OUTLINE

1. Introduction and Theory
2. Geologic Setting in Texas Study Area
3. Aquifers / Earth Tides / Geothermal Gradient
4. Applying Lightning Data in Study Area
5. Ties to Aquifers / Earth Tides / Geothermal Gradient
6. Conclusions
1.a. Introduction

We will compare lightning maps to a compendium of regional data types for:

- aquifers,
- fault lines,
- subsidence,
- earth tide data, and
- geothermal gradient.

We look forward to working with audience experts to integrated this new geophysical data type with public and private geotechnical data.

Lightning provides a framework for greater understanding of varied geological data sets including data used to map oil & gas prospects and geo-hazards.
Fault Trends and Geothermal Gradient

Fault trends by Ewing 1990
Geothermal Gradient Map
1.b. Lightning Theories and Facts

South 610
Conroe
Houston Area Surface Resistivity
- 20,000 Feet Deep

Sealy
East 610
Strike Density (NLDN) and Topography

1997 to 2007 Cloud-to-Ground Flash Density

Ave. Flash Density
strikes/sq.km/yr.
- 14 and up
- 10 to 14
- 8 to 10
- 6 to 8
- 5 to 6
- 4 to 5
- 3 to 4
- 2 to 3
- 1 to 2
- 0.5 to 1.0
- 0.1 to 0.5
- 0+ to 0.1

330 Lightning Detectors in the Continental US. Evergreen Data Set - 16 years of data available.
Lightning

Two conducting plates, the storm cloud and the earth, are separated by an insulating dielectric, the atmosphere. Voltage is created by collision of ice within the cloud and lightning bolts rebalance the charge between the plates.
Lightning Measurements/Attributes, & Wave Form

- Location / Time and Duration / # of Sensors
- Rise Time
- Peak Current
- Peak to Zero
- Polarity
- Chi Squared
- Number of Sensors
Lightning Theories and Facts

• Lightning occurs everywhere.

• Cloud to cloud lightning travels up to about 150 miles (250 km).

• Cloud to ground lightning follows terralevis/shallow earth currents which reflect geology. Some strikes do hit topography, vegetation, and infrastructure, but can be edited out from location and attribute data.

• Lightning Attributes contain data from various depths and image subsurface features and lineaments such as transforms, faults, drainage basins, and paleo channels.
<table>
<thead>
<tr>
<th>Lightning Attribute</th>
<th>Definition</th>
<th>Geological Attributes</th>
<th>Example</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>The average number of lightning strikes located in an IG-6 cell (269 x 153 meter or 881 x 503 feet cells at 30° Latitude).</td>
<td>Used to define lineaments which are associated with faulting. Minor topographic effects are distinguished from geologic influences during interpretation.</td>
<td><img src="image1" alt="Example Image" /></td>
<td><img src="image2" alt="Interpretation Image" /></td>
</tr>
<tr>
<td>Rise-Time</td>
<td>The time to go from background electrical noise to Peak Current in microseconds, averaged over IG6 cells.</td>
<td>Sees areas with higher resistance such as salt domes and fresh water associated with ponds, rivers, and aquifers. In this example, the blue region in the east, suggests the presence of shallow fresh water.</td>
<td><img src="image3" alt="Example Image" /></td>
<td><img src="image4" alt="Interpretation Image" /></td>
</tr>
<tr>
<td>Peak Current</td>
<td>The average Peak Current in kiloamps of lightning strikes falling in an IG6 cell.</td>
<td>Sees subsurface resistivity and is largely impacted by the negative lightning strikes. Voltage must be higher to get through depth.</td>
<td><img src="image5" alt="Example Image" /></td>
<td><img src="image6" alt="Interpretation Image" /></td>
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<tr>
<td>Peak Current absolute</td>
<td>The average Absolute Peak Current in kilo amps falling in an IG6 cell.</td>
<td>Sees subsurface resistivity and is largely impacted by the negative lightning strikes.</td>
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<tr>
<td></td>
<td></td>
<td>Voltage must be higher to get through depth. Note patterns are different.</td>
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<tr>
<td>Negative Peak Current</td>
<td>The average negative Peak Current in kilo amps falling in an IG6 cell.</td>
<td>Typically sees shallower resistivity, because strikes come at the beginning of a storm and are not as strong.</td>
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</tr>
<tr>
<td>Positive Peak Current</td>
<td>The average positive Peak Current in kilo amps falling in an IG6 cell.</td>
<td>Typically sees deeper resistivity because positive peak currents are associated with the most intense strikes occurring at the end of storms. As these strikes are less frequently, interpolation effects may be noticeable.</td>
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<tr>
<td>Peak-to-Zero</td>
<td>The time to go from Peak Current to background electrical noise in microseconds averaged over IG6 cells.</td>
<td>Good lineaments and is very closely tied to resistivity. Areas with low resistivity have a low P2Z value.</td>
<td></td>
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</tr>
<tr>
<td>Total Wavelet Time</td>
<td>The sum of Rise-Time + Peak-to-Zero Time or the Total Wavelet Time (TWT) as recorded by the NLDN.</td>
<td>Similar to Peak-to-Zero because the Peak-to-Zero time is typically larger than Rise-Time and so would be</td>
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<td>the dominant component of the Total Wavelet Time.</td>
<td></td>
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</tr>
<tr>
<td>Wavelet Symmetry</td>
<td>The ratio of Rise-Time to Total Wavelet Time. Wavelet Symmetry is inversely related to its Peak-to-Zero contribution.</td>
<td>Lineament patterns may be similar to that of Peak-to-Zero and Total Wavelet Time because the Peak-to-Zero</td>
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<tr>
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<td>time is typically the dominant component of all three of these lightning attributes.</td>
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<tr>
<td>Earth Tide Density</td>
<td>The cumulative tidal effect of the sum of lunar and solar gravity creates earth tides. There are more lightning strikes at high and low earth tides near faults.</td>
<td>It appears more conductive clays in the fault scarps, and disruption of shallow earth, terralevis, currents by faults create more lightning strikes at high and low earth tides.</td>
<td><img src="image1.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>Earth Tide Density greater than 75% of the monthly maximum rate</td>
<td>The density of lightning strikes which occur at greater than 75% of the monthly maximum earth tide.</td>
<td>As with each of the lightning attributes there are strong lineaments which are emphasized, like the horizontal and the up to the right at 45° from the bright events in the lower left.</td>
<td><img src="image2.png" alt="Image" /></td>
<td></td>
</tr>
<tr>
<td>Earth Tide Density less than 75% of the monthly maximum rate</td>
<td>The density of lightning strikes which occur at less than 75% of the monthly maximum earth tide.</td>
<td>With this attribute there are strong dipping to the southwest horizontal lineaments at the top of the example area which are not seen on other attributes.</td>
<td><img src="image3.png" alt="Image" /></td>
<td></td>
</tr>
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<tr>
<td>Earth Tide Gradient</td>
<td>Earth Tide Gradient is the first derivative of the Earth Tide, or the maximum ebb and flow of the Earth Tide. This attribute is the density of strikes at the gradient.</td>
<td>On several surveys the density of strikes tied to the gradient appears to highlight faults better than other attributes.</td>
<td>Image of a map showing a gradient pattern.</td>
<td>The presence of faults is highlighted through the density of lightning strikes.</td>
</tr>
<tr>
<td>Earth Tide Gradient greater than 75% of the monthly maximum rate</td>
<td>The density of lightning strikes which occur at greater than 75% of the monthly maximum earth tide gradient.</td>
<td>There are similar patterns to the Earth Tide Gradient and the Earth Tide, although this particular color bar is not very well normalized for data in the example area.</td>
<td>Image of a map showing a gradient pattern.</td>
<td>The similar patterns highlight the potential for fault lines.</td>
</tr>
<tr>
<td>Earth Tide Gradient less than 75% of the monthly maximum rate</td>
<td>The density of lightning strikes which occur at less than 75% of the monthly maximum earth tide gradient.</td>
<td>Again, this attribute shows a unique lineament in the top center which appears to be a down to the Gulf growth fault.</td>
<td>Image of a map showing a gradient pattern.</td>
<td>The unique lineament indicates a potential growth fault.</td>
</tr>
</tbody>
</table>
## Geological Significance of Lightning Attributes

<table>
<thead>
<tr>
<th>Lightning Attribute</th>
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<th>Color Bar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rise-Time Central Texas</td>
<td>The time to go from background electrical noise to Peak Current in microseconds, averaged over IG6 cells.</td>
<td>Sees areas with higher resistance. In this example there are 4 ponds in the bottom central part of the map which show up as anomalies, and the river is the curved line in the middle.</td>
<td><img src="image1.png" alt="Example Image" /></td>
<td>Appears to be related to shallow fresh water, and was used to make a detailed shallow stratigraphy map.</td>
<td><img src="color_bar.png" alt="Color Bar" /></td>
</tr>
<tr>
<td>Rate of Rise-Time Central Texas</td>
<td>Calculated by dividing the Peak Current by the Rise-Time giving results in kiloamps/ms</td>
<td></td>
<td><img src="image2.png" alt="Example Image" /></td>
<td></td>
<td><img src="color_bar.png" alt="Color Bar" /></td>
</tr>
<tr>
<td>Surface Resistivity Central Texas</td>
<td>Surface resistivity calculated from P2Z and Peak Current as defined in pending patent.</td>
<td>A sum of the resistivity at all depths beneath the surface location. As with other attributes there are lineaments.</td>
<td><img src="image3.png" alt="Example Image" /></td>
<td></td>
<td><img src="color_bar.png" alt="Color Bar" /></td>
</tr>
</tbody>
</table>
2. Geologic Setting in Texas Study Area
Aquifers / Faults / Stratigraphy / Subsidence

Rise-Time
Central Texas
Aquifers

- Brazos River Alluvium Aquifer
- Trinity - Edwards
- Carrizo - Wilcox
- Gulf Coast

Aquifers from Texas Water Development Board Report 380.
Houston – Galveston Area Subsidence in Gulf Coast Aquifer

From Houston Galveston Subsidence District 1906-2000 with permission
3. Applied Lightning Data in Texas Study Area

Earth Tides / Geothermal Gradient

Peak-to-Zero
Central Texas
Topography

Well Data, Faults, and 3-D Seismic

Green Dots are Well Locations

Rise-Time

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Negative Peak Current

Regional Scale

Colorado County, Texas

Peak-to-Zero
Rise-Time

Prospect Scale

Colorado County, Texas

Peak Current

Faults – Ewing (1990)

Counties

Faults – Ewing (1990)

Counties

07 October 2014

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GCAGS 22
Peak Current

Peak-to-Zero

Prospect Scale

Colorado County, Texas

07 October 2014

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GCAGS 23
Rate of Change of Lunar/Solar Tides
(Normalized Over Lunar Cycle)

North Texas Example

Florida Example

Green = Red/Gray

Red = Lightning Strike Frequency

Incoming Tide

Outgoing Tide

If Tidal Gradient had no effect
All Green Values = 1.0

Incoming Tide
Possibly Washes Out Biogenic Gas
Tidal Gradient when Strikes Occur

Tide Gradient Frequency

Outgoing Tide  Incoming Tide

Tide Gradient Lightning Frequency

Raccoon Bend
Hockley
Sealy
Strike Density at High Tidal Gradient

Tide Gradient Normalized Lightning Frequency

Tide Gradient Combined Frequency
For shallow depth lightning strike density is largely independent of temperature gradient.
Lightning strike density decreases with increasing temperature gradient.
Strike Density for Wells >3000 m (>9,843 Feet) Vs. Geothermal Gradient

Lightning strike density decreases more rapidly with increasing temperature gradient.
Lightning Strike Density for All Wells Vs. Geothermal Gradient

Negative Correlation Coefficient Increases with Depth, while the Geothermal Gradient also is Lower for Deeper Measurements.
Conclusions

- Lightning is a new geophysical data type.
- Strike locations and attributes primarily controlled by earth currents and geology.
- Lightning strikes highlight geological features and sediment/rock characteristics.
- Integration of lightning data provides a better understanding of the subsurface.
The Future of Lightning Analysis in Natural Resource Exploration . . .

. . . Resistivity Volumes!
The Geo-Team at DML
Thanks You for your Time!