Field Laboratory for Emerging Stacked Unconventional Plays (ESUP)

PI: NINO RIPEPI

CO-PIS: MICHAEL KARMIS, CHENG CHEN, ELLEN GILLILAND, BAHAREH NOJABAEI

VIRGINIA TECH

Objective, Project Team and Duration

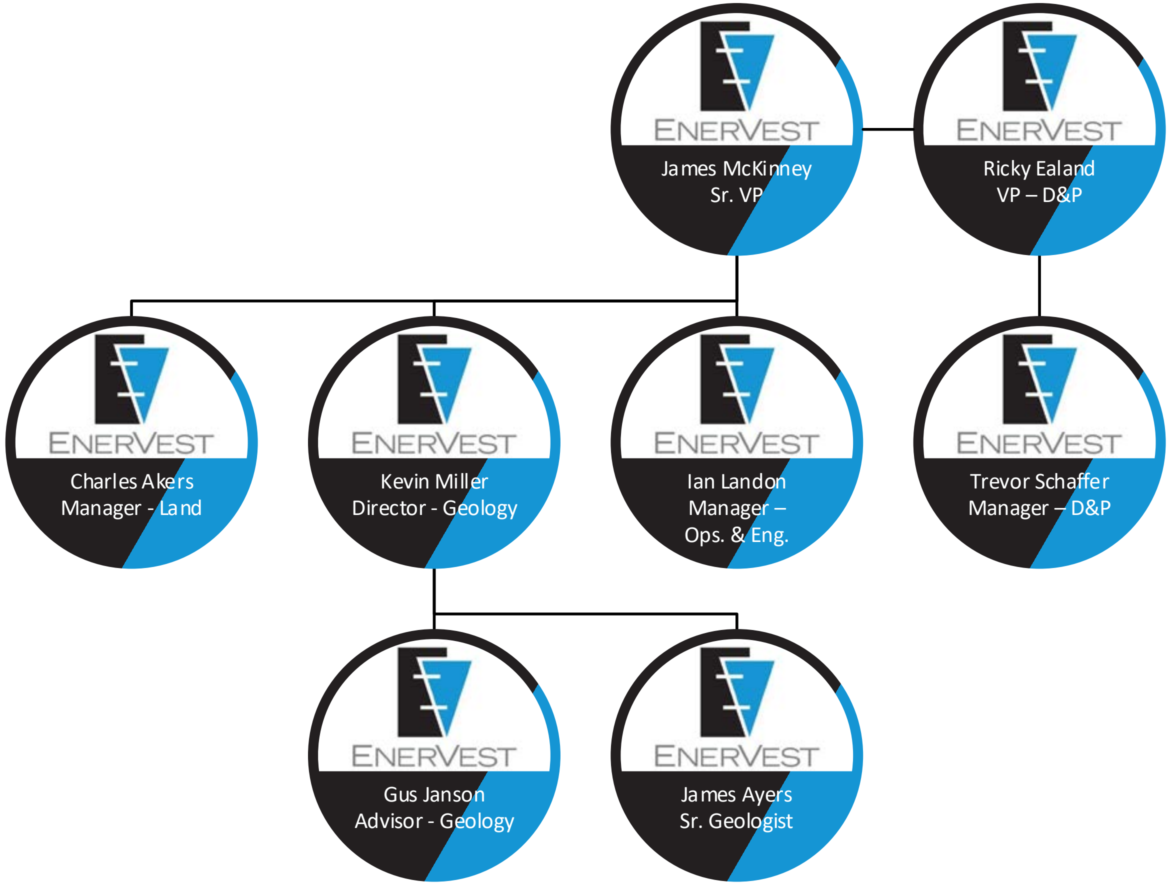
- Objective:
  - Investigate and characterize the resource potential for multi-play production of emerging unconventional reservoirs in Central Appalachia.
- Project Team
  - Virginia Tech
  - Virginia Center for Coal & Energy Research
  - EnerVest Operating, LLC
  - Pashin Geoscience, LLC
  - Gerald R. Hill, PhD, Inc.
- Funding: $11.1 million ($8 million federal)
  - Cost-Share:
    - EnerVest - Lower Huron horizontal well ($2.2 million), plus personnel time (100K+)
    - Virginia Tech - personnel time (800K+)
- Duration
  - April 1, 2018 – March 31, 2023 (5 years)

Objective and Goals

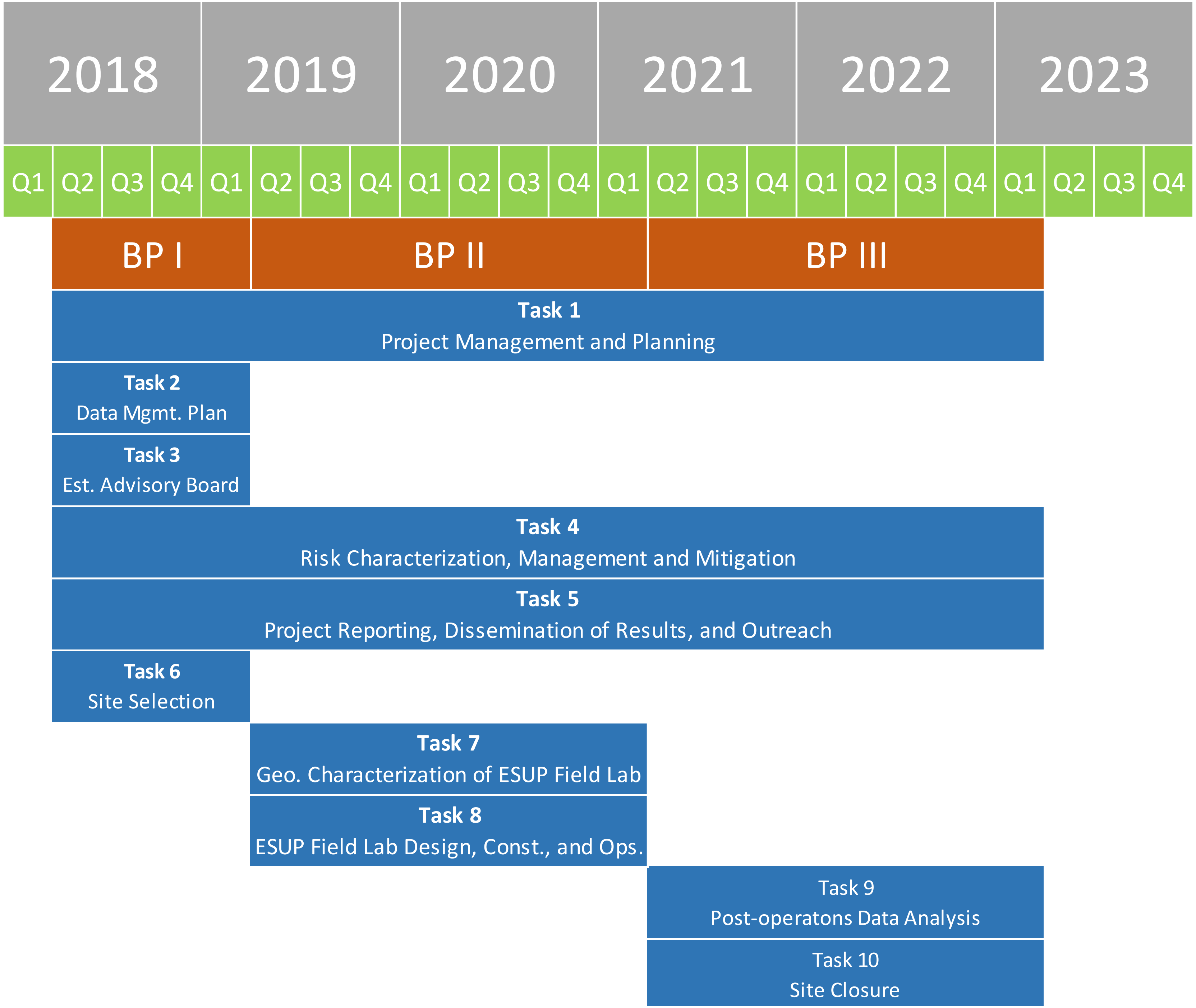
- Objectives:
  - Investigate and characterize the resource potential for multi-play production of emerging unconventional reservoirs in Central Appalachia.
  - **Goal 1:** Drill and selectively core a deep vertical stratigraphic test well up to 15,000 feet to basement through Conasauga-Rome Petroleum System
  - **Goal 2:** Drill at least one multi-stage lateral well in the Lower Huron Shale for completion using non-aqueous fracturing techniques, such as CO_2 or high rate N_2 with proppant
  - Laboratory analysis, reservoir simulation, and monitoring observations will be integrated.
  - An assessment will be made of the multi-play resource potential and a recommended strategy advanced for prudent development that considers regional **environmental** and **socioeconomic impacts**.

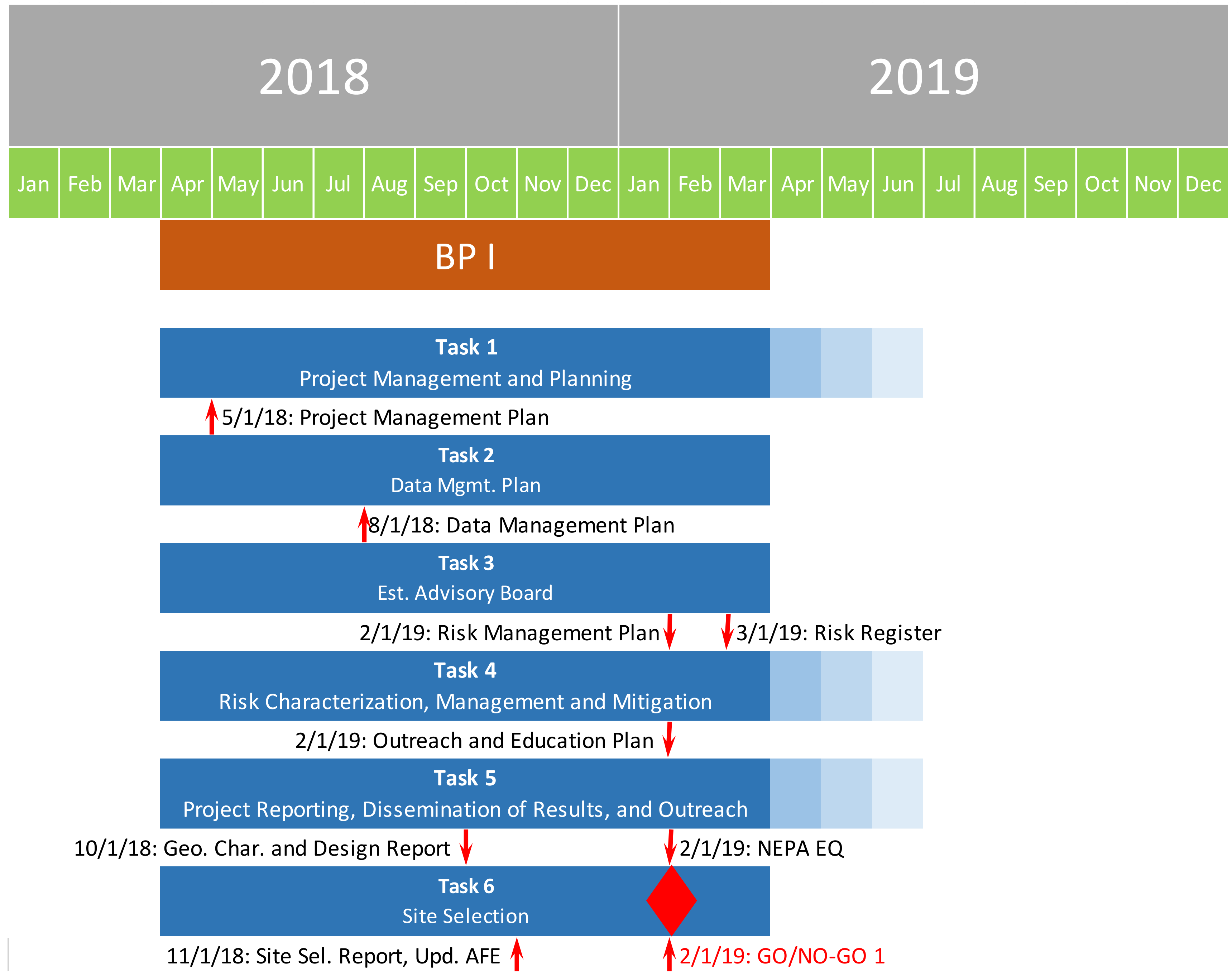
Project Team

Project Team

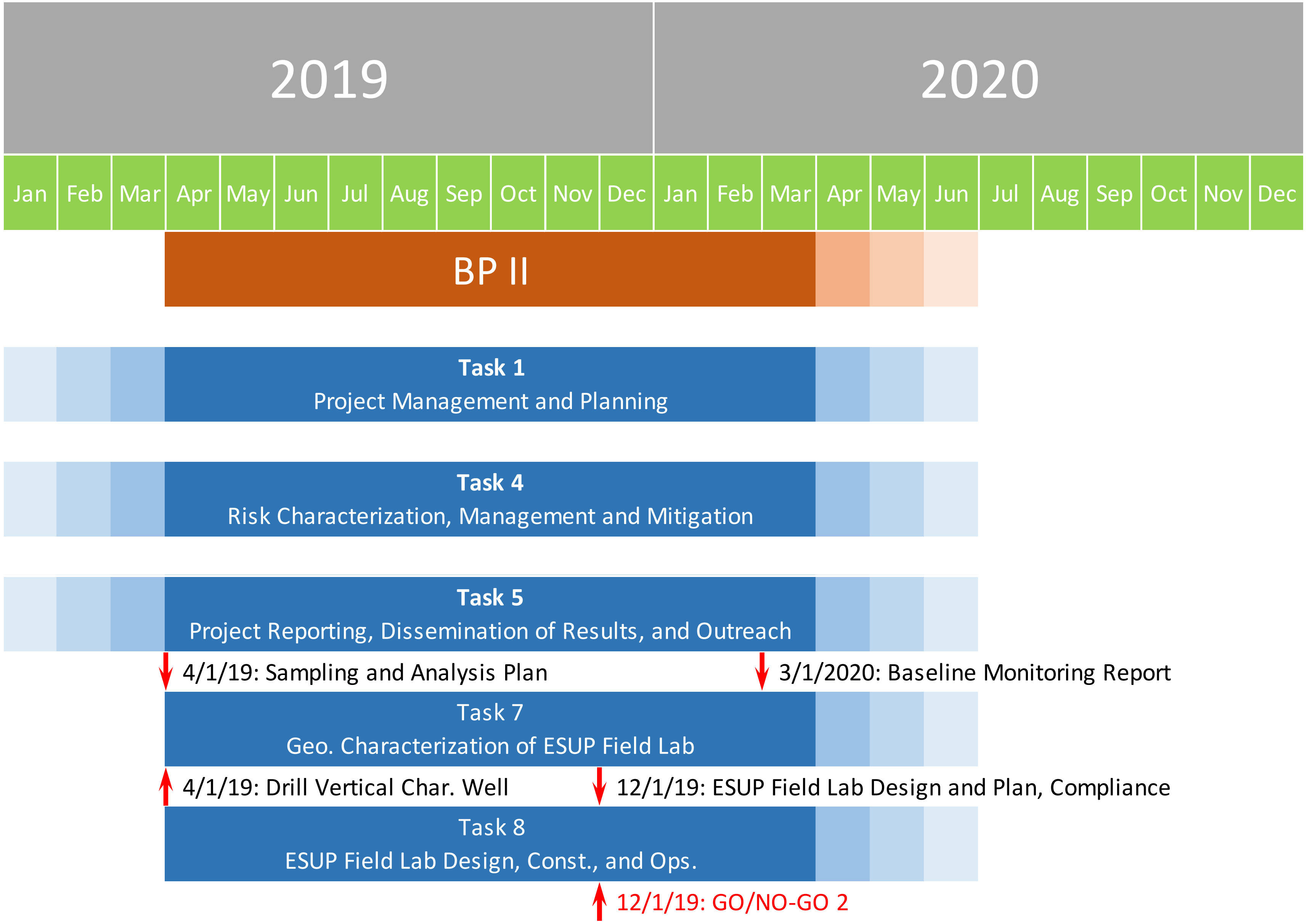


VIRGINIA TECH

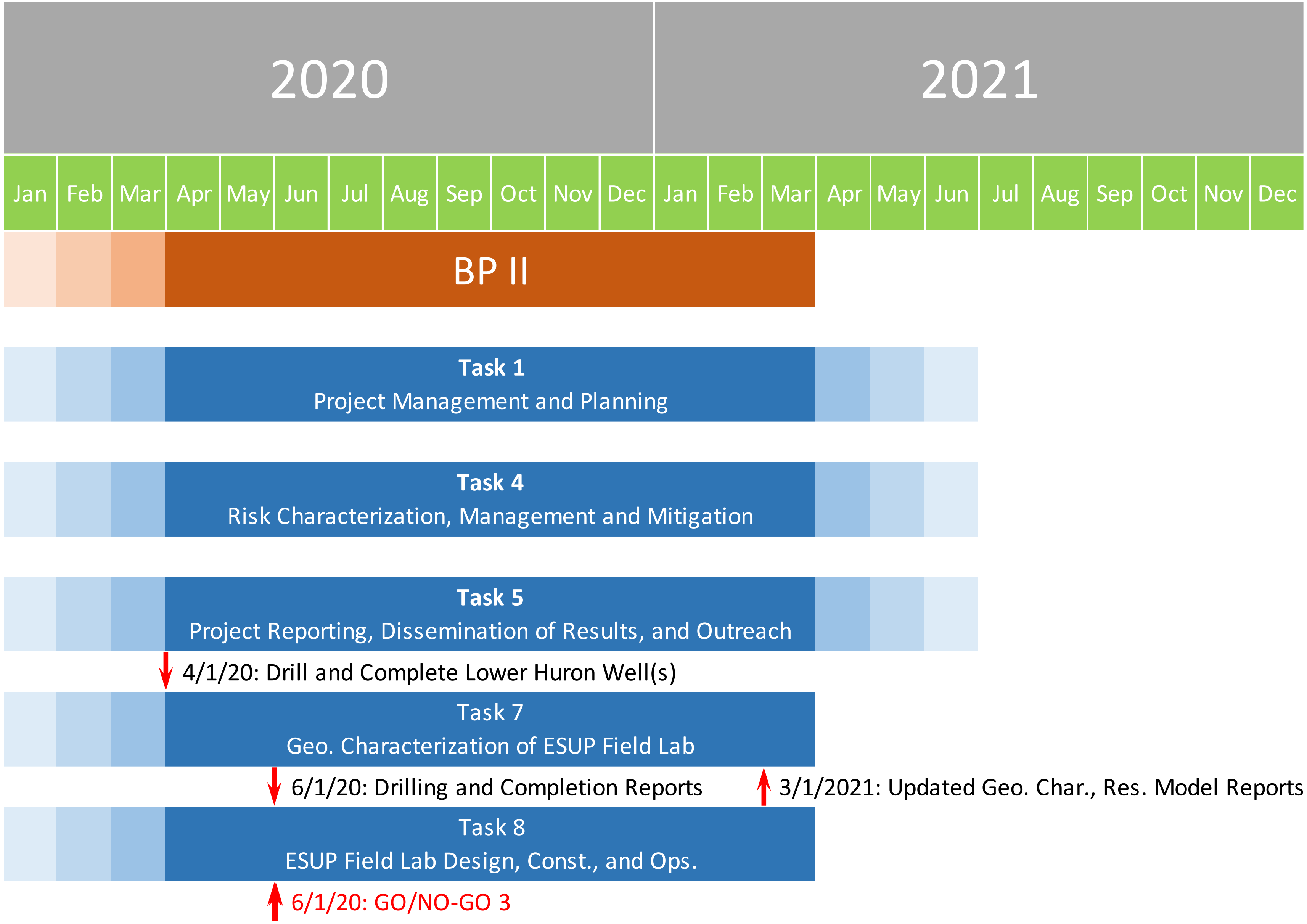

2018
2019
2020
2021
2022
2023
Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4
BP I
BP II
BP III
Task 1
Project Management and Planning
Task 2
Data Mgmt. Plan
Task 3
Est. Advisory Board
Task 4
Risk Characterization, Management and Mitigation
Task 5
Project Reporting, Dissemination of Results, and Outreach
Task 6
Site Selection
Task 7
Geo. Characterization of ESUP Field Lab
Task 8
ESUP Field Lab Design, Const., and Ops.
Task 9
Post-operatons Data Analysis
Task 10
Site Closure

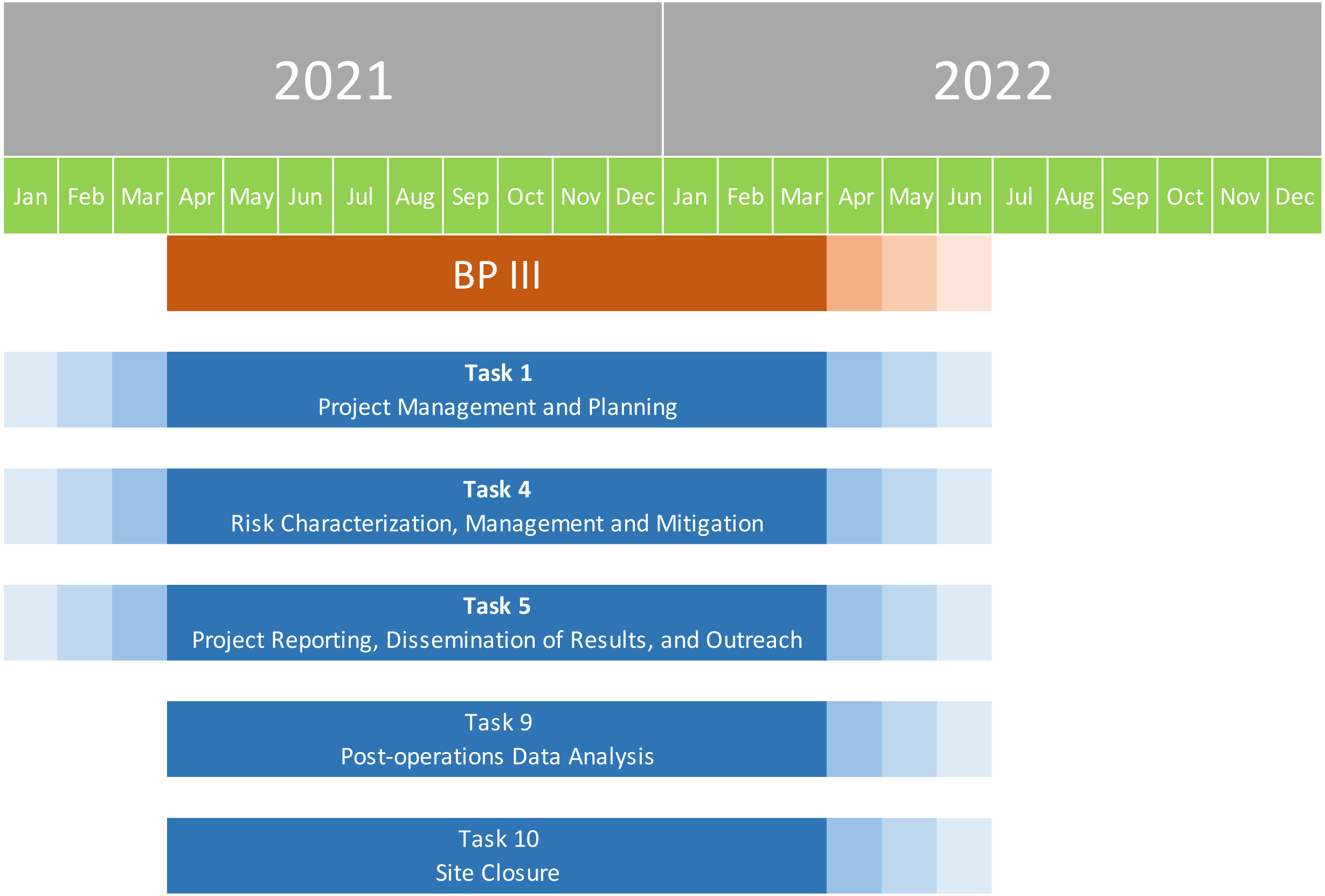


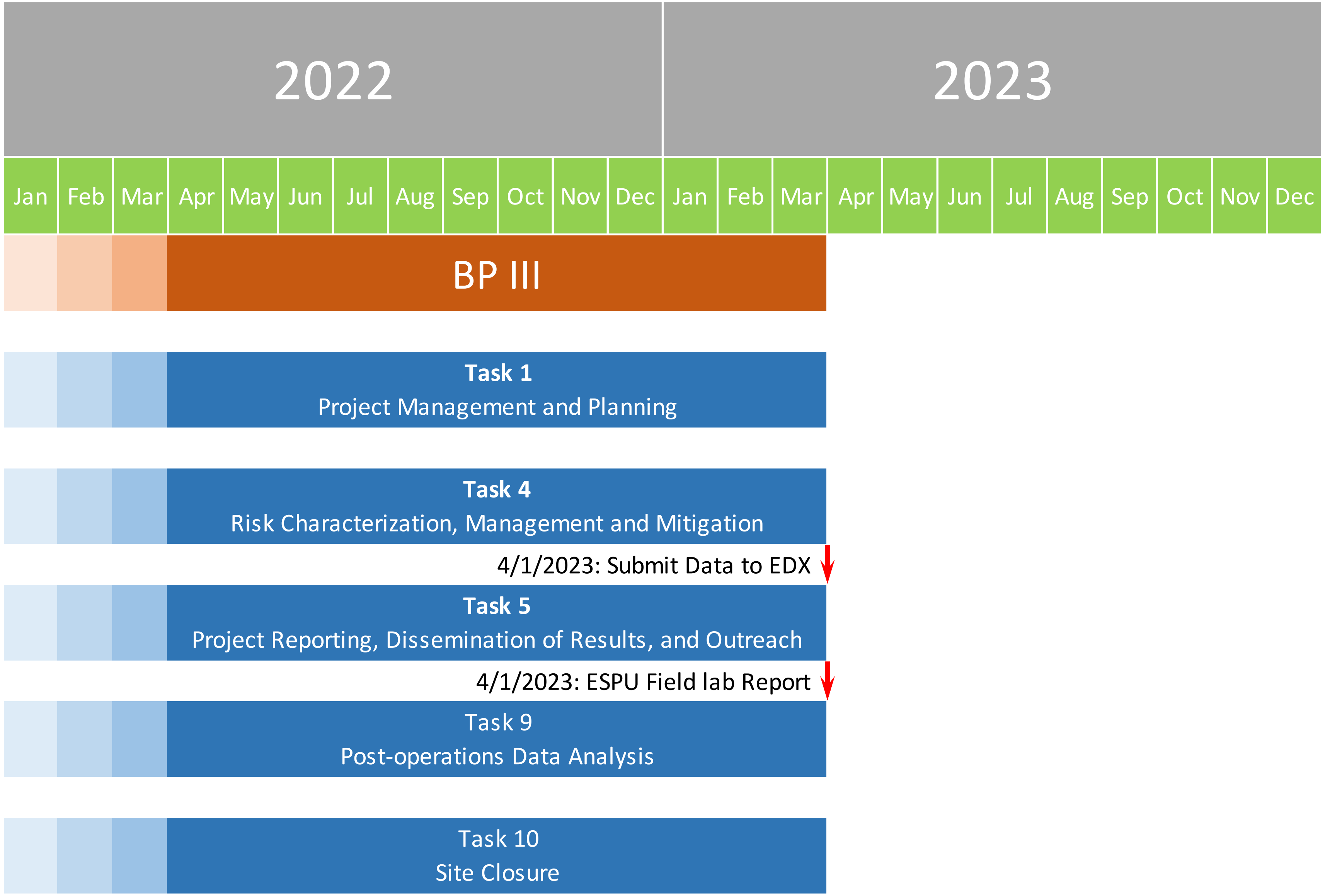
2018
2019
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
BP I
Task 1
Project Management and Planning
5/1/18: Project Management Plan
Task 2
Data Mgmt. Plan
8/1/18: Data Management Plan
Task 3
Est. Advisory Board
2/1/19: Risk Management Plan
3/1/19: Risk Register
Task 4
Risk Characterization, Management and Mitigation
2/1/19: Outreach and Education Plan
Task 5
Project Reporting, Dissemination of Results, and Outreach
10/1/18: Geo. Char. and Design Report
2/1/19: NEPA EQ
Task 6
Site Selection
11/1/18: Site Sel. Report, Upd. AFE
2/1/19: GO/NO-GO 1



2019
2020
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
BP II
Task 1
Project Management and Planning
Task 4
Risk Characterization, Management and Mitigation
Task 5
Project Reporting, Dissemination of Results, and Outreach
4/1/19: Sampling and Analysis Plan
3/1/2020: Baseline Monitoring Report
Task 7
Geo. Characterization of ESUP Field Lab
4/1/19: Drill Vertical Char. Well
12/1/19: ESUP Field Lab Design and Plan, Compliance
Task 8
ESUP Field Lab Design, Const., and Ops.
12/1/19: GO/NO-GO 2


2020
2021
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
BP II
Task 1
Project Management and Planning
Task 4
Risk Characterization, Management and Mitigation
Task 5
Project Reporting, Dissemination of Results, and Outreach
4/1/20: Drill and Complete Lower Huron Well(s)
Task 7
Geo. Characterization of ESUP Field Lab
6/1/20: Drilling and Completion Reports
3/1/2021: Updated Geo. Char., Res. Model Reports
Task 8
ESUP Field Lab Design, Const., and Ops.
6/1/20: GO/NO-GO 3


2021
2022
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
BP III
Task 1
Project Management and Planning
Task 4
Risk Characterization, Management and Mitigation
Task 5
Project Reporting, Dissemination of Results, and Outreach
Task 9
Post-operations Data Analysis
Task 10
Site Closure



2022
2023
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
BP III
Task 1
Project Management and Planning
Task 4
Risk Characterization, Management and Mitigation
4/1/2023: Submit Data to EDX
Task 5
Project Reporting, Dissemination of Results, and Outreach
4/1/2023: ESPU Field lab Report
Task 9
Post-operations Data Analysis
Task 10
Site Closure

Advisory Stakeholder Group (ASG)

- High priority task
- Membership discussion with individuals has commenced
- Plan for approximately 8 Board Members
  - Technical Experts with experience in geology and shale development in the region
  - Environmental community representatives
  - Local Community leaders, including elected officials

The Historic Big Sandy Devonian Shale Field vs. Horizontal Development and NORA Field

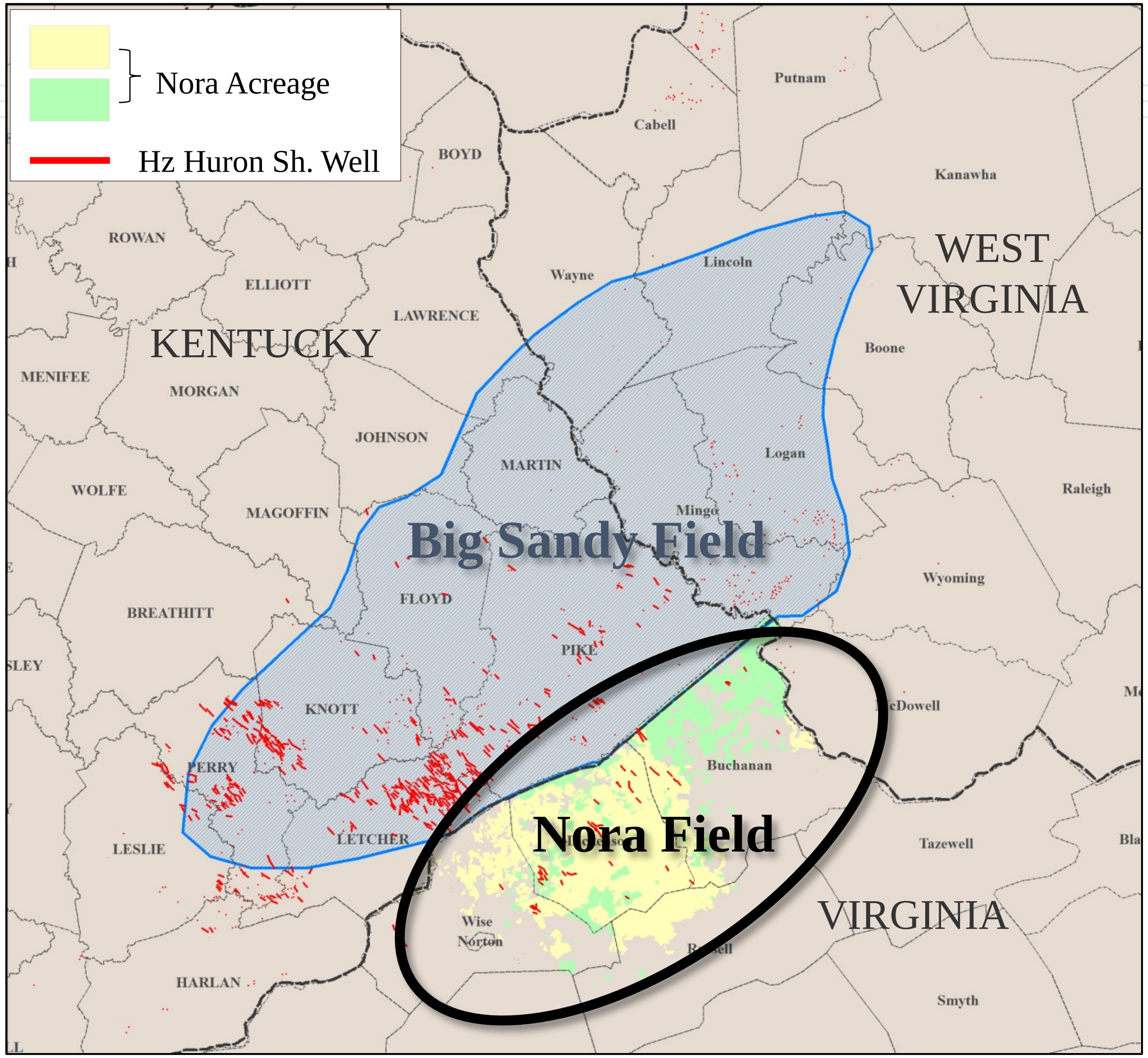
Big Sandy Field Summary

Discovery: 1915
Location: E Kentucky – SW West Virginia
Wells Drilled: >10,000
1st Hz Well: 2006 (IHS Data)
Hz Wells Drilled: ~950 (IHS Data)
Cum Prod: >2.5 Tcfg (estimated)
Target(s): Lower Huron Sh., Cleveland Sh.
Reservoir: Naturally Fractured Black Shale
Huron Thickness: 100-300 ft.

Source: The Atlas of Major Appalachian Gas Plays

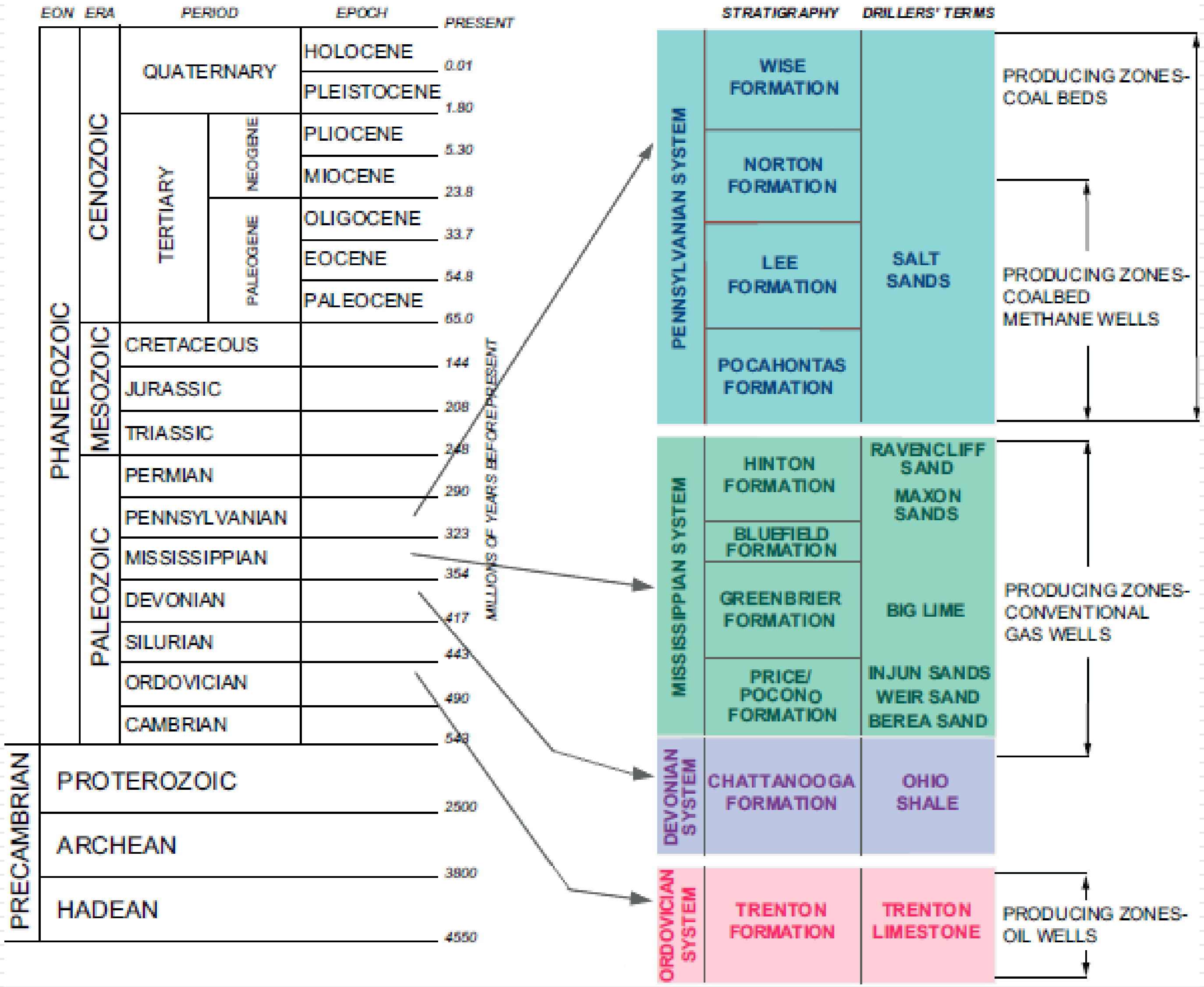
Nora Area Summary

Discovery: 1948
Location: W Virginia
Wells Drilled: ~700 (IHS Data)
1st Hz Well: 2007 (IHS Data)
Hz Wells Drilled: ~60
Target(s): Lower Huron Sh., Rhinestreet Sh.
Reservoir: Black Shale
Huron Thickness: 100-300 ft.



Nora Field - Stratigraphy

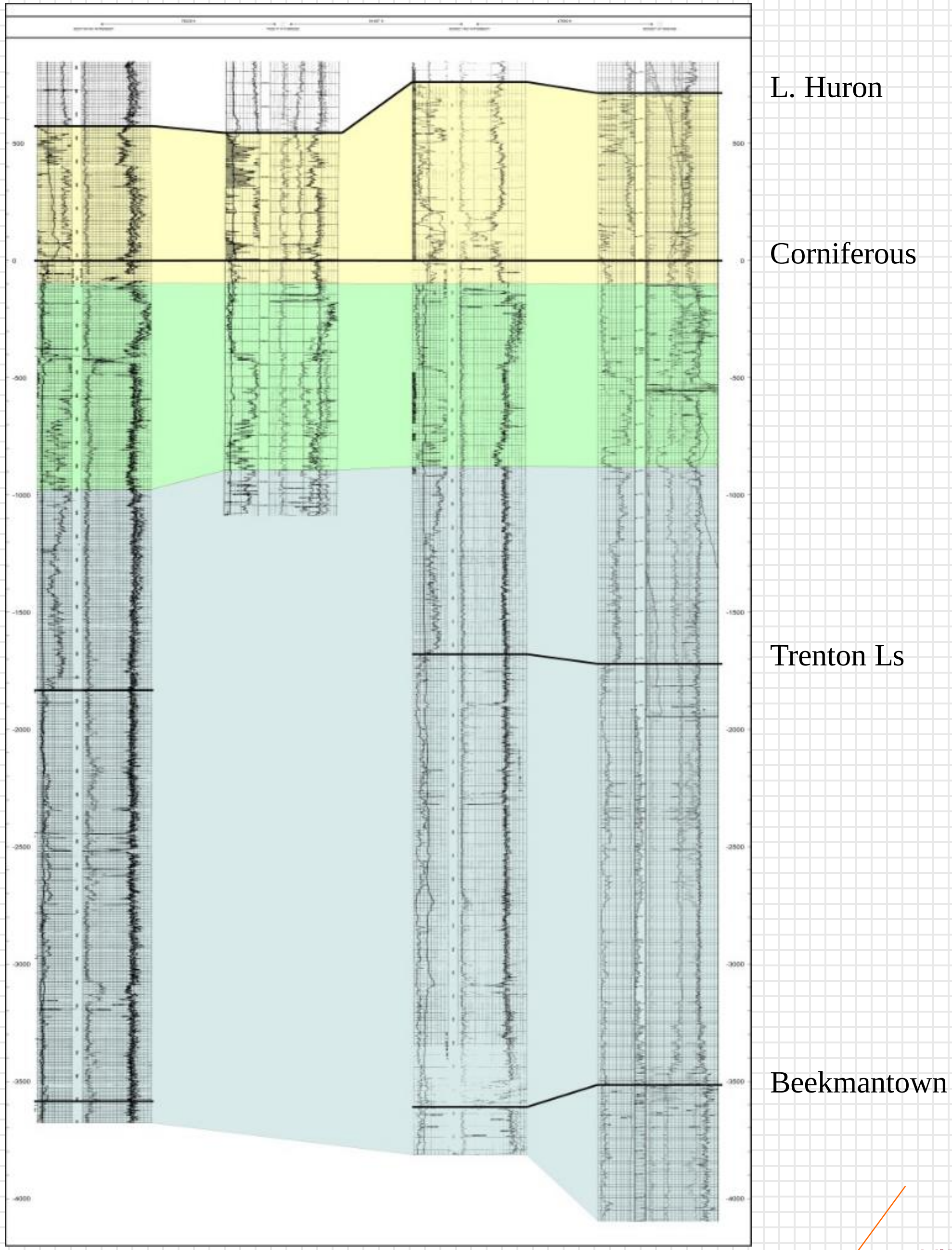
- Current Stacked Unconventional Plays
  - **Coalbed Methane (Pennsylvanian)**
  - **Big Lime (Mississippian)**
  - **Weir Sand (Mississippian)**
  - **Berea Sand (Mississippian)**
  - **Lower Huron Shale (Devonian)**



VA DMME, 2017

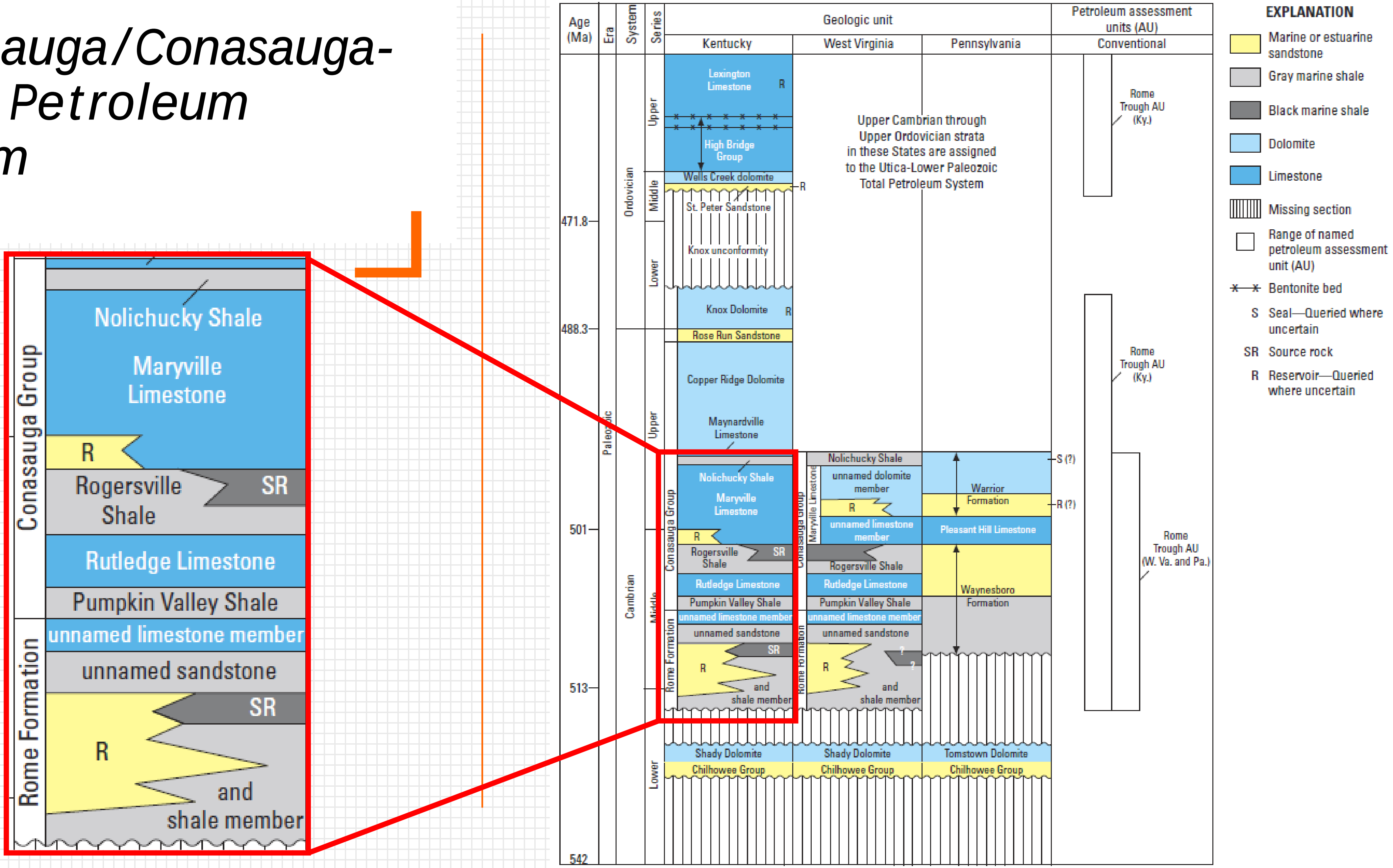
Deep Targets for Vertical Characterization Well

Devonian	Huron Shale	☆
	Olentangy Shale	
	Rhinestreet Shale	☆
	Marcellus Shale	☆
	Corniferous (Onondaga) Ls	
	Oriskany Ss	☆
Silurian	Salina Dol / Ls	
	Keefer Ss / Big Six Ss	☆
	Clinton Group / Rose Hill Fm	☆
	Tuscarora Ss / Clinch Ss	☆
Ordovician	Juniata / Sequatchie Shale	
	Trenton Ls	☆
	Black River Ls	☆
	Beekmantown Grp / Knox Dol / Rose Run Ss	☆
Cambrian	Copper Ridge / Conococheague Dol	
	Conasauga (Nolichucky / Rogersville / Pumpkin Valley Shale)	☆
	Rome Fm	
	Basal Ss	
	PreCambrian Basement	



EnerVest, 2018

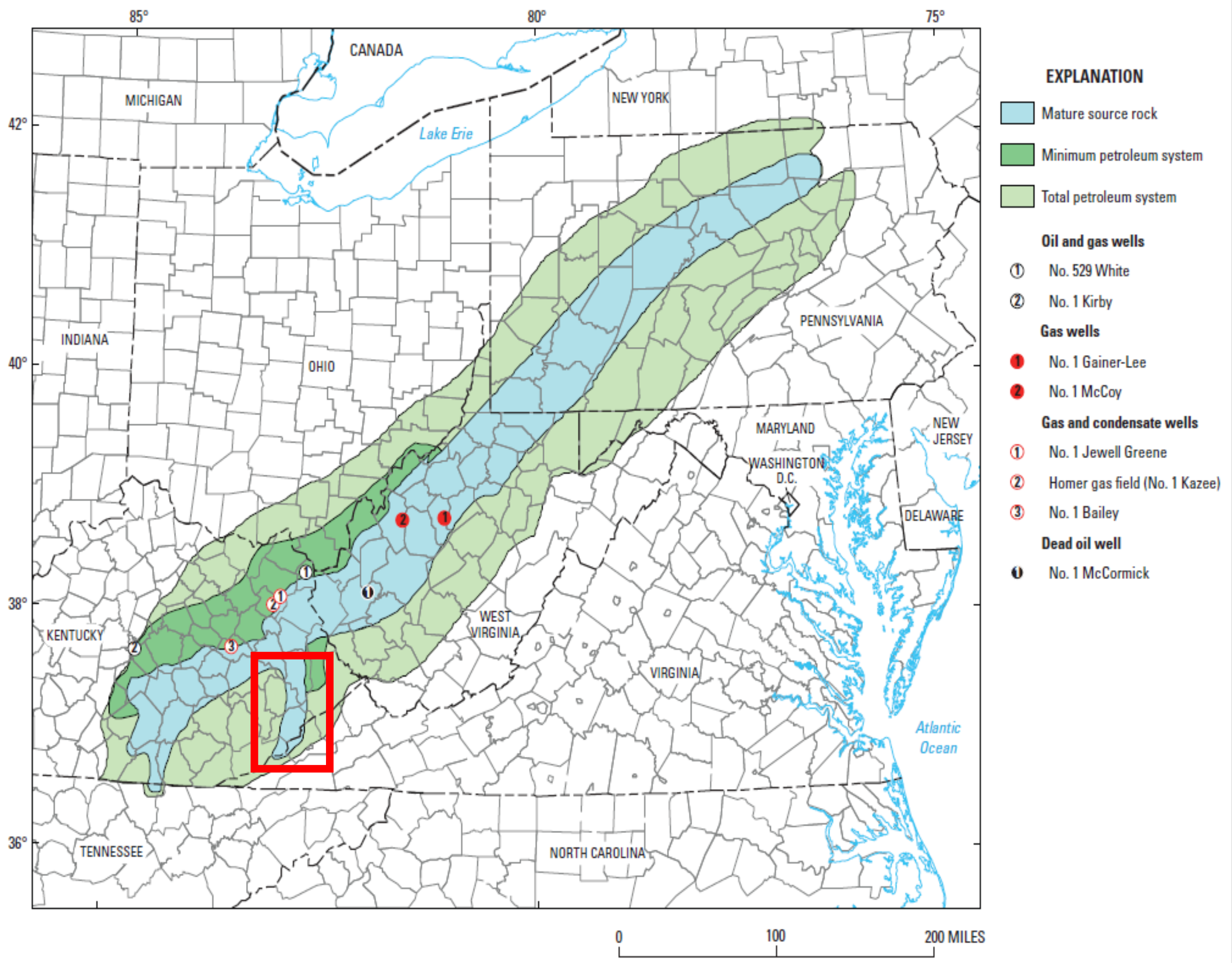
Conasauga/Conasauga-Rome Petroleum System



USGS, 2014

Conasauga/Conasauga-Rome Petroleum System

- Geochemical evidence suggests Cambrian source rocks are present in the Rome Trough
  - Correlated with oils in Homer Gas field, KY
- Rome Trough primarily in eastern KY, WV, and PA
- Floyd Embayment (red) extends system boundaries into SW VA

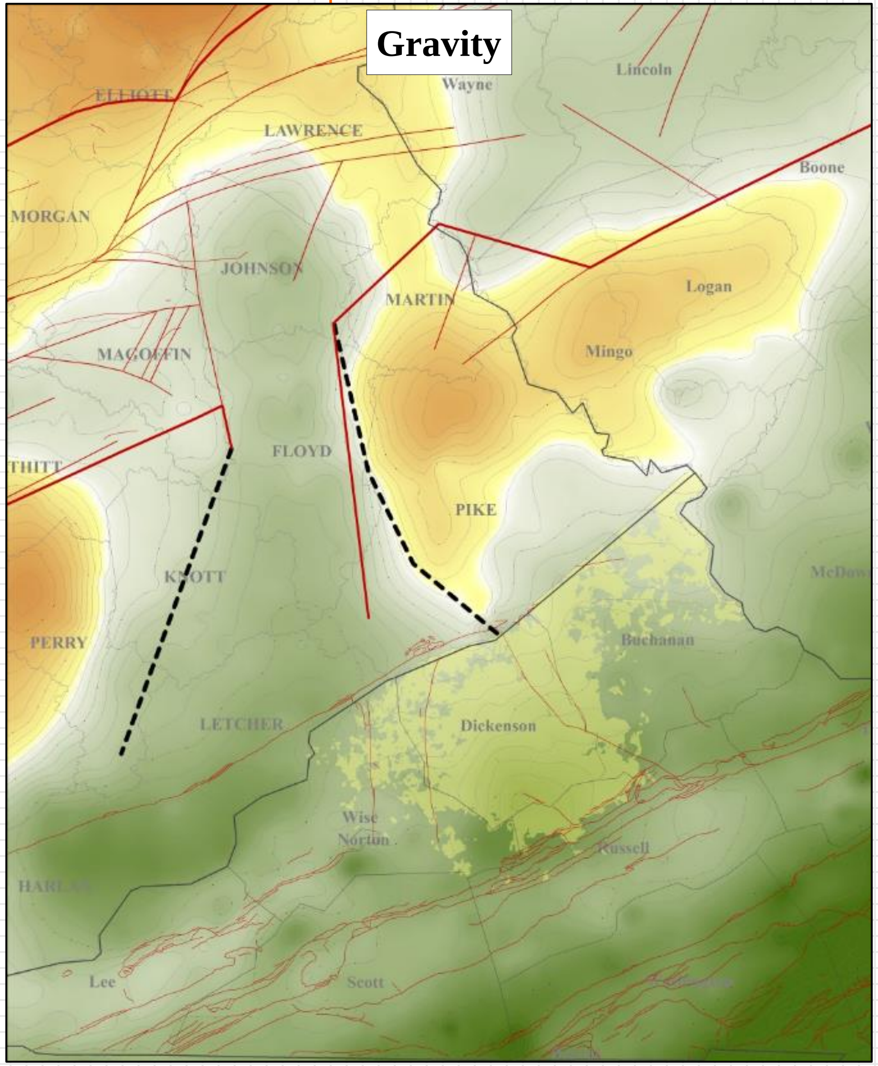


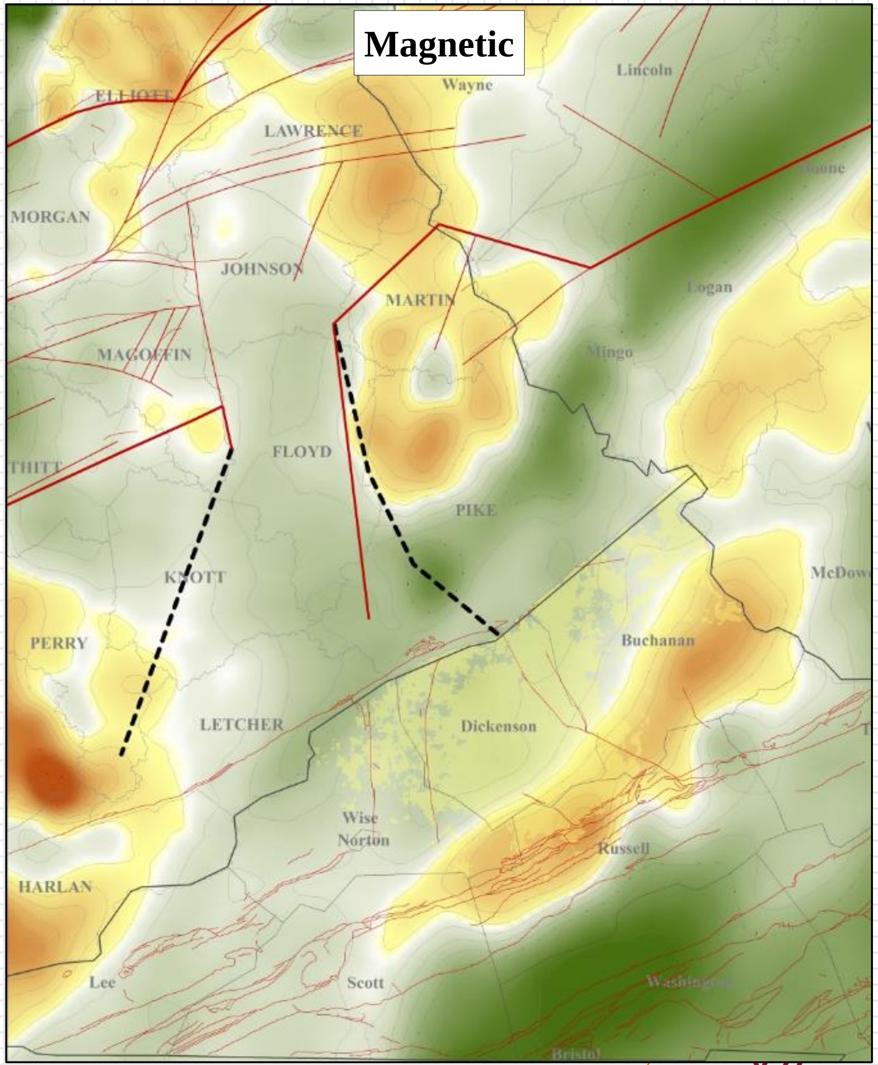
USGS, 2014

VIRGINIA TECH

Rome Trough Structure
Gravity and Magnetic Data

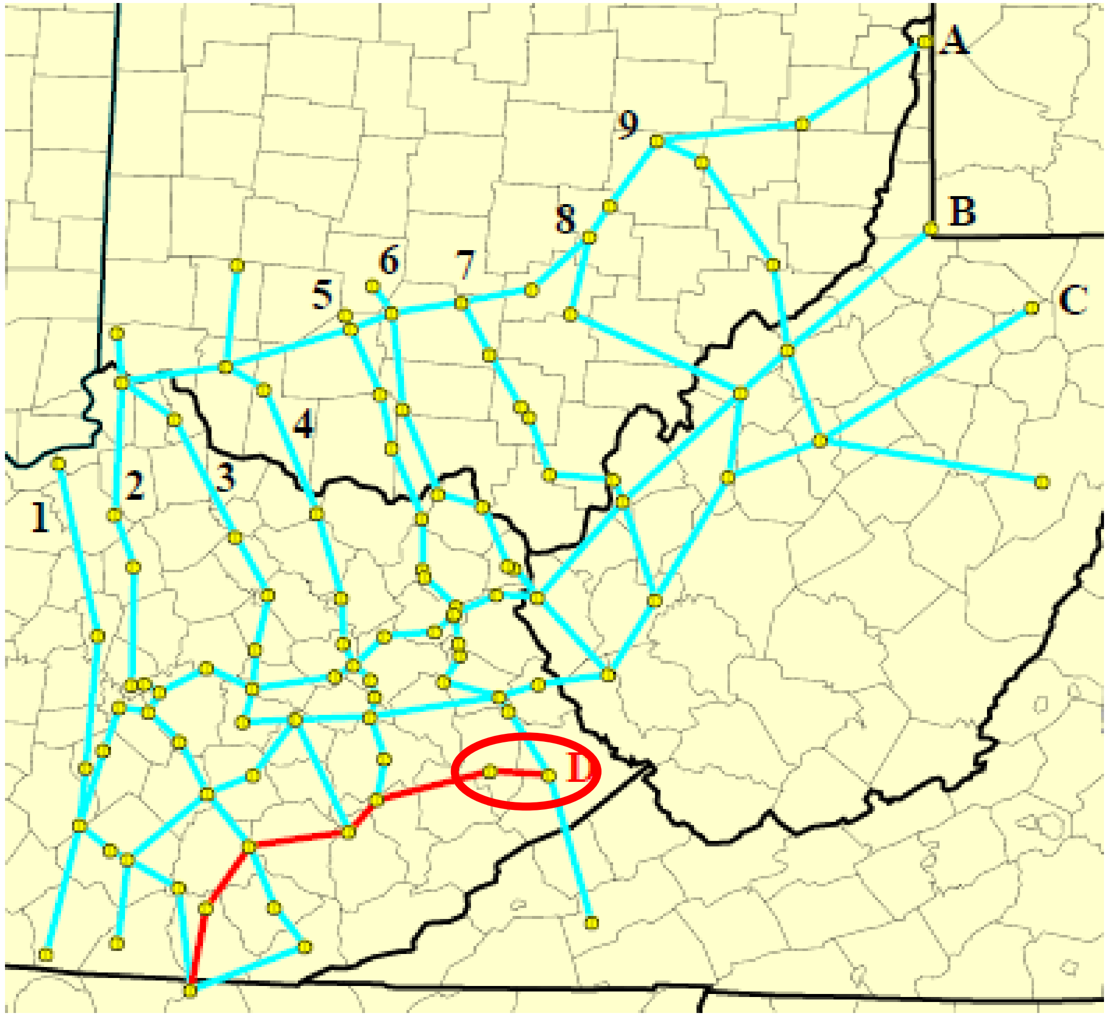
- Magnetic and gravity anomalies are proxies for Rome Trough and Precambrian structure
- The borders of the Floyd Embayment are ambiguous and are poorly understood in Virginia
- Gravity and magnetic data suggests that the Floyd Embayment intersects western portions EnerVest acreage

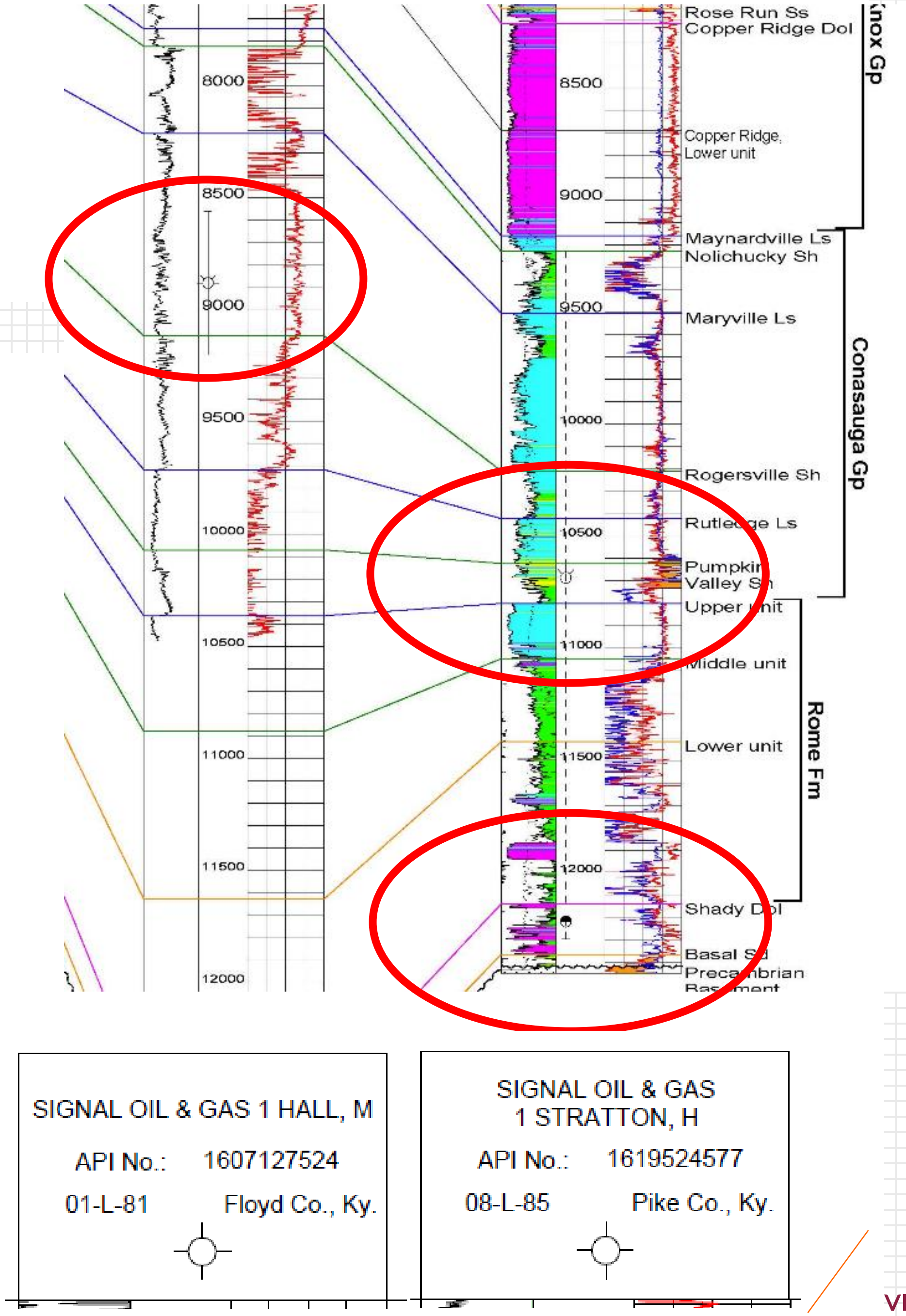




EnerVest, 2018

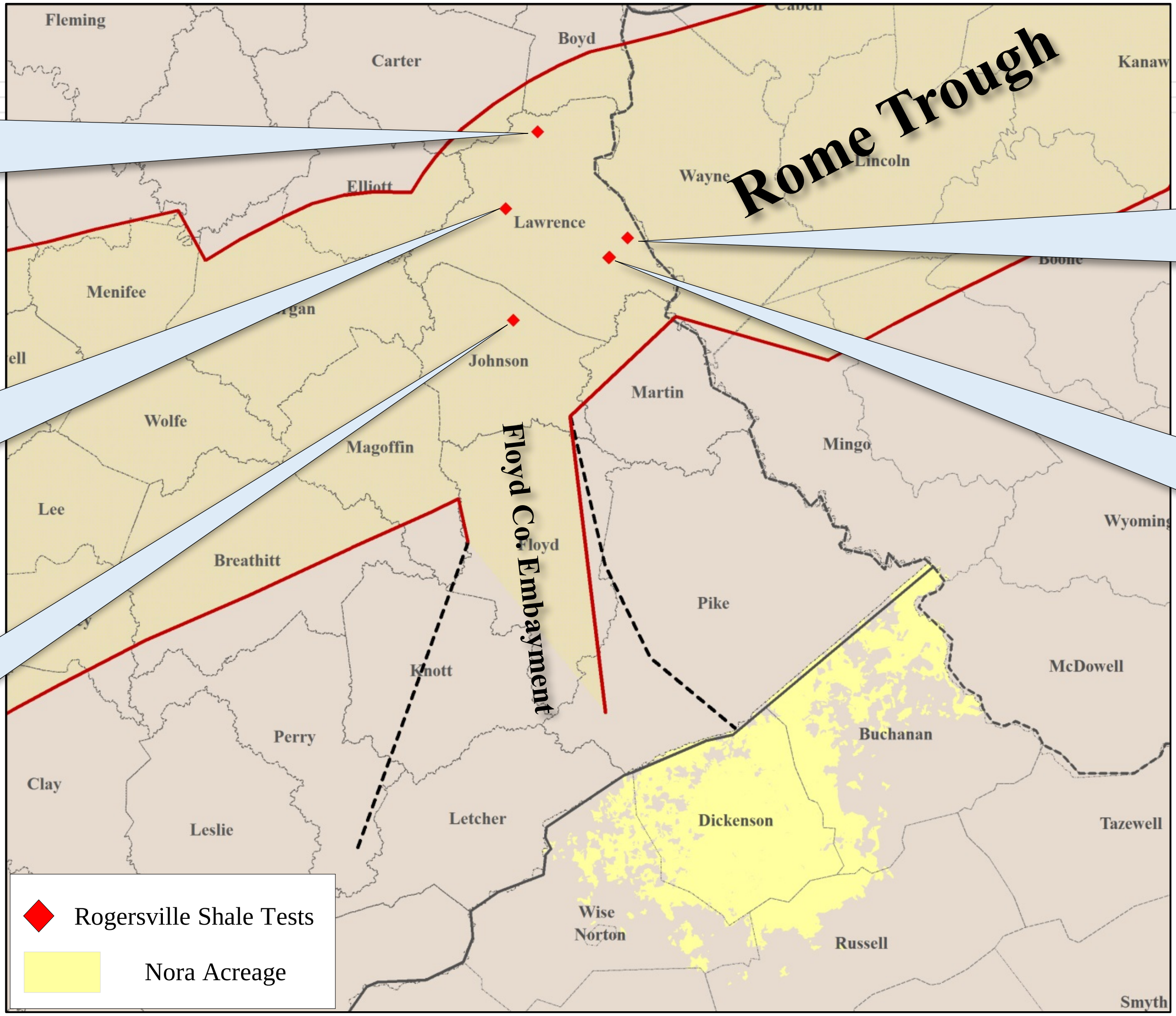
Oil and Gas Shows near VA





VIRGINIA TECH.

Recent Rogersville Shale Activity



Stevens J et al #LAW 1
Chesapeake Appalachia

Vertical Strat Test

TD Date: 5/19/2015
Fm @ TD: Rome Fm
TD: 11,651 ft.

Young S #1
Bruin Exploration (Cimarex)

Vertical Strat Test

TD Date: 5/30/2014
Fm @ TD: Rome Fm
TD: 12,169 ft.

EQT Prod Co #572360 H
Horizontal Tech Energy Co (EQT)

Horizontal Rogersville Test

TD Date: 6/7/2015
Fm @ TD: Rogersville Shale
TD: 13,383 ft. MD
Shut In

JH Northrup Estates #LAW 1
Chesapeake Appalachia

Vertical Strat Test

TD Date: 9/3/2015
Fm @ TD: Shady Dolomite
TD:15,950 ft.

Walbridge Holdings #1H
Bruin Exploration (Cimarex)

Horizontal Rogersville Test

TD Date: 2/23/2017
Fm @ TD: Rogersville Shale
TD: 16,108 ft. MD
Temporarily Abandoned

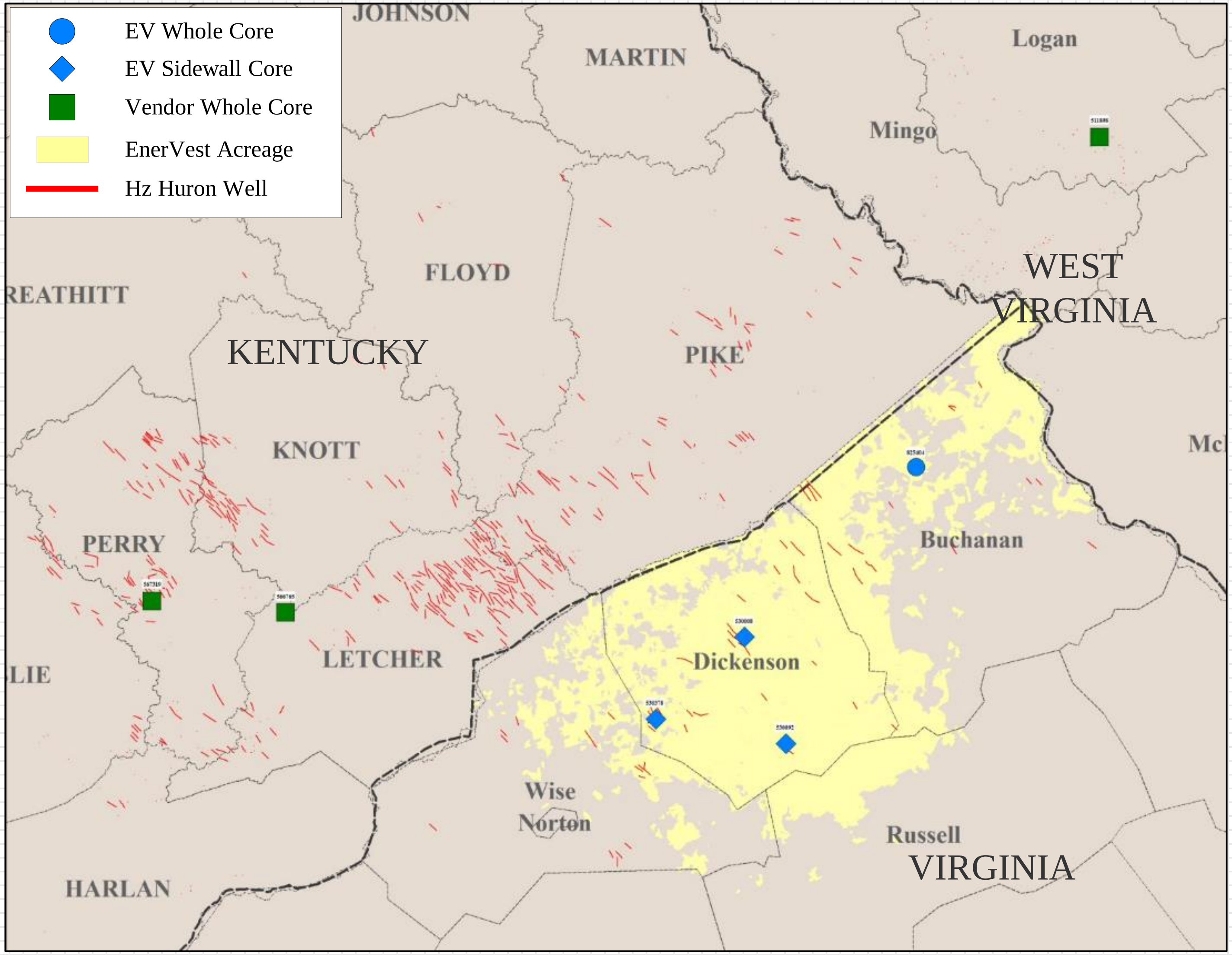
Lower Huron Core Distribution

Core Inventory

- 4 Whole Cores
- 3 Sidewall Cores

Cores By State

- VA: 4
- KY: 2
- WV: 1



EnerVest, 2018

VIRGINIA TECH

Nora Field – Petrophysical Summary

- Water Saturation
  - Reservoir has high Vclay (30-50%), all non-swelling clays that are typical of higher maturity reservoirs
  - Reservoir is “dehydrated” - contains less water than would be anticipated in a high clay content reservoir
  - The above factors (along with pressure) contribute to issues with water based completions

- Maturity - directly related to depth
  - Kentucky wells are less mature (shallower); Virginia wells are more mature (deeper)
  - The Virginia Lower Huron play is within the dry gas window of Huron play
- TOC
  - Fairly high at 2-3% average (up to 8% in areas)
- Porosity
  - Fairly low 4-6% total (2-3% gas-filled porosity)
- Desorbed & Adsorbed Gas
  - Adsorbed gas likely accounts for 30-60% of total GIP – important consideration in regards to completion methodology

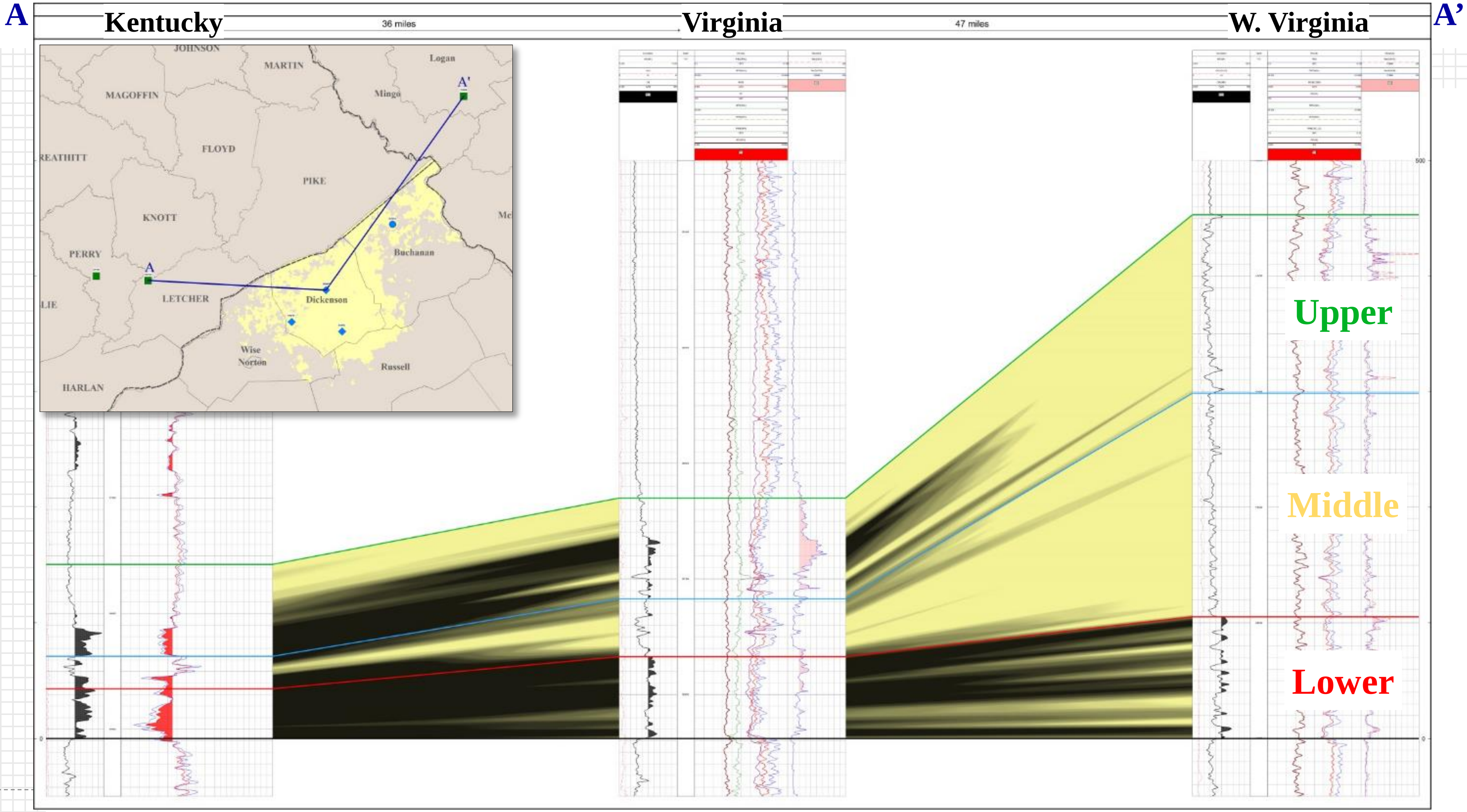
EnerVest, 2018

Lower Huron Petrophysical Cutoffs

	2% TOC	3% TOC	4% TOC	5% TOC	6% TOC
Gamma (API)	216	264	312	360	407
Rhob (g/cc)	2.68	2.64	2.59	2.55	2.50
Resistivity (Ohmm)	37	61	99	160	259

- A series of maps were generated for each of the above petrophysical cutoffs for each of the following intervals:
  - Lower Huron Undifferentiated
  - "Lower" Lower Huron
  - "Middle" Lower Huron
  - "Upper" Lower Huron
- Combination maps were also generated combining multiple cutoffs
  - i.e. 264 API & 2.64 g/cc = 3% TOC
- Mapping was utilized to high grade Lower Huron potential with EnerVest's acreage position

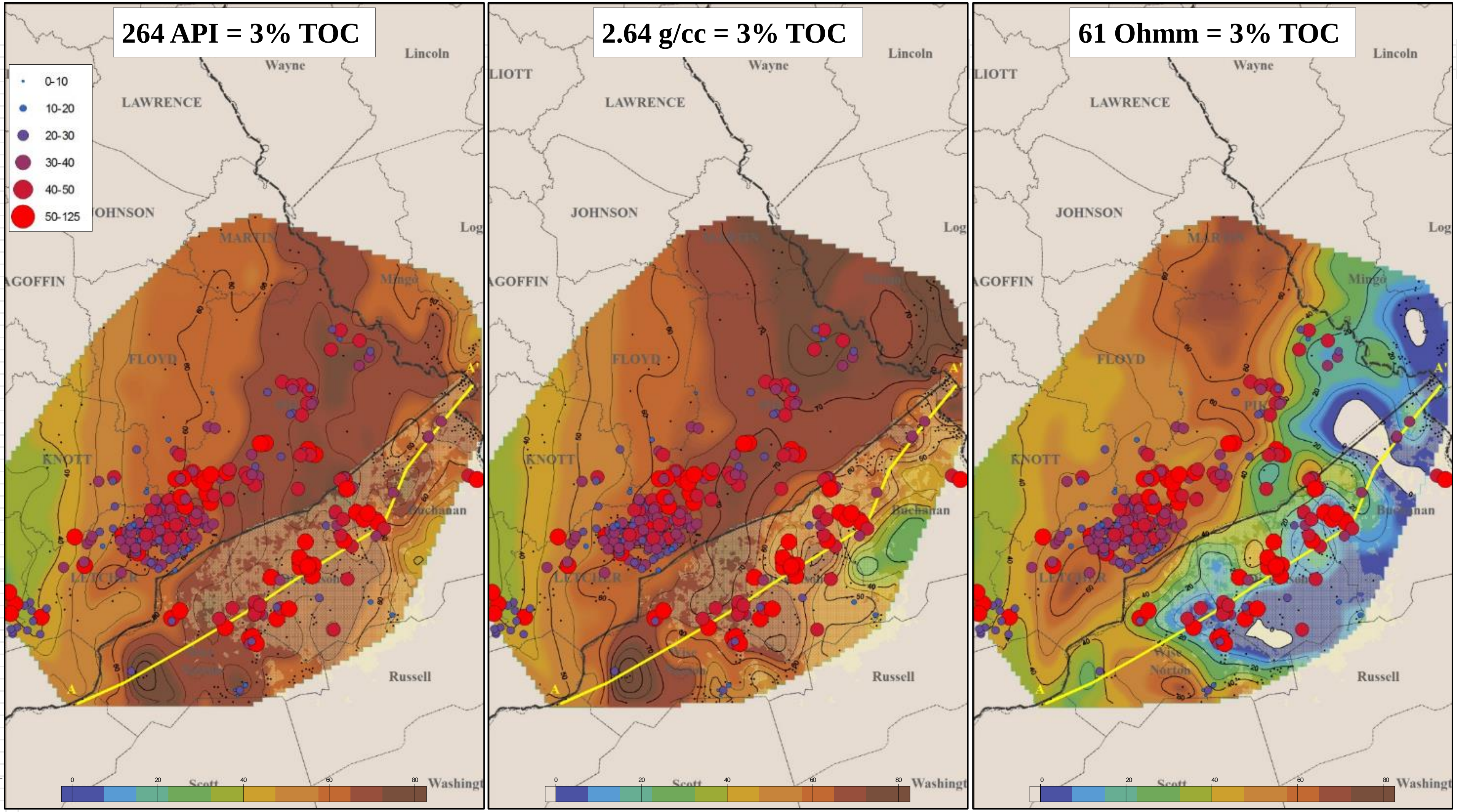
Lower Huron Delineation/Nomenclature



EnerVest, 2018

“Lower” Lower Huron

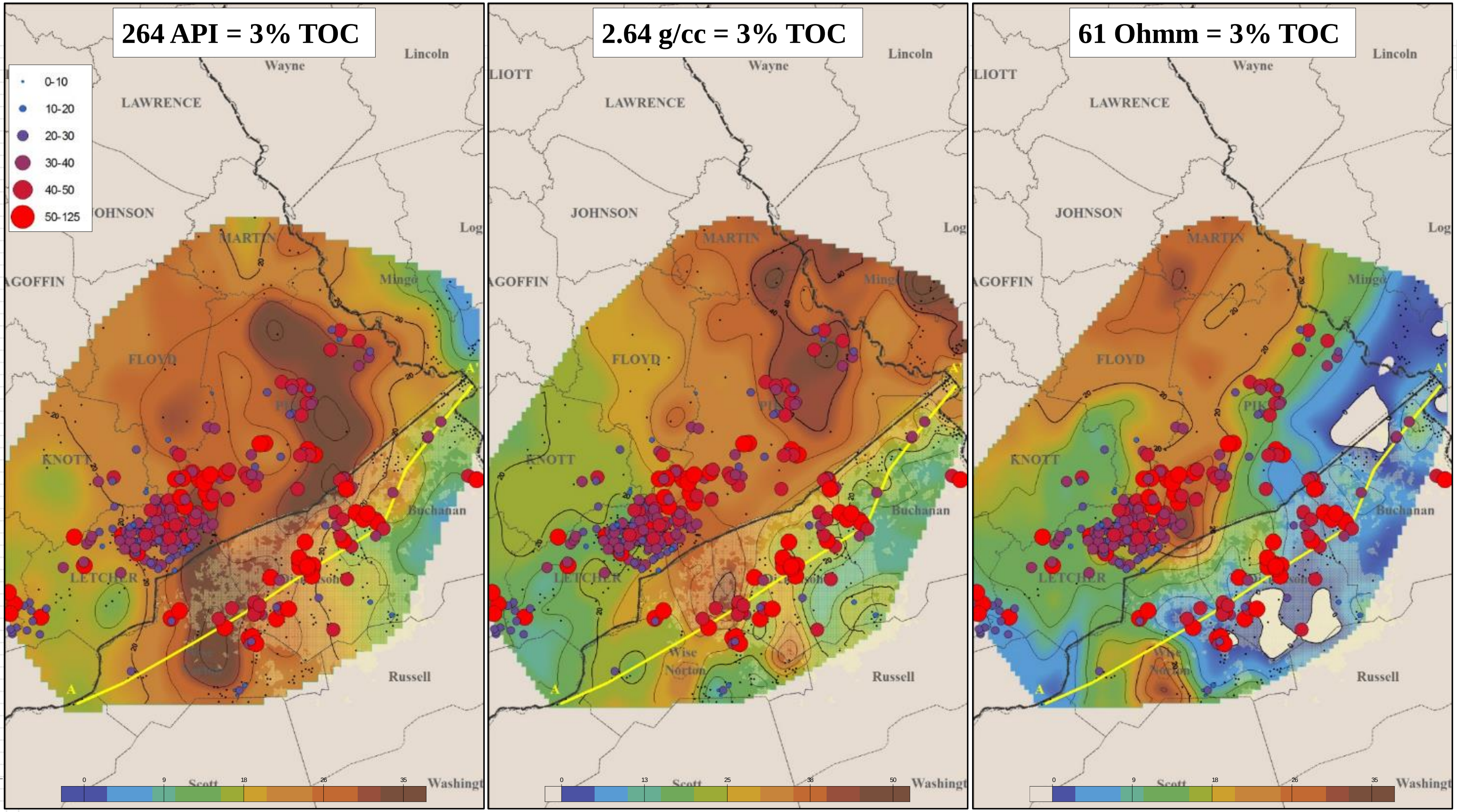
Thickness exceeding 3% TOC (feet) vs. Normalized initial 2-year production (MMcf/1000’ lateral)



EnerVest, 2018

“Middle” Lower Huron

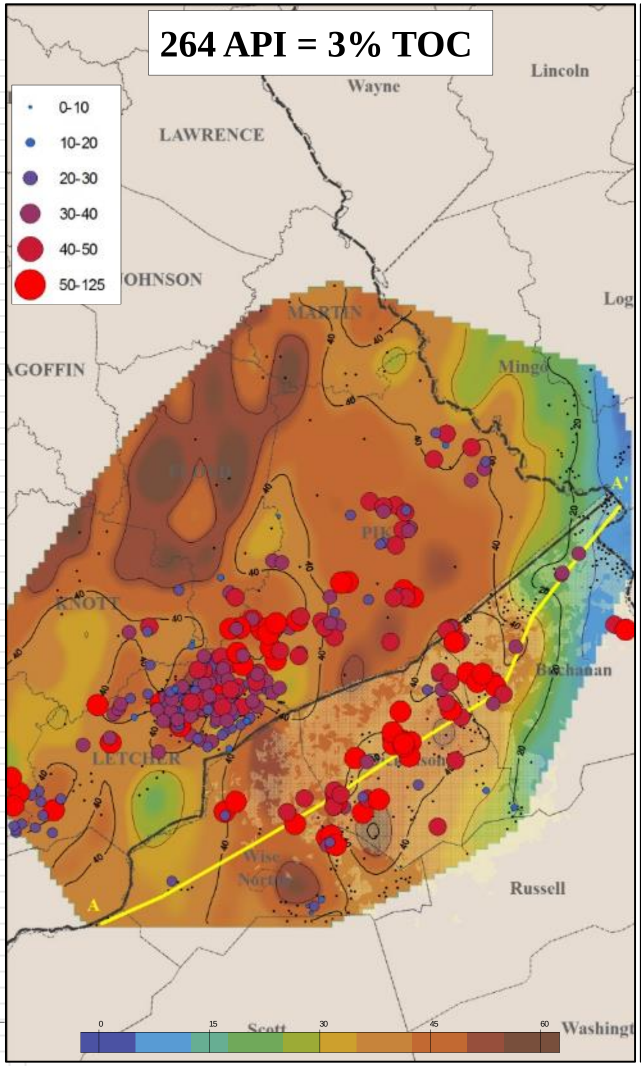
Thickness exceeding 3% TOC (feet) vs. Normalized initial 2-year production (MMcf/1000’ lateral)

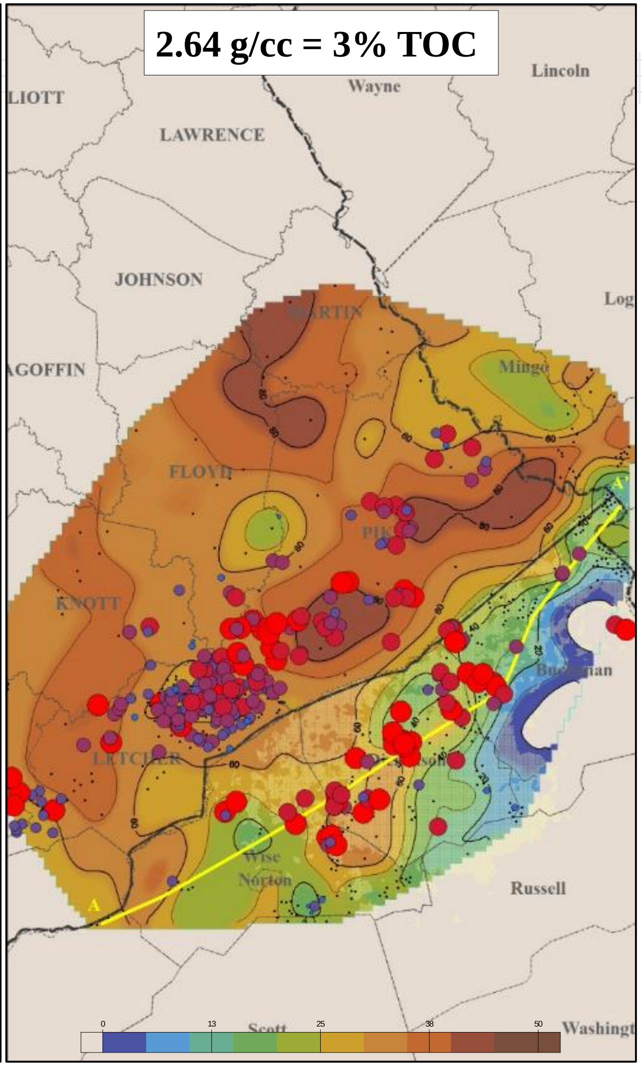


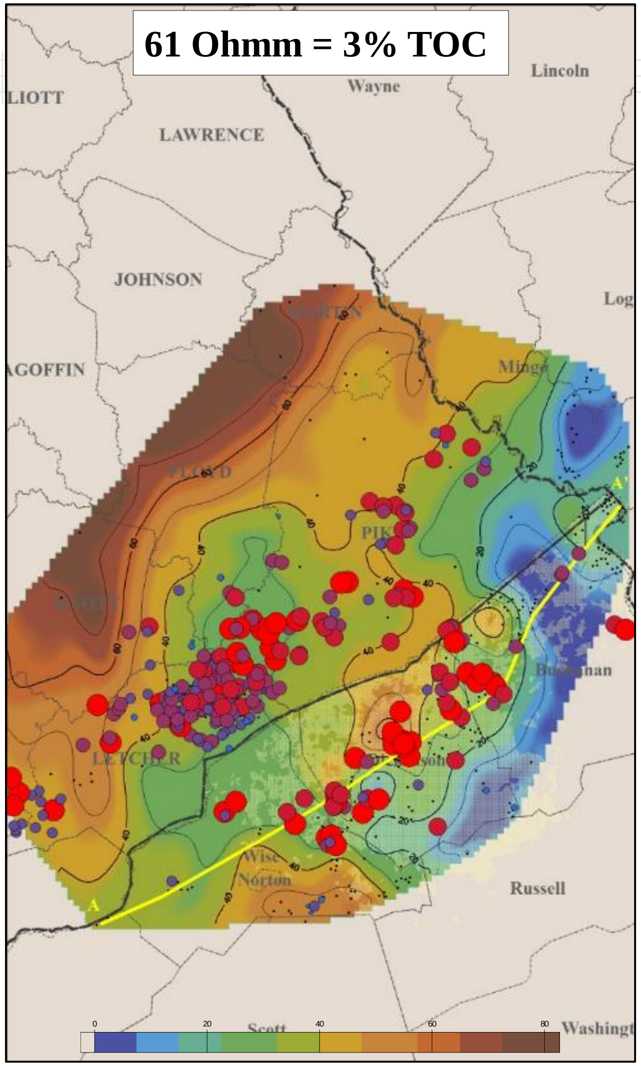
EnerVest, 2018

“Upper” Lower Huron

Thickness exceeding 3% TOC (feet) vs. Normalized initial 2-year production (MMcf/1000’ lateral)



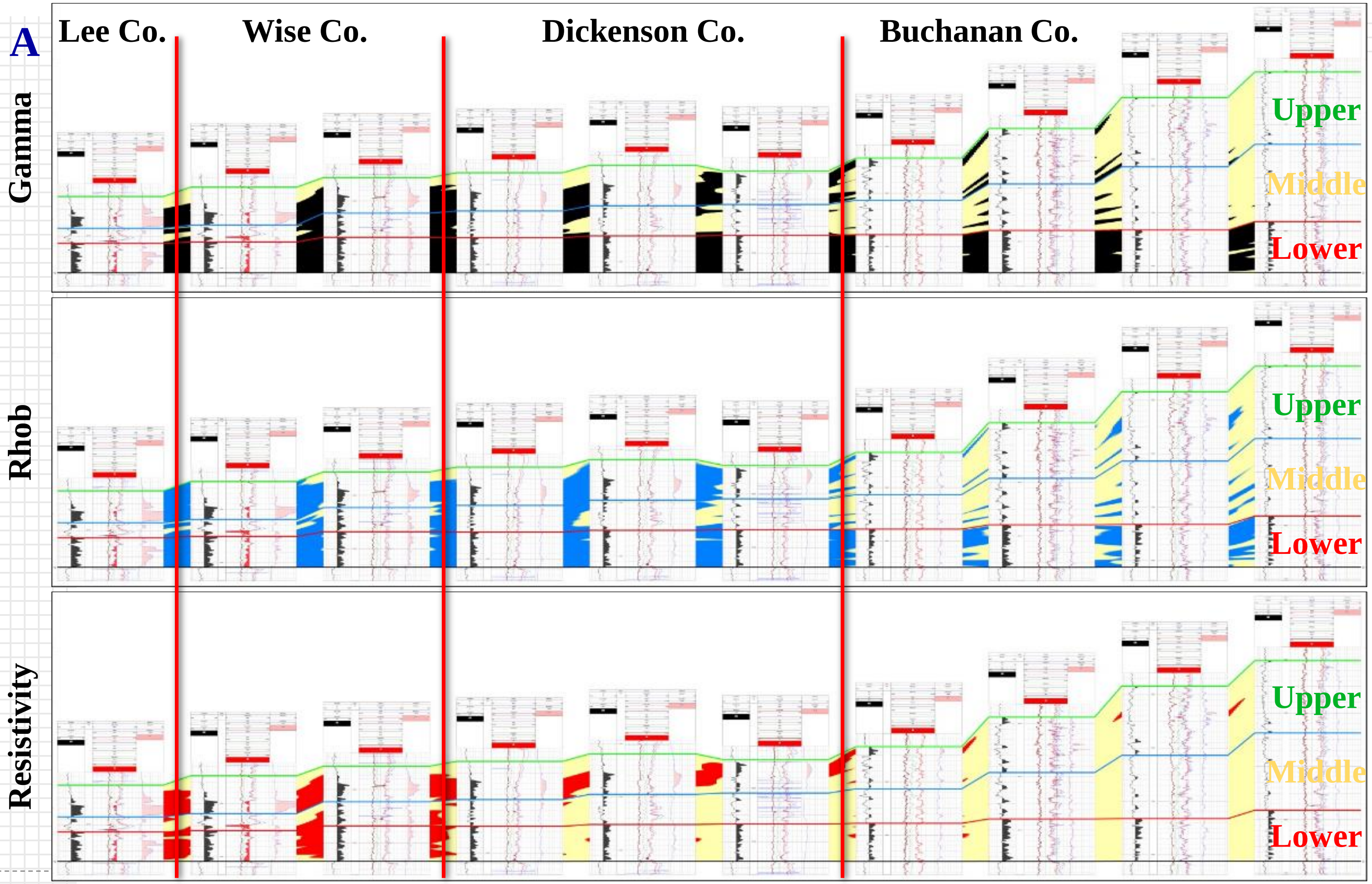


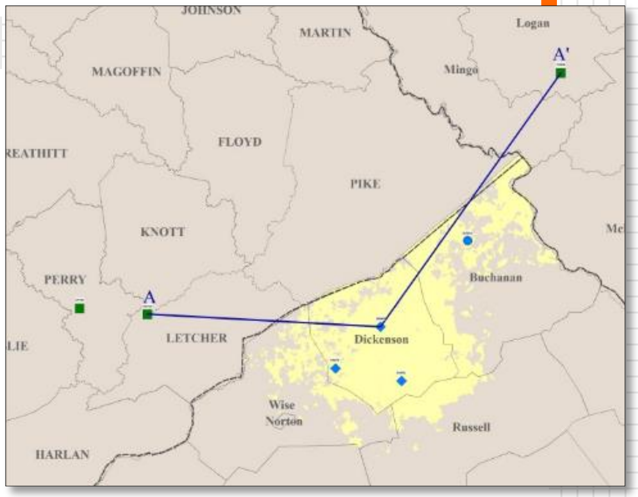


EnerVest, 2018

Well Log TOC Correlation

Gamma, Rhob, Resistivity Interpolation = 3% TOC



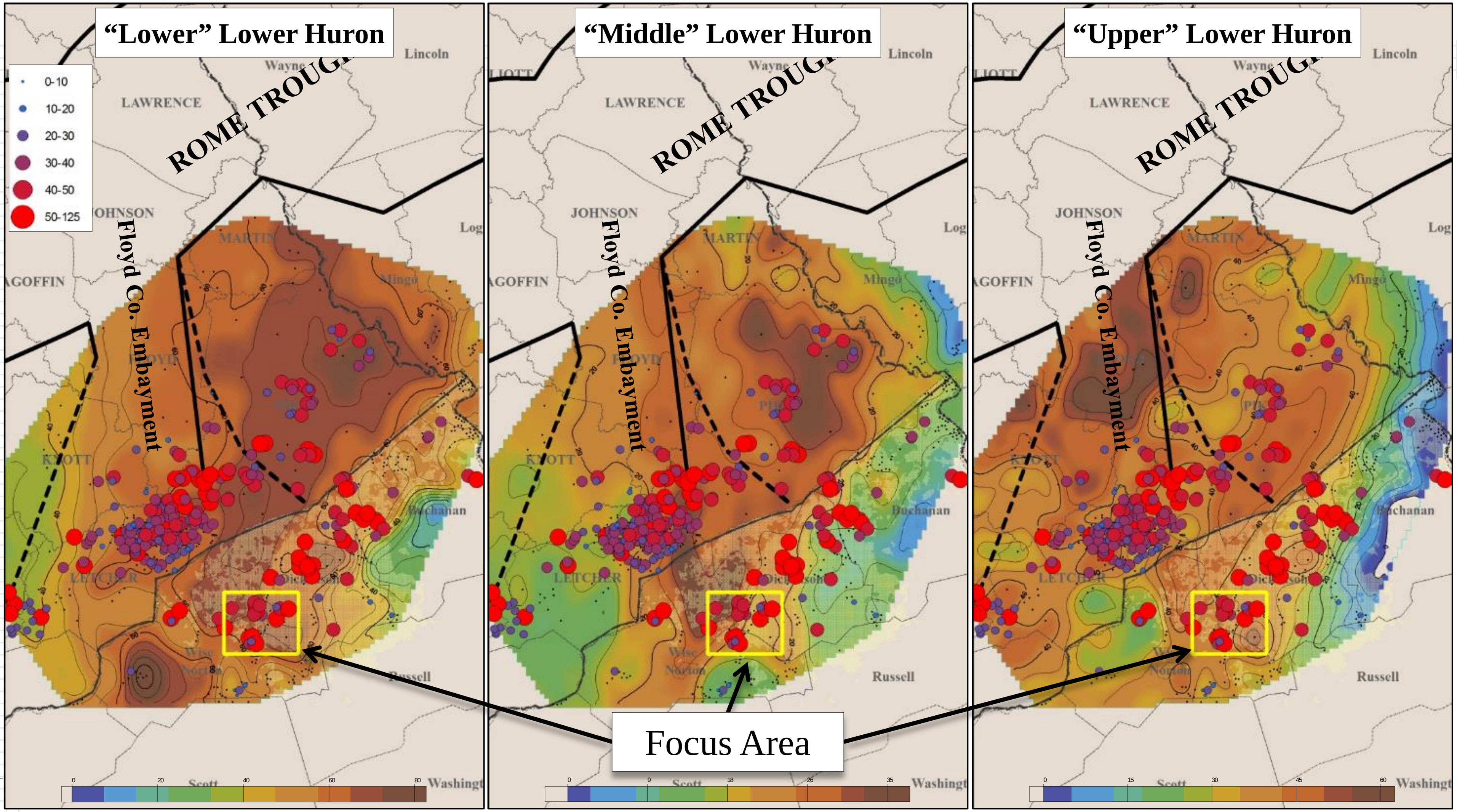


EnerVest, 2018

VIRGINIA TECH

Focus Area Determination

Combined Gamma/Rhob Cutoff Mapping (264 API & 2.64 g/cc = 3% TOC)



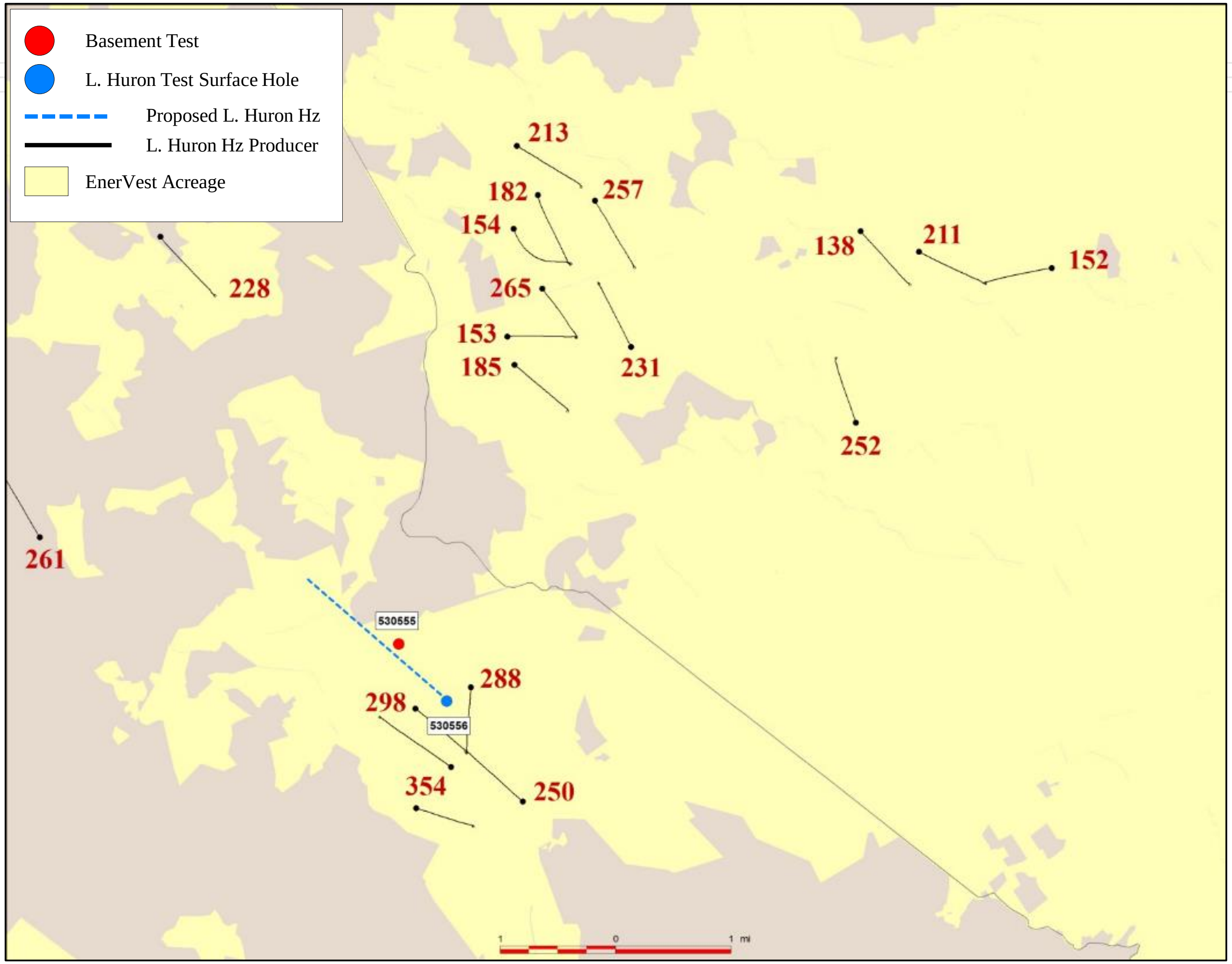
EnerVest, 2018

VIRGINIA TECH

Potential Test Locations

Normalized EUR (MMcf/1000' lateral)

- Petrophysics suggests optimal location for Lower Huron horizontal well
- Gravity and magnetic data suggests location is also suitable for deep vertical well
- Both wells in close proximity is optimal for ESUP Field Laboratory studies



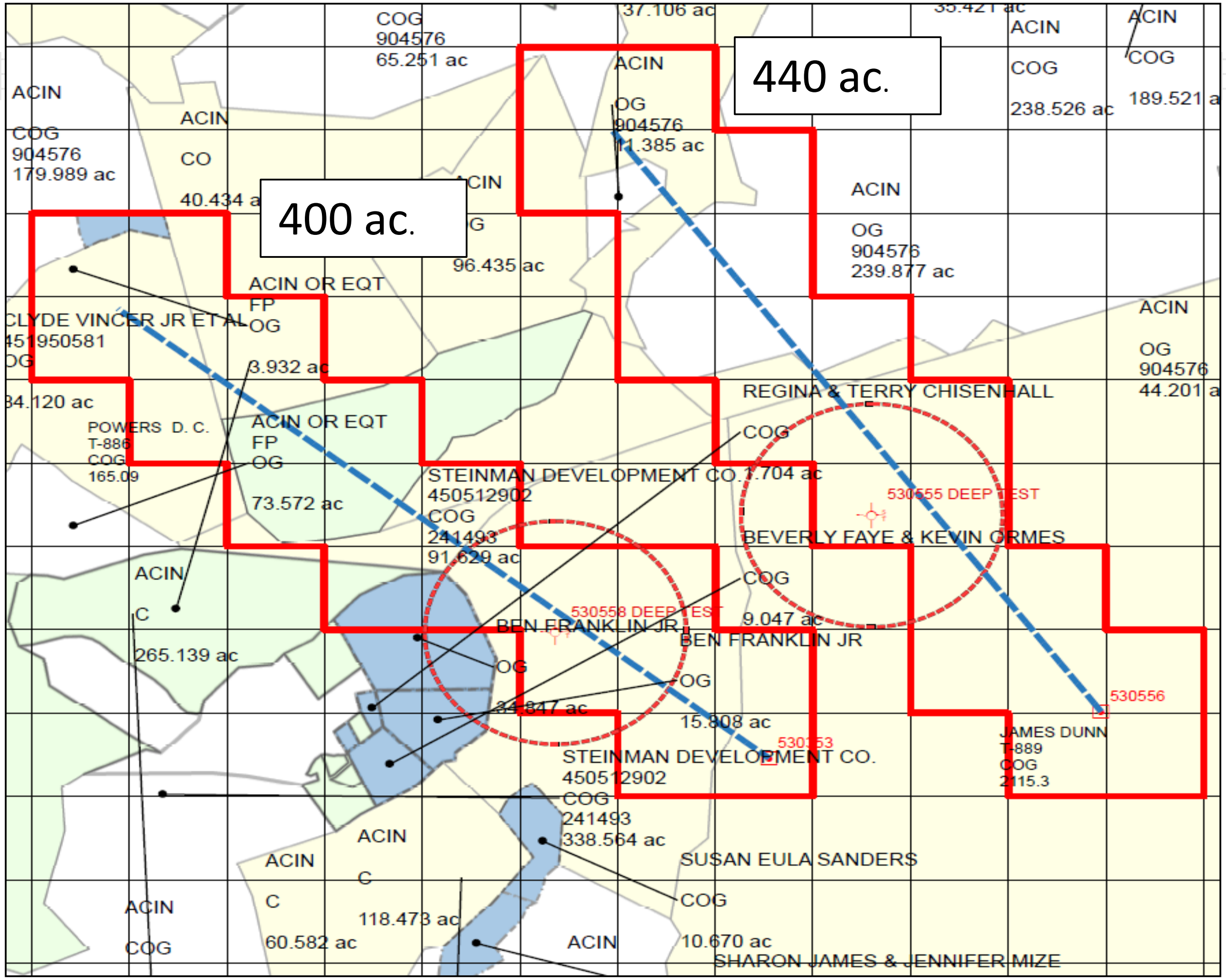
EnerVest, 2018

VIRGINIA TECH.

Land Overview

Potential Test Locations

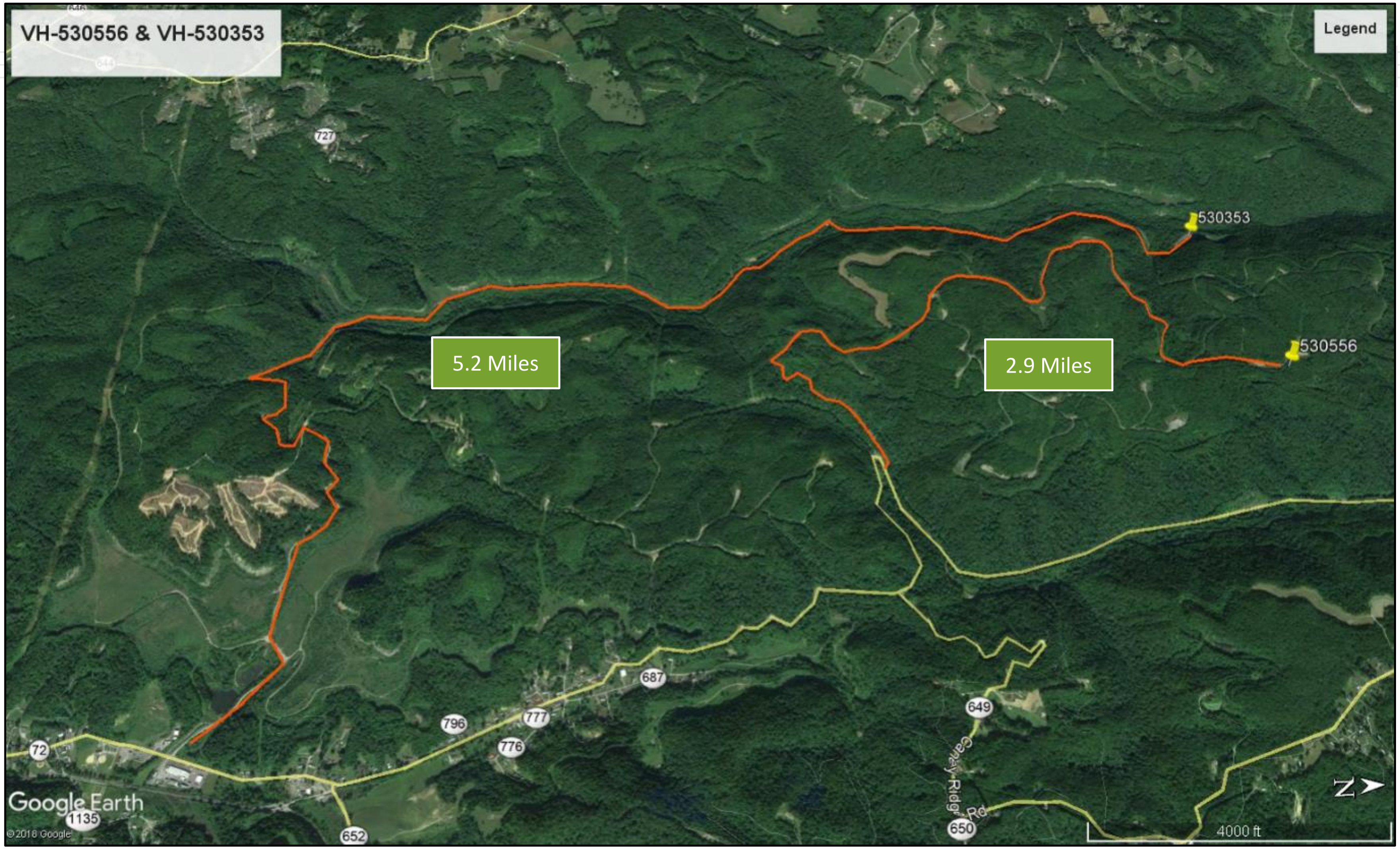
- Potential site (440 ac.) favorable with respect to road access and cultural impact
- 2nd Potential site (400 ac.) favorable with respect to land control issues
- Both sites are favorable with respect to geology and infrastructure availability



EnerVest, 2018

Land Overview

Potential Test Locations: Road Access, Cultural Impact

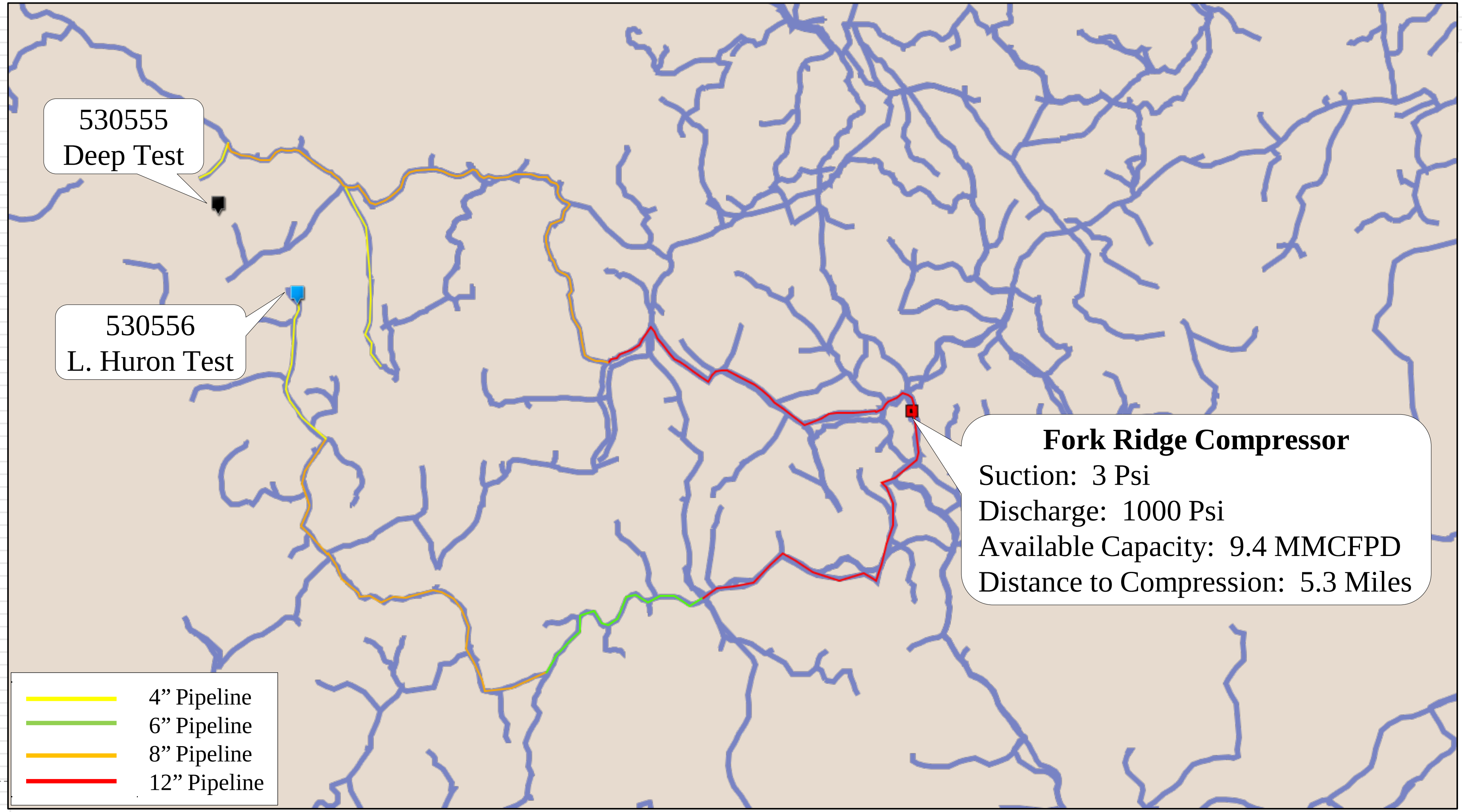


EnerVest, 2018

VIRGINIA TECH.

Land Overview

Potential Test Locations: Infrastructure Availability



EnerVest, 2018

Nora Field – Reservoir Pressure

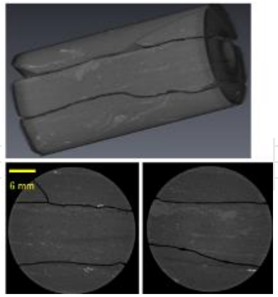
- Reservoir pressure gradient significantly lower than any of the major US shale plays

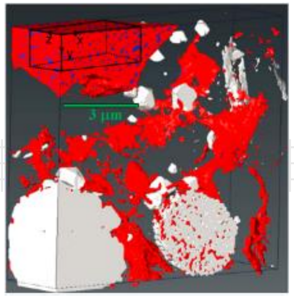
- Low reservoir pressure significantly limits completion options
  - Historic completions dominated by N_2 fracs and limited ability to place proppant
  - Water fracs – Can fluid from large scale SW jobs be recovered in low pressure environment? Artificial lift requirements?
  - Foam fracs in cemented completions difficult to initiate

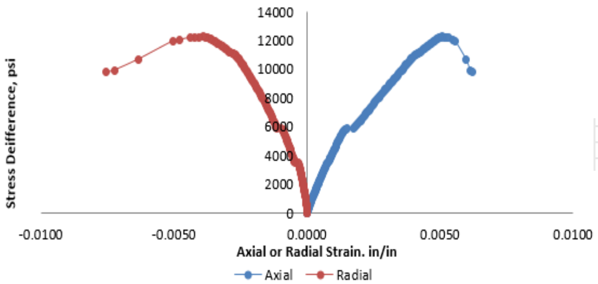
Play	Pore Pressure (#/ft)
Utica	0.65 - 0.9
Marcellus	0.50 - 0.80
Eagle Ford	0.7
Barnett	0.4 - 0.52
Play	**Pore Pressure (#/ft)**
Woodford	0.52
Fayetteville	0.43
Antrim	0.35
Lower Huron	0.22

EnerVest, 2018

Core Analysis Workflow







Digital Rock Analysis

- X-ray CT and SEM scanning
- Visualization of microfractures
- Rock density variation
- Nano-scale shale structure
- Pore-scale flow modeling

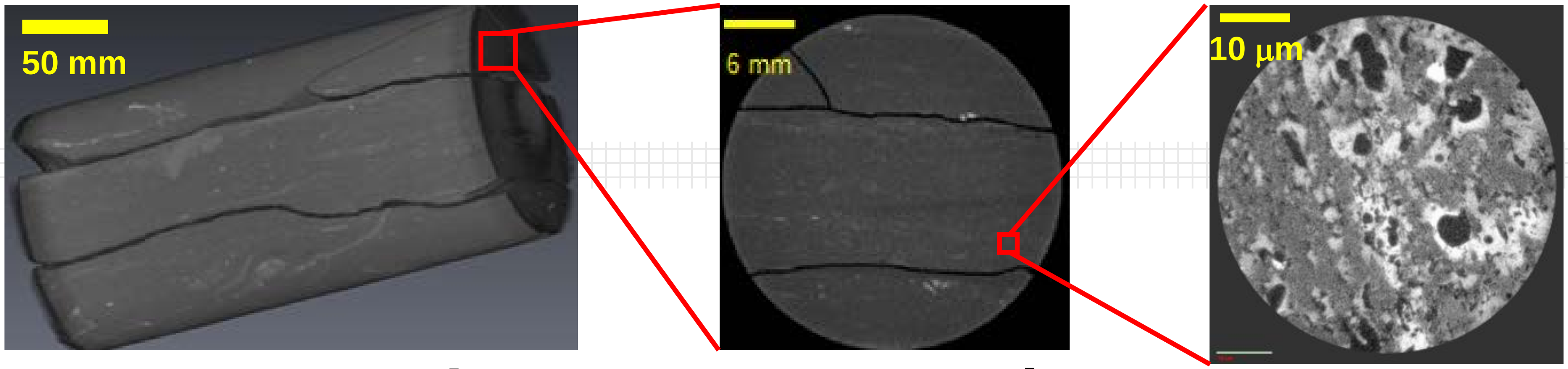
Geomechanical Analysis

- Poisson’s ratio and Young’s modulus
- Confined and unconfined compressive strength
- Brinell hardness number
- Brazillian tensile strength
- These properties are critical for fracturing design

Petrophysical Analysis

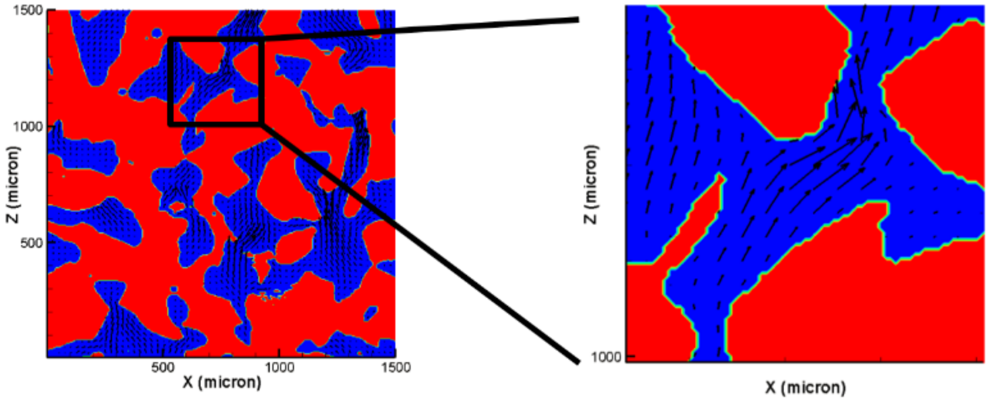
- RockEval tests for total organic carbon (TOC)
- X-ray Diffraction Analysis (XRD) for mineralogy
- Permeability measurement using pulse decay permeameter (PDP-200), NanoK, and SMP-200 (all equipment from CoreLab)
- Fracture Conductivity Cell
- These properties are critical for finding the “sweet spots”

Core Analysis Workflow



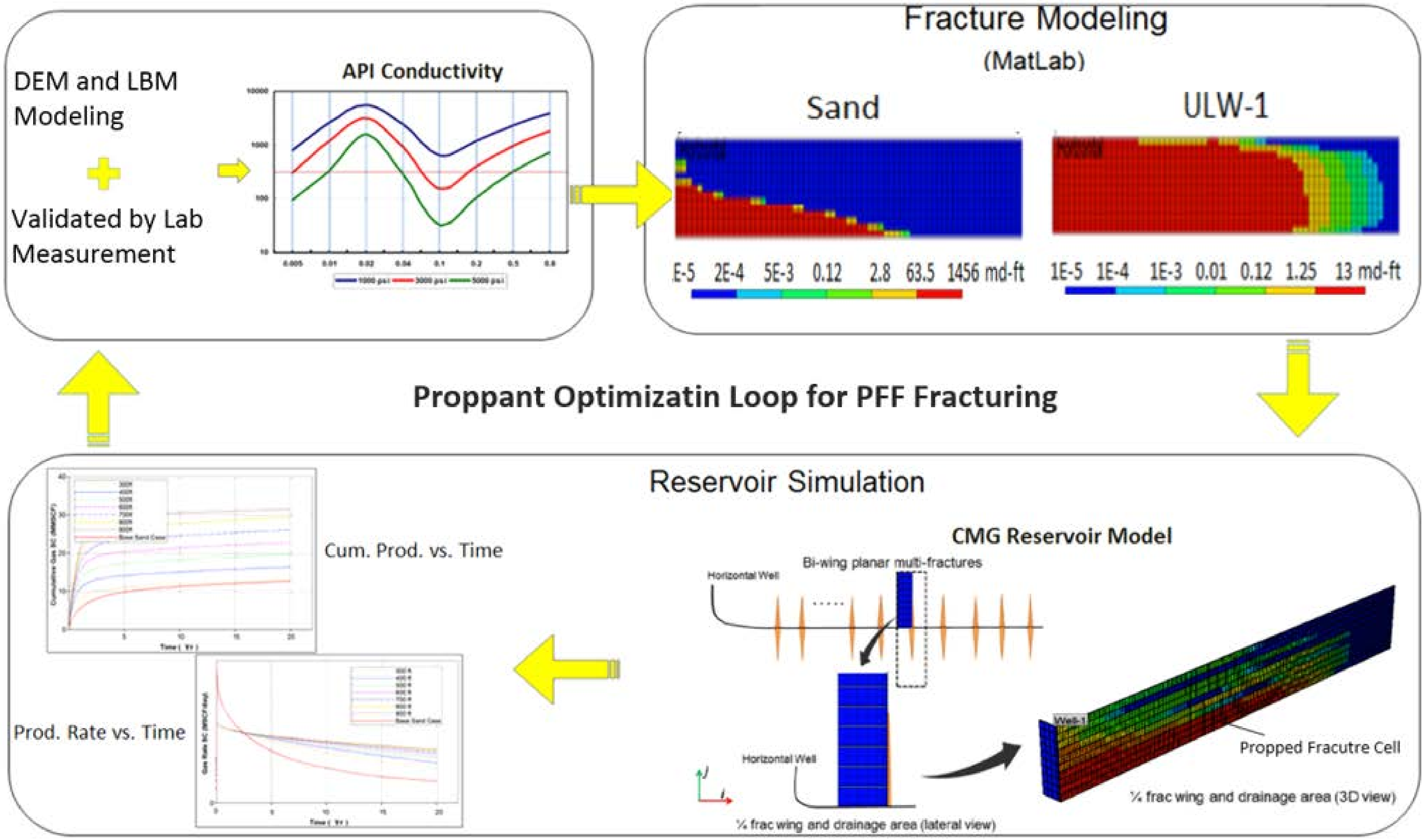
0.25 mm/pixel | 25 µm/pixel | 64 nm/pixel

3D, multiscale X-ray CT scanning from core to nm scales.



- Lattice Boltzmann (LB) Method is used for pore flow simulation based on the CT images.
- It is a meso-scale numerical method to recover macroscopic hydrodynamics.

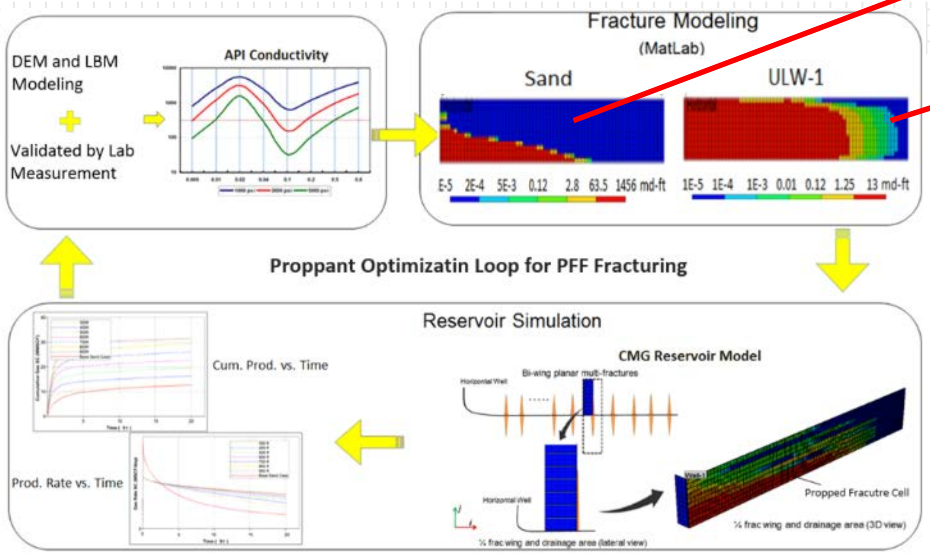
Optimization of Fracturing and Proppant Placement



Proppant pumping optimization to achieve the highest return on fracturing investment (ROFI) (Gu et al., 2017, SPE-185071).

VIRGINIA TECH

Optimization of Fracturing and Proppant Placement

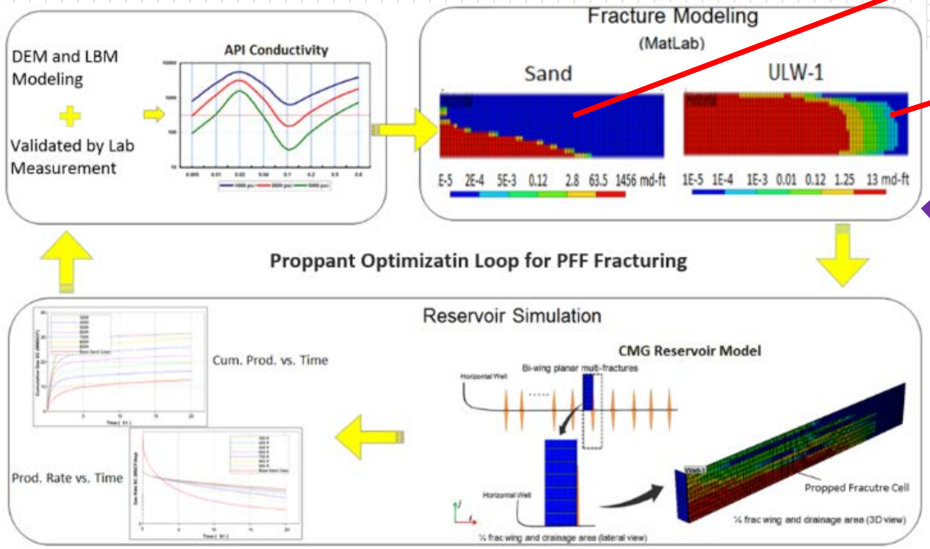


Regular sand proppant:
Fast settlement near the well

Ultra-light-weight proppant:
Uniform placement along fracture

VIRGINIA TECH

Optimization of Fracturing and Proppant Placement

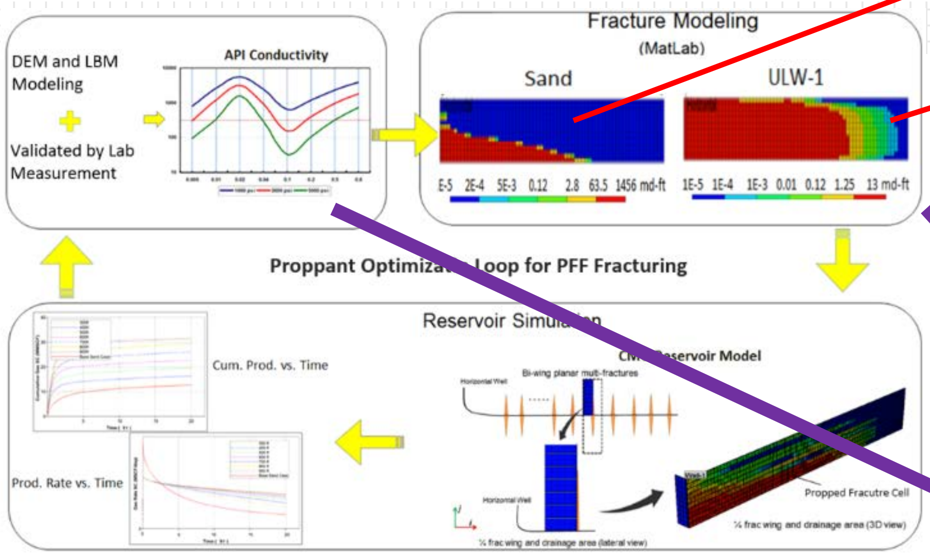


Regular sand proppant:
Fast settlement near the well

Ultra-light-weight proppant:
Uniform placement along fracture

Fracture modeling gives *proppant concentration* (lb/ft^2) distribution in fracture length and height directions

Optimization of Fracturing and Proppant Placement



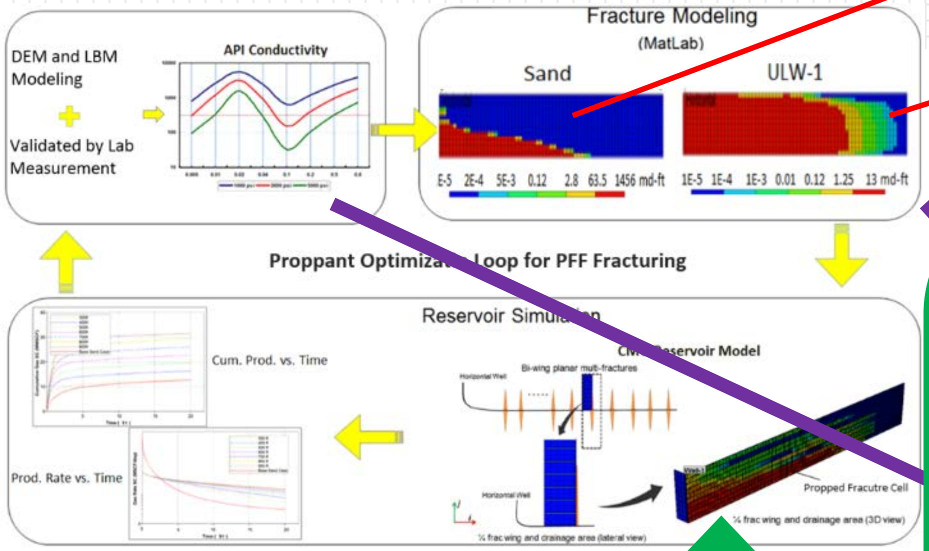
Regular sand proppant:
Fast settlement near the well

Ultra-light-weight proppant:
Uniform placement along fracture

Fracture modeling gives *proppant concentration* (lb/ft^2) distribution in fracture length and height directions

Pore-scale, DEM/LB-coupled modeling gives "*fracture conductivity vs proppant concentration*" curves under various closure pressures (Fan et al., 2018)

Optimization of Fracturing and Proppant Placement



Regular sand proppant:
Fast settlement near the well

Ultra-light-weight proppant:
Uniform placement along fracture

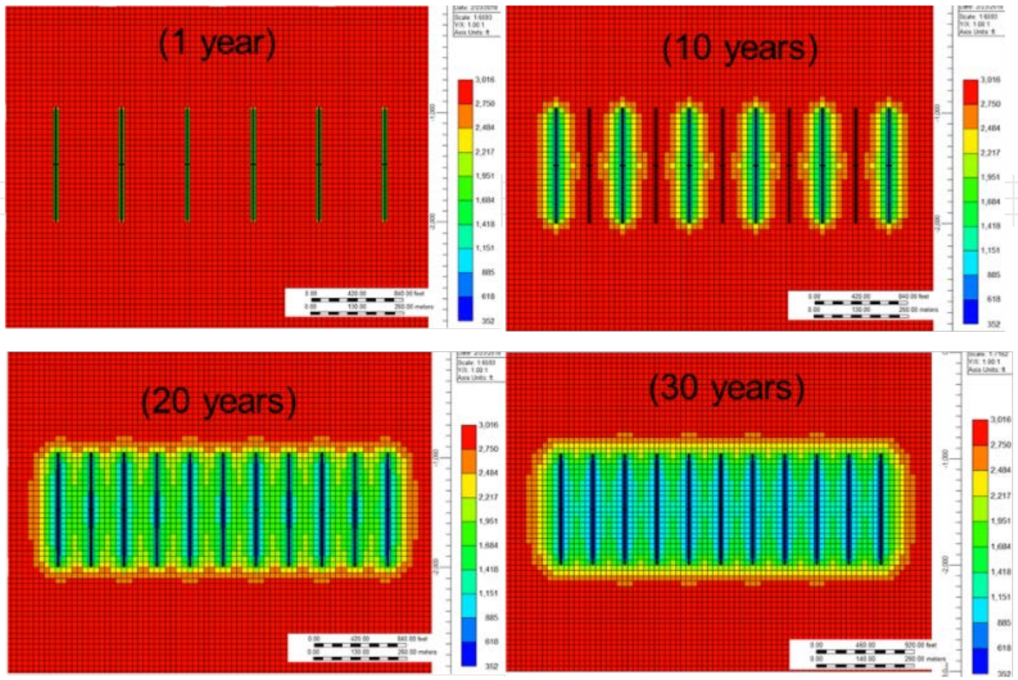
Fracture modeling gives *proppant concentration* (lb/ft^2) distribution in fracture length and height directions

Pore-scale, DEM/LB-coupled modeling gives “*fracture conductivity vs proppant concentration*” curves under various closure pressures (Fan et al., 2018)

These two pieces of information are combined to obtain *fracture conductivity* distribution in the hydraulic fracture for larger-scale reservoir simulation

Reservoir Simulation Model

- Simulations will be used to design the ESUP Field Laboratory, including designs for drilling, completions, and monitoring.
- The modeling effort will include the use of a commercial reservoir simulator (if applicable) and the development of an in-house simulation tool.



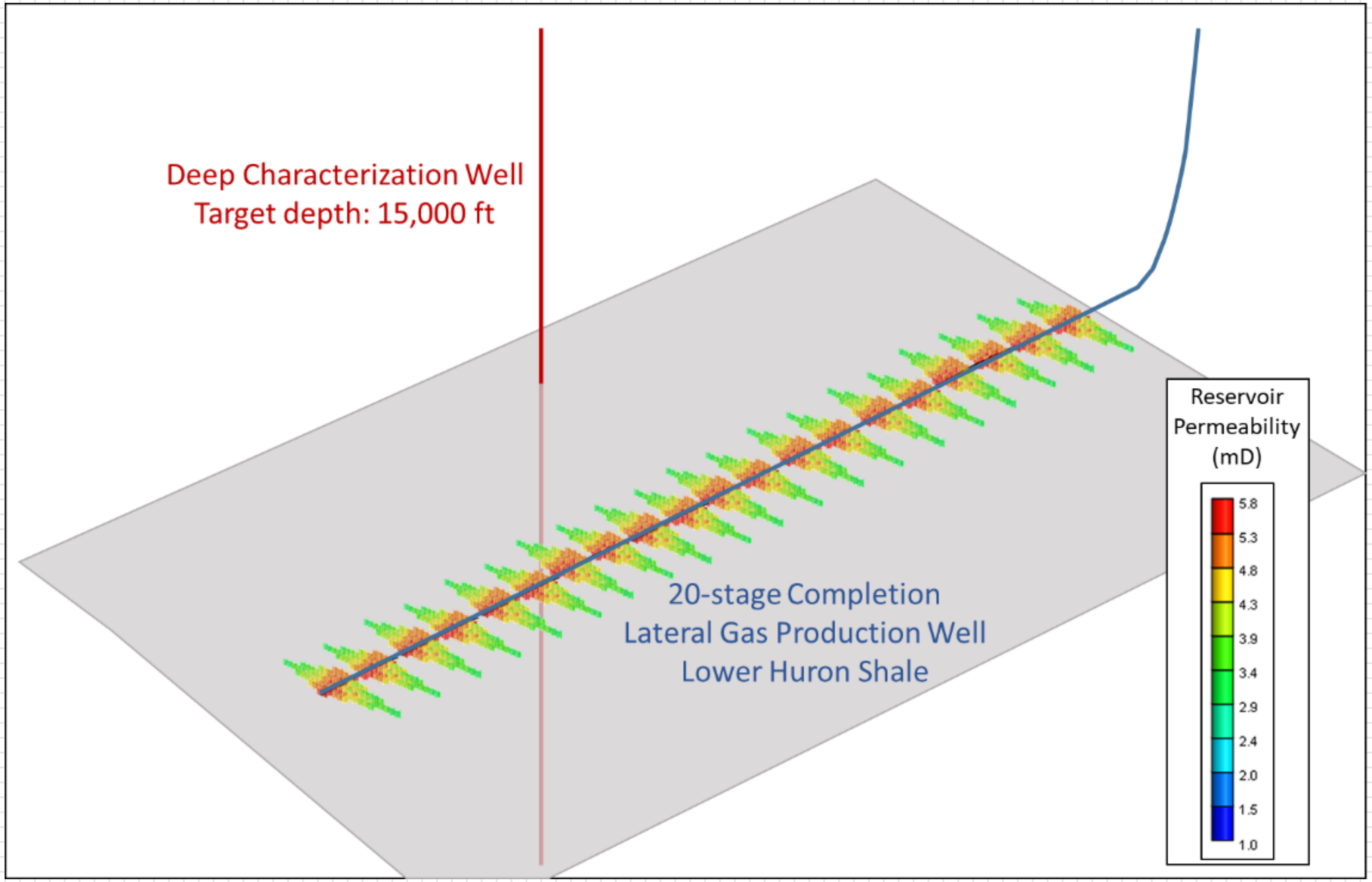
- The in-house simulation model includes diffusion and nano-porous media confinement effects, and that can simulate reservoir response to hydraulic fracturing with non-aqueous fluids such as CO2.
- Fast, yet accurate, compositionally-extended black oil models will be developed that can incorporate the complexities associated with shale reservoirs during treatment and production.

VIRGINIA TECH

Monitoring Program

- Monitoring + Operations Timeline
  - Historical data→ Simulations→ Define Area of Review (AOR)
  - Baseline data acquisition
  - Monitoring while Drilling
  - Characterization data→ HF design
    - Non-aqueous fluid
    - Alternative/multiple proppants
  - Monitoring of HF treatment
  - Post-operations monitoring

Schematic Overview of ESUP Field Lab

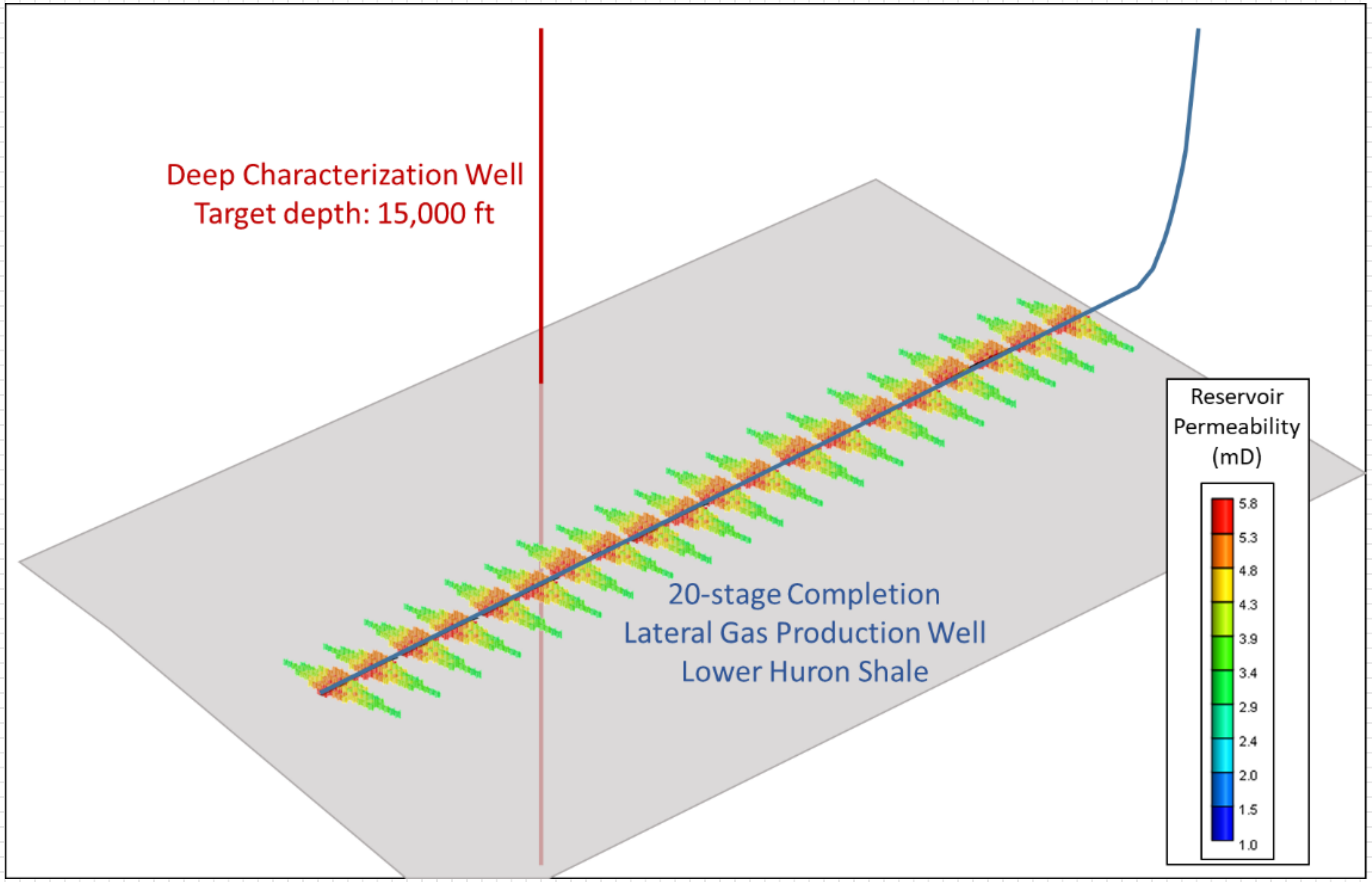


VIRGINIA TECH

Monitoring Program

- Potential Methods: Atmospheric, Near-surface, Subsurface, Sub-reservoir Technologies
  - Offset gas and water sampling
  - Tracer studies
  - Reservoir imaging (e.g., microseismic monitoring)
  - Deep monitoring installation in Deformation monitoring
  - Production monitoring

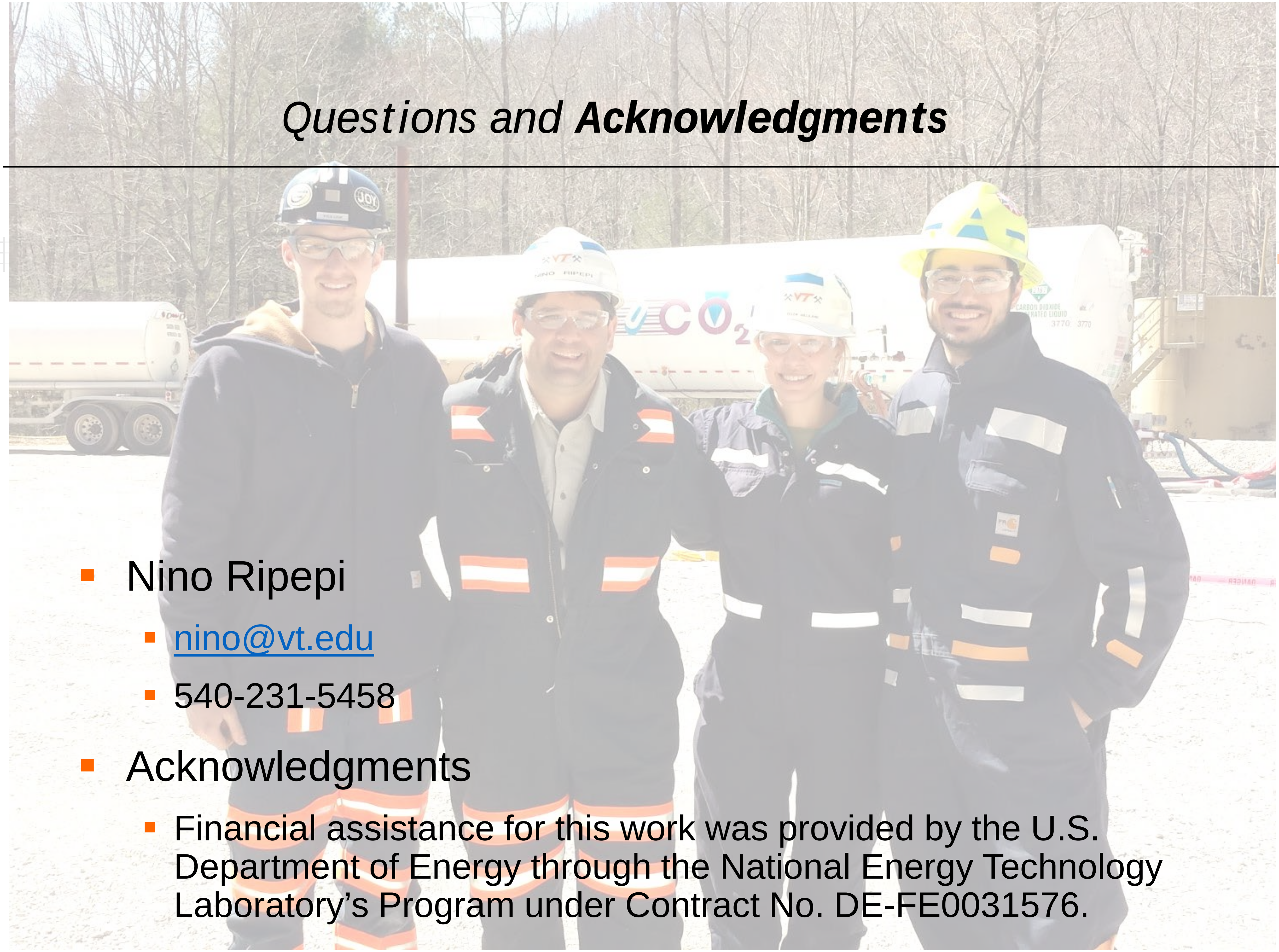
Schematic Overview of ESUP Field Lab



- Deliverables: Sampling and Analysis Plan, Initial (Baseline) Monitoring Report, Final Scientific/Technical Report, NETL-EDX Final Project Files

VIRGINIA TECH

Questions and ***Acknowledgments***



- Nino Ripepi
  - nino@vt.edu
  - 540-231-5458

- Acknowledgments

  - Financial assistance for this work was provided by the U.S. Department of Energy through the National Energy Technology Laboratory's Program under Contract No. DE-FE0031576.

VIRGINIA TECH