PROJECT DE-FE0002225:

Actualistic and geochemical modeling of reservoir rock, CO_2 and formation fluid interaction, Citronelle oil field, Alabama

West Virginia University & University of Alabama

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U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the
Infrastructure for CO_2 Storage

August 21-23, 2012

Presentation Outline

- Benefits
- Overview & Project Map
- Reservoir Geochemical Characterization
- Formation Fluid Geochemistry
- Geochemical Modeling
- Summary

Benefit to the Program

- Develop technologies that will support industries' ability to predict CO_2 storage capacity in geologic formations to within ±30%

- Conduct field tests through 2030 to support the development of BPMs for site selection, characterization, site operations, and closure practices.

- Project results maintained on a website:

  https://sites.google.com/site/citronellefluidrockproject/

Benefits Statement

- This project is assessing fluid- rock-supercritical CO_2 interaction through integrated geochemical characterization and modeling of reservoir rock and fluid recovered from the Citronelle field CO_2 injection site.
- Results will determine the potential diagenetic alteration of reservoir rock and formation fluid properties due to injection of supercritical CO_2 into mature conventional hydrocarbon reservoirs.

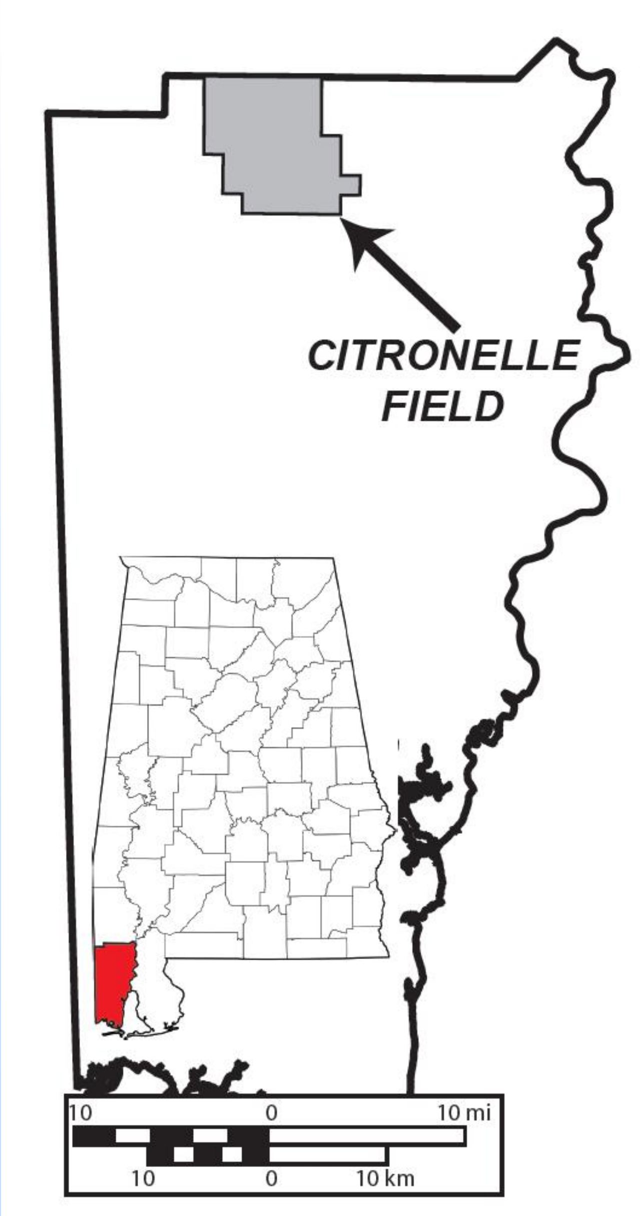
Benefits Statement

- Research methods will use:
  - widely-available and low-cost technologies to assess the geochemical composition of reservoir rock and formation fluids
  - the TOUGH family of reservoir simulation programs to perform reactive transport modeling of fluid-rock interactions.

Project Overview: Goals

- Apply a suite of conventional geochemical analytical techniques to reservoir rock and formation fluid samples
  - *Anticipated benefits:* *improve evaluation of formations and fields sites for development, capacity, containment, risk, and monitoring of CO_2 storage and EOR performance*

Overview: Citronelle Oil Field

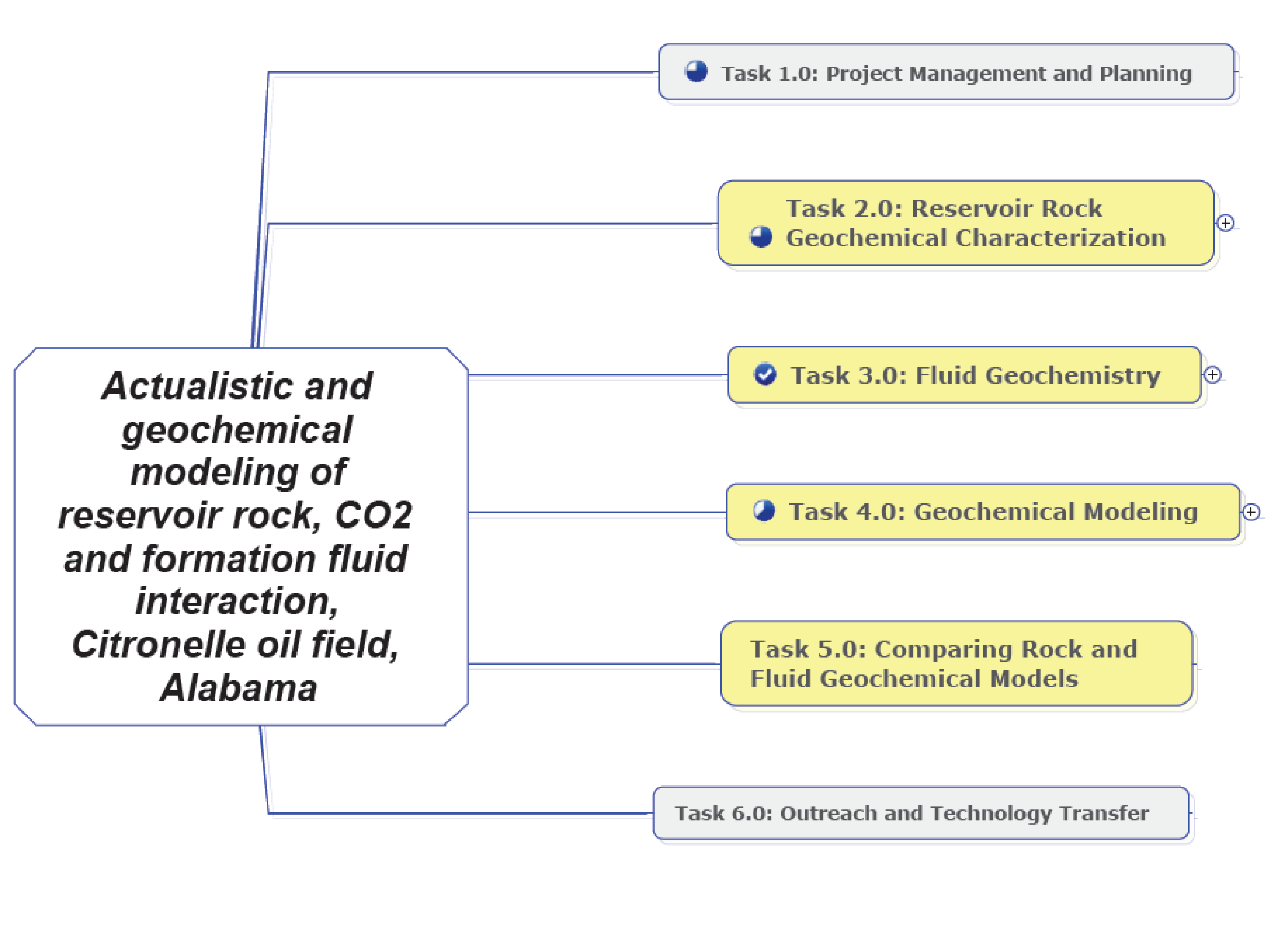


- Located in Mobile County, Alabama
- Oil discovered: 1955
- Mature petroleum field
- Pre-existing hydrocarbon production infrastructure
- Site of on-going DOE project on CO_2-EOR and supercritical CO_2 injection for geological carbon sequestration

Project Overview: Objectives

1. **Reservoir Rock Geochemical Characterization**
   – Sample cores of Rodessa Fm. reservoir sandstone
   – Apply petrographic, bulk rock geochemical and phase-specific analytical techniques
2. **Formation Fluid Geochemical Analysis**
   – Sample formation fluid from wells surrounding CO_2 injector
   – Analyze fluid geochemistry to model mineral phase saturation
3. **Geochemical Modeling**
   – PHREEQC, TOUGH2/ECO2N and TOUGHREACT
4. **Comparing Rock and Geochemical Models**
5. **Outreach and Technology Transfer**

Project Map

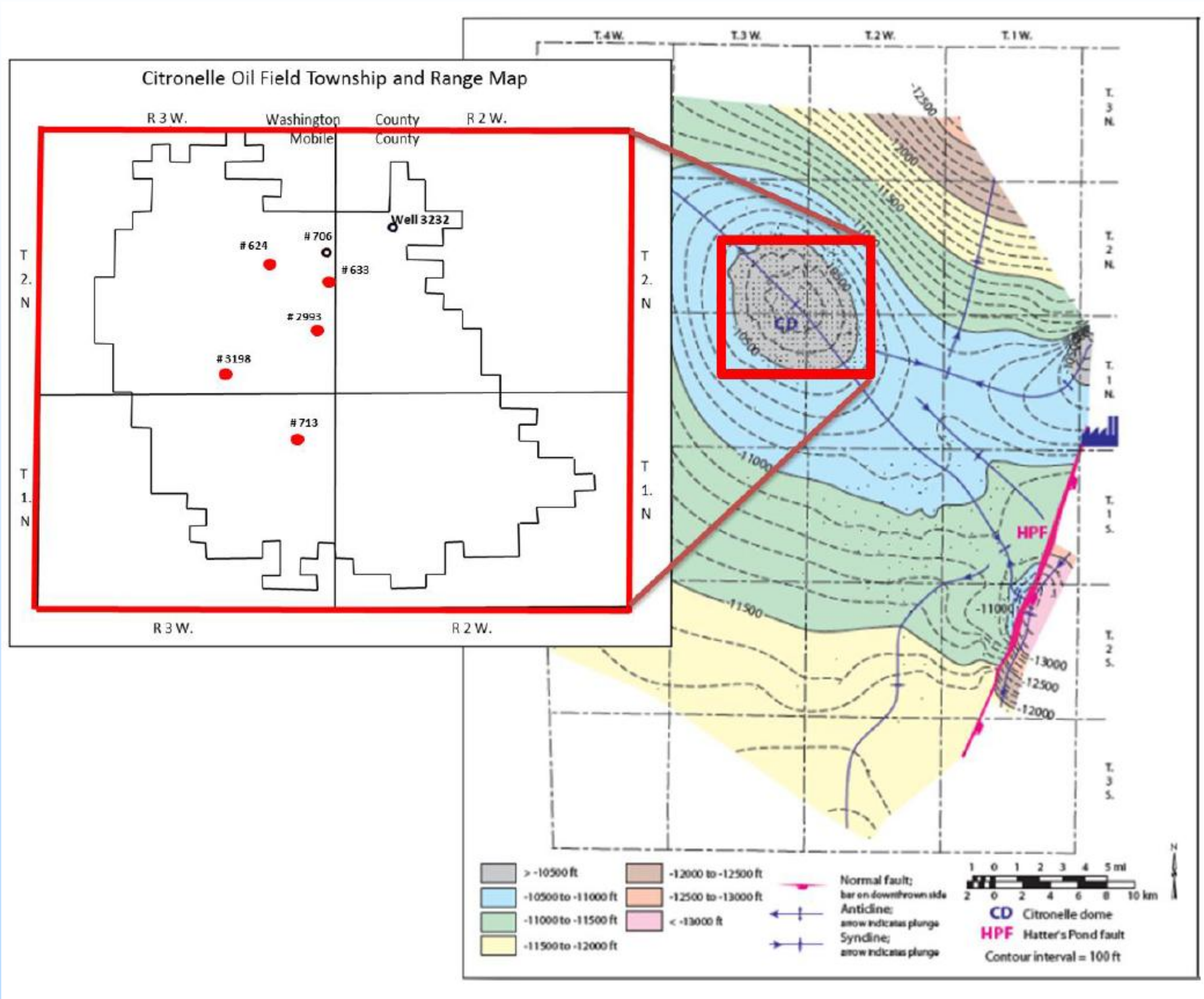


Task 1.0: Project Management and Planning
Task 2.0: Reservoir Rock Geochemical Characterization
Actualistic and geochemical modeling of reservoir rock, CO2 and formation fluid interaction, Citronelle oil field, Alabama
Task 3.0: Fluid Geochemistry
Task 4.0: Geochemical Modeling
Task 5.0: Comparing Rock and Fluid Geochemical Models
Task 6.0: Outreach and Technology Transfer

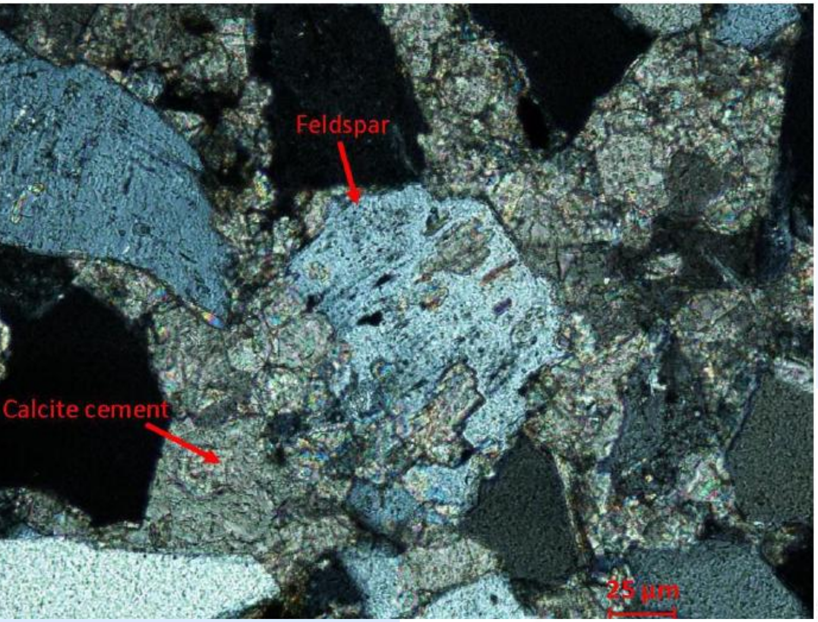
Technical Status: Task 2

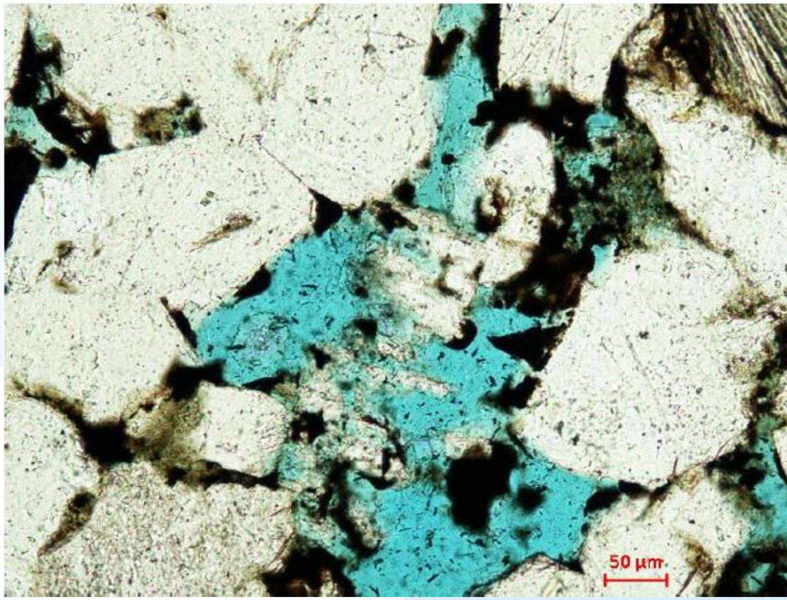
- Reservoir Geochemical Characterization (75% complete)
  - Petrographic analysis of thin-sections
  - Whole-rock geochemical analysis
  - SEM and CL imaging
  - Electron microprobe analysis

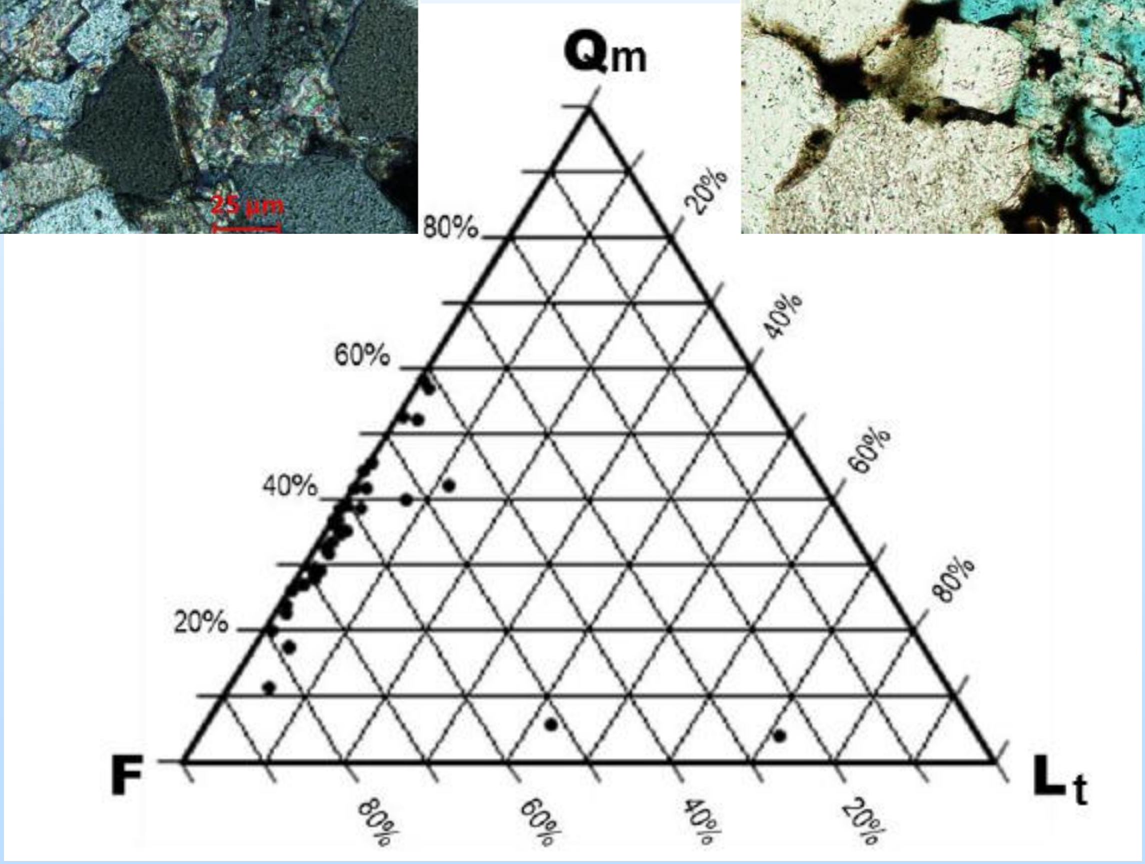
Cored Wells

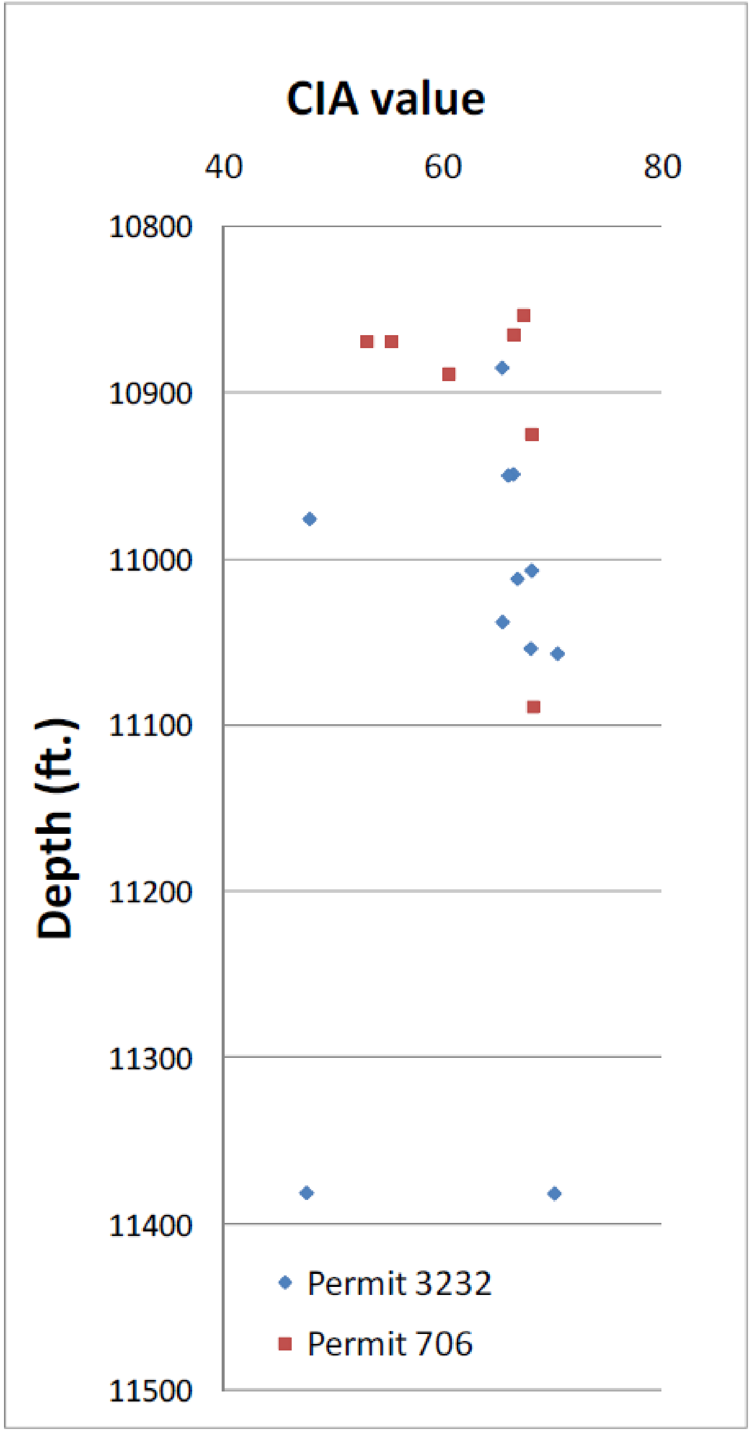

Citronelle Oil Field Township and Range Map
R 3 W.
Washington County
Mobile County
R 2 W.
Well 3232
706
624
633
2993
3198
713
T 2. N
T 1. N
R 3 W.
R 2 W.
T. 4 W.
T. 3 W.
T. 2 W.
T. 1 W.
T. 3 N.
T. 2 N.
T. 1 N.
T. 1 S.
T. 2 S.
T. 3 S.
CD
HPF
-12500
-12000
-11500
-11000
-10500
-13000
12500
-12000
> -10500 ft
-10500 to -11000 ft
-11000 to -11500 ft
-11500 to -12000 ft
-12000 to -12500 ft
-12500 to -13000 ft
< -13000 ft
Normal fault; bar on downthrown side
Anticline; arrow indicates plunge
Syncline; arrow indicates plunge
CD Citronelle dome
HPF Hatter's Pond fault
Contour interval = 100 ft
1 0 1 2 3 4 5 mi
2 0 2 4 6 8 10 km
N

Sandstone Mineralogy







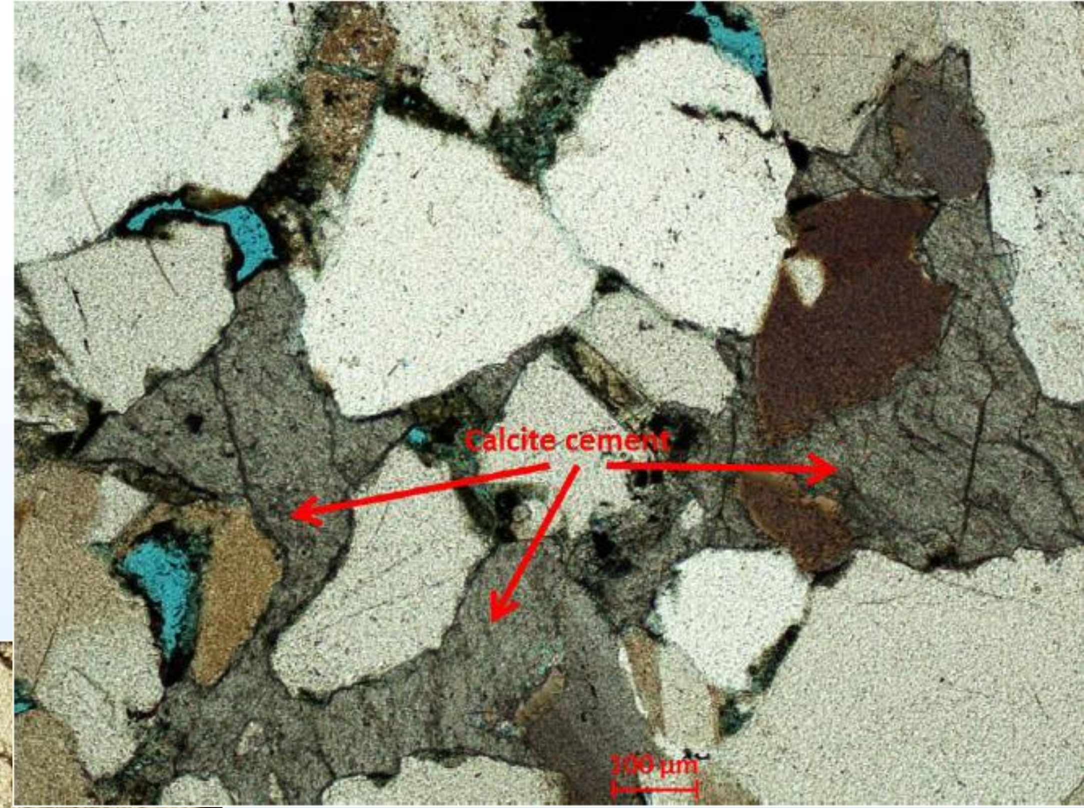


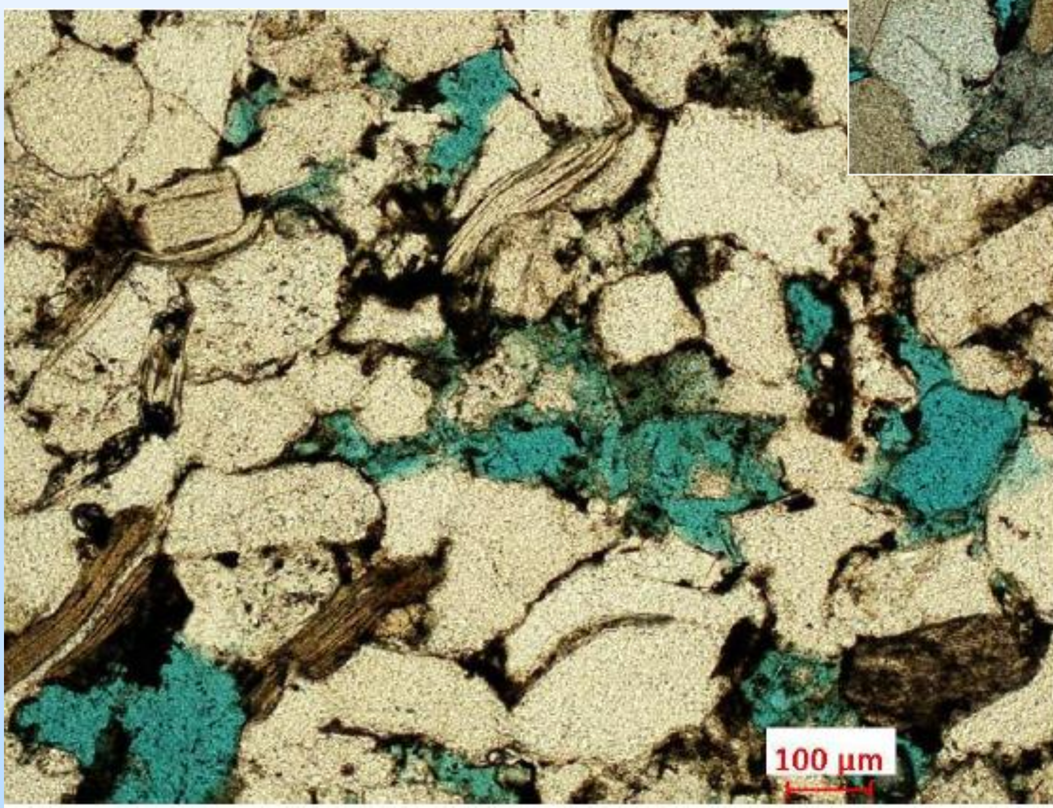
Chemical Alteration Index

$$CIA = \frac{Al_2O_3}{(Al_2O_3 + CaO + Na_2O + K_2O)}$$

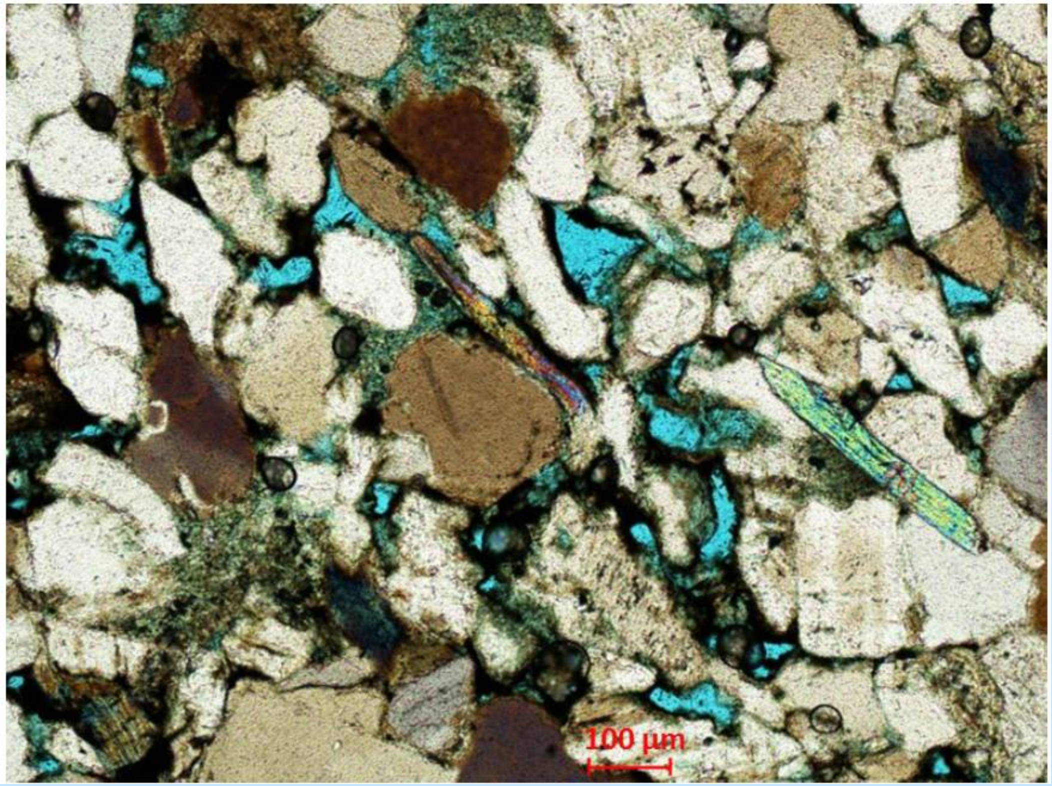
- Low alteration index (~65) reflects high feldspar content
- ≤50 due to extensive calcite cement

Sandstone cementation



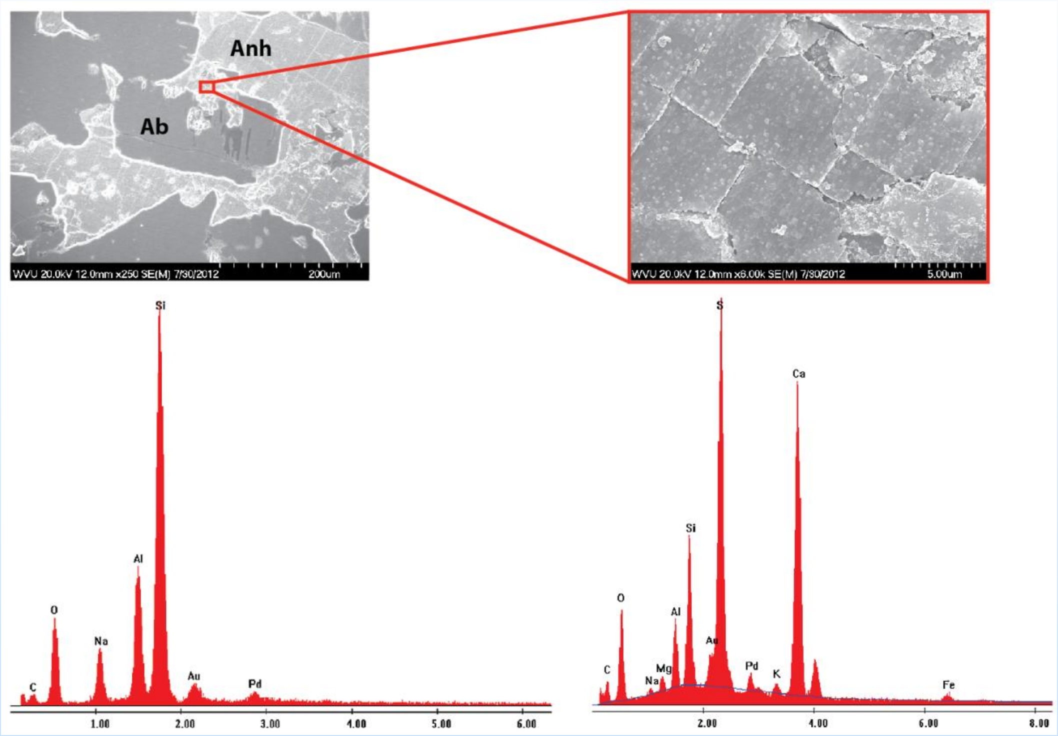


Diagenesis



- Early alteration and cementation of framework grains
  - Secondary porosity development
- Early hydrocarbon charge
- Late stage alteration of authigenic minerals

Diagenesis



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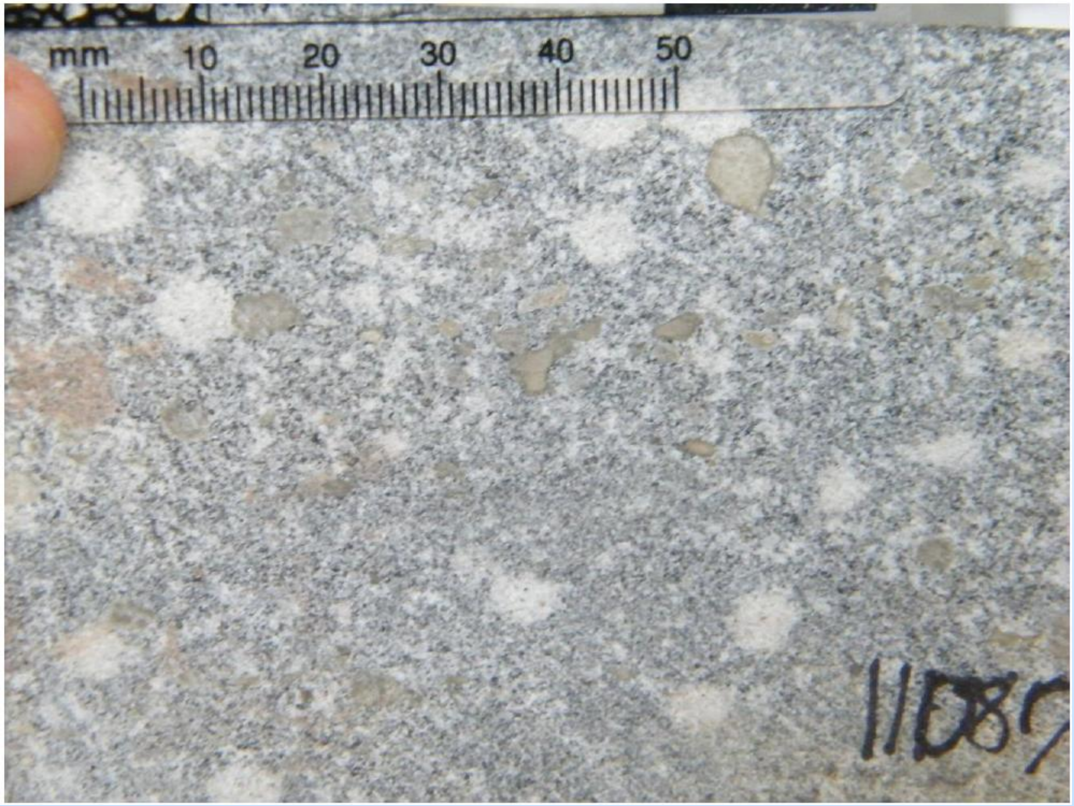
Diagenesis



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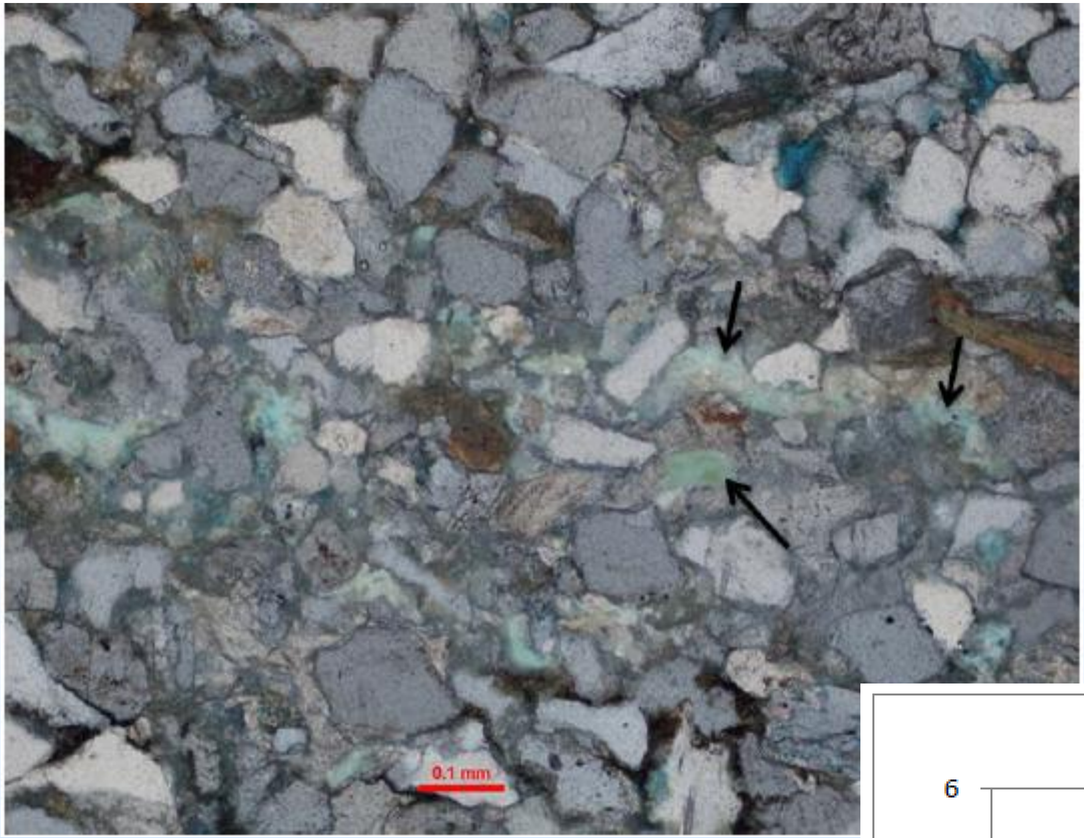
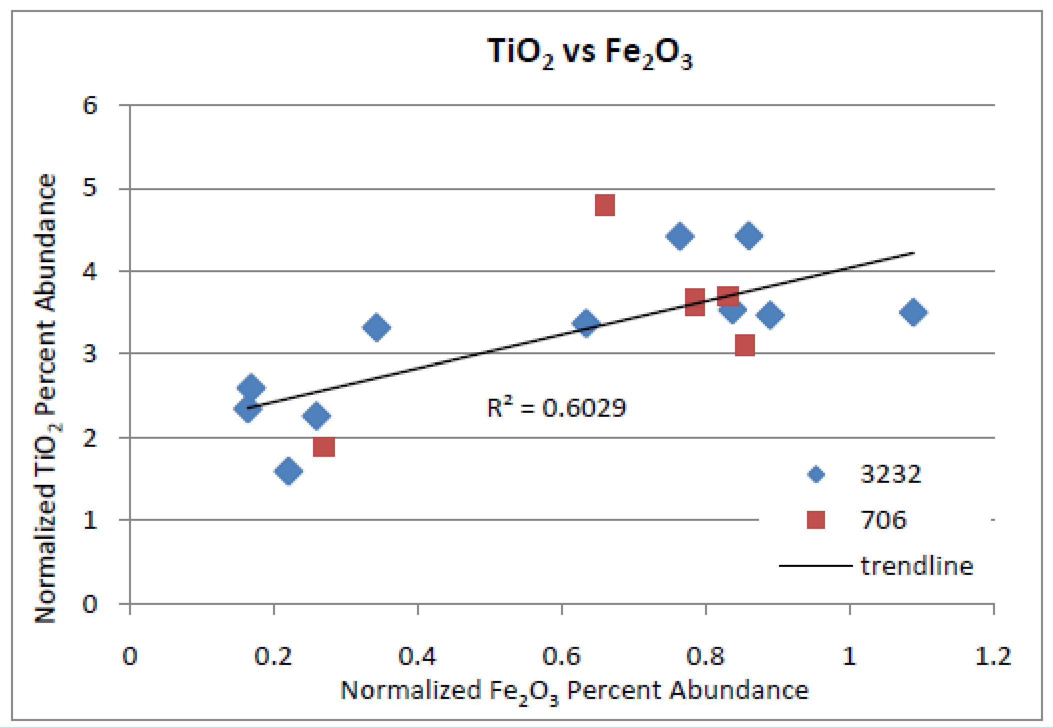
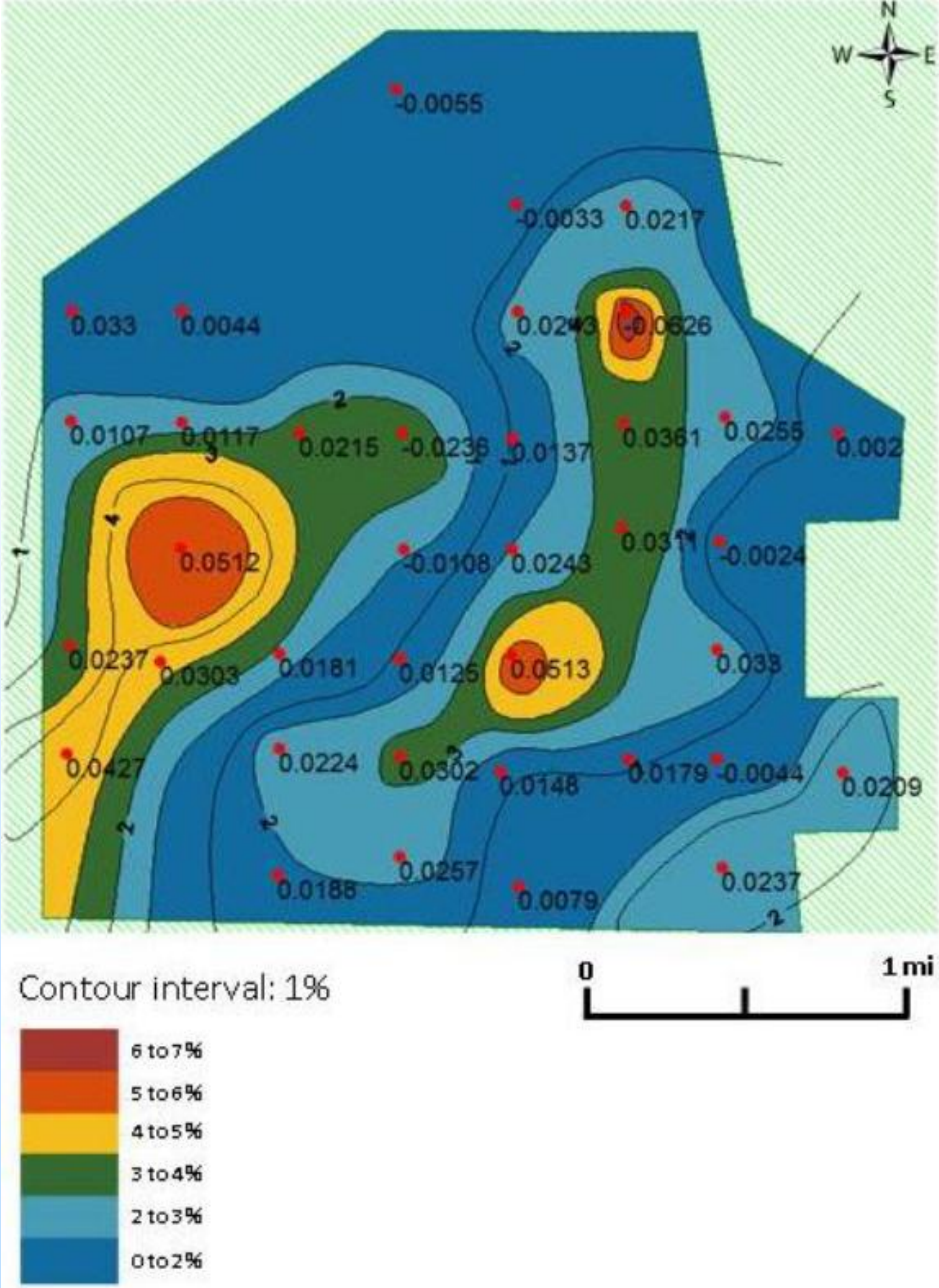
- Late stage alteration of authigenic minerals

Possible record of diagenetic Fe mobilization: Pseudo-rutile







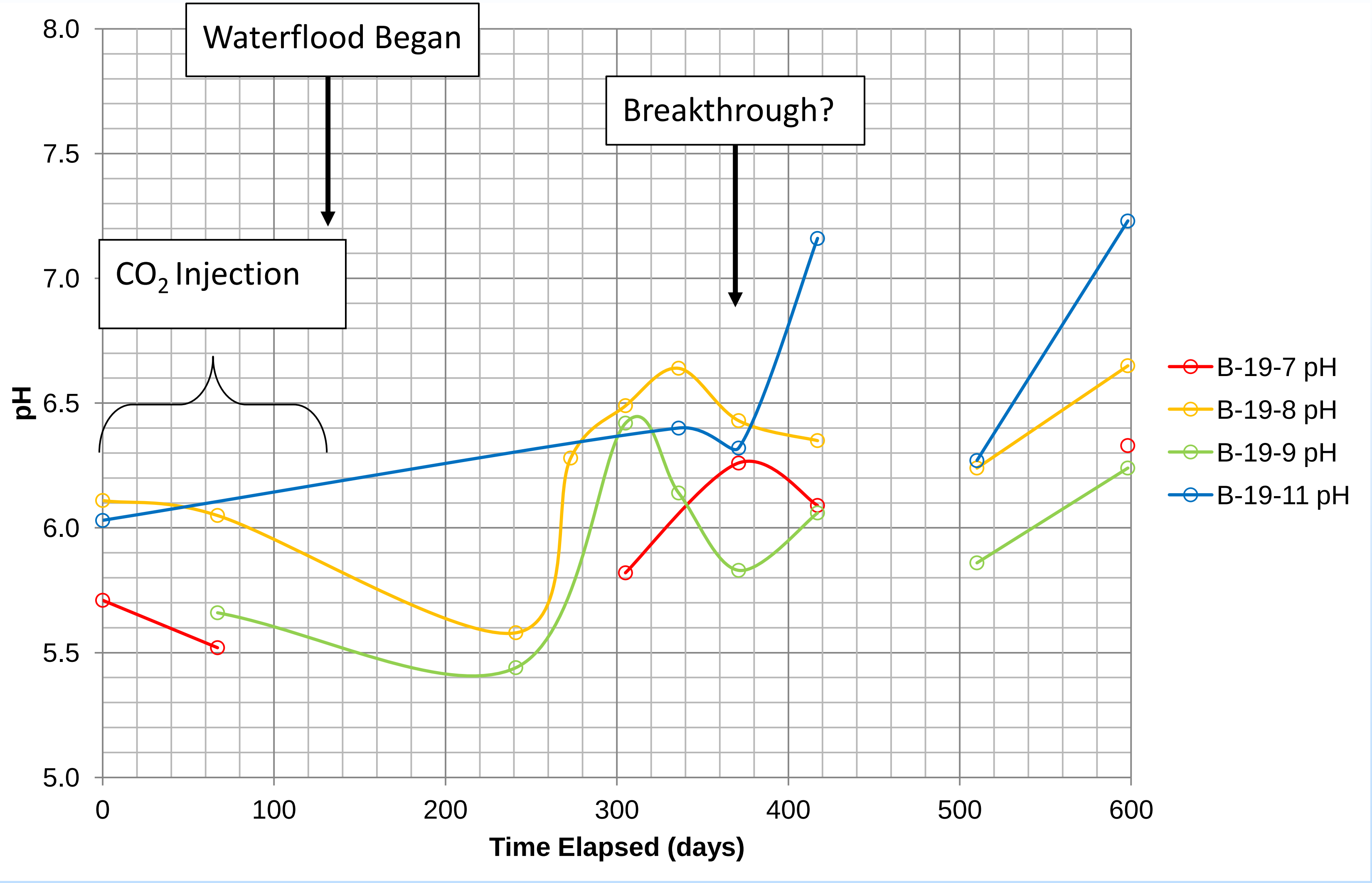
Bulk Porosity Distribution

- Determined through well log analysis
- Suggests variable distribution of porous lithofacies throughout field

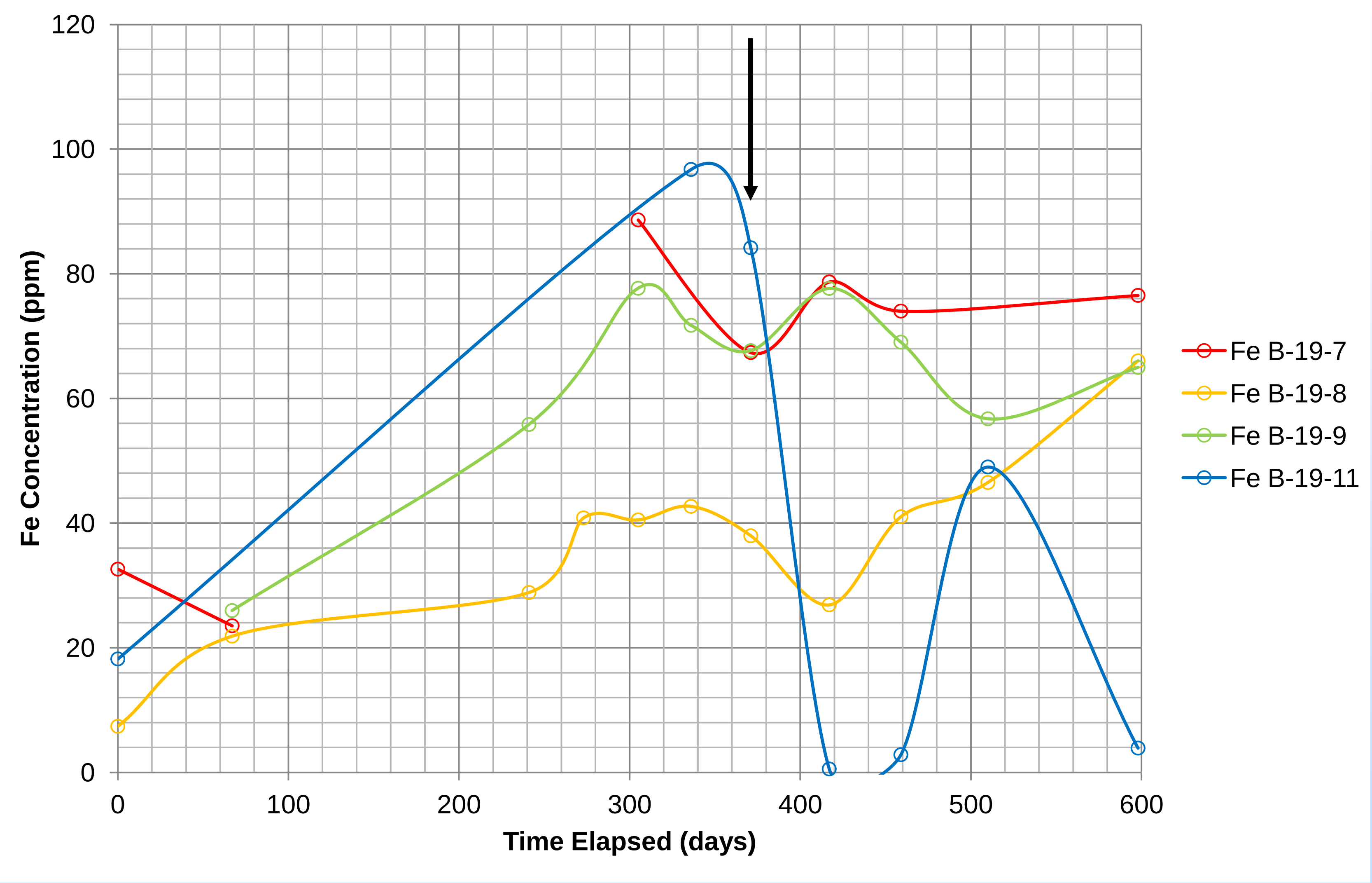
Technical Status: Task 3

- Formation Fluid Geochemistry (100% complete)
  - Sample collection (completed; 6/25/10 – 2/13/12)
  - Sample analysis
    - ICP-OES – Major & minor cation concentrations
    - ICP-OES with matrix matching – Trace element concentrations
    - IC – Major and minor anion concentrations
    - Small volume alkalinity titrations
  - Data compilation and plotting

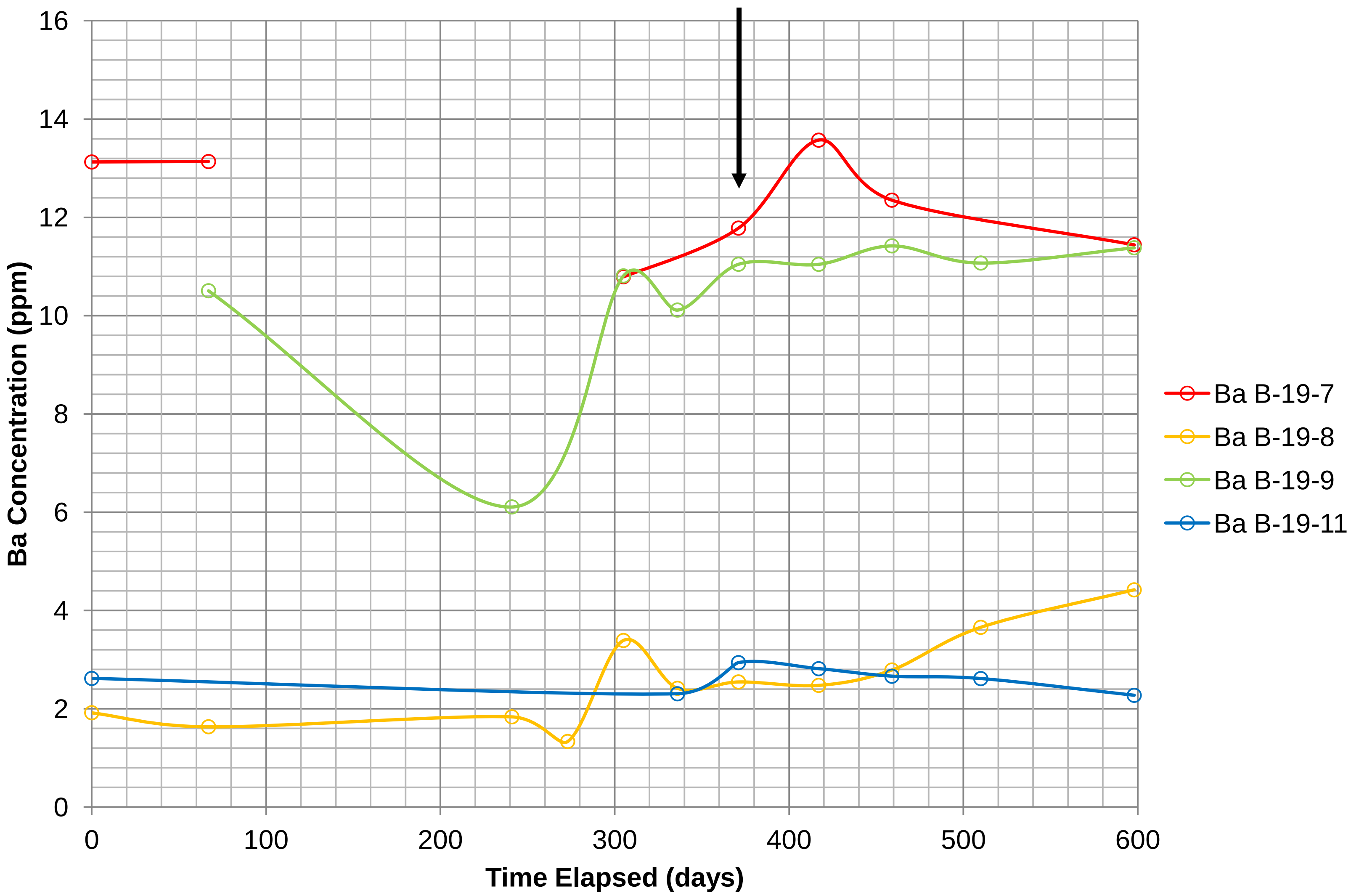
Formation Fluid pH



Formation Fluid Iron



Formation Fluid Ba



Technical Status: Task 4

- PHREEQC Modeling (100% completed)
  - Forward model runs for 25 °C and 110 °C
  - Aqueous speciation and charge balance
  - Mineral saturation index calculations
  - Plots of mineral SI values vs time for each well

Technical Status: Task 4, cont.

- TOUGHREACT Modeling
  - Four 1-D models will describe water flood in a CO_2 saturated rock matrix, from injector to each of the producing wells (B-19-7, B-19-8, B-19-9, and B-19-11).
  - Rock properties have been derived from point count data (S.S. mineralogy wt. %)
  - Primary aqueous species derived from inductively coupled plasma - optical emission spectroscopy (ICP-OES) and ion chromatography (IC) analyses of collected water samples.

- TOUGHREACT Modeling, cont.
  - Mineral phases: Those predicted by PHREEQC forward model calculations at 110 °C.
  - A preliminary 1-D model has been constructed to describe reactive-transport between the injection well and producing well B-19-8.
  - Dissolution and precipitation of mineral phases will be predicted along flow path in Q3.

Summary: Accomplishments to Date

- Detailed analysis of reservoir composition and heterogeneity
- Preliminary model for pre-injection rock diagenesis/interaction with connate waters
- Detailed geochemical analysis of formation fluid
- Preliminary modeling of mineral stability indicies and reactive transport modeling

Summary: Key Findings

– Significant increases in the concentrations of several elements (e.g., Ba, Ca, Fe, Mn, Sr) & pore fluid pH were observed for all wells
  - SI values for minerals present in the reservoir rock do not indicate mineral dissolution reactions that could explain the observed element concentration trends
  - More likely that ion exchange reactions between H+ (sourced from carbonic acid generated by the injection of supercritical CO_2) and cations on the surfaces of reservoir minerals are responsible for the observed element concentration trends.

Summary: Lessons Learned

- Reservoir compositional heterogeneity may play a role in rock alteration
  - Injection profile test of 3232 in January 2012 showed loss in injectivity to water following CO_2 injection in only the upper sand (Sand 14-1)
  - Injectivity to water decreased from ~140 to 20 bbl water/day

Summary: Future Plans

- Assess composition of non-porous seal lithologies for potential interaction with formation fluid
- Longer term sampling of formation fluid to assess kinetics of fluid-rock interactions
- Contrast fluid-rock interaction of injection site with other areas in the Citronelle field

Appendix

Organization Chart

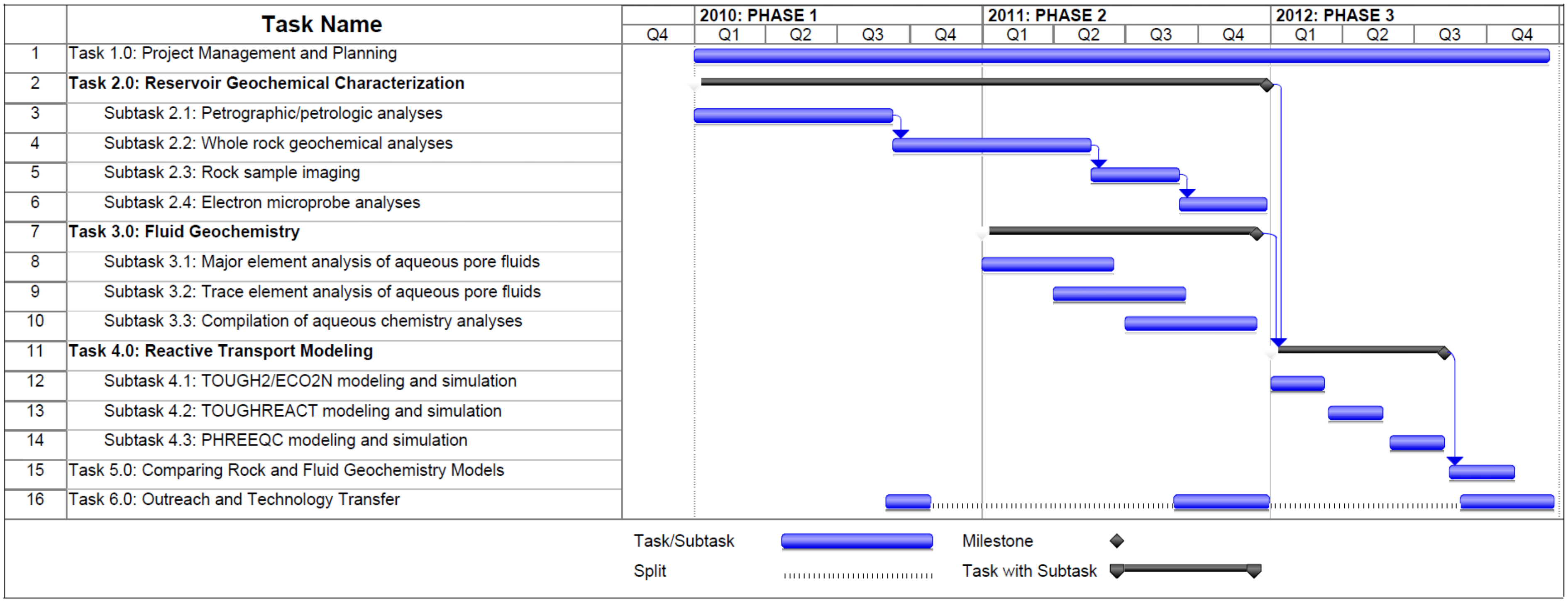
<u>Current:</u>

- West Virginia University
  - Dr. Amy Weislogel
  - George Case (undergraduate research assistant)
  - Asa Mullenex (undergraduate research assistant)
- University of Alabama
  - Dr. Rona Donahoe
  - Ted Donovan (M.S. Student)
  - Andrew Raulerson?

<u>Former:</u>

- West Virginia University
  - Keith Coffindaffer (M.S. Student)
- University of Alabama
  - Brittany Hollon (M.S. Student)
  - Kaitlin Jensen (undergraduate research assistant)
  - Jacob Spry (undergraduate research assistant)
  - Ziming Yue (Ph.D. Student – hourly)
  - Jordan Williams (undergraduate research assistant t)

Gantt Chart



Task Name
2010: PHASE 1
2011: PHASE 2
2012: PHASE 3
Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4
1 Task 1.0: Project Management and Planning
2 Task 2.0: Reservoir Geochemical Characterization
3 Subtask 2.1: Petrographic/petrologic analyses
4 Subtask 2.2: Whole rock geochemical analyses
5 Subtask 2.3: Rock sample imaging
6 Subtask 2.4: Electron microprobe analyses
7 Task 3.0: Fluid Geochemistry
8 Subtask 3.1: Major element analysis of aqueous pore fluids
9 Subtask 3.2: Trace element analysis of aqueous pore fluids
10 Subtask 3.3: Compilation of aqueous chemistry analyses
11 Task 4.0: Reactive Transport Modeling
12 Subtask 4.1: TOUGH2/ECO2N modeling and simulation
13 Subtask 4.2: TOUGHREACT modeling and simulation
14 Subtask 4.3: PHREEQC modeling and simulation
15 Task 5.0: Comparing Rock and Fluid Geochemistry Models
16 Task 6.0: Outreach and Technology Transfer
Task/Subtask
Milestone
Split
Task with Subtask

Bibliography

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- Coffindaffer, K., Case, G., and Weislogel, A.L., 2011, Reservoir Porosity Characterization for a Carbon Sequestration Target: Citronelle Field, Alabama: AAPG Search and Discovery Article #90131©2011 AAPG Eastern Section Meeting, Washington, DC, USA, 25-27 September 2011.
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- Weislogel, A.L., Hollon, B.E., Schwartz, J.J., and Coffindaffer, K., 2011, Geochemical Characterization of the Donovan Sand Reservoir for CO2 Sequestration, Citronelle Oil Field, Southwest Alabama: AAPG Search and Discovery, AAPG Annual Convention and Exhibition, April 10-13, 2011, Houston, Texas.