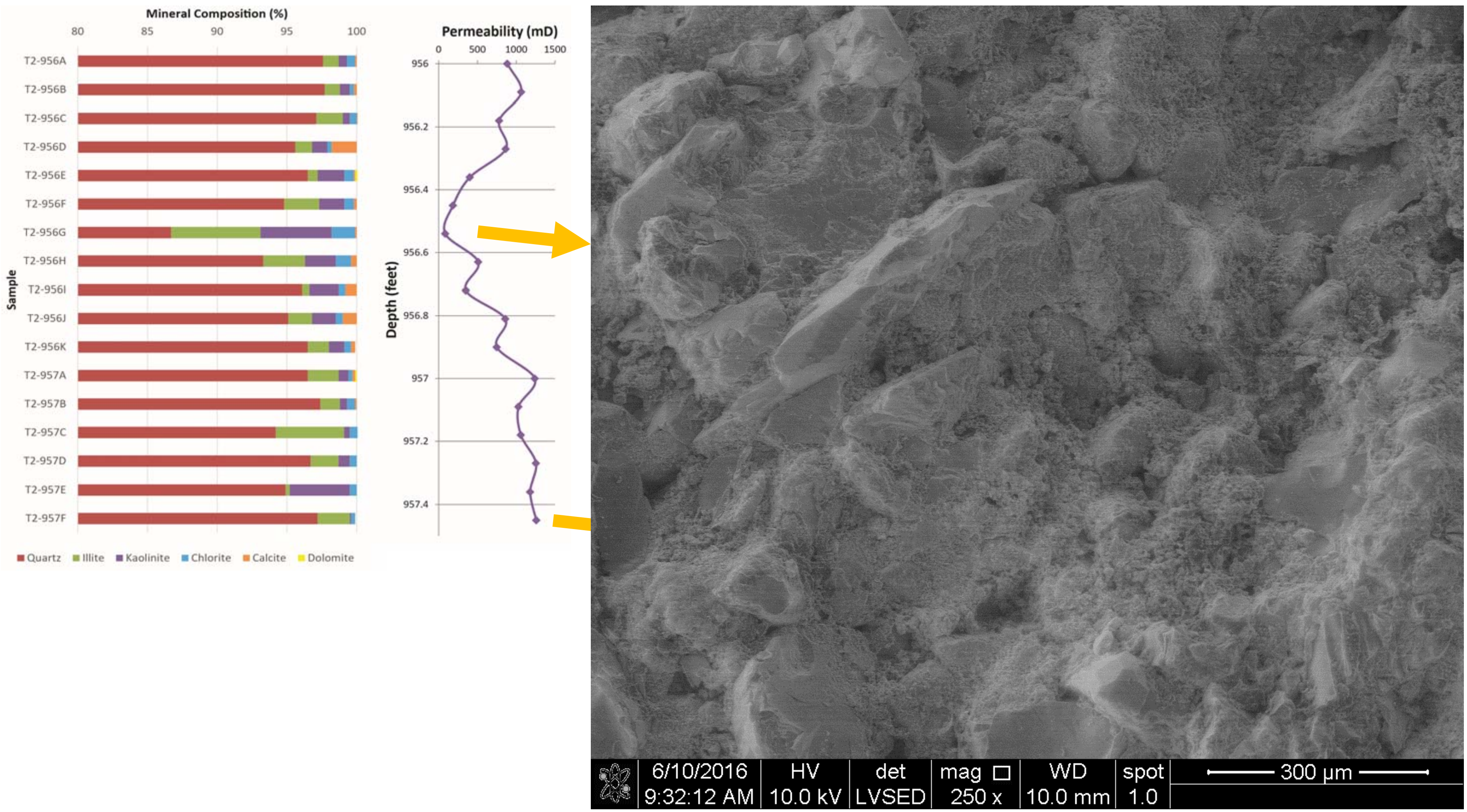



Mineral Composition (%)
0 10 20 30 40 50 60 70 80 90 100
Sample Depth (feet)
T2-954
T2-955
T2-956
T2-957
T2-958
T2-959
T2-960
T2-961
T2-962
T2-963
T2-964
T2-965
T2-966
T2-967
T2-968
T2-969
T2-970
T2-971
T2-972
T2-973
T2-974
T2-975
Quartz Illite Kaolinite Chlorite Calcite Dolomite
Permeability (mD)
0 500 1000 1500
Depth (feet)
954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975
Porosity (%)
10 15 20 25
Depth (feet)
954 955 956 957 958 959 960 961 962 963 964 965 966 967 968 969 970 971 972 973 974 975
3/6/2017
1:46:11 PM
HV
10.0 kV
det
LVSED
mag
250 x
WD
9.5 mm
spot
1.0
400 µm

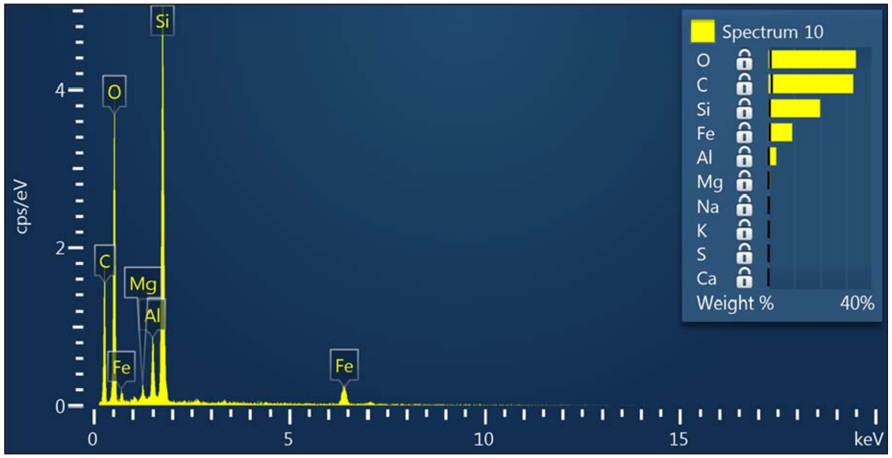
Fine-scale XRD

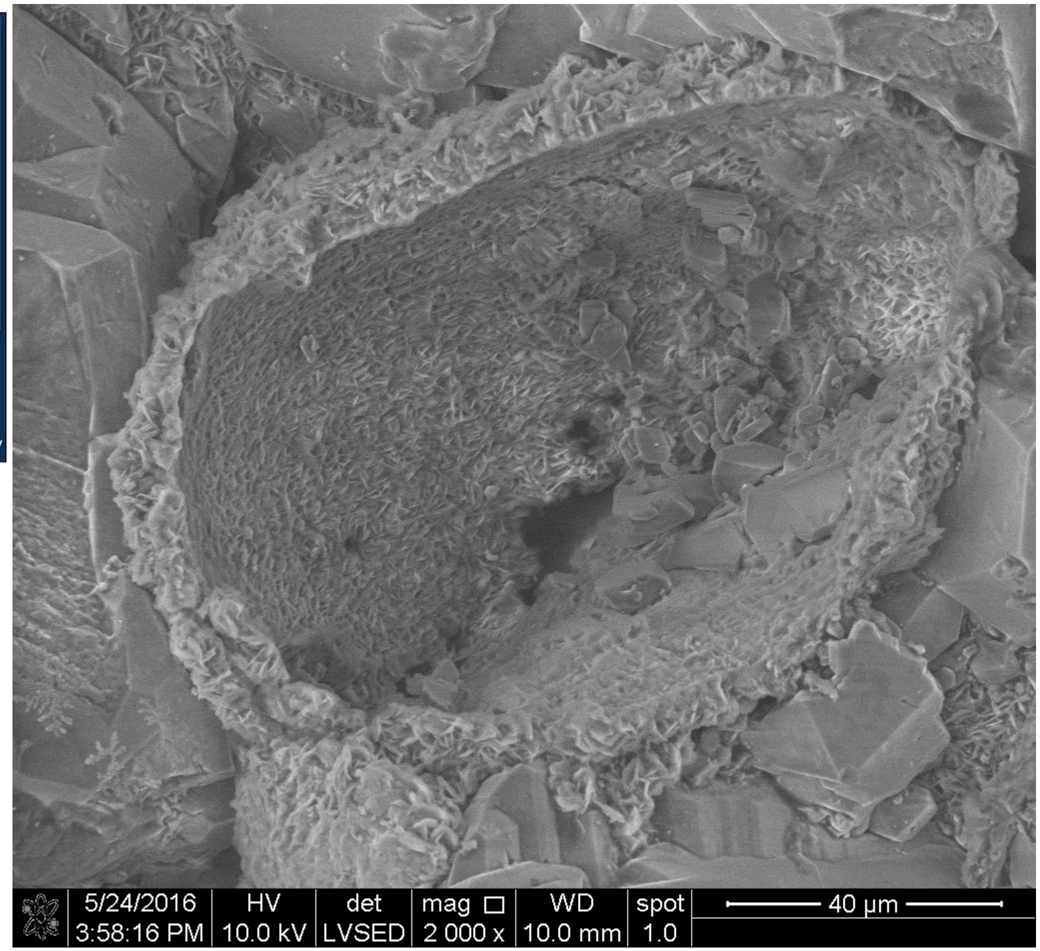





Mineral Composition (%)
80
85
90
95
100
Sample
T2-956A
T2-956B
T2-956C
T2-956D
T2-956E
T2-956F
T2-956G
T2-956H
T2-956I
T2-956J
T2-956K
T2-957A
T2-957B
T2-957C
T2-957D
T2-957E
T2-957F
Quartz
Illite
Kaolinite
Chlorite
Calcite
Dolomite
Permeability (mD)
0
500
1000
1500
Depth (feet)
956
956.2
956.4
956.6
956.8
957
957.2
957.4
6/10/2016
9:32:12 AM
HV
10.0 kV
det
LVSED
mag
250 x
WD
10.0 mm
spot
1.0
300 μm

Chlorite


Spectrum 10
O
C
Si
Fe
Al
Mg
Na
K
S
Ca
Weight %
40%
cps/eV
keV
0
5
10
15
0
2
4
Si
O
C
Mg
Al
Fe
Fe


5/24/2016
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10.0 kV
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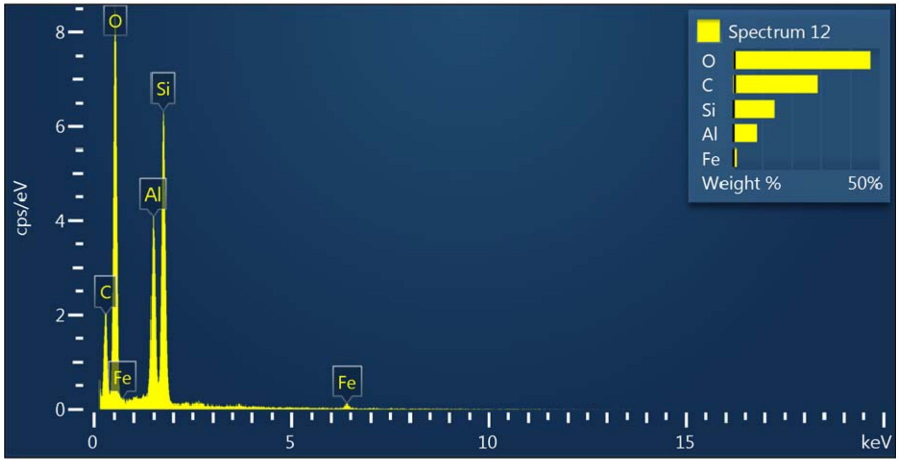
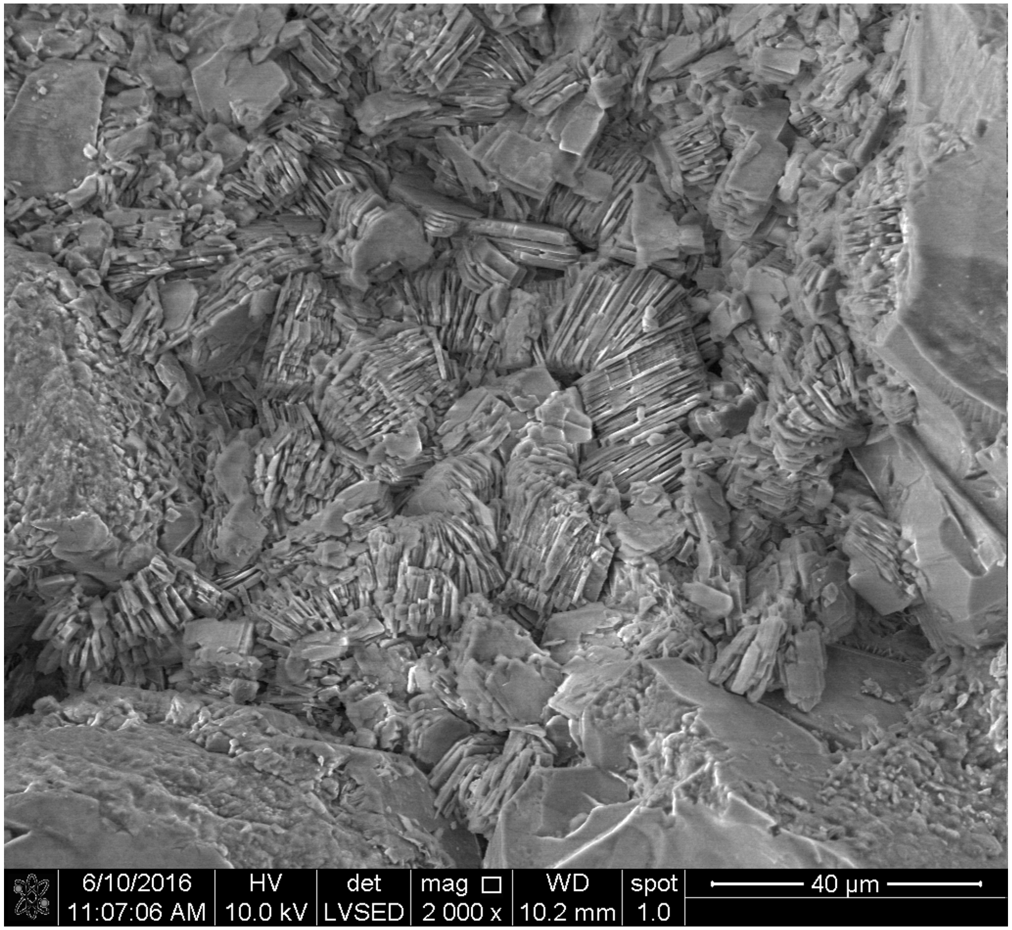
LVSED
mag
2 000 x
WD
10.0 mm
spot
1.0
40 µm

Kaolinite

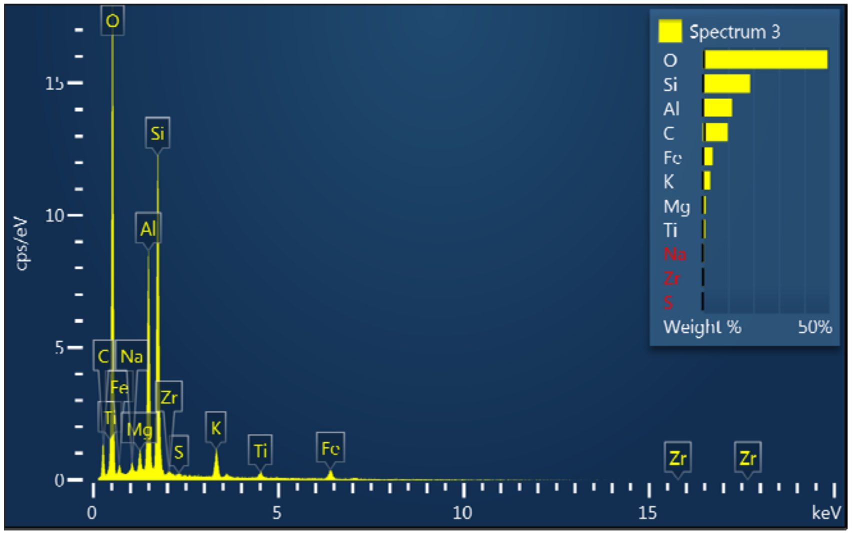


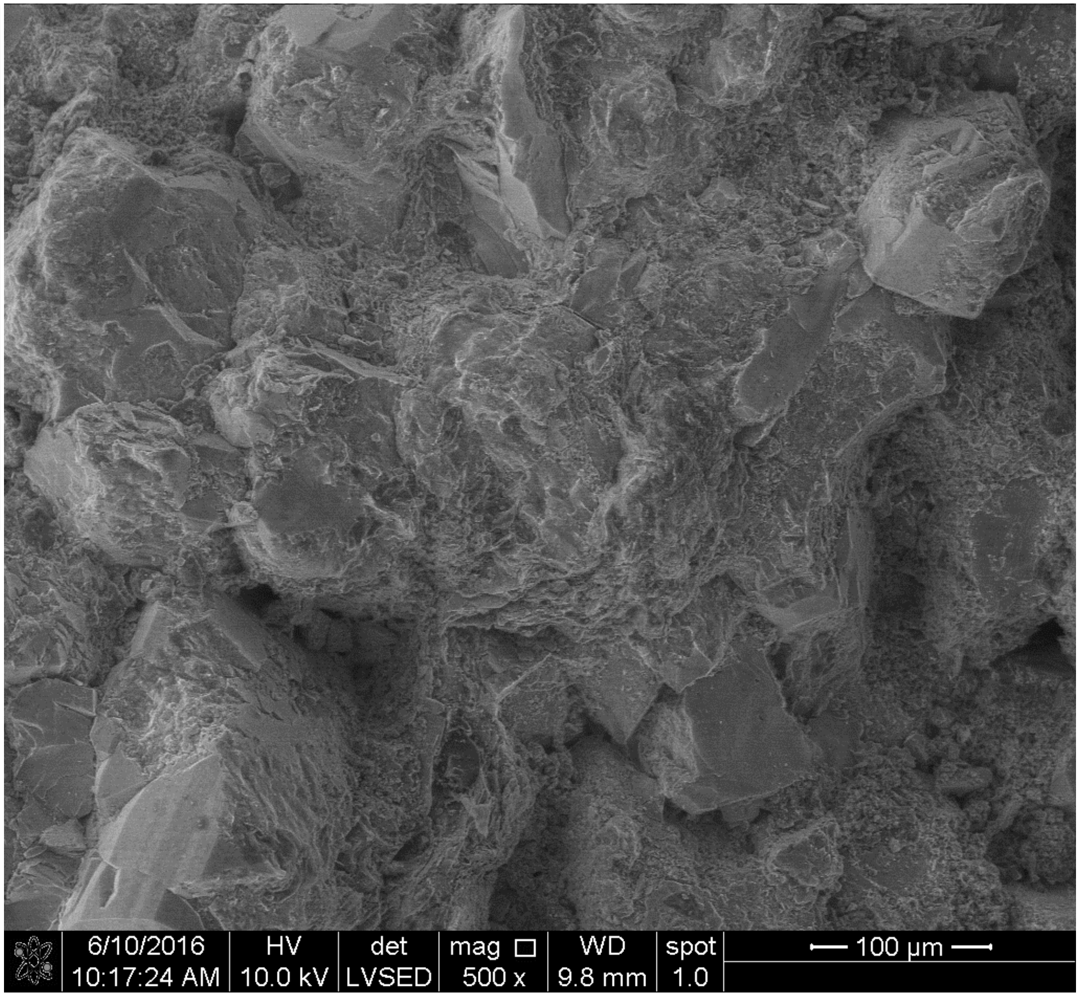
Spectrum 12
O
C
Si
Al
Fe
Weight %
50%
cps/eV
keV



6/10/2016
11:07:06 AM
HV
10.0 kV
det
LVSED
mag
2 000 x
WD
10.2 mm
spot
1.0
40 µm

Illite


Spectrum 3
O
Si
Al
C
Fe
K
Mg
Ti
Na
Zr
S
Weight %
50%
cps/eV
0
5
10
15
keV
O
Si
Al
C
Na
Fe
Zr
Ti
Mg
S
K
Ti
Fe
Zr
Zr


6/10/2016
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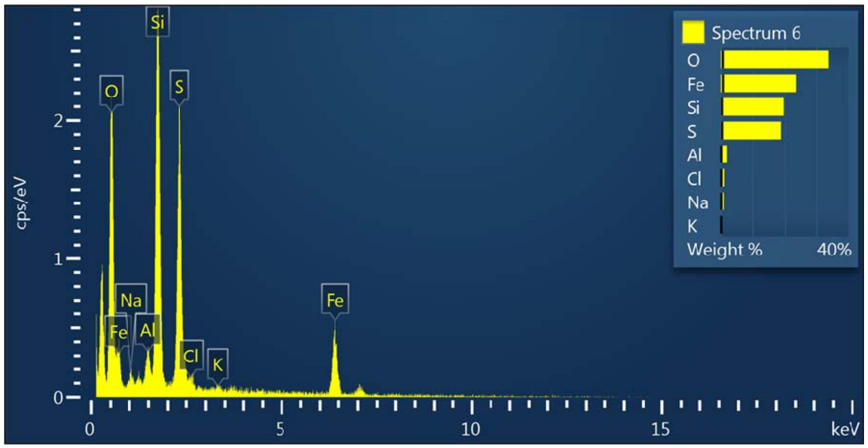
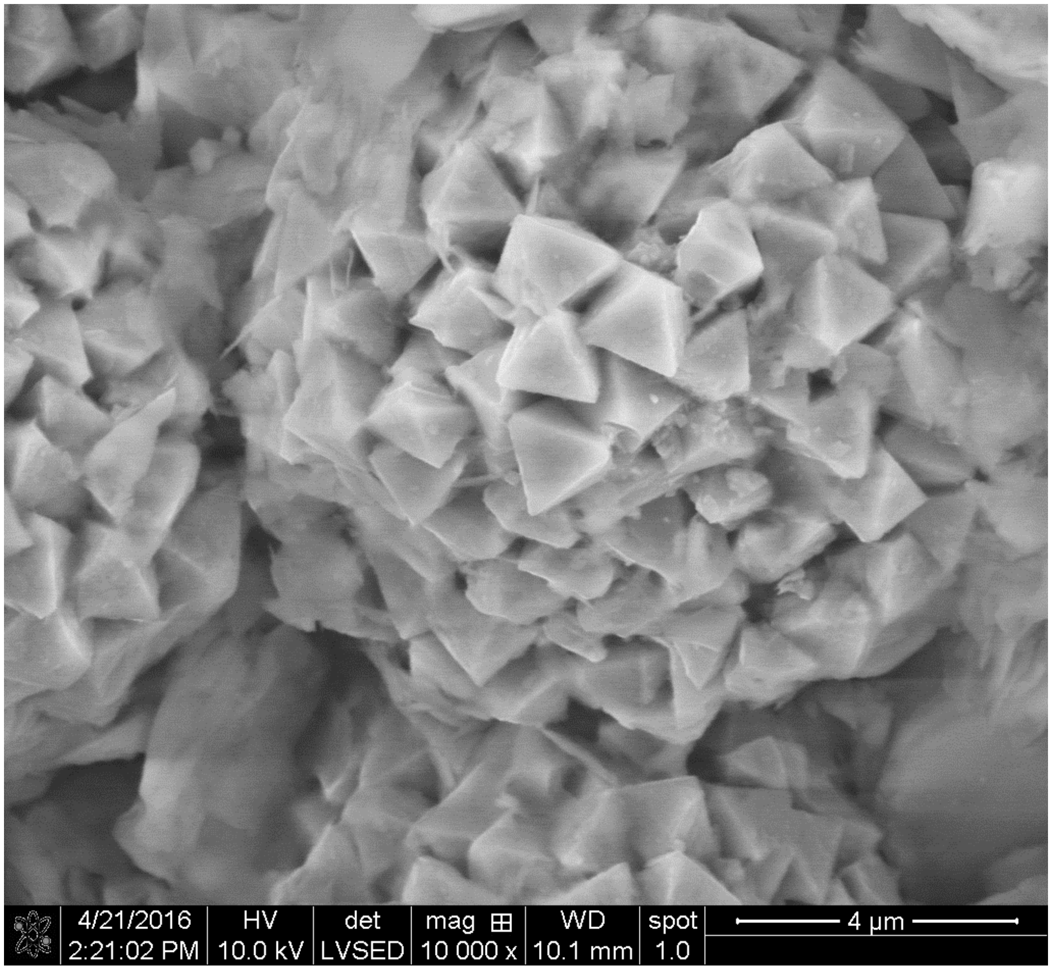
10.0 kV
det
LVSED
mag □
500 x
WD
9.8 mm
spot
1.0
100 μm

Pyrite



Spectrum 6
O
Fe
Si
S
Al
Cl
Na
K
Weight %
40%
cps/eV
keV
0
5
10
15



4/21/2016
2:21:02 PM
HV
10.0 kV
det
LVSED
mag
10 000 x
WD
10.1 mm
spot
1.0
4 µm

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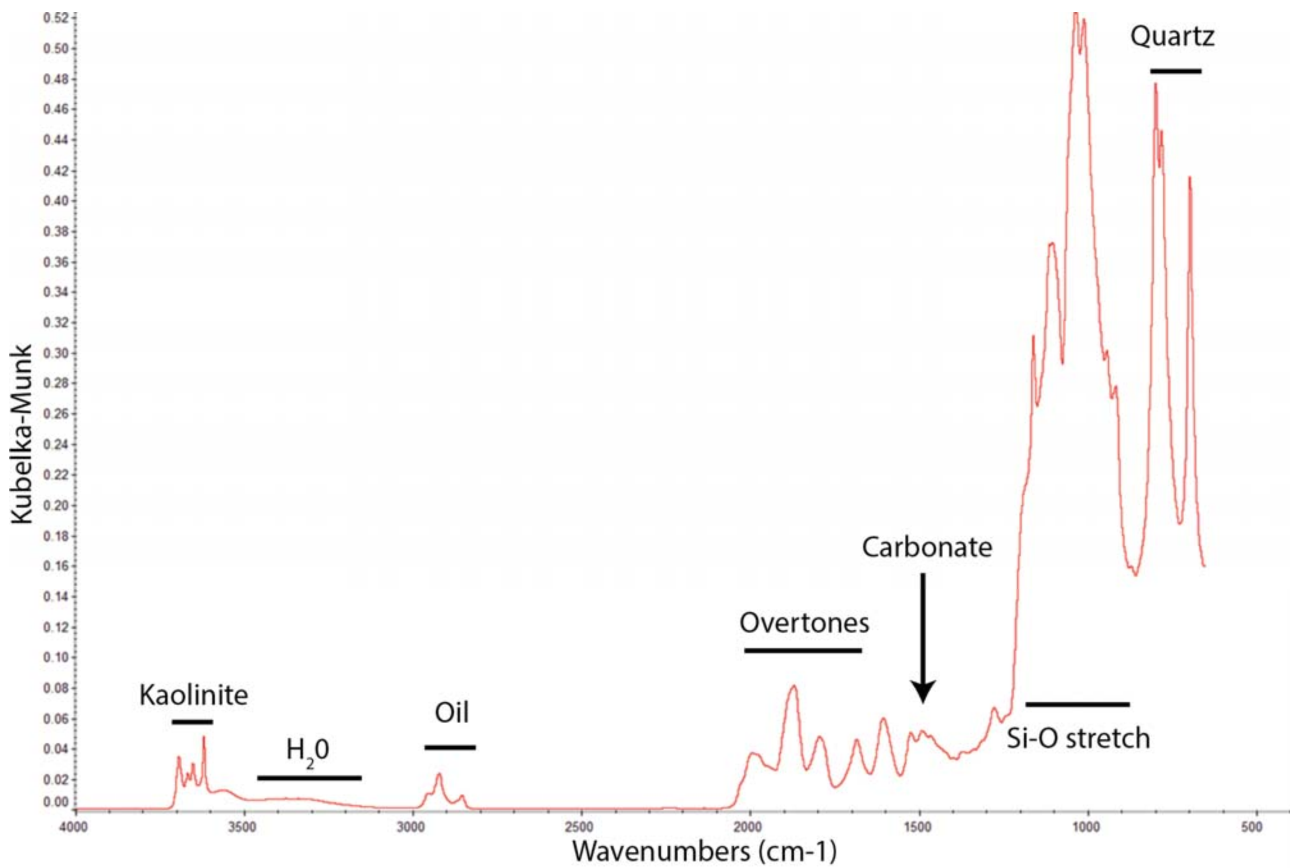
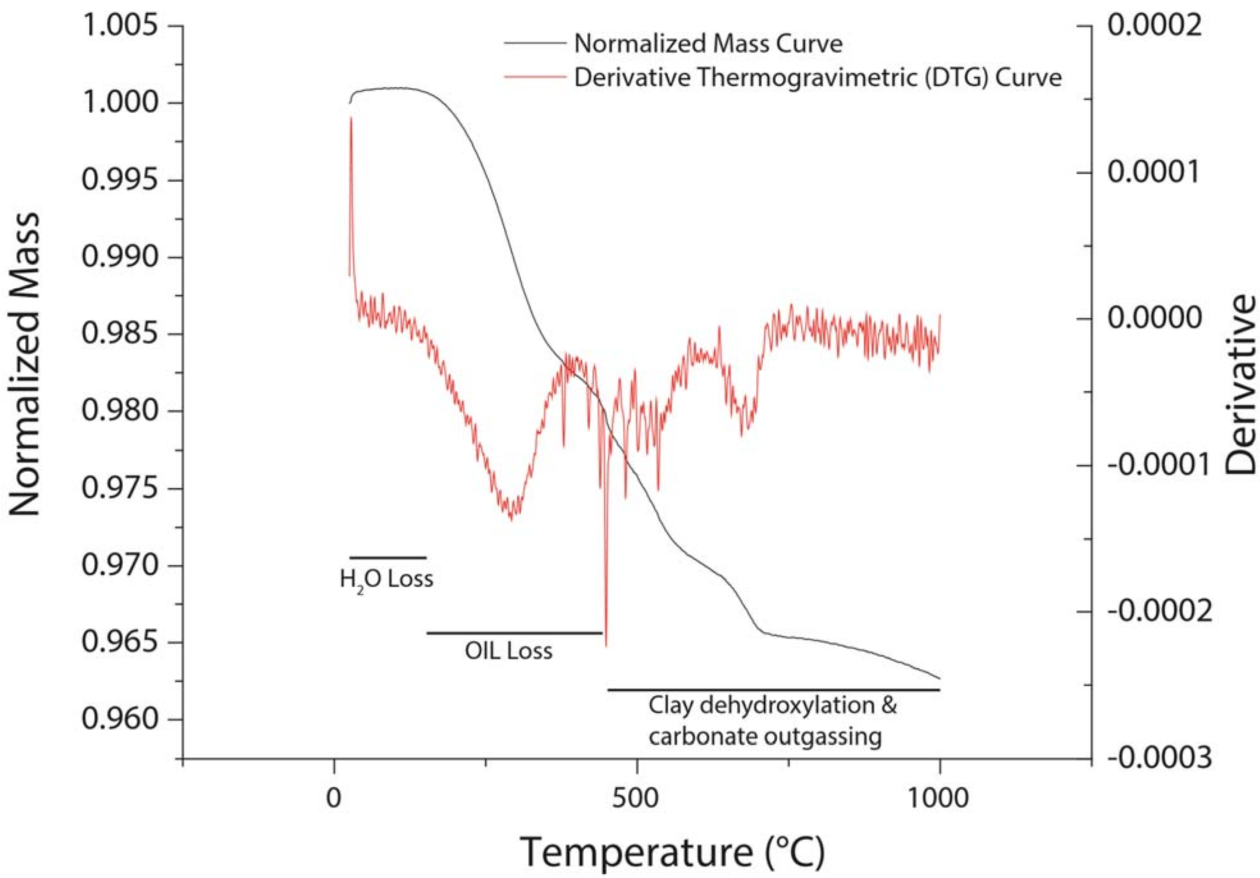
Ongoing Work: Integration of Datasets

- FT-IR: Used to confirm mineralogy but also ID and quantify non-crystalline phases/volatiles

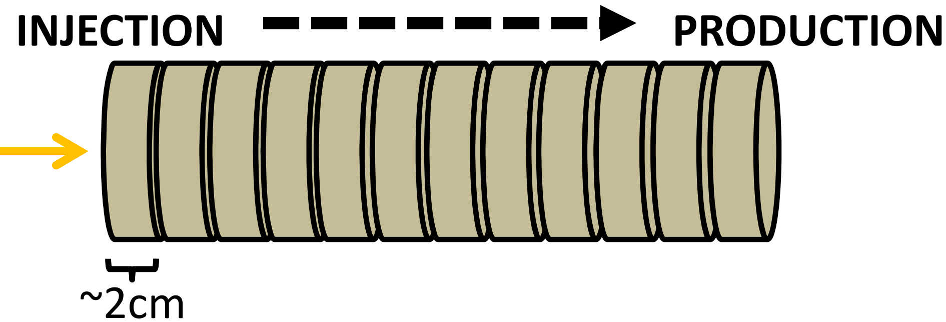


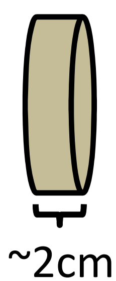
Ongoing Work: Integration of Datasets

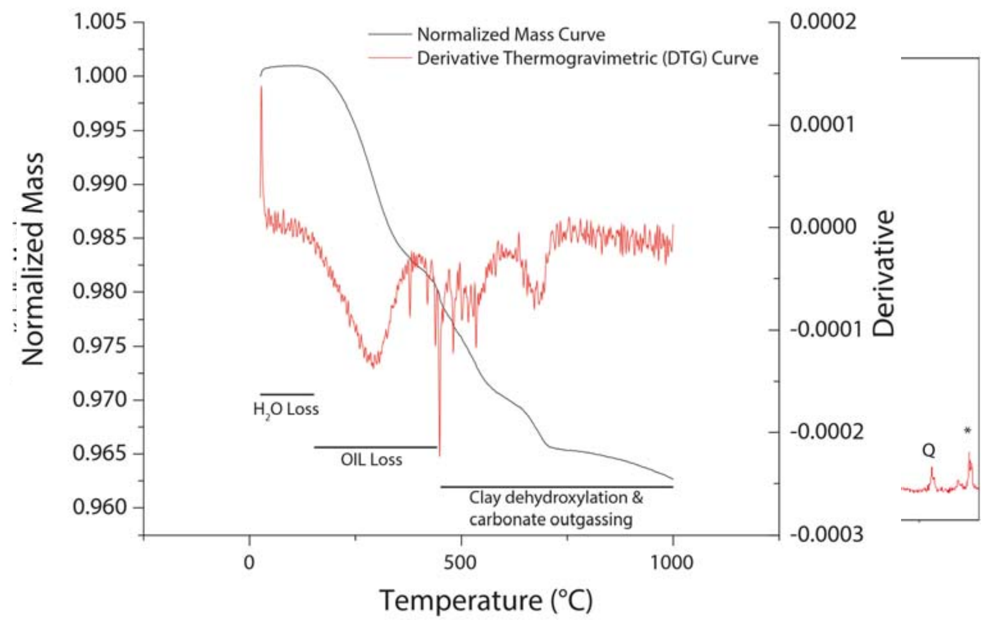
- TGA: Measures volatile mass loss as a function of temperature
  - Useful in determining oil loss and oil saturation



Ongoing Work: Post-Coreflood Forensics





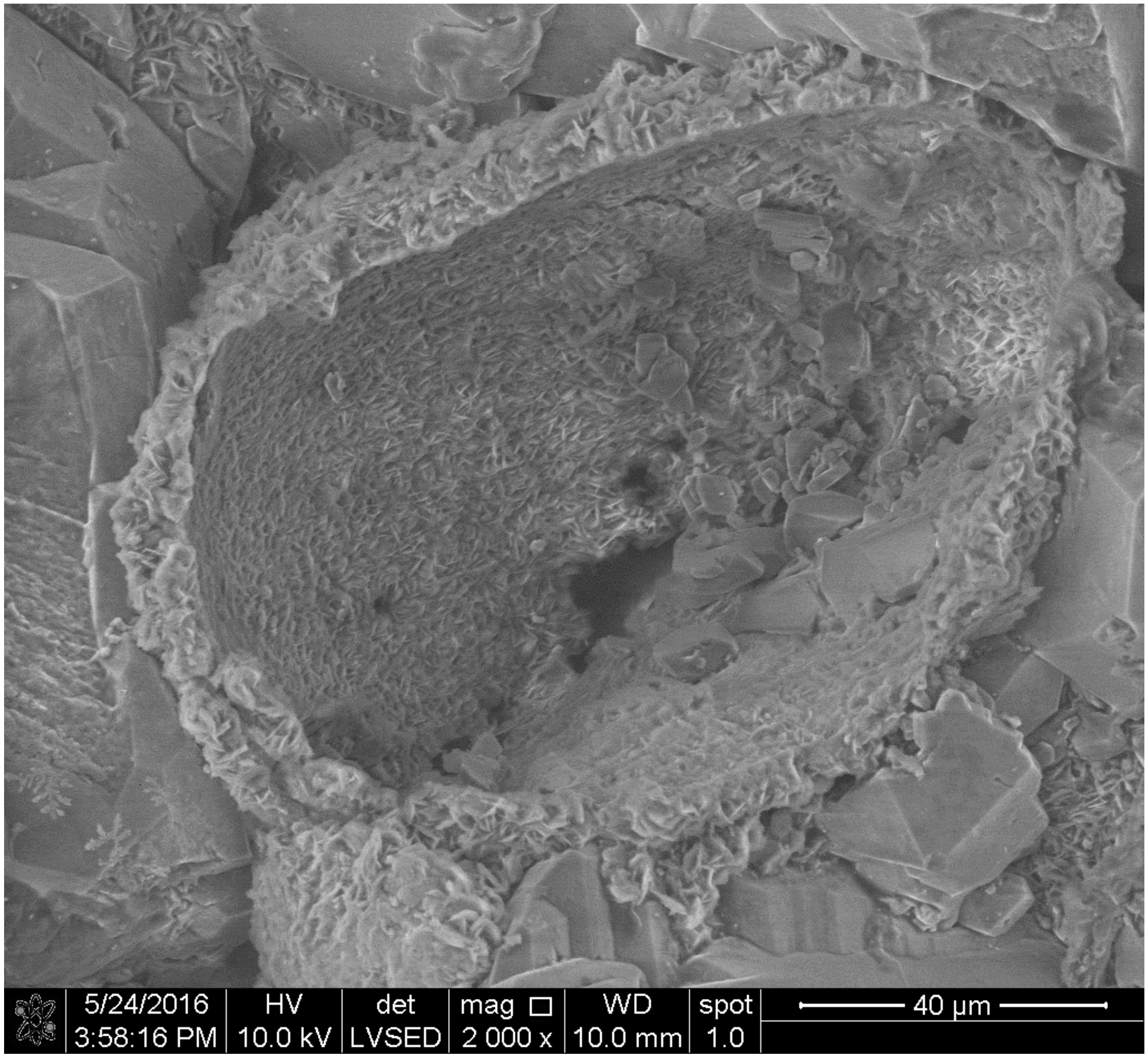


Summary

Combined methodologies in this study…

- 1. Determine the physical and chemical variabilities of Tar Springs Formation as they relate to mineralogy
- 2. Aid in constructing reservoir geometries and connectivity trends that feed into model simulations
- 3. Provide useful post-coreflood analysis data

Questions?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