Geologic Frameworks Derived from Lightning Maps and Resistivity Volumes*

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Abstract

A new geophysical exploration tool sourced by billions of naturally occurring electrical discharges from cloud to earth has been developed. Analysis of sixteen years of recorded North American lightning data have revealed non-random patterns of lightning strikes. When these data are cleaned, lightning strike density and newly-defined lightning attribute maps show interesting correlations to surface and subsurface geology.

To date, applications of this new and naturally sourced electromagnetic (NSEM) analysis technique include the exploration for groundwater, minerals and hydrocarbons, the identification of geohazards, as well as the optimal location of pipe and power lines and where additional insulation and grounding are required. Although lightning is a worldwide phenomenon guided by meteorological conditions, the precise location of strikes and their individual attributes are guided by shallow earth or terralevis electromagnetic currents. These currents are in turn highly influenced by lateral geological inhomogeneity caused by faults, fractures, mineralization, pore-fluids, and salinity variations. Lightning strikes and their attributes cluster around geologic features. Since surface and subsurface geology is a function of geologic time, geology is constant relative to the short time spans associated with lightning databases. This enables lightning data to be stacked similar to the way multi-fold seismic data is stacked and processed.

When processed in this manner, lightning strike density and attribute maps show clusters and lineations which appear to correlate to fresh water, some surface projections of faults, near surface fluvial depositional patterns, and possibly to hydrocarbon seeps, salt domes, hydrocarbons, and mineralization. A case study from the Texas Gulf Coast shows a “Rise Time” lightning attribute map that identified twenty-eight anomalies, each correlating back to a Tertiary aged oil or gas field.

Ongoing research utilizing patent pending algorithms show the electrical information contained in the lightning databases enables the calculation of resistivity and permittivity volumes. From these volumes, slices and cross-sections can be displayed, analyzed, and interpreted

similar to the way 3D seismic data are evaluated. These volumes can be calculated and displayed at the same bin spacing as any available 3D data volume where the right lightning databases are available, thus allowing the data to be easily integrated with available seismic and subsurface data**.**

Although NSEM is a derivative of potential field data having lower frequency and resolution, it has tremendous value for building regional geological frameworks. It can help identify trapping faults in the search for hydrocarbons, prospective mineral acreage, and hydrocarbon migration pathways. NSEM is a useful new reconnaissance mapping tool that can be used to determine where to acquire geophysical or geochemical data for detailed follow-up evaluations.

In addition, NSEM has potential to assist in a wide range of non-exploration applications such as the identification of subsurface contaminant plumes, the placement of power lines and pipelines, the identification of surface and subsurface geohazards, and the mitigation of risk associated with lightning strikes. A disaster investigation report is referenced to illustrate how an awareness of lightning strike density could have helped avoid a deadly coal bed methane explosion.

NSEM is a new geophysical data type with wide application to society. This data is significantly less expensive to acquire, process, and interpret than most, if not all, geophysical techniques on the market today. Its cost is about 1/100th of what it would cost to acquire typical 3-D seismic data and an entire project can be completed within two months. Three-dimensional resistivity and permittivity data can be viewed in cross-section and as horizontal slices. It can also be scaled to the same display parameters as any 2-D or 3-D geophysical data, which facilitates its calibration to other geophysical and geological data.

Introduction

While lightning occurs over most of the globe, some areas receive more strikes than others (Figure 1). The northern Gulf of Mexico is a particularly active area. Although lightning is a meteorological phenomenon, where it strikes the ground is related more to the geology and the terralevis (shallow earth) currents than to topography, vegetation, and infrastructure (Denham, Nelson, and Siebert, 2013). Figure 2 illustrates an up-going lightning strike, which demonstrates how large currents accumulate in the near surface geology.

Project sites in Texas and Arizona have been selected as specific examples of how lightning attributes assist in the interpretation of near surface geological features, aid in the identification of geohazards to highlight vulnerable areas at facilities, and highlight potential areas for mineral exploration and development. Figure 3 shows the topography at the Arizona study area on the left, and the lightning density on the right. Note there is not a significant correlation between lightning strike density and the tops of the mountains. This geological controlled distribution of lightning strikes has been reported at a previous AAPG Convention (Nelson, Denham, and Siebert, 2014). Also note that even in the deserts of Arizona 15 years of lightning strikes provide sufficient data to support lightning analysis. New technological breakthroughs for resistivity and permittivity attributes displayed as both surfaces and volumes are shown through a major copper deposit in Arizona.

Houston Area Lightning Interpretation

The Houston study area shown covers Houston, going from Sealy on the west to the San Jacinto Monument on the Ship Channel on the east, and from South Houston to The Woodlands in the north as shown in Figure 4. Lightning attribute analysis is derived from the digital strike data, and has similarities to seismic attribute analysis from acoustic data.

Rise Time, Peak Current, and Peak to Zero are the primary attributes for lightning data, and many more attributes have been identified and developed. Lightning data is unique in that it is a continuously growing evergreen data set with nearly 17 years of historical strike data captured to date. This provides an additional dimension of time for project analysis.

Figure 5 and Figure 6 shown Rise Time maps across the Houston study area. Here we highlight one very important aspect of lightning data, its ability to image geology related features in densely populated areas with extensive infrastructure networks that deter or obstruct conventional potential fields, seismic, and geologic imaging techniques. Since we have demonstrated previously that lightning tends to follow terralevis currents, which are influenced by geology, we know that the height of infrastructure is not the primary determining factor for lightning strike locations. Imagine collecting a seismic survey across the Houston area. Anomalous features, such as landfills and a few occasional cell towers are recognizable, and can be easily removed from attribute processing to remove distortion. However, explaining a few anomalies in large areas such as this is a subject for further analysis and research. Cleaned and processed lightning data can image lineament fabric, stream features, and surface water features without regard to surface infrastructure as shown in the interpretation on Figure 6.

Examining lightning data as a form of geohazard analysis provides an opportunity to image infrastructure and search for lightning hot spots. Figure 7 and Figure 8 show the Peak Current and a geologic interpretation across the Houston study area. These figures show that lightning strike strength follows geologically controlled fairways. The Peak Current attributes typically show lineaments related to geological structural fabric such as faults and fracture patterns, as shown in the interpretation.

Houston Ship Channel Lightning Density

Zooming in on the Houston Ship channel (Figure 9) shows numerous facilities and industrial plants. These kinds of hydrocarbon processing and storage sites have received many destructive and costly lightning strikes. The nearby San Jacinto Monument does not have any anomalous lightning strike density, despite being by far the tallest object in the area.

Some large refinery and storage facilities, like those shown in this area, have few options for location. The left side of Figure 9 shows individual lightning strikes occurring in this area over a 16+ year period. Over that time, it is noted that some areas have more strikes than others. This clustering is generally related to the underlying geological features, much like the attribute maps ignored infrastructure above. However, it has been noted by engineers specializing in grounding sensitive valuable assets, such as tank farms and some types of processing plants, there are more lightning strikes where there are hydrocarbon emissions compared to steam (Morris, 2015).

The right side of Figure 9 shows the filtered lightning Strike Density Attribute map across this same area. This map highlights trends in lightning strikes over specific portions of the facility. The green areas are relative hot spots for lightning strikes and may require additional grounding precautions. Lighting strike density analysis might also be a useful tool to prioritize work in times of tight maintenance budgets, or it might be used on a regional trend basis for selecting less dangerous locations for production facilities. Risk analysis related to strike probability can be generated from the analysis of the strike density attribute data derived from the lightning strike database. Some facilities such as landfills also have high lightning strike densities, possibly related to biogenic methane expelled from the site and facilitating lightning streamer development. By analysis, natural gas seeps associated with faults, fractures, gas chimneys, etc., likely have a lightning signature similar to that of landfills. Such features may contribute to hot spots on Lightning Density Attribute maps.

Imaging the areas where lightning tends to cluster because of geological factors enables managers to take the appropriate action to protect their assets from lightning strikes. In this difficult downturn period, hard choices for budget dollars are made. Having the ability to screen for areas that have experienced repetitive lightning strikes could present an opportunity to set priorities in protecting assets most at risk. For instance, consider the Sago coal mine disaster which is attributed to a lightning strike on 02 January 2006 at 6:26 AM in West Virginia. Lightning was the most likely ignition source (Gates, et.al. 2007).

In addition, it is interesting that "during 2007-2011, U.S. local fire departments responded to an estimated average of 22,600 fires per year that were started by lightning. In addition to the fires reported to local fire departments, federal and state wild land firefighting agencies reported an average of 9,000 wild land fires started by lightning to the National Interagency Fire Center per year in 2008-2012. These fires tended to be larger than fires started by human causes. The average lightning-caused fire burned 402 acres, nine times the average of 45 acres seen in human-caused wild land fires (Ahrens, 2013)."

Texas Gulf Coast

Lightning strike density and attribute maps show clusters and lineations which correlate to some surface projections of faults, near surface fluvial depositional patterns, possibly seeps, fresh water, possibly salt domes, hydrocarbons, and mineralization. As derived from Figure 6 in a 2013 AAPG paper (Nelson, Siebert, and Denham, 2013), a Texas Gulf Coast case study showed lightning attribute anomalies correlated to oil and gas fields.

The left half of Figure 10 shows a 3-D survey outline, fields, and fault patterns for a different Texas Gulf Coast case study. A 480 square mile 3-D seismic survey was interpreted and the fault plane patterns at about 500 ms are displayed. The right half of Figure 10 is the Rise-Time attribute map. Rise-Time, measured in micro-seconds, is a measure of the time it takes for a lightning stroke to reach its maximum current. The shorter the rise time the quicker and more explosive the lightning strike generally is, while lightning strikes having longer rise times generally possess much more energy over a given time.

The Rise-Time map shows the distribution of Rise-Time data accumulated over about 10 years of recorded lightning data. The blues represent the smallest rise times, or the quickest and most explosive lighting strikes in the area. The reds have the longest rise times and their patterns show the higher energy but less explosive lightning trends. The map clearly shows that Rise-Time distribution of data is strikingly non-random.

Instead, numerous circular to elongated anomalies are amply distributed across this map, with the majority of these anomalies comprised of larger rise time and higher energy lightning strikes. In addition, the orange and yellow faults striking east-west across the middle of the Rise-Time map (Figure 10, right panel**),** generally separates the northern low Rise-Time anomalies from the southern high Rise-Time anomalies.

The black stars on both maps indicate where Frio, Vicksburg, and Wilcox production correlate to Rise-Time closures. Twenty-six of the twenty-eight fields shown in the left panel of Figure 10 correlate to Rise-Time anomalies (93%). The lightning data patterns appear to be guided by the presence of stacked hydrocarbon reservoirs and their effect on rock resistivity, possibly related to electrical halos above the fields, as described by (Beard, 2015).

From an exploration perspective, based on a review of the Rise-Time map only four out of thirty-two anomalies within the 3-D outline did not correlate to a known oil or gas field (13%). Although wells would not have been drilled based on lightning data alone, the lightning data would have identified twenty-eight leads for follow-up seismic evaluation. Based on the notional integration of lightning and seismic data, the use of NSEM data as a reconnaissance tool could have resulted in an 87% exploration success rate.

Pinal County, Arizona Resistivity and Permittivity Volumes

Compared to the examples above, our project site in Arizona is of a dramatically different nature. The study area is in a desert, is related to a significant economic asset, and here we demonstrate the ability to create rock property data volumes from lighting databases. Specifically we are showing some very new lightning technology, the ability to generate resistivity and permittivity volumes.

Lightning attributes were evaluated across a known porphyritic copper deposit in Pinal County, Arizona and show impressive results and NSEM data's ability to identify commercial orebodies. Figure 11 is a Google Earth view showing the location of the copper deposit outlined in white. Figure 12 and Figure 13 show NSEM attributes "Negative Peak Current" and "Positive Peak Current" respectively, along with an interpretation of hydrothermal alteration halos.

Cloud to ground lightning can be in the form of positive or negative polarity strikes, a function of whether the lightning originates at the top or bottom of a cloud. Worldwide positive polarity lightning strikes occur less than 5% of the time but generally develop six to ten times the current and voltage of negative polarity lightning strikes. Positive Peak Current is the maximum current recorded for positive lightning strikes and Negative Peak Current is the maximum negative current recorded for negative strikes. Figure 12 and Figure 13 therefore show the distribution of the maximum charge recorded for every lightning strike across the study area during the past sixteen years.

Both attribute maps show similar peak current clusters. Whether the lightning originates as positive or negative polarity, maximum peak currents across the study area show annular cluster patterns around the porphyry copper deposit. In the case of the relatively stronger positive peak current attribute map, a series of concentric maximum peak current rings**,** separated by a ring of minimum peak current are observed. We believe the alternating nature of the lightning clusters is geologically controlled and represents lateral resistivity/conductivity changes of the host rock caused by igneous intrusion and resulting hydrothermal alteration. Annular mineralogical and orebody halos are often associated with porphyritic copper deposits and we believe the radial resistivity patterns reflect the underlying geology and our ability to identify porphyry copper deposits.

The negative peak current attribute map in Figure 12 also shows linear patterns. These lineations appear to trend in a consistent manner, subparallel and generally striking northeast. The patterns are defined by clusters of low peak current negative polarity lightning strikes. These represent linear trends of the lowest peak current strikes and are believed to be guided by igneous dikes or sills emplaced during igneous intrusion. This interpretation is supported by the presence of dikes and sills reported in the North Silver Bell porphyry copper deposit located 50 miles to the southwest (Thoman, Zonge, and Liu, 1996).

Figure 14 and Figure 15 reintroduce rock property volumes derived from a lightning database (Haggar and Nelson, 2014). The new analytics shown here were developed by (Denham, 2015) where a summary of his resistivity calculation is available. His assumptions and calculations are reasonable based on the large archives of lightning data available and the number of lightning strikes recorded within small areas. In Arizona, as shown on Figure 3, there are up to 45 lightning strikes per square kilometer over the time data are available.

Figure 14 shows images from the resistivity volume generated over the Resolution Copper Mine area. The window at the bottom shows a resistivity section through the mine. The location of this line is highlighted on the horizontal resistivity slice in the upper right window. Figure 15 is the same basic display, only the vertical and horizontal cross-sections are derived from the permittivity volume.

Preliminary analysis of the resistivity volume shows promising results across the porphyry copper deposit. The resistivity profile (Figure 14), shows an inner high resistivity zone bounded on both sides by less resistive rock. This resistivity pattern matches known porphyry copper deposit signatures consisting of an inner high resistivity region partially or completely surrounded by a lower resistivity outer region (Morrison and Lo, 2009). The resistivity profile also supports the interpretation of the lightning attribute maps in that the lightning-sourced resistivity profile also shows evidence of hydrothermal alteration zones. We are still working to calibrate the vertical axes of these rock property volumes. Further work is needed to determine how closely the laterally changing lightning-sourced resistivity and permittivity volume data will correlate to changing mineralogical assemblages and their associated ores.

Summary

We have introduced NSEM, a new geophysical data type with wide application to society. It can be utilized in the petroleum, environmental, civil engineering, mining, and geohazard industries. These data are significantly less expensive to acquire, process, and interpret than most, if not all, geophysical techniques on the market today. Its cost is about 1/100th of what it would cost to acquire typical 3-D seismic data and an entire project can be completed within two months. Three-dimensional resistivity and permittivity data can be viewed in cross-section and as horizontal slices. It can also be scaled to the same display parameters as any 2-D or 3-D geophysical data, which facilitates its calibration to other geophysical and geological data.

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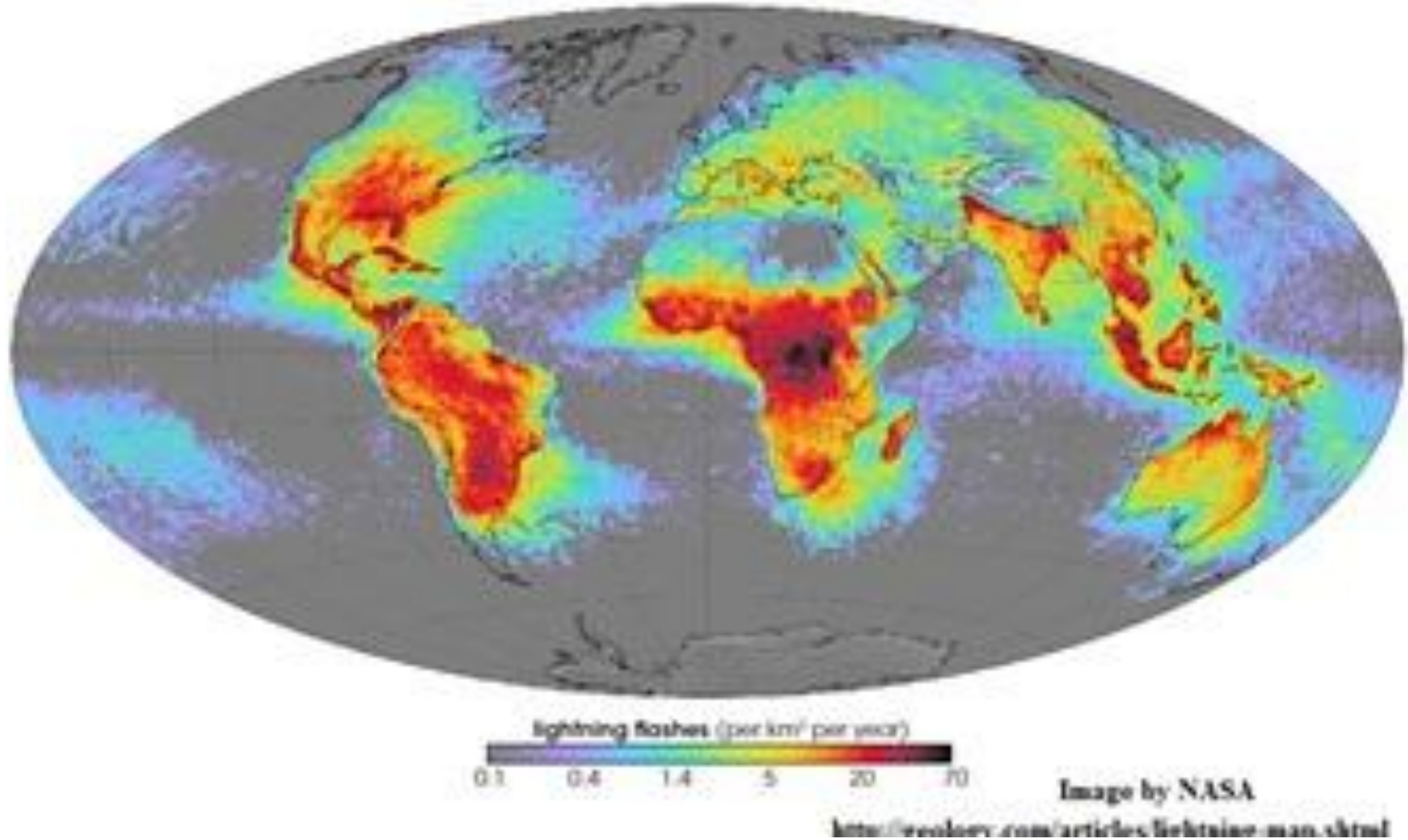

Figure 1. Worldwide lightning strikes density from NASA via geology.com. (http://geology.com/articles/lightning-map.shtml).

Figure 2. Up-going lightning strikes like this appear to be tied to electrical current build-up in the geology.

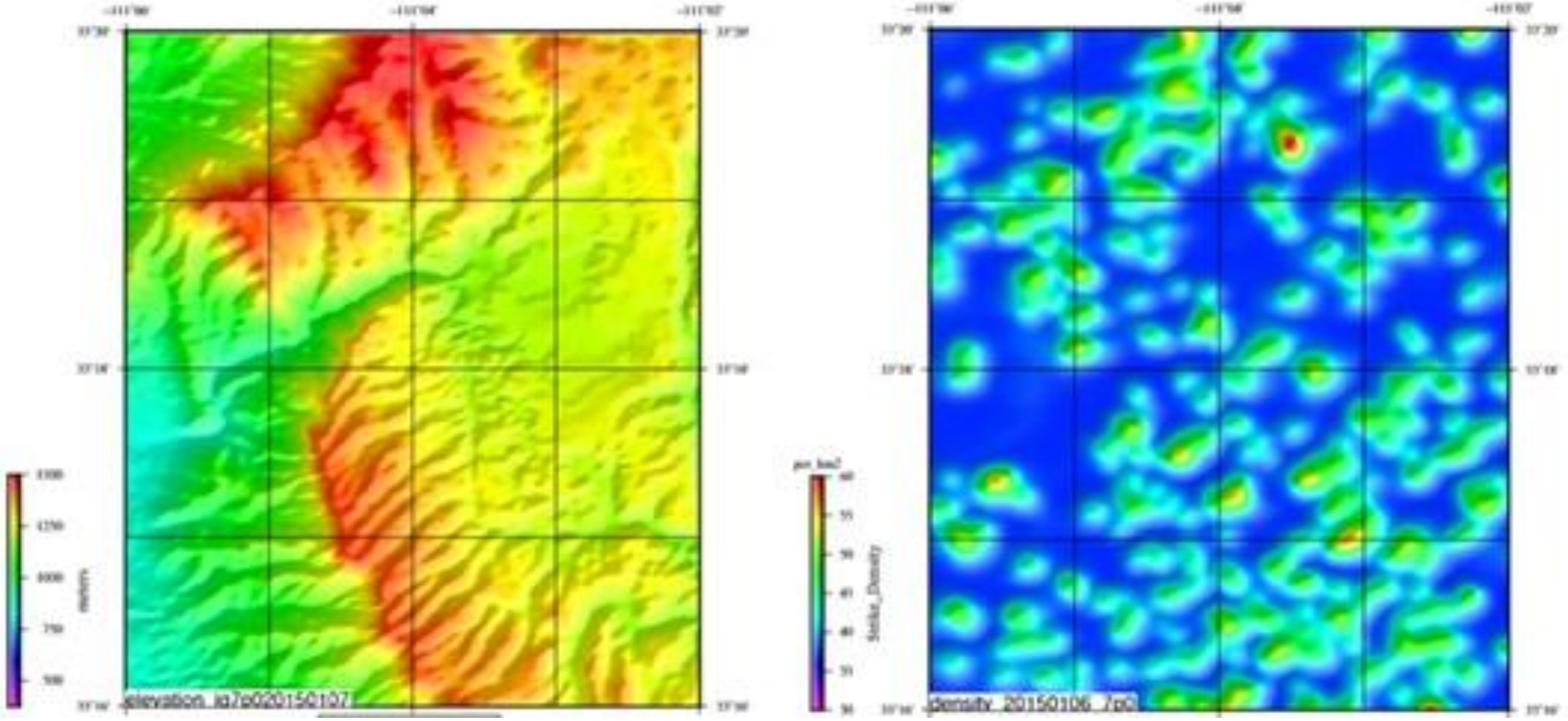

Figure 3. Topography (left) and Lightning Density (right) around the Resolution Copper Mine, Pinal County, Arizona.

Figure 4. Houston, Texas lighting analysis area is yellow box and Ship Channel analysis area is red box. This area goes from Sealy in the west to the San Jacinto Monument and Shipping channel in the east, and from south Loop-610 in the south almost to The Woodlands in the north (GoogleEarth™ image).

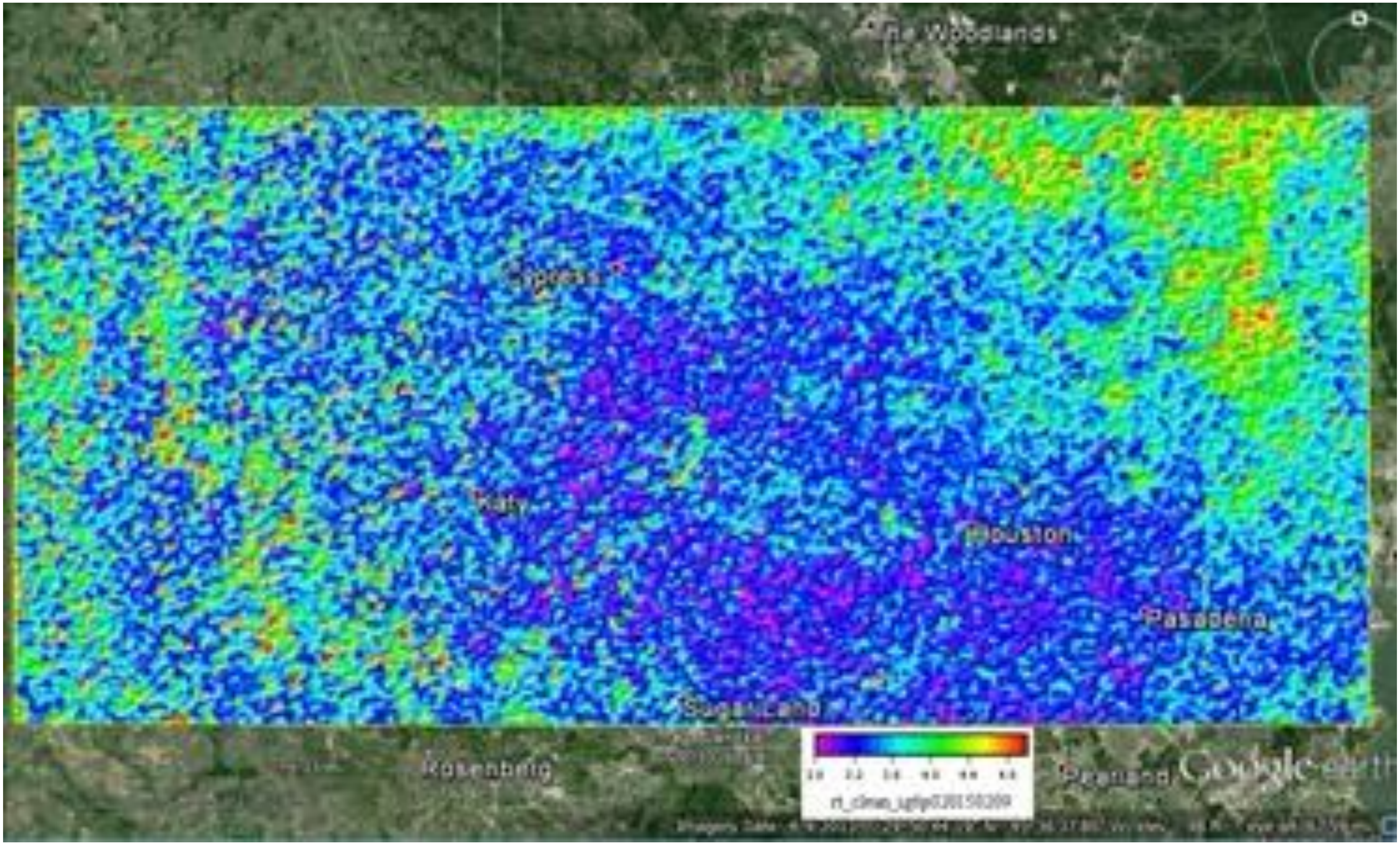

Figure 5. Rise-Time over the Houston, Texas area.

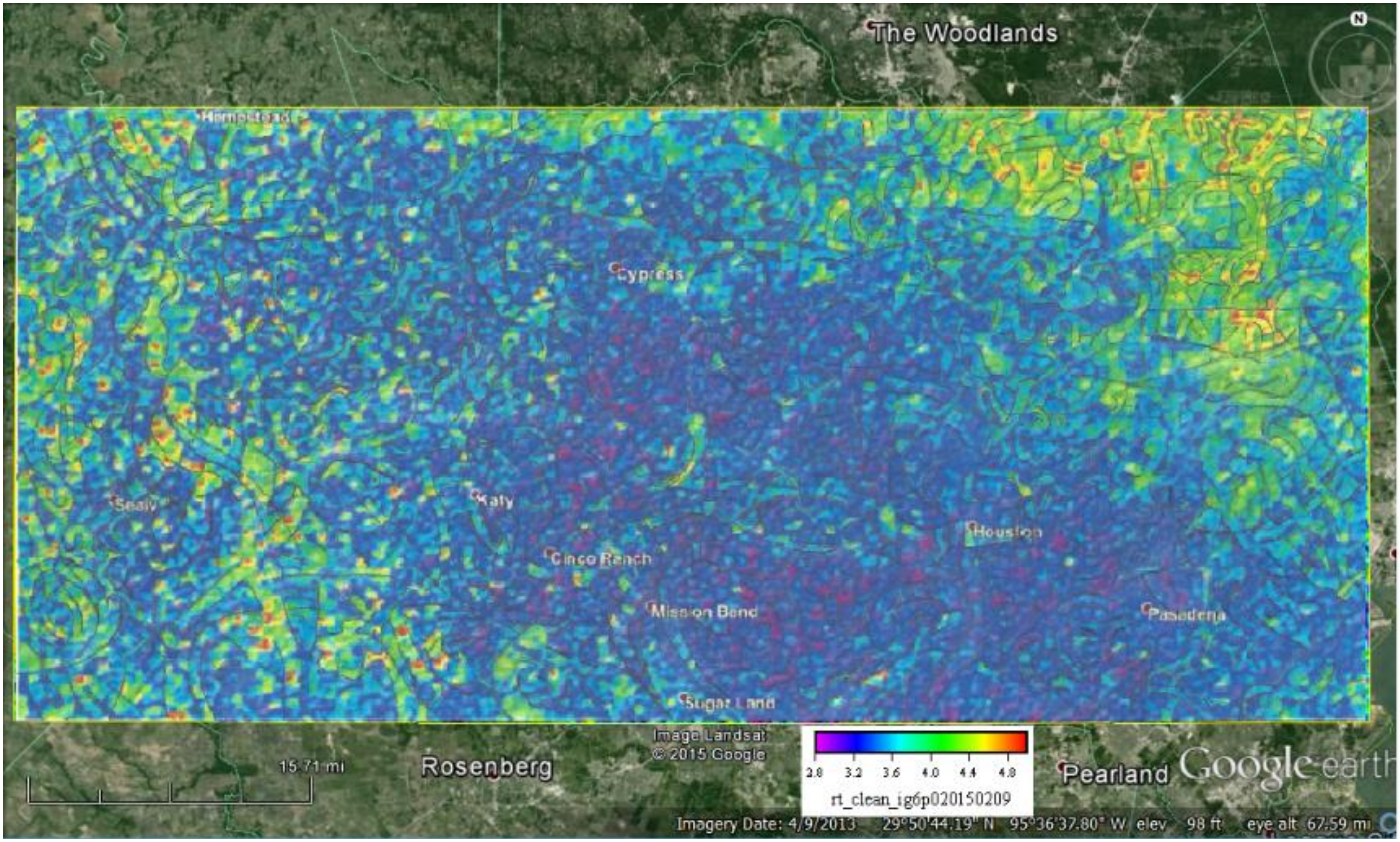

Figure 6. Lineaments identified on a Rise-Time lightning attribute map of the area surrounding Houston.

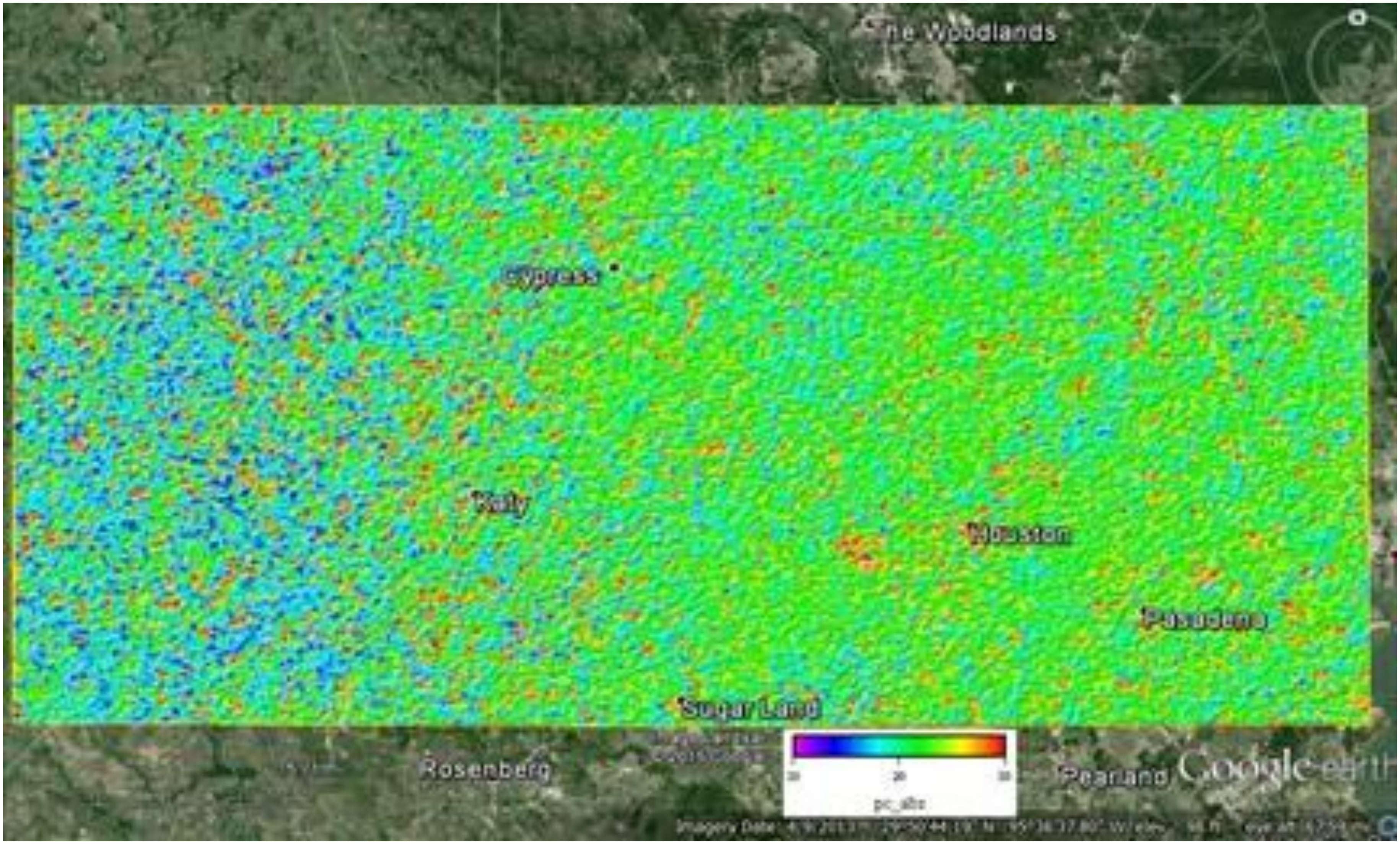

Figure 7. Peak Current.

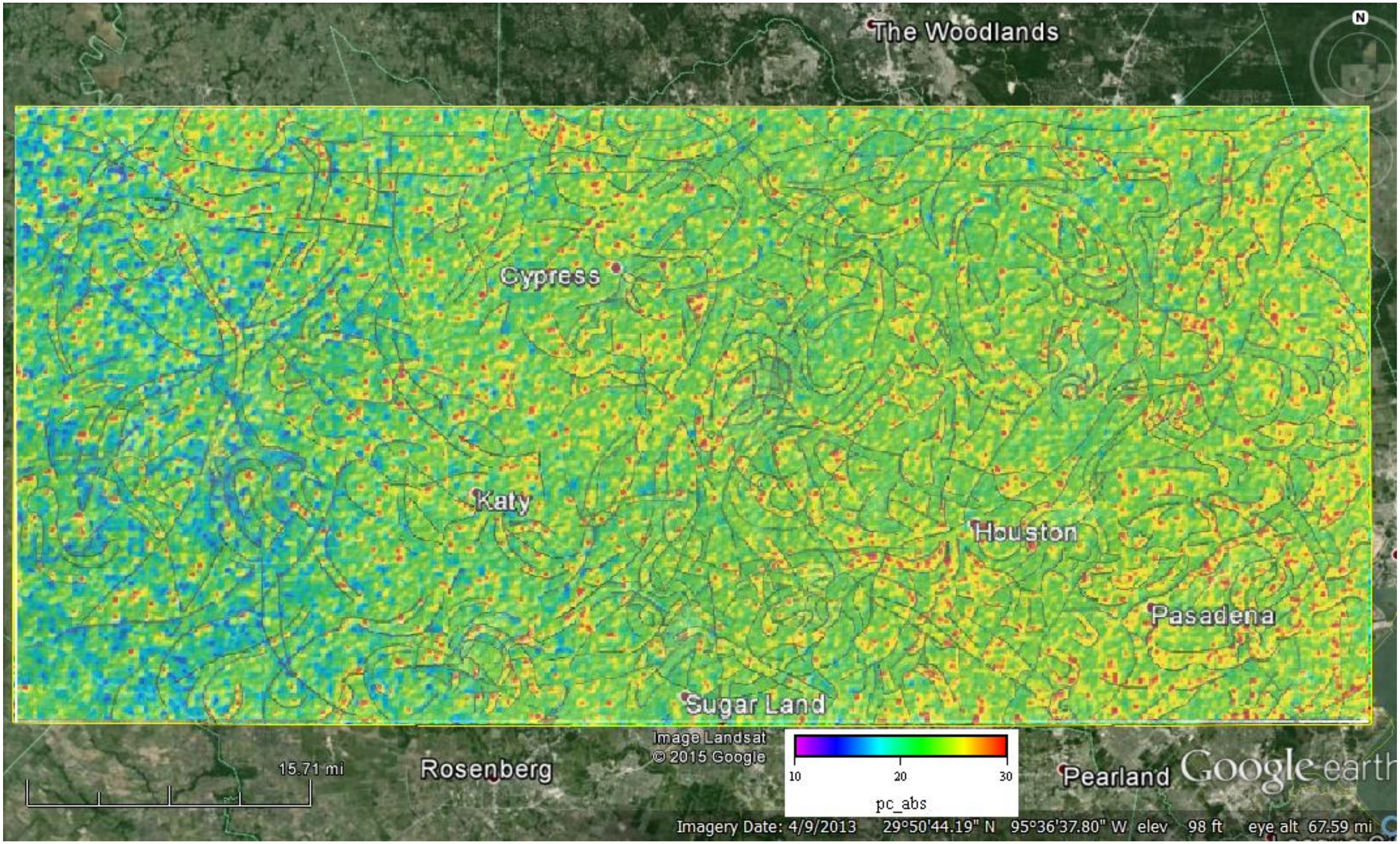

Figure 8. Lineaments identified on a Peak Current lightning attribute map of the Houston, Texas area.

Figure 9. Individual lightning strikes plotted for an area in the Houston Ship Channel, Texas with filtered lightning density map covering the red area in Figure 4 in Houston, Texas.

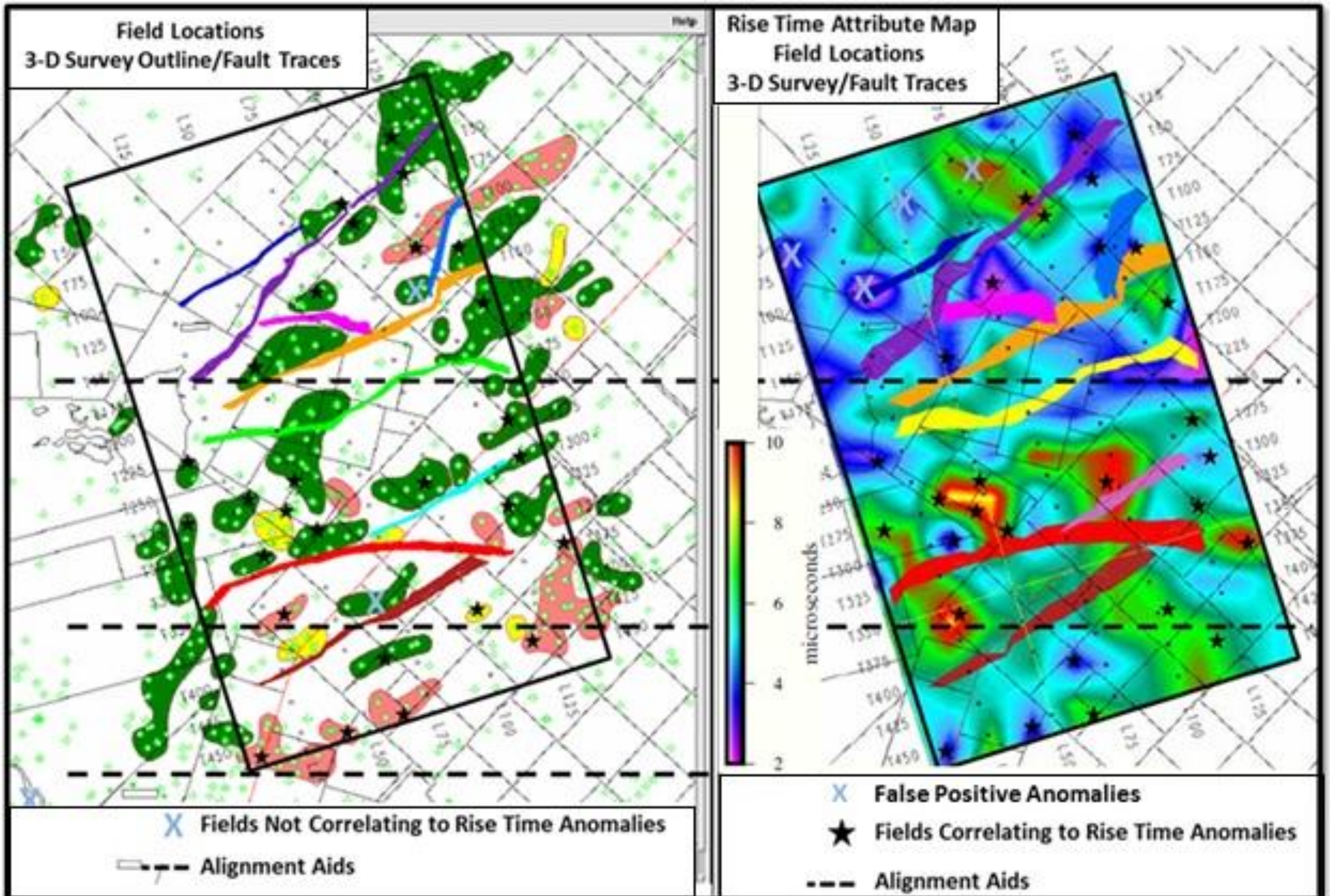

Figure 10. Field Map from the Texas Gulf Coast showing oil and gas fields, outline of 3-D survey and fault traces. Black stars designate oil and gas fields that correlate to "Rise Time" lightning on the right.

Figure 11. The Resolution Copper Mine lightning analysis area in Pinal County, Arizona (GoogleEarth™).

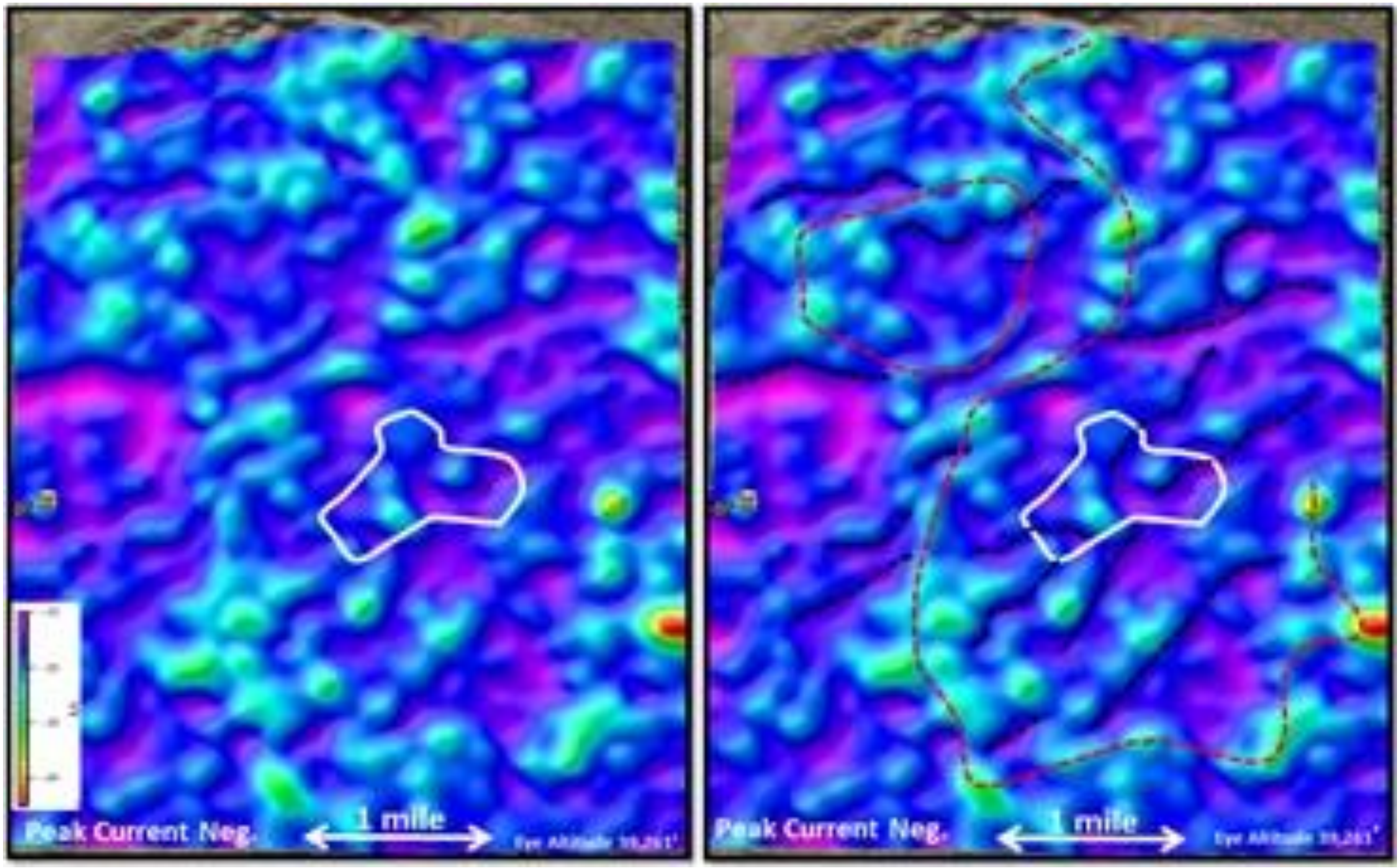

Figure 12. Negative Peak Current across the Resolution Copper porphyry with hydrothermal alteration and potential dike swarm interpretation on the right.

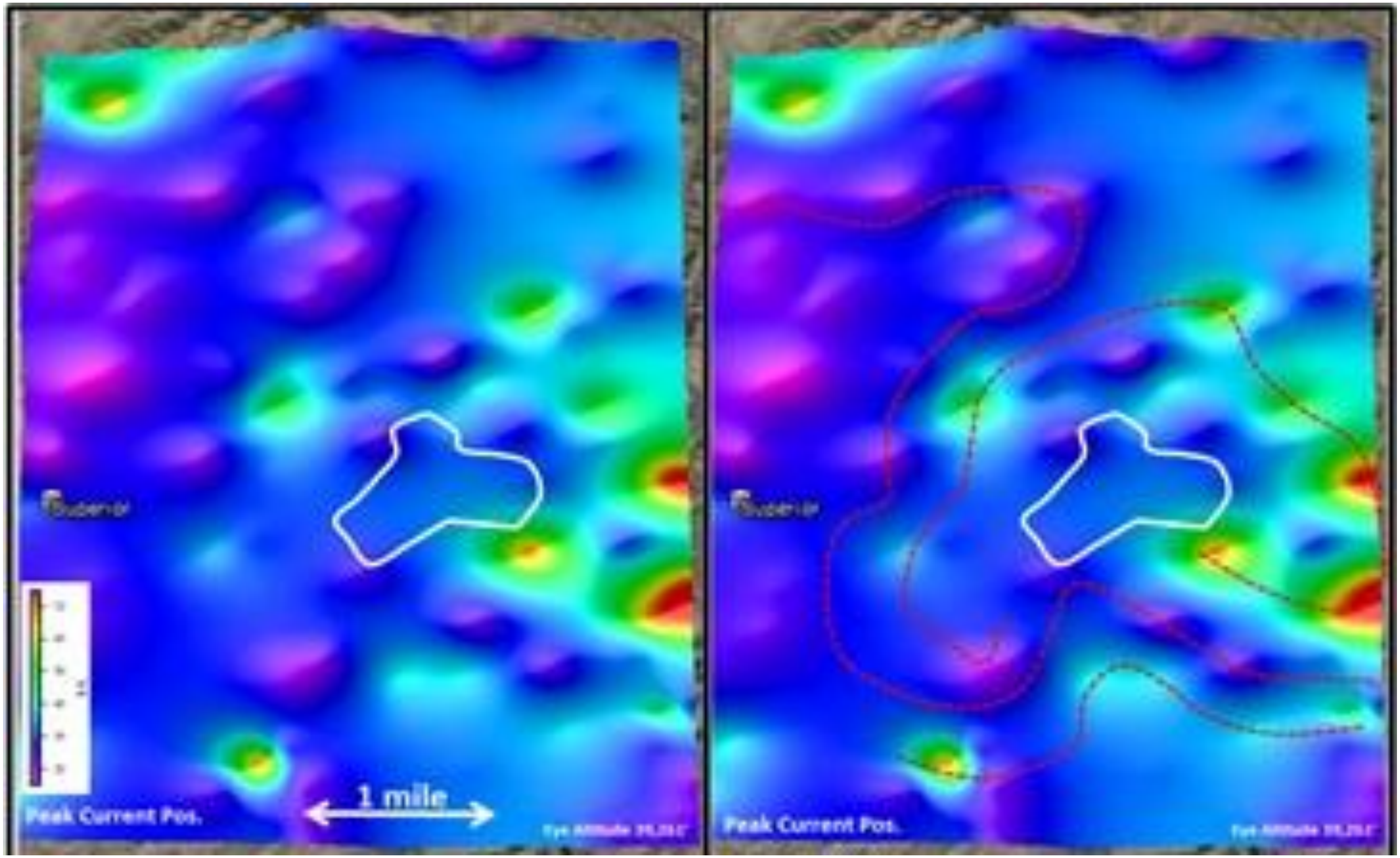

Figure 13. Positive Peak Current across the Resolution Copper porphyry copper deposit with showing interpreted halo effect associated with the hydrothermal zone interpretation on the right.

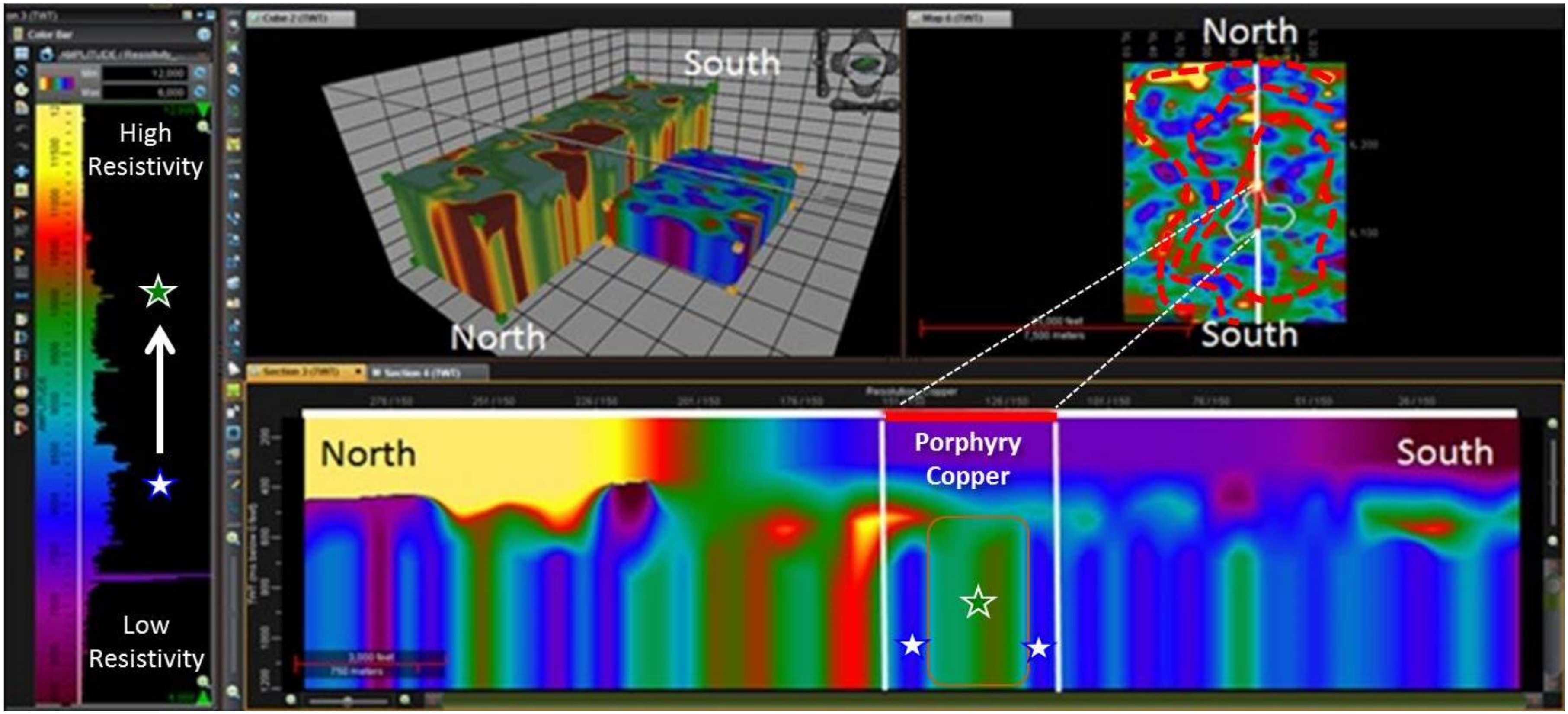

Figure 14. Probes, vertical, and horizontal resistivity slices from a resistivity volume at the Resolution Copper Mine porphyry deposit, Pinal County, Arizona. Innermost copper ore zone bounded by less resistive rock, possibly associated with hydrothermal alteration zones.

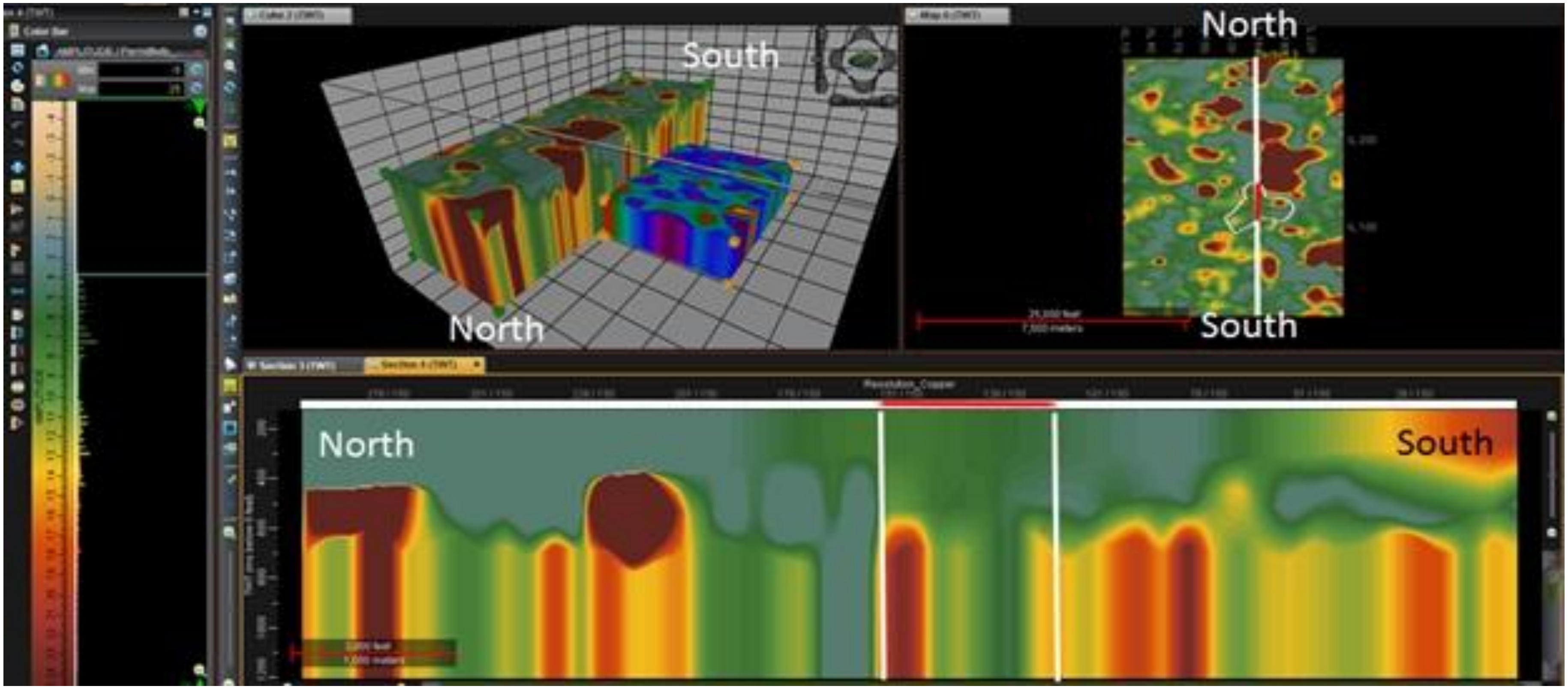

Figure 15. Probes, vertical, and horizontal resistivity slices from a permittivity volume across the Resolution Copper Mine porphyry deposit, Pinal County, Arizona.