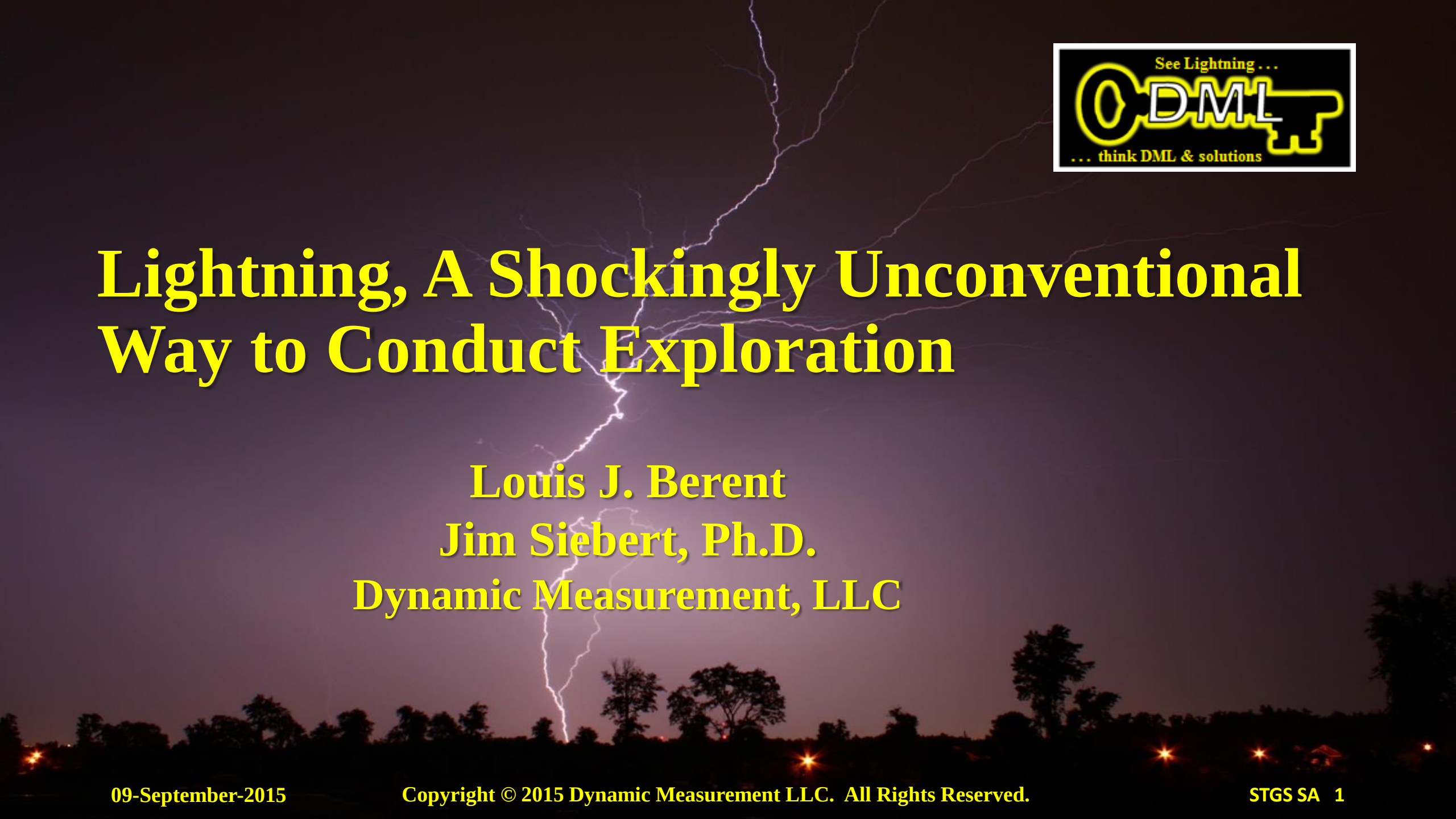


Lightning, A Shockingly Unconventional Way to Conduct Exploration

Louis J. Berent
Jim Siebert, Ph.D.
Dynamic Measurement, LLC

Outline

Lightning, and why it is tracked, stacked & mapped!

Natural Sourced Electromagnetism (NSEM) – a new geophysical data type.

Examples of using NSEM to interpret geologic features.

NSEM overview.

LIGHTNING, & WHY IT IS TRACKED, STACKED & MAPPED

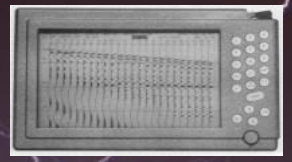
Can Lightning Hit the Same Place Twice?

Time-Line of New Geophysical Data Types

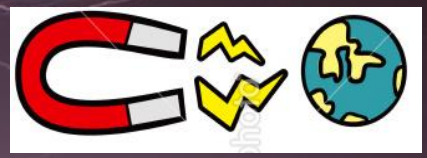
1752

1833

1920s

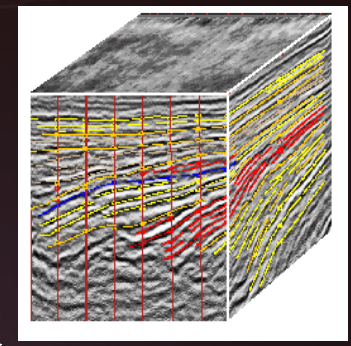


1950s

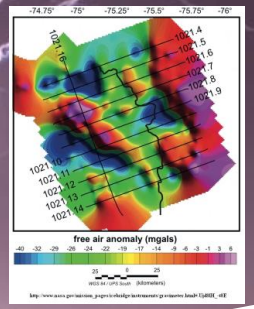


1960s/70s

1974

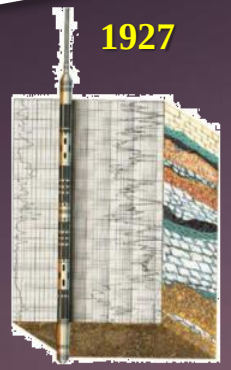


1936

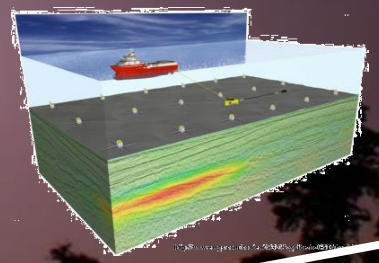


1931

1927

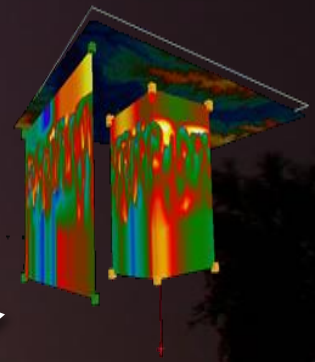


1997



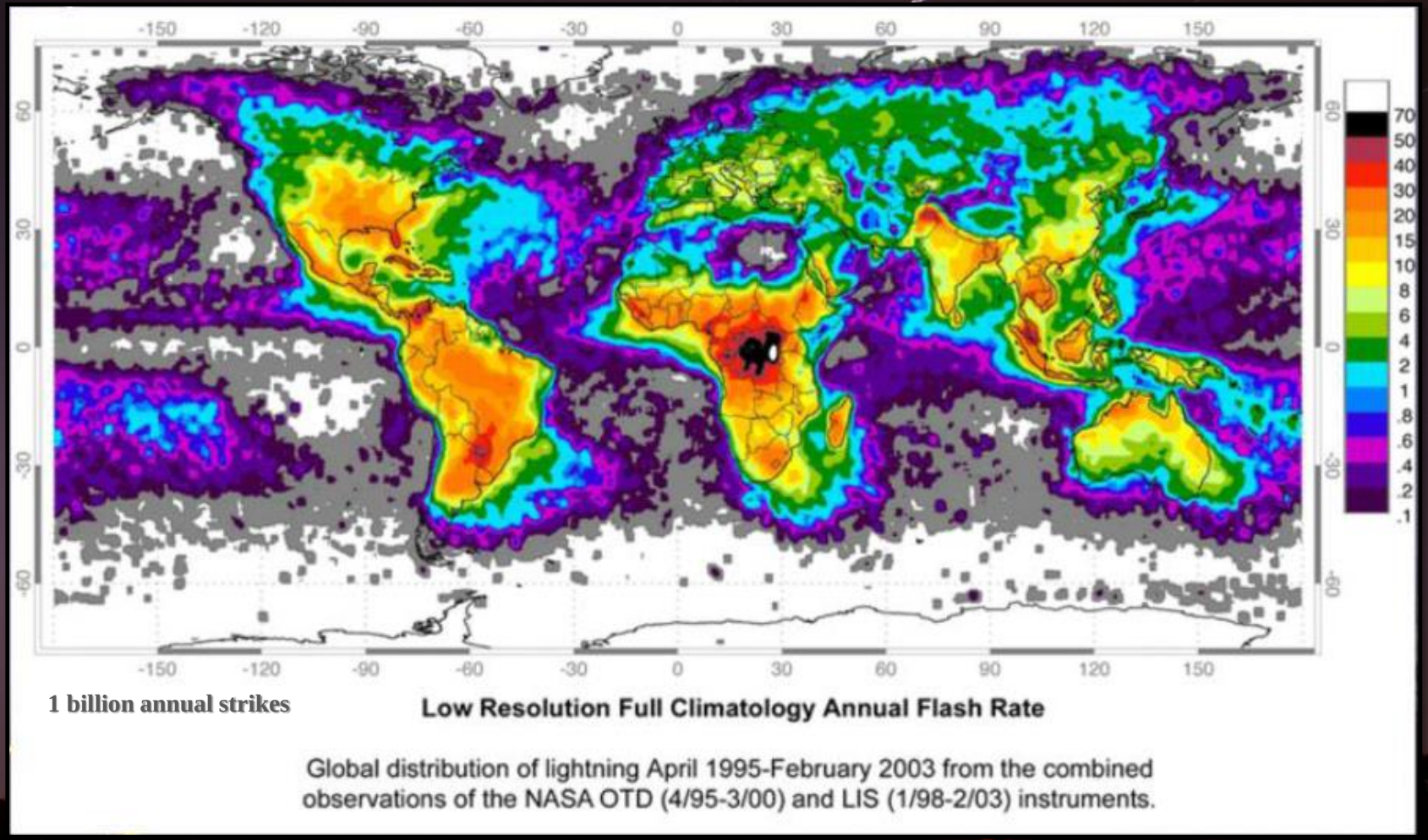
2008

2015



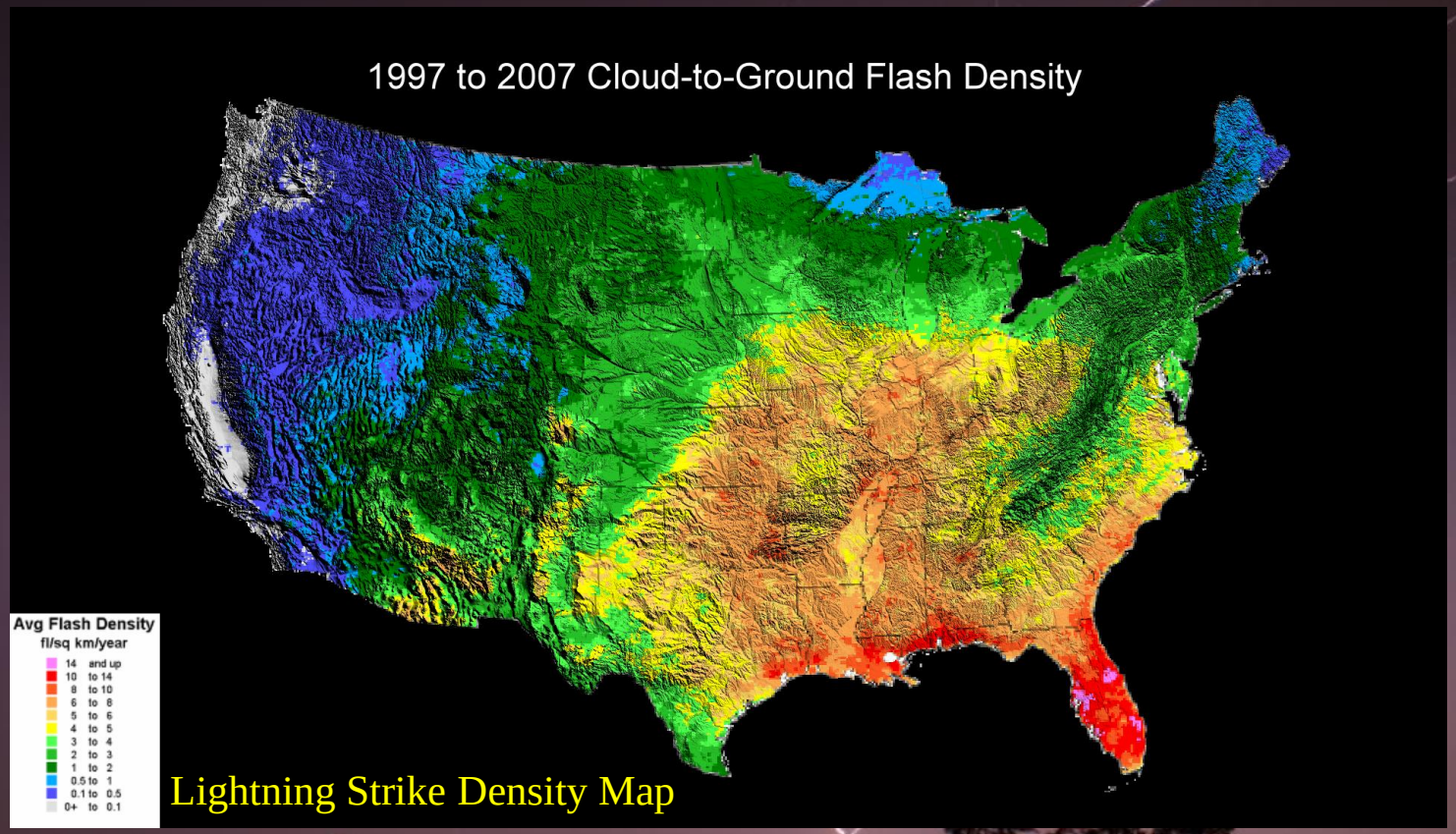
Each data type triggered a step change
in new revenues and cost avoidance
for upstream oil and gas companies.

350 Million Annual CG Lightning Strikes
Uneven Distribution



Global distribution of lightning April 1995-February 2003 from the combined observations of the NASA OTD (4/95-3/00) and LIS (1/98-2/03) instruments.

25 Million Annual U.S. Lightning Strikes
17 Year Database, Rich Database to Mine

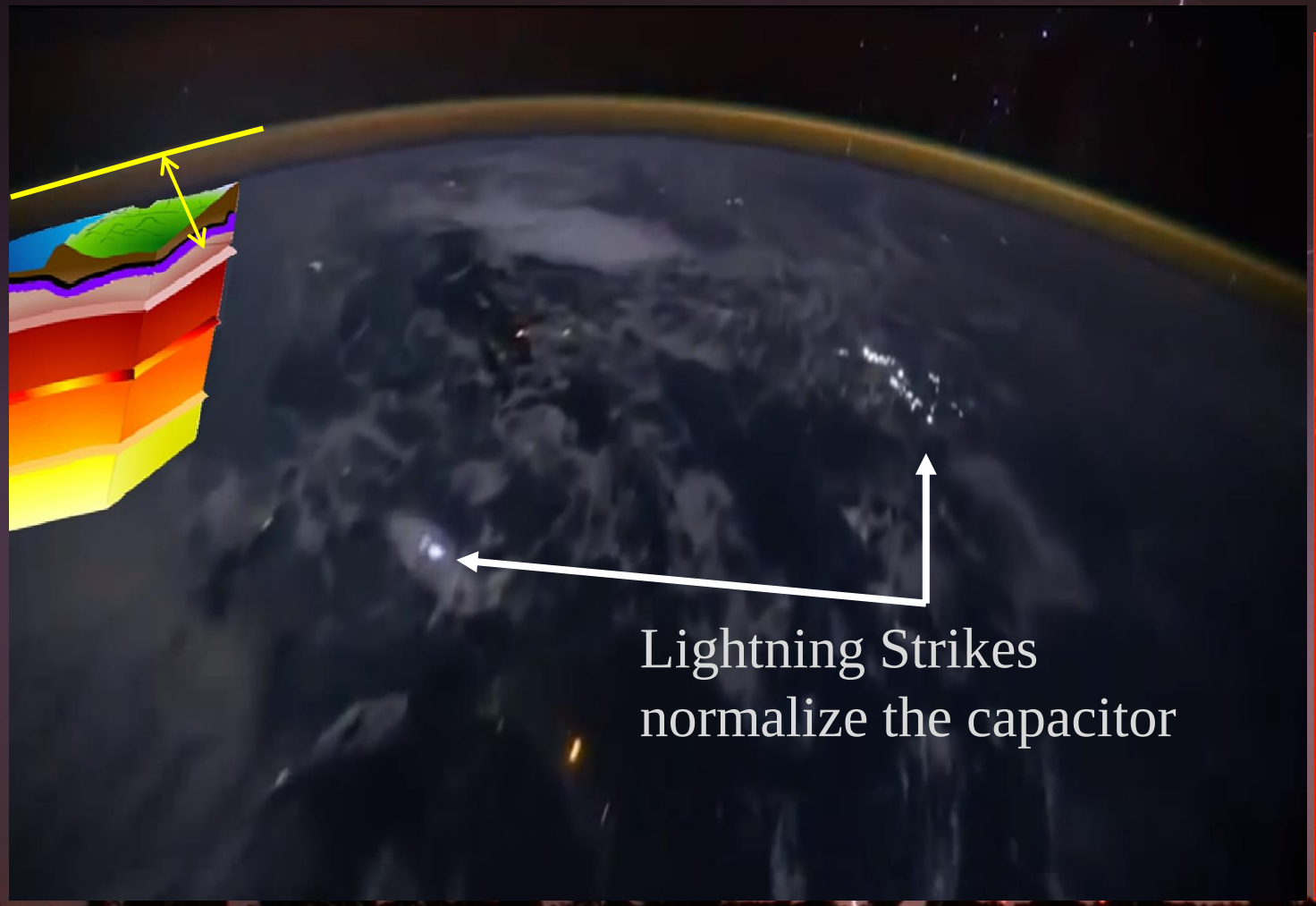


Lightning Strike Density Map

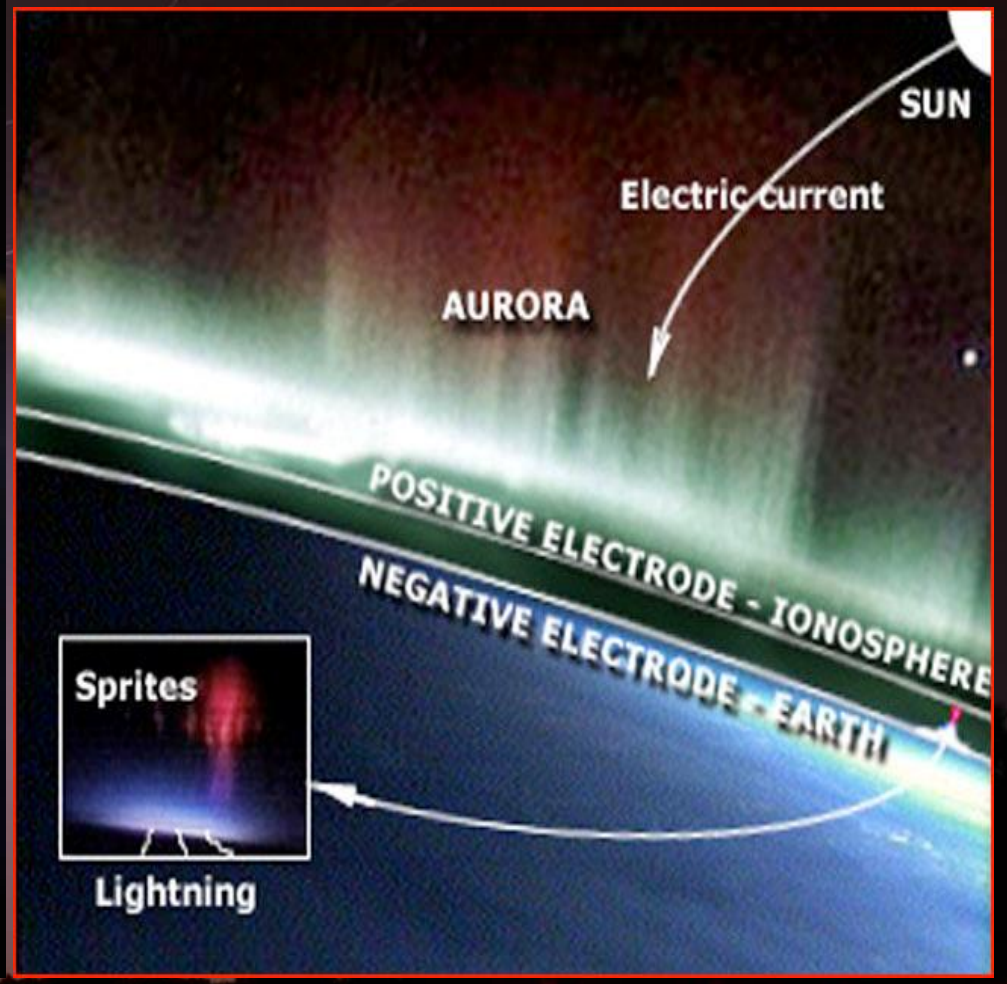
Lightning strikes - uneven distribution but not random!

Lightning strike density regionally controlled by meteorology, and locally controlled by terralevis (shallow earth) currents.

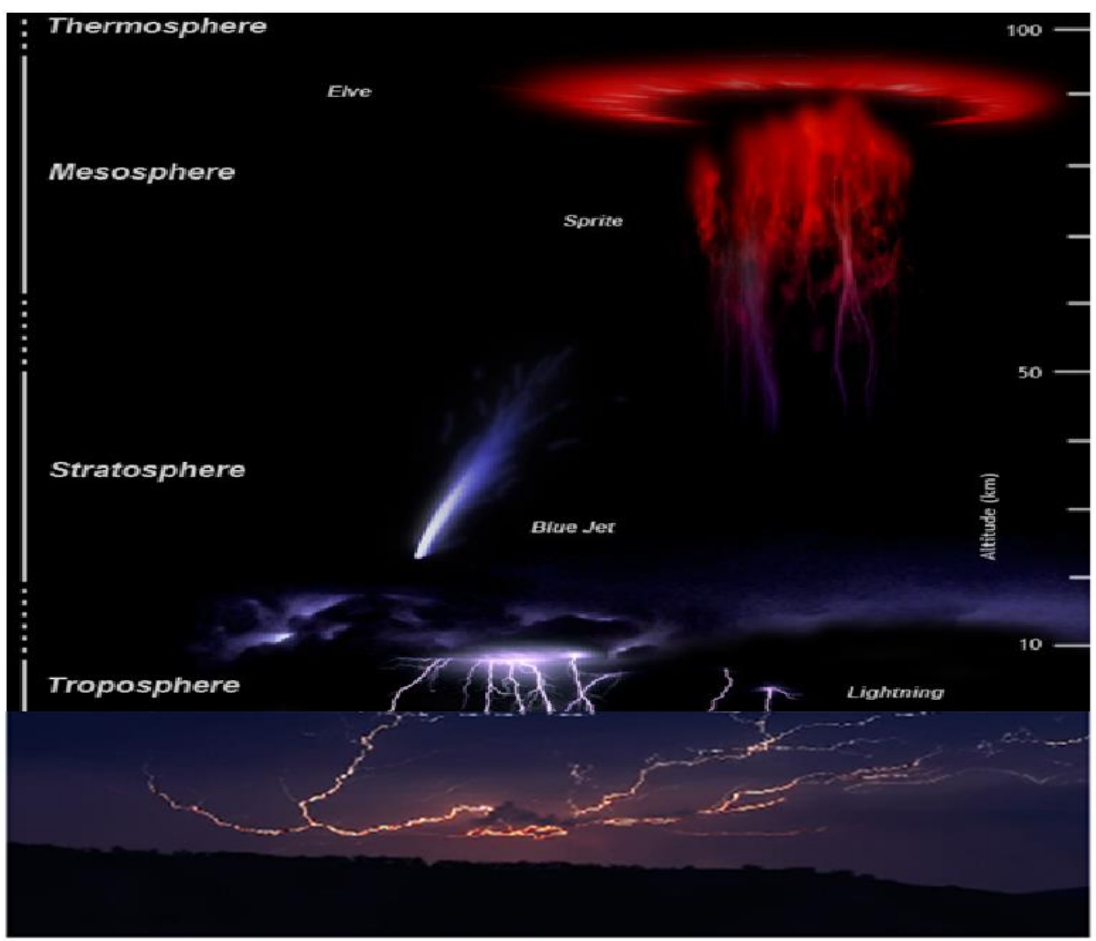
Earth: A Self-Repairing Capacitor

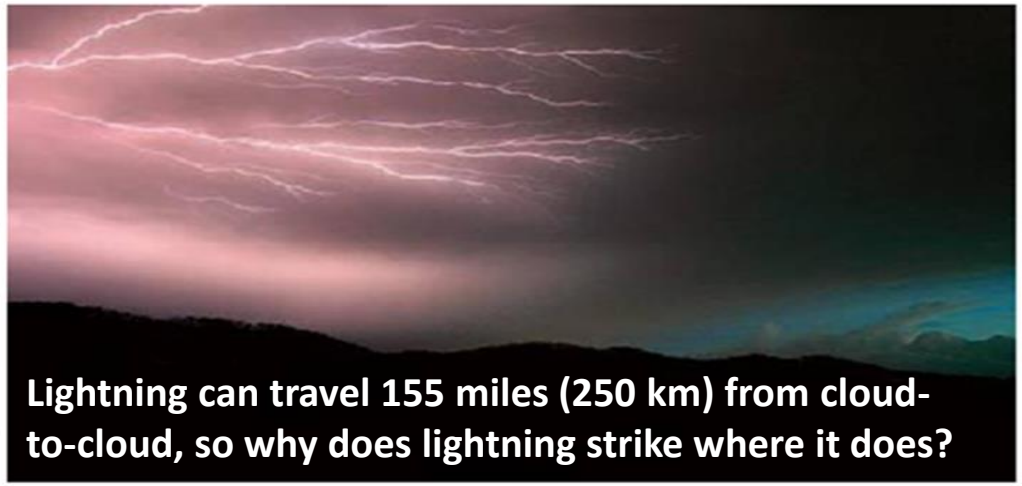


Lightning Strikes
normalize the capacitor



Geologically Controlled Telluric Currents
Primary Lightning Influence





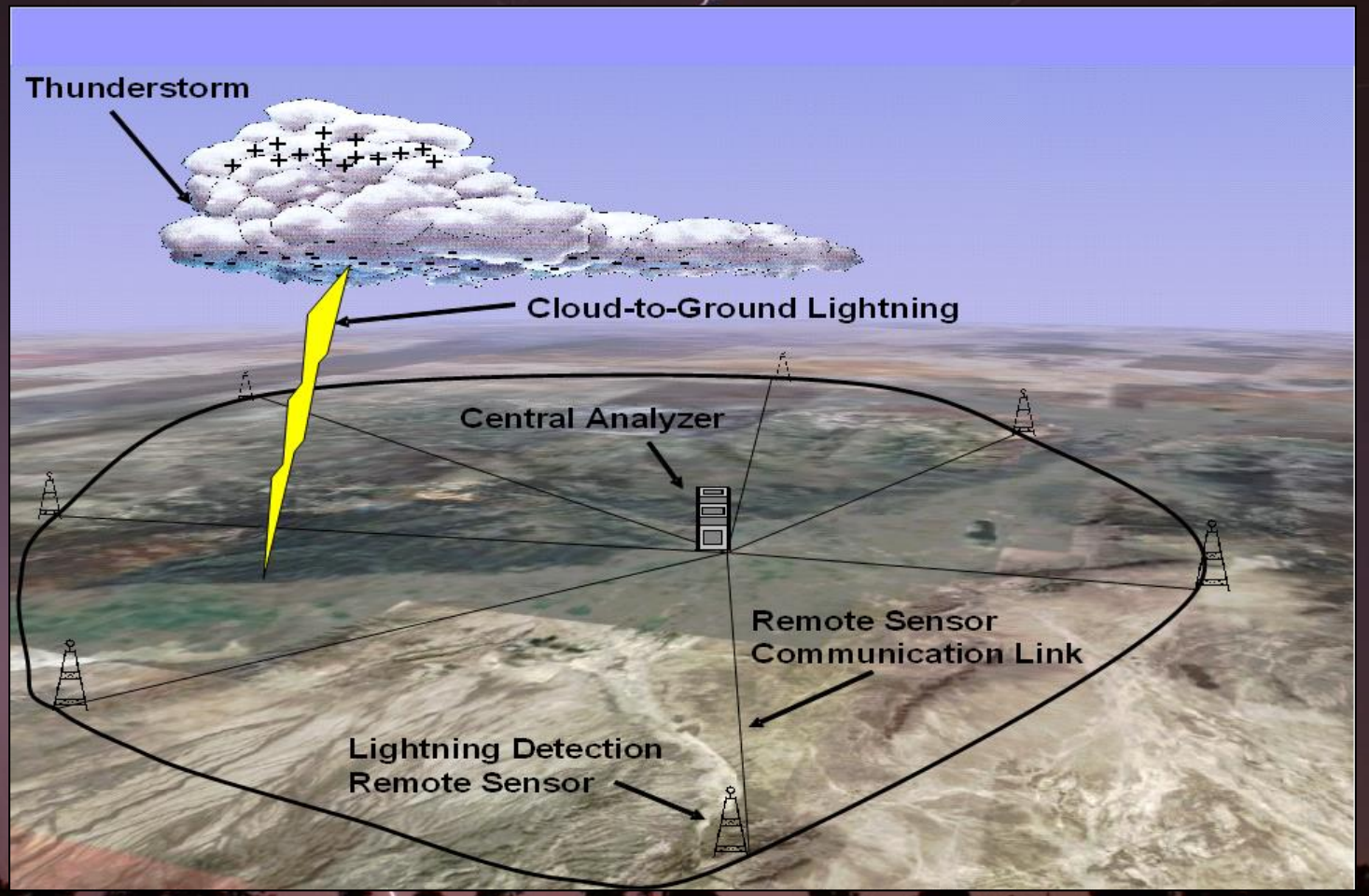
Lightning can travel 155 miles (250 km) from cloud-to-cloud, so why does lightning strike where it does?

Strike locations primarily controlled by earth's electromagnetic currents.

Why is lightning recorded?

Early Storm Warning - Safety - Insurance - Meteorology

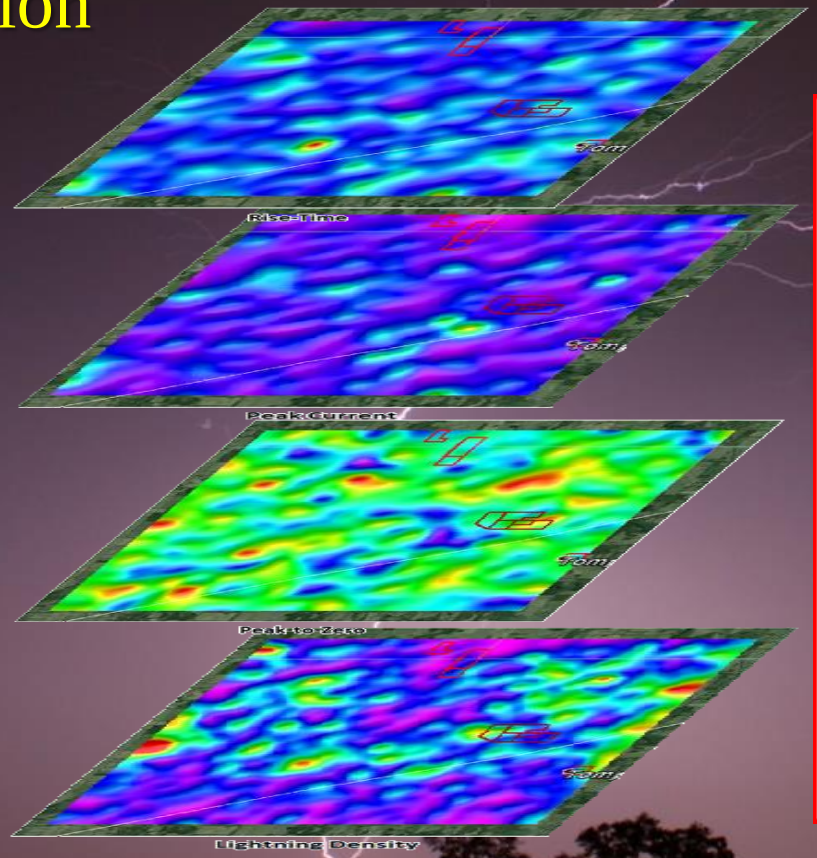
How is Lightning Data Collected?
330 Sensors Record U.S. Lightning Strike Locations

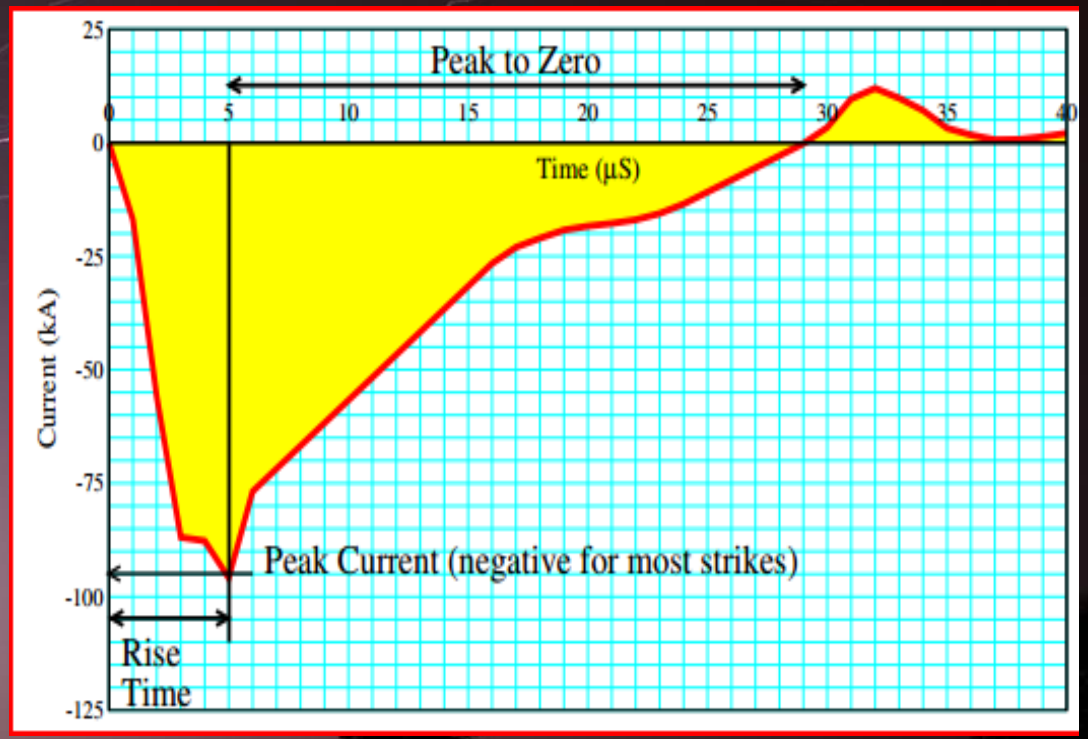


Horizontal Resolution 650’- 980’ (200-300 meters)

Lightning Strike Measurements

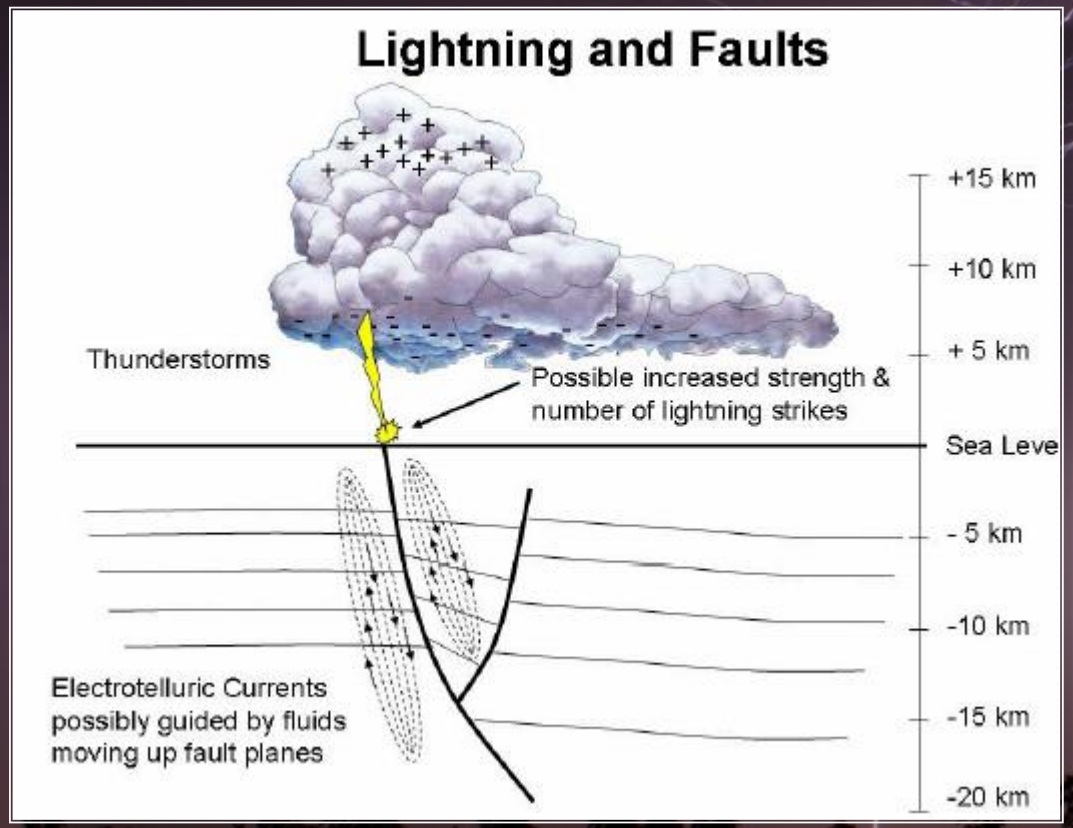
- Location
- Time and Duration
- Rise Time
- Peak Current
- Polarity
- Peak-to-Zero
- Density

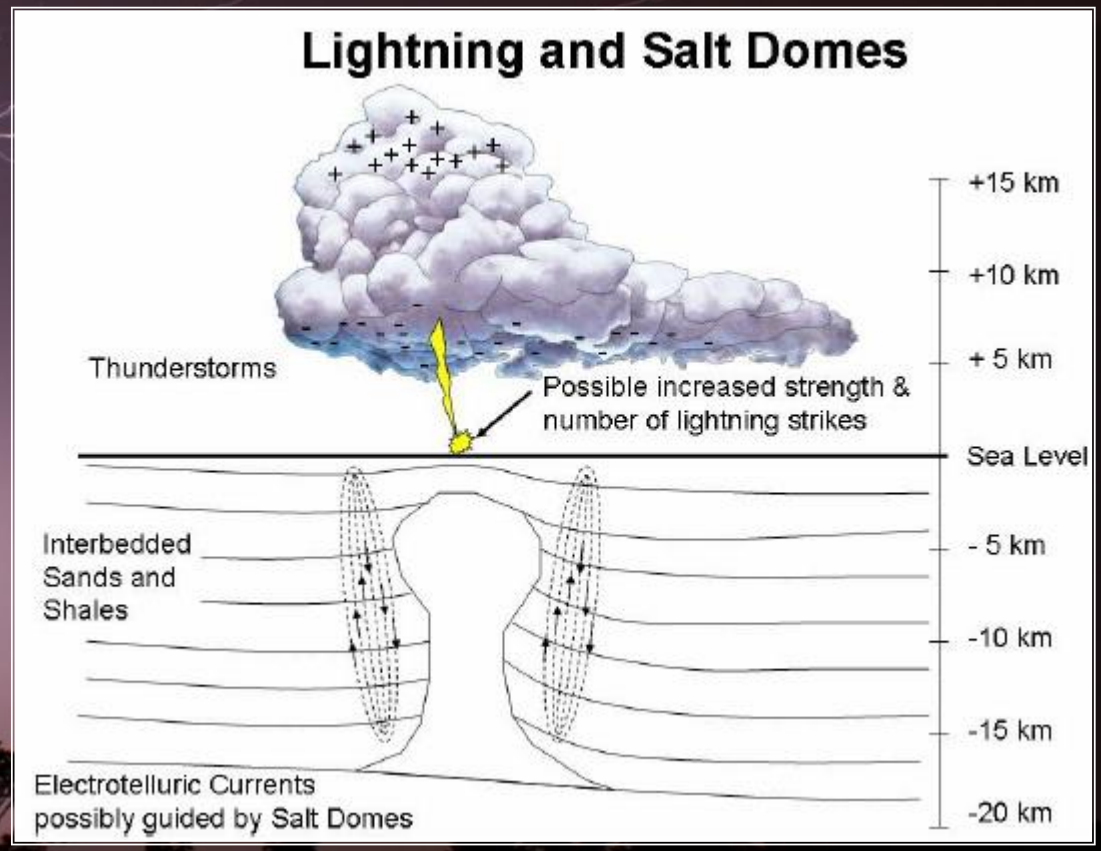




Telluric Currents, Lightning & Geology

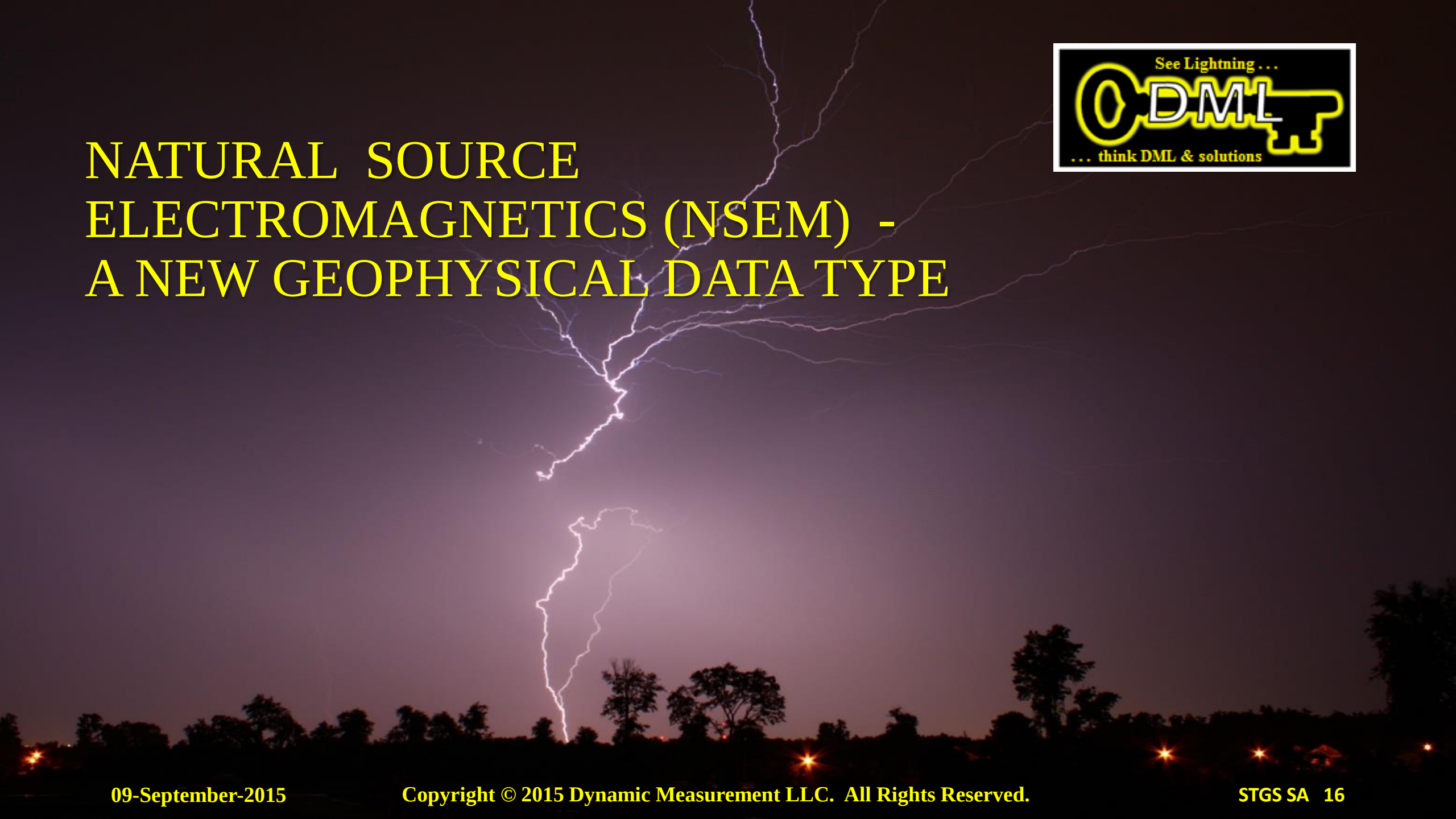
Earth Currents Modified by Geology ➡ Prone to Lightning





Lightning bypasses tall objects and…

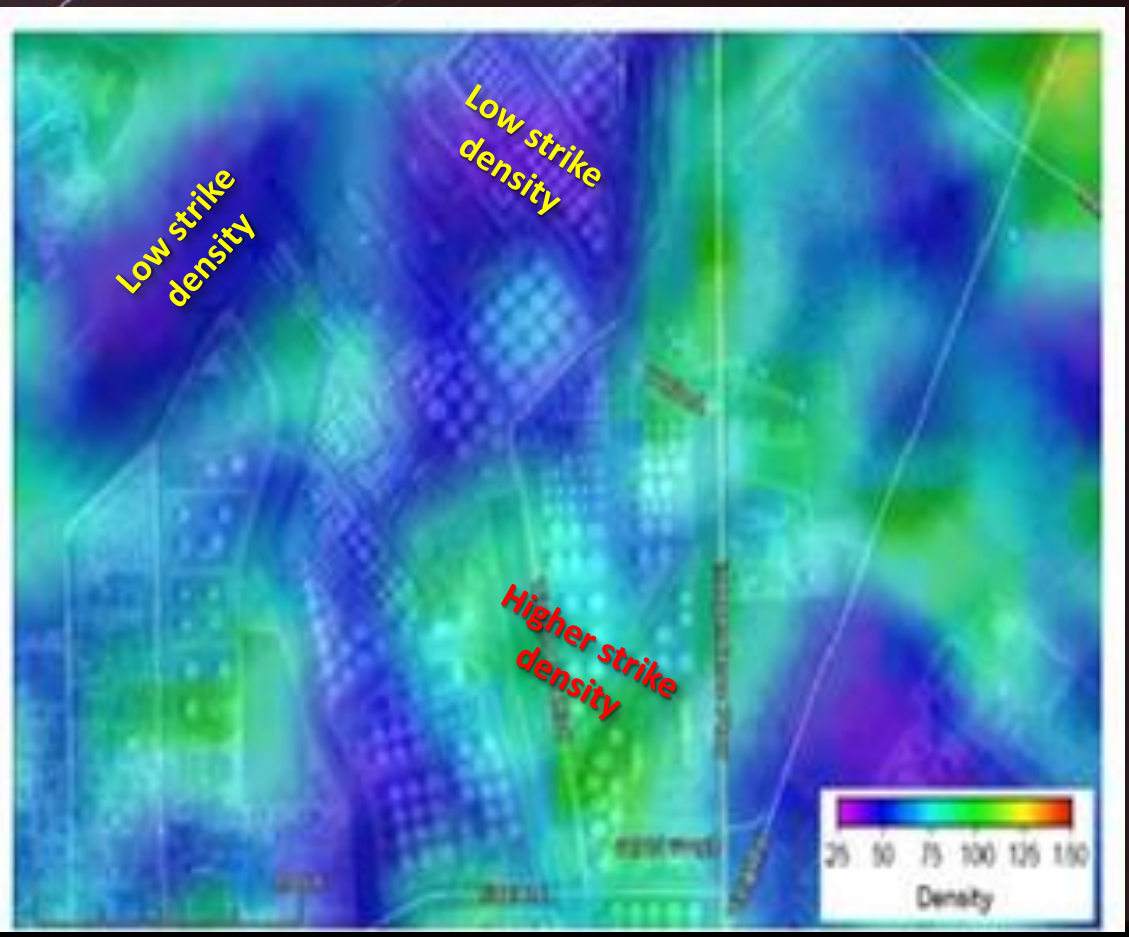
…infrastructure expected to attract lightning.



NATURAL SOURCE ELECTROMAGNETICS (NSEM) - A NEW GEOPHYSICAL DATA TYPE

Does Infrastructure Control Lightning?

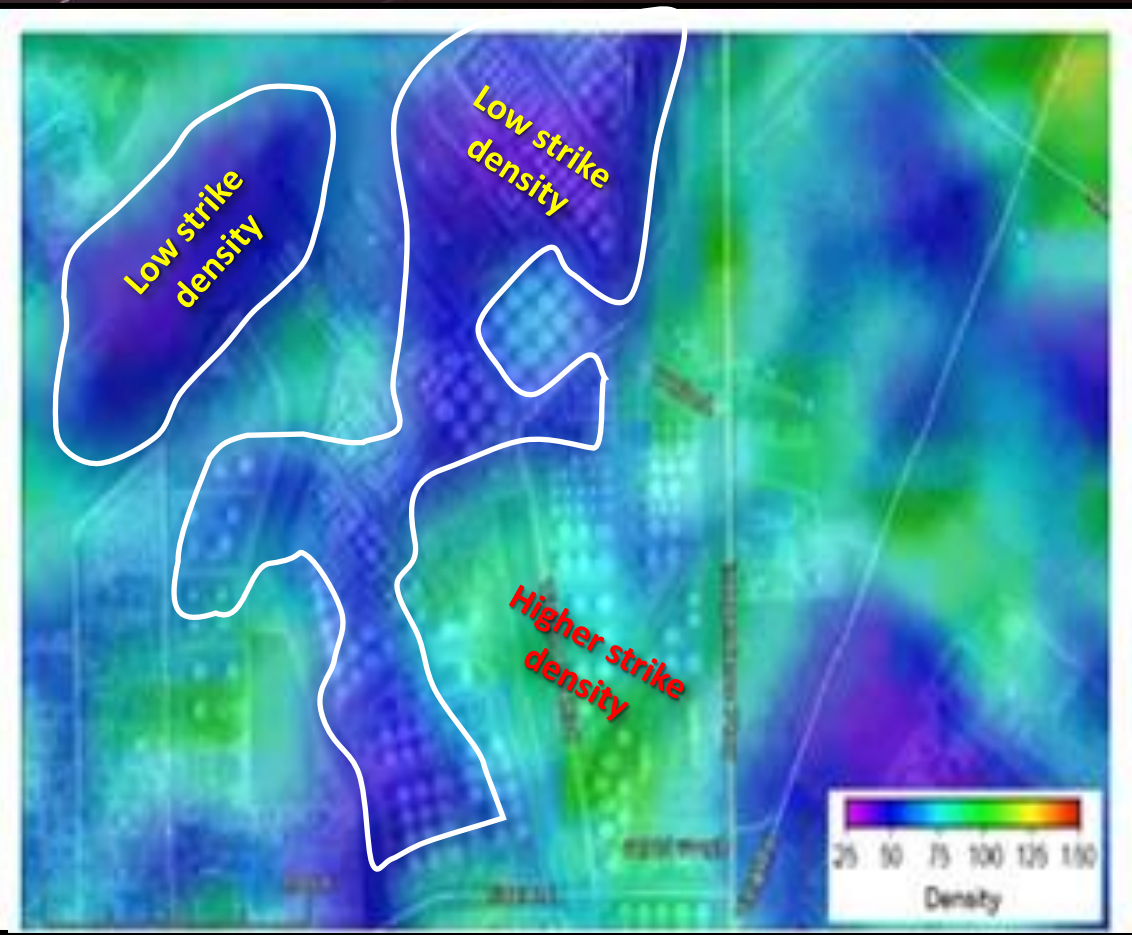
Oil Storage Facility (Tank Farm), Ship Channel, Houston



Strike Density Attribute Map

Approximately 60% of Tank Farm Experienced Low Strike Density

Oil Storage Facility (Tank Farm), Ship Channel, Houston



Strike Density Attribute Map

Proven & Patented Technology

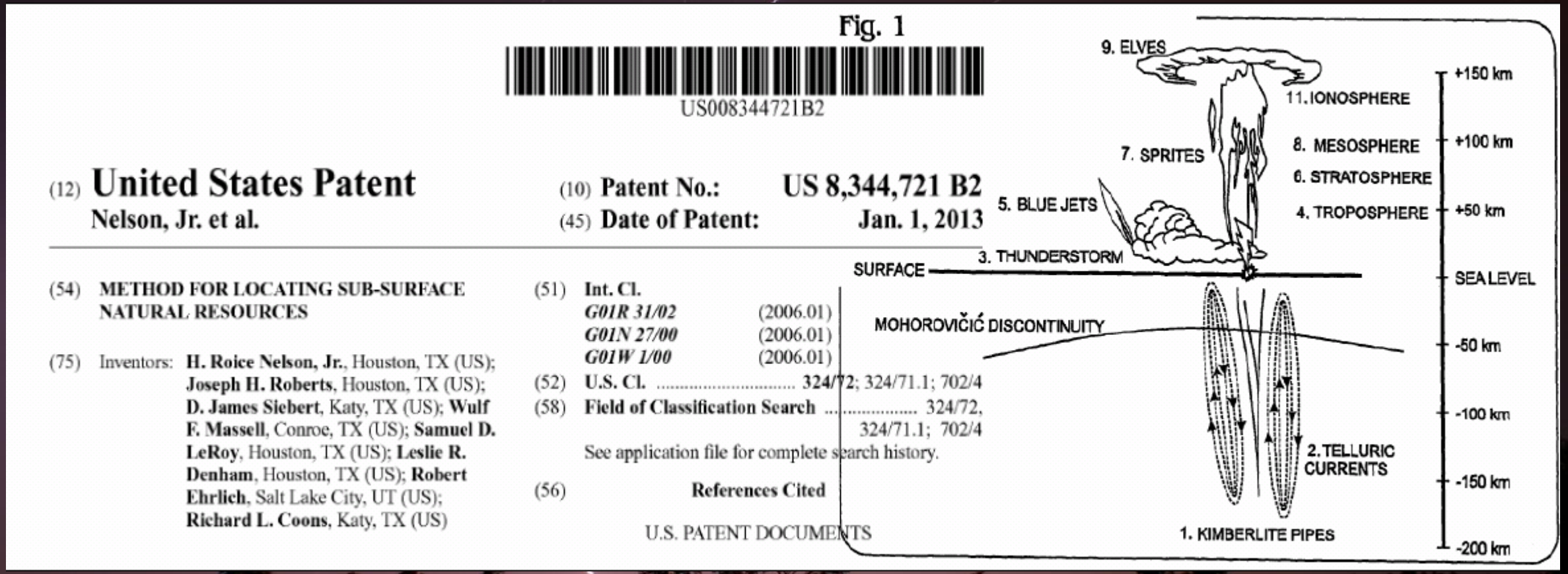


Fig. 1

US008344721B2

(12) **United States Patent**
Nelson, Jr. et al.

(10) **Patent No.: US 8,344,721 B2**
(45) **Date of Patent: Jan. 1, 2013**

(54) **METHOD FOR LOCATING SUB-SURFACE NATURAL RESOURCES**

(75) Inventors: **H. Roice Nelson, Jr.**, Houston, TX (US); **Joseph H. Roberts**, Houston, TX (US); **D. James Siebert**, Katy, TX (US); **Wulf F. Massell**, Conroe, TX (US); **Samuel D. LeRoy**, Houston, TX (US); **Leslie R. Denham**, Houston, TX (US); **Robert Ehrlich**, Salt Lake City, UT (US); **Richard L. Coons**, Katy, TX (US)

(51) **Int. Cl.**
G01R 31/02 (2006.01)
G01N 27/00 (2006.01)
G01W 1/00 (2006.01)

(52) **U.S. Cl.** **324/72**; 324/71.1; 702/4

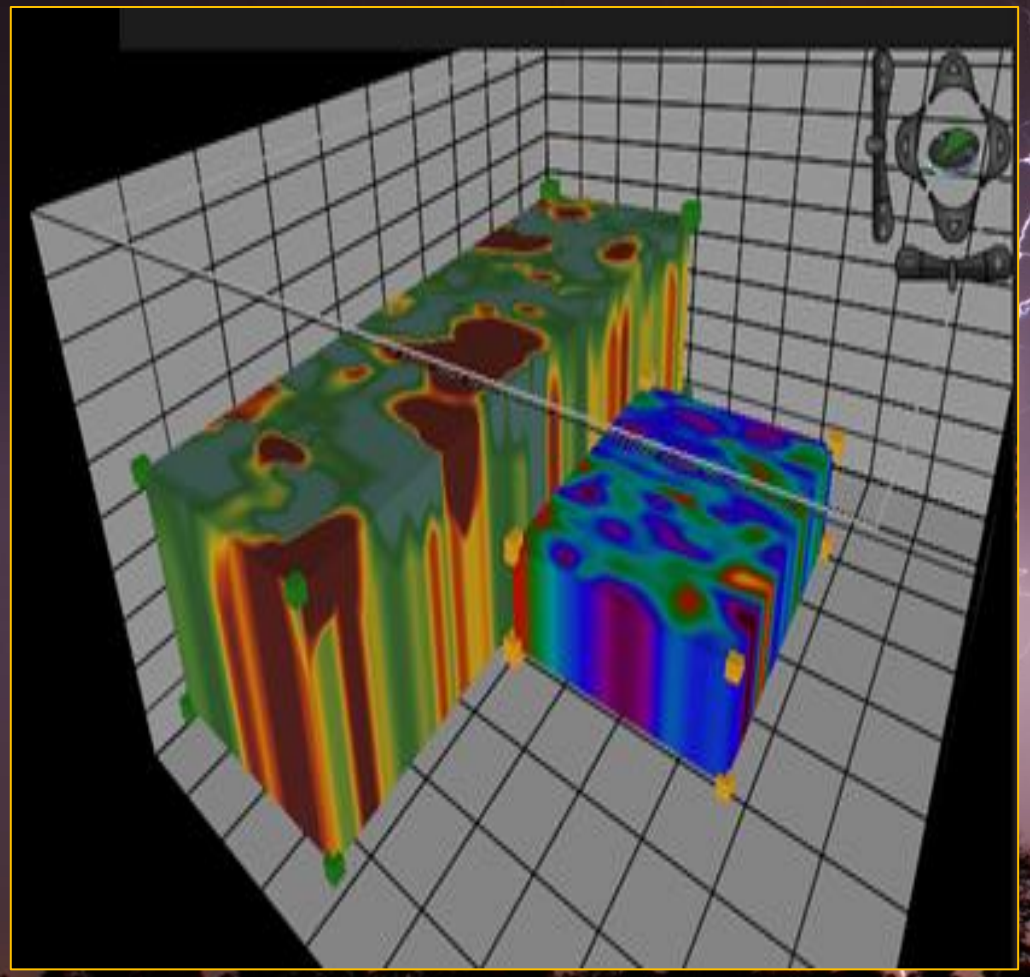
(58) **Field of Classification Search** 324/72, 324/71.1; 702/4

See application file for complete search history.

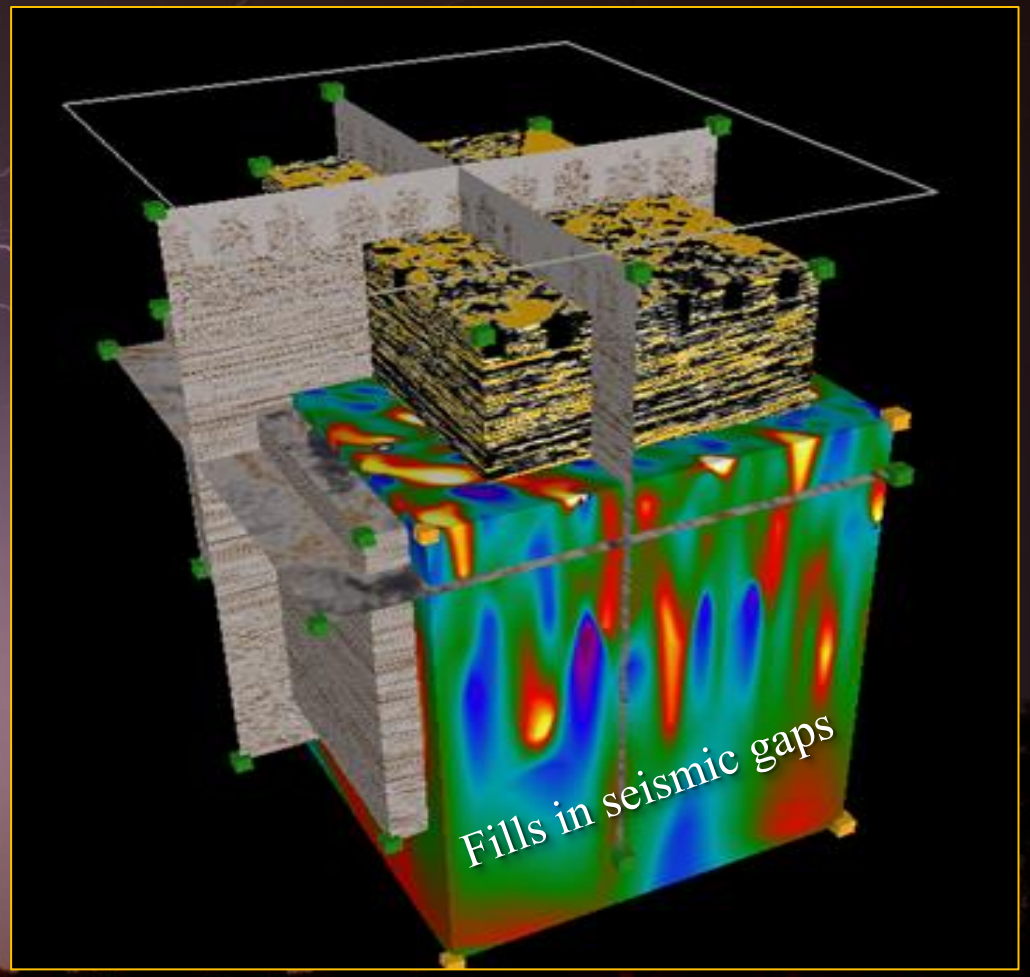
(56) **References Cited**

U.S. PATENT DOCUMENTS

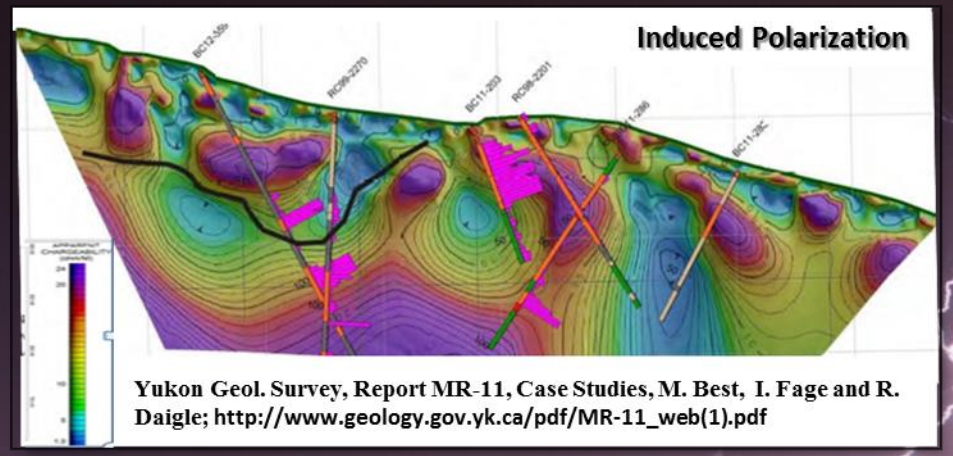
Resistivity & Permittivity Volumes
Easily Integrated with 3-D Seismic & Well Data



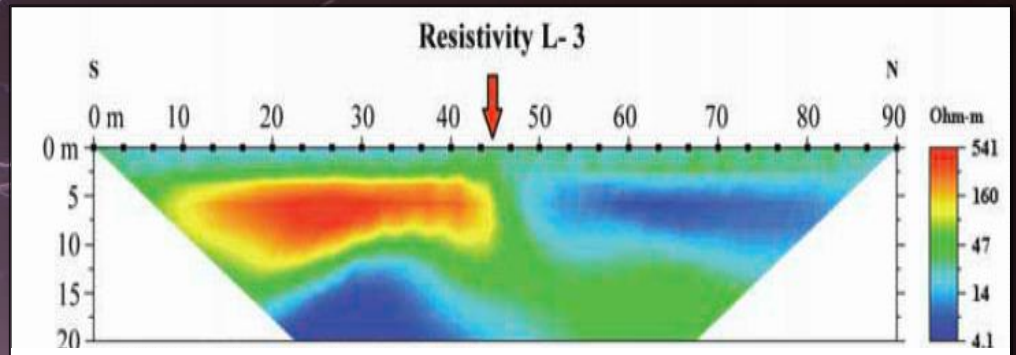
Inlines
Crosslines
Arb Lines
Slices



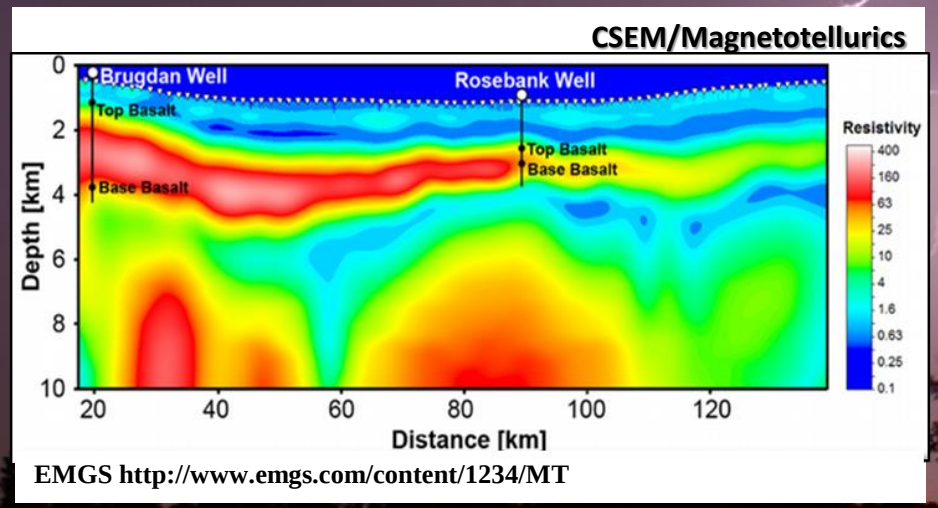
Resistivity & Permittivity Volumes Easily Integrated with Near-Surface Geophysical Data



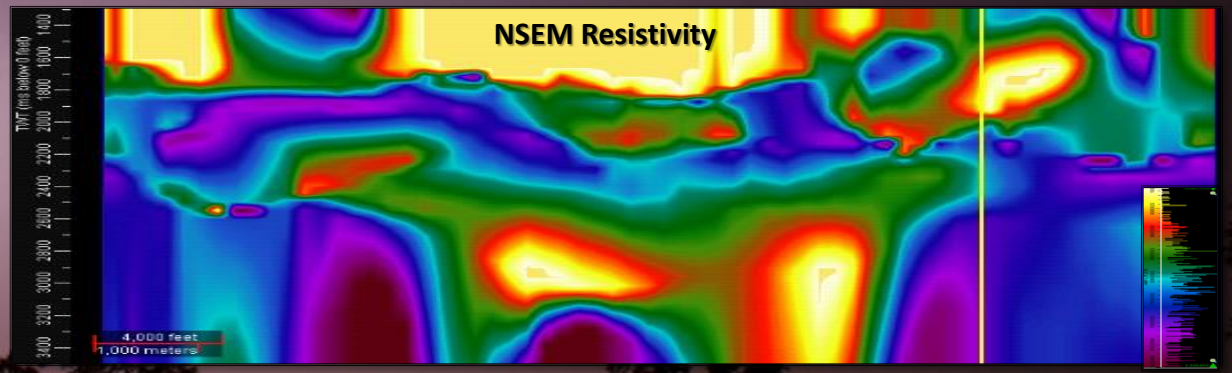
Yukon Geol. Survey, Report MR-11, Case Studies, M. Best, I. Fage and R. Daigle; http://www.geology.gov.yk.ca/pdf/MR-11_web(1).pdf



2D Resistivity Imaging Profile, Willow Creek Fault, Mustafa Saribudak, The Leading Edge, 2006



EMGS http://www.emgs.com/content/1234/MT



Lightning Strikes Are Not Random!

Influenced by Lateral Changes in Rock Properties:

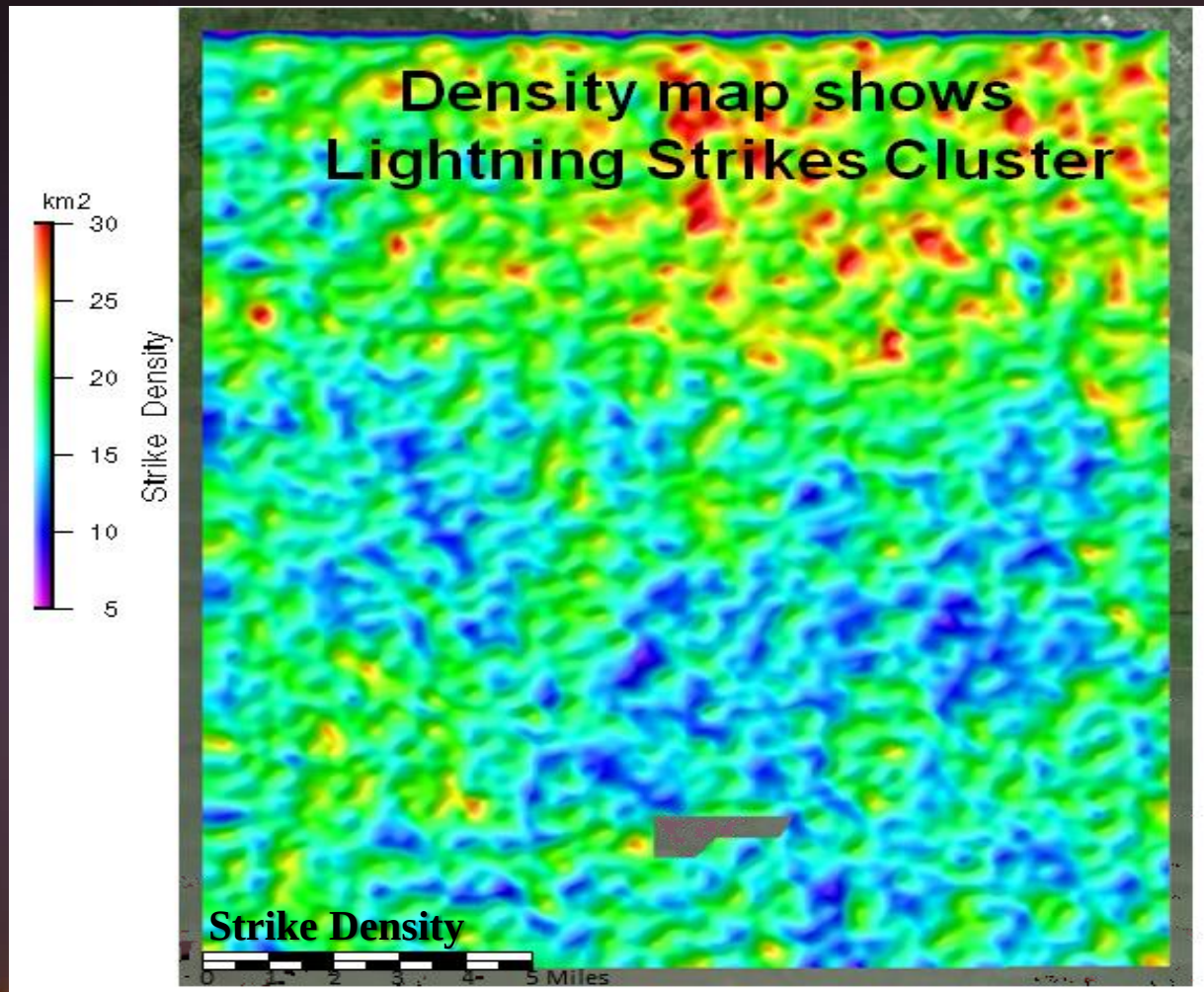
- Faults
- Fracture Swarms
- Salinity
- Pore Fluids
- Porosity
- Permeability
- Mineralization

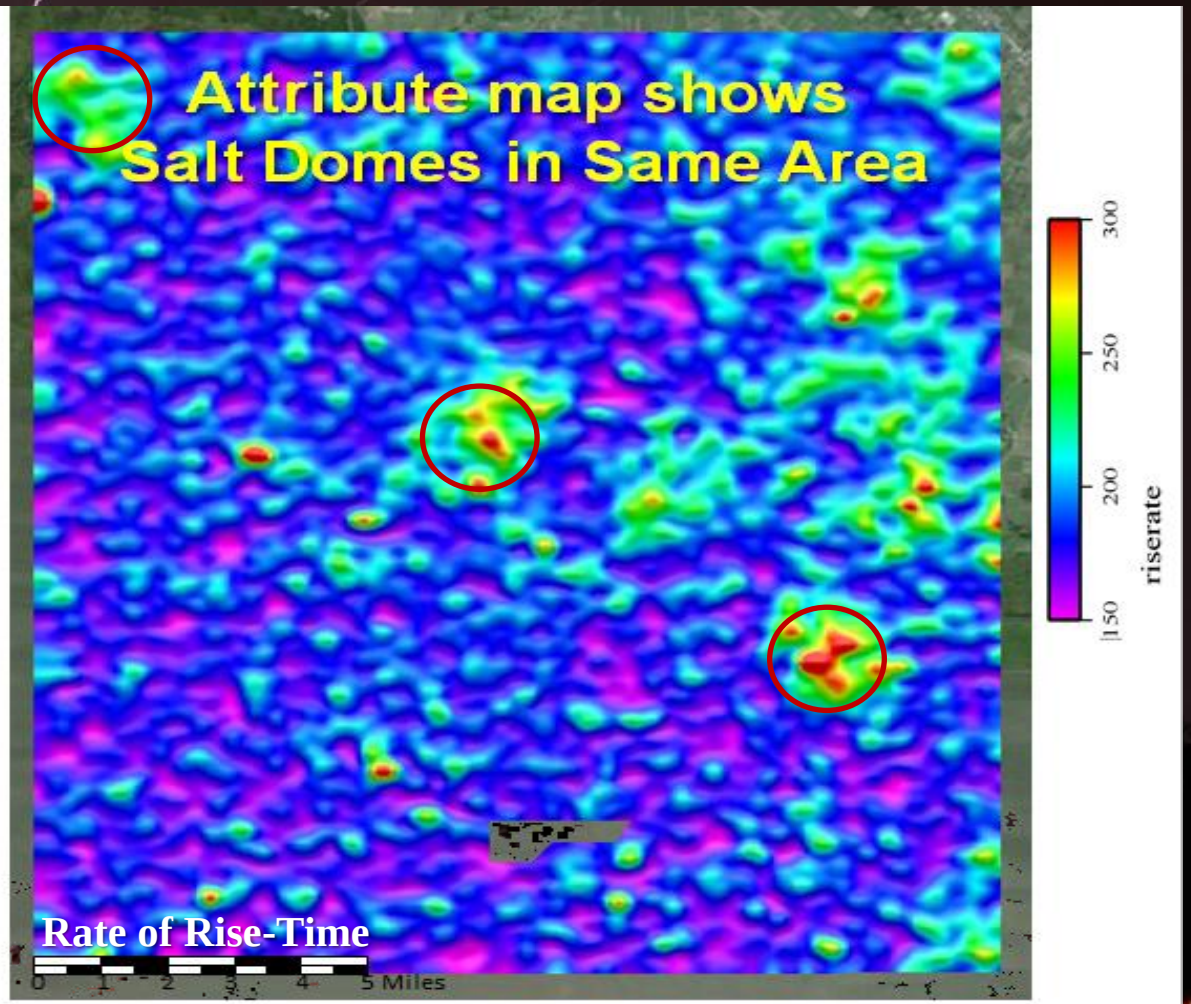
Upward lightning shows electrostatic charge builds up in the ground, as well as in the atmosphere.

EXAMPLES OF USING NSEM TO INTERPRET GEOLOGIC FEATURES

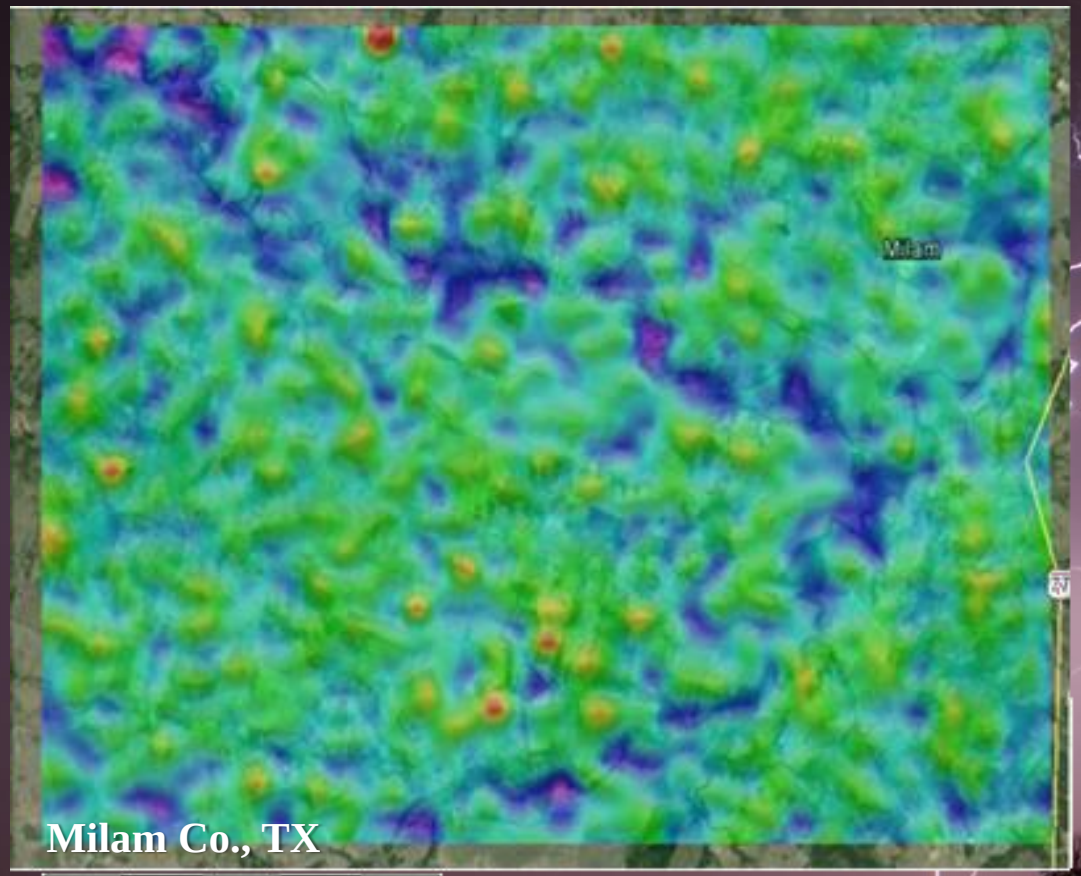
- Iberia Parish, Louisiana
- Milam Co., Texas
- Texas Gulf Coast - Regional
- Colorado Co., Texas - Prospecting
- Hockley Salt Dome, Harris County, Texas
- Pinal Co., Arizona

NSEM Correlates To Geology:
Iberia Parish, LA Salt Domes

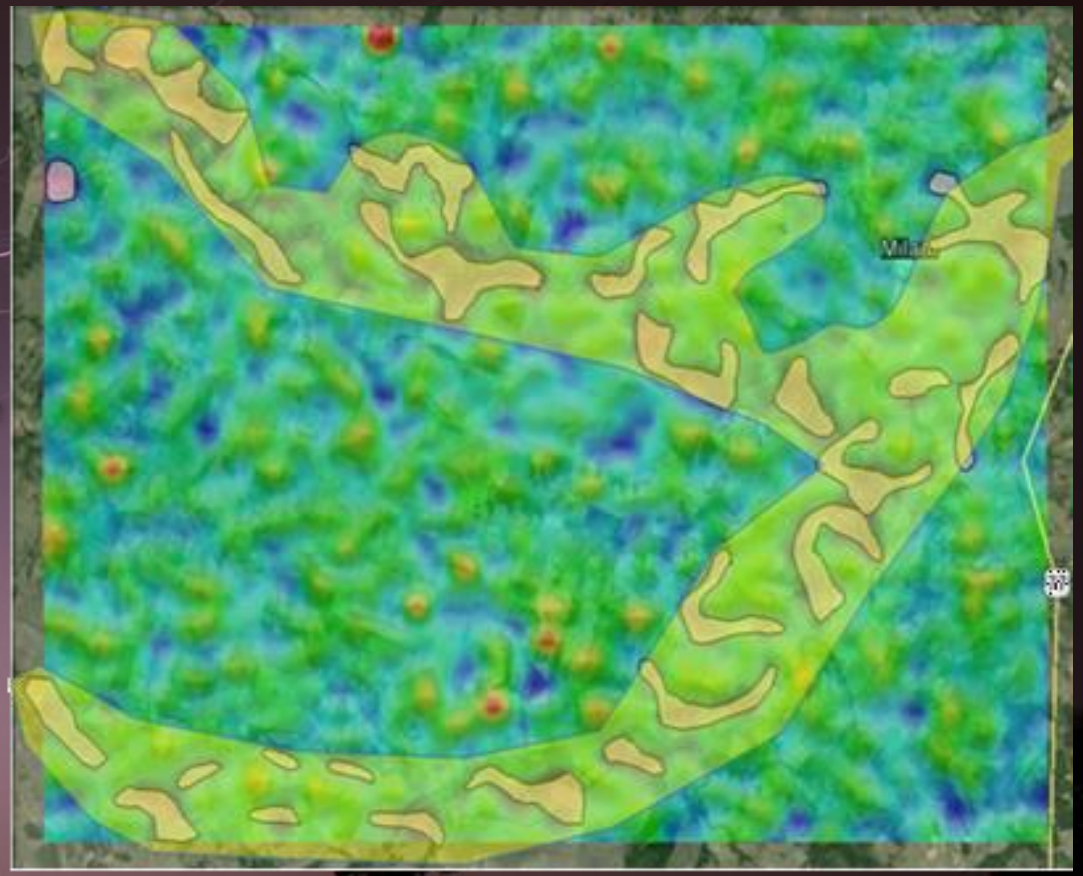




NSEM Correlates To Geology:
Milam Co., TX Fluvial Depositional Patterns

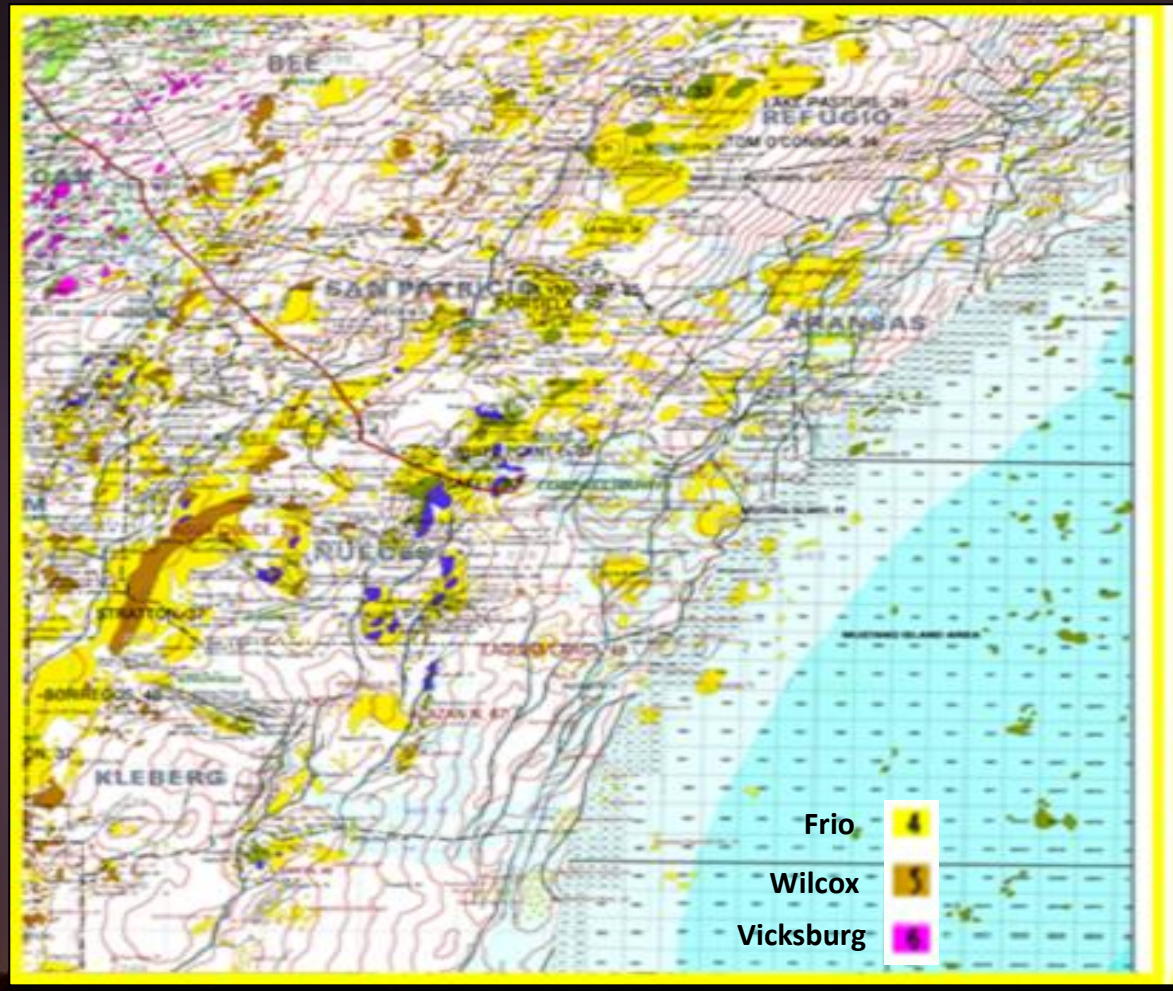


Lightning Attribute
Rate of Rise-Time

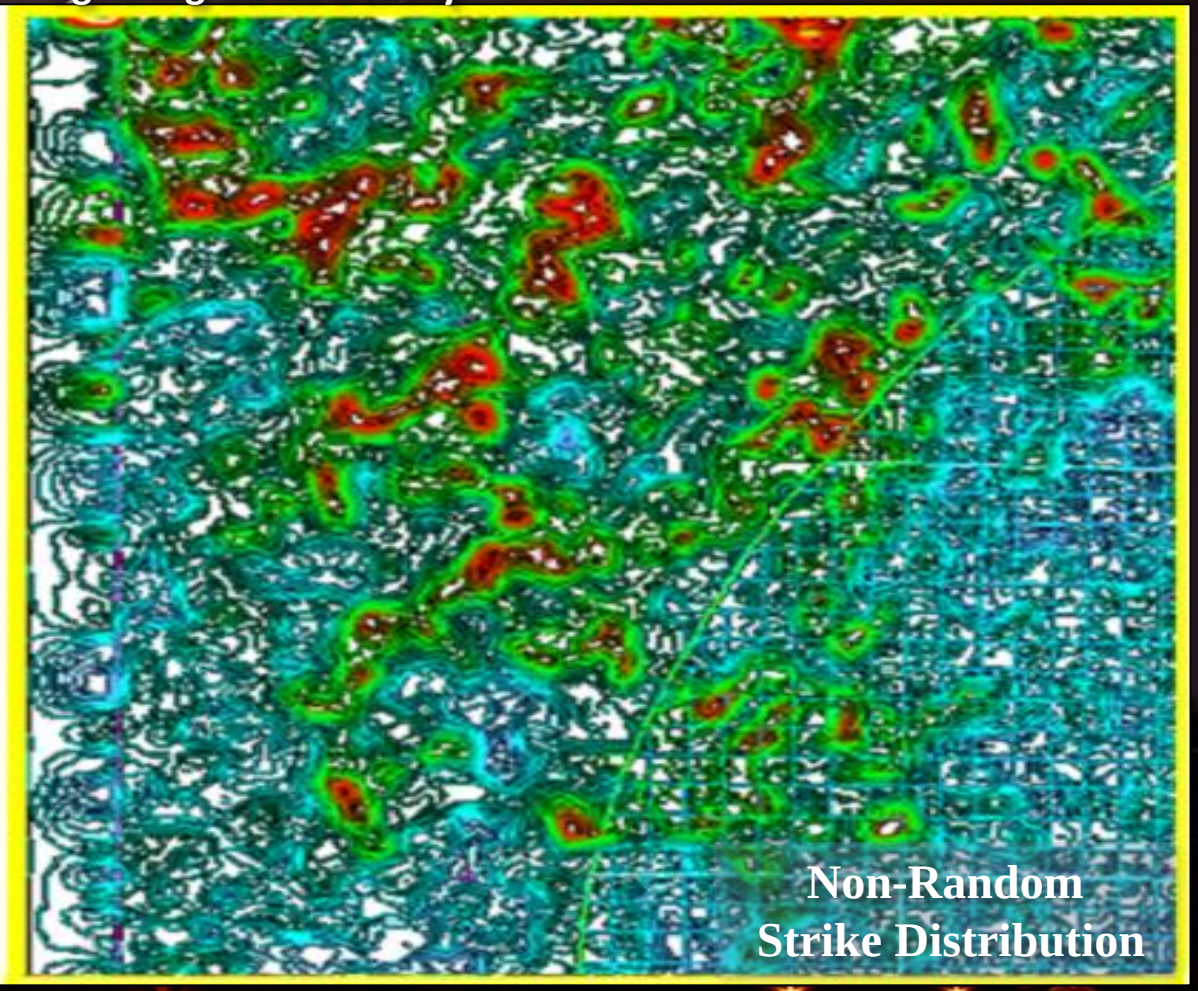


NSEM Correlates To Geology:
Texas Gulf Coast Regional Correlation

Structure & Field Outlines



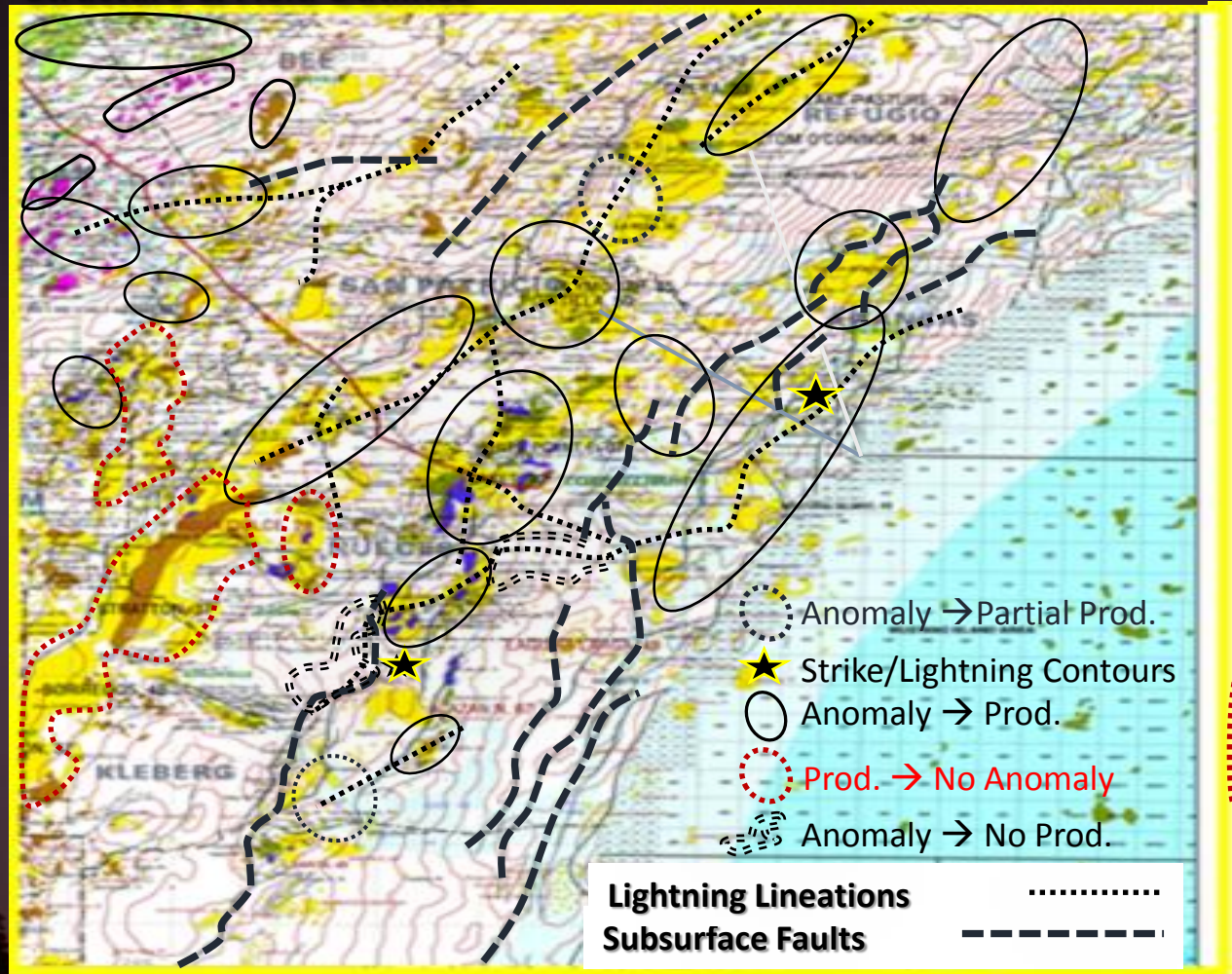
Lightning Strike Density



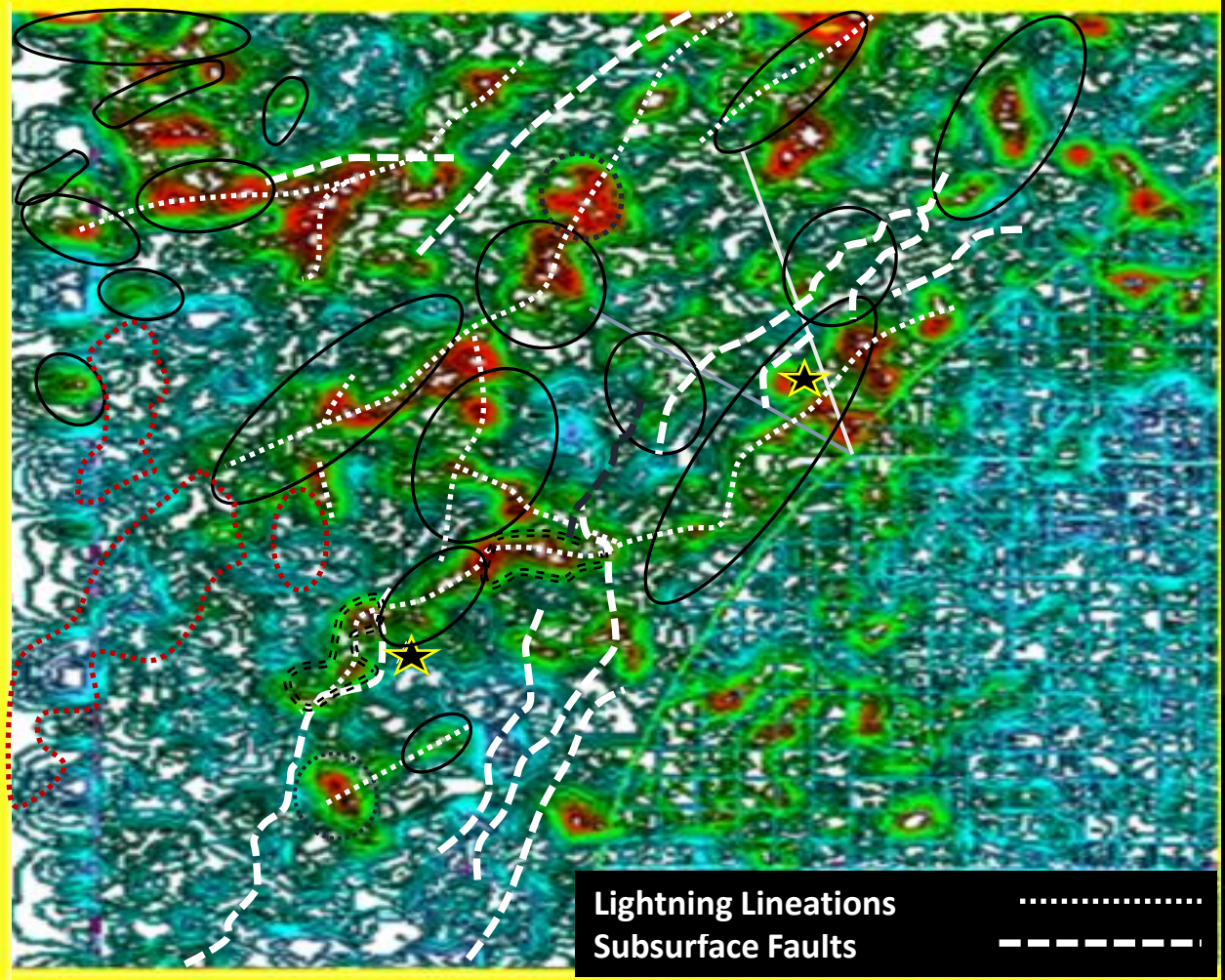
NSEM Correlates To Geology:
Fault Patterns and Hydrocarbon Accumulations

See Lightning . . .
DML
. . . think DML & solutions

Structure & Field Outlines



Lightning Strike Density



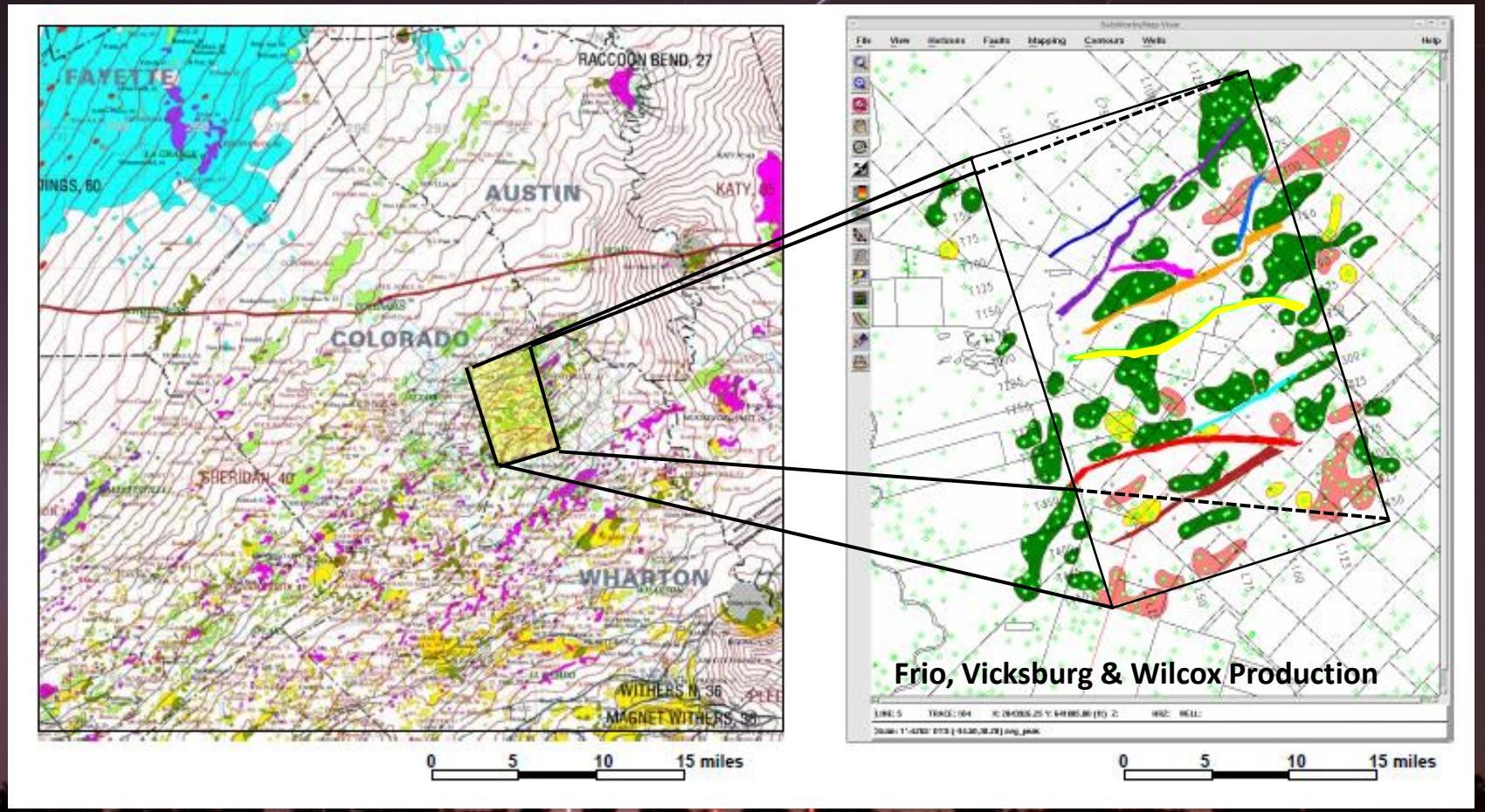
Observations

- Lightning strikes are non-random.
- Lightning strikes generally correlate to field locations.
- Faults do not appear to cut across lightning lineaments, generally striking parallel/sub-parallel to lightning features.

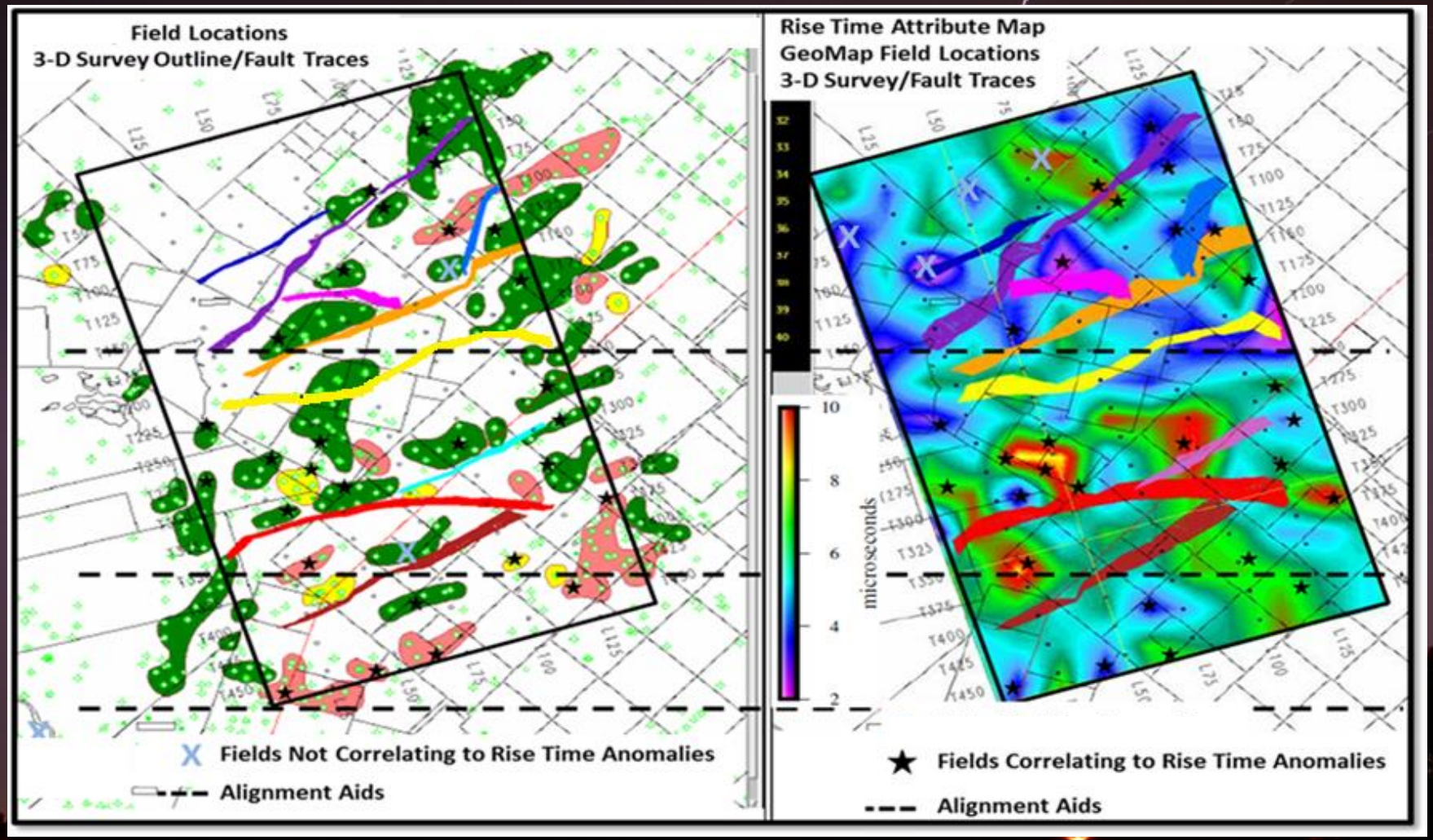
Conclusions

- Local geology influences where lightning strikes occur.
- NSEM has potential to locate hydrocarbons.
- NSEM has potential to delineate subsurface fault patterns.

NSEM Correlates To Geology:
Colorado County, TX



Effective Reconnaissance Mapping
Prospect Scale Field Correlations



87% of lightning attribute anomalies (Rise Time) correlate to Frio, Vicksburg or Wilcox production.

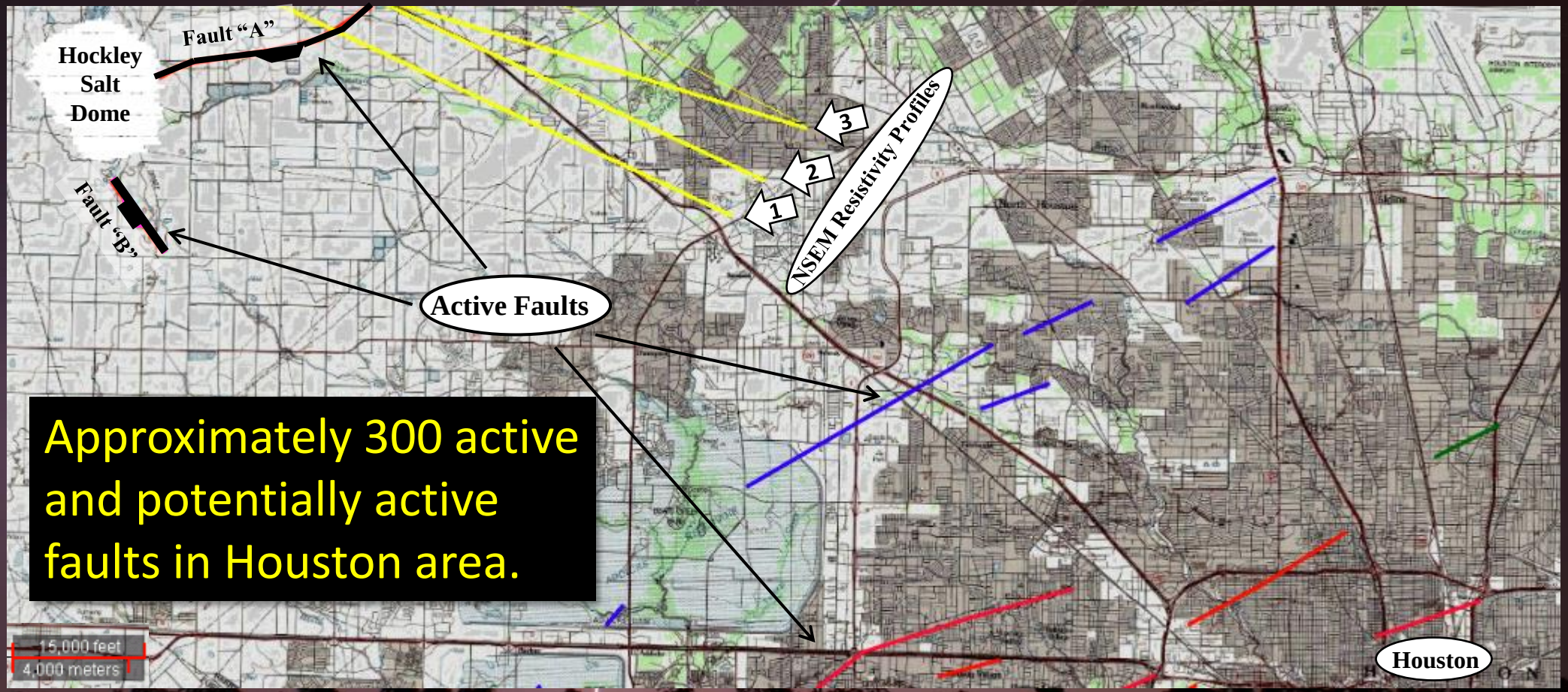
Observations

- Rise-Time lightning attribute shows non-random patterns.
- 26 of 28 fields (93%) correlate to Rise-Time anomalies.

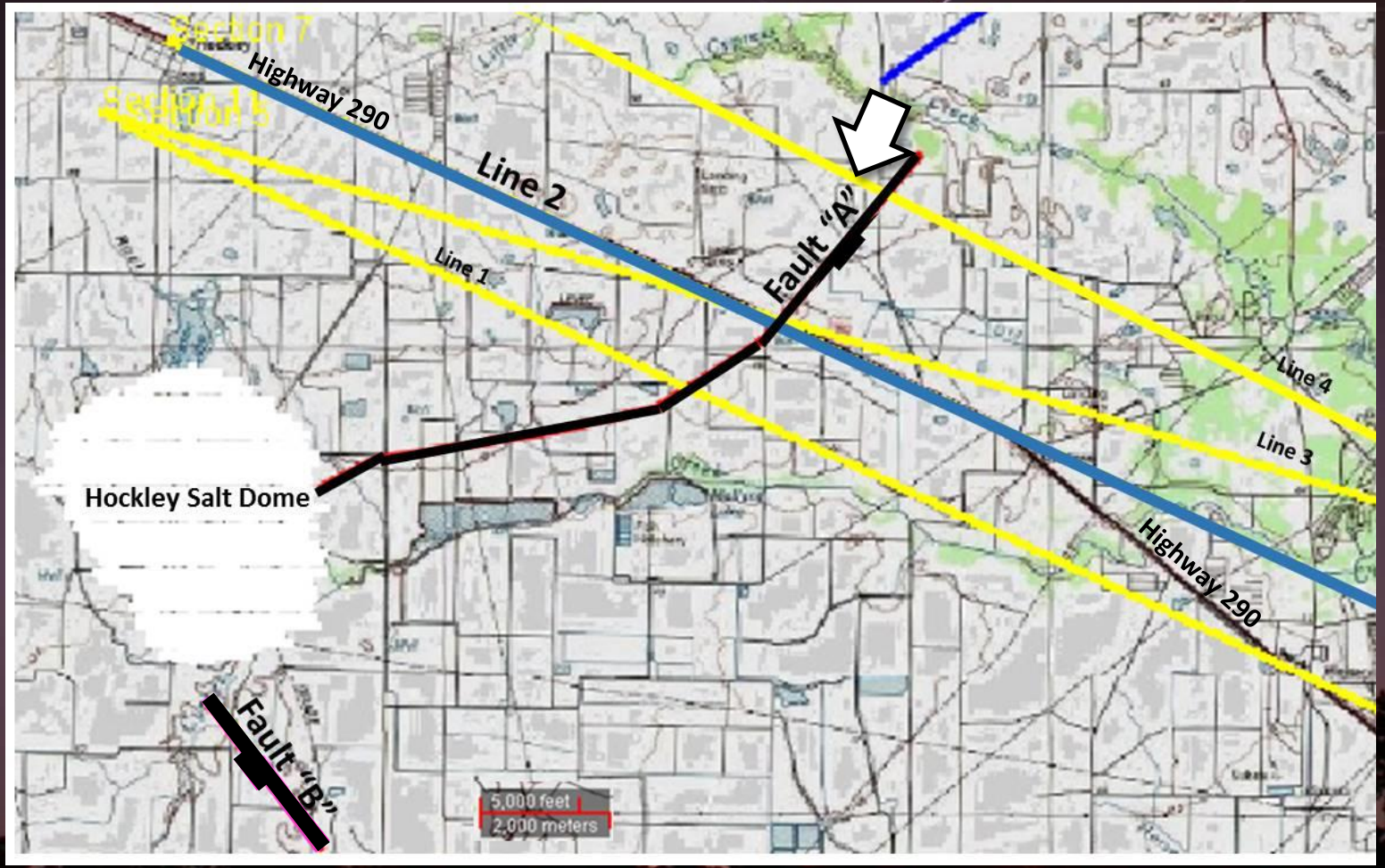
Conclusions

- NSEM identified 32 leads in study area.
- Reconnaissance mapping would have justified seismic data follow-up resulting in the generation of 28 prospects.
- NSEM reconnaissance mapping would have resulted in an 87% success rate.

Houston/Harris County Area Active Faults



NSEM Correlates To Geology:
Active Faults, Harris Co., TX



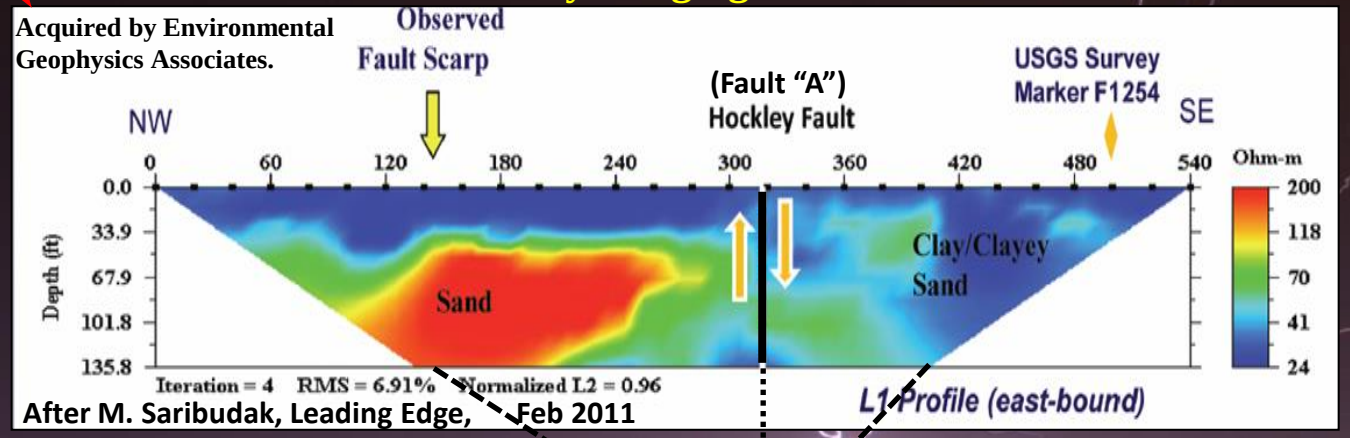
Hockley Radial Fault "A"

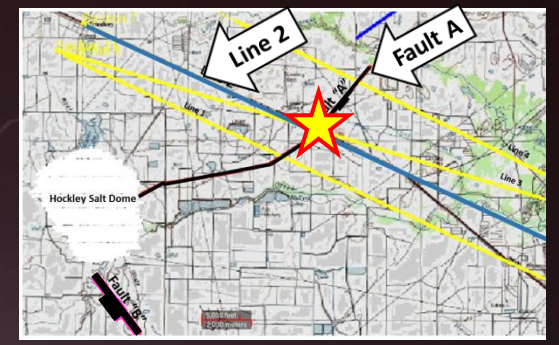
Resistivity profile "Line 2" displayed in next slide.

Line 2 Ties Fault "A" to Subsurface

See Lightning . . .
DML
. . . think DML & solutions

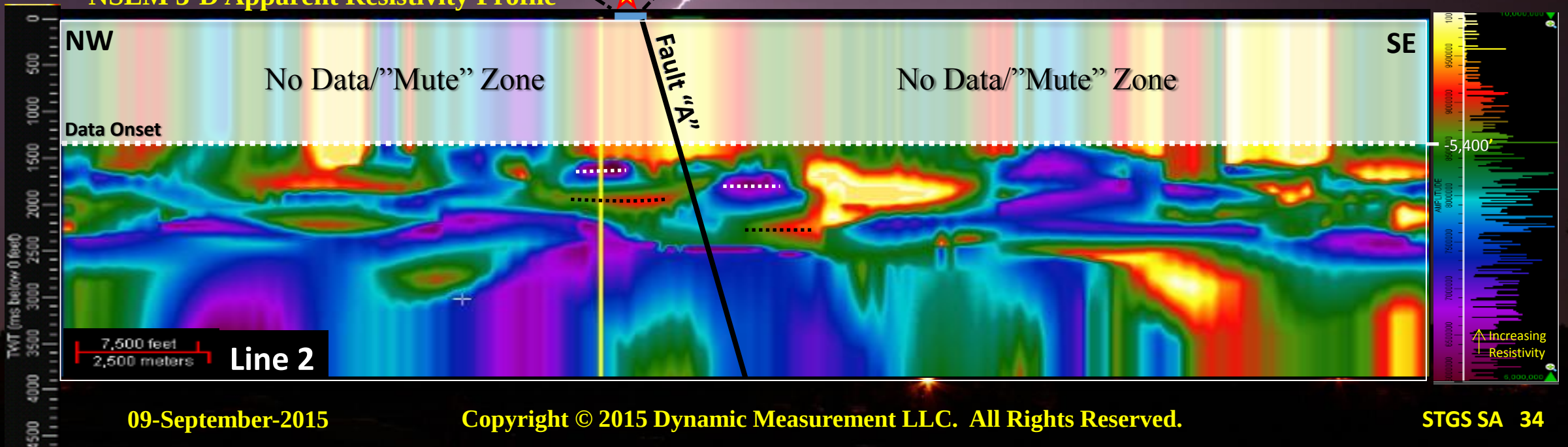
Conventional 2-D Resistivity Imaging Profile





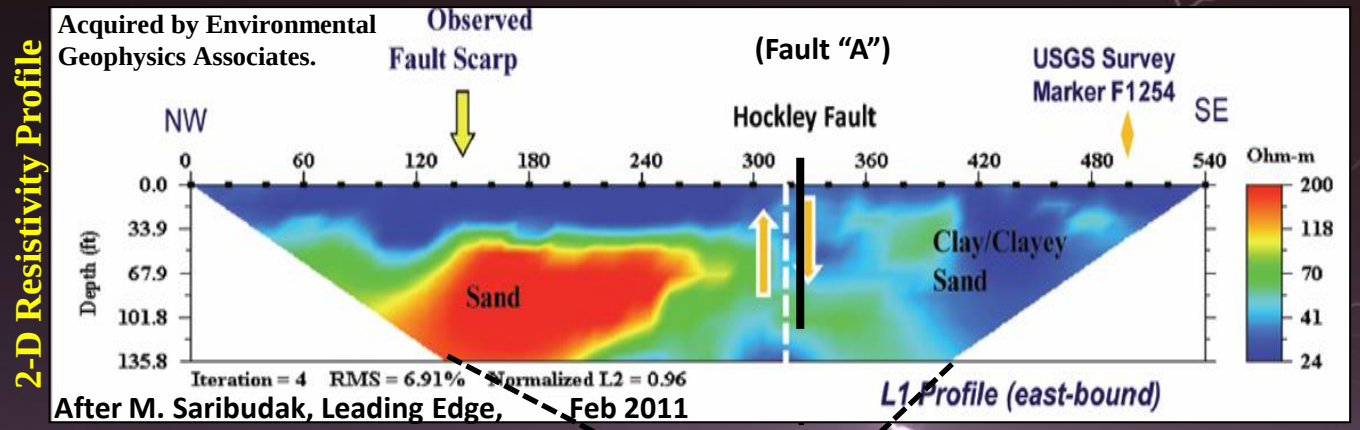
Line 2

NSEM 3-D Apparent Resistivity Profile

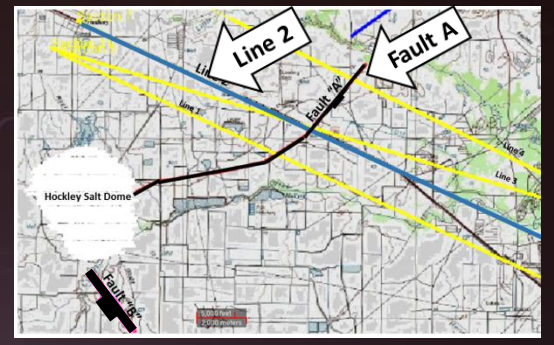


NSEM Reveals Additional Faulting

3-D Data Provides Interpretive Checks & Balances



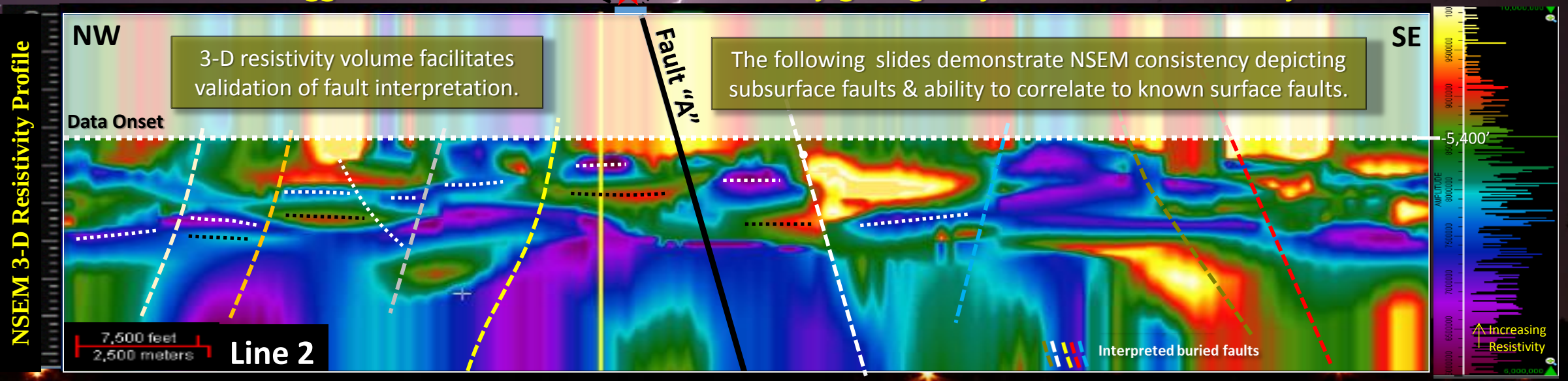
After M. Saribudak, Leading Edge, Feb 2011



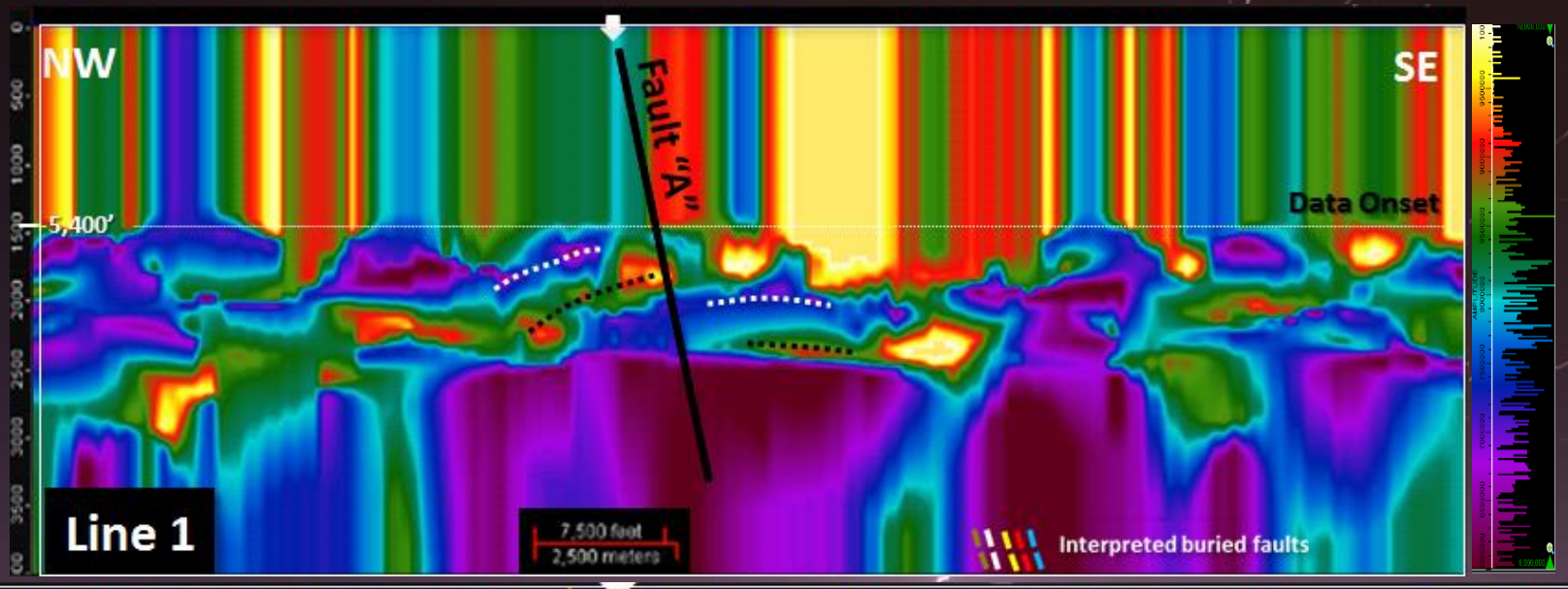
Line 2

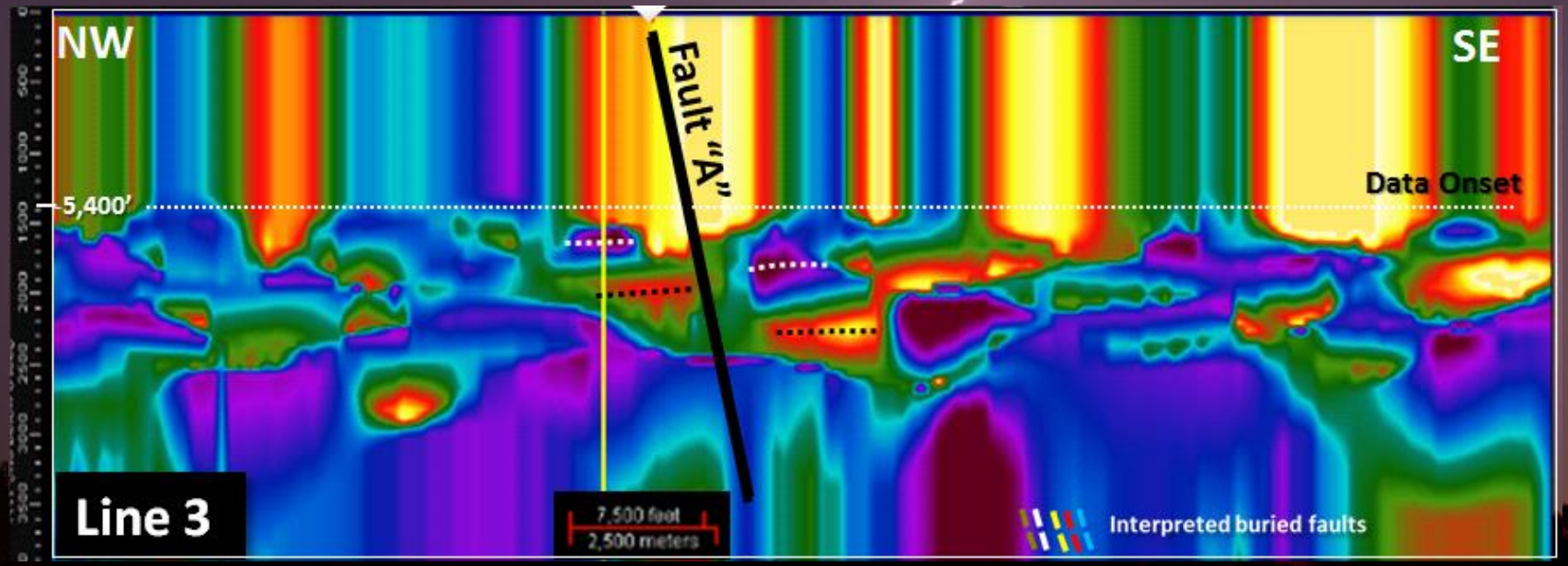
Additional faults suggested.

Are they geologically reasonable , internally consistent, valid?

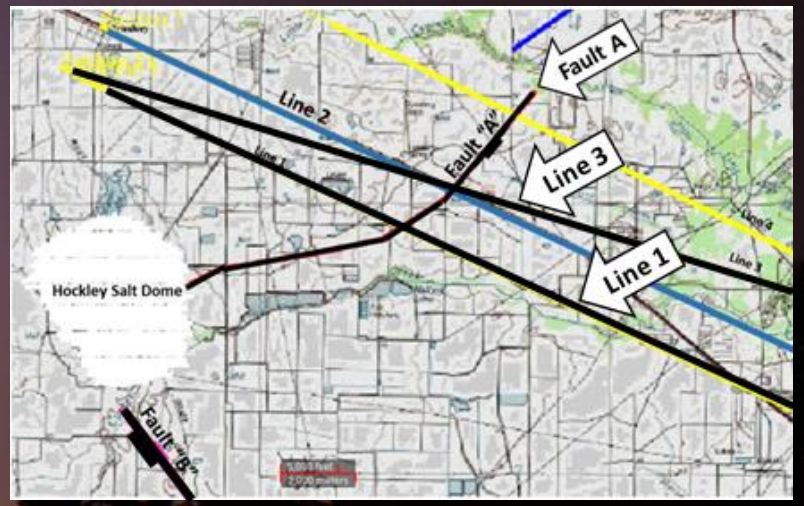


Lines 1 & 3 Tie Fault "A" to Subsurface

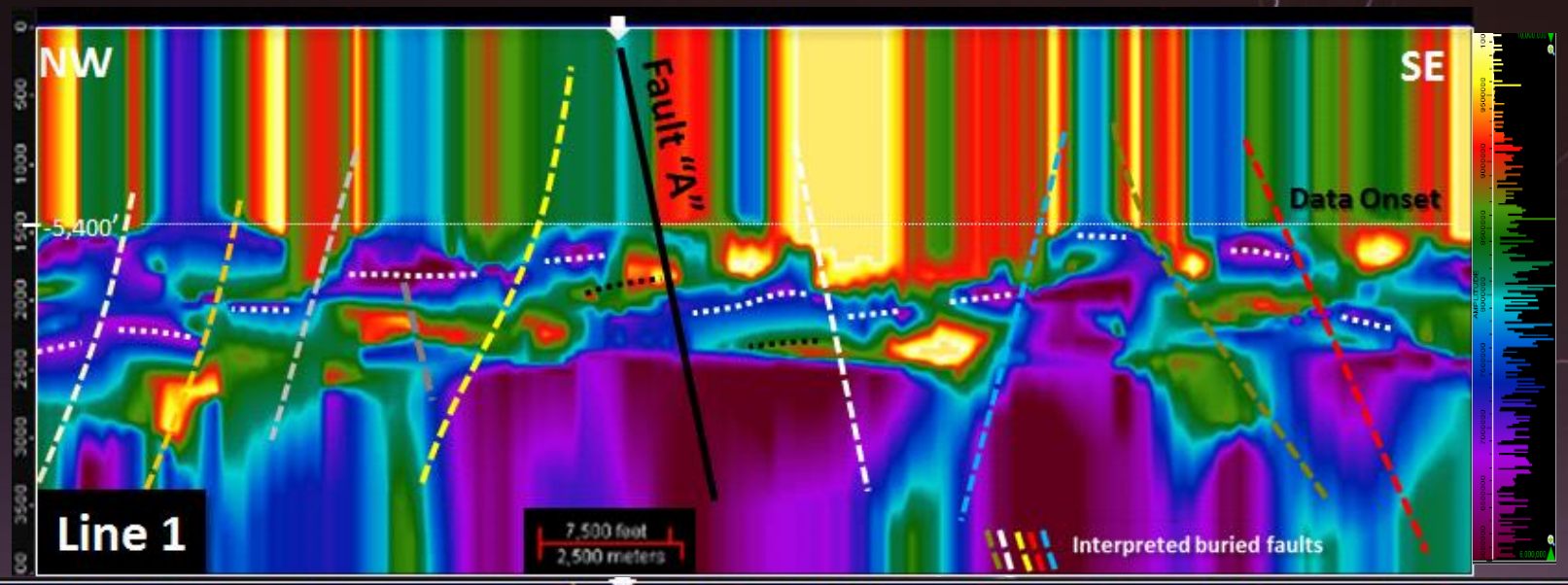


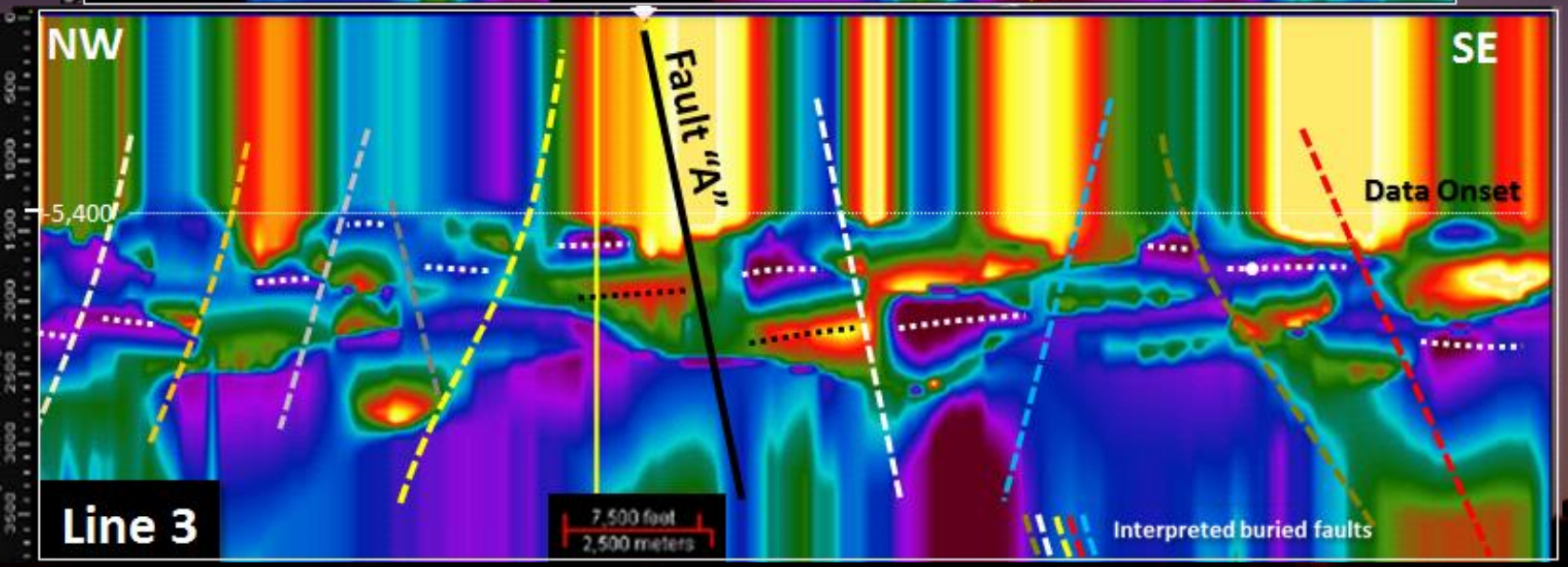


NSEM demonstrates consistency identifying Fault "A'.

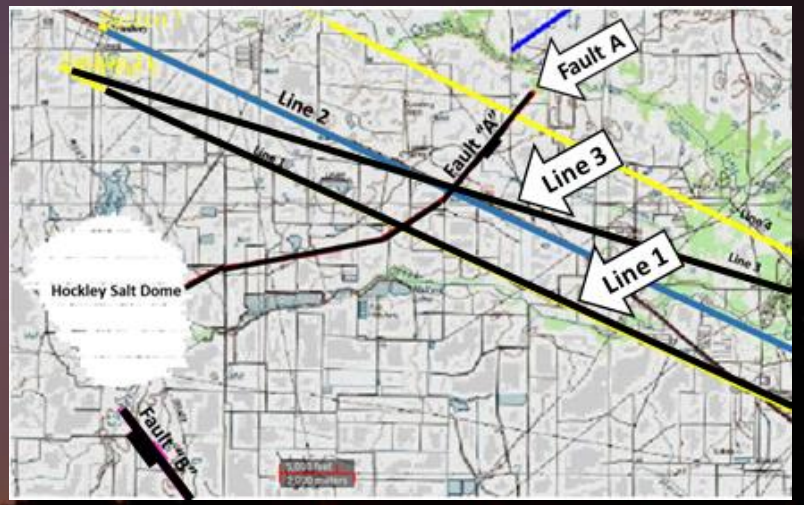


Lines 1 & 3 Also Reveal Additional Faults

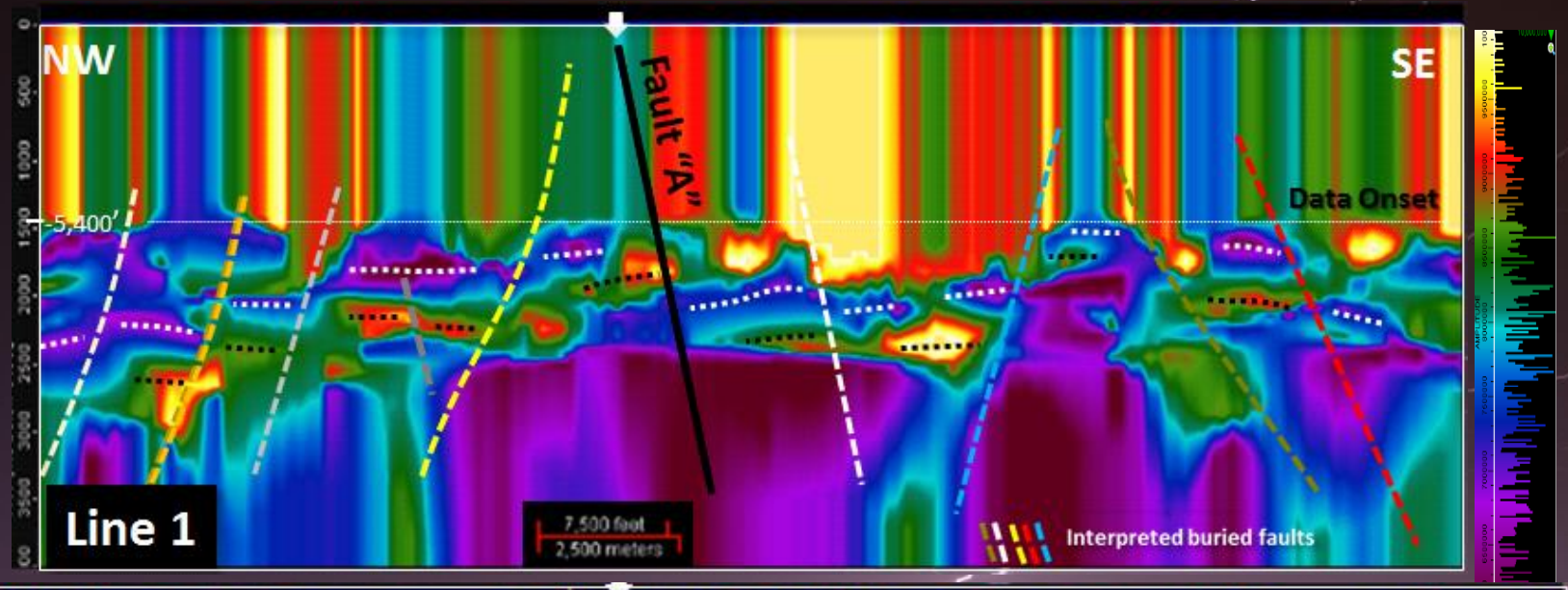


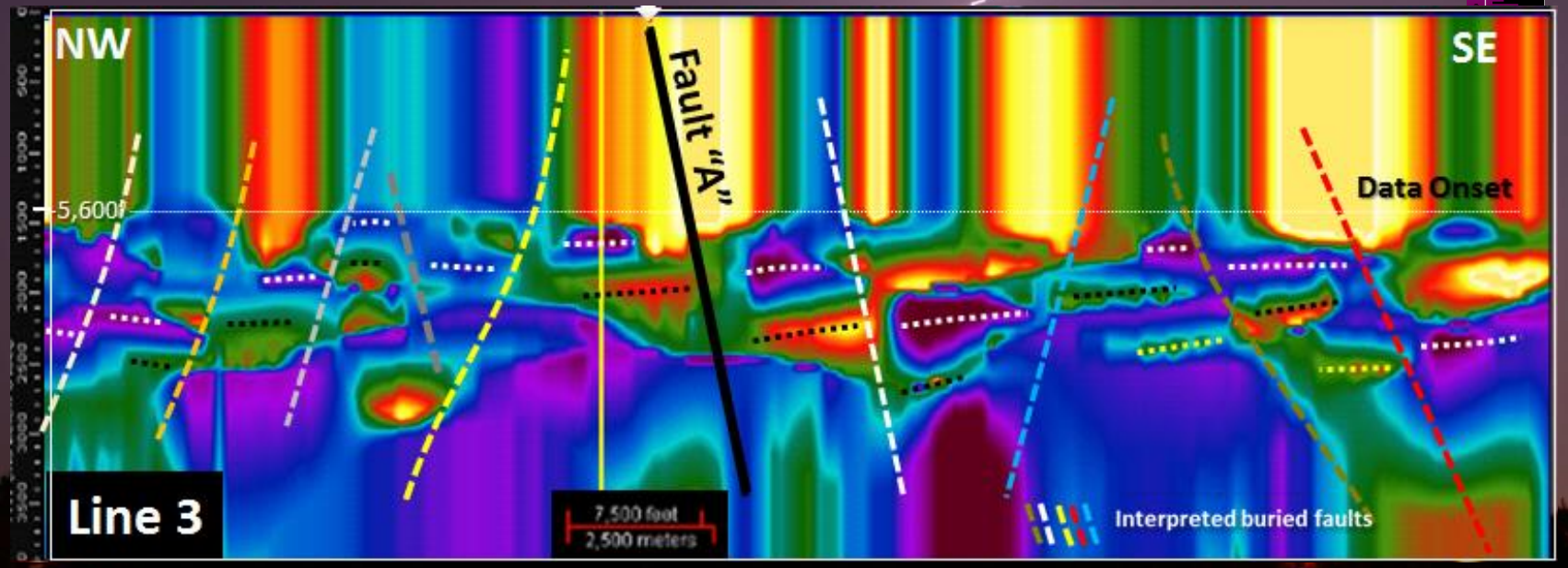


NSEM demonstrates internal consistency mapping nine faults on multiple profiles.



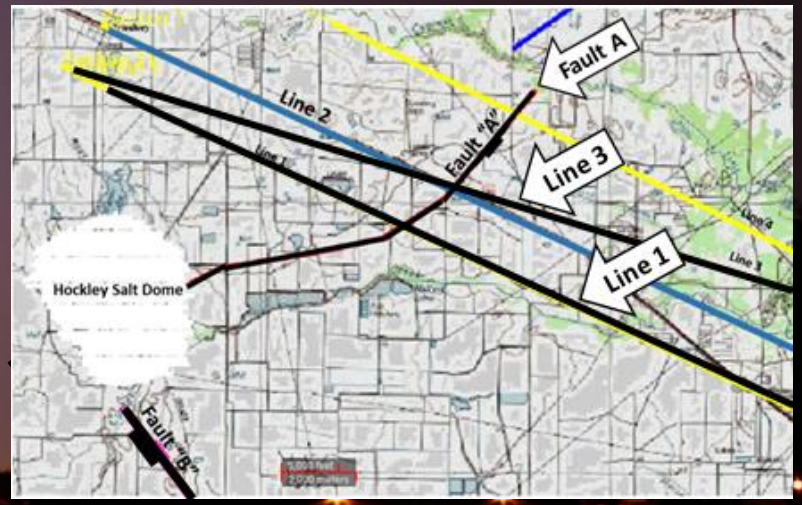
NSEM Builds Reliable Structural Framework





Dotted lines highlight as many as 3 resistivity offsets.

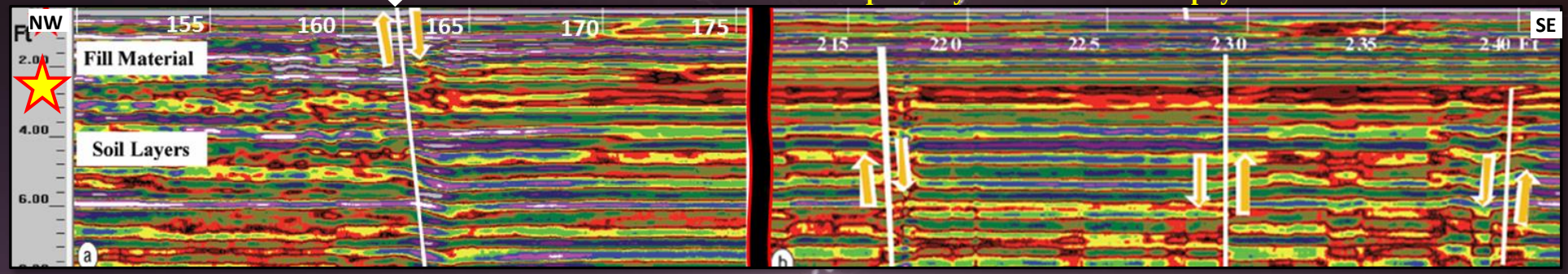
3-D NSEM enables structural and fault plane mapping.

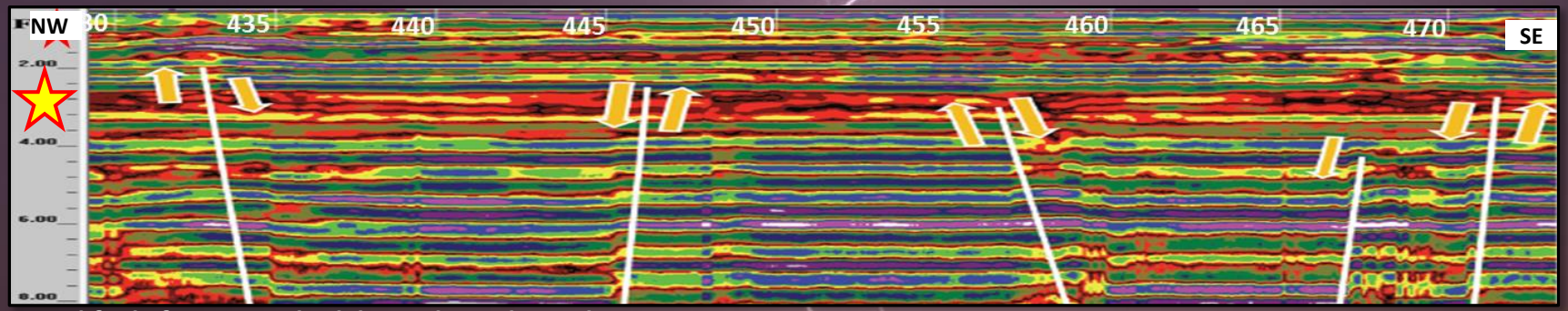


Ground Penetrating Radar
Shallow Micro-Faulting Adjacent to Fault "A"

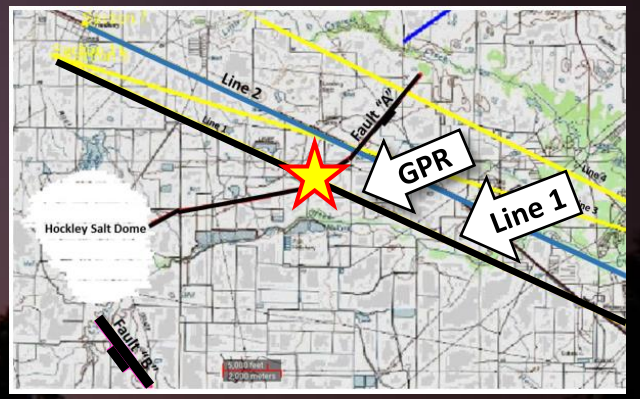
Hockley Fault (Flt. "A")

GPR acquired by Environmental Geophysics Associates



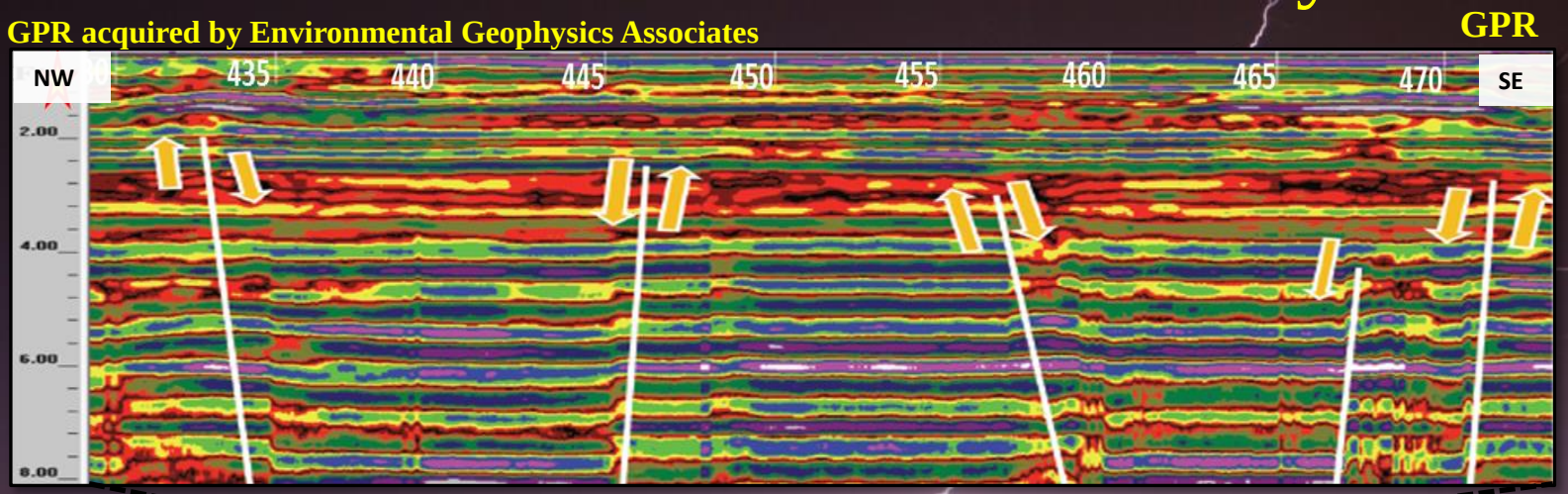


Modified after M. Saribudak, Leading Edge, Feb 2011

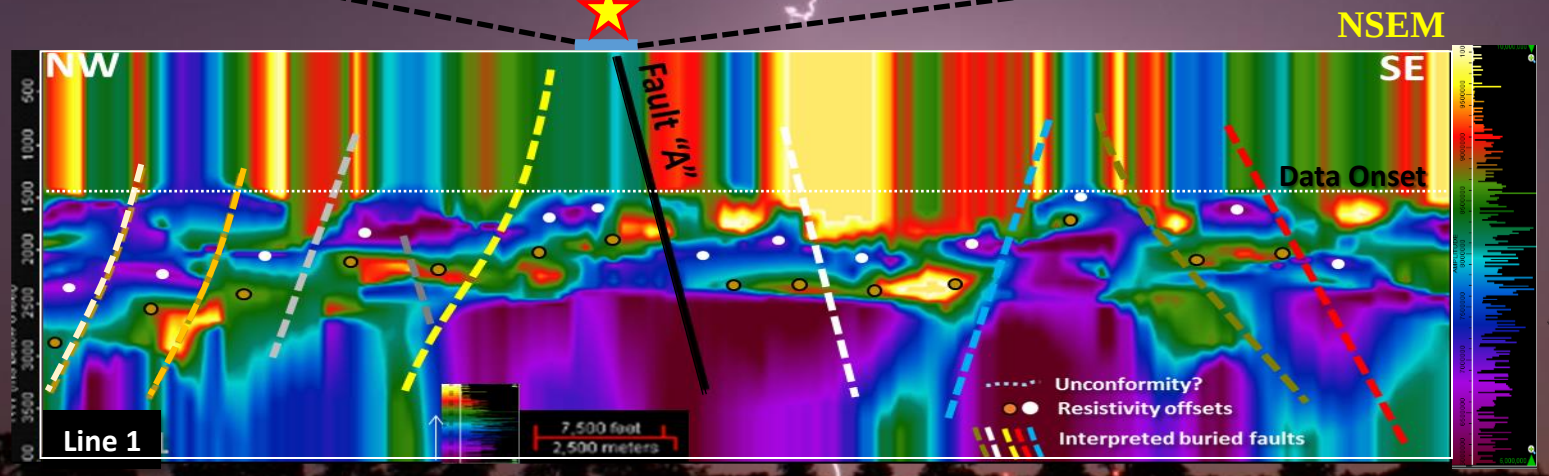


GPR & NSEM
Similar Micro/Macro Structural Styles

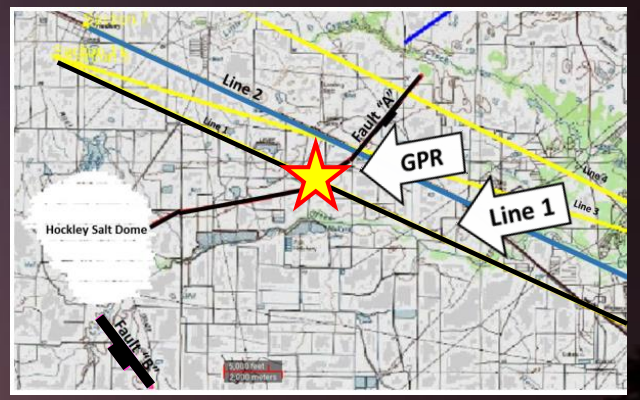
GPR acquired by Environmental Geophysics Associates



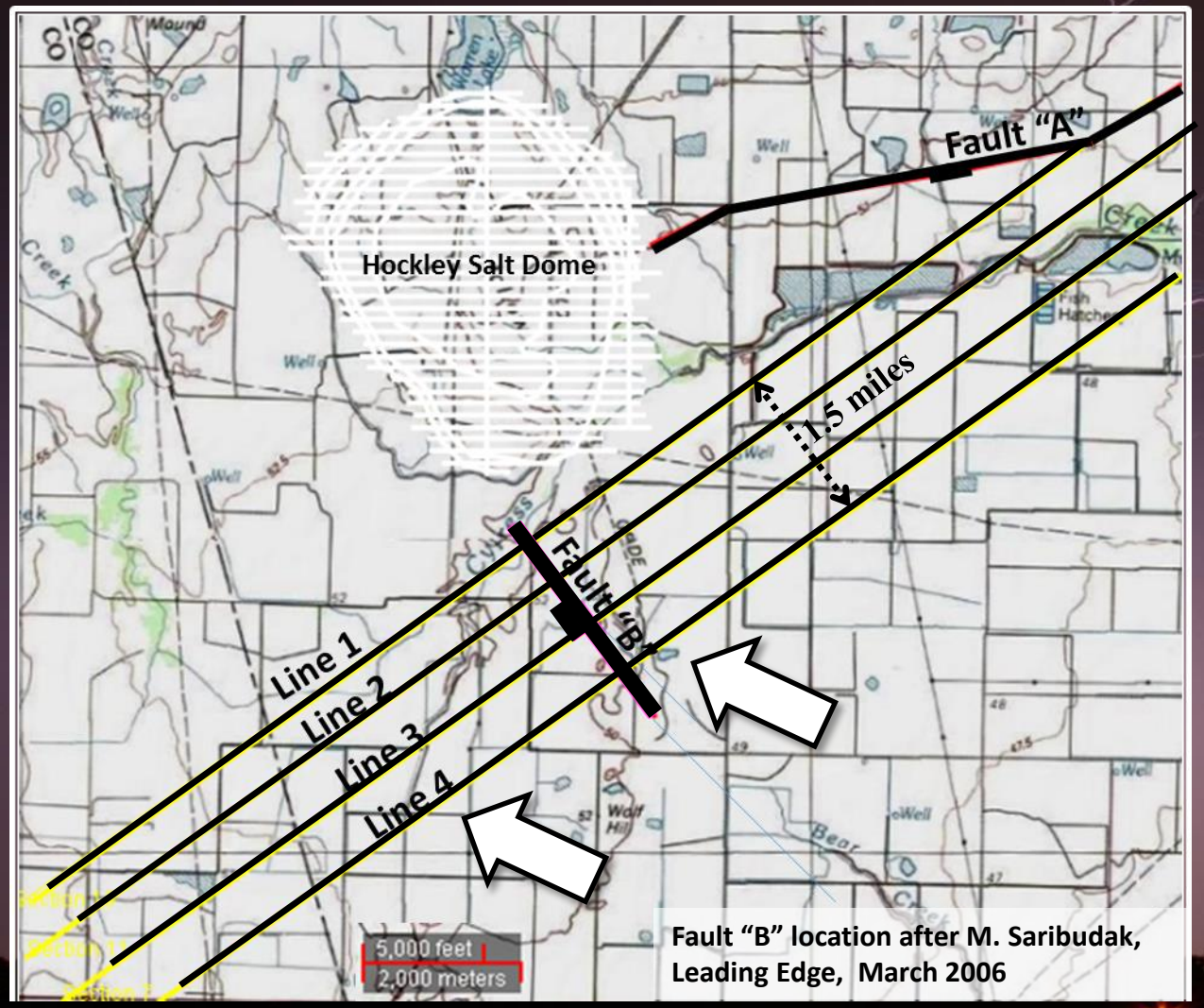
After M. Saribudak, Leading Edge, Feb 2011



Horsts, grabens & half-graben structures identified.



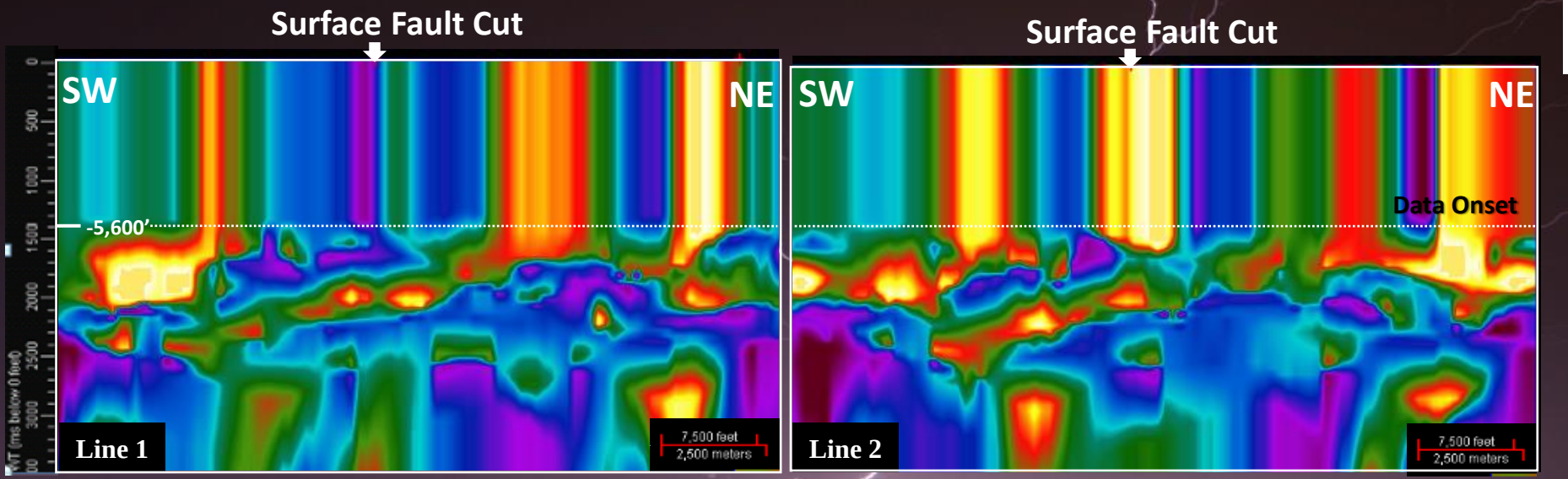
Hockley Radial Fault "B"

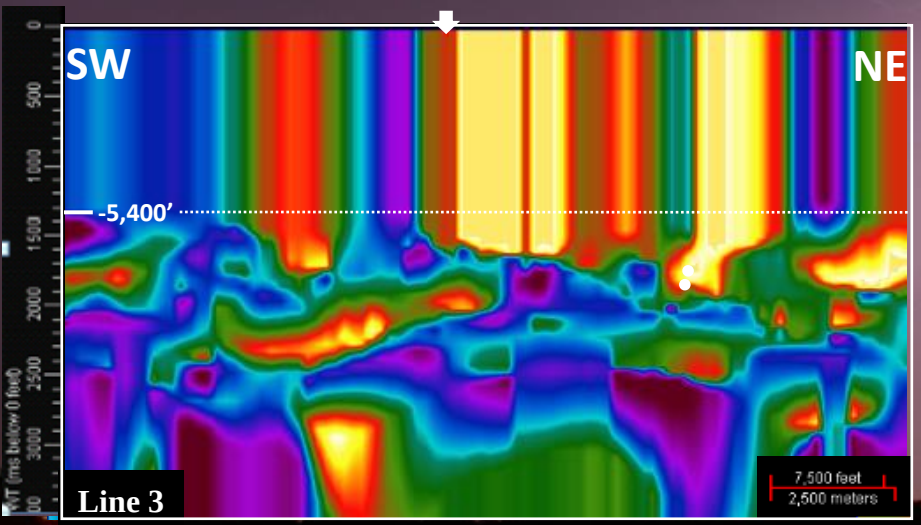


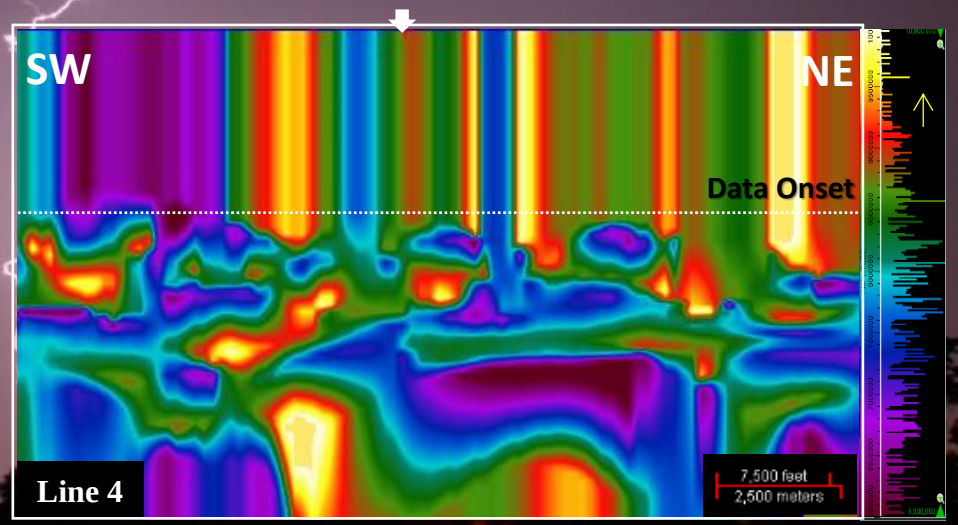
A 1½ mile distance along the Fault "B" trace is sampled with resistivity profiles.

Resistivity Lines 1-4 are displayed on next slide.

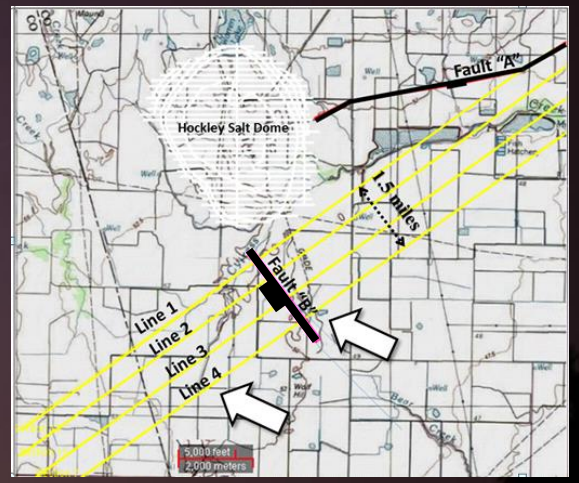
Hockley Radial Fault "B" Lines 1-4



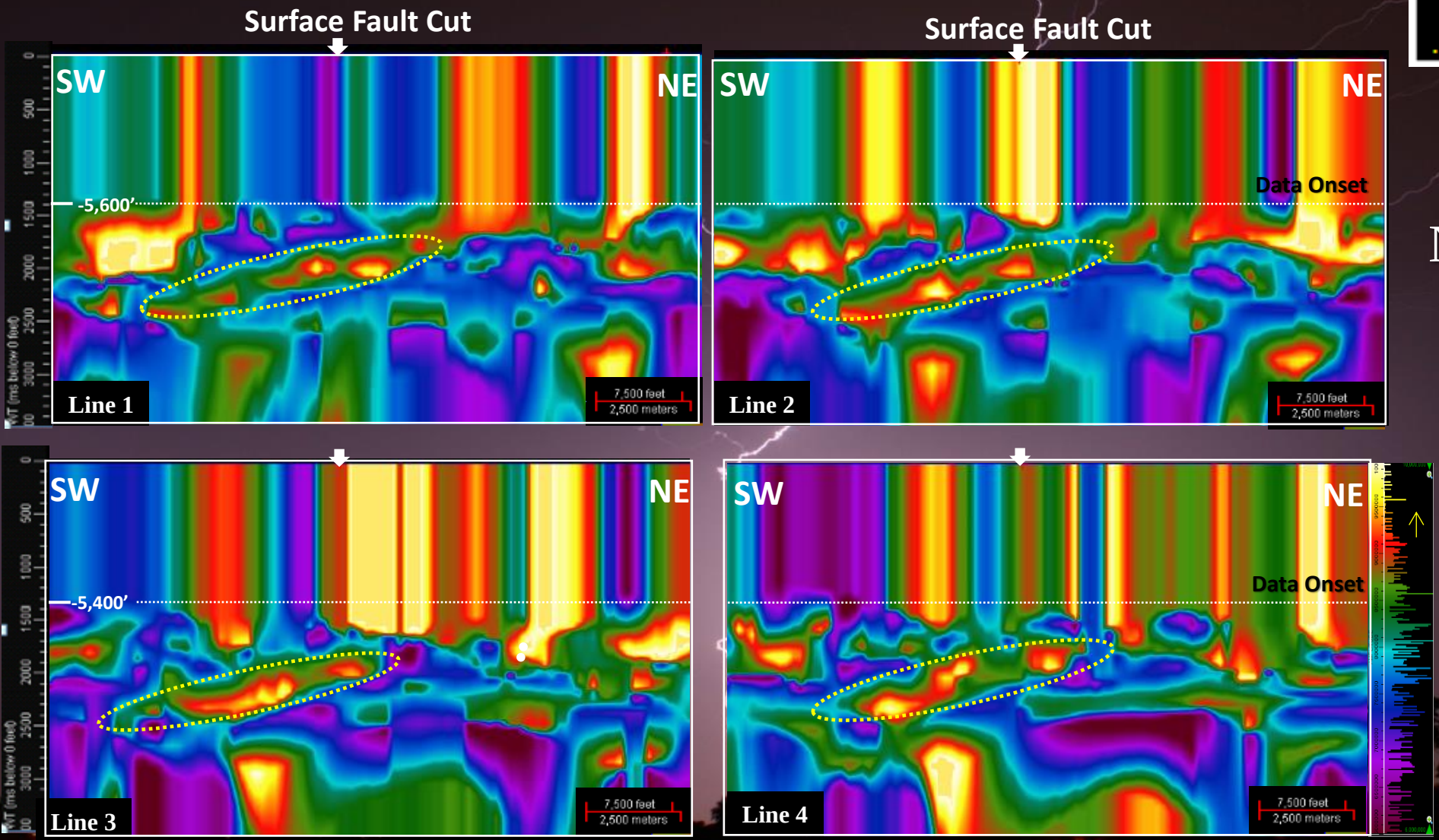




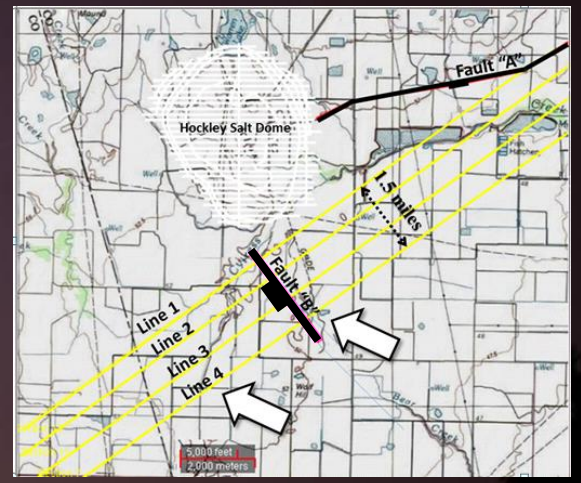
Lines ½ mile apart.
Note similar character.



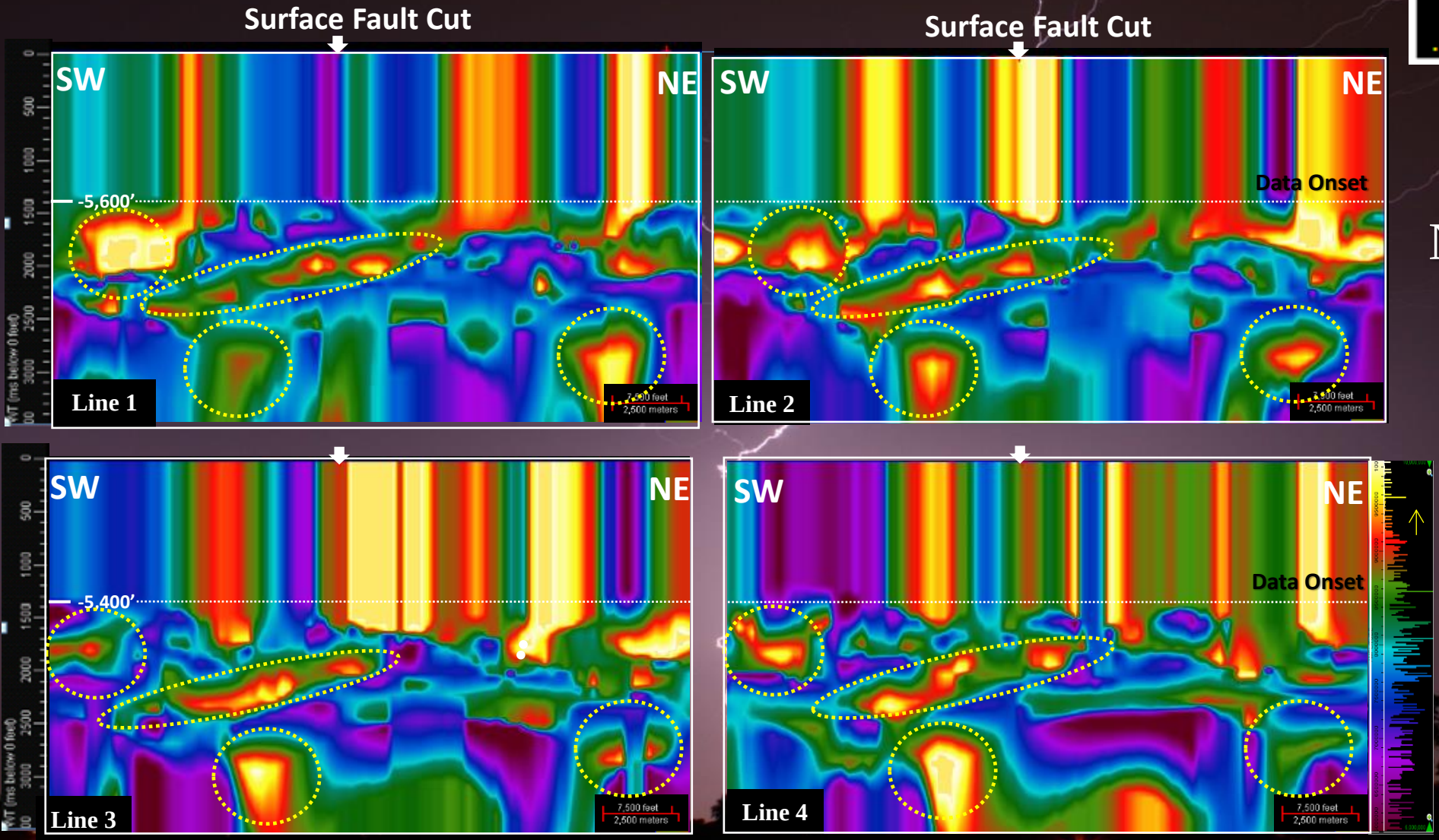
Similar Character Spanning 1.5 Miles



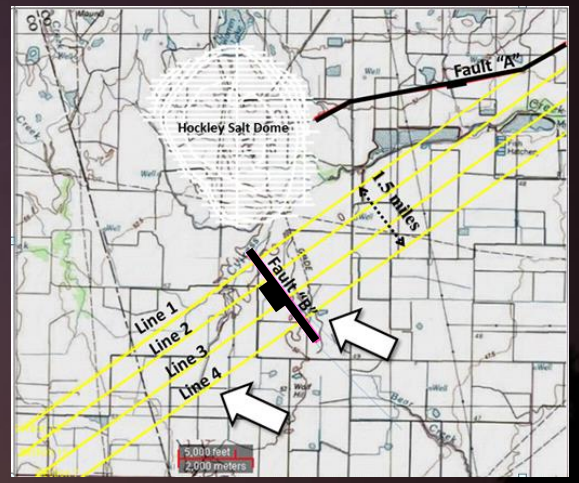
Lines ½ mile apart.
Note similar character.



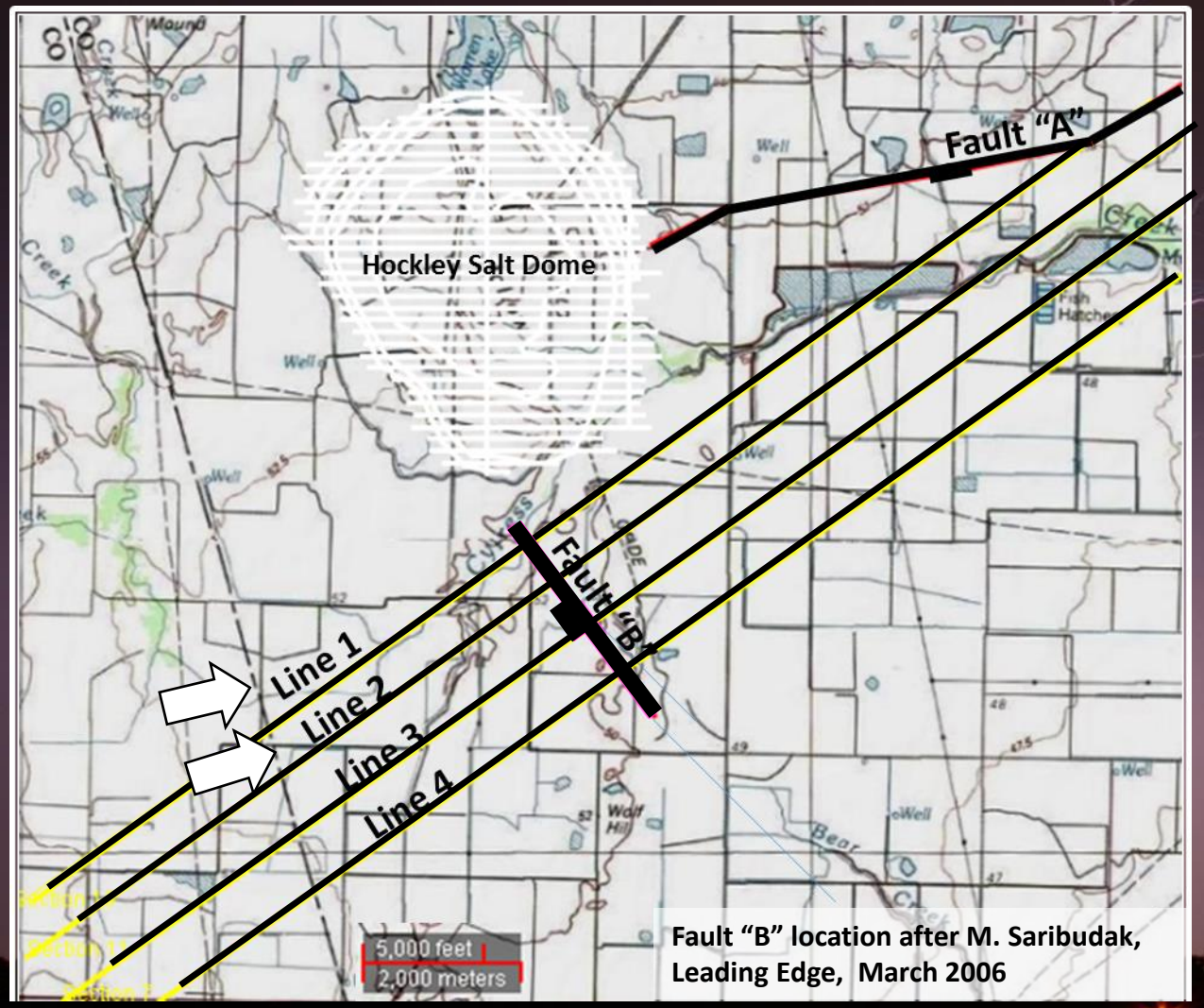
Numerous Features Correlate Line to Line



Lines ½ mile apart.
Note similar character.



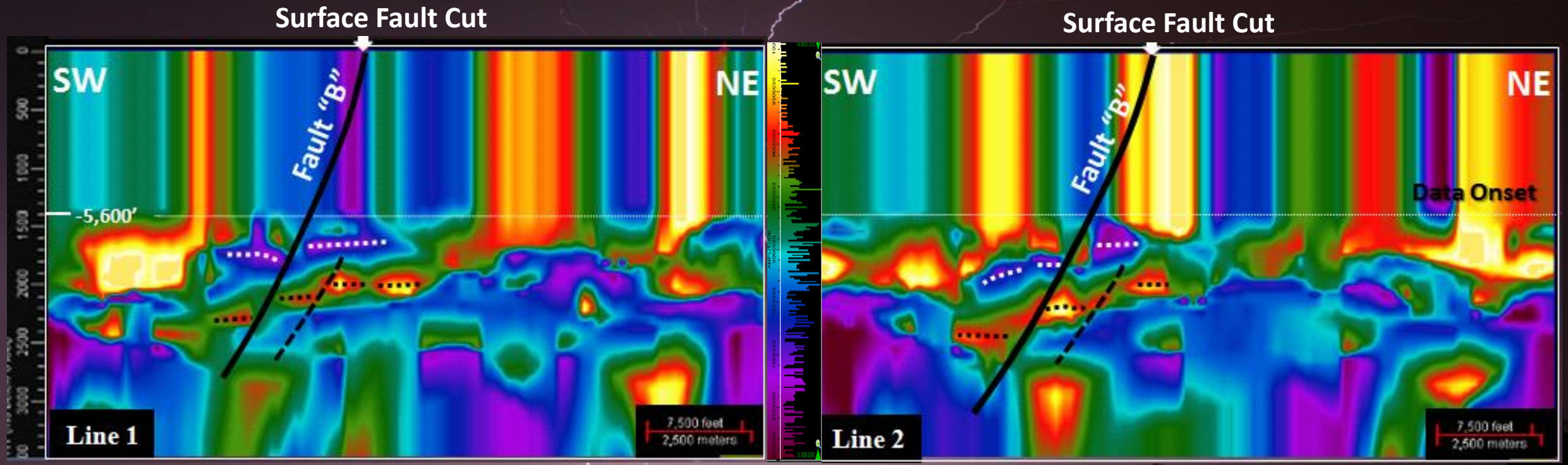
Hockley Radial Fault "B"



Fault "B" location after M. Saribudak, Leading Edge, March 2006

Resistivity Lines 1 & 2 displayed on next slide.

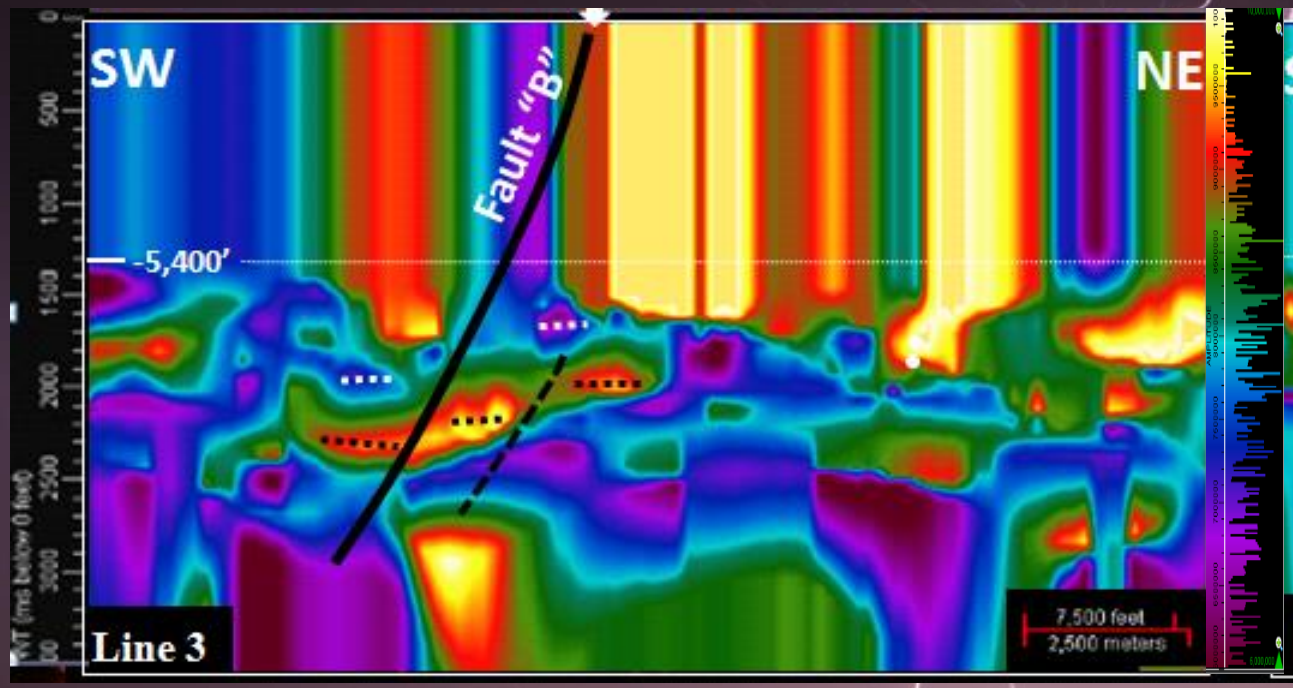
NSEM Ties Surface Fault "B" to Subsurface



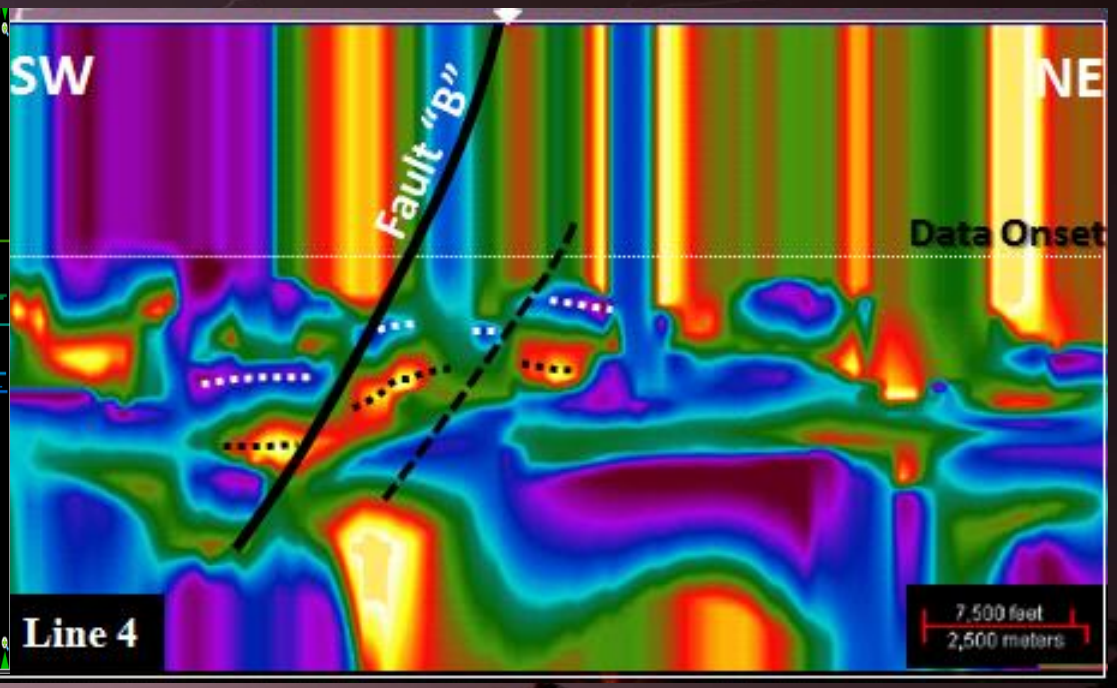
Lines 1 & 2 show consistent subsurface fault criteria.

NSEM Ties Surface Fault "B" to Subsurface

Surface Fault Cut

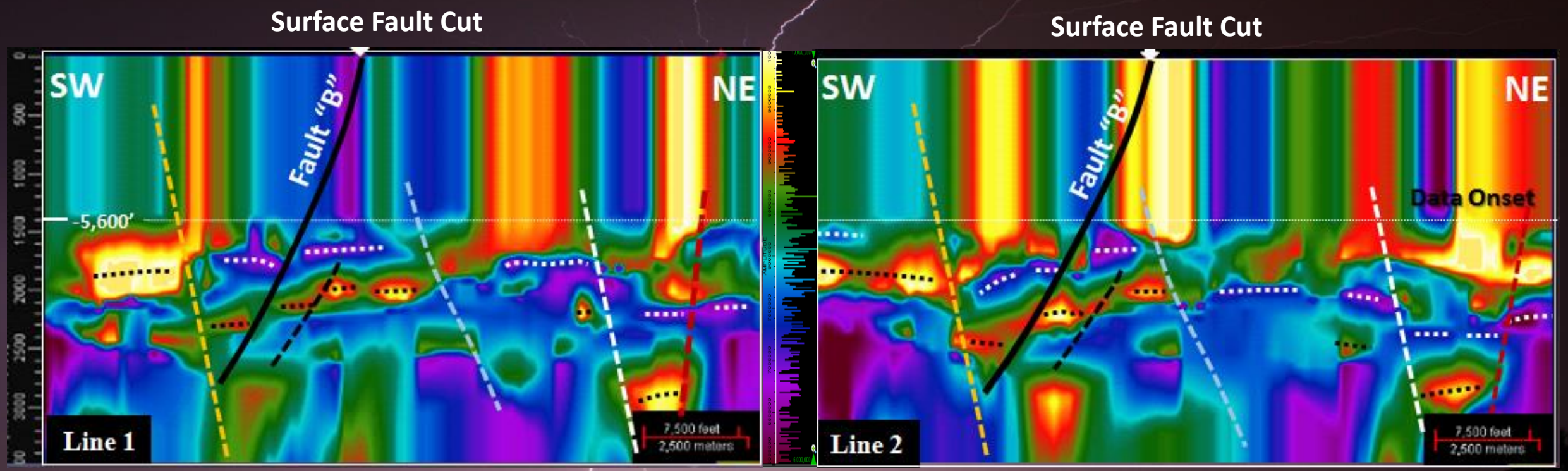


Surface Fault Cut



Lines 3 & 4 show similar consistent subsurface fault criteria.

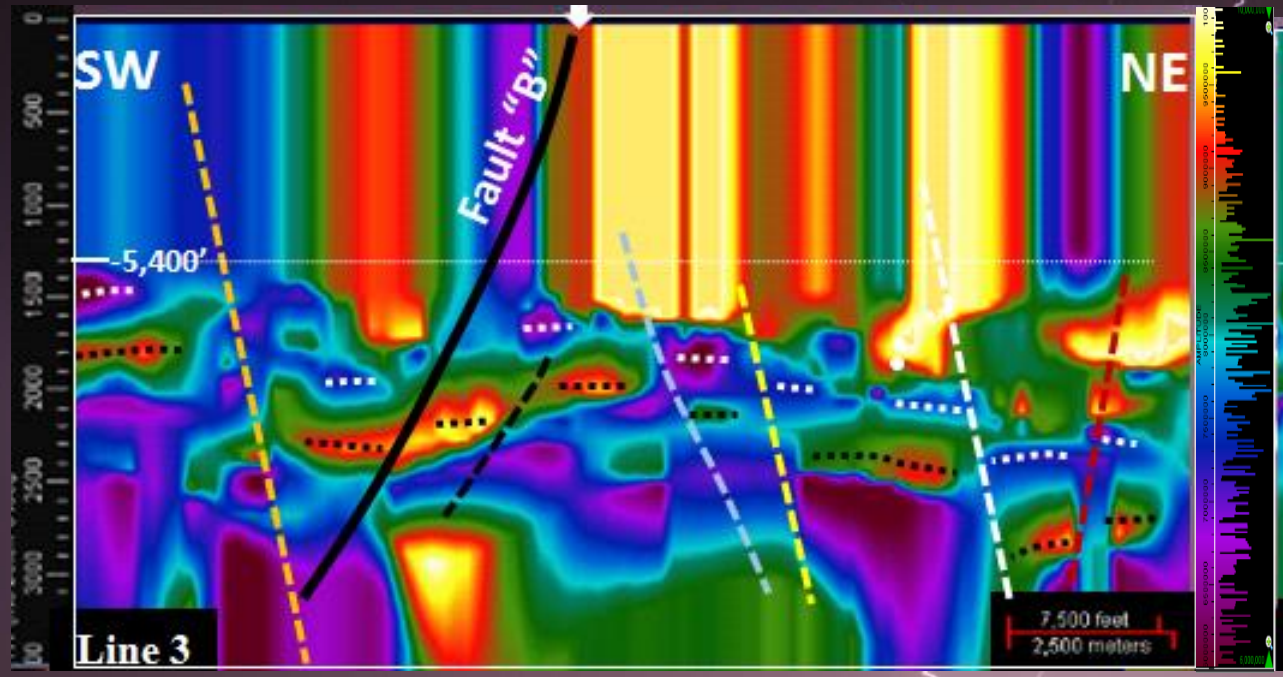
NSEM Shows Additional Faulting
Lines 1 & 2



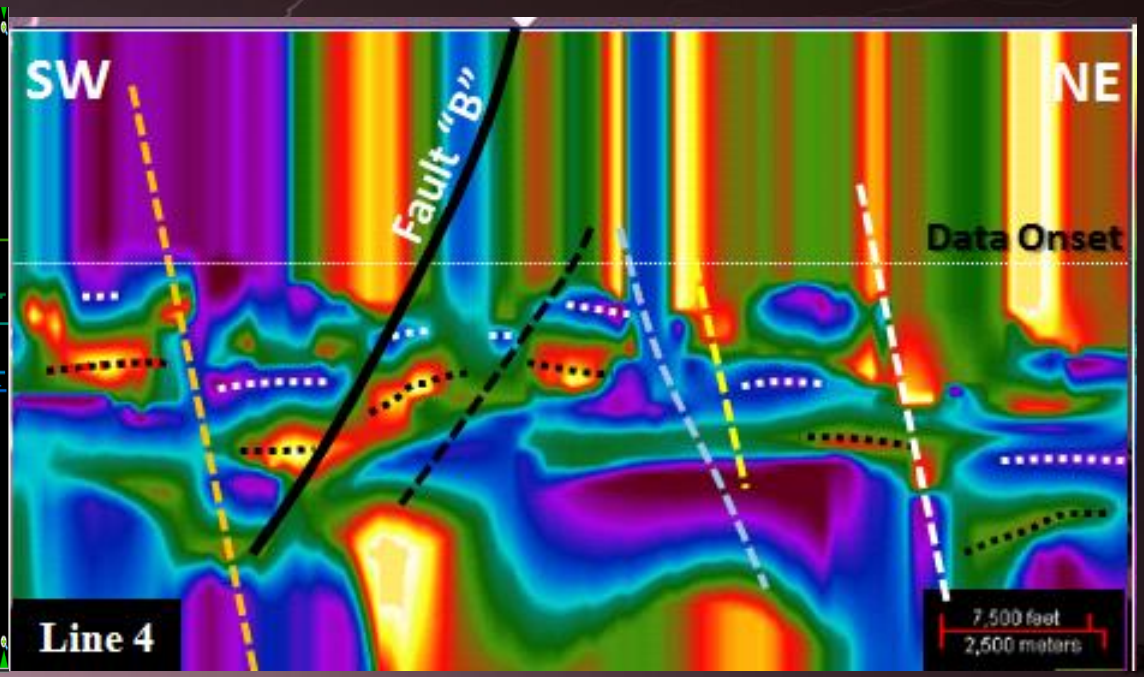
Six geologically reasonable faults consistently interpreted on both lines.

NSEM Shows Additional Faulting
Lines 3 & 4

Surface Fault Cut

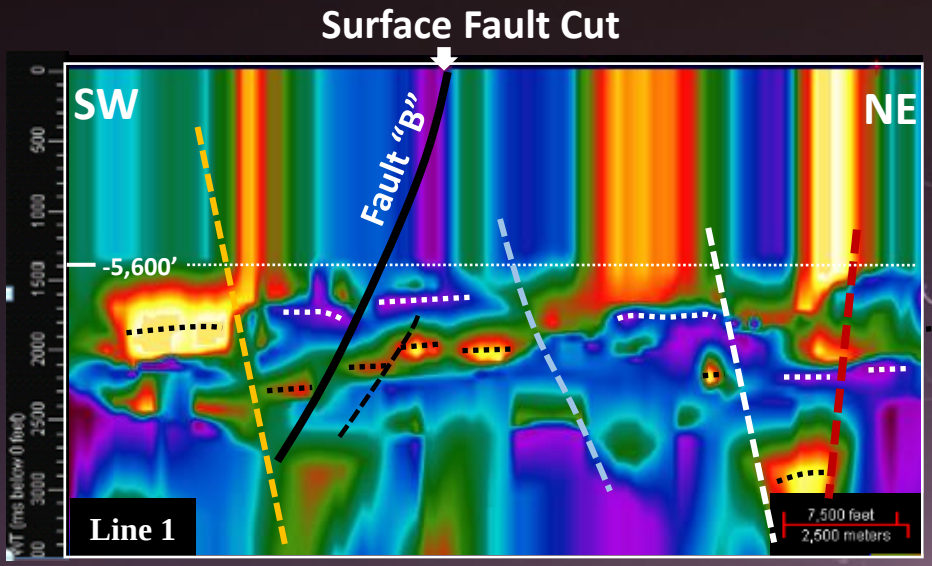


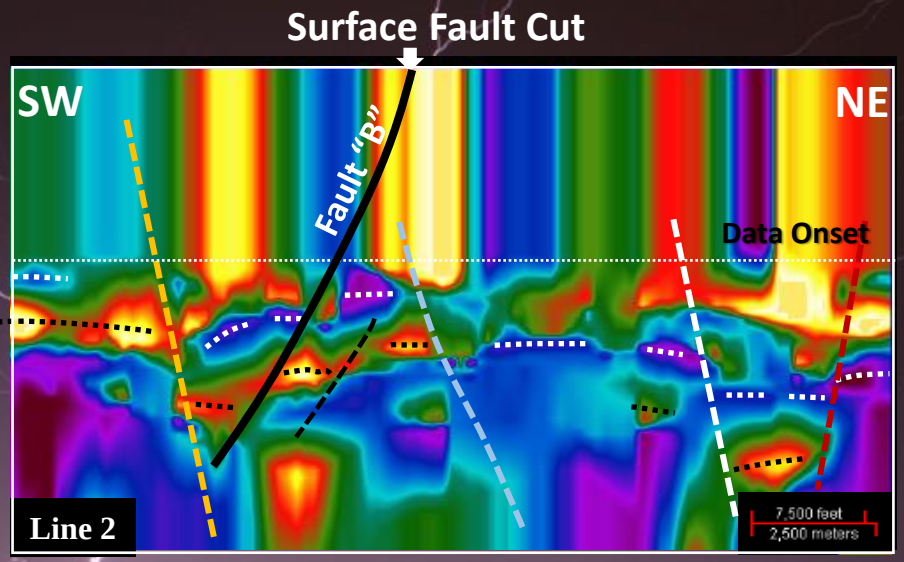
Surface Fault Cut

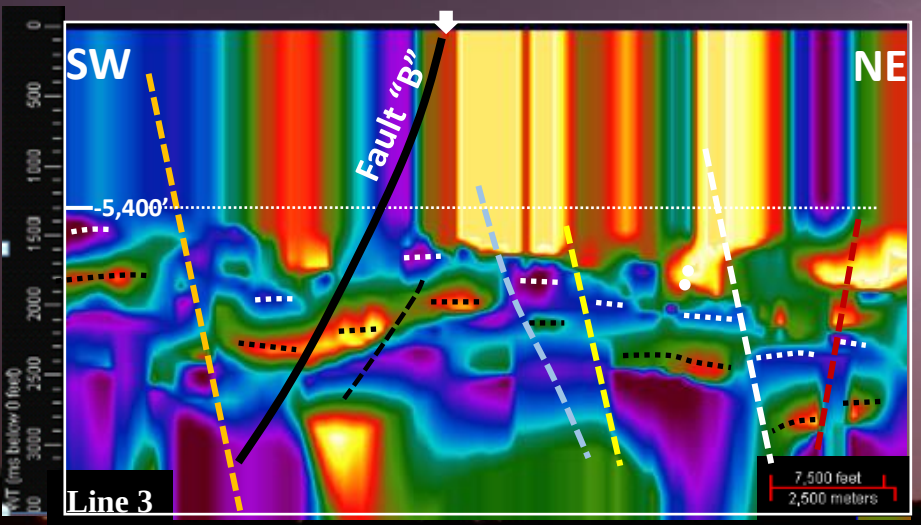


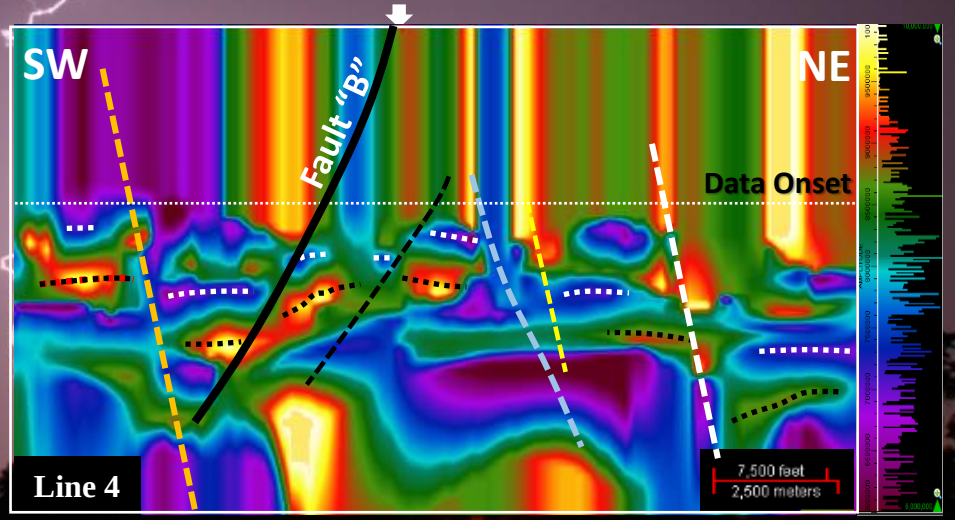
The same fault patterns on lines 1 & 2 can be interpreted on lines 3 & 4 above

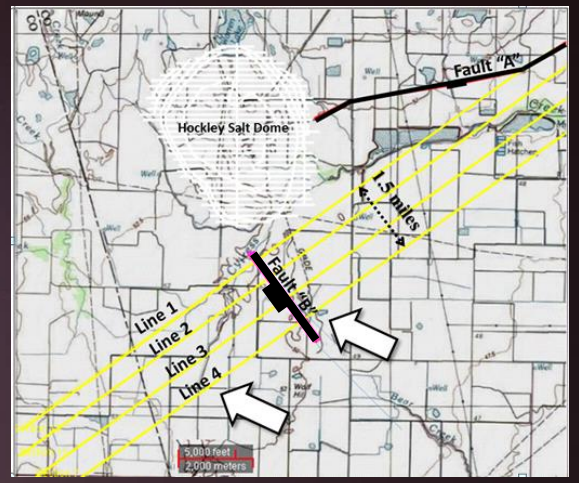
NSEM Shows Consistent Interpretation



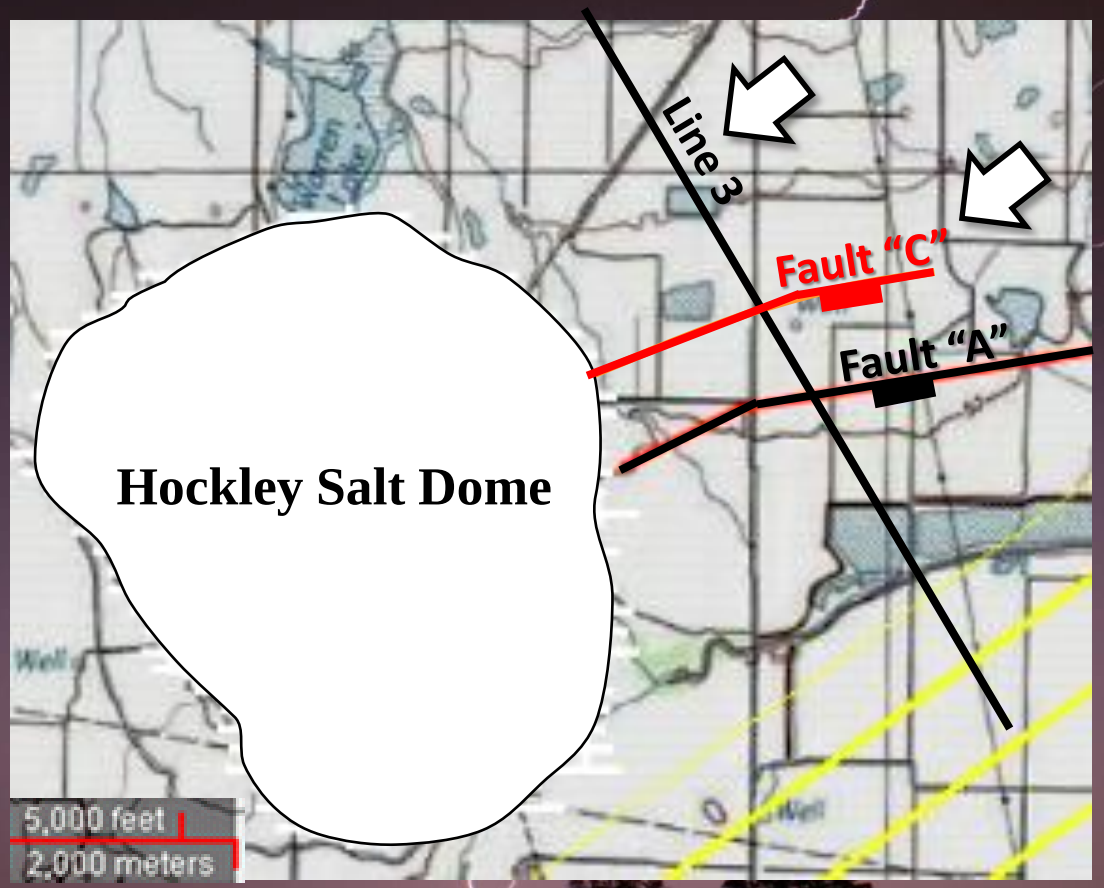






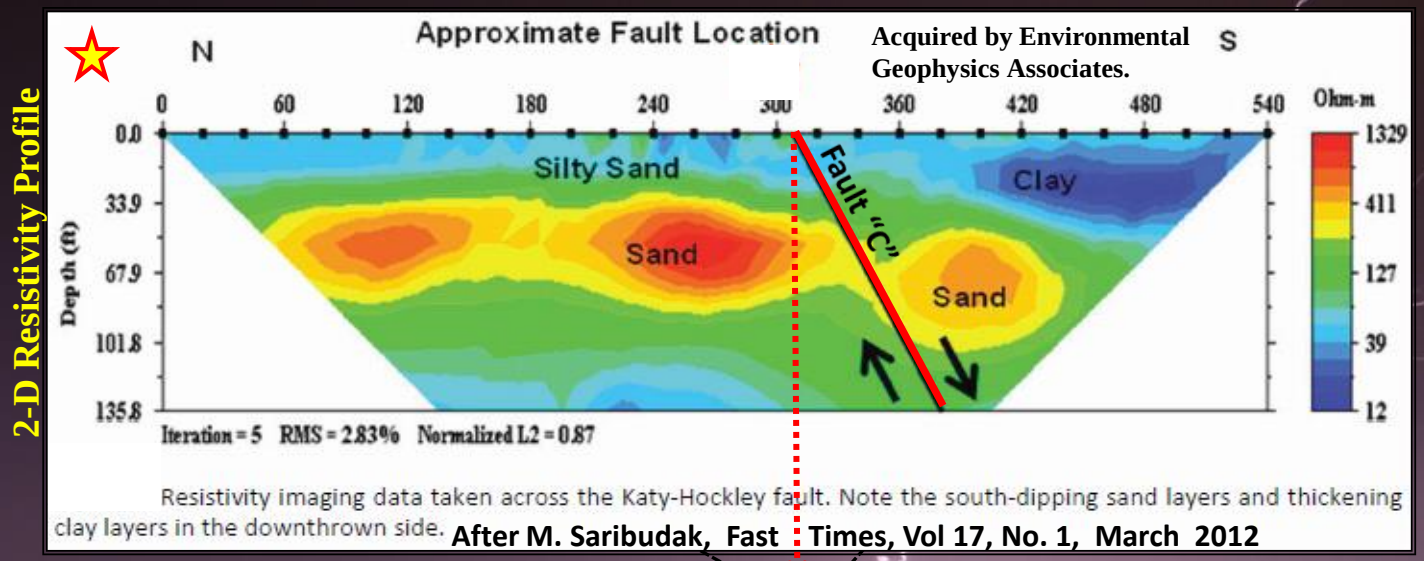


Hockley Radial Fault "C"

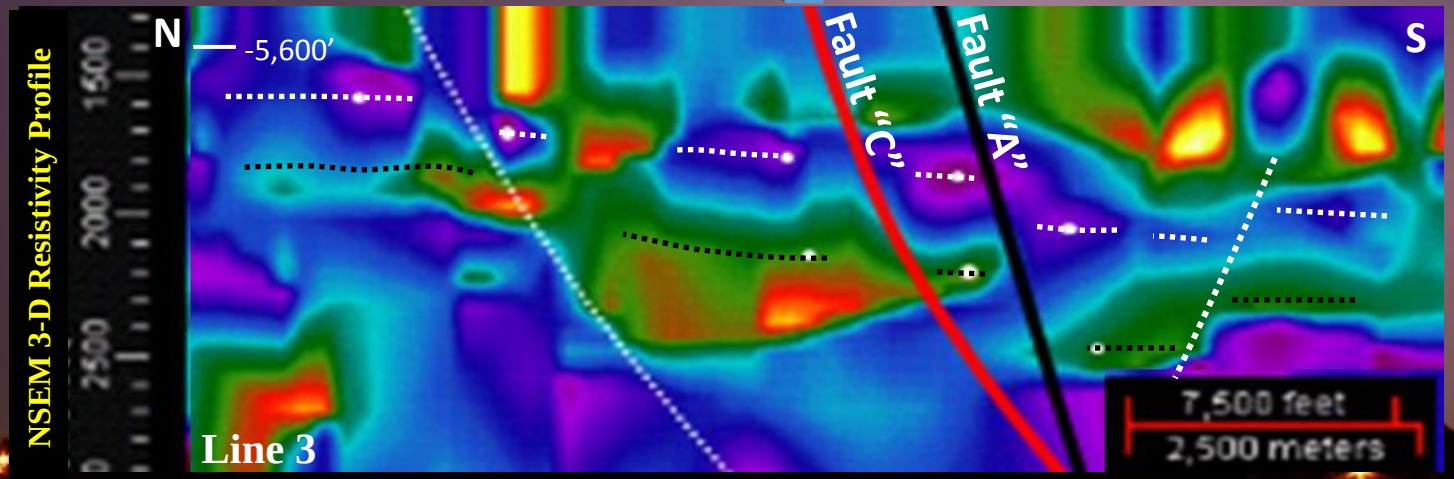


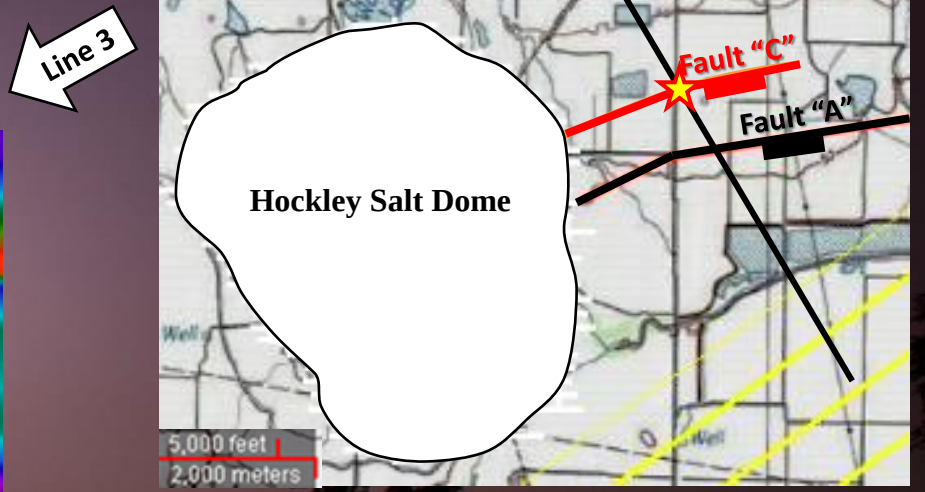
Apparent resistivity profile "Line 3" displayed next.

NSEM Ties Fault "C" to Subsurface



NSEM resistivity profile duplicates 2-D resistivity fault signature & ties Faults "A" and "C".





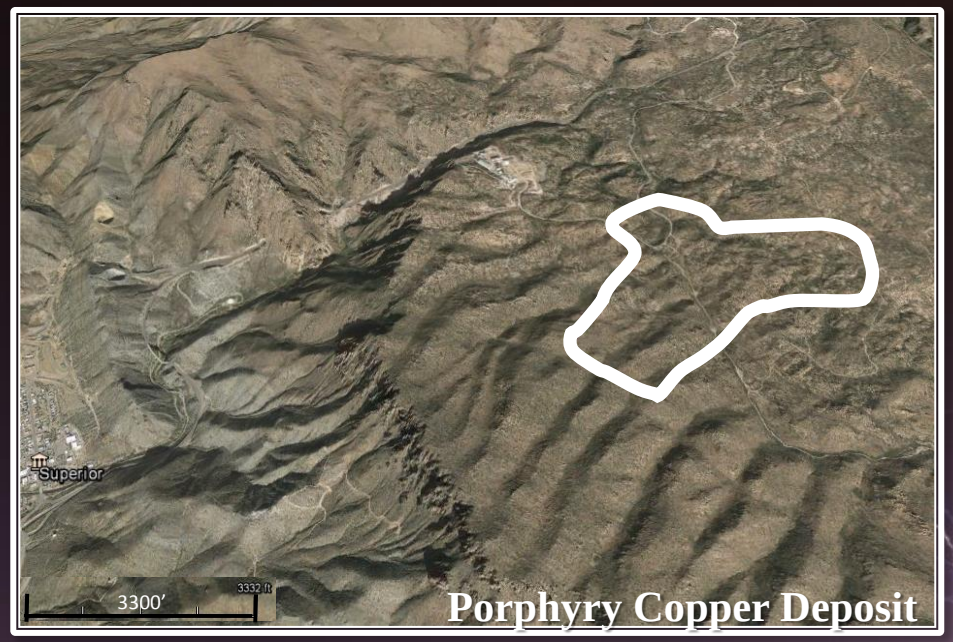
Observations

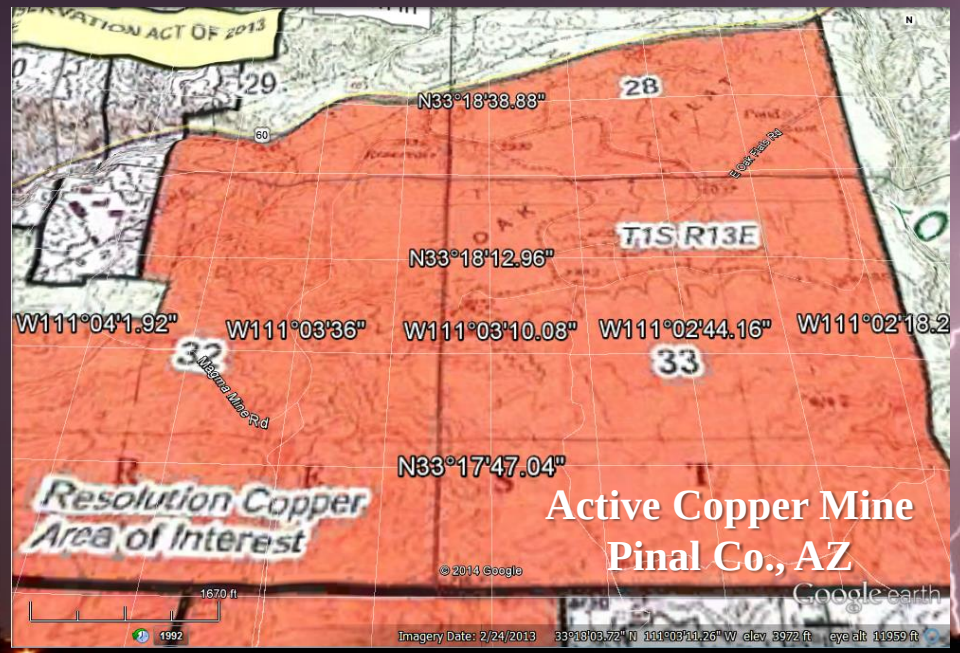
- 3-D NSEM resistivity data was able to tie surface faults and extend fault interpretations to deeper than 5,600’.
- 3-D NSEM fault criteria was credible and at least as good as conventional 2-D resistivity imaging.
- In some cases NSEM could identify two to three resistivity layers offset across the faults.

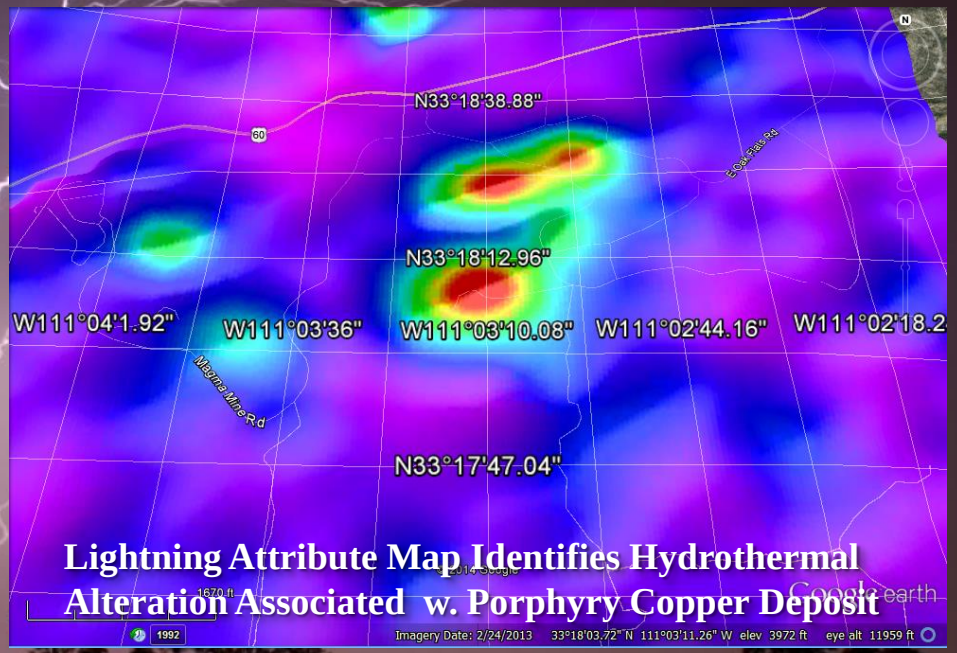
Hockley Fault Conclusions

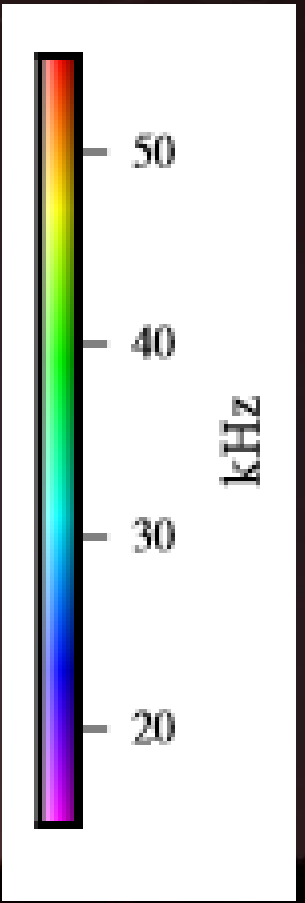
- 3-D NSEM resistivity can be interpreted similar to 3-D seismic data to build structural frameworks.
- 3-D NSEM resistivity appears capable of mapping faults, generating leads and delineating areas of interest for follow-up seismic evaluation.

NSEM Correlates To Rock Properties: Mineral Exploration

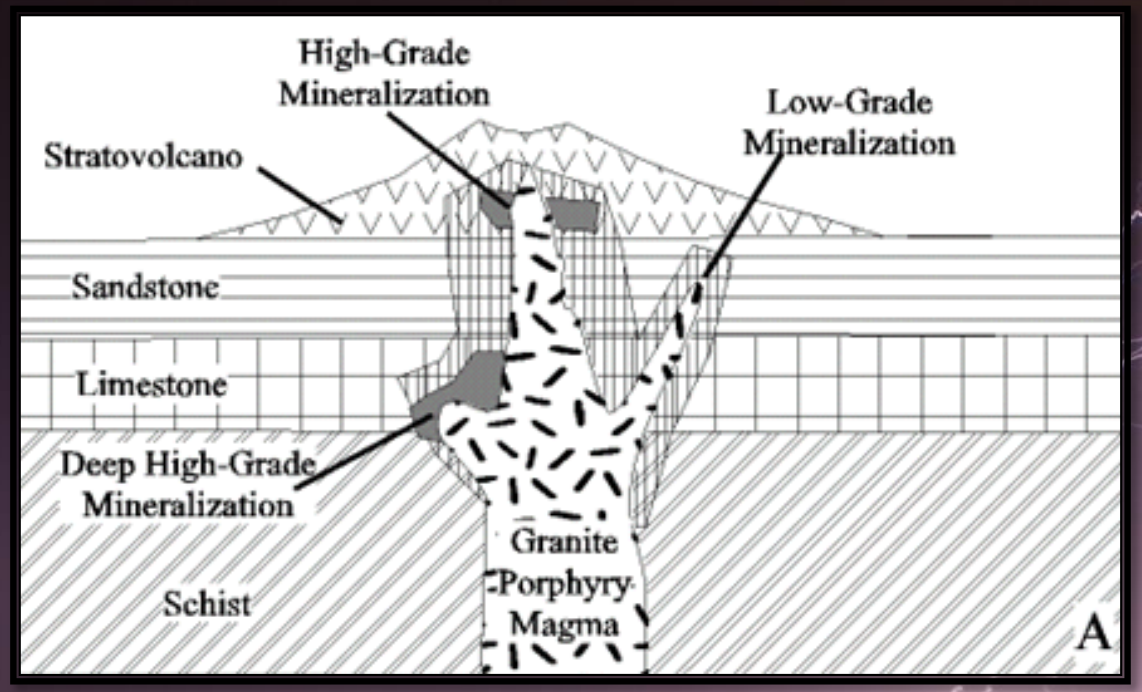






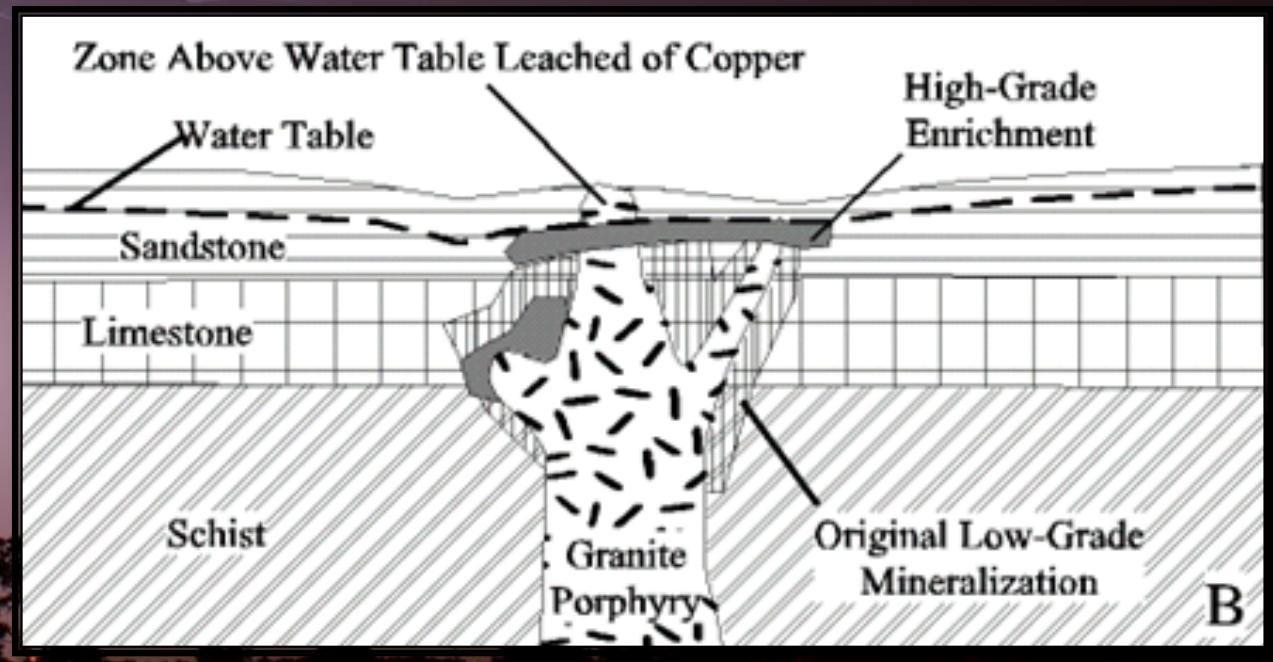


Formation of a Porphyry Copper Deposit



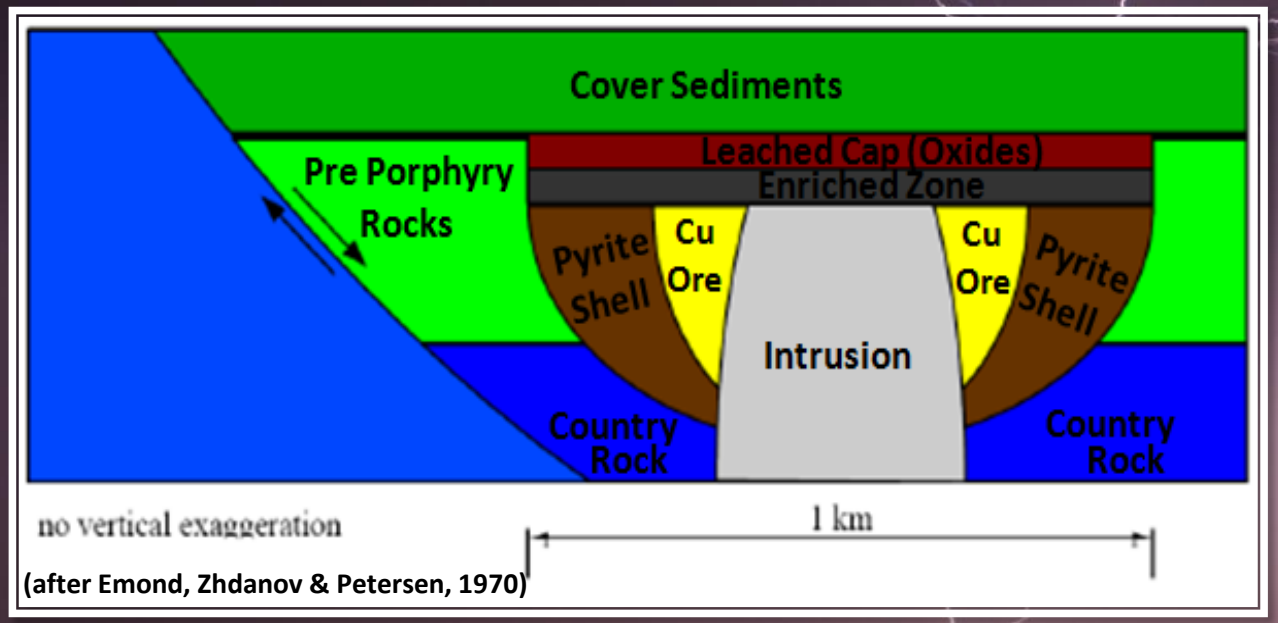
- Magma chamber feeds upward intrusion of molten rock into shallow sedimentary rocks.
- Magma & associated hot mineral-rich fluids come in contact with host rocks & generate chemical/mineral changes creating low-grade copper mineralization.

- Erosion strips away overburden subjecting low-grade mineralized areas to weathering.
- Rainwater leaches Cu and redeposits it below at the water table, creating concentrations of high-grade Cu deposits.



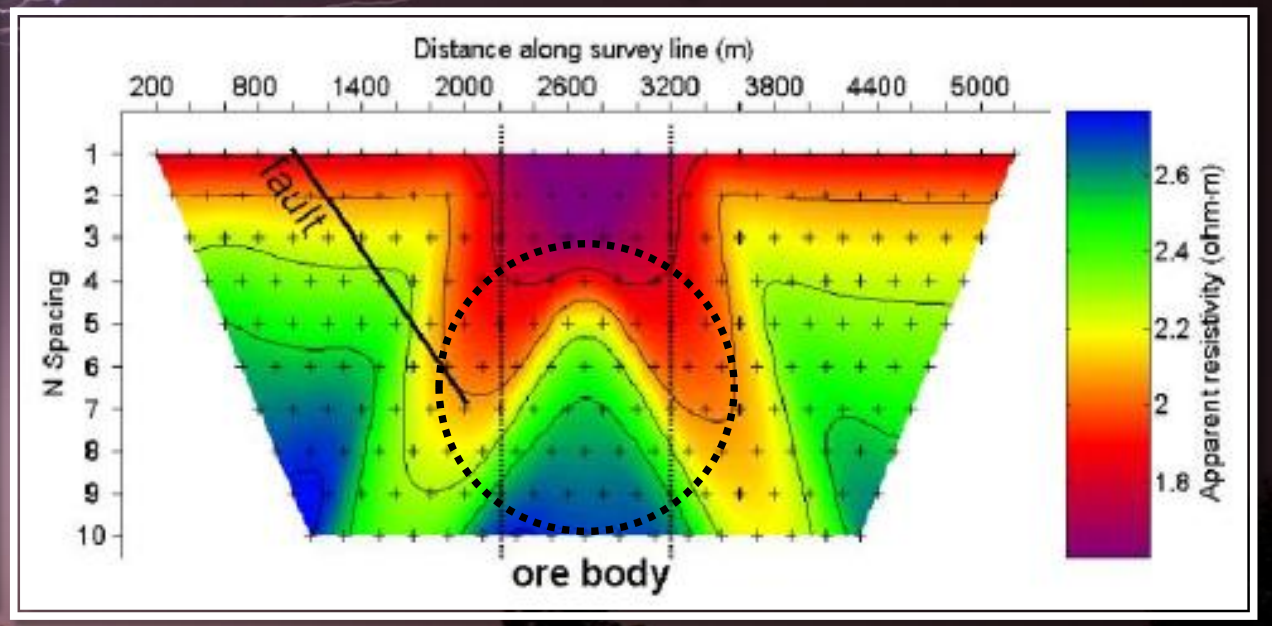
Simplified Porphyry Copper Deposit Model

Typical Mineral Zones of a Porphyry Deposit



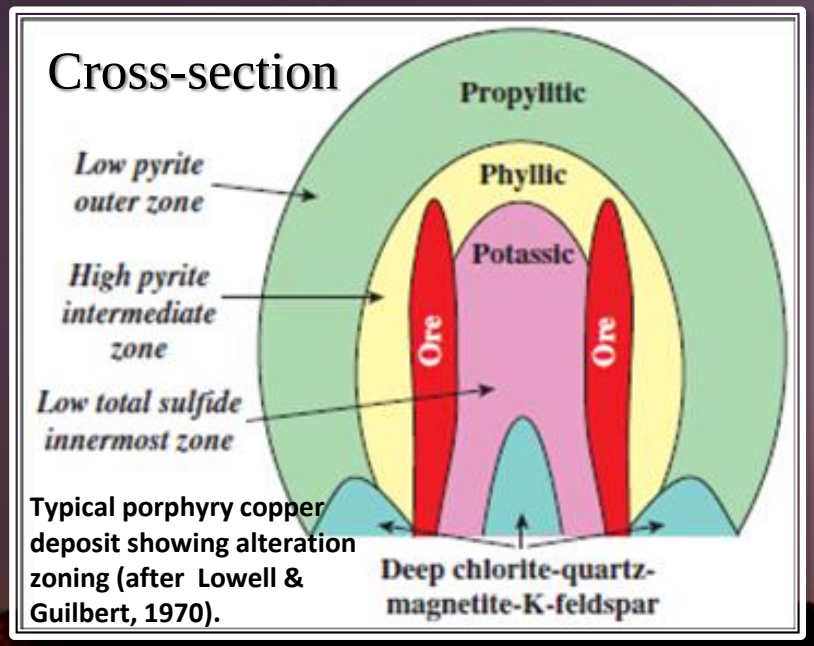
(after Emond, Zhdanov & Petersen, 1970)

Conductivity anomaly surrounds more resistive ore body in center.

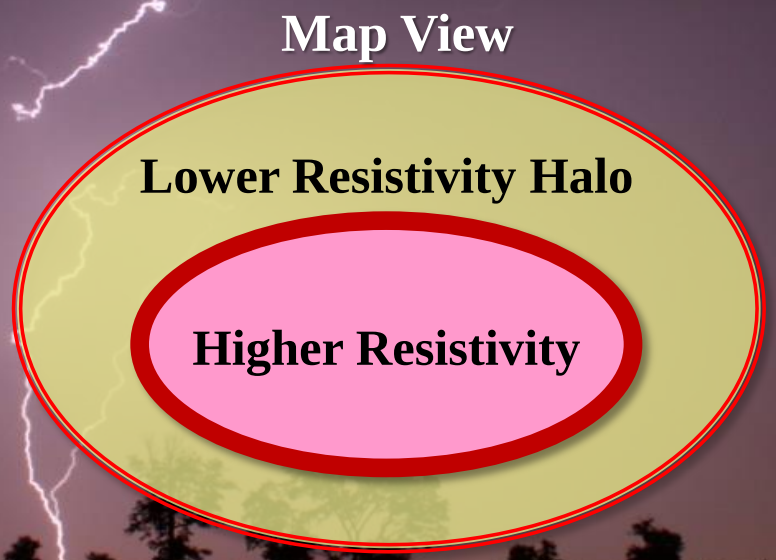


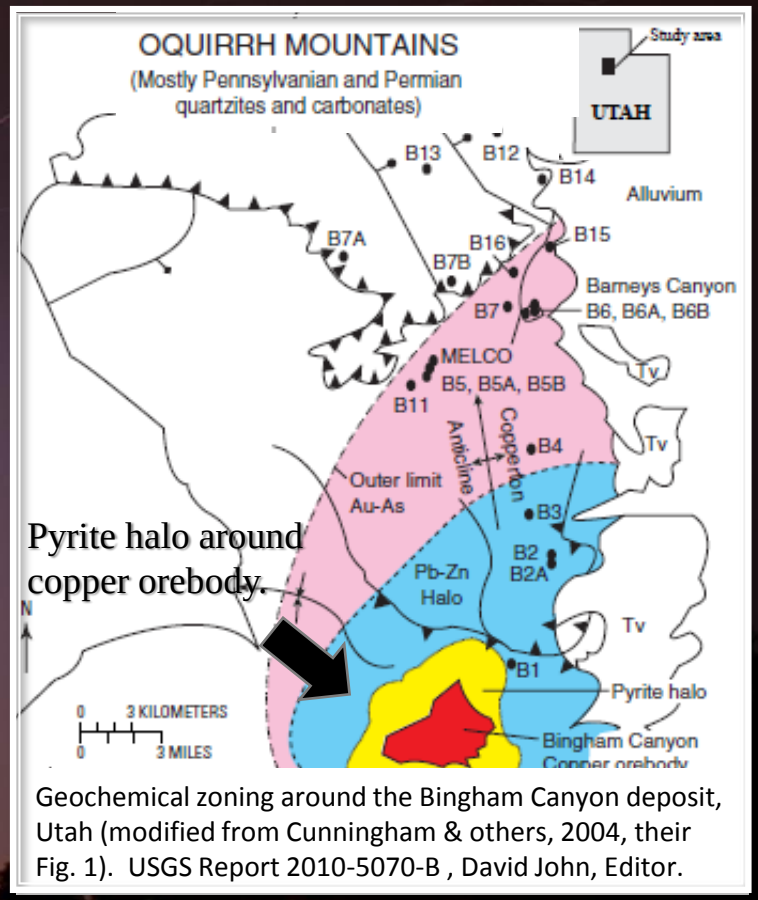
Porphyry Copper Deposit Signature

- Multiple igneous intrusions present.
- Contact metamorphism/alteration halos.
- Inner high resistivity zone partially or completely enclosed by outer conductive zone.



Typical porphyry copper deposit showing alteration zoning (after Lowell & Guilbert, 1970).

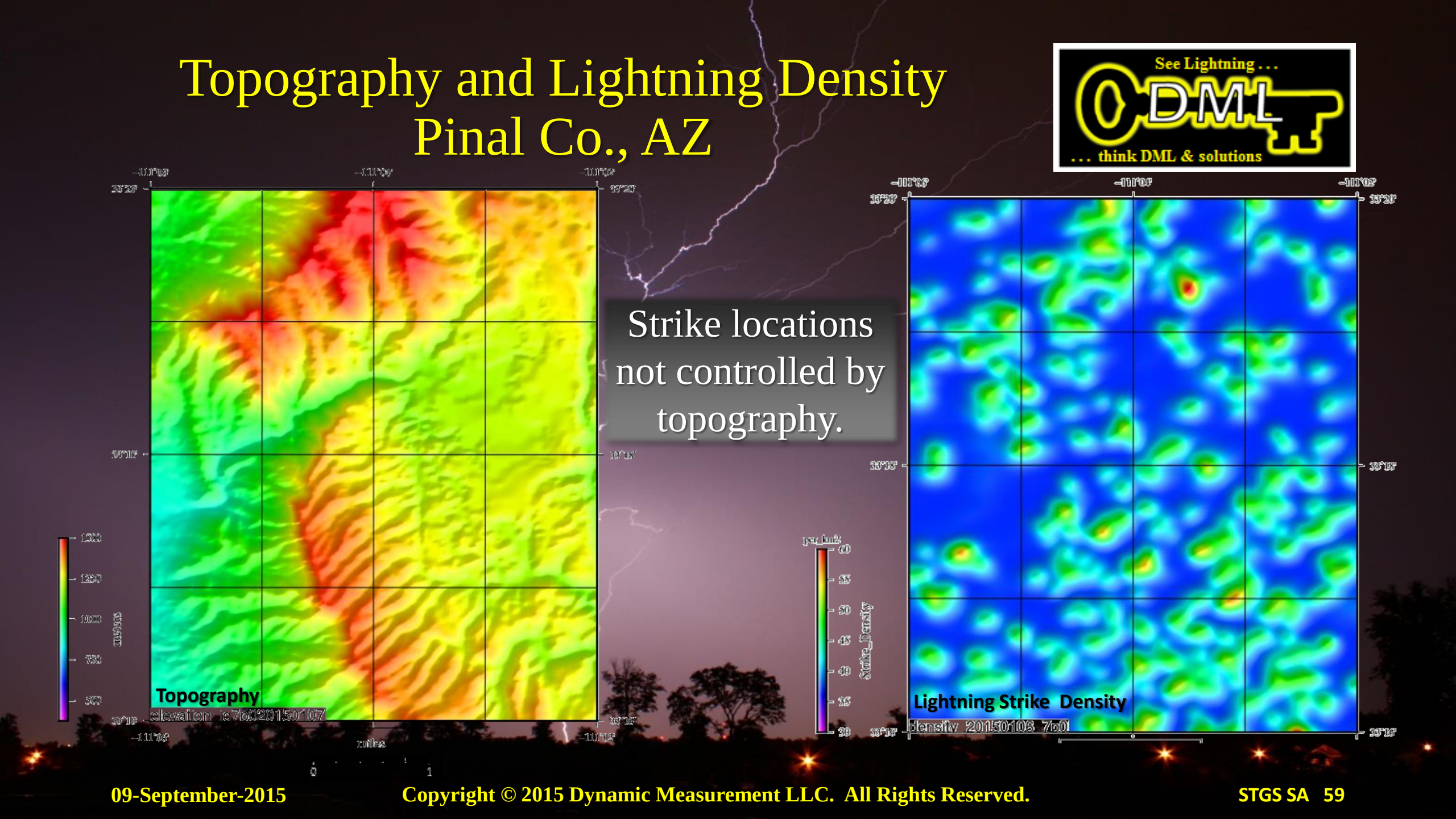




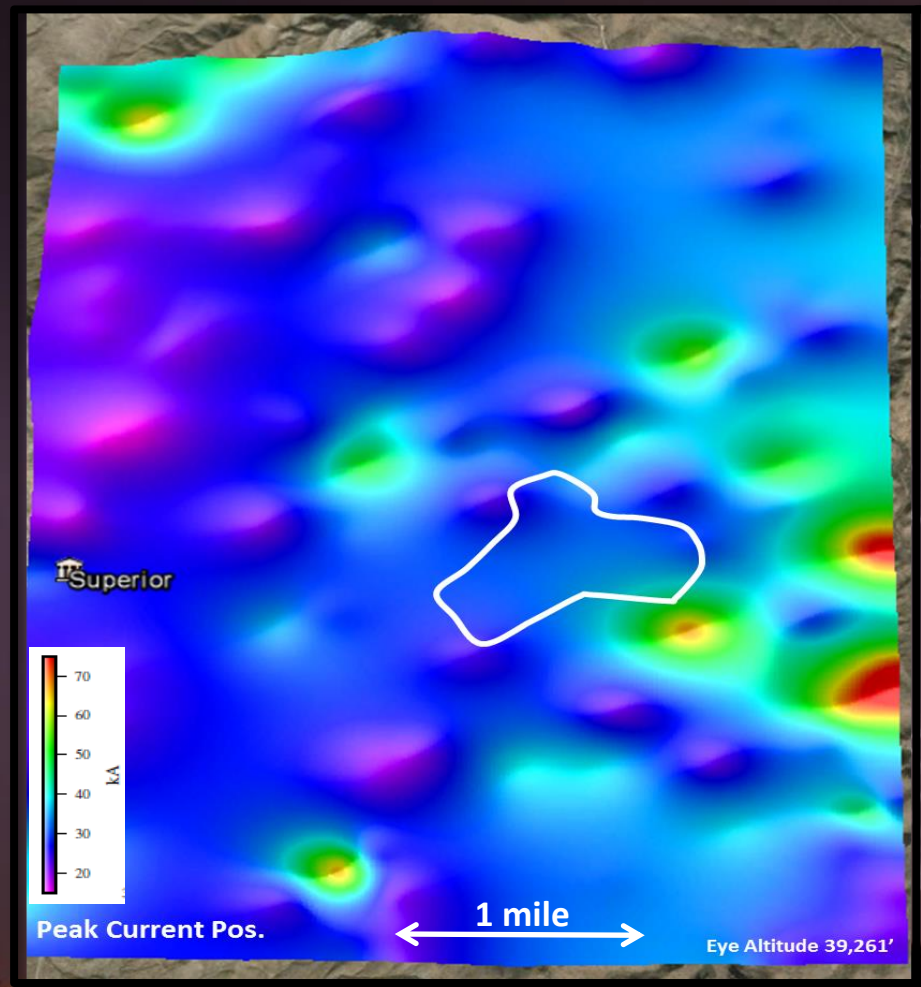
Pyrite halo around copper orebody.

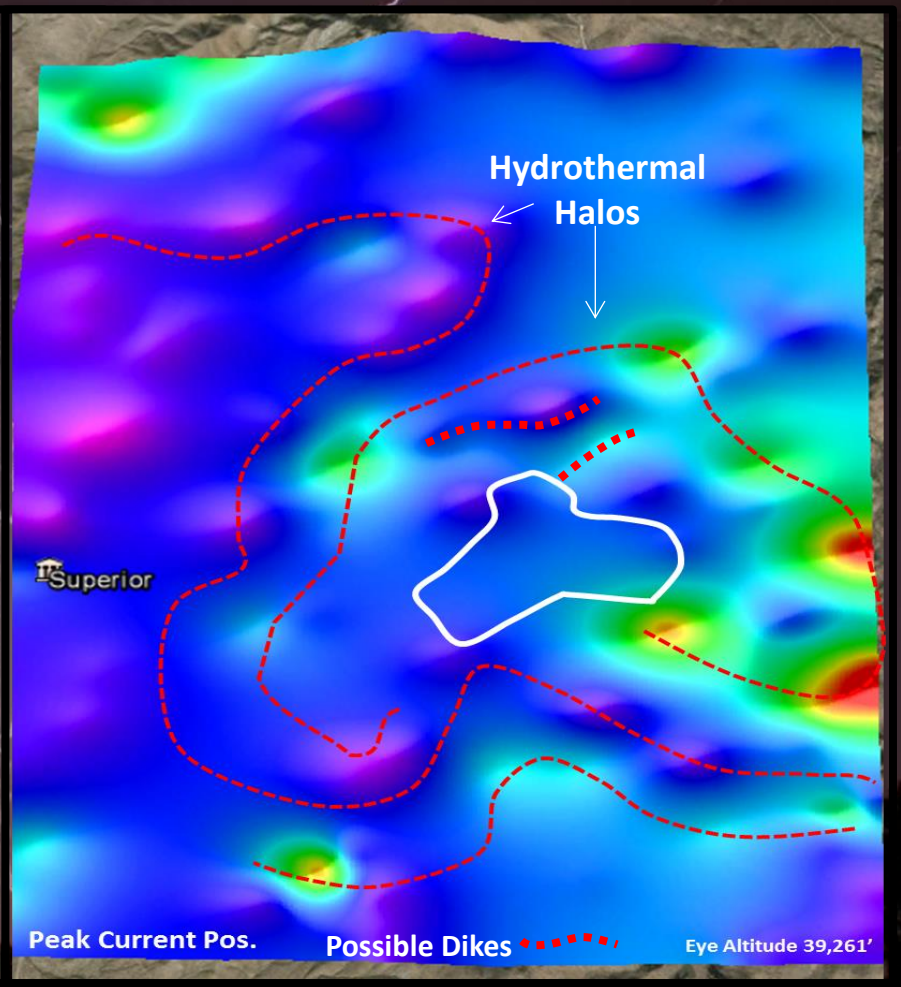
Geochemical zoning around the Bingham Canyon deposit, Utah (modified from Cunningham & others, 2004, their Fig. 1). USGS Report 2010-5070-B , David John, Editor.

Topography and Lightning Density
Pinal Co., AZ



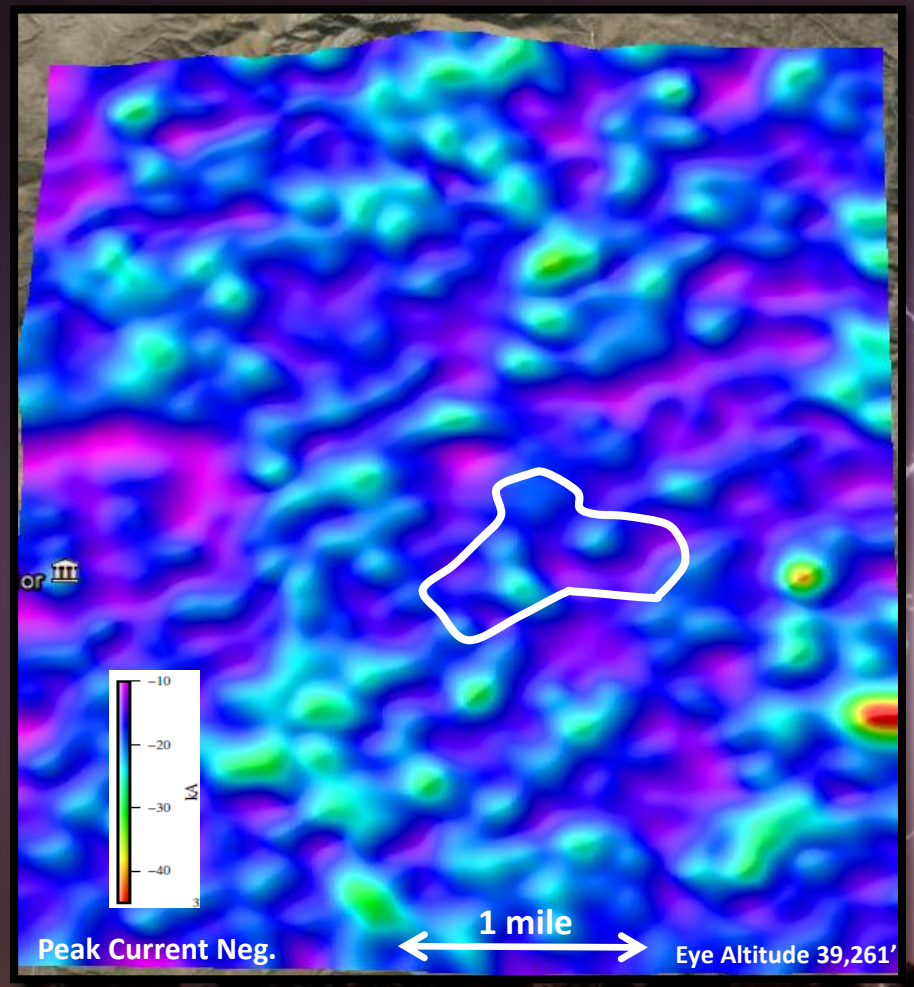
Positive Peak Current
Resolution Copper Mine

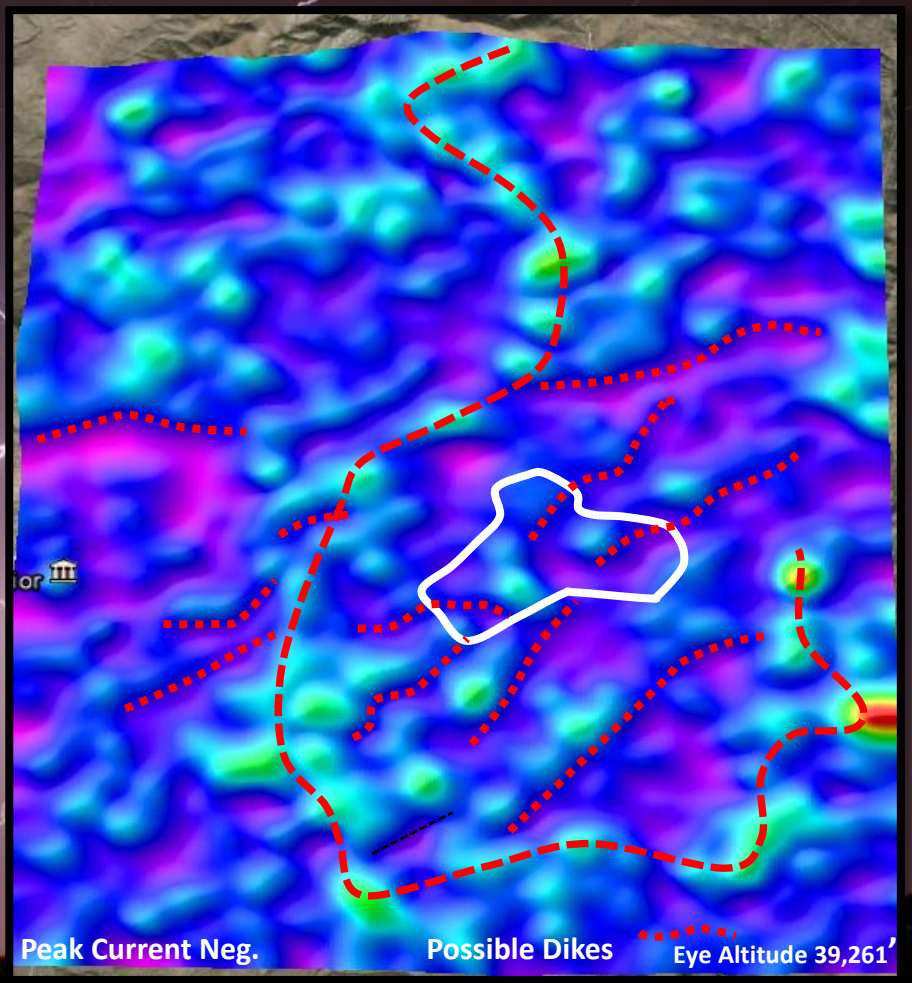




Hydrothermal Alteration
& Dike Interpretation

Negative Peak Current
Resolution Copper Mine



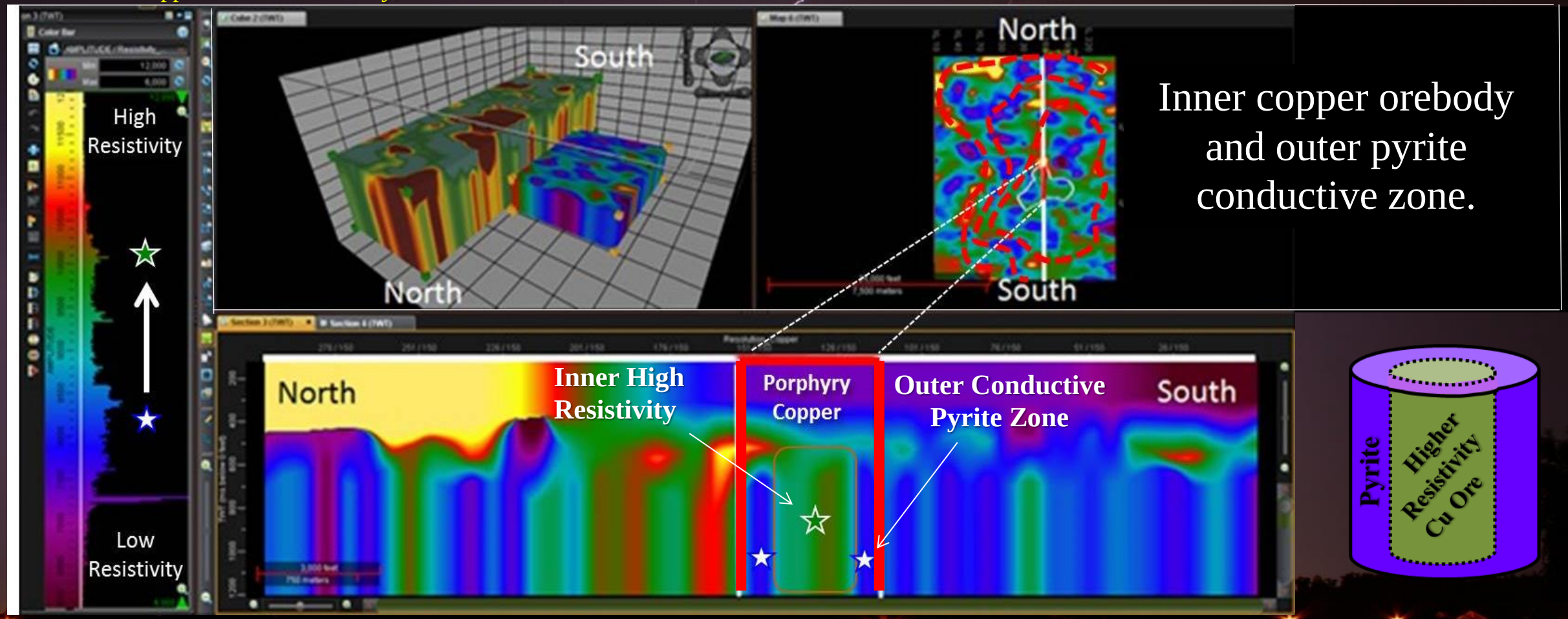


Shows pyrite halo partially enclosing copper orebody.

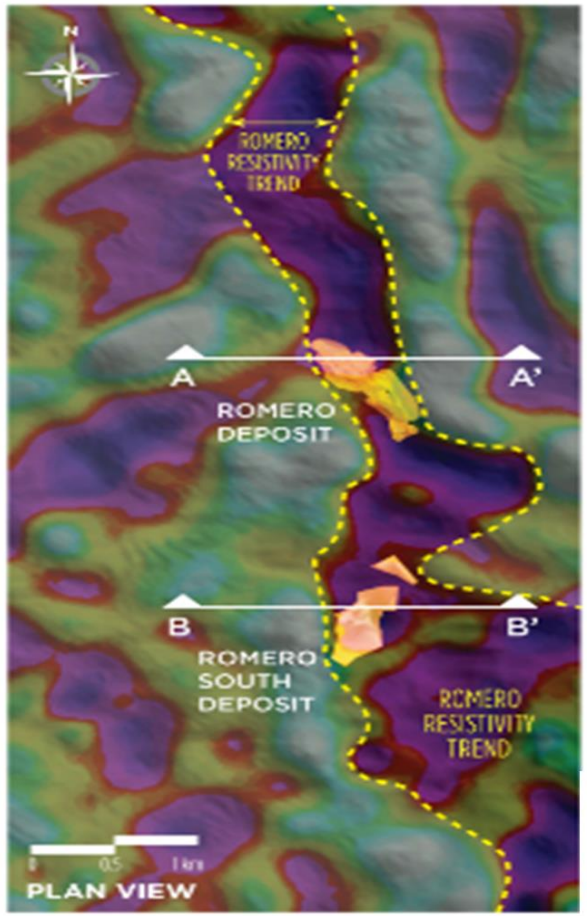
Presence of dikes indicative of Cu.

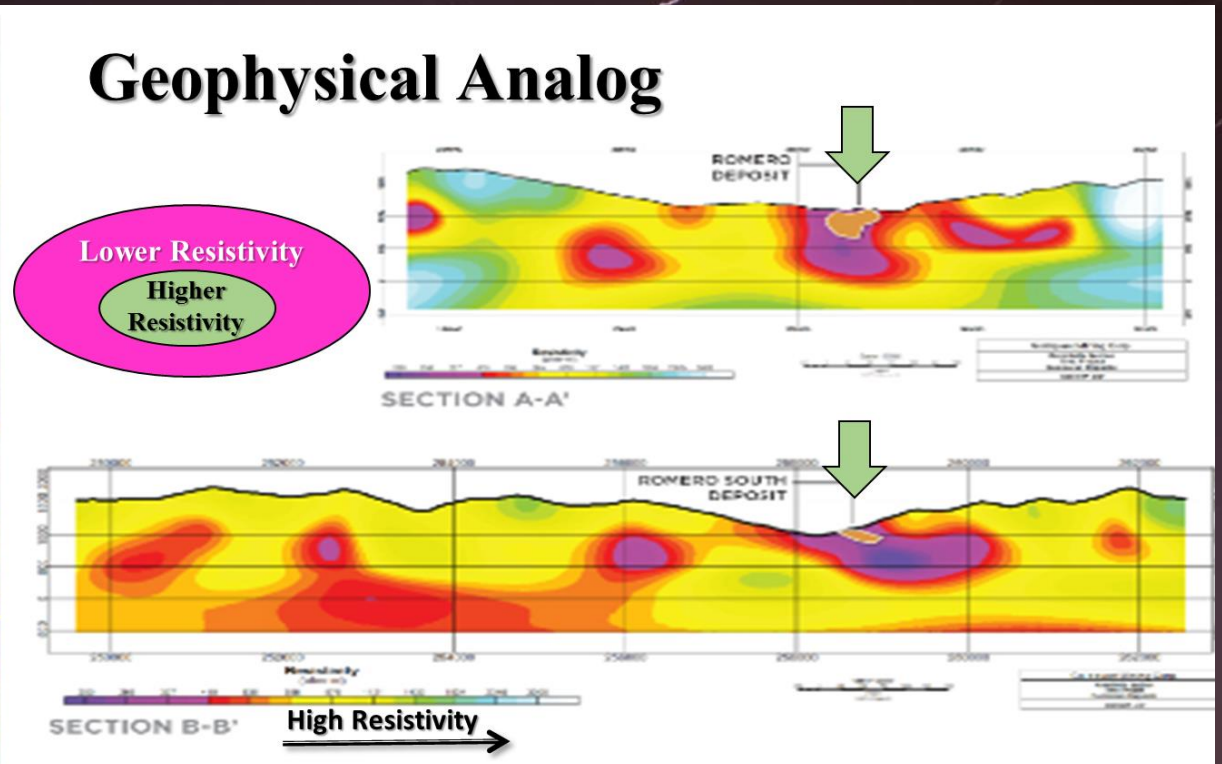
3-D Resistivity Profile Through Mine
Reveals Porphyry Copper Signature

Resolution Copper Mine Pinal County, AZ



Copper Deposit Analog
Romero Resistivity Trend, Dominican Republic





After Geotech 2014 ZTEM Survey for Goldquest (www.goldquest.com) , Seismic Resistivity Signature of Romero Au/Cu Resistivity Trend, Dominican Republic, http://www.marketwire.com/library/MwGo/2014/4/14/11G014504/Images/GQC-2014-ZTEMSurvey-ResistivitySignature(April1520-1141602677010.jpg

Traditional resistivity profiling shows same Cu signature as NSEM.

Note same inner high resistivity core surrounded by lower resistivity halo.

Observations

- Annular lightning attribute clusters suggest lateral resistivity changes caused by igneous intrusion & hydrothermal alteration.
- Linear trends of positive & negative peak current believed to be guided by igneous dikes/sills emplaced during igneous intrusion.
- 3-D NSEM resistivity data shows same electromagnetic signature used by mining industry to map porphyry copper deposits.

Mineral Exploration Conclusions

- NSEM data has the potential to explore for any mineral commonly found by conventional electrical geophysical prospecting methods.
- NSEM data has the ability to map subsurface rock properties which can also be applied to unconventional oil and gas exploration.

NSEM OVERVIEW

- NSEM can identify regional fault trends, generate leads, map rock properties and has demonstrated remarkable potential to identify hydrocarbon accumulations.
- NSEM can be calibrated to, and integrated with, seismic and subsurface geology, potential field and near surface geophysical data.
- NSEM can fill in between or extend beyond 3-D surveys and can supplement 2-D seismic data.
- NSEM cost 1% of 3-D seismic and can be acquired, processed and interpreted within 6-8 weeks.

DML's Technology is being Recognized

GULF COAST ASSOCIATION OF GEOLOGICAL SOCIETIES

www.gcags.org

Dear Kathleen,

Congratulations! You have been selected to receive the First Place Grover E. Murray Best Published Paper Award for your paper, "Aquifers, Faults, Subsidence, and Lightning Databases" published in the 2014 GCAGS *Transactions*.

• • •

Mary Broussard
2013-2014 GCAGS President
Email: Mary_Broussard@fmi.com

See updates at:

GCAGS Houston
SEG New Orleans
WTGS Midland

Acknowledgments

Thanks to Louis Berent for the case studies demonstrating how NSEM can be used as a reconnaissance tool, how it can identify and map faults and for developing the NSEM signatures for finding porphyry copper deposits.

Additional thanks to Les Denham for his resistivity and permittivity algorithms that helped produce the 3-D volumes of lightning-sourced data from which these resistivity profiles were extracted and to Roice Nelson helping to extract the resistivity profiles used in this study.

Appreciation is also expressed to Mustafa Saribudak of Environmental Geophysics Associates, for his geophysical investigations of the active faults in the Hockley & Tomball areas, several of which were used to help validate NSEM's ability to identify subsurface faults.

Lightning, A Shockingly Unconventional Way to Conduct Exploration

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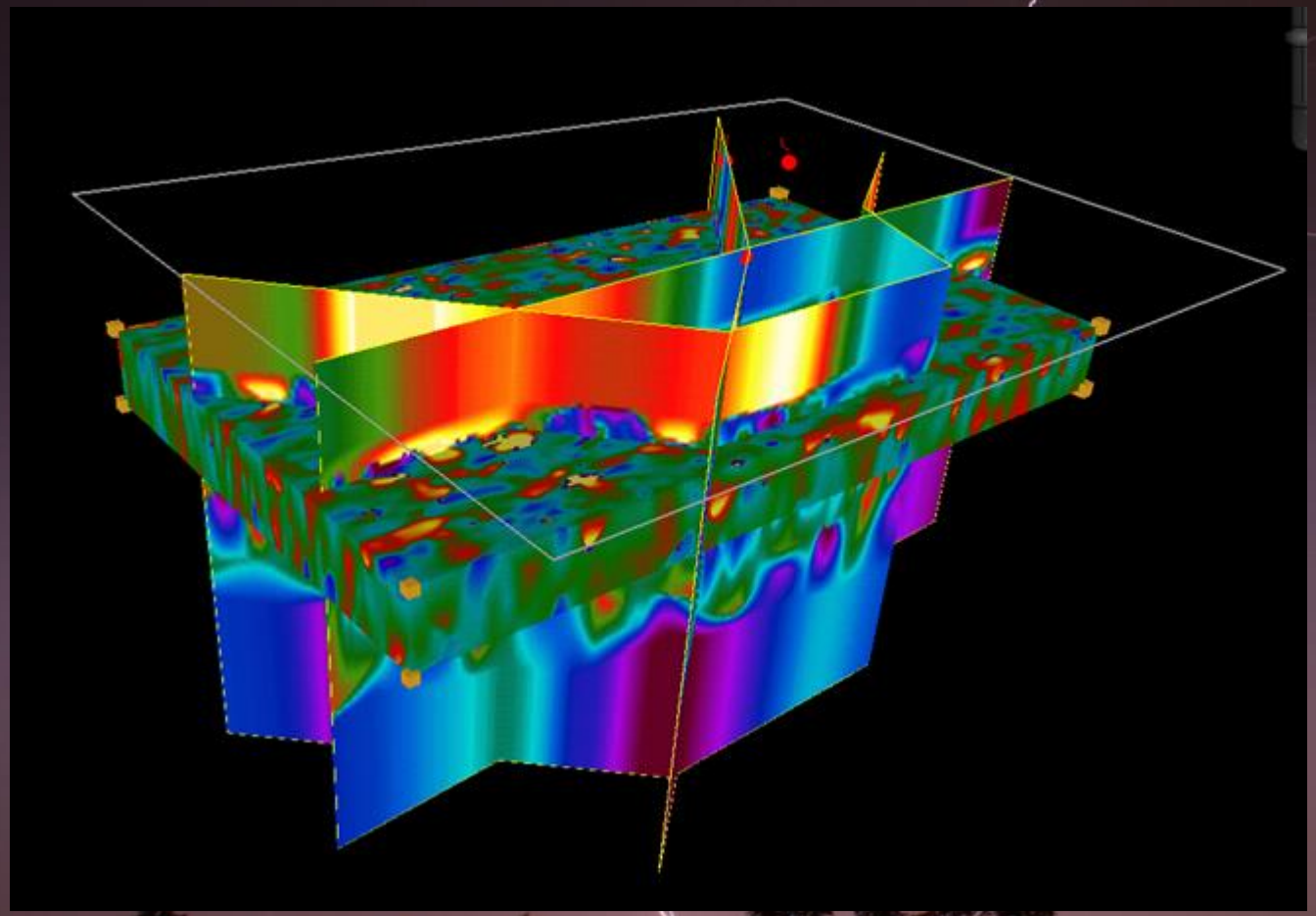
Appendix



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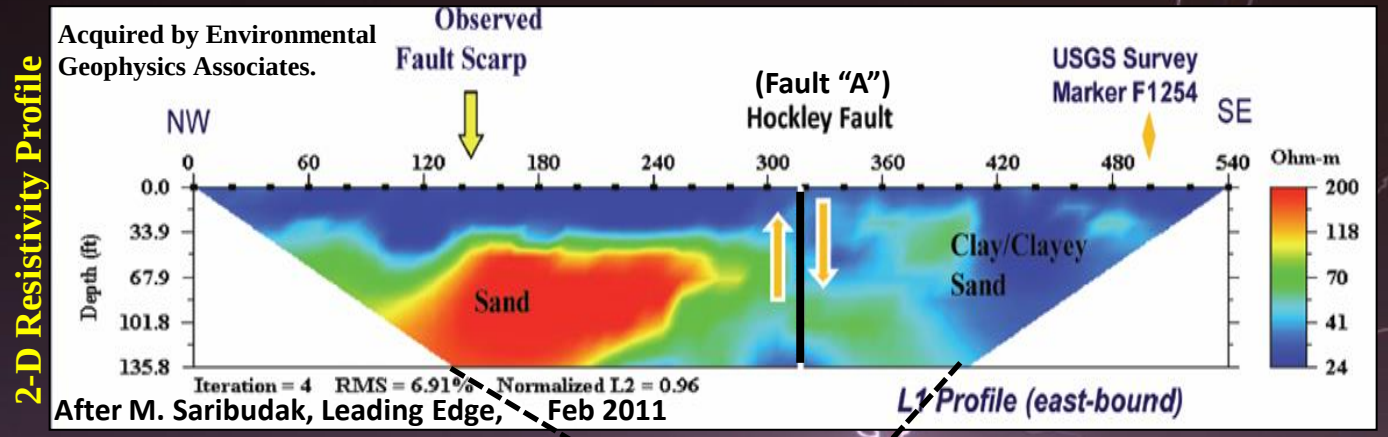
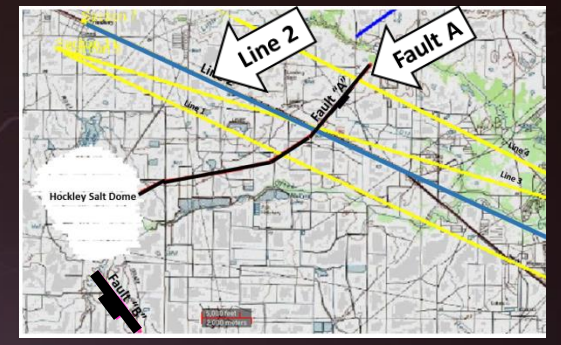
Saribudak, Mustafa, 2D Resistivity Imaging Investigation of Long Point, Katy-Hockley, Tomball and Pearland Faults, Houston, TX., Fast Times, Mar 2012.

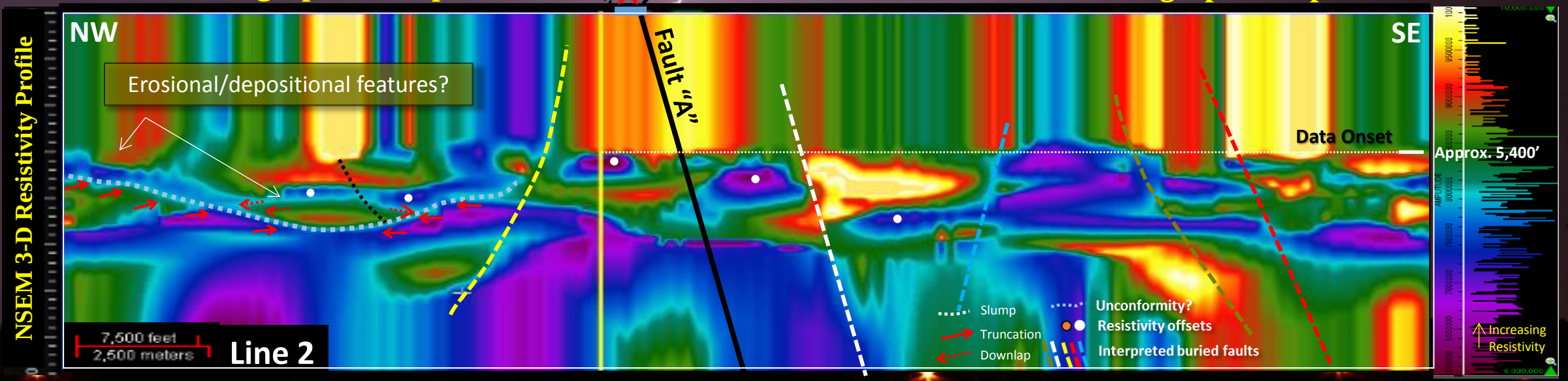
Sequence Stratigraphy?



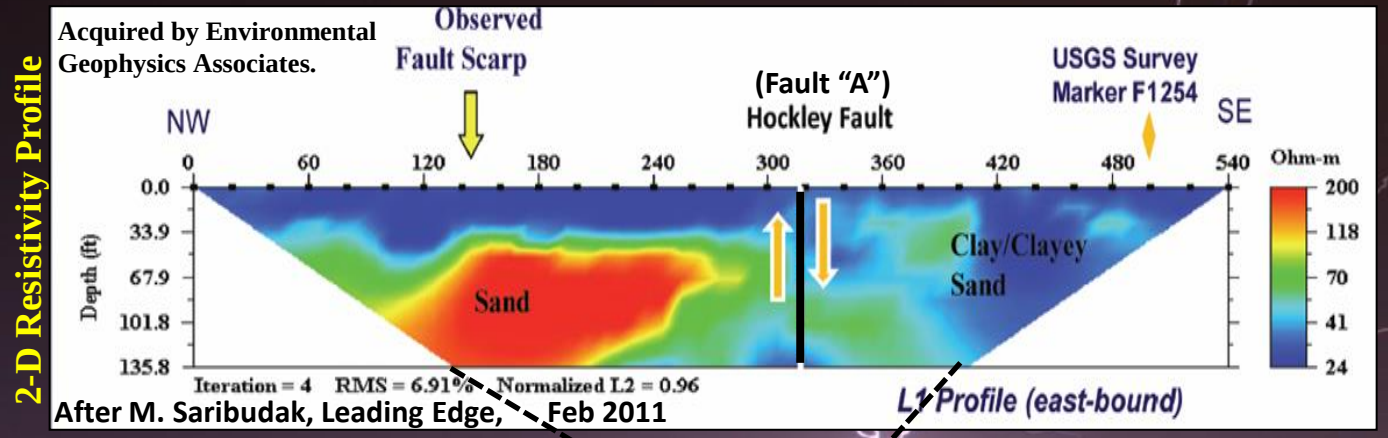


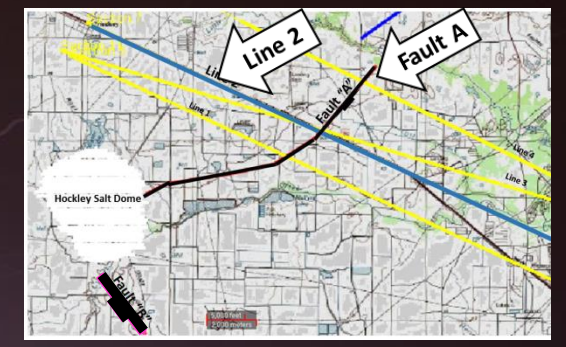
Line 2

Alternate stratigraphic interpretation. **Potential identification of stratigraphic traps?**



Sequence Stratigraphy?

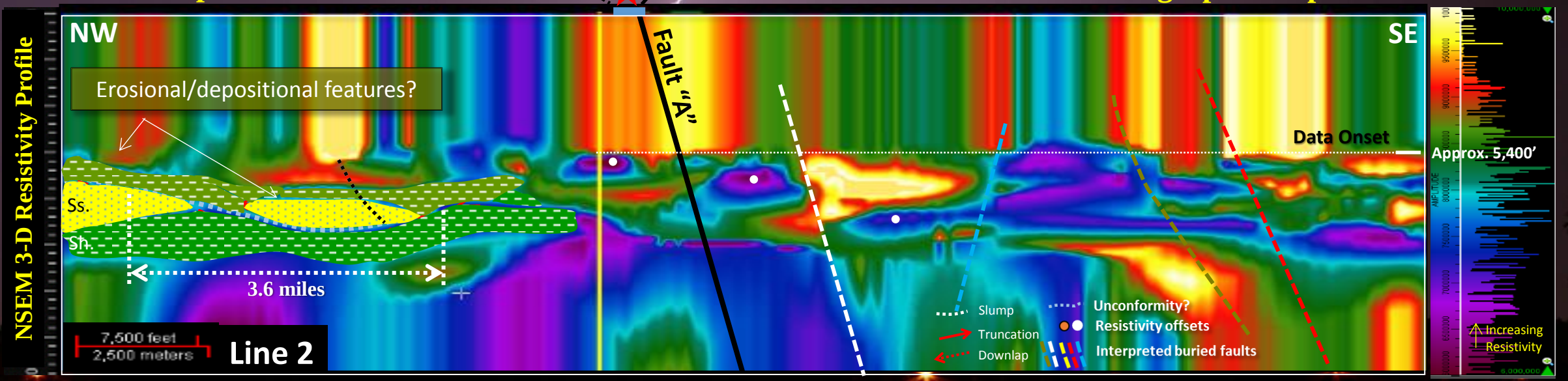




Line 2

Strike line parallel to channel.

Potential identification of stratigraphic traps?

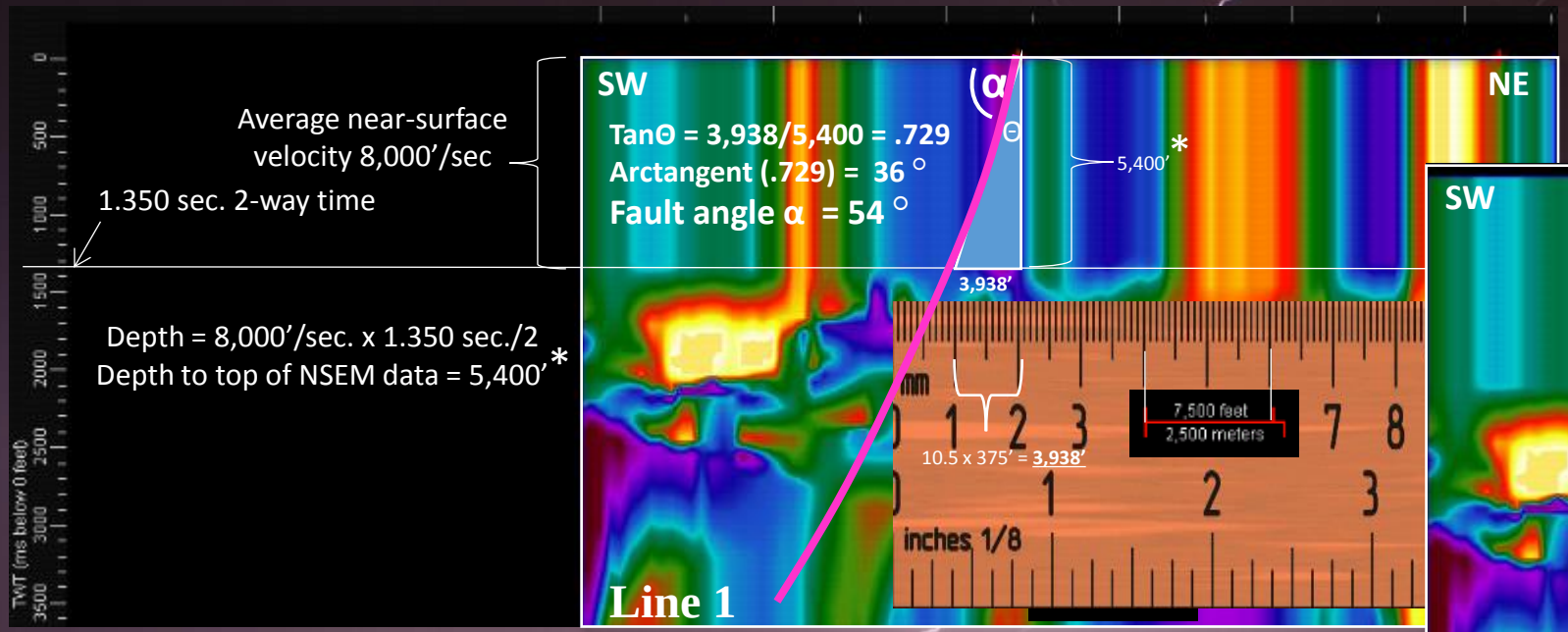


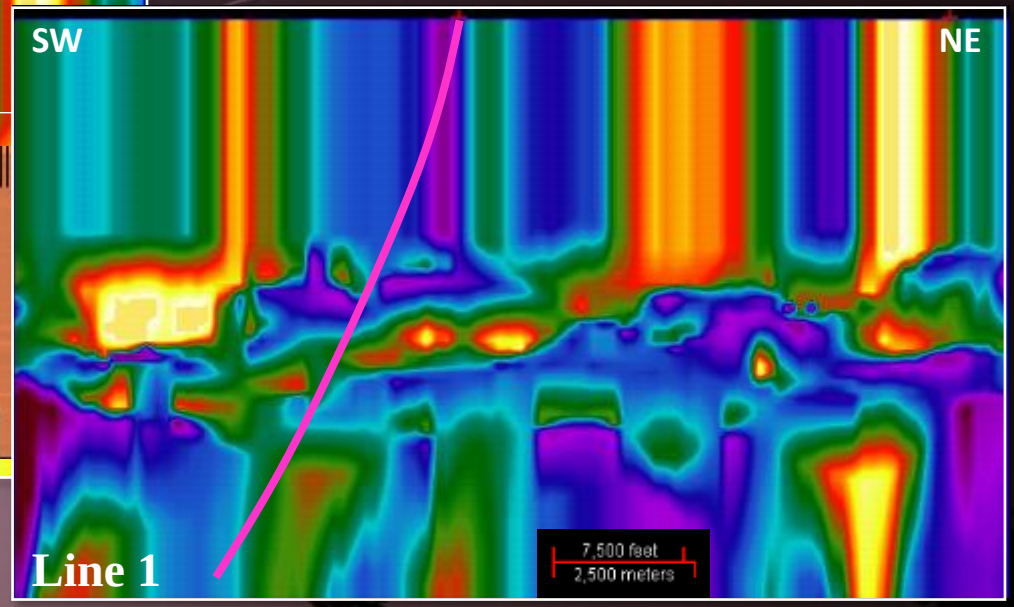
Fluvial Analogues

Possible analogues provided by nearby Brazos River and other meandering fluvial systems.

Line 2 possibly parallel to paleo-channel, encountering 3.6 miles of coalescing point bars within meander belt.

Fault Plane/Heave Constraints
Katy-Hockley Fault: 54 ° @ 5,400’
(*assuming 8000’/sec velocity)





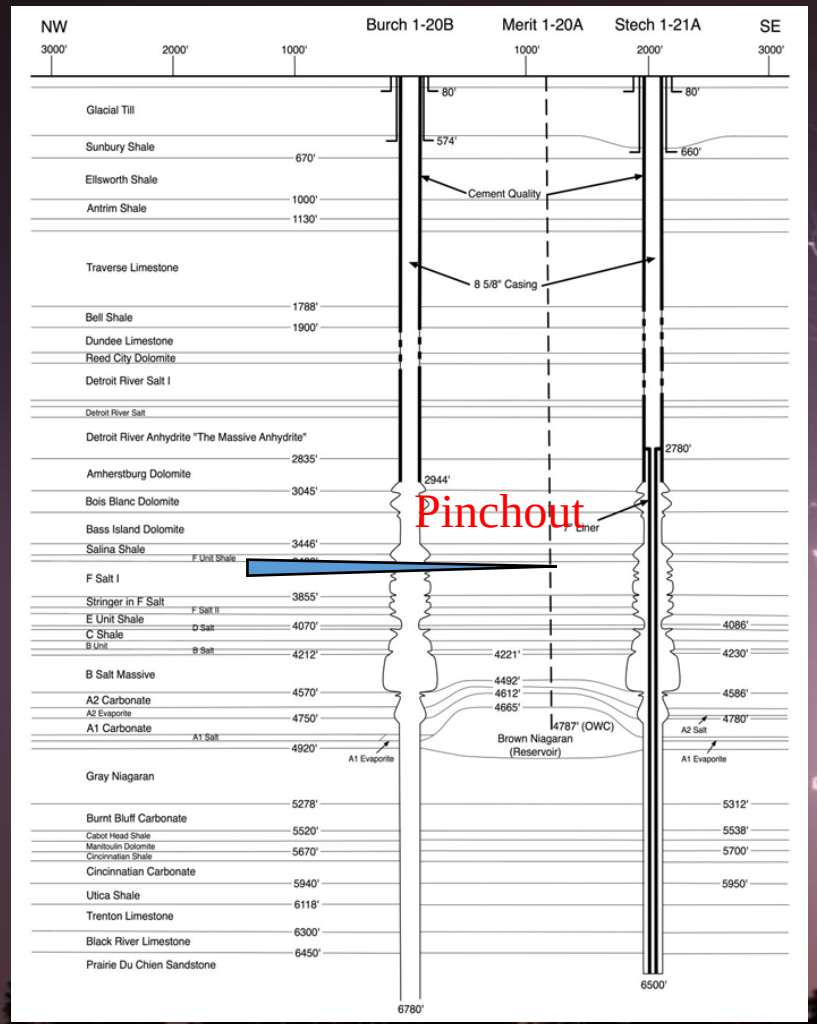
*** @ 4000’/sec**
TanΘ = 3,938/2,700 = 1.46
Arctangent (.972) = 56 °
Fault angle α = 34 °
Note: probably too low an angle for such a shallow depth even though fault is listric. Need independent depth profile for these faults.

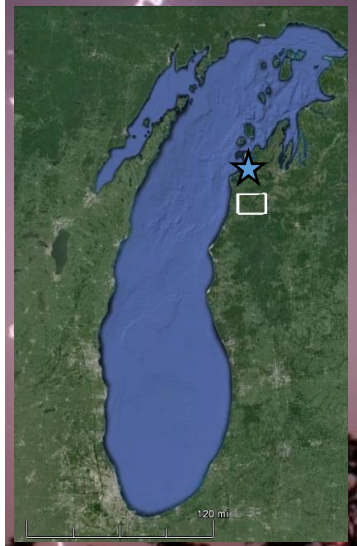
*** @ 6000’/sec**
TanΘ = 3,938/4,050 = .972
Arctangent (.972) = 44 o
Fault angle α = 46 °
Note: again, likely too low an angle at this depth.

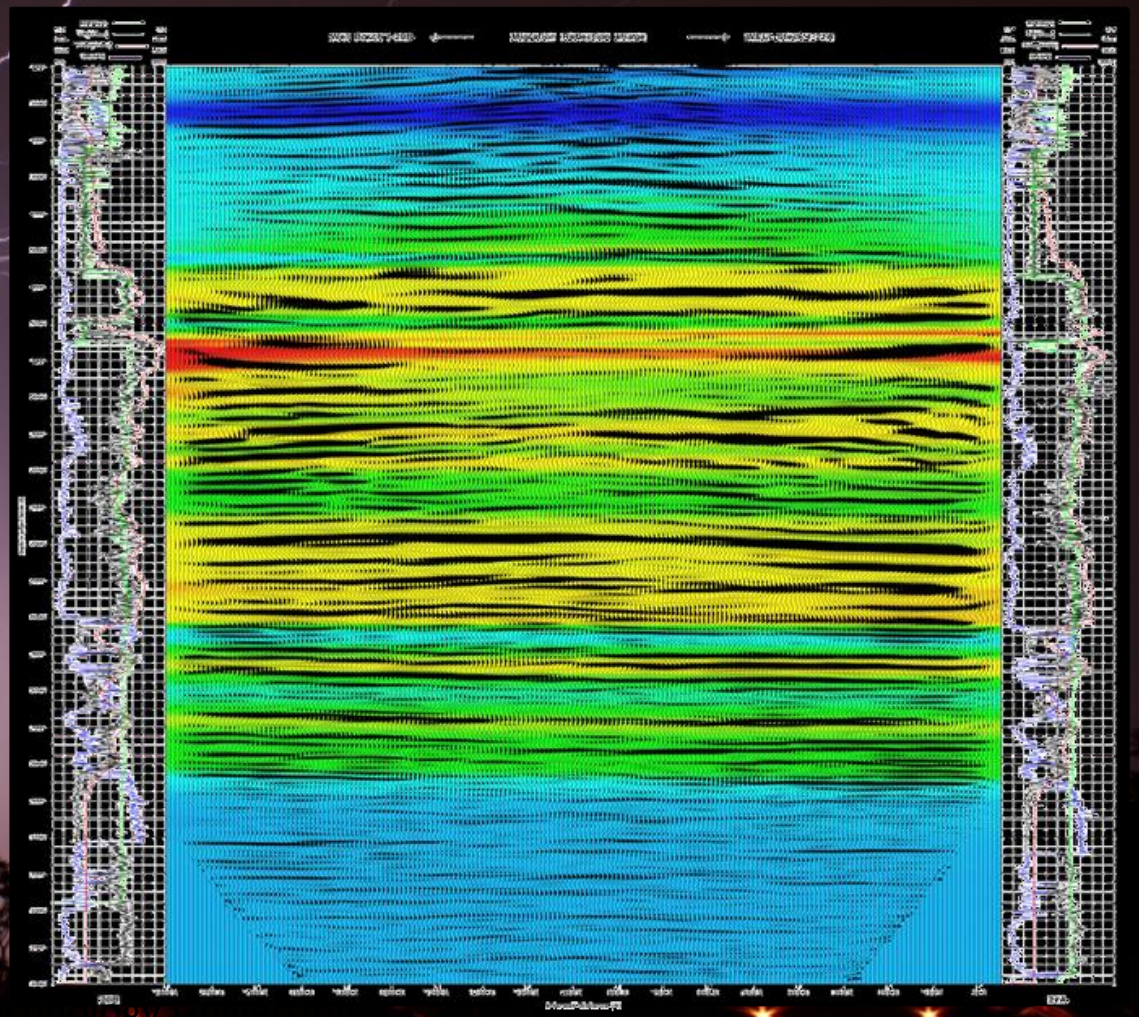
Michigan Technology University
Cross Well Tomography

Depth and Amplitude Calibration

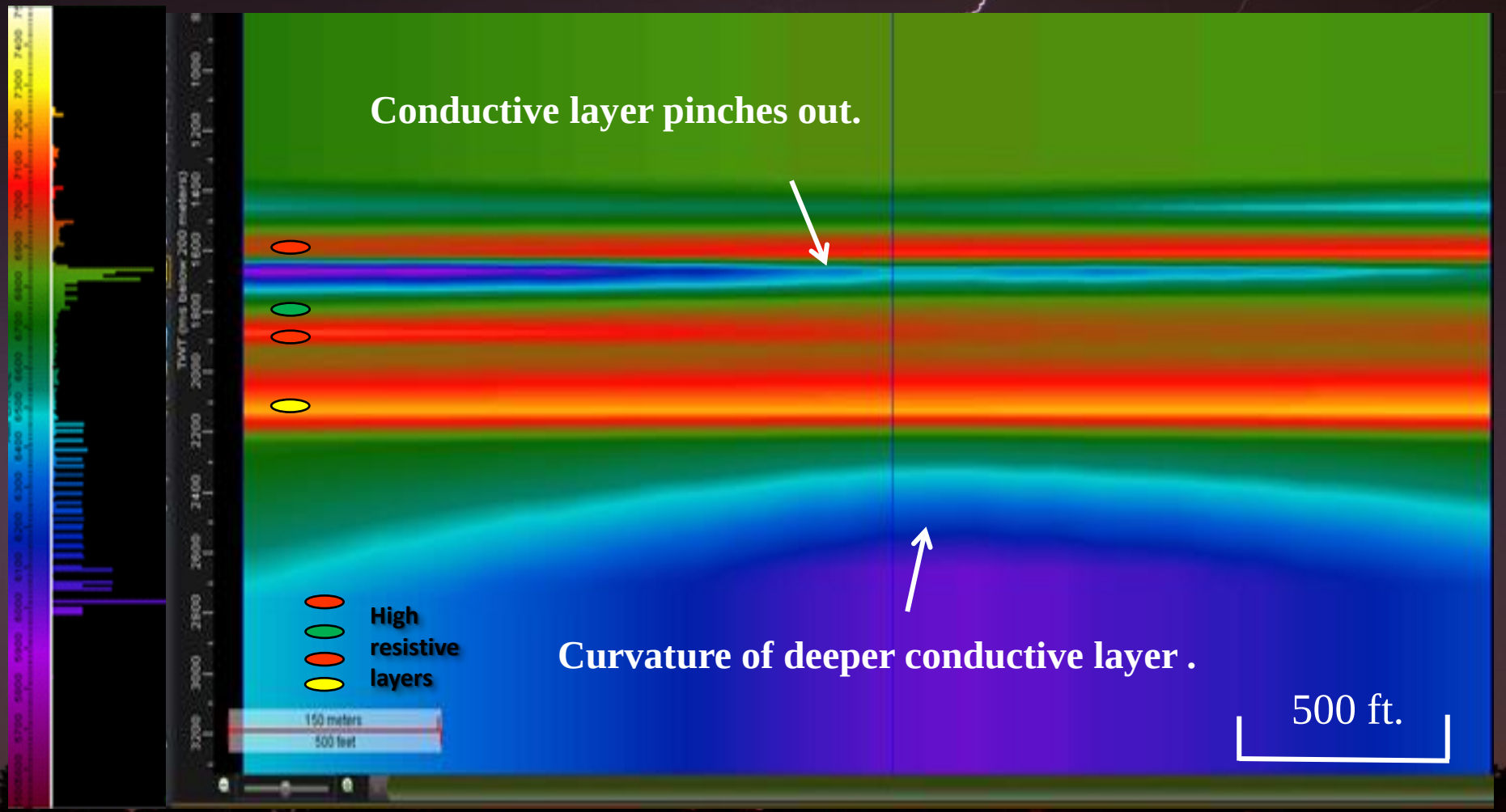
MTU Test Site with Cross-Well Tomography

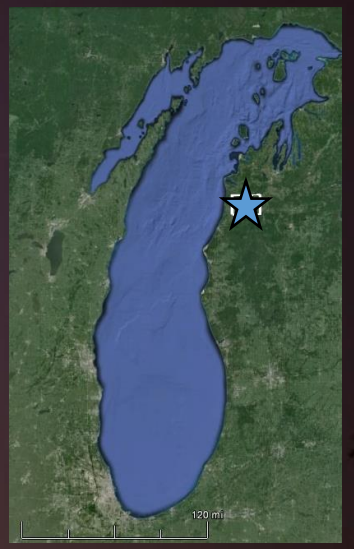






Resistivity Section Between MTU Test Site Wells





1
2
3

MTU Test Site Wells Overlaid on Resistivity Section