An Introduction to "Natural Source Electromagnetics" and its applications to petroleum and mineral resource exploration.

This presentation supports the poster sessions titled:
"Harnessing Lightning in the Hunt for Hydrocarbons" and
"An Unconventional Exploration Tool for Unconventional Exploration,"
both presented at the 2017 annual AAPG convention held in Houston, TX , on April 3rd and 5th respectively.

Louis J. Berent
Dynamic Measurement, LLC
Houston, Texas

Presentation Objectives

- Reveal how lightning is neither random nor predictable.
- Provide evidence showing how & why geology can influence the type & location of lightning strikes as well as their measurable attributes.
- Demonstrate how lightning-sourced data can be utilized to map geologic features.
- Illustrate how lightning-sourced electromagnetic data can be used for reconnaissance mapping & prospecting.

Outline

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

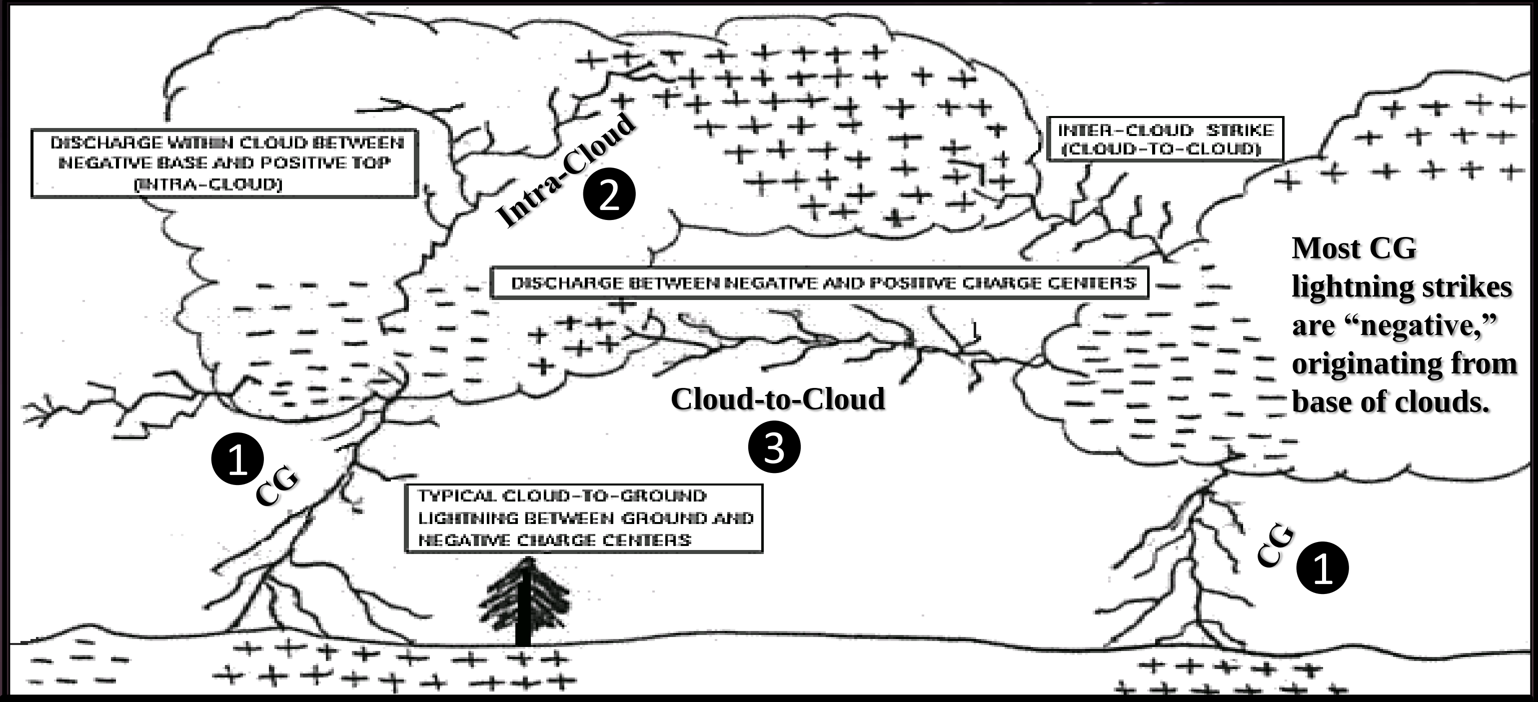
Natural Source Electromagnetics (NSEM) –
a new geophysical data type.

Examples of using NSEM to interpret geologic features.

NSEM overview.

Current Projects

Lightning: an atmospheric discharge of electricity that ionizes the air to create highly conductive plasma channels.



1. Cloud-to-Ground (CG) 2. Intra-Cloud 3. Cloud-to-Cloud

Adapted from: NASA, Global Hydrology Resource Center Website, Lightning & Atmospheric Electricity Research, Description of Lightning Discharge Process (https://lightning.nsstc.nasa.gov/primer/primer2.html).

- Hot moist air rises: freezes to form ice crystals.
- Turbulent winds: ice, hail, water droplet collisions.
- Clouds become polarized:
  + ions carried to top clouds,
  - ions gravitate to base.
- Static charge buildup: when charge strength exceeds insulating property of atmosphere, sudden high-voltage static discharge.

Nature of Lightning
"Step Leaders" & "Streamers"

Step Leaders: intensely charged channels of downward zig-zagging/branching electrons seeking positive ions to discharge built-up static energy.

Streamers: rising stream of positive charge attracted to downward seeking electron step leaders when step leaders are within 30' - 300'.

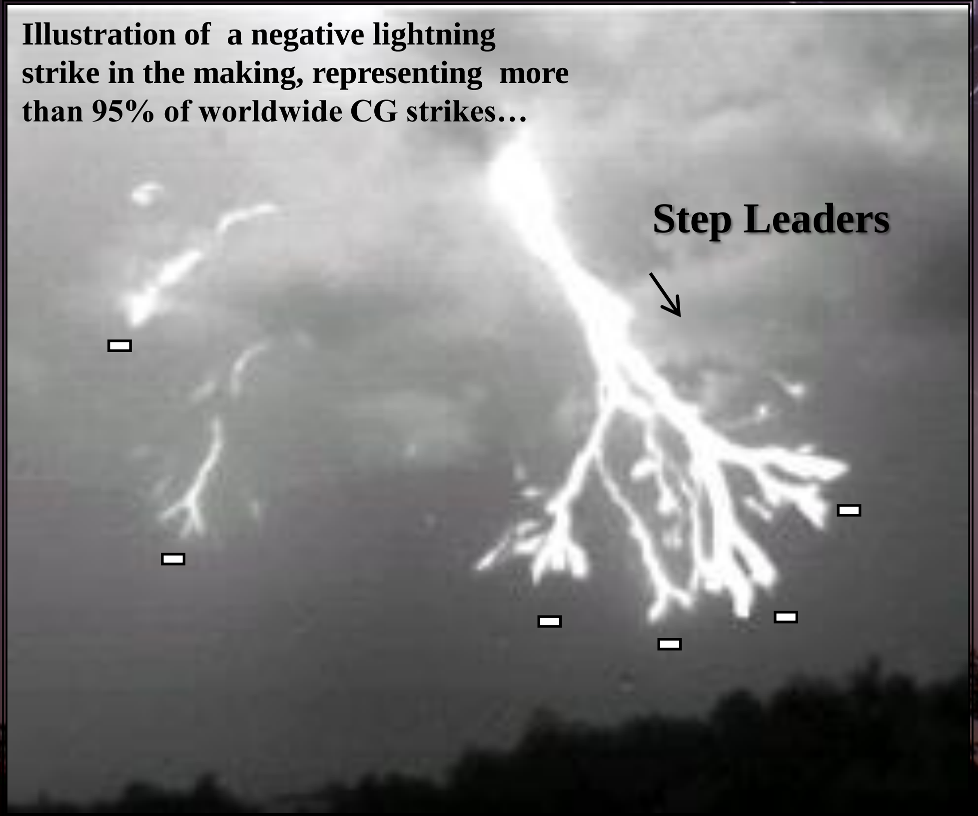
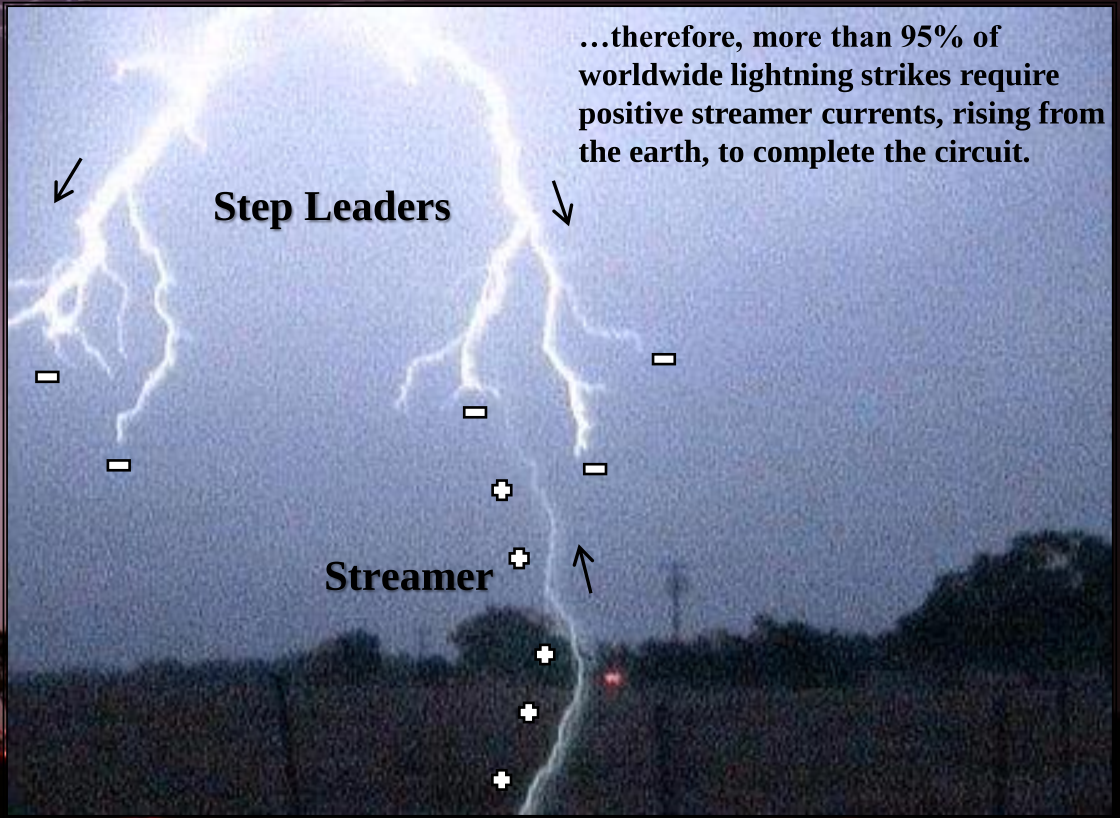


Illustration of a negative lightning strike in the making, representing more than 95% of worldwide CG strikes…



…therefore, more than 95% of worldwide lightning strikes require positive streamer currents, rising from the earth, to complete the circuit.

Failed Lightning Strikes & Streamers

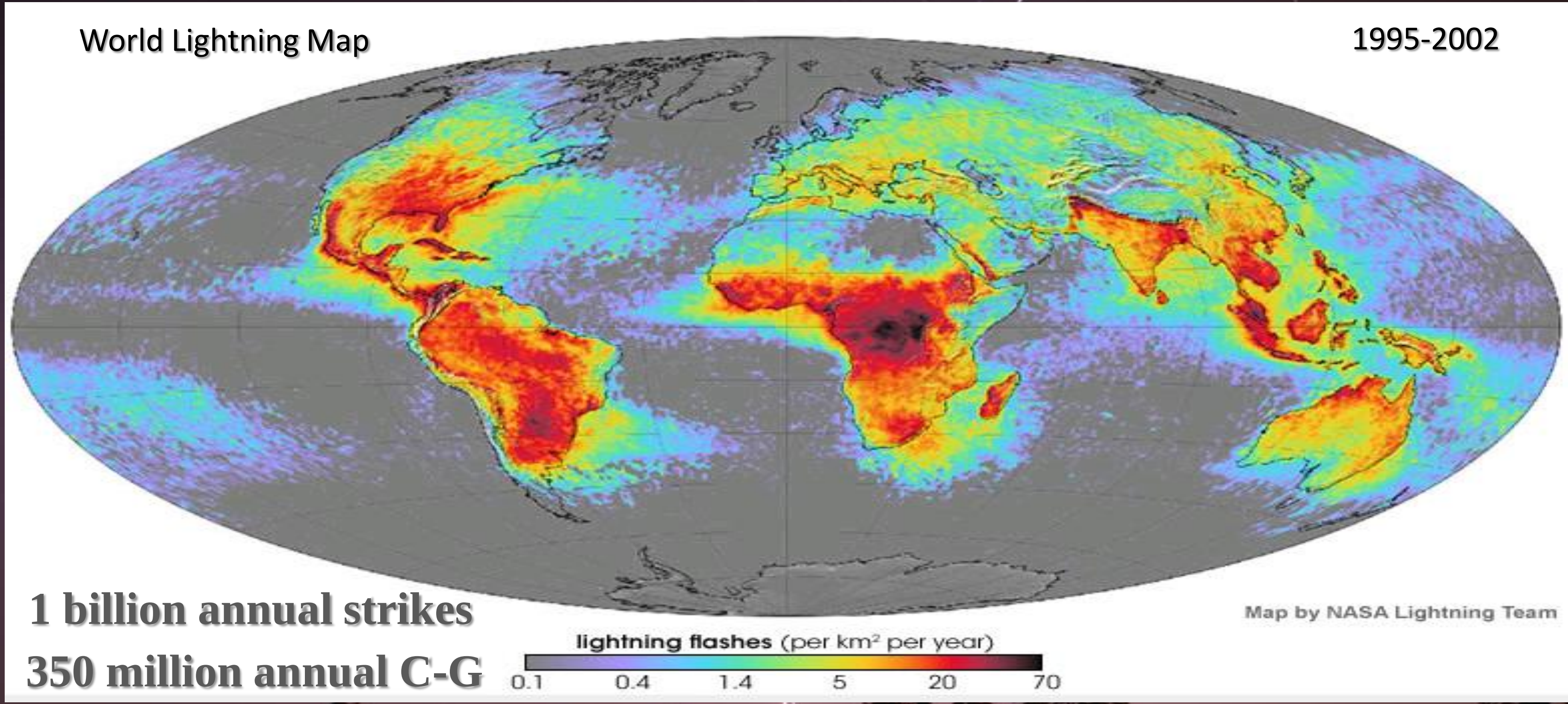
Two streamers launched from tree, but only one connects with a step leader to produce a strike.

Note streamer launched from telephone pole also does not connect with a step leader to produce a strike.

Illustrates competing factors influencing strike location, one of which is geology.

Why is lightning tracked & mapped?

Uneven cloud-ground distribution, but not random.

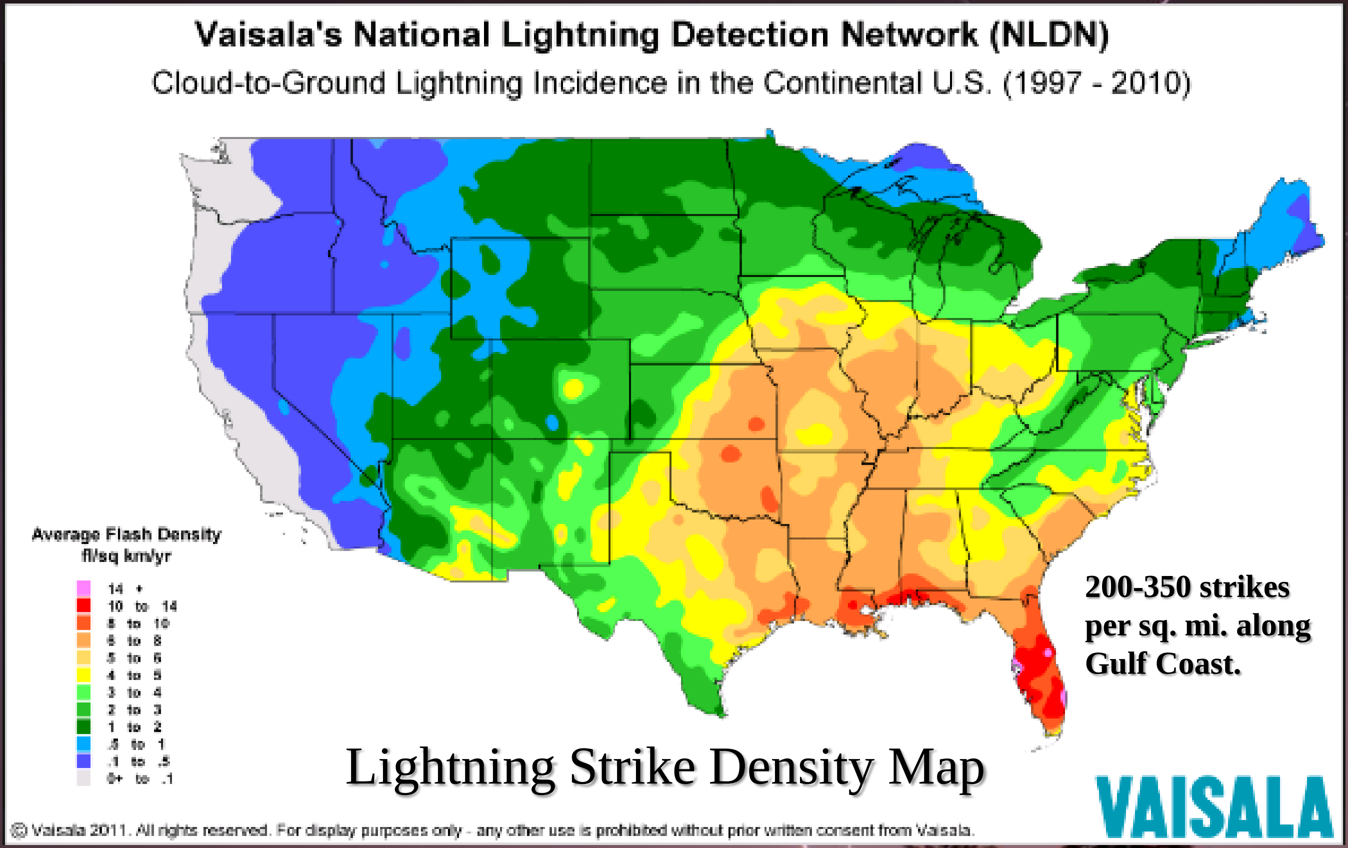


1 billion annual strikes

350 million annual C-G

- Storm tracking
- Safety warnings
- Insurance
- Forest fire forecasting
- Hurricane tracking
- Research & now…
- Natural resource exploration!

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

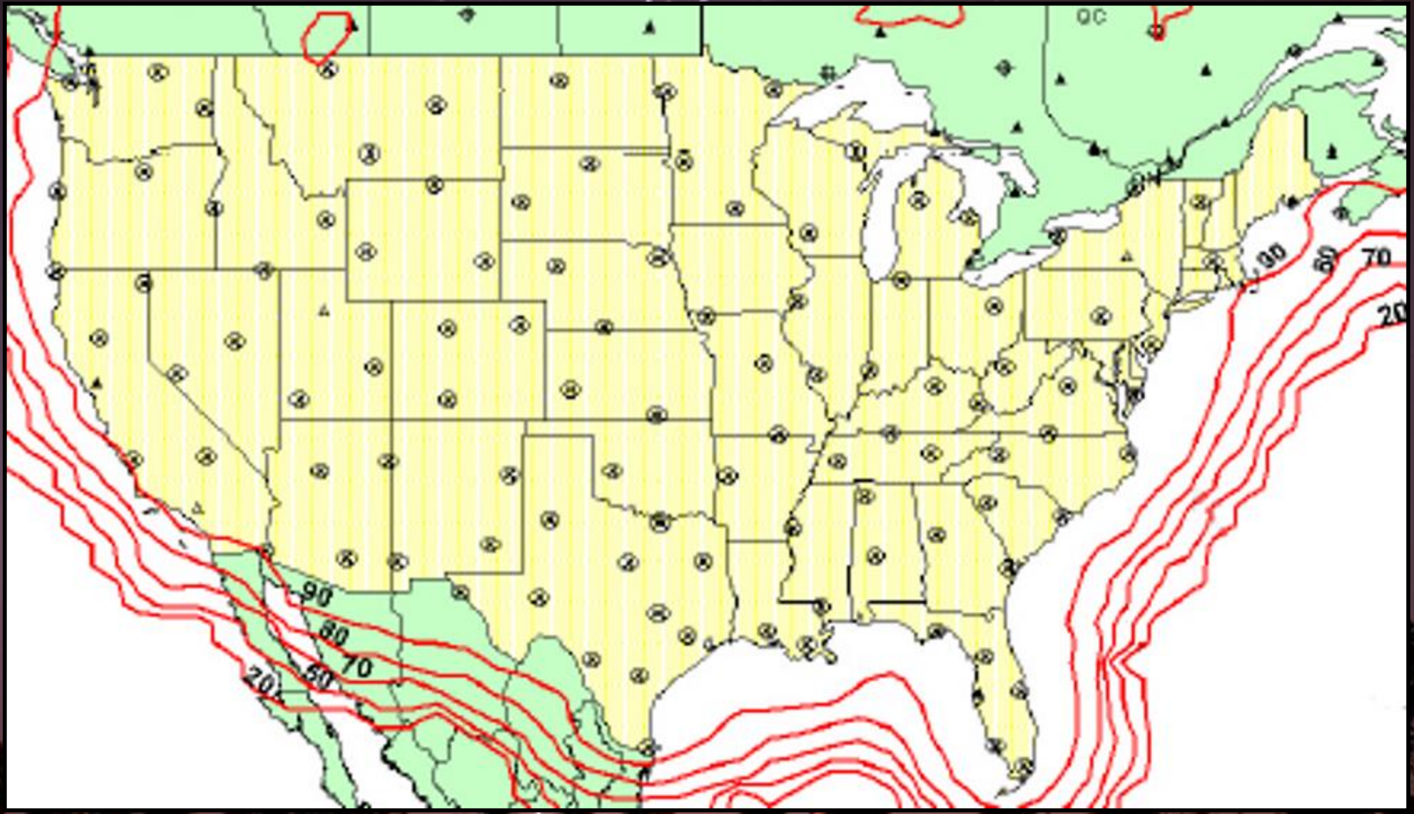


Lightning patterns in U.S. neither random nor uniform.

Evidence will be presented to show that despite strike density being regionally controlled by meteorology, lightning is locally influenced by geologically-sourced perturbations of the Earth's telluric currents.

Collection of Lightning Data

National Lightning Detection Network
115 Sensor Locations in U.S.



A typical Texas lightning strike is recorded by 16 -24 sensors.

Sensors within 600 mi of a strike can contribute to its triangulation.

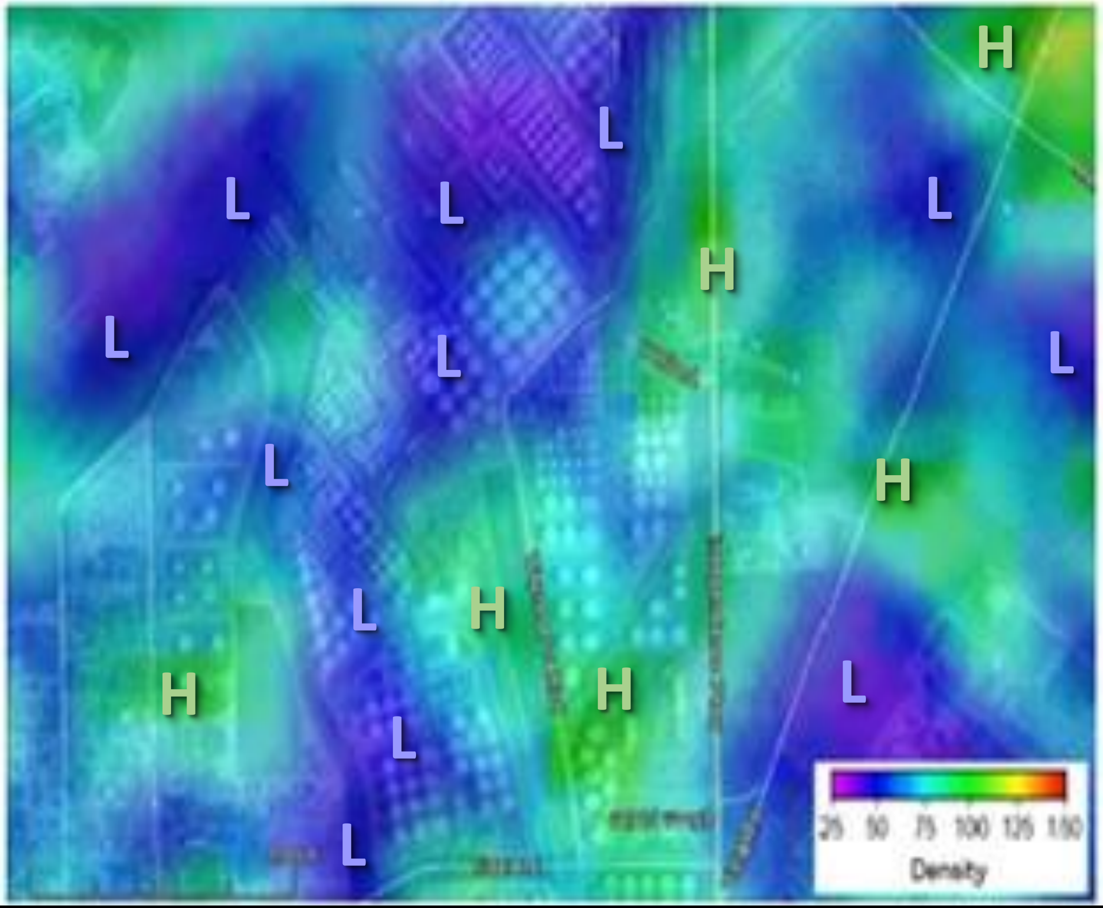
Empirical results show location error from reasonably dense database is 35-70'.

Lightning can travel 155 mi. from cloud-to-cloud, so what influences its strike locations? The Earth's electromagnetic field is the primary regional influencer, but……… ….there appear to be other factors contributing to non-random, non-uniform worldwide strike patterns.

Does Infrastructure Control Lightning?

DYNAMIC MEASUREMENT

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



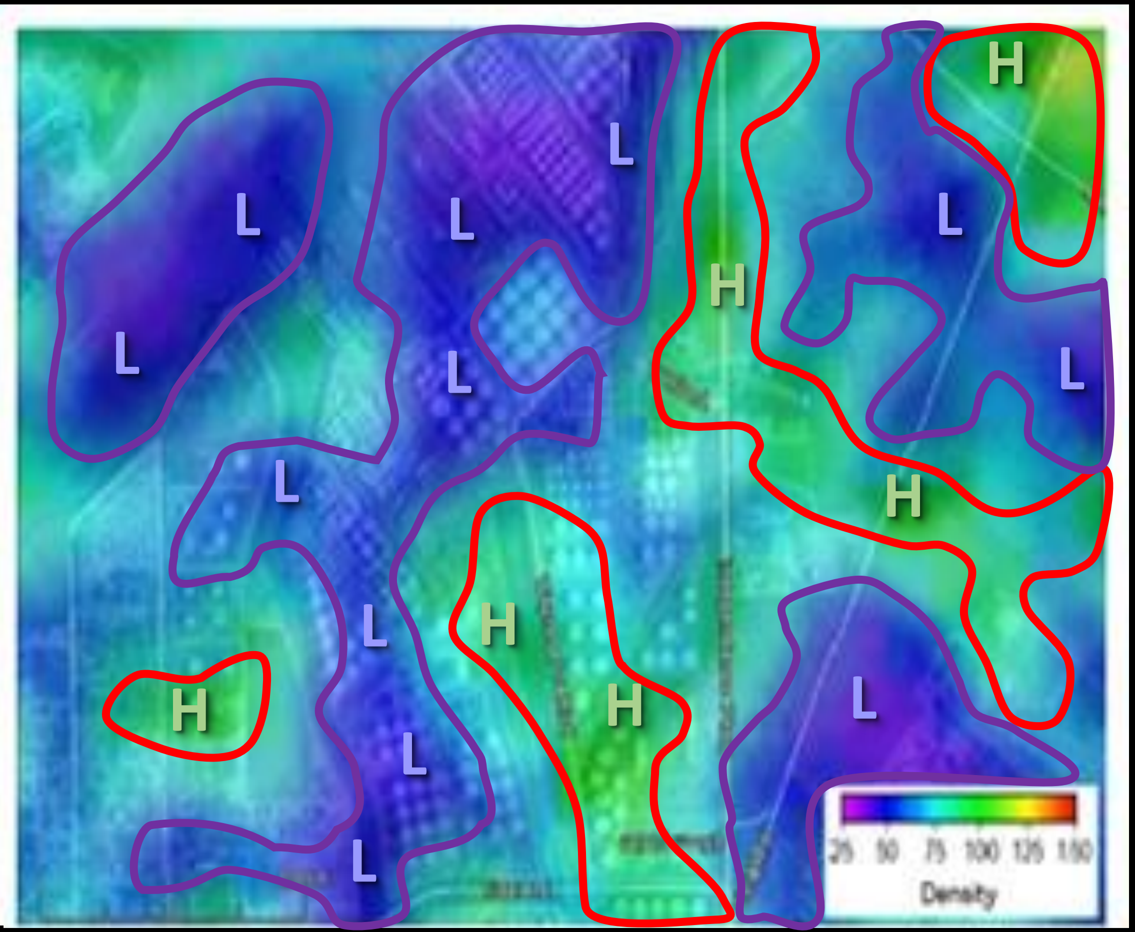
Strike Density Attribute Map Overlay

L Low strike density

H High strike density

Approximately 60% of Tank Farm Experienced Low Strike Density

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



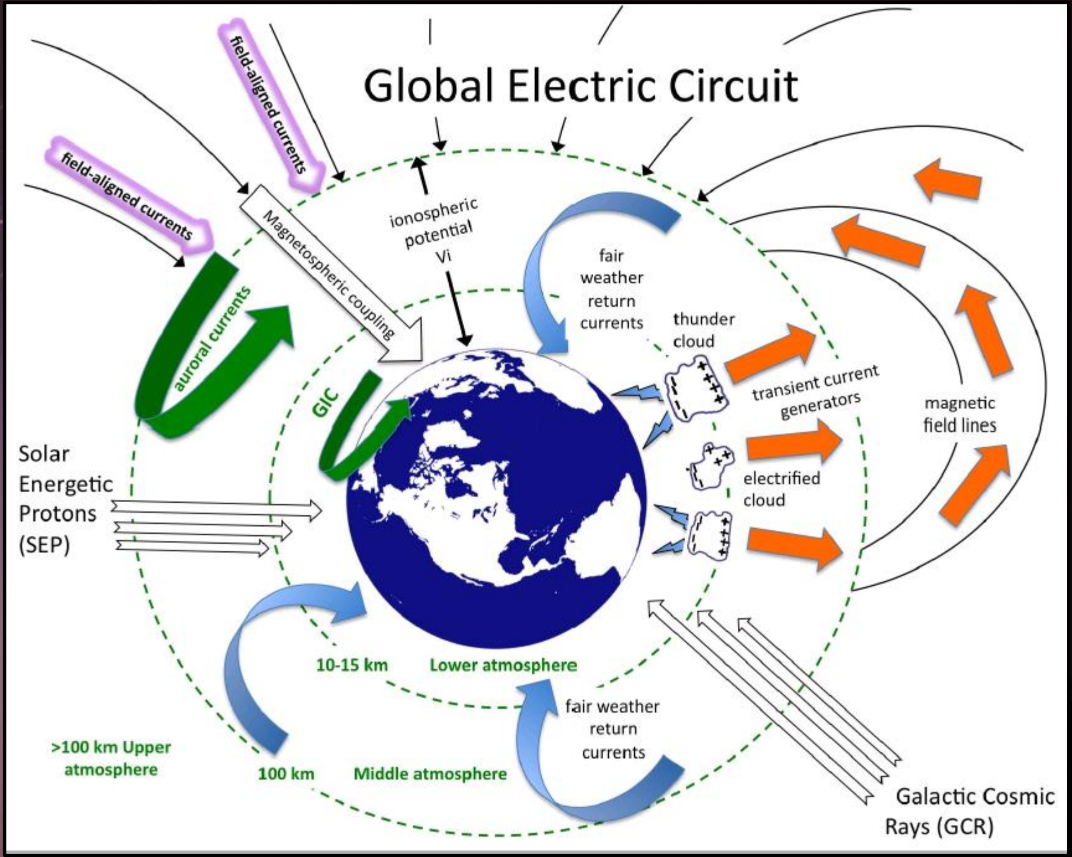
Strike Density Attribute Map Overlay

Lightning can bypass tall objects and…

…infrastructure expected to attract lightning.

The Electrified Earth (Global Electric Circuit)

- A global circuit exists between crust, mantle, various layers of atmosphere & magnetosphere.
- This circuit is maintained by: 1) global thunderstorm activity; 2) electric fields/currents generated in upper atmosphere from solar activity & magnetosphere interaction.
- Voltages approaching one billion volts generated in thunderclouds; currents associated with aurora nearly one million amperes.
- Lightning, an atmospheric discharge of electricity: a visual reminder of the electrical nature of clouds.



Above image provided by Dr. Jeffrey Forbes, Univ. of Colorado, Boulder & courtesy of the National Science Foundation.

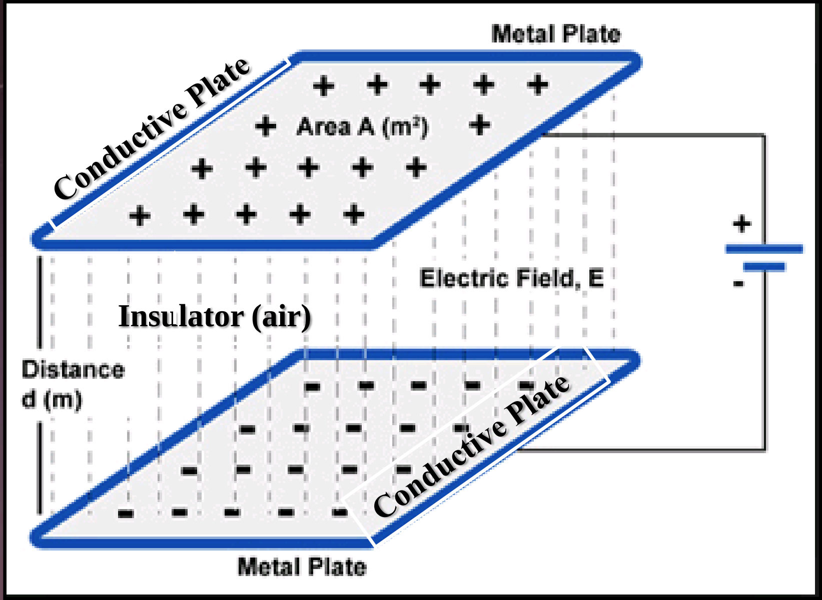
Telluric Currents

- Earth is a complex electrical conductor; its conductivity varies with location & depth based on geology & tectonic history.
- Telluric (Earth) currents are natural electric currents flowing on the surface & within the Earth’s crust, mantle, bodies of water and atmosphere.
- These telluric currents are induced electromagnetically by geomagnetic field fluctuations in the ionosphere & magnetosphere.
- Space weather events such as solar flares, corona mass ejections & magnetic storms can cause large electric current variations responsible for these magnetic field fluctuations which in turn induce telluric currents.
- Space weather & lightning are responsible for the strongest telluric currents.
- A lightning bolt is analogous to a wire carrying current & creates a strong circular magnetic field, also inducing telluric currents.
- A lightning pulse, like a dynamic seismic charge, includes all frequencies, creating induced telluric currents at all depths.

Capacitors

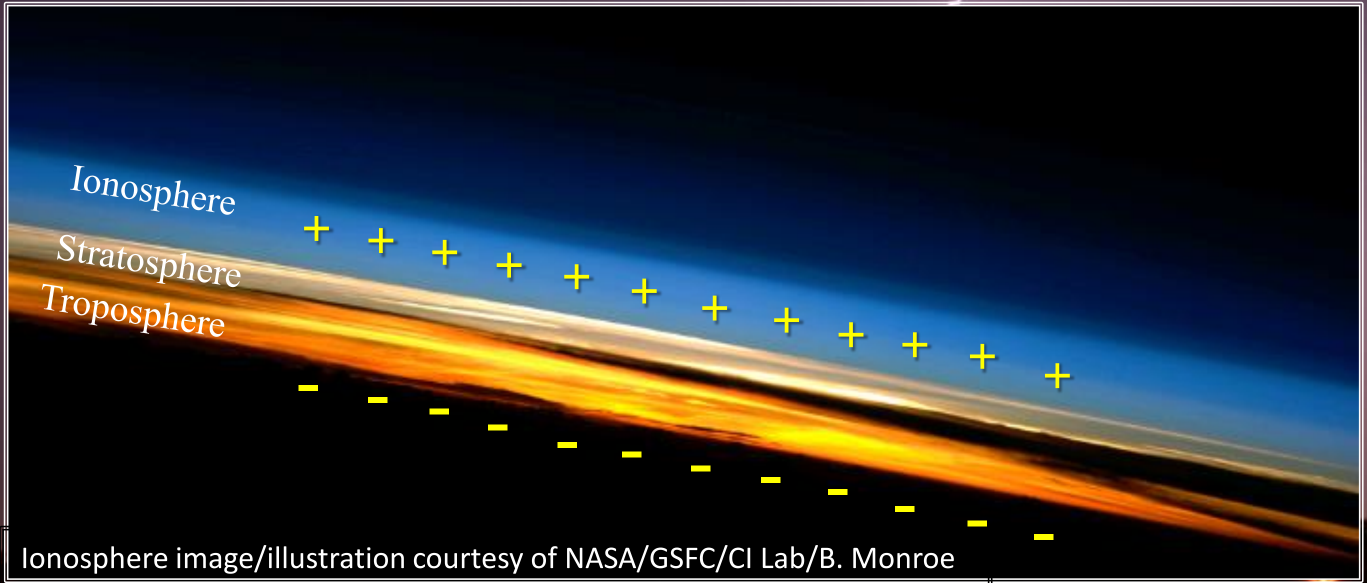
- Capacitors store electric charge & in their simplest form consist of two oppositely charged conducting plates separated by an insulator.
- Electric charge on one plate attracts opposite charge to the other, creating an electric field between them.
- As the capacitor's charge increases its electric field increases & the insulator's ability to continue separating opposite charge weakens.
- If the capacitor's charge & its electric field exceed the insulator's ability to separate opposite charge, the insulator will fail destroying the capacitor & releasing its stored energy.
- If the energy build-up is slow & the insulator is air or liquid, the <u>insulator may repair itself & allow subsequent energy storage.</u>

Capacitor

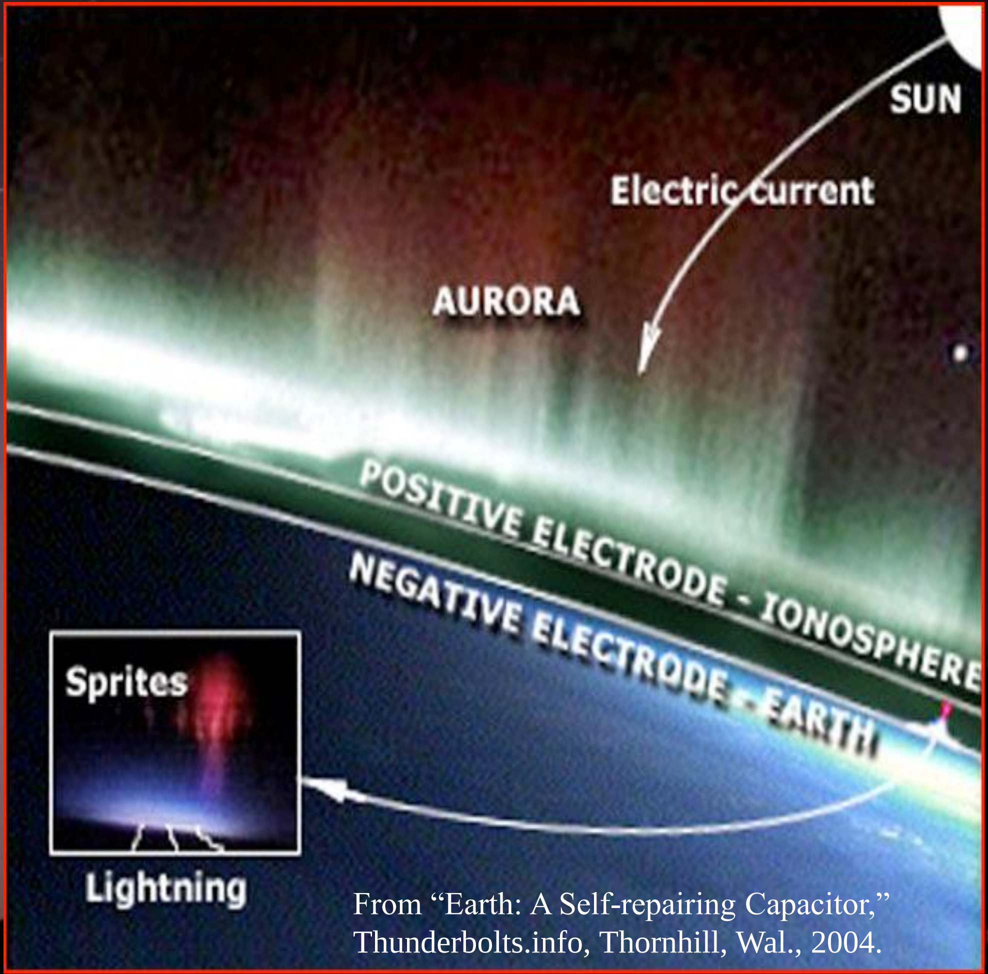


Earth: A Self-Repairing Capacitor

- Earth's surface & ionosphere can be viewed as two oppositely charged conducting plates forming a natural capacitor, with the atmosphere serving as an insulator between them.
- During fair weather, the ground is typically negatively charged whereas positive charge is generally associated with the ionosphere.



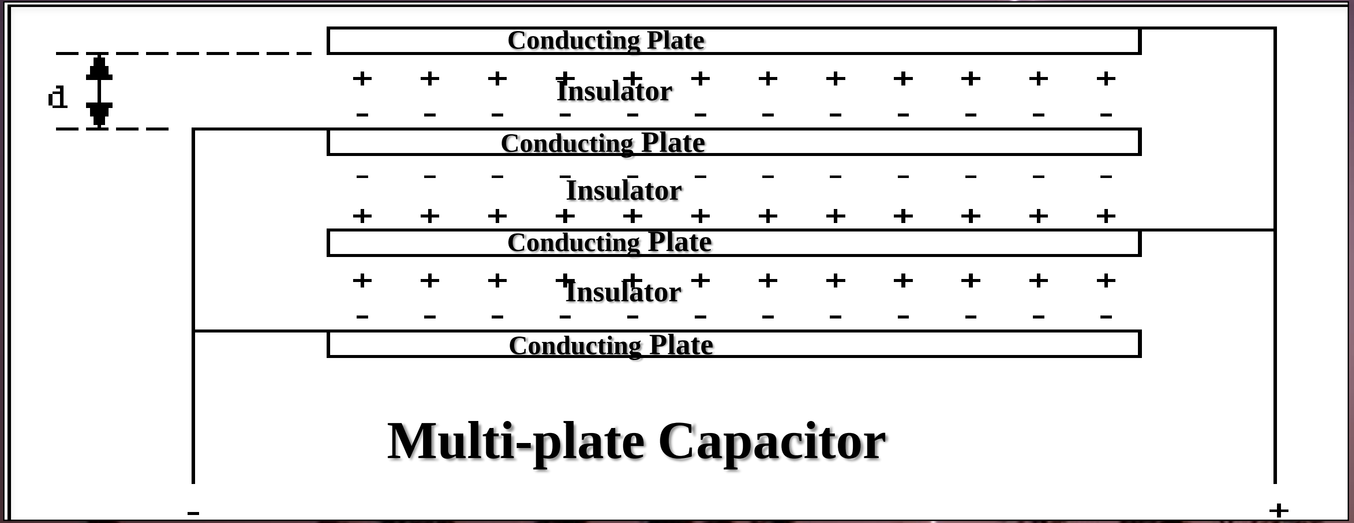
Ionosphere image/illustration courtesy of NASA/GSFC/CI Lab/B. Monroe

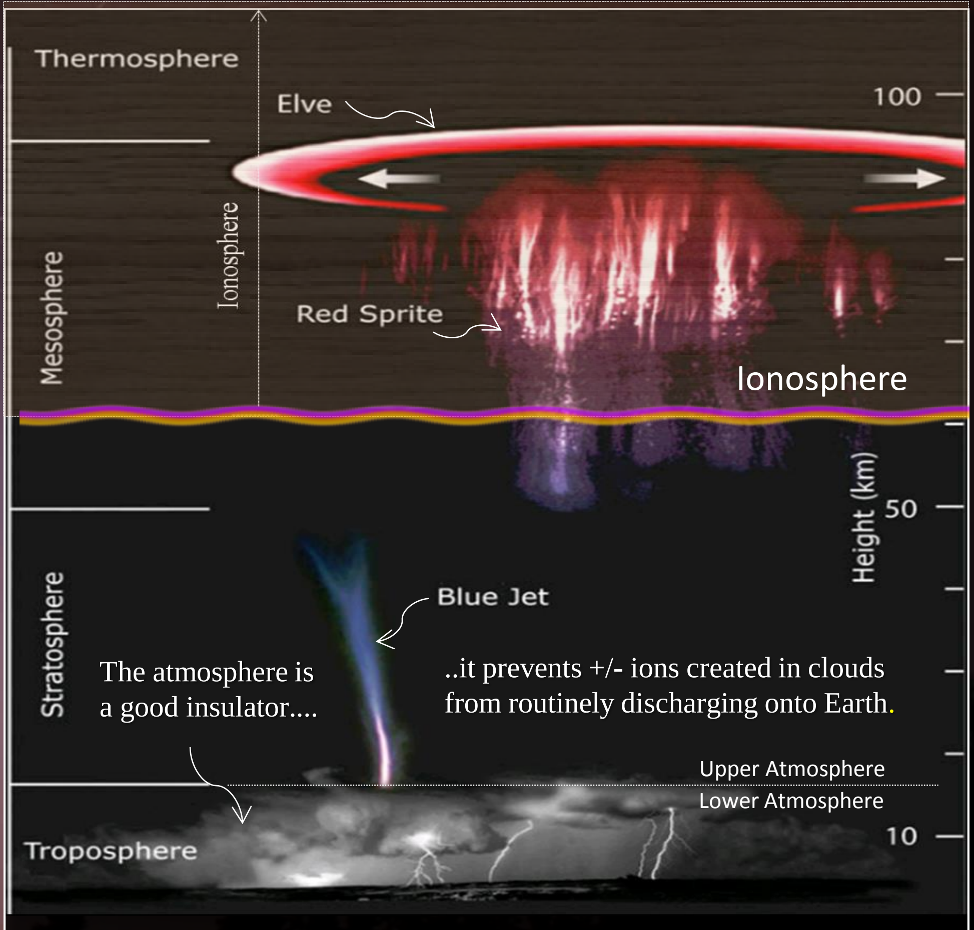


From "Earth: A Self-repairing Capacitor," Thunderbolts.info, Thornhill, Wal., 2004.

Earth: A Natural Multi-plate Capacitor

- Electrical discharge phenomena & lightning occur throughout the atmosphere, both above & below the lower atmospheric clouds & within the ionosphere.
- Atmospheric & ionospheric lightning phenomena suggest the ground, clouds & ionosphere together may interact as a natural multi-plate capacitor.





Atmospheric lightning & electrical-discharge phenomena, European Space Agency, Thunderbolts.info, 11/05.

Lightning Strikes Are Not Random!

Influenced by Lateral/Vertical Variation of Rock Properties:

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

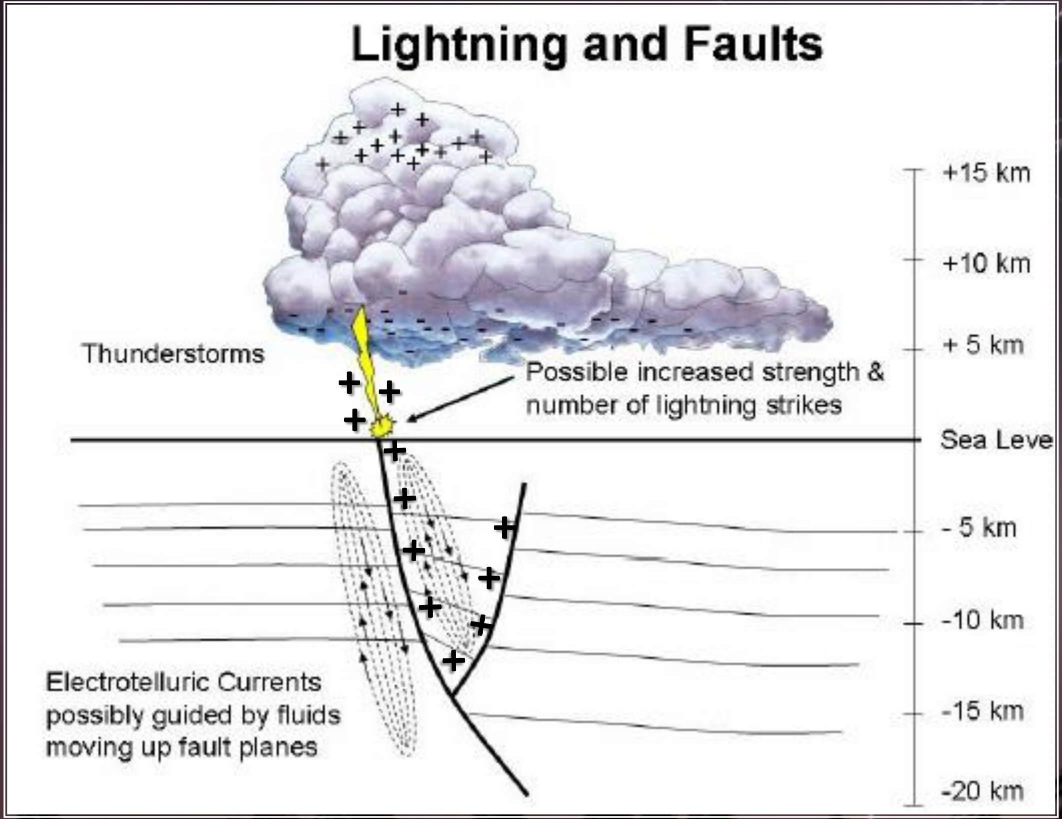
Upward lightning shows electrostatic charge builds up in the ground, as well as in the atmosphere.

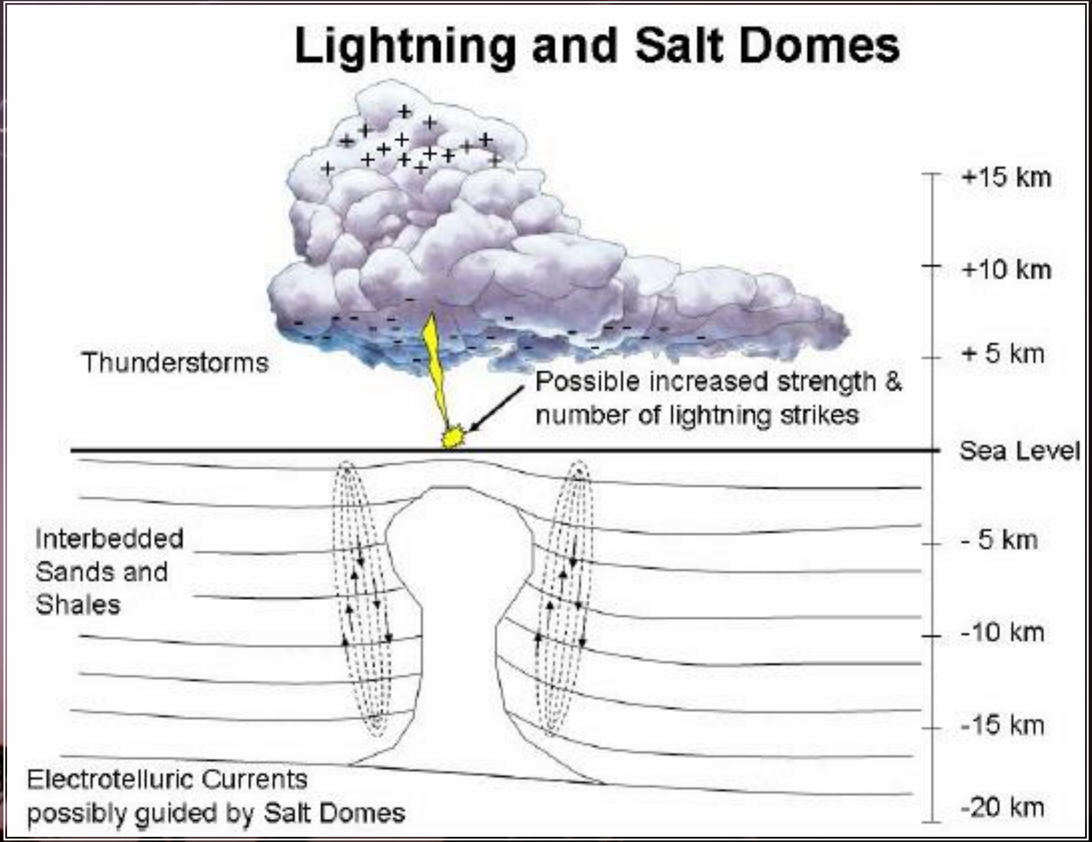
Geology driven electrical rock property heterogeneity facilitates surface/subsurface polarization & subsequent induction of current triggered by storm cloud proximity.

Induced currents perturb telluric currents and hence influence lightning.

Telluric Currents, Lightning & Geology

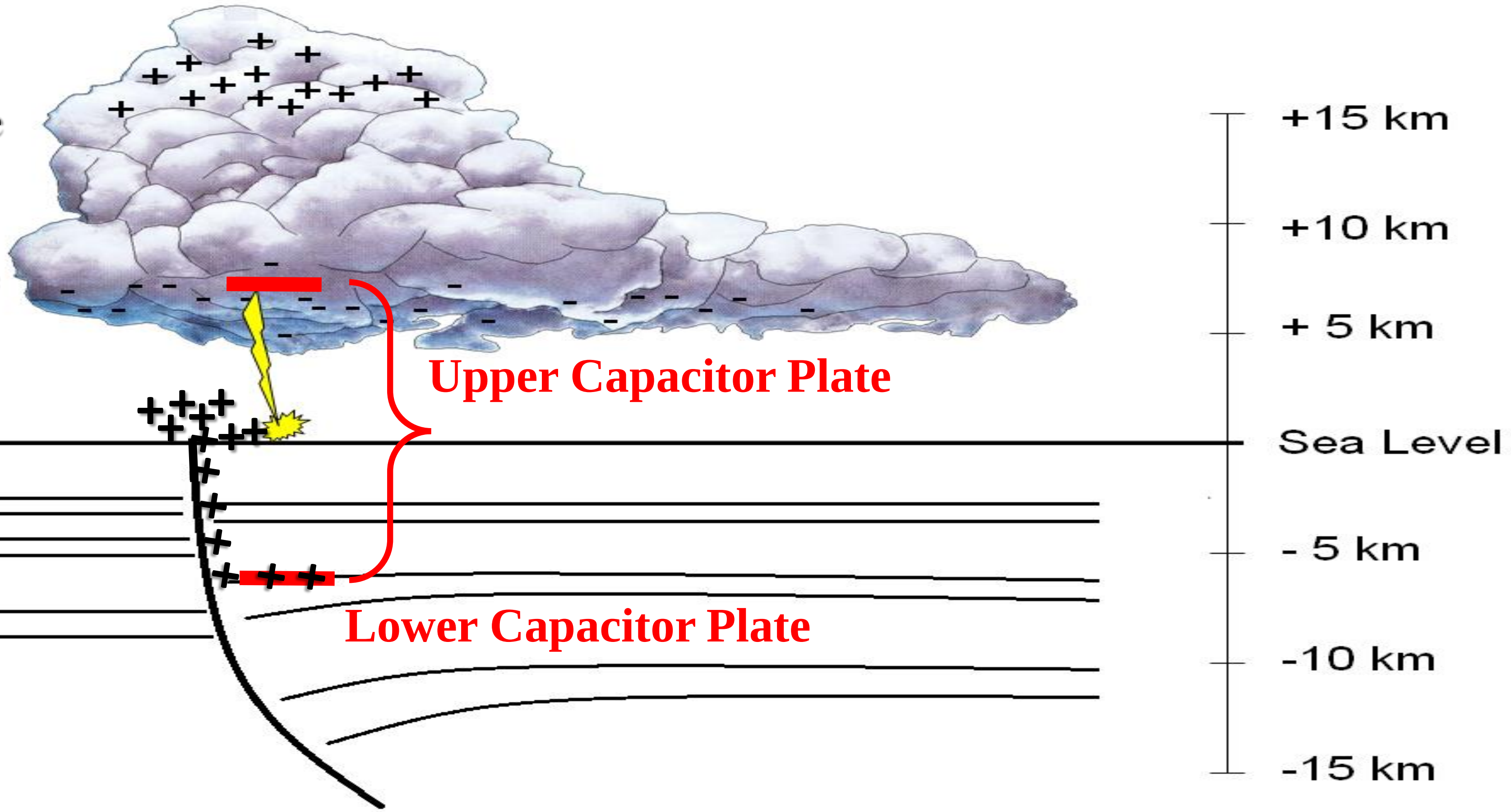
Earth Currents Modified by Geology ⇨ Prone to Lightning





Multi-layer Capacitor Model: Subsurface-to-cloud layer system

Each strike represents the discharge associated with a unique capacitor.



Peak current of each strike assumed to be proportional to cloud height, i.e. the equivalent of half the distance to the bottom capacitor plate.

The corresponding depth below Earth's surface to the bottom plate represents depth of geologic influence on telluric currents & hence to lightning & its attributes.

How Does Geology Influence Lightning?

The next series of images represent the culmination of theoretical, field & laboratory work of Dr. Friedemann Freund, who has formulated and written extensively about his Rock Stress Electromagnetic Signal Theory.

Dr. Freund's findings provide independent support for Dynamic Measurement's empirical field results and theoretical argument linking geology to lightning strike patterns and lightning attributes.

Dr. Freund is affiliated with the NASA Ames Research Center, the Carl Sagan Center and the SETI Institute, located in Mountain View, CA and the Department of Physics at San Jose State University, San Jose, CA.

Dr. Freund's theory will now be applied to the field of NSEM.

Stress-Induced Currents in the Laboratory

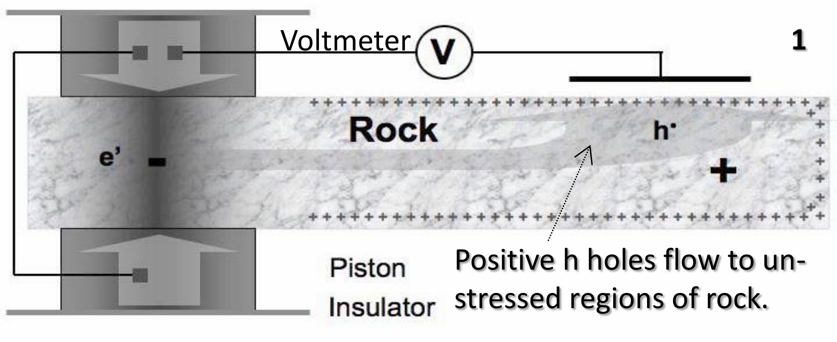
DYNAMIC MEASUREMENT

- Although silicate minerals are primarily insulators, most can behave as semiconductors because they contain dormant electronic charge carriers, i.e. electricity that can be activated by stress.
- * When rocks are subjected to stress, first positive and then negative charge carrying currents are produced (positive or "h holes" and electrons respectively).
- * These stress-induced currents flow toward the unstressed region of rock samples and from the interior to the rock's exterior, ultimately ionizing the air.
- Thus, faulted areas appear to offer a plentiful supply of dormant charge carriers that when triggered by the attraction of overhead storm clouds, can provide the necessary current flow, in the form of "streamers," to attract opposite charged step-leaders.

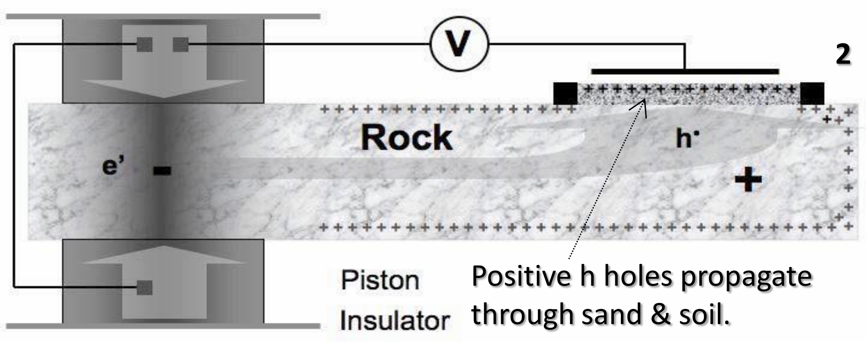
* Demonstrated by F. Freund, "Toward a unified solid state theory for pre-earthquake signals," Acta Geophysica 58(5):719-766 · Oct. 2010.

Stress Produces A Rock Battery in the Lab

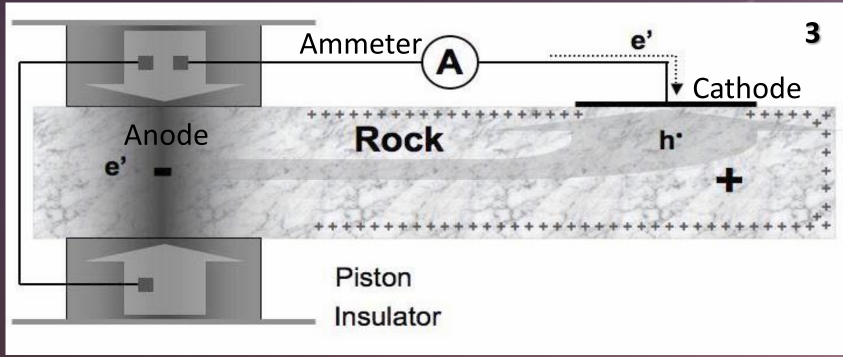
Stress-Induced Currents



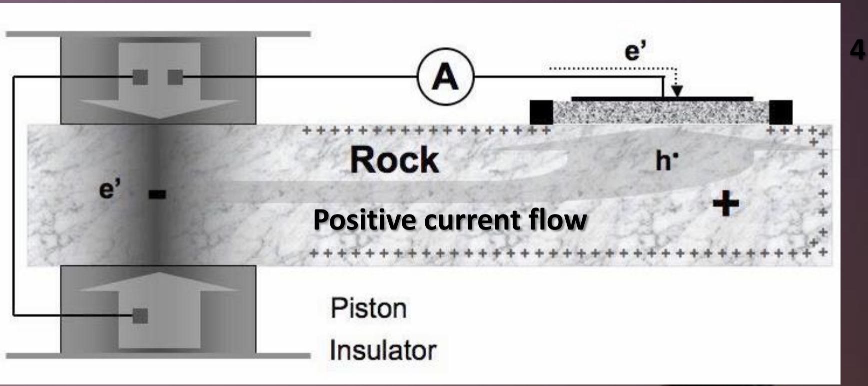
Set-up to measure the positive surface potential with a capacitive sensor.



Potential difference measured between unstressed rock & piston, indicating build-up of surface & subsurface charge.



Battery circuit completed by placing copper contact (cathode) on rock. Ammeter measures current.



Demonstrates that positive h hole current also flows through sand and soil.

Stress produces positive charge carrying currents in the lab.

"Loading simulates tectonic stresses causing existing dislocations to move & new ones to be generated in response to shear forces acting on mineral grains."

"Dislocations activate h charge carriers alongside electrons" **(Freund, 2002; Freund et al., 2006)**

Above fig. modified from Friedemann Freund, "Toward a unified solid state theory for pre-earthquake signals," Acta Geophysica 58(5):719-766 · Oct. 2010.

Stress-Induced Changes of Electrical Rock Properties -

- Creation of dormant charge carriers.
- Localized electrical currents generated.
- Provides reservoir of positive and negatively charged particles.
- Streamers capable of influencing lightning.

Conductivity of dry granite increases with uniaxial stress.

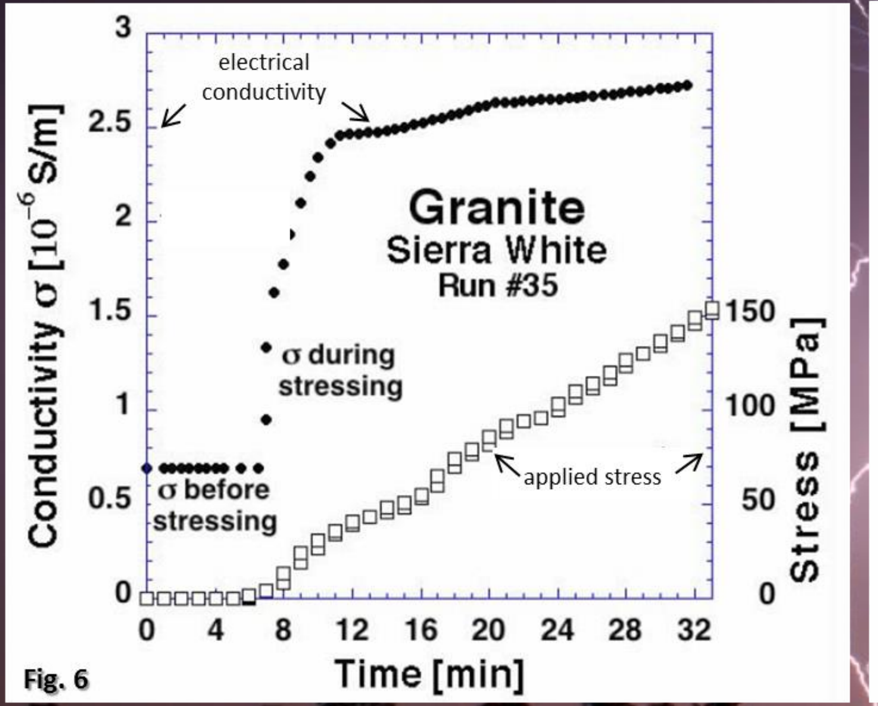


Fig. 6

Surface potential of gabbro increases with stress, initially strongly positive then weakly negative.

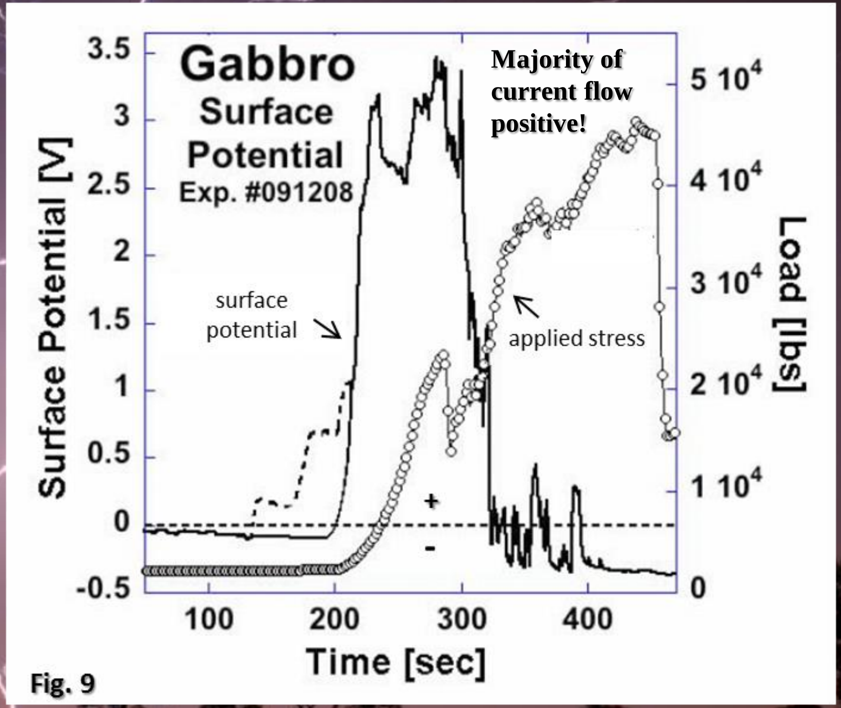


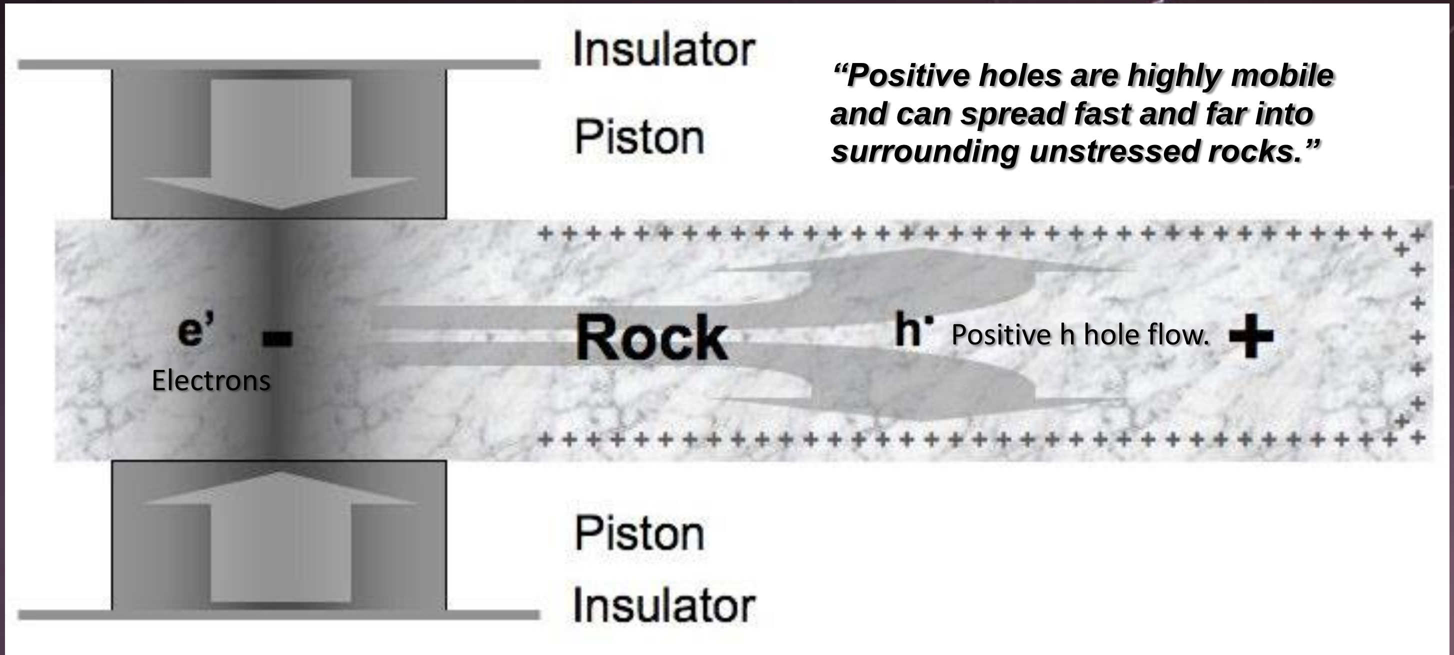
Fig. 9

Above figures modified from F. Freund, "Toward a unified solid state theory for pre-earthquake Signals," Acta Geophysica - October 2010, DOI: 10.2478/s11600-009-0066-x . * From F. Freund's rock stress-EM signal theory.

* Recent studies by F. Freund suggest that stress-induced increases in conductivity and the generation of both positive and negative currents and surface potential, are not solely influenced by improved grain-to-grain contacts.

* It is likely that changes in electrical rock properties are caused by an increase in the number of electrons, negative ions and positive hole charge carriers produced when rock volumes are stressed.

Stress-Induced Positive Charge Carriers



*"In the lab, highly mobile positive holes flow out of the stressed rock volume several meters into the surrounding unstressed rocks.

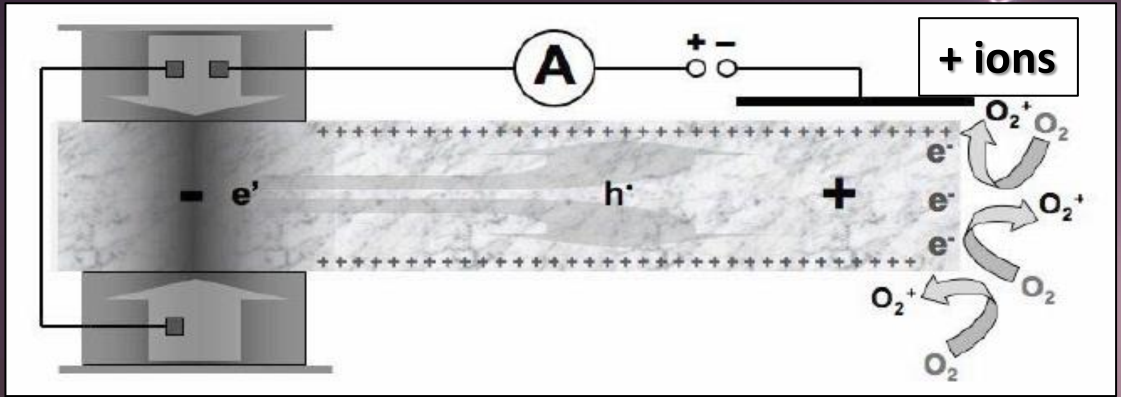
In the field, the positive current flow would presumably involve several kilometers."*

The vast majority of stress induced electrical currents produced in the lab are positive.

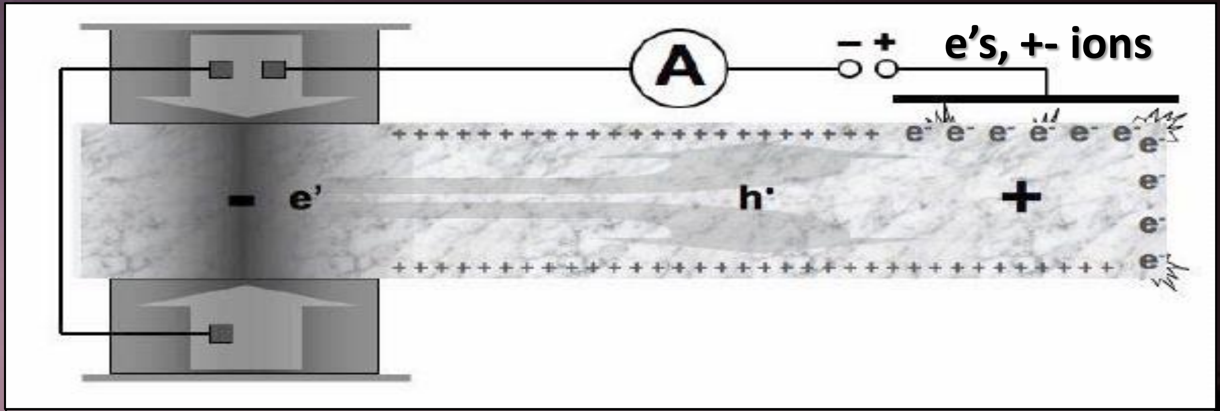
* Diagram and quotes from F. Freund, M. Lazarus, G. Duma, "Top-down and Bottom-up Coupling between Ionosphere and Solid Earth," Poster, NASA, CA; SETI Institute, CA; San Jose State Univ., CA; Lancaster Univ. UK; ZAMG, Vienna, Austria.

Lab & Field Ionization of Air Molecules

- Laboratory experiments demonstrate how stress-induced currents can promote ionization of neutral gas molecules at the Earth's surface, producing free electrons and positive and negative ions.
- In the vicinity of faults a plentiful supply of airborne ions would be available during thunderstorms to feed both positive and negative streamers.



Lab set-up demonstrates how air molecules (O_2)) , are ionized when rock samples are stressed, resulting in + airborne ions capable of forming into streamers during thunderstorms. In the above set-up, the + ions would attract negative lightning.



"When electric fields at the rock surface increase sufficiently, electrons can accelerate to cause impact-ionization of neutral gas molecules, triggering corona discharges. This produces free electrons & negative & positive airborne ions."

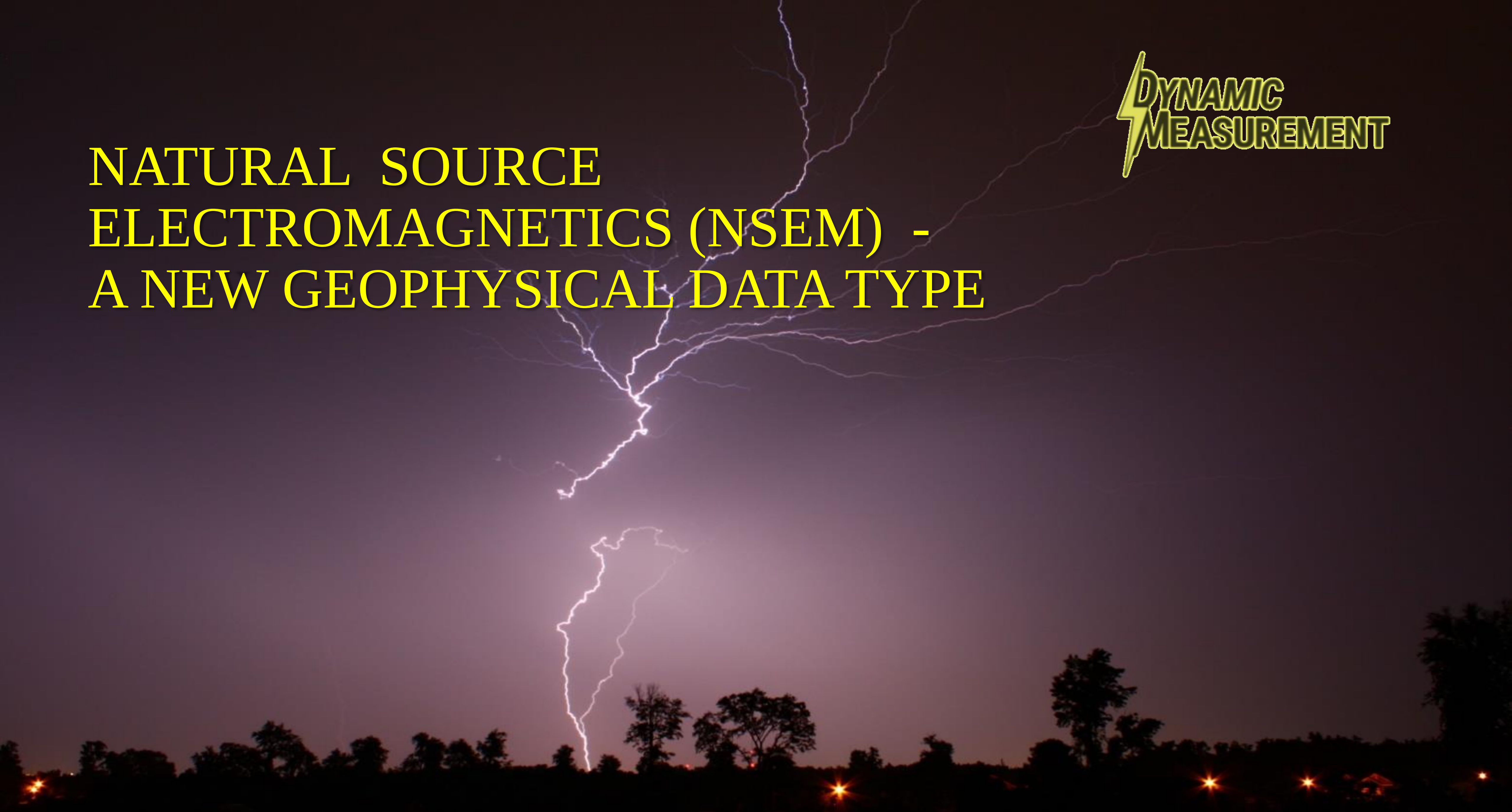
Above fig.'s modified from F. Freund, "Toward a unified solid state theory for pre-earthquake signals," Acta Geophysica 58(5):719766 · Oct. 2010.

Connection to the Atmosphere & Lightning

- * Field data associated with earthquake-producing faults show dramatic pre-earthquake atmospheric/ionospheric anomalies caused by the emission of electromagnetic energy.
- One such emission is the "Earthquake Lightning" phenomenon, the worldwide appearance of plasma that often appears in the sky during fair weather conditions prior to earthquakes & believed to be related to faults.
- * These atmospheric/ionospheric electromagnetic anomalies have been intimately linked to the semi-conductor behavior of rocks & their associated dormant charge carrying currents documented in the lab.
- The ability of stressed segments of the crust to essentially store dormant charge carrying currents provides one link to how geology may influence lightning.

* From Friedemann Freund, "Toward a unified solid state theory for pre-earthquake signals," Acta Geophysica 58(5):719766 · Oct. 2010.

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



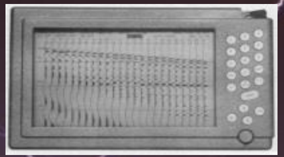
Time-Line of New Geophysical Data Types

Dynamic Measurement

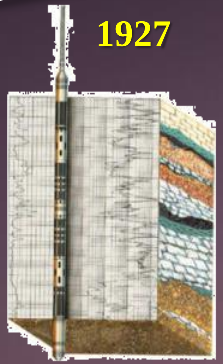
1752

1833

1920s

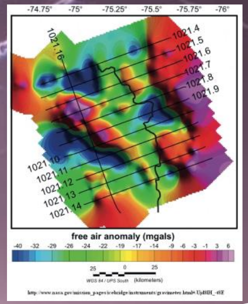


1927

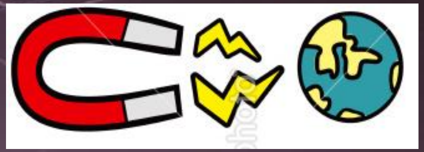


1931

1936

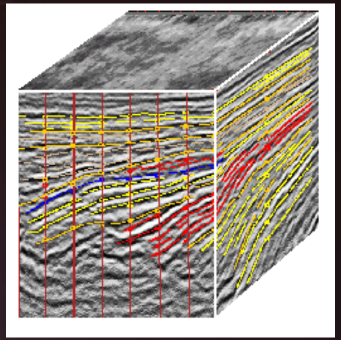


1950s

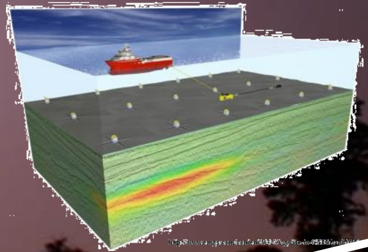


1960s/70s

1974

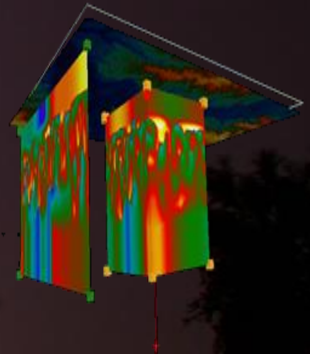


1997



2008

2015



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

Proven & Patented Technology
(two existing patents, a third to be submitted)

DYNAMIC MEASUREMENT

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)

(73) Assignee: **Vaisala Oyj**, Helsinki (FI)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 391 days.

(21) Appl. No.: **12/655,810**

(22) Filed: **Jan. 7, 2010**

(65) **Prior Publication Data**

US 2011/0163733 A1 Jul. 7, 2011

(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

5,417,282 A * 5/1995 Nix 166/248
2010/0023267 A1* 1/2010 Karabin et al. 702/4

* cited by examiner

Primary Examiner — Amy He
(74) *Attorney, Agent, or Firm* — Portland Intellectual Property, LLC

(57) **ABSTRACT**

A method for locating sub-surface natural resources. The method utilizes lightning data to discern relatively likely locations for finding the sub-surface natural resources.

16 Claims, 8 Drawing Sheets

DYNAMIC MEASUREMENT

US009523785B2

(12) **United States Patent**
Denham et al.

(10) **Patent No.:** **US 9,523,785 B2**
(45) **Date of Patent:** **Dec. 20, 2016**

(54) **METHOD FOR DETERMINING GEOLOGICAL SURFACE AND SUBSURFACE RESISTIVITY**

(71) Applicant: **Dynamic Measurement, LLC**, Cedar City, UT (US)

(72) Inventors: **L. R. Denham**, Houston, TX (US); **H. Roice Nelson, Jr.**, Cedar City, UT (US); **D. James Siebert**, Katy, TX (US)

(73) Assignee: **Dynamic Measurement, LLC**

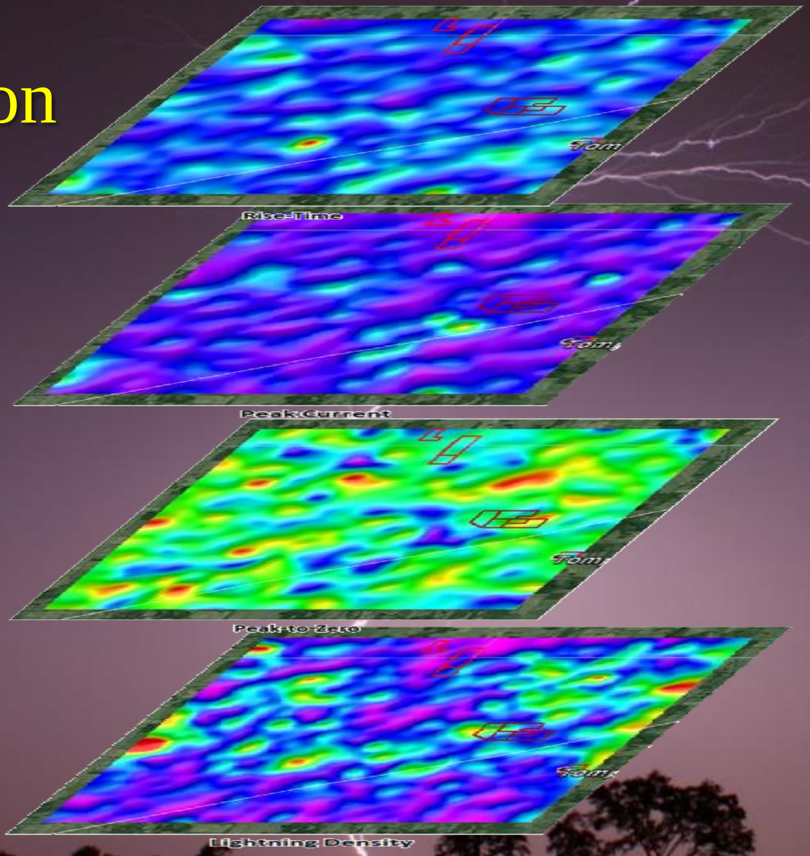
(57) **ABSTRACT**

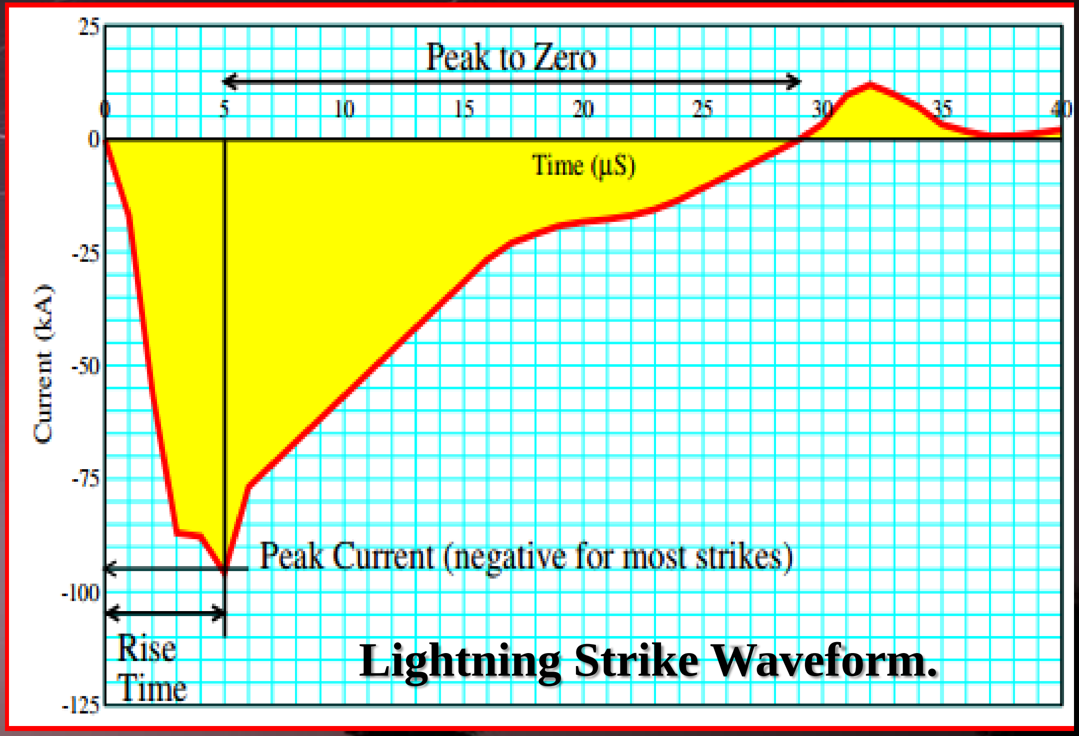
A method for determining geological subsurface resistivity. The method includes obtaining a set of lightning parameters associated with a lighting strike received by a geological volume of material, the set of lightning parameters including an indicium of the current of the lightning strike at a first initial time and an indicium of the current of the lightning strike at a first decay time subsequent to the first initial time, and inferring the resistance of the volume of geological material, at least in part, from the set of lightning parameters.

6 Claims, 2 Drawing Sheets

Lightning Strike Measurements ("Attributes")

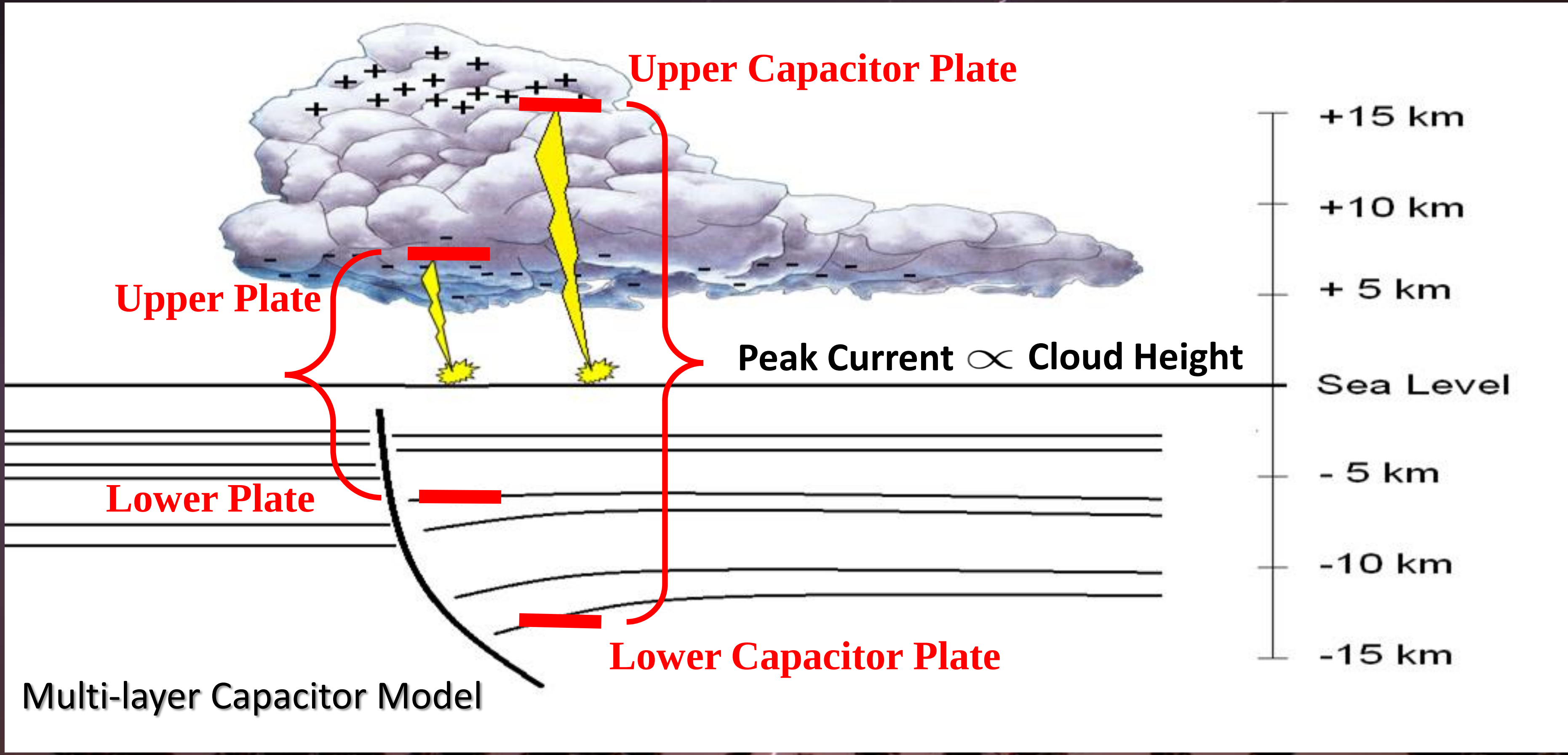
- Location
- Time and Duration
- Rise Time
- Peak Current
- Polarity
- Peak-to-Zero
- Density





Lightning Strike Waveform.

Depth of Electrical Energy Penetration - Function of Strike Strength



Millions of lightning strikes grouped by peak current.

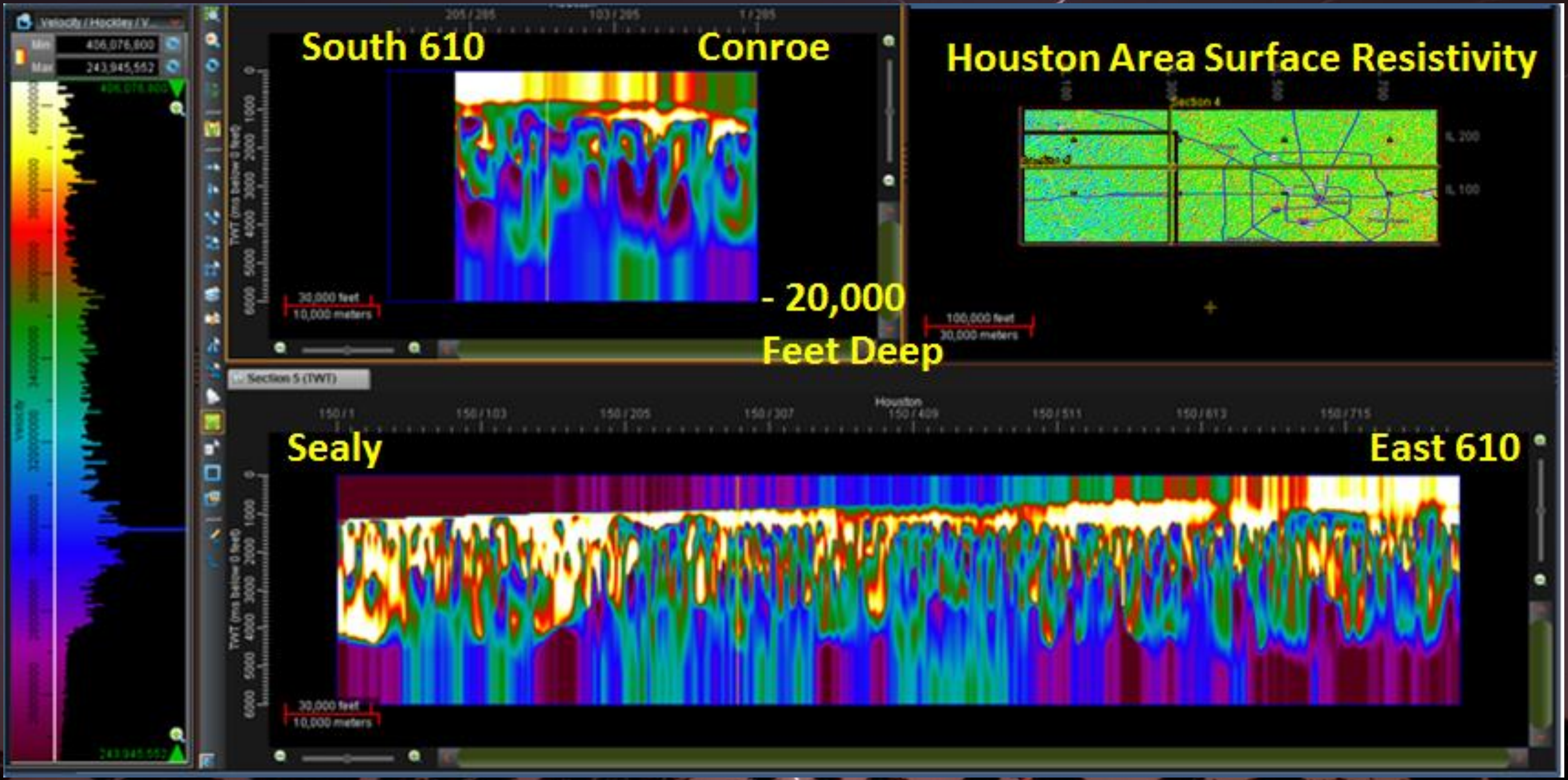
Strike data therefore grouped by depth.

Provides basis for generating 3-D apparent resistivity volumes.

3-D Resistivity Volumes

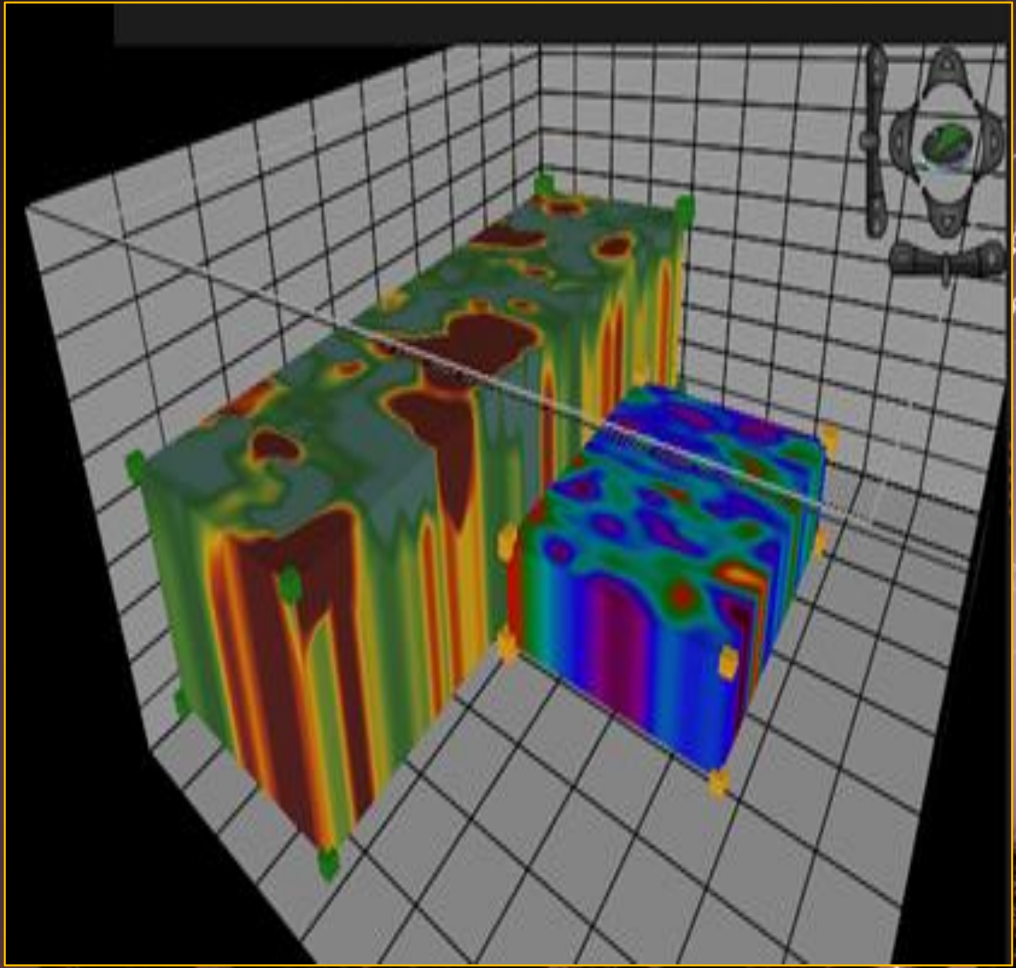
- Data traces uniformly sampled in time/depth with same # samples in each trace as required by 3-D seismic interpretation software.
- For each trace a depth & resistivity grid is generated & sampled.
- Resistivity values interpolated between sampled points with respect to depth, producing samples at uniform intervals.
- Typical sample interval approximately 160’.
- Typical trace length 125 samples.
- No sample interval/trace length restrictions beyond those imposed by SEG-Y format.

NSEM Correlates To Geology:
Houston, TX Resistivity Cross-Section

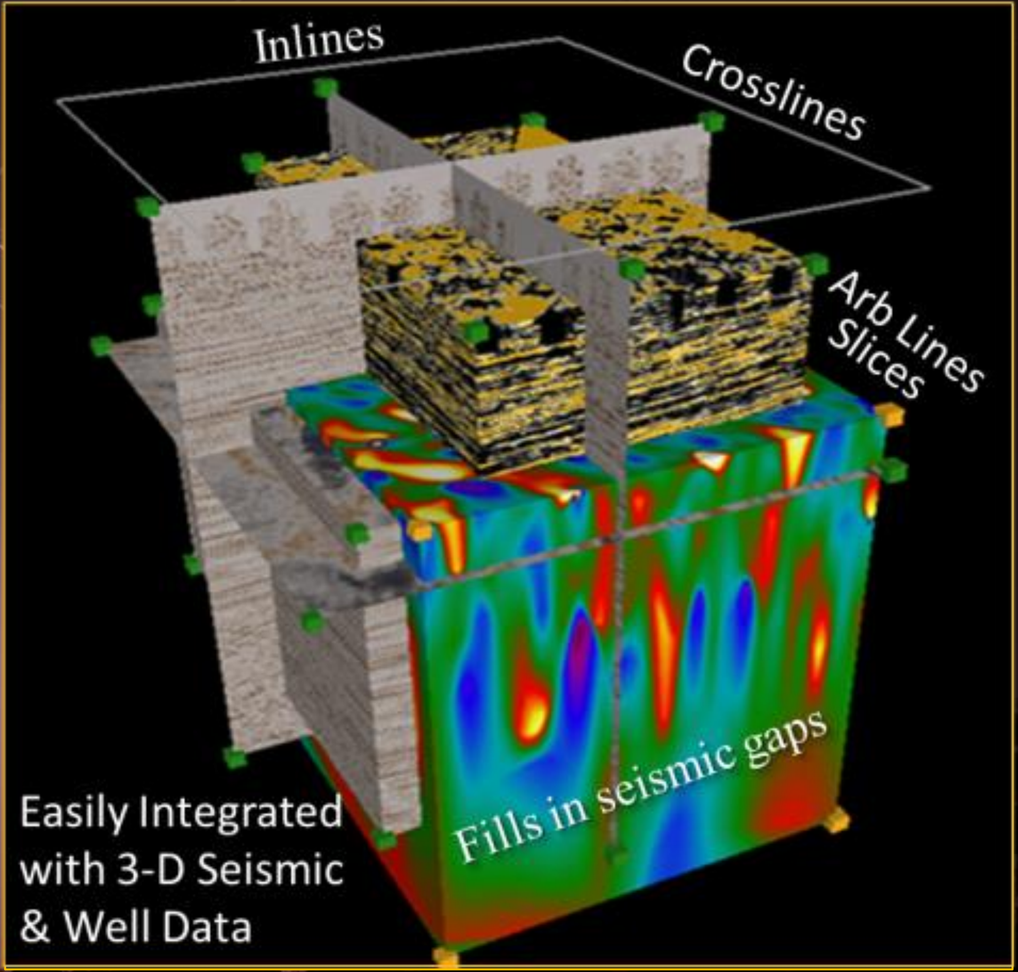


Based on assumptions between cloud height, peak current, the depth of the earth's lower capacitor for each strike, and the similarities between lightning physics & the physics describing relaxation oscillators, the math for converting lightning's electrical measurements to resistivity volumes has been developed & patented.

Resistivity & Permittivity Volumes - Interpreted with 2-D/3-D Seismic & Well Data



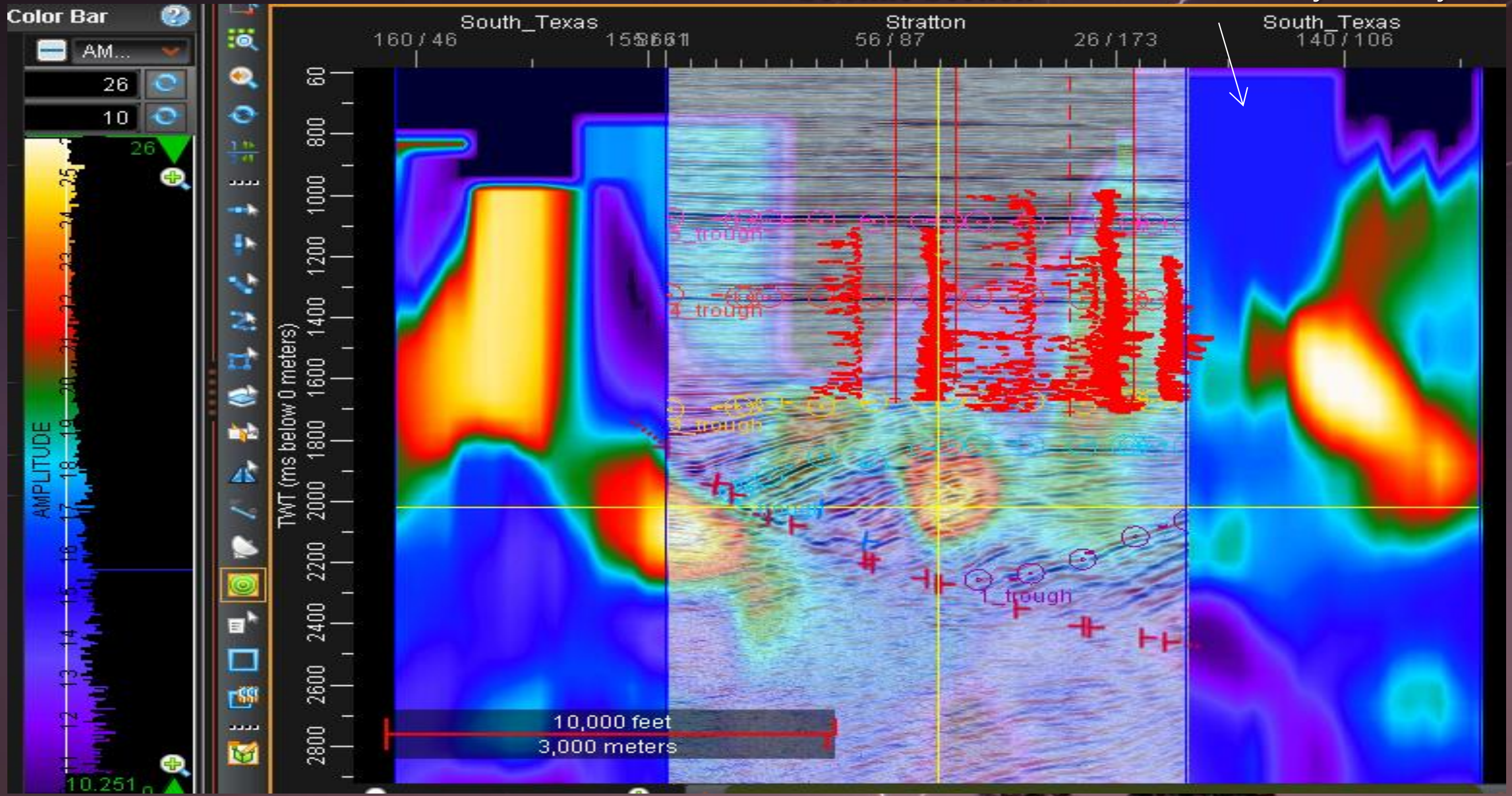
Inlines
Crosslines
Arb Lines
Slices



Display, Integrate & Interpret 3-D NSEM

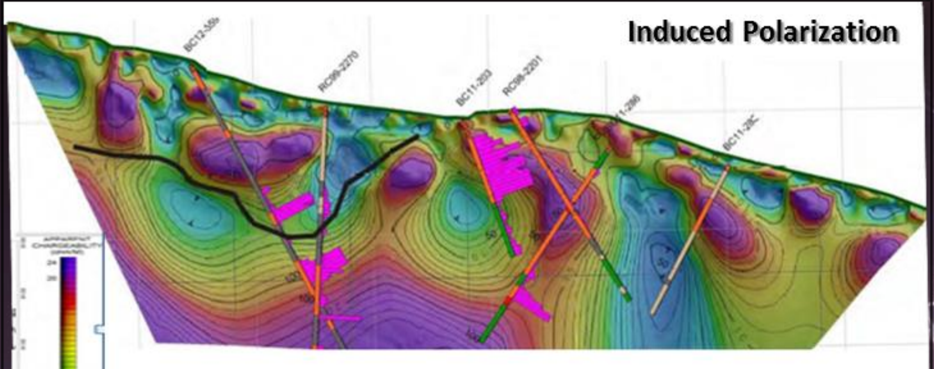
Seismic Section

NSEM Resistivity Underlay

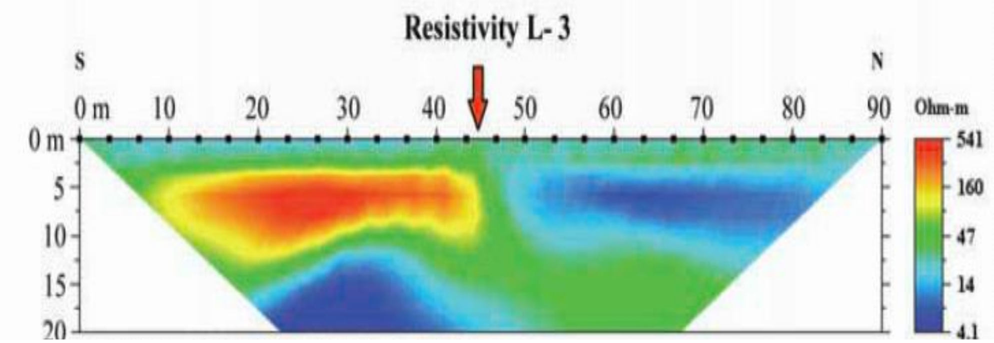


- Seismic & apparent resistivity sections & slices can be displayed in the same seismic project to facilitate data integration & correlation of features.
- Interpreters can display well logs, synthetic seismograms, seismic & resistivity profiles along any line, trace or arbitrary line direction for data calibration & interpretation.

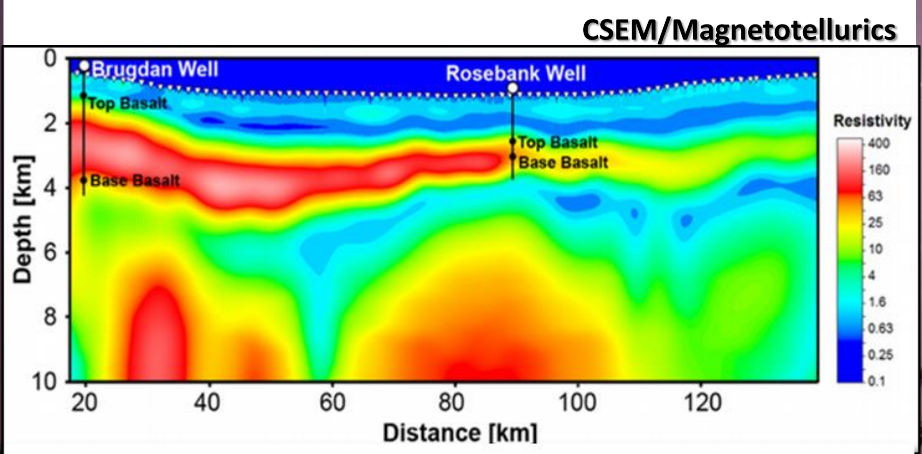
Resistivity & Permittivity Volumes
Easily Integrated w. Near-Surface Geophysical Data



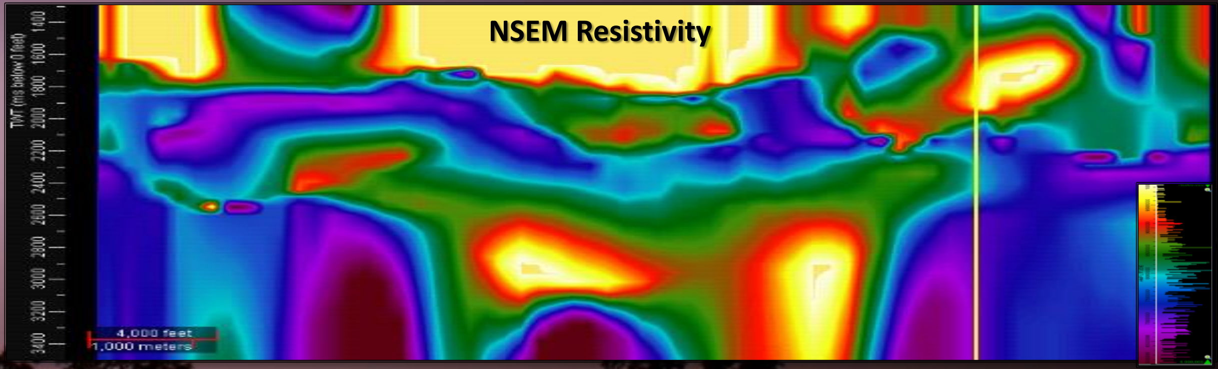
Yukon Geol. Survey, Report MR-11, Case Studies, M. Best, I. Fage and R. Daigle; http://www.geology.gov.yk.ca/pdf/MR-11_web(1).pdf



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



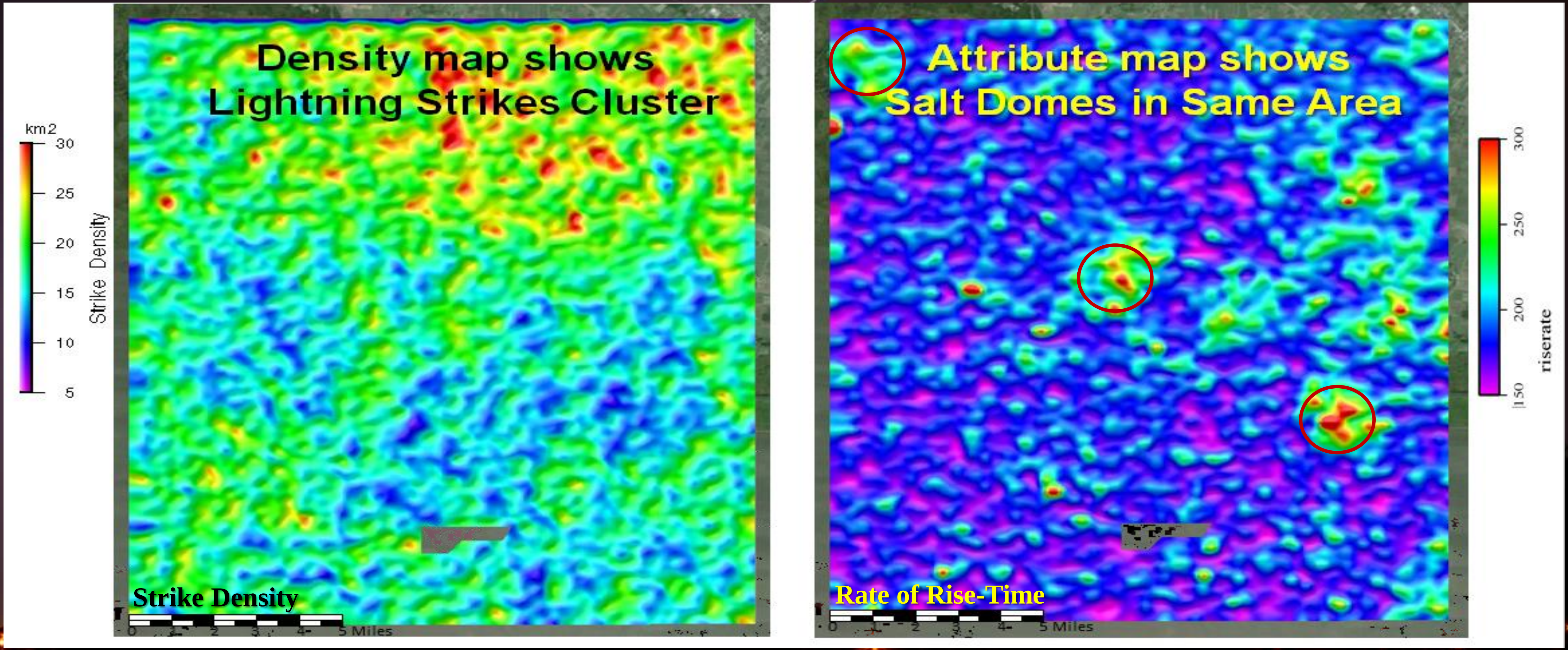
EMGS http://www.emgs.com/content/1234/MT



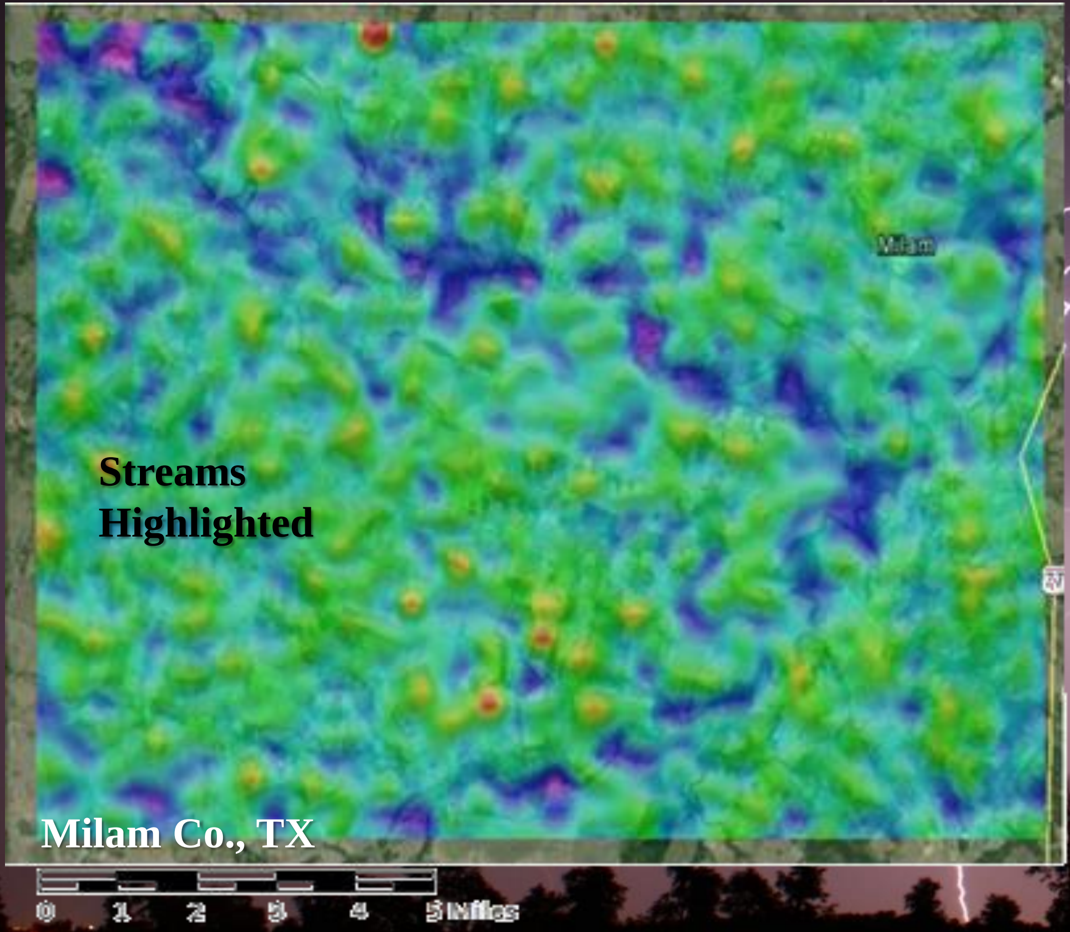
Examples of Using NSEM to Interpret Geologic Features

- Salt Domes - Iberia Parish, Louisiana
- Fluvial Deposition - Milam Co., TX
- Regional Trends - TX Gulf Coast
- Reconnaissance Mapping/Prospecting - Colorado Co., TX
- Mapping Faults - Hockley Salt Dome, Harris County, TX
- Rock Properties & Applications – Porphyry Cu & Sweet Spots
- Stratigraphic Mapping, Prospect Generation - Houston, TX

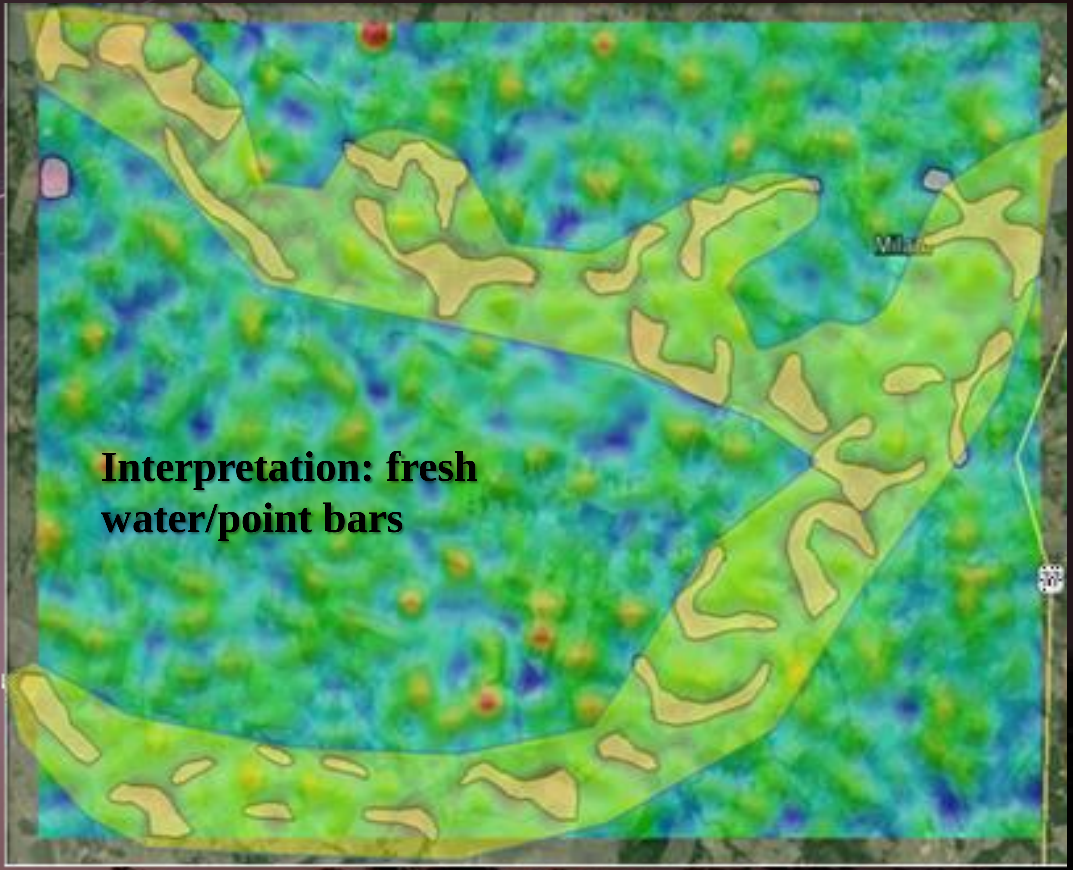
NSEM Correlates To Geology:
Salt Domes - Iberia Parish, LA



NSEM Correlates To Geology:
Fluvial Deposition - Milam Co., TX



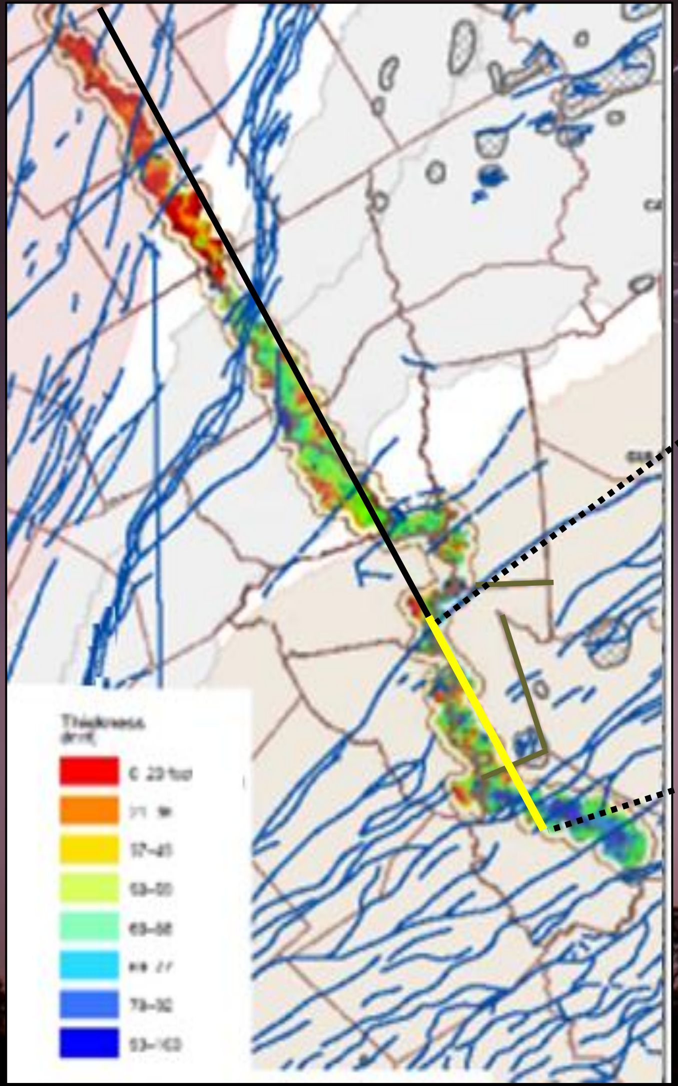
Lightning Attribute
Rate of Rise-Time

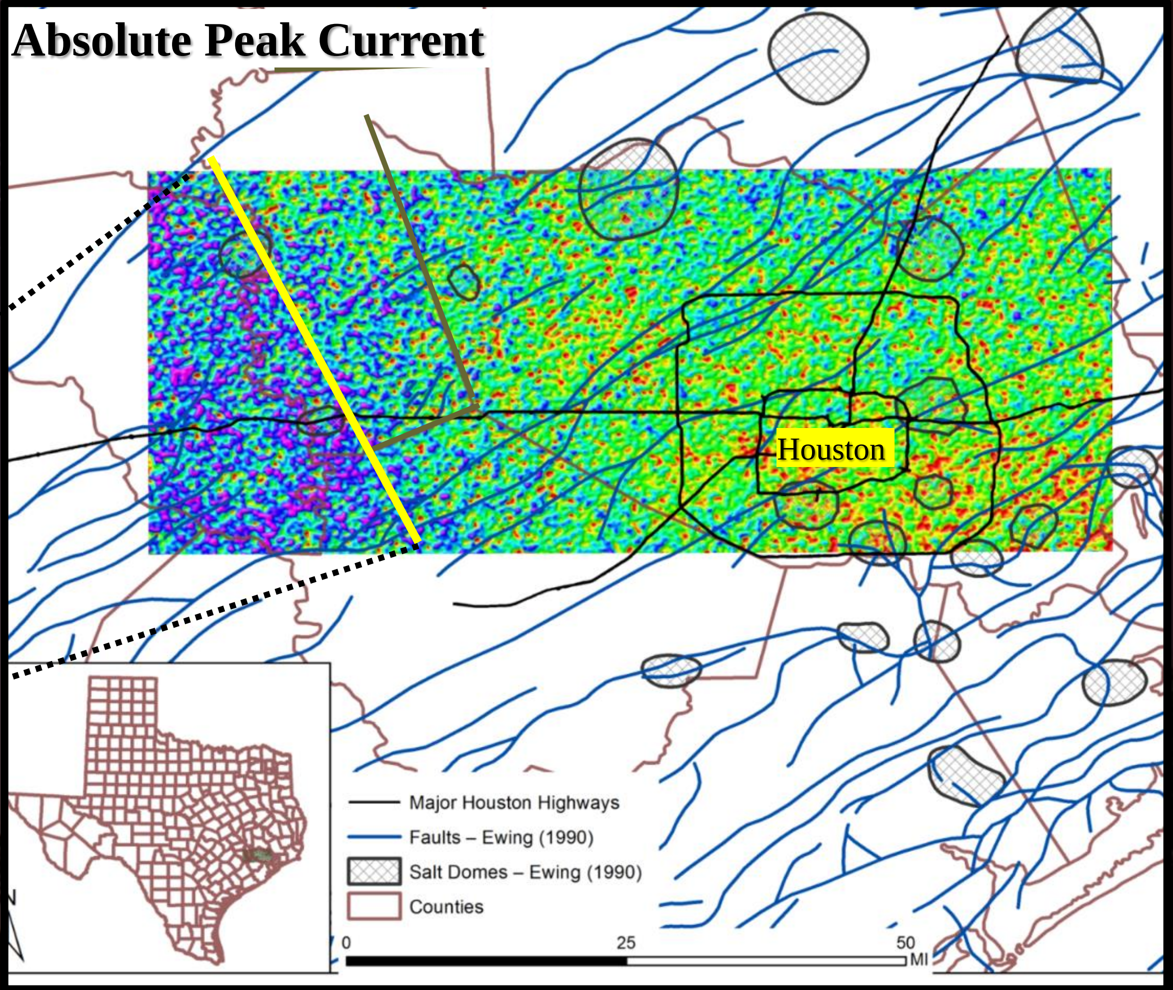


NSEM Correlates To Geology: Alluvium & Cretaceous Transform Fault

Brazos River Alluvium Aquifer

The black and yellow lines represents a Cretaceous transfer fault, separating lower Peak Current on the west from higher Peak Current on the East. This transfer fault controls the location of the Brazos River & is why it is the straightest & fastest river in Texas & why there is a straight line Brazos River Aquifer along the river channel.

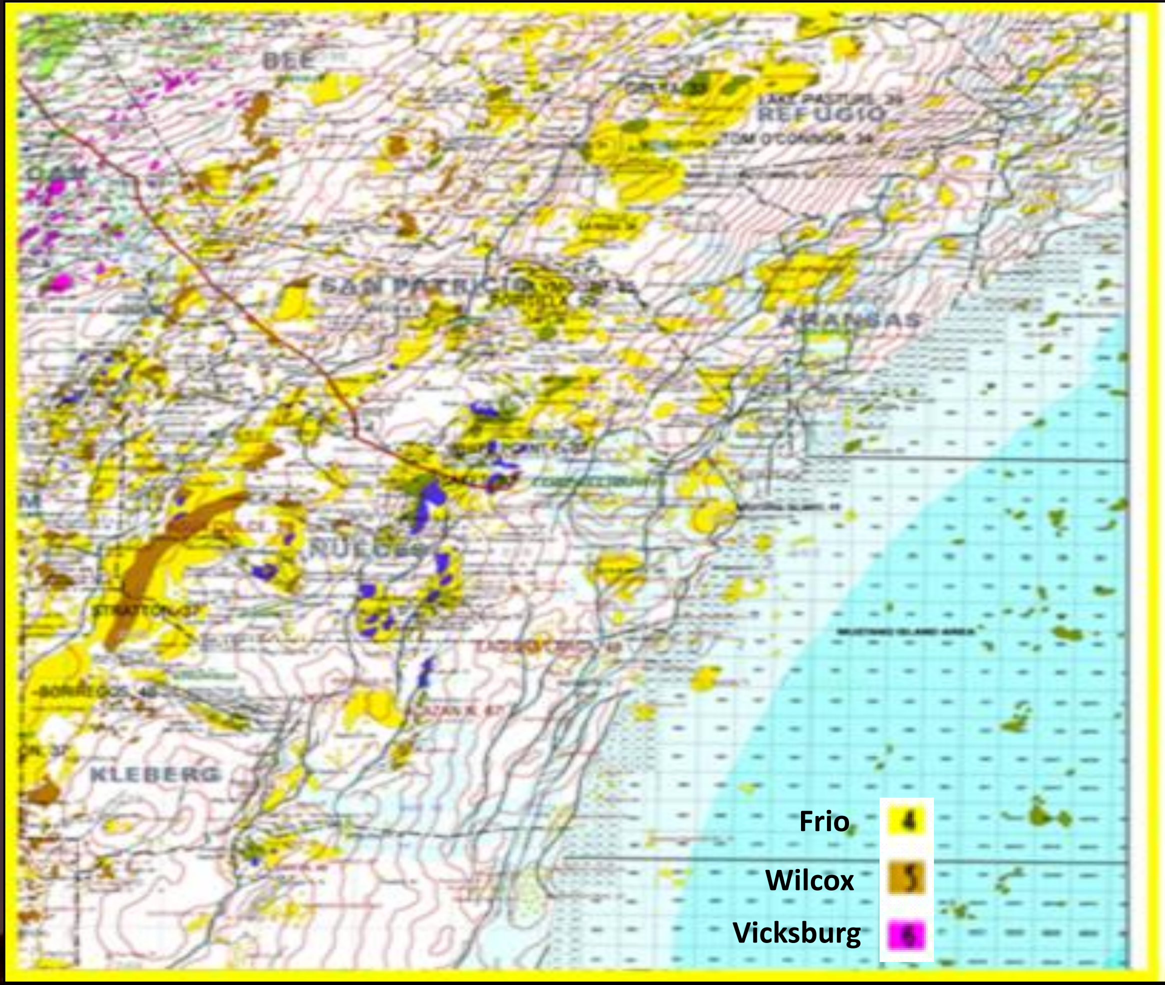




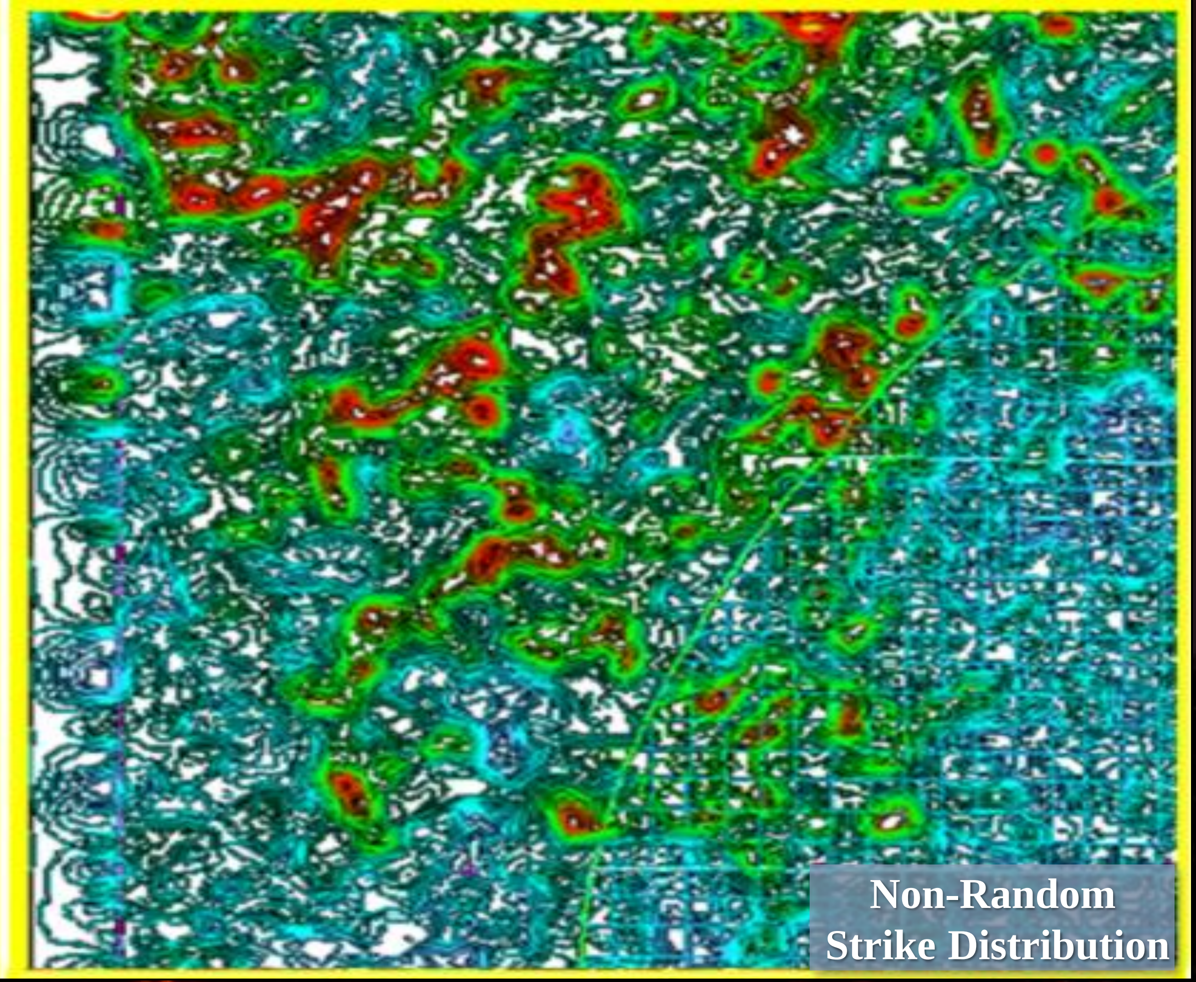
NSEM Correlates To Geology: Regional Trends - TX Gulf Coast

DYNAMIC MEASUREMENT

Structure & Field Outlines

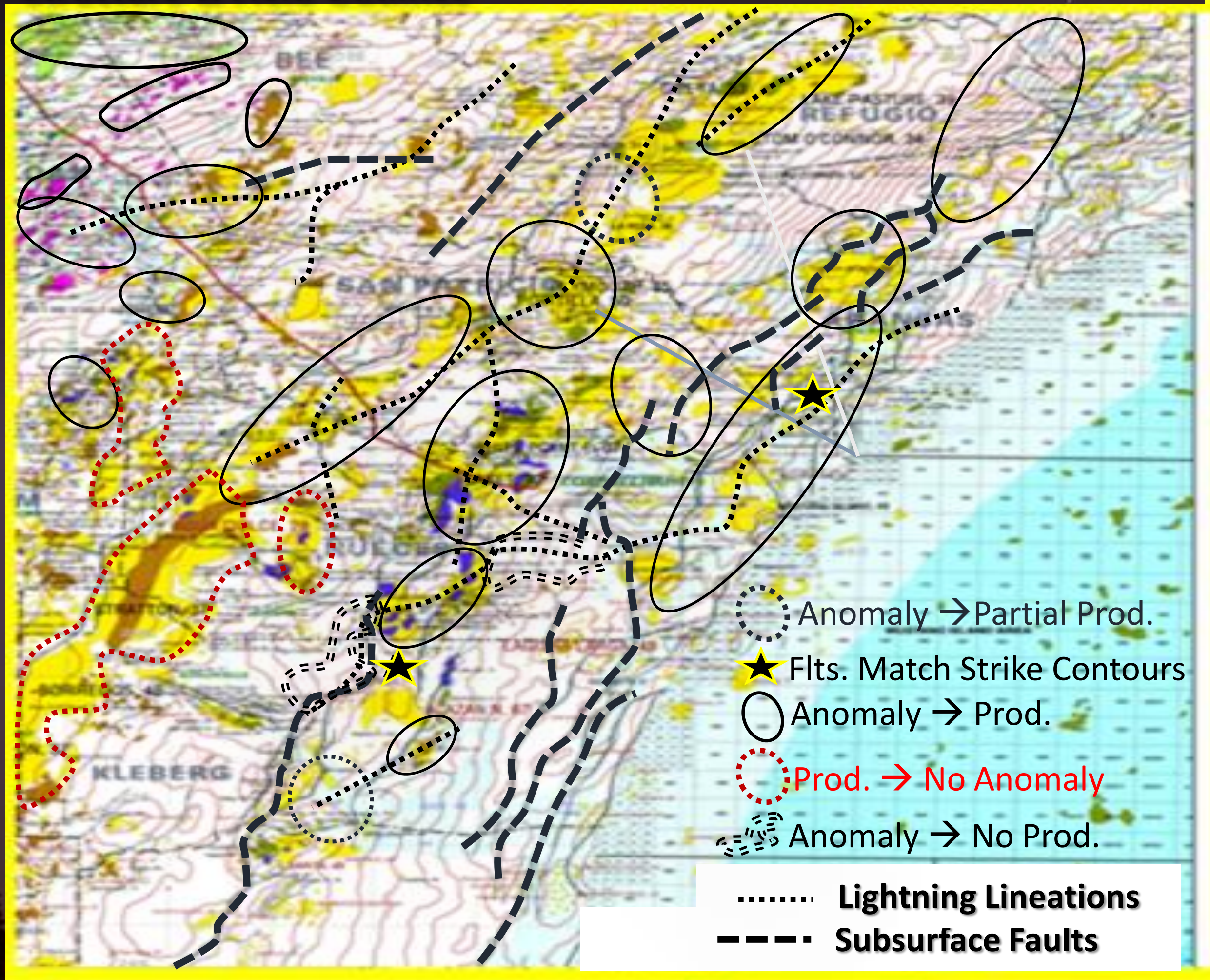


Lightning Strike Density

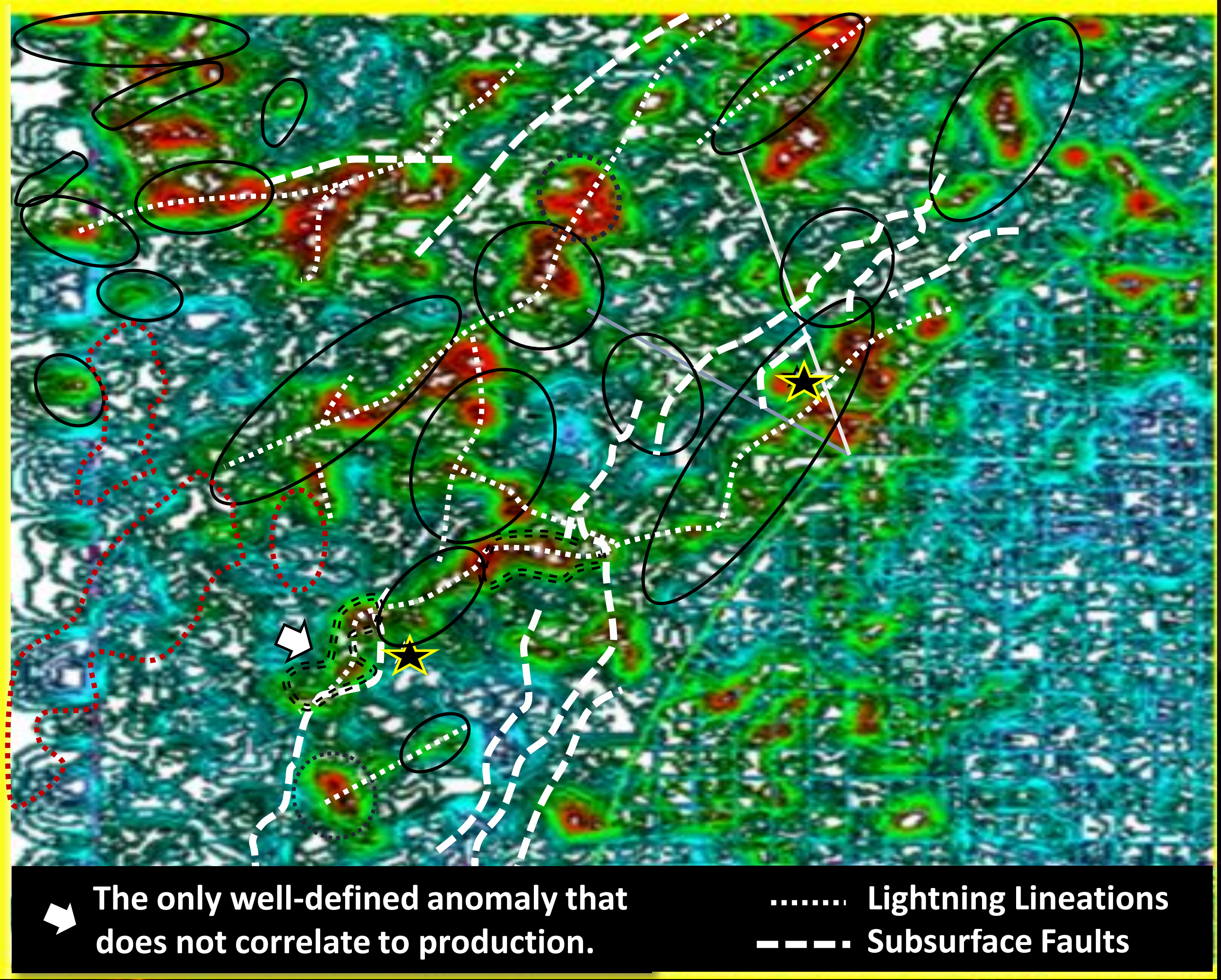


NSEM Correlates To Geology:
Fault Patterns & Hydrocarbon Accumulations

Structure & Field Outlines



Lightning Strike Density



Observations

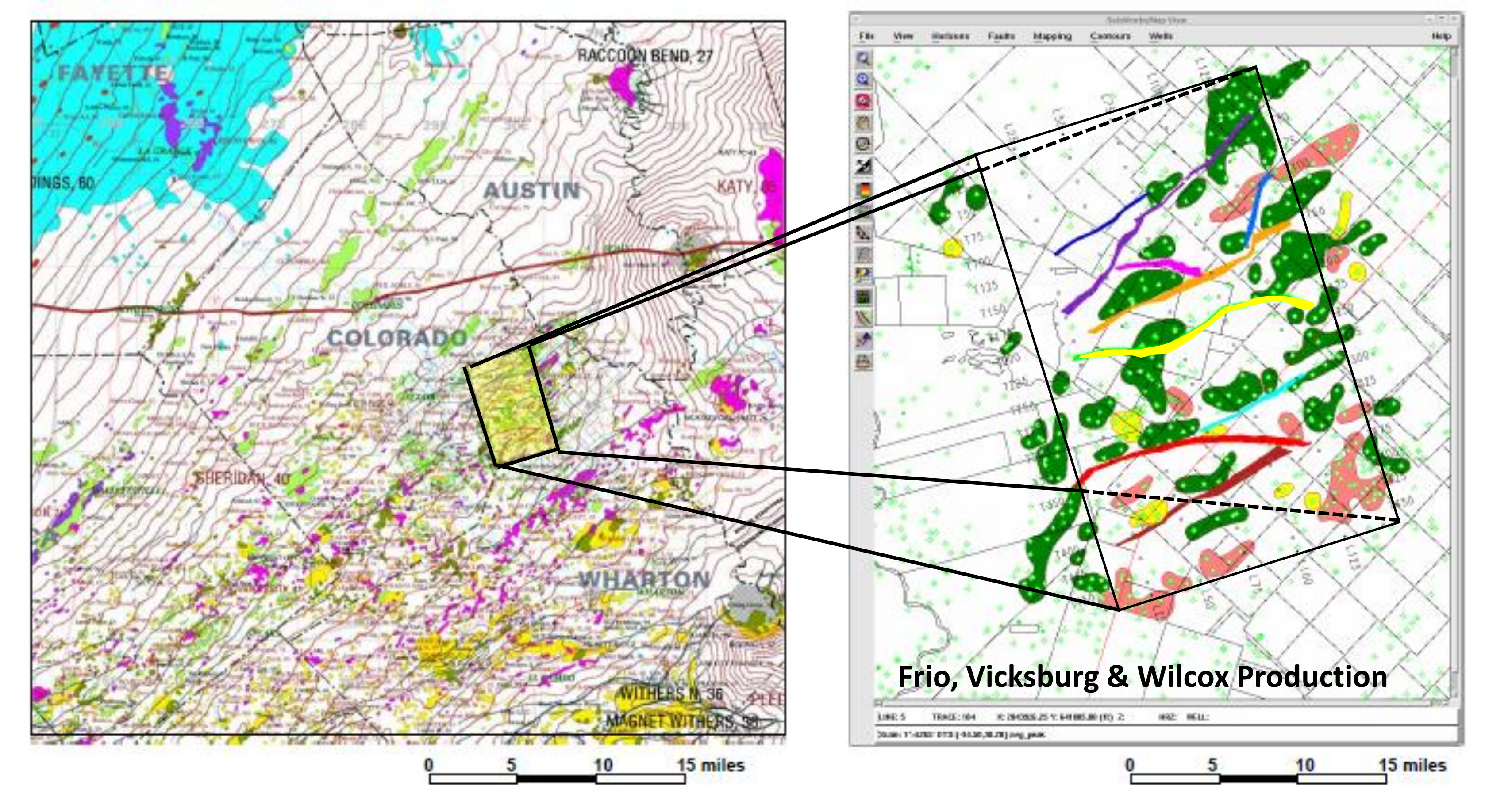
DYNAMIC MEASUREMENT

- Lightning strike locations are not random.
- Show NE/SW lineations similar to field locations.
- Faults generally strike parallel to sub-parallel to lightning features; 2 curved flts. (★) coincide w. strike density contours.

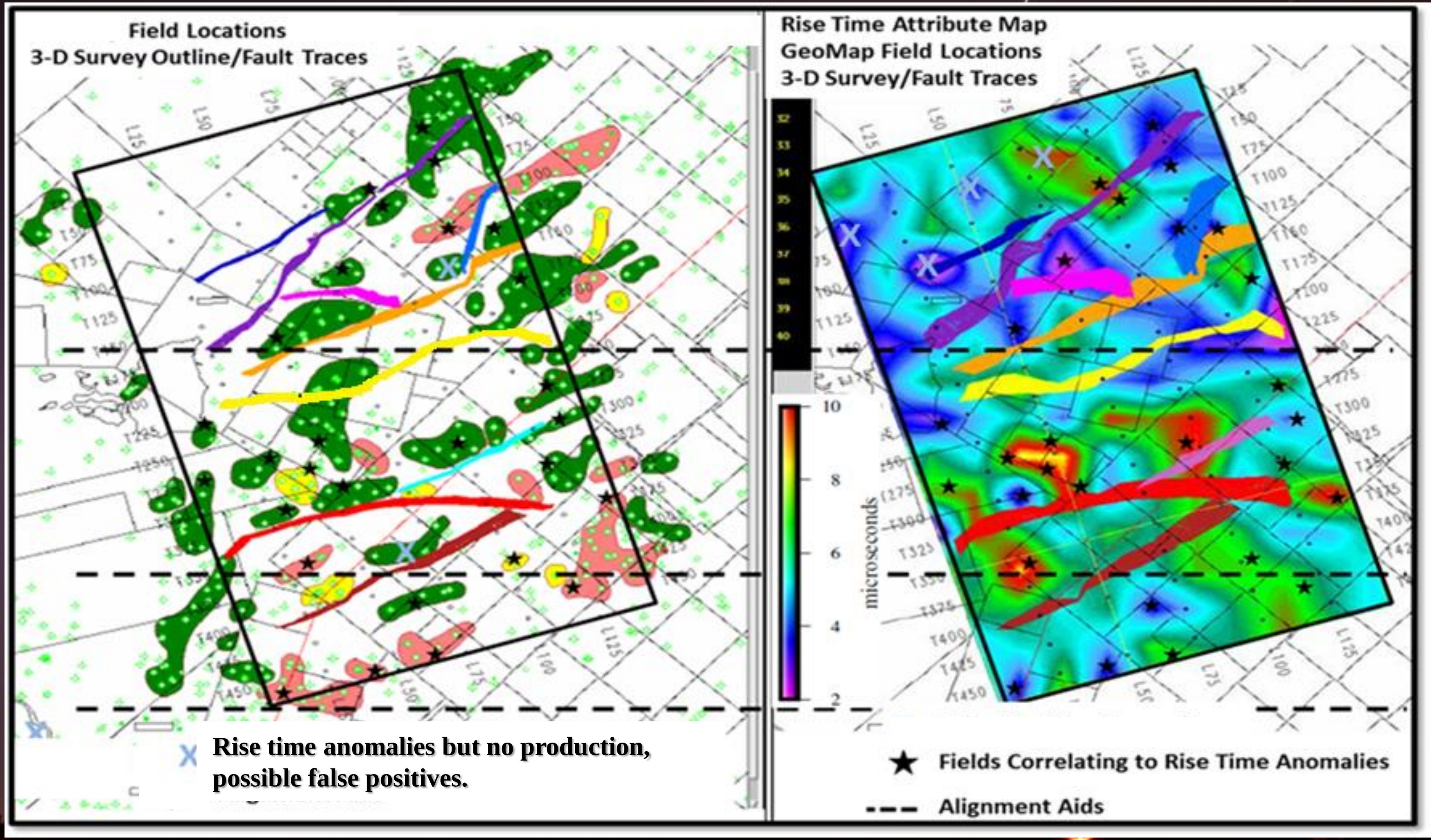
Conclusions

- Local geology can influence where lightning strikes occur.
- Potential to locate hydrocarbons (micro-seepage along flts).
- NSEM has potential to delineate subsurface flt. patterns.

NSEM Correlates To Geology:
Reconnaissance Mapping/Prospecting
Colorado County, TX



Effective Reconnaissance Mapping
Rise Time Prospect Scale Field Correlations



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

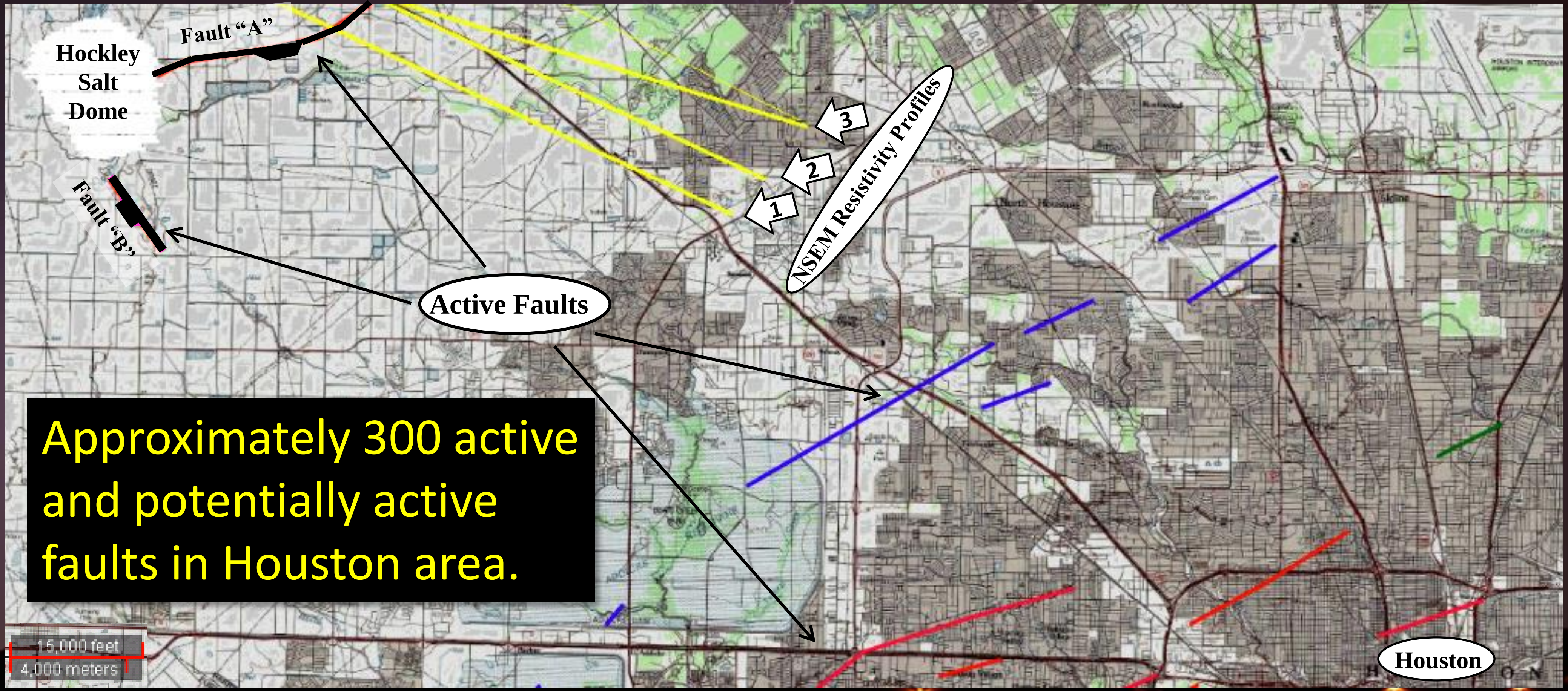
Observations

- Rise-Time attribute map shows non-random patterns.
- NSEM identified 32 leads in study area (☆/x).

Conclusions

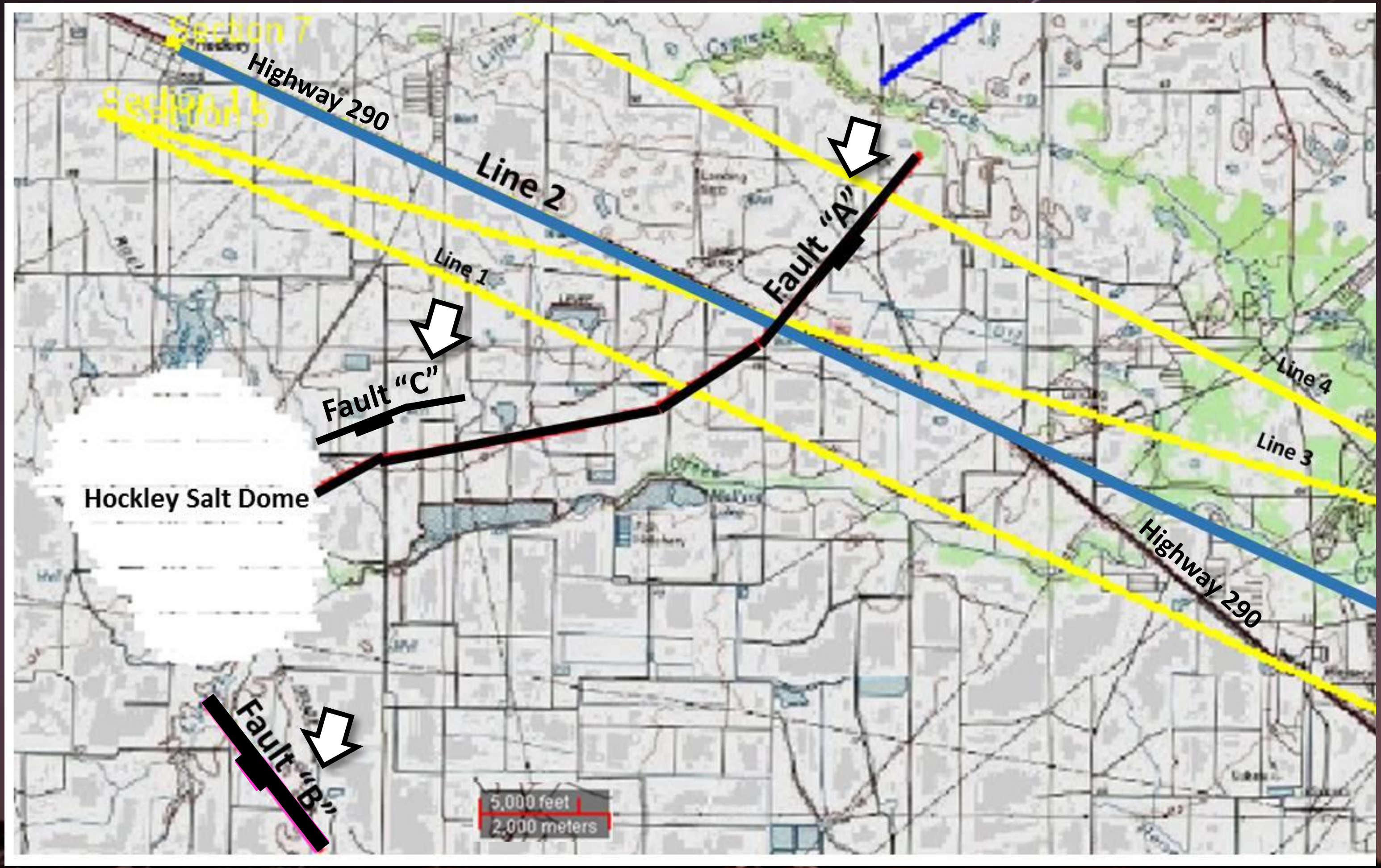
- If these leads were pursued with follow-up seismic data purchase, acquisition and reprocessing, 28-32 drillable prospects would have been generated.
- ★ If NSEM had been utilized for reconnaissance mapping, at least an 87% drilling success rate would have been realized.

NSEM Correlates To Geology:
Mapping Faults @ Hockley Salt Dome
Houston & Harris County Area



Approximately 300 active and potentially active faults in Houston area.

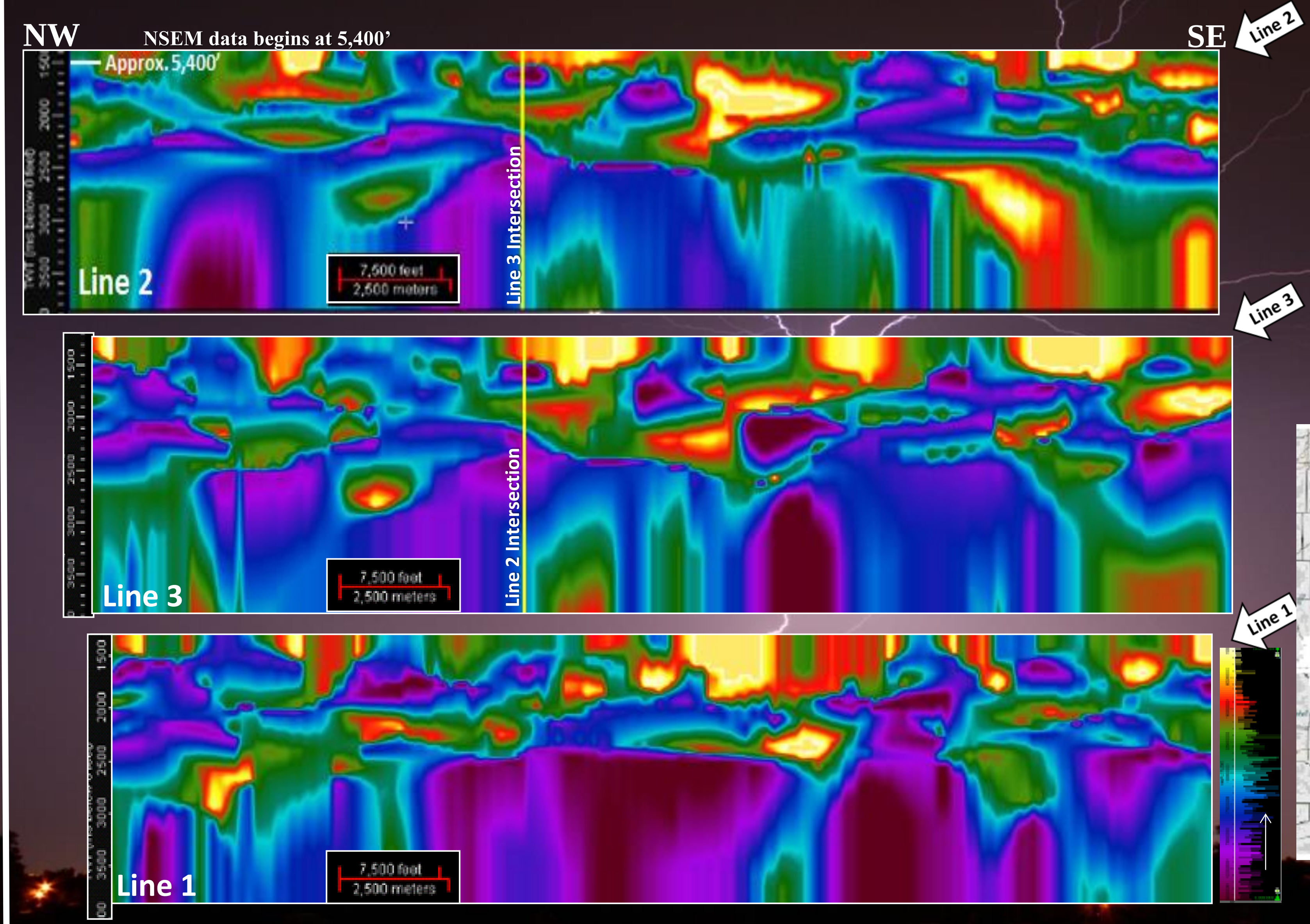
NSEM Correlates To Geology: Three Active Faults, Harris Co., TX



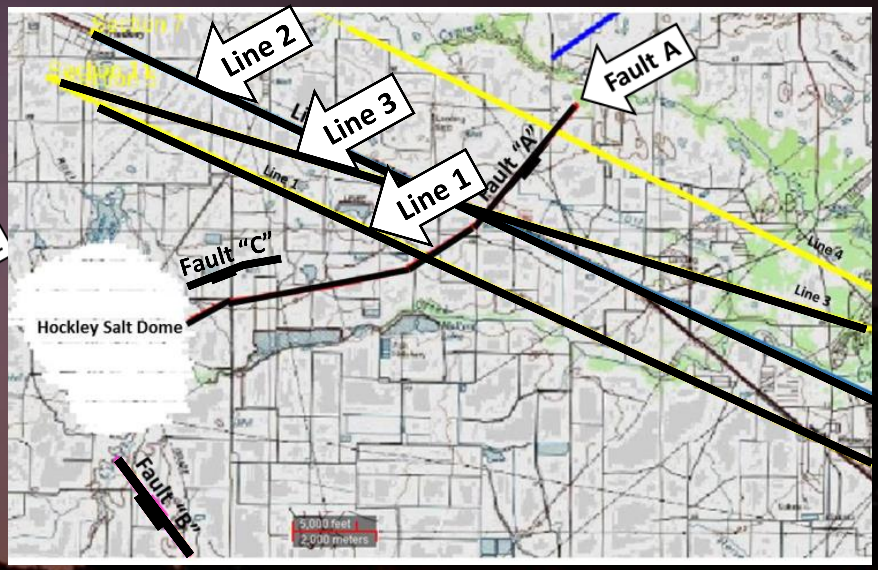
Map shows location of three active faults that have been documented with near-surface geophysical techniques.

The next group of slides will demonstrate how NSEM can identify these faults in the subsurface.

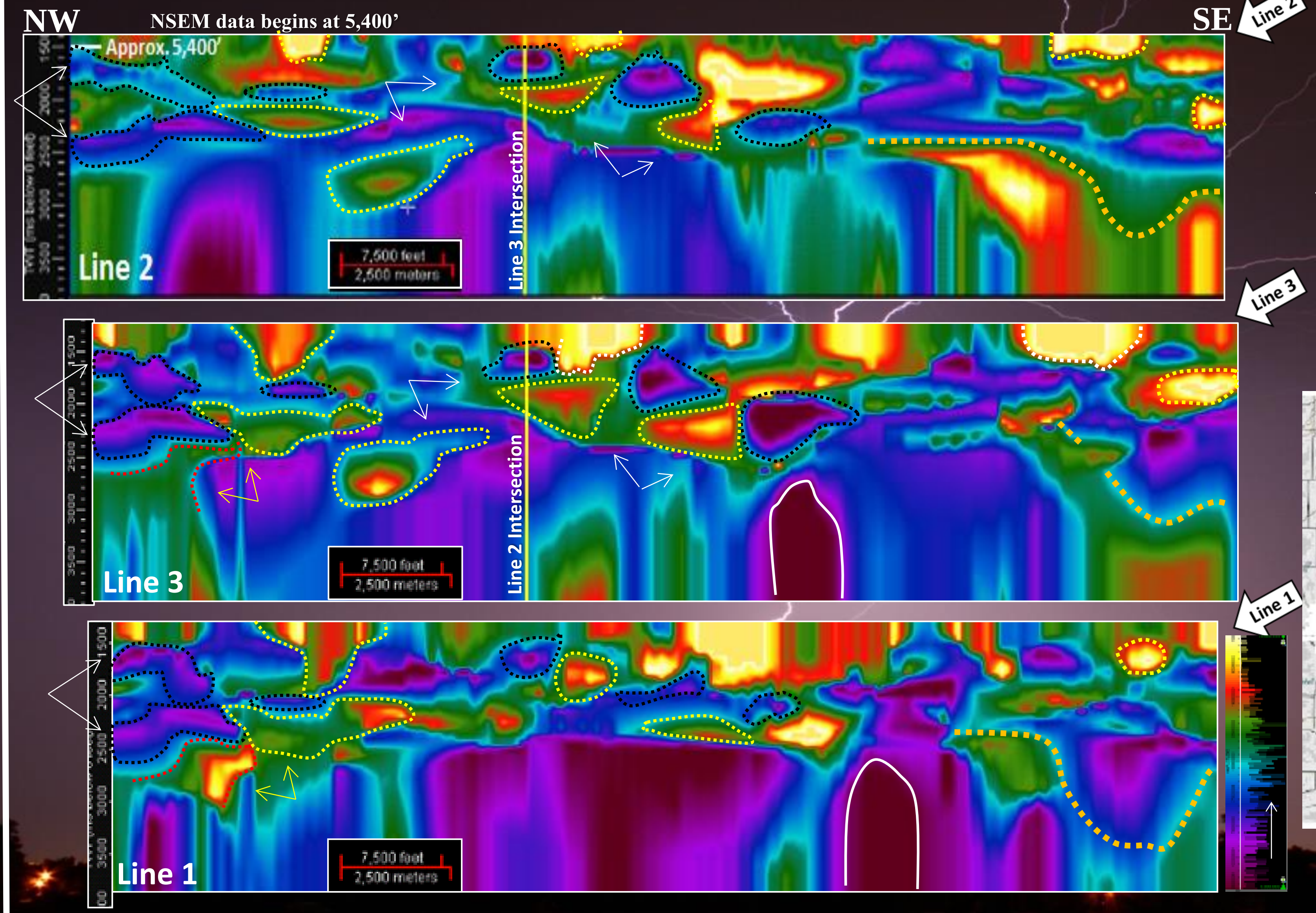
NSEM Resistivity Profile Comparisons



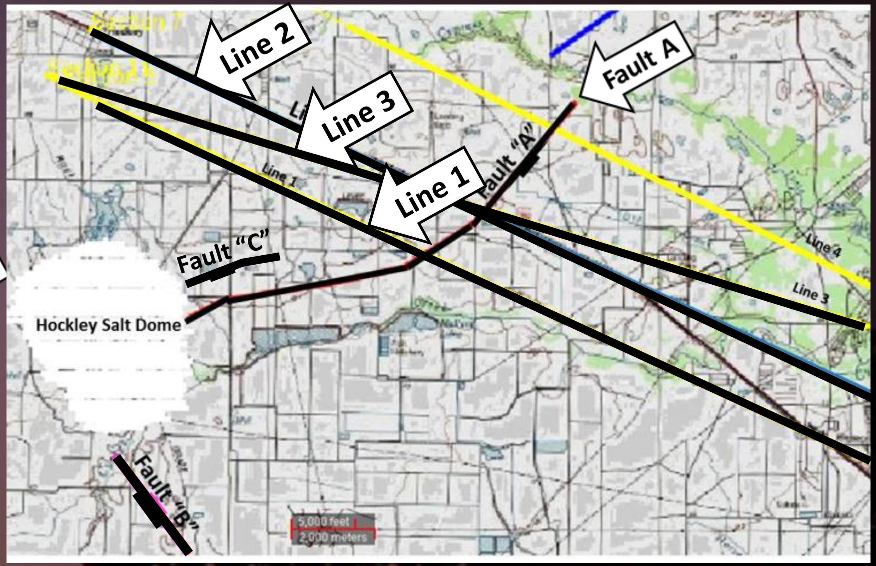
Similar resistivity patterns from line to line would be required to identify consistent fault patterns.



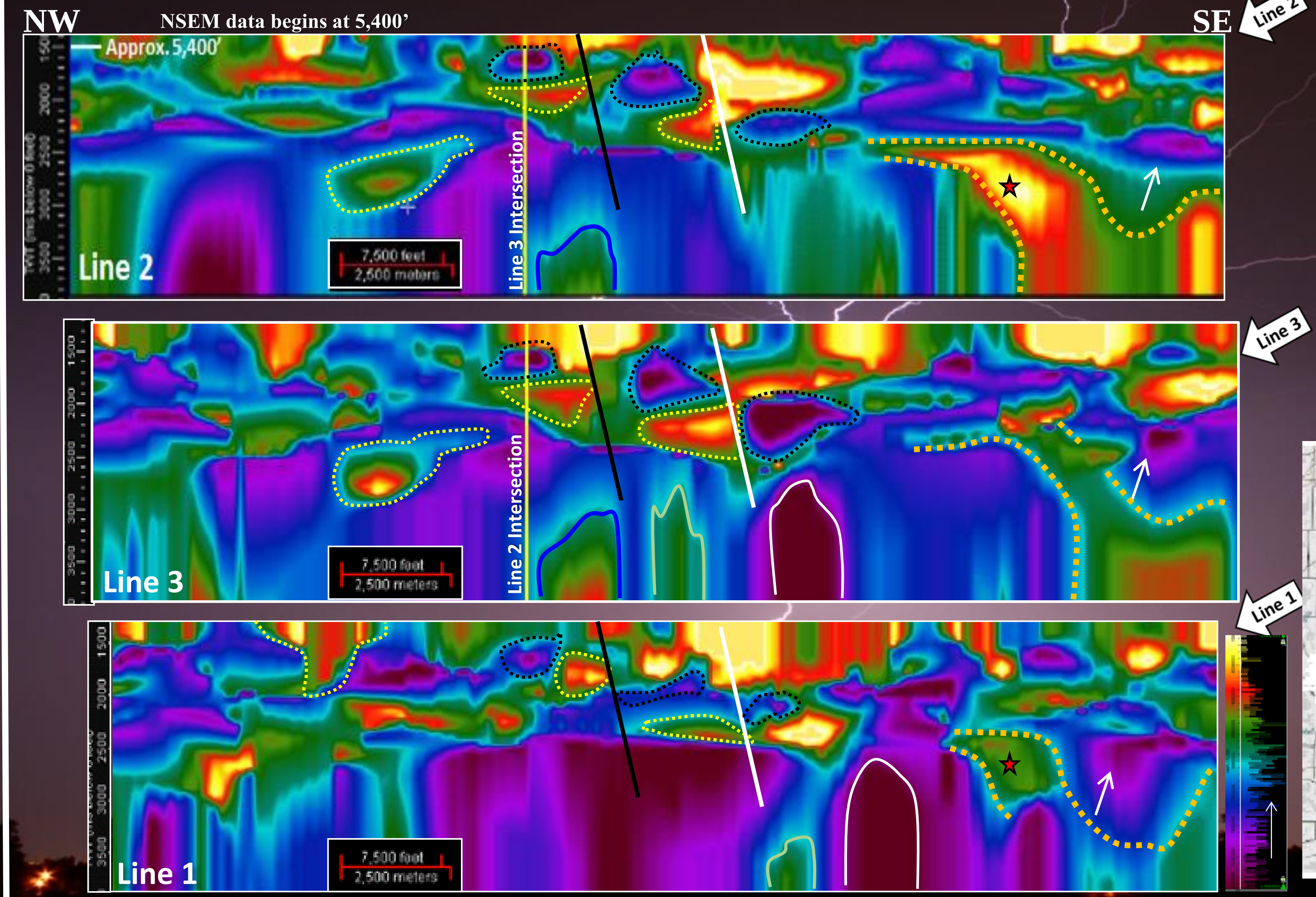
Pattern Recognition



Note similar patterns adjacent to the intersection of lines 2 and 3 and where lines 1 and 3 converge to the northwest.

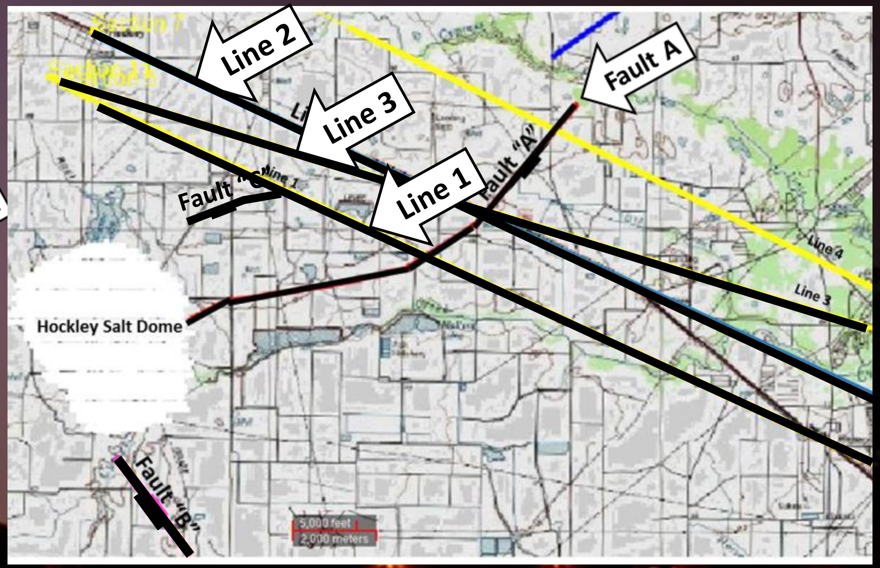


Resistivity Discontinuities & Offsets



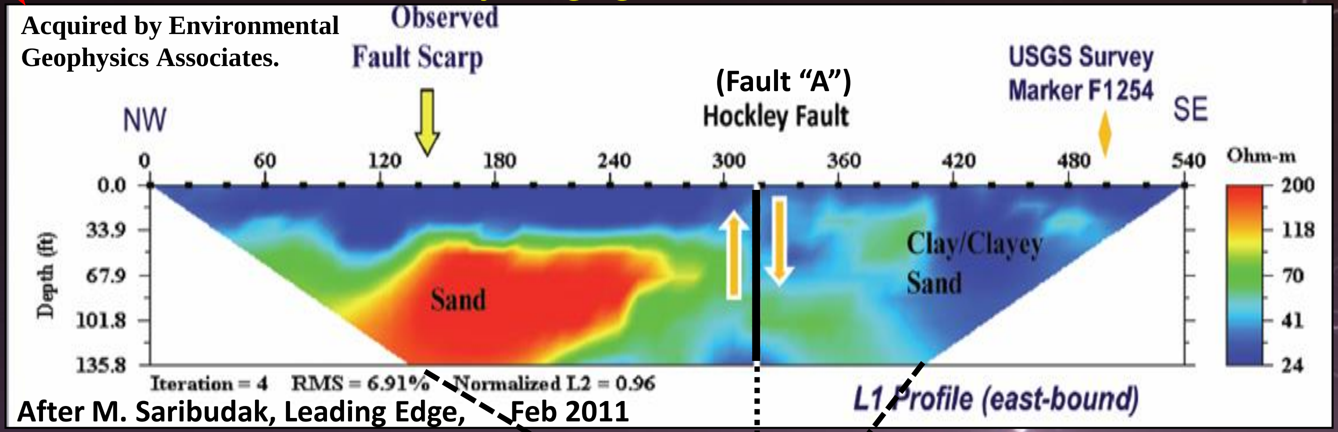
Breaks in resistivity and offsets could suggest faulting.

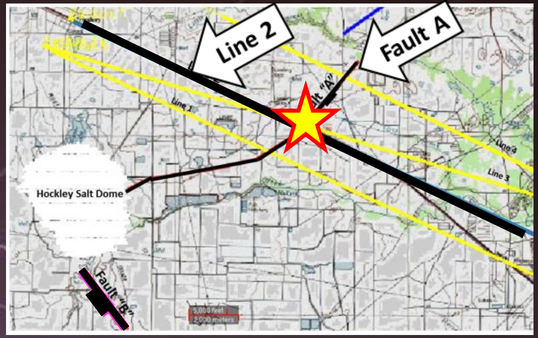
Can documented surface faults validate NSEM-derived subsurface faults?



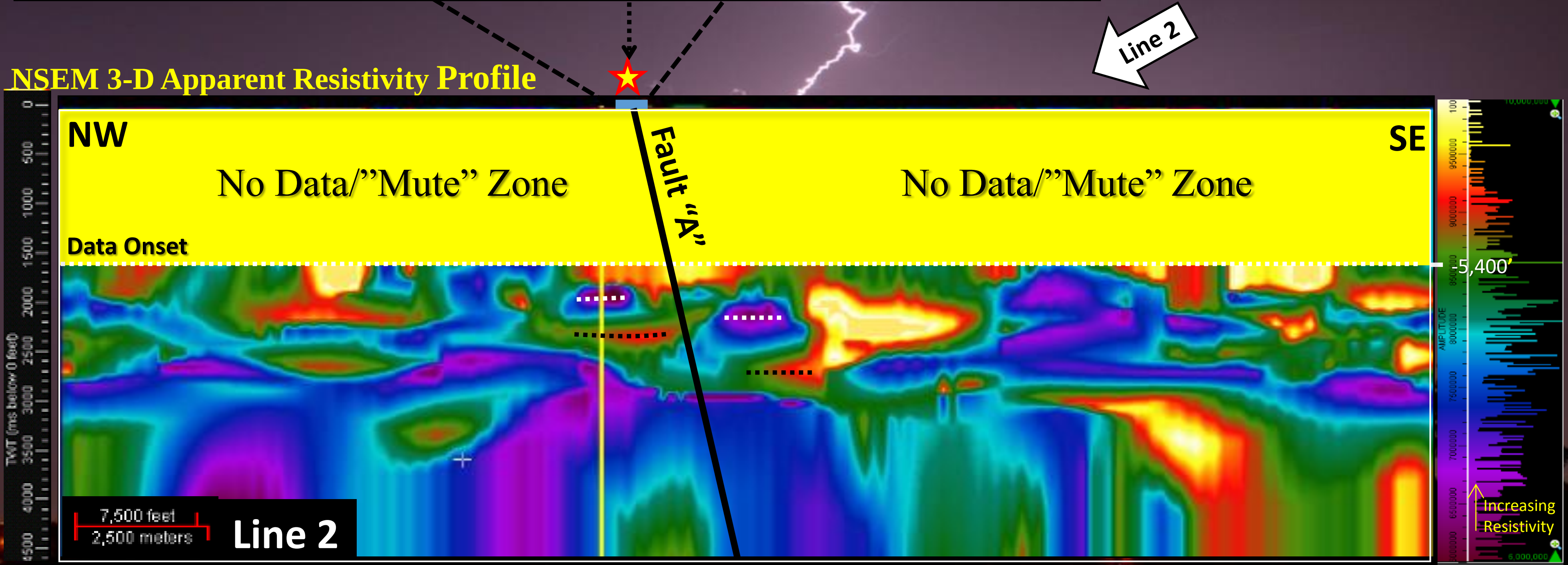
Conventional Resistivity Validates NSEM Interpretation

Conventional 2-D Resistivity Imaging Profile



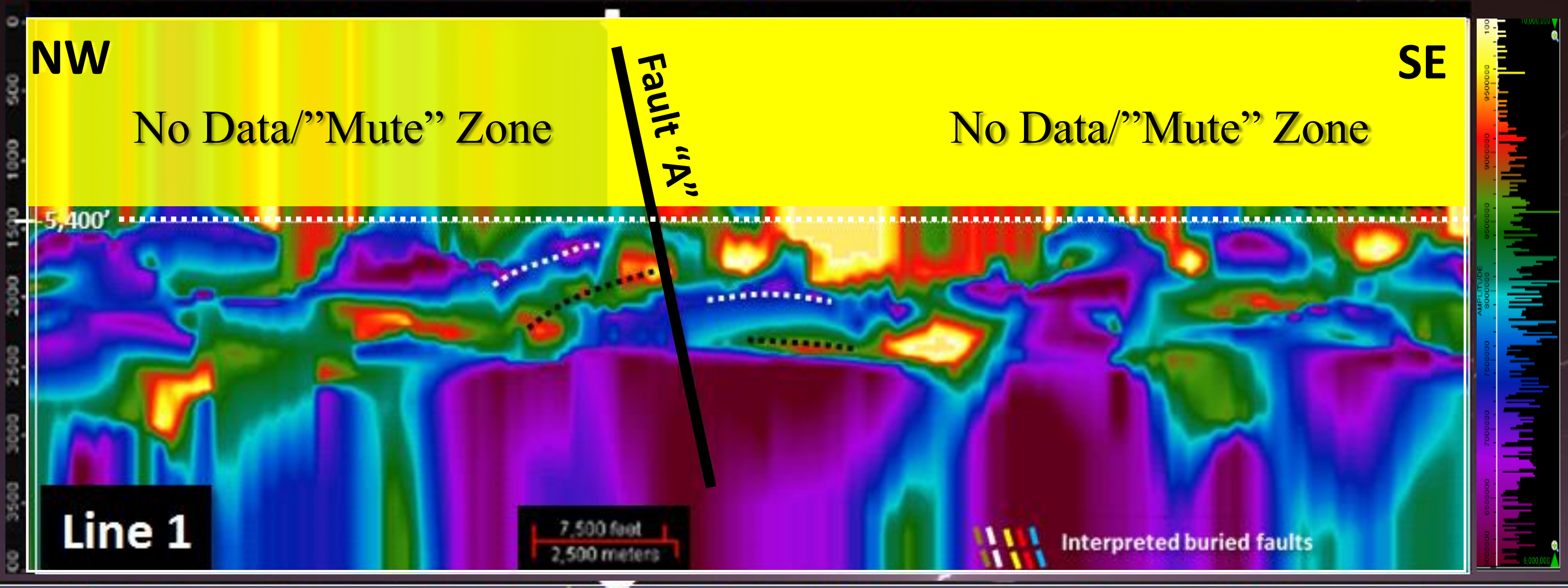


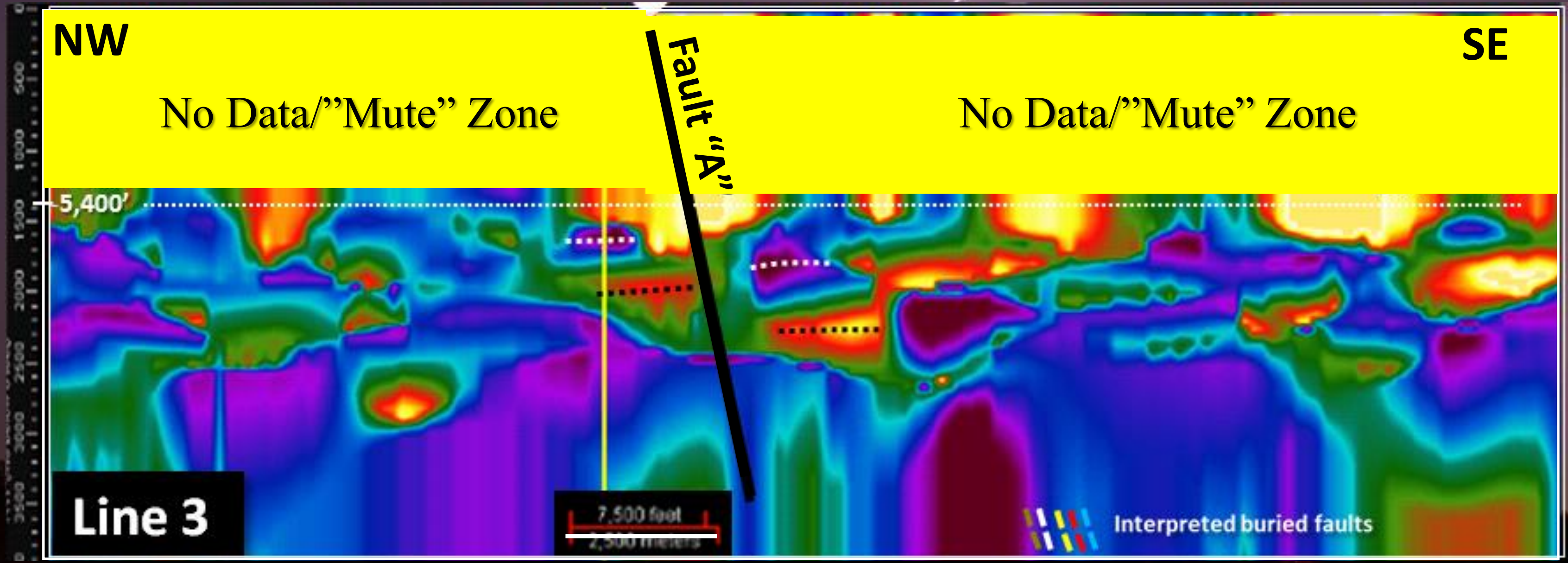
NSEM 3-D Apparent Resistivity Profile



- Extracted NSEM 2-D profile coincides with location of published data and documented surface expression of active fault.
- Subsurface fault interpretation of NSEM profile ties documented active Hockley Fault ("A").
- Note NSEM fault criteria - two resistivity layer offsets.

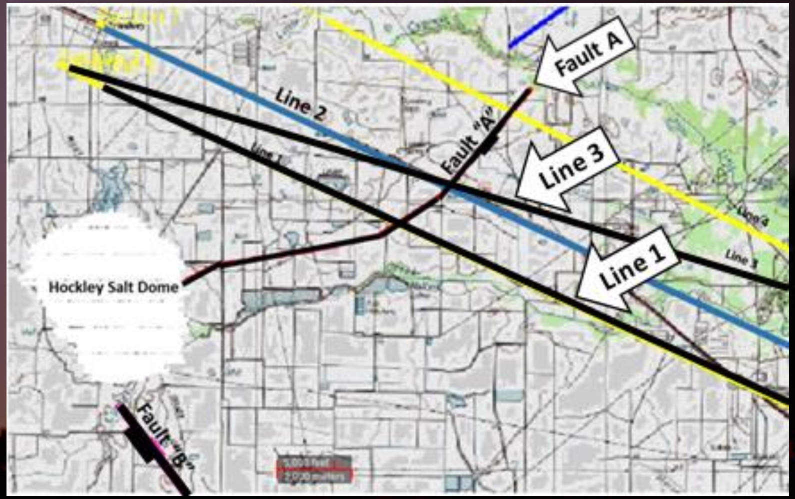
Lines 1 & 3 also Tie Fault "A" to Subsurface





White arrow marks intersection with documented fault trace.

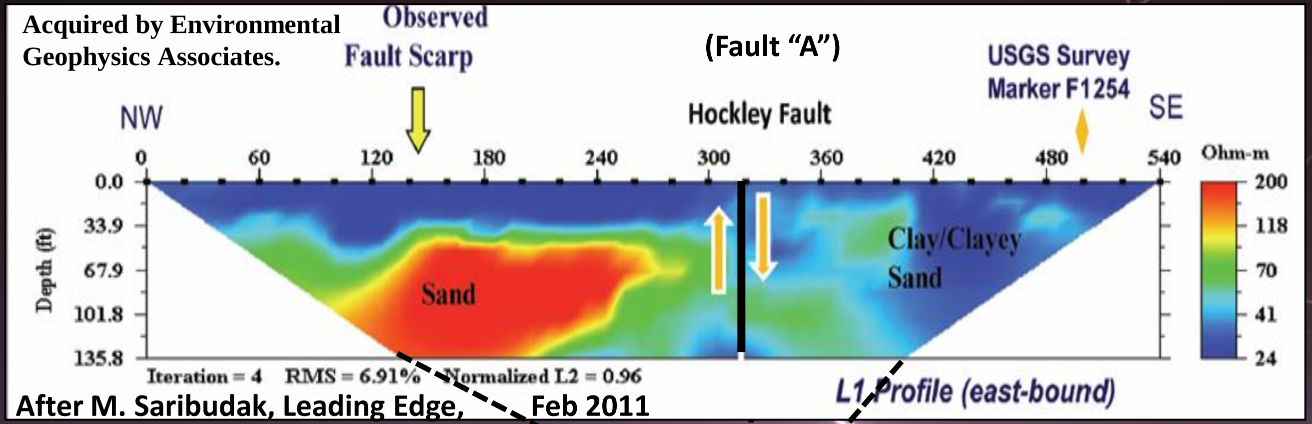
NSEM demonstrates consistency identifying this active fault at depth.

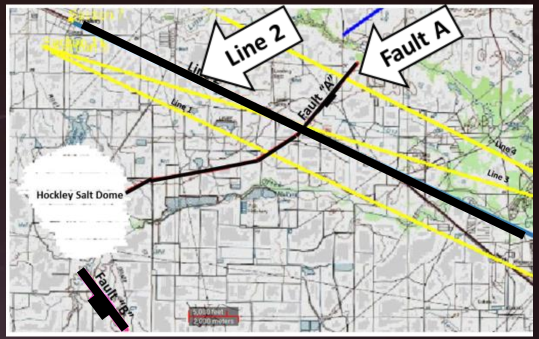


NSEM Line 2 Suggests Additional Faulting

3-D Data Provides Interpretive Checks & Balances

2-D Resistivity Profile

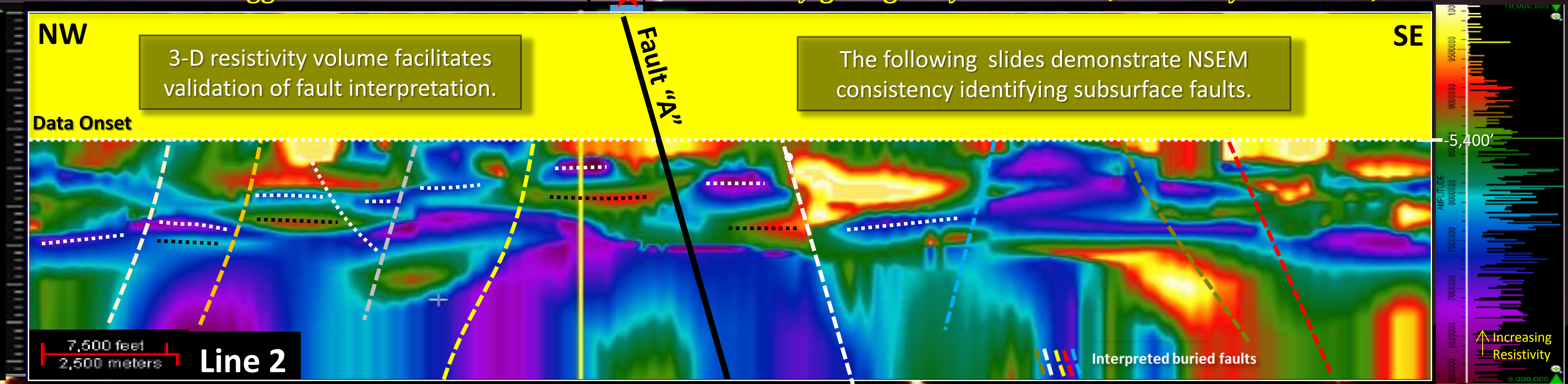




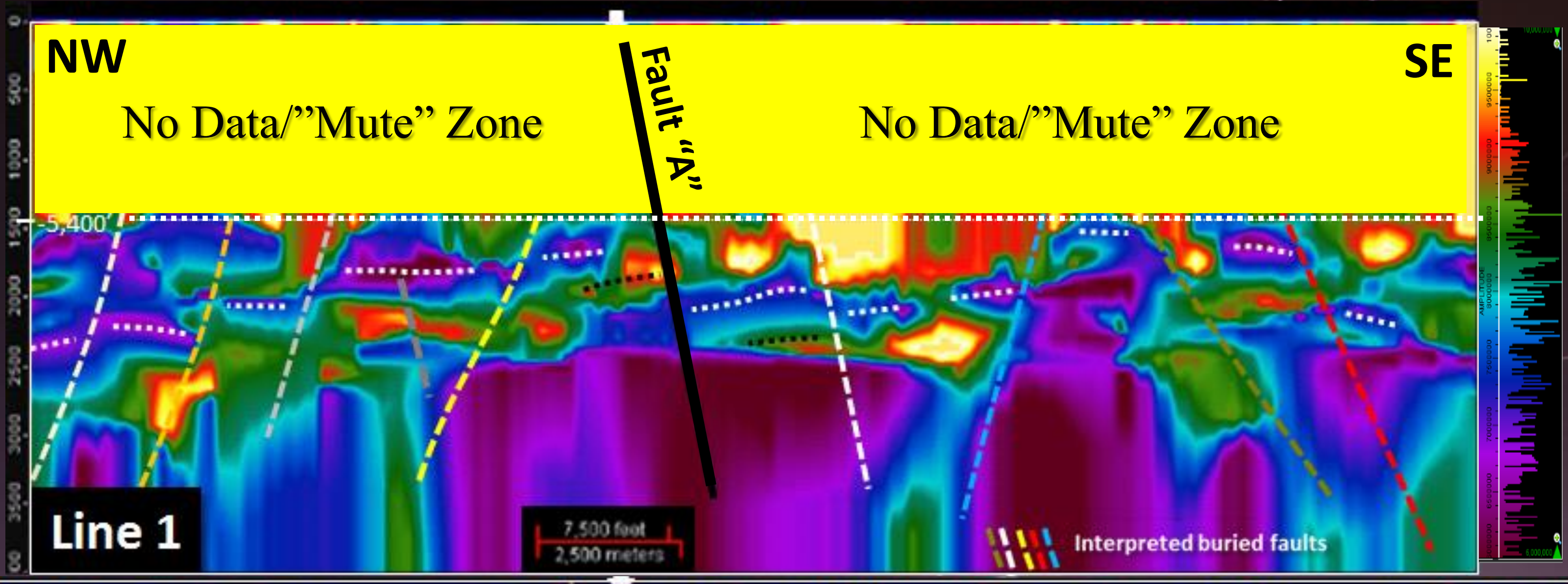
Additional faults suggested.

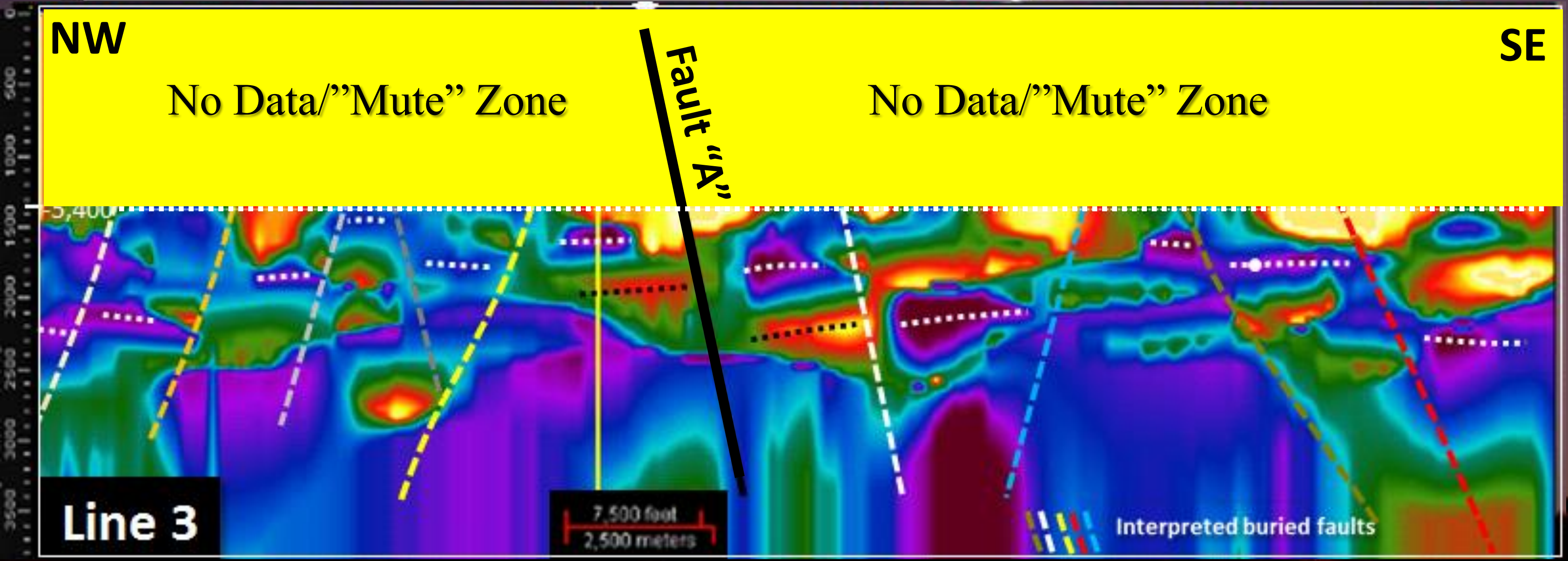
Are they geologically reasonable , internally consistent, valid?

NSEM 3-D Resistivity Profile



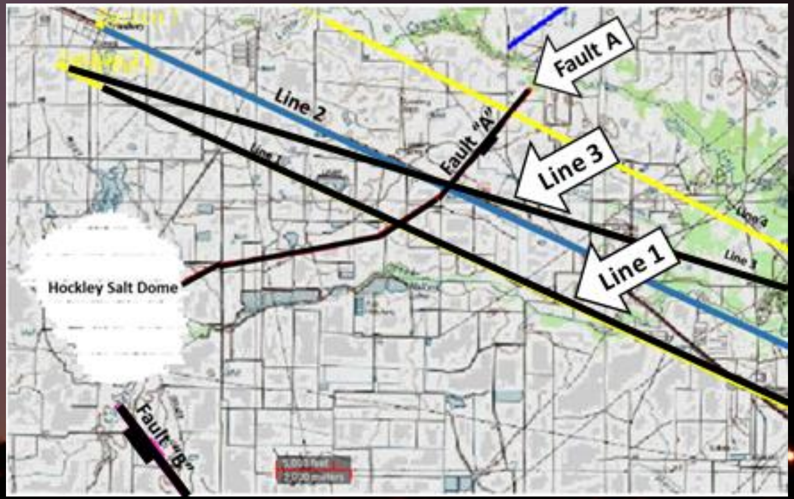
Lines 1 & 3 Also Suggest Additional Faults



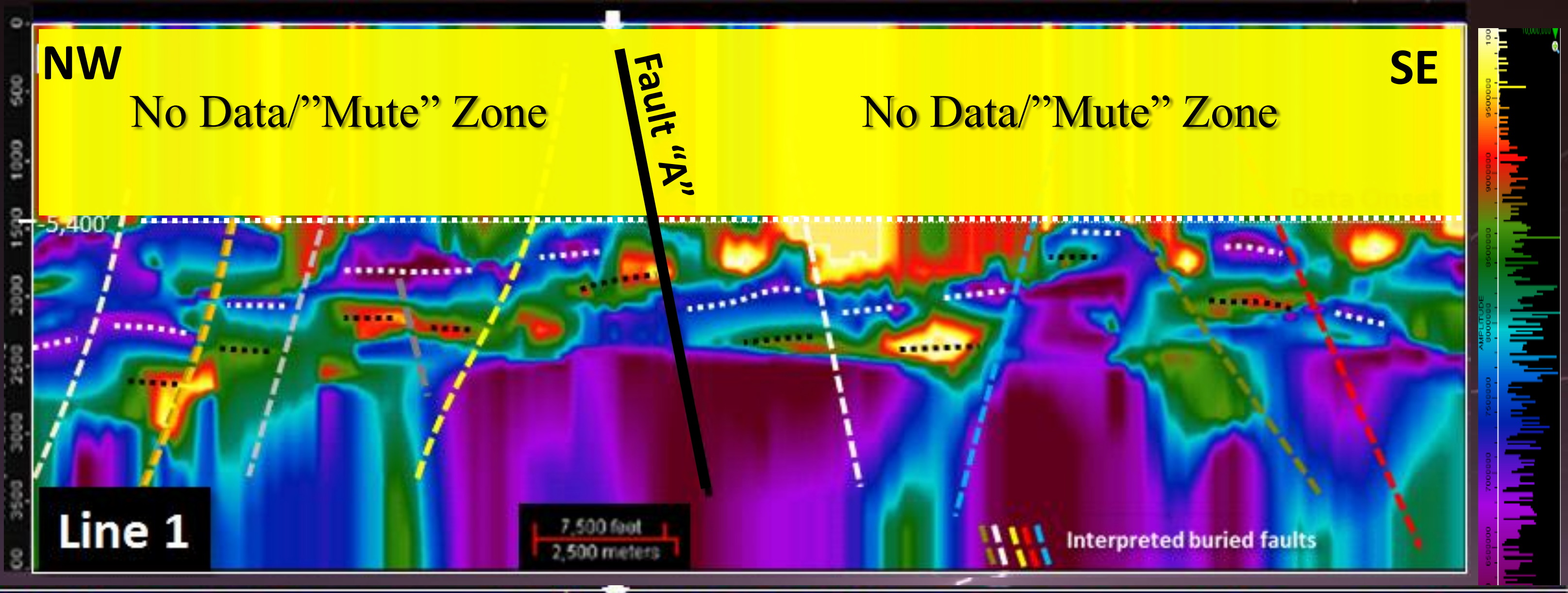


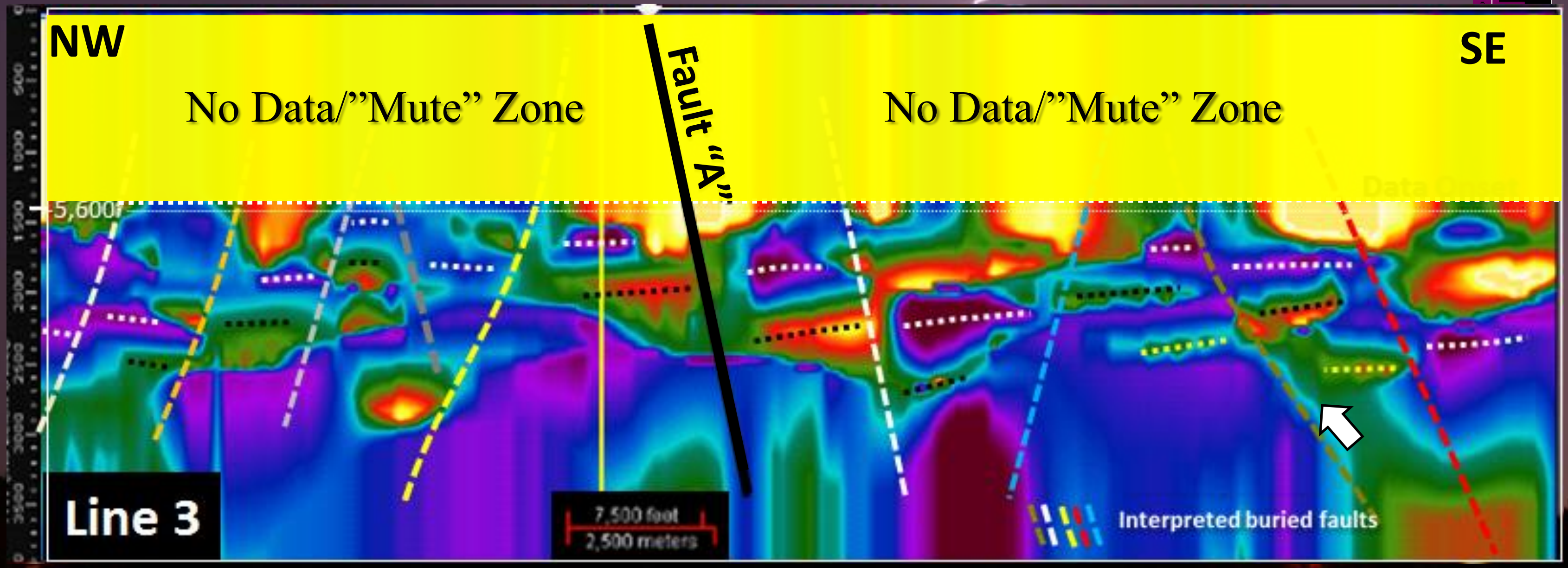
The same 9 color-coded faults are identified on all 3 lines.

NSEM demonstrates internal interpretive and structural consistency and ability to map faults at the prospect level.



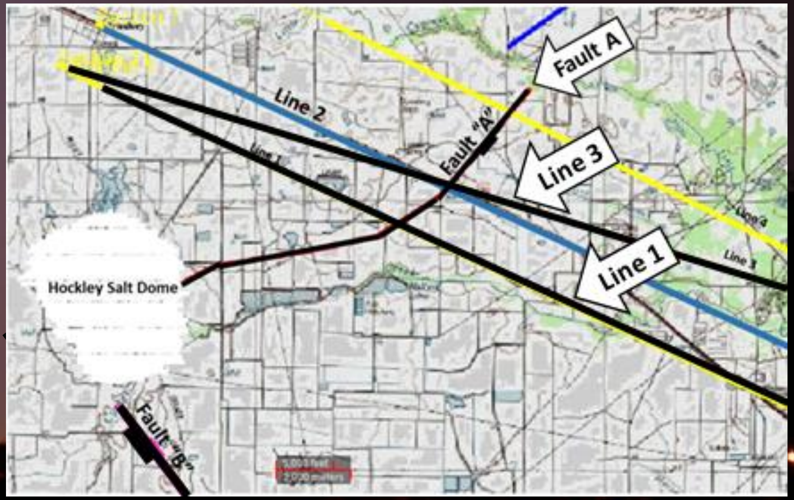
NSEM Builds Reliable Structural Framework





Of 20 faults displayed on these profiles, 19 defined by two resistivity layer offsets; one by three (see white arrow line 3).

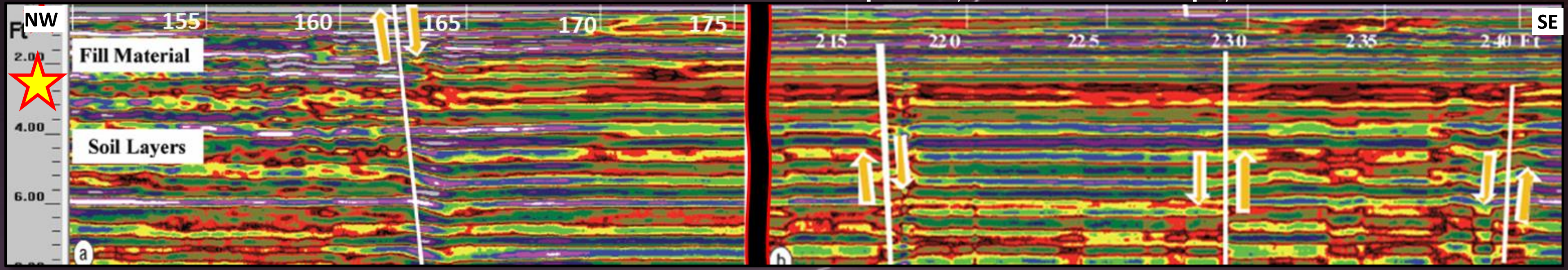
3-D NSEM enables structural and fault plane mapping.



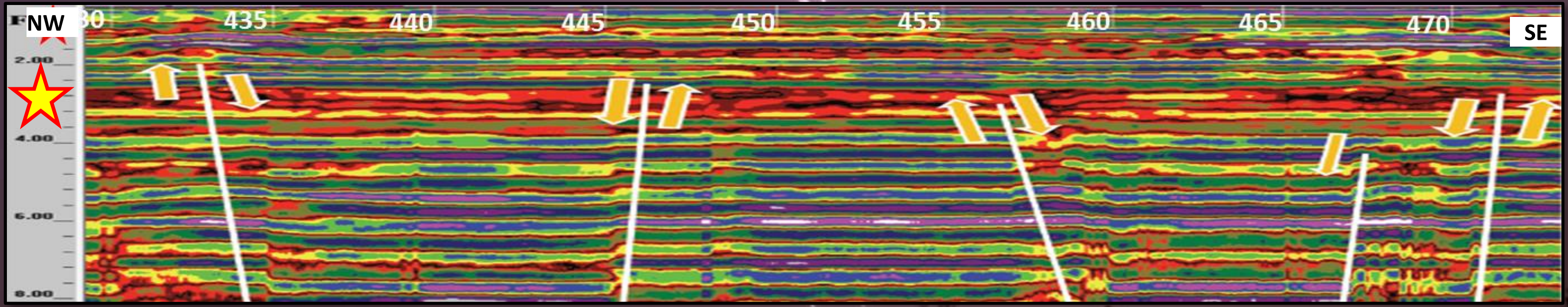
Ground Penetrating Radar
Shallow Micro-Faulting Adjacent to Fault "A"

Hockley Fault (Flt. "A")

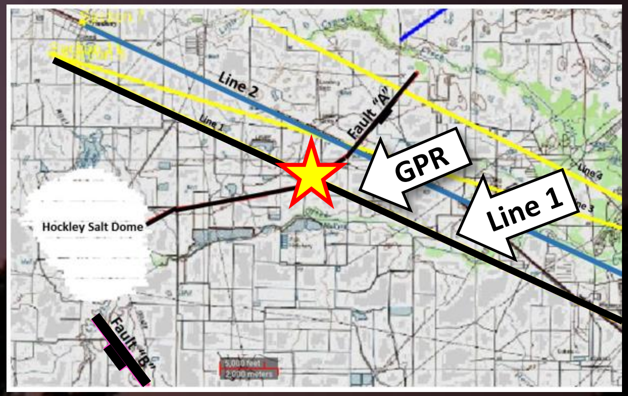
GPR acquired by Environmental Geophysics Associates



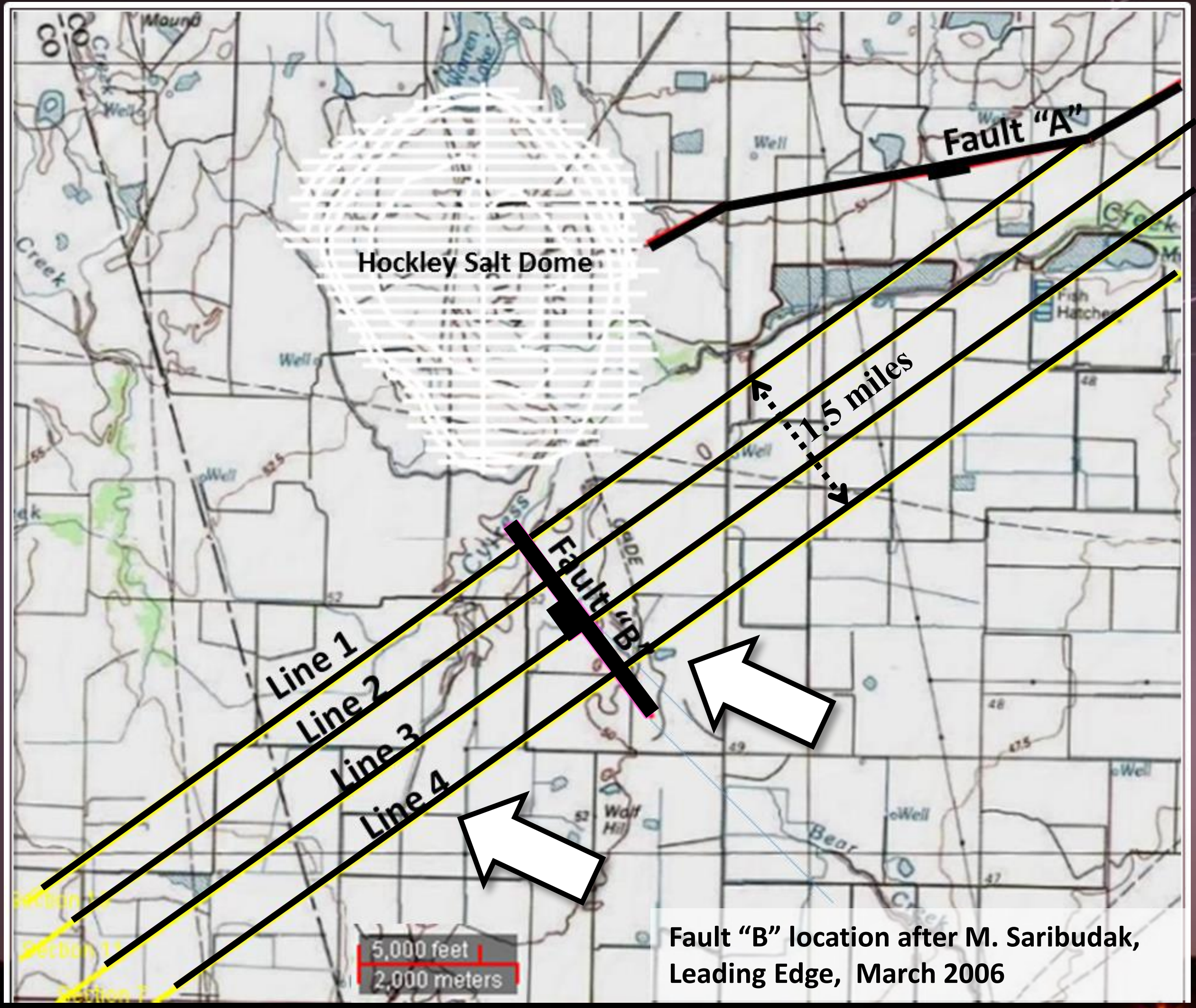
GPR/NSEM show similar micro (shallow) and macro (deep) structural styles: horsts, grabens and half-grabens.



Modified after M. Saribudak, Leading Edge, Feb 2011



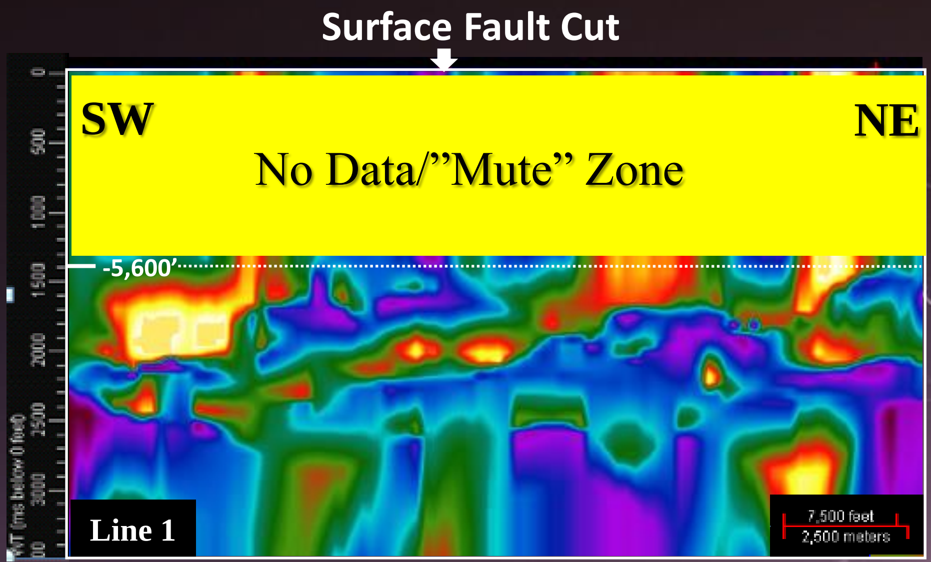
Hockley Radial Fault "B"

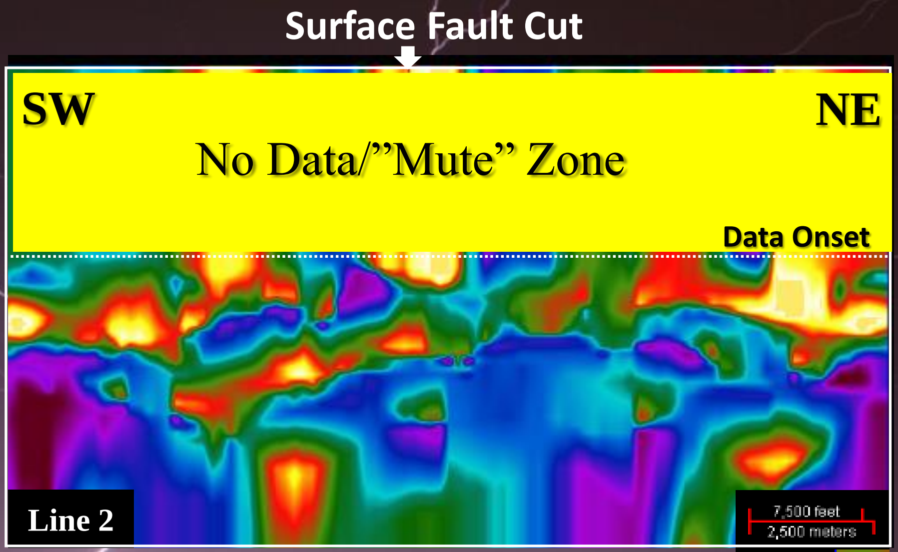


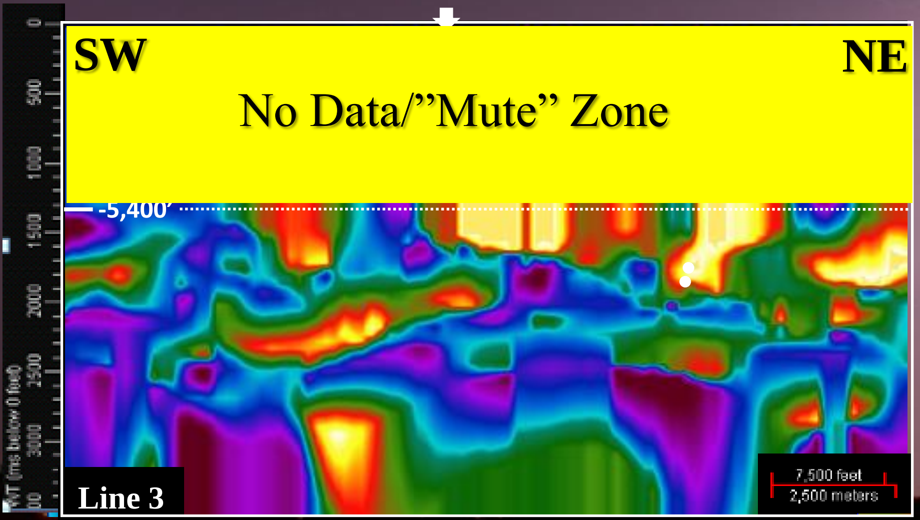
A 1½ mile distance along the Fault "B" trace is sampled with resistivity profiles.

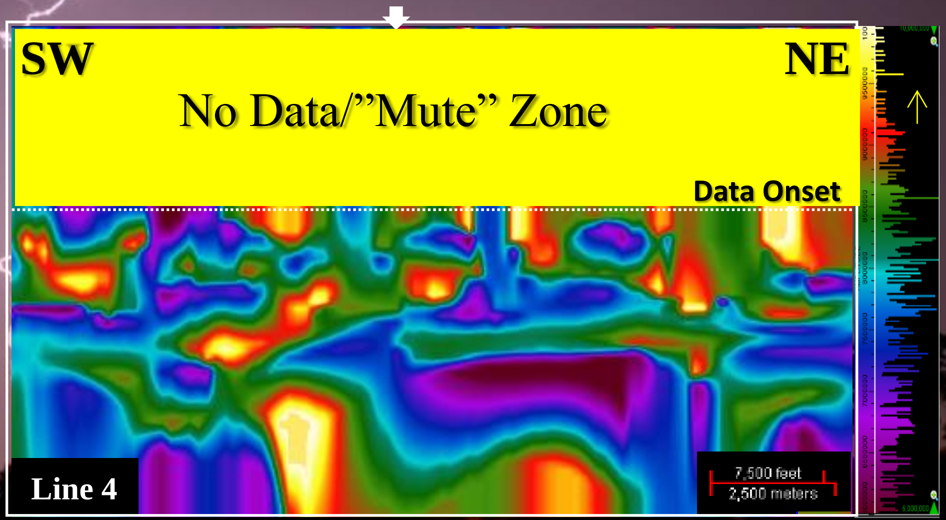
Resistivity Lines 1-4 are displayed on the next slide.

Hockley Radial Fault "B" Lines 1-4

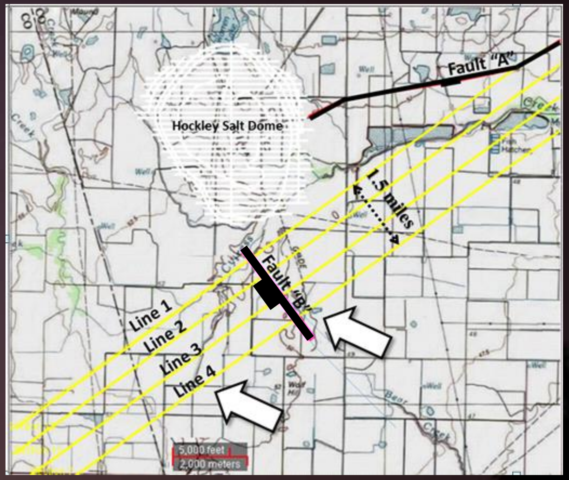






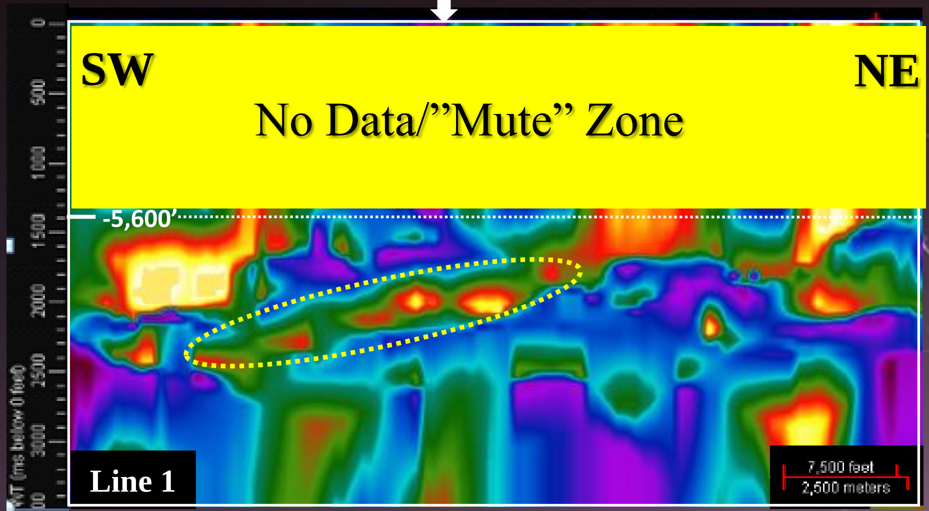


Profiles ½ mile apart.
Note similar character.

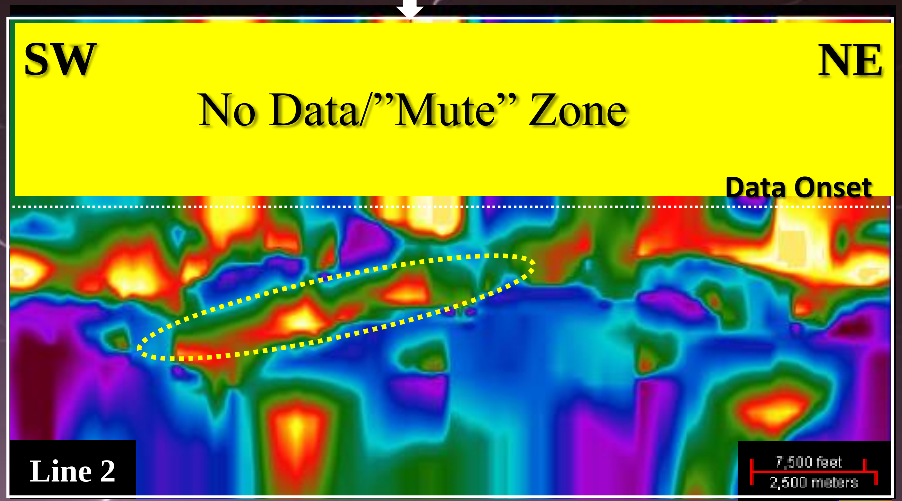


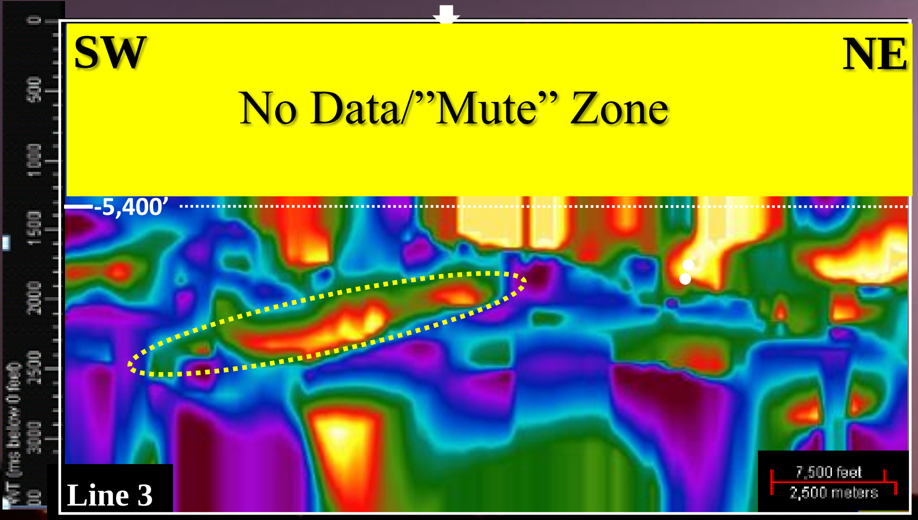
Similar Character Spanning 1.5 Miles

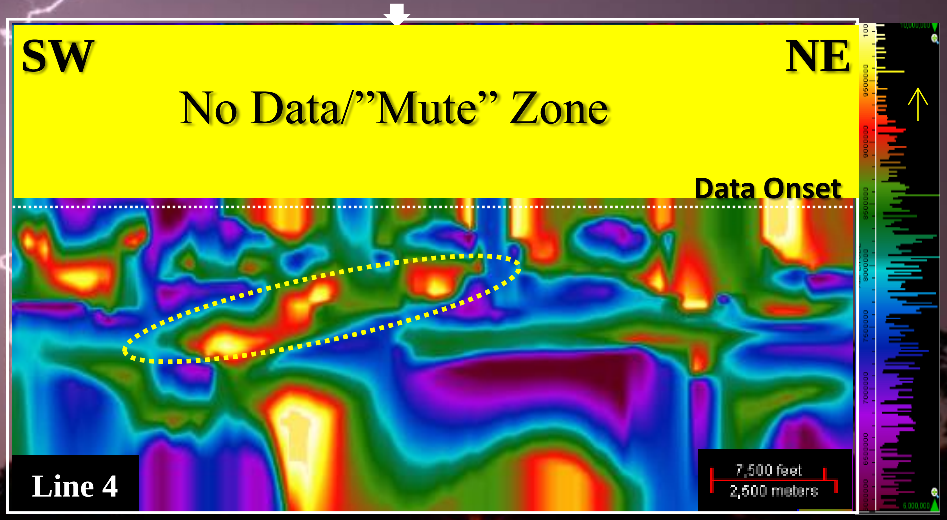
Surface Fault Cut



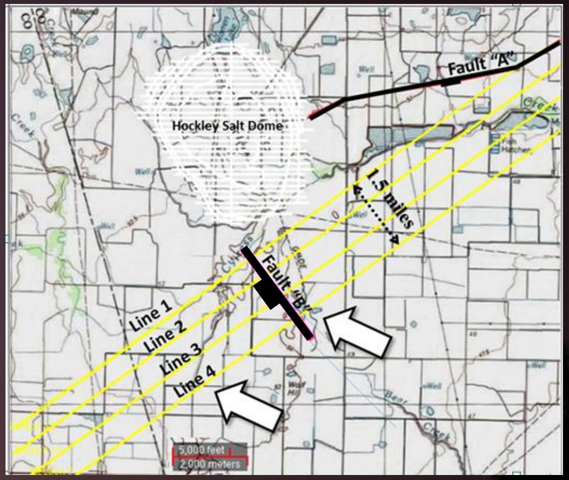
Surface Fault Cut



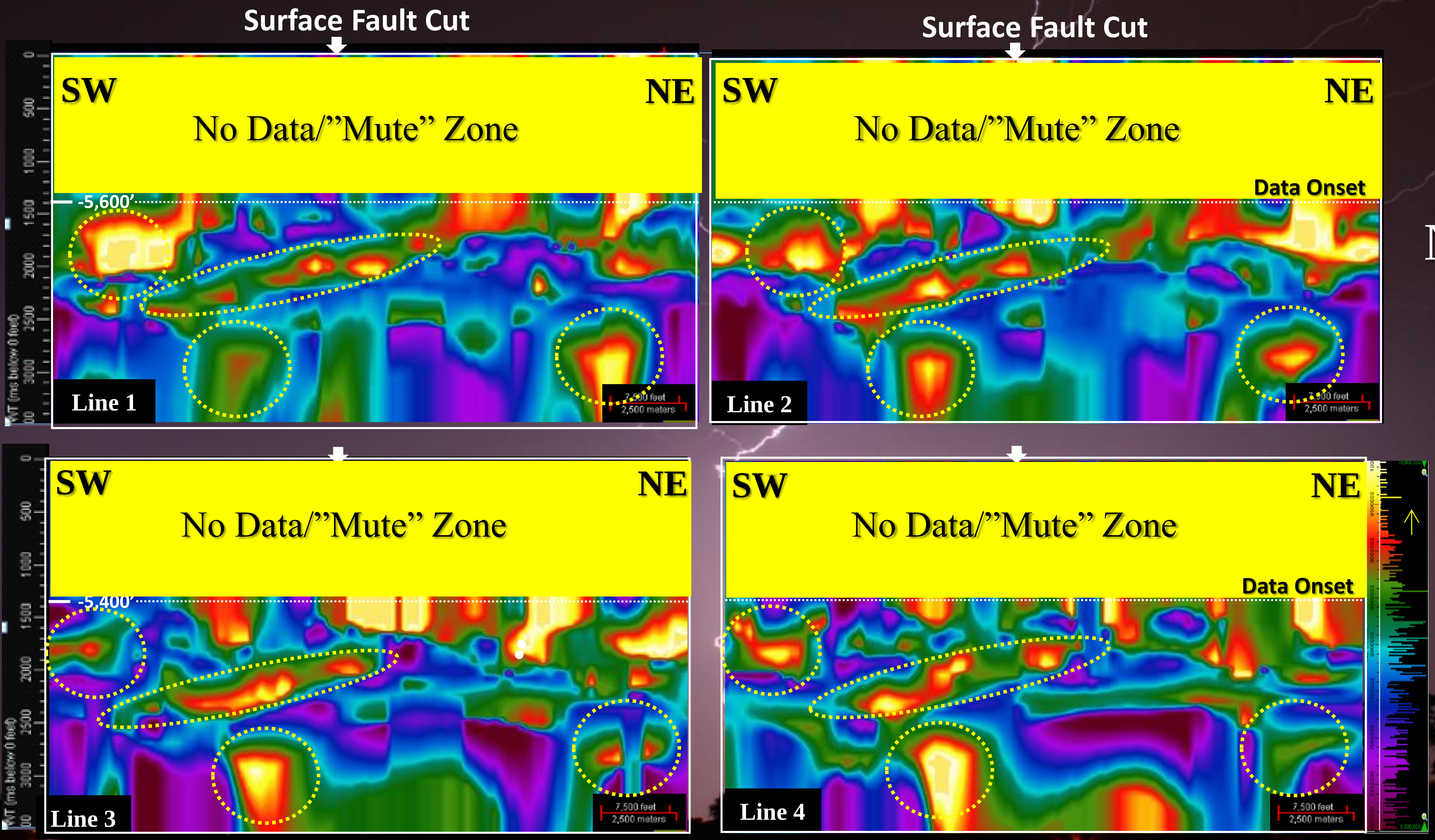




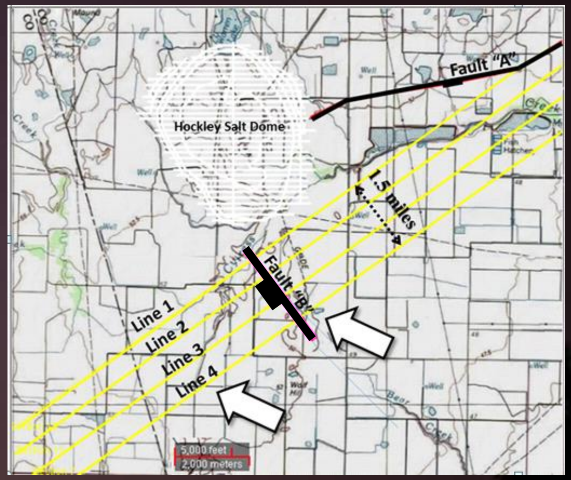
Lines ½ mile apart.
Note similar character.



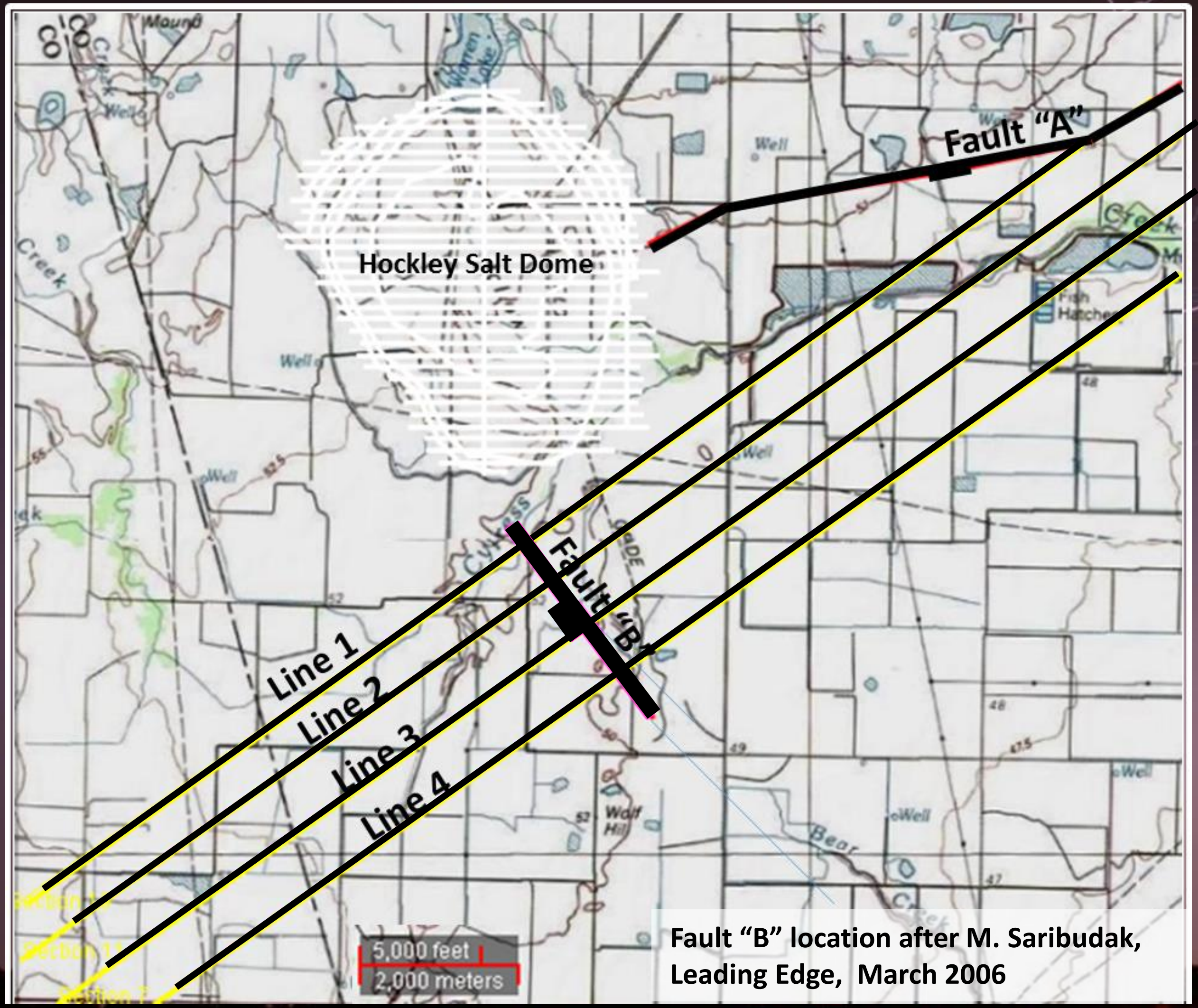
Numerous Features Correlate Line to Line



Lines ½ mile apart.
Note similar character.



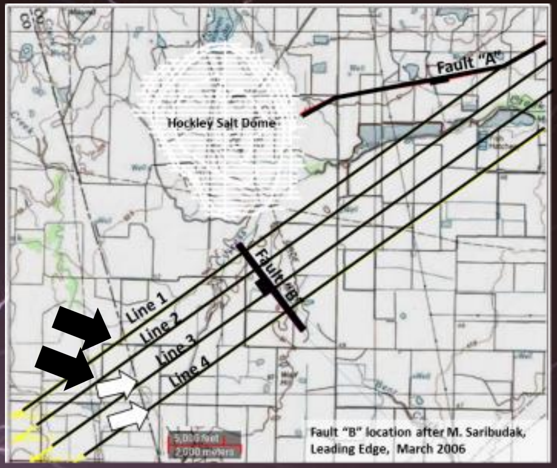
Hockley Radial Fault "B"

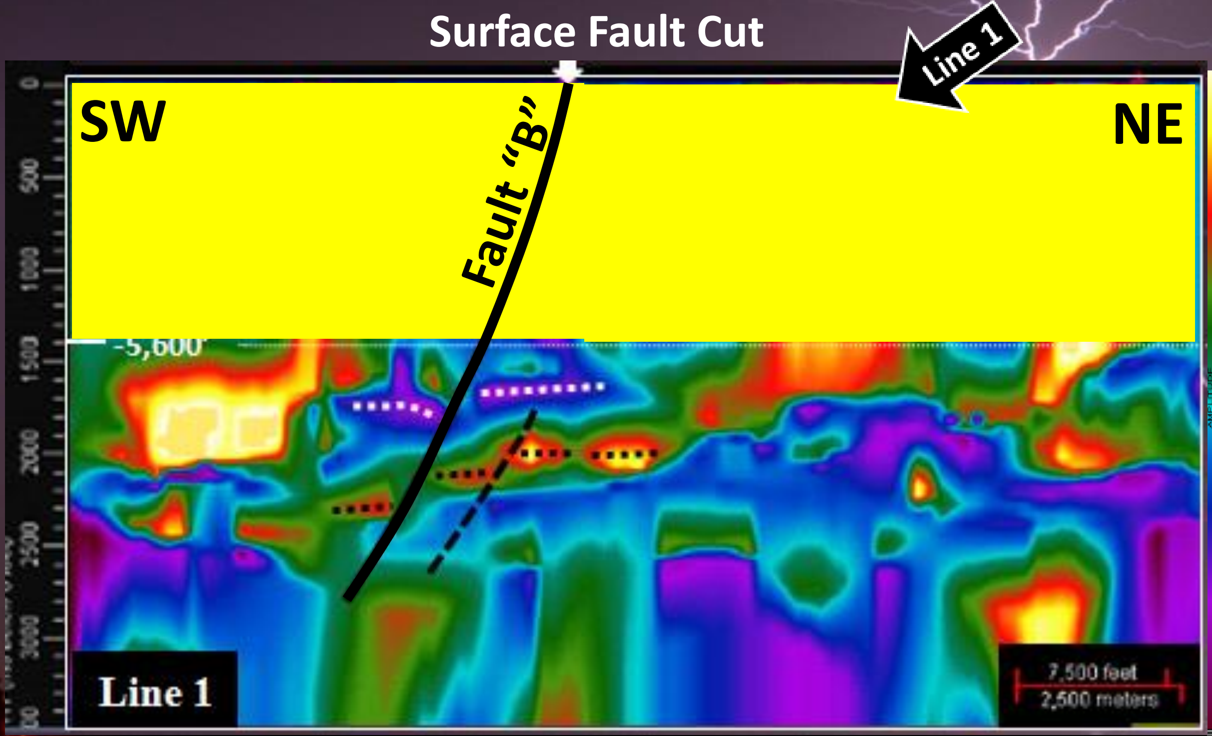


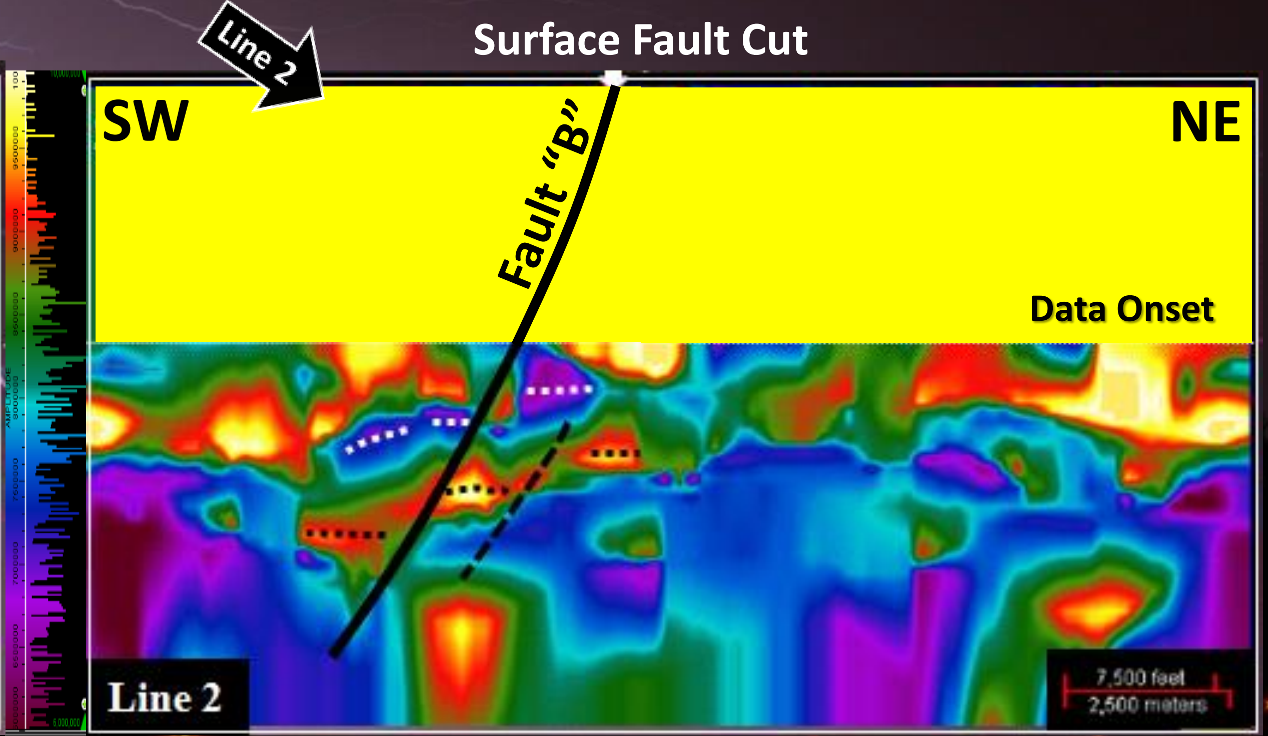
Now let's review these four apparent resistivity lines to determine whether they can identify Fault "B" in the subsurface.

As with Fault "A", trigonometric constraints based on depth, heave, fault surface dip and sense of throw must be satisfied.

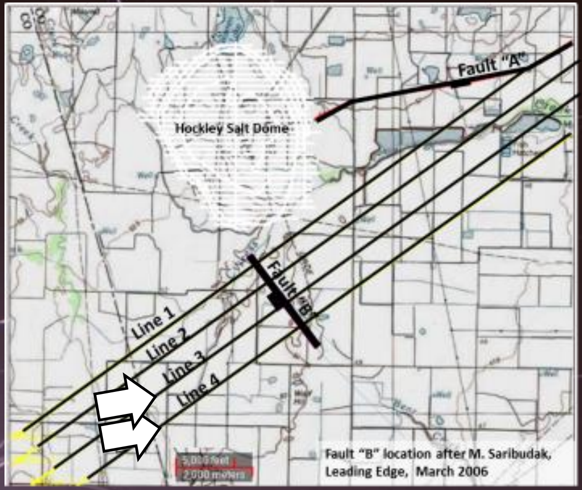
NSEM Profiles 1 & 2 Show Similar Fault Criteria & Both Tie Surface Fault "B."

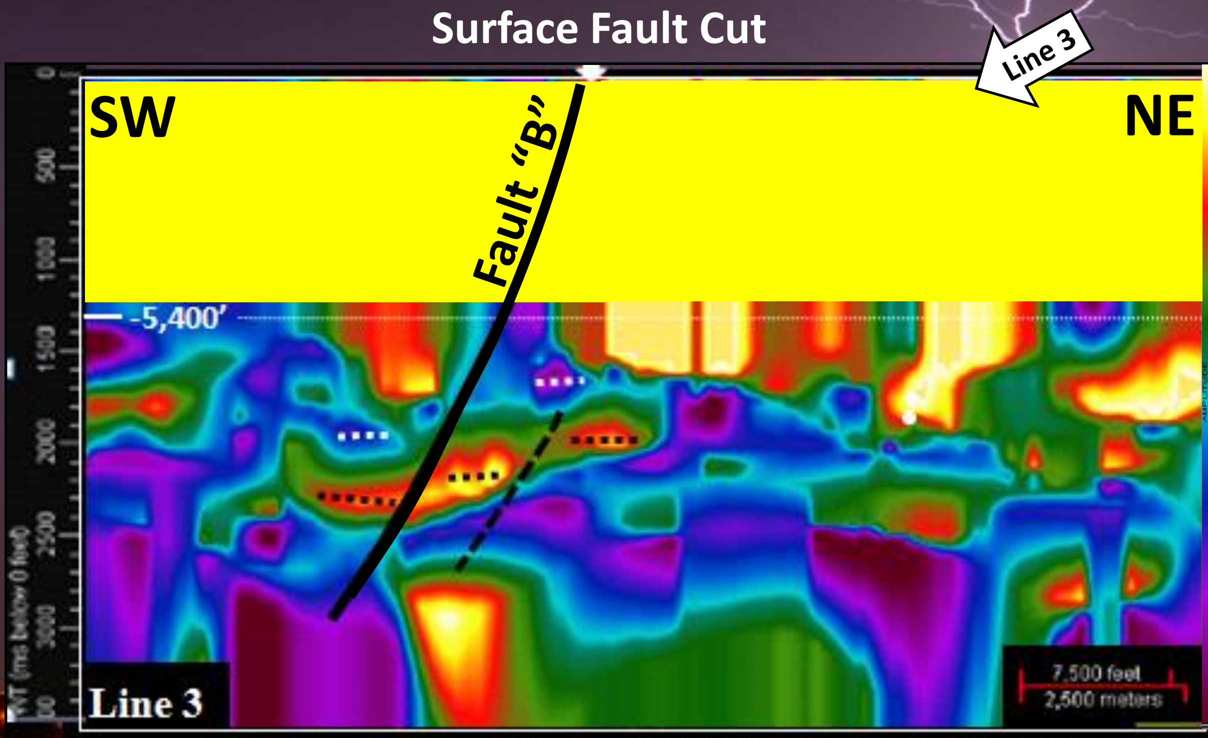


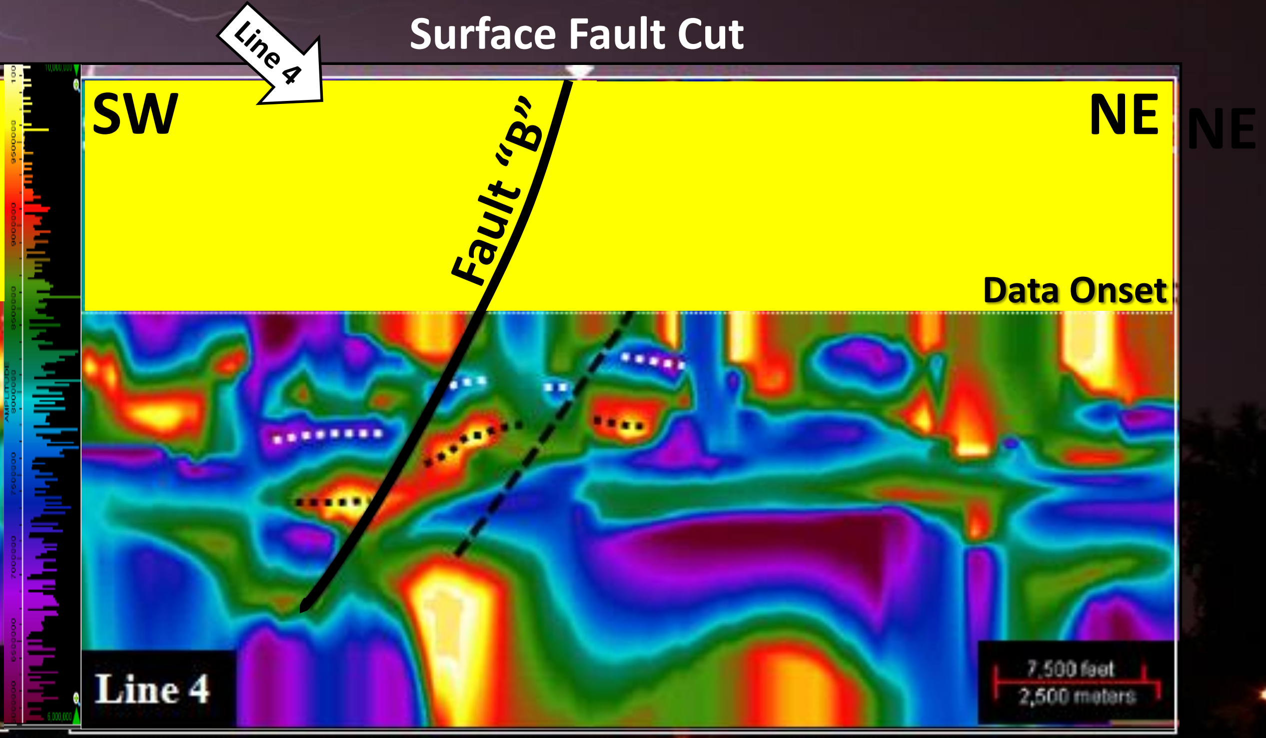




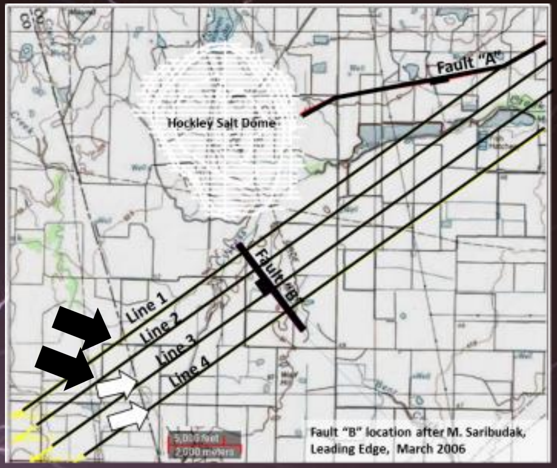
NSEM Profiles 3 & 4 Show Similar Fault Criteria & Both Tie Surface Fault "B."

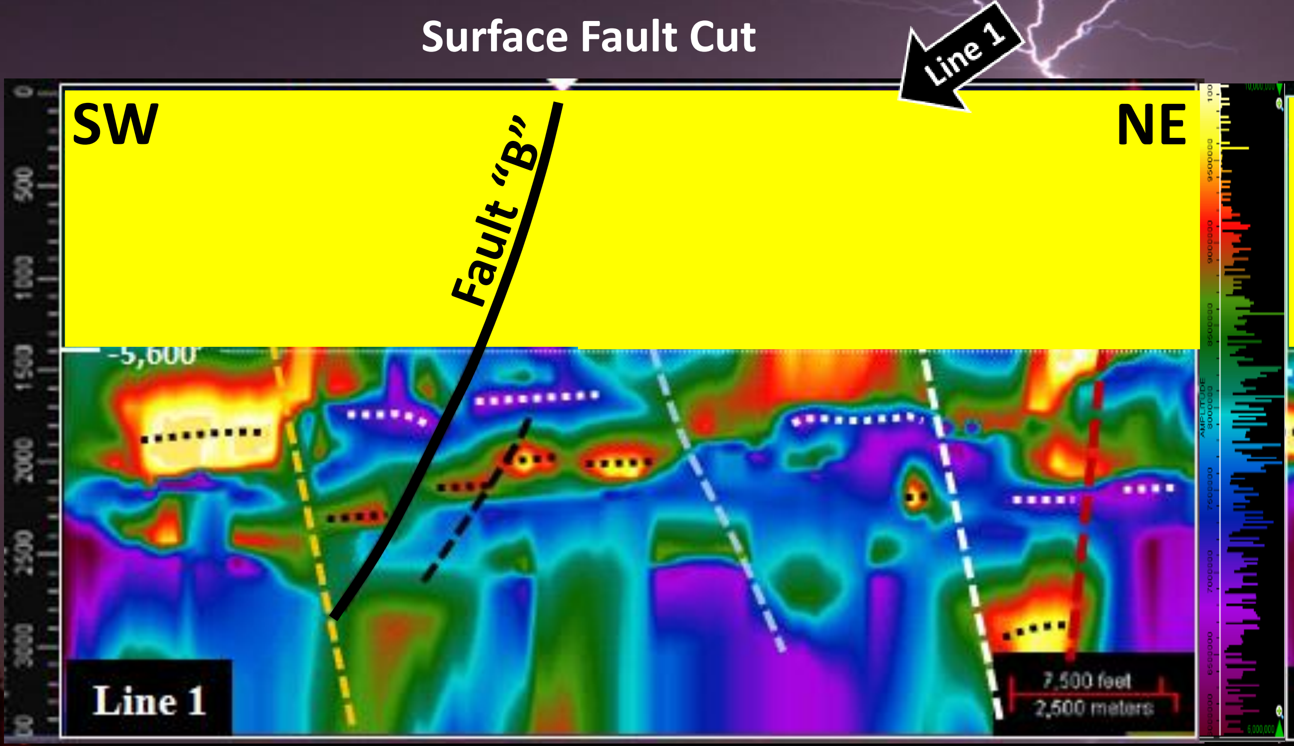


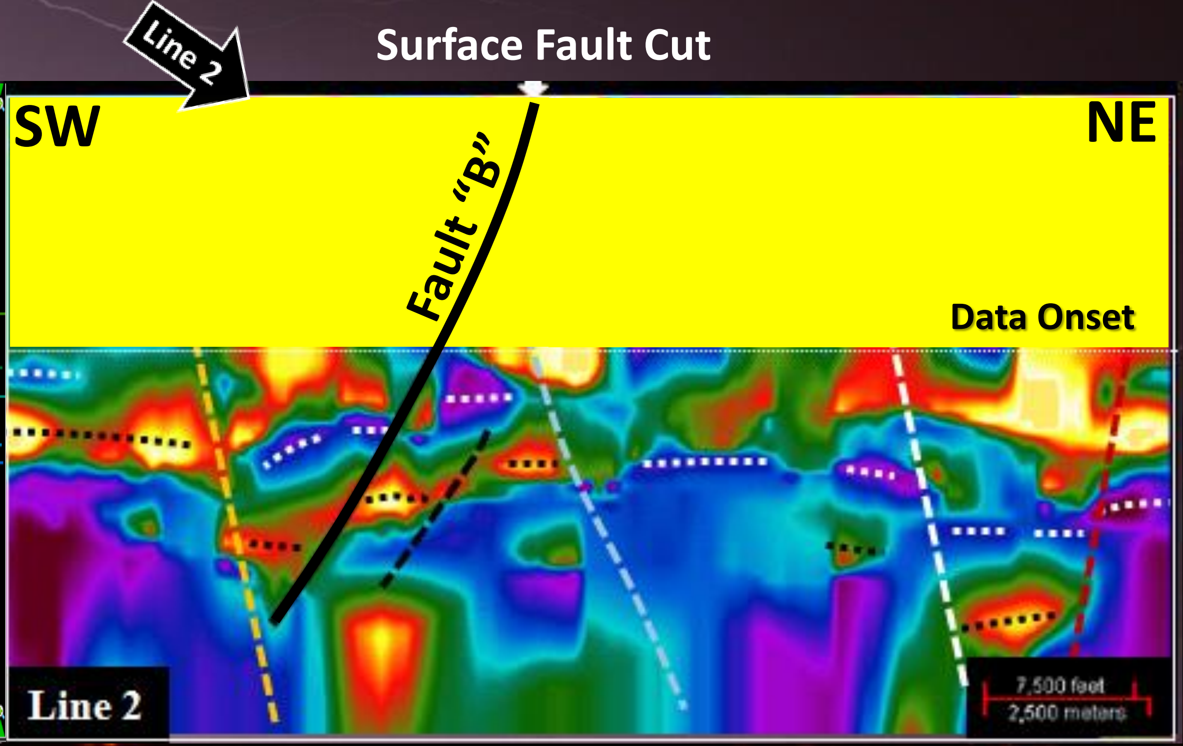




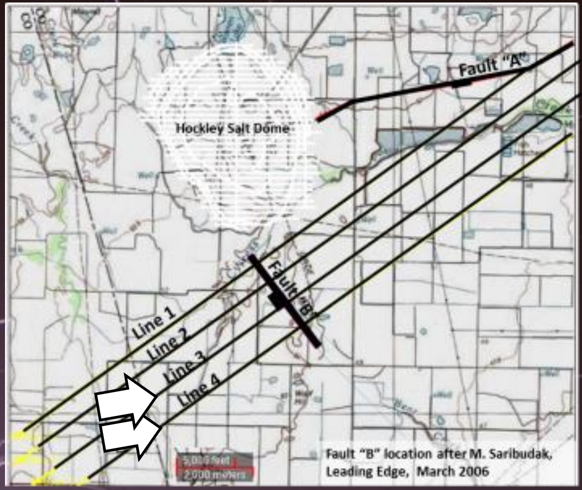
NSEM Profiles 1 & 2 Show Consistent Fault Criteria for Five Additional Faults.

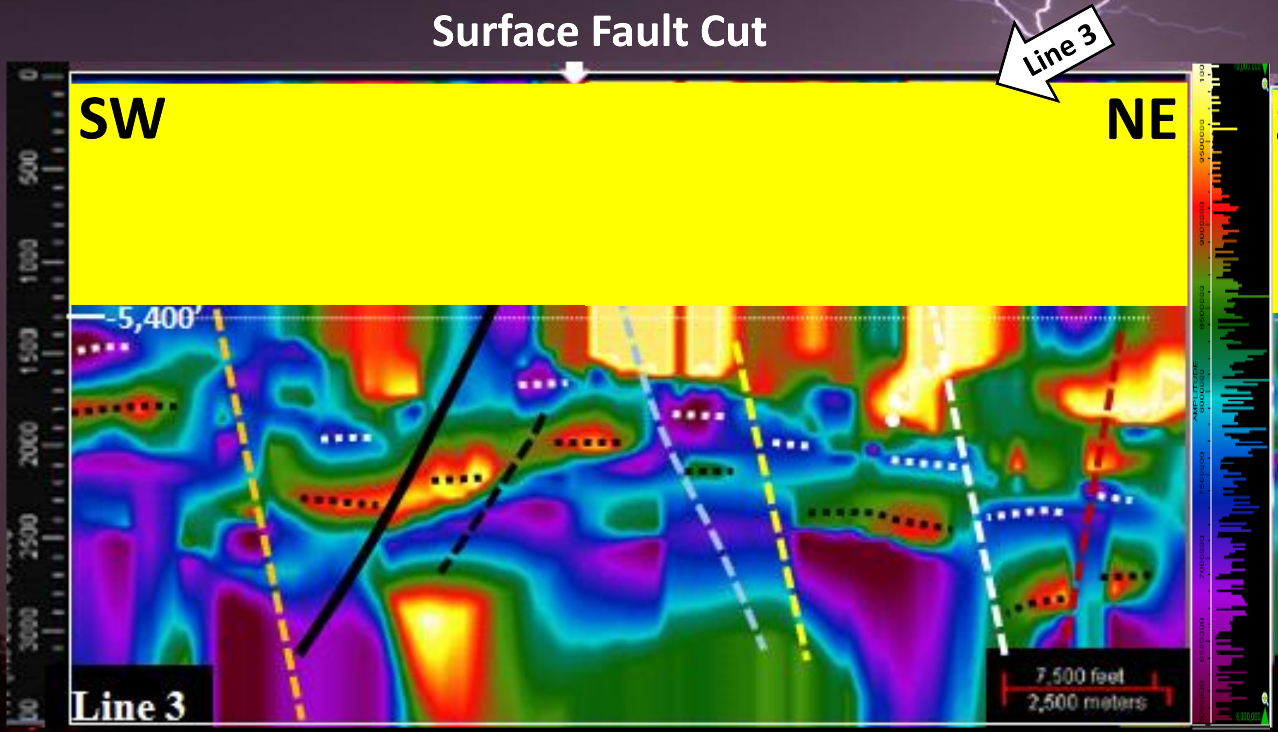


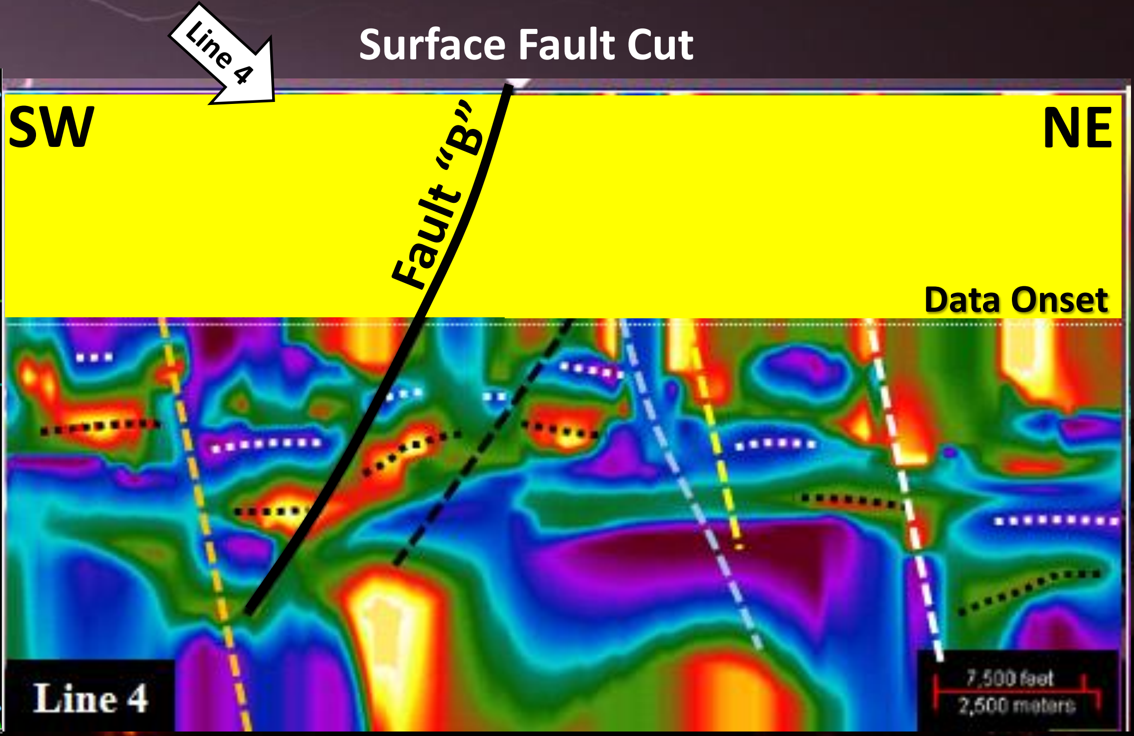




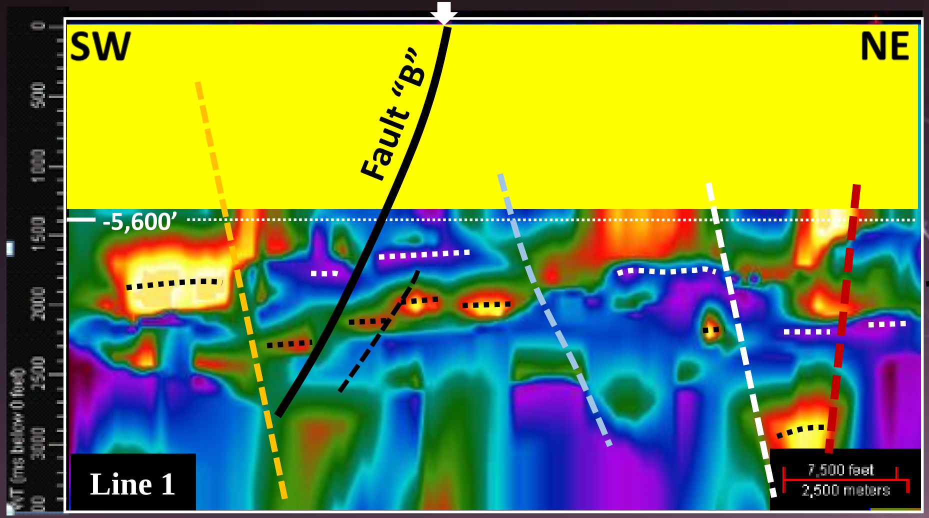
NSEM Profiles 3 & 4 Show Consistent Fault Criteria for Five Additional Faults.

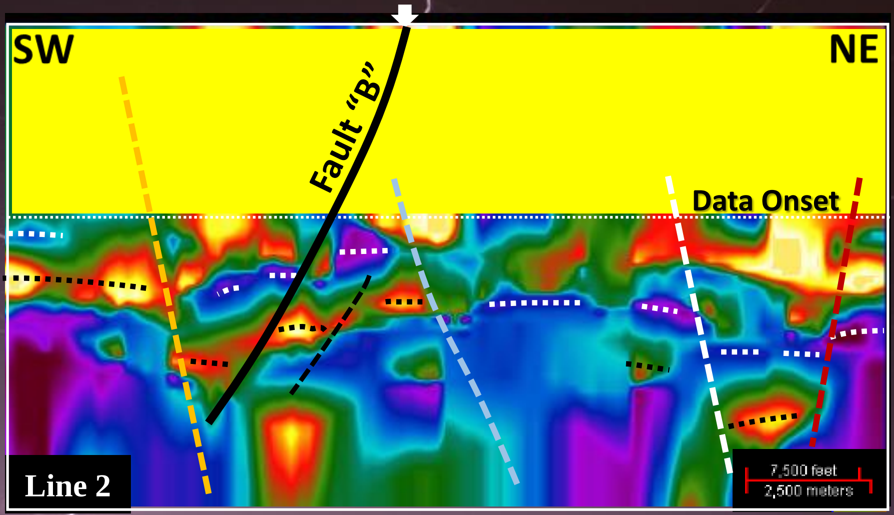


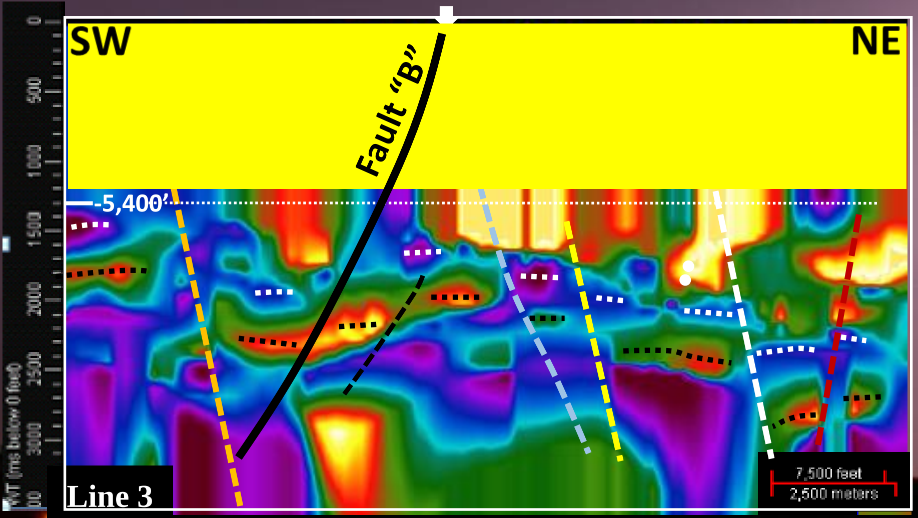


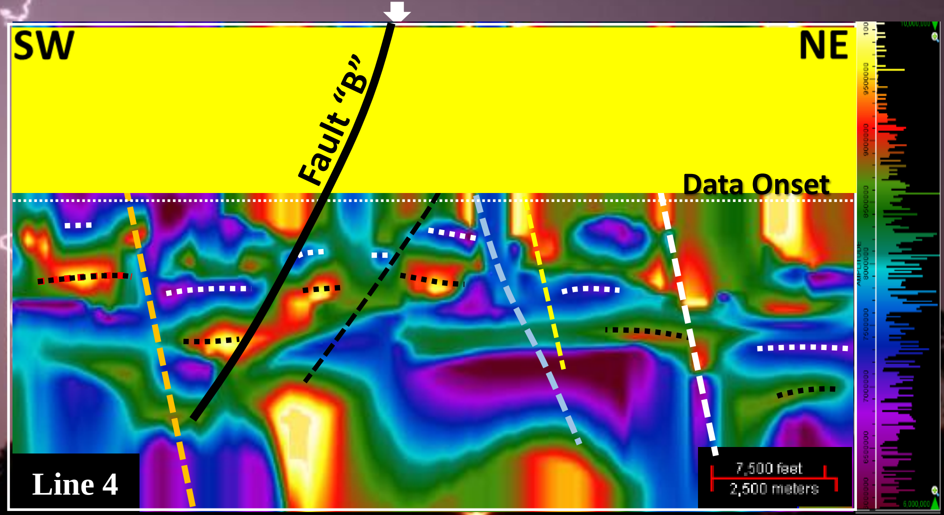


Consistent Fault Criteria On All Profiles!

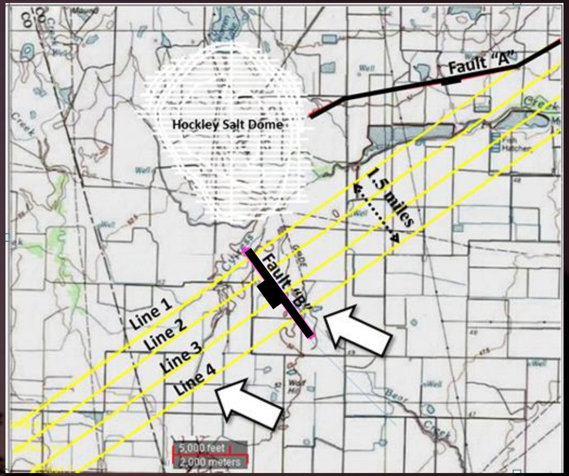




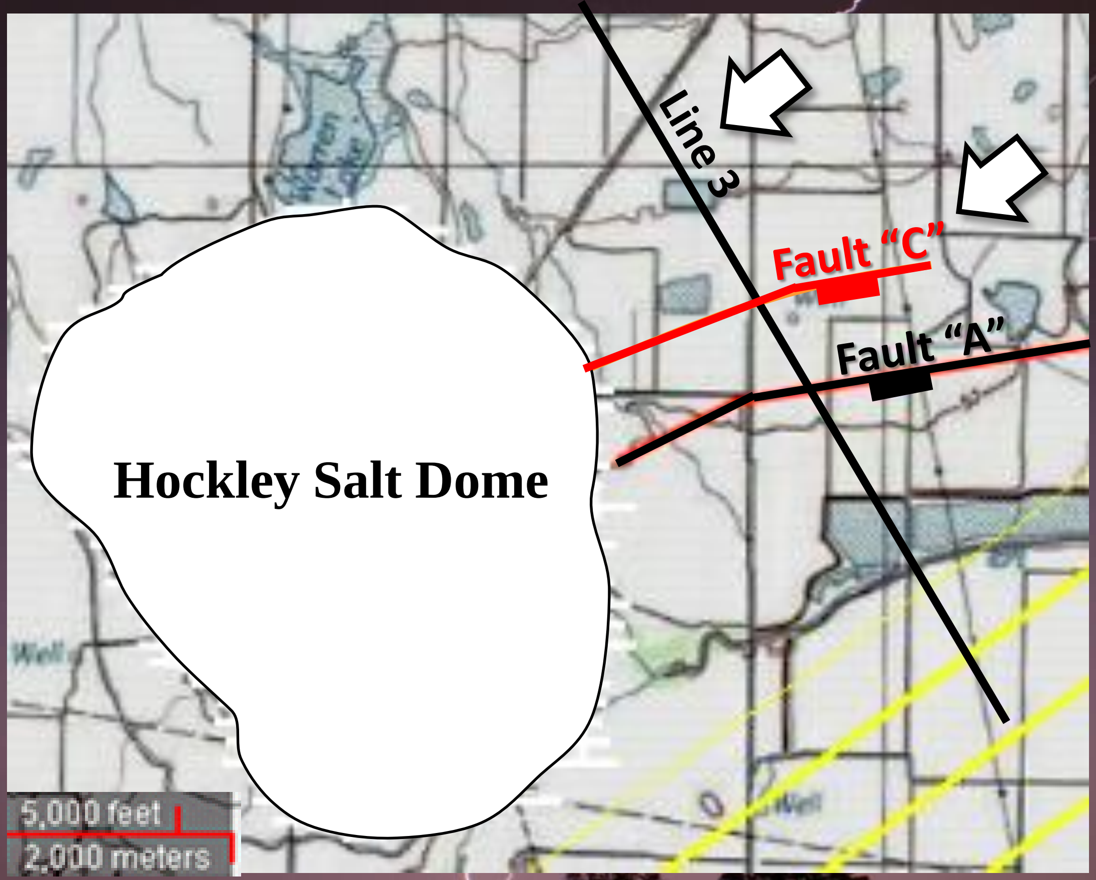




As many as 7 faults consistently identified on 4 resistivity profiles spanning 1.5 miles.

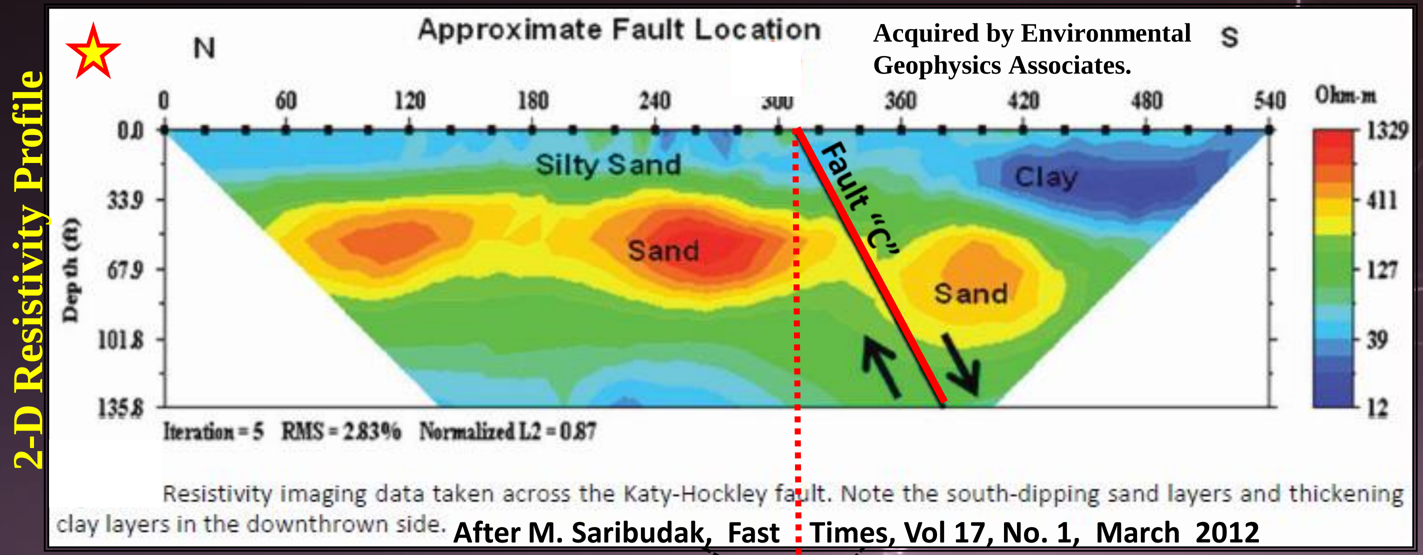


Hockley Radial Fault "C"

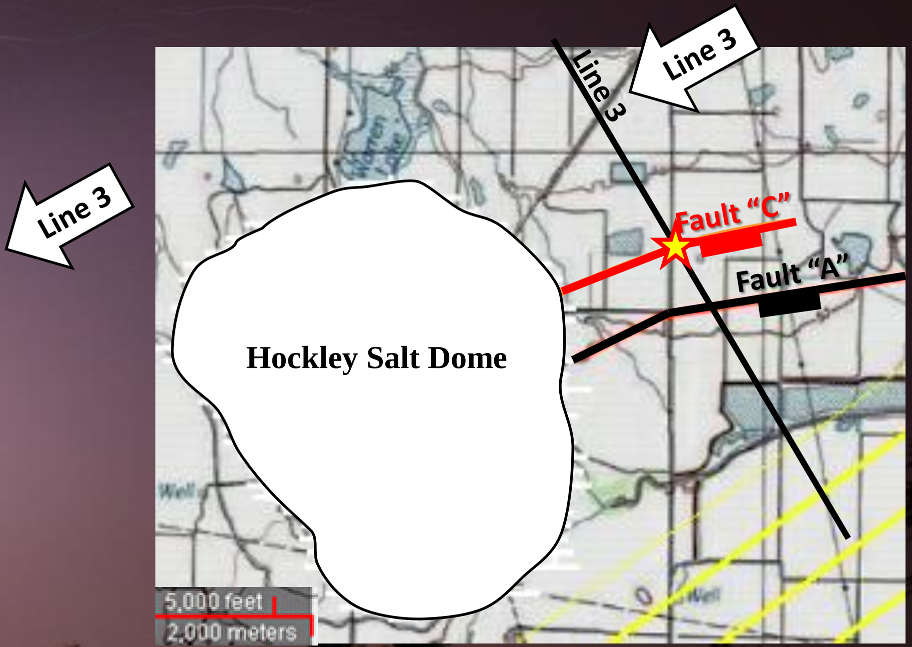


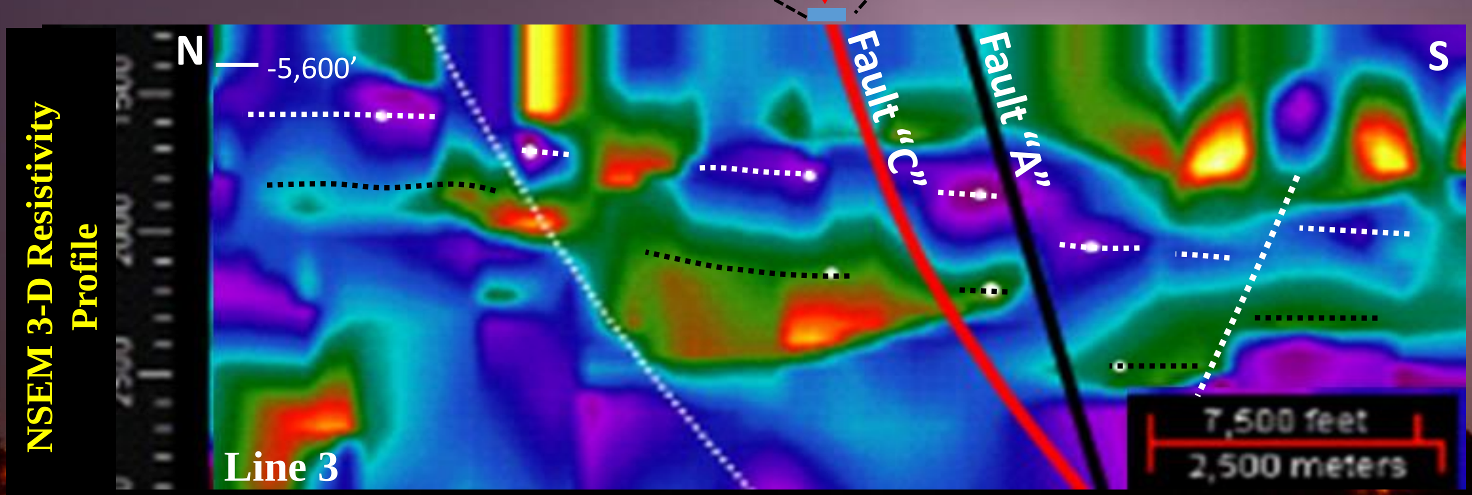
Apparent resistivity profile "Line 3" displayed next.

NSEM Fault Interpretation Again Validated by Conventional Resistivity!



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





Observations

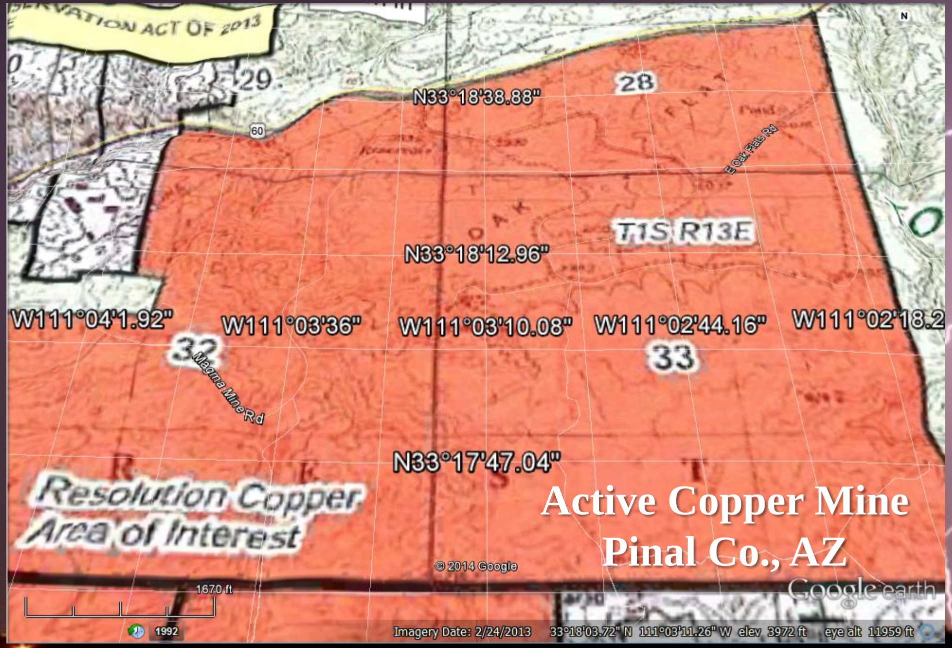
- 3-D NSEM resistivity data was able to tie surface faults and extend fault interpretations to deeper than 5,600’.
- 3-D NSEM fault criteria was credible and at least as good as conventional 2-D resistivity imaging.
- In most cases NSEM fault criteria was based on the offset of at least two resistivity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

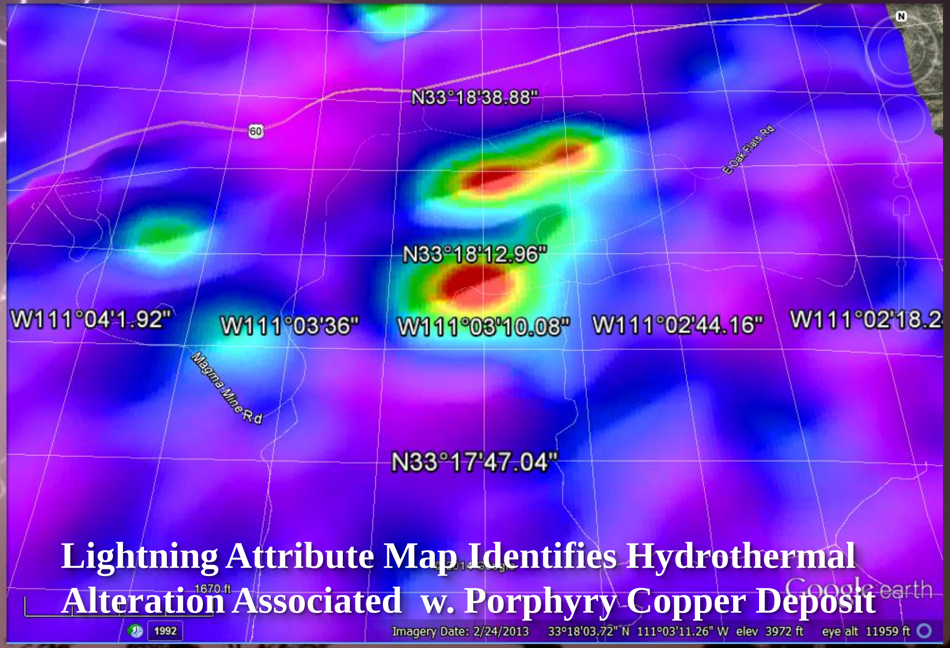
Hockley Fault Conclusions

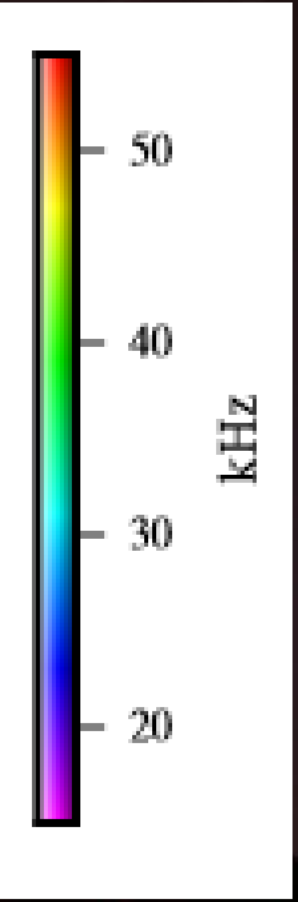
- 3-D NSEM resistivity can be interpreted similar to 3-D seismic data to build structural frameworks.
- 3-D NSEM resistivity can be integrated with and calibrated to other near-surface and potential field geophysical data to expand the depth and aerial extent of investigated areas.
- NSEM is scalable and can provide both reconnaissance data for follow-up detailed geophysical evaluation or it can focus on specific faults and previously identified anomalies.

NSEM Correlates to Rock Properties:

Mineral & Unconventional Resource Exploration



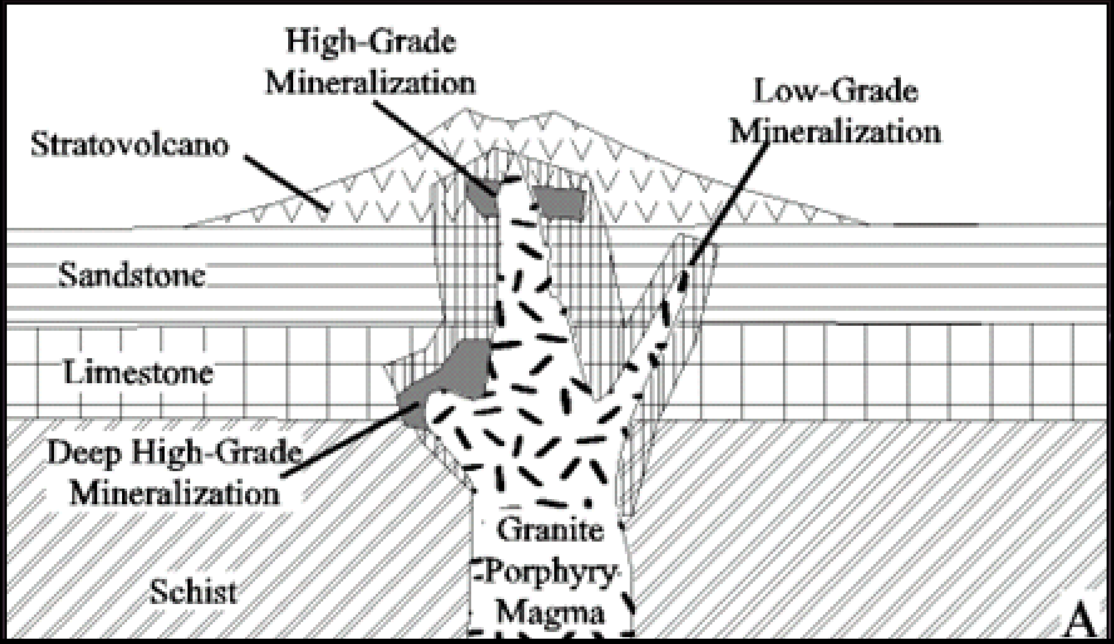




Mapping of Porphyry Copper Deposits

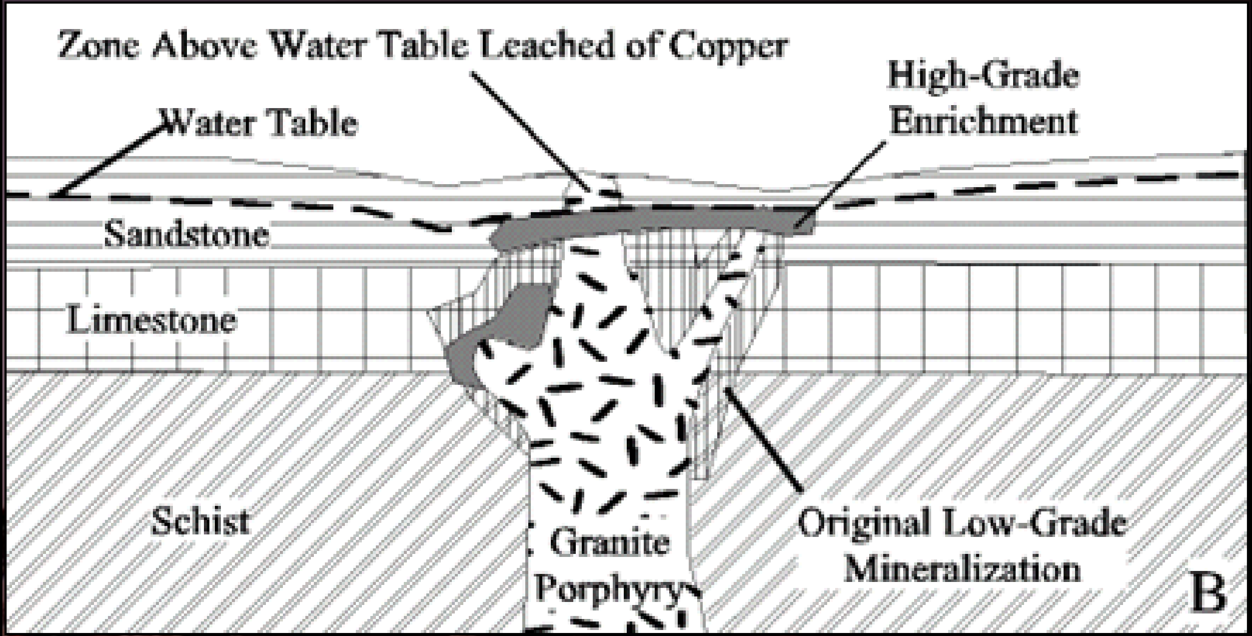
- NSEM is also a patent pending rock property mapping tool.
- Following a brief description of the general geology of porphyry copper deposits and the near-surface geophysical exploration technique used to identify them, a case study in Pinal Co., AZ is presented.

Formation of a Porphyry Copper Deposit



After Stephen J. Reynolds, Dept. Geology, Arizona State University

- 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.



- 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.

Porphyry Copper Resistivity Signature

US 20090251146A1

(19) **United States**
(12) **Patent Application Publication**
Morrison et al.

(10) **Pub. No.: US 2009/0251146 A1**
(43) **Pub. Date: Oct. 8, 2009**

(54) **DETECTION OF PORPHYRY COPPER DEPOSIT USING NATURAL ELECTROMAGNETIC FIELDS**

(75) Inventors: **Edward B. Morrison**, Stouffville (CA); **Bob Bak Lo**, Markham (CA)

Correspondence Address:
FAEGRE & BENSON LLP
PATENT DOCKETING - INTELLECTUAL PROPERTY
2200 WELLS FARGO CENTER, 90 SOUTH SEVENTH STREET
MINNEAPOLIS, MN 55402-3901 (US)

(73) Assignee: **Geotech Airborne Limited**, St. Michael (BB)

(21) Appl. No.: **12/062,795**

(22) Filed: **Apr. 4, 2008**

Publication Classification

(51) **Int. Cl.**
G01V 3/16 (2006.01)

(52) **U.S. Cl.** **324/330**

(57) **ABSTRACT**

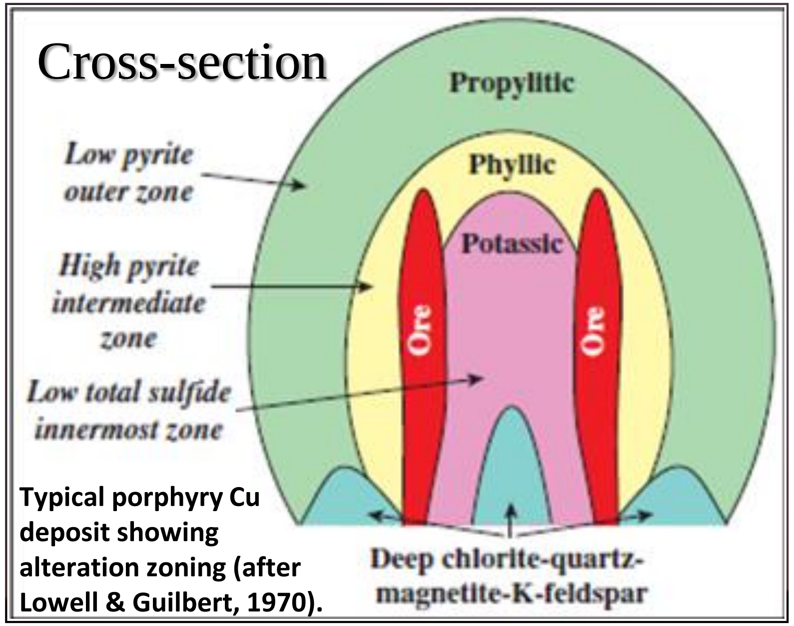
A method for identifying a possible porphyry copper deposit which includes flying an airborne sensor over a survey area measuring natural electromagnetic fields in the survey area, and then determining, in dependence on the measured natural electromagnetic fields, if one or more sub-areas in the survey area have a resistivity pattern that corresponds to a predetermined resistivity signature for a porphyry copper deposit. The predetermined resistivity signature includes a higher resistivity inner region at least partially surrounded by a lower resistivity outer region

This proven and patented mineral industry exploration technique maps porphyry copper deposits via resistivity sourced from natural electromagnetic fields.

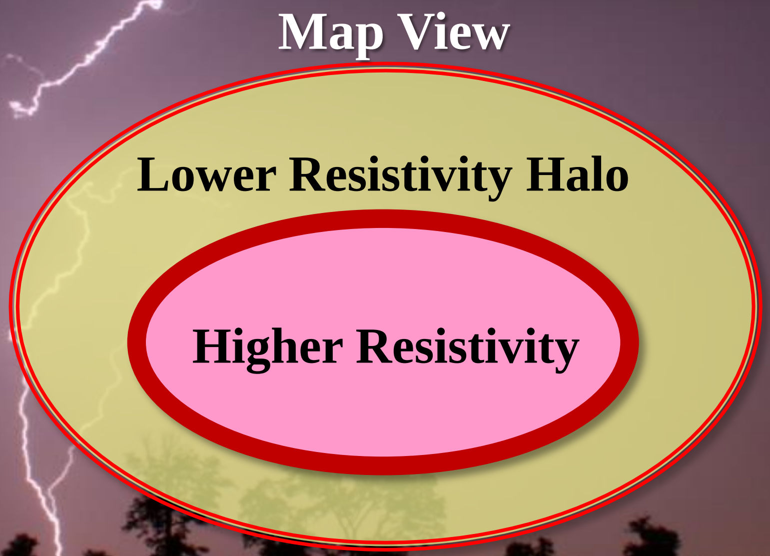
NSEM duplicates this technique for a fraction of the cost via resistivity sourced from existing lightning strike databases.

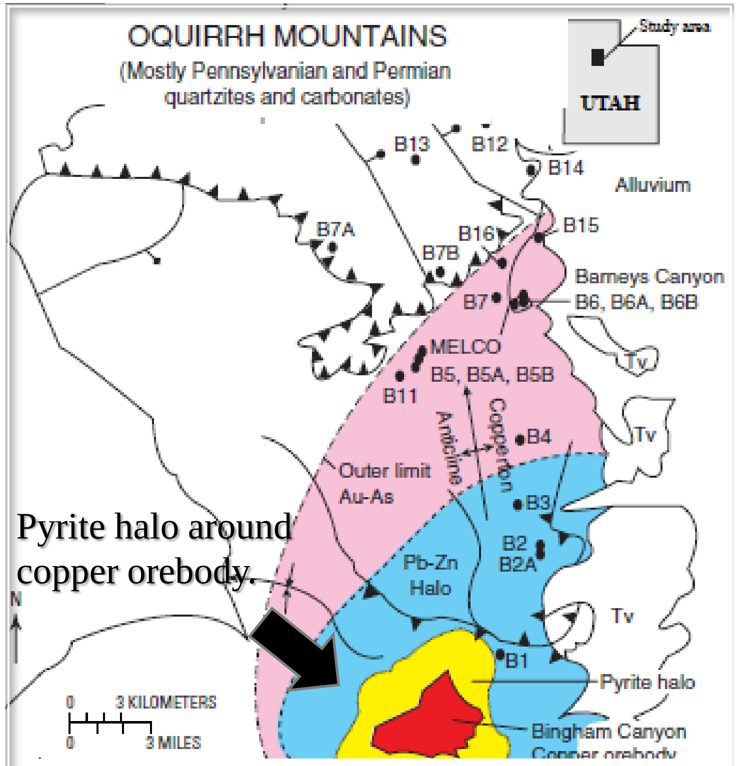
Total Porphyry Copper Signature

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



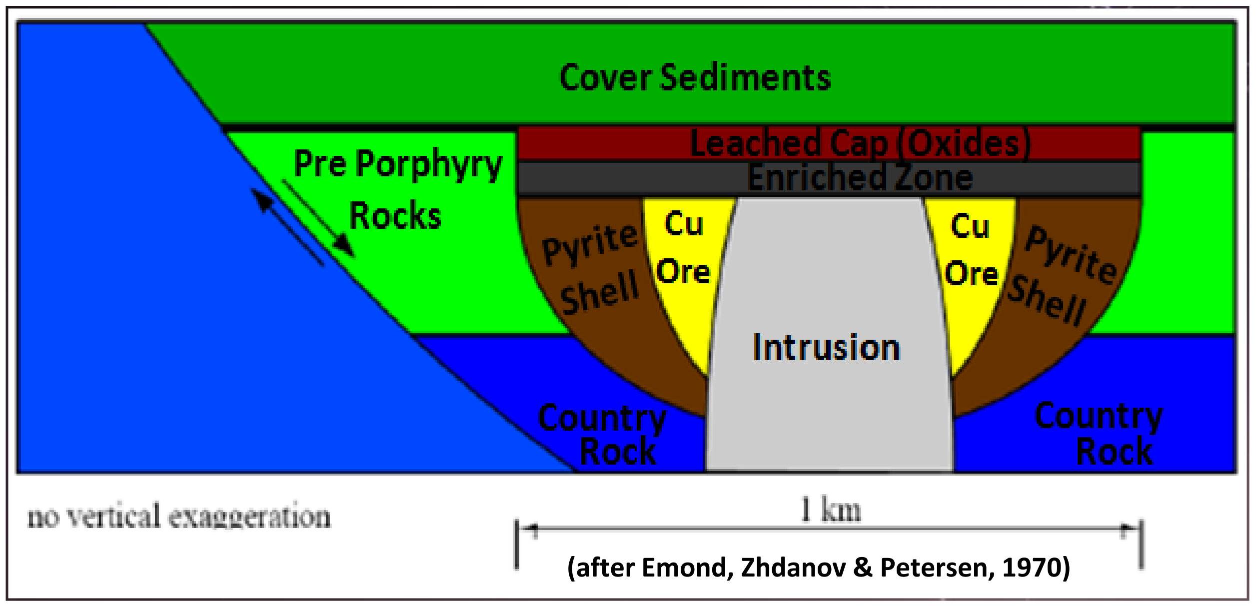
Typical porphyry Cu deposit showing alteration zoning (after Lowell & Guilbert, 1970).





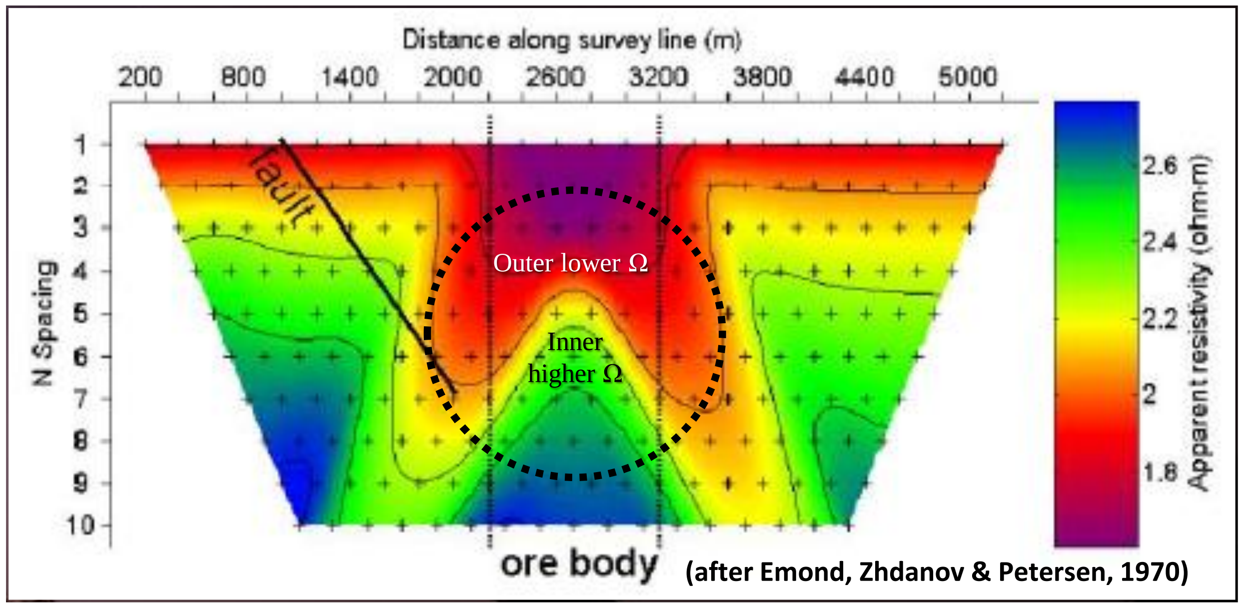
Geochemical zoning around the Bingham Canyon deposit, Utah (modified from Cunningham & others, 2004, their Fig. 1). USGS Report 2010-5070-B , David John, Editor.

Simplified Porphyry Copper Deposit Model
Typical Rock/Mineral Zones & Resistivity Signature



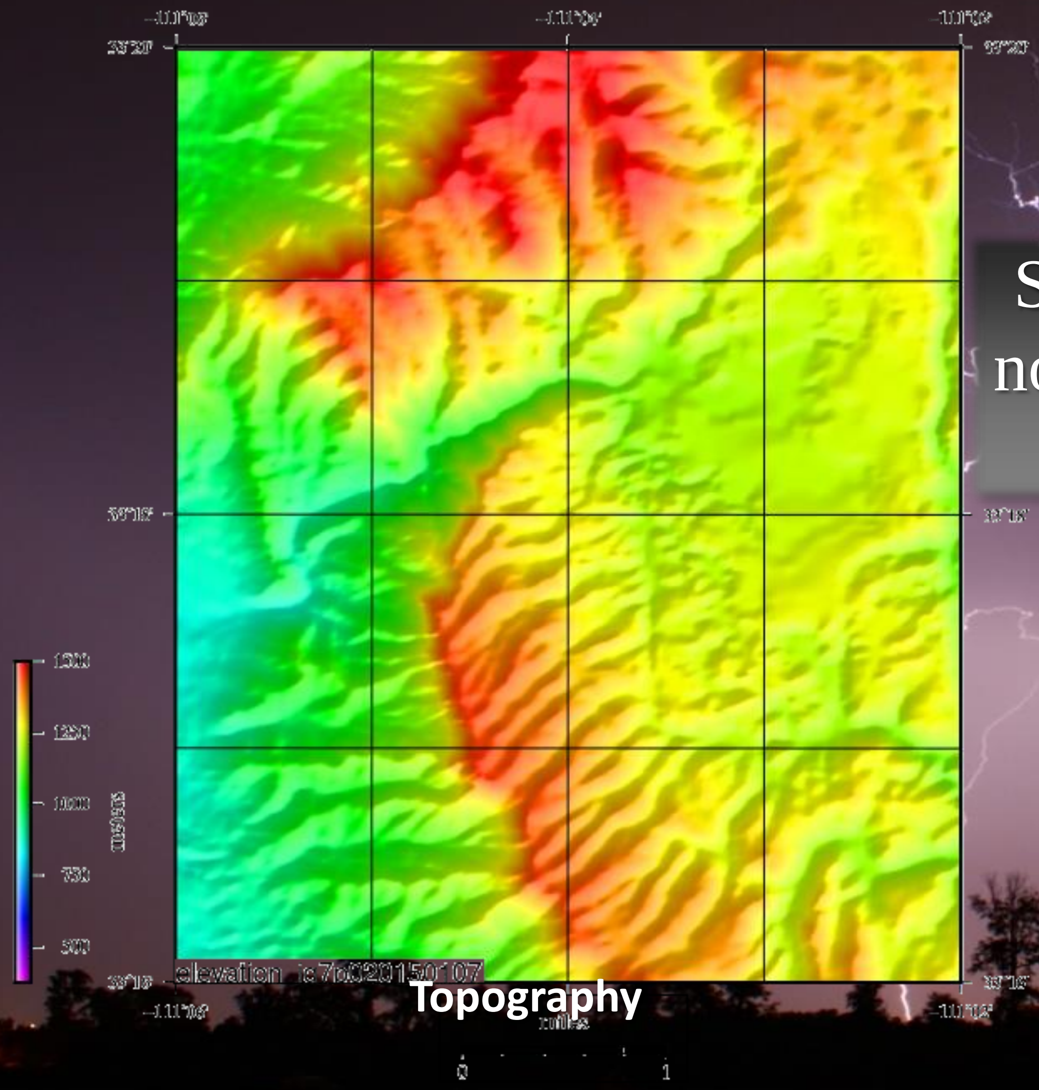
(after Emond, Zhdanov & Petersen, 1970)

Conductivity anomaly surrounds more resistive ore body in center.

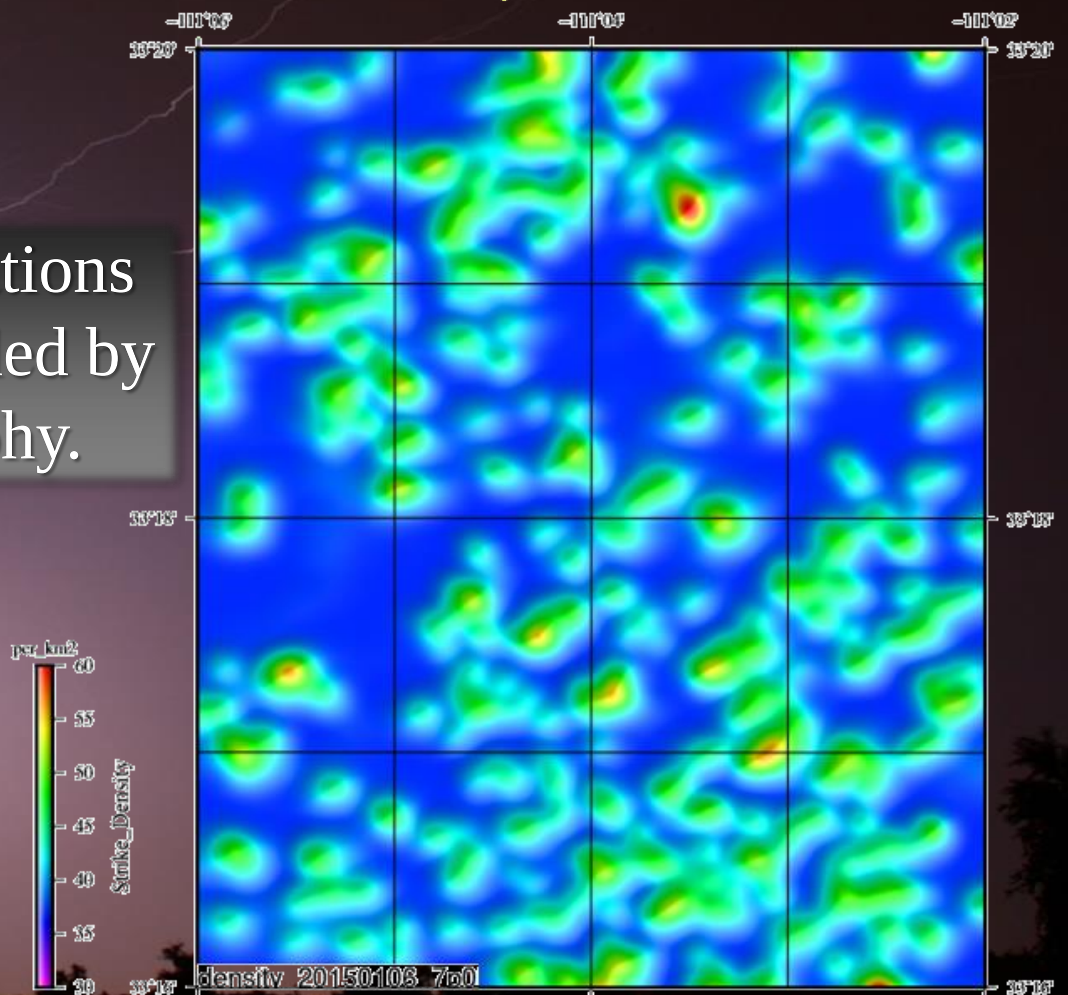


(after Emond, Zhdanov & Petersen, 1970)

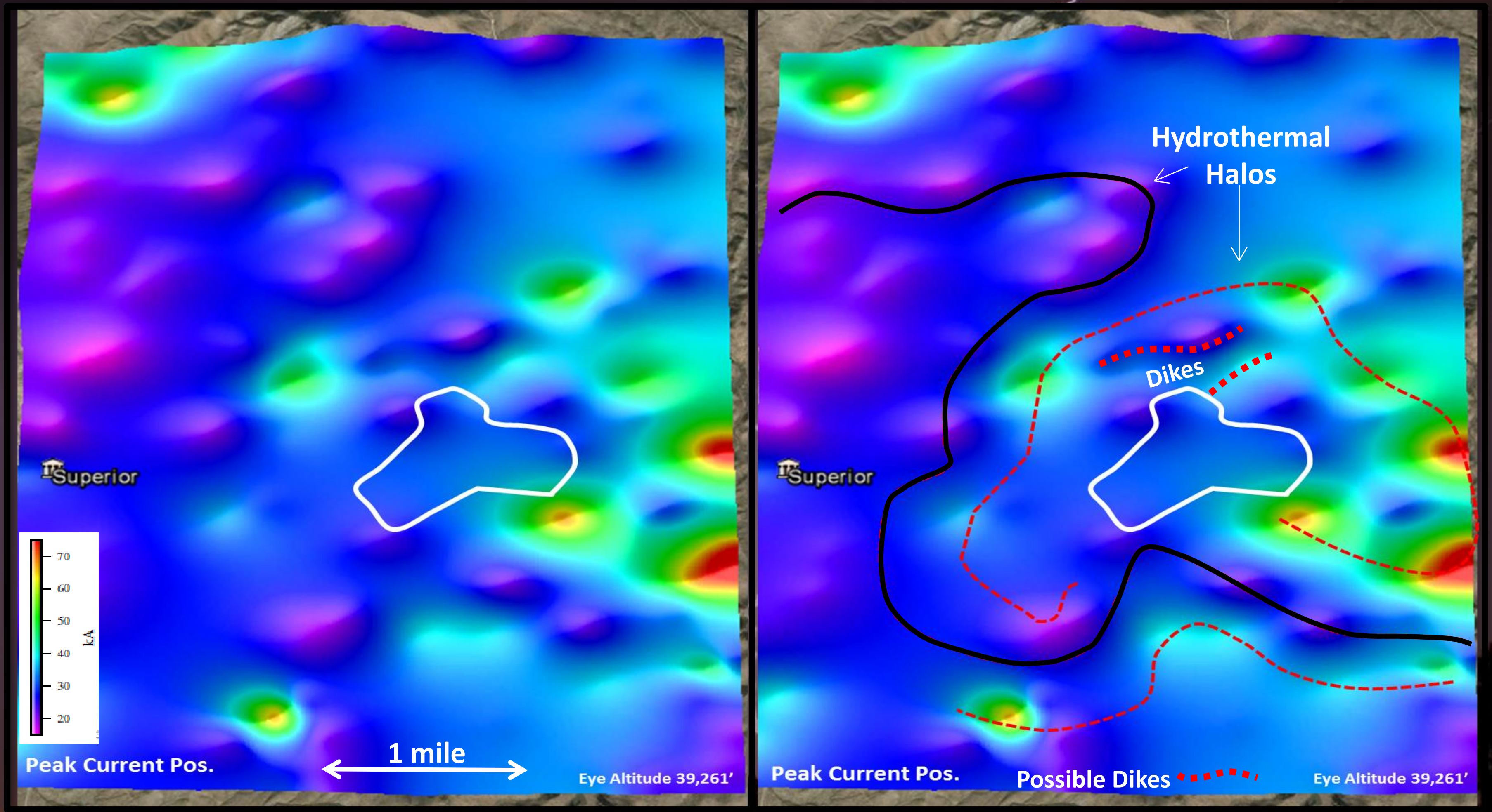
Case Study: Resolution Copper Mine
Pinal Co., AZ



Strike locations not controlled by topography.



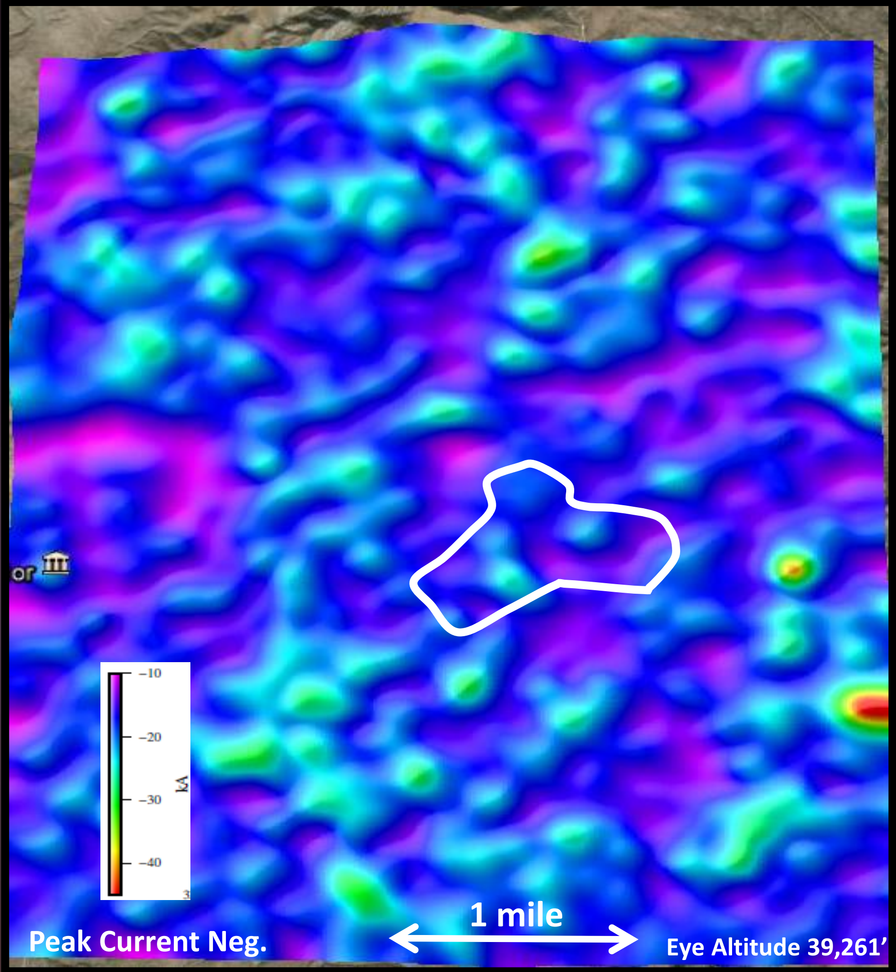
Positive Peak Current
Resolution Copper Mine

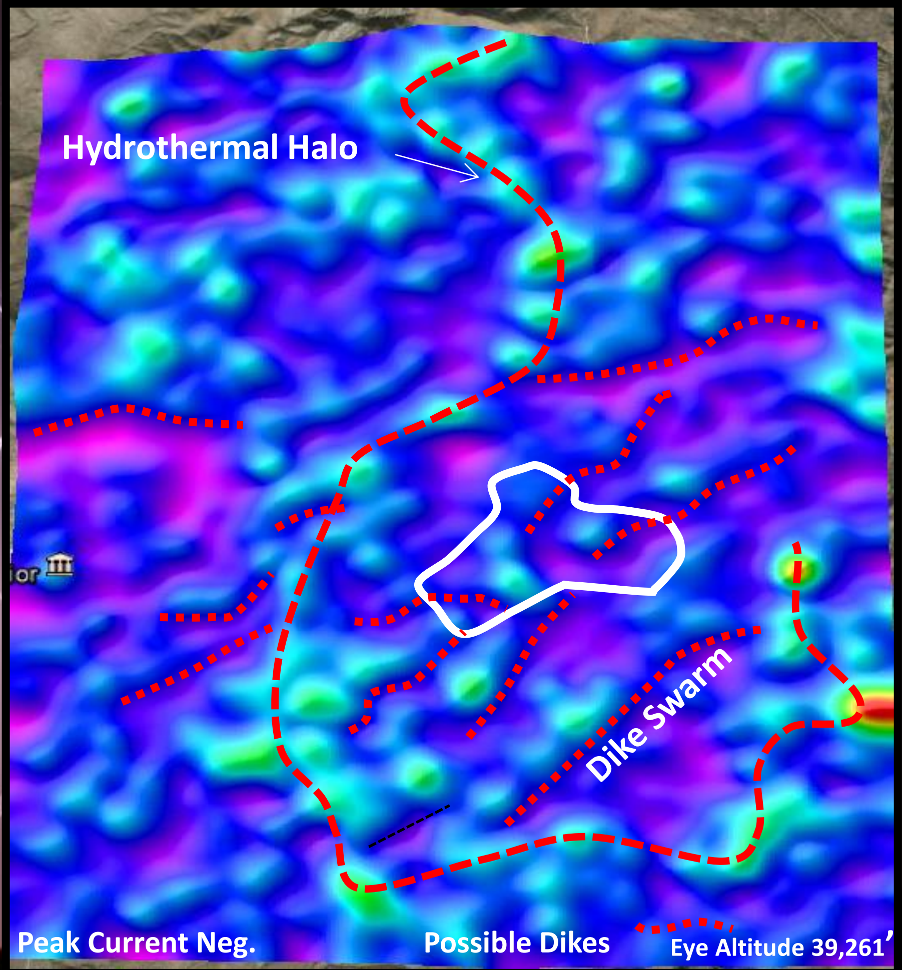


Geology Influences
Peak Current

Hydrothermal Alteration
& Dike Interpretation

Negative Peak Current
Resolution Copper Mine





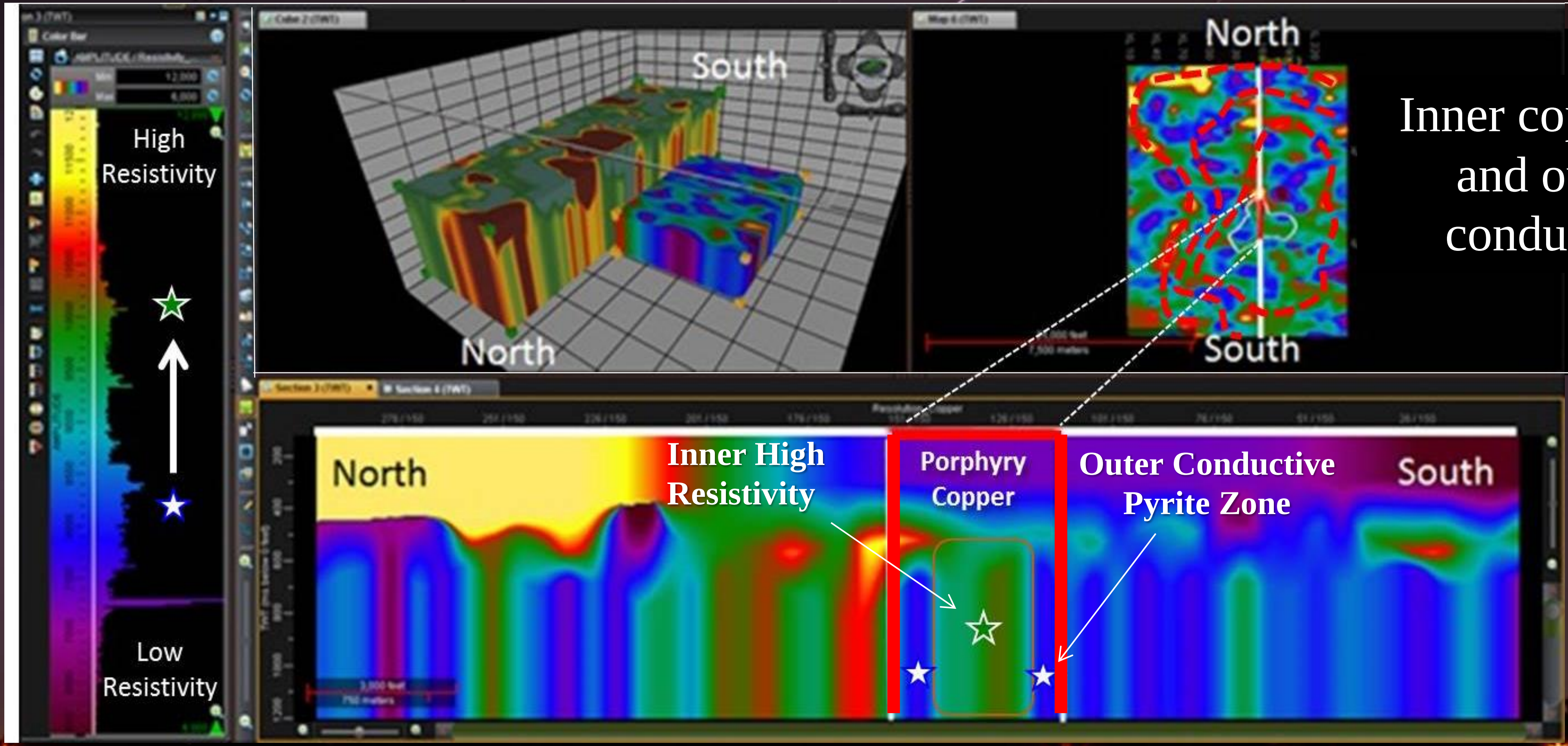
Lightning attribute pattern unrelated to topography.

Pyrite halo partially enclosing copper orebody.

Presence of dikes, indicative of porphyry copper.

3-D Resistivity Profile Through Mine
Reveals Porphyry Copper Signature

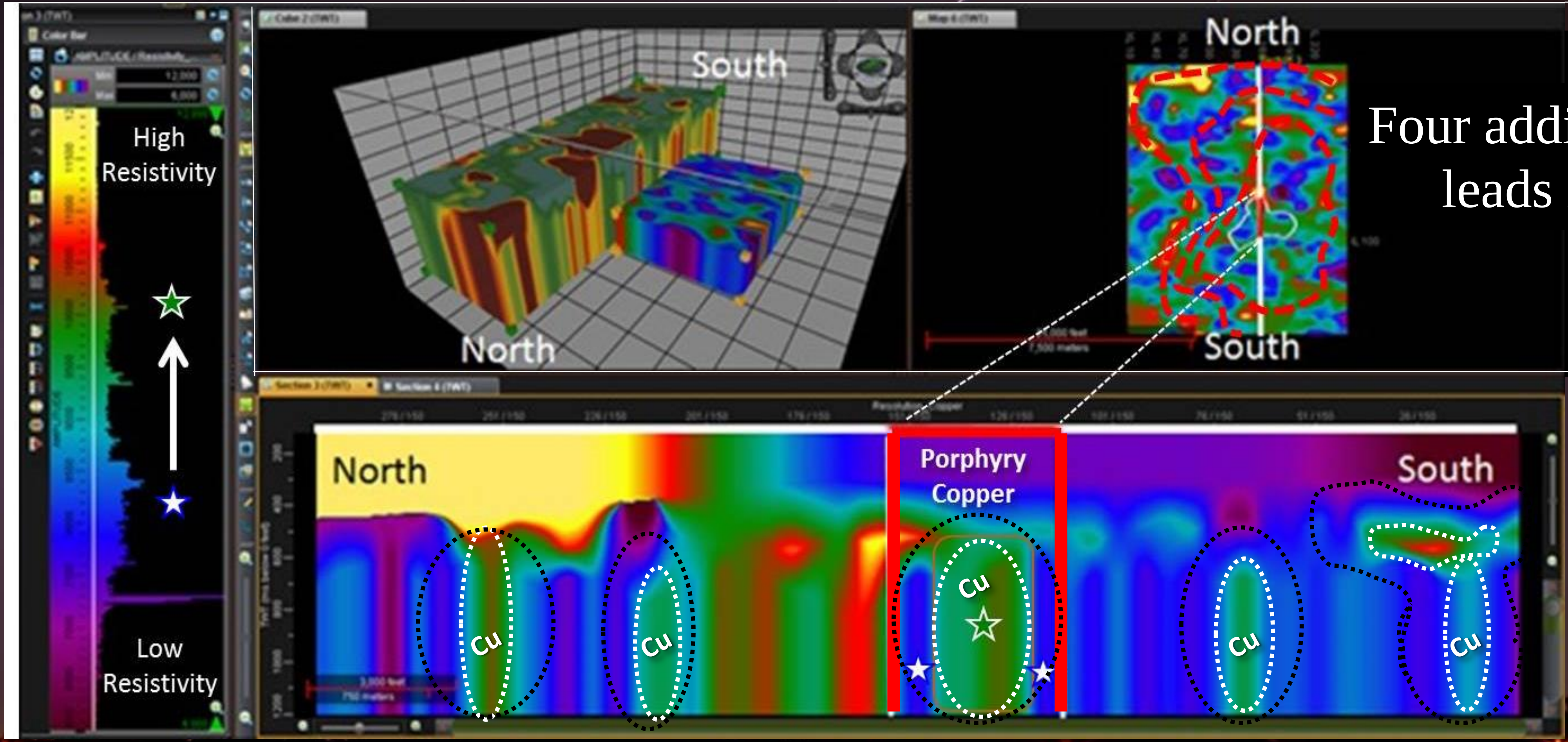
Resolution Copper Mine Pinal County, AZ



Inner copper orebody and outer pyrite conductive zone.

Mapping Rock Properties with Lightning

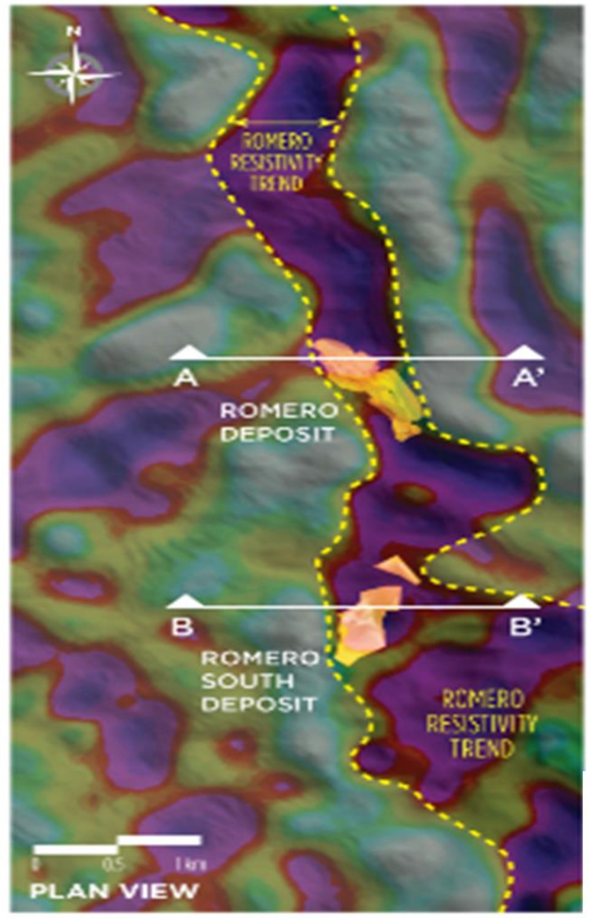
Resolution Copper Mine Pinal County, AZ

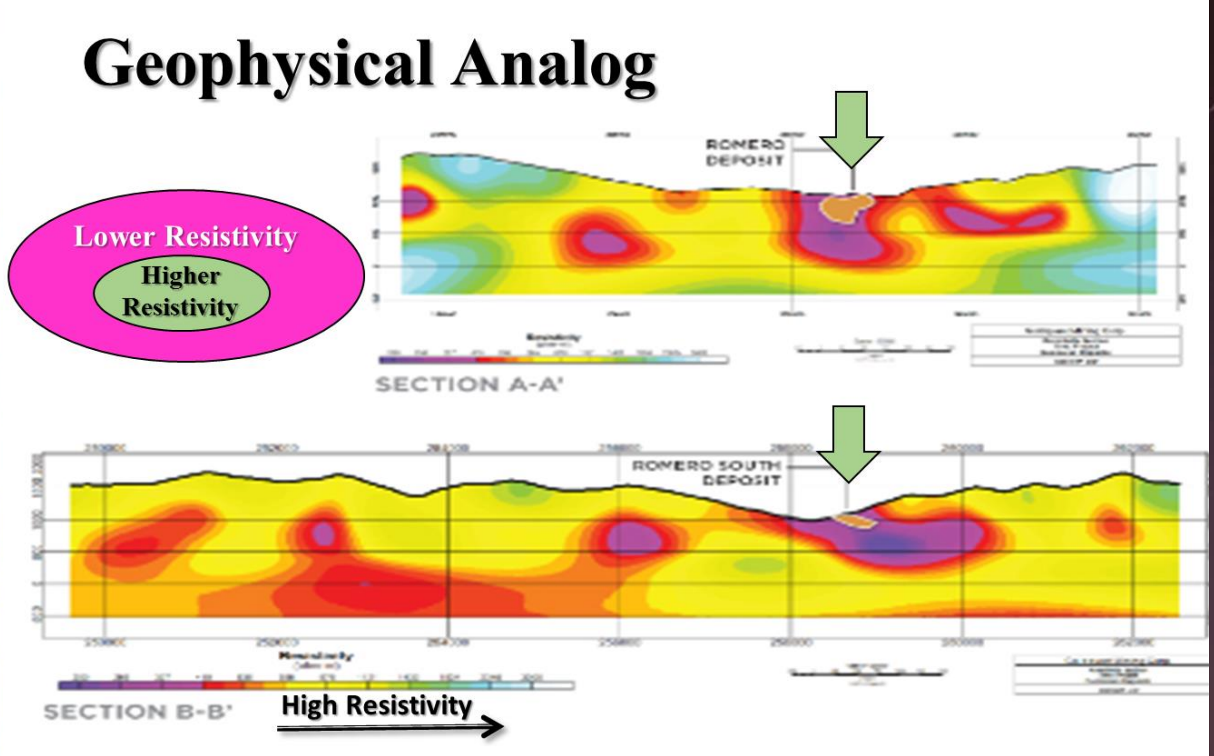


Four additional copper leads identified.

Copper Deposit Analog
Romero Resistivity Trend, Dominican Republic

DYNAMIC MEASUREMENT





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 that is surrounded by a 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 has the ability to map subsurface rock properties which can be applied to unconventional oil and gas exploration.

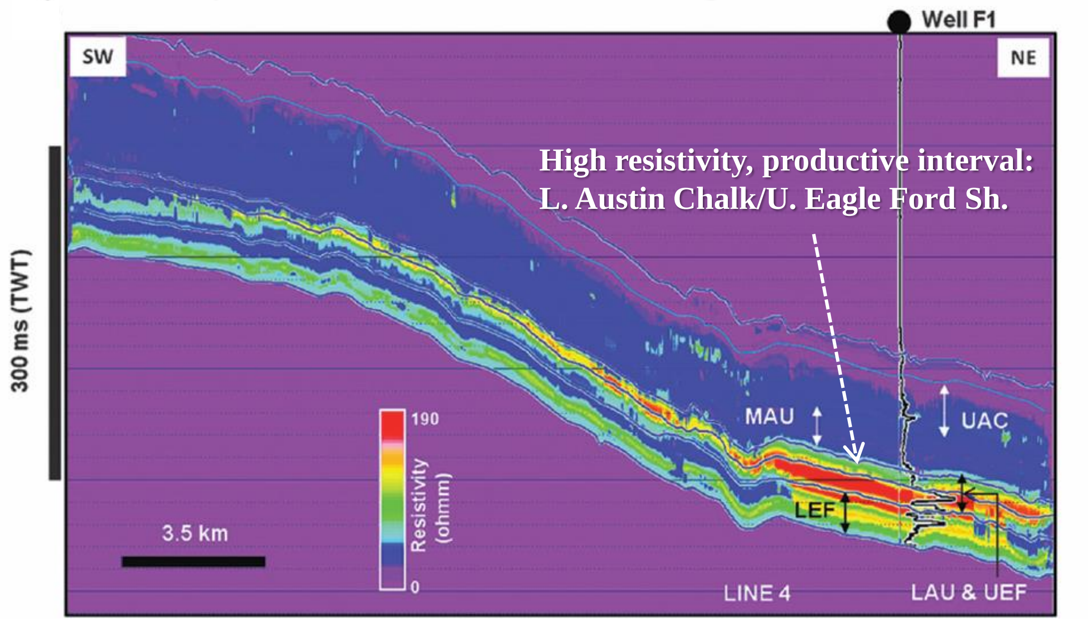
The Same Rock Properties Influencing NSEM May Help Define Unconventional Sweetspots

*BEG publication defines L. Austin Chalk & Eagle Ford Shale exploration sweetspot model in Maverick Basin.

BEG's South Texas sweetspot model:

- **High Resistivity**
- High Total Organic Carbon
- High Acoustic Impedance (brittleness)
- Low Bulk Volume Water

Resistivity volume transect through Austin Chalk



After Ogiesoba and Eastwood, see reference cited below.

"Seismic multiattribute analysis for shale gas/oil within Austin Chalk & Eagle Ford Shale in a submarine volcanic terrain, Maverick Basin, South Texas," Osareni C. Ogiesoba & Ray Eastwood BEG, Interpretation, Nov. 2013.

Unconventional Exploration Conclusions

Dynamic Measurement

- NSEM can provide apparent resistivity maps of unconventional reservoirs in depth & 2-way time for calibration to logs & seismic data.
- NSEM apparent resistivity inlines, crosslines & arbitrary lines can tie well data & be displayed, interpreted & integrated with well logs & seismic data.
- NSEM can be used as a reconnaissance mapping tool to high-grade resistivity sweet spots for subsequent in-depth evaluation.
- NSEM can be employed in other basins in search for Austin Chalk & Eagle Ford Shale sweet spots.
- NSEM can be similarly utilized in search for sweet spots in any unconventional trend relying on resistivity as a key predictive tool.

Stratigraphic Mapping & Prospect Generation - North Houston

- Mapping subsurface faults.
- Calibrating to known active fault systems.
- Mapping resistivity anomalies
- Prospect generation!

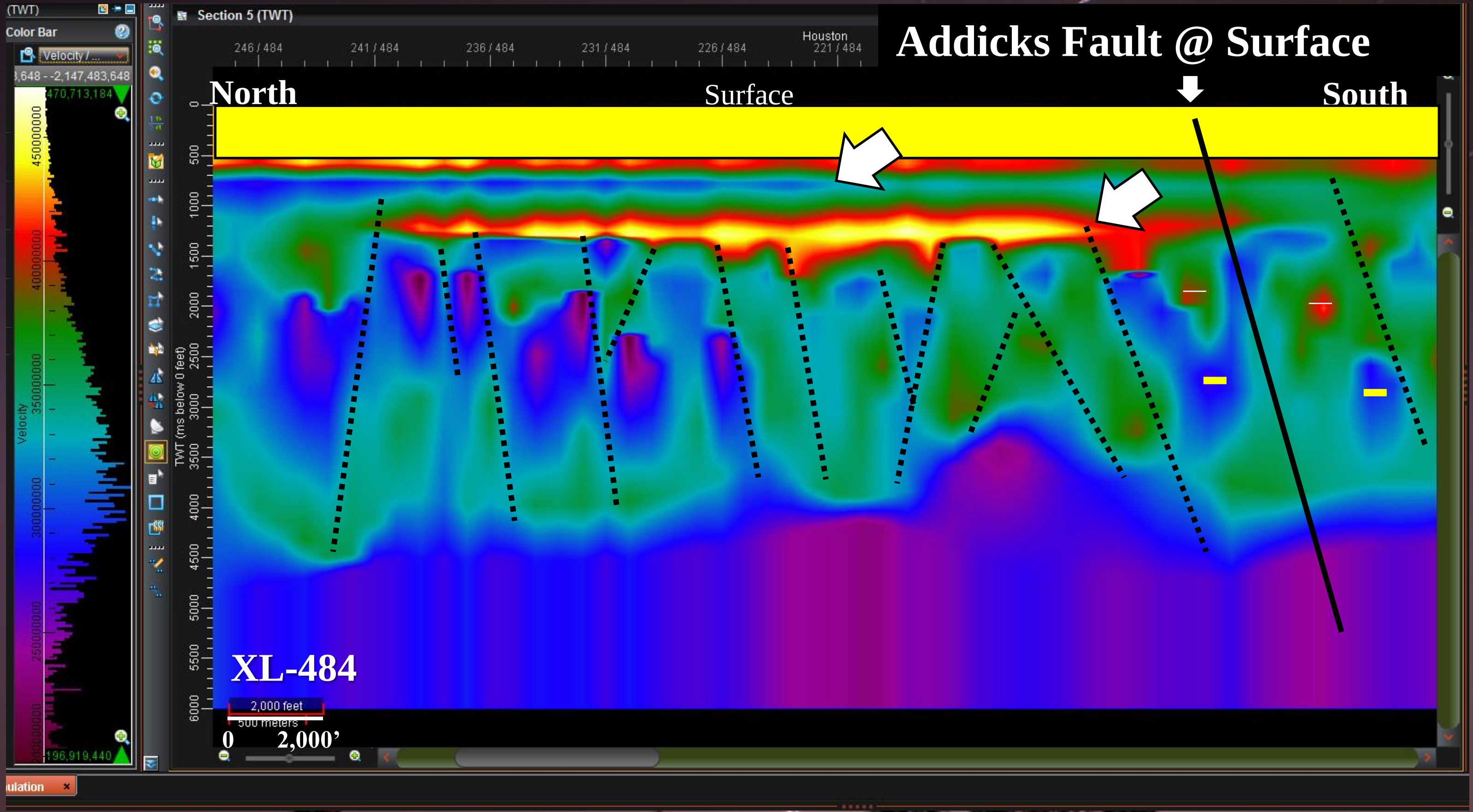
Active & Subsurface Fault Mapping

North Houston, Harris County, TX

DYNAMIC MEASUREMENT

Approximate
Location Map

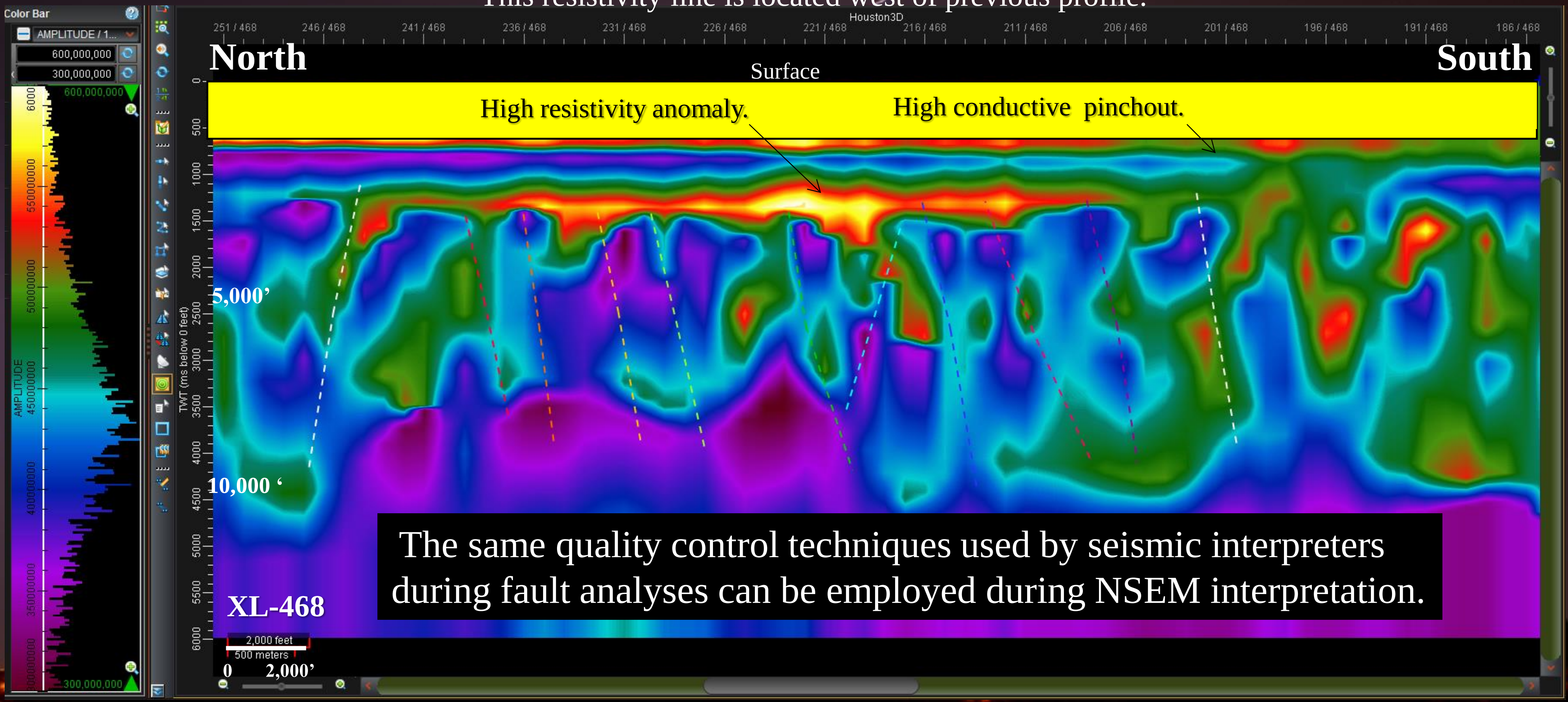
NSEM Maps Stratigraphy & Faults
North Houston, TX



- Crossline extracted from Houston area 3-D resistivity volume.
- Solid black fault interpreted on NSEM profile ties documented active fault in N. Houston.
- NSEM maps subsurface faults, pinchouts & again demonstrates ability to map stratigraphic traps.

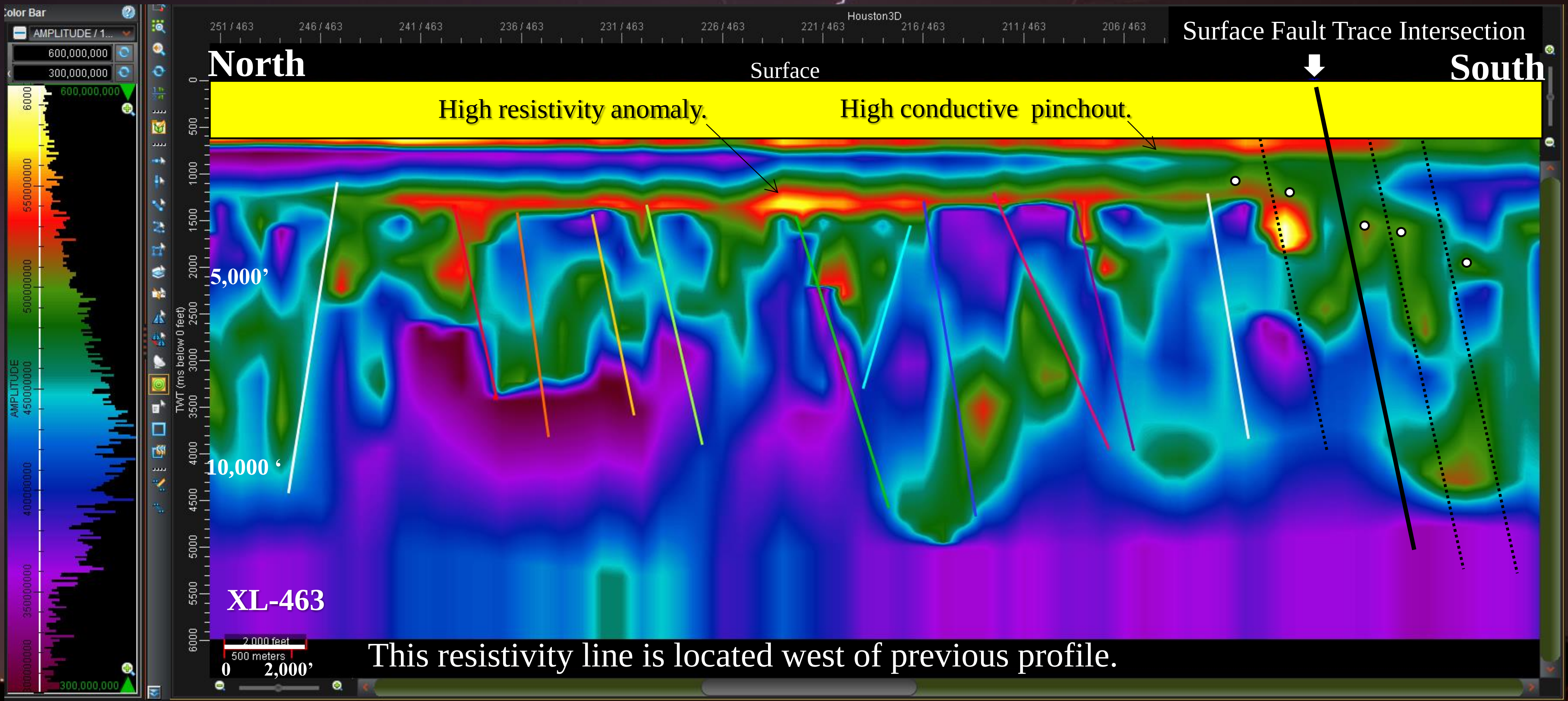
3-D Fault Analysis Quality Control
Triangulated Fault Segments & Fault Plane Maps

This resistivity line is located west of previous profile.

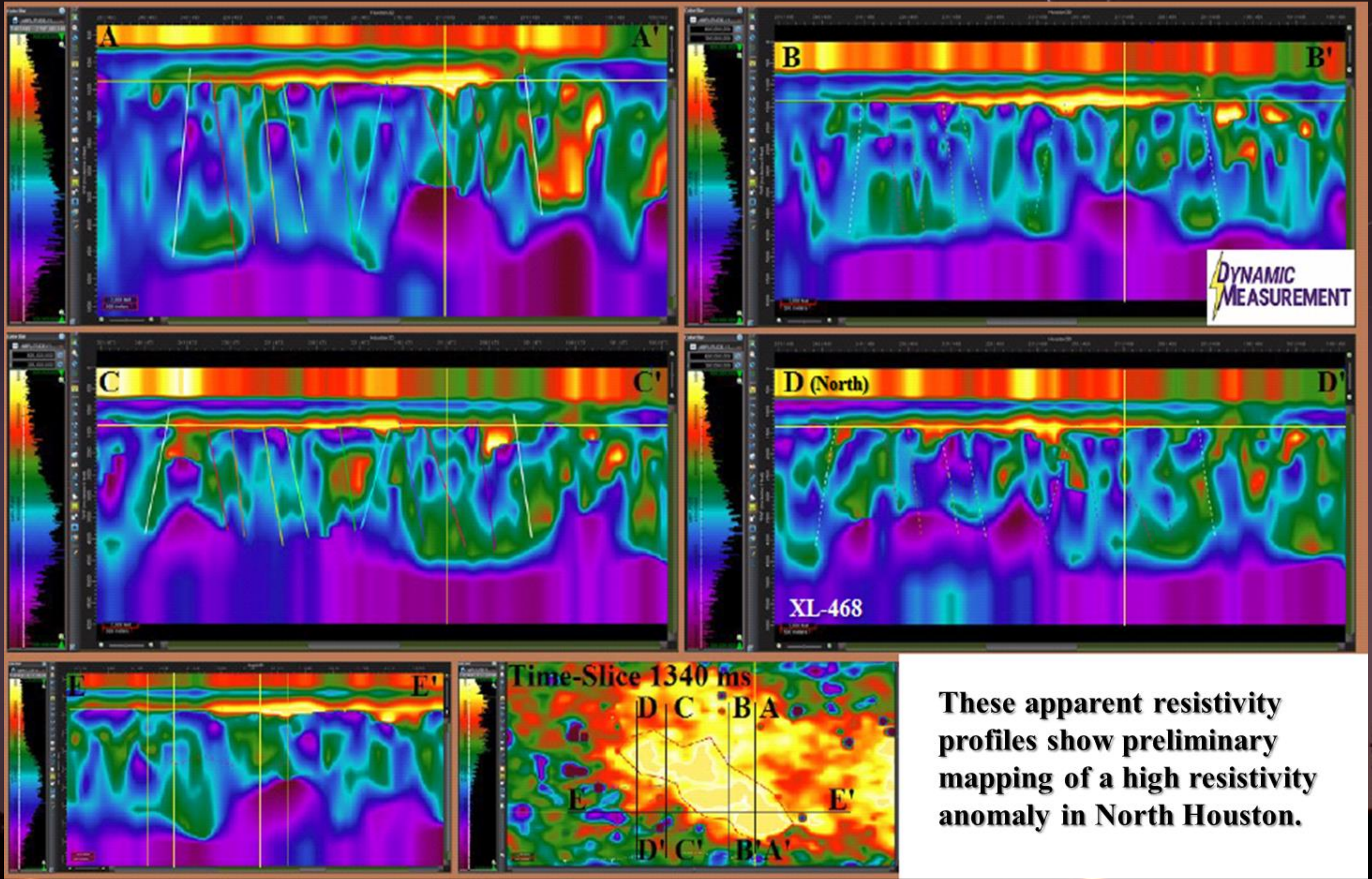


The same quality control techniques used by seismic interpreters during fault analyses can be employed during NSEM interpretation.

NSEM Reveals Structure & Stratigraphy
Potential Faults, Pinchouts & Resistivity Anomalies



NSEM Generates Prospects



These apparent resistivity profiles show preliminary mapping of a high resistivity anomaly in North Houston.

This shallow high apparent resistivity anomaly-based prospect, likely containing gas, was discreetly generated in a large city w/o “boots on the ground,” surface or mineral owner authorization or delays related to infrastructure, government regulation or permit fees.

Preliminary analyses of the NSEM electrical rock property volume indicates the presence of a stratigraphic trap based on the apparent high resistivity pinchout in four directions. Additional geologic support for this prospect and the inherent support for the validity of NSEM as an unconventional geophysical exploration tool, is provided by consistent fault patterns observed on all cross-lines. Data interpreted by Roice Nelson, CEO, Dynamic Measurement, LLC

Dynamic Measurement

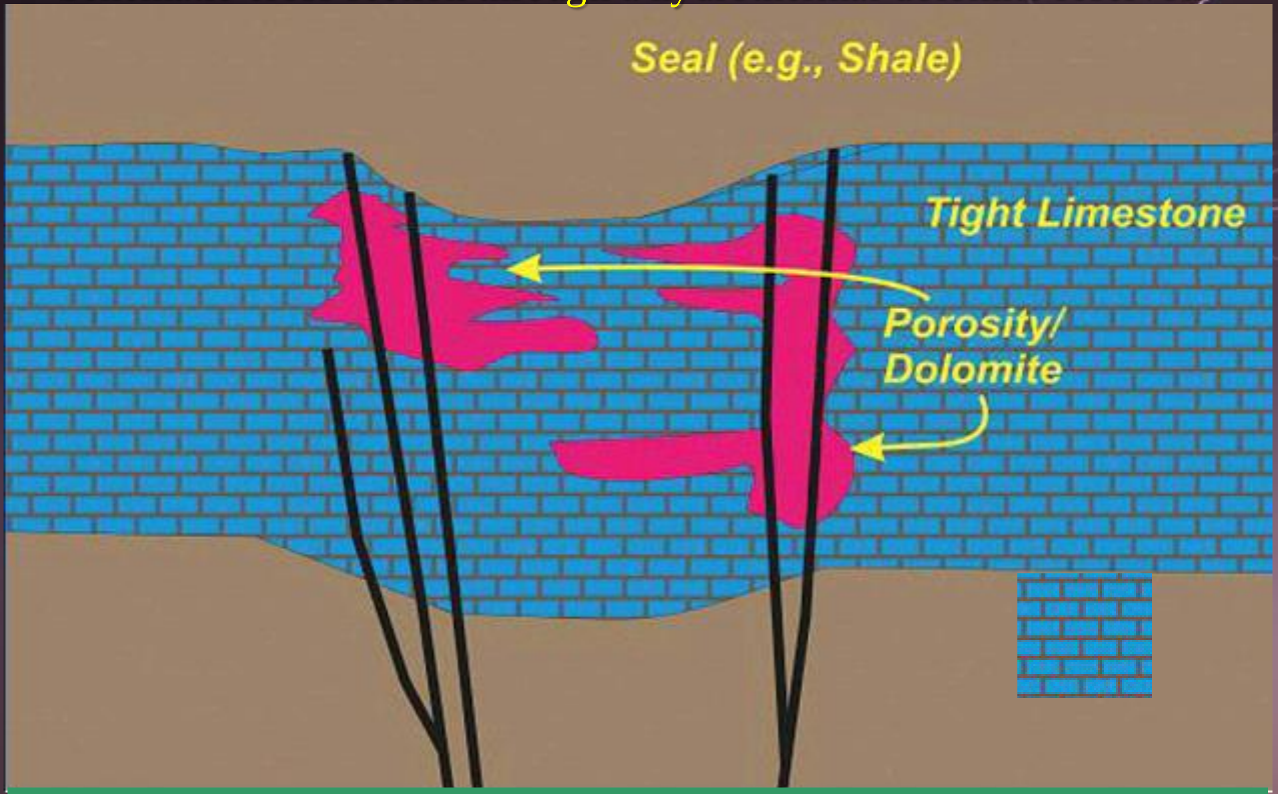
Additional NSEM Applications

Exploration & Enhanced Oil Recovery Operations

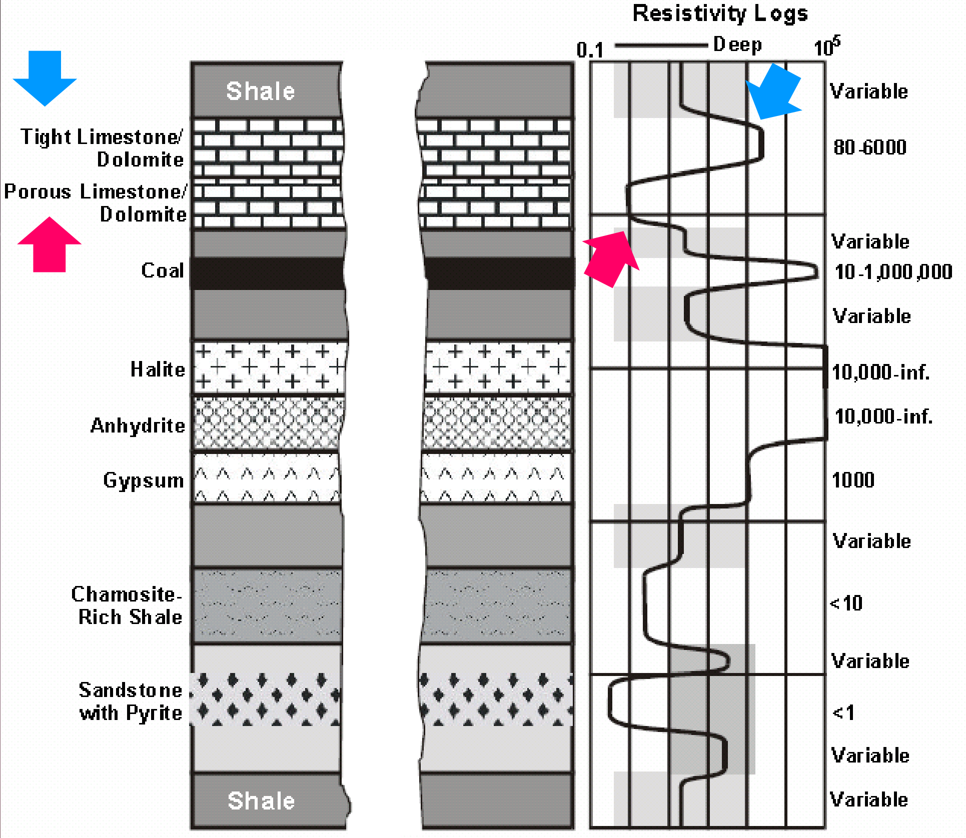
- Hydrothermal Dolomites
- Monitoring CO_2 Injection

Hydrothermal Dolomites
Large Resistivity Contrasts ➡ NSEM Anomalies

Schematic cross section through a hydrothermal dolomite reservoir.



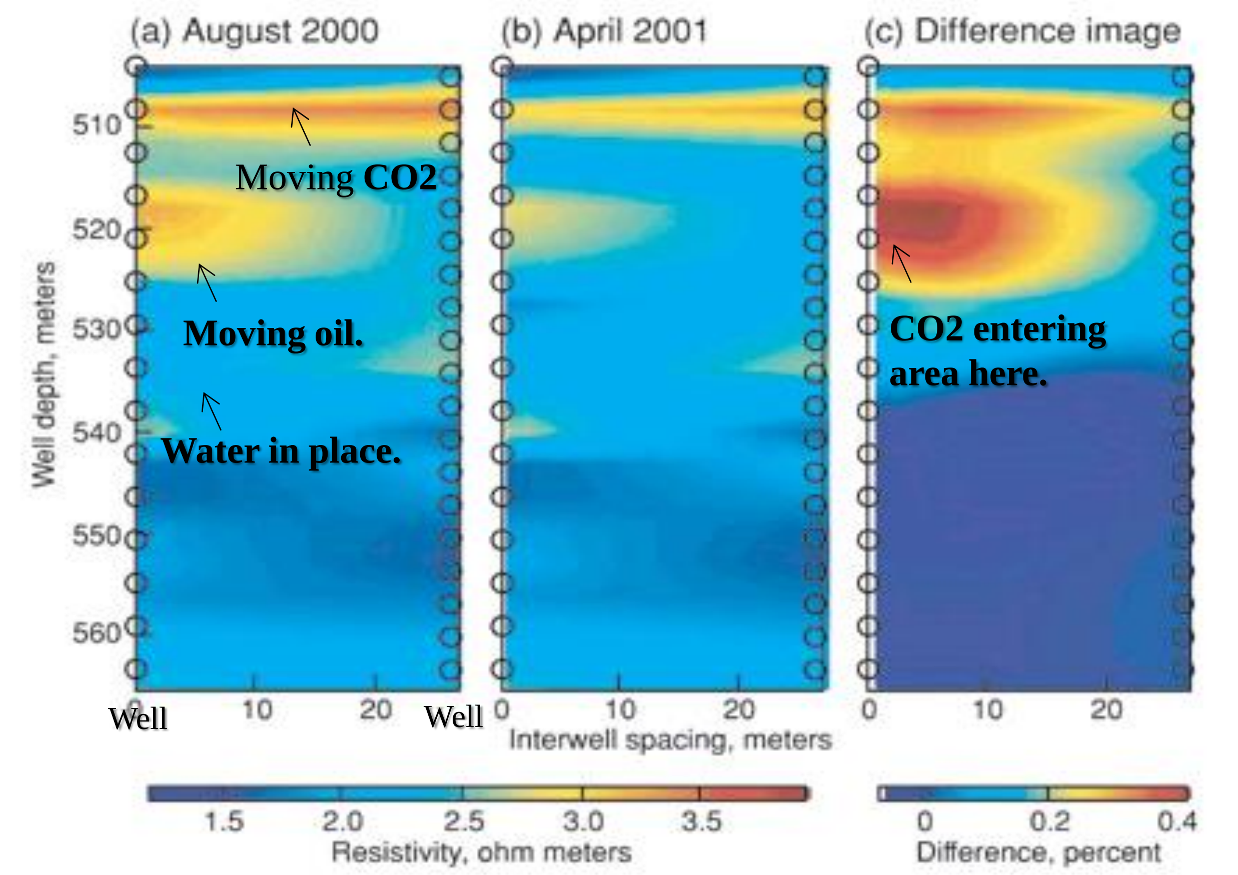
Adapted from: "Lessons Learned from 3-D Seismic Attribute Studies of Hydrothermal Dolomite Reservoirs," B. Hart, J. Sagan, O. Ogiesoba, Canadian Society Exploration Geophysicists Recorder Focus Article, May 2009; Earth & Planetary Sciences Dep't, McGill University Montreal, Canada.



Adapted from: Petrophysics MSc. Class Notes, Chapter 19.3; Electrical Logging, Dr. P. Glover, University of Leeds, UK

CO_2 Enhanced Oil Recovery Operations Monitoring Operations with Electrical Methods

2-D Crosswell Electromagnetic Imaging



Adapted from: "Locked in Rock Sequestering Carbon Dioxide Underground," Science & Technology, May 2005, p. 12-19, A. Heller.

Electrical methods such as Crosswell Electromagnetic Imaging & Electrical Resistivity Tomography are useful for monitoring the migration of CO_2 in the subsurface.

DML can generate multi-year time lapse maps and support EOR operations at a fraction of the cost of competing techniques.

Current DML Projects

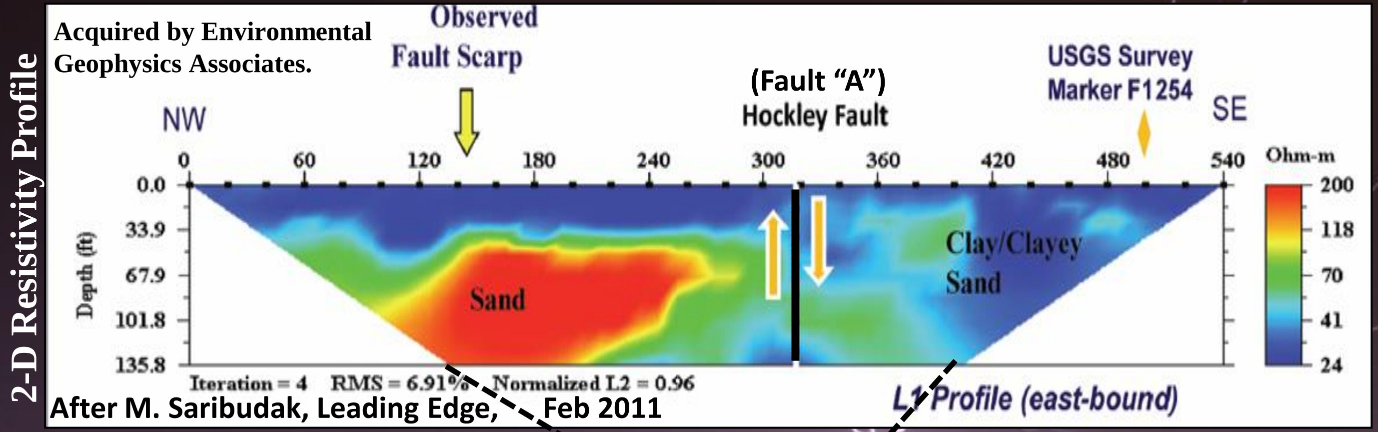
- Sequence Stratigraphy – Hockley, Texas
- 3-D Seismic Calibration Project – South Texas

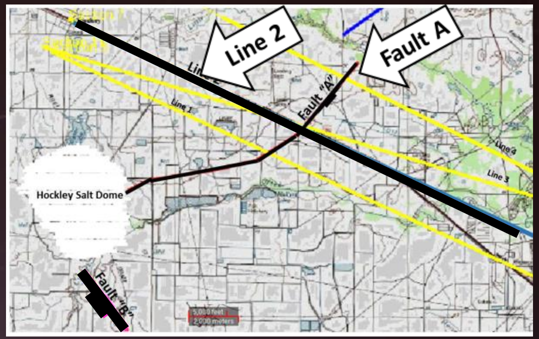
Hockley, Texas

DYNAMIC MEASUREMENT

- Recent evaluation suggests NSEM may have resolution to identify and map erosional and depositional features.
- Successful seismic interpretations often require distinguishing between stratigraphic and structurally influenced features.
- An alternate stratigraphic/fault interpretation of NSEM is offered, demonstrating its additional potential to identify stratigraphic traps.
- A final interpretation will be presented once all data has been thoroughly reviewed and integrated with available seismic data.

Sequence Stratigraphy

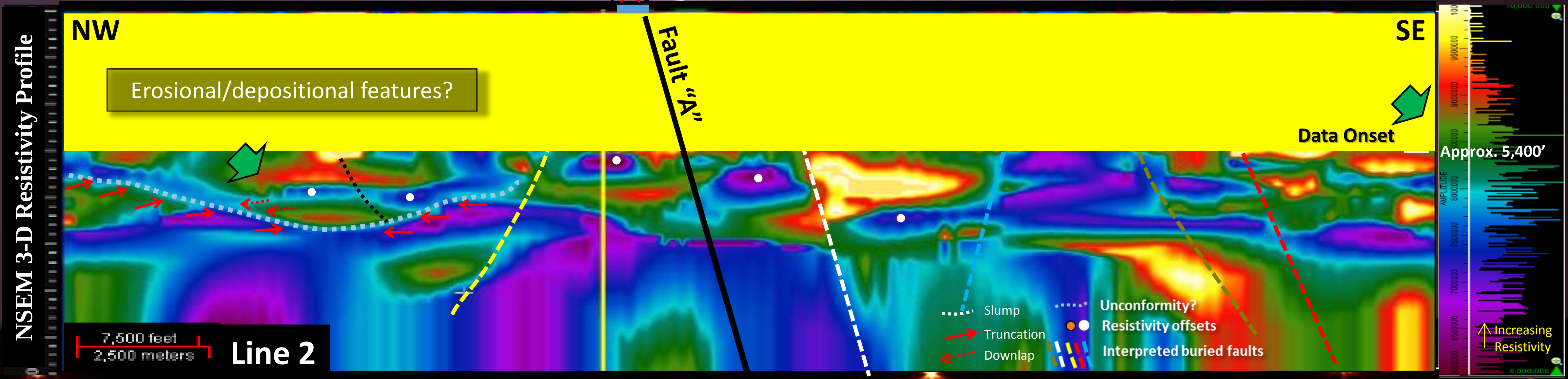




Line 2

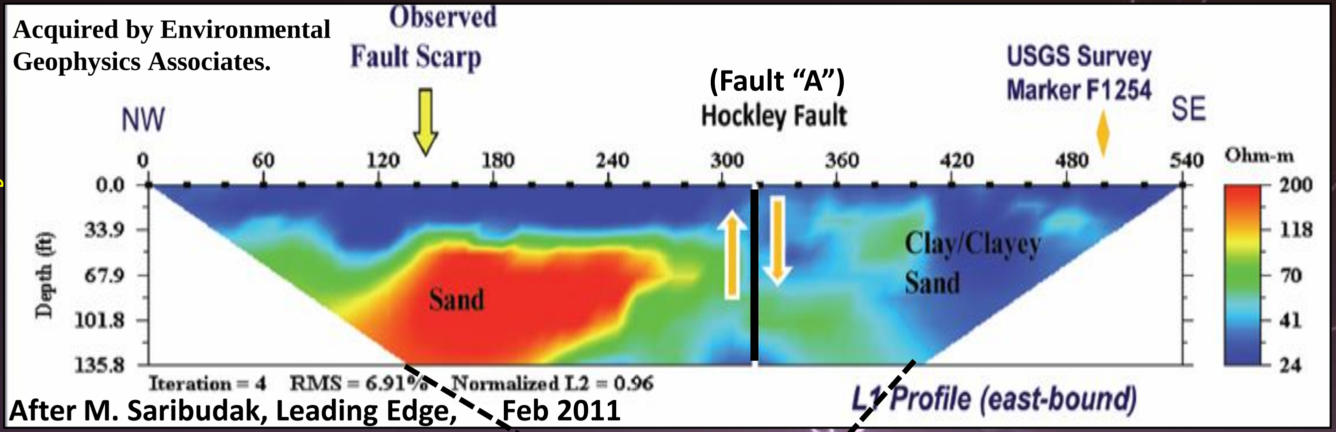
Alternate stratigraphic interpretation.

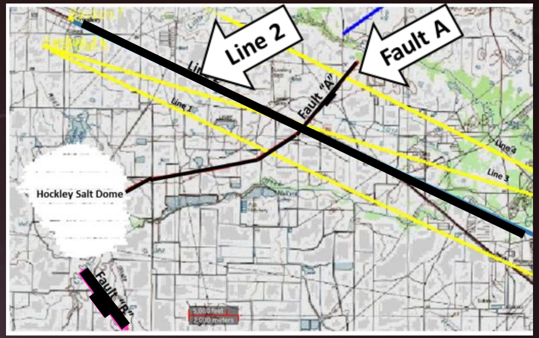
Potential identification of stratigraphic traps?



Mapping Stratigraphy with NSEM?

2-D Resistivity Profile

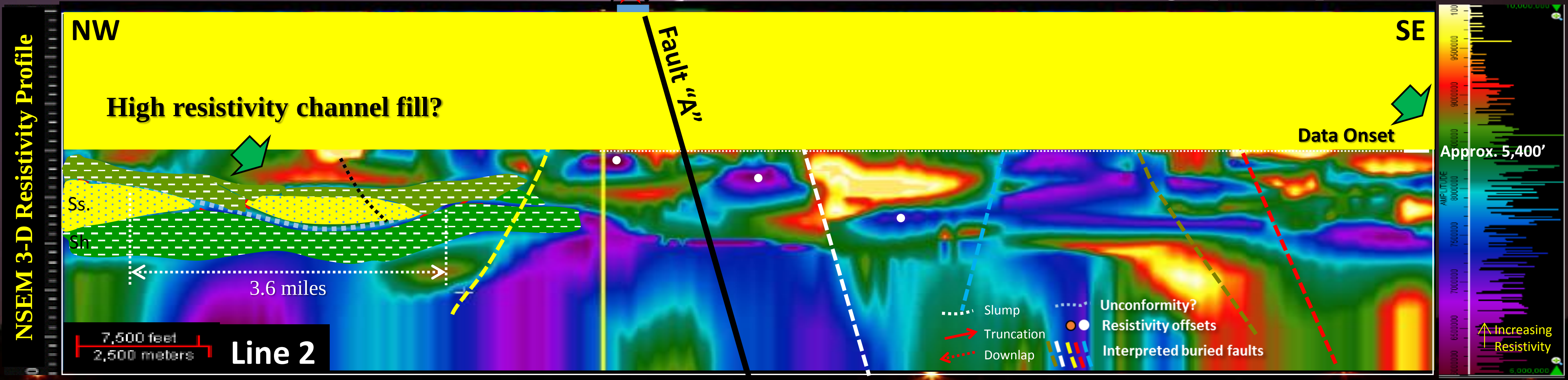




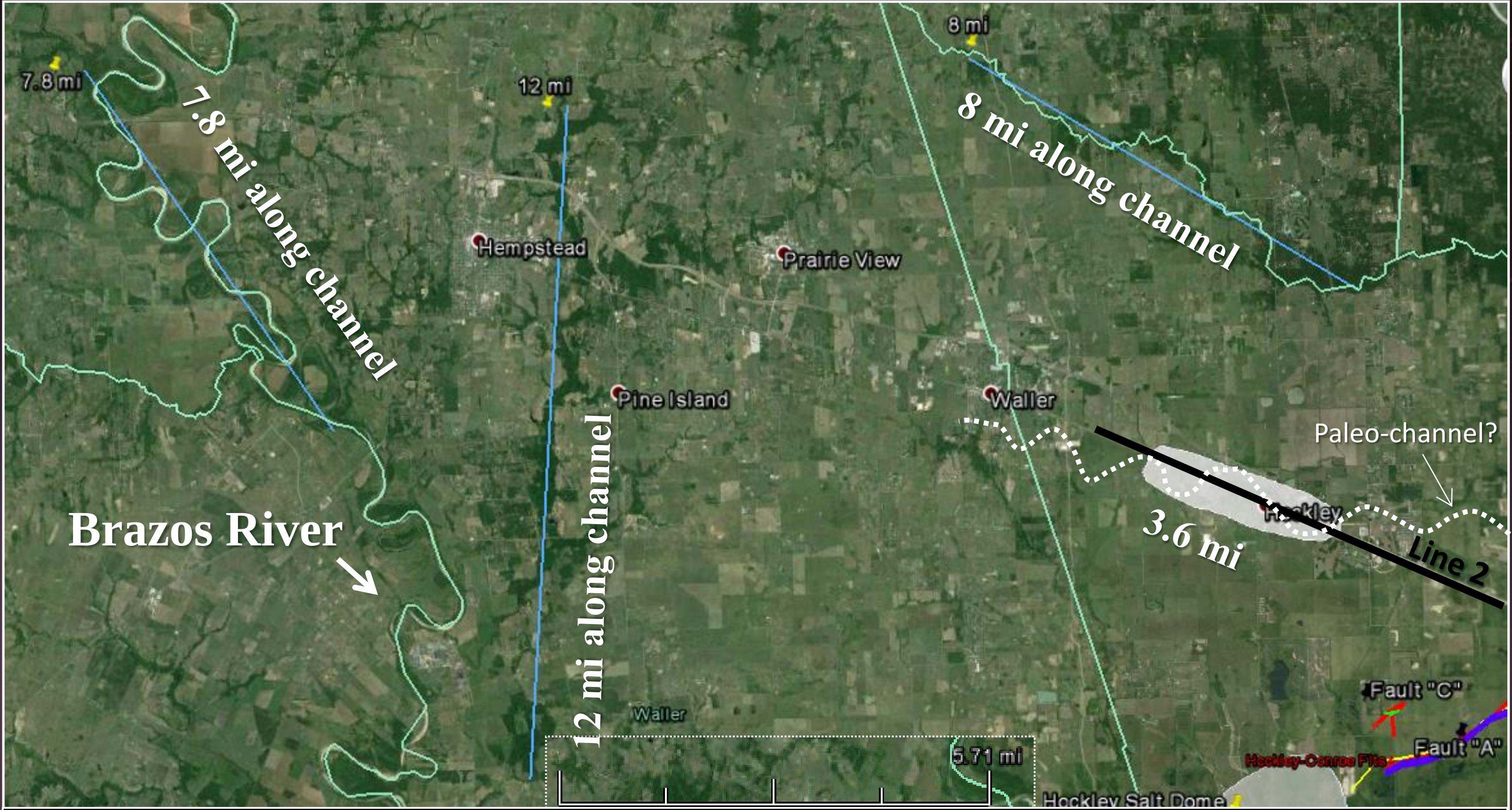
Strike line parallel to channel.

Potential identification of stratigraphic traps?

NSEM 3-D Resistivity Profile



Fluvial Analogues



This stratigraphic interpretation of line 2 would imply the series of faults interpreted down-thrown to the yellow fault on lines 1 and 3 (slide #55) would have died out to the NW before reaching line 2. Lines 1 and 3 converge to the NW and not surprisingly show similar character downthrown to the yellow fault. Their character here is sufficiently different from that of line 1 suggesting this alternate structural and stratigraphic interpretation is plausible.

DYNAMIC MEASUREMENT

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

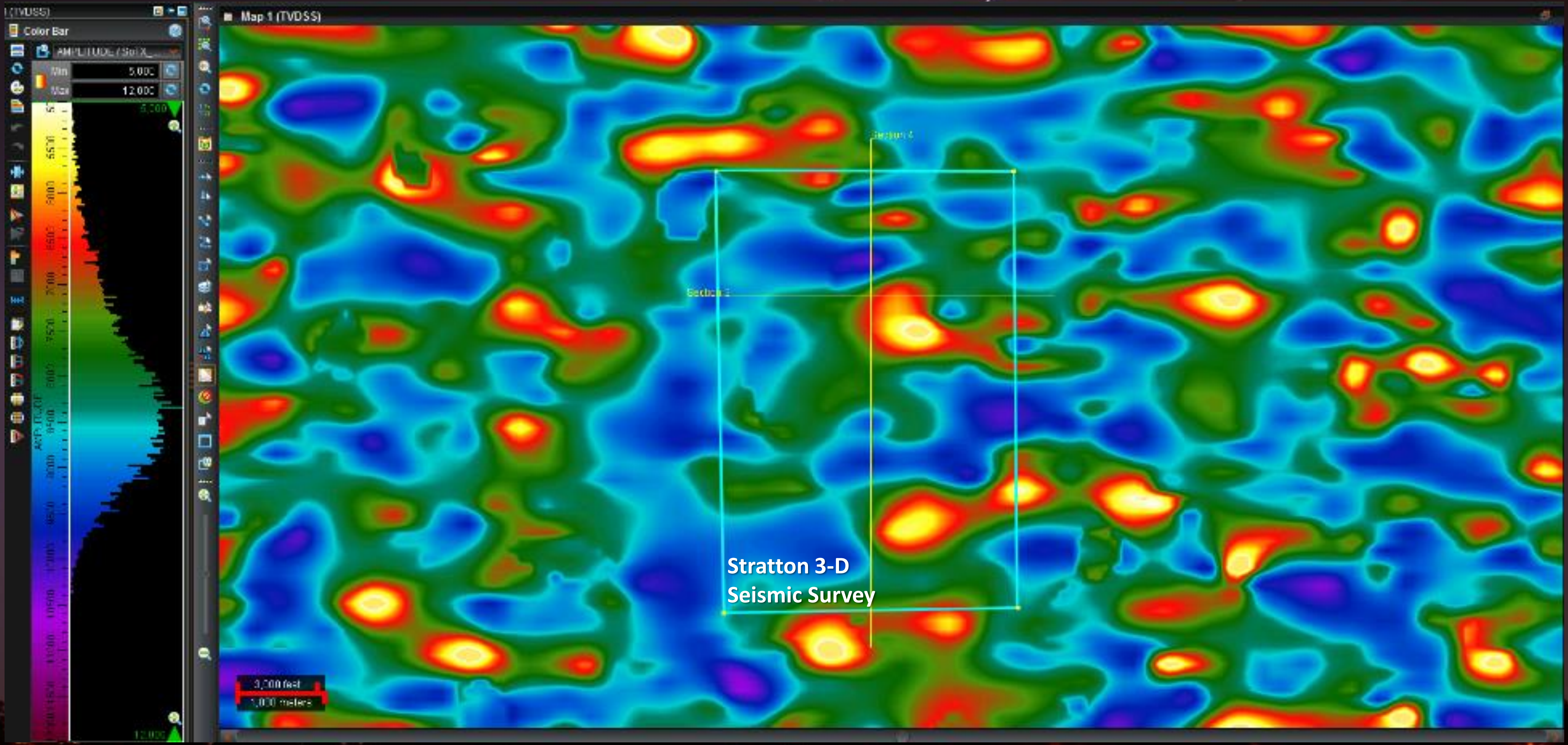
Line 2 possibly parallel to paleo-channel, encountering 3.6 miles of coalescing point bars within meander belt.

3-D Seismic Calibration

Bureau of Economic Geology
South Texas Stratton Project
Public Domain 3-D Seismic Data

- Resistivity Slices
- Mapping Faults & Rock Properties

Resistivity Slice
Interpretation in Progress

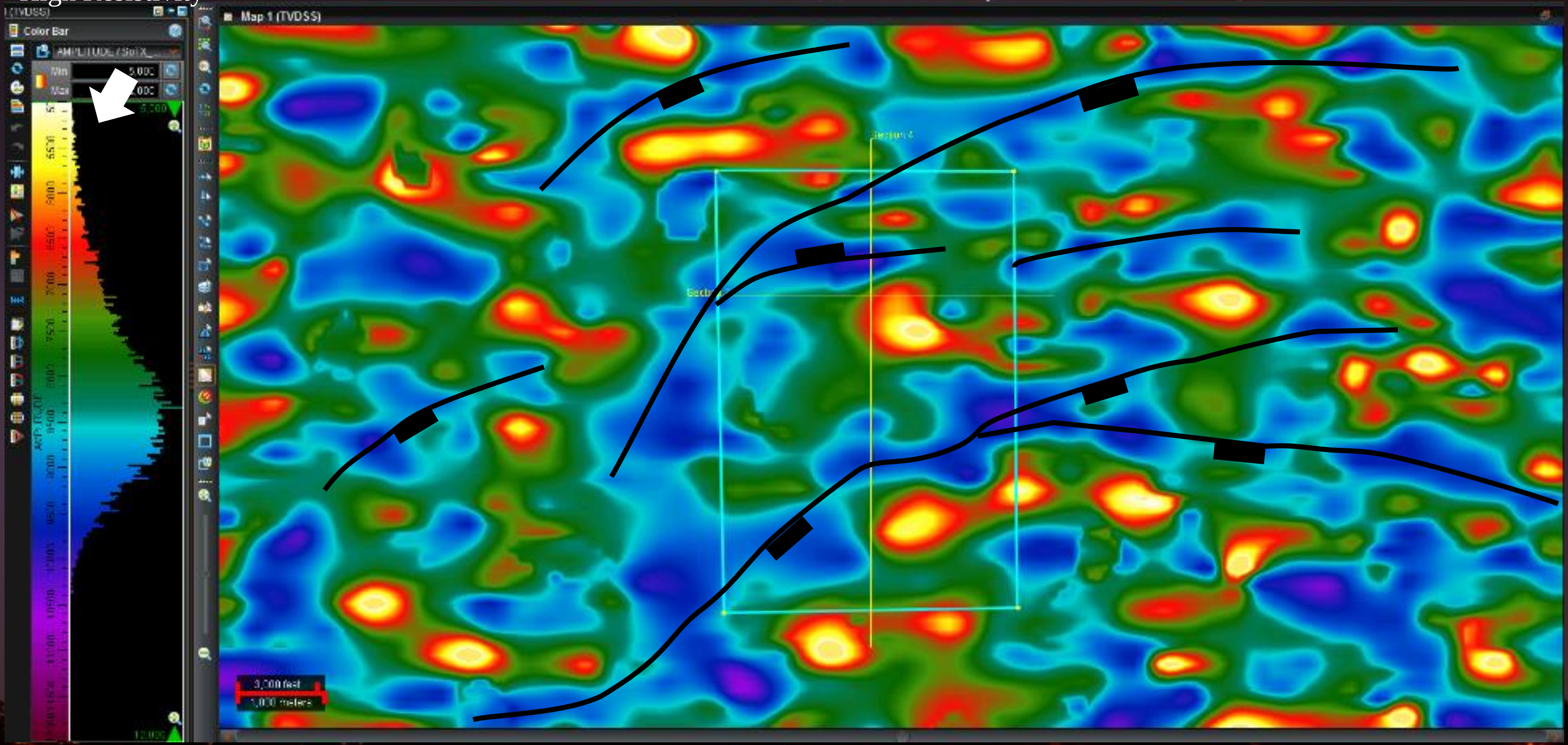


Apparent resistivity shows non-random patterns.

Laterally varying electrical properties of sedimentary rocks, and their associated fault surfaces, influence NSEM.

Potential to Map Faults w. Resistivity Slices

High Resistivity

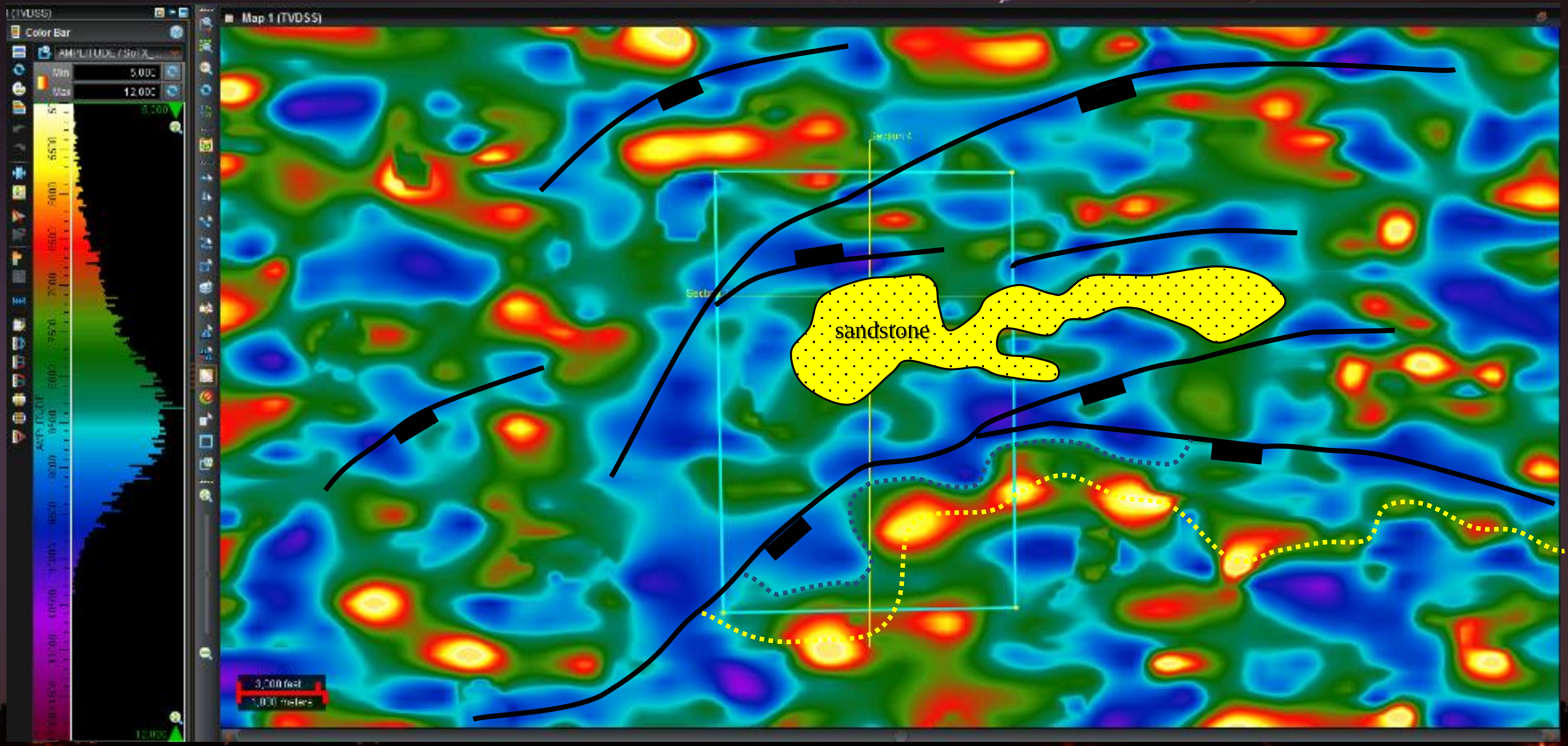


Low Resistivity

Distribution of high & low resistivity lineaments suggest geological influence on lightning & the presence of faults.

Note: data currently being integrated with BEG seismic/ subsurface dataset to identify nature of NSEM patterns.

Potential to Map Rock Properties/Hydrocarbons



High resistivities possibly assoc. with sandstones, i.e. potential reservoirs.

NSEM resistivity slice analogous to time slice, showing distribution of electrical rock properties.

Interpretation is obviously speculative, subject to seismic & subsurface data validation (currently in progress).

NSEM OVERVIEW

- NSEM can map regional & individual faults, rock properties & the presence of orebodies; it can generate leads, & has demonstrated remarkable potential to identify hydrocarbons.
- NSEM can be calibrated to, & integrated with, seismic & subsurface geology, potential field & near surface geophysical data.
- NSEM can fill in between or extend existing data or can be employed independently as a reconnaissance tool.
- When combined with other data, it can narrow down feasible interpretations, high grade prospects and reduce drilling risk.

Lightning data is available world-wide and can be utilized as a reconnaissance tool to generate leads as part of frontier, new venture and exploration programs.

Any Questions?

Dynamic Measurement, LLC.

DYNAMIC MEASUREMENT

For questions regarding:

- Proprietary/Speculative Data Sales
- Project Design/Management
- Seismic, Subsurface, NSEM Data Integration
- Seismic Structural/Stratigraphic Interpretation
- Conventional/Unconventional Lead/Prospect Generation
- Exploitation Mapping/Drill-Site Delineation
- Detailed Fault Analyses

Contact:

Louis Berent
Consulting Geophysicist
Houston, TX
Office: 281 370-5296
Cell: 832 352-3795
ljberent@dynamicmeasurement.com
berent-geophysical@earthlink.net

Acknowledgments

Thanks to Les Denham of Dynamic Measurement, LLC (DML) for his resistivity & permittivity algorithms that helped produce the 3-D apparent resistivity volumes from which the resistivity profiles were extracted.

Thanks also to Roice Nelson & Jim Siebert of DML, for their pioneering work with Natural Source Electromagnetics, & for Roice's kind assistance extracting the resistivity profiles displayed in this presentation. I also appreciate several of the slides I borrowed from Roice's image inventory.

A special thanks to Friedemann Freund of NASA Ames Research Center, for his excellent laboratory work, theoretical discussions and permission to use figures from his publications.

Appreciation to Mustafa Saribudak of Environmental Geophysics Associates for permission to redisplay several of his figures from previous publications & to Shuhab Khan of the University of Houston, for his geophysical investigations & maps of the active faults in the Hockley & Tomball areas, several of which were used to help validate NSEM's ability to identify subsurface faults.

References

Ace Composition Explorer, 2008, About SWEPAM data: http://www.srl.caltech.edu/ACE/ASC/level2/.

Ahrens, Marty, Lightning fires and lightning strikes, http://www.nfpa.org/research/reports-andstatistics/ fire-causes/lightning-fires-and-lightning-strikes, June 2013.

Baba, Y., and V. A. Rakov, 2008, Influence of strike object grounding on close lightning electric fields: JOURNAL OF GEOPHYSICAL RESEARCH, 113. (D12109, doi:10.1029/2008JD009811)

Baba, Y., and V.A. Rakov, Influence of strike object grounding on close lightning electric fields: Journal of Geophysical Research, 113. (D12109, doi:10.1029/2008JD009811).

Berent, L., Nelson, H.R. (2015), Lightning, A Shockingly Unconventional Way to Conduct Exploration, presentation at 2nd Annual Texas Hydro-Geology Workshop, Cave Without A Name, Boerne, TX, Sep 25, 2015.

Berent, L., Nelson, H.R. (2016), Lightning Sparks Interest in the Unconventional Mapping of Active Subsurface Faults, Abstract and oral presentation, GCAGS Explore & Discover Article #00097, http://www.gcags.org/exploreanddiscover/2016/00097_berent_and_nelson.pdf, Annual GCAGS Convention, Corpus Christi, TX, Sep 19, 2016.

Berent, L., Nelson, H.R. (2017), An Unconventional Tool for Unconventional Exploration, AAPG Abstract & Paper Poster #2614153, Theme Unconventional Resources, Annual AAPG Convention, Houston, TX, Apr 5, 2017.

Berent, L., Nelson, H.R. (2017), Harnessing Lightning in the Hunt for Hydrocarbons, AAPG Abstract & Poster Paper #2614175, Theme Emerging Frontiers and New Technology, 2017 Annual AAPG Convention, Houston, TX, Apr 3, 2017.

Berent, L., Siebert, D.J. (2015), Lightning, A Shockingly Unconventional Way to Conduct Exploration, Abstract and presentation to South Texas Geological Society, San Antonio, TX, Sep 9, 2015.

Bruning, E. C., W. D. Rust, D. R. MacGorman, M. I. Biggerstaff, and T. J. Schuur, 2010, Formation of charge structures in a supercell: Monthly Weather Review, 138, 3740–3761. (doi: http://dx.doi.org/10.1175/2010MWR3160.1).

Cagniard, L., 1953, Basic theory of the magneto-telluric method of geophysical prospecting: GEOPHYSICS, 18, 605–635.

Cheesman, S.J., Edwards, R.N., and Chave, A. D., 1987, On the theory of sea-floor conductivity mapping using transient electromagnetic systems: GEOPHYSICS, 52, 204-217.

Chen, L., Y. Zhang, W. Lu, D. Zheng, Y. Zhang, S. Chen, and Z. Huang, 2012, Performance evaluation for a lightning location system based on observations of artificially triggered lightning and natural lightning flashes: Journal of Atmospheric and Oceanic Technology, 29, 1835–1844. (doi: http://dx.doi.org/10.1175/JTECH-D-12-00028.1). Gatlin, P. N., and S. J. Goodman, 2010, A total lightning trending algorithm to identify severe thunderstorms: Journal of Atmospheric and Oceanic Technology, 27, 3–22. (doi: http://dx.doi.org/10.1175/2009JTECHA1286.1).

Cooray, V., R. Montano, and V. Rakov, 2004, A model to represent negative and positive lightning first strokes with connecting leaders: Journal of Electrostatics, 60, 97–109.

Denham, L. (2015) Using Lightning for Exploration, Geophysical Society of Houston, Potential Fields Special Interest Group, Jan 15, 2015.

Denham, L., Siebert, D. J. (2015), Interpreting resistivity from lightning strikes, Abstract and SEG Poster Presentation, New Orleans, LA, Oct 21 2015.

Denham, L., Siebert, D. J. (2015), Potential Field & Electromagnetic Methods Applied to Basin Studies, American Geophysical Union-Society of Exploration Geophysicists Workshop, Keystone, Co., Apr 14, 2015.

Denham, L. (2013), Lightning data and resource exploration, Abstract, 2013 Annual SEG Convention, Houston, TX.

Denham, L.R., Nelson, H. R., and Siebert, D. J. (2013), Lightning data and resource exploration, SEG Annual Convention, Houston, Texas, 25 September 2013.

Denham, L.R., Nelson, H.R., Siebert D.J (2013), Lighting data and resource exploration, NS/HA E-P1: Multidisciplinary Studies and Applications, SEG Annual Meeting, 2013.

Denham, L. (2015), Using lightning for exploration, Geological Society of Houston Potential Fields SIG, Houston, Texas, 15 January 2015.

Denig, W. F. (2013), Sunspot numbers - international: http://www.ngdc.noaa.gov/nndc/struts/results?t=102827&s=5&d=8, 430, 9.

Duncan, P. M., and Eisner, L. (2010), Reservoir characterization using surface microseismic, GEOPHYSICS, 75, no. 5, 75A139-146.

Engelkemeir, R. M., Khan, S.D. (2008), Lidar mapping of Faults in Houston, TX, USA, Geosphere, Feb 2008.

Erwin, E. H., (2009), List of daily American sunspot numbers in x-y format, 1944-present: http://www.ngdc.noaa.gov/ stp/SOLAR/ftpsunspotnumber.html. (Downloaded 2009-10-30).

Gates, R.A., et.al. (2007), Report of Investigation Fatal Underground Coal Mine Explosion, 02 January 2006, Sego Mine, Tallmansville, Upshur County, WV, 09 May 2007.

Haggar, K., Denham, L. and Nelson, H.R. (2015), Aquifers, Faults, Subsidence and Lightning Databases, 2014 Grover Murray Best Published Paper Award, 1st Place, Gulf Coast Association of Geological Societies, Houston, TX, Sep 22, 2015.

Haggar, K. and Nelson, H. R. (2014), Using resistivity from lightning databases in exploration, Joint Lafayette Geological Society-SIPES, Lafayette, LA, and 19 November 2014.

Hagger, K. (2015) Plan Build & Protect Remotely Mapped Geology with Natural Sourced Electromagnetic Analysis, Mississippi River Commission, Baton Rouge, LA, Mar 27, 2015.

References Continued

Hagger, K., Berent, L. and Nelson, H.R. (2015) 2103407 Geologic Frameworks Derived from Lightning Maps and Resistivity Volumes, Oral presentation, AAPG Annual Convention, Denver, CO, Jun 02, 2015.

Hagger, K., Denham, L. and Berent, L. (2015), Analysis of the Goose Point area near Lacombe, LA, Validates New Geophysical Data Type - Natural Source Electromagnetism (NSEM) for Detection of Lineaments tied to Faults and Sedimentary Features, second consecutive 2015 Grover E. Murry Best Published Paper Award, GCAGS Annual Convention, Houston, TX, Sep 22 2015.

Hagger, K., Denham, L.R., Nelson, H.R. (2014), Aquifers, Faults, Subsidence, and Lightning Databases, Annual Grover Murray Best Paper Award, 2014 Gulf Coast Assoc. of Geological Societies, Oct 7, 2014, Lafayette, LA.

Hembury, Nikki, and Holle, R. (2011), Flash of inspiration – latest innovations in worldwide lightning detection: Meteorological Technology International, 48, May 2011.

Jerauld, J., M. A. Uman, V. A. Rakov, K J. Rambo, and G. H. Schnetzer, 2007, Insights into the ground attachment process of natural lightning gained from an unusual triggeredlightning stroke: JOURNAL OF GEOPHYSICAL RESEARCH, 112. (D13113, doi: 10.1029/2006JD007682).

Keller, G.V., and F.C. Frischknecht, 1967, Electrical methods in geophysical prospecting: Pergamon Press.

Khan, S. D. et al. (2013), A geophysical investigation of the active Hockley Fault System near Houston, TX, Geophysics, Jul-Aug 2013.

Krider, E. P. (1986), The Earth's Electrical Environment: Studies in Geophysics, 34.

Loke, M. H. (2012), Tutorial: 2-d and 3-d electrical imaging surveys: online. (http://www. geoelectrical.com/coursenotes.zip).

Lyons, Uliasz, and Nelson (1998), Large Peak Current Cloud-to-Ground Lightning Flashes during the Summer Months in the Contiguous U.S., Meteorological Society of America.

Morrison, E., Detection of Porphyry Coper Deposit Using Natural Electromagnetic Fields, 8 October, 2009, Patent Publication Number WO2009121160 A1

Murphy, M. J., R. L. Holle, and N. W. S. Demetriades, 2008, Cloud-to-groundlightning warnings using electric field mill and lightning observations. (http: //www.vaisala.com/Vaisala%20Documents/ Scientific%20papers/Cloud-to ground_lightning_warnings_using_electric_field_ mill_and_lightning_observations.pdf).

Murphy, M., N. Demetriades, K. Cummins, and R. Holle, 2007, Cloud lightning from the U.S. National Lightning Detection Network: Presented at the, International Commission on Atmospheric Electricity. (13th International Conference on Atmospheric Electricity, Beijing).

Murphy, Martin J., Holle, Ronald L., Demetriades, Nicholas W. S., 2008, Cloud-to-ground lightning warnings using electric field mill and lightning observations: reprint 20th International Lightning Detection Conference.

Nabighian, M. N., 1991, Electromagnetic Methods in Applied Geophysics: Society of Exploration Geophysicists.

Nelson, H. R., Jr., Denham, L.R., and Siebert, D. James, Telluric and Earth Currents, Lightning Strike Locations, and Natural Resource Exploration, AAPG 2014 Annual Convention, #1841677, 19 April 2014.

Nelson, H. Roice, Jr., D. James Siebert, and L. R. Denham. Lightning data - the new EM "seismic" data: Presented at EM Workshop, SEG Annual Meeting, 2012.

Nelson, H. Roice, Jr., D. James Siebert, and Les R. Denham, Lightning Data, A New Geophysical Data Type, AAPG Annual Meeting, 2013.

Nelson, H. Roice, Jr., Roberts, Joseph H., Siebert, D. James, Massell, Wulff, LeRoy, Samuel D., Denham, L.R., Ehrlich, Robert, Coons, Richard L., July 7, 2011, Method for locating sub-surface natural resources: U. S. Patent Application 2011/0163733 A1.

Nelson, H., D. Siebert, and L. Denham, 2013, Lightning data, a new geophysical data type: Presented at the, AAPG. (paper 155646 expanded abstract, AAPG Convention, Pittsburg, PN).

Nelson, H.R. (2016), Lightning Analysis for Mapping Faults and Identifying Exploration Sweetspots, Abstract and oral presentation, Rocky Mountain Pacific Coast Annual AAPG Convention, Las Vegas, NV, Oct 4, 2016.

Nelson, H.R., Jr. (2013), Lightning Strikes - A New Exploration Tool, AAPG Explorer Interview, Tulsa, OK, Jun 02, 2013.

Nelson, H.R., Jr. (2014) Technical Review presented to U.S. Corps of Army Engineers, New Orleans Division, Dec 19, 2014.

Nelson, H.R., Jr. (2014), Finding Faults with Mother Nature, Hart Energy E&P Editorial/Interview, Feb 3, 2014.

Nelson, H.R., Jr. (2014), Geological Facts of Life, Remotely Mapping Geology with NSEM, Technical Review to South Louisiana Flood Protection Agency, New Orleans, LA, Dec 17, 2014.

Nelson, H.R., Jr., Siebert, D. James, and Denham, L.R., Lightning data, a new geophysical data type, AAPG 2013 Annual Convention, #1556546, Pittsburgh, Pennsylvania 08 April 2013

Nelson, H.R., Siebert, D.J., Denham, L.R. (2012), Lightning data – the new EM "seismic" data, 2012 SEG Annual Convention Workshop, Las Vegas, NV, Nov 8, 2012.

Nelson, H.R., Siebert, D.J., Denham, L.R. (2013), Lightning Data, A New Geophysical Data Type, Oral Presentation, Abstract 1556546, Pittsburg, PA, May 20, 2013.

Nelson, H.R., Siebert, D.J., Denham, L.R. (2014), Mapping Faults and Natural Resources with Lightning Data, CPS-SEG 2014 Conference: Advancing Geophysical Innovation, May 20, 2014, Beijing, China.

Nelson, H.R., Siebert, D.J., Denham, L.R. (2014), Telluric and Earth Currents, Lightning Strike Locations and Natural Resource Exploration, 2014 AAPG Annual Convention, Oral presentation, Apr 9, 2014, Houston, TX.

References Continued

Nelson, Jr., H. Roice, Siebert, D. James, and Denham, Les R., November 2012, Lightning Data: the new EM "seismic" data, SEG Workshop - Integrating EM and Seismic.

Noble, J.E. et al. (1996), Estimated depth to the water table & estimated rate of recharge in outcrops of the Chicot & Evangeline aquifers near Houston, TX. 1996.

Orville, Richard E., February 2008, Development of the National Lightning Detection Network, Bulletin of the American Meteorological Society, Volume 89, Number 2.

Orville, Richard E., February 2008, Sparked by technology – the history of the national lightning detection network: BULLETIN OF THE AMERICAN METEOROLOGICAL SOCIETY, 89.2.

Orville, Richard E., Huffines, Gary R., Burrows, William R., and Cummins, Kenneth L., May 2011, The North American Lightning Detection Network (NALDN – Analysis of Flash Data: 2001-2009, Monthly Weather Review, Volume 139.

Orville, Richard E., March 2012, personal communication.

Pearson, S. O., and H. S. G. Anson, 1921, Demonstration of some electrical properties of neon filled lamps: Proceedings of the Physical Society of London, 34, 175–176. (doi: 10.1088/1478-7814/34/1/435).

Rakov, V. A., and M. A. Uman, 2003, Lightning: physics and effects: Cambridge.

Rakov, V. A., V. Kodali, D. E. Crawford, M. A. U. J. Schoene, K. J. Rambo, and G. H. Schnetzer, 2005, Close electric field signatures of dart leader return stroke sequences in rocket-triggered lightning showing residual fields: Journal of Geophysical Research, 110. (D07205, doi: 10.1029/2004JD005417).

Rakov, V.A., and M.A. Uman, Lightning: physics and effects, Cambridge, 2003.

Saribudak, M. (2006), Geophysical mapping of the Hockley growth fault in northwest Houston, TX and recent surface observations, The Leading Edge, Feb 2011.

Saribudak, M. (2006), Integrated geophysical studies over an active growth fault in Houston, The Leading Edge, March 2006.

Saribudak, M. (2011), 2-D Resistivity Imaging Investigation of Long Point, Katy-Hockley, Tomball & Pearland Faults, Houston, TX., Houston Geological Society Bulletin, Nov 2011.

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

Saribudak, Mustafa, 2-D Resistivity Imaging Investigation of Long Point, Katy-Hockley, Tomball & Pearland Faults, Houston, TX., Houston Geological Society Bulletin, Nov 2011.

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

Saribudak, Mustafa, Geophysical mapping of the Hockley growth fault in northwest Houston, TX and recent surface observations, The Leading Edge, Feb 2011.

Saribudak, Mustafa, Integrated geophysical studies over an active growth fault in Houston, The Leading Edge, March 2006.

Siebert, D. J., Berent, L., Nelson, H. R. (2016), Lightning, A Shockingly Unconventional Technology for Exploration, West Texas Geological Survey January 2016 Bulletin, Midland Texas, Vol 55, Number 3, 16-23.

Siebert, D.J. (2015) Lightning Discoveries & Technologies - How this Phenomenon Affects Electric Utilities, Electricity Today, Feb 10, 2015.

Siebert, D.J., Chief Meteorologist, Houston Fox News, Lightning, A New Key for Pipeline Protection, Pipeline & Gas Journal, Interview, Feb, 2014. Vol 241, No. 2.

Siebert, J., Berent, L., Nelson, H. R. (2014), Lightning, A Shockingly Unconventional Technology for Exploration, Southwest AAPG Convention, Wichita Falls, TX Apr 14, 2014.

Thoman, Mark W., Zonge, Kenneth L., and Liu, Dexin, Geophysical Case History of North Silver Bell, Pima County, Arizona: A Supergene-Enriched Porphyry Copper Deposit, Zonge International Case History, 1996.

Uman, M. A., 1984, Lightning: Dover. Zhang, W., Y. Zhang, D. Zheng, and X. Zhou, 2012, Lightning distribution and eyewall outbreaks in tropical cyclones during landfall: Monthly Weather Review, 3573–3586. (doi: http://dx.doi.org/10.1175/MWR-D-11-00347.1).

Wilt, M.J., Morrison, H. F., Lee, K.H., and Goldstein, N.E., 1989, Electromagnetic sounding in the Columbia Basin, Yakima, Washington: GEOPHYSICS, 54, 952-961.

Xiaobing Jin, Zhongming Chen, Qiming Ma, Yiding Li, and Junwei Pu, The Correlations between the Lightning Density Distribution of Sichuan Province and the Seismic Area: International Journal of Geosciences, 2013, 4, 380-386. (doi:10.4236/ijg.2013.42036)

This presentation supports the poster sessions titled:
"Harnessing Lightning in the Hunt for Hydrocarbons" and
"An Unconventional Exploration Tool for Unconventional Exploration,"
both presented at the 2017 annual AAPG convention held in Houston, TX , on April 3rd and 5th respectively.