Groundwater and Surface water
How do they interact and How does it affect our lives?

The Clear Picture From Using Airborne Electromagnetic Surveys to Build a Hydrogeologic Framework and Improved Understanding

John Day Regional Airport
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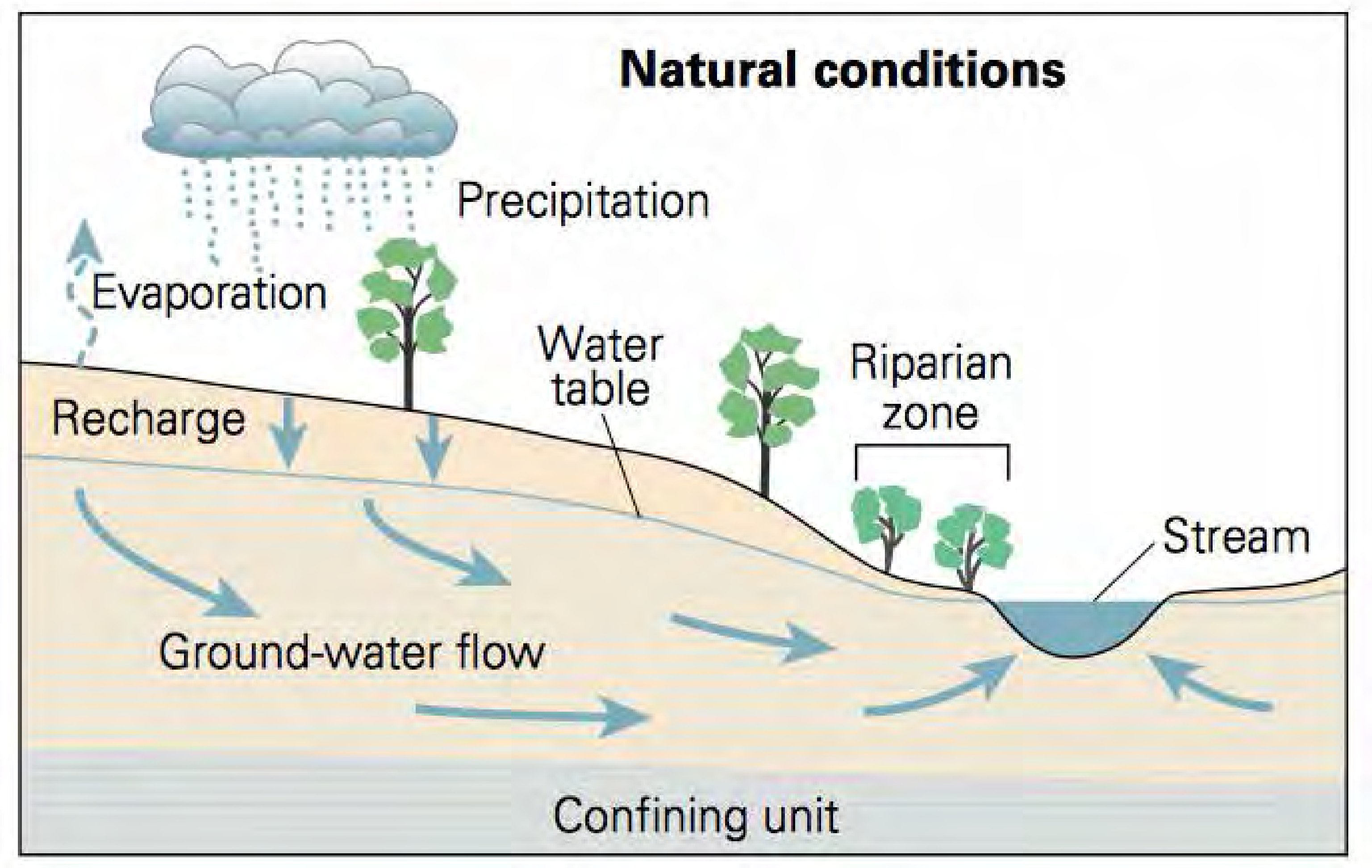
Outline

- Introduction- Groundwater /Surface Water Relationships Traditional Understanding
- How dose AEM work
- Calibration
- Specifications
- Survey Planning
- Examples from Nebraska
  - Lower Elkhorn Natural Resources District
  - Elkhorn River
  - Clarkson and Howells
  - Sarpy County
  - Survey Planning
- How Do We Use AEM Survey Results to Manage Our Water?

GROUNDWATER AND SURFACE WATER- HOW THEY INTERACT



Simple model from Galloway, USGS

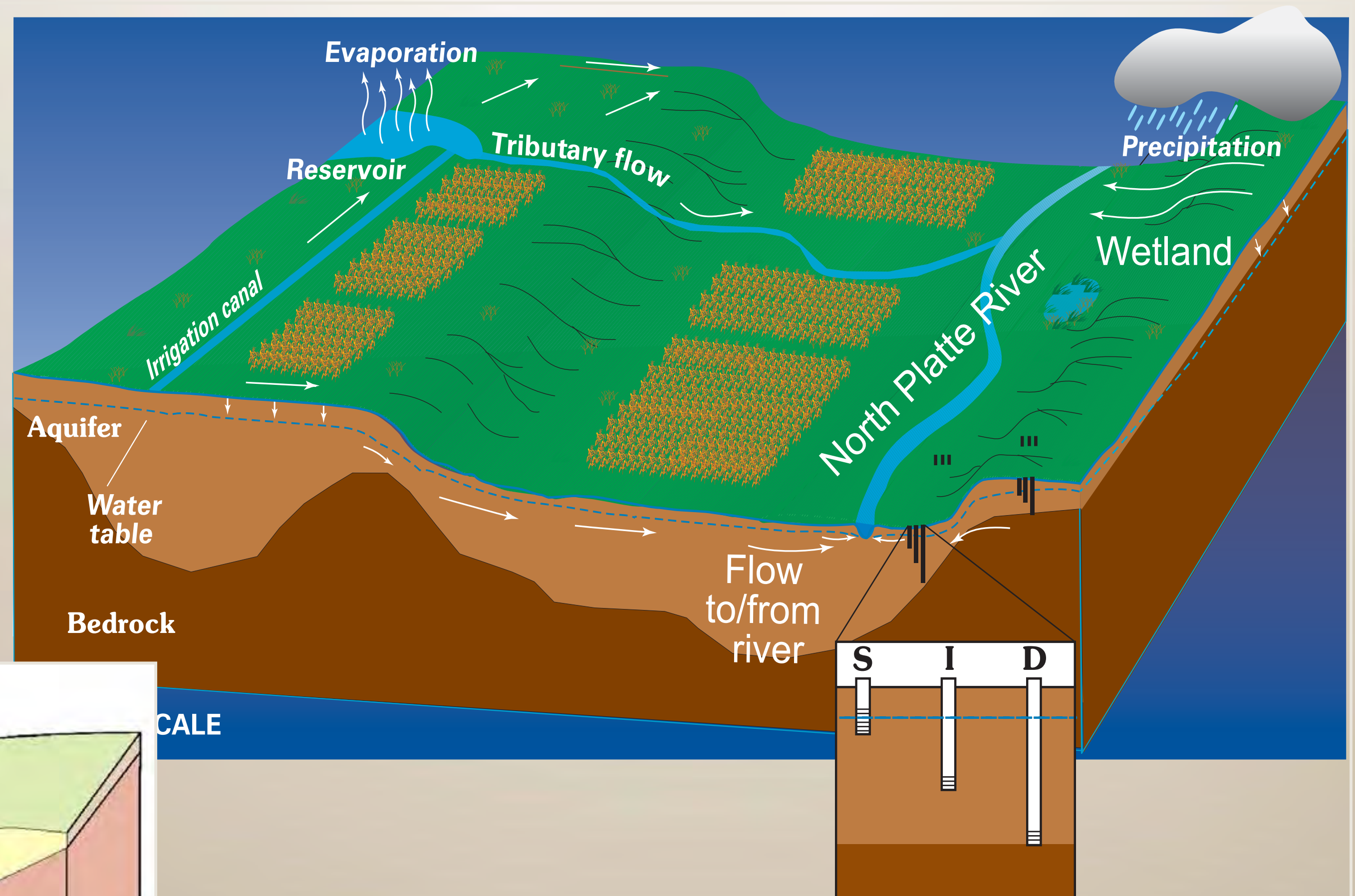
From the Simple to Complex there are many ways to evaluate Groundwater and Surface Water Interactions

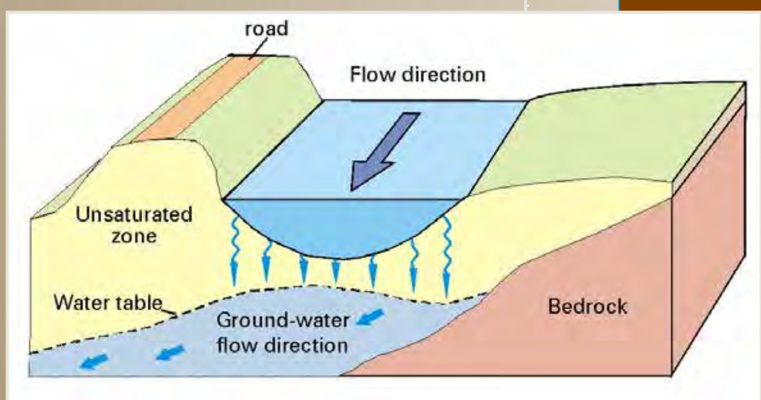
- Water table maps
- Surface water maps
- Topographic maps
- Stream gauge analysis and historical records
- Water well development records
- Precipitation records
- Snow pack measurements
- Water use records
- Water quality analysis
- Soil moisture balance models
- Groundwater surface water models

This is to name a few!

The key to understanding to put all of this information into the **Framework** that **Best Matches the Natural Conditions**

Groundwater and Surface Water are related by flow





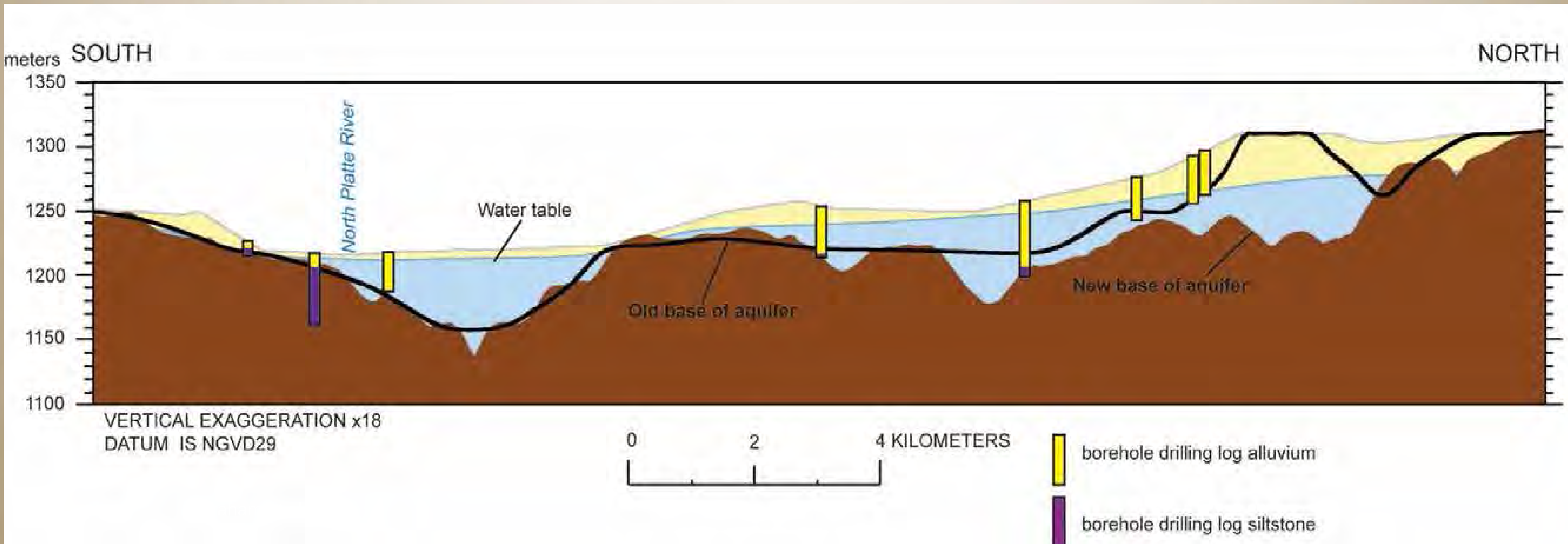
COHYST, 2006

Simple Model from the
North Platte River, Nebraska

- Examples of Recharge and Discharge related to flow, both SW and GW
- Water can move between both systems.
- The driving force is gravity
- The change in storage in both systems creates change to the water supply
- Precipitation is a key component

What happens between Geologic Logs?

The missing information for Groundwater – Surface Water Relationships



Take-Away Message – You can drill a lot of holes and still not accurately map the geology of interest

Moving Forward to a Better Hydrogeologic Framework

- Traditional Frameworks use all of the information available such as boreholes, surface surveys, water chemistry and surface water/groundwater record analysis.
- What is missing is the near continuous information from **Airborne Electromagnetic Surveys (AEM)** which ***"fills in"*** the blanks in the subsurface.
- ***<u>All</u>*** existing subsurface data becomes part of the new framework.
- This is extremely important to have when considering the subsurface flow to and from surface water.
- It allows for characterization of aquifer properties, mapping of recharge zones, groundwater flow boundaries and other critical flow components.
- Improved water management comes form a complete understanding of the the ***<u>Hydrogeologic Framework</u>*** combined with the ***<u>Surface Water System</u>***

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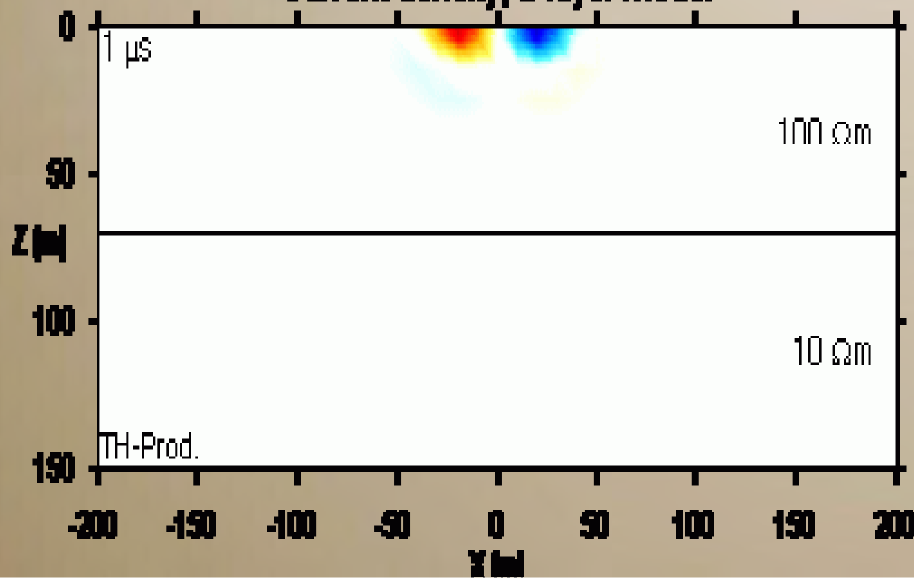
How do we build a framework?

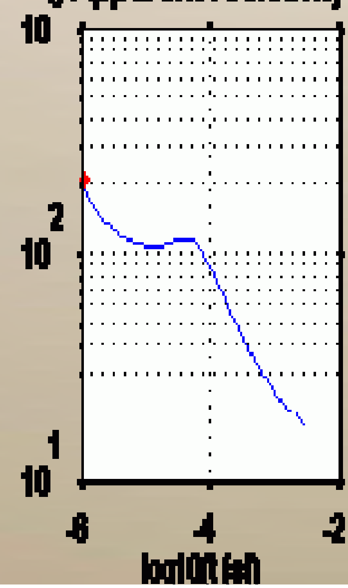
- Understand the current problem- water supply, water use, management goals.
- Design a survey which provides the information to make informed decisions to the above items.
- Work with the people who are involved in the water use and management through out the survey to gain insight as work proceeds.
- Collect the AEM data.
- Interpret the data.
- Report the data.
- Make recommendations based on the results

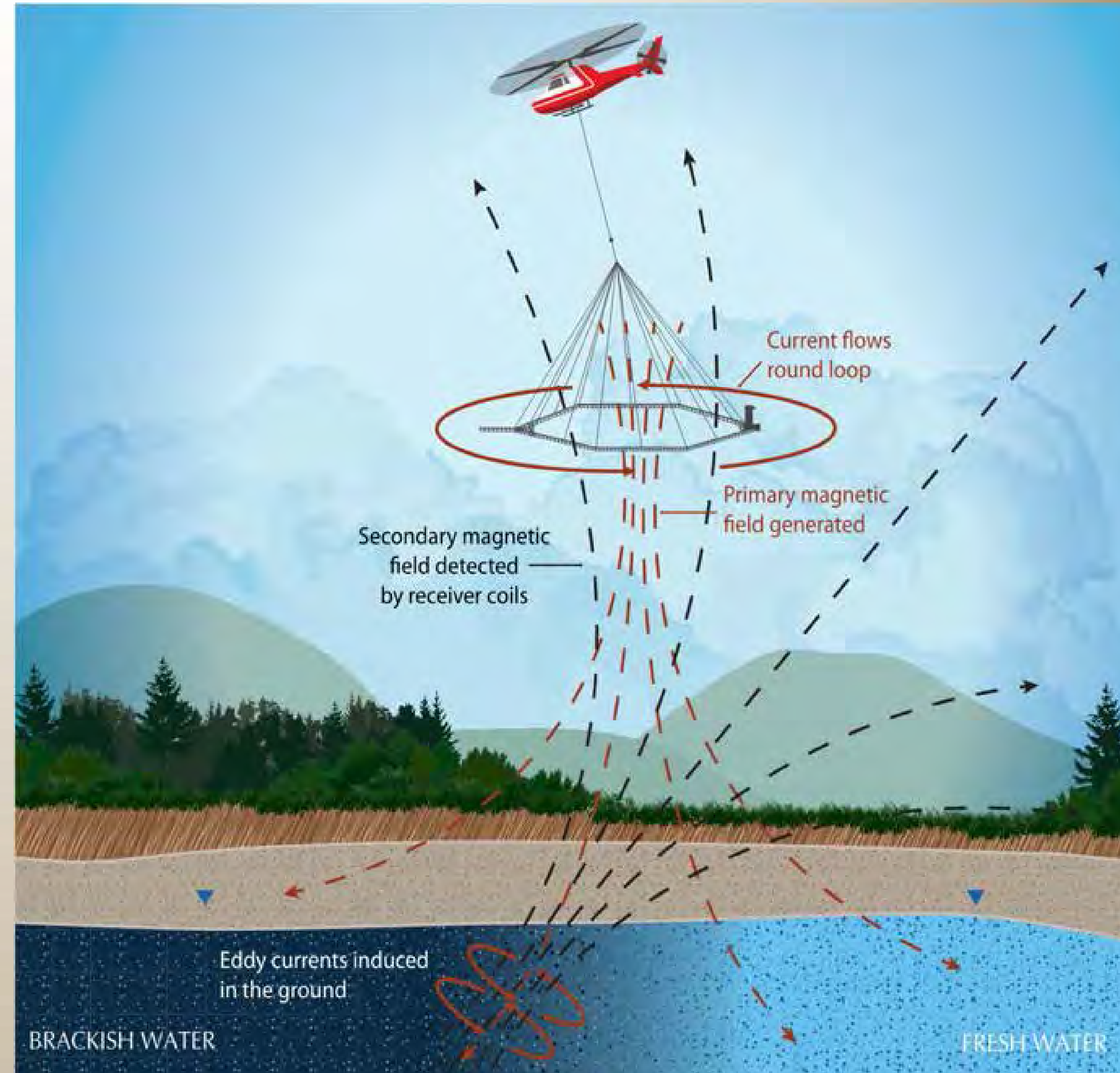
SO, HOW DOES AEM WORK?

Current density, 2-layer model



Apparent resistivity



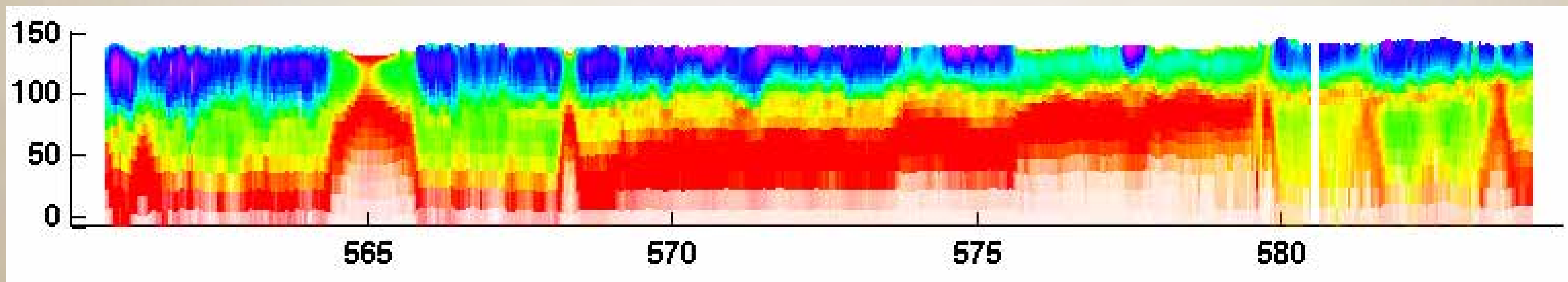


Modified from E. Auken, Unv. Aarhus, Denmark


N79FX

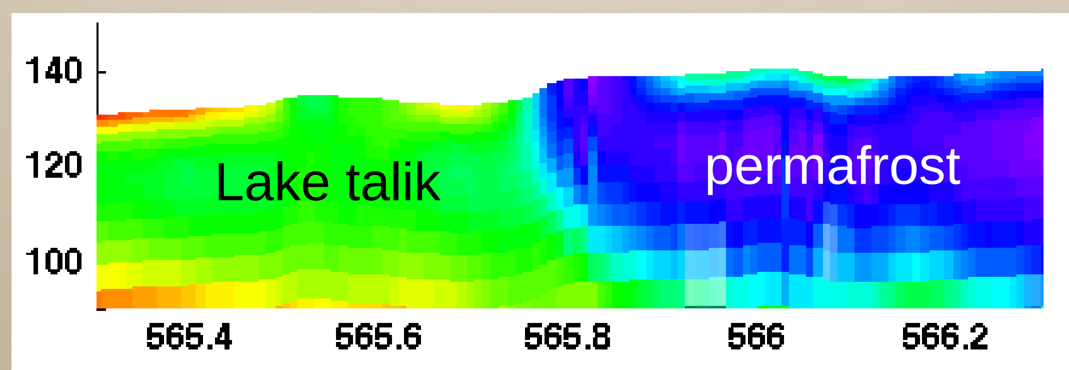
Why airborne geophysics?

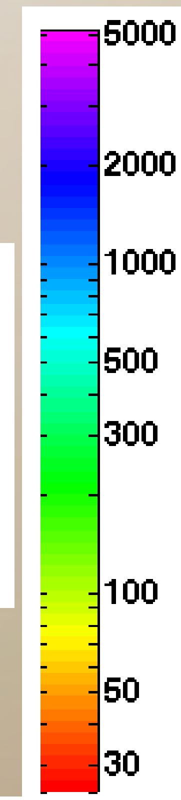
Airborne resistivity
~ 100 km / hour



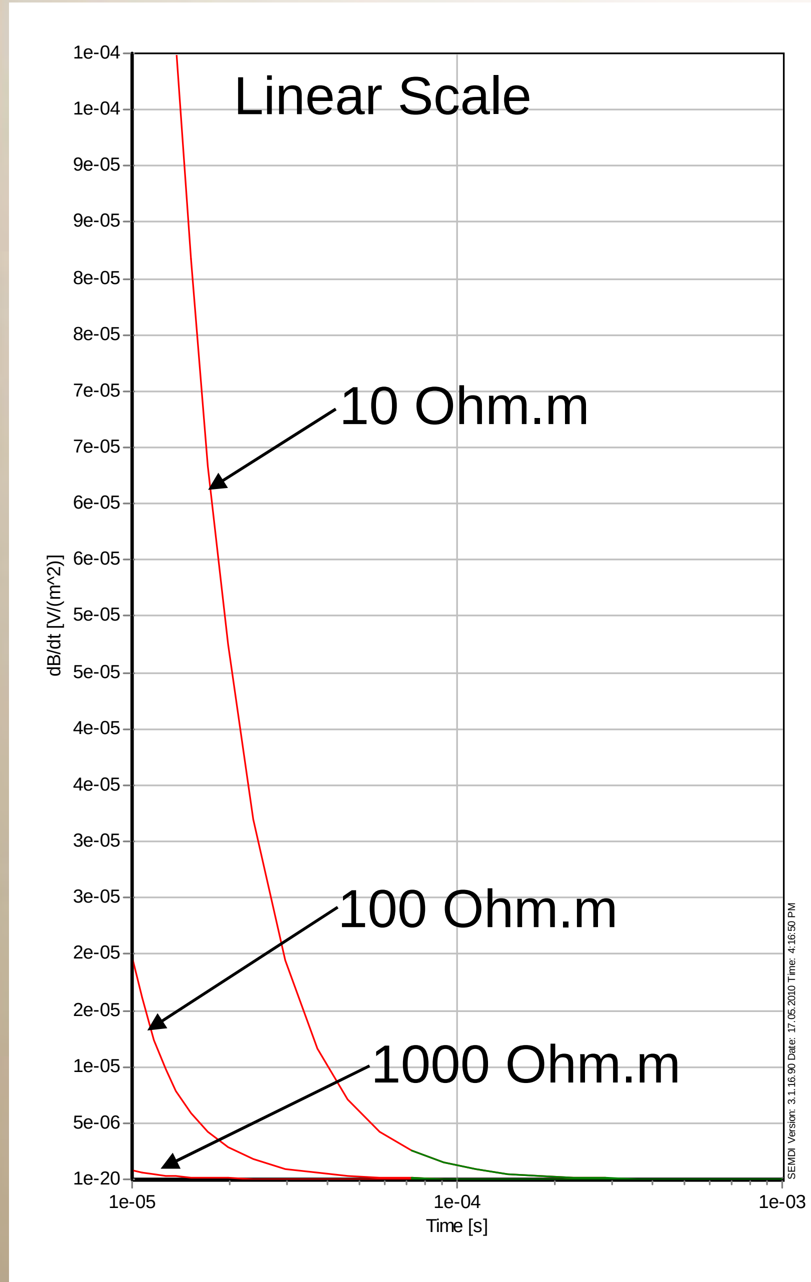
Abraham, 2012
Minsley et. al., 2012

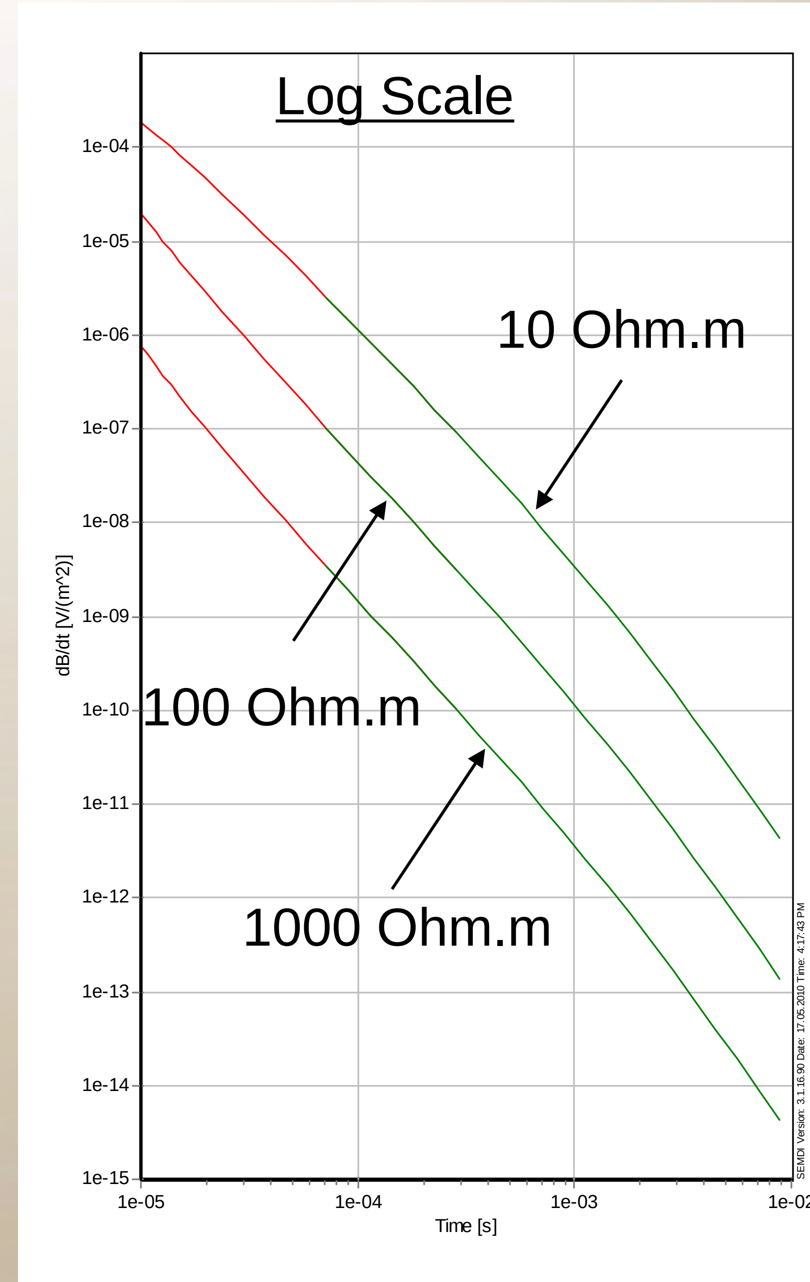
Ground-based resistivity
~ 1 km /day





VOLTAGE VS TIME – 10, 100, AND 1000 OHM-M

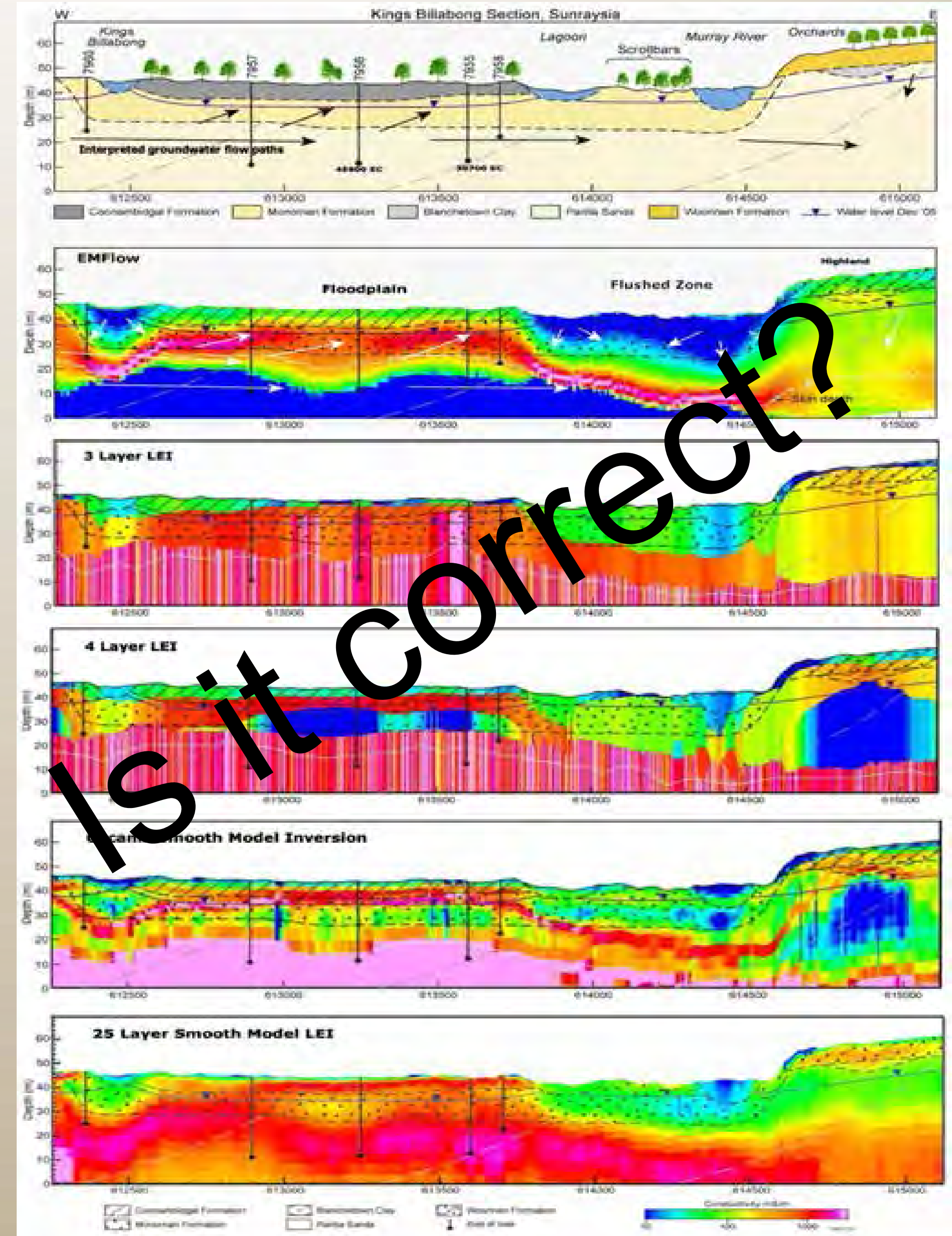




Abraham, 2011

WHY CALIBRATE?

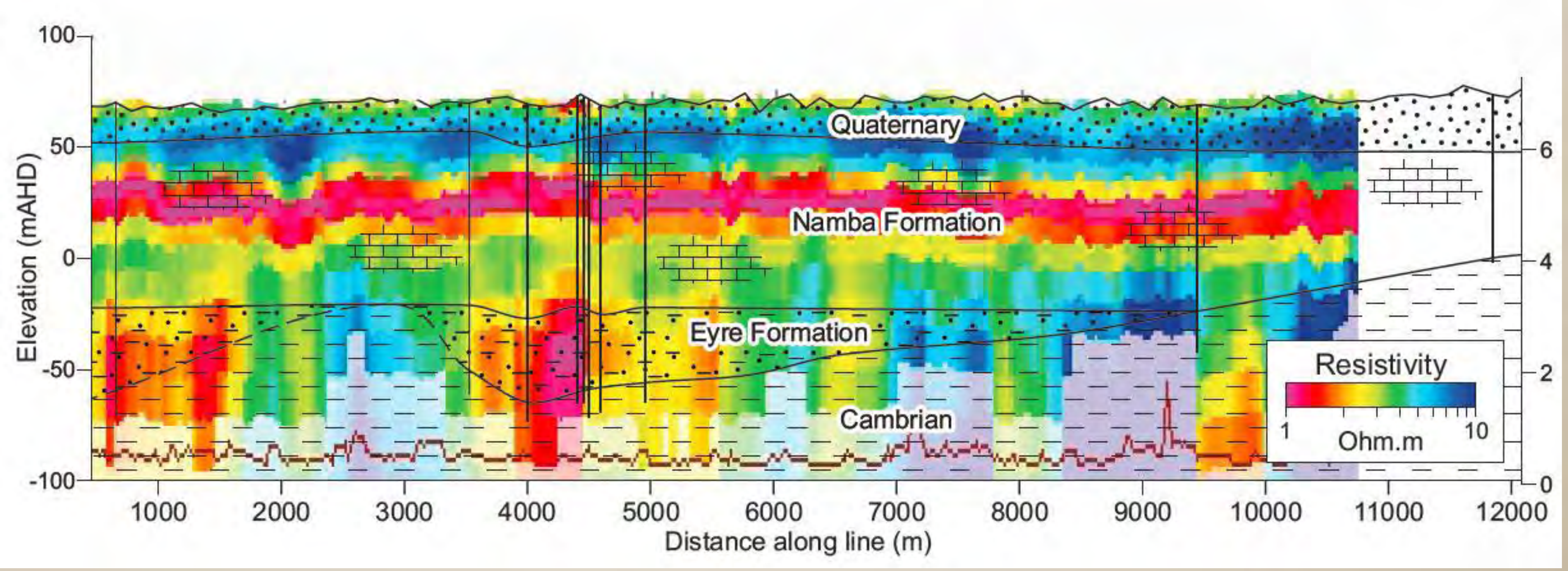
- Need to provide accurate models of conductivity and depth for environmental applications
- Data is used to target drilling, manage salinity risk and groundwater resources.
- Unknown/assumed quantities of AEM system/geometry that affect conductivity models



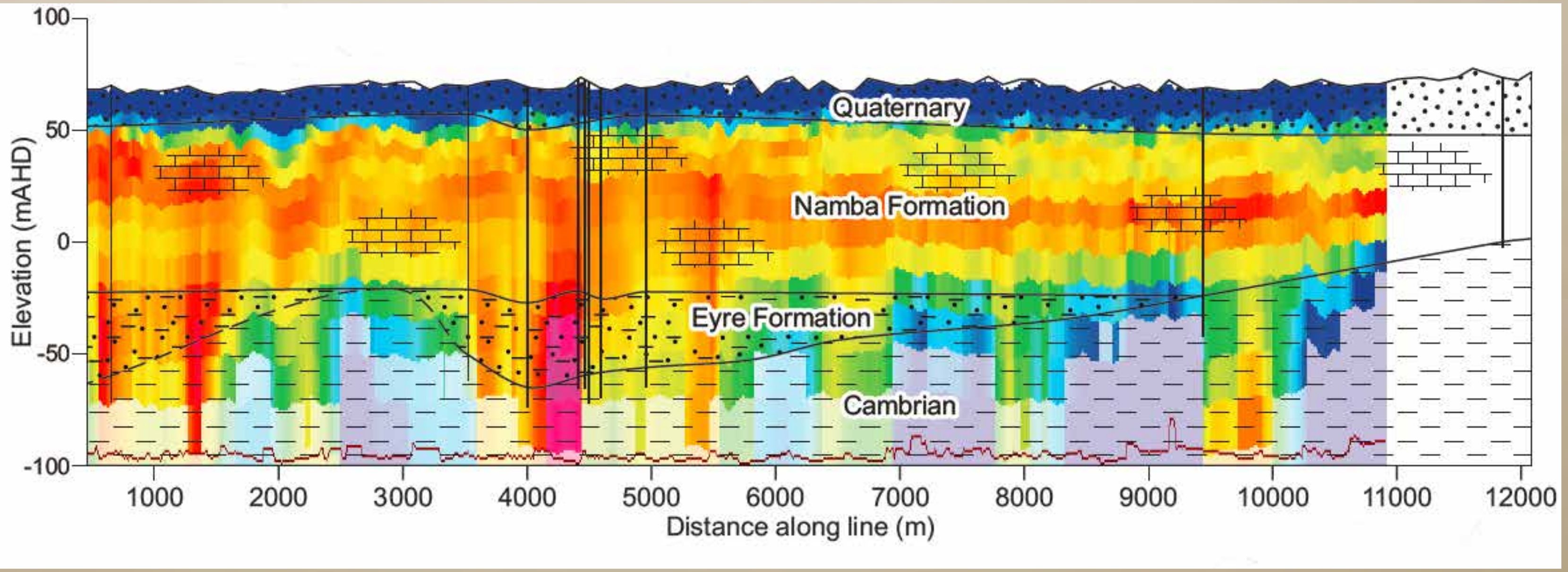
Andrew Fitzpatrick, 2010

CALIBRATION

Non calibrated Data



Calibrated Data



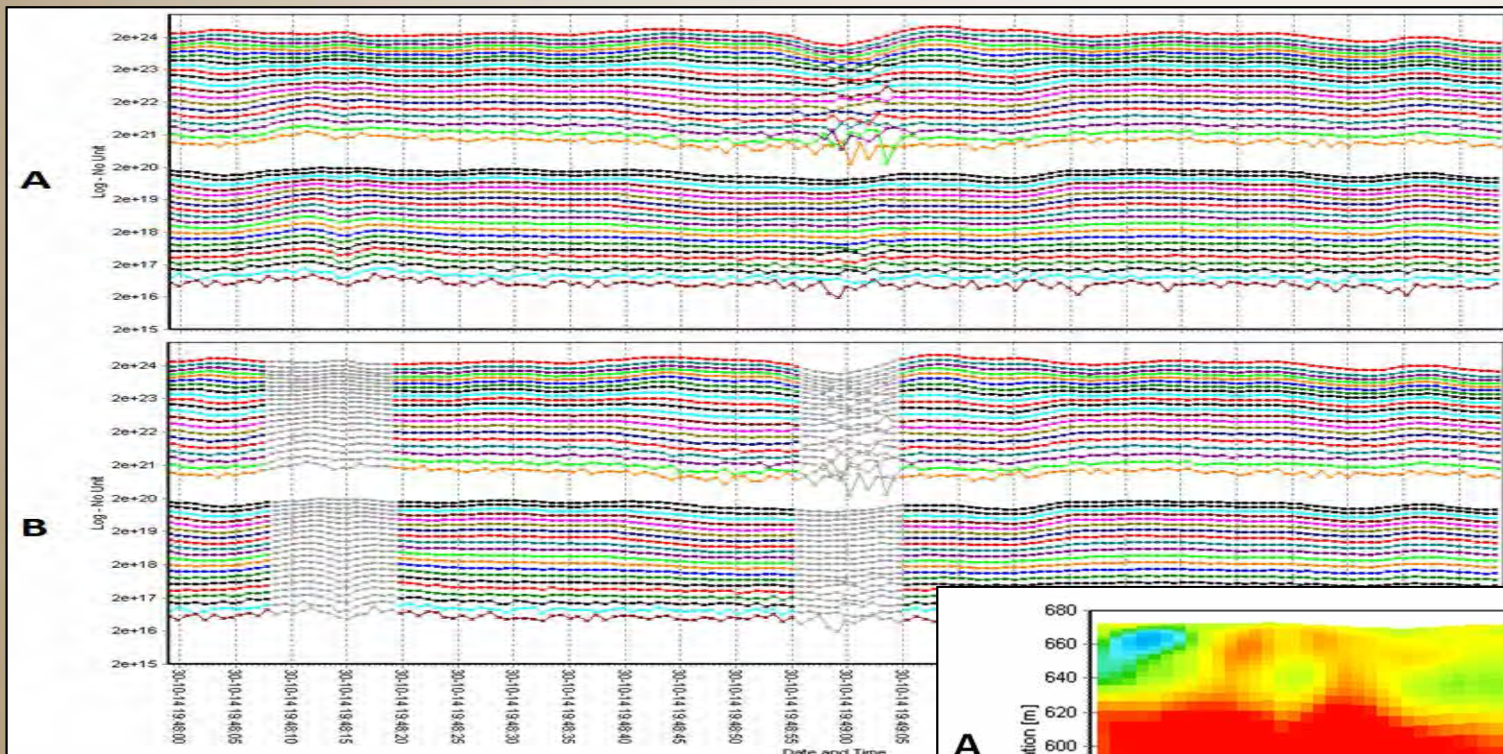
Powers, 2011

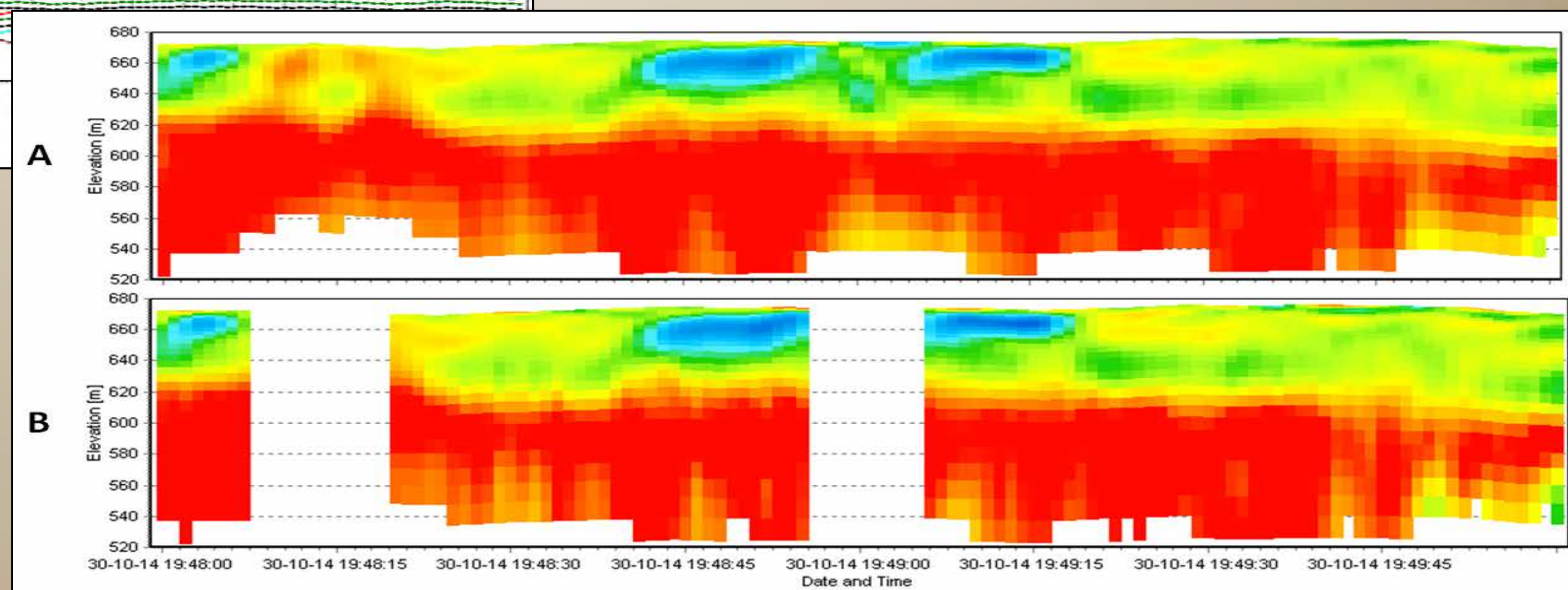
SPECIFICATIONS

- Acquisition
  - Bandwidth of system
  - Tx Waveforms
  - Tx Current
  - Time gates
  - Position
  - Speed
  - Height
  - Tilt
  - Data format
  - Deconvolution
  - Calibration
  - Drift
- Inversion
  - Algorithm
  - Errors/Noise
  - Processing
  - Filters
  - Tilt/height/topo
  - Constraints 2D, 3D
  - Deterministic/Stochastic
  - Additional Data
    - Borehole geophysics
    - Ground geophysics
    - Geological surfaces

In Field QA/QC and Inversion

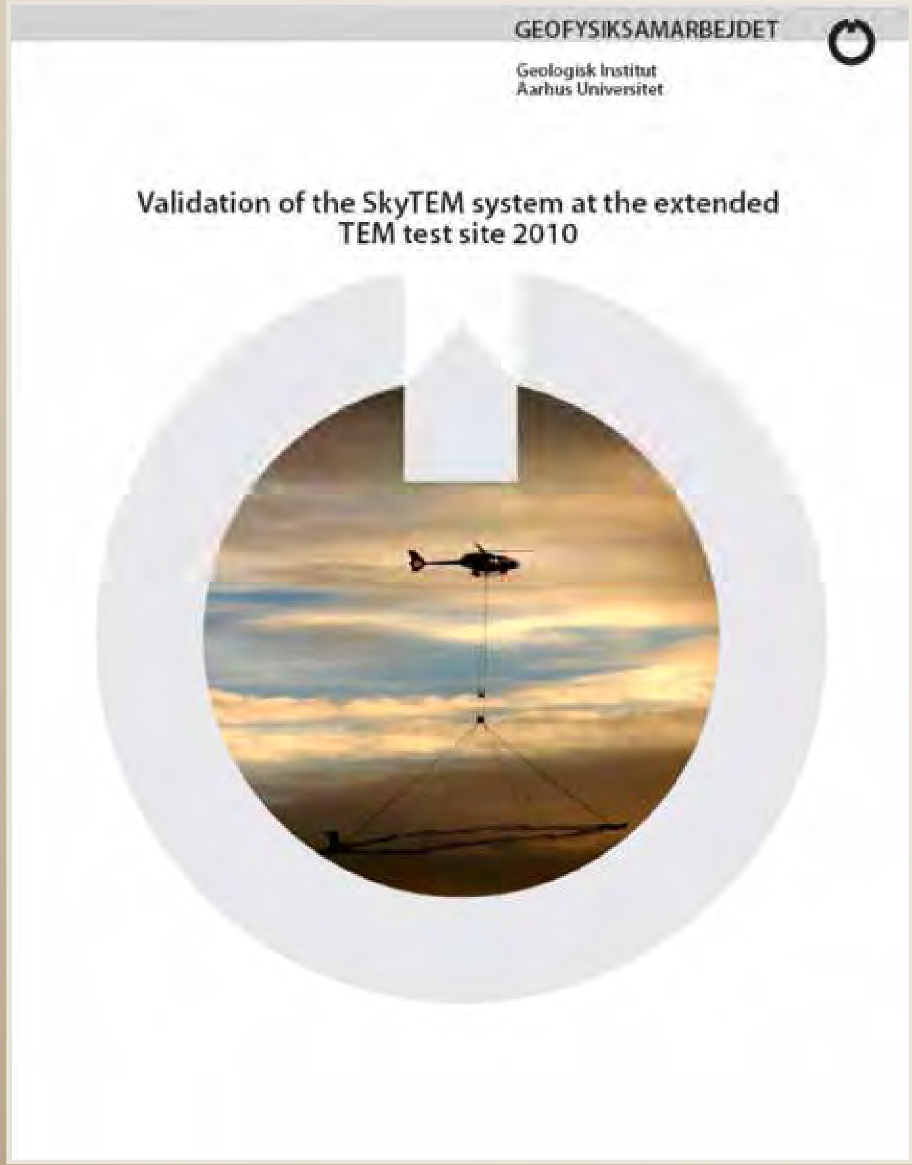
- Within 24 hours we invert

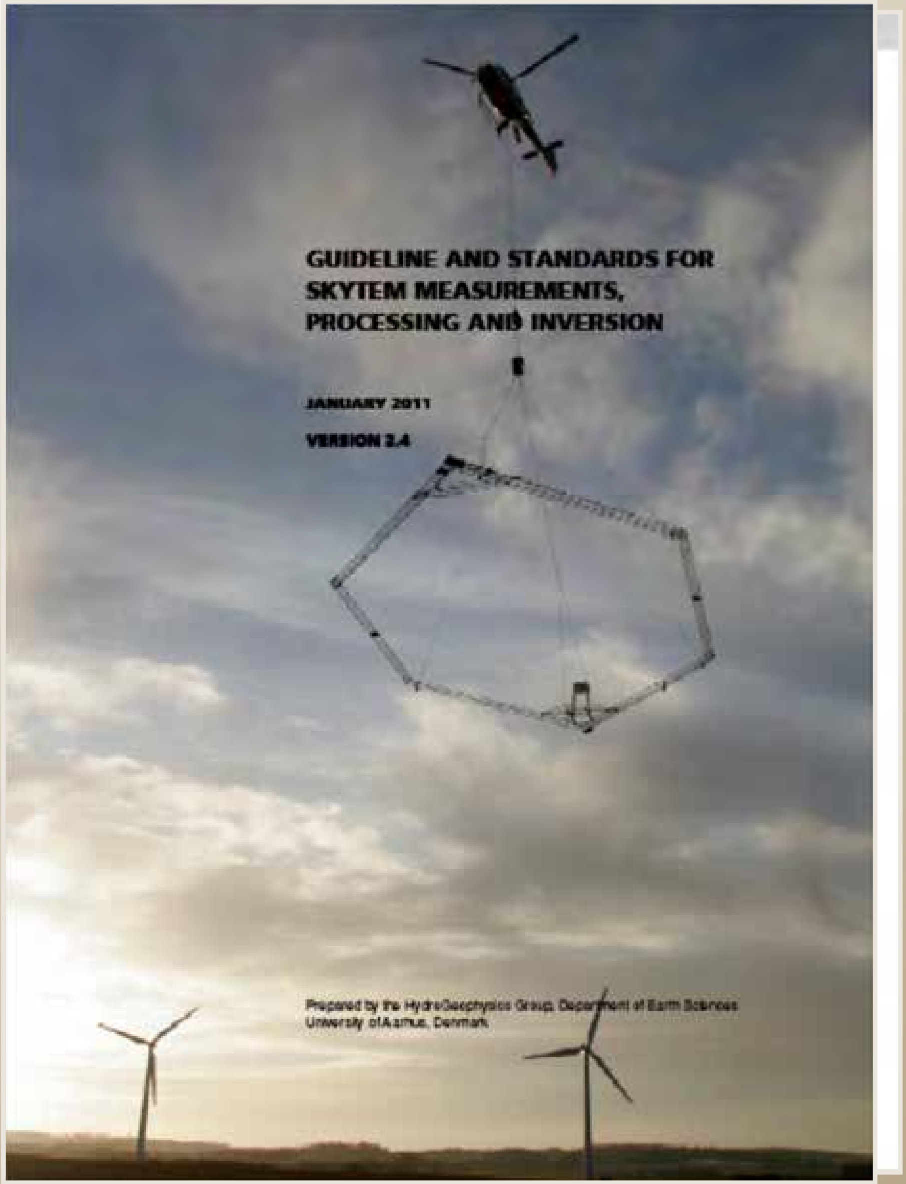




Abraham et al., 2016

GEOPHYSICAL TEST SITE IN DENMARK





Andrea Viezzoli, Tim Munday, and Anders Vest Christiansen, 2011

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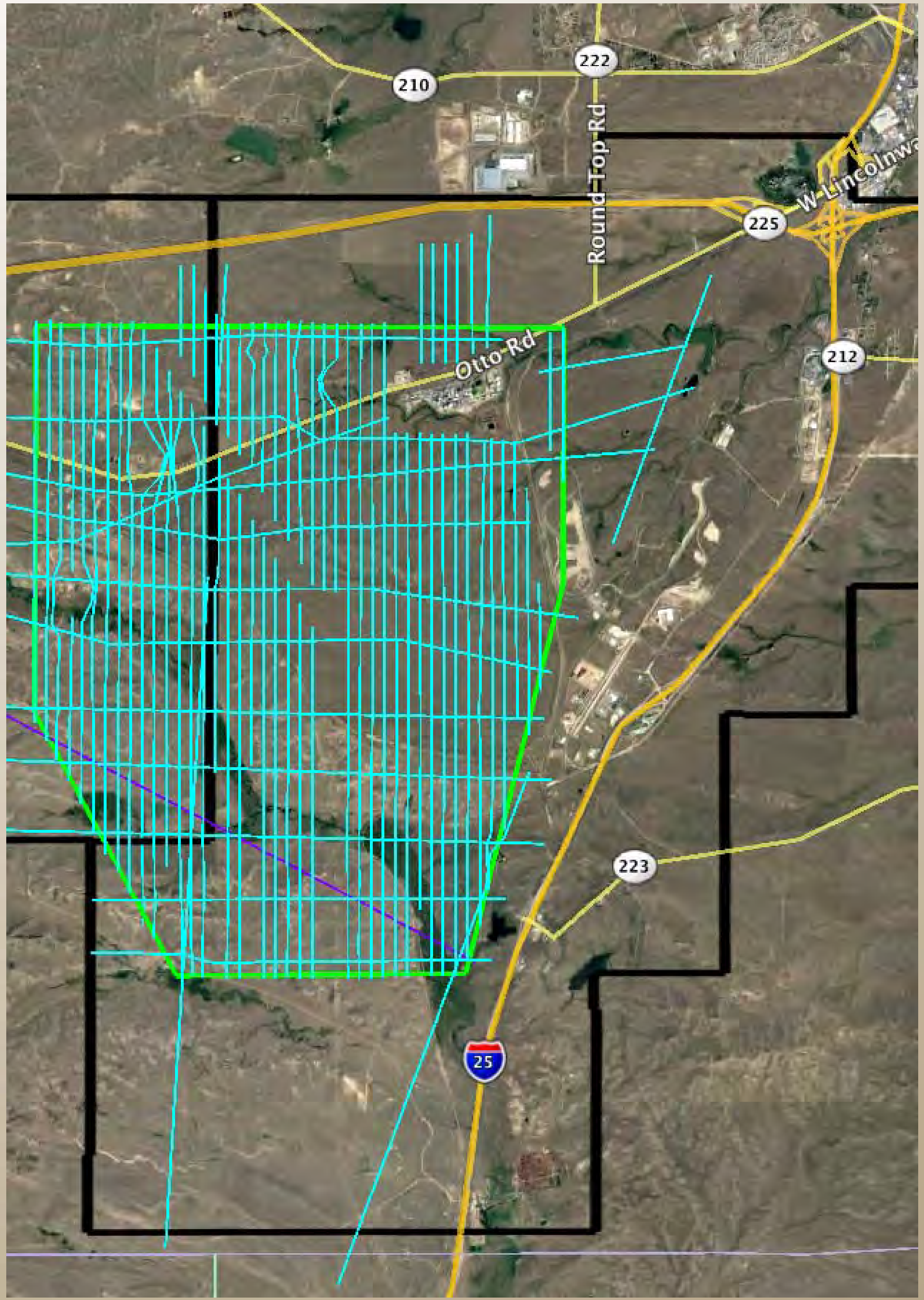
Survey Planning

- Geological trends
- Infrastructure
- FAA rules/Safety
- Multiple Surveys
- Airport distance
- Weather



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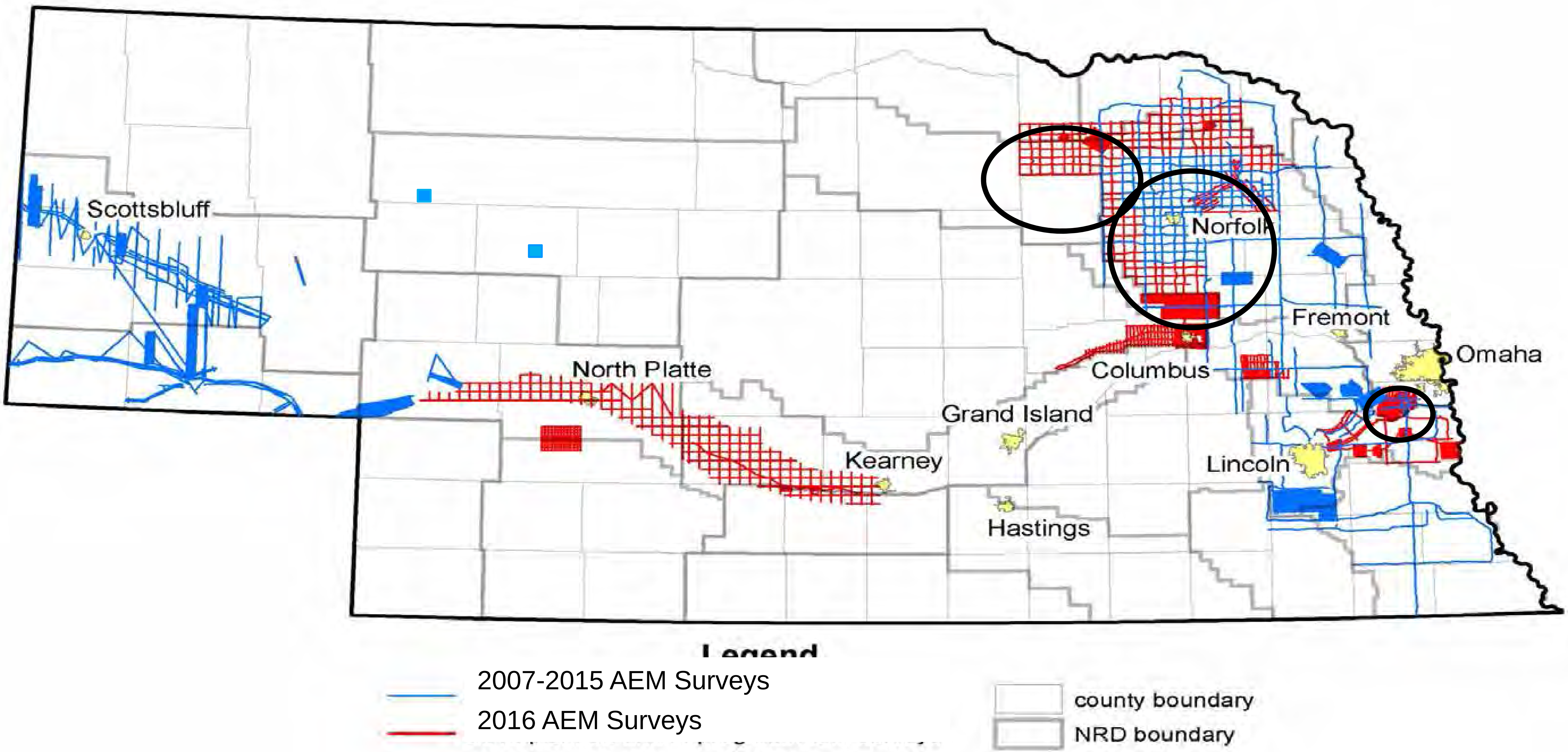
NEBRASKA AIRBORNE ELECTROMAGNETIC (AEM) SURVEYS 2007-2016



Abraham et al., 2016

History of AEM for Groundwater in Nebraska

- **2007** ENWRA (RESOLVE) — **1,170** line-km
- **2008** NPNRD and SPNRD (RESOLVE) — **1,375** line-km
- **2009** ENWRA (RESOLVE) — **1,419** line-km
- **2009** NPNRD and SPNRD (RESOLVE) — **937** line-km
- **2009** USGS Sand Hills Study (AeroQuest IV) — **571** line-km
- **2010** USGS Western NE Study (SkyTEM 304) — **1,900** line-km
- **2010** Test flights SkyTEM 304, HeliTEM, RESOLVE, VTEM — **1,776** line-km
- **2011** USACE Mead (RESOLVE) — **471** line-km*
- **2012** USGS Crescent Lakes Study (VTEM) — **578** line-km
- **2013** LENRD, LPSNRD, and Madison (SkyTEM 304) — **1,830** line-km
- **2014** LENRD, ENWRA (SkyTEM 508) — **2,446** line-km
- **2015** Spring ENWRA (SkyTEM 508) — **1,100** line-km
- **2016** July ENWRA, CP-TPNRD, NCORP (SkyTEM 304) — **9,300** line-km

*non-ENWRA Member project

Total 25,479 line-km

(Photos: Jared Abraham, Jesse Korus, Areoquest, Fugro, Geotech, Fugro)

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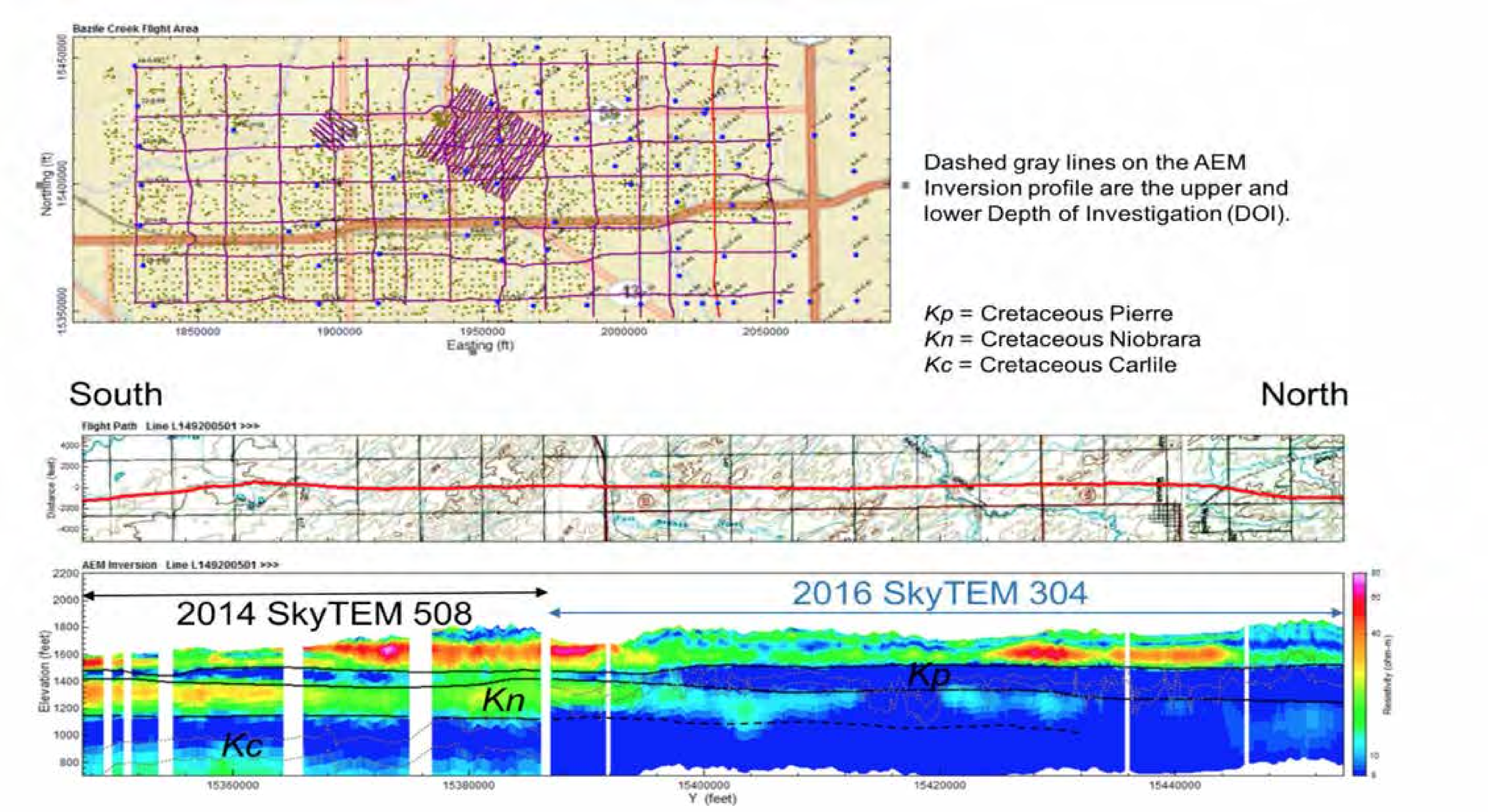
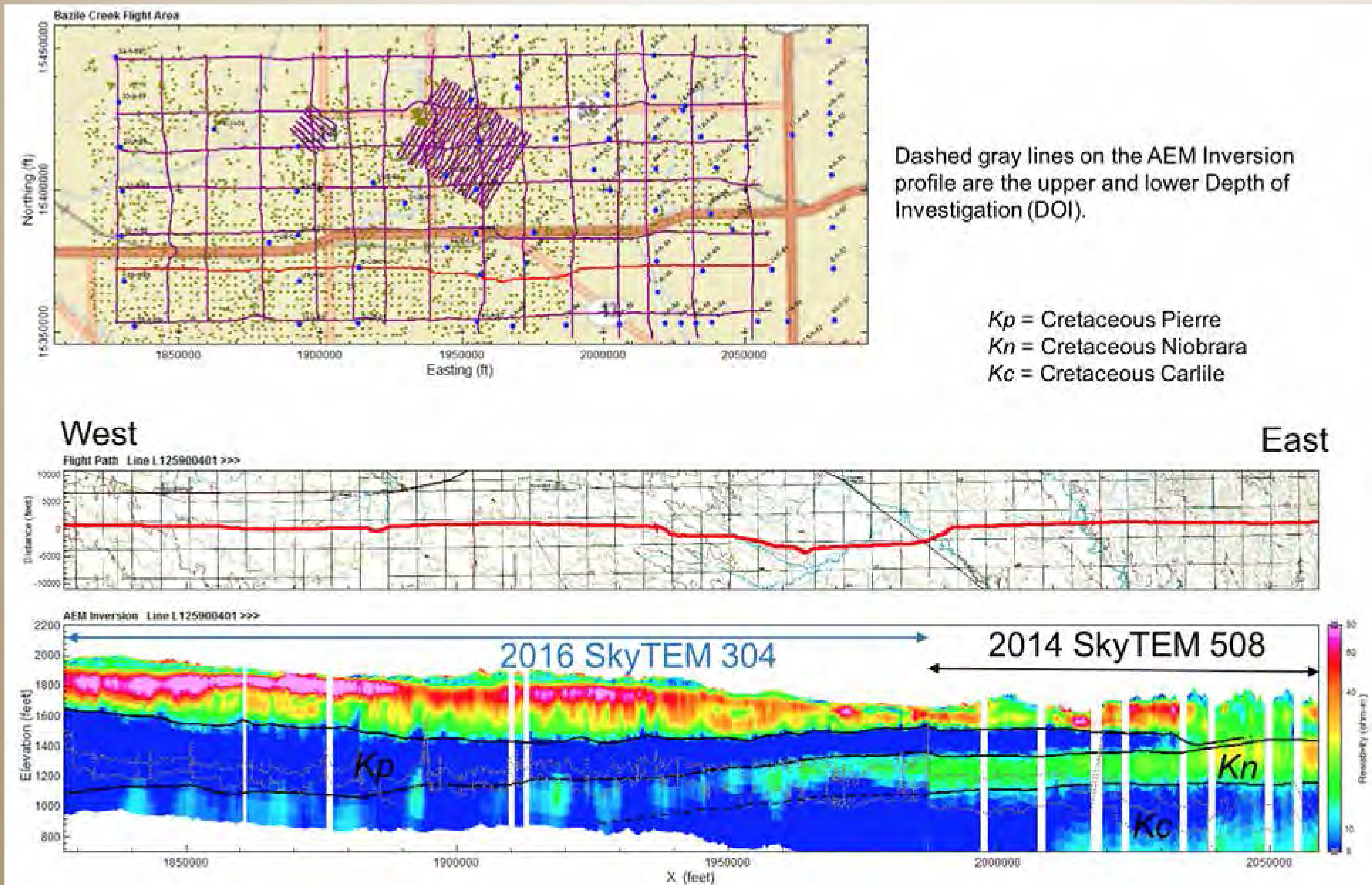
NORTH-SOUTH FLIGHT LINE (2014 AND 2016)



Abraham et al., 2016

10 miles

East West Flight Line (2014 and 2016)



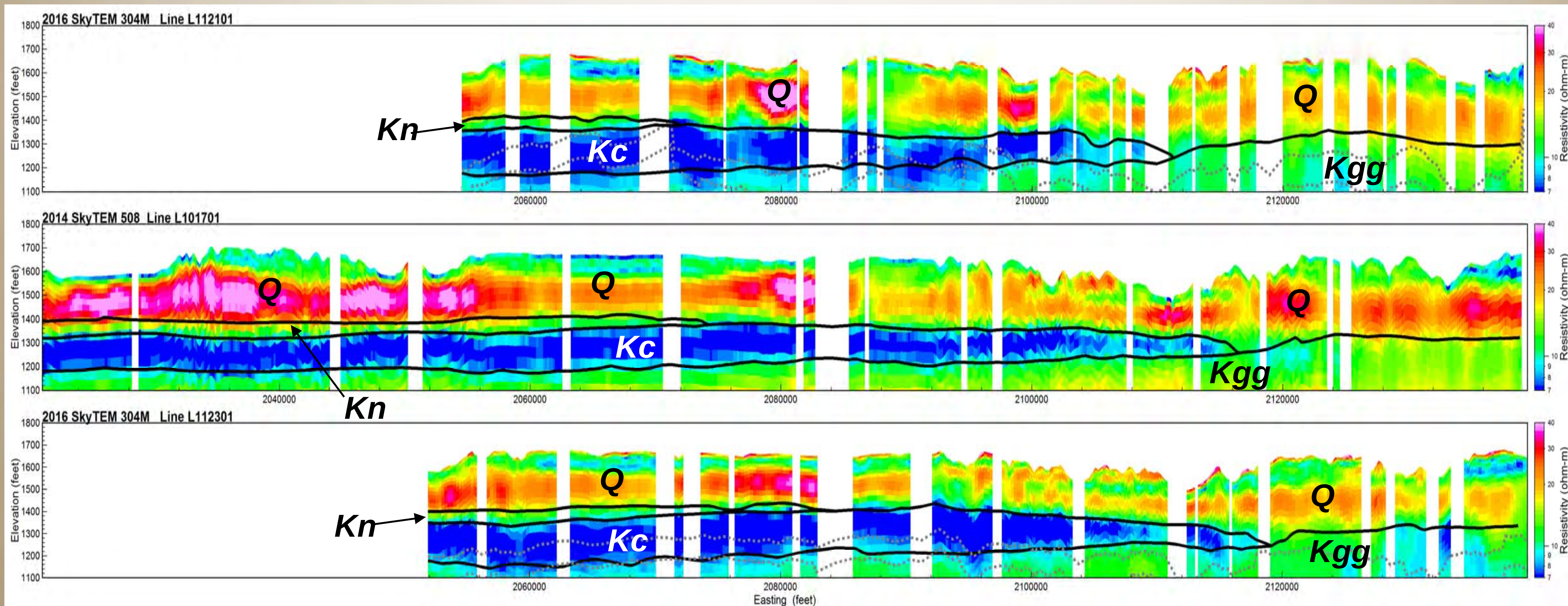
Abraham et al., 2016

10 miles

- Calibration
- Monitoring
  Current/Waveform
- Processing
- Inversion Parameters

Parallel East-west lines (2014 and 2016)

West East

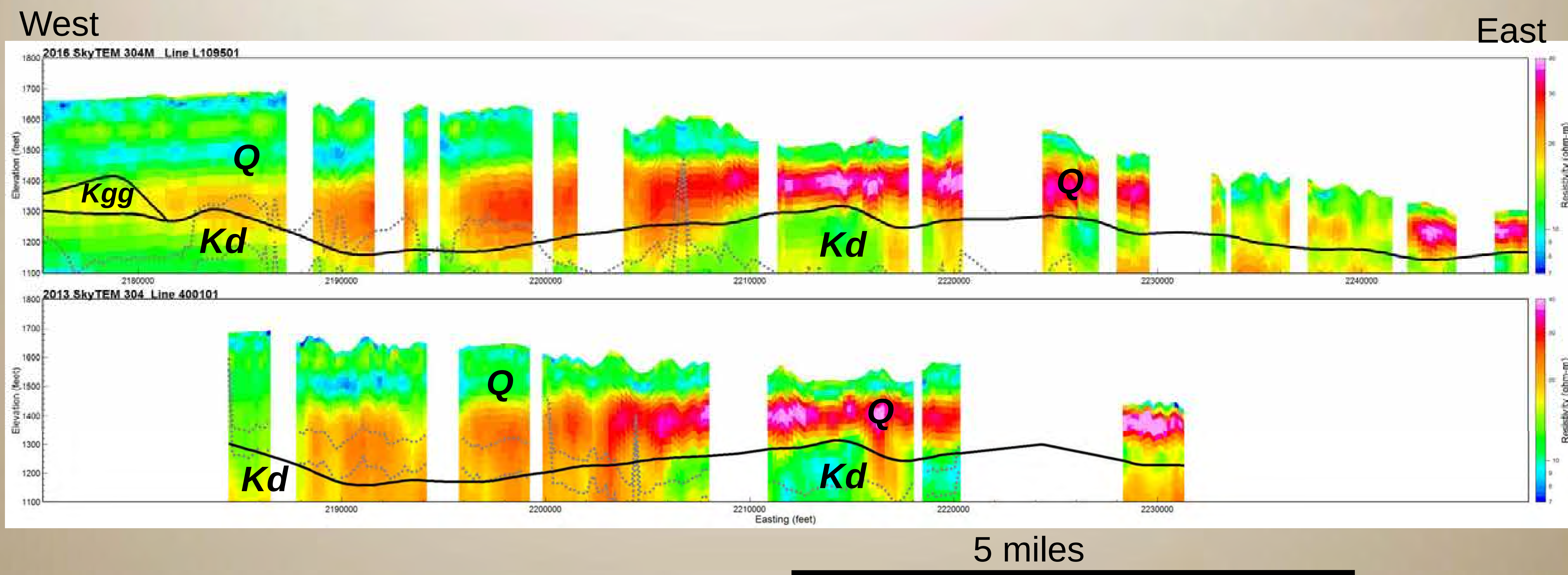


Q = Quaternary
Kn = Cretaceous Niobrara Formation
Kc = Cretaceous Carlile Shale
Kgg = Cretaceous Greenhorn Limestone and Graneros Shale

10 miles

Dashed gray lines on the AEM Inversion profile are the upper and lower Depth of Investigation (DOI). On 2014 L101701 DOI is below elevation extent of figure

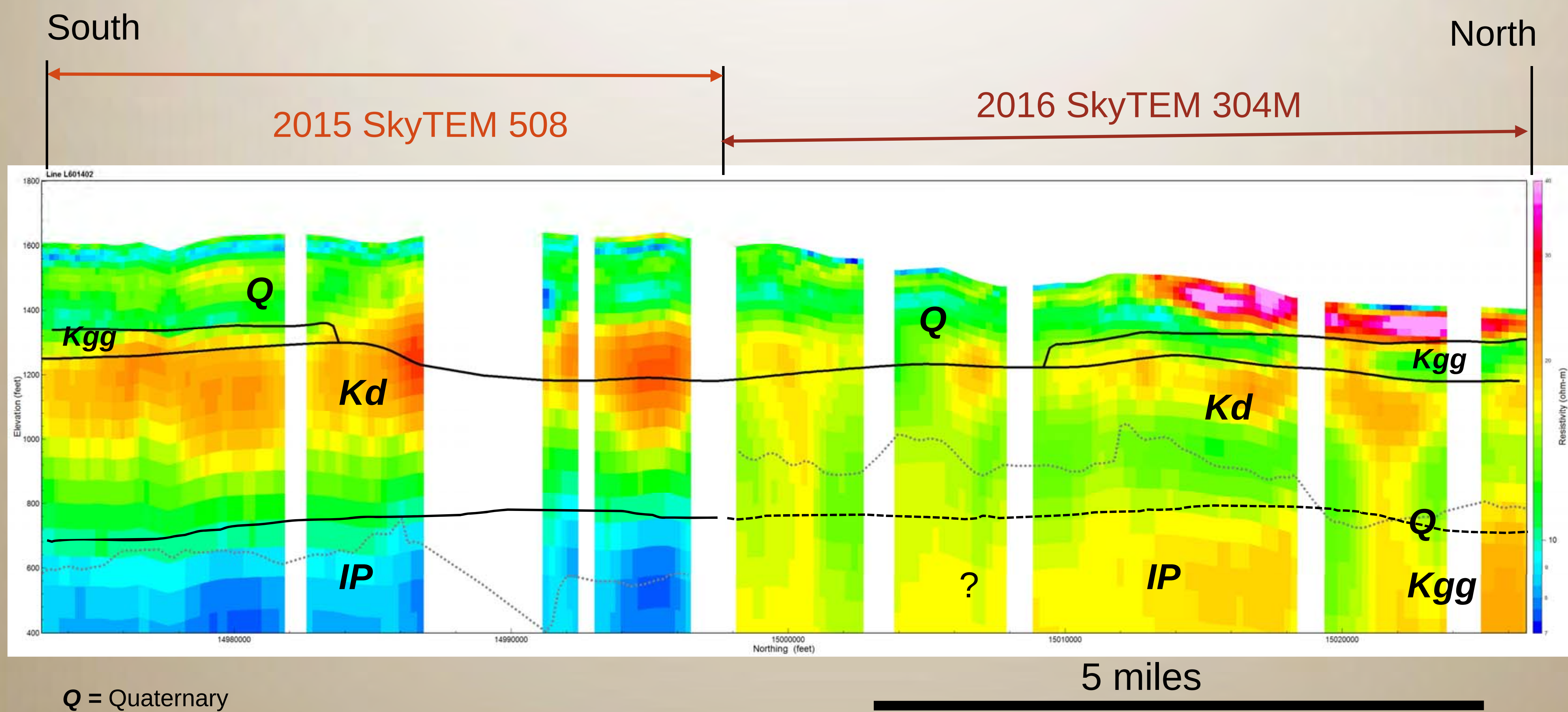
Parallel East-west lines (2013 and 2016)



Q **=** Quaternary
Kgg = Cretaceous Greenhorn Limestone and Graneros Shale
Kd = Cretaceous Dakota Group

Dashed gray lines on the AEM Inversion profile are the upper and lower Depth of Investigation (DOI).

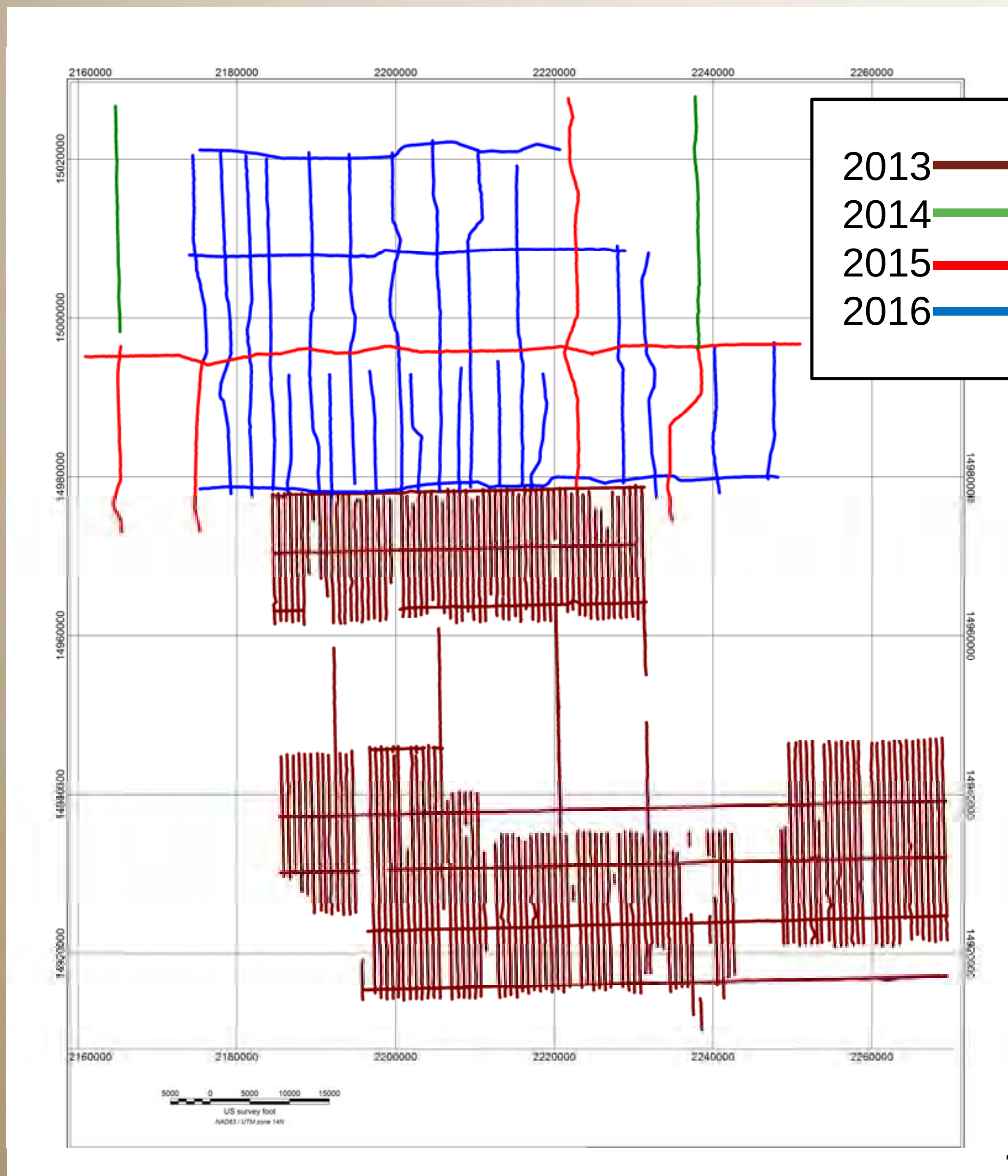
North-south line (2015 and 2016)

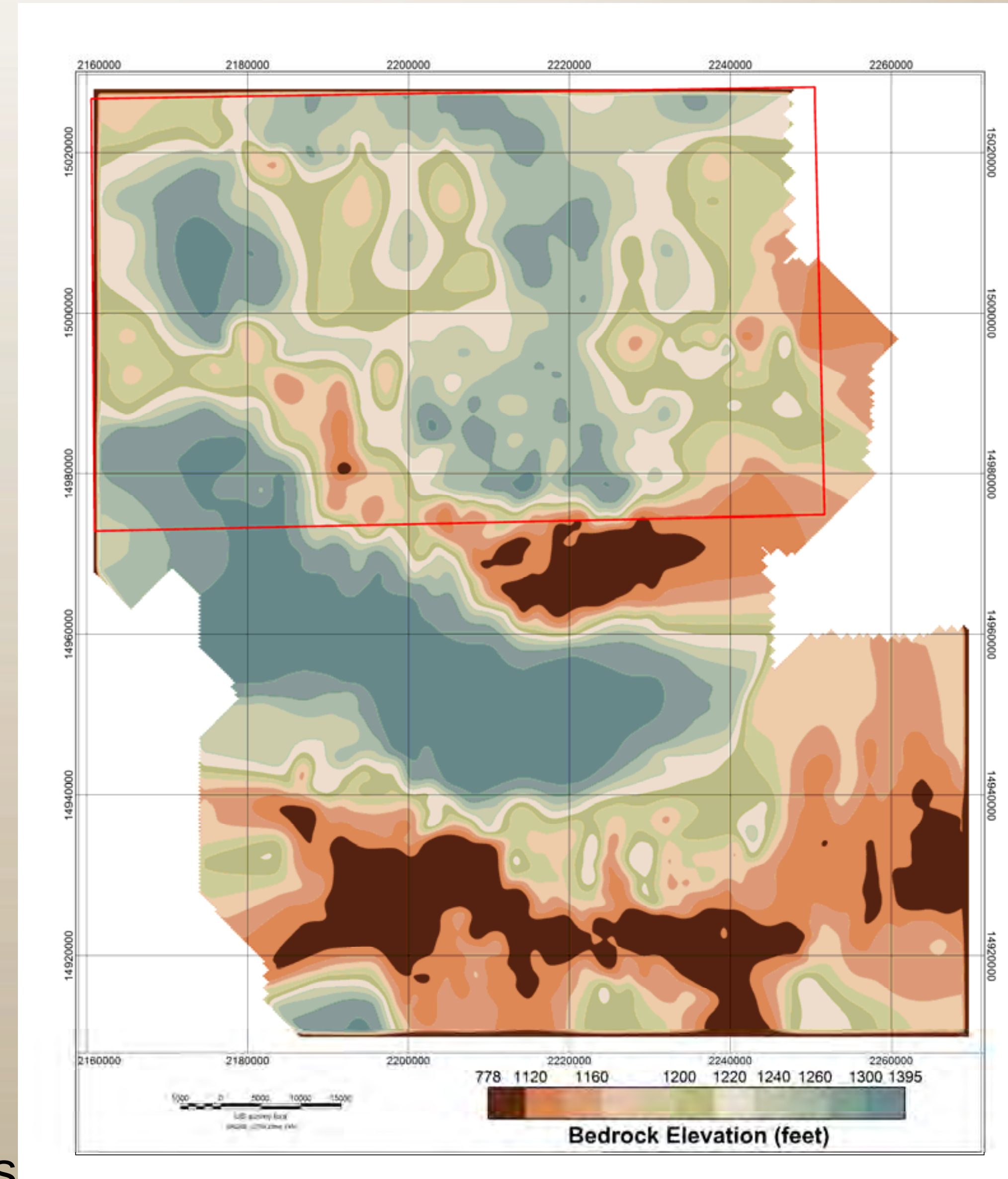


Q **=** Quaternary
Kgg = Cretaceous Greenhorn Limestone and Graneros Shale
Kd = Cretaceous Dakota Group
IP = Undifferentiated Pennsylvanian

Dashed gray lines on the AEM Inversion profile are the lower Depth of Investigation (DOI).

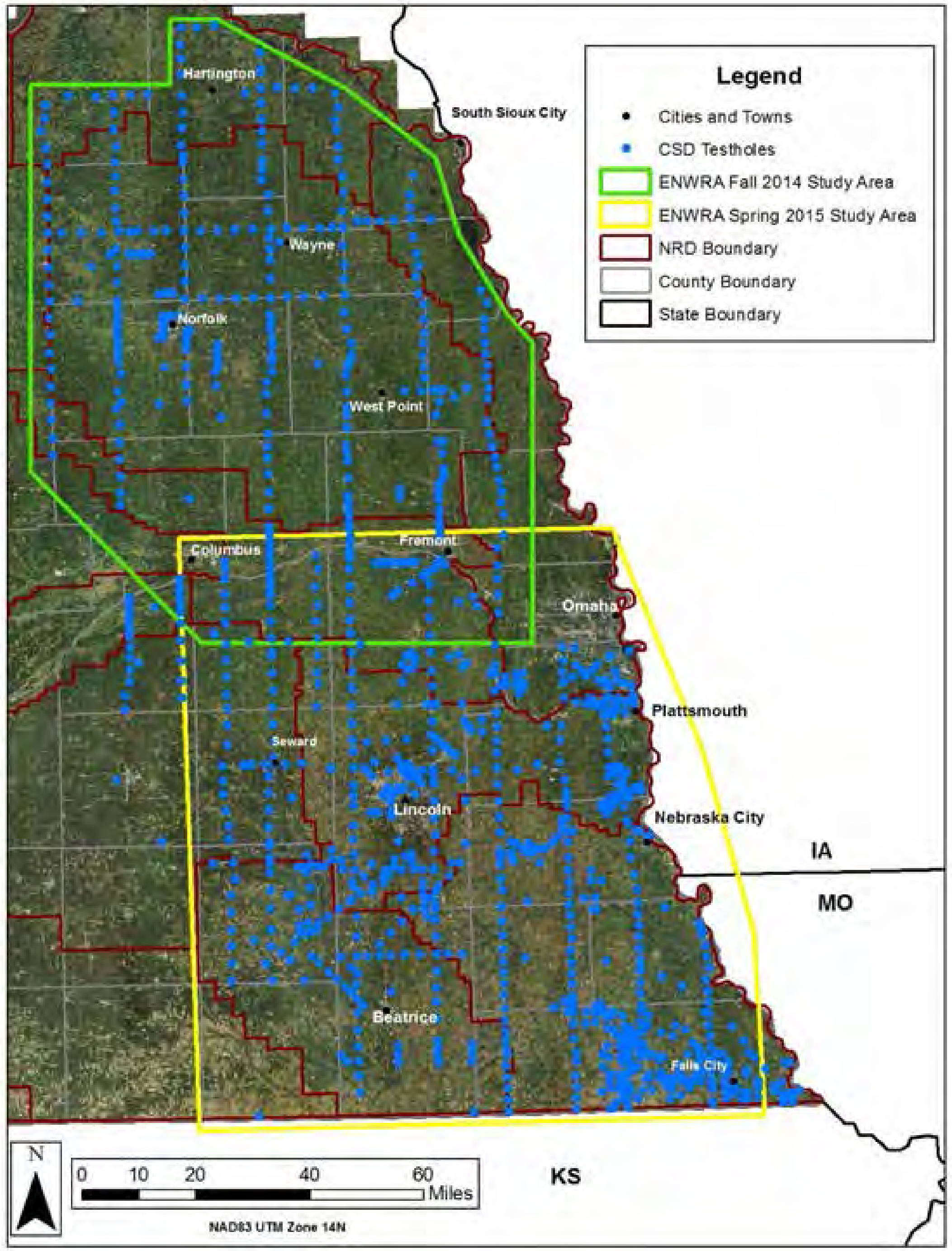
SURFACE BEDROCK FROM COMBINES LINES (2013, 2014, 2015, 2016)

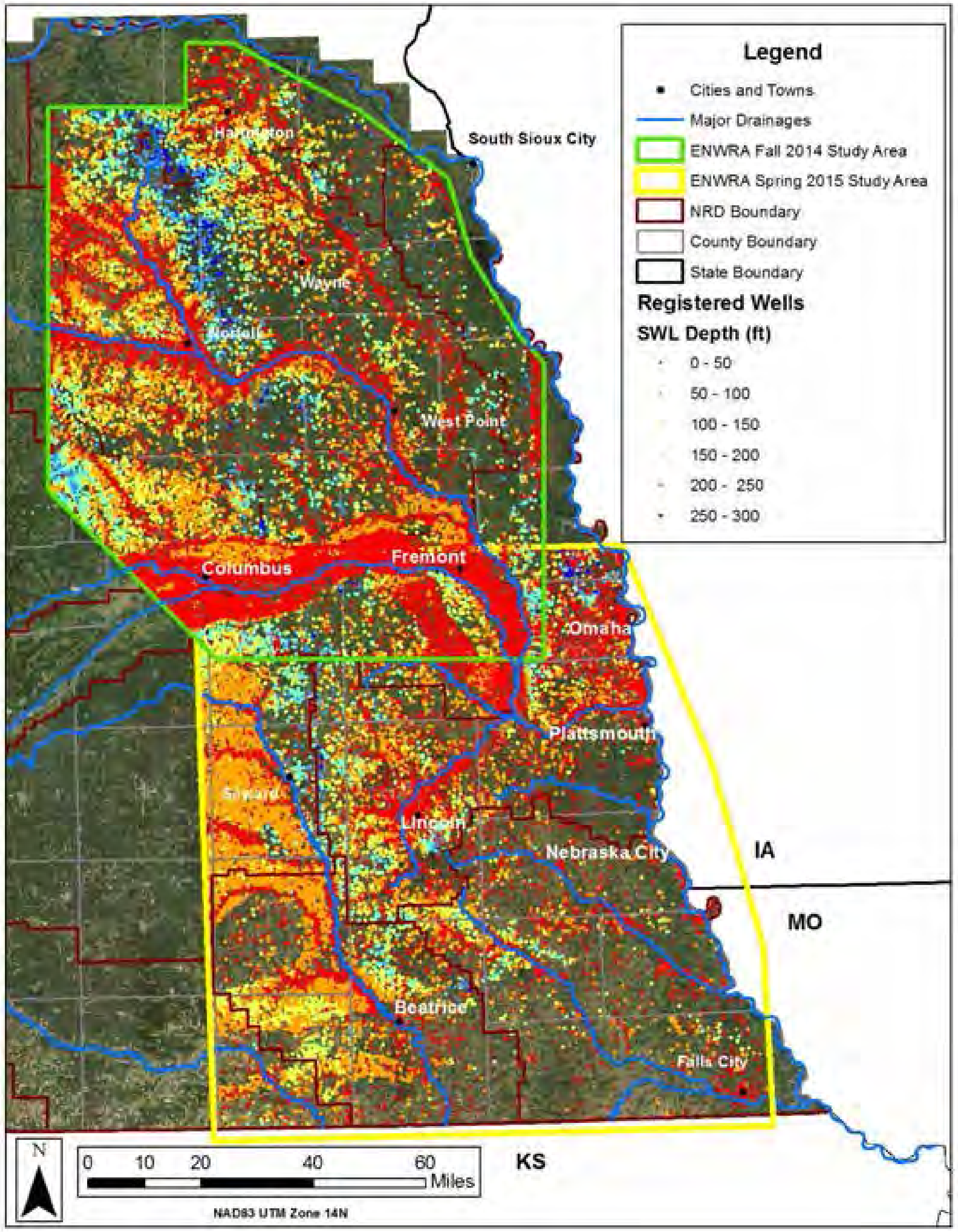




10 miles

BACKGROUND BOREHOLE DATA





Abraham et al., 2016

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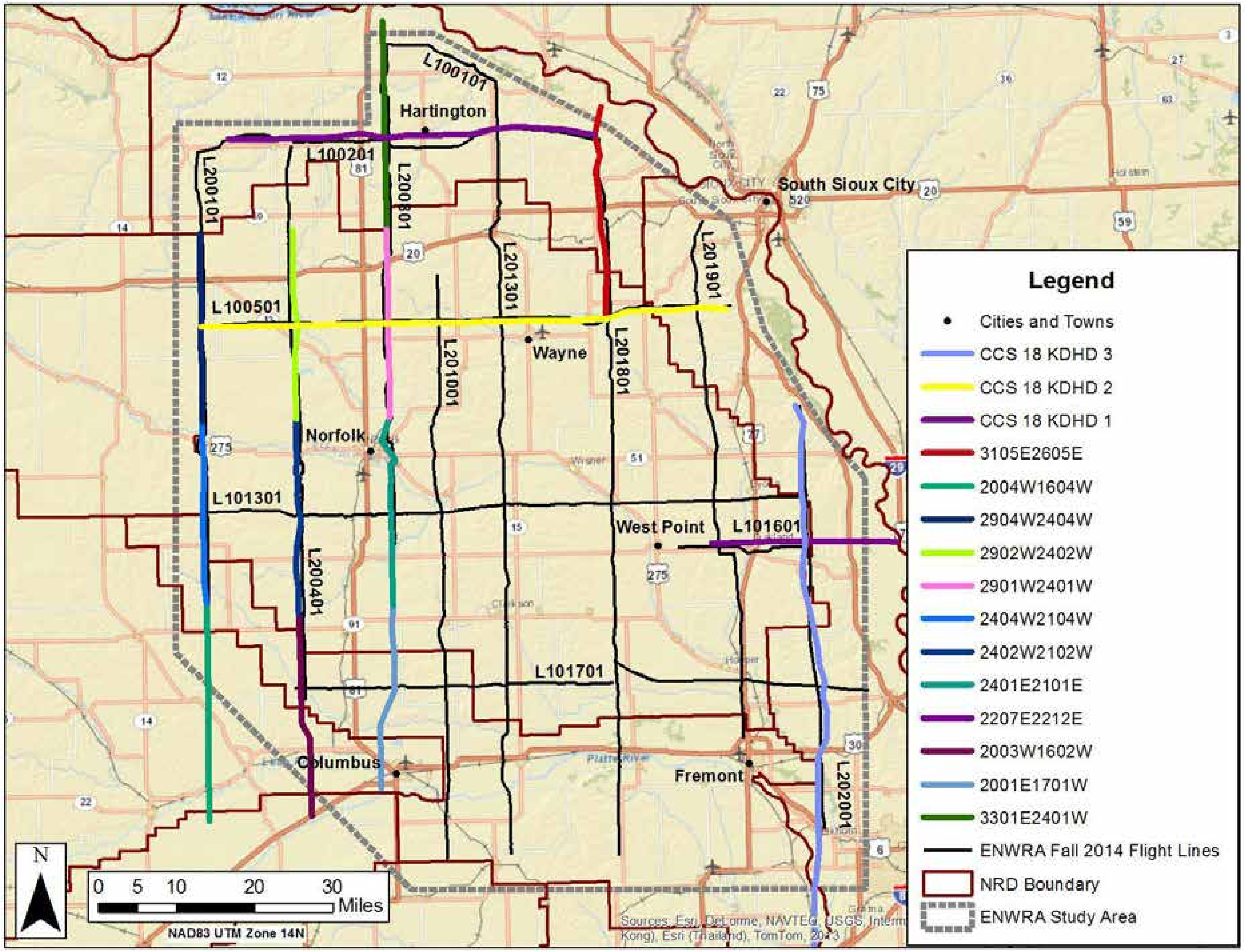
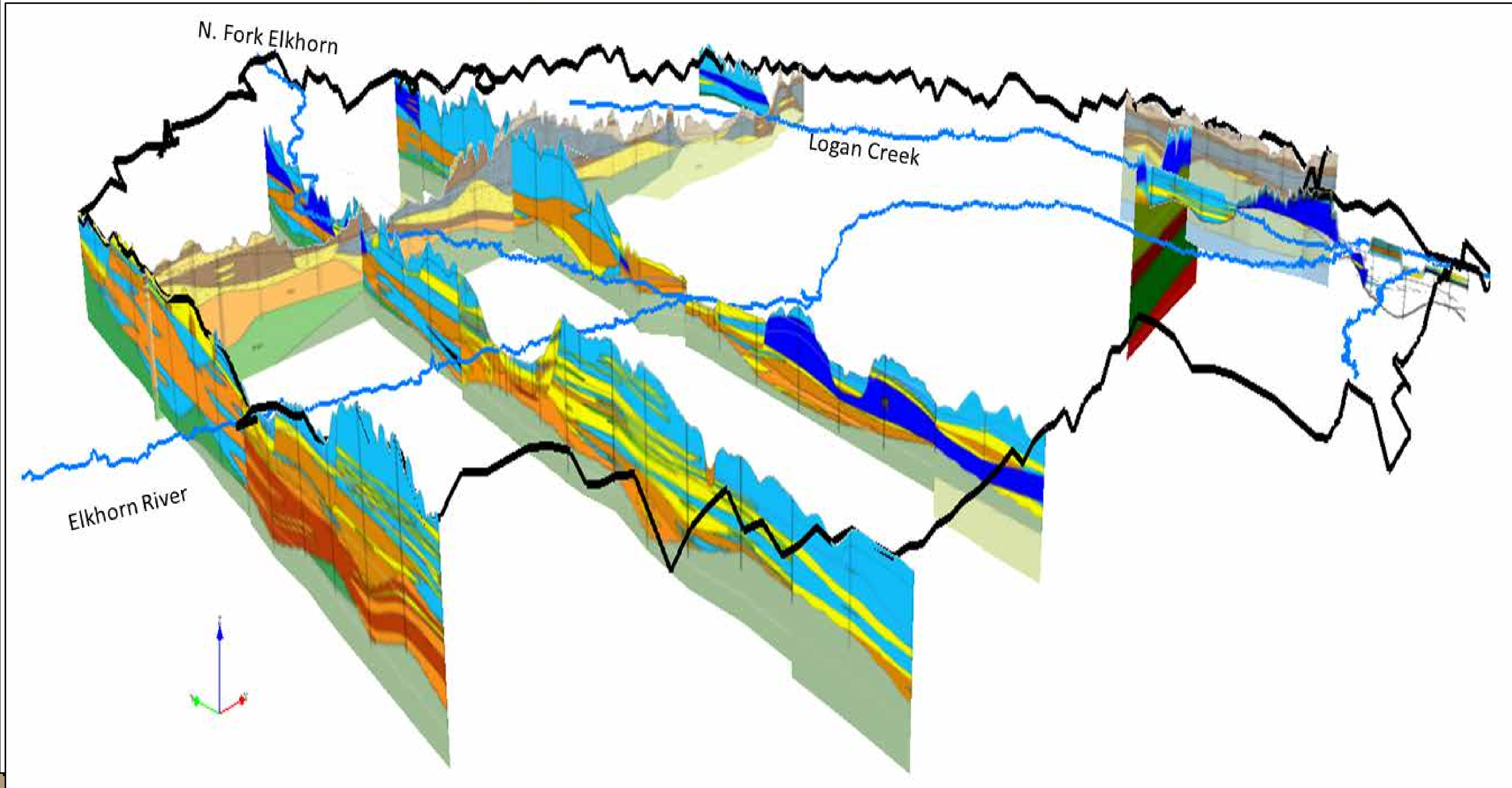
CSD Historical Cross Sections

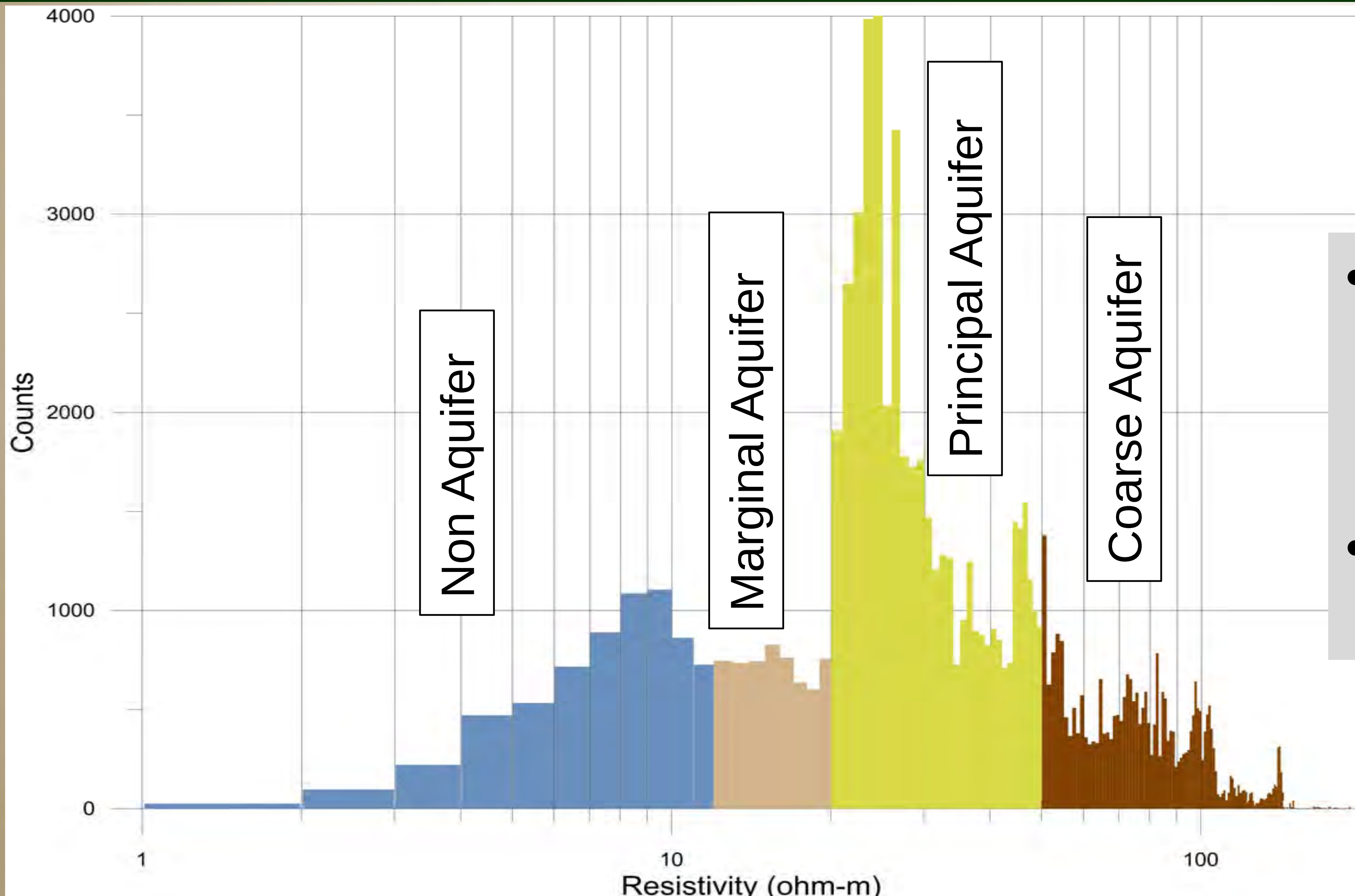


Abraham et al., 2016

CSD Cross Sections



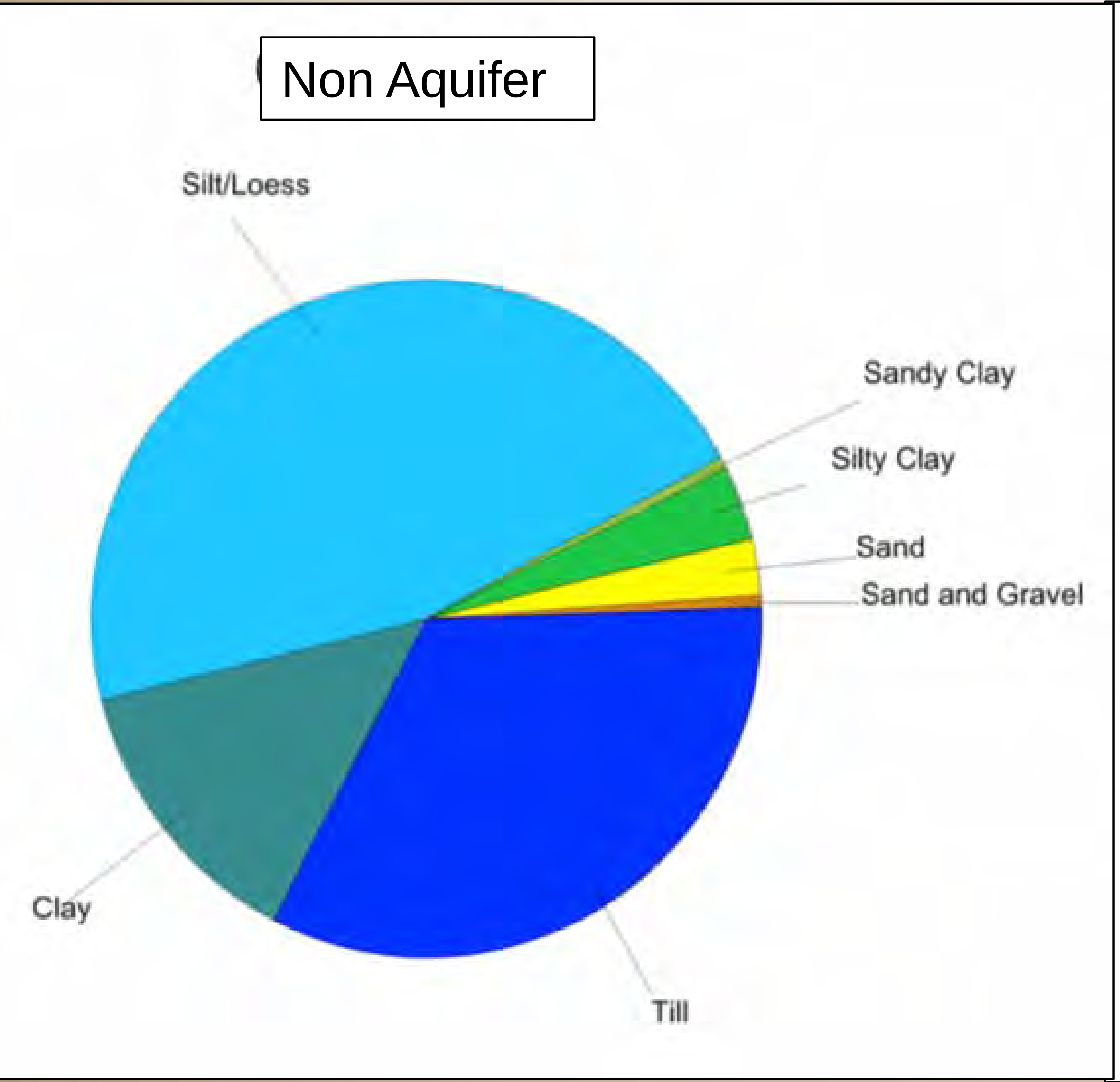
Resistivity versus Lithology and Aquifer Materials

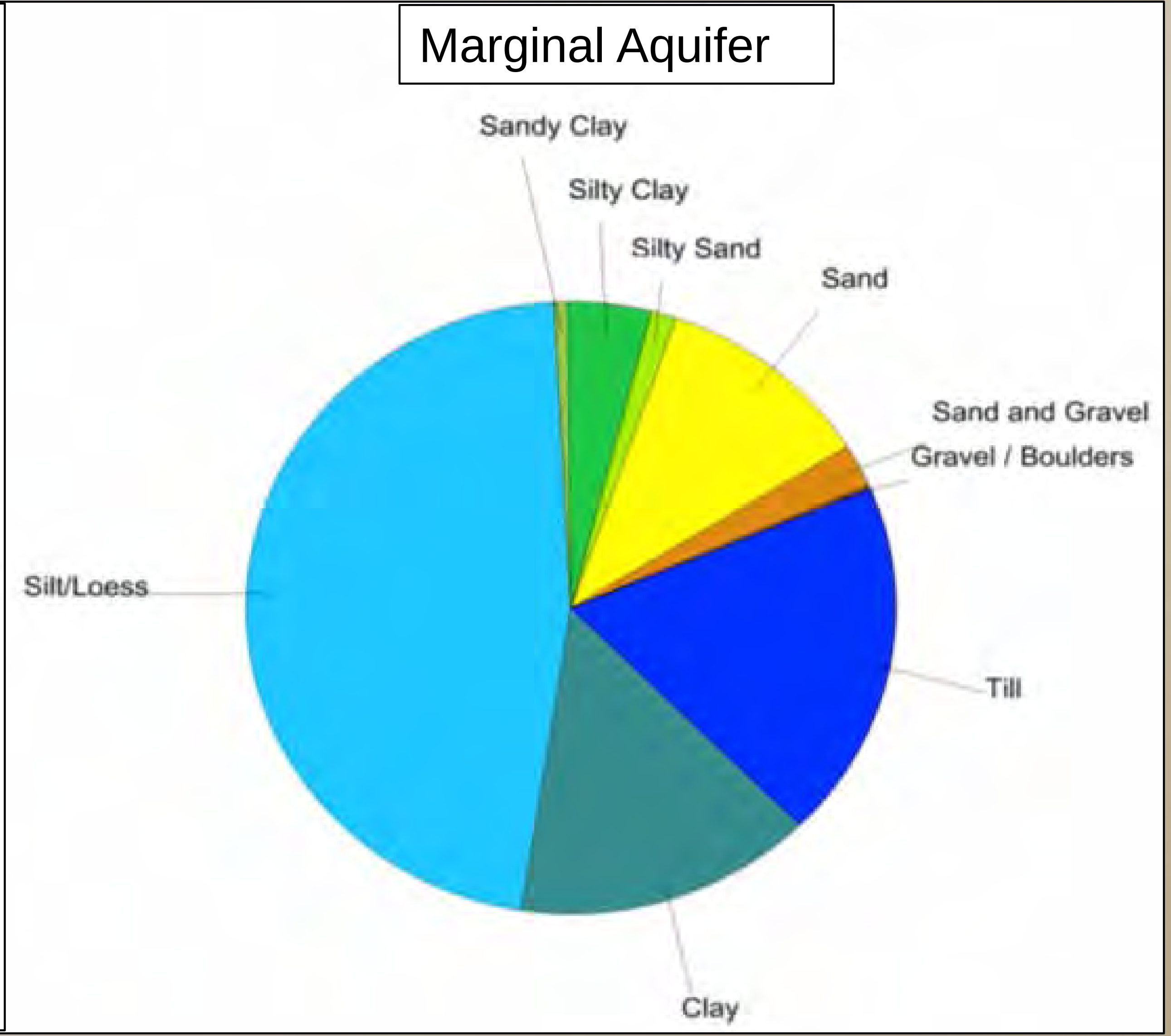


- 39 CSD boreholes with lithology and resistivity geophysical logs
- ~209,000 individual measurements

Abraham et al., 2016

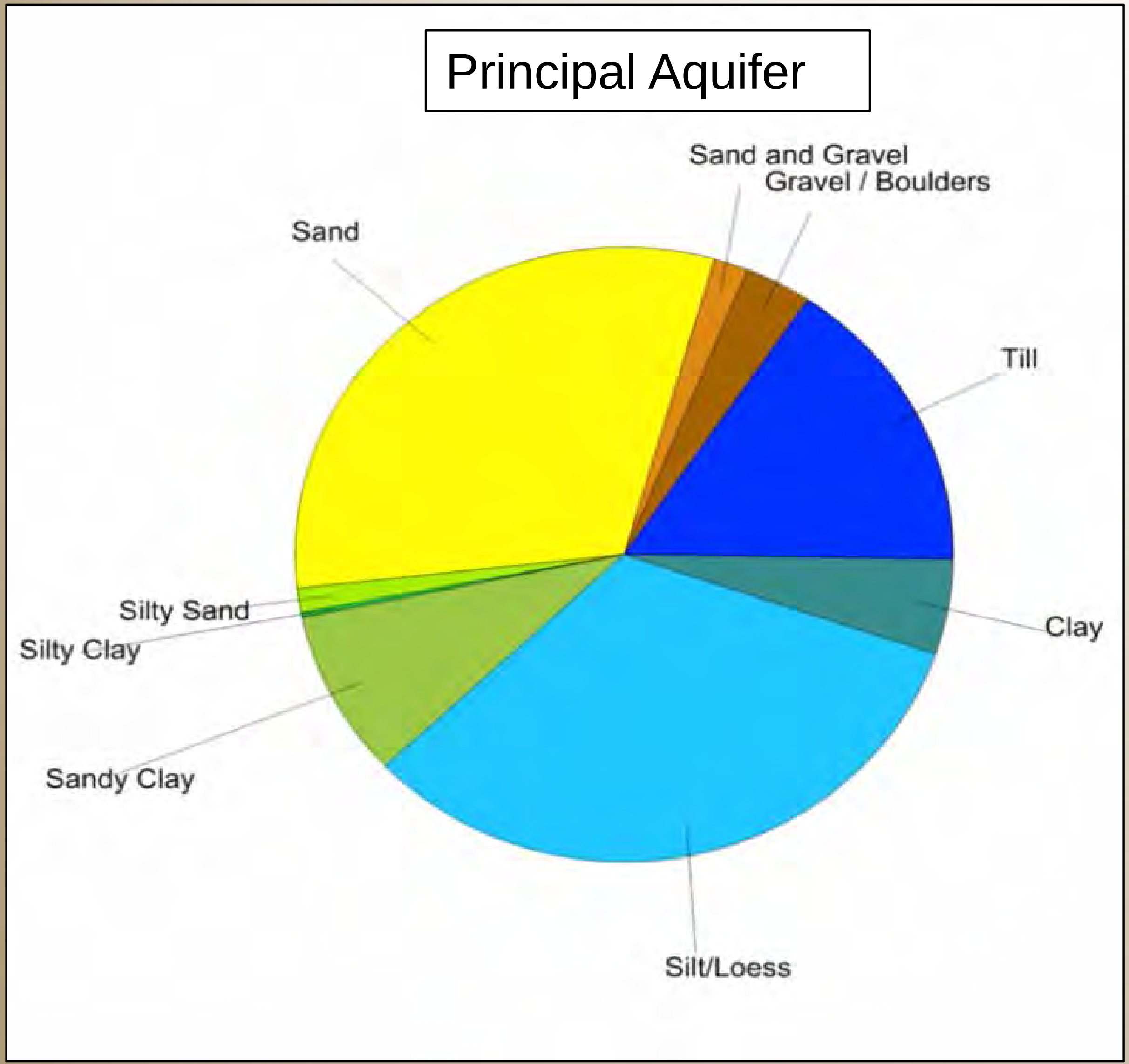
LITHOLOGY VERSUS AQUIFER MATERIAL

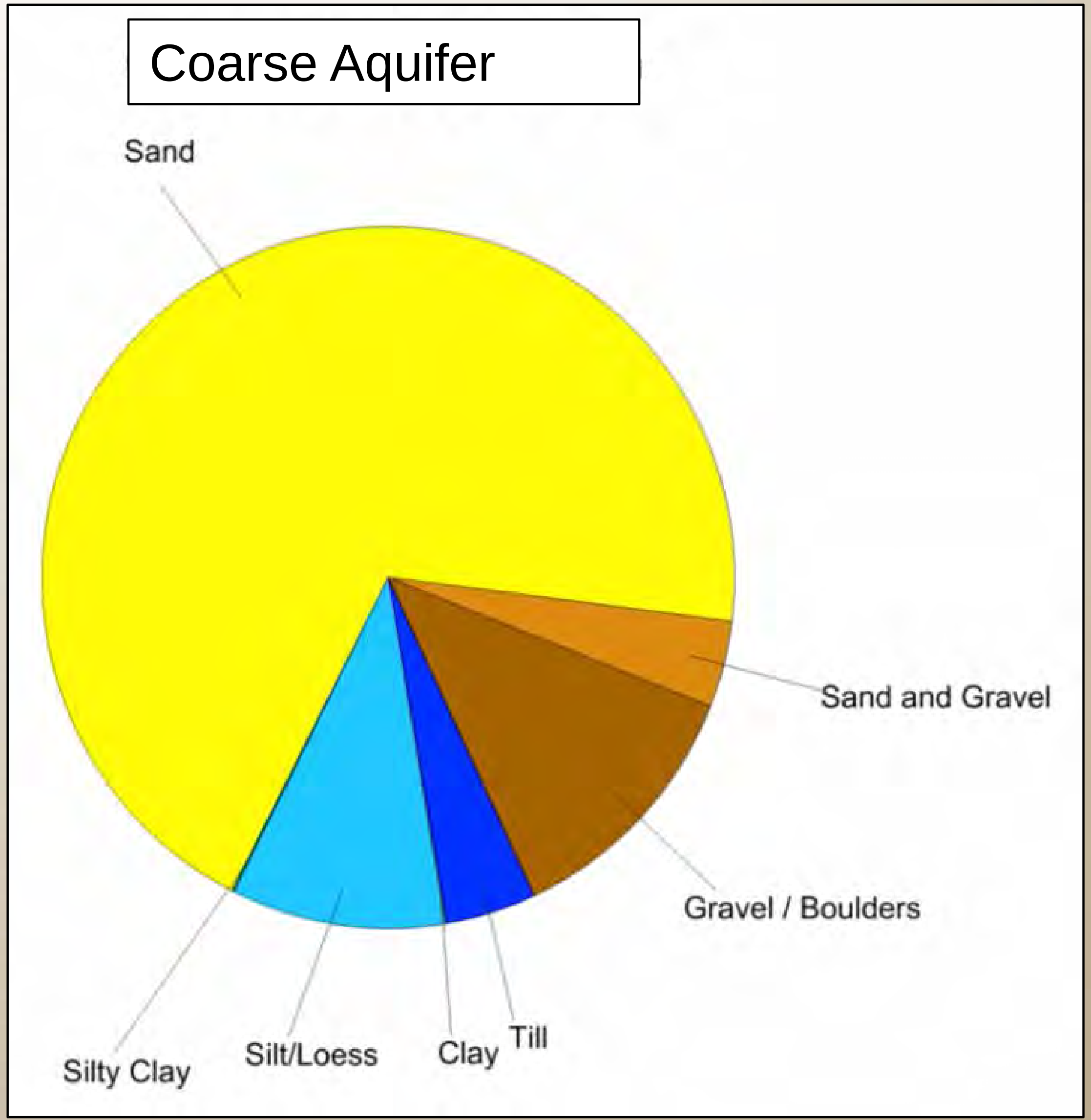




Abraham et al., 2016

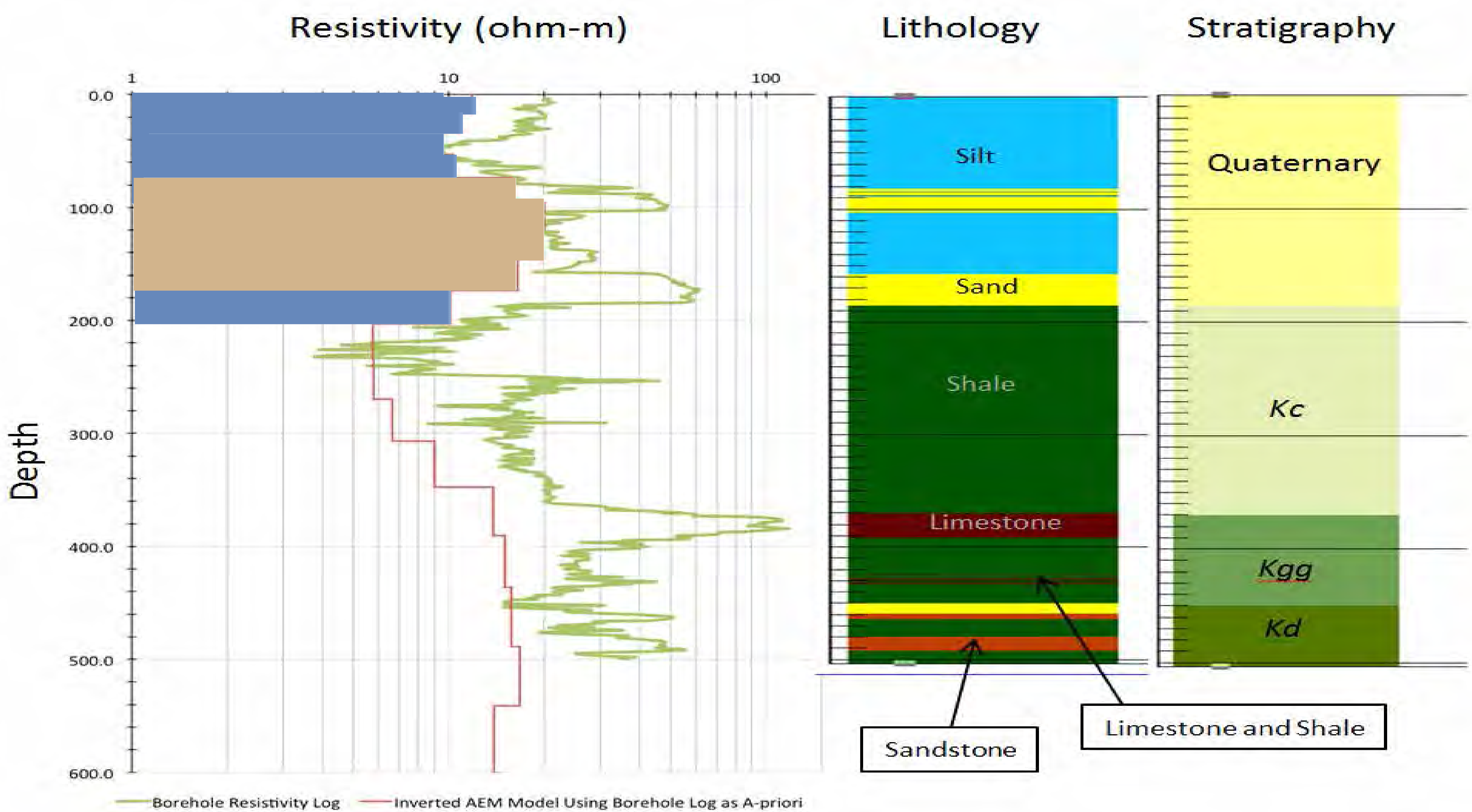
Lithology versus Aquifer Material



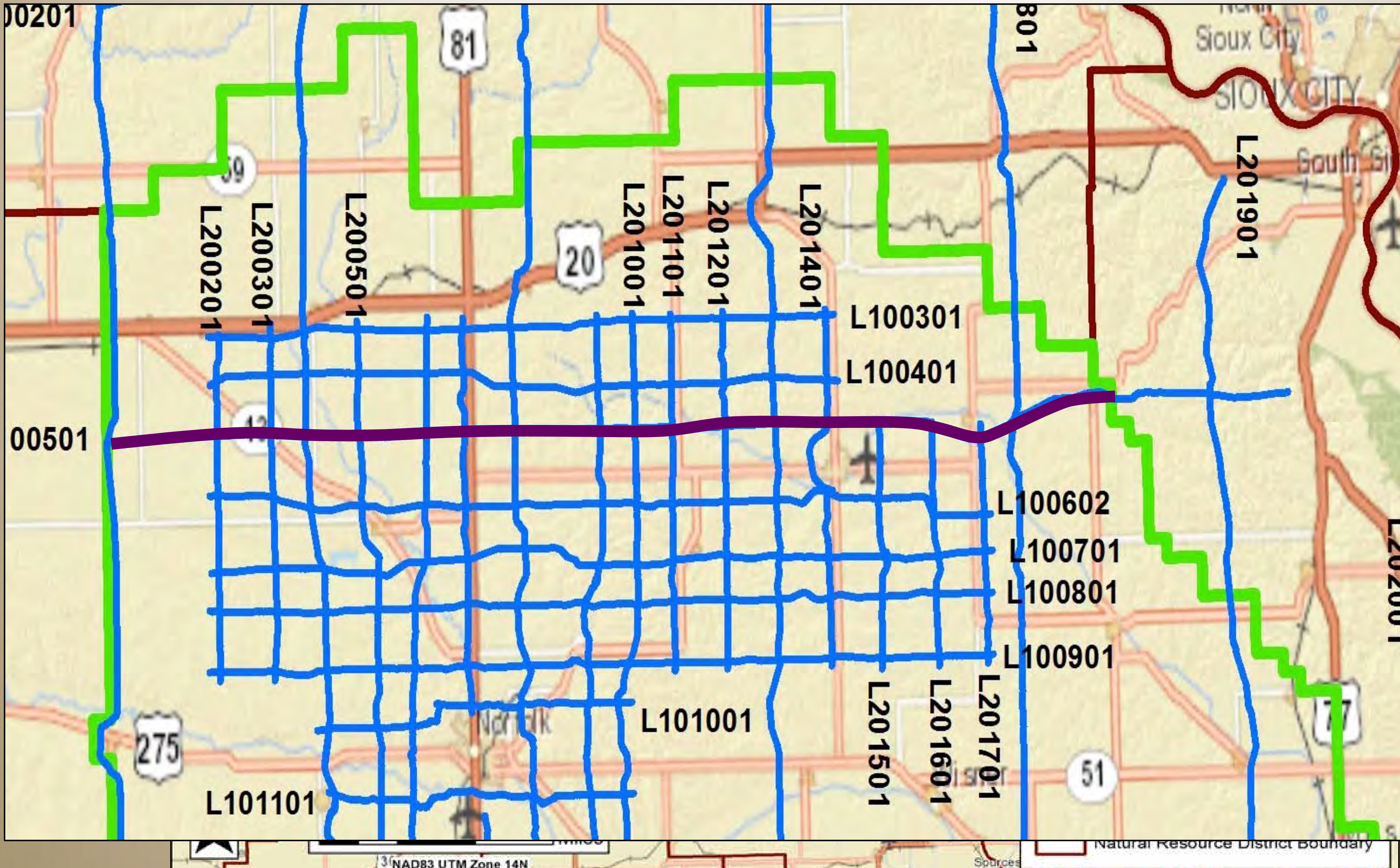


Abraham et al., 2016

CSD 5-GT-80 300 METERS OFF LINE



Example Cross Section



Abraham et al., 2016

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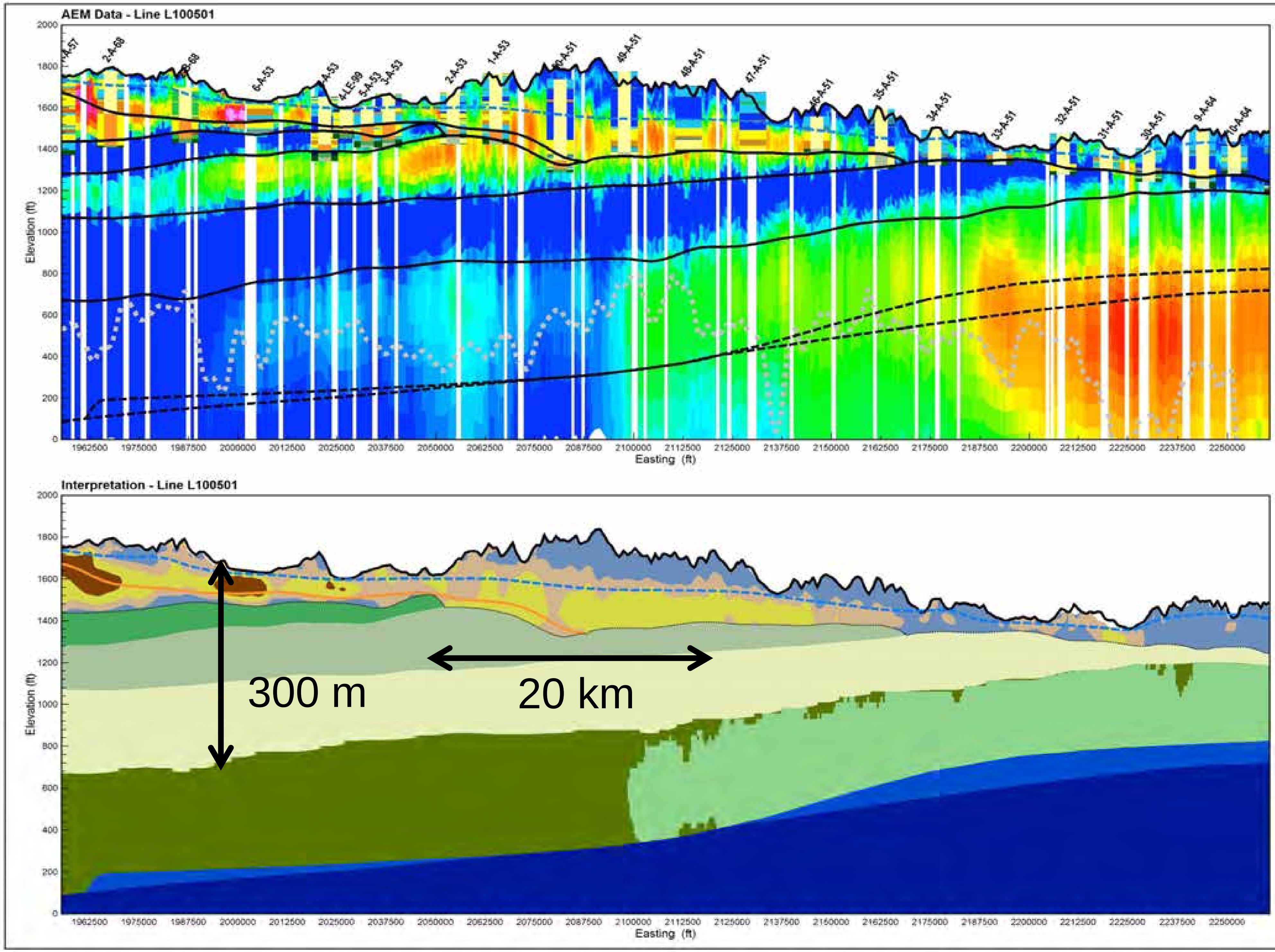
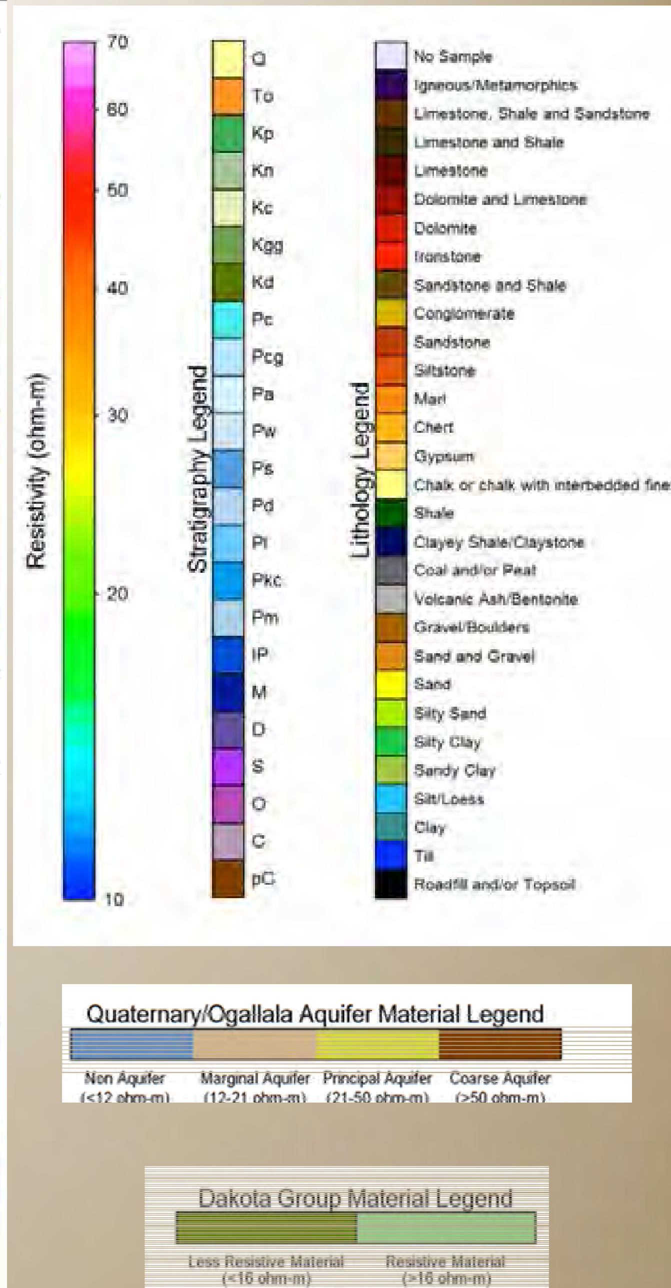
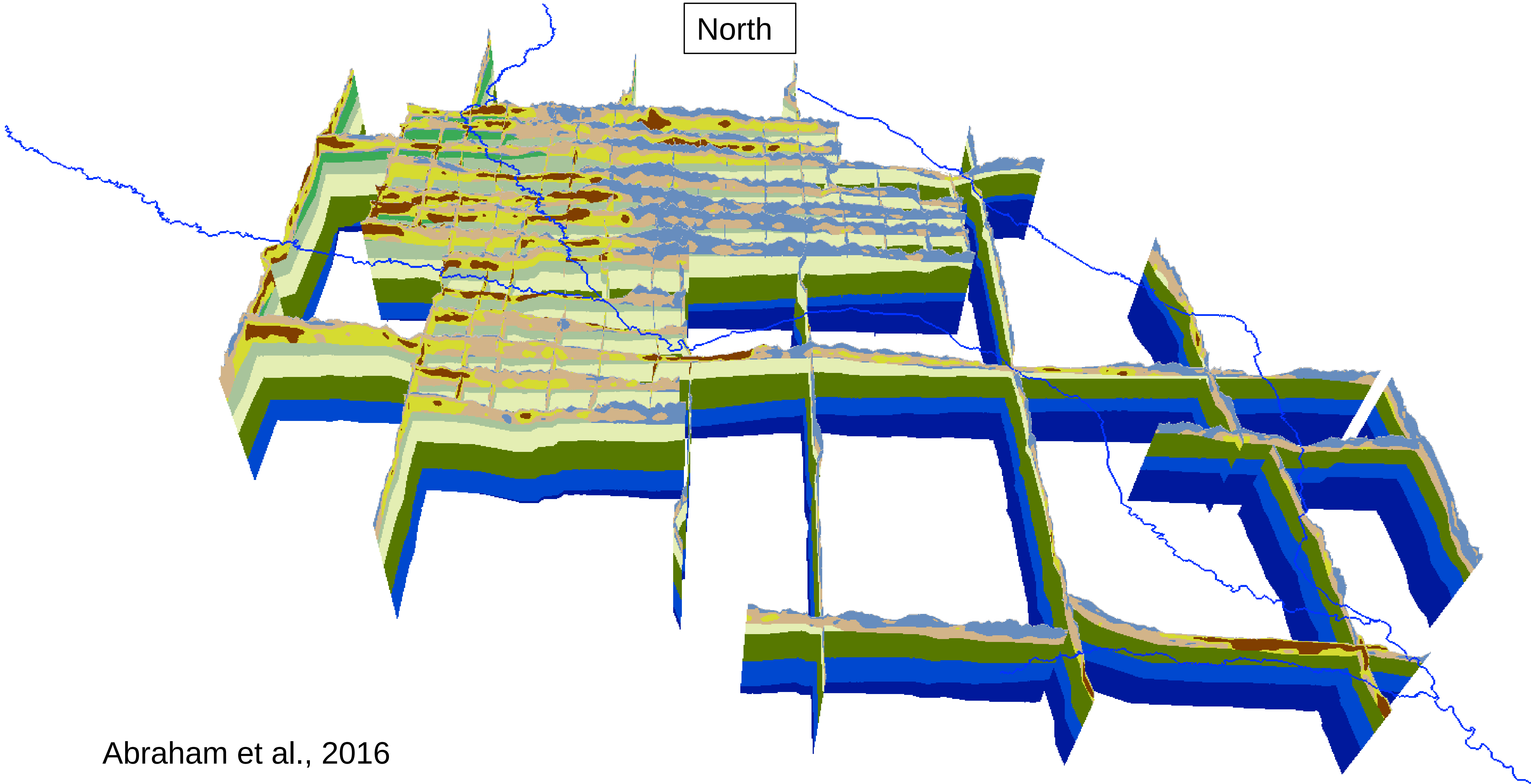




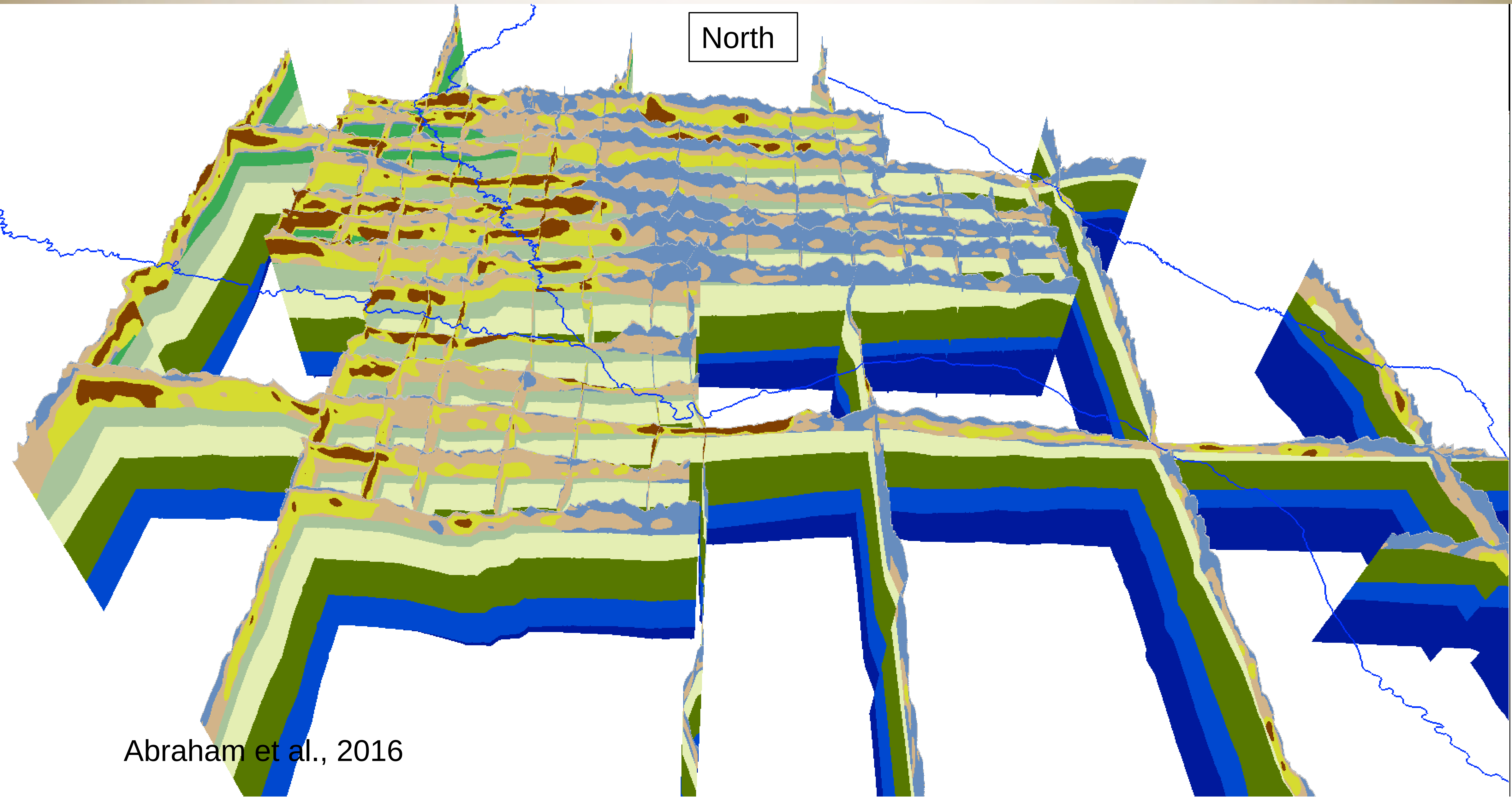
Carney, et al., 2015

3D of the 2014 AEM in LENRD



Abraham et al., 2016

3D of the 2014 AEM in LENRD



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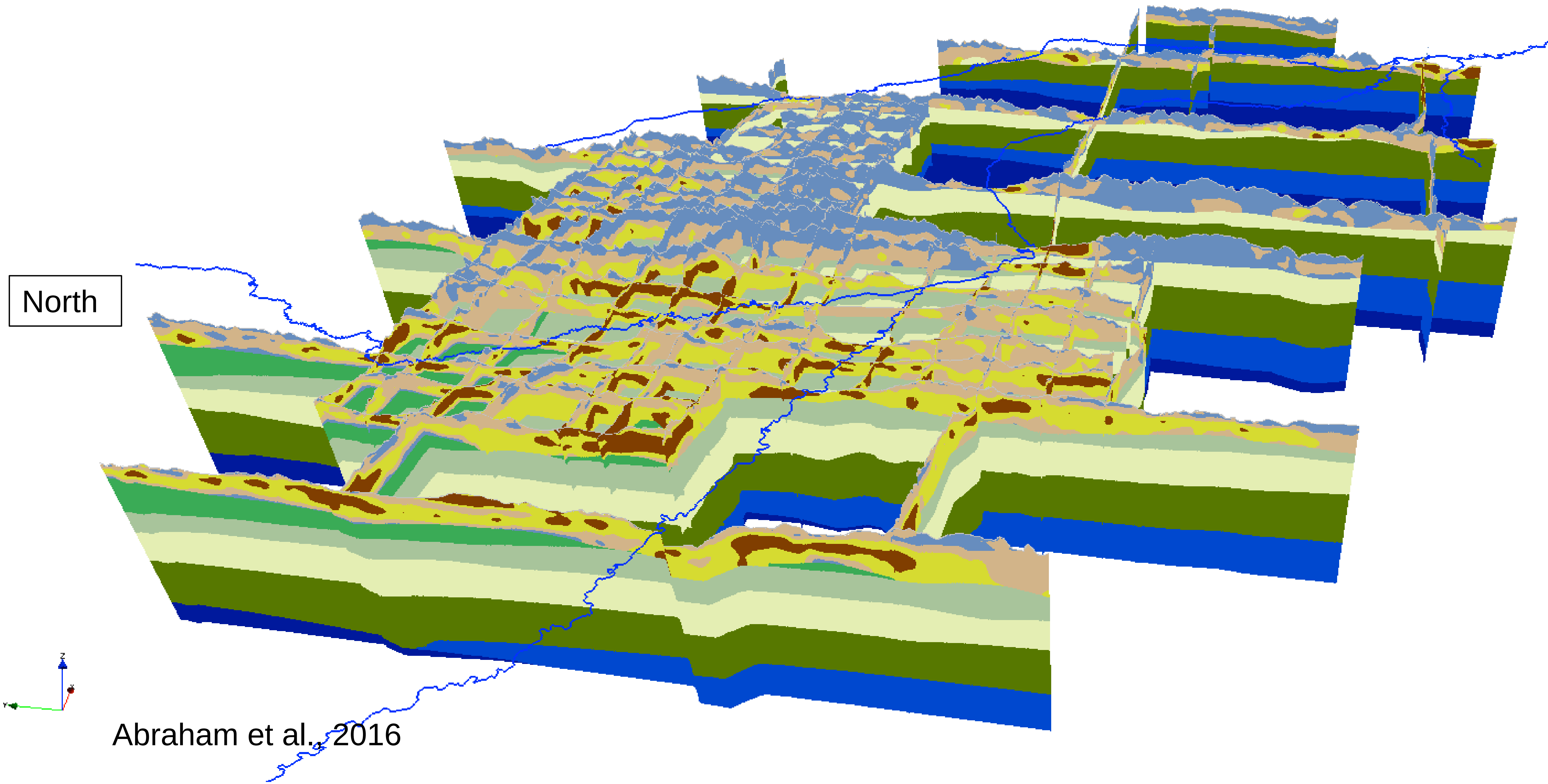

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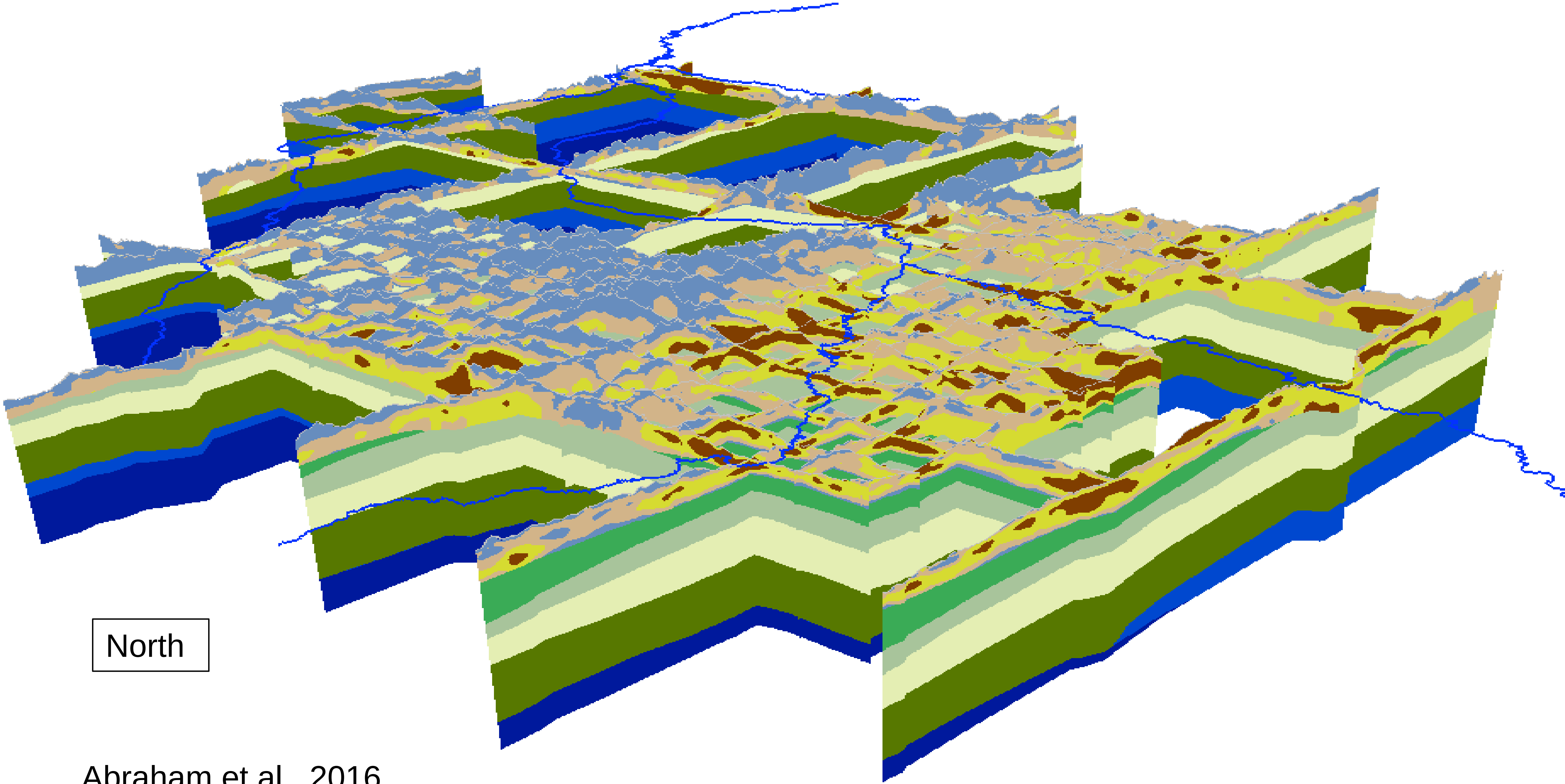
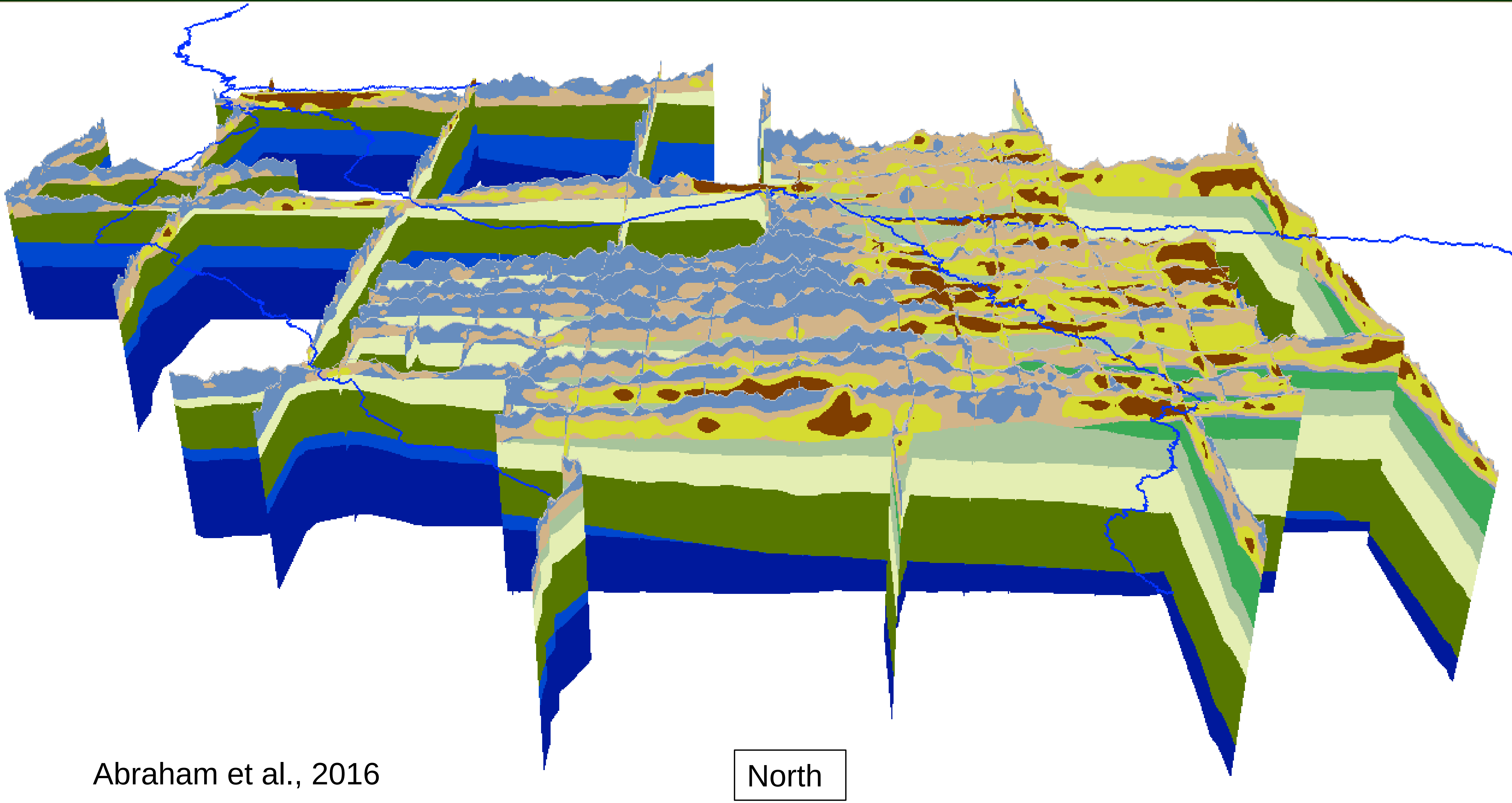


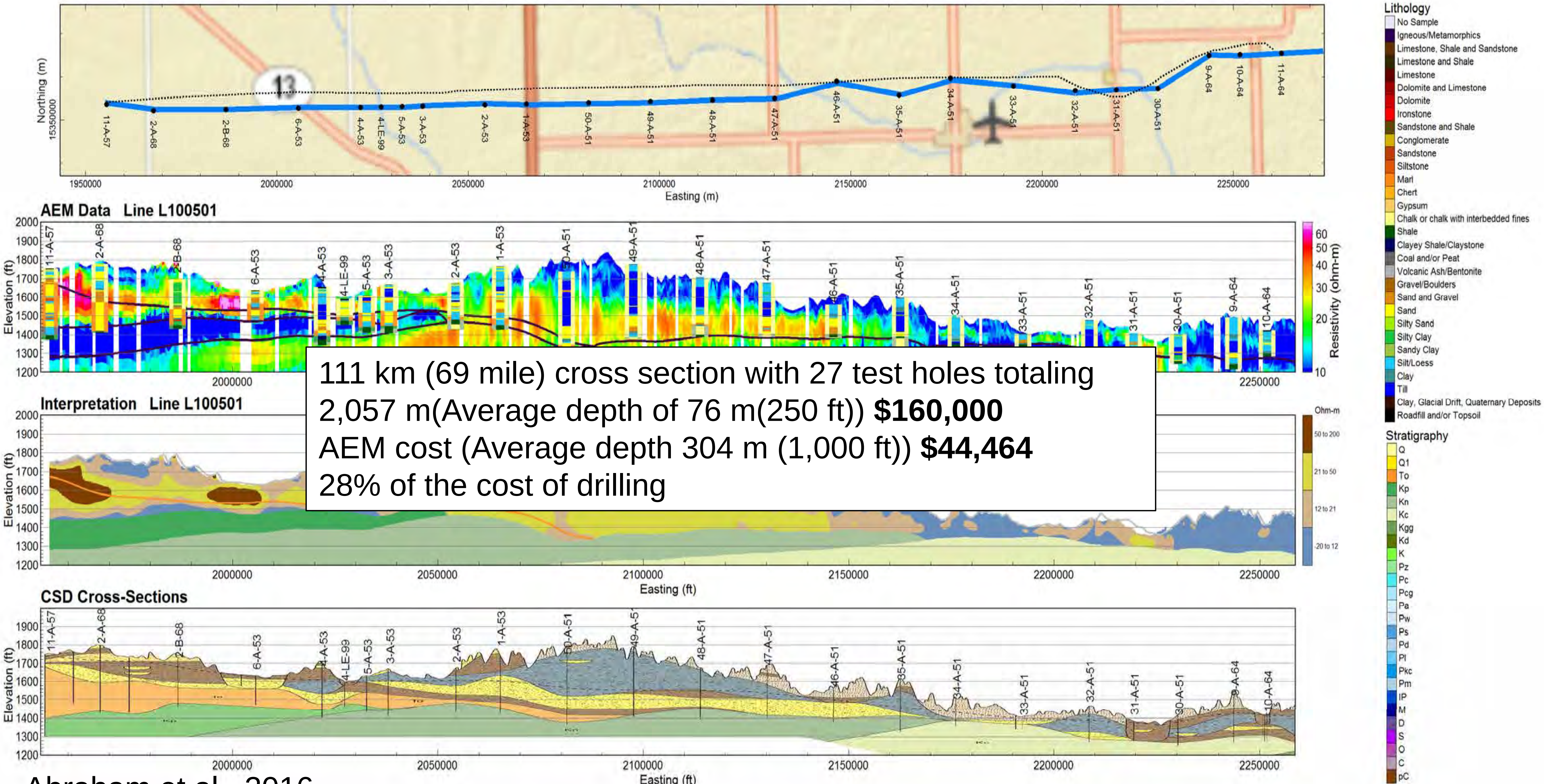
Abraham et al., 2016

3D OF THE 2014 AEM IN LENRD



Abraham et al., 2016

AEM versus CSD Cross Section



111 km (69 mile) cross section with 27 test holes totaling 2,057 m(Average depth of 76 m(250 ft)) **$160,000**

AEM cost (Average depth 304 m (1,000 ft)) **$44,464**

28% of the cost of drilling

Abraham et al., 2016

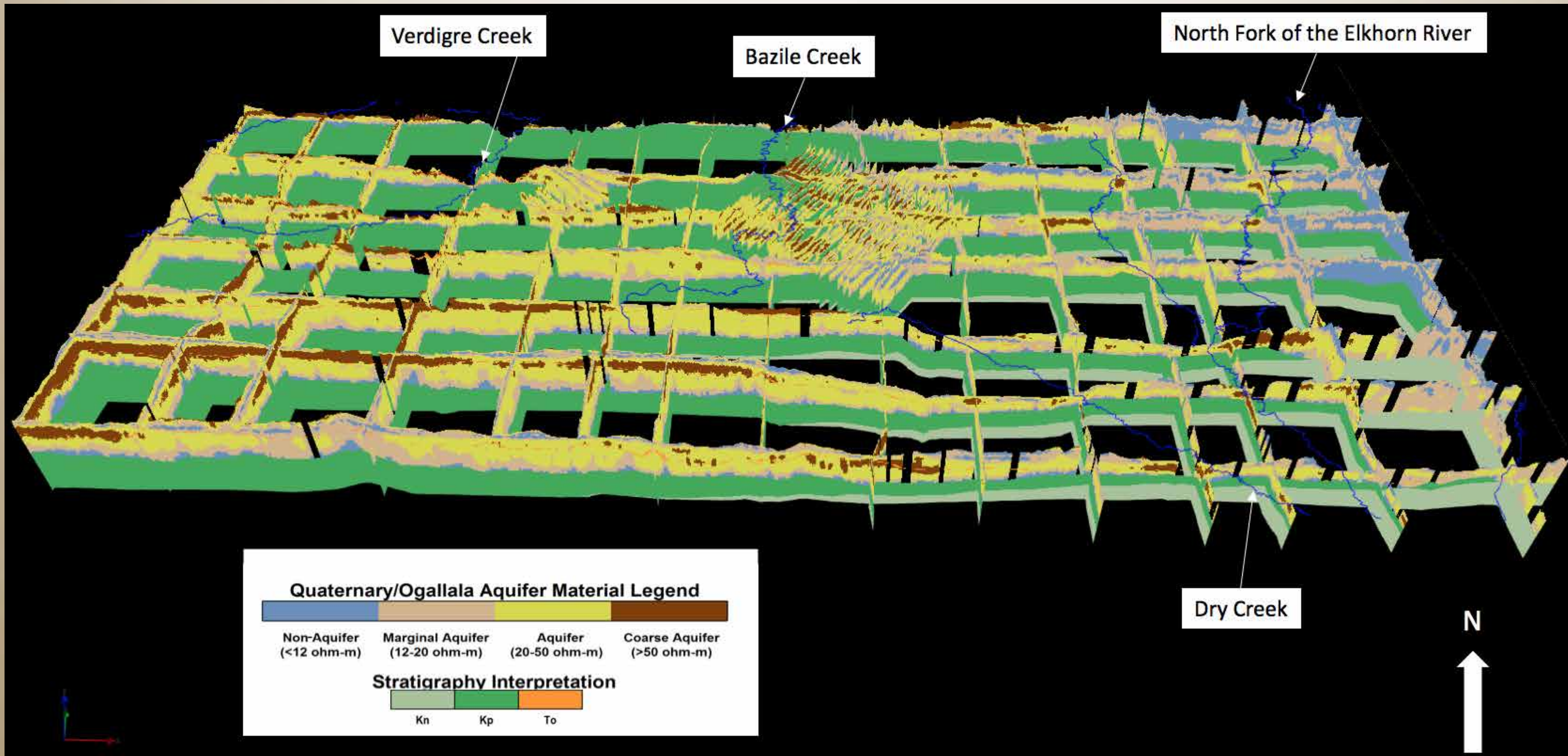
Bazile Groundwater Management Area (BGMA)
(Upper Elkhorn, Lower Niobrara, Lewis and Clark, and Lower Elkhorn NRD's)

White = 2016 BGMA lines
Orange = 2014 ENWRA and LENRD lines
Pink = 2016 LCNRD lines
Green = 2016 LENRD lines

Abraham et al., 2016

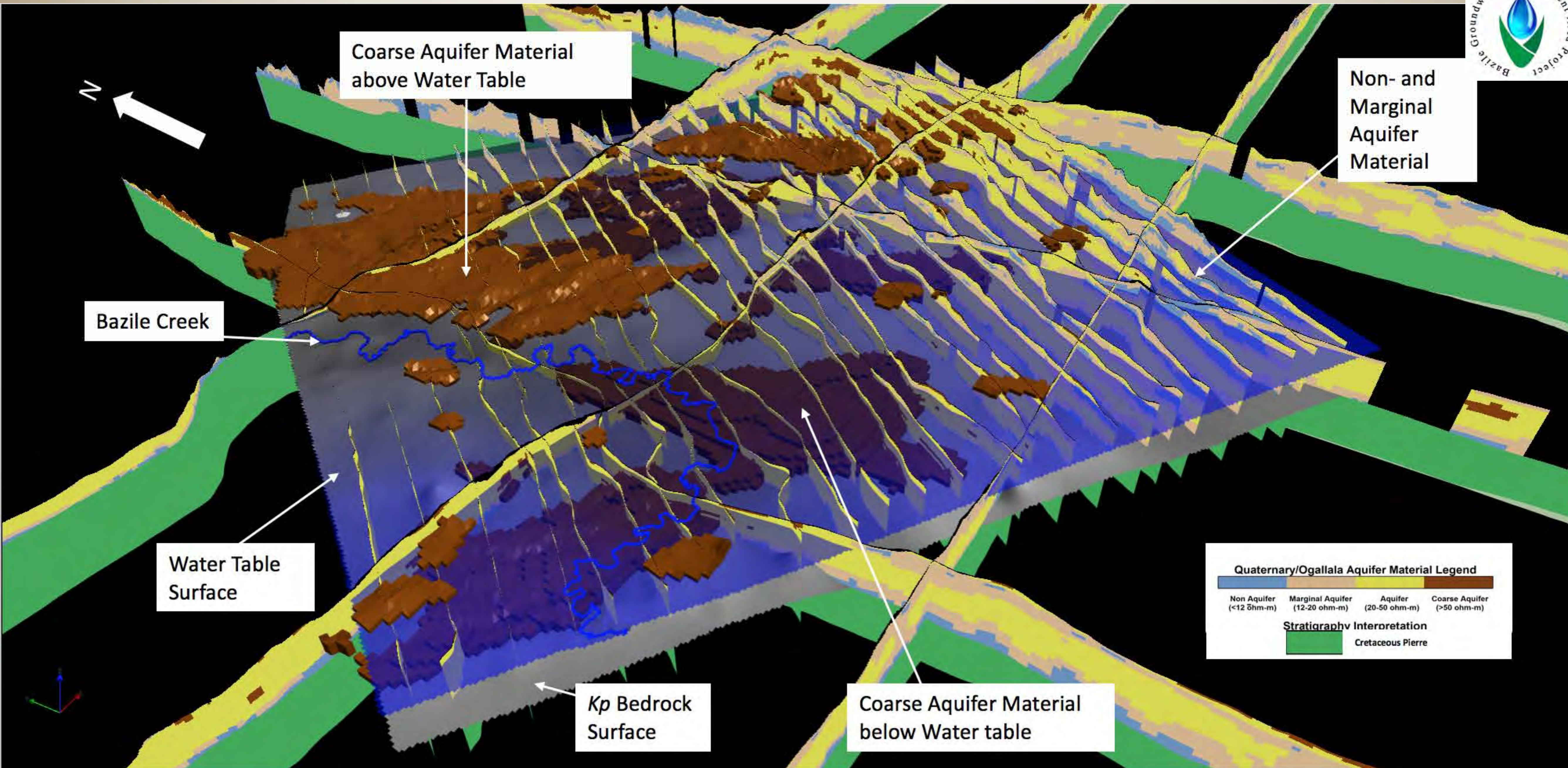
- 0.25-0.33 mile (402-531 m) spaced block flights over well head protection areas
- 3 x 3 mile grids
- Approximately 644 line-miles (1,036 line-km)
- SkyTEM 304M system-first time gate 10 μsec, 1.6 μsec wide and last time gate of 7.5 msec
- Aarhus Workbench SCI was used with 30 layer smooth inversion. First layer 9.8 ft (3 m).

BGMA 3D



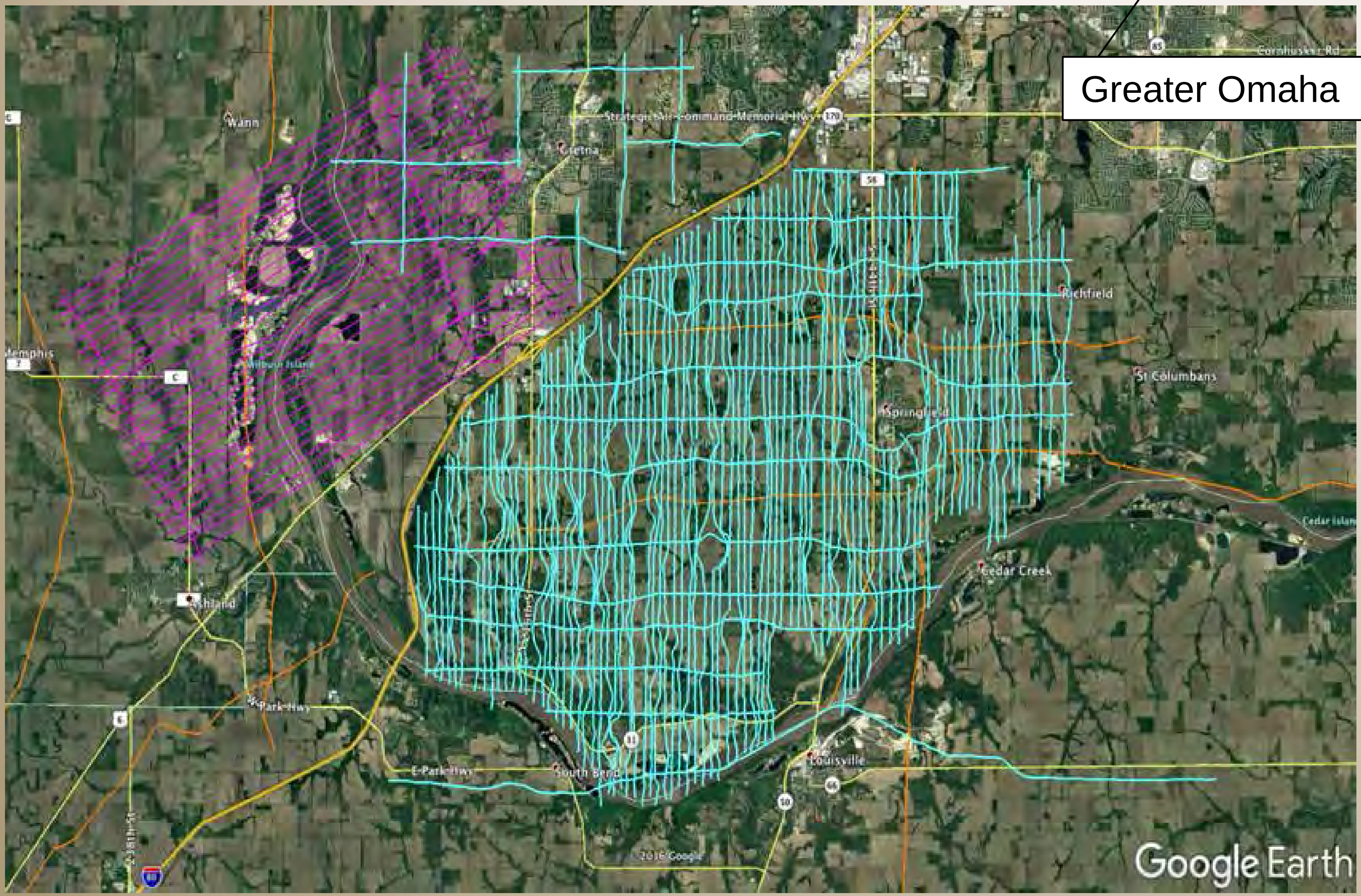
Abraham et al., 2016

CREIGHTON WELLHEAD PROTECTION AREA



Abraham et al., 2016

Sarpy County



Turquois = 2016 Sarpy County lines
Orange = 2015 ENWRA lines
Lavender = 2007 Ashland lines

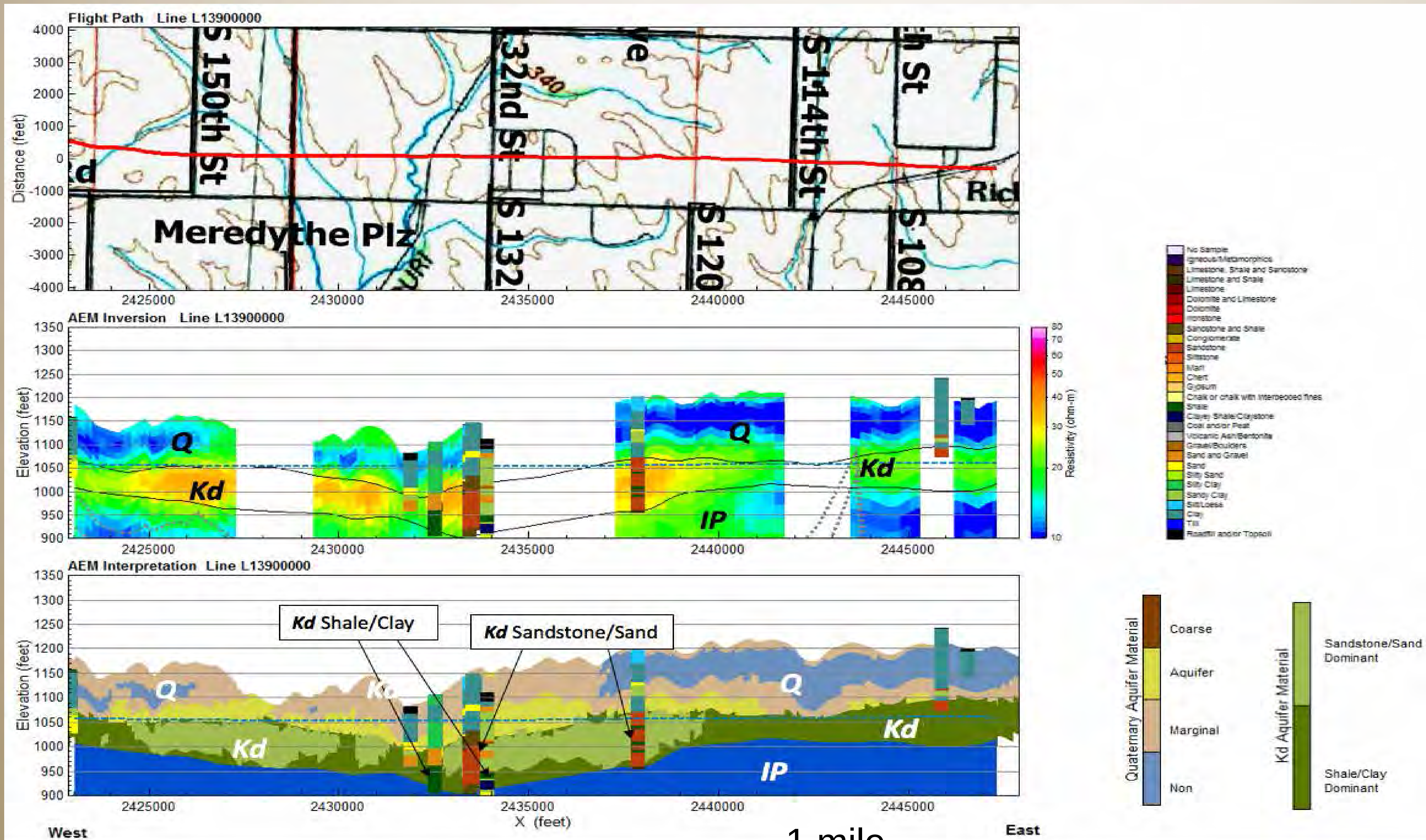
Abraham et al., 2016

PAPIO-MISSOURI RIVER NATURAL RESOURCE DISTRICT

- Block flight lines were spaced approximately 0.60 miles (1 km) in the east-west direction and approximately 0.11-0.14 miles (200 m-250 m) in the north south directions.
-
- The Gretna Recon area lines were separated by approximately 1.10 miles (1.77 km) in the east-west direction and approximately 1.0 miles (1.62 km) in the north-south direction.
- Approximately total of 631 line-miles (1022 line-km).
- SkyTEM 304M system-first time gate 10 µsec, 1.6 µsec wide and last time gate of 8.4 msec
- Aarhus Workbench SCI was used with 30 layer smooth inversion. First layer 9.8 ft (3 m).

AGF Aqua Geo Frameworks

Sarpy County Interpreted Sections

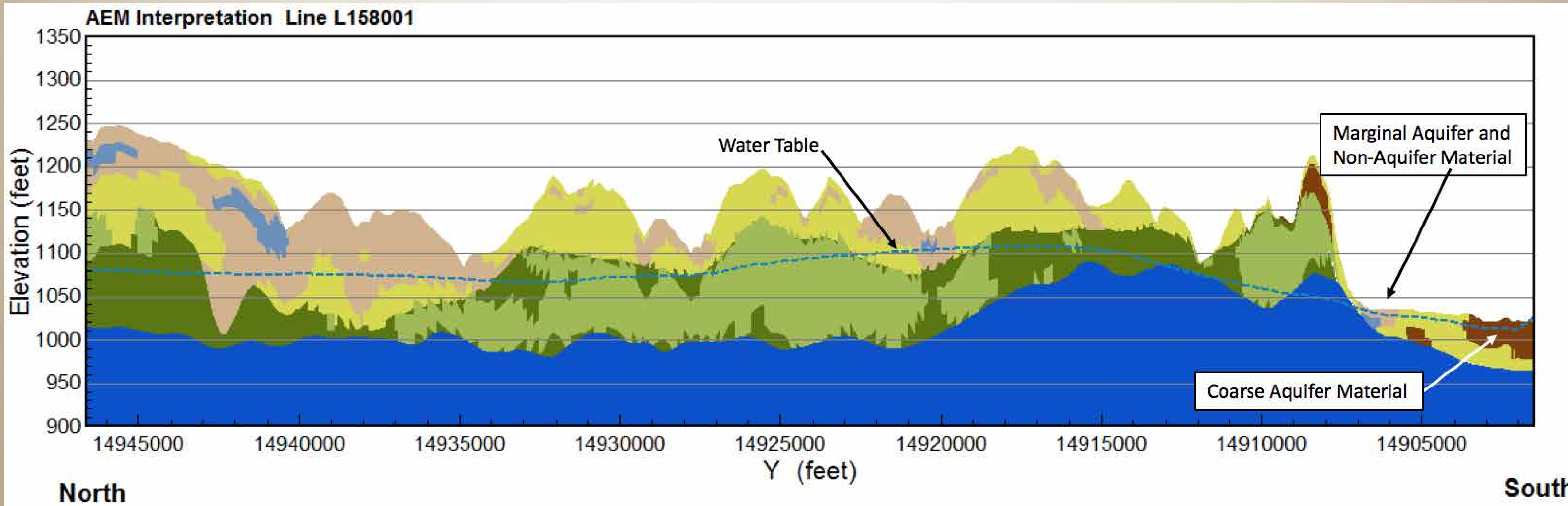


1 mile

Abraham et al., 2016

Sarpy County Interpreted Sections

PAPIO-MISSOURI RIVER NATURAL RESOURCE DISTRICT

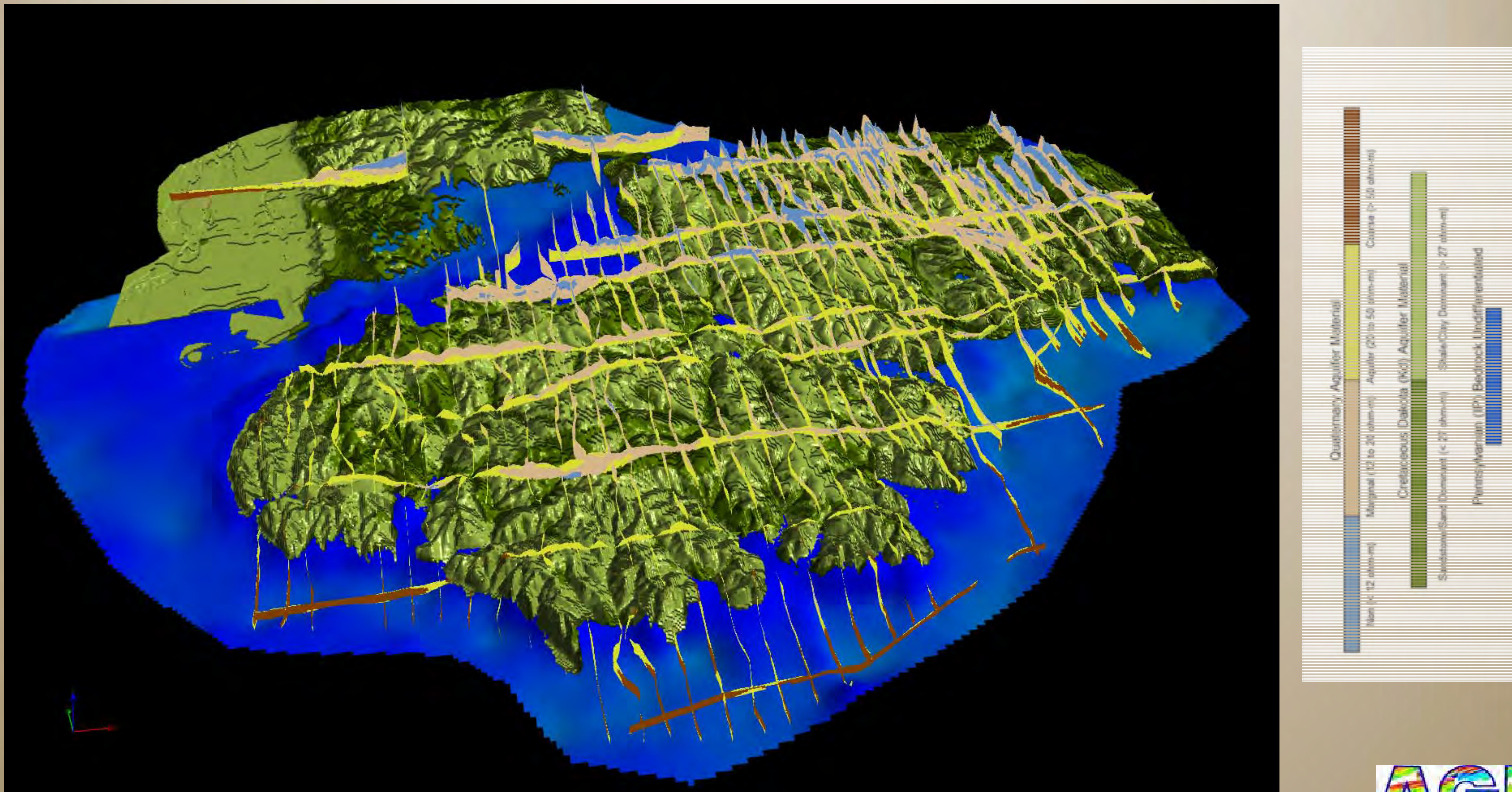


Abraham et al., 2016

1 mile

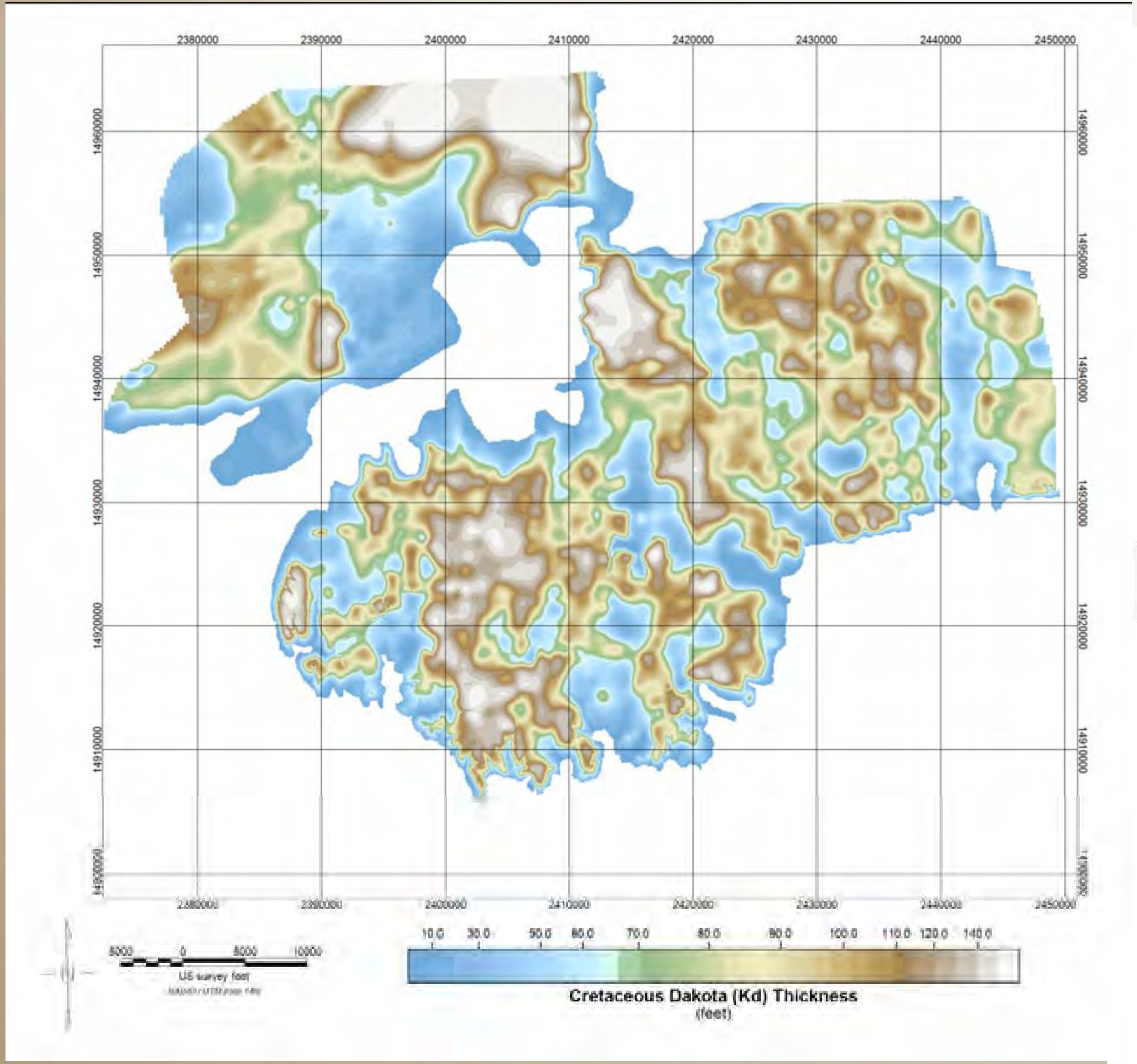
Aqua Geo Frameworks

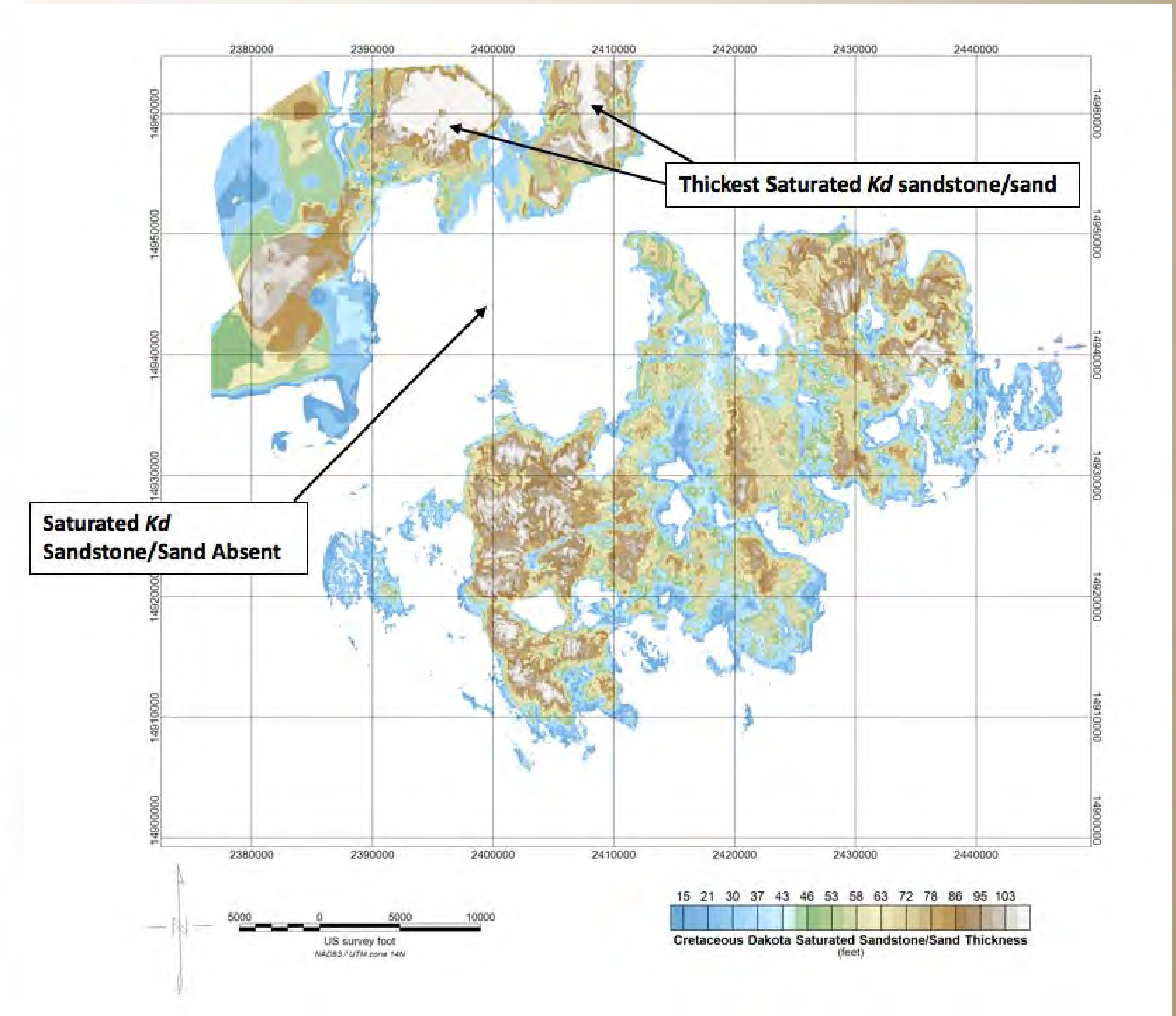
Sarpy County Cretaceous Dakota on Pennsylvanian



Abraham et al., 2016

Sarpy County Cretaceous Dakota Thickness





Abraham et al., 2016

Sarpy County Estimate of Groundwater in Storage KD

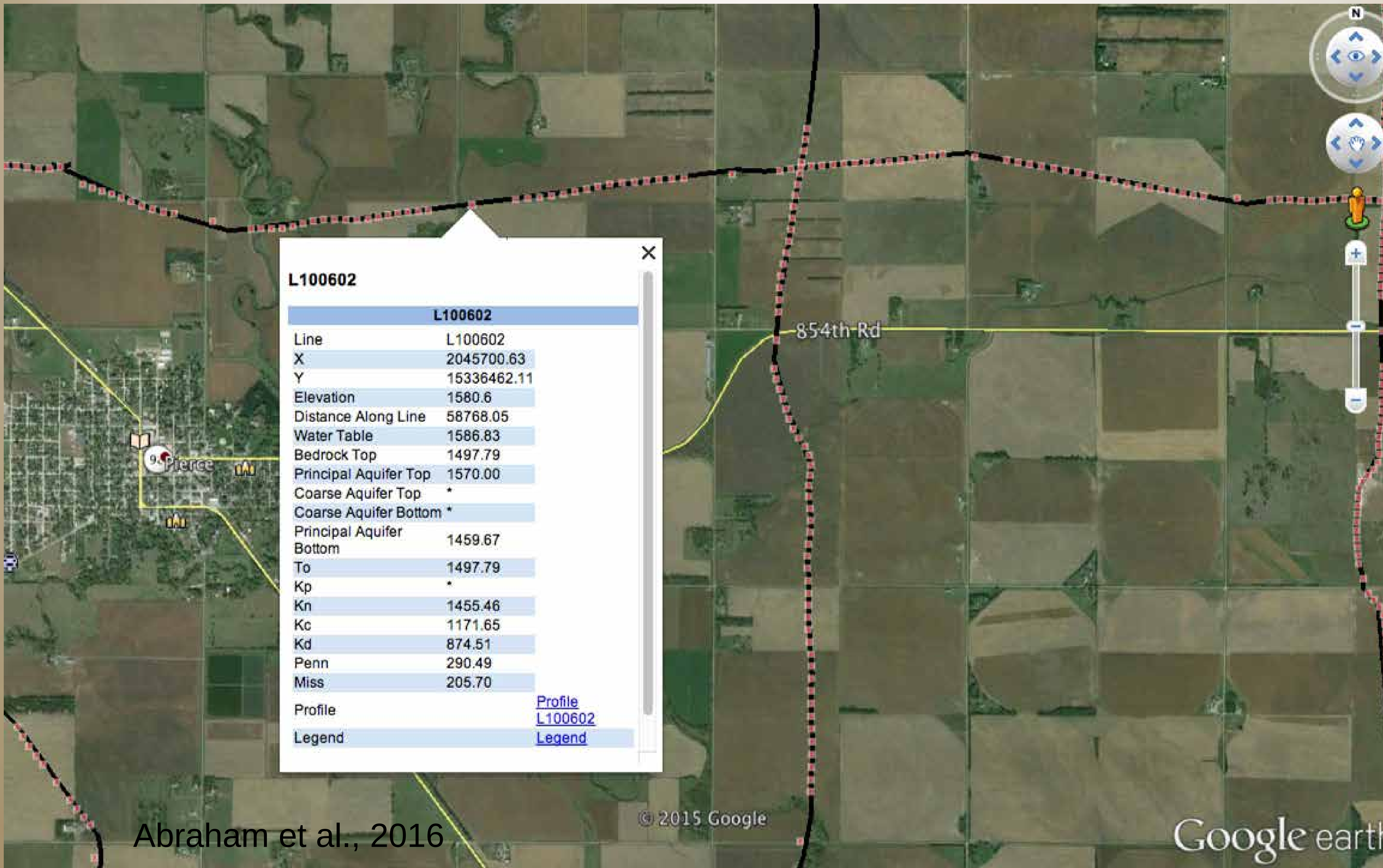
PAPIO-MISSOURI RIVER NATURAL RESOURCE DISTRICT

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre-ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Shale/clay	60,784,808,389	1,395,427	0.4	558,171	0.02	11,163
Sandstone/sand	93,907,386,203	2,155,817	0.35	754,536	0.05	37,727
TOTAL	154,692,194,592	3,551,244		1,312,707		48,890

Abraham et al., 2016

AGF Aqua Geo Frameworks

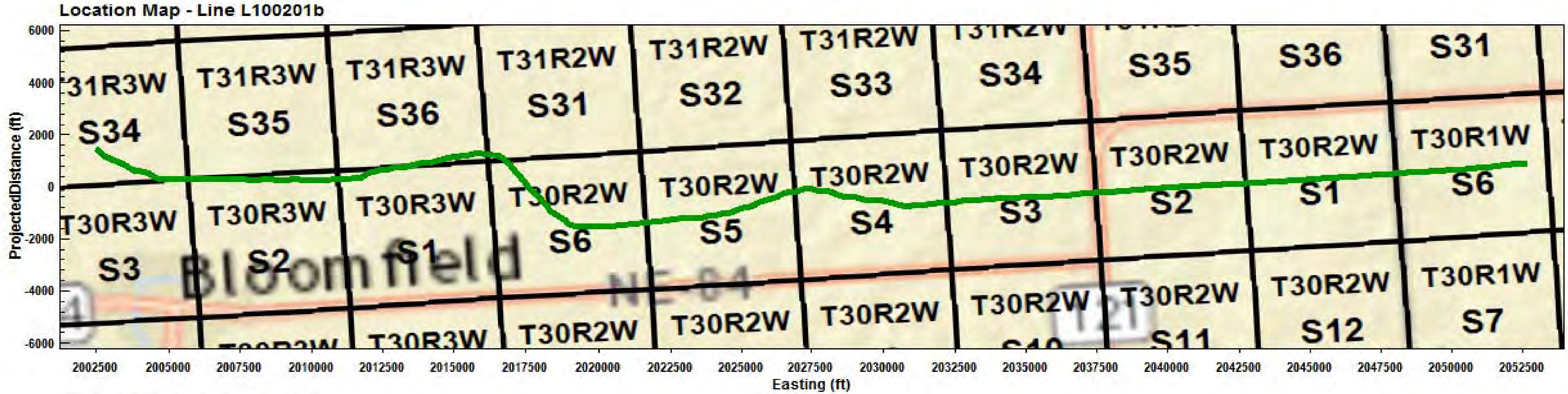
GOOGLE EARTH FILES

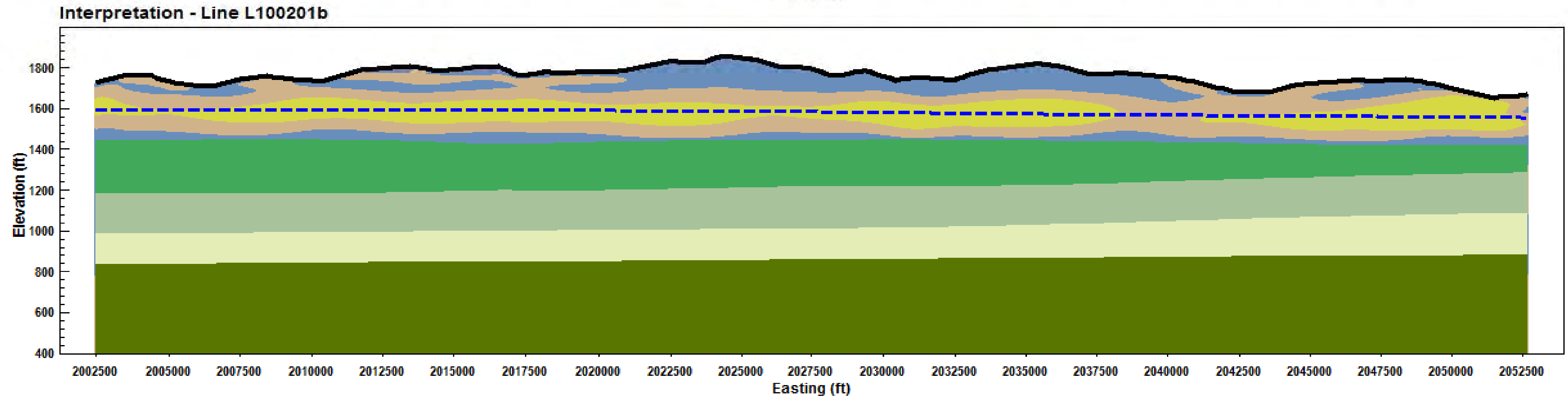


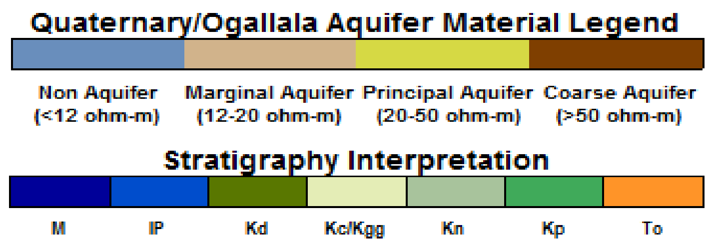
L100602

L100602	
Line	L100602
X	2045700.63
Y	15336462.11
Elevation	1580.6
Distance Along Line	58768.05
Water Table	1586.83
Bedrock Top	1497.79
Principal Aquifer Top	1570.00
Coarse Aquifer Top	*
Coarse Aquifer Bottom	*
Principal Aquifer Bottom	1459.67
To	1497.79
Kp	*
Kn	1455.46
Kc	1171.65
Kd	874.51
Penn	290.49
Miss	205.70
Profile	Profile L100602
Legend	Legend

Abraham et al., 2016





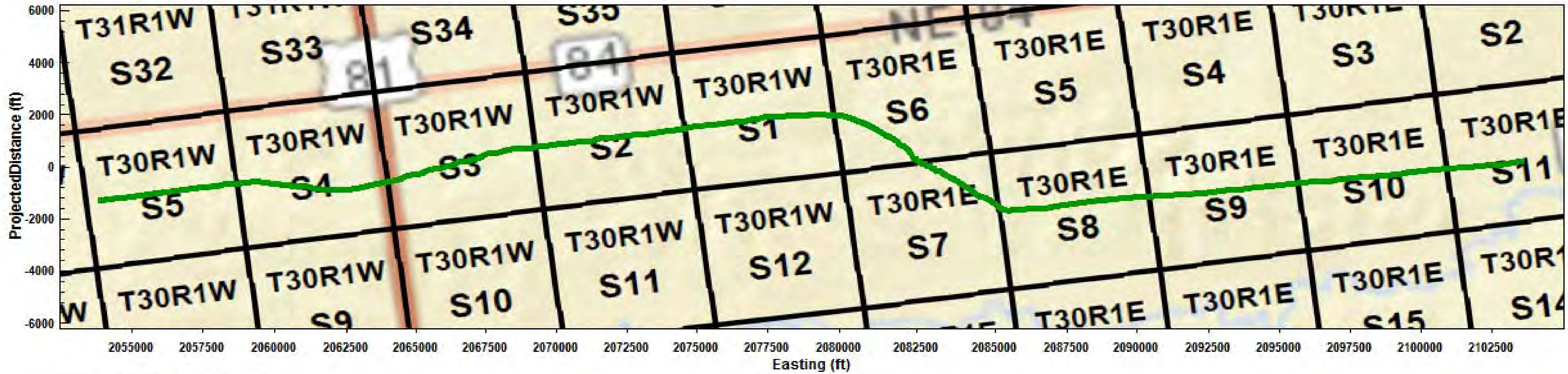


Interpreted geologic sections from AEM data and flight line location map provided in conjunction with Google Earth kmz file. Interpreted sections and flight lines have been broken into 10 mile (or shorter) segments. The projected downline distance is equal for the flight line (top image) and the AEM data interpretation (bottom image). The CSD 1995 water table is shown as a dashed blue line on the interpretation image. Additional information regarding the use of these figures and the AEM data may be found in the report titled "Airborne Electromagnetic Geophysical Surveys and Hydrogeologic Framework Development for Selected Sites in the Eastern Nebraska Water Resources Assessment".

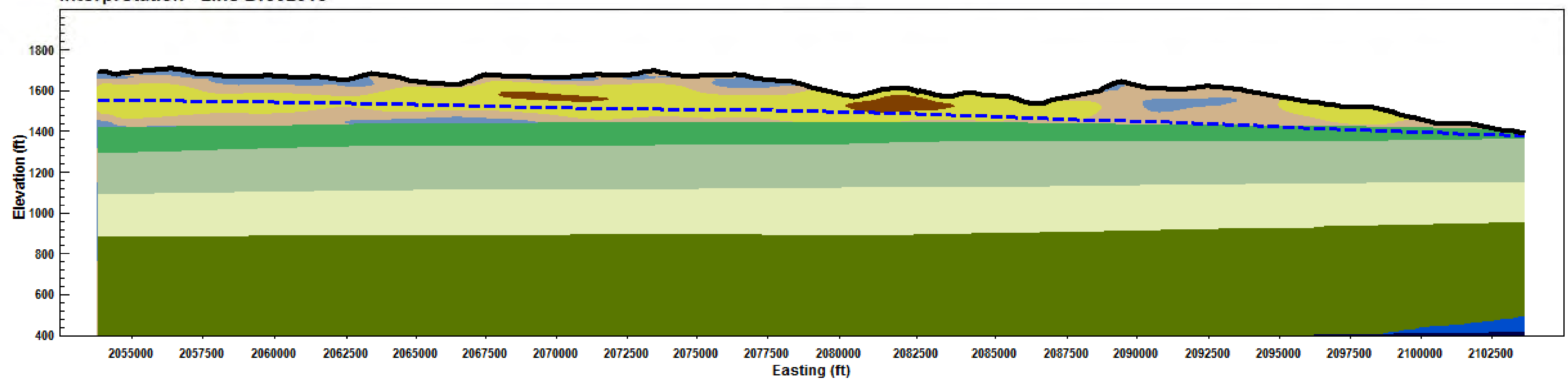
ENWRA
Eastern Nebraska Water Resources Assessment

Abraham et al., 2016

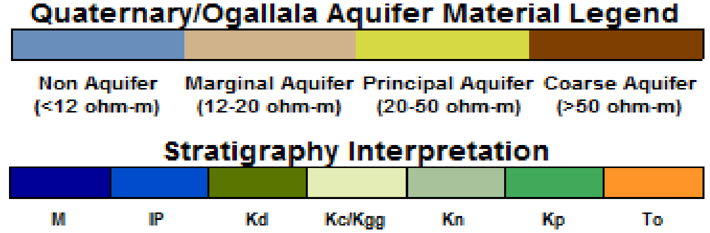
Location Map - Line L100201c



Interpretation - Line L100201c



Quaternary/Ogallala Aquifer Material Legend

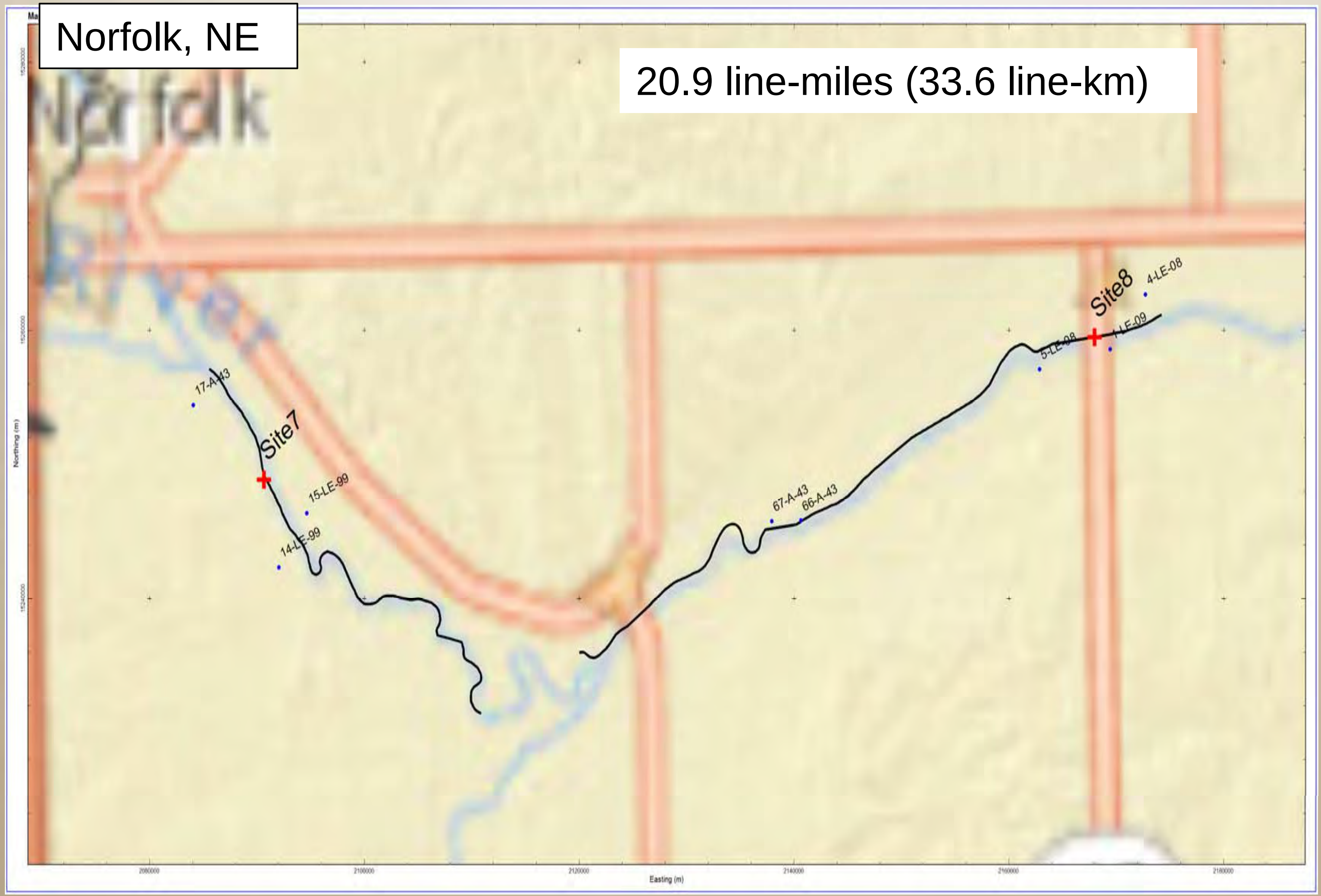


Interpreted geologic sections from AEM data and flight line location map provided in conjunction with Google Earth kmz file. Interpreted sections and flight lines have been broken into 10 mile (or shorter) segments. The projected downline distance is equal for the flight line (top image) and the AEM data interpretation (bottom image). The CSD 1995 water table is shown as a dashed blue line on the interpretation image. Additional information regarding the use of these figures and the AEM data may be found in the report titled "Airborne Electromagnetic Geophysical Surveys and Hydrogeologic Framework Development for Selected Sites in the Eastern Nebraska Water Resources Assessment".

ENWRA
EASTERN NEBRASKA WATER RESOURCES ASSESSMENT

Abraham et al., 2016

SkyTEM 301 Flight Lines



Flight Height
Mean: 145 ft (44.2 m)
Min: 116.5 ft (35.5 m)
Max: 204.7 ft (62.4 m)

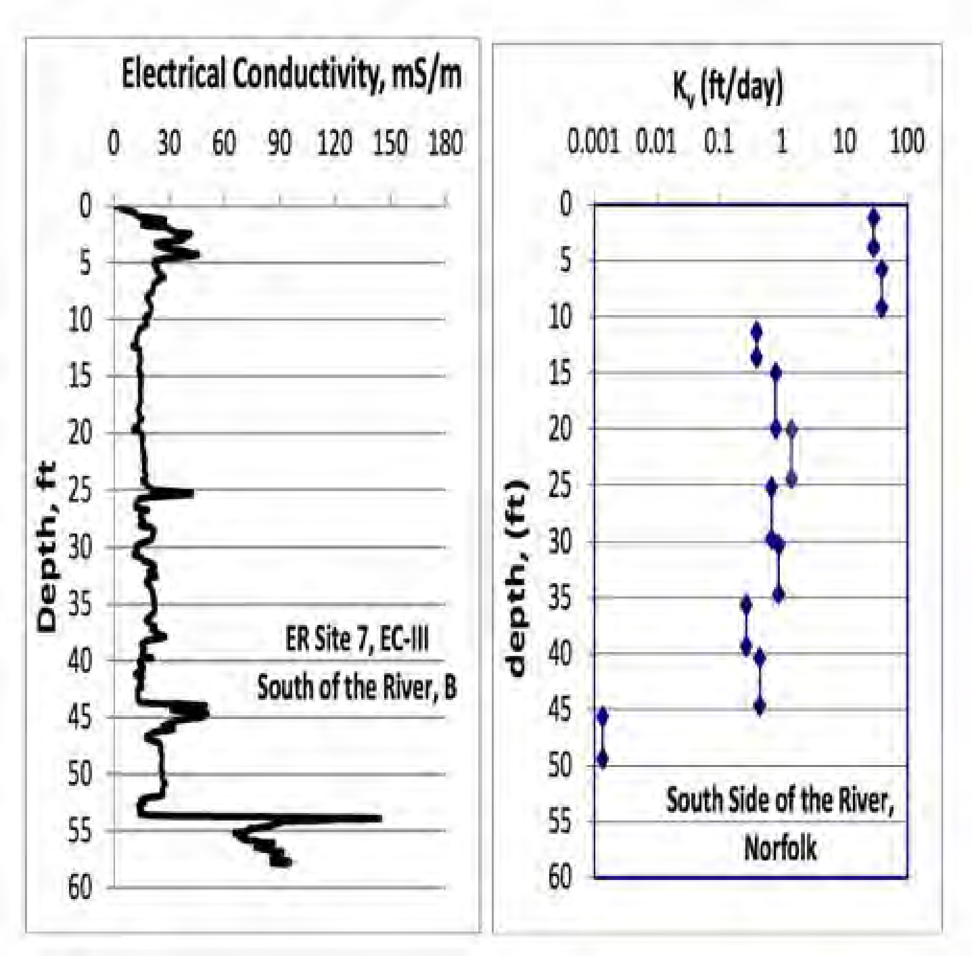
Abraham et al., 2015

CSD Geoprobe and Vertical Hydraulic Conductivity (Kv)

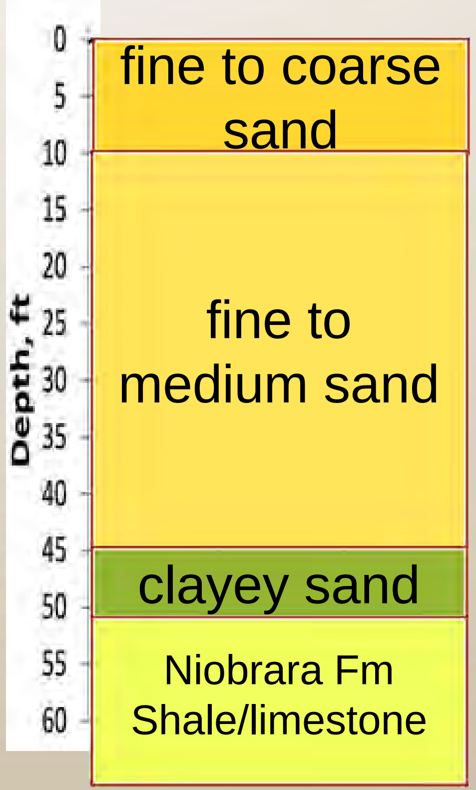
Geoprobe
Lithology Cores
EC logs
and
Infiltration Tests

Streambed Hydrology Tests in the Lower Elkhorn River and its Tributaries, Nebraska
2010
Susan Olafsen Lackey and Xun-Hong Chen Conservation and Survey Division
School of Natural Resources
University of Nebraska-Lincoln

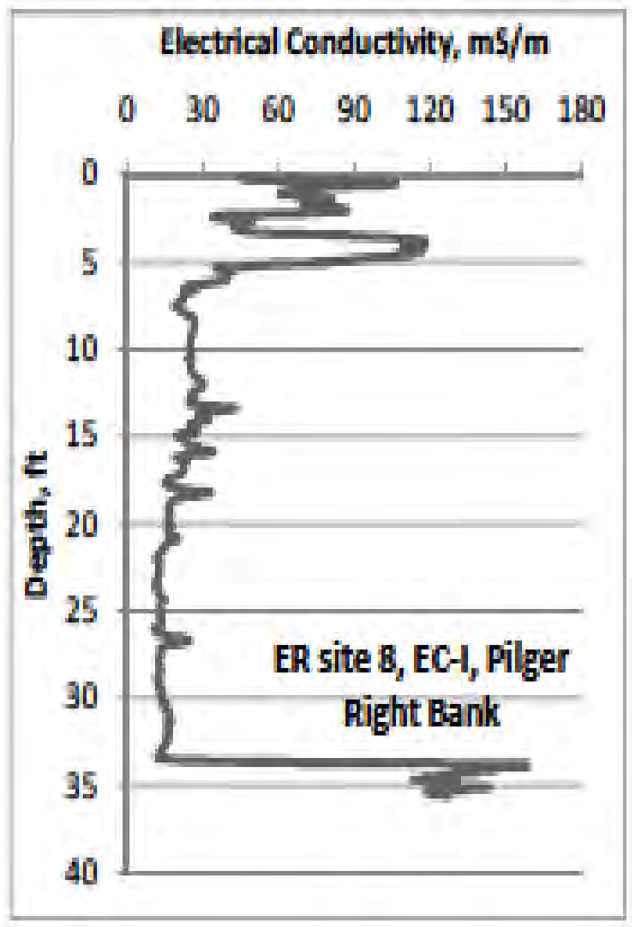
CSD Elkhorn River Site 7

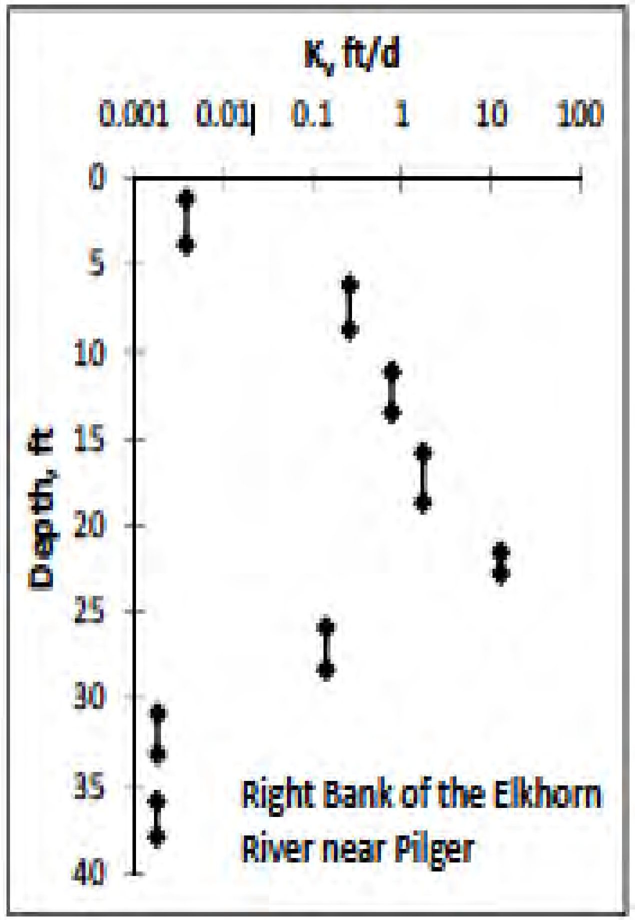


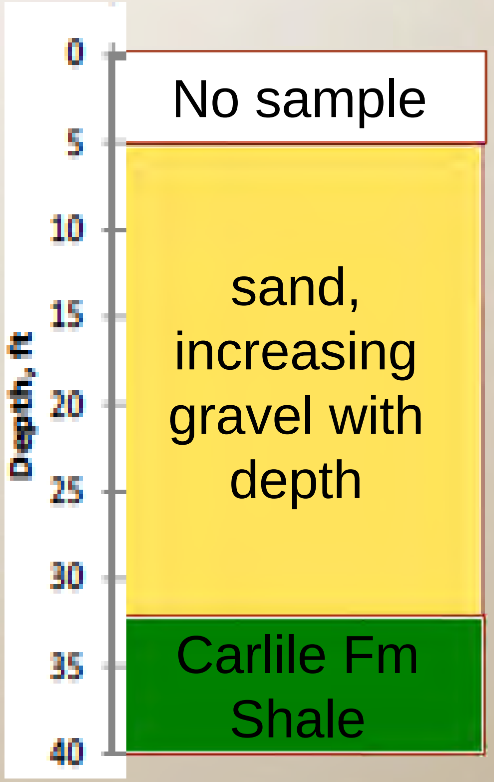
Lackey and Chen, 2010



CSD Elkhorn River Site 8

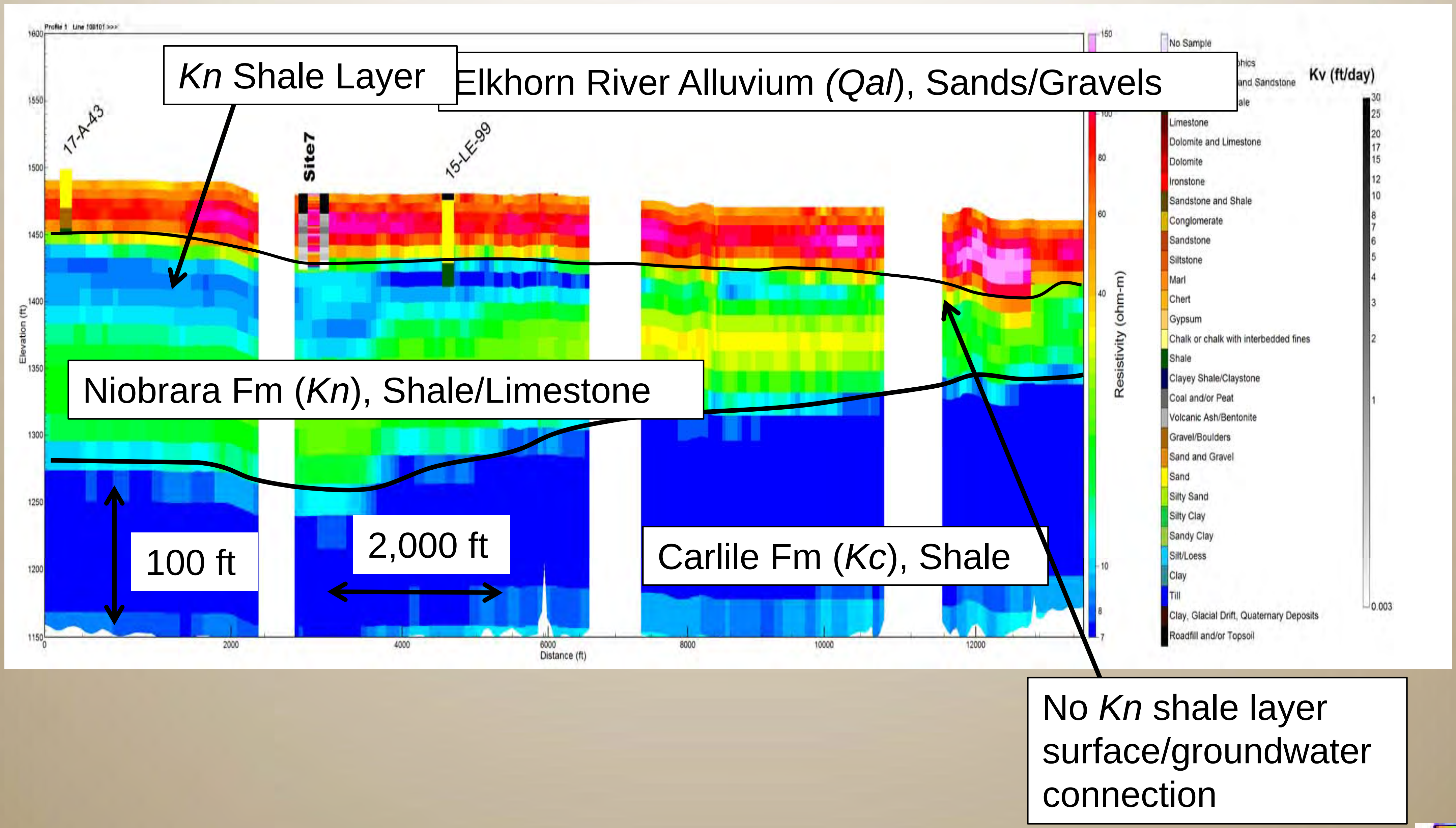






Lackey and Chen, 2010

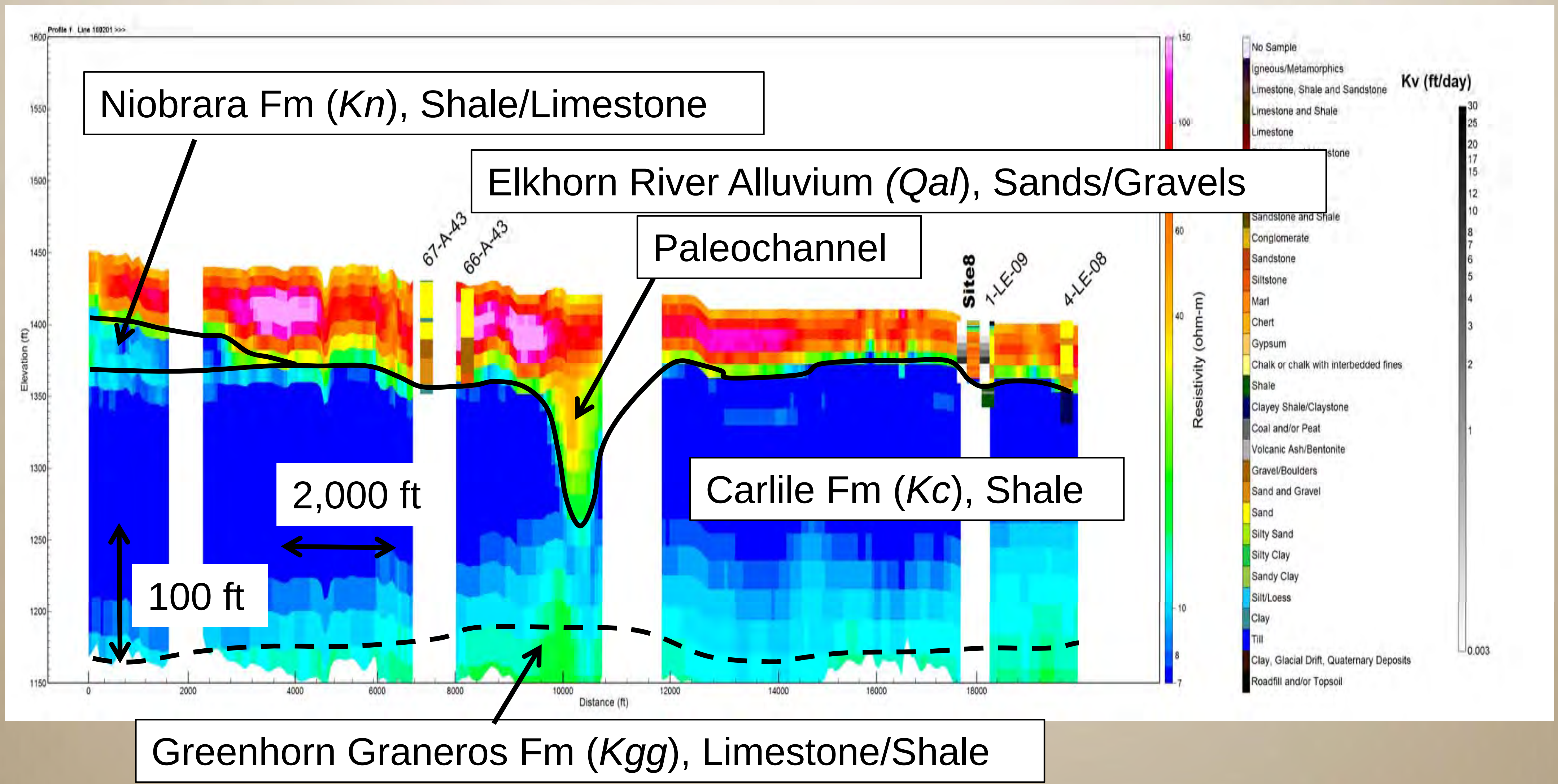
RESISTIVITY MODEL (L100101)



Abraham et al., 2015

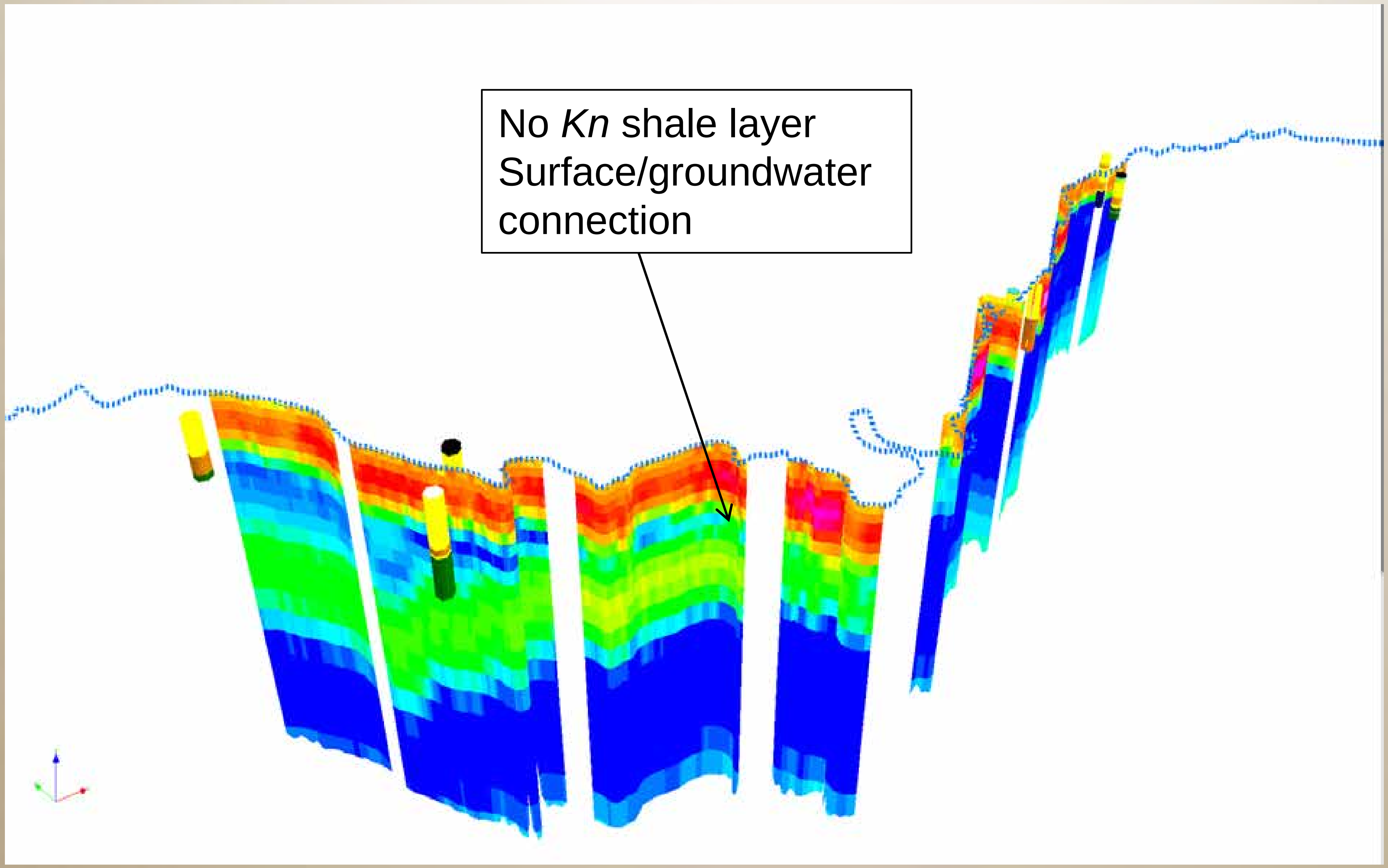
AGF Aqua Geo Frameworks

RESISTIVITY MODEL(L100201)



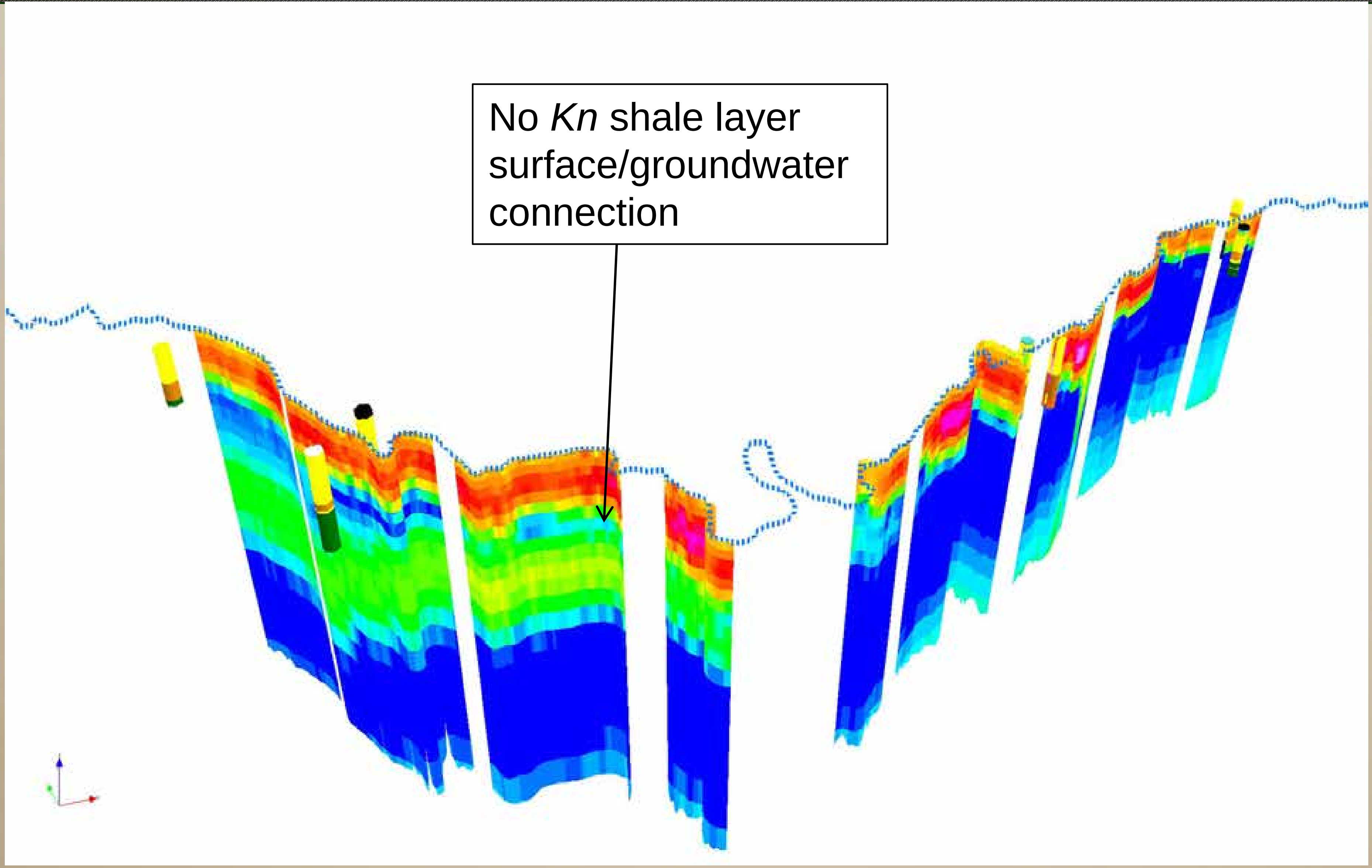
Abraham et al., 2015

3D View



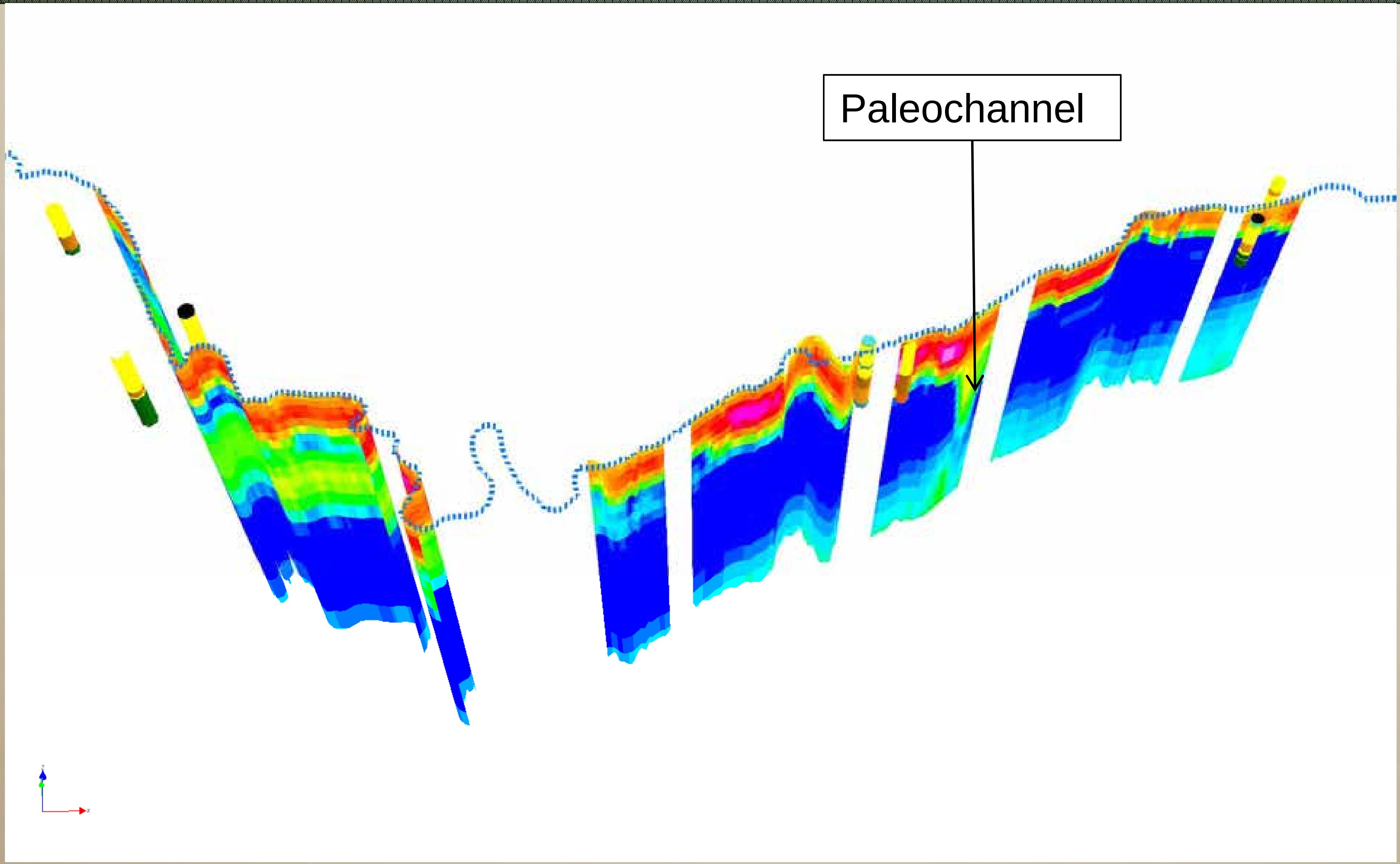
Abraham et al., 2015

3D VIEW



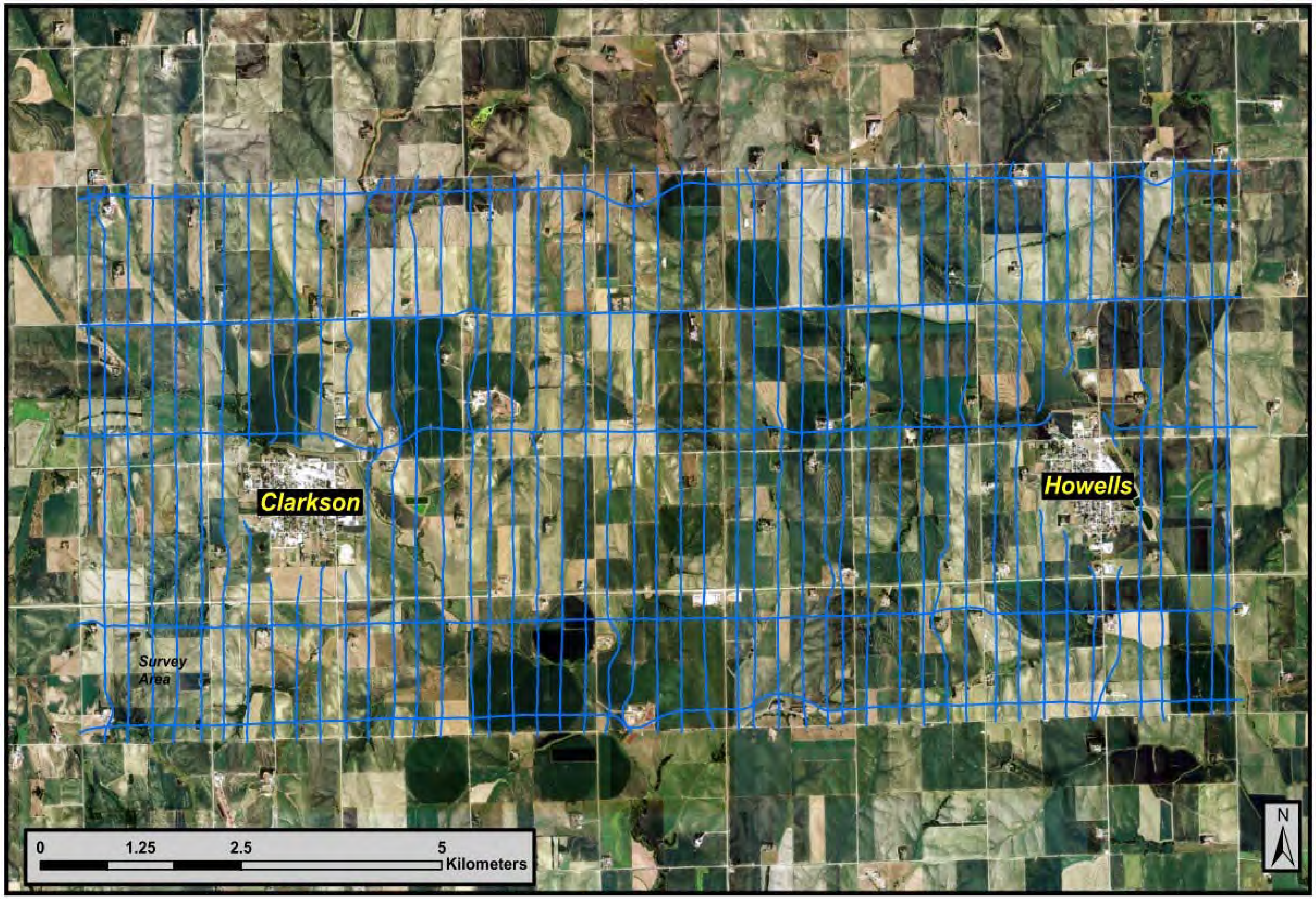
Abraham et al., 2015

3D View



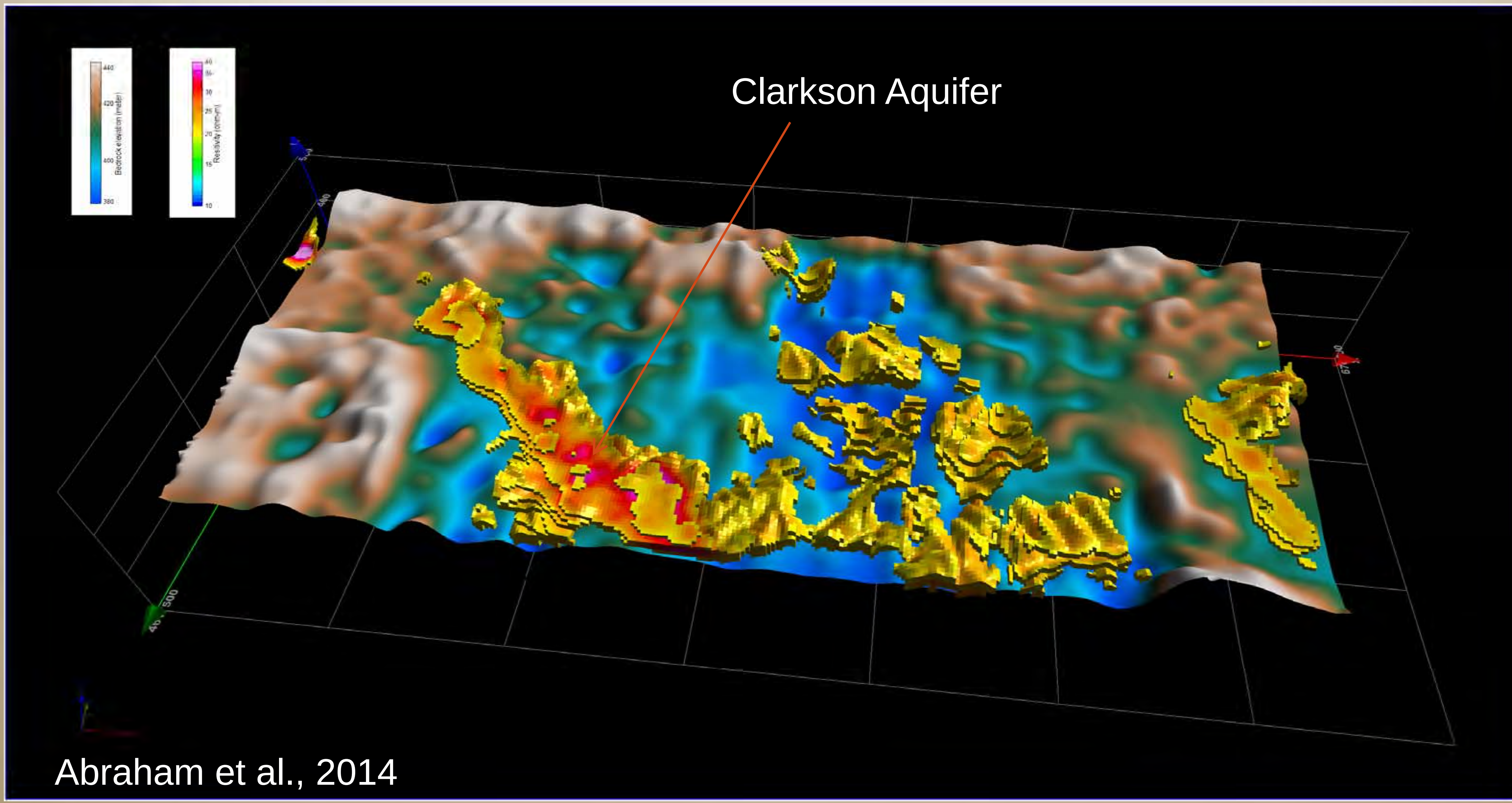
Abraham et al., 2015

Were to find water for Municipality

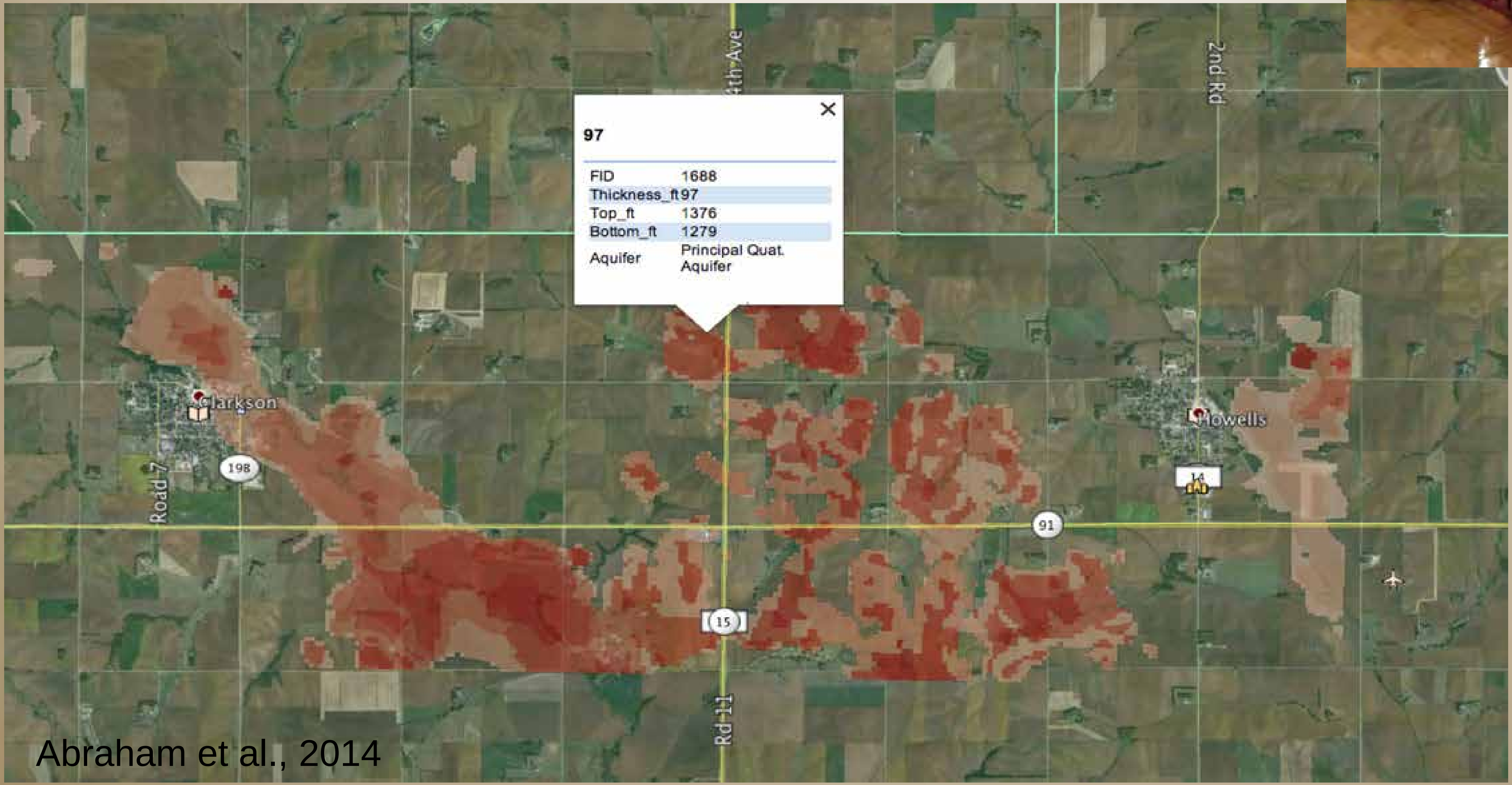


Abraham et al., 2014

APPROXIMATELY 131.5 MILLION CUBIC METERS (106,608 ACRE-FOOT) OF RECOVERABLE GROUNDWATER (WHEN SATURATED)

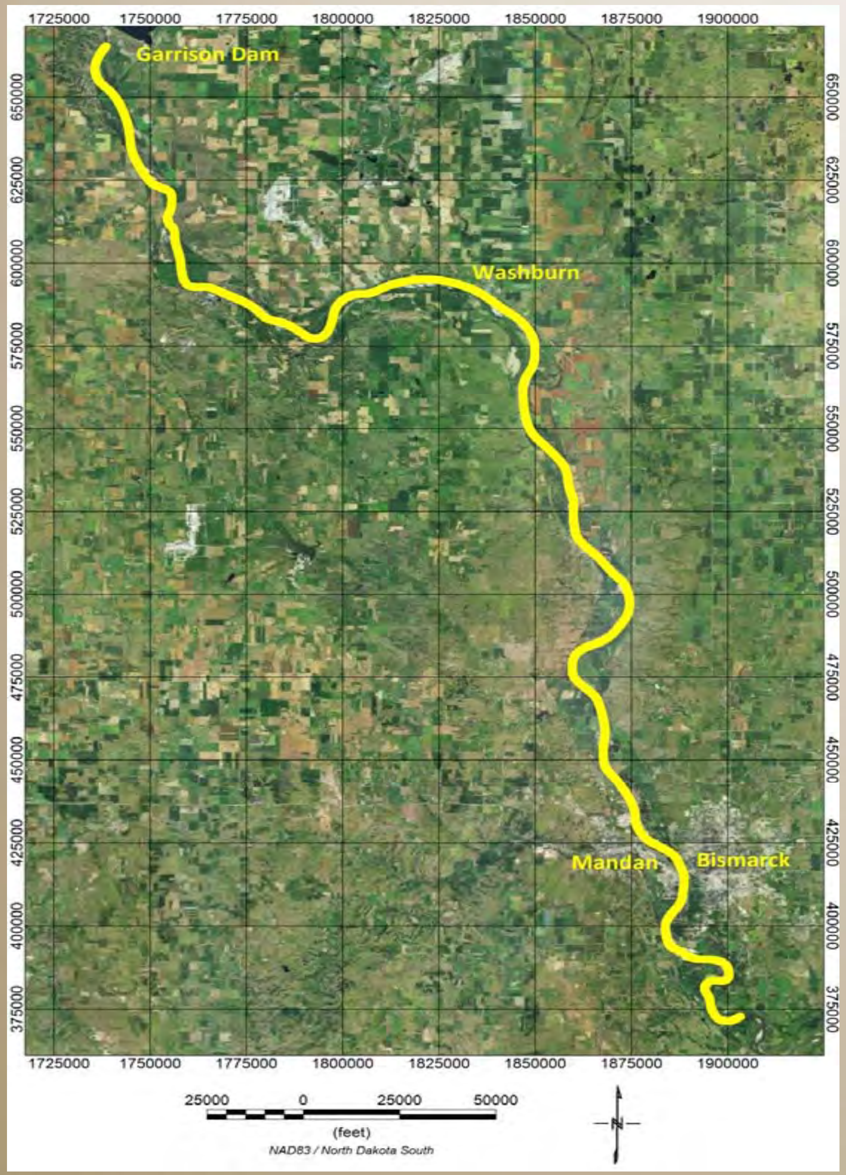


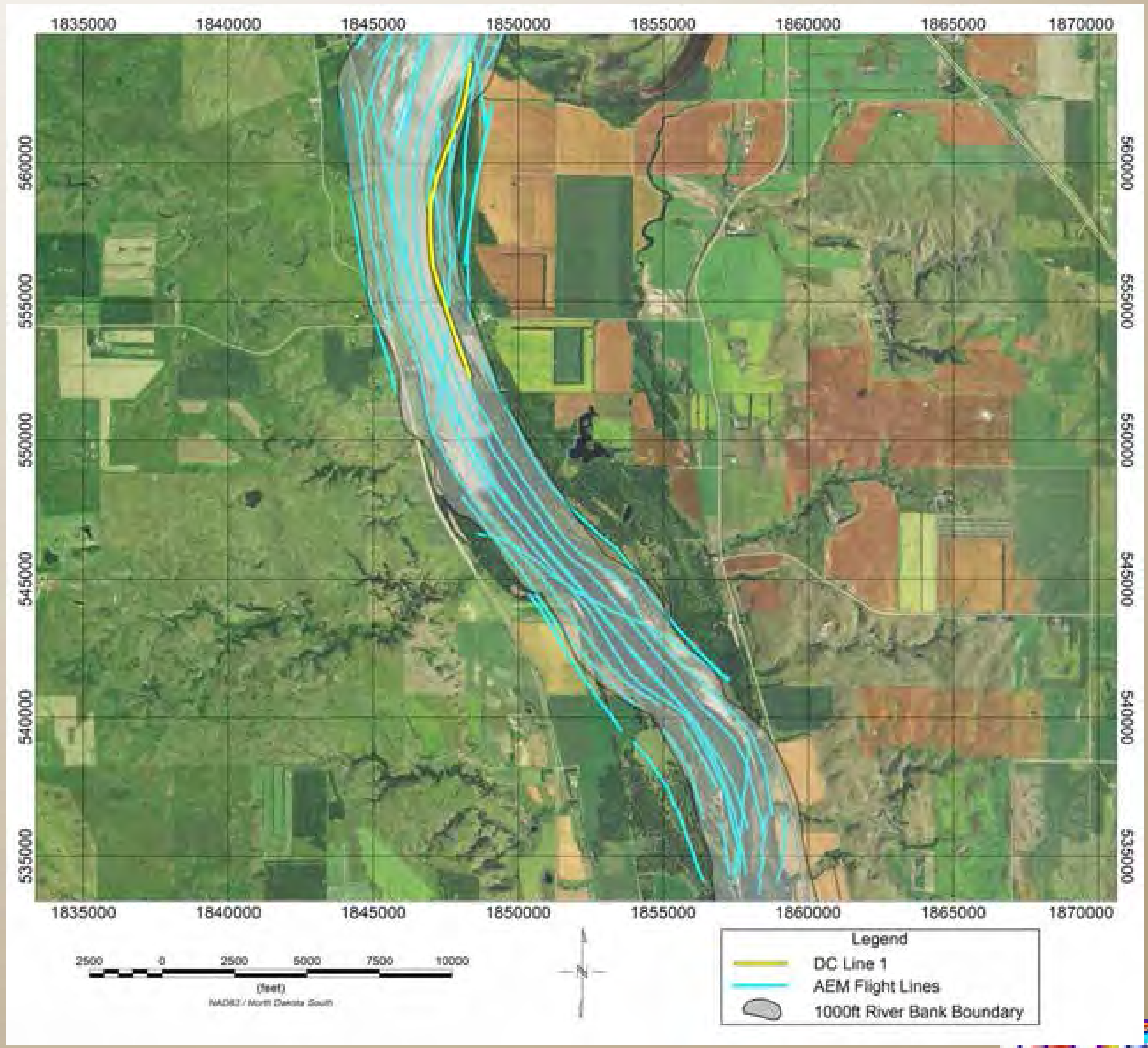
Final Products as Google Earth Files



Abraham et al., 2014

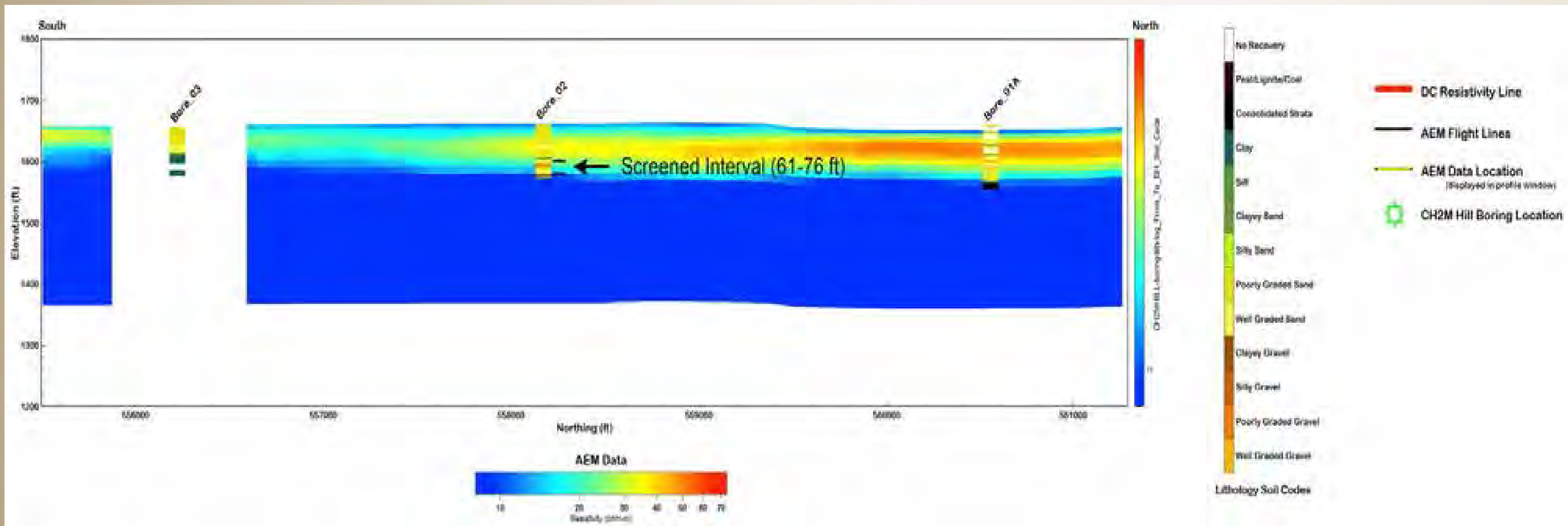
Were to acquire land to build a water extraction field for a pipeline in North Dakota

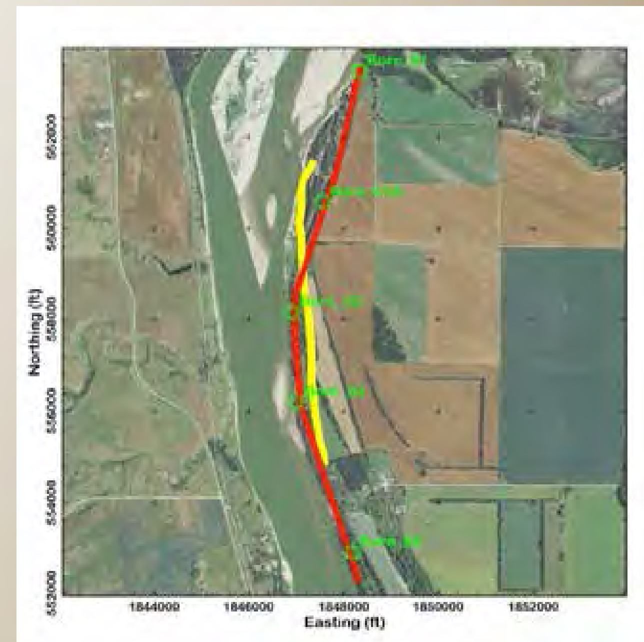


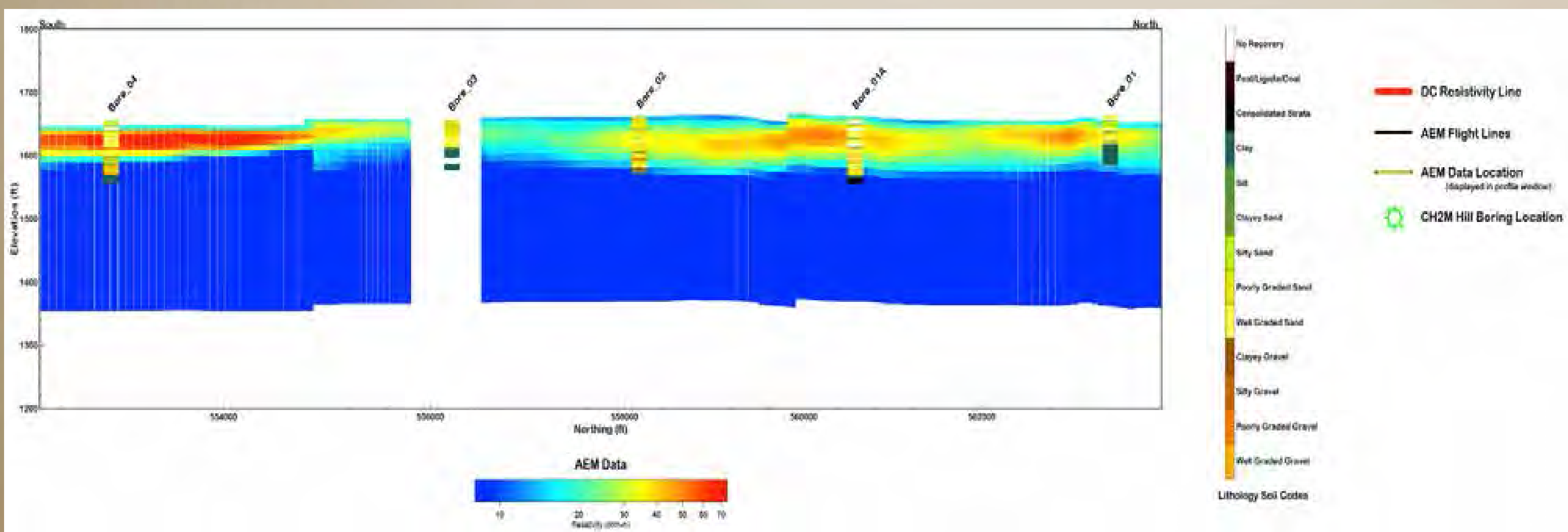


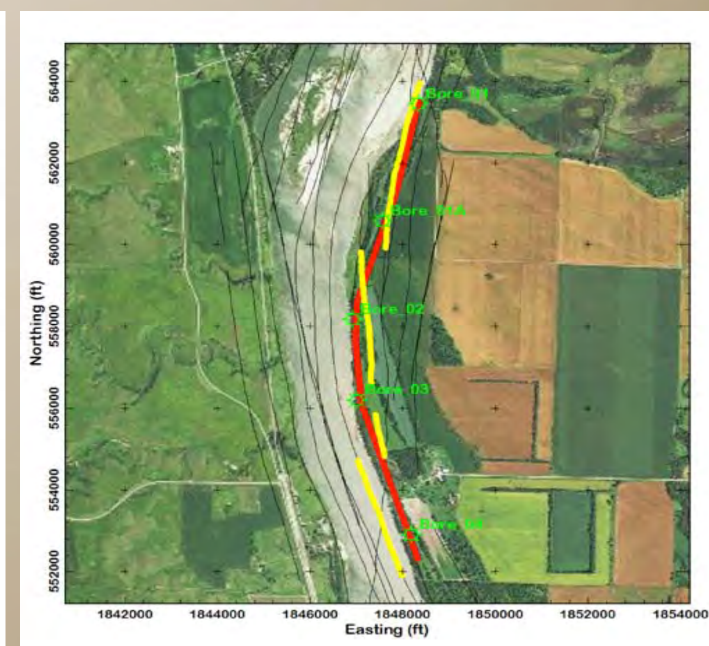
Meglich and Abraham 2015

CROSS SECTIONS AND BOREHOLES





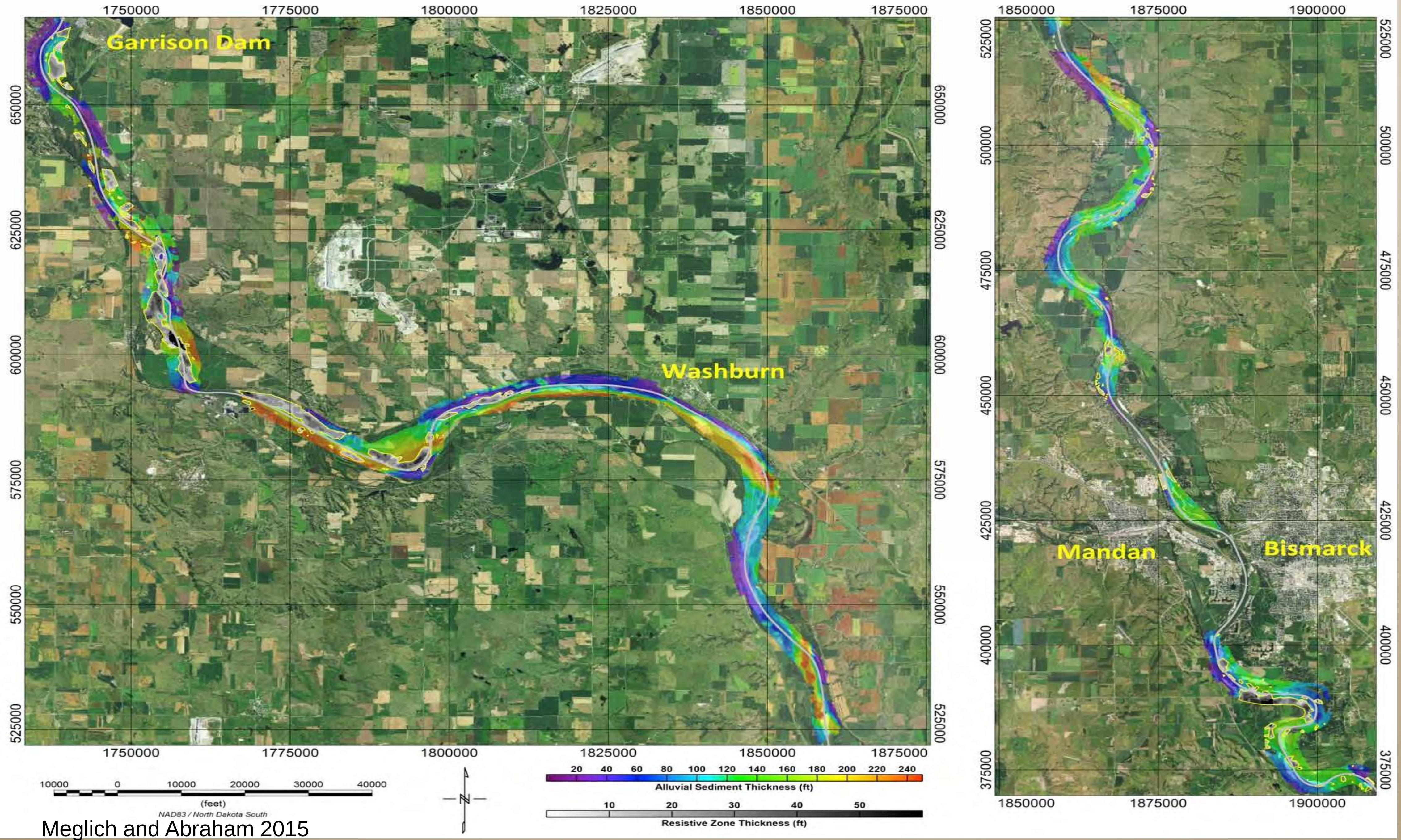




Meglich and Abraham 2015

Aqua Geo Frameworks

Alluvial Sediment Thickness

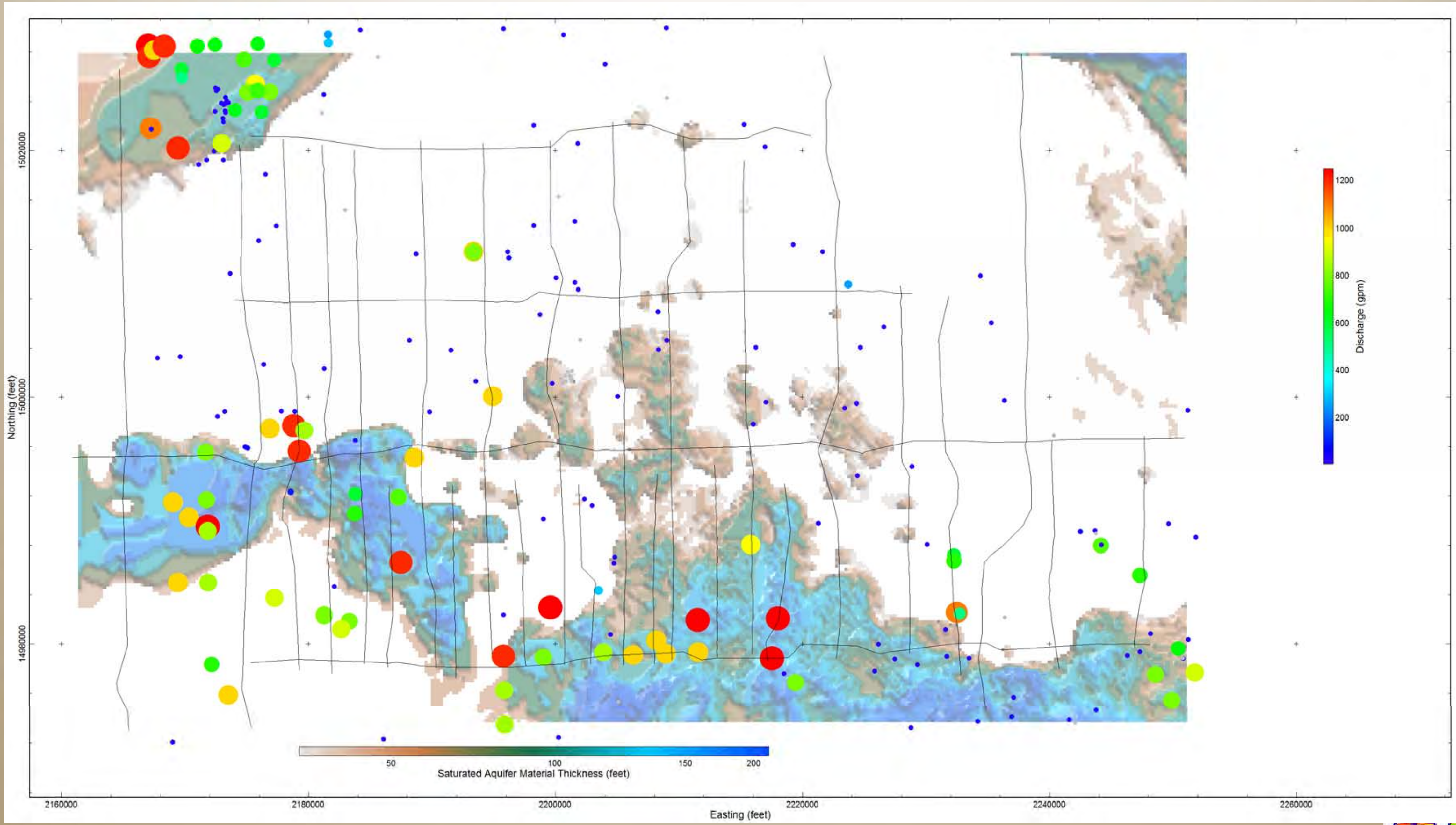


Meglich and Abraham 2015

FUTURE OF AEM

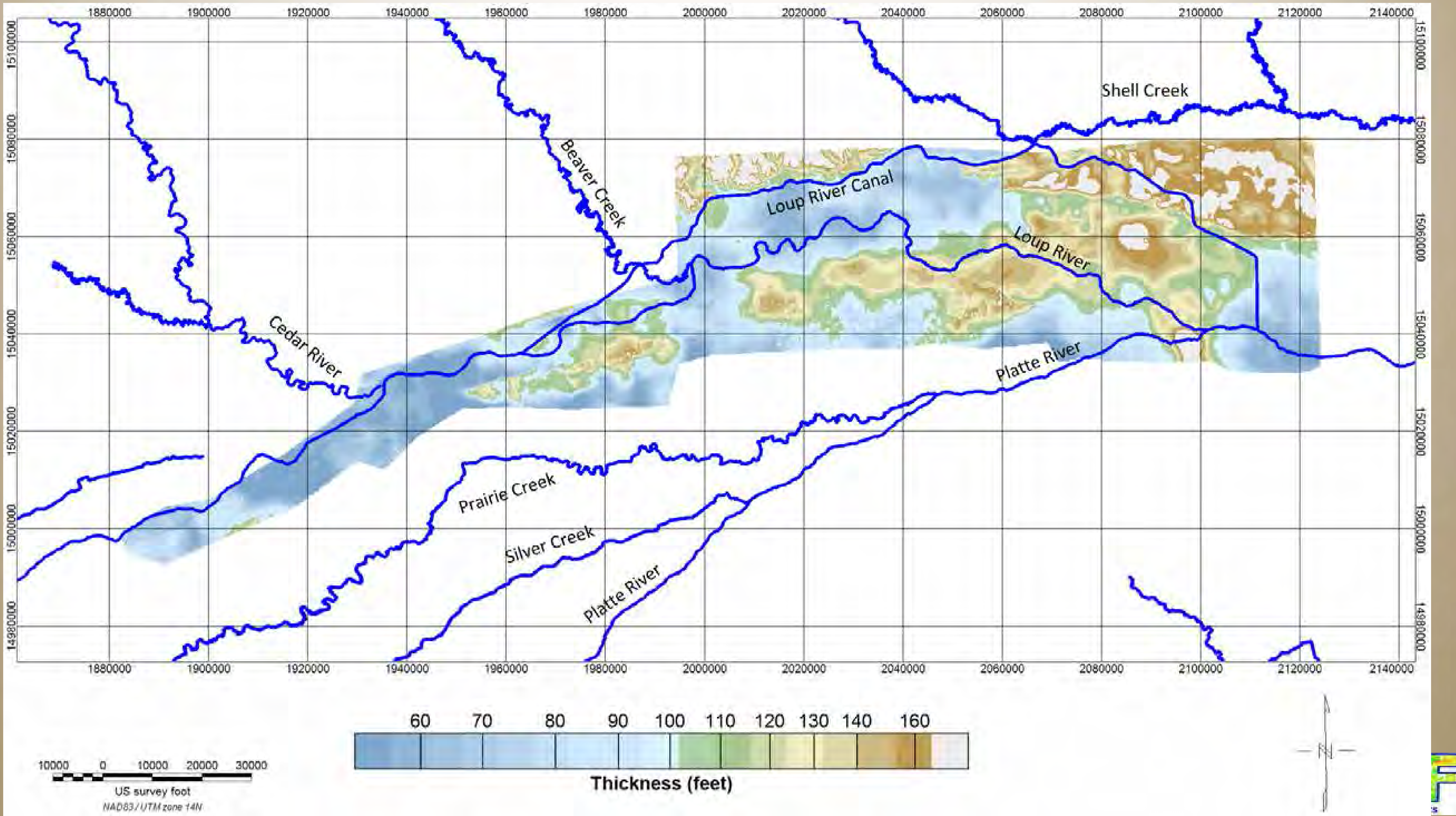
- Systems
  - Improved power
  - Higher signal to noise
  - Multiple Rx
  - Wider bandwidth (shallow and deep)
- Inversion
  - Improved inversion using Tx current waveform
  - Multiple components in inversion
  - Voxel based inversion
- Interpretation
  - Integration with groundwater flow models
  - Multiple data source 3D platforms

HOW DO WE USE AEM SURVEY RESULTS TO MANAGE OUR WATER?

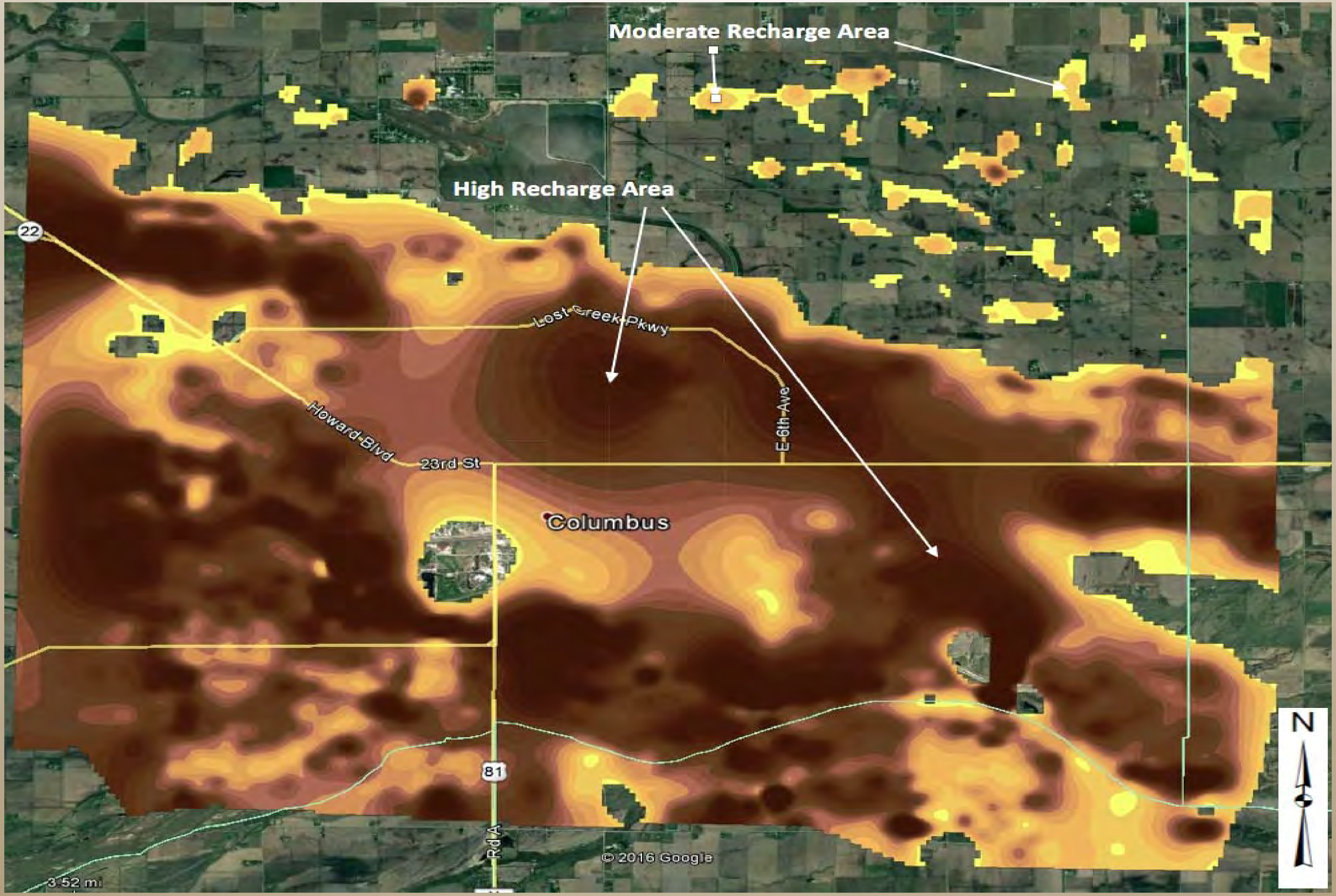


Saturated Thickness versus Water Well Production

Lower Loup NRD Quaternary Materials Thickness Related to Surface Water



Lower Loup NRD Recharge Areas



How Much Groundwater in Storage?

Aquifer Material Type	Aquifer Volume (ft^3)	Aquifer Volume (acre-ft)	Average Porosity	Groundwater in Storage Volume (acre-ft)	Average Specific Yield	Extractable Water Volume (acre-ft)
Non-Aquifer	26,041,730,737	597,836	0.40	239,134	0.02	4,783
Marginal	55,593,791,131	1,276,259	0.35	446,691	0.05	22,335
Aquifer	112,657,476,450	2,586,263	0.20	517,253	0.15	77,588
Coarse	55,334,987,231	1,270,318	0.25	317,580	0.15	47,637
TOTAL	249,627,985,550	5,730,678		1,520,657		152,343

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jcannia@aquageoframeworks.com