Integration of Airborne Electromagnetic and Sediment Log Data for Characterization of the High Plains Aquifer in Portions of Groundwater Management District 4

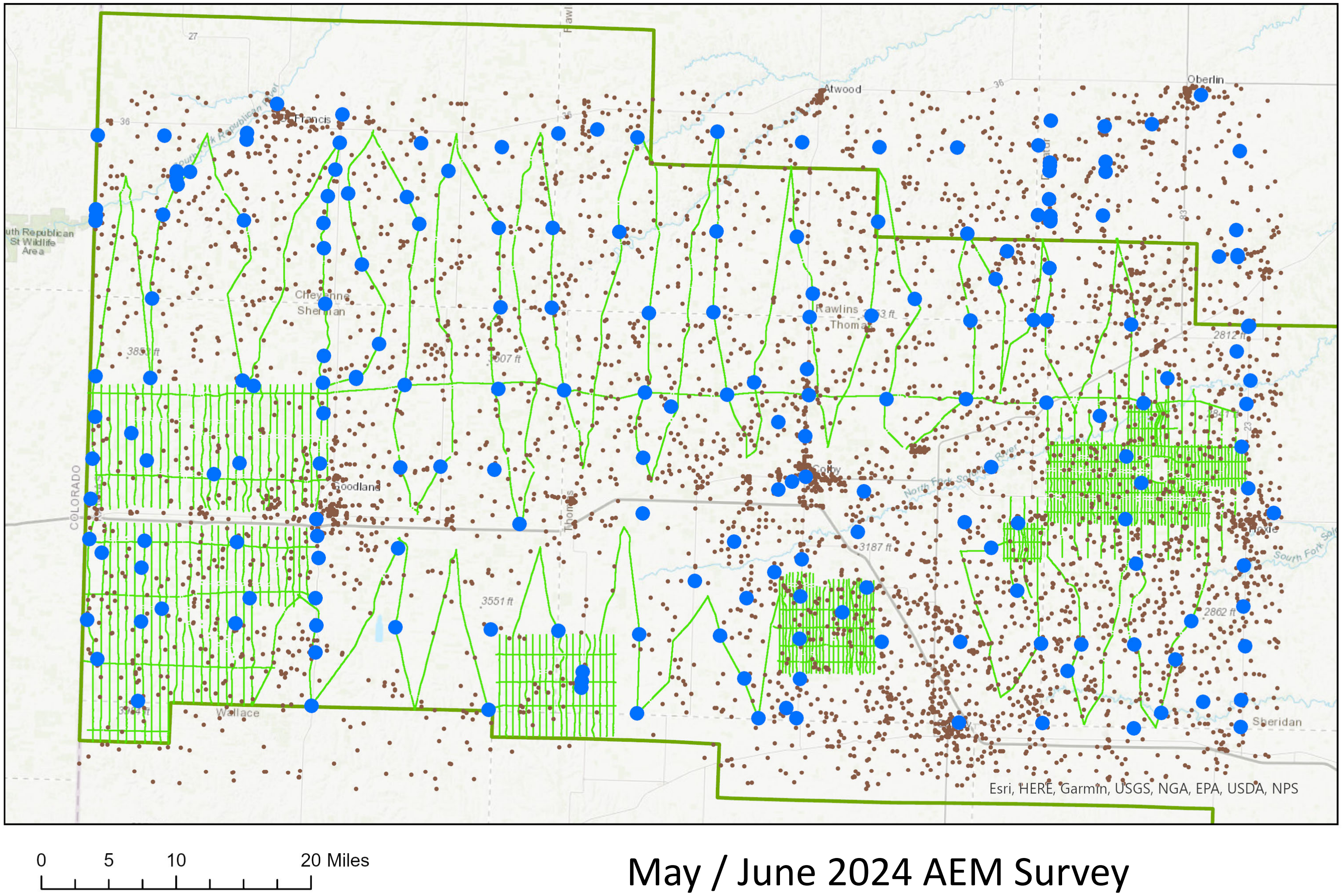
Geoffrey C. Bohling, Gaisheng Liu, Jon J. Smith, Diana Ortega-Ariza, Tony Layzell, and James J. Butler, Jr.

Kansas Geological Survey

Governor's Conference on the Future of Water in Kansas

Manhattan, KS, Nov. 14, 2024

AEM Soundings and Sediment Logs



May / June 2024 AEM Survey

Green: AEM Soundings (~138,000) Blue: Bulletin Logs (208) Brown: WWC5 Logs (~5,500)

Integration Motivation

- Sediments are primary control on aquifer permeability and storage
- Logs describe sediments directly but are
  - Qualitative and subjective
  - Imprecisely located (most by legal coordinates)
  - Sparser (~2.5-mile well spacing)
- AEM data reflect sediments indirectly but are
  - Quantitative
  - Precisely located
  - Denser (~85 feet along flight lines, ¼- to ½-mile line spacing in detailed areas)
- Integrate for quantitative, dense representation of sediment distribution (hydrostratigraphy)

Sediment Logs

- Bulletin Logs
  - From KGS county geological bulletins (1945-1969) and a 1969 USGS report
  - High quality, detailed logs prepared by geologists
  - Sparsely distributed
- WWC5 Logs
  - Water well drillers' logs in the KGS's WWC5 database
  - Highly variable in quality and significantly less detailed
  - Much more abundant

Typical Logs

WWC5

Lithologic Log (Log data entered by KGS.)		
	From: 0 ft. **to** 40 ft.	top soil
	From: 40 ft. **to** 46 ft.	sand
	From: 46 ft. **to** 85 ft.	sand, clay
	From: 85 ft. **to** 91 ft.	sand and sand strips
	From: 91 ft. **to** 115 ft.	sand, fine
	From: 115 ft. **to** 122 ft.	sand, clay
	From: 122 ft. **to** 150 ft.	sand and sand rock strips
	From: 150 ft. **to** 156 ft.	sand rock, hard
	From: 156 ft. **to** 160 ft.	good sand
	From: 160 ft. **to** 172 ft.	sandy clay and sand strips
	From: 172 ft. **to** 174 ft.	sand
	From: 174 ft. **to** 177 ft.	sandy clay
	From: 177 ft. **to** 178 ft.	ochre

Bulletin*

6-38-31ccc. Sample log of test hole in the SW cor. sec. 31, T. 6 S., R. 38 W.; drilled August 1949. Surface altitude, 3,527.5 feet.	**Thickness, feet**	**Depth, feet**
Quaternary--Pleistocene		
Sanborn formation--Peoria silt member		
Silt, dark-brown	2	2
Silt and fine to very fine sand; contains stringers of soil caliche, 10 to 25 feet	23	25
Tertiary--Pliocene		
Ogallala formation		
Silt and clay, sandy, light-brown	8	33
Gravel, coarse, and some plastic silt and clay	8	41
Silt and fine sand, plastic, brown; contains sand and gravel at base	9	50
Gravel, coarse; contains a little silt and fine sand	3	53
Silt and fine sand, plastic, brown; contains sand and gravel	8	61
Mortar bed, soft	18	79
Sand, medium to coarse, and fine to coarse gravel	15	94
Sand, fine, and plastic silt	3	97
Sand, fine to coarse; contains some fine gravel	6	103
Sand, fine to coarse, and fine to coarse gravel	4	107
Sand, fine to coarse, and fine to coarse gravel; contains brown plastic silt and clay	6	113
Silt and clay, sandy, brown	17	130
Sand, fine to coarse, and fine gravel, partially cemented; contains some silt and very fine sand	25	155
Silt and very fine sand, plastic, brown; contains more sand from 165 to 170 feet	15	170
Silt and very fine sand, plastic, brown; contains much sand	20	190
Sand, fine to coarse; contains silt and clay	20	210
Sand, fine to medium; contains silt and clay	68	278
Cretaceous--Gulfian		
Pierre shale		
Shale, yellow-brown to greenish	1	279
Shale, dark blue-black	9	288

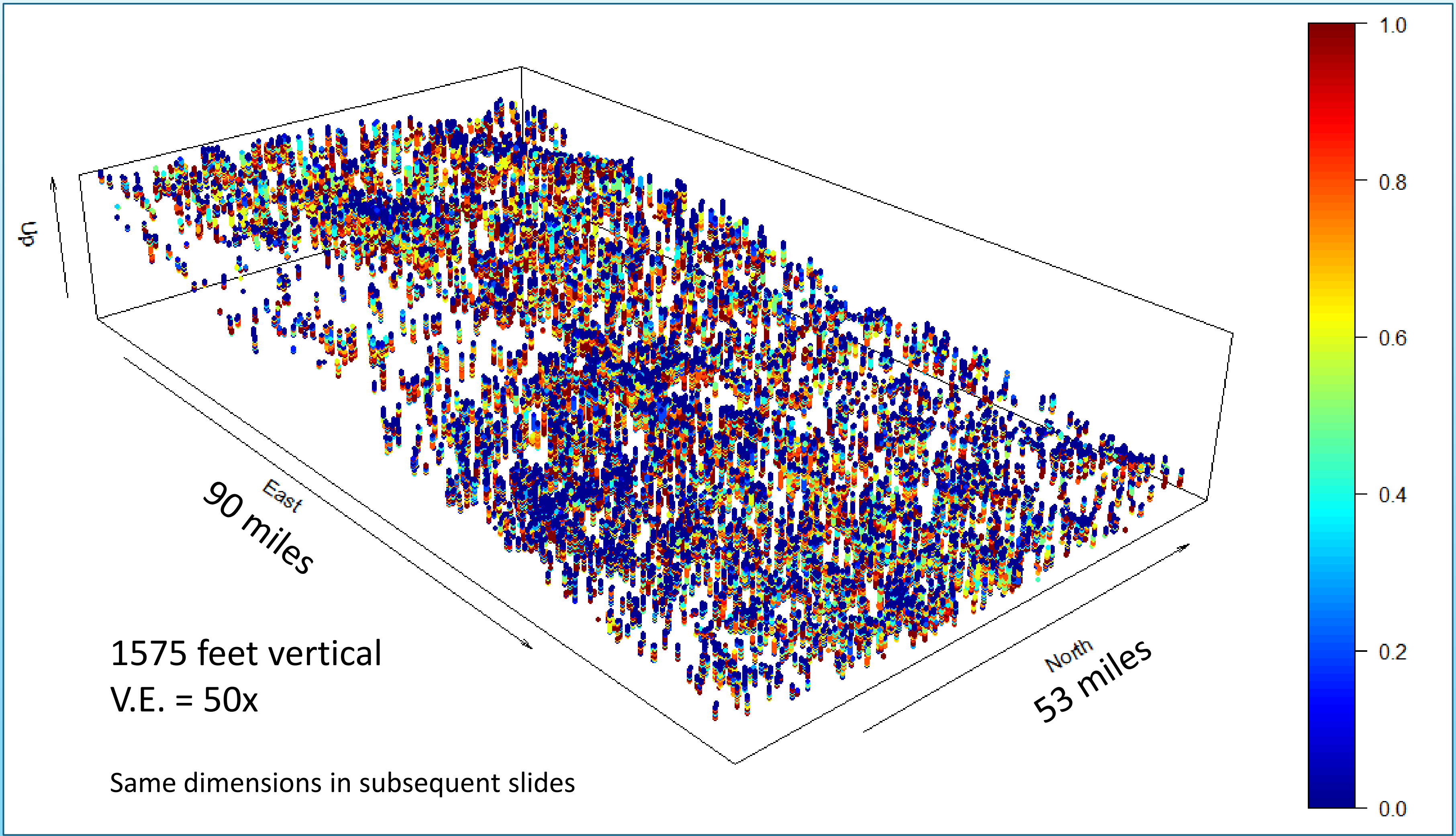
*G.C. Prescott, Jr., 1953, Geology and Ground-water Resources of Sherman County, Kansas, KGS Bulletin 105 (https://www.kgs.ku.edu/General/Geology/Sherman/index.html)

Fine / Coarse Split (Modest Start)

- Fine: shale, clay, silt[1] (incl. silty sands)
- Coarse: sand & gravel (incl. cemented[2] s & g)
- Overall proportions (whole area):
  - Bulletin: 42% fine, 58% coarse
  - WWC5: 45% fine, 55% coarse
- Will work with finer divisions (more sediment types) later

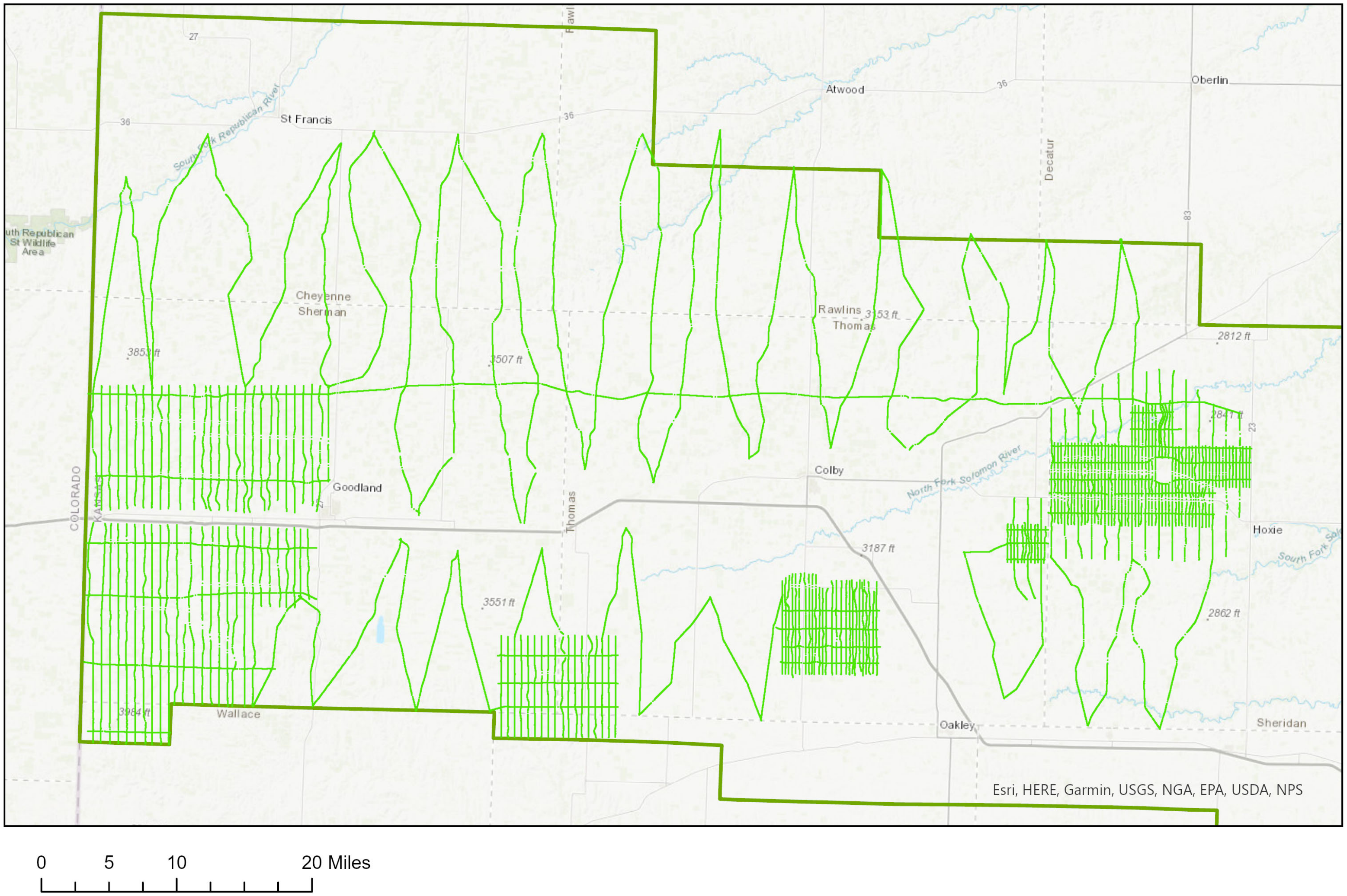
[1]silt: hydraulically and electrically intermediate
[2]cement: reduces permeability but may be difficult to distinguish electrically

Proportion Coarse in Logs



Bulletin (208) and WWC5 (~5,500) logs; abundant but imprecise
Proportion Fine = 1 – Proportion Coarse (invert color scale)

AEM Flight Lines



~2,500 miles; ~138,000 sounding locations at ~85 ft spacing along lines

How AEM works:

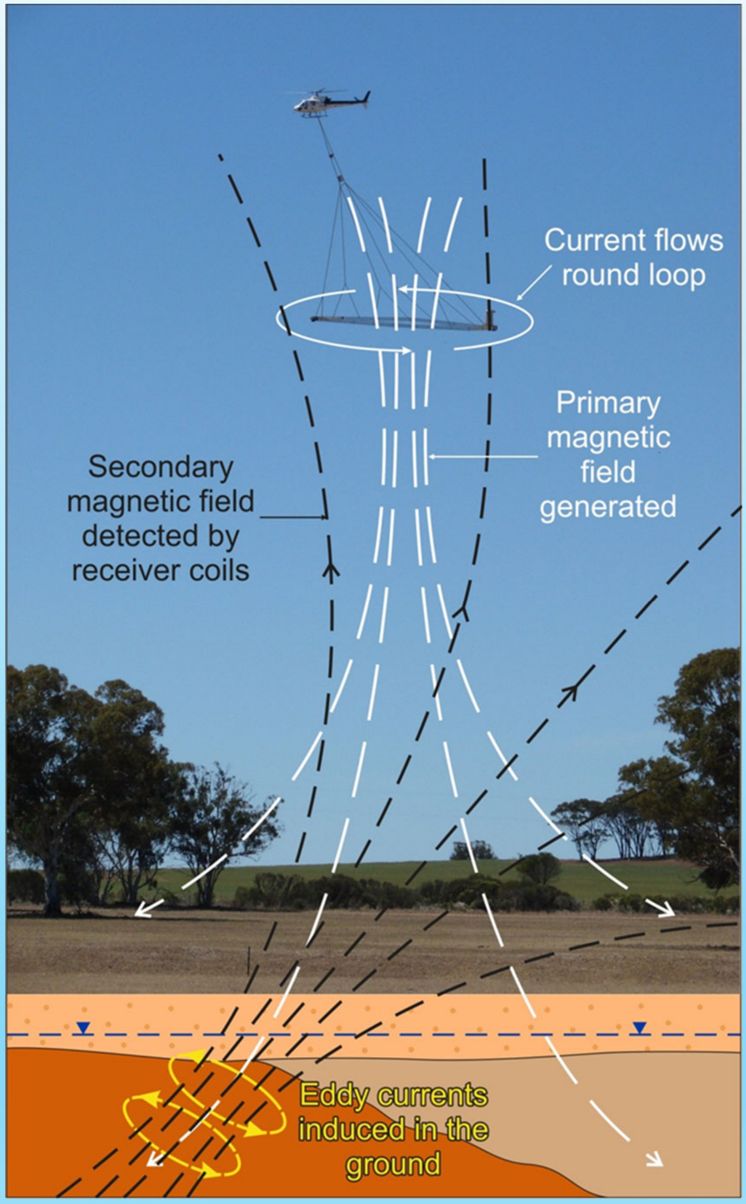
The transmitter fires discrete electromagnetic pulses that generate a primary magnetic field.

The pulses induce eddy currents in the subsurface that generate a secondary magnetic field, i.e. the “response”.

The receiver “listens” for this response – **we are measuring** this secondary magnetic field.

This measurement provides information on electrical resistivities in the subsurface.

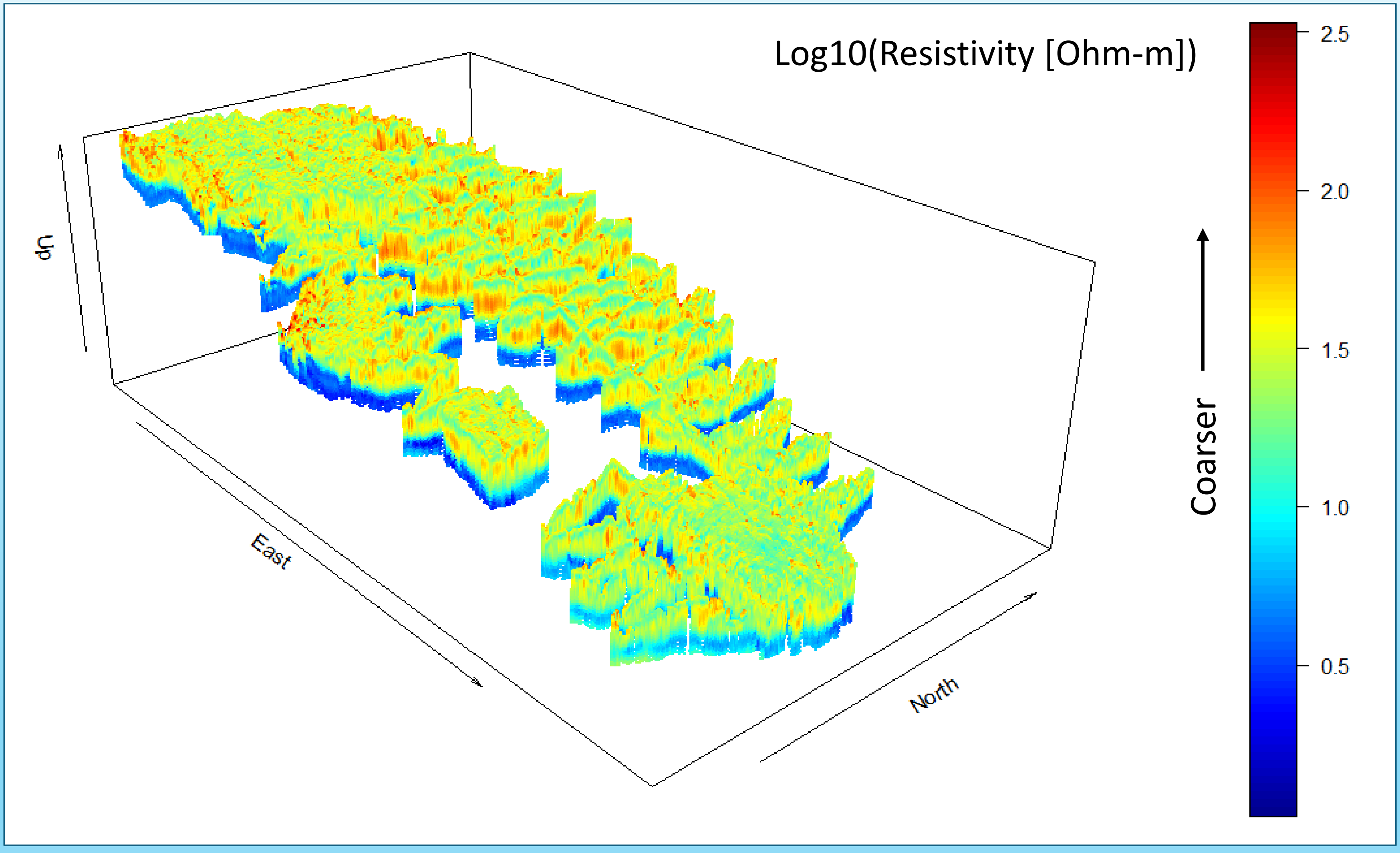
Sands and gravels have higher resistivities, while clays and shale bedrock have lower resistivities.



AEM Resistivities

- Subsurface resistivities estimated from AEM measurements in a way that encourages spatial continuity
  - *Smooth inversion*
  - Sediment logs used for QA/QC after the fact
- Stanford colleagues working on resistivity estimation process incorporating log info
  - *Sharp inversion*
  - Stay tuned

AEM Resistivities



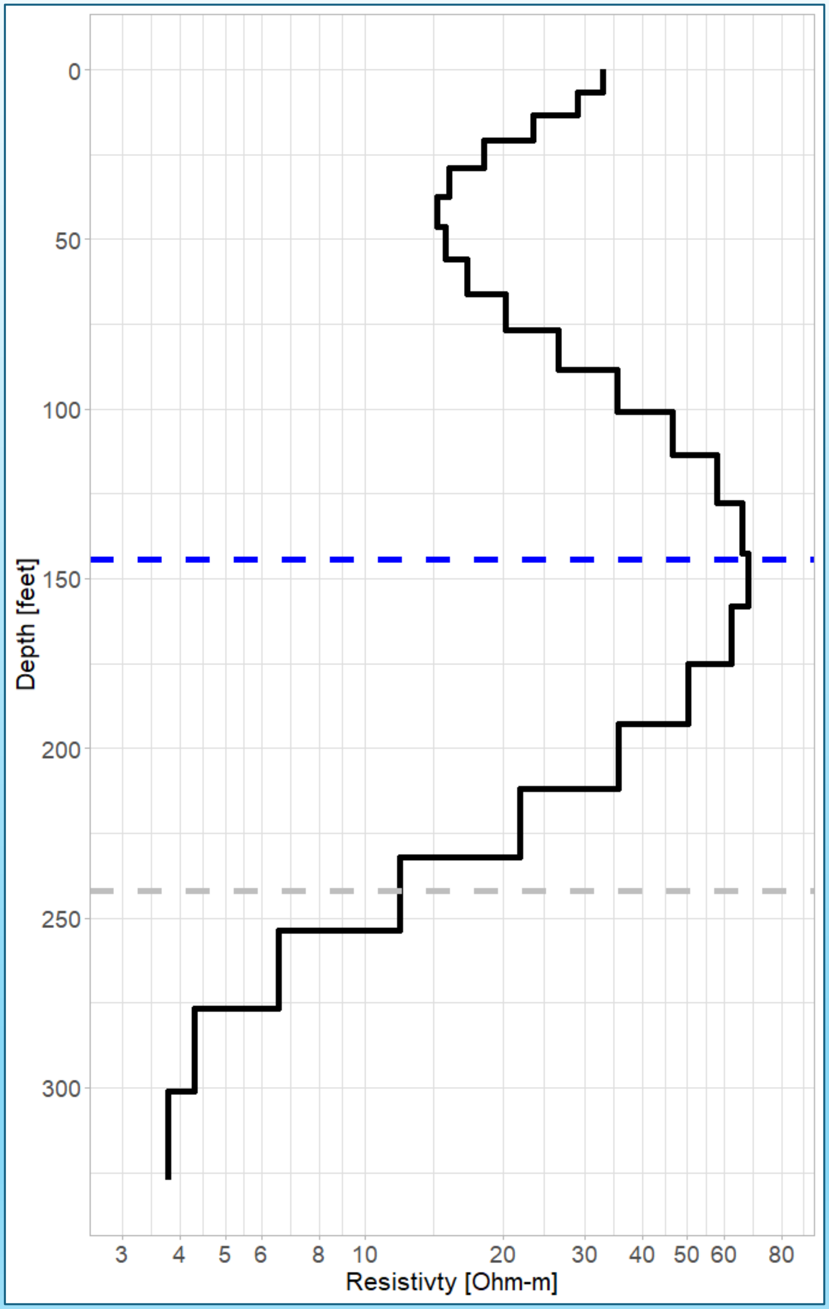
Filtered out a fair amount of bedrock

Single AEM Sounding

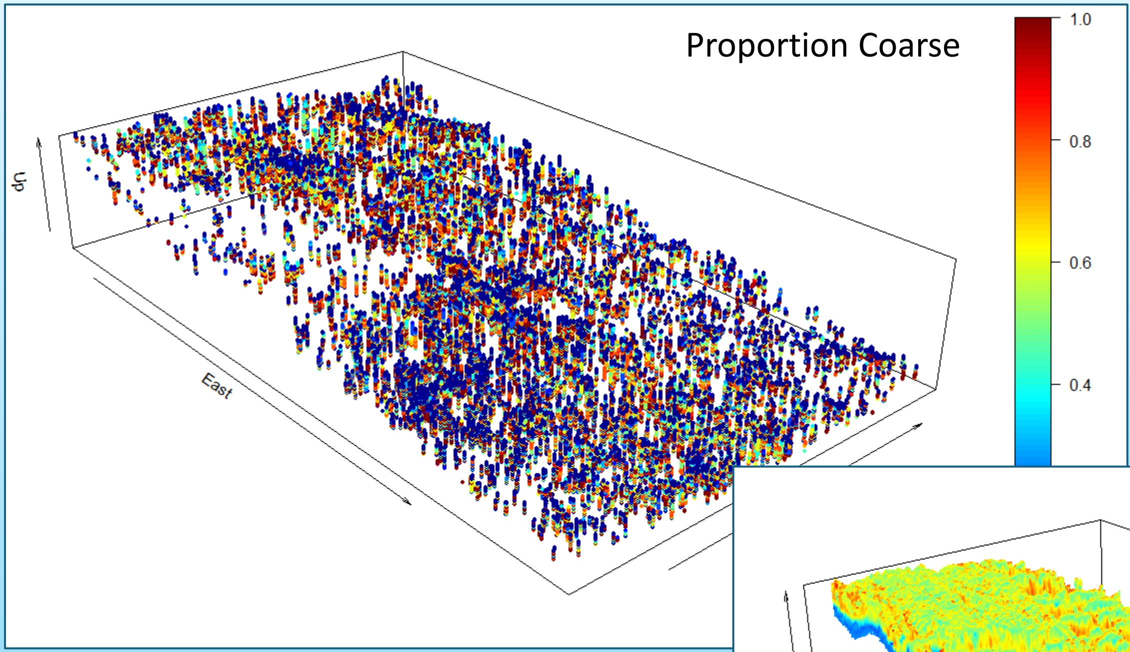
Layers increase in thickness with increasing depth, reflecting decreasing resolution with depth

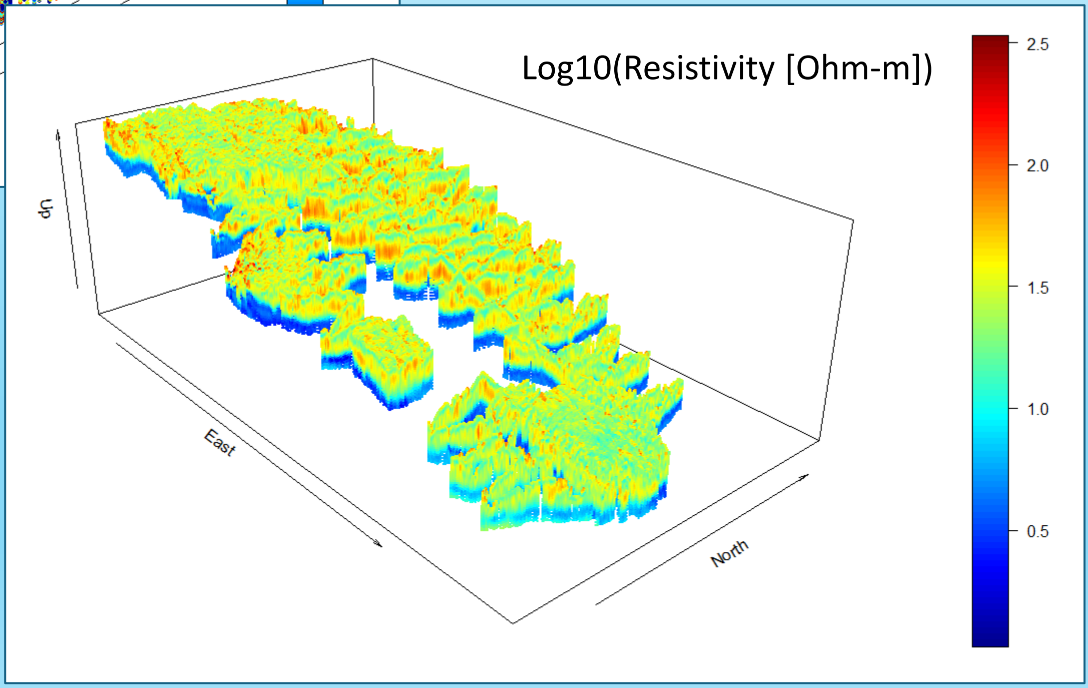
Blue dashed line: Interpolated Jan. 2024 water level (possibly lower in May/June); pore water reduces resistivity

Gray dashed line: Bedrock surface interpolated (smoothly) from logs



How to Integrate Logs and AEM?



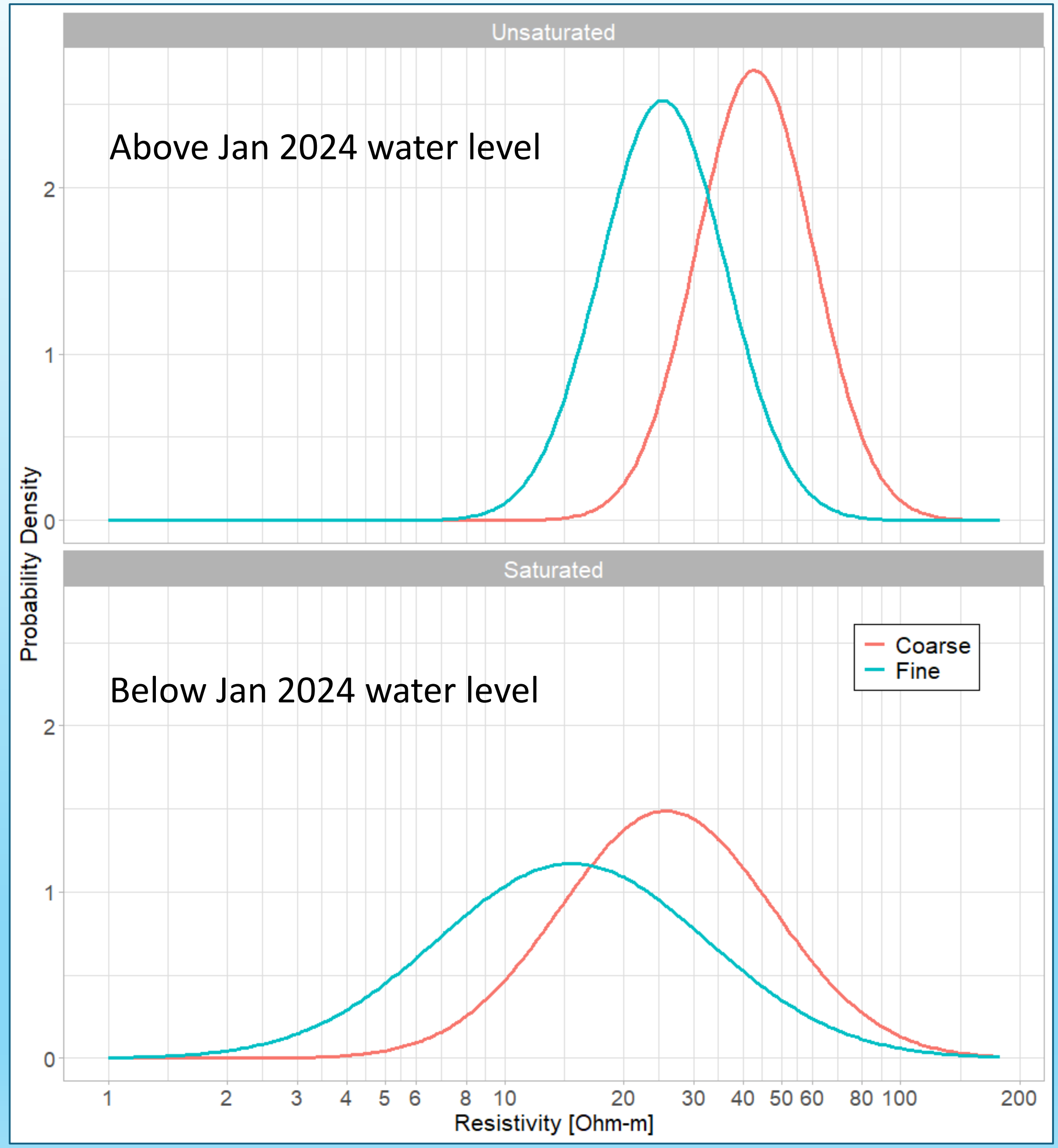


1. Estimate Resistivity Distributions

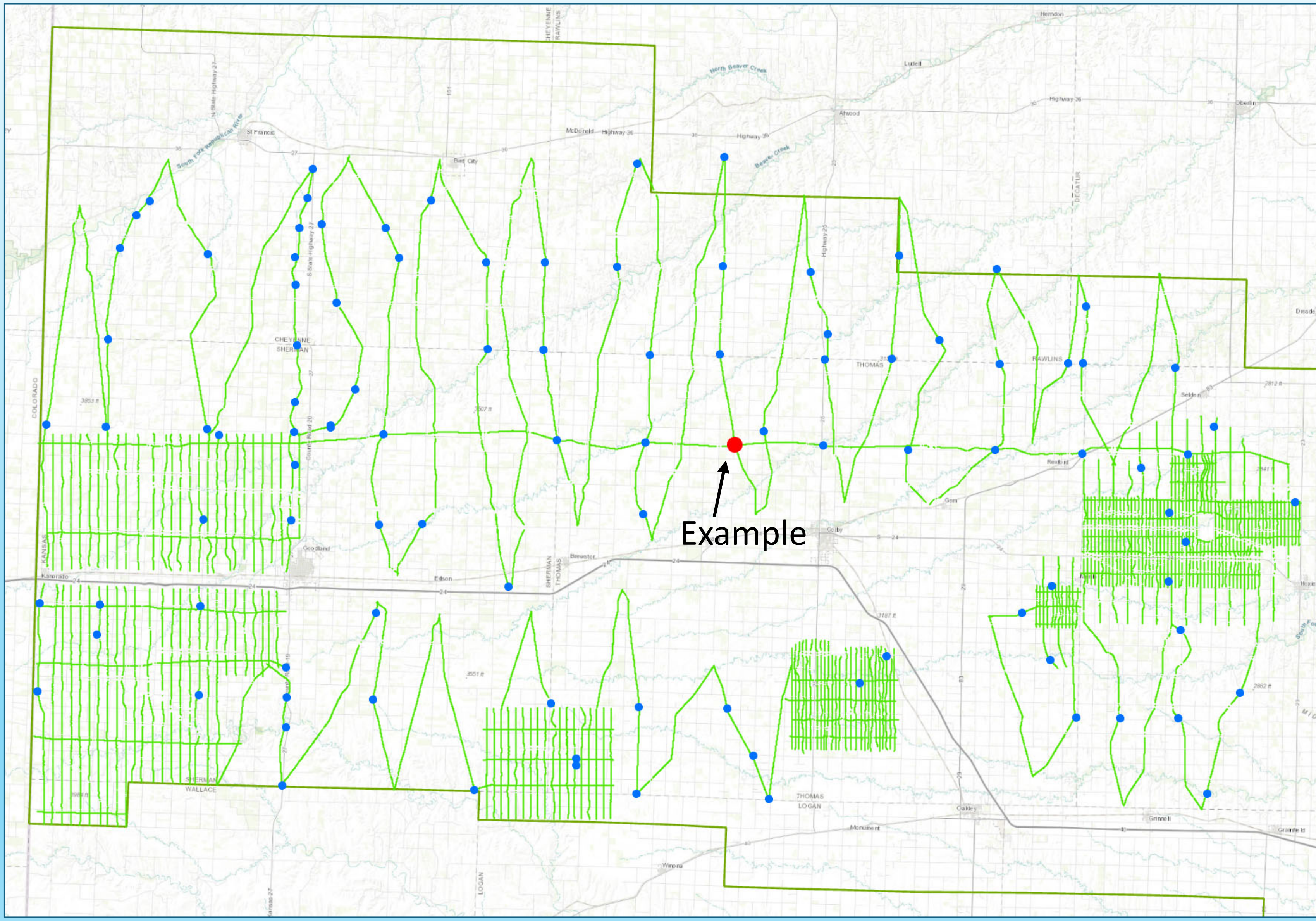
Distributions represent likelihood of different resistivities for each sediment type

From comparison of 103 pairs of bulletin logs and AEM soundings within 250 m (820 ft) of each other, segmented into common 10-foot intervals

Saturation reduces resistivity and increases variation



Bulletin Log / AEM Comparison Locations



Example Log / AEM Comparison

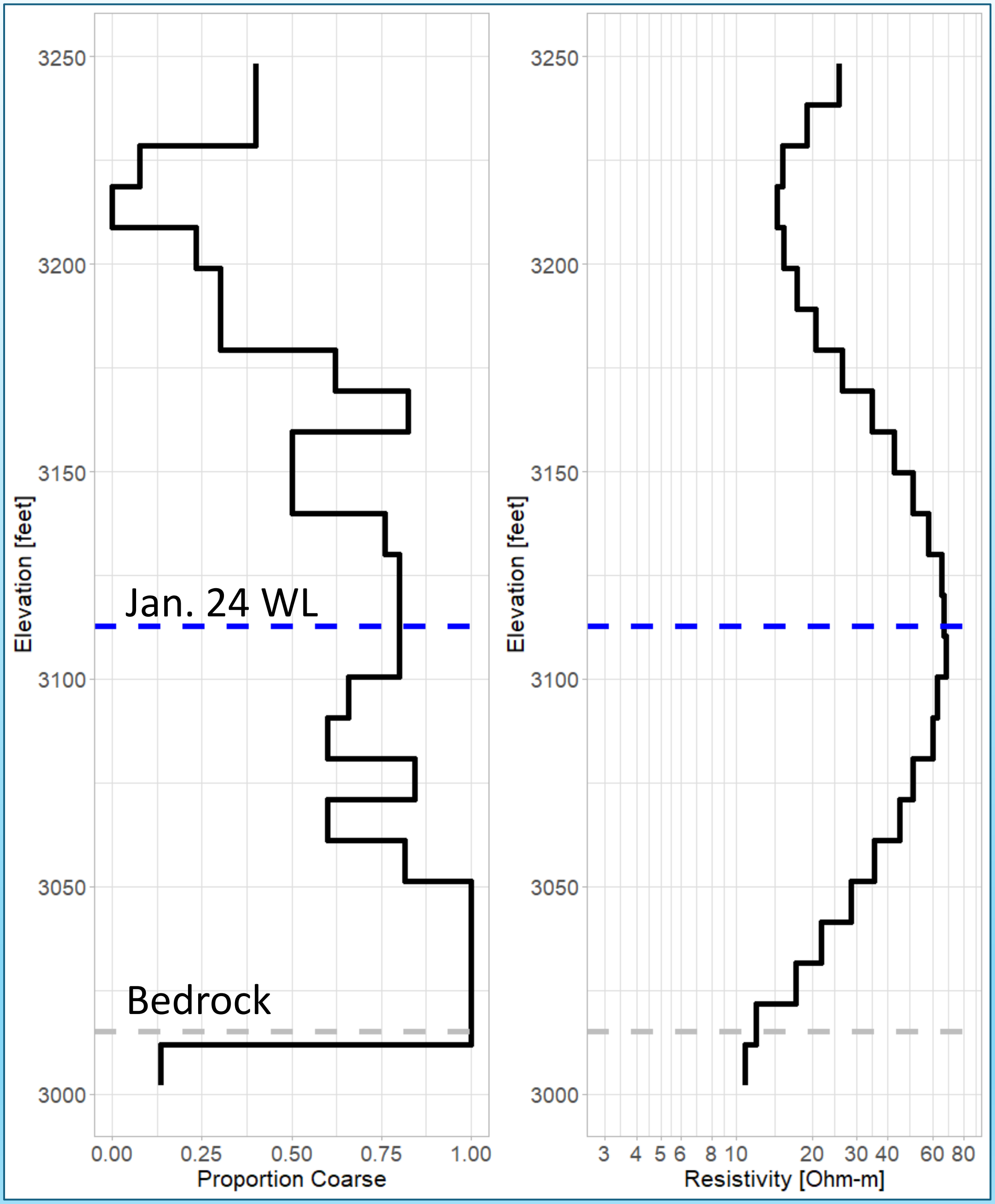
Bulletin log represented in terms of percentage coarse

Same AEM sounding as before

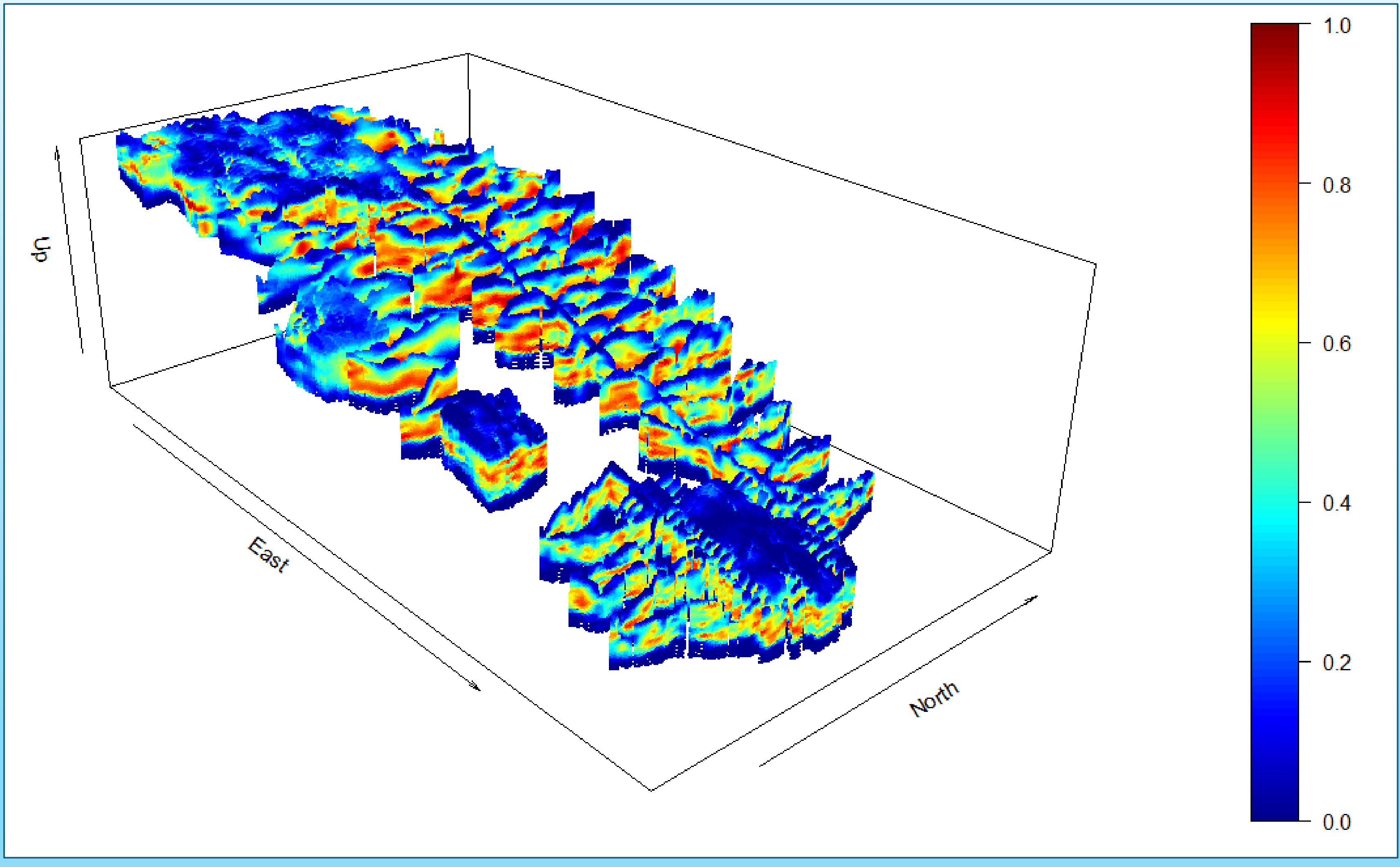
Nominally 11 feet apart

Both segmented to common 10-foot intervals on elevation

Total of 2,744 10-foot intervals over the 103 Log / AEM pairs



2. Co-Locate Data



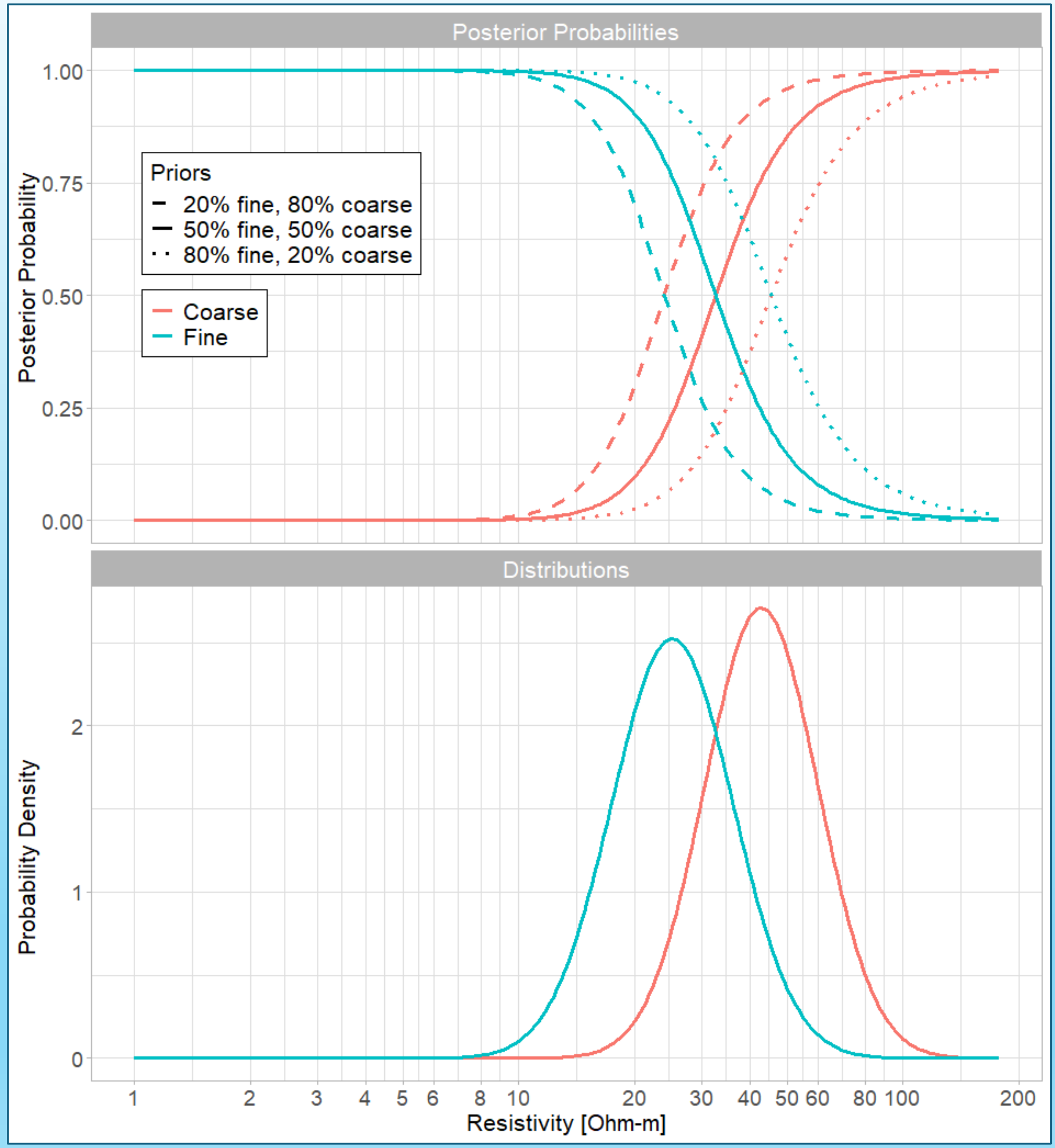
Proportion coarse interpolated from (all) logs to AEM data locations

3. Apply Bayes' Theorem

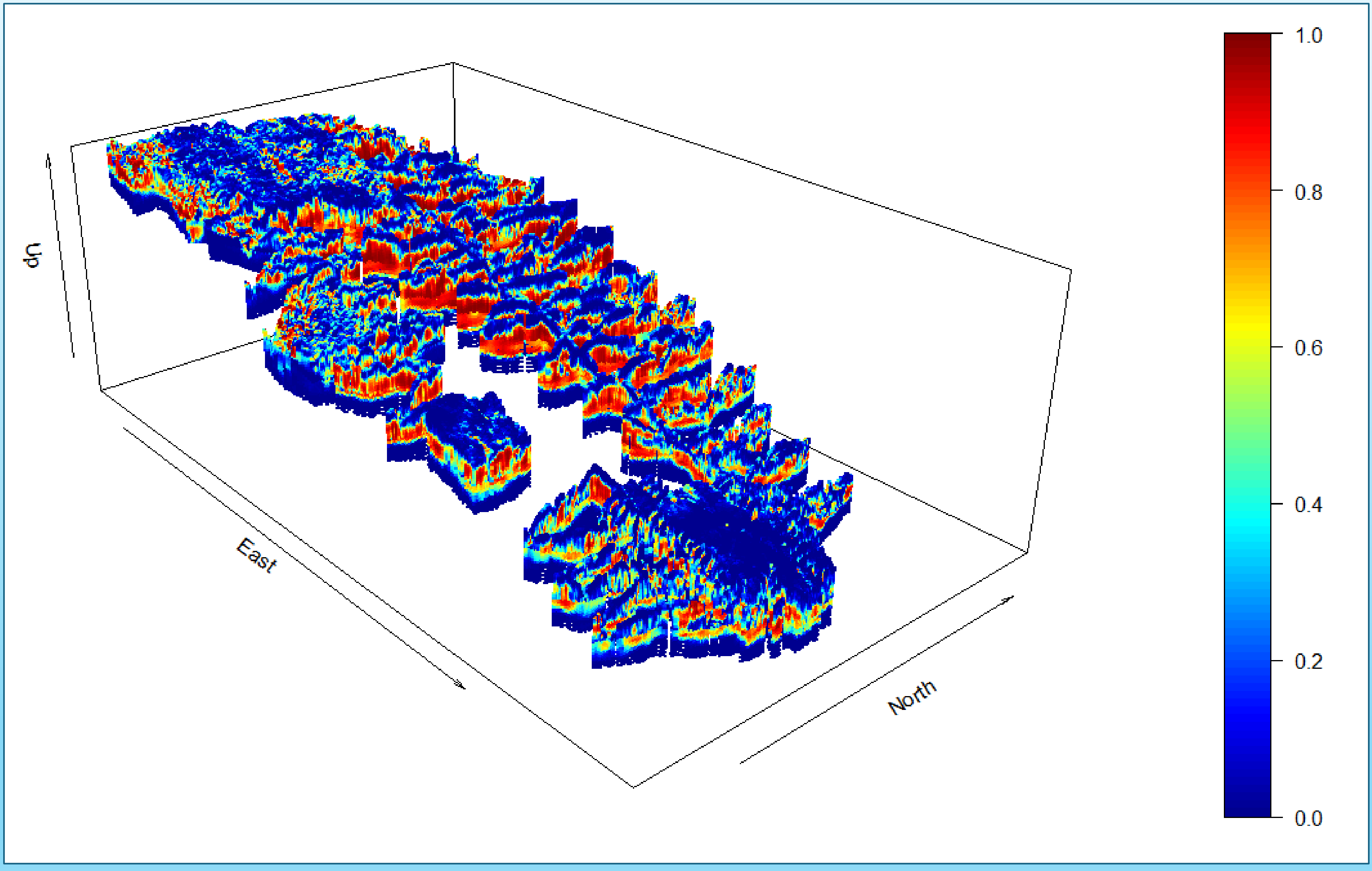
- Prior probabilities
  - Expectations before making a new observation
  - Prior probabilities of fine/coarse at each AEM data location interpolated from logs (previous slide)
- Posterior probabilities
  - Expectations after making new observation
  - Observations are AEM resistivity values
- Example: Logs say fines dominate at data location
  - *And* resistivity is low there
    - Resistivity supports prior expectation
    - Posterior probability fine > prior probability fine
  - *But* resistivity is high there
    - Resistivity contradicts prior expectation
    - Posterior probability fine < prior probability fine

Distributions to Posterior Probabilities, Unsaturated Zone

Increasing prior probability for fine pushes “decision point” (50/50 posterior probability) further to the right and vice versa

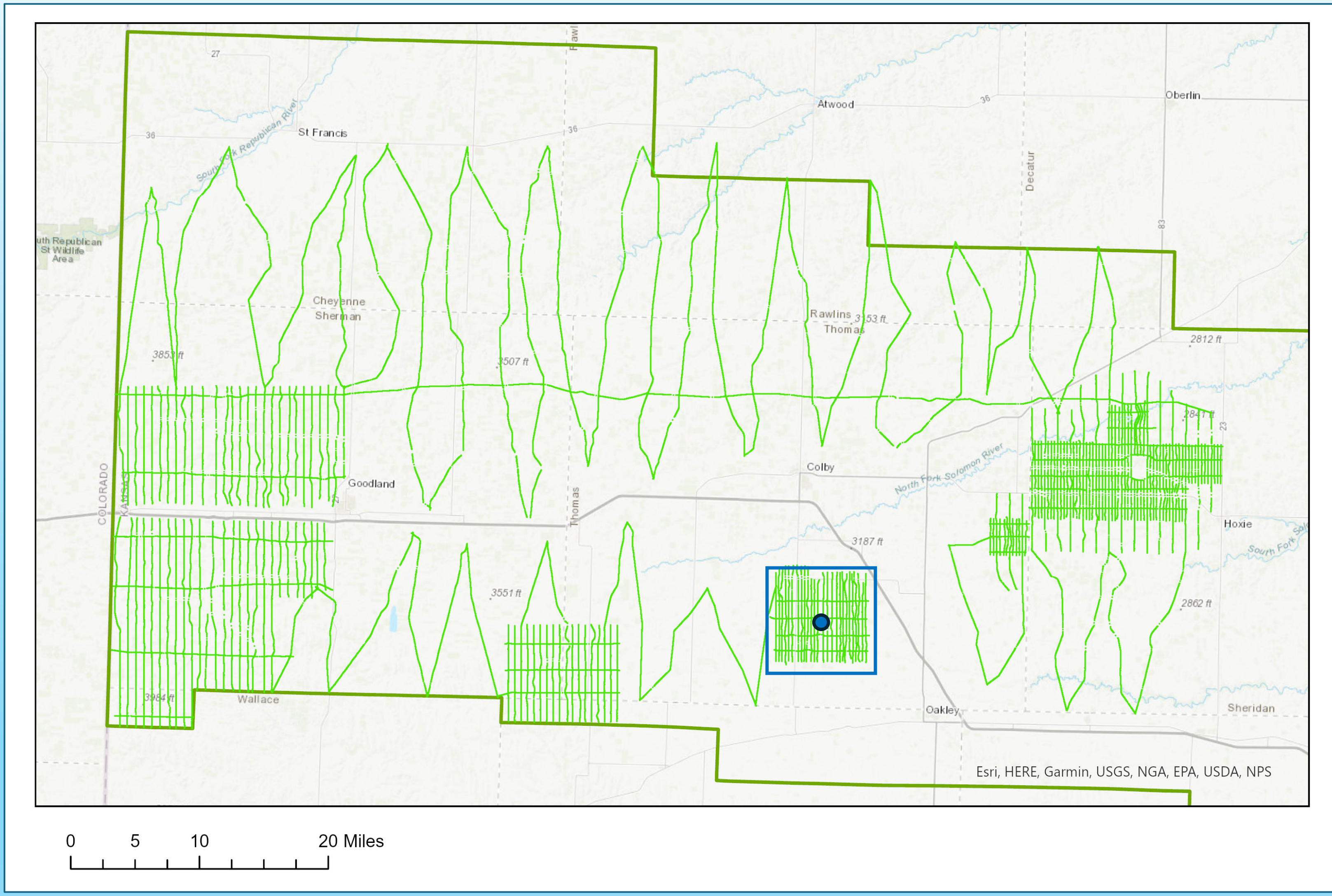


Posterior Probability Coarse



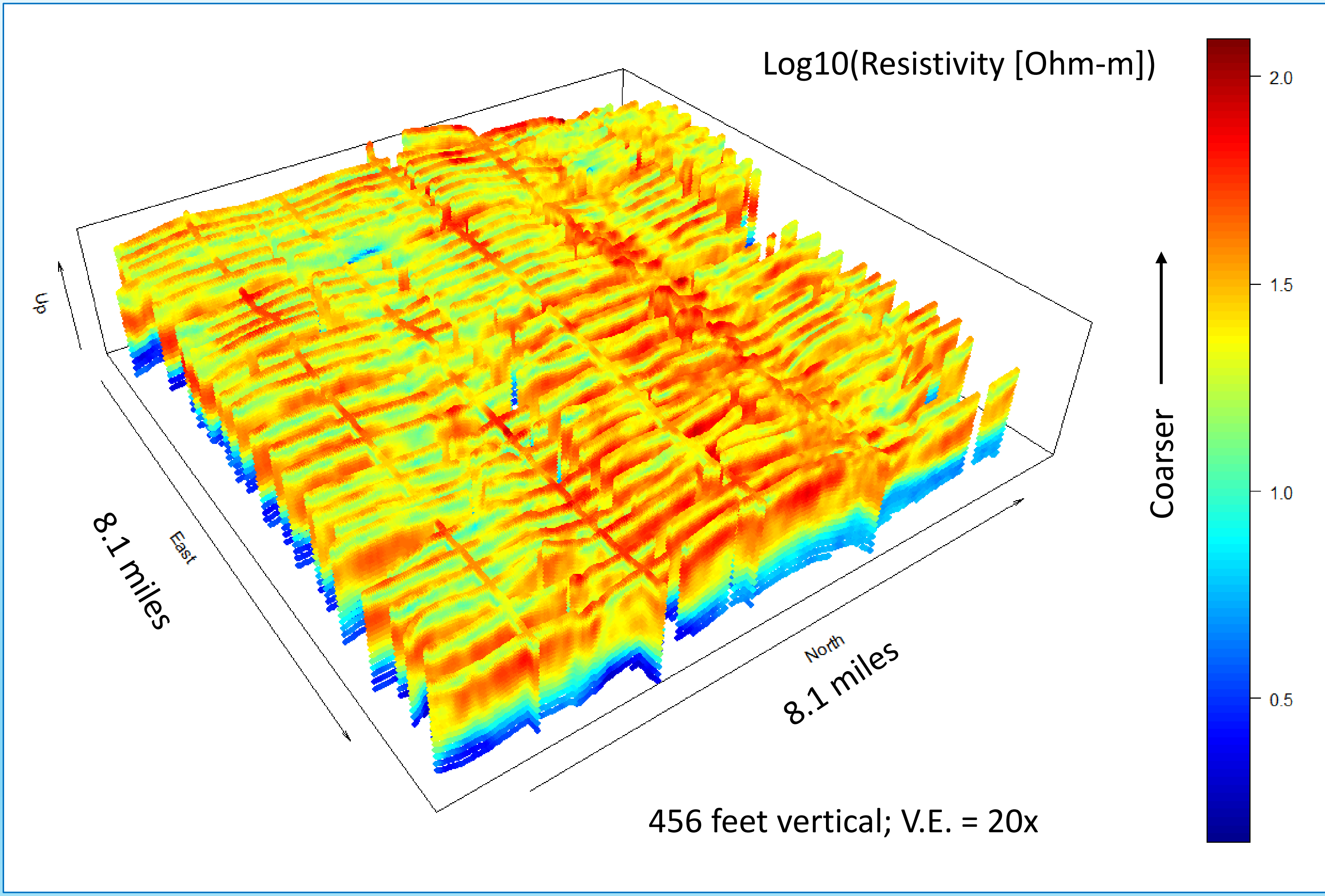
Generalized information from logs sharpened by local detail from AEM

Thomas County Index Well Area



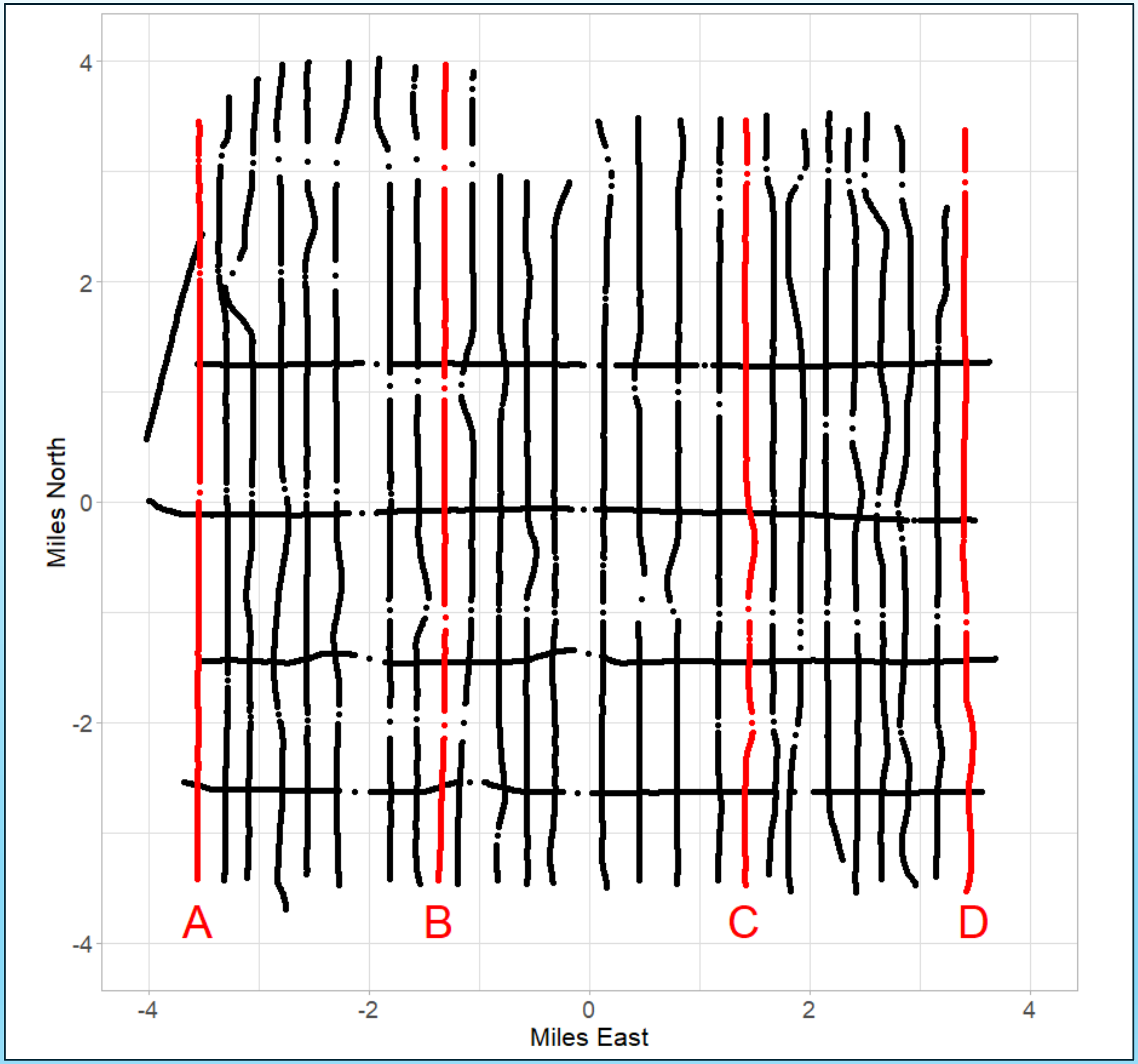
One of three original HPA index wells; hourly water level measurements since 2007

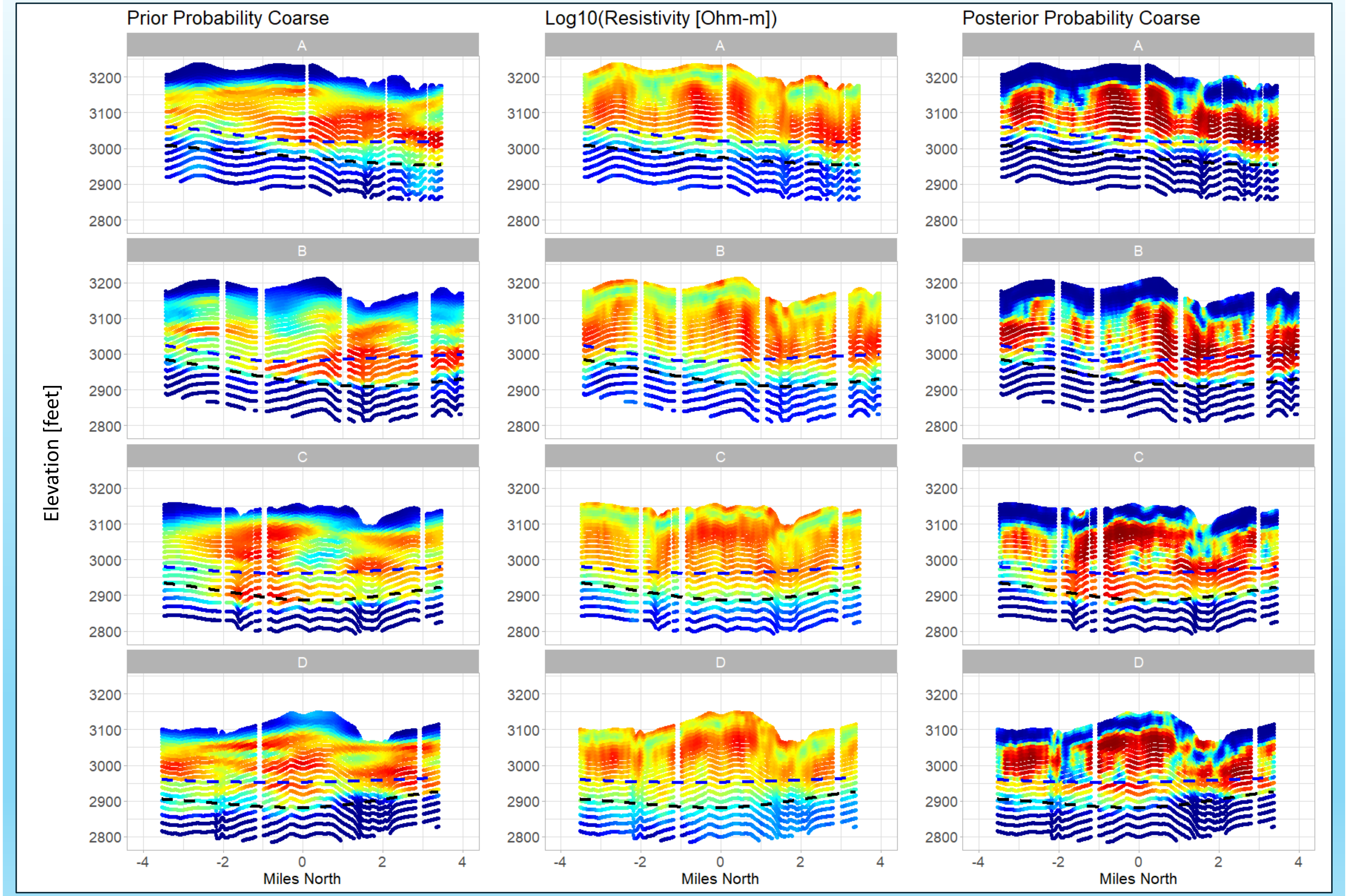
IW Area Resistivities



IW Area Flight Lines

Profiles along highlighted lines in next slide



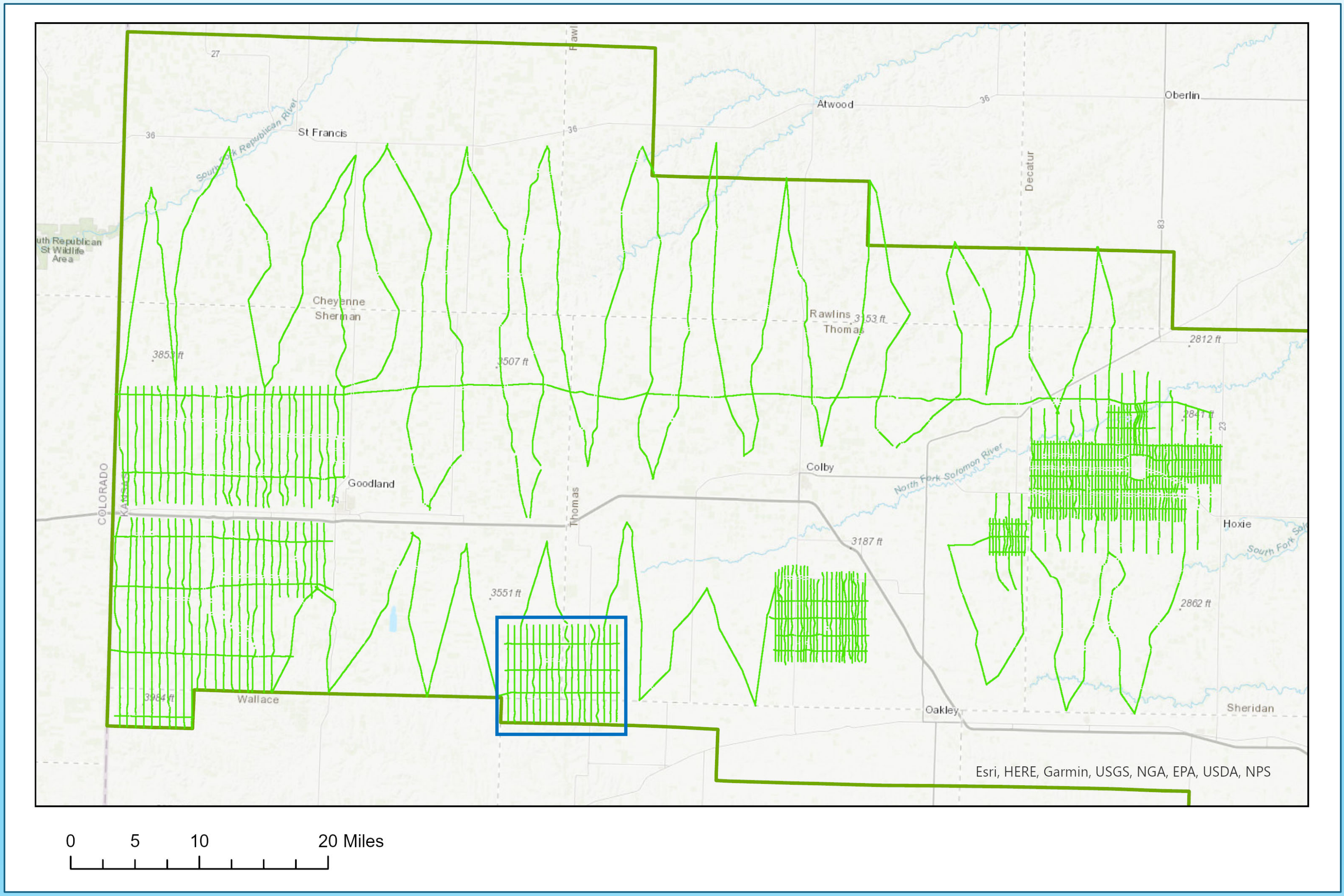

Prior Probability Coarse
Log10(Resistivity [Ohm-m])
Posterior Probability Coarse
A
B
C
D
Elevation [feet]
3200
3100
3000
2900
2800
-4
-2
0
2
4
Miles North

Future Work

- Stanford work on sharp inversion
  - Resistivity estimation process incorporating sediment variation information in logs
- Use of more sediment types
  - e.g., clay, silt, sand & gravel, cemented s & g
- Integration of geological conceptual models
- Incorporation of results into GMD4 flow model
- And probably much more

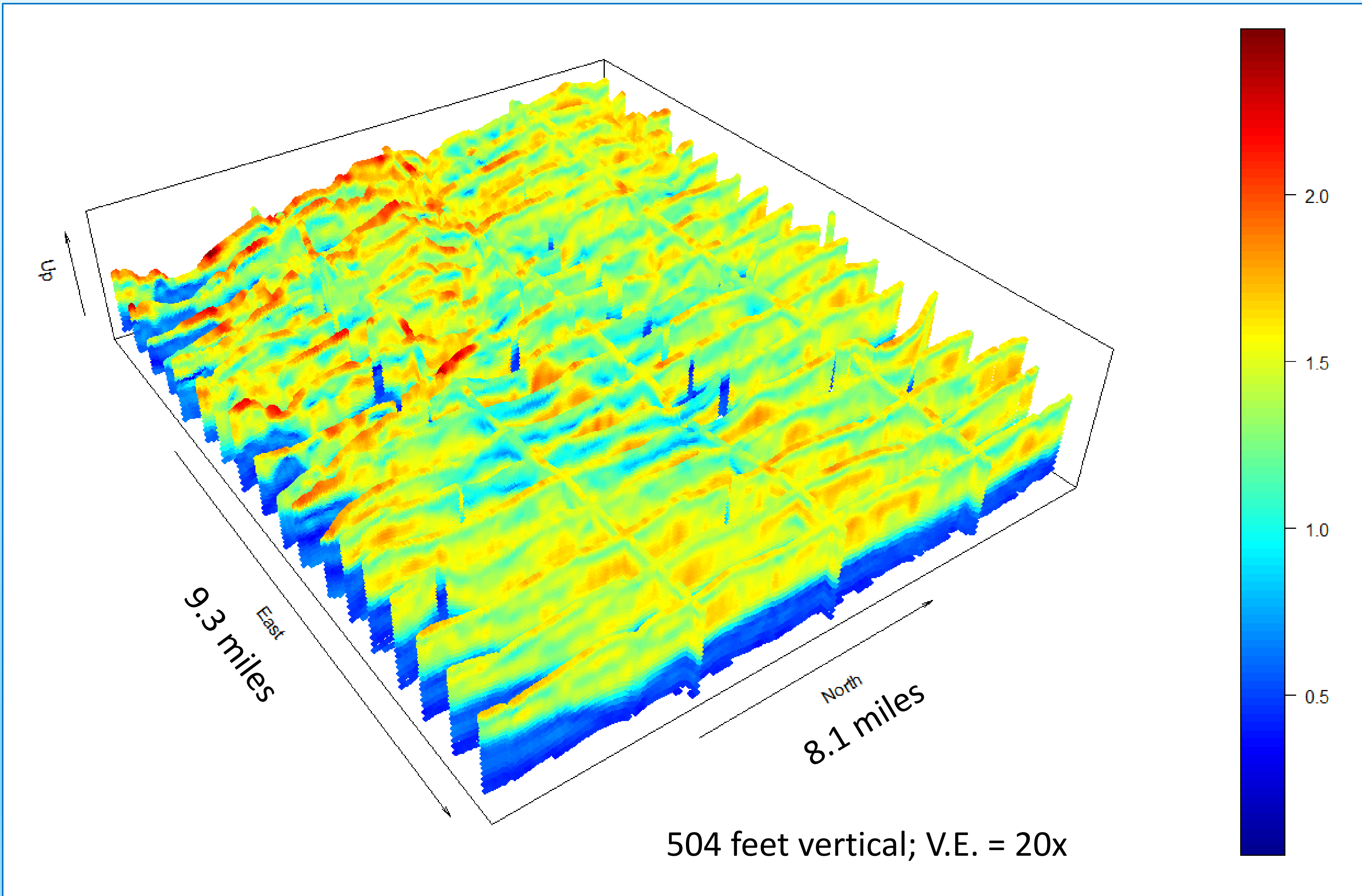
We’ve Only Just Begun

Sherman-Thomas County Area

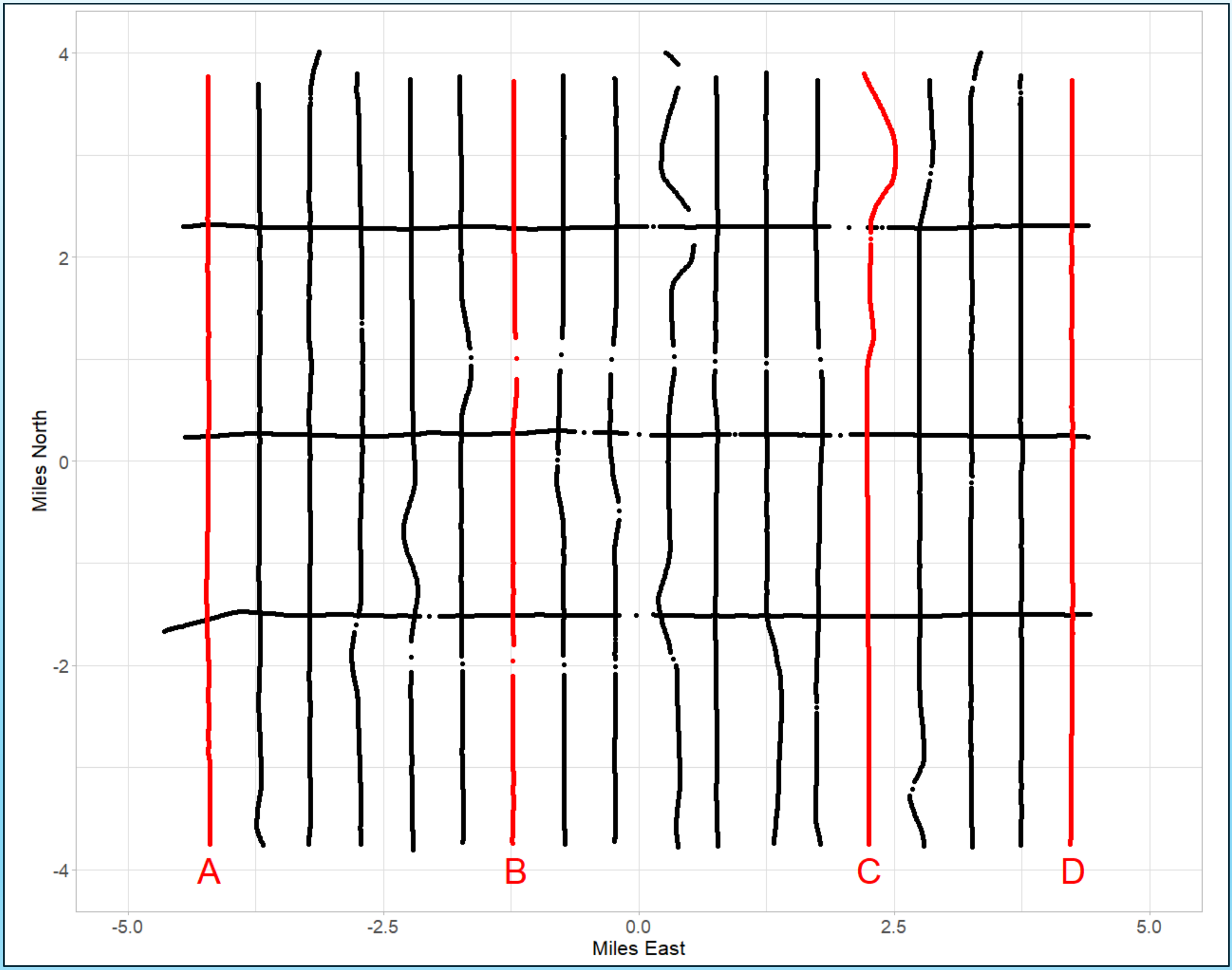


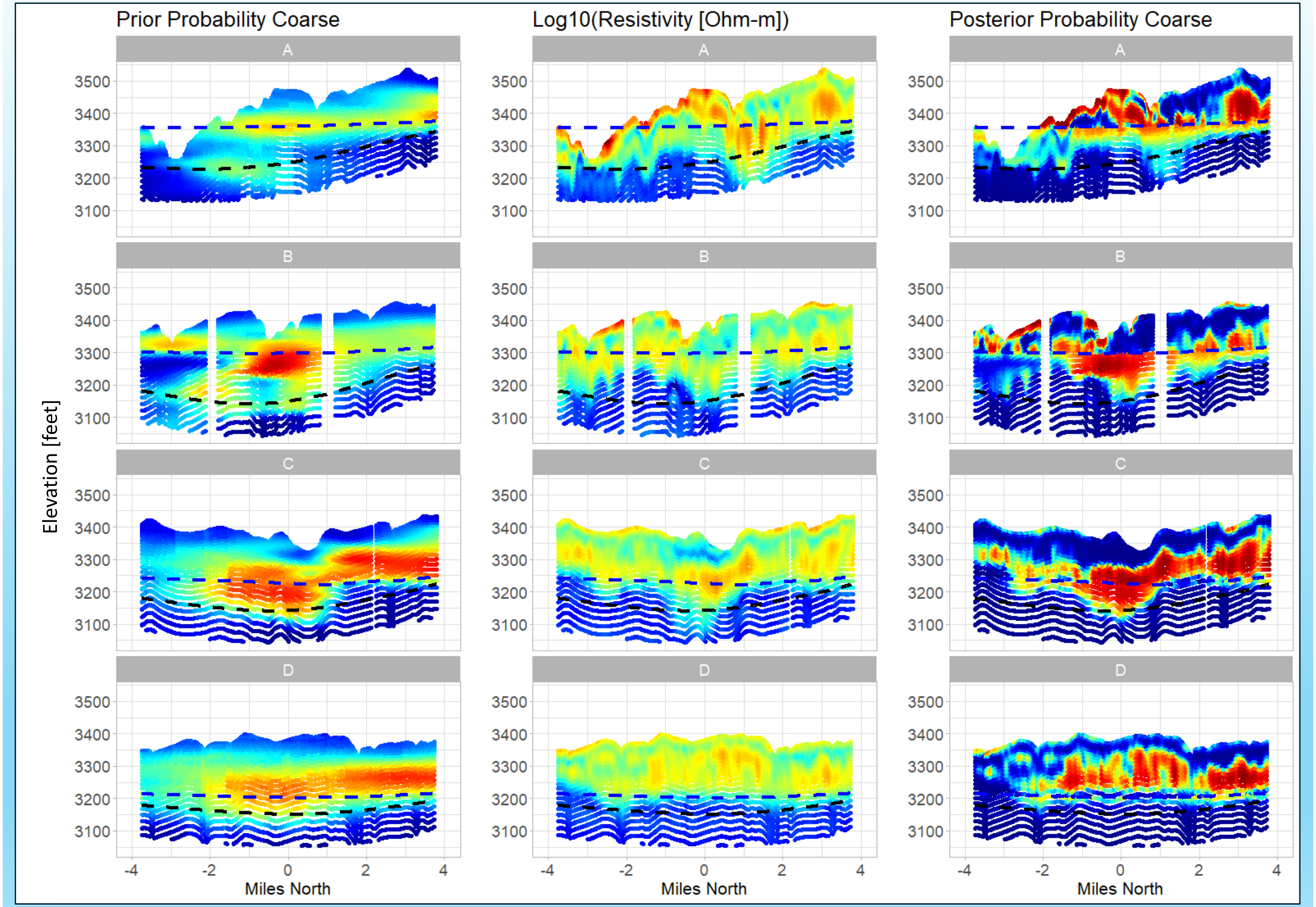
Isolated pod of irrigation wells; unusual topography

Sherman-Thomas Area Resistivities



Sherman-Thomas Area Flight Lines




Prior Probability Coarse
Log10(Resistivity [Ohm-m])
Posterior Probability Coarse
A
B
C
D
3500
3400
3300
3200
3100
Elevation [feet]
-4
-2
0
2
4
Miles North

Detailed Survey Areas

- SD-6: Sheridan 6 LEMA
  - Area of considerable interest and extensive research
  - ~0.25-mile line spacing (between N-S lines)
- TCIW: Thomas County Index Well Area
  - Hourly water level measurements since 2007 at IW
  - ~0.25-mile line spacing
- ST: Sherman-Thomas County Line Area
  - Isolated pod of irrigation wells; unusual topography
  - ~0.5-mile line spacing
- SW: Southwestern Area
  - GMD4 groundwater flow model mismatch area
  - ~0.6-mile line spacing

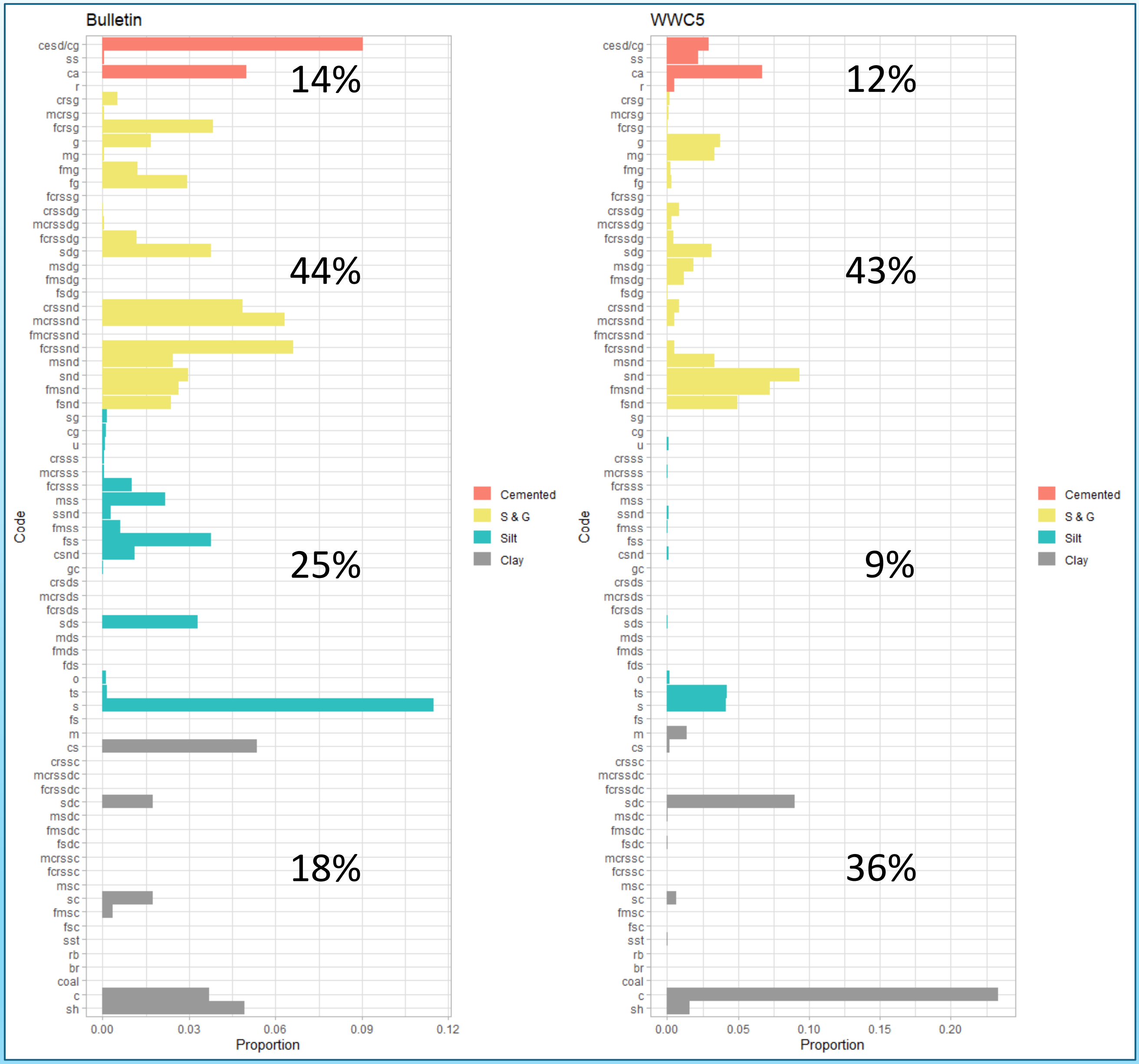
4-Part Division

Clay means shale & clay; bulletin logs go a little deeper into shale than WWC5

Silt includes silty sands

S&G means clean sands & gravels

Cemented is cemented sand and/or gravel*, caliche, and the occasional limestone



*including “mortar beds” in bulletin logs and “sand rock” & such in WWC5 logs

Distributions to Posterior Probabilities, Saturated Zone

Posterior probability curves are a little odd due to spread of fine distribution; “catches up” with coarse distribution at high resistivities