

**Lineament Mapping using Remote Sensing Techniques and
Structural Geology for CO₂ Sequestration Site Characterization in
Central New York State**

By

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of
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Abstract

This study identified lineaments from satellite images and Digital Elevation Models (DEMs) utilizing image processing techniques that enhance variations in spectral and spatial reflectivity and topography. In flat-lying sedimentary sequences Lineaments are commonly surface expressions of tectonic fractures and faults in the bedrock, emphasized on the surface by topography, drainage, and vegetation - many can be identified by remotely sensed data. Knowledge of fault locations can prevent unsuitable site selection for CO₂ sequestration where CO₂ could migrate up fault systems. Lineament patterns also give insight into the fracture fabric of the region- an important consideration for CO₂ sequestration. Various data sets, including multispectral satellite imagery (Landsat and ASTER) and DEMs, as well as geological data describing fractures, faults, and hydrology, were used to map and validate the lineament distribution in the study area. Linear features were enhanced with tonal, topographic and textural changes by digital image processing of the satellite imagery and DEMs. Lineaments were then extracted manually using ArcMap (ArcGIS 9.2 – ESRI). Lineaments longer than 1 km were identified, digitized and stored in a geo-database together with attributes describing their length, orientation and other characteristics. Lineament categories included vegetation, drainage, and topography. Rose diagrams and statistics of length and number of lineaments in each 10⁰ orientation bin were used to characterize the lineament distribution in each remotely sensed data set. The primary lineament orientations from both ASTER imagery and topography trended northeast and northwest in the study area of central New York State. These trends agreed with some of the EarthSat (1997) lineament sets from Landsat images and also corresponded to some published fracture and fault systems but do not reflect the most abundant sets.

Chapter 1 – Introduction

A. Significance

One of the main driving forces behind global warming is CO₂ emissions from burning fossil fuels (Sadorsky, 2009). According to Holloway (2005), 22 billion tons of CO₂ are emitted into the atmosphere annually - a majority resulting from burning of fossil fuels for production of electricity at power plants. Consequently, CO₂ sequestration near power generation plants is being examined as a potential solution to the CO₂ problem. Geological CO₂ sequestration is the process in which CO₂ is captured at smoke stacks of coal-burning power plants, transformed into a super-critical liquid, transported via pipeline or truck and then injected into the subsurface (Figure: 1.1). Knowing where faults are located can prevent selecting areas unsuitable for CO₂ sequestration where a potential leak can occur. Knowledge of fracture sets is critical because fractures can enhance CO₂ storage capacity; however, a large number of open faults intersecting the ground surface (indicated by lineaments) in a particular region indicate that the region should not be considered for CO₂ capture and storage due to potential CO₂ leakage.

B. Objective

The objective of this research was to identify and map lineaments in central New York State (NYS) to assist in characterizing potential sites for carbon dioxide (CO₂) subsurface sequestration.

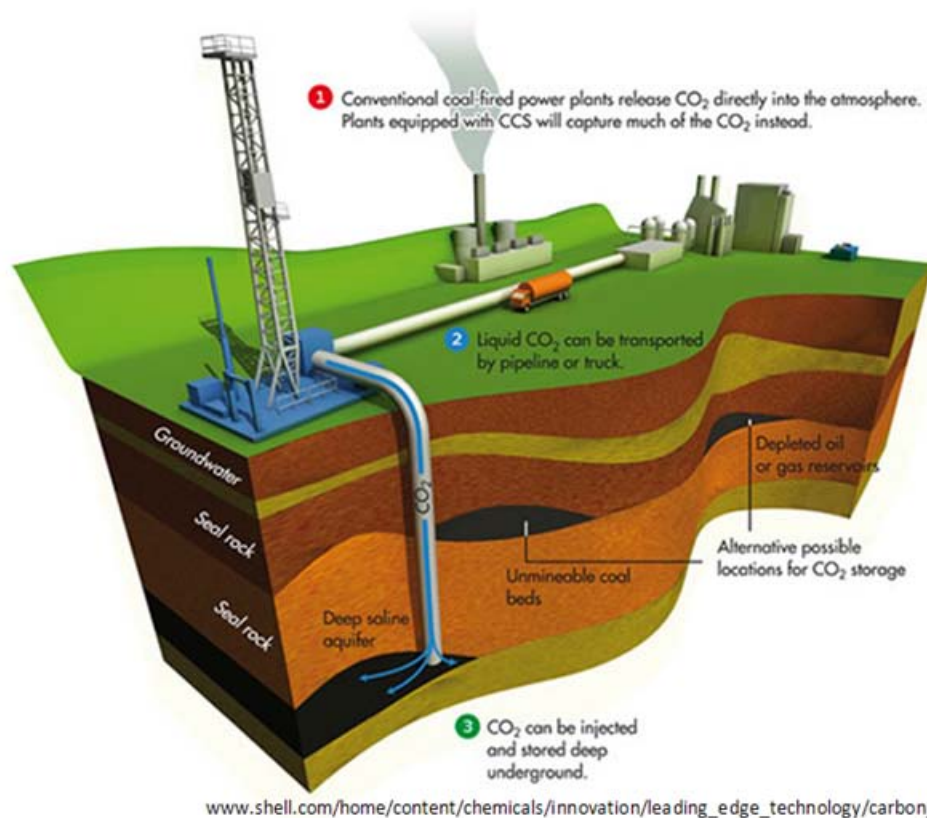


Figure: 1.1 – Cartoon of the carbon dioxide capture and storage or sequestration (CCS) process

C. *Site Location*

The Finger Lakes region of Central NYS is an area that covers eight counties and contains five AES power plants that are prospective sites for the CO₂ capture and storage project (Figure: 1.2). The counties are Yates, Steuben, Schuyler, Chemung, Cayuga, Tompkins, Chenango, and Broome (Figure: 1.3). The power plants considered for potential CO₂ sequestration in the project are AES Cayuga, AES Greenidge, AES Hickling, AES Jennison, and AES Westover (Figure: 1.3). Grid 1 covering a 225 km² area surrounding the AES Cayuga Power plant (Figure: 1.4) was examined in Phase I of this project; this phase involved digitizing lineaments from 15 satellite images and DEM shaded relief representations. Lineaments were digitized for the entire project area during Phase II. The project area was sub- divided into three

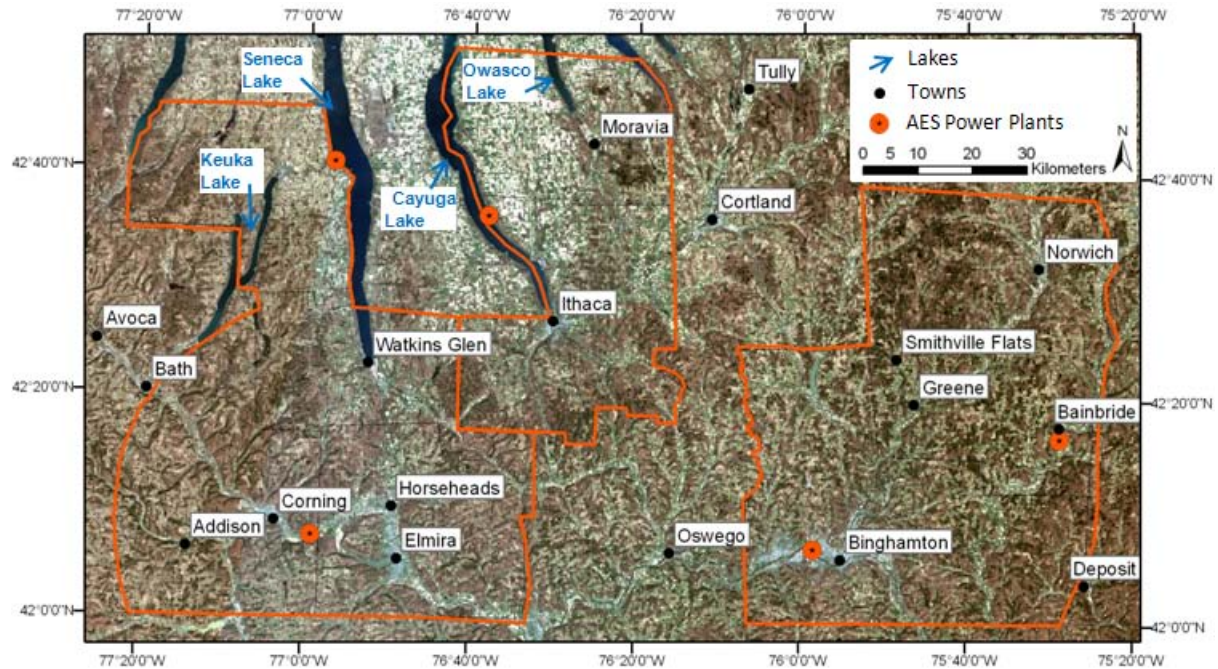


Figure: 1.2 - Site map with AES power plants, project boundary, town names and lake names; base map is a Landsat ETM+ true-color composite mosaic, April, 2001 (see section 4.A.1 for details on Landsat image processing)

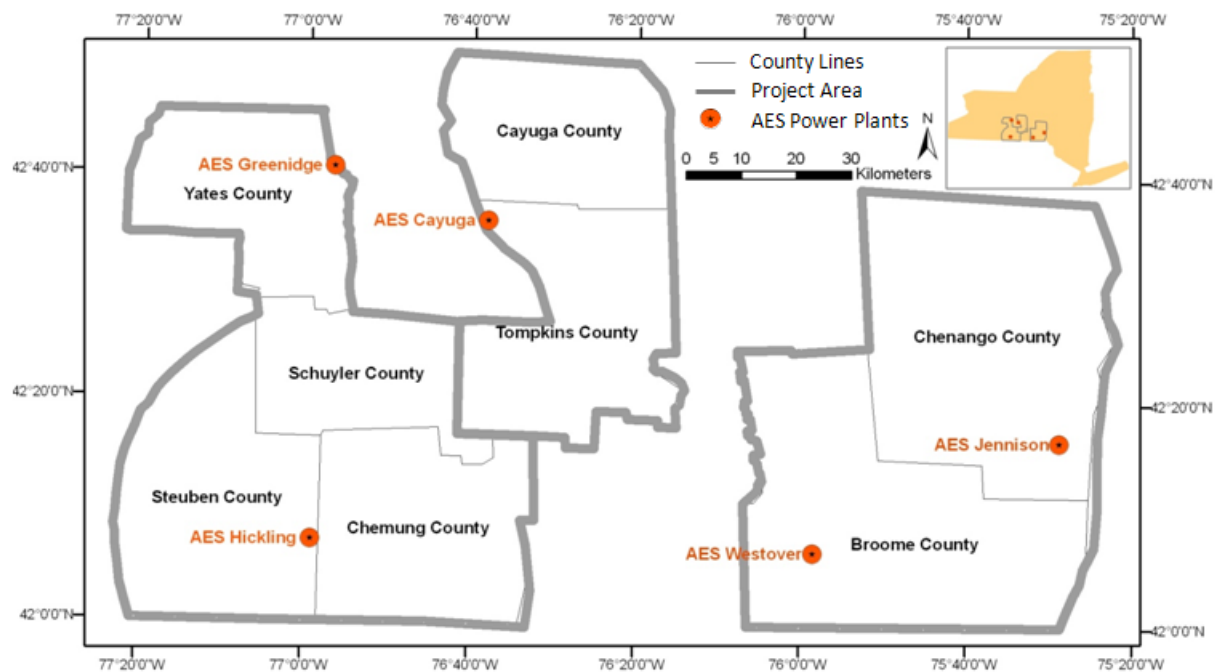


Figure: 1.3 - Site map with AES power plants, project boundaries, county lines and names and included the western, central and eastern focus areas

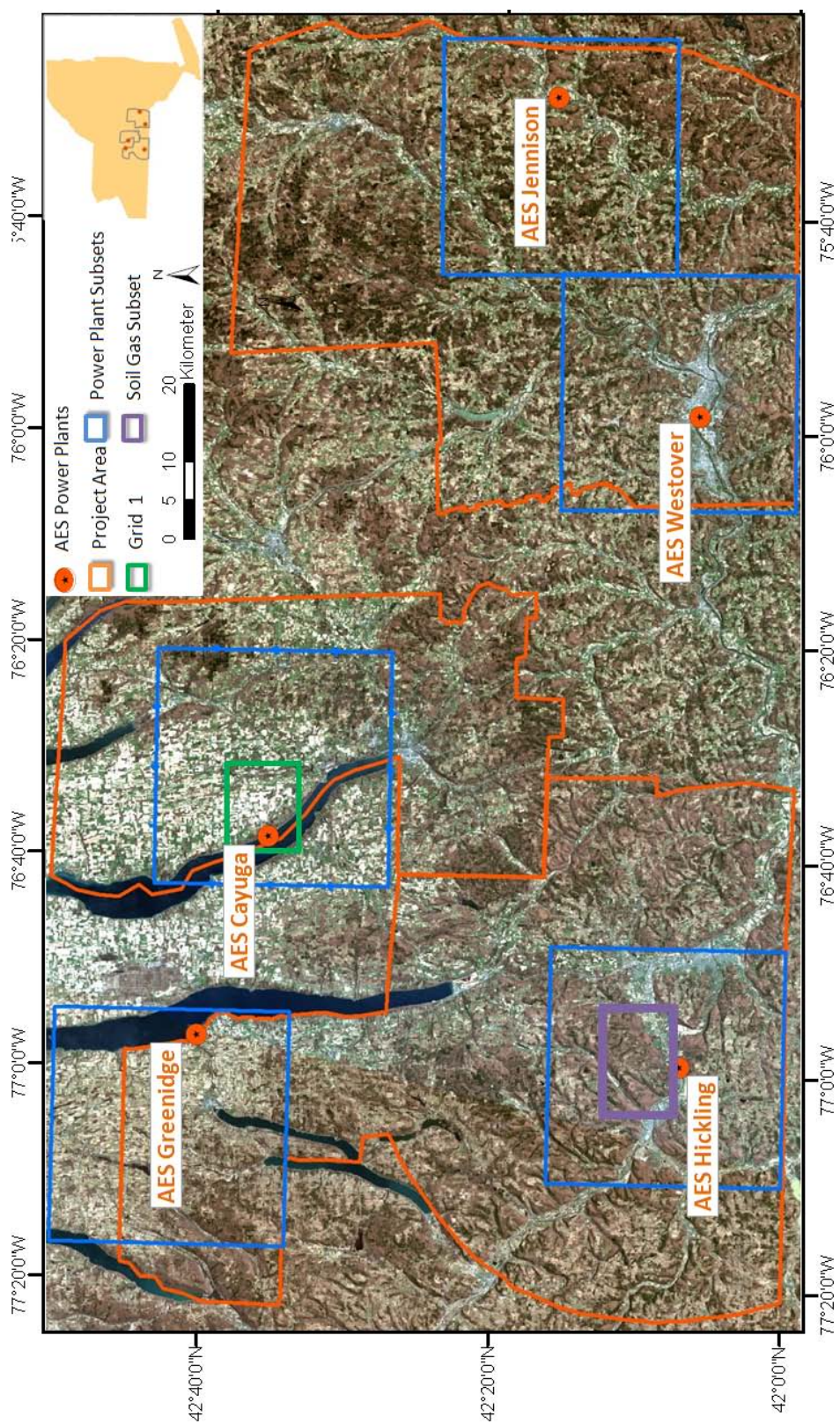


Figure: 1.4 – Site map with AES power plants, project boundaries, important subsets for detail studies and grid 1 for phase I testing; base map is a Landsat true-color composite

The boundaries of these focus areas were used to separate analyses performed during Phase II. During Phase III a larger area around Grid 1 and the AES Cayuga power plant was chosen for a more detailed investigation; this region is labeled as the Cayuga subset in Figure: 1.4. The Cayuga subset location was selected because of the potential CO₂ reservoir storage capacity and reservoir depth.

D. Chapter Summaries

This thesis is separated into eight chapters detailing work performed during this two-year project, with three appendix sections that have additional material. The geological background chapter provides background on the regional tectonics and stratigraphy and their effect on the current structural geology of the Appalachian basin. The data chapter introduces the various data types used in this project, including satellite imagery, DEMs, and various auxiliary data sets. This project was completed in four major steps that are explained in detail in the methodology chapter and include 1) image processing, 2) lineament identification and digitizing, 3) lineament analysis and 4) geological interpretation. The results section is divided into the three phases in which the work was completed and provides maps, rose diagrams, basic statistics and additional analyses of the digitized lineaments. In the geological interpretation chapter the relationship between known structural geology and the digitized lineaments from ASTER imagery and shaded relief DEMs is examined. The discussion incorporates results, observations and relationships to provide insight into the structural geology from lineament investigations for CO₂ site suitability studies. The last chapter of this thesis looks to the future of this project and explores more investigations that can strengthen the results and conclusions of this project.

Chapter 2 – Geological Background

A. Geological History

The Appalachian Mountains were formed during the closing of the Iapetus Ocean, related seaways and marginal basins; this happened over several orogenic events (van Staal, 2007). These orogenic events occurred from Late Cambrian to Permian and included three major events (the Taconic, Acadian and Alleghanian Orogenies) and several smaller orogenies (van Staal, 2007). The basement rocks of New York State (NYS) comprise metavolcanics and metapelites from the Precambrian Grenville terrain (Figure: 2.1; Isachsen et al., 1991). These rocks are only exposed in the Adirondack region and represent the Grenville orogeny in western New York. Elsewhere throughout the state, Early Paleozoic to Carboniferous sediments with varying thickness from erosion and deposition overlie the basement rock in an angular unconformity (Isachsen et al., 1991). The aforementioned deposits record marine transgressions that ended with the assembly of Pangaea during the Late Permian. The deposits were then covered by till of varying thickness from the last advancement of the Ontario Lobe of the Laurentide Ice Sheet approximately 14,000 years ago (Isachsen et al., 1991).

The structural geology of NYS can be understood by reviewing the regional tectonics and stratigraphy. The current structural geology within the surface rocks of the project area resulted from primarily the Alleghanian Orogeny acting on inter-bedded shales, limestones, siltstones and sandstones deposited from Middle Devonian to Late Devonian.

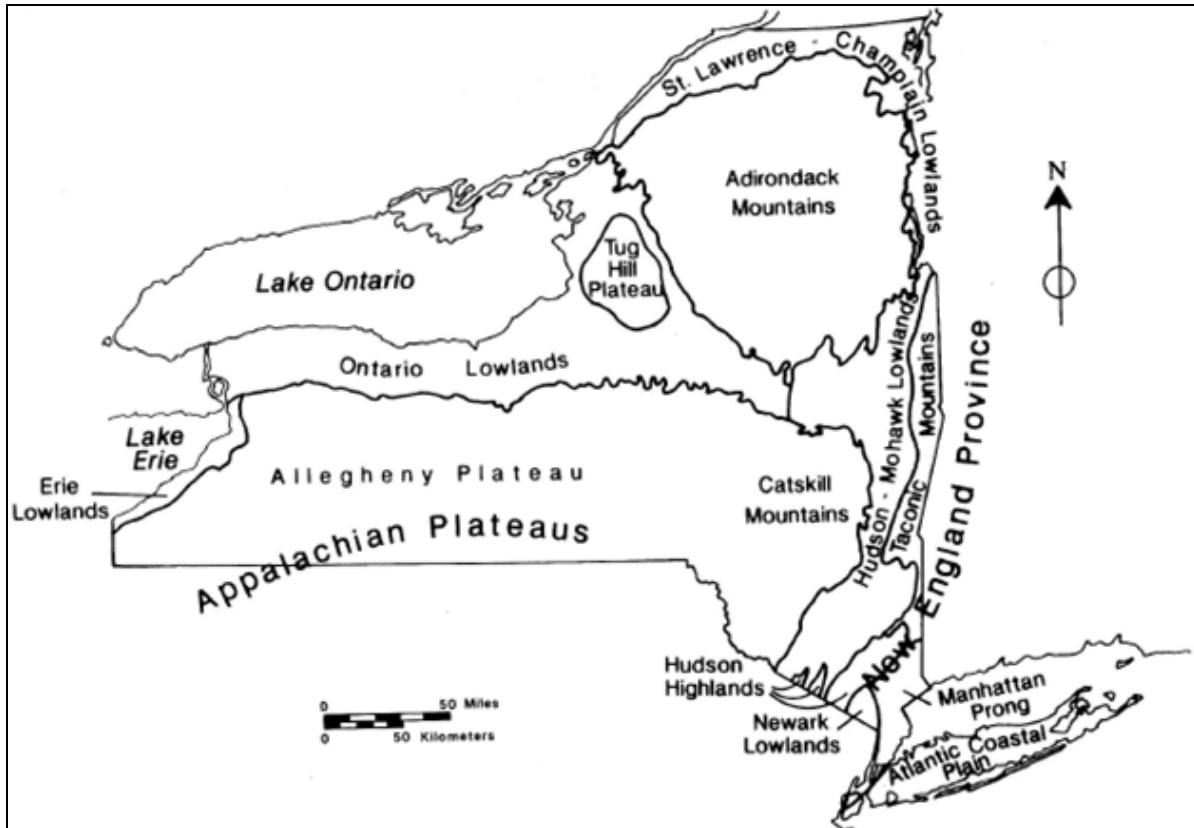


Figure: 2.1: Bedrock geology regions of New York State (Isachsen et al., 1991)

B. Regional Tectonics

The Alleghanian Orogeny occurred from 330 to 250 million years ago, building the Appalachian Mountains when the Gondwana (proto-Africa) continent collided and attached to the east coast of Laurentia (proto-North America) (Hatcher, 2002; Isachsen et al., 1991). The Alleghanian Orogeny initiated with an oblique approach of proto-Africa (Gondwana) forming a forebulge and subsequent erosion of most of the Mississippian and some Devonian sediments (Lash and Engelder, 2006). After this initial collision there was a clockwise rotation of the principal stresses resulting in the pivoting of proto-Africa around New York and an interlocking of the two land masses [Figure: 2.2; Lash and Engelder, 2006; Hatcher, 2002]. This initial

collision, named the Lackawanna phase (Engelder and Geiser, 1980), is recorded in central NYS and eastern Pennsylvania in joints trending north-northwest (e.g. Engelder and Geiser, 1980; Zhao and Jacobi, 1996). The later rotation of the maximum compressive stress resulted in north trending joints (Zhao and Jacobi, 1996) and was named Main phase by Engelder and Geiser (1980).

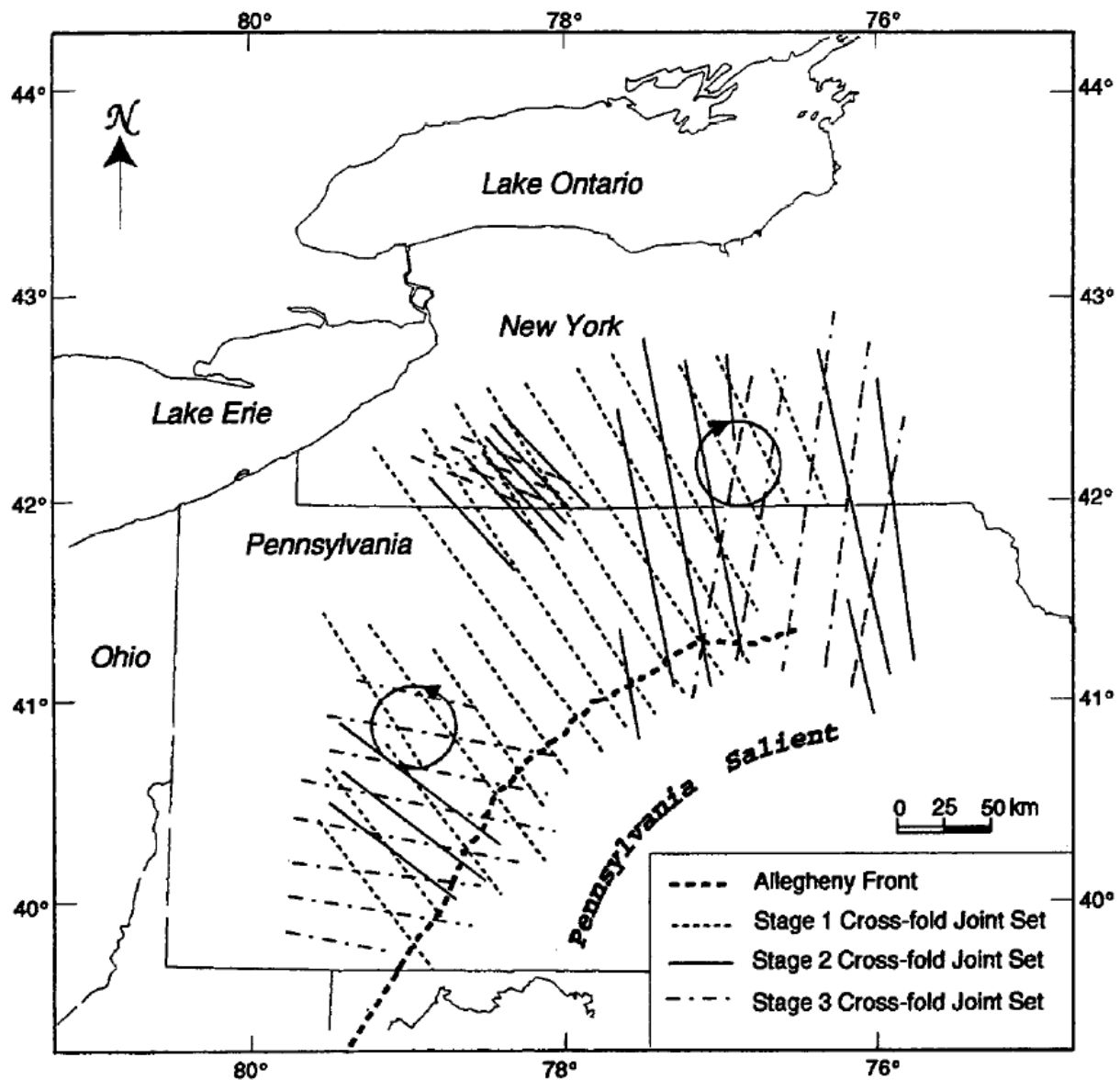


Figure: 2.2 – Rotation directions (indicated by circles with arrows) of the maximum compressive stresses during the Alleghanian Orogeny and main joint sets trajectories (Zhao and Jacobi, 1996)

During the second phase of the Alleghanian Orogeny the maximum principal stress was directed northwestward across the Appalachian basin and resulted in a décollement along a weak Silurian salt layer. This stress resulted in the northwestward movement of the overlying Devonian and Carboniferous rocks as “transported layers”. These transported layers underwent “layer-parallel shortening” of 10% without significant folding (Figure: 2.3). The evidence for the layer-parallel shortening is observed and documented in the deformation of deformed fossils, pencil cleavage, spaced cleavage, and brittle deformation of blind thrusting and drape folds (e.g. Engelder and Geiser, 1979).

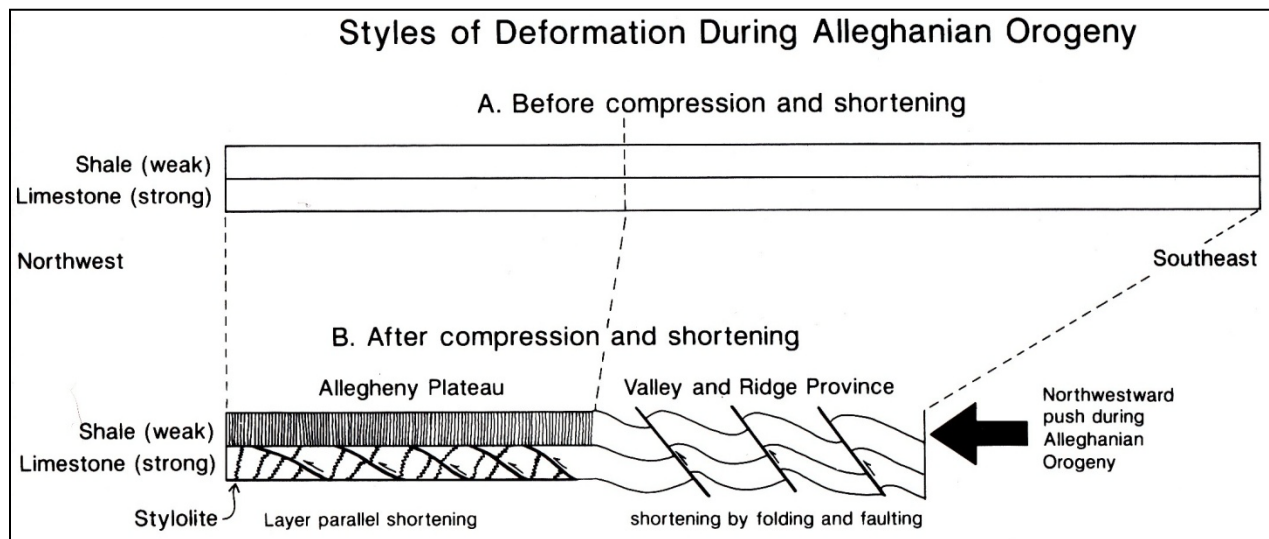


Figure: 2.3 – Schematic explaining the layer parallel shortening that occurred in the Appalachian Basin (Isachsen et al., 1991)

C. Stratigraphy

In the Allegheny Plateau layer-parallel shortening schematic (Figure: 2.3) demonstrates the important role stratigraphy plays on structural geology. Stratigraphy controls how the

deformation from the stress is recorded - whether it is ductile or brittle. This is based in part on the rock type, rock strength and depositional environment.

The stratigraphic sequence in the study area is ~8000 meters thick and is comprised primarily of inter-bedded shales, siltstones and sandstones with significant Cambrian-Ordovician and middle Devonian carbonates (Van Diver, 2003; Broughton et al., 1966 and Isachsen et al., 1991). The area underwent repeated cycles of transitions from deep water to shallow water to non-marine environments; these changes resulted from uplift and varying erosional output (e.g. Ettensohn and Barron, 1981). Depositional environments within this region show cycles of transgression and regression of the shoreline including basin, slope, shelf, shore zone and terrestrial, while the general shoreline movement progressed westward over time (Ettensohn and Barron, 1981). These depositional cycles were recorded in the middle and late Devonian units exposed in the project area with over 50 million years deposition represented in the Appalachian basin (Figure: 2.4). The outcrop “belts” trend east-west and are younger at the surface in the southern part of the state and older in the north near Syracuse due to a slight 2° southward dip of the units across central NYS (e.g. Isachsen et al., 1991). Most of the cycles vary up-section from limestone to shales with coarser deposits with a provenance toward the east. The thickness of each unit varies across the project area due to original depositional variability.

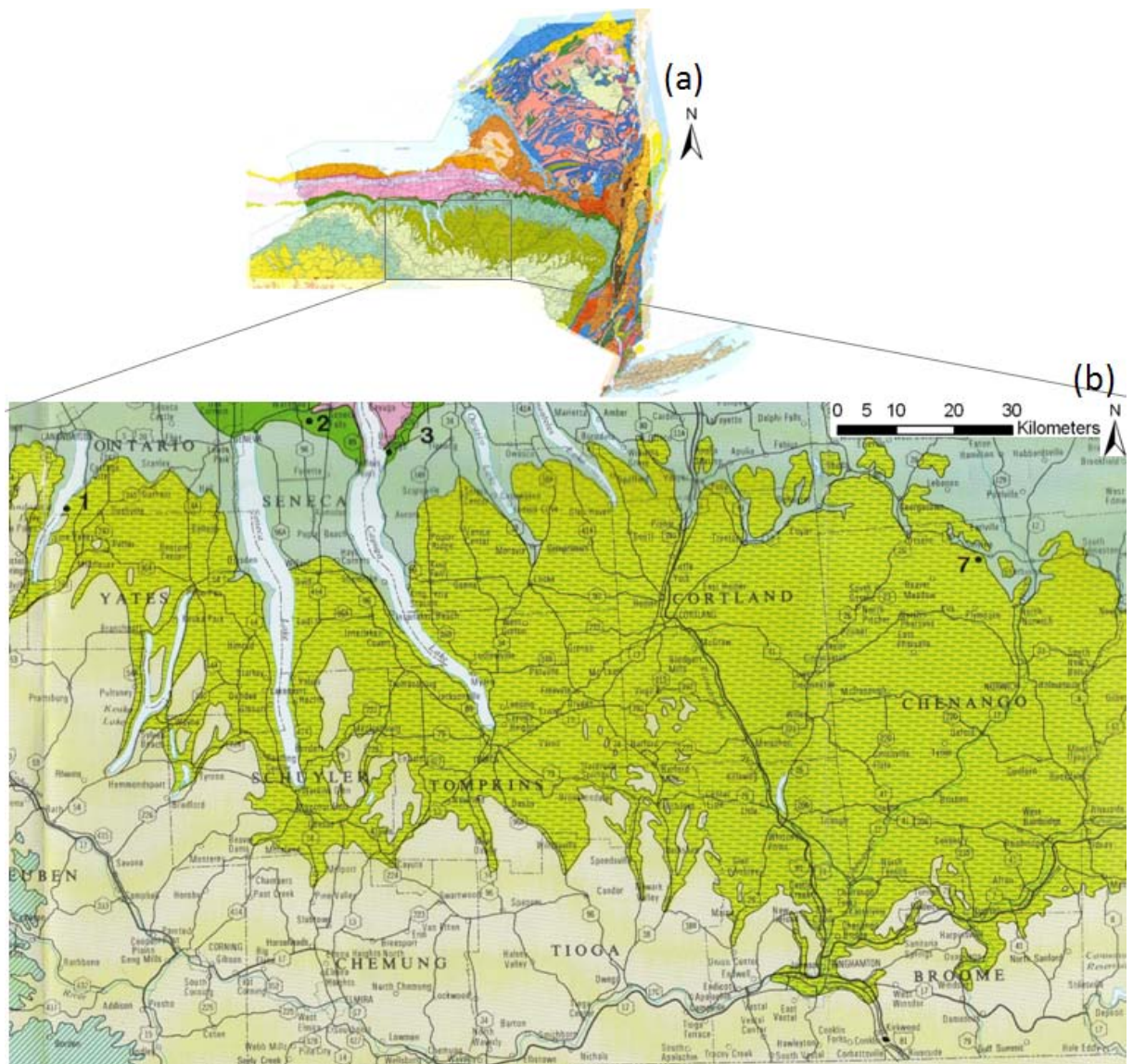


Figure: 2.4 – (a) Geologic map of NYS and (b) Geologic map section of project area (Isachsen et al., 1991)

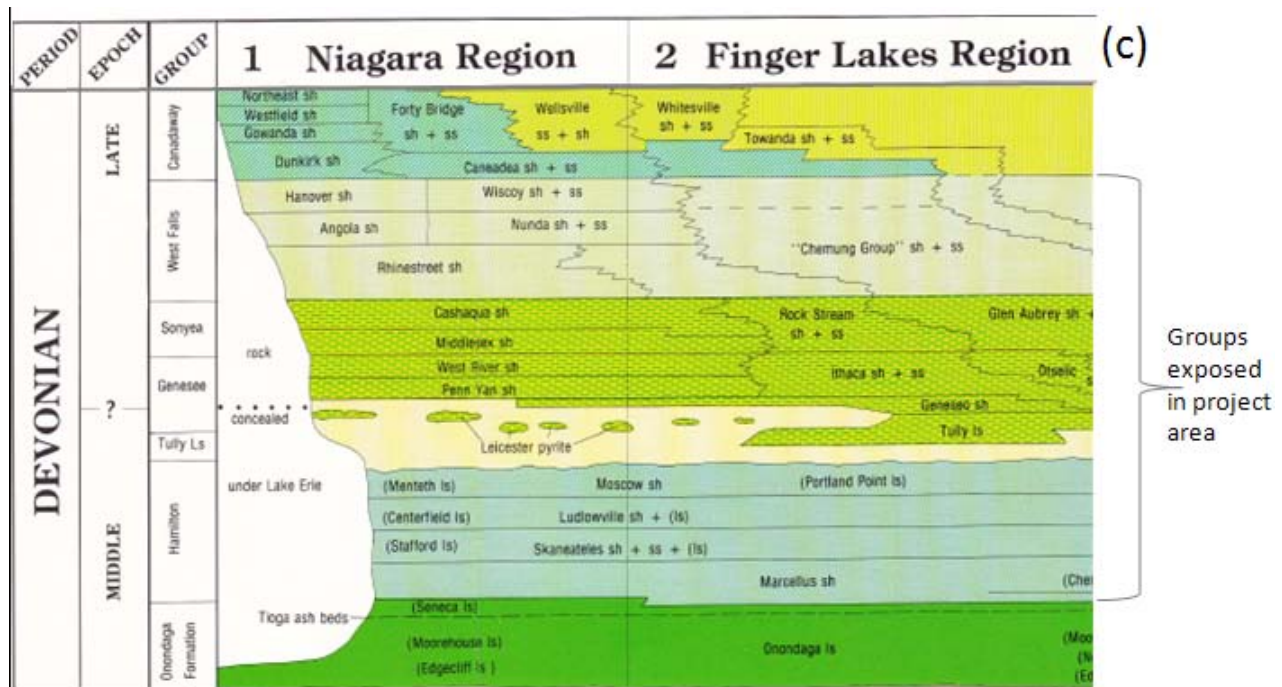


Figure: 2.4 – (c) Geological strata exposed in the project area (Isachsen et al., 1991)

The oldest unit of the sequence in the study area is the Hamilton Group (aqua color in Figure: 2.4), deposited in the Middle Devonian - 390 Ma (e.g. Isachsen et al., 1991; Brett et al., 2007). The depositional environment changed over time from a shelf to deeper basin with tidal flats, offshore bars, and channels representing an underwater part of the “Catskill Delta” (e.g. Isachsen et al., 1991). This unit is mostly shale inter-bedded with sandstone, limestone and includes the now well-known Marcellus shale at the base of the sequence. The overlying sequence is a textured lime green color in Figure: 2.4 and contains the Tully Limestone, Genesee and Sonyea units. This includes the Genesee black shale overlying the Tully limestone at the base (Smith and Jacobi, 2000). These were deposited Middle to Late Devonian in depositional environments varying from oxygen-rich shorelines to anoxic environments (Isachsen et al., 1991). The upper sequence in the project area is the West Falls Group (light-yellow color in Figure: 2.4) and it was deposited in Late Devonian (Isachsen et al., 1991). The depositional

environment varied from non-marine to offshore low oxygen environment, resulting in the formation of sandstones and shales (Isachsen et al., 1991; Smith and Jacobi, 2000).

D. Structural Geology

The structural geology of the Allegheny plateau is complex and pervaded with folds, faults, fractures, fracture intensification domains (FIDs), joints and fault zones. The principal component of stress (σ_1) applied to central NYS during the Alleghanian Orogeny was projected in a northerly (NNW to NNE) direction across the study area, promoting the development of fractures parallel to σ_1 and faults perpendicular to σ_1 (Isachsen et al., 1991). Due to this relationship between σ_1 , fractures, and/or faults, evidence of this correlation was anticipated in the transported layers in the project area (Figure: 2.3). These fractures and faults are possible throughout the section above the décollement.

1. Fractures and Fracture Intensification Domains (FIDs)

Fracture Intensification Domains (FIDs) are typically master fractures that are closely spaced (compared to surrounding) with fracture spacing greater than two fractures per meter and fracture strikes that describe the FID trend (Jacobi, 2002). FIDs are important to lineament studies; Jacobi (2002) identified a relationship between FIDs and lineaments observed in remote sensing data and soil gas anomalies. Lineaments with lengths greater than 0.5 km are commonly related to FIDs and soil gas anomalies are usually less than 50 m wide (Jacobi, 2002).

Engelder and Geiser (1979, 1980) mapped systematic joint sets to compare the orientation and development of joints to the orientation and magnitude of finite strain recorded in Upper Devonian rocks in NYS. The information was gathered from field observation and

mapping. Engelder and Geiser (1980) defined a joint as an extension fracture generally transverse to bedding with no appreciable displacement while a joint set was defined as a group of more than two joints with similar attributes (e.g. orientation). Recorded outcrop observations included vertical and horizontal extents, joint spacing and description of joint filling, surface and degree of weathering. The orientations of the joints were averaged from three to ten measurements. Set I joints were cross-joints that generally strike parallel to the maximum compressive strain and were occasionally filled with calcite. Set II joints strike sub-parallel to regional fold axes. The spacing of the joints was thought to be regular in the sandstones and siltstones and less regular in the shales (Figure: 2.5).

Some of the mean fracture strikes observed in the project area for Joint Set 1a and Joint Set 1b were 004° and 337° (West Falls Group), 001° and 342° (Sonyea Group), 005° and 340° (Genesee Group) respectively (Engelder and Geiser, 1980). Overall Joint Set 1a and 1b varied in orientation from east to west in a radial pattern with orientations ranging from 316° to 17° in the project area. Joint Set II varied in orientation from 241° to 112° with an arcuate pattern from east to west (Engelder and Geiser, 1979; 1980). Joint Set III was constantly oriented at 060° in all outcrops. The angular difference between Set III and Set II increased towards the west with the largest difference apparent near the Steuben/Chemung County border. It is difficult to distinguish between Set III and Set II in the eastern section of the study area so eastern fractures with the same orientations were defaulted to Joint Set II.

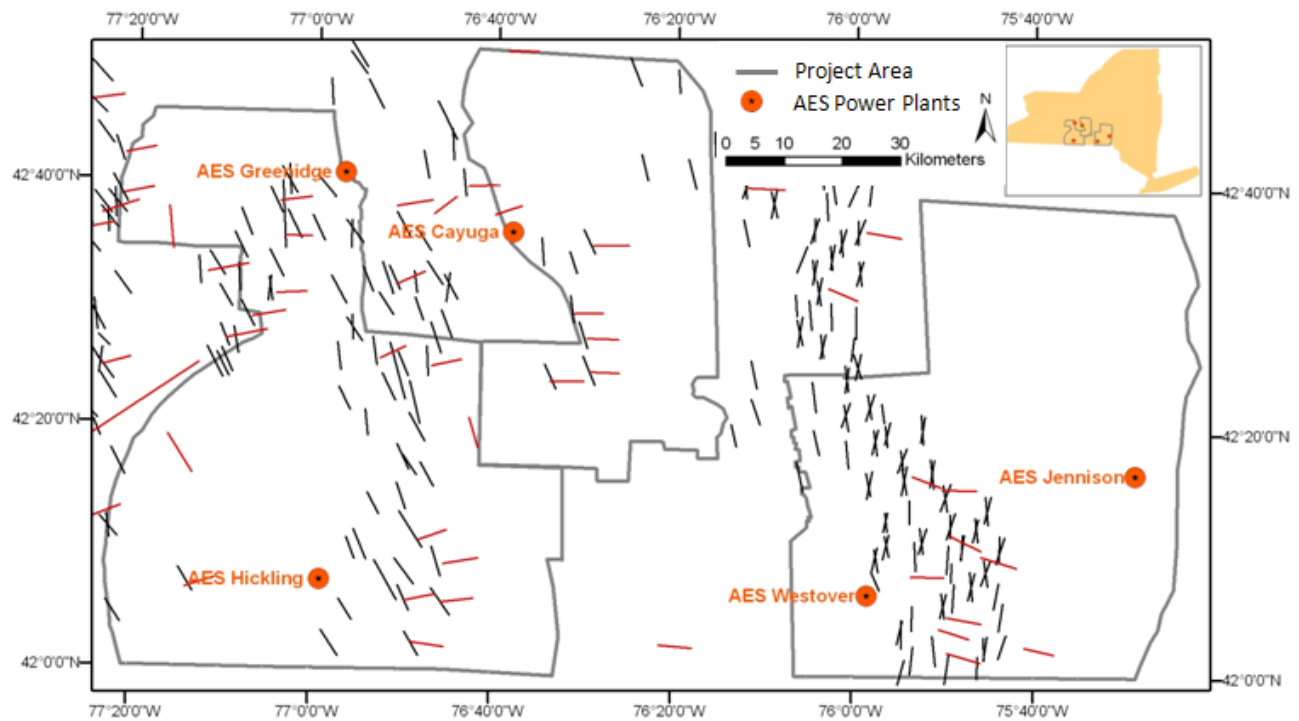


Figure: 2.5 – Set Ia and Ib (black) and Set II (red) joints mapped by Engelder and Geiser (1980)

Terech (2006), McGuire (2007) and Jacobi (2007) mapped fractures in the field and calculated the fracture frequency at each site in (Figure: 2.6); fracture frequency or joint spacing is the distance between two fractures with similar orientations. The following attributes were recorded for all fractures identified in the field by Terech (2006) and Jacobi (2007): the fracture set number, spacing between fractures, strike, dip, dip direction, apparent fracture length, apparent fracture height, lithology of fractured bed, lithology thickness, fracture abutting relationship, and fracture character. McGuire (2007) and Jacobi (2007) recorded the orientation (strike and dip), exposed length and length of the fracture surface, spacing between fractures, bedrock type, and linearity of fractures for each fracture identified in the field. These data were entered into excel and maps were created using ArcMap and Illustrator. Fracture frequencies mapped by Terech (2006) and Jacobi (2007) were greatest in NNE ($20^{\circ} - 29^{\circ}$) and WNW ($290^{\circ} - 299^{\circ}$) orientations and the least in the EW (80° to 89°) and NW ($330^{\circ} - 339^{\circ}$) orientations. The

most abundant fracture orientations for McGuire (2007) and Jacobi (2007) were NNE ($9^{\circ} - 40^{\circ}$), WNW ($282^{\circ} - 304^{\circ}$) and NS ($345^{\circ} - 9^{\circ}$) and the less abundant orientations were NE ($41^{\circ} - 55^{\circ}$), ENE ($56^{\circ} - 84^{\circ}$), and NNW ($323^{\circ} - 344^{\circ}$).

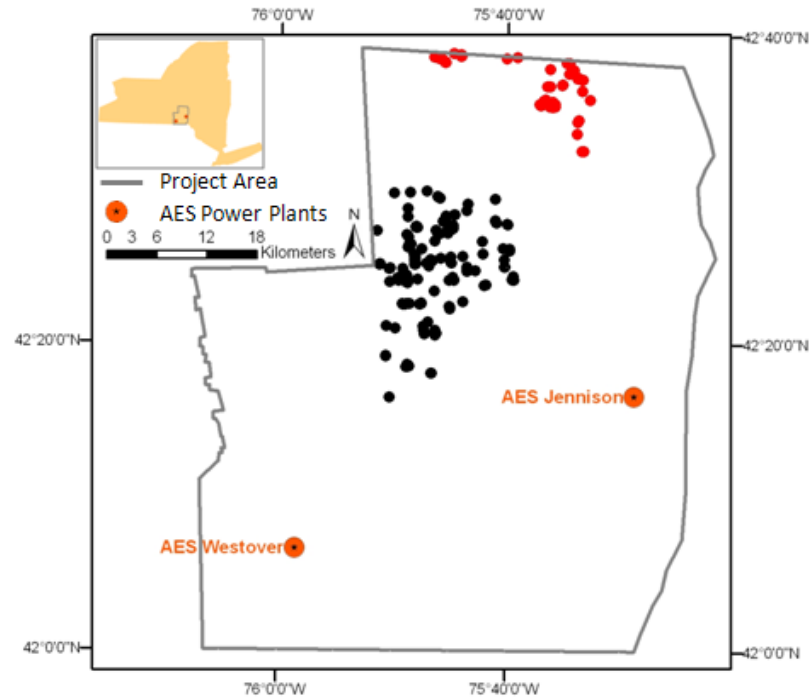


Figure: 2.6 – Terech, (2006) and Jacobi (2007) fracture data (red) and McGuire (2007) and Jacobi (2007) fracture data (black) mapped during field studies

2. Faults and Fault Zones

The complex fault systems of NYS include north-striking fault systems (e.g., the Clarendon-Linden Fault System located east of Buffalo) that are considered to be reactivated Precambrian basement faults. Other fault systems in NYS include reactivated NNE- and NE-striking faults in the eastern part of the study area, NW-striking fault systems throughout the entire study area, and an arcuate fault system that strikes ENE to E-W in the study area (Jacobi, 2002).

Bradley et al. (1941) mapped faults from bedrock exposures at streambeds, road cuts and quarries across Yates and Steuben counties. The faults were nearly vertical normal faults and

high-angle thrust faults with trends of northeast, north-northwest, east-west and north-south (Figure: 2.7). Bradley et al. (1941) also mapped several fault zones that were mainly found along creek outcrops (such as Fall Creek, Slate Creek and Purdy Creek) as faults, micro-faults, and folds in shale units. These zones were interpreted as zones of deformation during deposition and display both brittle and ductile deformation (Figure: 2.7).

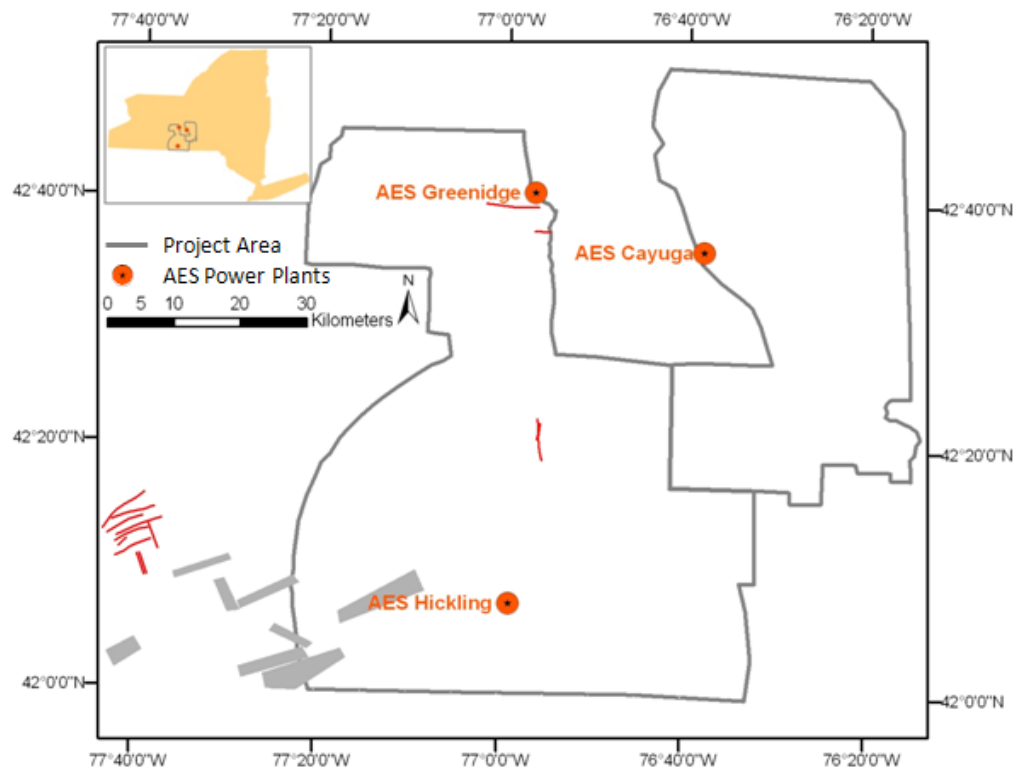


Figure: 2.7 – Faults (red) and fault zones (gray) mapped by mapped by Bradley et al. (1941)

Isachsen and McKendree (1977) transcribed fault information from the 1971 State Geologic Map with additional details added from the general literature (e.g., published theses, maps, reports and field notes from 1971 to 1977). Some details on the map include dip of fault planes, separation, location and width of breccias (Figure: 2.8).

Their methodology can be summarized as follows:

- 1) All faults and prominent topographic features from the 1971 State Geology Map were transcribed and additional information extracted from other map sources;
- 2) General literature such as published theses; maps, reports and field notes were used to complete the maps;
- 3) Landsat Earth Resource Technology Satellite (ERTS) multispectral bands 5 and 7 dated from 1972 to 1974 with 70 to 80 meter resolution were used to identify linear features at a scale of 1:500,000 and 1:250,000.

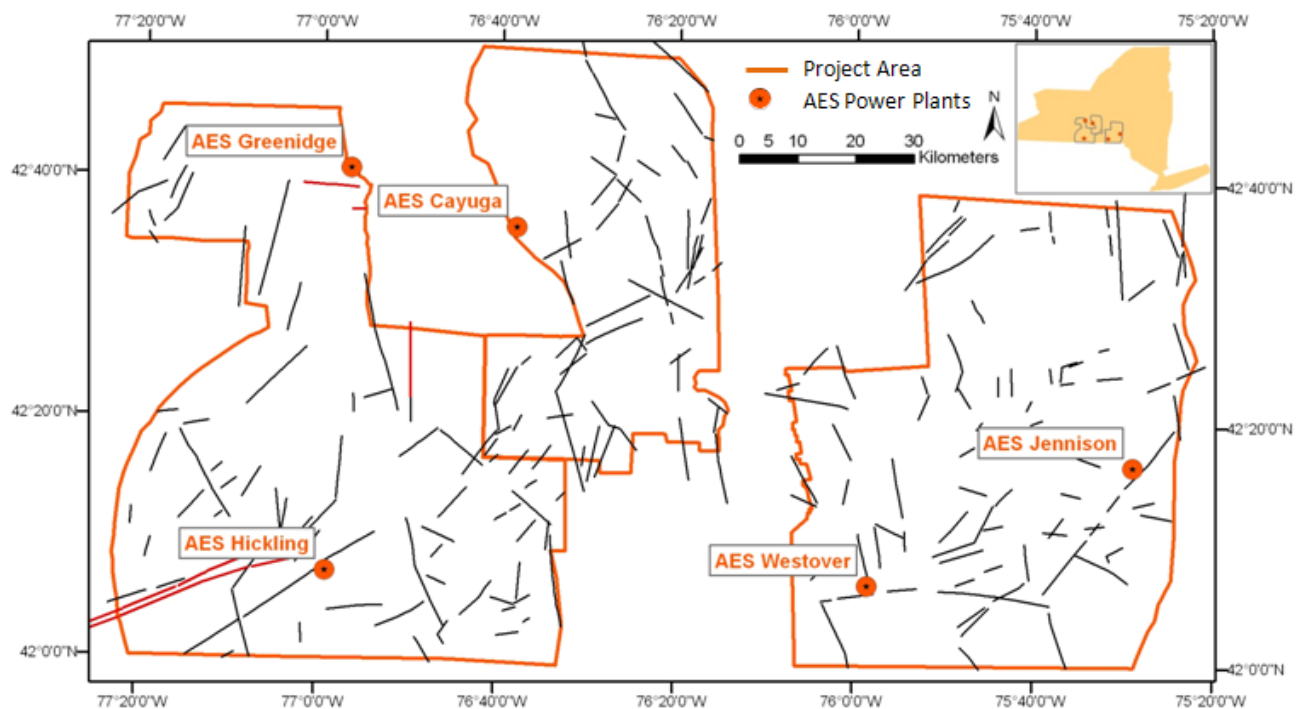


Figure: 2.8 – Linear features (black) and faults (red) mapped from a previous geologic maps and Landsat imagery (Isachsen and McKendree, 1977)

The faults described by Murphy (1981) were derived mainly from well logs and Landsat lineaments as part of the National Waste Terminal Storage Program (Figure: 2.9). Abrupt changes in unit thicknesses and depth from one well to the next indicated strike-slip faults. Thrust faults were indicated in well logs with over-thickening and repetition of horizons in a formation.

Murphy (1981) suggested the occurrence of two right-lateral strike slip fault zones, one extending from Himrod, NY toward Pennsylvania along the western shore of Seneca Lake (Figure: 2.9). The second fault was an echelon right-lateral strike-slip tear fault of the Cayuga Creek Valley that extended from west of Ithaca southward toward Pennsylvania (Figure: 2.9). This study also identified a 25 km long normal fault with some right-lateral strike-slip movement near the arm of Keuka Lake.

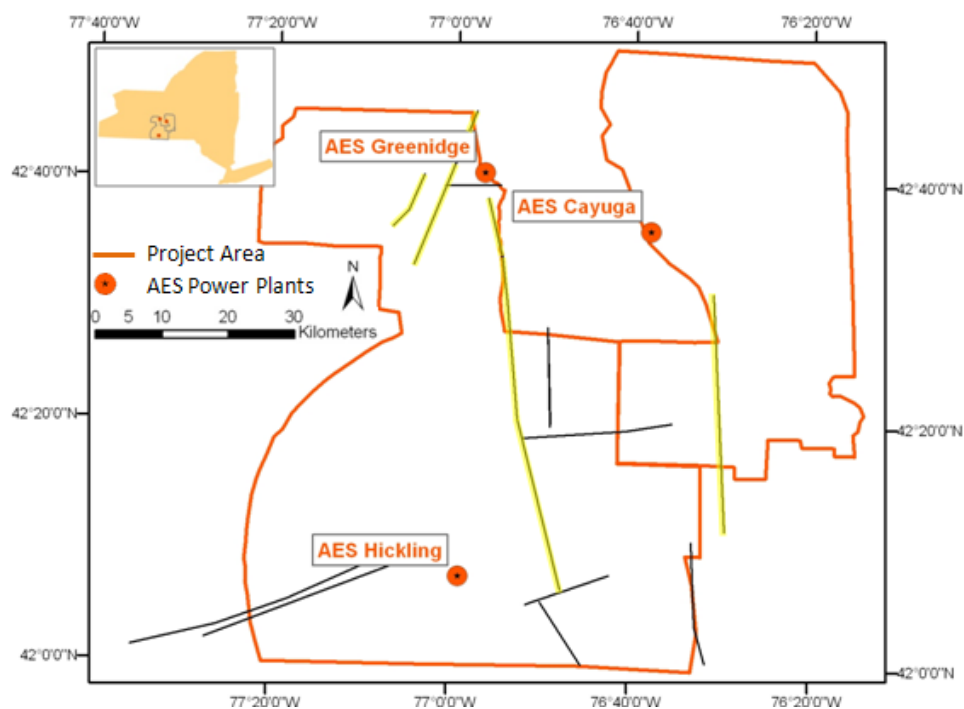


Figure: 2.9 –Map of south-central NY with mapped faults, faults highlighted are mentioned in text (Murphy, 1981)

Jacobi (2002) utilized the EarthSat (1997) lineaments to identify fault zones or lineament bundles (Figure: 2.10). These lineament bundles were identified based on density of lineaments and the continuous nature of lineaments. These bundles showed a spatial relationship to Fracture Intensification Domains (FIDs) identified by Jacobi (2002) in the field.

The faults described by Jacobi and Fountain (2007) were mapped as part of a Department of Energy (DOE) and New York State Energy Research and Development Authority (NYSERDA) project to gain a better understanding of the Ordovician Trenton/Black River and its natural gas potential in the Appalachian Basin of NYS. Jacobi and Fountain (2007) combined traditional and innovative techniques to determine fault locations. They utilized multiple datasets that included detailed fracture analyses of soil gas, seismic reflection, outcrop stratigraphy, well logs, and aeromagnetic and gravity anomalies. The main fault trends identified by Jacobi and Fountain (2007) were ENE and NE, as detected by lineaments, veins and release bend features in veins, soil gas, 2D seismic reflection, and fracture analyses (Figure: 2.10 and 2.11). These faults are considered reactivated basement faults.

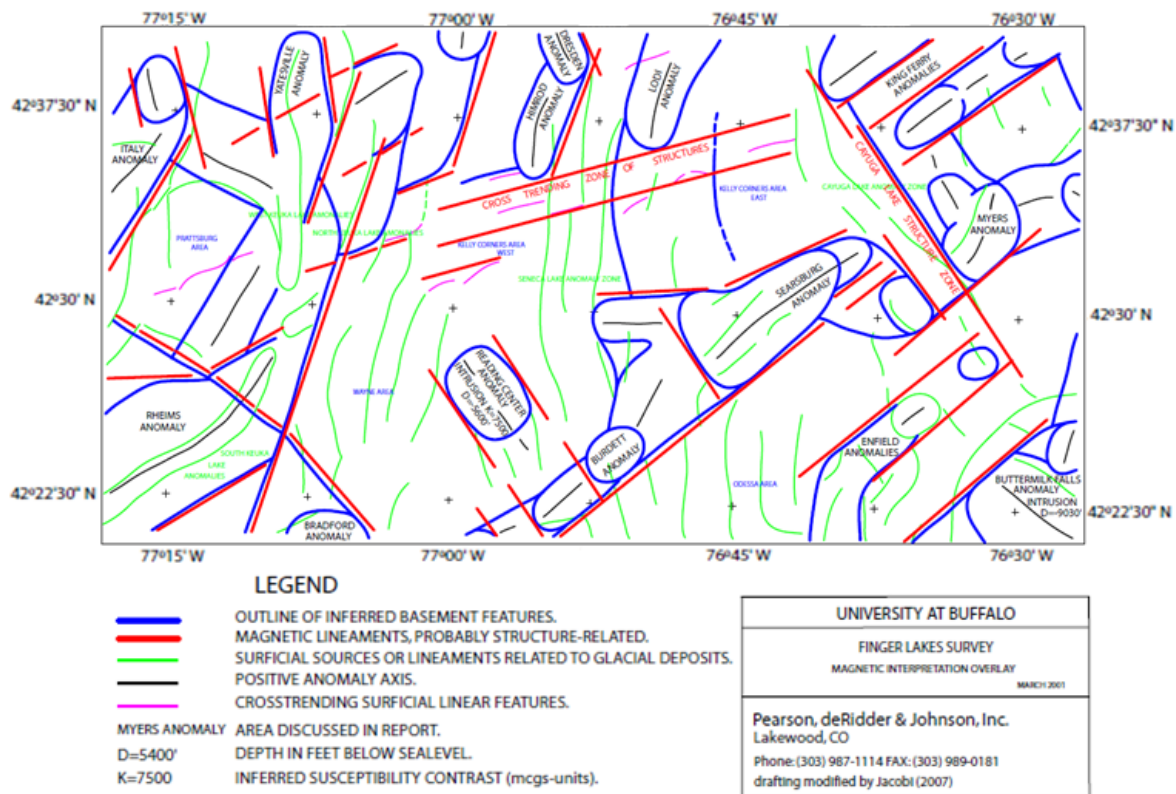


Figure: 2.10 – Inferred basement features mapped by Jacobi and Fountain (2007)

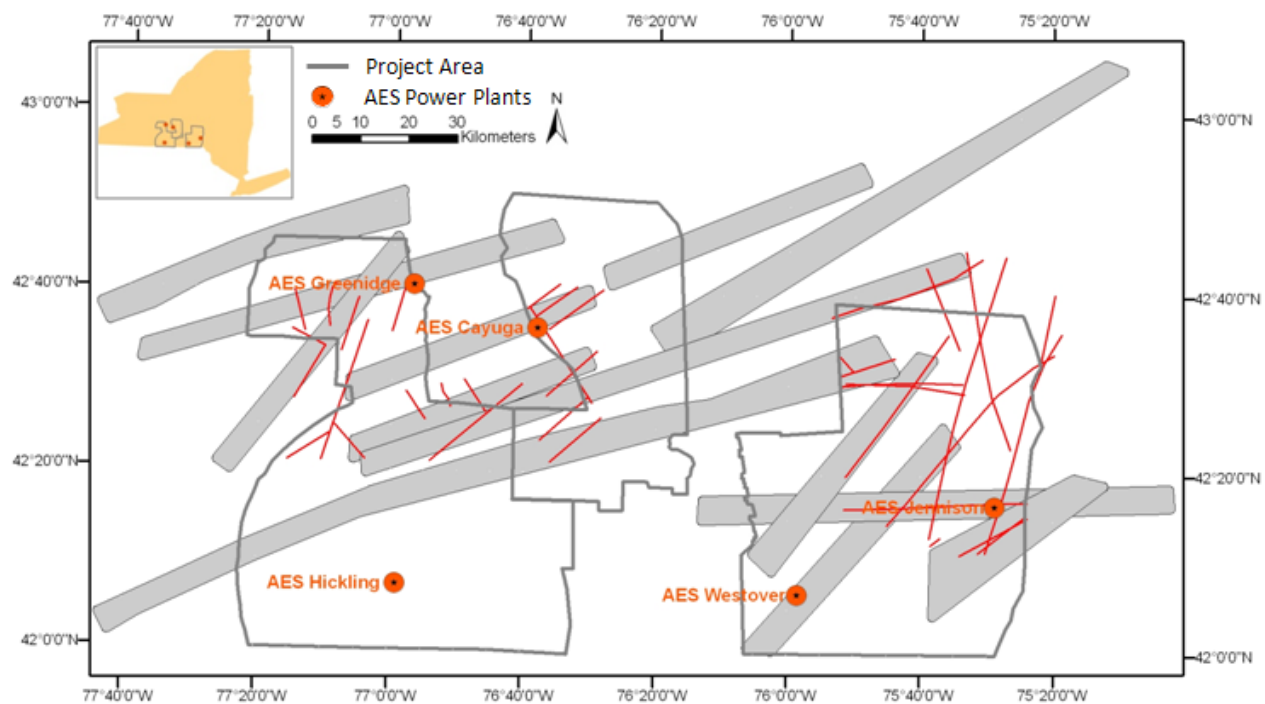


Figure: 2.11 – Map of inferred basement faults (in red) and fault zones (in gray) identified from EarthSat (1997) lineaments (Jacobi, 2002)

E. *Lineament Mapping*

Lineaments are surface expressions of structural features on the surface as geomorphological features. The lineaments digitized in this project can be related to structural geology of the region (Cruz et al., 2005; Everett et al., 2003). According to Jacobi (2002) faults that were previously overlooked due to their subtle properties can be detected and mapped by identifying and groundtruthing lineaments. Lineaments longer than 0.5 km regularly relate to fracture intensification domains (FIDs) and shorter lineaments around 100 m are found to be parallel to fractures (Jacobi et al., 2002).

Some lineament identification and digitizing projects in NYS include Isachsen and McKendree (1977), Everett et al., (2003) and Cruz et al., (2005). Previously identified lineament trends in NYS include NS (related to reactivated Precambrian basement trends), NW (western

NYS), NW and NS (central NYS), and an arcuate NE (western NYS) to E-striking (central and eastern NYS) (Jacobi, 2002 and 2010).

1. Isachsen and McKendree (1977)

Linear features were mapped by Isachsen and McKendree (1977) using multiple sources to compile and create the preliminary brittle structure map of New York State (Figure: 2.8). Lineaments were defined and identified as “any relatively sharp, straight, alignment of drainage, topography, or tonal contrast which may be of natural origin” (Isachsen and McKendree, 1977).

2. EarthSat Project (Everett et al., 2003)

The 1997 EarthSat project created digital interpretive and analytical geologic tools for fracture analysis to assess the fractured reservoir for hydrocarbon production in NYS (Everett et al., 2003). Ten Landsat Thematic Mapper (TM) images acquired from 1984 to 1986 were mosaicked to cover most of NYS and displayed with band combination R(7) G(4) B(2). The mosaic was divided into four image maps at a scale of 1:250,000. Lineaments were digitized on these four images by mapping lithologic boundaries, structure and unusual or anomalous vegetation patterns. The Landsat mosaic was also used to digitize regional tectonic features such as basins, basin boundaries, uplifts, and major fault/fracture zones at a scale of 1:500,000 (Figure: 2.12). The mean lineament trend of the 2869 lineaments in the Finger Lakes region was 60°.

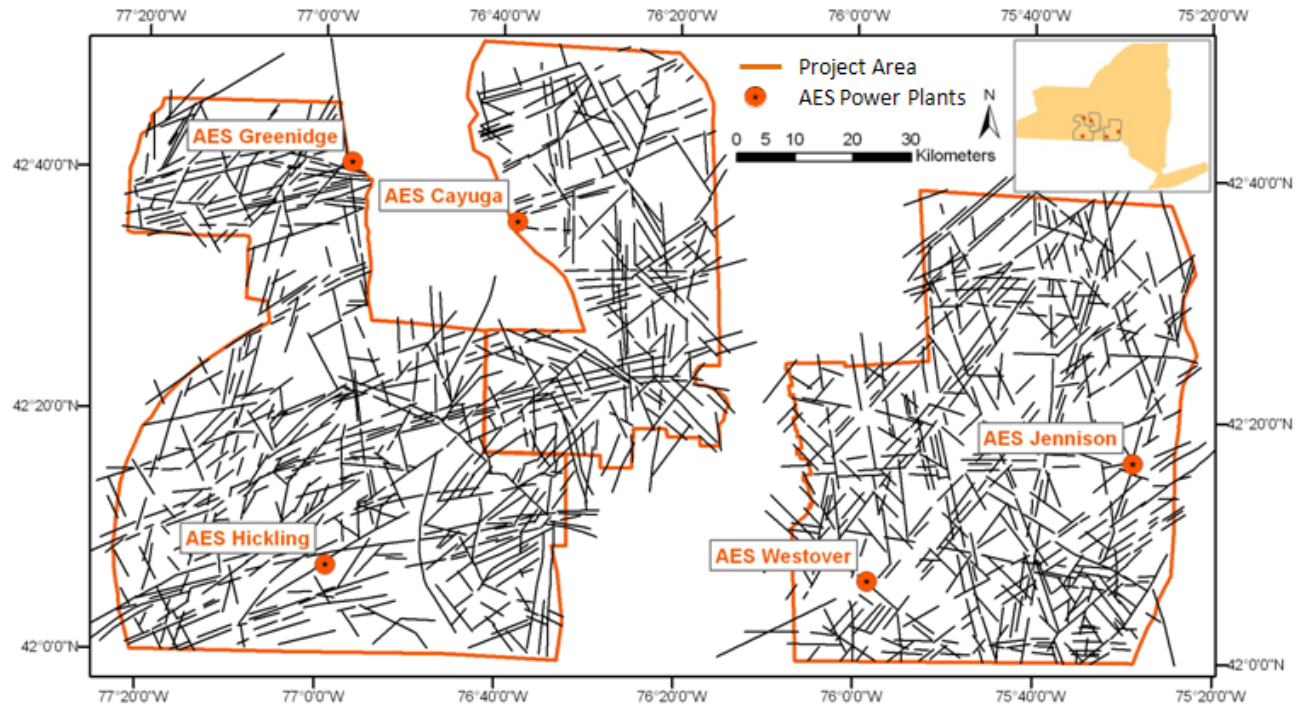


Figure: 2.12 – Lineaments mapped from Landsat TM imagery, for project area from Finger Lakes map sheet (Everett et al., 2003)

3. Cruz (2005)

The objective of Cruz (2005) was to investigate the performance of optimal image enhancements for lineament mapping. Cruz (2005) applied a Principal Component Analysis for fusing Landsat and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite imagery to enhance linear features. Cruz (2005) found the fused ASTER/Landsat composite optimal for identifying lineaments that relate to strike parallel fractures (ENE trending and EW trending) and PC ASTER image optimal for identifying lineaments related to cross strike fractures (NW trending and NNW trending). Lineaments were identified at various scales that include 1:200,000, 1:50,000 and 1:25,000; these lineaments were then merged into a single file (Figure: 2.13). The study area in Cruz (2005) was located primarily in the region between Cayuga and Seneca Lakes - mostly outside the project area - but a slight overlap allowed for some comparison of lineaments.

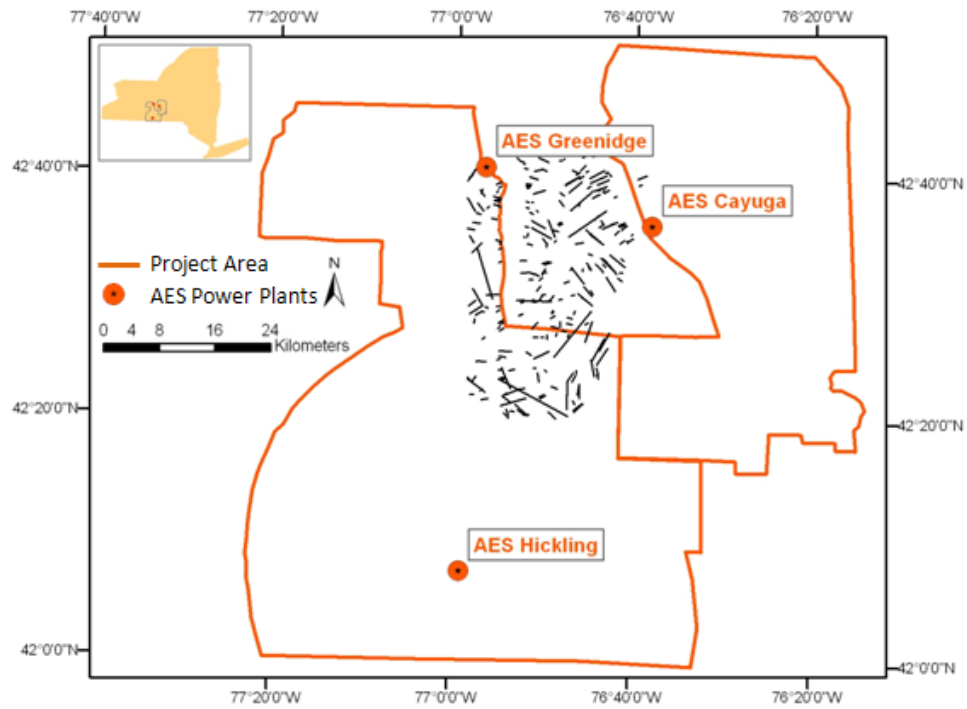


Figure: 2.13 – Lineaments mapped from ASTER PCA as a color composite R(PC2), G(PC1), B(PC4) (Cruz, 2005)

Chapter 3 – Data

Most of the data used in this project were acquired using remote sensing tools. The main data sets were Landsat and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite images, and Digital Elevation Models (DEM) obtained from USGS and National Aeronautics and Space Administration (NASA) websites. Auxiliary data sets used as GIS layers include streams, roads, railroads, and digitized drumlin outlines.

A. Landsat Imagery

Landsat images are easily accessible and frequently used for lineament identification (e.g., Rahiman and Pettinga, 2008). Landsat Enhanced Thematic Mapper Plus (ETM+) imagery is obtained from a sensor that orbits the Earth at a height of 705 km on a Sun-synchronous orbit (Jensen, 2005). This aids in identifying structural features because a specific location on an image will have the same sun illumination angle on multiple images over time. Moreover, Sun-synchronous satellites pass over any given latitude at almost the same local time during each orbital pass, resulting in roughly the same illumination angle at neighboring images, making them ideal for generating image mosaics. Landsat ETM+ multispectral imagery consists of six 28.5 meter resolution spectral bands in the Visible and Near Infrared (VNIR) and Shortwave Infrared (SWIR) domains (wavelengths: 0.45 μ m to 2.35 μ m) as well as one 15 meter resolution panchromatic visible band and one thermal band (Jensen, 2005). The size of a Landsat scene is 185 km by 185 km, covering 31,450 km². Because the multispectral visible bands of Landsat imagery have lower spatial resolution than that of the ASTER (28.5 m vs. 15 m), Landsat data were only used in the experimental stages (Phase I) for Grid 1, which is a small 225 km² area around the AES Cayuga power plant (Figure: 1.4).

Landsat images were obtained free of charge from the Earth Resources Observation and Science (EROS) Center of USGS by using the Global Visualization viewer (<http://glovis.usgs.gov/>). The images captured by the Landsat sensors are identified with their path (longitudinal) and row (latitudinal) designations in a Worldwide Reference System (WRS). Four Landsat scenes were needed to cover the project area with the following paths: 15 & 16, and rows: 30 & 31 (Figure: 3.1).

Every 16 days the Landsat satellite passes over the same location on the Earth resulting in a temporal resolution of 16 days. Various acquisition times throughout the seasons provide images with different snow cover, tree canopy coverage and soil moisture content providing a robust and diversified dataset for lineament identification.

Image selection was based on the following criteria:

- (1) time of year, preferably leaf-off canopy conditions and no snow in early spring or late fall;
- (2) cloud cover (less than 30%);
- (3) the ability to use the image as part of a mosaic (the availability of other cloud-free images, preferably from the same year/season).

Based on the above criteria a total of 12 Landsat 7 ETM+ images were selected with dates of April 28th 2001, June 15th 2001 and October 16th 1999 and covered Grid 1. The images for the final mosaic were dated April 19th 2001 and April 28th 2001 and covered the project area. The georeferenced Landsat images were downloaded in GeoTIFF image format.

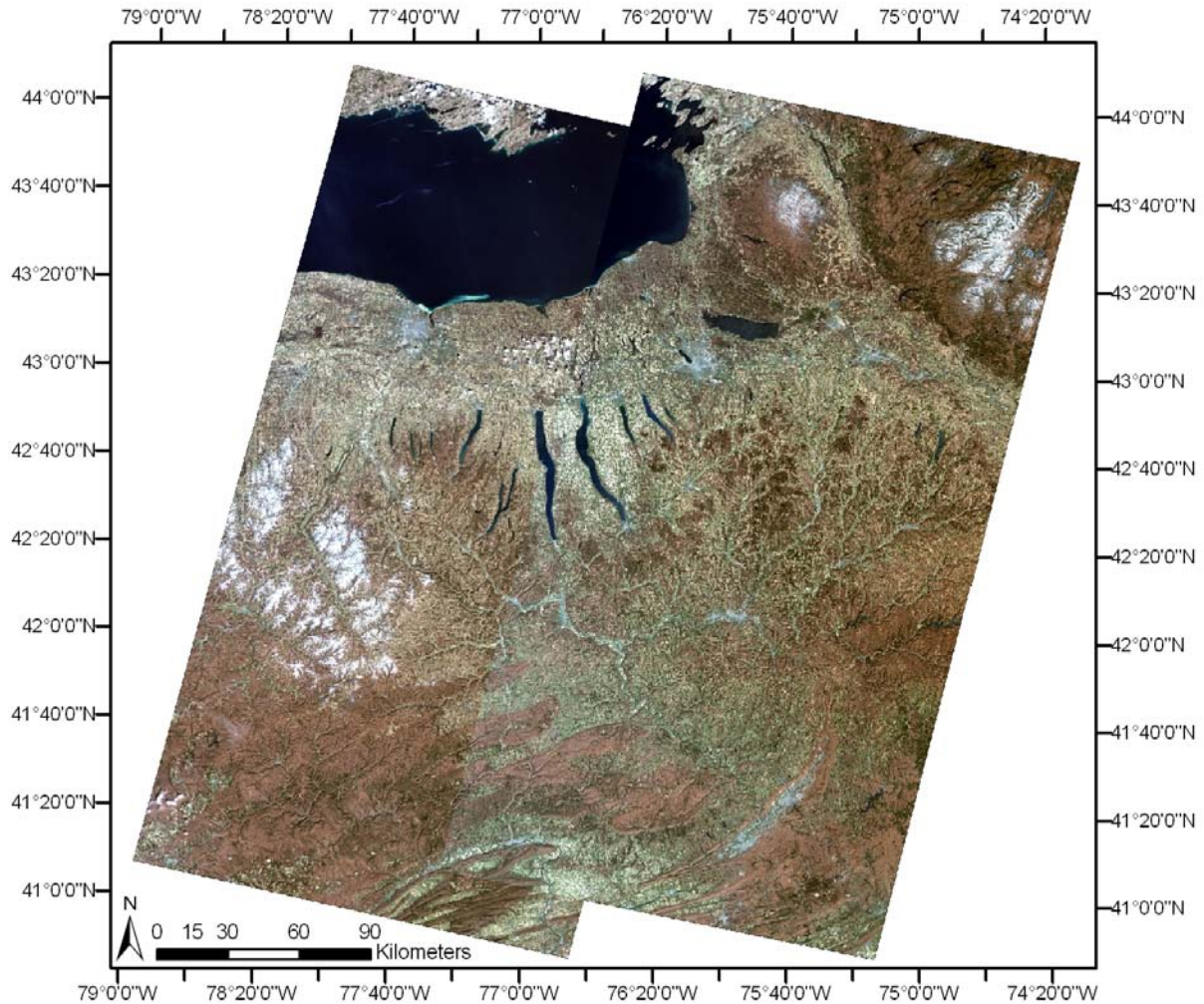


Figure: 3.1 – Landsat imagery – true-color composite R(3) B(2) G(1) covering the project area with four scenes (see section 4.A.1 for details on Landsat image processing)

B. ASTER Imagery

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery is a rich source of geologic information because of its good spectral resolution in the short-wave infrared domain (Jensen, 2005). The ASTER mission started in 2000; its sensor captures high spatial resolution images with a scene size of 60 km by 60 km and 14 spectral bands, ranging from visible to thermal wavelengths (Jensen, 2005). The temporal resolution of the ASTER

images is 16 days with a sun-synchronous polar orbit. Images obtained by the Visible and Near-Infrared Radiometer (VNIR) and Shortwave Infrared Radiometer (SWIR) in band-1 to band-9 with wavelengths ranging from 0.52 μm to 2.430 μm were used for this study. The VNIR bands have a resolution of 15 m and the SWIR bands have a resolution of 30 m.

All ASTER Images were obtained from NASA's Earth Observing System (EOS) Clearinghouse (ECHO) Warehouse Inventory Search Tool (WIST) website (<http://wist.echo.nasa.gov>). Eleven ASTER images were required to cover the project area; these images were selected to provide seamless transitions and proved suitable for a mosaic (Figure: 3.2).

Image selection was based on the same criteria as for Landsat imagery:

- (1) time of year, preferably leaf-off canopy conditions in early spring or late fall;
- (2) cloud cover (less than 30%);
- (3) the ability to use the image as part of a mosaic (the availability of other cloud-free images, preferably from the same year/season).

Based on the criteria above, 11 September images from a four-year time period were selected. These images, used for the final mosaic shown in Figure 3.2, were dated September 3rd 2001, September 6th 2002, September 20th 2004, September 5th 2005 and September 14th 2005. Downloaded images were Level L1A and were processed as validated images plus radiometric and geometric coefficients. All ASTER images were downloaded in Hierarchical Data Format (HDF) image format.

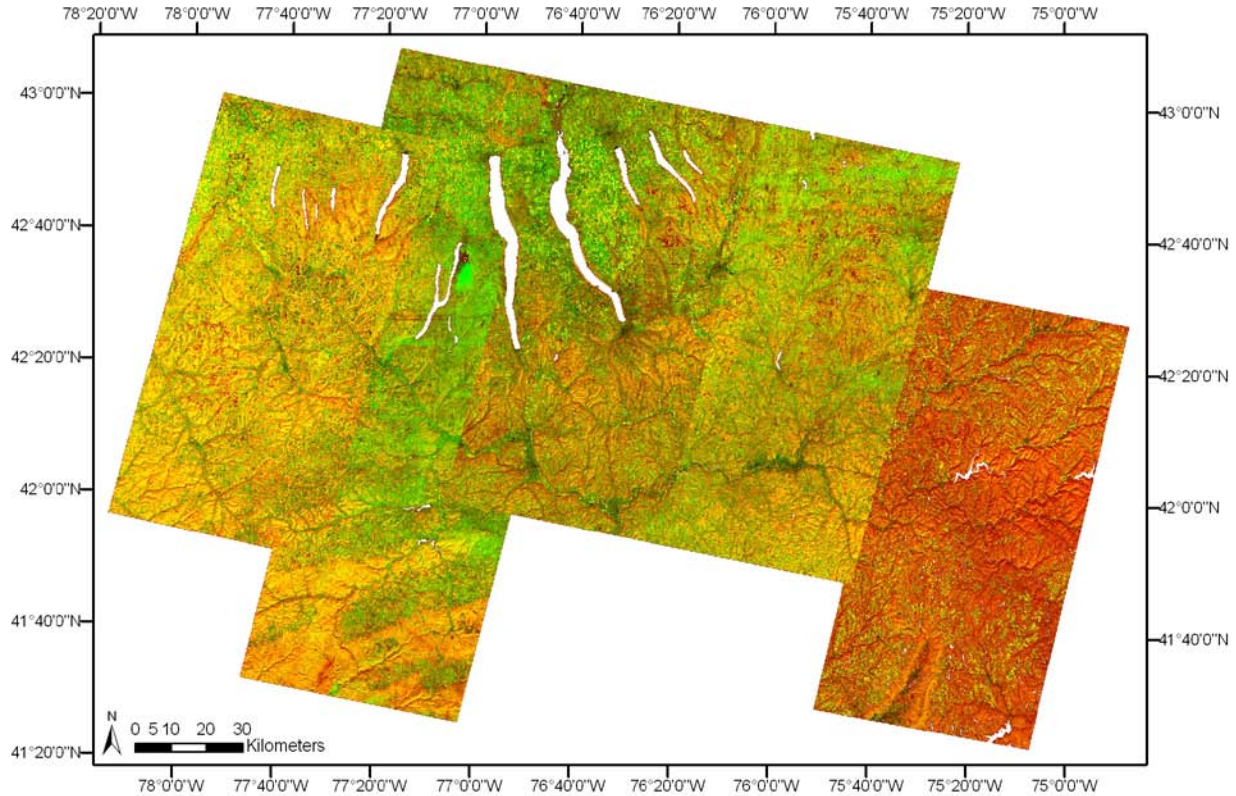


Figure: 3.2 – Principal component composite of 11 ASTER images mosaicked to cover the project area and displayed with PC composite bands R(PC2), G(PC3N), (see section 4.A.2 for details on ASTER image processing)

C. Digital Elevation Model

A Digital Elevation Model (DEM) is a representation of the surface topography sampled in a regular grid. Bare-earth DEMs represent the Earth's surface after removing man-made objects and vegetation; therefore, they are especially useful for identifying geomorphological features and mapping topographic lineaments. USGS's National Elevation Data set (NED) contains bare-earth DEMs at three resolutions- 1 arc-second (~30 m), 1/3 arc-second (~10 m) and 1/9 arc-second (~3 m). The NED layers are derived from a variety of data sources including cartographic, photogrammetric, and Light Detection And Ranging (LIDAR). The DEM for this

project's focus area was available at a resolution of 10 m or 1/3 arc-second from the U.S Geological Survey's National Map Seamless Server website (<http://seamless.usgs.gov/>).

The bounding coordinates of the selected DEM are North: 42°58'56.33", South: 41°57'28.44", West: 77°44'39.00", and East: 75°17'7.25". The DEM was downloaded in six Tagged Image File Format (Tiff) (Figure: 3.3).

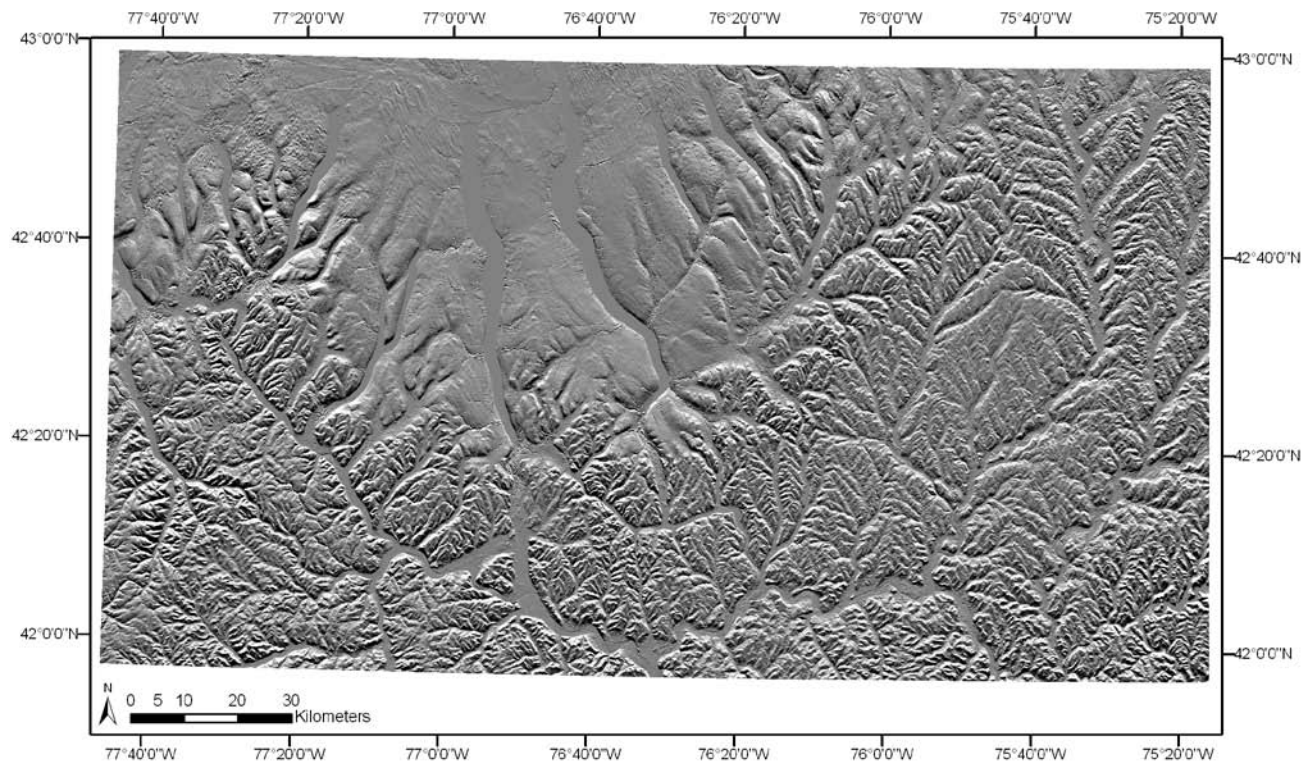


Figure: 3.3 – Shaded relief DEM from six, 10 meter resolution DEM tiles; sun angle/elevation is 25° and sun azimuth is 0°

D. Auxiliary Data

Other datasets were used to aid in visual interpretation, lineament identification, and digitizing. Most of the data were available from Cornell University Geospatial Information Repository (CUGIR - <http://cugir.mannlib.cornell.edu/mapbrowse.jsp?series=counties>). Each dataset was downloaded for each of the eight counties listed below from the 2000 census. The counties include Yates, Steuben, Schuyler, Chemung, Cayuga, Tompkins, Chenango, and

Broome (Figures: 3.4 – 3.6). The digitized drumlins were obtained directly from Dr. Dale Hess (Hess, 2009). The drumlins were manually digitized from a DEM producing two datasets. The first digitized polygons are along the outline of the drumlin (Figure: 3.7) and the second digitized lines are along the longest axis of the drumlin (Hess, 2009).

The GIS vector layers depicting roads, railroads, and streams were downloaded from the Cornell University Geospatial Information Repository (CUGIR) website (www.cugir.mannlib.cornell.edu).

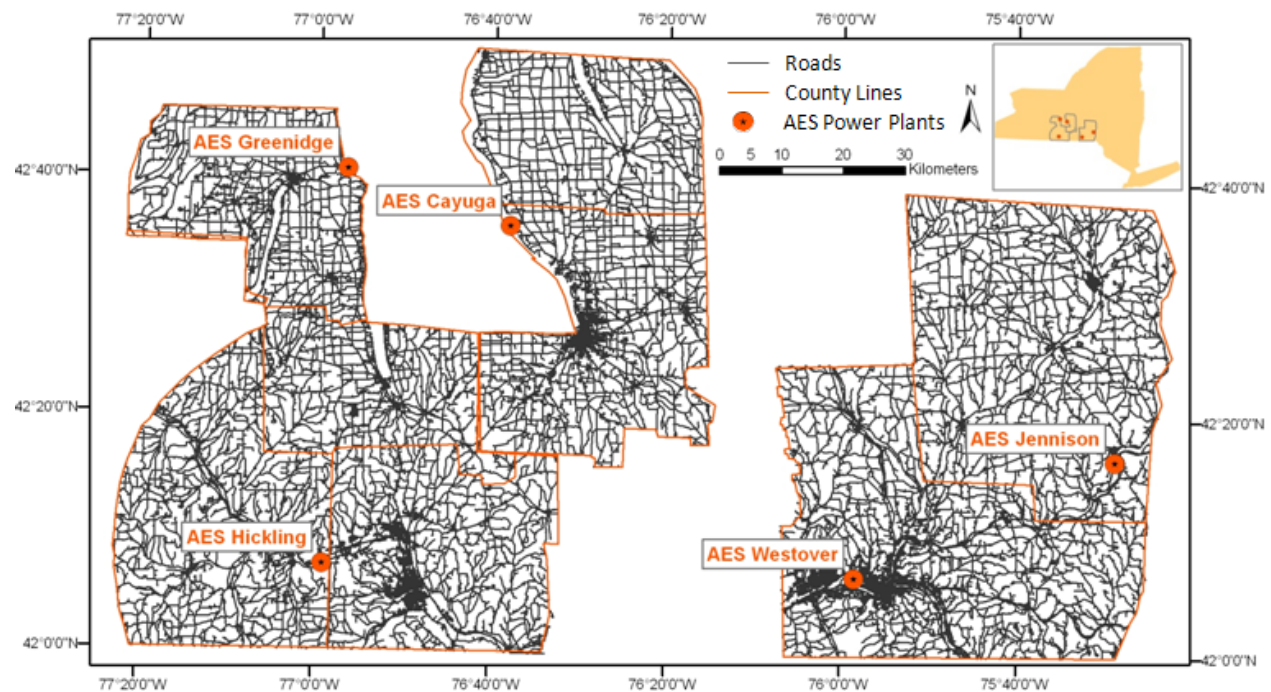


Figure: 3.4 – Roads within the project area (major roads only)

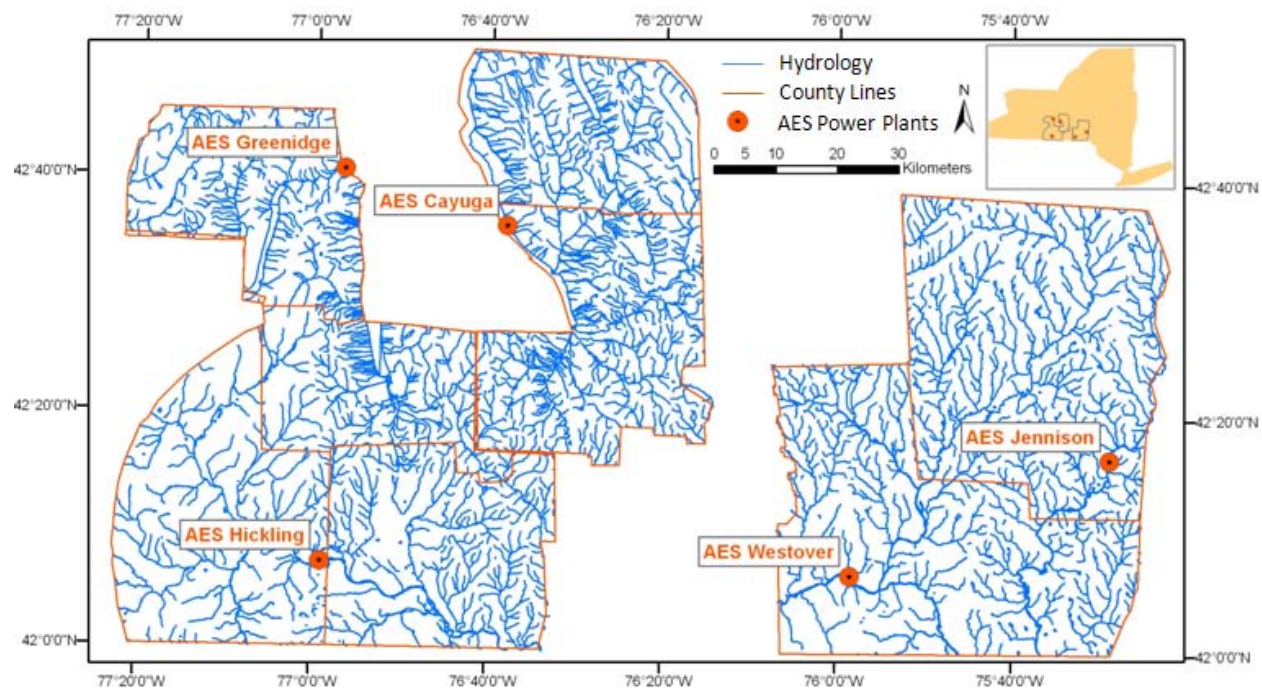


Figure: 3.5 – Hydrologic features, such as rivers and streams, within the project area

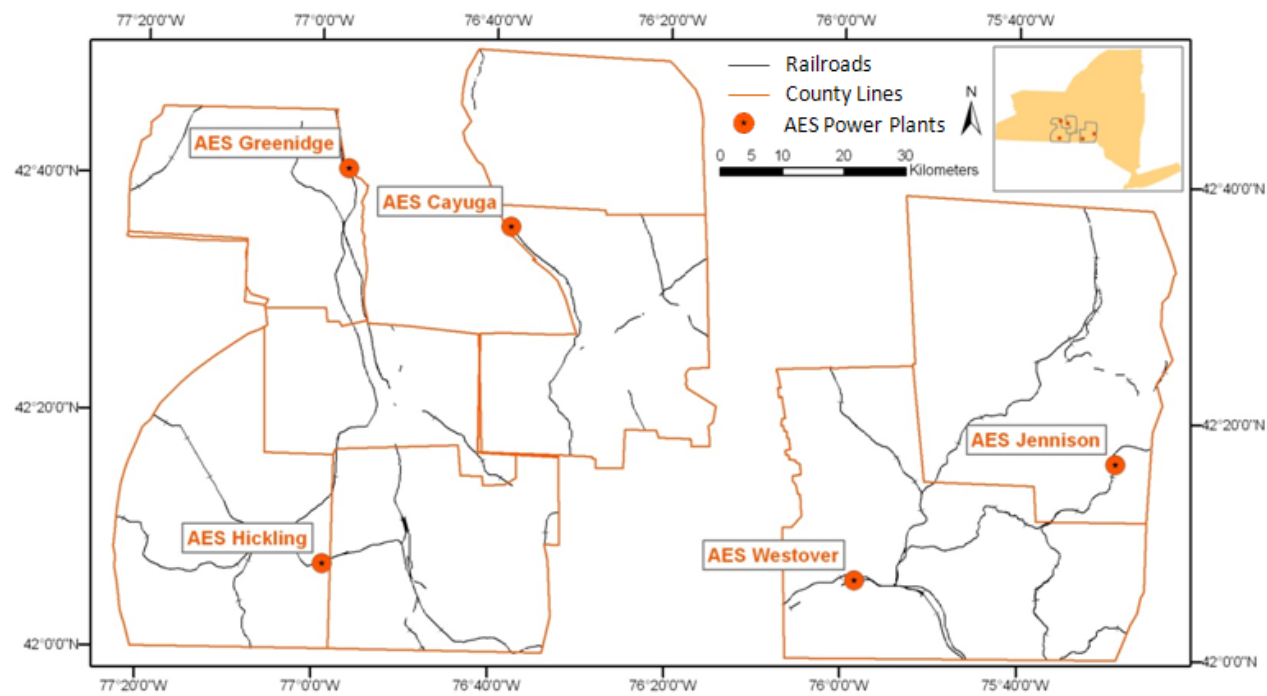


Figure: 3.6 – Railroad tracks within the project area

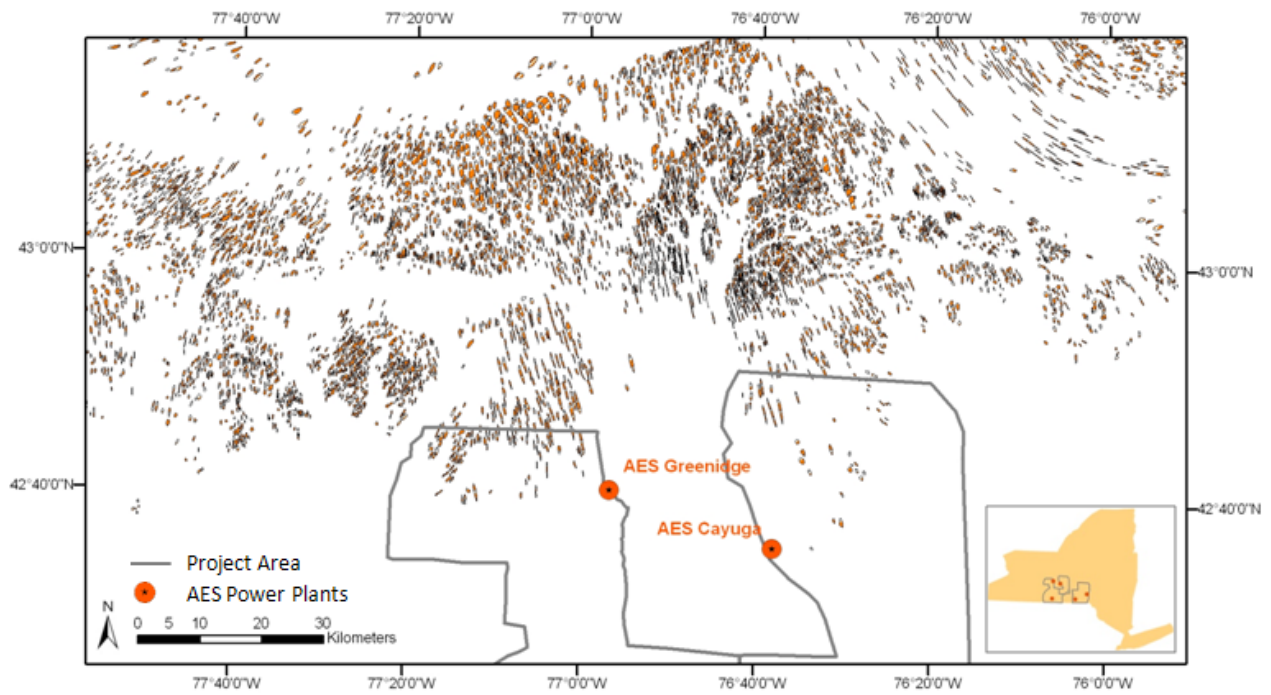


Figure: 3.7 – Drumlins in western NYS, digitized from a DEM by Hess (2009)

Chapter 4 – Methodology

This project was accomplished by completing the methodology outlined in Figure: 4.1.



Figure: 4.1 – Steps used to complete project

Remote Sensing Background

Remote sensing is obtaining reliable information and observations about physical objects and environments without actually being in direct contact. In this study we used satellite imagery and DEMs from non-contact sensors to map lineaments (Jensen, 2000). Lineaments are rectilinear or slightly curvilinear mappable surface linear features that differ distinctly from the patterns of adjacent features and presumably reflects a subsurface phenomenon (O'Leary et al., 1976). According to Rahiman and Pettinga (2008), the subsurface of the Earth can be investigated using lineaments as evidence for tectonic fractures in the bedrock which are emphasized on the surface by geomorphological features such as topography, drainage, and vegetation.

Remote sensing provides synoptic coverage with spatial, temporal and spectral data, allowing lineament mapping over large areas (Jensen, 2007). Lineaments are mapped from images by detecting changes in the surface reflectivity due to changes in vegetation coverage and topography. The satellite imagery used in this project includes Landsat Enhanced Thematic Mapper Plus (ETM+) and Advanced Spaceborne Thermal Emission and Reflection Radiometer

(ASTER) imagery (Jensen, 2005; Abrams, 2000). DEM shaded relief representations are used for identifying lineaments that can be interpreted as topographic expressions. The use of remote sensing identifies lineaments that can be related to geological features such as faults and fractures in areas lacking sufficient outcrops (e.g., Rahiman and Pettinga, 2008).

Image processing techniques based on spectral and spatial variation of reflectivity and topography enhance differences in moisture content, vegetation health, topographic changes and overall tonal patterns, providing improved detection of lineaments. A commonly used technique for lineament mapping is band combinations, where various combinations of image bands are selected as RGB channels for color display. Principle component analysis is also commonly used, which is a statistical digital image processing technique used to reduce the redundancy of multispectral remote sensing images (Lillesand et al., 2004). A shaded-relief representation of Digital Elevation Models (DEM) enhances the expression of lineaments for identification and digitizing by creating shadows based on the direction of artificial sun illumination. Throughout this work, I will use “R(x)” for the red channel, “G(x)” for the green channel, “B(x)” for the blue channel of color composite images and “x” for band numbers.

A. Image Processing and Enhancement

Digital image processing is the manipulation of images using a series of procedures to improve their appearance for visual analysis and interpretation (Jensen, 2005; Lillesand et al., 2004). I applied different image processing methods for enhancing the appearance of linear features by emphasizing tonal, topographic and textural changes. For example, I used a false-color composite display of different band and principal component combinations of ASTER and Landsat imagery (see Appendix II for a list of color composite images generated as part of this

study) and shaded-relief representations of the DEM with different illumination angles to make the identification of lineaments easier and more robust. Image mosaicking is used to combine multiple scenes to produce a single image file. Color balancing was used to minimize the brightness and contrast differences between the different scenes; the master scene was selected interactively based on the image with the most balanced color (not too dark or light). The positioning of images and the selection of the image used for the mosaic in regions where several images overlapped were done interactively; this relied heavily on cloud cover and overall image quality. All image processing was performed using ENVI 4.5 software (ITT Visual Image Solutions).

1. Landsat Imagery

The preprocessing and processing steps of Landsat images included layer stacking, cropping, georeferenced mosaicking, band combinations and principal components (PC) transformation. The layer-stacking tool combines the VNIR, SWIR, and LWIR bands into a new multiband file which enables the manipulations of all bands simultaneously. The cropping tool was used to remove artifacts along the edges of the images. The four images, covering the focus area, were combined into a seamless mosaic by utilizing the georeferenced mosaicking tool.

Color composite images were created from different band combinations. The false color composite that combines one visible (VIS), one near-infrared (NIR) and one short-wave infrared (SWIR) band (R(7), G(4), and B(2)) usually shows a large color variation for different surface materials and is therefore frequently used for geologic interpretation (Figure: 4.2). This composite shows the vegetation in green color, due to the high reflectance of vegetation in NIR, and detects differences in vegetation and moisture content (Jensen, 2005). The true or natural color composite of R(3), G(2), B(1) shows the image in its natural state as if the viewer were on

the satellite platform (Figures: 1.2, 3.1, 4.3). Band combination R(4), G(5), B(3) enhances the water-land boundaries within the image (Jensen, 2005). The combination of R(5), G(3), B(4) was found to highlight drainage patterns (e.g. Fernandes da Silva et al., 2005). This project relied mostly on using true color and R(7) G(4) B(2) false color composites; my experiments indicated that the other two composites did not provide additional information so they were excluded from the study.

Principal Component Analysis (PCA) is a very effective method for analyzing multispectral satellite imagery. Previous research demonstrated the suitability of false color composite images using PC band combinations, for example R(PC2) G(PC1) B(PC4) for lineament extraction (Cruz et al. (2005); Drechsel et al. (2004); Everett et al. (2003); Everett et al. (2004)). PCA transforms the original image bands into uncorrelated output bands. The maximum variance of the original data set is retained in the first PC band and the variance decreases toward higher order PC bands. The first three principal component bands typically provide more than 90% of the variance. PCA is often used for dimensionality reduction and for creating color composite images with maximum information content. Comparison of different color composites indicated that the PC band combination of R(PC1), G(PC2), B(PC3) provided the best enhancement of linear features and tonal differences for my study (Figure 4.4). Lastly a Gaussian low pass filter was applied to reduce the noise in the image.

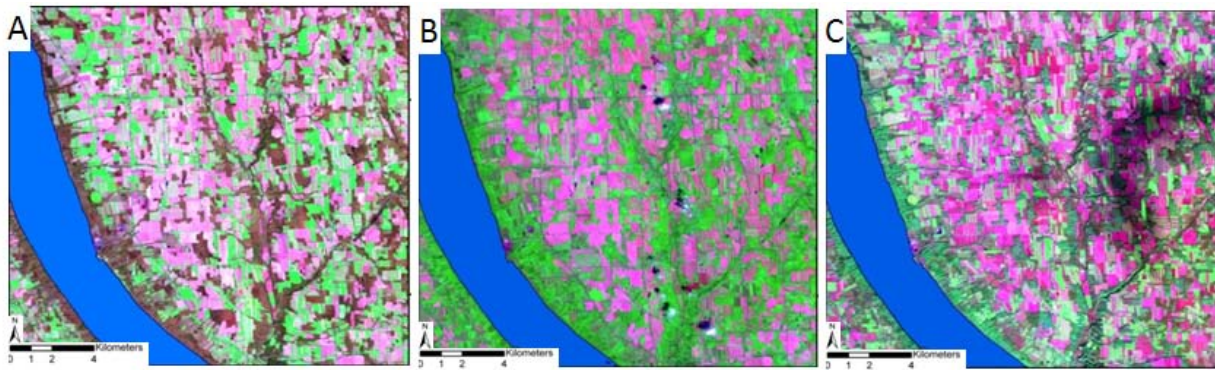


Figure: 4.2 – False color Landsat color composite; band combination R(7), G(4), B(2) for Grid 1 (A) image acquired April 28th 2001 (B) image acquired June 15th 2001 and (C) image acquired October 16th 1999



Figure: 4.3 – True color Landsat color composite; band combination R(3), G(2), B(1) for Grid 1 (A) image acquired April 28th 2001 (B) image acquired June 15th 2001 and (C) image acquired October 16th 1999

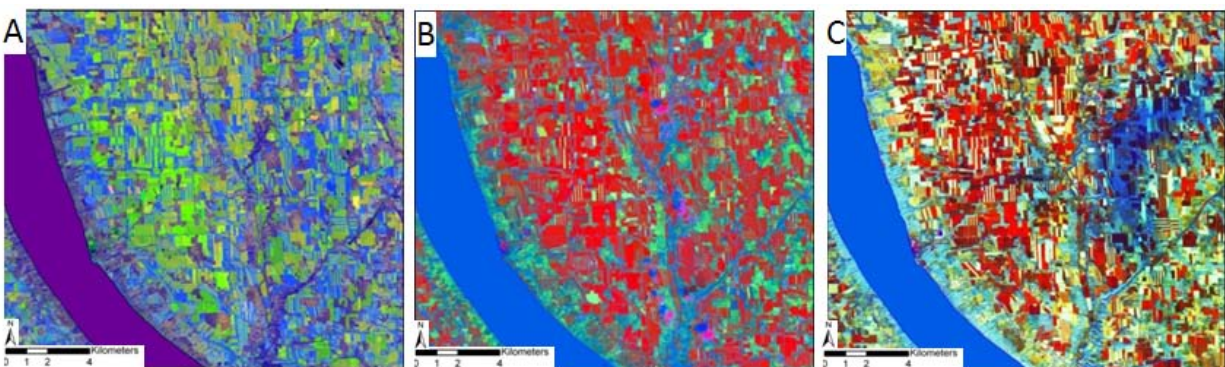


Figure: 4.4 – Principal component Landsat color composite; band combination R(PC1), G(PC2), B(PC3) for Grid 1 (A) image acquired April 28th 2001 (B) image acquired June 15th 2001 and (C) image acquired October 16th 1999

2. ASTER Imagery

ASTER image processing included georeferencing, layer stacking, masking, georeferenced mosaicking, principal components (PC) transformation, and a low pass Gaussian filtering. The first step of the processing was creating a geometrically and radiometrically corrected geographically referenced image from the full resolution, unprocessed instrument data (Level 1A) using the georeferencing tool of ENVI. The layer stacking tool was used to combine the VNIR and SWIR bands into a new multiband, 15 meter resolution file, enabling the manipulation of all bands simultaneously. A mask was applied to all images to remove the water bodies within the image to improve further image processing; exclusion of low reflectivity values over lake water improves the performance of principal component analyses (Cruz et al., 2005). The eleven ASTER scenes were combined to form a single image using the georeferenced mosaicking tool with color balancing to create a final mosaic. Lastly a low pass Gaussian filter was applied to reduce the noise in the image.

A band combination of R(2), G(3N), B(1) bands into a color composite provided the greatest color contrast for extracting linear features (Figure 4.5A) among all attempted possible band combinations. The PC band combination of R(PC2), G(PC1), B(PC3) provided the best overall image due to its enhanced linear features and tonal differences (Figure 4.5B). All VNIR and SWIR bands were used for the PCA.

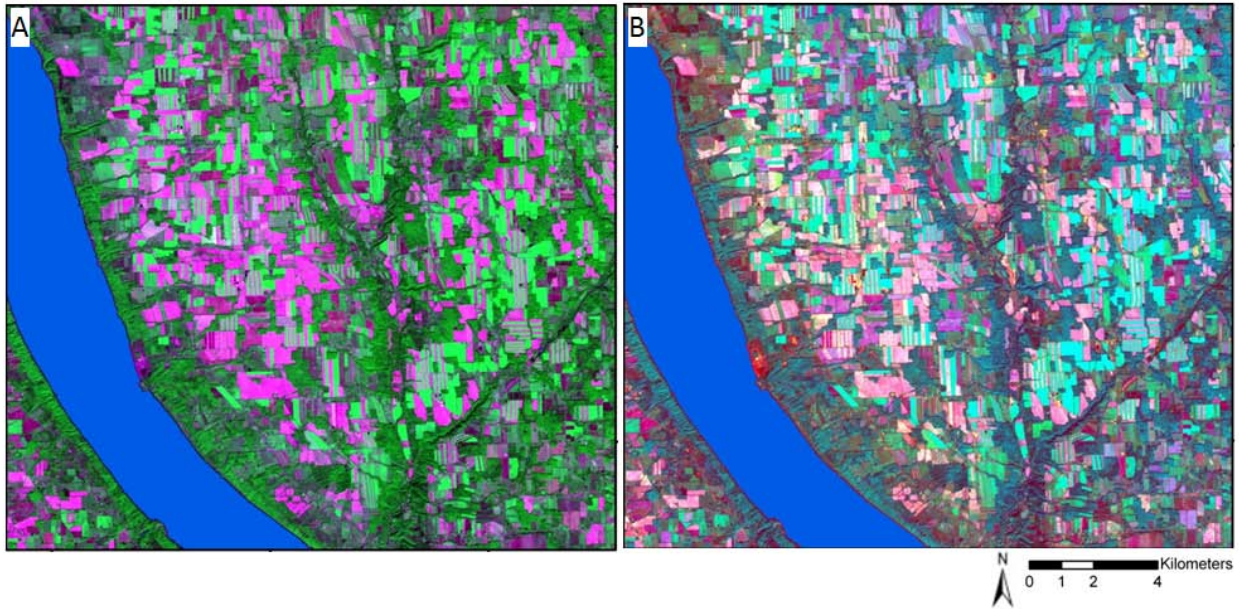


Figure: 4.5 – ASTER September 14th 2005 image for Grid 1. (A) color composite of R(2), G(3N), B(1); (B) color composite of R(PC2), G(PC1), B(PC3) principal components

3. Digital Elevation Model

National Elevation Data set (NED) DEMs do not require any preprocessing. However, attention should be paid for selecting DEM visualizations suitable for lineament mapping. While a simple gray scale or color image of a DEM depicts the general topography of the terrain, it lacks subtle details and therefore is not suitable for lineament mapping. Different visualization methods, especially shaded relief representations of DEMs, have been effectively used for enhancing terrain features to support lineament extraction. For example, Peña and Abdelsalam (2006) mapped lineaments using shaded relief DEMs in Southern Tunisia. For a shaded relief representation, the brightness of a grid cell is determined by the angle between the surface normal and illumination direction, creating an illusion of a terrain illuminated from a user defined position of the sun.

The two main inputs the user provides for creating a hill shade map are the solar elevation angle (angle from the horizon) and the solar illumination angle or azimuth (orientation of the sun's rays with respect to north). I selected a solar elevation angle of 45° . Subsequently the angle was changed to 25° because lower sun angles were more effective in enhancing subtle topographic changes in low relief regions such as our study area (e.g. Peña and Abdelsalam; 2006). The lower sun angle resulted in more shadows, thus increasing the ease of lineament identification. Varying the sun illumination angle promotes identification of more lineaments on the different views of the same area since the lineaments orthogonal to the illumination angle are enhanced. Solar illumination directions of 0° , 45° , 90° , 270° and 315° , perpendicular to the prominent lineaments in the region, were selected to enhance the linear features (Figure 4.6). Four illumination angles were used for Grid 1, but only 0° was utilized for the entire project area; this resulted in the reduction or elimination of North-South trending lineaments (parallel with the solar illumination direction) from the final lineament data set derived from the DEM.

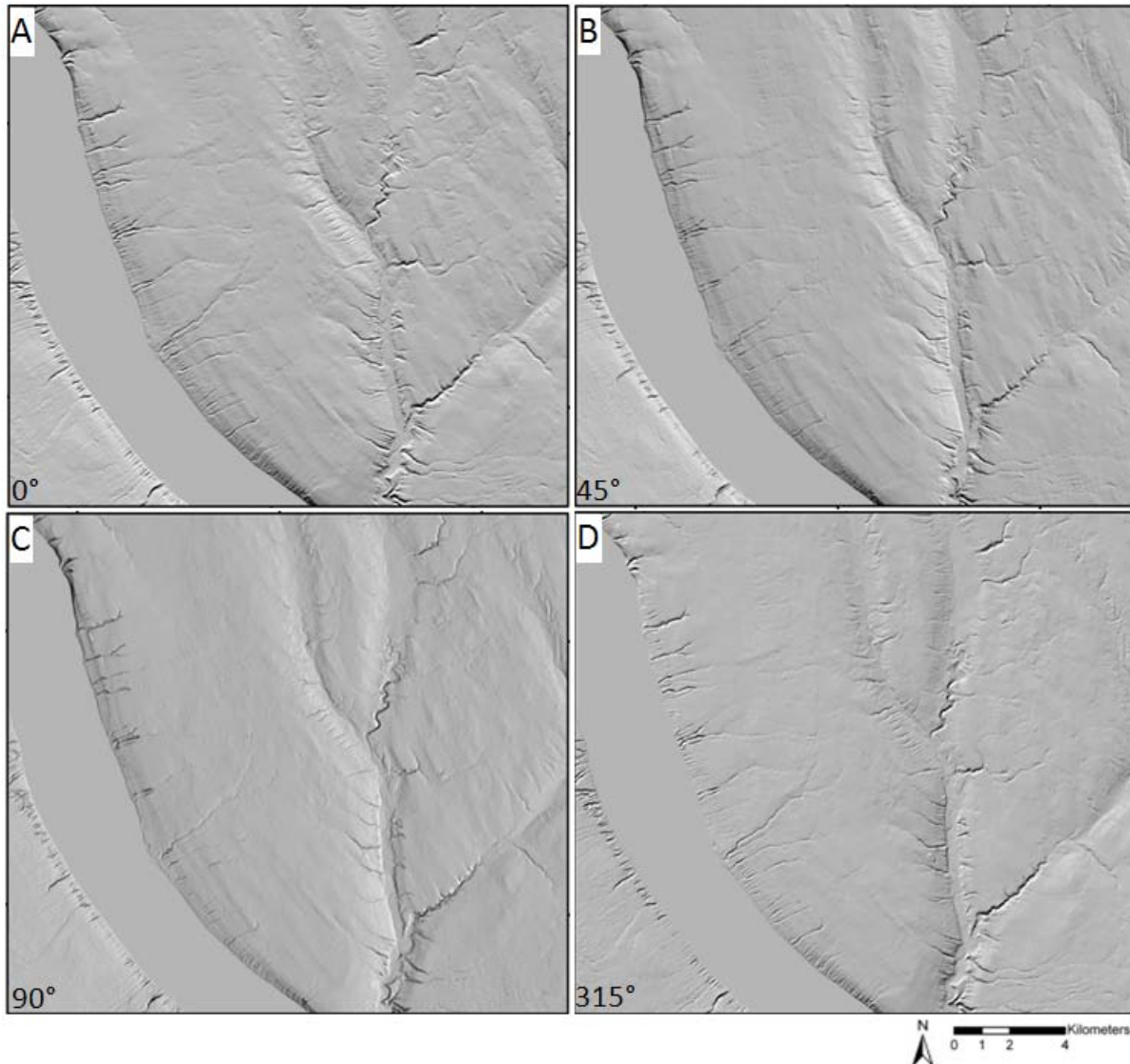


Figure: 4.6 – 10 m resolution NED DEM, shaded relief representation for Grid 1 with sun angle 45° and azimuth of (A) 0°, (B) 45°, (C) 90° and (D) 315°

B. Lineament extraction, analysis and interpretation

The methodology followed in this project was similar to the one presented by Rahiman and Pettinga (2008) who used four major steps in lineament analysis: (1) acquisition of lineament data from multiple images, (2) analysis to identify significant data, (3) presentation as statistical and spatial plots, and (4) comparison of lineaments with fracture data from the field. The lineament extraction and analysis of this project was accomplished in three phases. During

Phase-I I focused on digitizing and analyzing lineaments in a small area (Grid 1) using multiple satellite imagery and shaded relief DEMs at a scale of 1:65,000. In Phase-II I extracted and analyzed lineaments at a scale of 1:125,000 for the entire project area, but only from the ASTER PC color composites and shaded relief DEMs illuminated from the north. In Phase-III lineaments were extracted and analyzed for the Cayuga power plant subset at a scale of 1:25,000 for a detailed study.

1. Lineament extraction

Color composite images and shaded relief DEMs were imported into a ArcGIS 9.3 project and displayed with some auxiliary data including roads, railroads, drumlin outlines and hydrology. The auxiliary data were overlain on the image mosaic or map to assure that man-made features were not mistakenly identified as a structurally-related lineament. This created a situation in which geological structures coincident with man-made features could mistakenly be excluded.

To store the digitized lineaments as polylines together with associated lineament information such as the length, orientation and category, a geodatabase was created using ESRI's ArcCatalog. The category described the type of lineament based on the clues used for mapping, namely drainage pattern, tonal variation, vegetation difference, or the presence of a series of connecting lakes. A lineament was selected if its straight (non-curved) length was greater than a pre-determined minimum length. For curved lineaments multiple strength line segments were used to digitize the lineament.

For quality control weekly meetings were held throughout the lineament identification process with Dr. Jacobi and Dr. Csatho, both of whom confirmed identified lineaments and

identified new ones. We discussed the criteria used for identification and why a given linear feature was a lineament or not. This process helped re-focus the operator's eyes and provided different viewpoints of the lineament identification. Additionally the previous week's work was re-reviewed by Dr. Jacobi to ensure that all possible lineaments were identified. The lineament extraction, which includes identification and digitizing, was accomplished in three phases. The scale at which lineaments were digitized varied from 1:25,000 (Cayuga subset); 1:65,000 (Grid 1) and 1:125,000 (entire project area), and the minimum length of digitized lineaments was 0.5 km, 0.5 km and 1 km, respectively.

2. Lineament Analysis

According to Peña and Abdelsalam (2006), the objective of a lineament analysis is to derive information about geological structures from the length, azimuth direction and spatial distribution of lineaments. The statistical analyses of the lineaments in the present study were based on the length of the lineaments and provided the total count (number of lineaments), and the total, maximum, median length and average length as well as the standard deviation of the length (all in meters). This was accomplished by converting the ArcGIS geodatabase into a Microsoft Excel spreadsheet where the analysis was performed.

Rose diagram analyses were generated to show the orientation distribution of the lineaments. Grapher Six (Golden Software Inc.) and RockWorks (RockWare) software tools were utilized to construct rose diagrams. Since ArcGIS, the program in which the lineaments were digitized, does not calculate the orientation of lineaments automatically, a data field was added and named orientation/azimuth in the attribute table of the ArcMap geodatabase. With the assistance of Cheri Cruz, a script downloaded from <http://www.ian-ko.com/> calculated and

stored the azimuth of the lineament in the new orientation/azimuth field. After this step was completed, rose diagrams were made using RockWorks.

After the completion of Phase I to Phase III, additional analyses beyond the basic statistics and the rose diagrams were performed. Additional analyses performed on the digitized lineaments for the entire project area and the Cayuga power plant subset included the generations of histograms, spatial rose diagram analysis and generation of lineament density maps. The histograms made with a bin size of 2° , supported the interpretation of the distribution of the digitized lineaments. A spatial rose diagram analysis was performed to determine changes in trends across the entire project area and Cayuga power plant subset by making rose diagrams in each 56.25 km^2 (Cayuga Subset) and 225 km^2 (project area) regions. Rose diagrams across the project area and Cayuga subset were examined to determine variations in lineament orientations that may be related to, or influenced by, changing tectonic stresses. The last analysis was the creation of lineament density maps to improve our overall understanding of the clustering or grouping of lineaments with specific orientations. Density maps display the number of lineaments per a defined area. Density maps for all orientations as well as for specific orientation ranges were generated using RockWorks and Surfer. Reviewing the lineament population distribution for lineaments digitized during Phase II and Phase III identified the specific orientation ranges used in the density maps.

3. Geologic Interpretation

The geologic interpretation for this project was accomplished with two analyses - fabric and stratigraphic analysis. The fabric analysis allowed for various datasets (e.g. faults, fractures and fault zones) to be evaluated and compared to the digitized lineaments resulting in the fabric

compilation table (Tables 6.1 – 6.4). In ArcGIS, buffers were first placed around geologic structures (e.g. fractures, faults and fault zones). A buffer is a zone around a map feature, which covers its neighborhood up to a predetermined distance. Additionally, a buffer is a circle around a point feature (e.g., location of a fracture measurements) and a corridor along a linear feature (e.g., a fault). The next step was the identification of the digitized ASTER lineaments that lay at least partially within the buffer. Finally the orientations of these selected lineaments, which are located fully or partially in the buffer zone, were examined. If the orientation of a lineament was within 20° of the trend of the buffered geologic structure (for the fault zones the average trend was used) the lineament was selected and incorporated into the fabric analysis table (Figure: 4.7). A buffer size of 1 km was used for fault and fault zones. Engelder and Geiser's (1979 and 1980) fractures were represented by 5 km-long linear features, oriented along the fracture trend (per conversation with Dr. Jacobi; Figure: 4.7), and then a buffer size of 1 km was applied, resulting in an 7 km long, 2 km wide feature for each fracture measurement. Other fracture data was represented by point data and a 1 km buffer was applied. The fabric analysis table consists of the total lengths and counts of those ASTER lineaments, which were selected based on the above criteria (location and orientation) as well as the total length and counts of those structures that have at least one selected ASTER lineament within their buffers. In the fabric tables, the results were organized according to orientation ranges (e.g. NW, NE ENE etc.). From this analysis I determined the orientations of ASTER lineaments that are best supported by mapped geologic structures such as fractures, field fracture frequency data, faults, and fault zones.

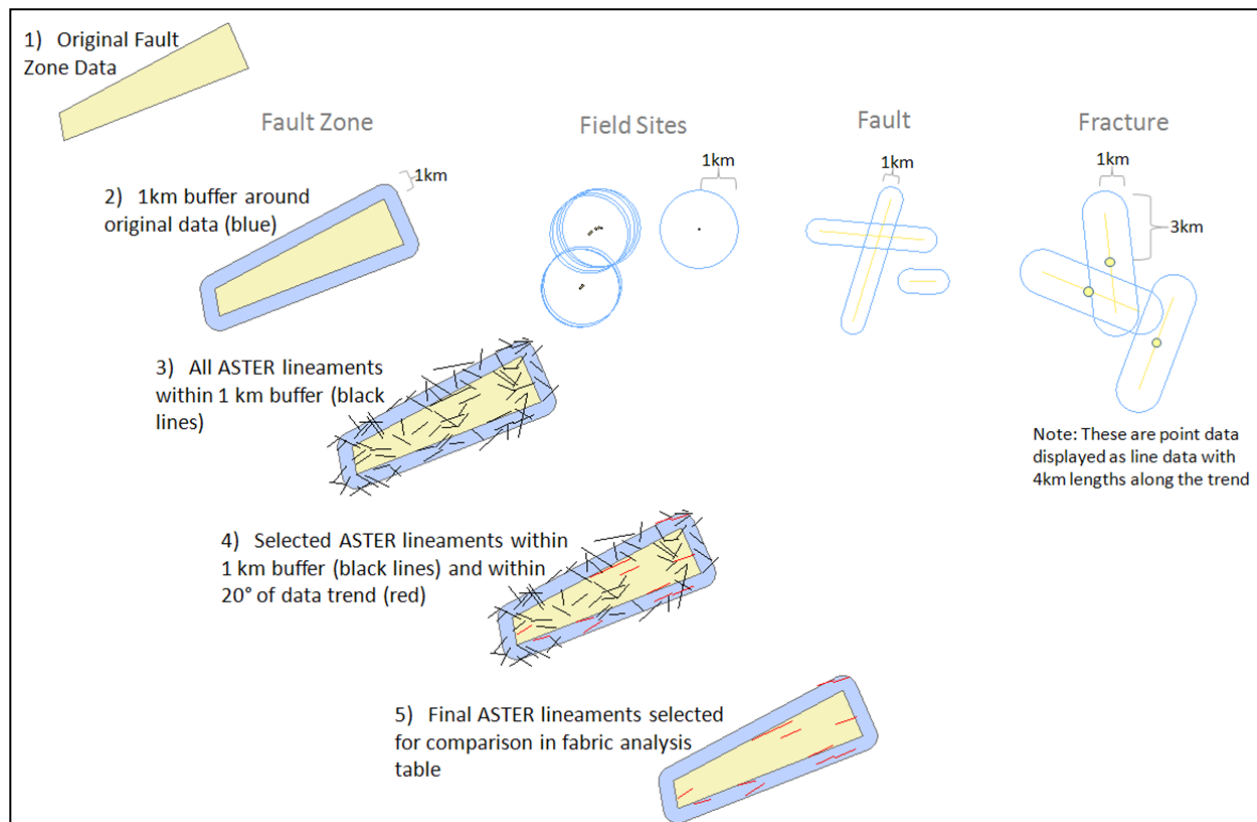


Figure: 4.7 – Schematic showing the buffering of geologic structures for ASTER lineament selection. ASTER lineament and structure orientations are compared in the fabric analysis tables (Table 6.1 – 6.4)

Another analysis that aided in the geologic interpretation was the stratigraphic analysis. This analysis was used to gain insight into possible variation of lineament orientation with respect to the age and tectonic history of different geologic formations. I utilized three depositional groups exposed in the project area: (1) the Hamilton Group, (2) the Tully Ls, Genesee and Sonyea Groups (combined in geologic map) and (3) the West Falls Group. The geologic map of NYS (plate 2 – Isachsen et al., 1991) was used as a base map in ArcGIS to identify the boundaries between the three groups. ASTER lineaments within the geologic units were selected and separated into individual files in ArcGIS; these files were used to make rose diagrams in RockWorks.

Chapter 5 – Results

A. Lineament Mapping

1. Phase I – Selection of best remote sensing data and image processing methods for lineament mapping

The purpose of this initial phase was to select the best images and DEM representations for lineament mapping from a comprehensive set of products (Table: 5.1). A small test site, covering a 225 km² region east of Cayuga Lake and the AES Cayuga power plant, was selected for this part of the study (Figure: 1.4, Grid 1). This region was also previously studied by Cruz (2005). I mapped lineaments from 15 different satellite image products and shaded relief DEMs at a 1:65,000 scale (Figures: 5.1 – 4.5). Only lineaments longer than 0.5 km were mapped; previous work by Jacobi (2002) and Jacobi et al. (2002) suggested lineaments in excess of 0.5 km correlated best with fracture intensification domains (FIDs). This phase of the lineament identification process took place between April 2009 and July 2009.

Landsat Imagery – April 28th 2001, June 15th 2001 and Oct. 16th 1999
True-Color composite R(3),G(2), B(1)
False-Color composite R(7),G(4), B(2)
Principal Component R(PC1),G(PC2), B(PC3)
ASTER Imagery – Sept. 14th 2005
Color composite R(2),G(3N), B(1)
Principal Component R(PC2),G(PC1), B(PC3)
DEM – Sun elevation angle 45° - Shaded relief map
Sun Illumination 0°
Sun Illumination 45°
Sun Illumination 90°
Sun Illumination 315°

Table 5.1: Satellite image composites and shaded relief DEMs generated in Phase I

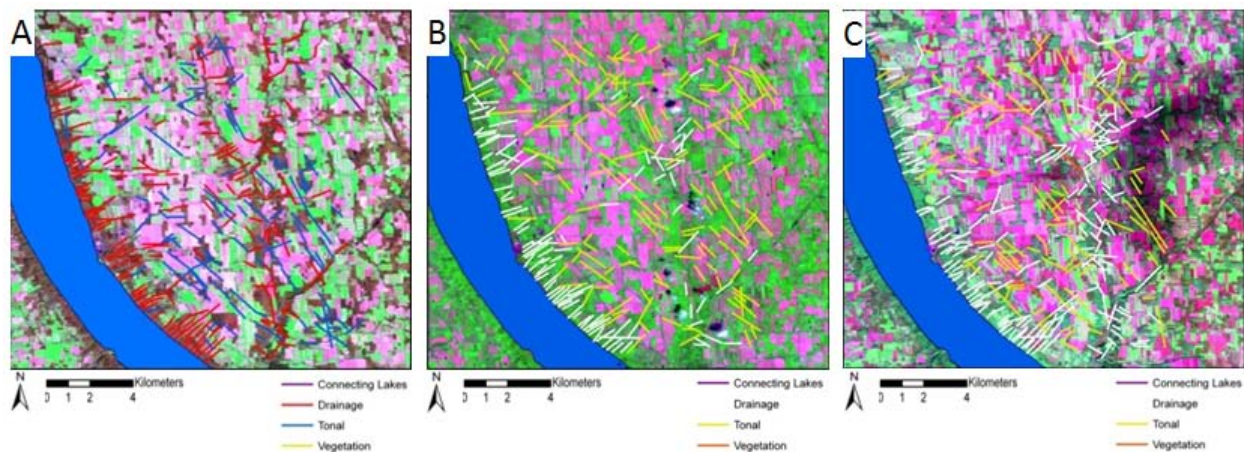


Figure: 5.1 – Phase I - False color Landsat color composite; band combination R(7), G(4), B(2) for Grid 1 with digitized lineaments (A) image acquired April 28th 2001 (B) image acquired June 15th 2001 and (C) image acquired October 16th 1999

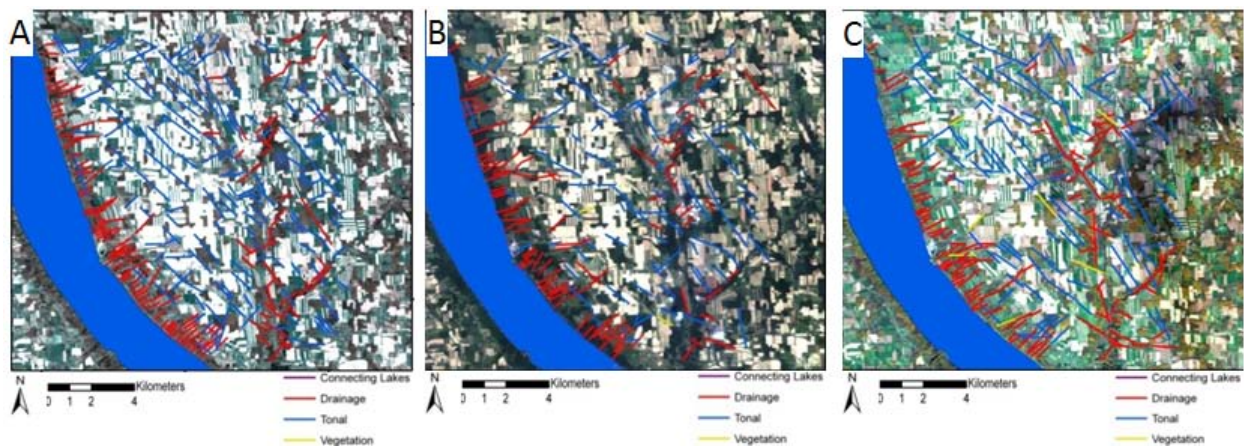


Figure: 5.2 – Phase I - True color Landsat color composite; band combination R(3), G(2), B(1) for Grid 1 with digitized lineaments (A) image acquired April 28th 2001 (B) image acquired June 15th 2001 and (C) image acquired October 16th 1999

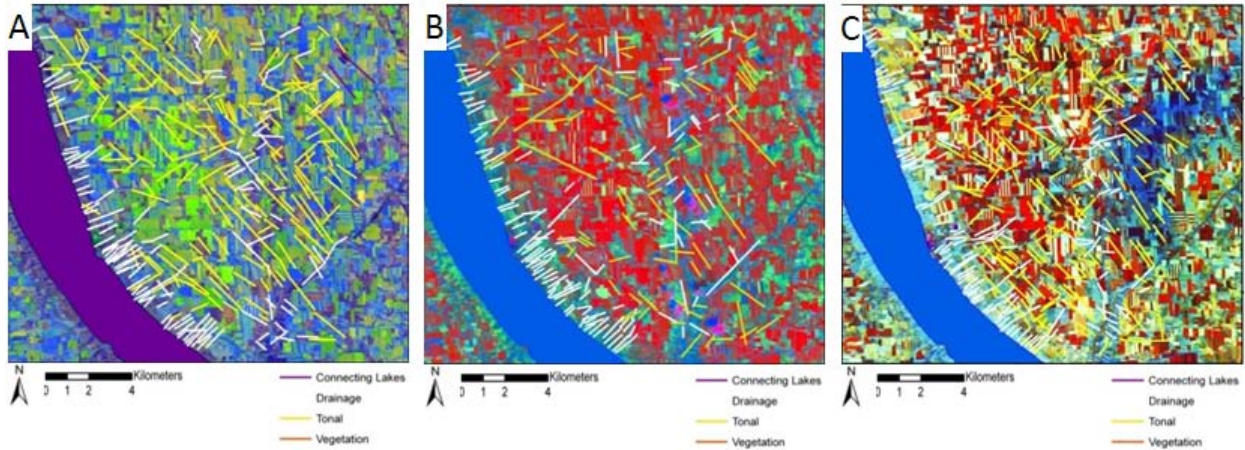


Figure: 5.3 – Phase I - Principal component Landsat color composite; band combination R(PC1), G(PC2), B(PC3) for Grid 1 with digitized lineaments (A) image acquired April 28th 2001 (B) image acquired June 15th 2001 and (C) image acquired October 16th 1999

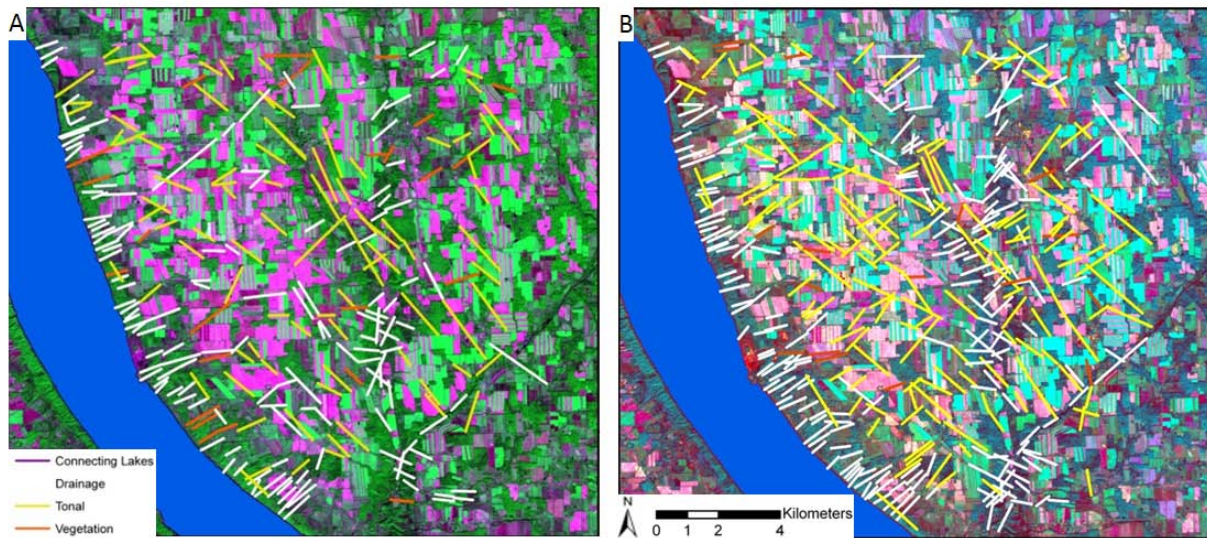


Figure: 5.4 – Phase I - ASTER September 14th 2005 image for Grid 1 with digitized lineaments (A) color composite of R(2), G(3N), B(1) and (B) color composite of R(PC2), G(PC1), B(PC3) principal components

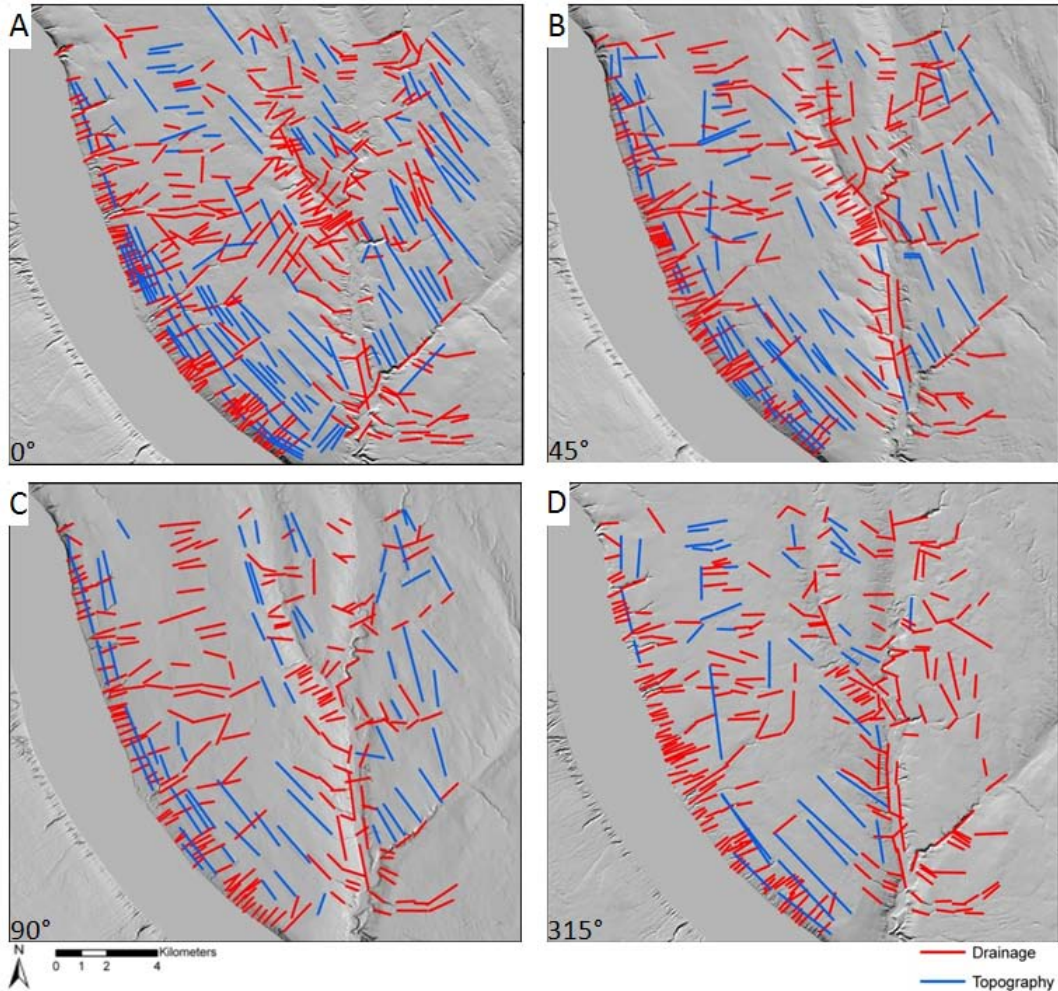


Figure 5.5: Phase I – 10 m resolution NED DEM, shaded relief representation for Grid 1 showing digitized lineaments with sun elevation/angle 45° and azimuth of (A) 0°, (B) 45°, (C) 90° and (D) 315°

Basic statistics of the lineaments (i.e. count, total length, average length, median length, maximum length, and standard deviation of length) are shown in Table 5.2. The distribution of lineament orientations displayed on rose diagrams with 10° bins (Figures 5.6 – 5.8).

In Phase I, various image enhancing and visualization techniques were tested for ease of lineament recognition by increasing the contrast of the image. Of all 15 images reviewed for lineaments, the ASTER PC composites and shaded relief DEM with sun illumination angle of 0°

had the highest lineament count and total length. Therefore only these data products were used for the remainder of the project. Lineaments were more easily recognized on these images and overall these two images displayed more linear features than the others. The lineaments digitized from most satellite images revealed a primary trend of 55° and a secondary trend of 315°. Lineaments digitized from all shaded relief DEMs typically had a primary trend of 65° and a secondary trend of 325°. These trends indicate that the lineaments identified could be related to NE or ENE trending faults and NW trending fractures in the region (Jacobi, 2002; Engelder and Geiser, 1980).

	Total Count	Total Length m)	Average Length m)	Median Length (m)	Standard Deviation
ASTER Imagery					
Sept. 2005 Color Composite	252	221,044	887	802	164
Sept. 2005 Principal Component Composite	364	320,762	839	733	168
Digital Elevation Model					
Shaded Relief DEM with sun azimuth (0°)	454	404,530	858	688	167
Shaded Relief DEM with sun azimuth (90°)	270	233,561	861	655	151
Shaded Relief DEM with sun azimuth (45°)	357	299,702	890	773	139
Shaded Relief DEM with sun azimuth (315°)	300	243,598	874	727	281
Landsat Image					
April 2001 True Color Composite	281	254,040	746	741	158
April 2001 False Color Composite	267	227,942	800	688	123
April 2001 Principal Component	292	302,306	940	844	138
June 2001 True Color Composite	189	170,027	849	808	157
June 2001 False Color Composite	256	229,003	868	790	135
June 2001 Principal Component	209	190,473	867	754	237
Oct. 1999 True Color Composite	229	222,011	970	775	315
Oct. 1999 False Color Composite	277	227,335	825	724	128
Oct. 1999 Principal Component	294	246,950	823	749	165

Table: 5.2 – Phase I - Statistics of lineaments extracted from different remote sensing data in Grid 1. Lineament extraction scale was 1:65,000 and minimum lineament length is 0.5 km (see Table 5.1 for details on band combinations)

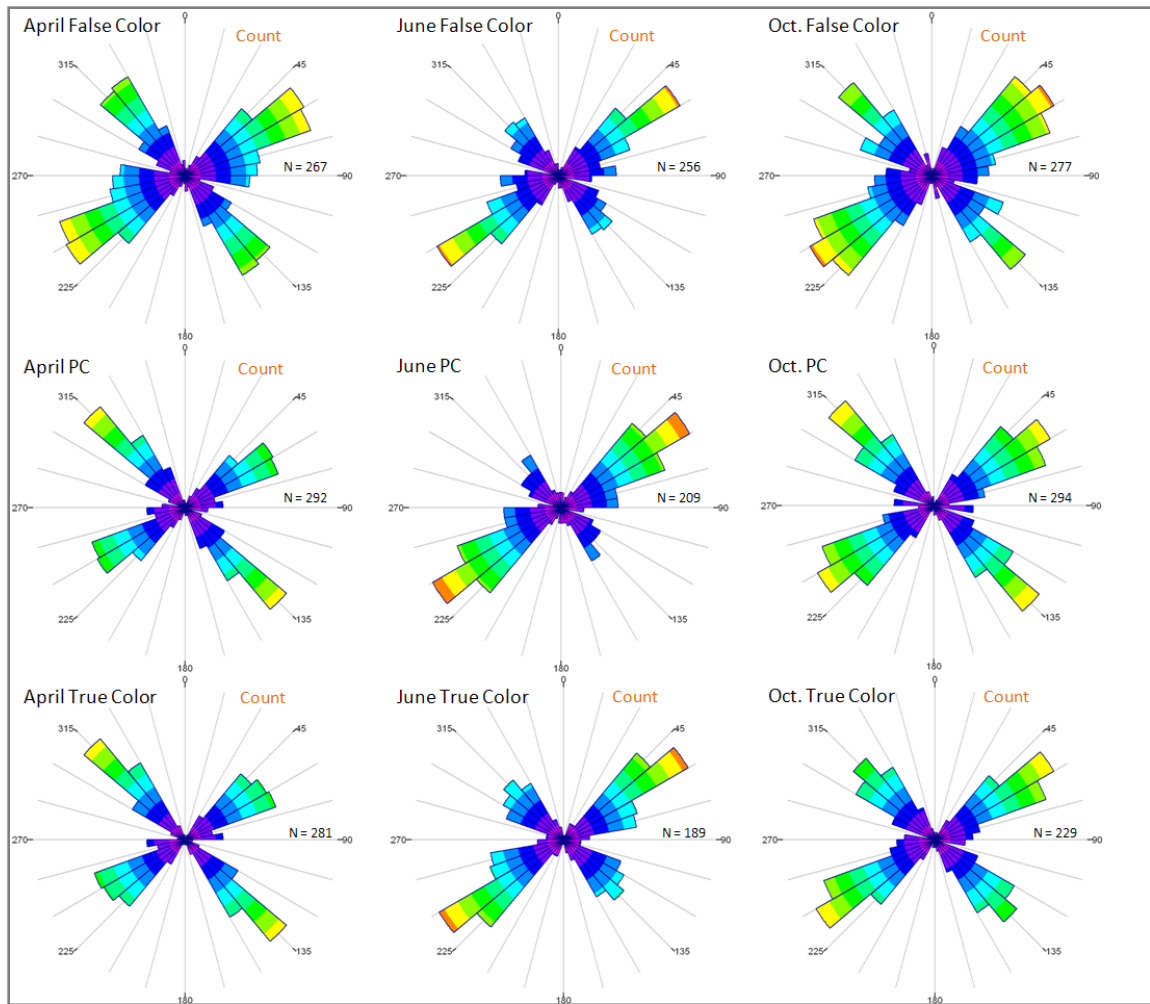


Figure: 5.6 – Phase 1 - Rose diagrams of Landsat lineament orientations in Grid 1, lineaments digitized from Landsat ETM+ imagery. Lineament extraction scale was 1:65,000 and minimum lineament length is 0.5 km. N is the total number of lineaments digitized from the image

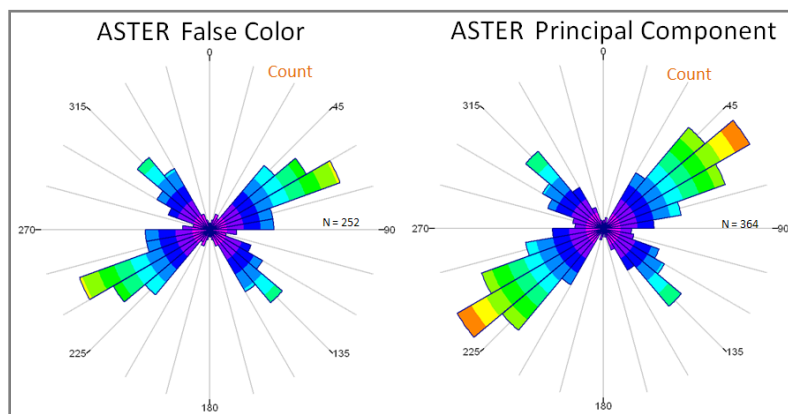


Figure: 5.7 – Phase I - Rose diagrams of ASTER lineament orientations in Grid 1, lineaments digitized from ASTER imagery. Lineament extraction scale was 1:65,000 and minimum lineament length is 0.5 km. N is the total number of lineaments digitized from the image

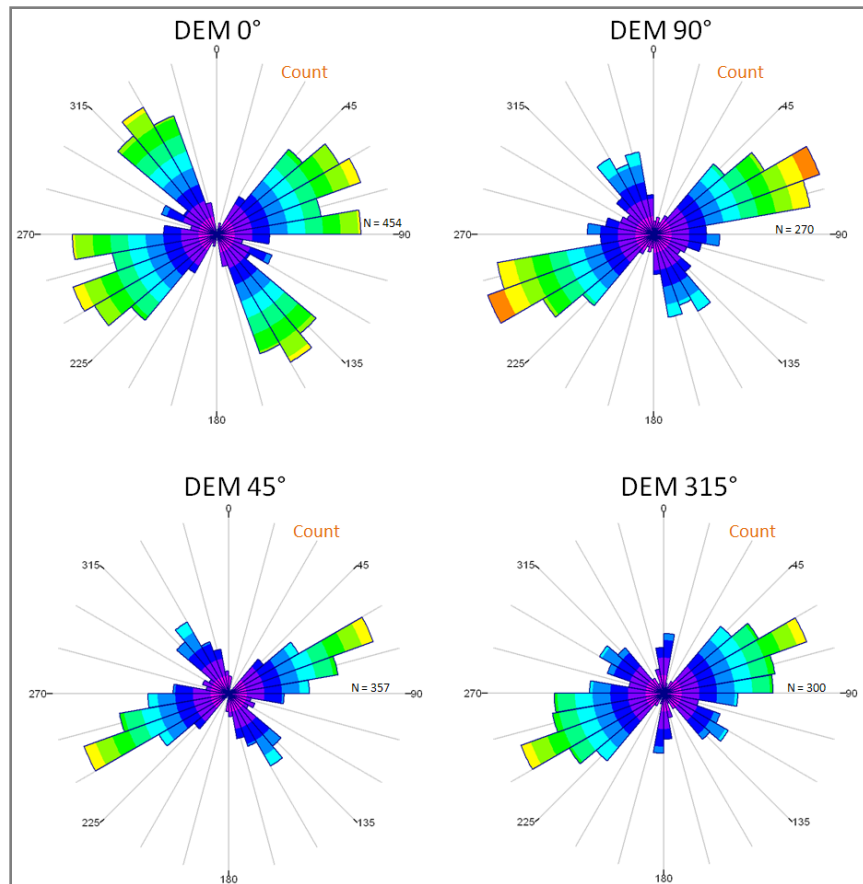


Figure: 5.8 – Rose diagrams of topographic lineament orientations in Grid 1, lineaments digitized from shaded relief DEMs. Solar illumination (azimuth) angles are 0, 45, 90 and 315 degrees, solar elevation angles is 45 degrees, lineament extraction scale was 1:65,000 and minimum length is 0.5 km. N is the total number of lineaments digitized from the image

2. Phase II – Lineament analysis of the entire project area

Phase II encompassed the entire project area of eight counties (Figure: 1.4). For this larger region, a smaller scale of 1:125,000 and a larger minimum lineament length of 1 km were used. Based on the result of the Phase I analysis, we selected the ASTER Principal Component composite of (R(PC2),G(PC1), B(PC3)) and shaded relief DEMs with a sun illumination angle of 0° for lineament mapping (Table: 5.3; Figures: 5.9, 5.10 and S5.1- S5.6). This phase took 4 months to complete with the identification criteria and quality control

described in section 4.B.1. Phase II was completed in December 2009. ** Note: Figure numbers starting with “S” are found in Appendix 1 as supplemental figures.

ASTER Imagery
Principal Component R(PC2), G(PC1), B(PC3)
DEM – Sun elevation angle 25°
Sun Illumination 0°

Table 5.3: ASTER color composites and shaded relief DEMs used in Phase II

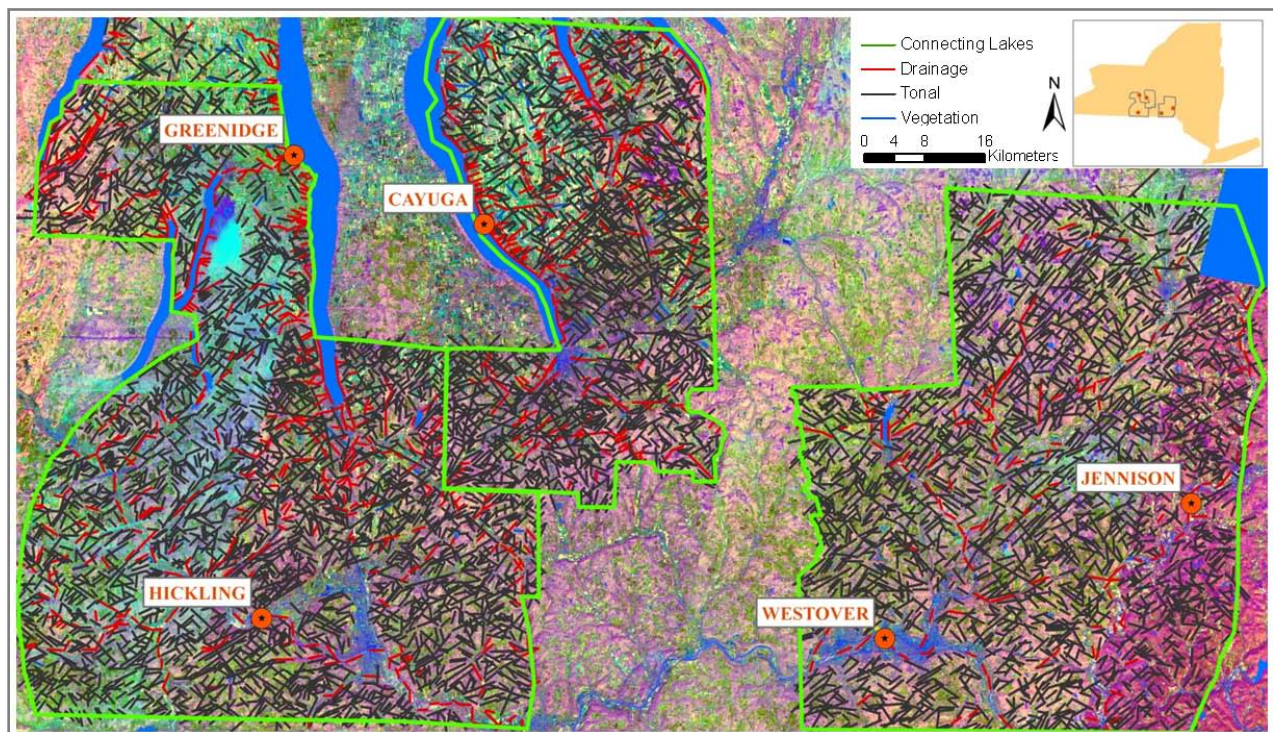


Figure: 5.9 – Phase II –ASTER principal component color composite mosaic with digitized lineaments over the entire project area; Principal Component composite R(PC2),G(PC1), B(PC3)

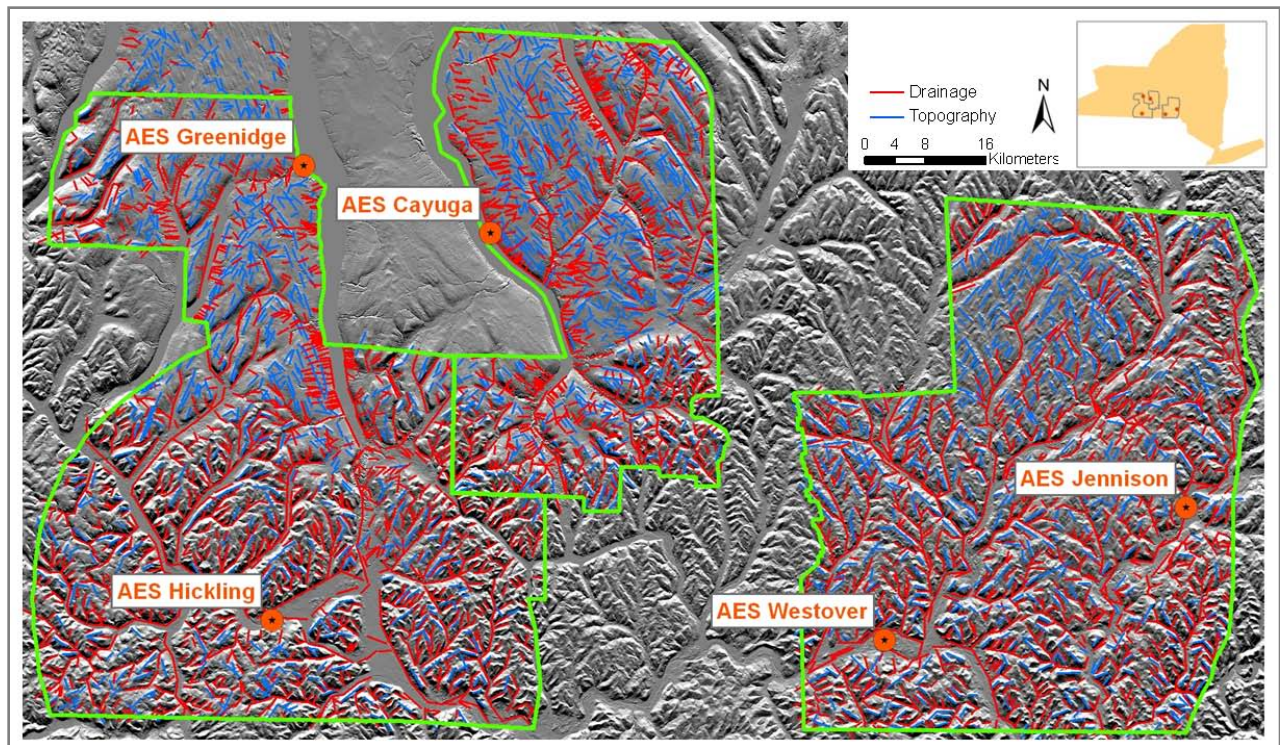


Figure: 5.10 – Phase II – DEM shaded relief representation displaying digitized lineaments over the entire project area; sun elevation/angle is 25° and sun azimuth is 0°

The statistical lineament analysis for Phase II was conducted on the entire population of lineaments as well as on the lineaments of western, central and eastern focus areas separately. Analyzing lineaments within individual focus areas could identify any regional fault and fracture trends or changes across the project area related to the regional tectonics. Variations in relationships between lineaments and land use/cover can also be analyzed by separating the lineaments of these focus areas. Basic statistics of the lineaments (i.e. count, total, average, median and maximum length, and standard deviation of length) are shown in Table 5.4. RockWorks (RockWare Inc.) software was used to create the rose diagrams for the entire project area, and western, central and eastern focus areas. Each rose diagram was created with petals of 10° and based on total count (Figures: 5.11 and Table: 5.5).

	Total Count	Total Length (m)	Average Length (m)	Median Length (m)	Maximum Length (m)	Standard Deviation
Project Area						
ASTER Principal Component Composite	7,113	12,957,610	1,822	1,581	9,597	834
Shaded Relief DEM with sun azimuth (0°)	5,025	8,299,260	1,652	1,418	13,206	760
Western Focus Area						
ASTER Principal Component Composite	3,246	5,615,555	1,730	1,494	9,597	789
Shaded Relief DEM with sun azimuth (0°)	2,049	3,327,423	1,624	1,393	13,206	786
Central Focus Area						
ASTER Principal Component Composite	1,715	3,024,483	1,763	1,529	7,719	791
Shaded Relief DEM with sun azimuth (0°)	1,334	2,071,999	1,553	1,350	7,586	656
Eastern Focus Area						
ASTER Principal Component Composite	2,168	4,357,595	2,010	1,783	8,190	902
Shaded Relief DEM with sun azimuth (0°)	1,652	2,921,826	1,769	1,523	8,961	790

Table: 5.4 – Phase II - Length statistics of lineaments digitized from ASTER imagery and shaded relief DEM

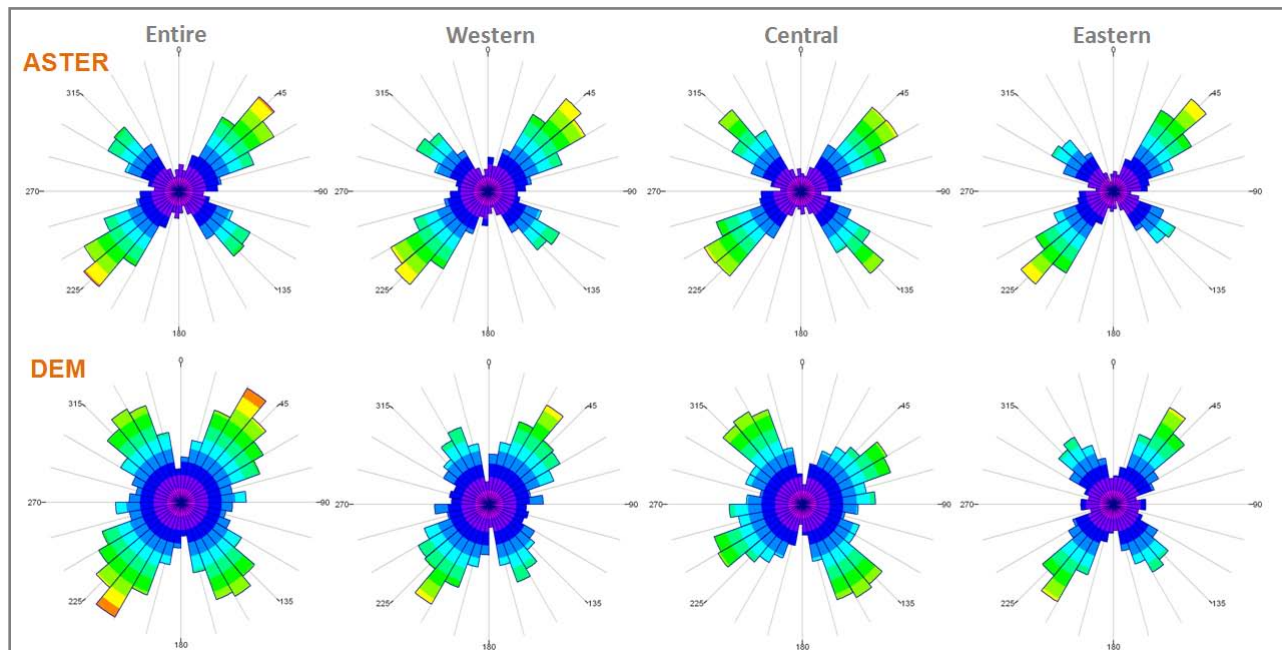


Figure: 5.11 – Phase II - Rose diagrams of lineament directions digitized from ASTER imagery and shaded relief DEMs. See Table 5.4 for total lineament counts.

	Primary Trend	Secondary Trend	Max Bin Population	Max Bin Percent
Project Area				
ASTER Principal Component Composite	NE (45°)	NW (310°)	919	6.45%
Shaded Relief DEM with sun azimuth (0°)	NNE to NE (35°)	NW to NNW (330°)	488	4.79%
Western Focus Area				
ASTER Principal Component Composite	NE (45°)	NW (305°)	404	6.21%
Shaded Relief DEM with sun azimuth (0°)	NNE to NE (35°)	NNW (330°)	212	5.15%
Central Focus Area				
ASTER Principal Component Composite	NE (50°)	NW (315°)	206	6.00%
Shaded Relief DEM with sun azimuth (0°)	NW (325°)	NE to ENE (60°)	119	4.44%
Eastern Focus Area				
ASTER Principal Component Composite	NE (45°)	NW (305°)	313	7.21%
Shaded Relief DEM with sun azimuth (0°)	NNE to NE (30°)	NW to NNW (325°)	207	6.07%

Table 5.5: Phase II – Primary and secondary orientation trends of lineaments digitized from ASTER imagery and shaded relief DEMs

3. Phase III – Detailed study around Cayuga Power Plant

This final phase focused on a smaller area around the Cayuga Power Plant because this plant was favored for CO₂ sequestration based on preliminary data from other group members of this multidisciplinary project. The Phase III study encompassed an area of 225 km² with the AES Cayuga power plant centered latitudinally with a shift eastward (Cayuga Subset – see Figure 1.4 for location). A scale of 1:25,000 was selected for digitizing to obtain a detailed data set with the minimum lineament length of 0.5 km. Lineaments were digitized both on the ASTER PC color composite image and on the 0° illumination angle shaded relief DEM with sun elevation angle 25°. This phase was completed by April of 2010 (Figures 5.12 – 5.13). Statistics and rose diagrams of the lineaments from the Cayuga Subset are shown in Table: 5.6 - 5.7 and Figure 5.14.

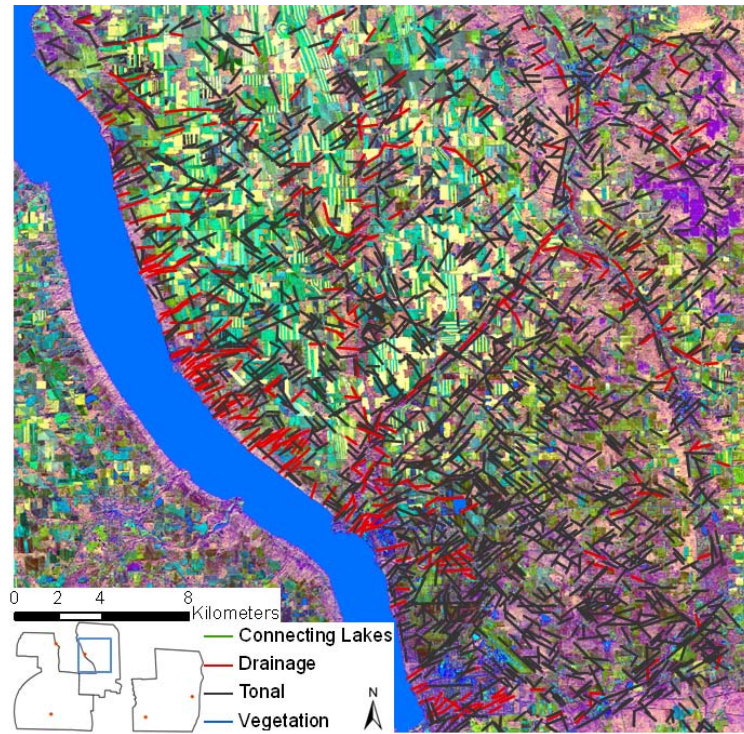


Figure: 5.12- Phase III – ASTER principal component color composites with digitized lineaments, Cayuga Subset; Principal Component composite R(PC2),G(PC1), B(PC3)

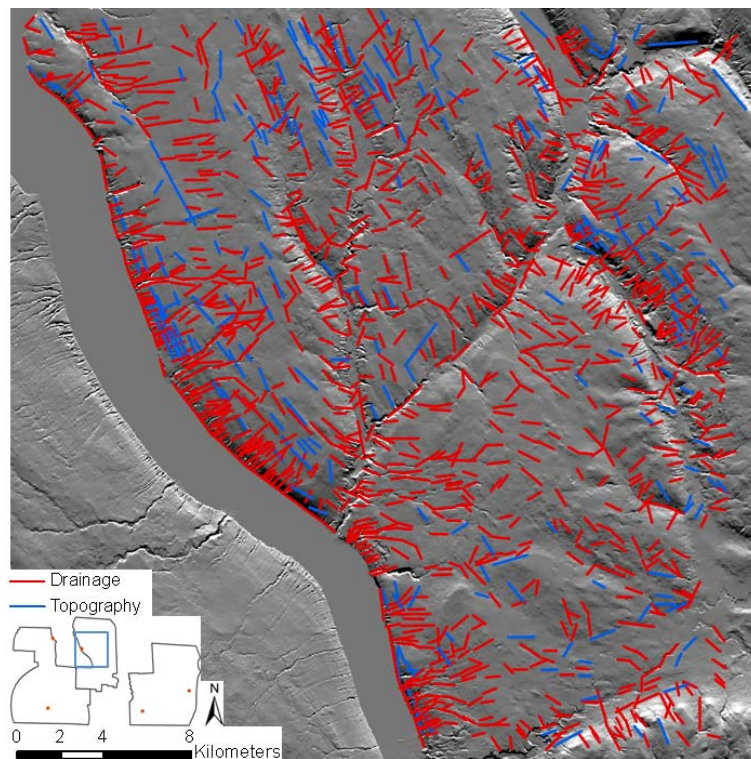


Figure: 5.13- Phase III – Shaded relief DEM with digitized lineaments for Cayuga subset; 25° sun elevation and 0° sun illumination direction

	Total Count	Total Length (m)	Average Length (m)	Median Length (m)	Maximum Length (m)	Standard Deviation
Cayuga Subset						
ASTER Principal Component Composite	2,048	1,498,832	719	650	3,524	246
Shaded Relief DEM with sun azimuth (0°)	1,398	1,018,360	728	640	4,042	275

Table 5.6: Phase III - Length statistics of lineaments digitized from ASTER imagery and shaded relief DEM, Cayuga subset

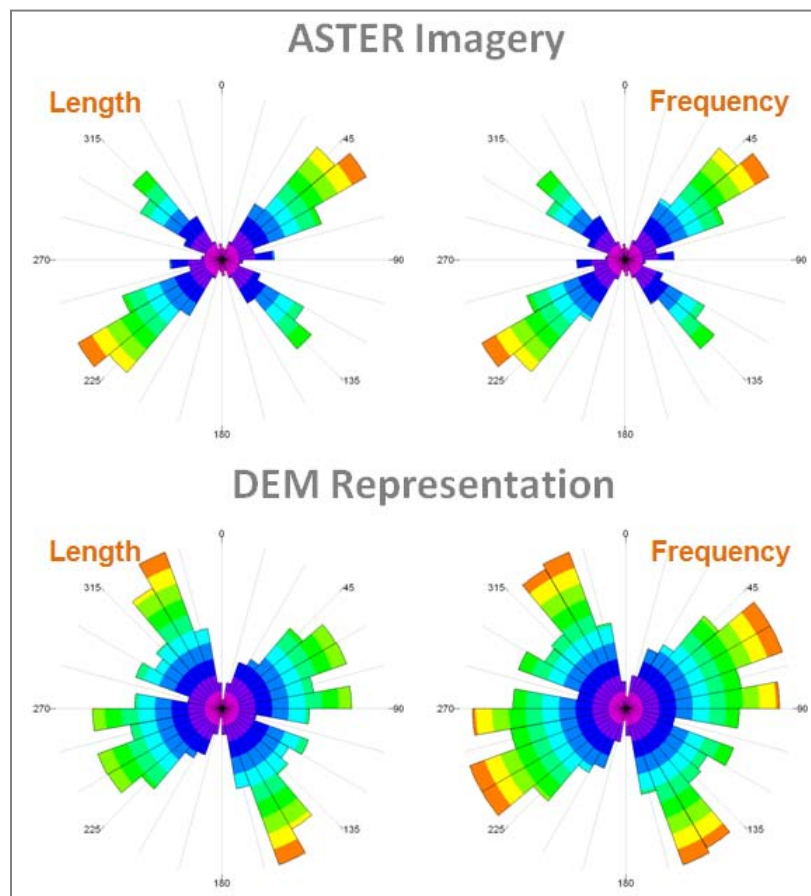


Figure: 5.14 – Phase III - rose diagrams showing orientation distribution of lineaments digitized from ASTER imagery and shaded relief DEM, Cayuga subset. See Table 5.6 for total counts

	Primary Trend	Secondary trend	Max Bin Population	Max Bin Percent
Cayuga Subset				
ASTER Principal Component Composite	NE (55°)	NW (315°)	348	8.35%
Shaded Relief DEM with sun azimuth (0°)	NNW (340°)	NE to ENE (60°)	128	4.58%

Table 5.7: Phase III - Identifies the primary trends with statistics and secondary trend of ASTER and shaded relief DEMs digitized lineaments for the Cayuga subset

B. Additional Analyses

1. Histograms

In order to gain a better understanding of the distribution of the digitized lineaments, histograms were made for each dataset based on lineament orientation. The histograms were made using the histogram tool in the RockWorks Utility based on count per orientation with bin size of 2°. A total of five histograms were made, including the ASTER and DEM lineaments for the entire project area, the ASTER and DEM lineaments for the Cayuga power plant subset datasets, and a histogram with all datasets combined (Figures 5.15 and S5.7 – S5.10). In order to define orientation groups that could be used for all datasets, the histogram with all lineaments (project area and Cayuga subset) was used. After reviewing the combined histogram by Dr. Jacobi and myself, it was determined that there was a total of eight groups and includes WNW (285 – 301), NW (301 - 335), NNW (335 – 350), NS (350 – 11), NNE (11 -21), NE (21 – 59), ENE (59 – 79) and EW (79 – 105) (Figure 5.16). Each of these groups were separated by noticeable breaks in the histogram distribution by low points; the breaks include 285°, 301°, 335°, 350°, 11°, 21°, 59° and 79°.

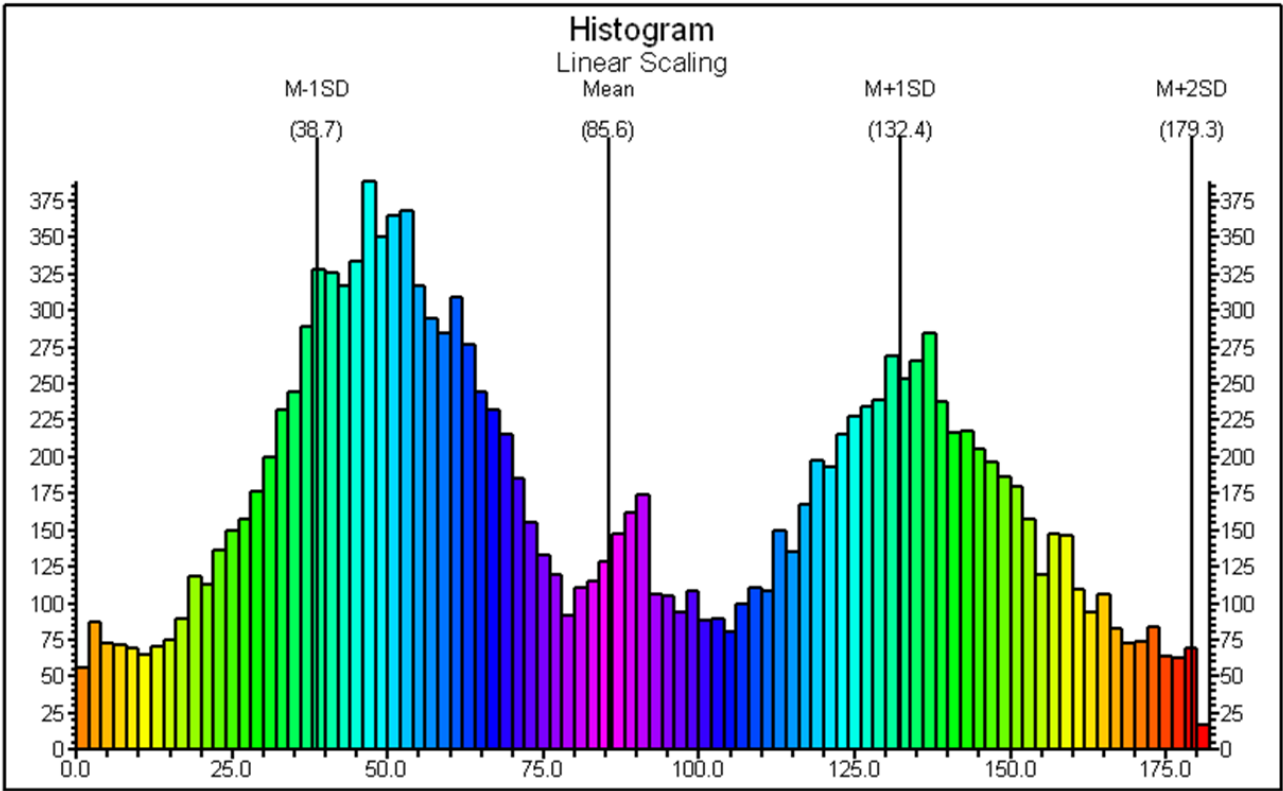


Figure: 5.15 - Histograms of all digitized lineaments (ASTER and DEM) for the entire project area and Cayuga subset. Horizontal axis is direction ($^{\circ}$), bin size of 2° , vertical axis is count

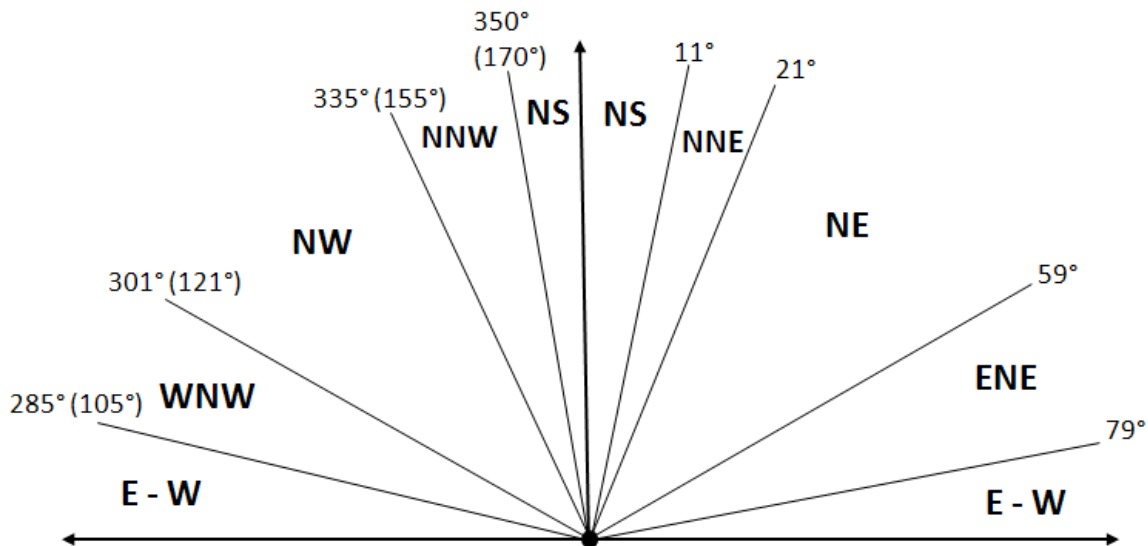


Figure: 5.16 - Azimuth distribution of orientation groups for all digitized lineament orientations

2. Rose Diagrams

A detailed rose diagram analysis of the lineaments digitized from the ASTER images was performed for the Cayuga subset (Phase III, lineament digitization scale 1:25,000; minimum lineament length 0.5 km) and for the entire project area (Phase II, lineament digitization scale 1:125,000; minimum lineament length 1 km). To determine changes in trends across the region, it was divided smaller sub-regions with a grid pattern and rose diagrams were produced for each grid cell (Figures: 5.17A and 5.18A). A grid cell size of 7.5 km by 7.5 km (56.25km²) was selected for the Cayuga subset and 15 km by 15 km (225km²) grid for the entire project area. All lineaments that were fully and partially within a grid cell were considered for the rose diagram of the respective grid cell. This resulted in a total of 13 rose diagrams for the Cayuga subset (Figure: 5.17B) and 55 rose diagrams for the entire project area (Figure: 5.18B). Each rose diagram was based on the number of lineaments (count) in each orientation bin of 10°. These rose diagrams were then overlaid on a grey scale Landsat image mosaic (Band 8, panchromatic, 15 m resolution band) to show changes in the patterns and distribution of the lineaments based on primary and secondary trends (Figures: 5.17 – 5.18).

For the Cayuga subset with lineaments digitized at a scale of 1:25,000, the primary trend was NE (21° to 59°) and the secondary trend was NW (301° to 335°). There was not a dramatic difference in rose diagrams across the subset; this made it difficult to interpret the small but important variations in trends. The secondary trend of NW is almost as strong as the primary trend in the eastern part of the Cayuga region, with one rose diagram having a stronger NW than NE trend. Weak EW trends are observed in the eastern part of the Cayuga subset and ENE trend occurs along the east coast the lake. This ENE trend may be due to drainage patterns of short drainages perpendicular to the lakeshore.

In the full project area where lineaments were digitized at a scale of 1:125,000, the primary trend was also in the NE (21° - 59°) group with some variations toward NNE (11° - 21°) and ENE (59° - 79°). The secondary trend was in the NW (301° - 335°) group with some variations toward NNW (335° - 350°) and WNW (285° - 301°). The small changes in the rose diagrams across the project area made it difficult to relate them to the regional tectonics, however a closer look at fault distribution and field data will reveal a more firm relationship. In the southeastern part of the western focus area there were seven rose diagrams with a third and much smaller trend of NS (350° - 360° and 0° - 11°). The primary trend of rose diagrams in the eastern focus area was uniform with little variation from NE (45°) but the secondary trend varied greatly with trends ranging from NW (300°) to NW (335°). The identification of a slight clockwise rotation of the prominent lineament orientations from the western part of the project area to the eastern part of the project area was recognized. This analysis compares to known faults with similar clockwise rotation in the region, suggesting a relationship of the lineaments to regional faults.

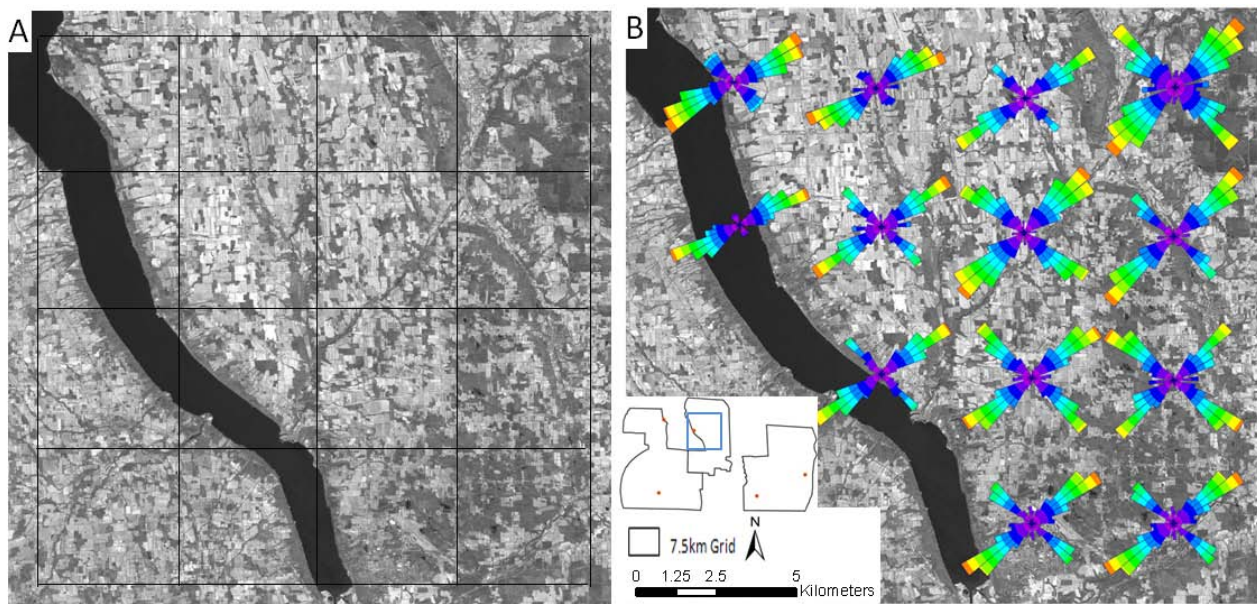


Figure: 5.17 – Detailed rose diagram analysis of ASTER lineaments, Phase III, Cayuga subset. Grid cell size is 7.5 km by 7.5 km

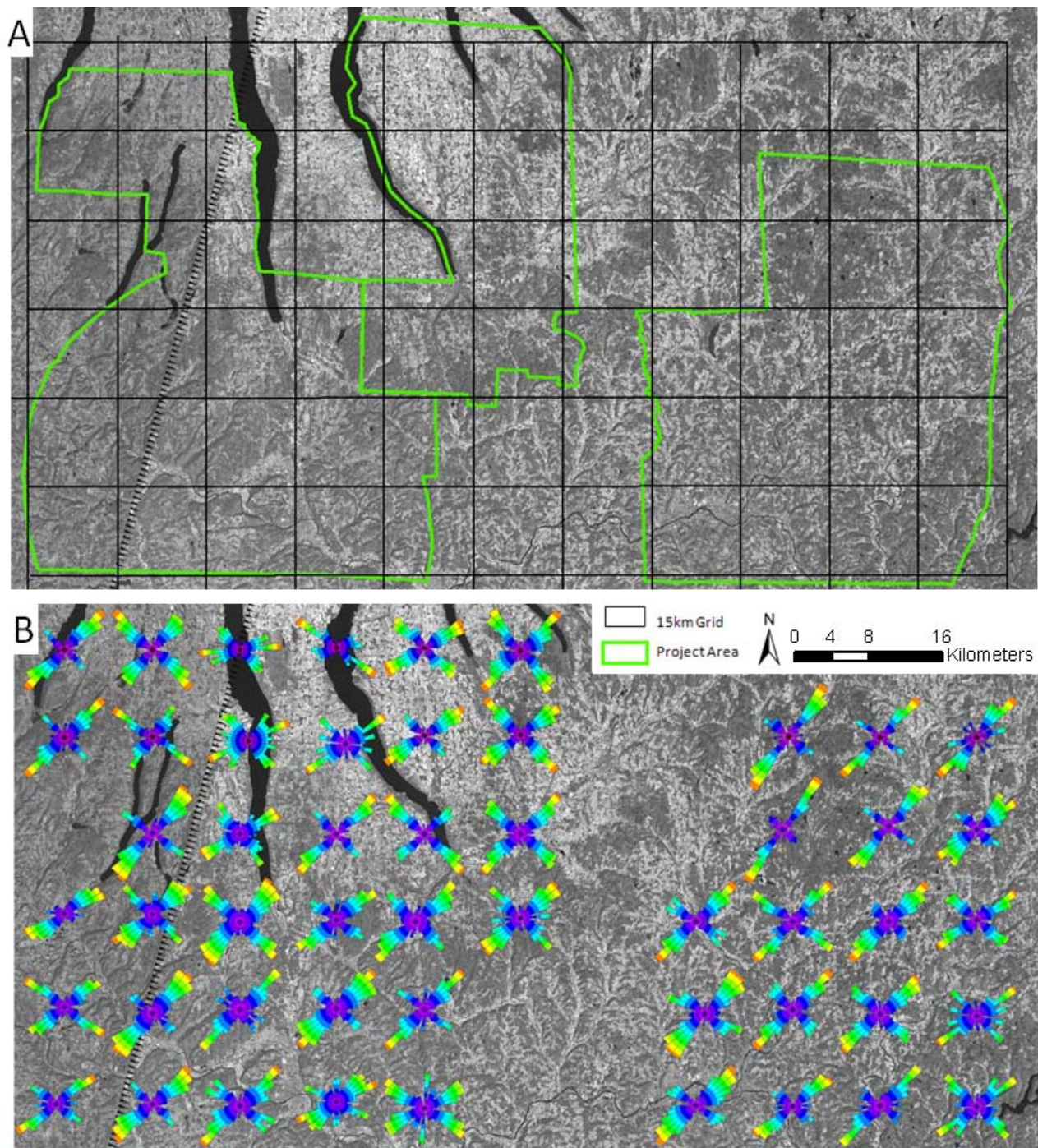


Figure: 5.18 – Detailed rose diagram analysis of ASTER lineaments, Phase II, entire project area

3. Lineament Density Maps

A lineament density map shows the number of lineaments per unit area, facilitating the identification of regions with high lineament density and areas lacking lineaments. To obtain a density map, a grid structure is defined and each lineament that is at least partially within a grid cell it is counted toward the total number of lineaments in this grid cell. Density maps for the entire project area (Phase II, Figure 5.19, 5.20, 5.23 – 5.31 and S5.11 – S5.22) and the Cayuga power plant subset (Phase III, Figure 5.21, 5.22, 5.32 – 5.40 and S5.23 – S5.31) were compiled from the lineaments extracted from ASTER imagery and from the shaded relief DEM. Density maps were computed from all lineaments as well as by selecting lineaments within the specific orientation groups determined in section 5.B.1 (WNW ($285^{\circ} - 301^{\circ}$), NW ($301^{\circ} - 335^{\circ}$), NNW ($335^{\circ} - 350^{\circ}$), NS ($350^{\circ} - 11^{\circ}$), NNE ($11^{\circ} - 21^{\circ}$), NE ($21^{\circ} - 59^{\circ}$), ENE ($59^{\circ} - 79^{\circ}$) and EW ($79^{\circ} - 105^{\circ}$)). These density maps with specific lineament orientation groups will be referred to as filtered density maps or density map of specific orientation.

Density maps, based on lineament count, were made using the lineation gridding tool in RockWorks Utilities. Different grid cell sizes (node spacing) were used for the whole project area (.333 square mile for all orientations and 0.125 square mile for the specific orientations) and the Cayuga subset (.05 square miles). The density grid files were then exported from RockWorks, converted into format that could be imported into Surfer utilizing MatLab (see code in appendix III) and imported into Surfer 8 (Golden Software) for its better contouring capabilities. Maps were then created for all orientations and for specific orientations; two additional maps show a density grid from all lineament orientations with lineaments and roads overlaid (Figures: 5.19 – 5.32 and S5.11 – S5.31).

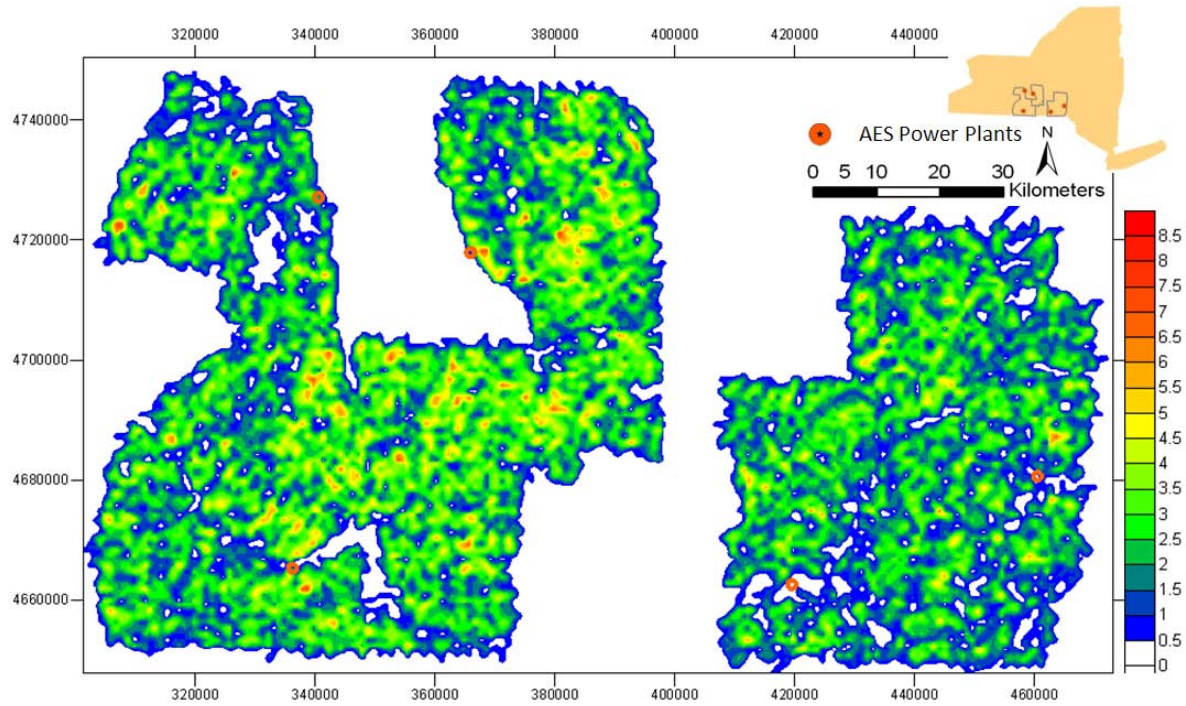


Figure: 5.19 – Lineament density map from all ASTER lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meter in UTM (N18) projection system, Phase II, entire project area

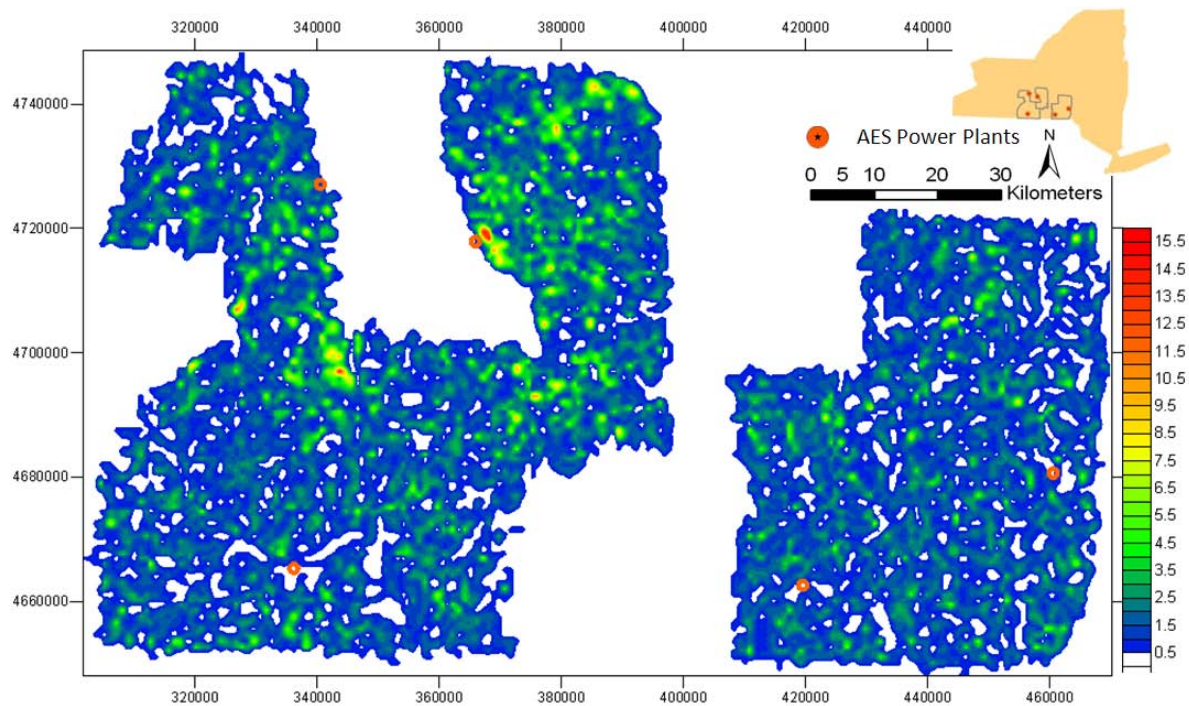


Figure: 5.20 –Lineament density map from all DEM lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meter in UTM (N18) projection system, Phase II, entire project area

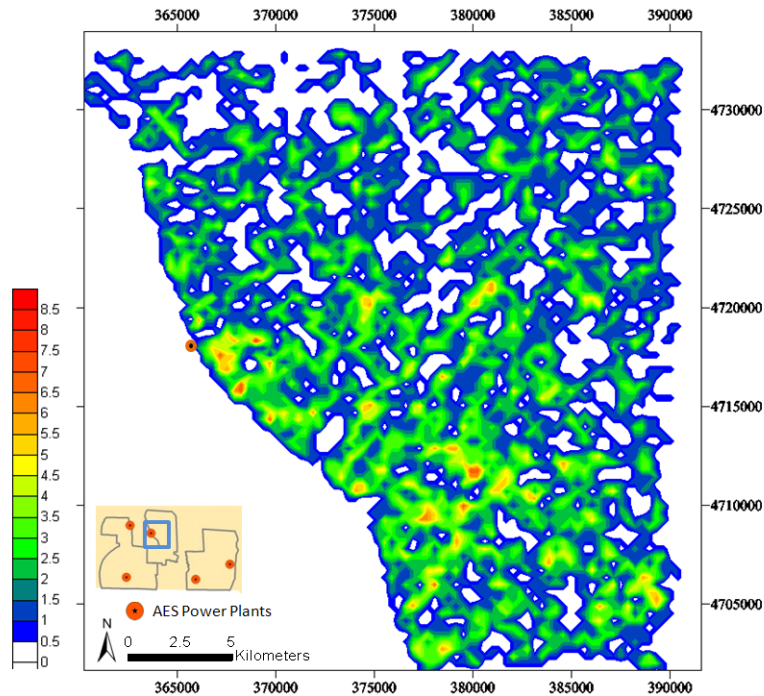


Figure: 5.21 – Lineament density map from All ASTER lineaments, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

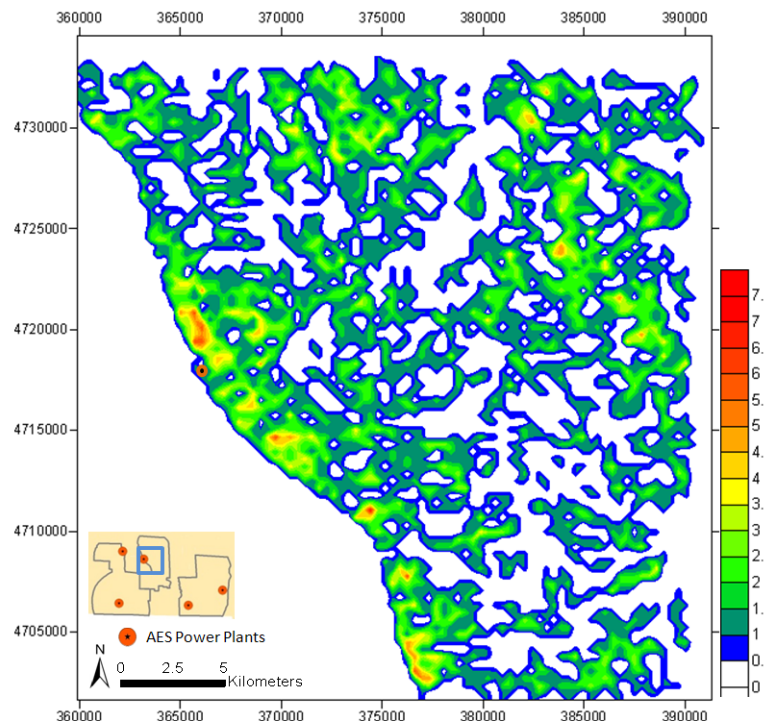


Figure: 5.22 – Lineament density map from All DEM lineaments, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

Various lineament density trends were identified on both the ASTER and DEM density maps; these are along color changes of high (oranges and reds) or low (blues and greens) lineament densities. In the project area the ASTER lineament density trends identified includes NE, NS, NNW, ENE and NW and the DEM lineament density map revealed NE, NW, NNW, NS, and NNE lineament density trends (Table 5.8 and Figures: 5.19, 5.20, 5.23 – 5.31). In the Cayuga Subset the ASTER lineament density trends identified includes NE and NS. The DEM lineament density map revealed NS, NW, NNW and NE lineament density trends (Table: 5.8 and Figures: 5.21, 5.22, 5.32 – 5.40). The filtered lineament density maps provided the most insight into the spatial distribution of the lineaments based on density trends and clustering of the lineaments.

For the project area, the most identified lineament density trend was NE, the second was NS, the third was NNW. The NE density trend was expected since it is the primary trend of the rose diagrams and is related to regional faults (Jacobi, 2002). The typical secondary NW trend from the rose diagrams was replaced by the NS density trend as an un-expected secondary trend based on ASTER or DEM lineaments. These NS density trends could be related to NS faults that are recorded in NYS by Murphy (1981) and Bradley et al. (1941).

The most identified density trends for the Cayuga subset was NS and NE. The NS trends in this region are typical for the regional geology and correspond to the right-lateral Cayuga Lake Fault Murphy (1981) and the prominent NS valleys observed on EarthSat (1997). The NE density trend was expected and relates to regional faults mapped by Jacobi (2002).

In addition to identifying trends and clusters we can formulate a relationship between the orientations displayed on the filtered density maps and the trends that are recognized. These trends are either sub-parallel or sub-perpendicular to the filtered density orientations. I deduce

that sub-parallel lineaments (e.g. NE trends identified on the NE filtered density map) are related to regional faults; and sub-perpendicular lineaments (e.g. NS trends identified on the NE filtered density map) are related to regional fractures.

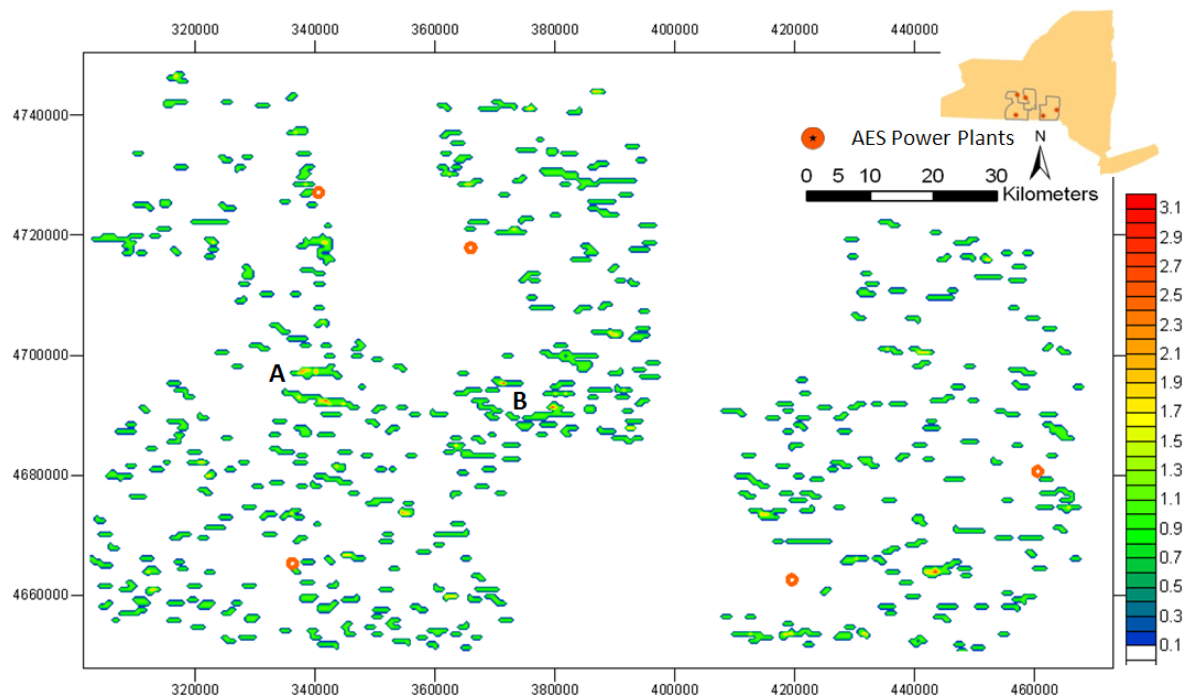


Figure: 5.23 – Lineament density map from EW ASTER lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meter in UTM (N18) projection system, Phase II, entire project area (Letters indicate areas with clusters described text)

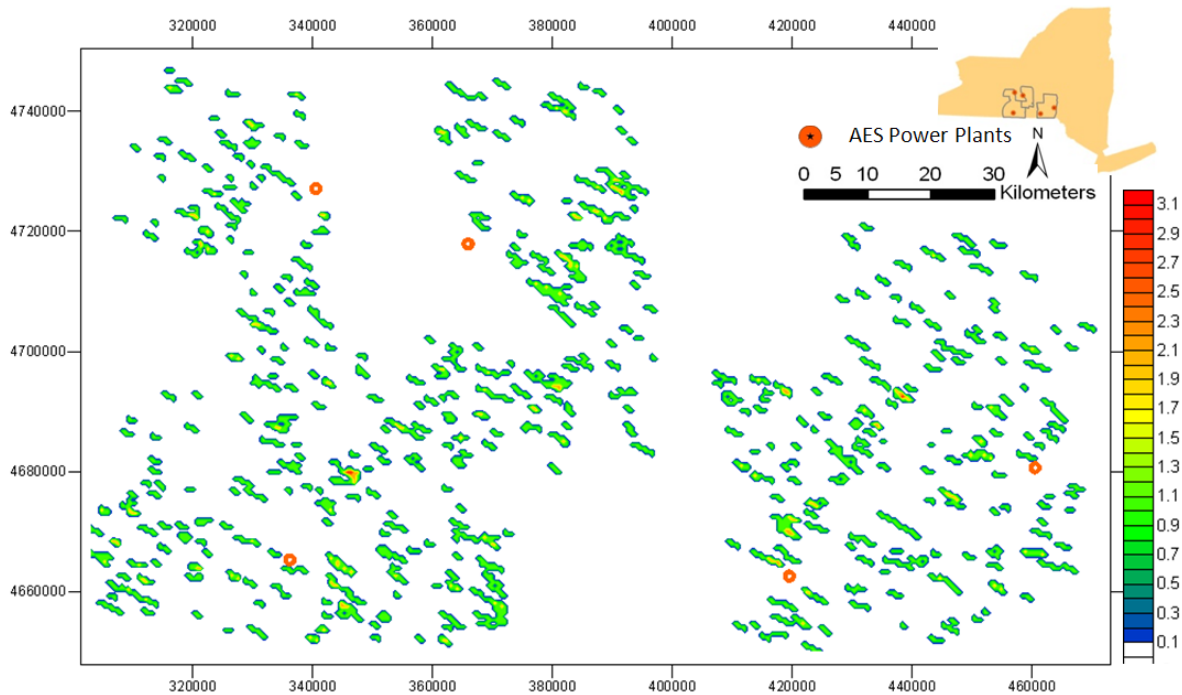


Figure: 5.24 – Lineament density map from WNW ASTER lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meter in UTM (N18) projection system, Phase II, entire project area

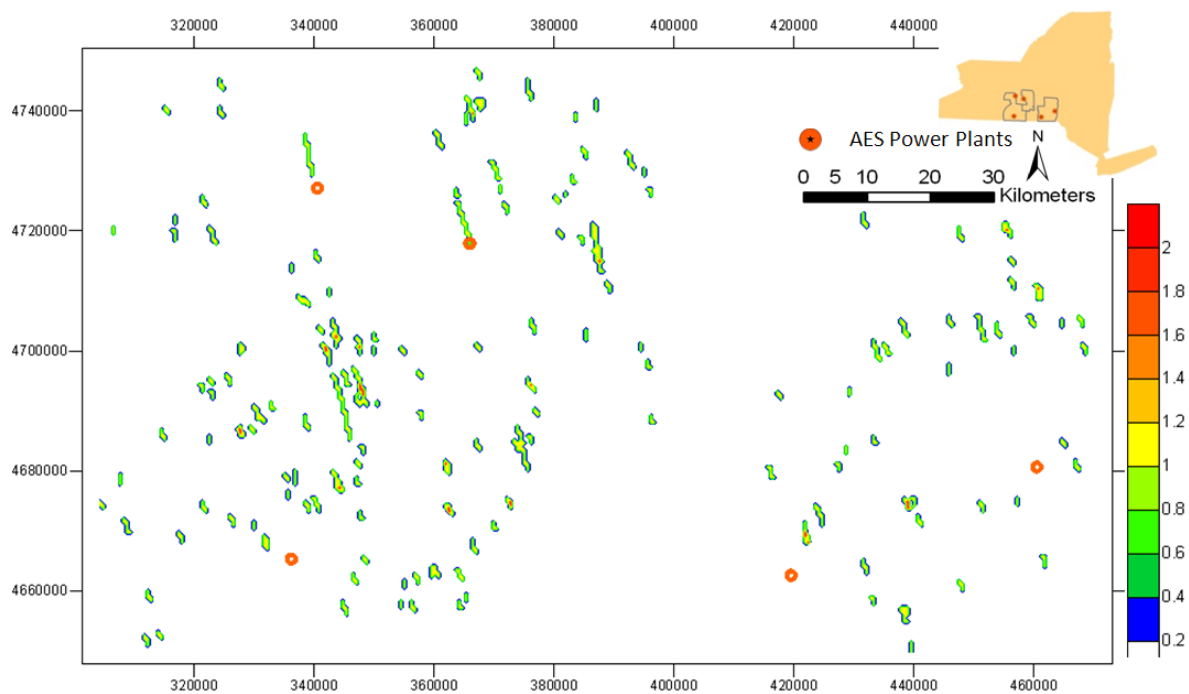


Figure: 5.25 – Lineament density map from NNW ASTER lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase II, entire project area

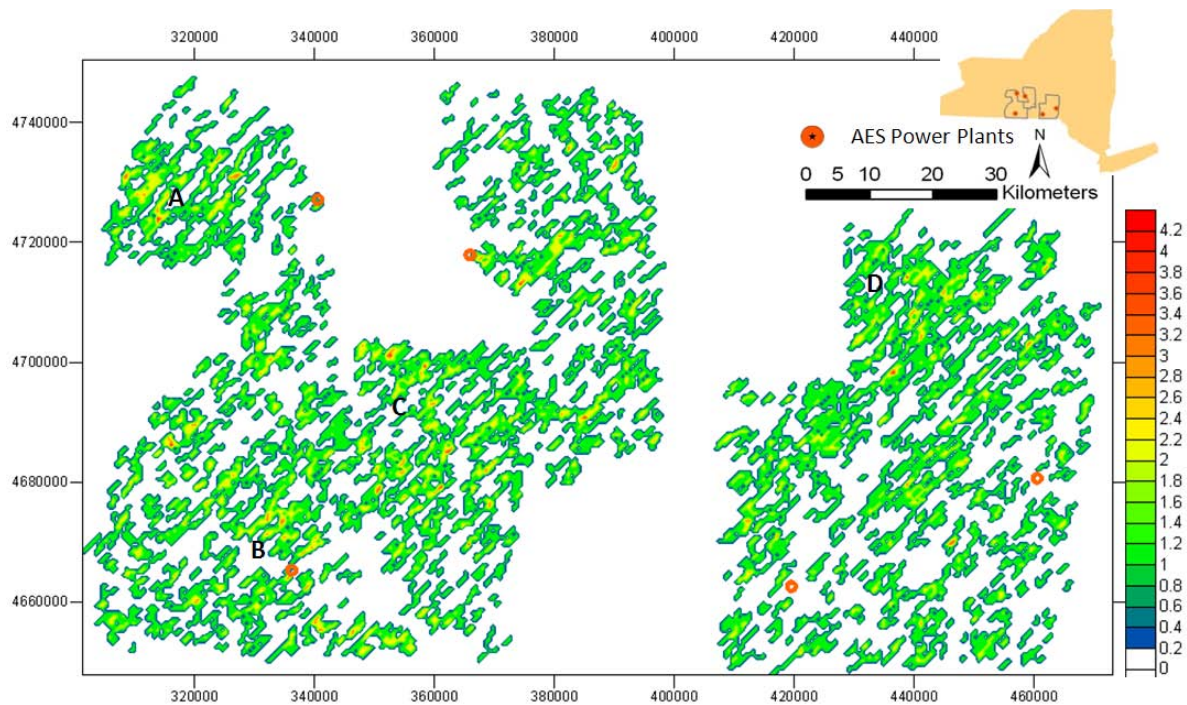


Figure: 5.26 – Lineament density map from NE ASTER lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meter in UTM (N18) projection system, Phase II, entire project area (Letters indicate areas with clusters described text)

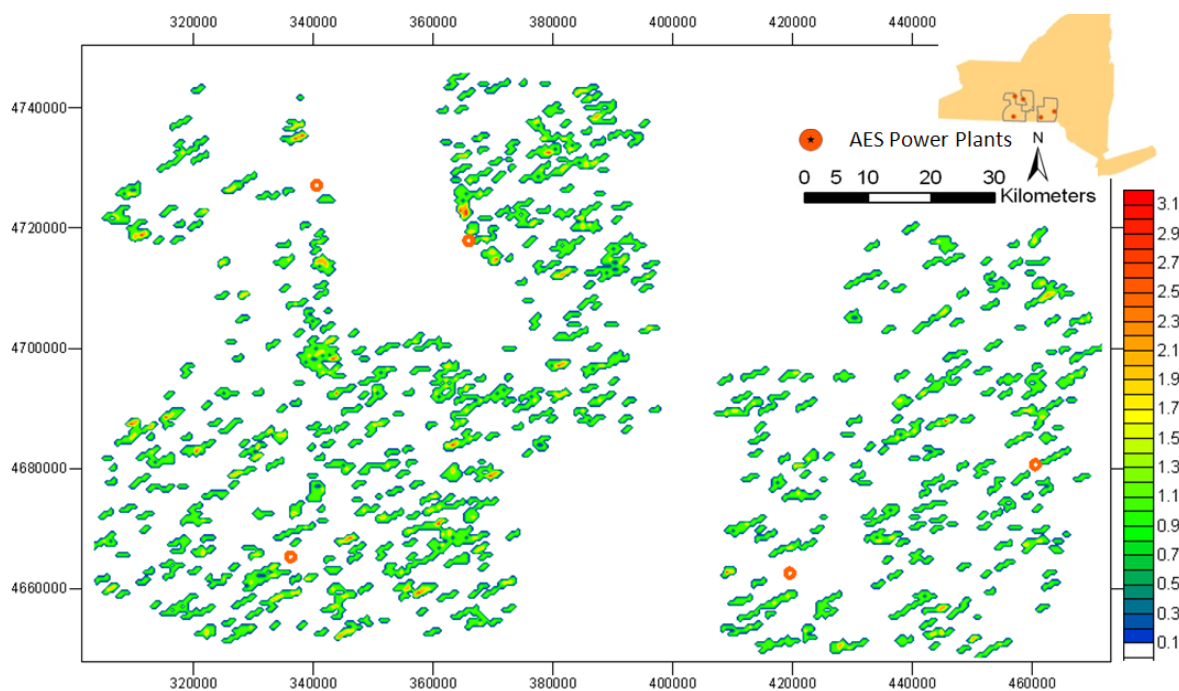


Figure: 5.27 – Lineament density map from ENE ASTER lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase II, entire project area

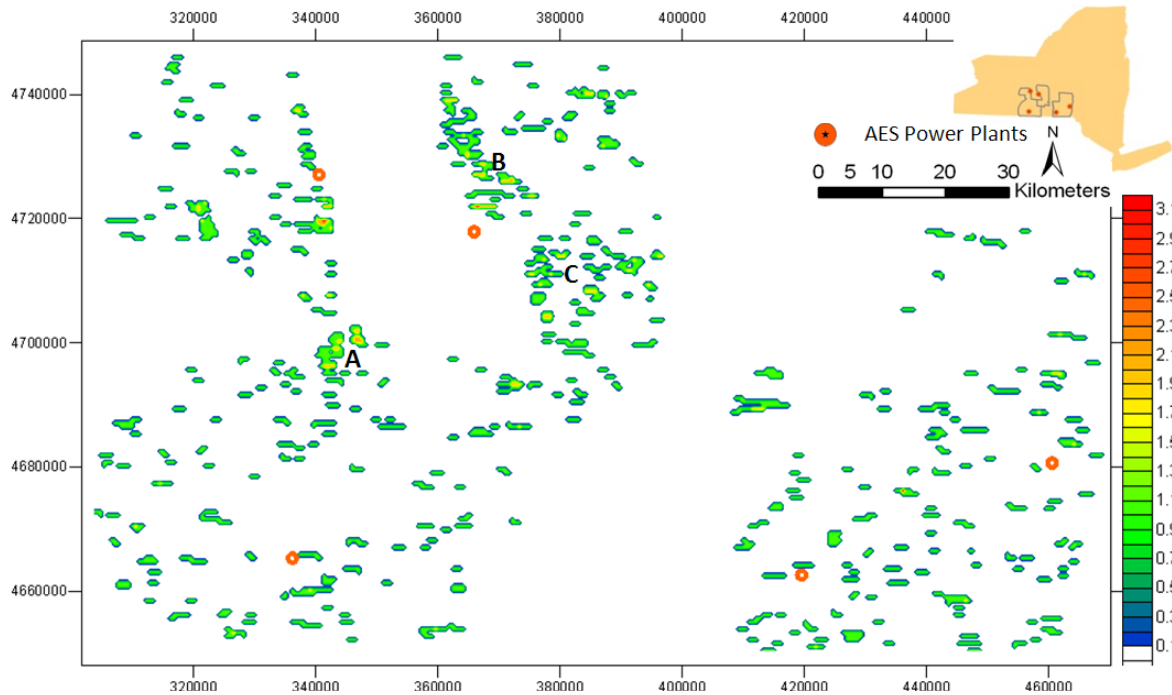


Figure: 5.28 – Lineament density map from EW DEM lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase II, entire project area (Letters indicate areas with clusters described text)

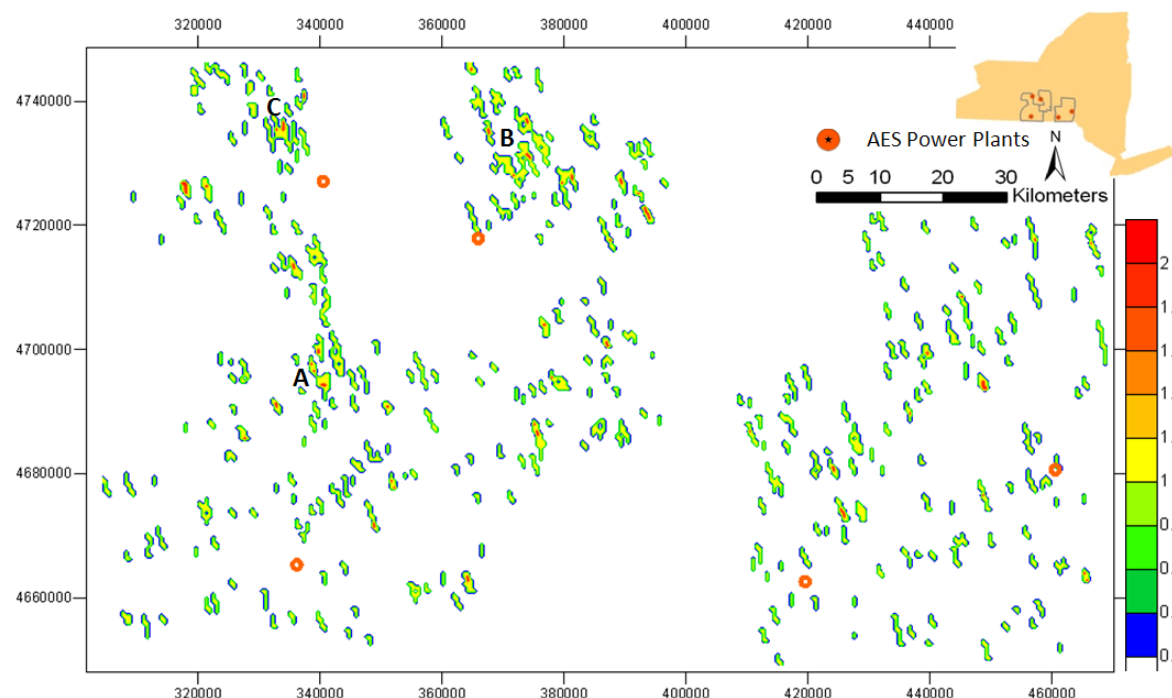


Figure: 5.29 – Lineament density map from NNW DEM lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase II, entire project area (Letters indicate areas with clusters described text)

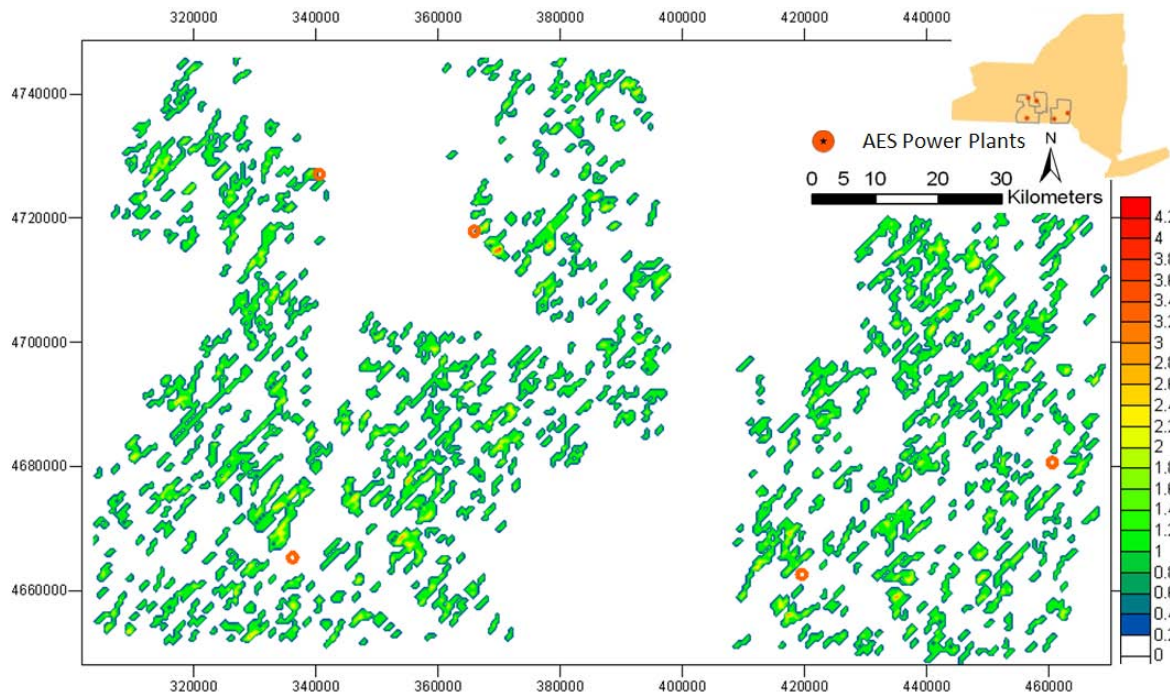


Figure: 5.30 – Lineament density map from NE DEM lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase II, entire project area

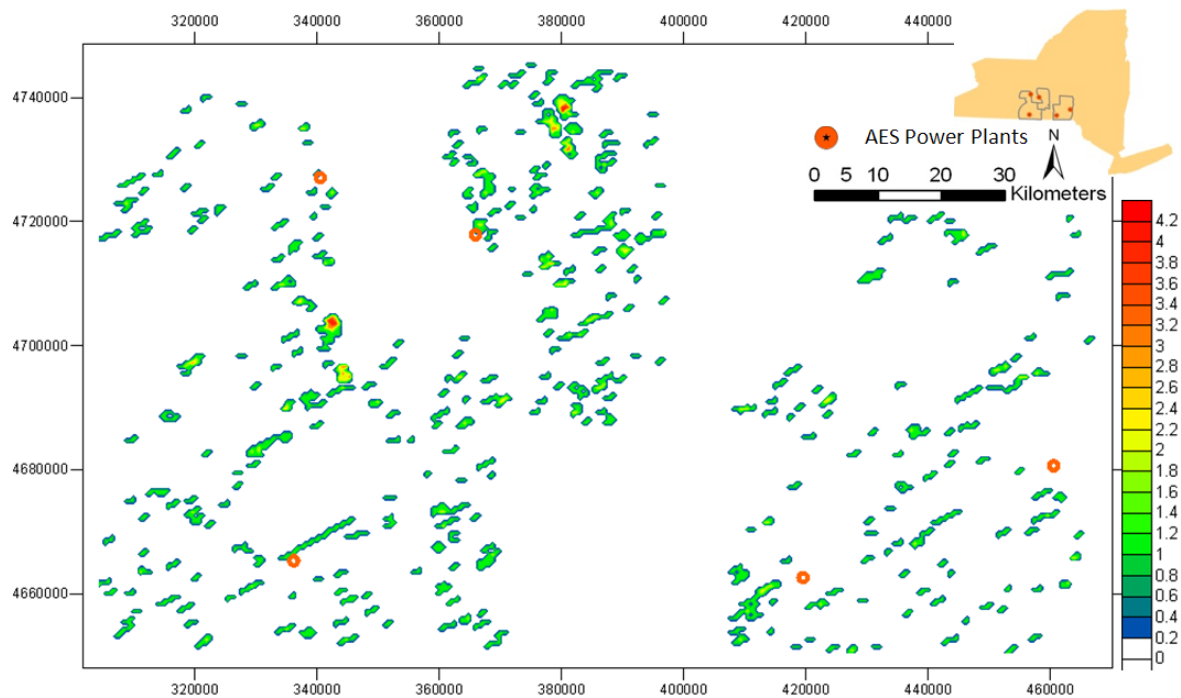


Figure: 5.31 – Lineament density map from ENE DEM lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase II, entire project area

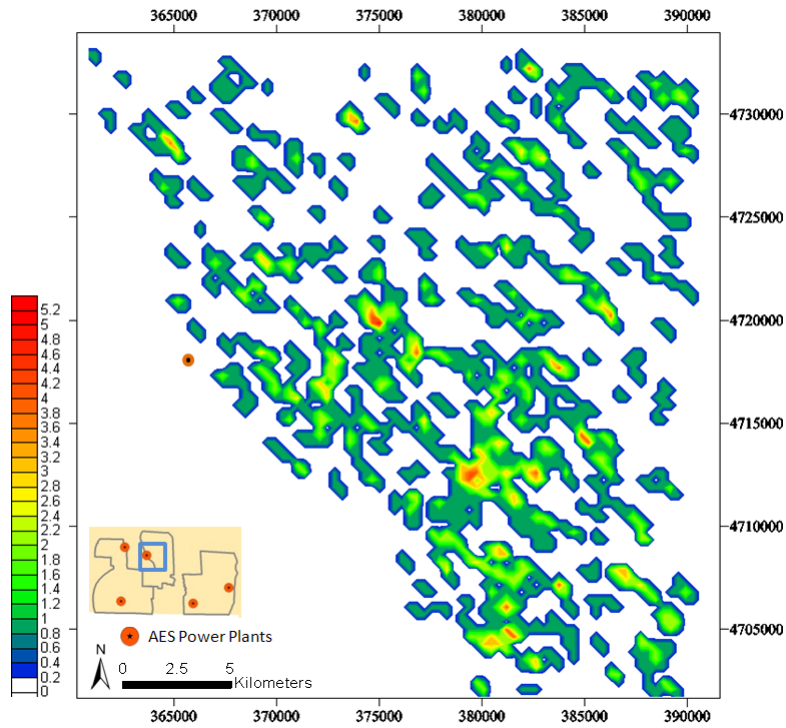


Figure: 5.32 – Lineament density map from NW ASTER lineaments, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

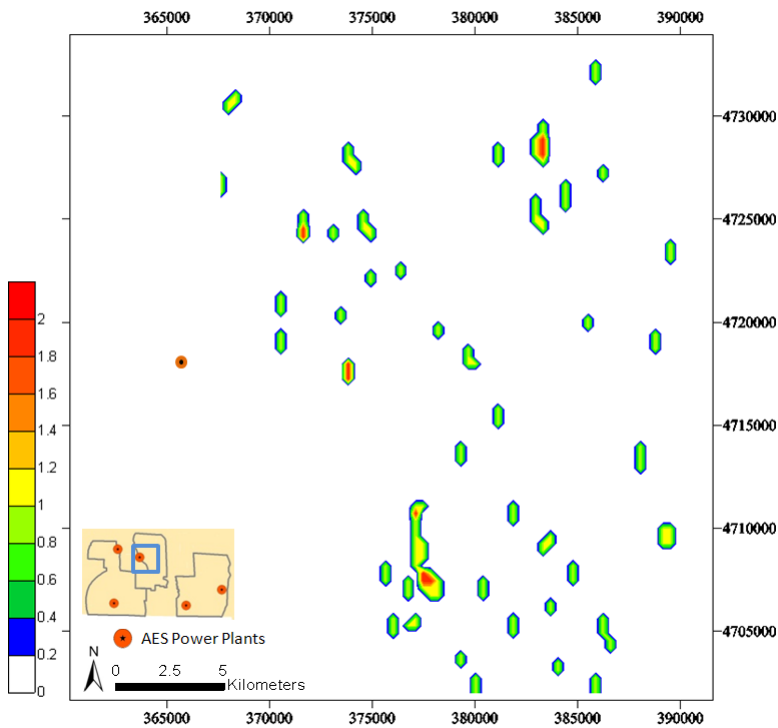


Figure: 5.33 – Lineament density map from NS ASTER lineaments, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

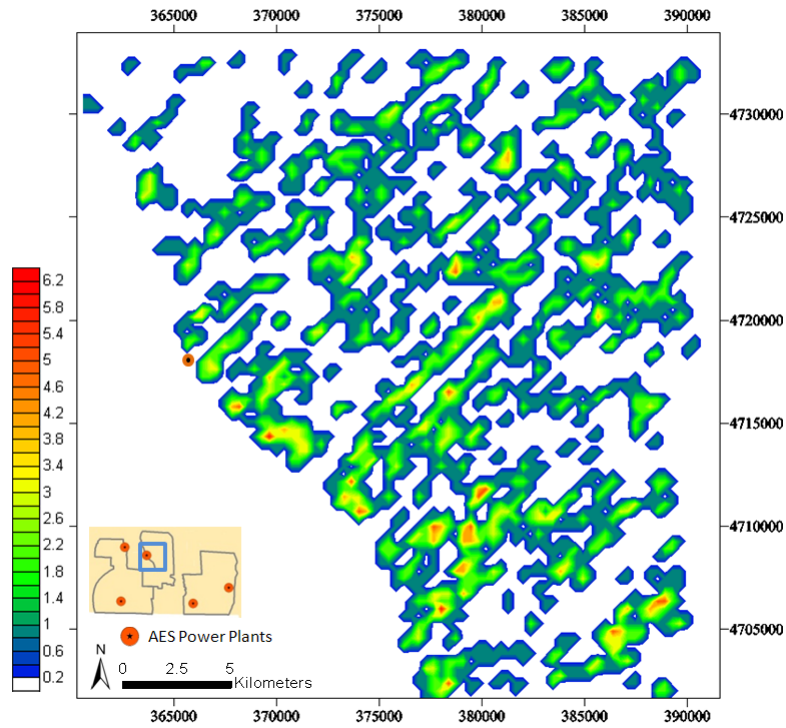


Figure: 5.34 – Lineament density map from NE ASTER lineaments, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

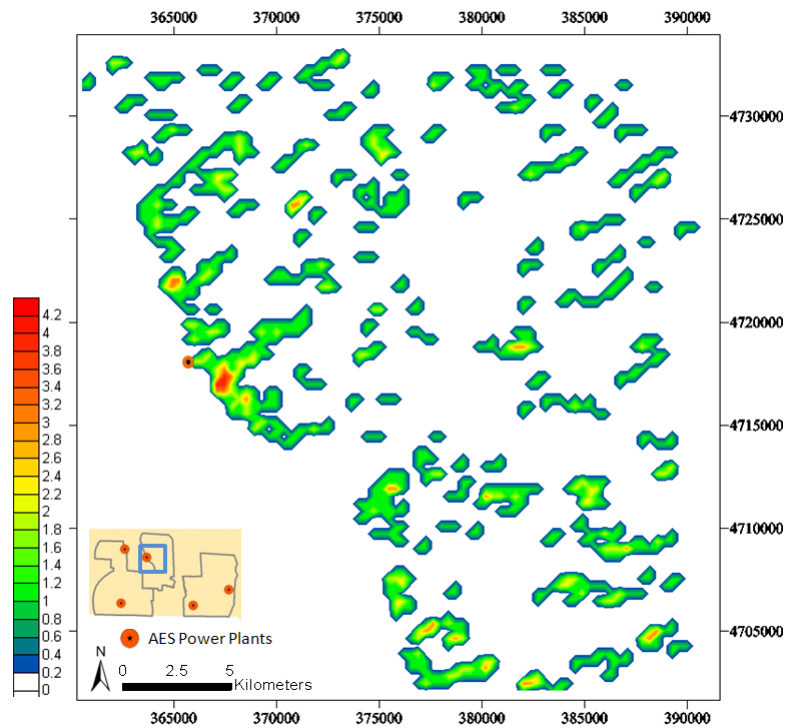


Figure: 5.35 – Lineament density map from ENE ASTER lineaments, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

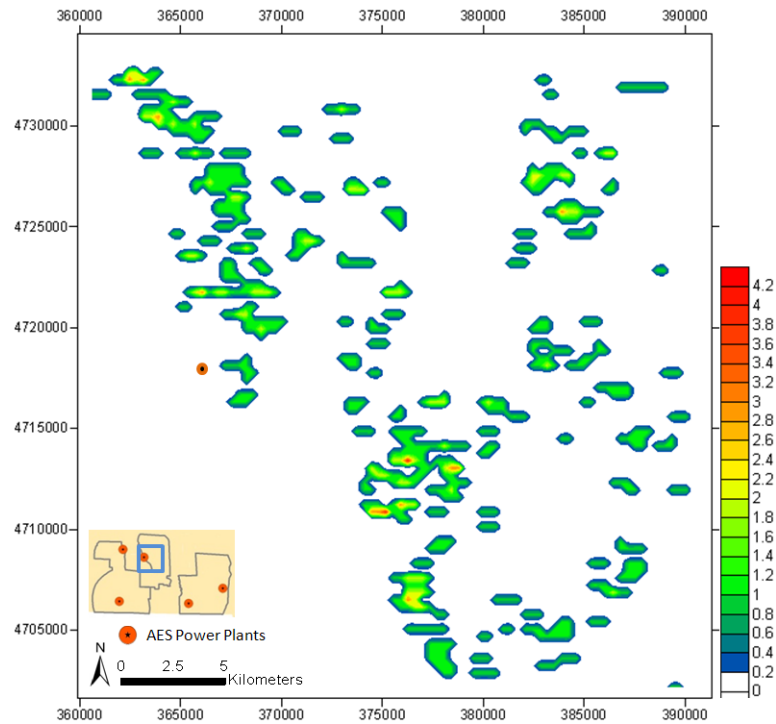


Figure: 5.36 – Lineament density map from EW DEM lineaments, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

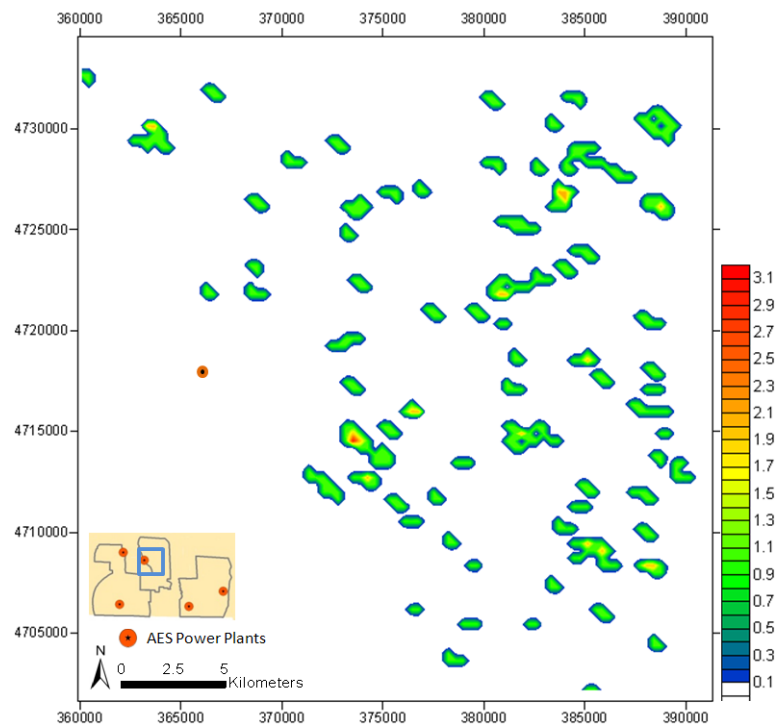


Figure: 5.37 – Lineament density map from WNW DEM lineaments, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

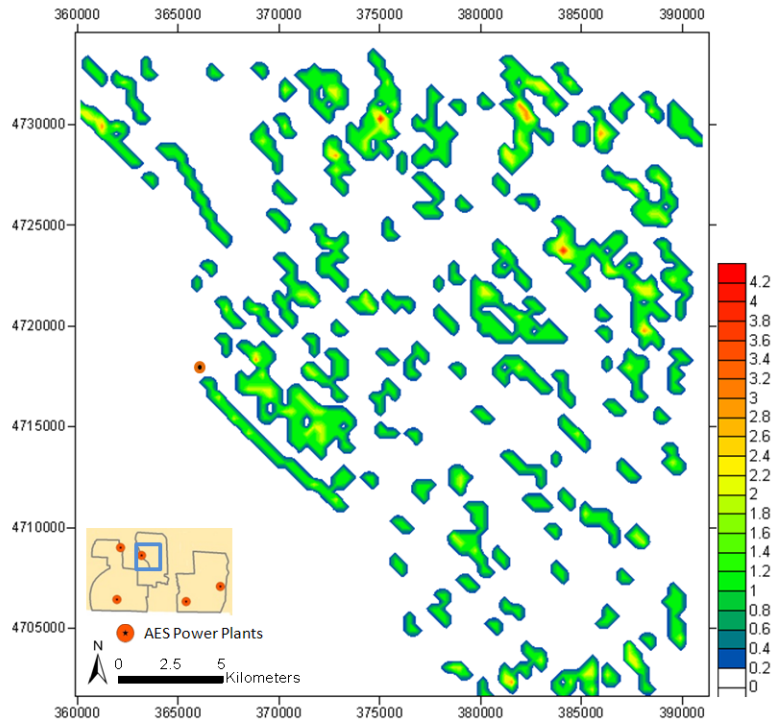


Figure: 5.38 – Lineament density map from NW DEM lineaments, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

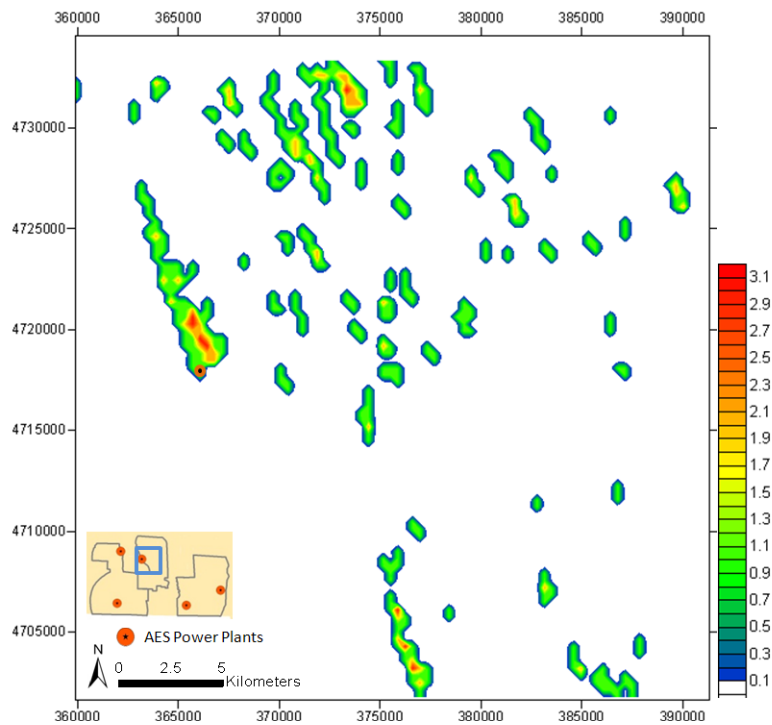


Figure: 5.39 – Lineament density map from NNW DEM lineaments, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

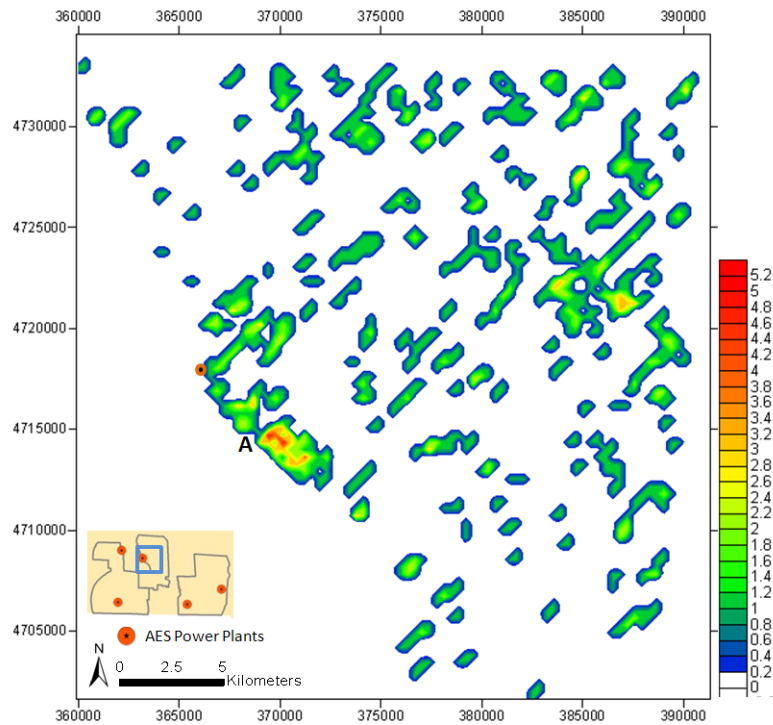


Figure: 5.40 – Lineament density map from NE DEM lineaments, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga Subset (Letters indicate areas with clusters described text)

		Lineament Orientation Groups							
		EW	WNW	NW	NNW	NS	NNE	NE	ENE
		(79° – 105°)	(285° – 301°)	(301° - 335°)	(335° – 350°)	(350° – 11°)	(11° - 21°)	(21° – 59°)	(59° – 79°)
Lineament Density Map (Filtered)	ASTER Project Area								
	All Orientations		X		X	X	X	X	X
	EW	X						X	
	WNW							X	
	NNW				X	X			
	NE			X		X		X	
	ENE			X	X	X		X	X
	DEM Project Area								
	All Orientations			X			X	X	
	EW	X							
	NNW				X	X		X	
	NE				X		X	X	
	ENE			X		X			X
	ASTER Cayuga Subset								
	All Orientations		X			X	X	X	X
	NW			X		X		X	
	NS					X			
	NE					X		X	
	ENE							X	
	DEM Cayuga Subset								
	All Orientations			X	X	X		X	
	EW					X	X		
	WNW			X			X	X	
	NW			X	X	X			
	NNW				X	X			
NE			X				X		

Table: 5.8: Identifies ASTER and DEM lineament trends for the project area and the Cayuga subset; red X's denotes sub-parallel trends and black X's denote sub-perpendicular trends

In addition to identifying lineament density trends, the density maps also identified cluster of lineaments; these were used to locate areas with potential relationships to the region's structural geology. These clusters were easily identified on the filtered lineament density maps across the project area. The filtered density map of EW (79° - 105°) identified two areas of high ASTER lineament densities, the first located (A) southwest of Seneca Lake and the second located (B) south of Cayuga Lake with the possibility of a regional connection (Figure: 5.23). The filtered density map of NE (21° - 59°) lineament orientation displayed four major areas of higher ASTER lineament densities: (A) west of the AES Greenidge power plant, (B) a second one north of the AES Hickling power plant, (C) a third south of Seneca Lake and (D) a fourth one in the northern part of eastern focus area (Figure: 5.26).

The filtered density map of NNW (335° - 350°) DEM lineament orientations identified some clustering in (A) the region just southwest of Seneca Lake, (B) north of the Cayuga power plant and (C) north of the Greenidge power plant (Figure: 5.29). The filtered density map of EW (79° - 105°) DEM lineament orientations identified three lineament clusters – (A) southwest of Seneca Lake and a second (B) north of Cayuga power plant and third (C) east of Cayuga Lake (Figure: 5.28). These EW lineament trends could be related to Alleghanian thrusts evident in the Devonian units and is documented in several locations by Jacobi (2002).

The ASTER and DEM Cayuga subset filtered orientation density maps identified various trends and clusters. The density map of NE (21° - 59°) DEM lineament orientation identified a cluster (A) along the shoreline south of the Cayuga power plant; this can be related to the Auburn Fault Systems or Auburn Fault Extension located around Cayuga, Owasco and Oneida Lakes or drainage related lineaments (Figure: 5.40).

Chapter 6 – Geologic Interpretation

The geologic interpretation of the lineaments was based on fabric and stratigraphic analyses and comparison to previous work. These analyses explored the relationship between my digitized lineaments and the impact of millions of years of tectonics on the structural geology of my study area. The fabric analysis compared my lineaments to fracture, fault and fault zone data and allowed for a limited ground truthing of remotely-sensed lineaments. The stratigraphic analysis investigated lineament variations within depositional units and historical tectonic events.

A. Fabric Analysis

A correspondence between the lineaments and the geologic dataset was established using the method described in section 4.B.2. First, a buffer was made around each structural feature. A lineament was selected if it was contained at least partially within the buffer and its orientation was within 20° of the trend of the buffered structure. The selected lineaments and the corresponding structural geological features are summarized in the fabric compilation tables (Tables: 6.1 – 6.4).

1. Fractures

Set I & set II fracture data from Engelder and Geiser (1979, 1980) were imported into Arc GIS by digitizing the field site locations and fracture trends from figures 3 and 6 in Engelder and Geiser (1980). Fractures were represented by 5 km-long linear features, which were oriented along the fracture trend. To establish a relationship between the fractures and the ASTER lineaments, 1 km buffer zones were created around these linear features corresponding to the

fractures. Finally the ASTER lineaments that are fully or partially within these buffers and within 20° of the fracture trends were identified. The selected ASTER lineaments and the corresponding fracture sites were then used to generate the fabric tables, as well make maps and rose diagrams for the entire project area, western focus area, central focus area and eastern focus area (Figures: 6.1 and S6.1 – S6.5). The fabric compilation table (Table: 6.1) shows the number and total length of fracture data and ASTER lineaments within determined orientations of EW (259° – 281°), WNW (281° – 304°), NW (304° – 326°), NNW (326° – 348°), NS (348° – 11°), NNE (11° – 34°), and ENE (56° – 79°). Since no fracture distribution data was available from the author, a uninformed, equally spaced and unbiased orientation grouping of approximately 22° was used. For the eight orientation groups the 180° was equally divided among them. This was used for the fracture data in both rose diagrams and table.

The Set I fracture data was similar to the ASTER lineaments in the NNW (326° - 348°) and NW (304° - 326°); these similarities are based on trend degrees that match. The ENE (56° – 79°) and EW (259° – 281°) orientation groups show the most similarity between the ASTER lineaments and the Set II fracture data. The rose diagrams for the selected lineaments used in this fabric analysis were very similar to the fracture data; this similarity suggests a relationship between the ASTER digitized lineaments and the fractures in the project area. This close similarity between rose diagrams is not recognized in either the fault or fault zone data.

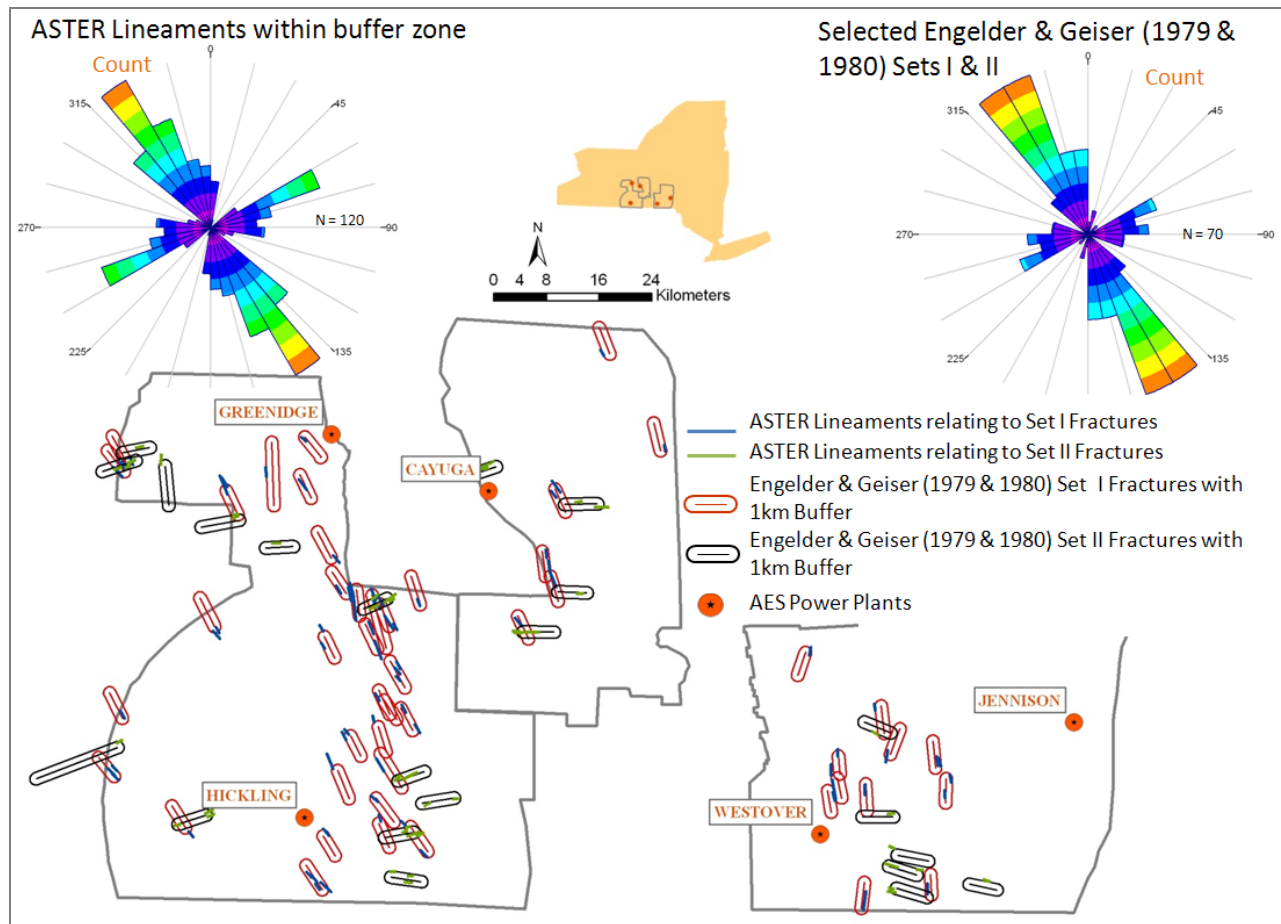


Figure 6.1: Engelder & Geiser (1979 & 1980) Set I & II fractures with 1 km buffer and corresponding ASTER lineaments (digitization scale: 1:125,000; Phase II), rose diagrams of selected lineaments and fractures, based on count

Fractures	EW		WNW		NW		NNW		NS		NNE		ENE	
	# of Fractures	Length (km)	# of Fractures	Length (km)	# of Fractures	Length (km)	# of Fractures	Length (km)	# of Fractures	Length (km)	# of Fractures	Length (km)	# of Fractures	Length (km)
Engelder & Geiser (1979) Set I					11	Data Point	25	Data Point	10	Data Point	2	Data Point		
Engelder & Geiser (1979) Set II	8	Data Point	3	Data Point					1	Data Point			10	Data Point
ASTER Lineaments	Count	Length (km)	Count	Length (km)	Count	Length (km)	Count	Length (km)	Count	Length (km)	Count	Length (km)	Count	Length (km)
ALL	127	212	215	412	253	473	100	180	77	134	138	238	255	462
Engelder & Geiser (1979) Set I					23	33	36	61	16	29	2	3		
Engelder & Geiser (1979) Set II	13	21	5	8					1	2			27	40

Table: 6.1 – Fabric compilation table, based on fracture measurements from Engelder and Geiser (1979, 1980). ASTER lineaments within the buffer and 20° of fracture trends are selected, number of lineaments and fractures (count) and total length (km) are shown

Other datasets used in the fabric compilation table were from Terech (2006), McGuire (2007) and Jacobi (2007). These datasets contained point data representing the field sites at which fracture frequencies were recorded. A buffer was applied around each point with a radius of 1 km. ASTER Lineaments within this buffer and corresponding to the fracture orientation were used in the fabric compilation table (Table: 6.2) and recorded the number and total length of ASTER lineaments within fracture sites.

The following orientation groups were computed and published by the author and were used during their own research for data distribution. For the Terech (2006) data, I used orientations of EW ($265^{\circ} - 277^{\circ}$), WNW ($277^{\circ} - 322^{\circ}$), NW ($322^{\circ} - 342^{\circ}$), NS ($342^{\circ} - 7^{\circ}$), NNE ($7^{\circ} - 45^{\circ}$), and ENE ($45^{\circ} - 85^{\circ}$). For McGuire (2007), I used orientations of EW ($265^{\circ} - 282^{\circ}$), WNW ($282^{\circ} - 304^{\circ}$), NW ($305^{\circ} - 323^{\circ}$), NNW ($323^{\circ} - 344^{\circ}$), NS ($345^{\circ} - 9^{\circ}$), NNE ($9^{\circ} - 40^{\circ}$), NE ($41^{\circ} - 55^{\circ}$), and ENE ($56^{\circ} - 84^{\circ}$).

This analysis revealed a relationship between the fracture data from Terech (2006) and McGuire (2007) with the ASTER digitized lineaments. The most similar trend when comparing these datasets is NNE and then a secondary trend of WNW. These similarities in trends are unique to this dataset and do not appear in any other datasets. This can be explained with the location of available the data from Terech (2006) and McGurire (2007). These datasets were recorded only in the northern and central part of the eastern focus area and covered a very small region of the project area.

Fracture	EW		WNW		NW		NNW		NS		NNE		NE		ENE	
	Count	Length (km)	Count	Length (km)	Count	Length (km)	Count	Length (km)	Count	Length (km)	Count	Length (km)	Count	Length (km)	Count	Length (km)
McGurie (2007) (ALL)	11	22	42	93	54	119	16	32	18	31	66	149	47	136	37	71
McGurie (2007) (<2)	1	2	16	40	13	33	2	3	6	9	37	83	1	1.5	5	8
McGurie (2007) (2>4)	0	0	11	26	5	12	1	1	4	13	26	73	1	5	3	7
McGurie (2007) (>4)	0	0	10	26	6	14	4	11	5	13	8	25	0	0	3	5
Terech (2006) (ALL)	6	12	20	54	4	11			3	4	9	27			12	29
Terech (2006) (<2)	1	1	16	45	2	4			0	0	6	20			1	1
Terech (2006) (2>4)	0	0	18	51	2	7			1	1	9	27			1	2
Terech (2006) (>4)	0	0	16	48	1	2			0	0	7	18			0	0
Total	19	37	149	383	87	202	23	47	37	71	168	422	49	142.5	62	123

Table 6.2 - Fabric compilation table, based on fracture measurements from Terech (2006) and McGuire (2007). ASTER lineaments within 1 km buffer and 20° of fracture trends are selected, number of lineaments and fractures (count) and total length (km) are shown

2. Faults

The lineaments digitized from ASTER imagery were compared to fault data from Bradley et al. (1941), Murphy (1981), Isachsen and McKendree (1977), and Jacobi and Fountain (2007). ASTER lineaments were selected using 1km buffer around faults and within 20° of the fault trend. These selected ASTER lineaments and the fault data were then used to make maps and rose diagrams for the entire project area, western focus area, central focus area and eastern focus area (Figures: 6.2 and S6.6 – S6.10). The fabric compilation table (Table: 6.3) shows the number and total length of selected fault data and ASTER lineaments within determined orientations of EW (259° – 281°), WNW (281° – 304°), NW (304° – 326°), NNW (326° – 348°), NS (348° – 11°), NNE (11° – 34°), NE (34° – 56°), and ENE (56° – 79°). Since no fault distribution data was available from the authors, an uninformed equally spaced and unbiased orientation grouping of approximately 22° was used. For the eight orientation groups the 180° was equally divided among them. This was used for the fault data in both rose diagrams and tables.

The fabric compilation table examines the relationship between ASTER lineaments and fault data from Bradley et al. (1941), Murphy (1981), Isachsen and McKendree (1977), and

Jacobi (2007). The fabric compilation table identified the ENE orientation group as the primary trend and the NNE orientation group as the secondary trend. These orientation groups contained the highest number of matched lineaments to faults. The relationship between the faults and ASTER lineaments in the ENE secondary trend is clearly a result of the multiple long ENE trends in the western border of the western focus area. The NNE trend is strong in the eastern and western focus areas with multiple long NNE trending faults from Jacobi (2007). A relationship between ASTER lineaments and the NE faults can be visually identified in the project area map and is more substantial in the central focus area.

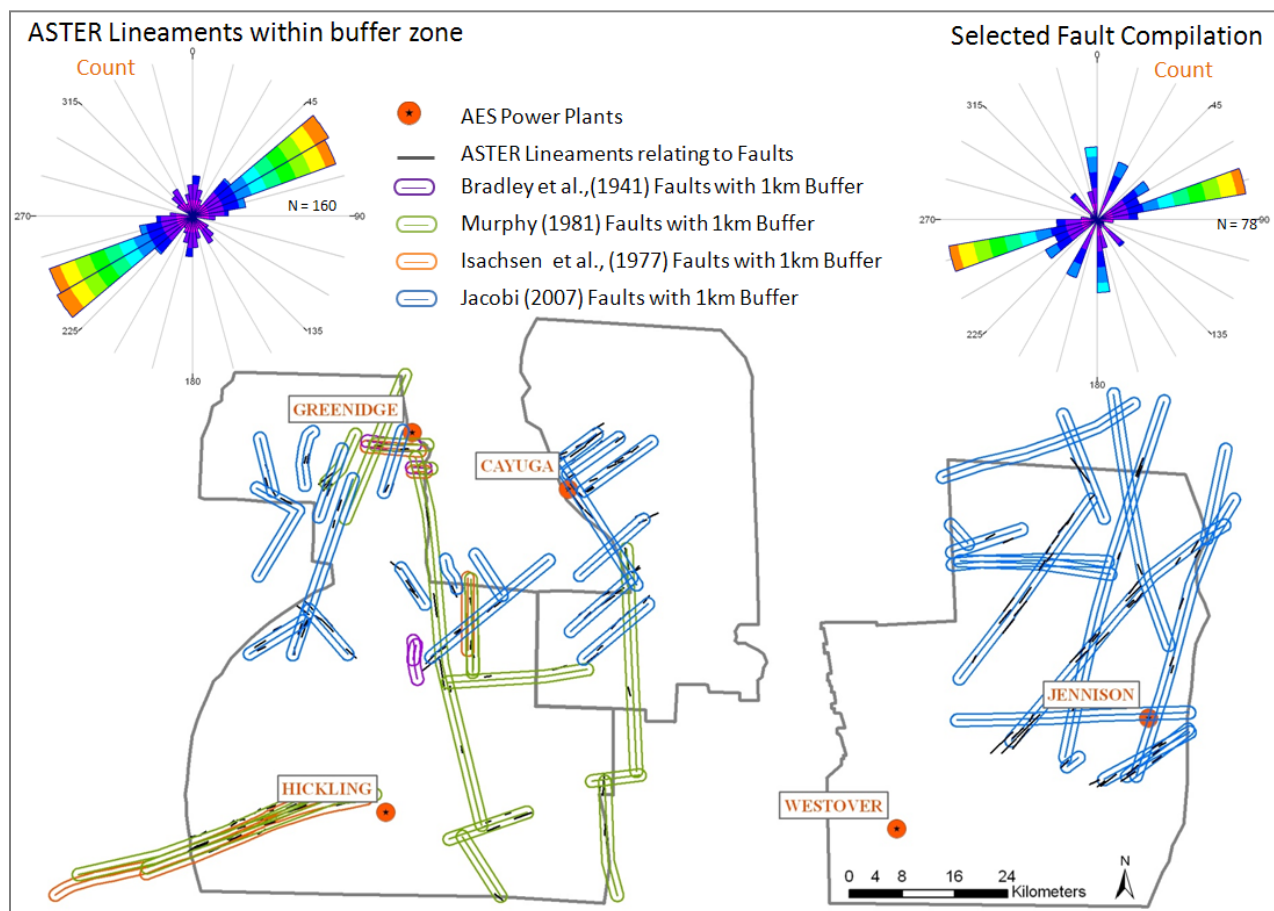


Figure 6.2: Selected faults from Bradley et al. (1941), Murphy (1981), Isachen et al. (1977), and Jacobi (2007) with 1 km buffer and corresponding ASTER lineaments (digitization scale 1:125,000; Phase II), rose diagrams of selected lineaments and faults, based on count

Fault Data	EW		WNW		NW		NNW		NS		NNE		NE		ENE	
	# of faults	Length (km)	# of faults	Length (km)	# of faults	Length (km)	# of faults	Length (km)	# of faults	Length (km)	# of faults	Length (km)	# of faults	Length (km)	# of faults	Length (km)
Isachsen and McKendree (1977)	2	10							1	12					2	85
Murphy (1981)	3	45					1	11	5	146	2	35			2	80
Bradley et al. (1941)	2	10														
Jacobi (2007)			1	7	3	40	4	74	1	9	6	197	3	65	10	136
ASTER Lineaments	Count	Length (km)	Count	Length (km)	Count	Length (km)	Count	Length (km)	Count	Length (km)	Count	Length (km)	Count	Length (km)	Count	Length (km)
ALL	118	203	203	390	275	535	104	189	87	154	133	245	390	792	270	474
Isachsen and McKendree (1977)	3	1							2	1					15	24
Murphy (1981)	9	15					1	2	16	32	4	9			27	41
Bradley et al. (1941)	3	3														
Jacobi (2007)			1	2	16	30	6	13	2	2	30	56	27	65	53	92

Table: 6.3 – Fabric compilation table, based on faults mapped by Bradley et al. (1941), Murphy (1981), Isachsen et al. (1977), and Jacobi (2007). ASTER lineaments within 1 km buffer and 20° of fracture trends are selected, number of lineaments and faults (count) and total length (km) are shown

3. Fault Zones

The ASTER digitized lineaments were also compared to the known fault zone data from Bradley et al. (1941) and Jacobi, (2002). ASTER lineaments within a 1 km buffer of the known fault zone and within 20° of the average fault zone trend were included in the analysis. Maps and rose diagrams illustrate orientations for the known fault zone data and corresponding to ASTER lineaments for the project area (Figures: 6.3 and S6.11 – S6.13). The fabric compilation table (Table 6.4) shows the number and total length of known fault data and ASTER lineaments within determined orientations of EW (259° – 281°), NW (304° – 326°), NE (34° – 56°), and ENE (56° – 79°). Since no fault zone distribution data was available from the authors, an uninformed equally spaced and unbiased orientation grouping of approximately 22° was used. For the eight orientation groups, the 180° was equally divided among them. The dataset only covered four of the eight orientation groups. This was used for the fault zone data in both rose diagrams and table.

The fault zone data for Bradley et al. (1941) and Jacobi (2002) matched a primary trend of ENE and a secondary trend of NE based on both the rose diagrams and the fabric compilation table. This analysis showed a similarity between fault zones and my lineaments with regard to the dominant structural orientations of ENE in fault zones and NE in my lineaments. The close proximity of the two trends suggests the presence of a dominant northeastern-trending structural trend.

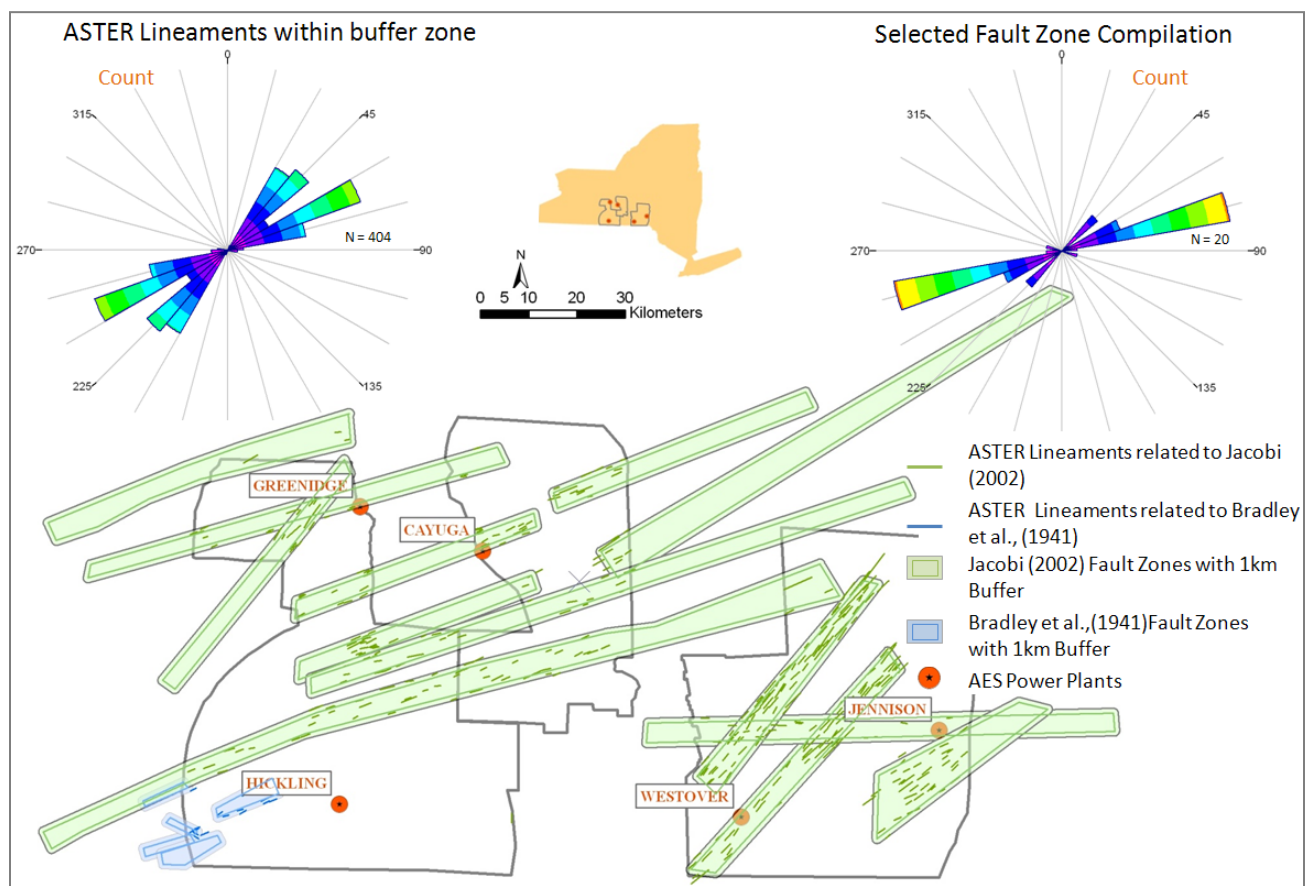


Figure 6.3: Selected fault zones from Bradley et al. (1941) and Jacobi (2002) with 1 km buffer and corresponding ASTER lineaments (digitization scale 1:125,000; Phase II), rose diagrams of selected lineaments and fault zones, based on count

Fault Zones	EW		NW		NE		ENE	
	# of Zones	Length (km)	# of Zones	Length (km)	# of Zones	Length (km)	# of Zones	Length (km)
Bradley et al. (1941)			1	8			4	53
Jacobi (2002)	1	99			3	185	9	776
ASTER Lineaments	Count	Length (km)	Count	Length (km)	Count	Length (km)	Count	Length (km)
ALL	188	333	504	939	710	1449	307	553
Bradley et al. (1941)			2	3			16	26
Jacobi (2002)	15	25			168	400	204	378

Table: 6.4 – Fabric compilation table, based on faults zones mapped by Bradley et al. (1941) and Jacobi (2002). ASTER lineaments within 1 km buffer and 20° of fault zone trends are selected, number of lineaments and fault zones (total count) total length (km) are shown

B. Stratigraphic Analysis

Within stratigraphic units, various tectonic stresses were recognized and related to various major tectonic events (Isachsen et al., 1991). The stratigraphic units (Hamilton, Tully, Genesee, Sonyea and West Falls Groups) exposed in the study area recorded one major orogenic event – the Alleghanian Orogeny. Some minor changes in applied stresses can be recorded in specific units with unique lithology and overall burial conditions that include pressure and temperature that may vary over time. This analysis examines the local stratigraphy to identify minor lineament orientation variations using rose diagrams for the following three stratigraphic units: (1) Hamilton Group (2) Tully, Genesee or Sonyea Group (mapped as a single group) and (3) West Falls Group exposed in the project area.

The stratigraphic analysis investigated the relationship between the orientation of ASTER lineaments and the surface extent of specific depositional groups. I divided the digitized lineaments into the three stratigraphic units based on the geologic map (Isachsen et al., 1991). Then rose diagrams of lineament orientations were drawn for each of the three stratigraphic layers: (1) the Hamilton Group with a total of 336 lineaments, (2) the Tully Ls, Genesee and

Sonyea Groups with a total of 4,217 lineaments and (3) the West Falls Group with a total of 3,267 lineaments (Figures: 6.4 and S6.14 – S6.15)

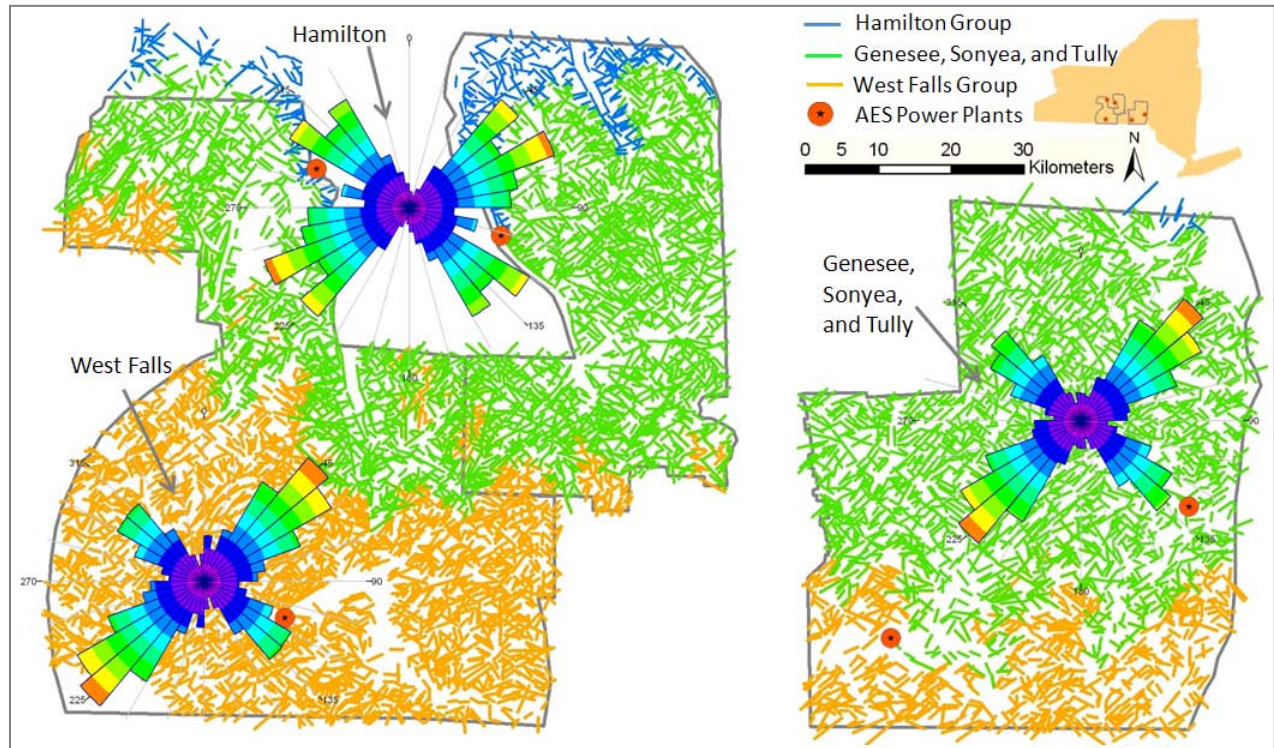


Figure 6.4: ASTER lineaments within different geologic units (Hamilton, Tully, Genesee, Sonyea and West Falls) with different colors corresponding to the different units, Hamilton group (blue), Tully, Genesee and Sonyea groups (green) and West Fall group (orange). Rose diagrams of lineament orientations are also shown.

The Hamilton Group, a much smaller unit compared to the other two, had a primary trend of 63° (ENE) with a secondary trend of 45° (NE) and a third trend of 305° (NW). The Genesee, Sonyea and Tully rose diagram and West Falls rose diagrams has a primary trend of 45° (NE) and the secondary trend of 310° (NW). These trends are more similar to other ASTER lineaments rose diagrams drawn throughout this project. The similarities between the lithology and tectonic history of the Hamilton, Tully, Genesee, Sonyea and West Falls Groups hindered the ability to identify unique lineament trends within the rose diagrams of units in the project area.

	Primary Trend	Secondary Trend
Project Area		
Hamilton Group	ENE (65°)	NW (305°)
Genesee, Sonyea and Tully	NE (45°)	NW (315°)
West Falls Group	NE (45°)	NW (310°)

Table: 6.5 - Identifies the primary and secondary trends of ASTER digitized lineaments for the each of the geological groups in the stratigraphic analysis

C. Comparison to Previous Work

Results from this work were compared with previous work done in the same region. Isachsen and McKendree (1997) used Landsat imagery to map linear features across NYS. In 1997 the EarthSat project also mapped lineaments across NYS utilizing Landsat imagery. Cruz (2005) used fused ASTER and Landsat images using Principle Component Analysis applying a similar image processing techniques and digitizing methodology and criteria to map lineaments around Seneca Lake. This project covered a larger area than the area studied by Cruz (2005) and used improved images and image processing techniques compared to EarthSat (1997) and Isachsen and McKendree (1977). Therefore this project provides a strong dataset for studying lineaments and the structural geology of central NYS with remote sensing.

I used ArcGIS tools to create maps to visualize and compare the spatial relationship among the lineaments of three data sets (Cruz, 2005; EarthSat, 1997; Isachsen and McKendree, 1977) with my ASTER lineaments. A map with the EarthSat (1997), Isachsen and McKendree (1977) and my ASTER lineaments aided in the understanding of the variations in length, orientations and locations of lineaments identified in the project area over several years. One of the main differences between ASTER digitized lineaments and the others are the consistently shorter length of ASTER lineaments. This can be explained by variations in the digitizing scales,

however this information is unknown or unpublished for both EarthSat (1997) and Isachsen and McKendree (1977) lineaments.

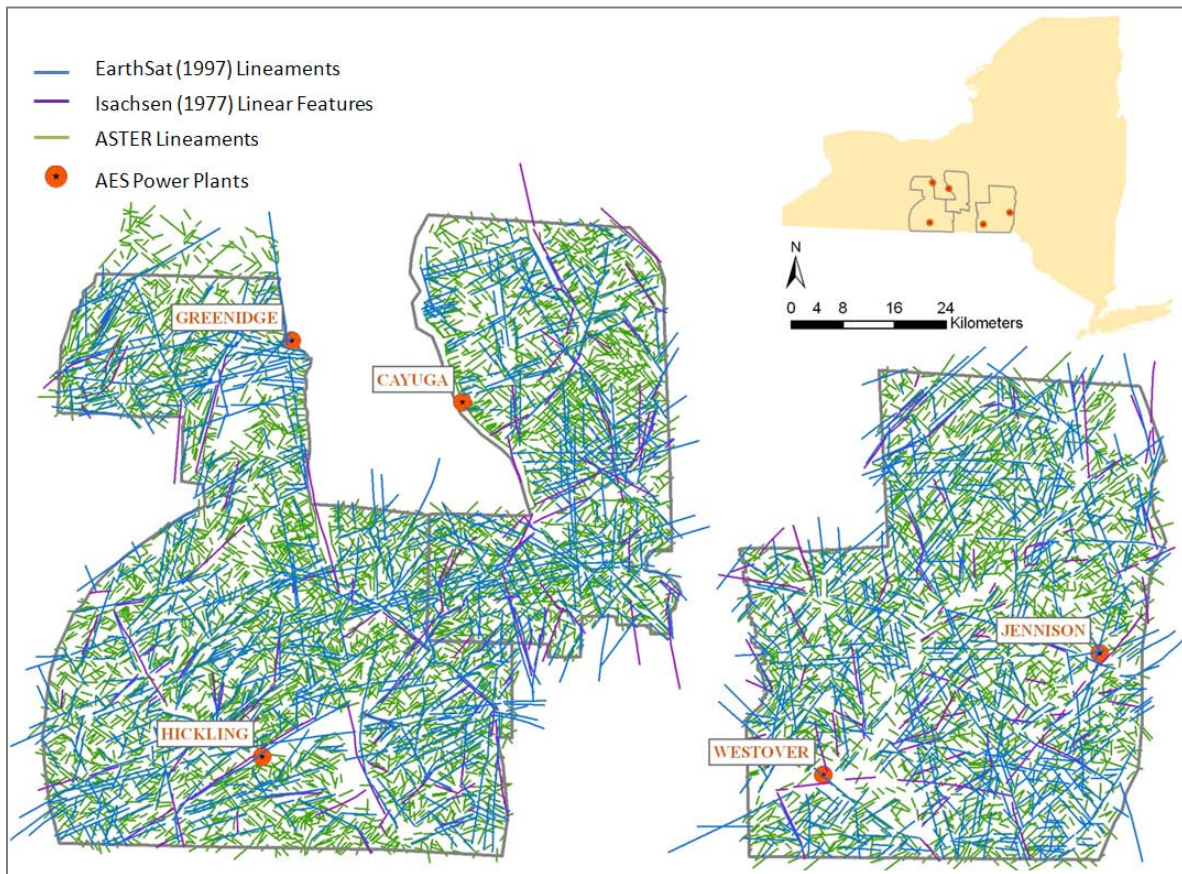


Figure 6.5: Map showing all EarthSat (1997) lineaments, Isachsen and McKendree (1977) linear features and ASTER lineaments (this thesis, Phase II)

Maps and rose diagrams were used to visually compare the lineaments based on location, orientation and lineament length. The EarthSat (1997) and Isachsen and McKendree (1977) datasets were available for the entire project area allowing a meaningful comparison. Maps and rose diagrams were made for the project area as a whole, the western focus area, the central focus area and the eastern focus area (Figures: 6.6 - 6.7 and S6.16 – S6.20). The lineaments digitized by Cruz et al. (2005) covered a smaller region around Seneca Lake making it necessary to generate a subset of the ASTER digitized lineaments (Figure: 6.8). It was difficult to gather a

relationship between Cruz et al. (2005) and the ASTER digitized lineaments because of the limited region of overlap in the datasets (the region around Seneca Lake). The primary trend of Cruz et al. (2005) lineaments was NS with a secondary trend of EW. The trends of both the ASTER lineaments and Cruz et al. (2005) were primarily the result of the lake boundary and drainage into the lake making it difficult to gain a good comparison.

In the larger scope of the entire project area, the rose diagrams of the Isachsen and McKendree (1977) lineaments and the ASTER lineaments compiled in this thesis show similar primary trends of NNE (35°) and NE (45°), respectively (Figure: 6.7). The secondary trend of Isachsen and McKendree (1977) was similar to the secondary trend of EarthSat (1997) with NNW (345°) and NS (355°), respectively (Figures: 6.6 – 6.7).

The Central Focus Area did not show any similarity among the datasets; the dominance of agricultural land and associated changes in crop and farm boundaries as a function of time can account for the lack of correlation in this region.

	Primary Trend	Secondary Trend
Project Area		
ASTER Lineaments	NE (45°)	NW (310°)
EathSat (1997)	ENE (75°)	NS (350°)
Isachsen and McKendree (1977)	NNW (345°)	NE (35°)
Western Focus Area		
ASTER Lineaments	NE (45°)	NW (305°)
EathSat (1997)	ENE (75°)	NNE (15°)
Isachsen and McKendree (1977)	NE (35°)	NS (350°)
Central Focus Area		
ASTER Lineaments	NE (50°)	NW (315°)
EathSat (1997)	ENE (75°)	NS (355°)
Isachsen and McKendree (1977)	NE (35°)	NNW (345°)
Eastern Focus Area		
ASTER Lineaments	NE (45°)	NW (305°)
EathSat (1997)	NE (45°)	NNW (345°)
Isachsen and McKendree (1977)	NS (355°)	NE (45°)

Table: 6.6 - Identifies the primary and secondary trends of ASTER digitized lineaments, EarthSat (1997) and Isachsen and McKendree (1977) for the project area and focus areas

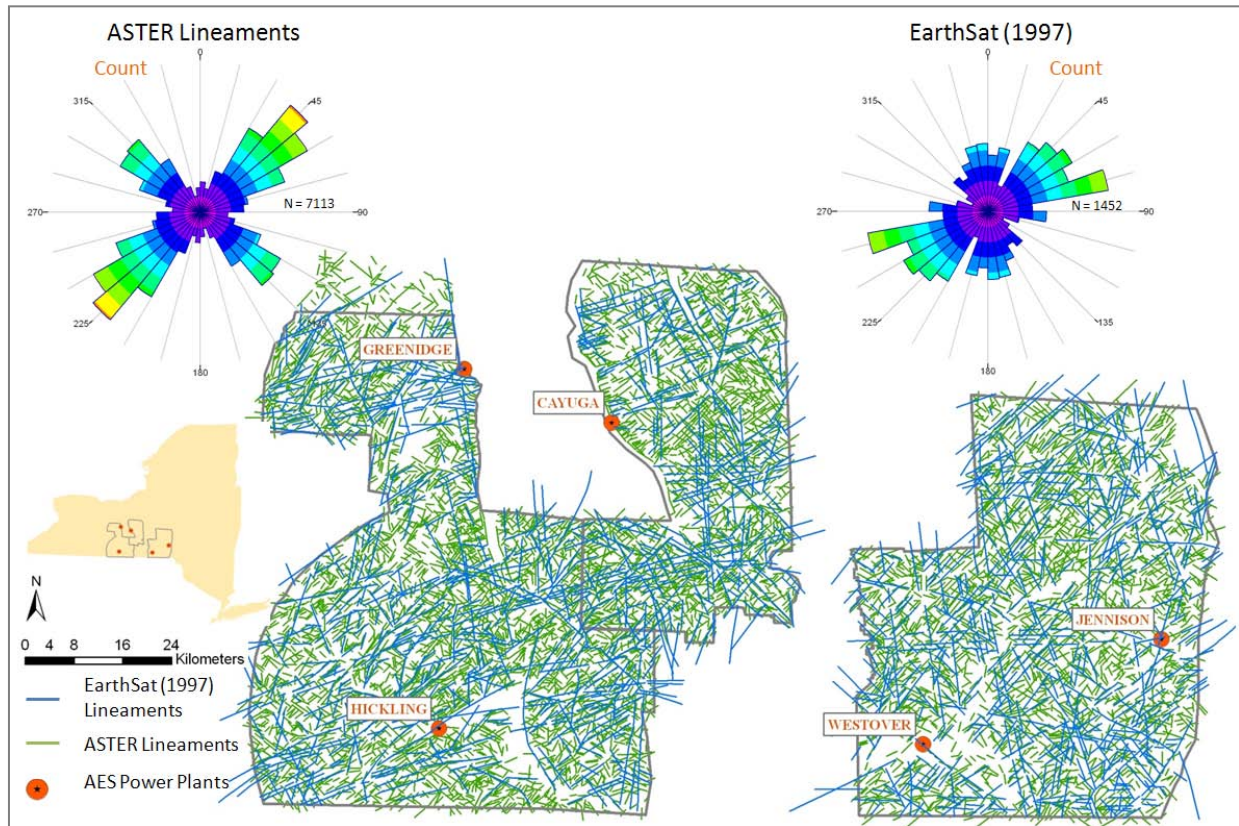


Figure 6.6: Map showing all EarthSat (1997) and ASTER lineaments (this thesis, Phase II), rose diagrams are based on count

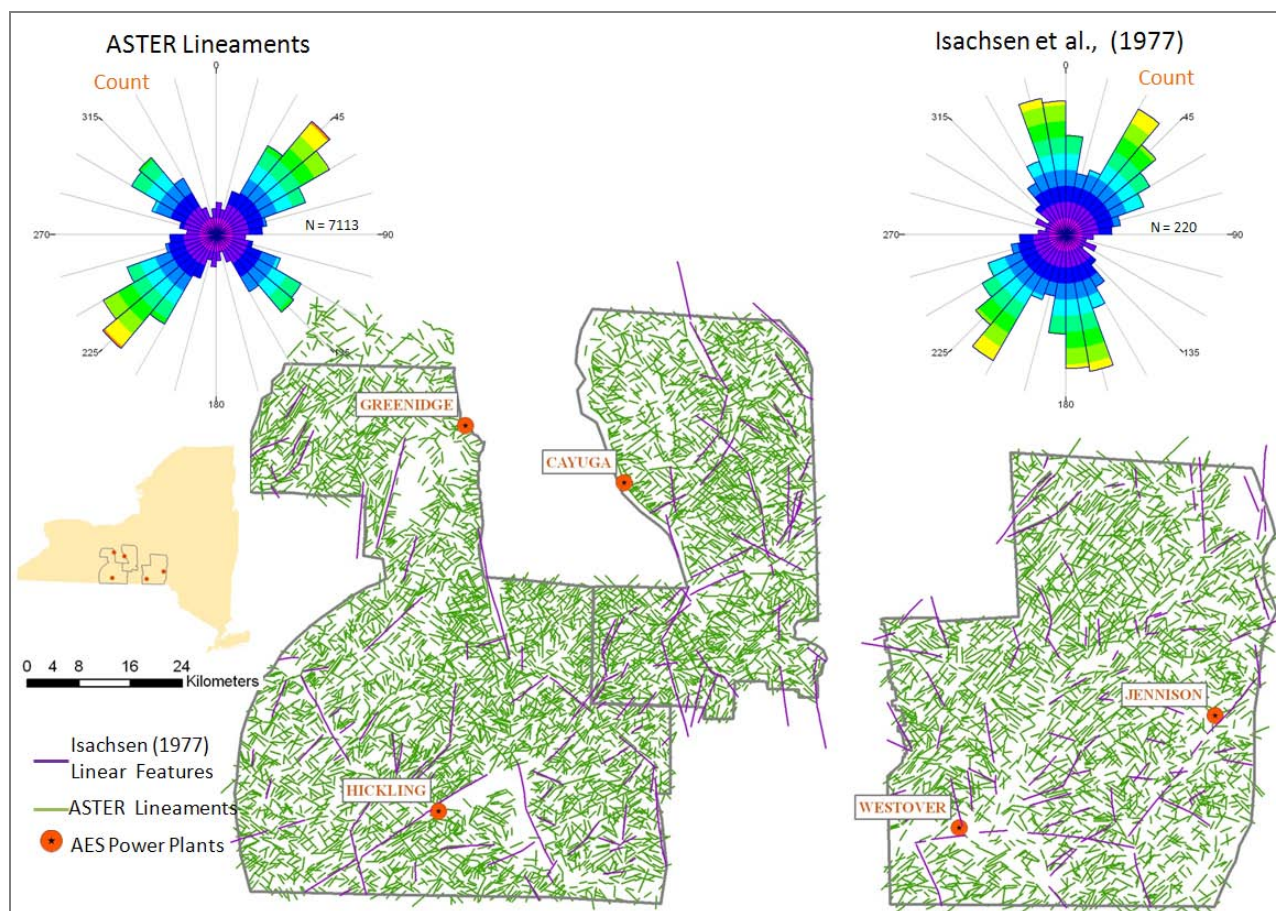


Figure 6.7: Map showing all Isachsen and McKendree (1977) linear features and ASTER lineaments (this thesis, Phase II), rose diagrams are based on count

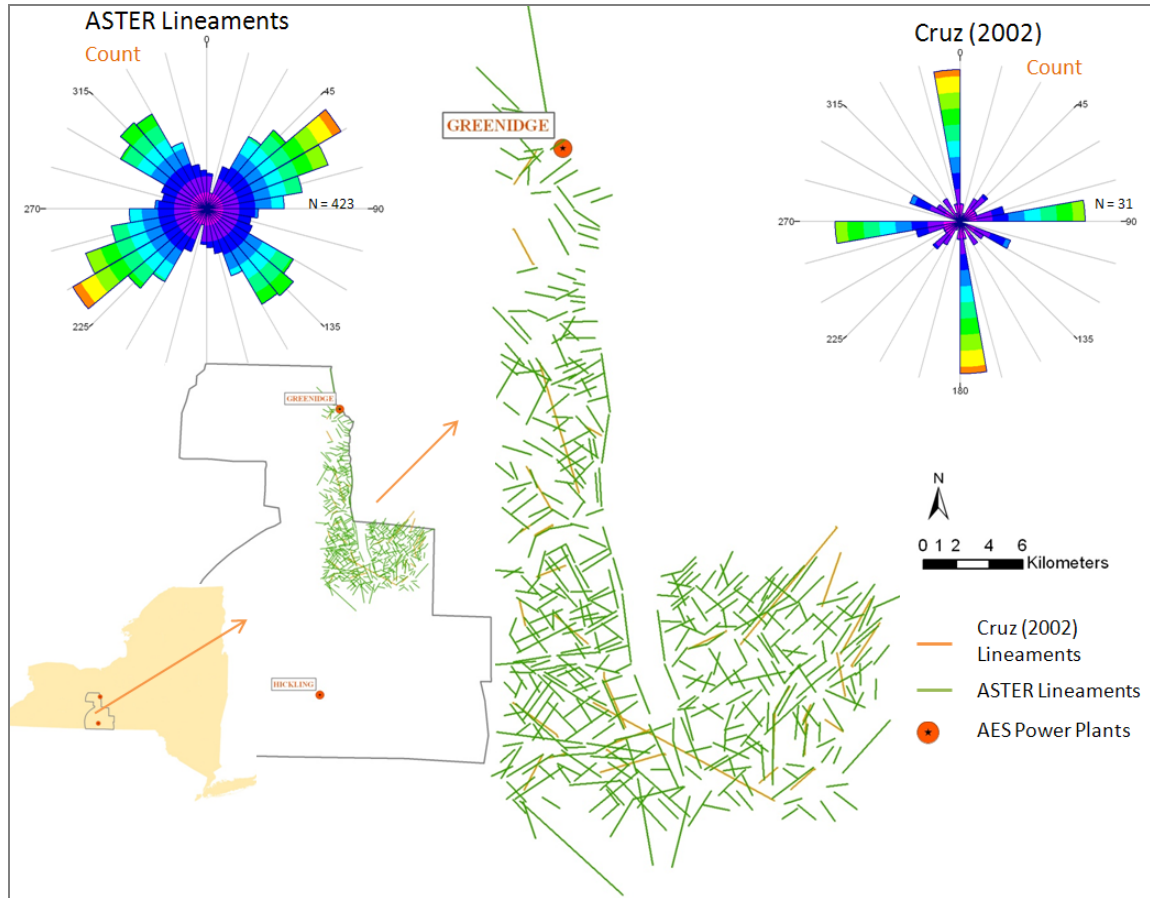


Figure 6.8: Map of the Seneca Lake region showing all Cruz (2002) lineaments and ASTER lineaments (this thesis, Phase II) and rose diagrams based on count

Lineament trends from EarthSat (1997), Isachsen and McKendree (1977) and ASTER (this study) are the most similar in the eastern focus area (Figures: 6.9 – 6.10). The ASTER lineament's primary trend of NE (45°) was identical to the NE (45°) trend in Earthsat (1997) and to the secondary NE (45°) trend in Isachsen and McKendree (1977). The primary trend for Isachsen and McKendree was NS (355°), which is similar to the secondary NNW (345°) trend from EarthSat - a trend missing in the ASTER data.

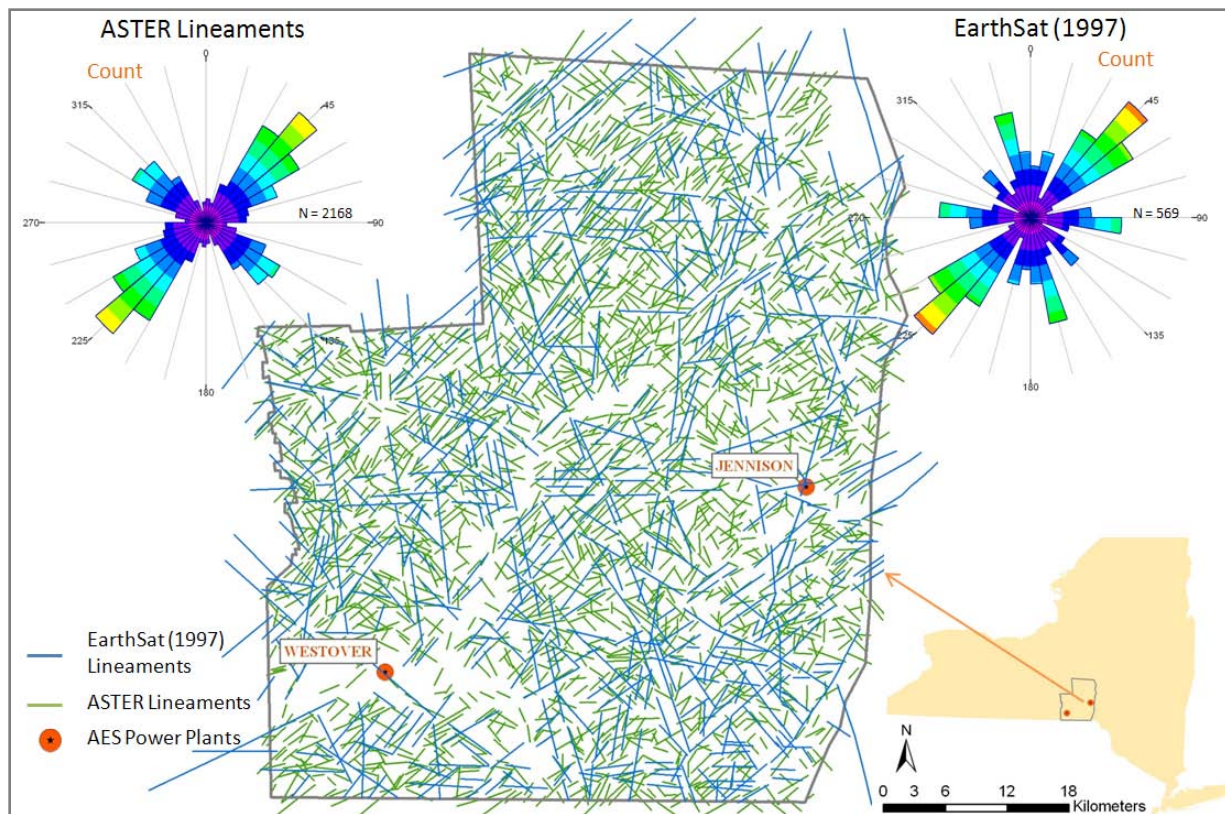


Figure: 6.9 - Map of the eastern focus area showing all EarthSat (1997) and ASTER lineaments (this study, Phase II) and rose diagrams based on count

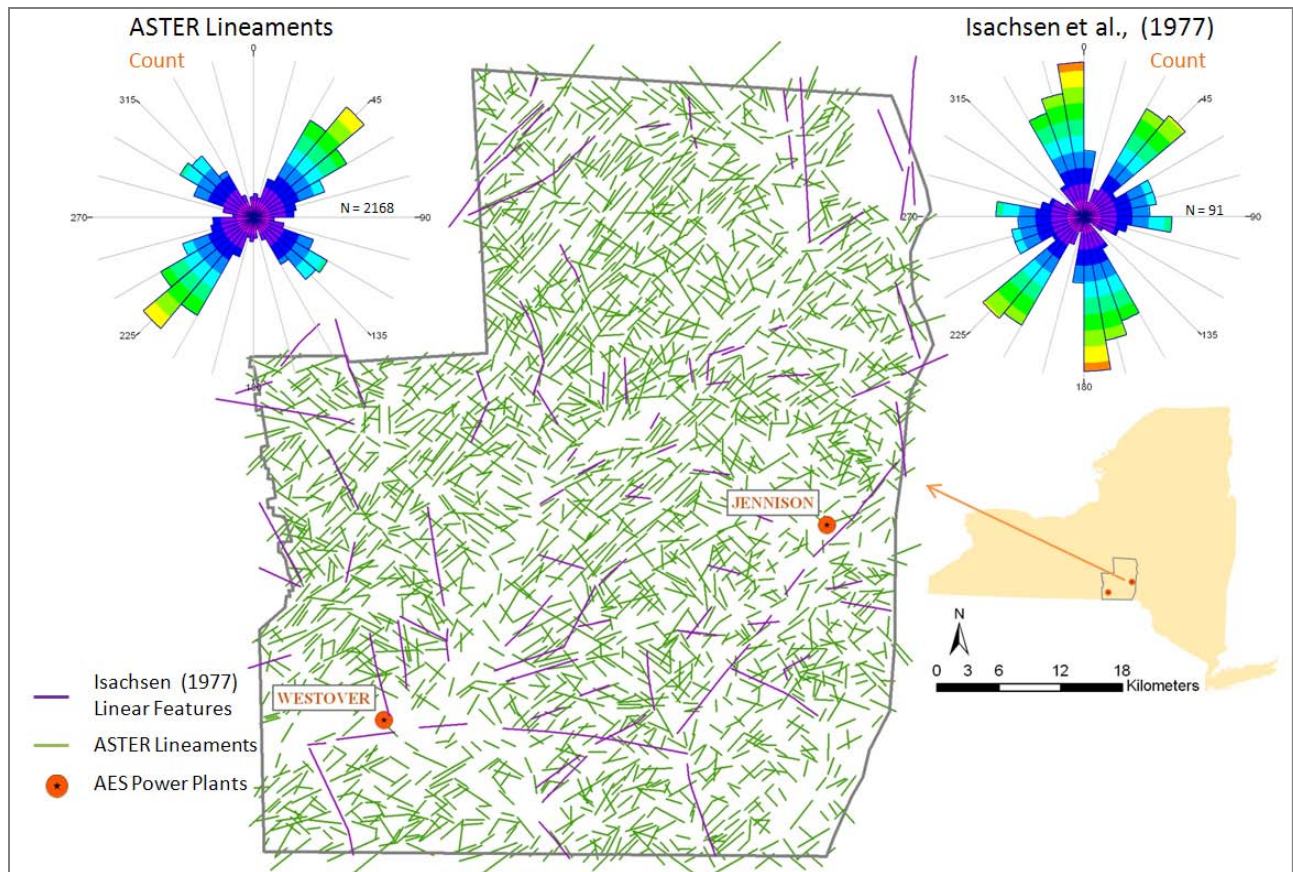


Figure: 6.10 - Map of the eastern focus area showing all Isachsen and McKendree (1977) linear features and ASTER (this project Phase II) lineaments and rose diagrams based on count

The western focus area showed some similarities between the lineament trends determined by the different studies, but the similarities are not as significant as in the eastern focus area. The primary trend of the Isachsen and McKendree (1977) linear features is NE (35°), which is similar to the ASTER lineaments with a primary trend of NE (45°; Figure: 6.11). The trends of the EarthSat (1997) lineaments are different from both the trends of the ASTER lineaments and the linear features of Isachsen and McKendree (1977).

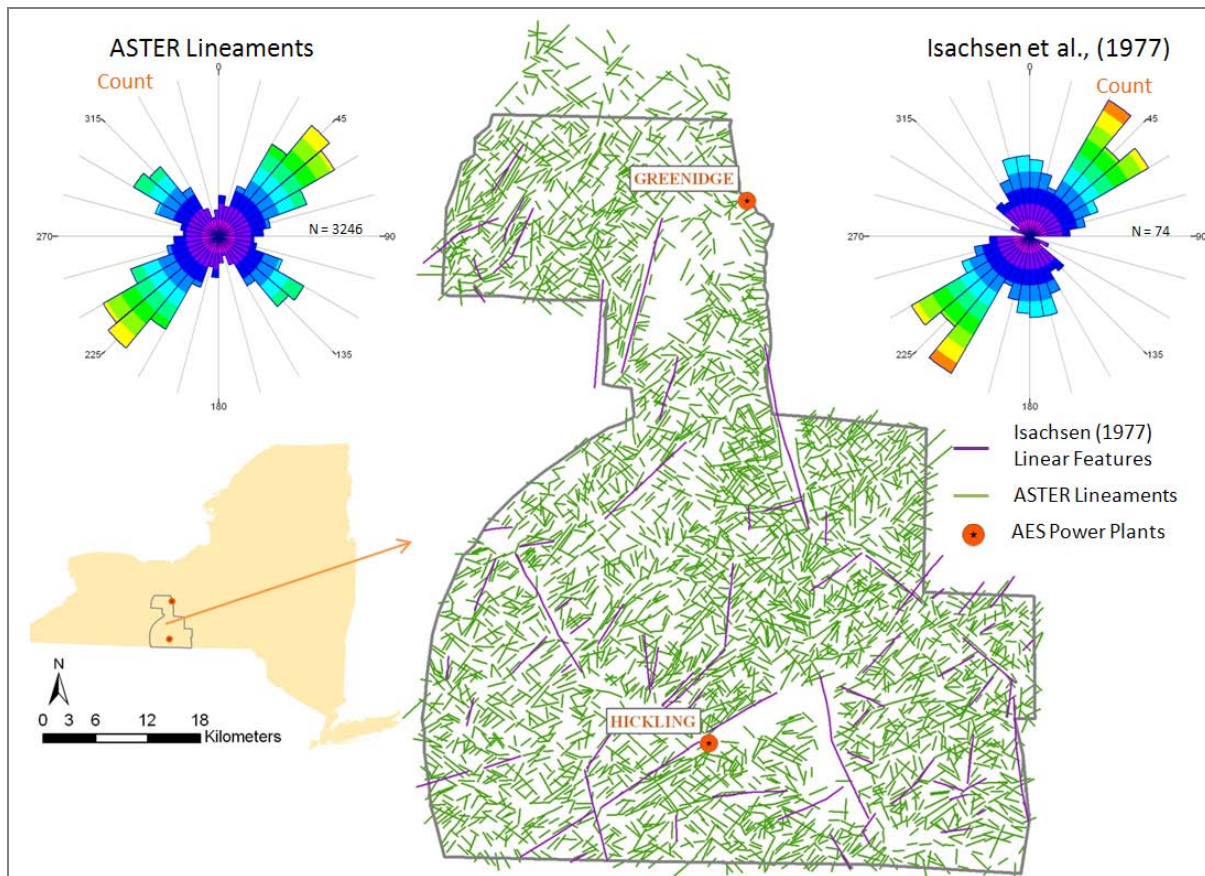


Figure: 6.11 - Map of the western focus area showing all Isachsen and McKendree (1977) linear features and ASTER lineaments (this study, Phase II) and rose diagrams based on count

Chapter 7 – Interpretation and Discussion

A. Project Expectations

The main goal of the project was to identify and digitize lineaments from various remote sensing data, including satellite imagery (Landsat and ASTER) and DEMs, for creating a comprehensive lineament map of an area of ~10,000 square km in central NYS. A consistent way of mapping lineaments was developed and maintained throughout the project that could be repeated in other locations for faster lineament identification over large regions. It was expected that the digitized lineaments could be related to known structural geology features, such as fractures and faults. The final goal of the project was to identify a region potentially suitable for CO₂ sequestration within the project area. The selected region would be further evaluated during the next phase of the multi-discipline project between NYSERDA, AES power plants and other private industry.

B. Lineament Mapping and Interpretation

1. Phase II

Following the experimental stage of Phase I, Phase II consisted of digitizing lineaments for the entire project area at a scale of 1:125,000. This process included the use of color composites of principal components derived from ASTER satellite images as well as shaded relief DEMs (section 4.B.1). A minimum lineament length of 1 km was chosen. Lineaments were mostly identified from tonal variations and vegetation patterns in the ASTER image, while on the shaded relief DEM, most lineaments were identified from topographic or drainage patterns.

The digitized ASTER lineaments have a primary orientation set of NE (45°), a secondary orientation of NW (315°) and a less pronounced trend at EW (90°; Figure: 5.11). Rose diagrams, based on both the total count and cumulative length, revealed similar trends.

The primary trend of lineaments digitized from the shaded relief DEM is NE (35°) and the orientation of the secondary set is NNW (330°; Figure: 5.11). Overall, the orientations of DEM lineaments exhibit relatively large variations compared to the tight grouping of lineament trends seen in the ASTER rose diagrams. There is also a significant difference between the focus areas with regard to primary trends and overall distribution of lineaments. The eastern focus area has the tightest grouping of DEM lineaments with a primary trend of NE (35°) and a rose diagram that is most similar to ASTER rose diagrams (Figure: 5.11). The western and central focus areas have the largest spreading of lineament trends with primary trends of NE (35°) and NW (325°) respectively. These differences in rose diagrams show that the DEMs are identifying different features than the ASTER imagery. These features may be more closely related to the glacial history of the region rather than related to the land use/land cover and structural geology.

2. Phase III

During Phase III, lineaments were digitized for the Cayuga subset at a scale of 1:25,000 from ASTER principle component color composites and a shaded relief DEM (see section 4.B.1). The primary trend of the ASTER lineaments is NE (55°) with the secondary trend of NW (315°; Figure: 5.14). The primary trend of the DEM lineaments is NNW (340°) with a secondary trend of NE (60°; Figure: 5.14).

3. Geological Interpretation of Regional Lineament Trends

Based on Everett et al. (2003) and Cruz et al. (2005), I expected the digitized ASTER and DEM lineaments to correspond to the structural features (faults and fractures) related to the tectonic stresses from the Alleghanian Orogeny. According to Jacobi (2007), Murphy (1981), Bradley et al., (1941) and Isachsen and McKendree, (1977) the primary trend of known faults in the project area is east-northeast and the secondary trend is north-south. The north-south trends are mainly located near and south of Seneca Lake and Cayuga Lake in well-known valleys (Jacobi, 2007; Murphy, 1981). Northeast trending faults documented by Jacobi (2002) are mainly in the Cayuga region.

Among the fault data gathered, the most well distributed and abundant dataset was from Jacobi (2007), while Murphy (1981) was the second most useful dataset used when comparing lineaments to structural features. The other fault datasets gathered were sporadic and repetitive. The digitized lineaments were compared to the structural geology using rose diagrams from which trends were reviewed for similarities and differences. These structural features were also used in the fabric compilation analysis, described in section 4.B.3.

i. Northeast trending lineaments

The primary trend identified from the ASTER lineaments is northeast; this trend is prominent across the project area. Jacobi (2007) identified northeast trending faults near Cayuga Lake from multiple sources including Landsat satellite imagery (EARTHSAT, 1997), aeromagnetic and seismic data, as well as well logs. Northeast striking faults were identified across NYS utilizing well logs, seismic reflection profiles, level lines of bedding surfaces, outcrop stratigraphy, and FIDs (Jacobi, 2002). This trend also correlated with proprietary data (Jacobi, per. communication).

I identified a rotation from northeast to east-northeast, possibly corresponding to changes in known fault orientations (Jacobi, 2007), in the ASTER lineaments of the Cayuga site by analyzing rose diagrams of smaller subsets of lineaments across the region (Section 5.B.2). This rotation from northeast to east-northeast is possibly related to Iapetan rifting or Rome Trough trends and to Alleghanian thrust tectonics (Jacobi, 2002).

The northeast trend is also identified as the primary trend in DEM digitized lineaments and could be attributed to geomorphologic features reflecting subsurface tectonics, such as reactivated basement faults.

ii. Northwest trending lineaments

The secondary trend identified in both ASTER and DEM lineaments is northwest. The main northwest structures identified in NYS are cross-strike discontinuities (CSDs) that were orthogonal to the Appalachian orogeny and related to reactivated Precambrian faults (Jacobi, 2002). The CSDs served as guides for Alleghanian thrusting tear faults during the Paleozoic and controlled sediment patterns (Jacobi, 2002). Northwest faults suspected in central NYS were identified using aeromagnetic data along with topographic and EarthSat (1997) lineaments (Jacobi, 2002).

Northwest lineaments can also indicate Fracture Intensification Domains (FIDs). Jacobi (2002) identified a relationship between FIDs, mapped by the UB Fracture Group, and Landsat lineaments identified by the EarthSat (1997) project; lineaments longer than 0.5 km commonly corresponded to FIDs. FIDs generally mark the location of nearby faults and therefore provide a link between the lineaments and faults. By ground-truthing lineaments mapped from remote sensing data, FIDs can be identified in the field and the location and extent of faults can be predicted (Jacobi, 2002). There is also evidence indicating a connection between FIDs and deep

thermogenic gas deposits based on soil gas anomalies with measurements 10x greater than normal levels (section 8.B.1). All lineaments mapped from ASTER imagery and DEMs in this study are longer than 0.5 km, potentially indicating FIDs.

The trends of northwest lineaments are also similar to the trends of Engelder and Geiser's set Ib cross strike joint set (1979 & 1980). Set Ib trajectories represent the compression direction at one stage during the Alleghanian orogeny as evidenced by penetrative fabric in outcrops (Engelder and Geiser, 1980).

The interpretation of the main lineament trends are based on a limited set of fault, fracture and joint field data. More work, especially ground-truthing of mapped ASTER and DEM lineaments would be necessary to expand and improve these interpretations.

4. Density Maps

The density maps, presented in section 5.B.3, identified lineament patterns that would be difficult to identify on traditional maps and thus improved our understanding of the relationships between the ASTER and DEM digitized lineaments and the structural features.

The most abundant trend identified on ASTER density maps of the entire project area is NE, as expected (Table 5.8). The second most abundant is NS, a great surprise considering that throughout the digitizing process this trend was missing (Table 5.8). Identifying the NS trend shows the importance of using density maps when analyzing lineaments. These trends are potentially related to N-striking short faults identified in the Finger Lakes region by Jacobi (2002). The NS trend is also recognized in the Cayuga subset ASTER density maps, with the most abundant trend being NS and the second being NE (Table 5.8). These NS trends in the Cayuga subset are potentially related to prominent NS valleys in the region and faults recognized

by Murphy (1981) and the NE trends are related to faults recognized by Jacobi (2000). The DEM density maps do not show any clear trends (Figure: 5.20).

The principal component of stress (σ_1) applied to central NYS during the Alleghanian Orogeny likely promoted the development of fractures parallel to σ_1 and faults perpendicular to σ_1 (Isachsen et al., 1991) – potential fractures and faults that potentially lineaments evidenced in the filtered density maps (Table 5.8). For example, fractures parallel to σ_1 (NNW), clustered along a fault perpendicular (NE) to this principal component stress, result in a NE trend/cluster in the NNW filtered density map (e.g., Figure: 5.25 and 5.29). Relatedly, NW faults can be identified with clustering of NE lineaments identified as fractures (e.g., Figure: 5.26 and 5.30). However, more research is needed to explore these relationships and compare trends to known faults and fractures of the region.

5. Relation to carbon sequestration

The primary and secondary lineament trends (northeast and northwest) in this region are potentially related to structural features such as faults and fractures in the subsurface, which in turn might provide potential connections to CO₂ reservoirs. These trends are not the most common trends of the region, however they are similar to other known trends and may be related to reactivated basement faults and FIDs (Jacobi, 2002). The data types, image processing techniques, lineament identification method and advanced interpretation techniques, such as density maps, fabric analysis, and rose diagrams allow for the identification of lesser-known structures, which are potentially related to the overall regional structural geology and are important for understanding the unknowns in the structural geology of NYS. The identification

of minor structures reflects positively on the methodology and image processing techniques used in this project, as well as the potential for future projects around the world.

The northeast trending lineaments are potentially related to reactivated basement faults based on the similarities of orientations and locations of the lineaments and faults. These reactivated basement faults extend to the Precambrian basement and intersect various thermogenic gas rich layers (Jacobi, 2002). These faults occur across NYS (Jacobi, 2002) and are not sufficiently studied or recognized by researchers; we need to gain a better understanding of these faults before CO₂ sequestration can be considered for this region. If CO₂ is stored in available reservoirs in the subsurface, these reservoirs have the potential to interact with northeast trending reactivated basement faults, thus providing a pathway for CO₂ migration to the surface.

The northwest lineaments are potentially related to FIDs across the project area. This relationship is based on similarities of the locations and orientations of the FIDs and the digitized lineaments. The FIDs in the project area were studied by Engelder and Geiser (1980), Terech (2006), McGuire (2007) and Jacobi (2007). Engelder and Geiser identified that FIDs have higher than normal soil gas readings, which are indicative of a connection with the thermogenic gases in the subsurface. CO₂ sequestration reservoirs are similar to the layers rich in thermogenic gases, Therefore areas with high density of northwest lineaments, potentially related to related to FIDs, indicate regions not favorable for CO₂ sequestration.

C. Improvements

Identifying and digitizing lineaments on shaded relief color DEMs from various illumination angles can explore lineaments unique to topographic expressions. The use of shaded

relief color DEMs makes it easier to identify minor topographic changes as color and shading variations. In addition I strongly suggest acquiring airborne LIDAR data for the region; this can greatly increase the resolution of available topographic data and thus enhances lineament identification possibilities.

Chapter 8 – Conclusions and Future Work

A. Conclusions

The use of ASTER imagery and shaded relief DEM in this study allowed for the identification of structural features, including topographic expressions, soil variations, and vegetation sensitivity. The image processing techniques (e.g. PCA) were ideal and resulted in large color variations of the ASTER imagery. Hillshading applied to the DEM worked well for enhancing low relief features, while varying the illumination angles allowed for the identification of lineaments of all orientations. The identification and digitizing process was ideal for this project's magnitude. Various analyses performed on the digitized lineaments provided a good understanding of the data, allowing it to be compared to the regional geology. During the study relationships between the digitized lineaments with faults and fractures of the region were recognized. The northeast trending lineaments are interpreted as expressions of regional faults, for example those near the Cayuga power plant, while NW lineaments are likely related to fractures and FIDs.

The geological interpretation of the digitized lineaments can be improved with more detailed analyses of the data in smaller regions with prominent faults to identify patterns and variations in lineaments relative to the faults. One aspect to consider is the scale at which the lineaments were digitized; for example can multiple smaller lineaments add up to a single larger structural feature or lineament? The full potential of using the relatively high resolution NED DEMs (10 meter) was not utilized in this project. The high resolution of the DEM can provide insight into the geomorphological features and structural geology when the subtle topographic variations are mapped using various shaded relief DEMs.

B. Recommendation for Future Work

1. Soil Gas Analysis

Soil gas analysis can be used to study the fractures and faults in regions where they can't be mapped directly in outcrops. Soil gas analysis has been used for 50 years, first to identify gas reservoirs and later to identify faults in which gases migrate to the surface (Fountain and Jacobi, 2000). Natural gas reservoirs are common in the Appalachian basin from the thermogenic production of petroleum (Fountain and Jacobi, 2000). A study performed by Fountain and Jacobi (2000) concluded that soil gas surveys could be used to map structures such as fractures that are related to faulting, particularly where natural gas reservoirs occur.

Soil gas analysis was performed for a small section of the project area with data that was provided by David Seneshen of Vista Geoscience (Figure 9.1). This soil-gas data was gathered along roads in the Quackenbush area; samples were gathered and analyzed to determine the methane to ethane ratios of the gas in the soils.

Comparison of soil gas data with locations of mapped lineaments can be used to detect lineament where high concentrations of thermogenic gases indicate open bedrock fractures. Thermogenic gases accumulate in the soil above open bedrock fractures as gas has a tendency to migrate upward. Therefore, the observed increase in the methane to ethane ratio over lineaments mapped from satellite imagery confirms that these lineaments are indeed surface expressions of fracture zones and faults connecting gas deposits with the surface.

The analysis of this small region simply overlaid the soil gas data on the lineament data. From this it is observed that there are multiple areas where the methane to ethane ratios is higher along lineaments and in some cases higher at lineament intersections. Current limitations to this

analysis are with the soil gas data, which was collected only along roads rather than a grid format and not obtained over a period of time; these factors hinder the ability to make more straightforward conclusions. With better soil gas data it is also possible to identify specific trends related to higher gas concentrations.

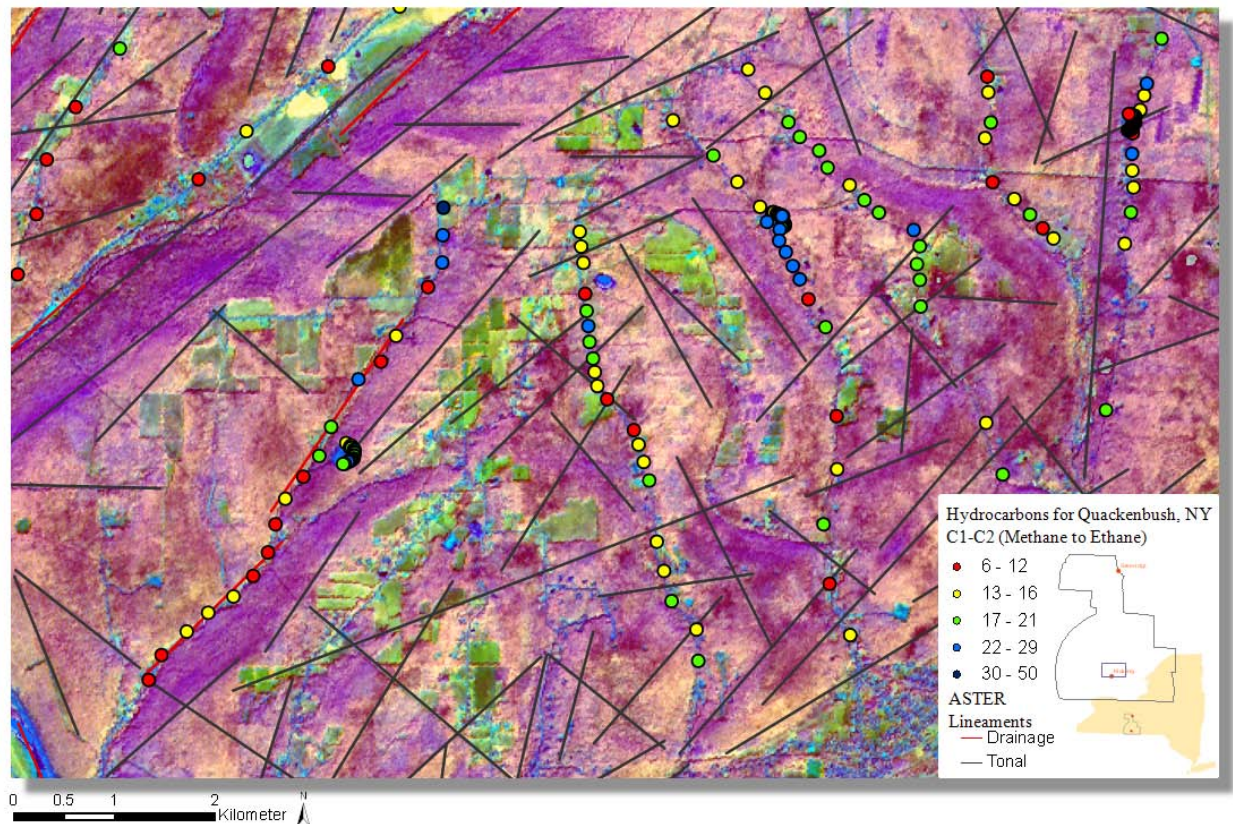


Figure: 8.1 ASTER Imagery for soil gas subset color composite R(PC2) G(PC1) B(PC3) principal component with soil gas data from D. Seneshen (Vista Geoscience)

2. Glacial Geomorphology

It is likely that some of the lineament trends in western NYS reflect the glacial history of the region. To test this hypothesis, I compared the trends of ASTER and DEM lineaments to drumlin orientations determined by Hess (2009). This was accomplished by isolating selected

lineaments and drumlin orientations within a small region slightly outside of the project area north of the Greenidge power plant (Figure 8.2).

The primary trend for the ASTER lineaments was NE (45°) and the secondary trend was NW (315°). The total count of lineaments was 74, with a max length of 5,014 m and mean length of 1,992 m. The maximum bin population was 11 lineaments and comprised 7.43% of entire lineament population.

The primary trend for the DEM lineaments was NW (340°). The total count of lineaments was 64, with a max length of 3,727 m and mean length of 1,588 m. The maximum bin population was 13 lineaments and comprised 10% of entire lineament population.

The primary trend for the drumlin orientation was NW (340°). The total count of lineaments was 69, with a max length of 4,342 m and mean length of 1,689 m. The maximum bin population was 22 lineaments and comprised 16% of entire lineament population.

As expected there is a strong relationship between the orientation of DEM lineaments and the elongation of the drumlins. Elimination of the primary NW (340°) trend, corresponding to the trend of drumlin orientations, could assist the identification of those lineaments that are related to structures rather than to glacial geology.

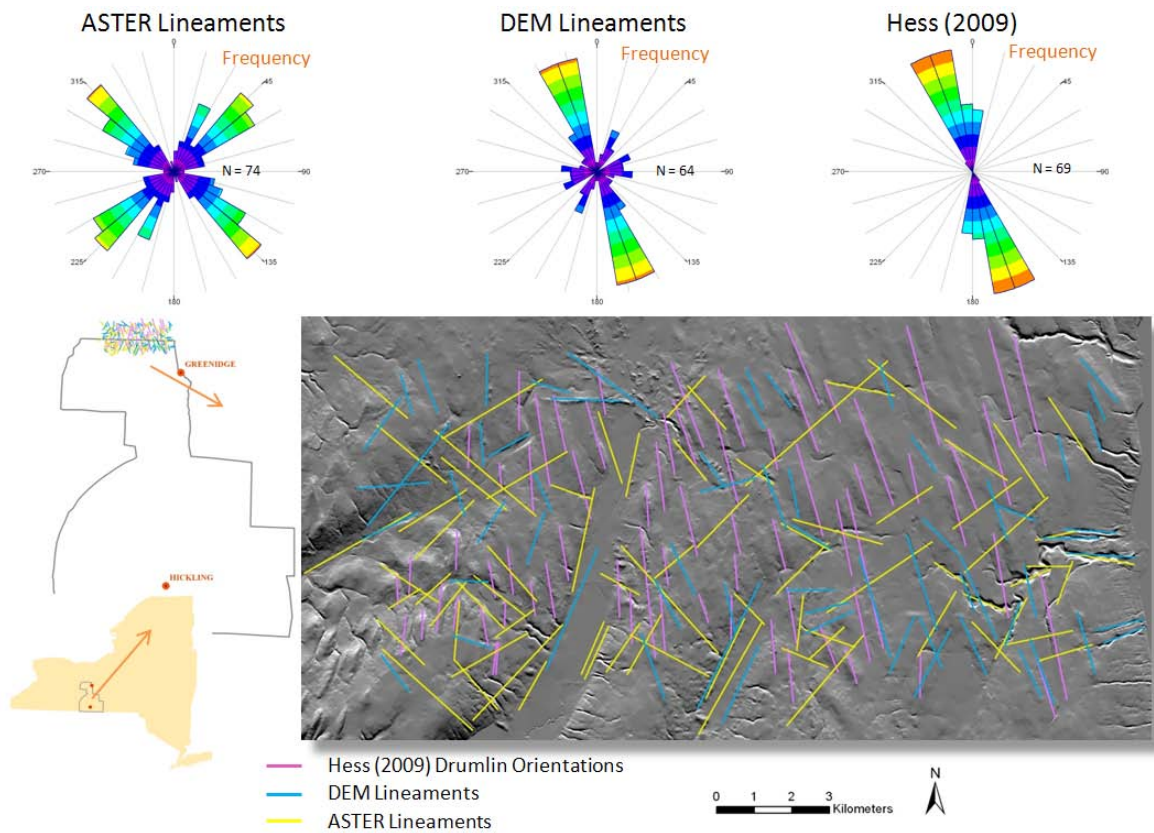


Figure: 8.2 - DEM base map with drumlin orientation data (Hess, 2009), selected ASTER and DEM digitized lineament within a same area; rose diagrams based on count

Appendix I

Supplemental Figures

Chapter 5

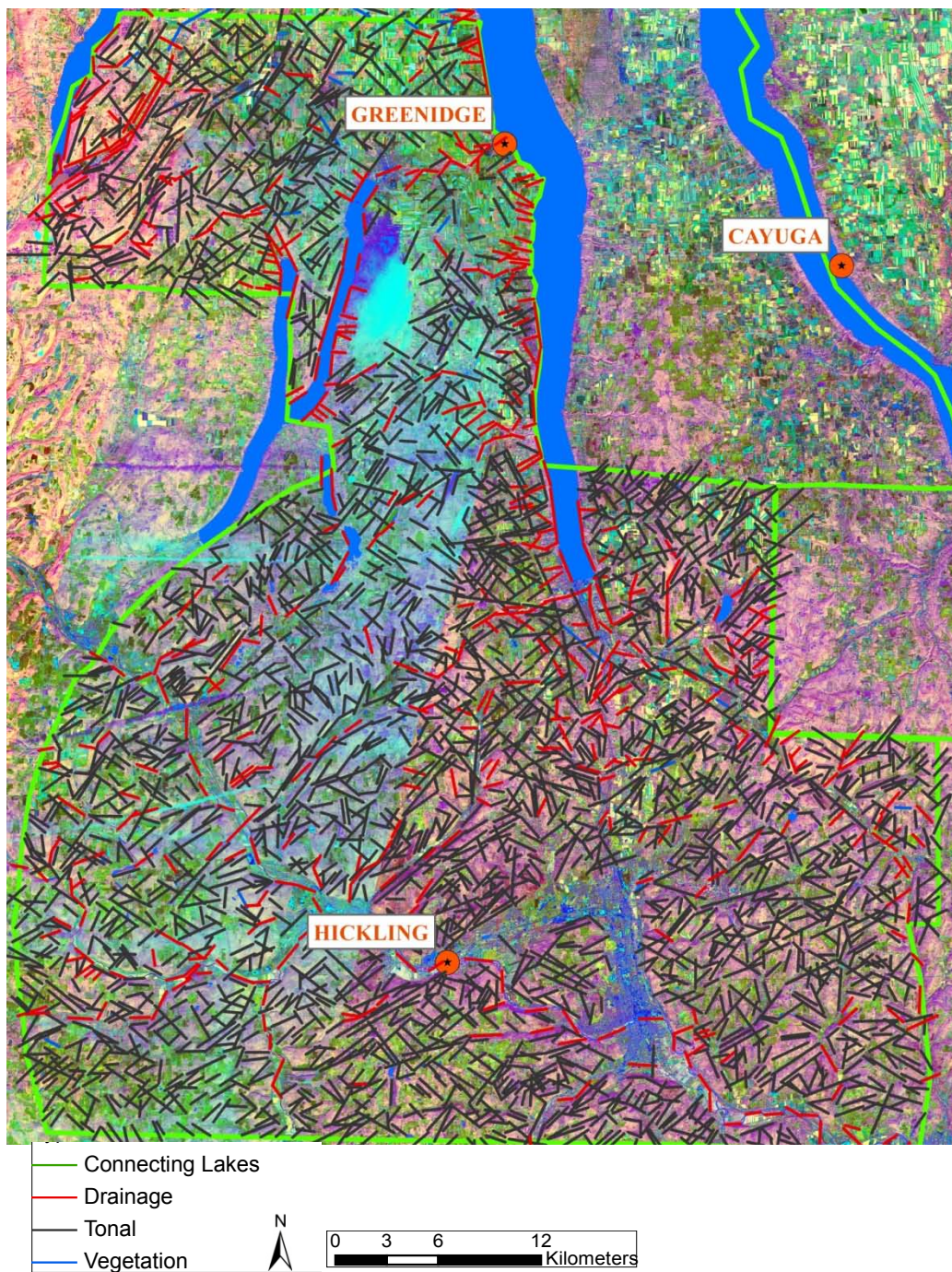


Figure: S5.1 - Phase III – PC ASTER imagery with updated digitized lineaments for project area (western focus area shown)

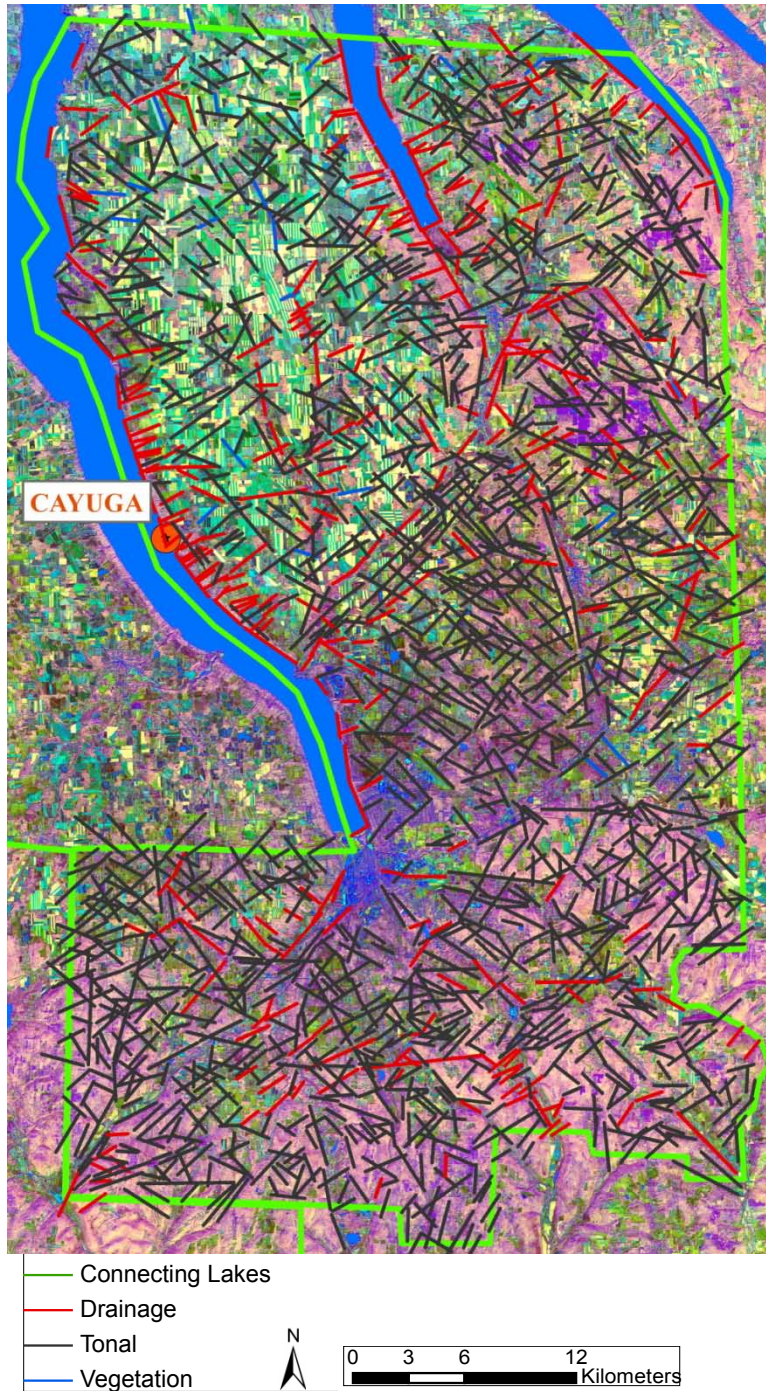


Figure: S5.2 - Phase III – PC ASTER imagery with updated digitized lineaments for project area (central focus area shown)

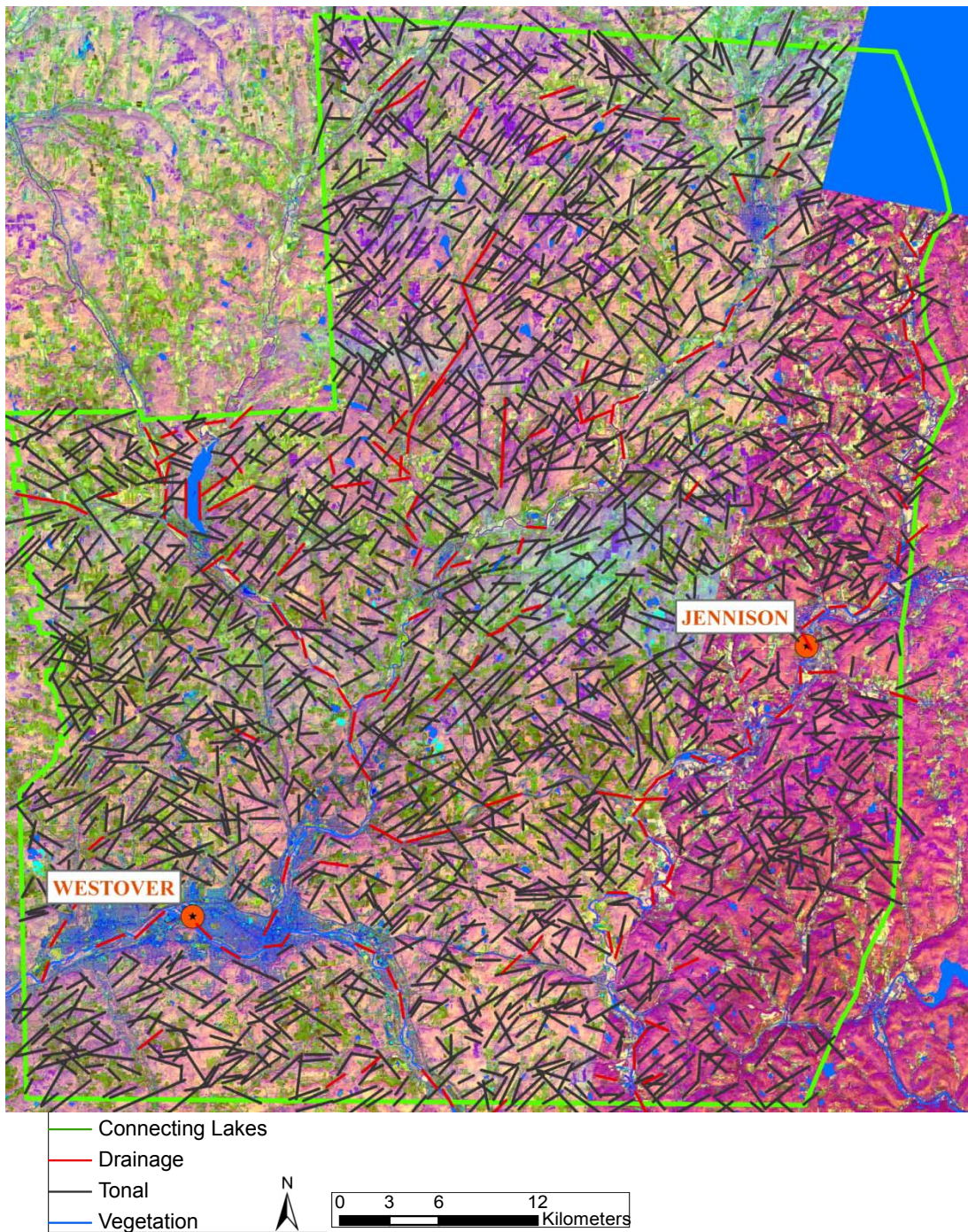


Figure: S5.3 - Phase III – PC ASTER imagery with updated digitized lineaments for project area (eastern focus area shown)

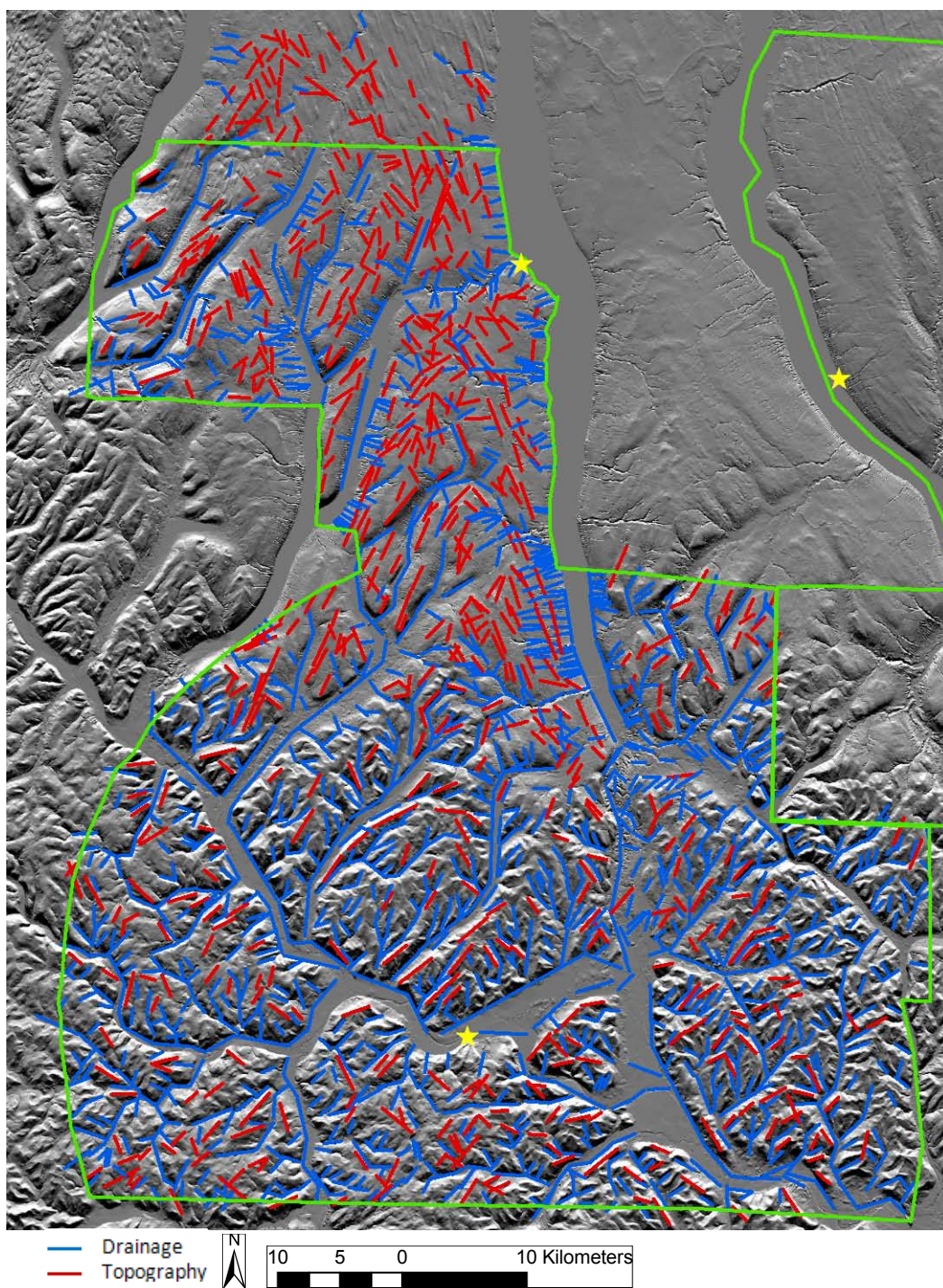


Figure: S5.4 – Phase II – DEM shaded relief representation with digitized lineaments for project area (western focus area shown)

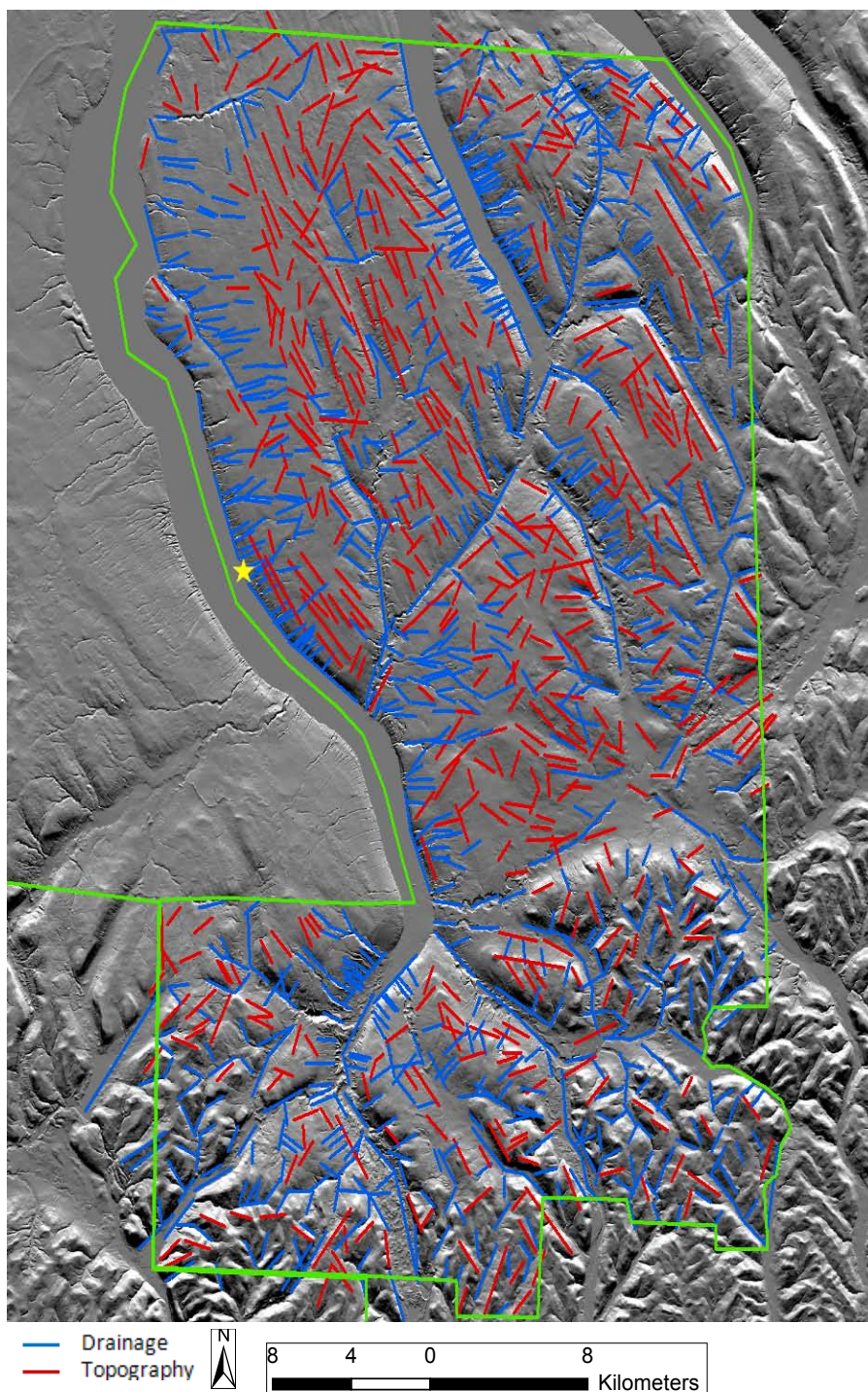


Figure: S5.5 – Phase II – DEM shaded relief representation with digitized lineaments for project area (central focus area shown)

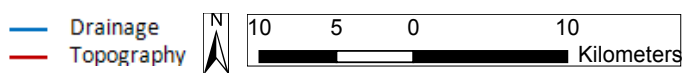
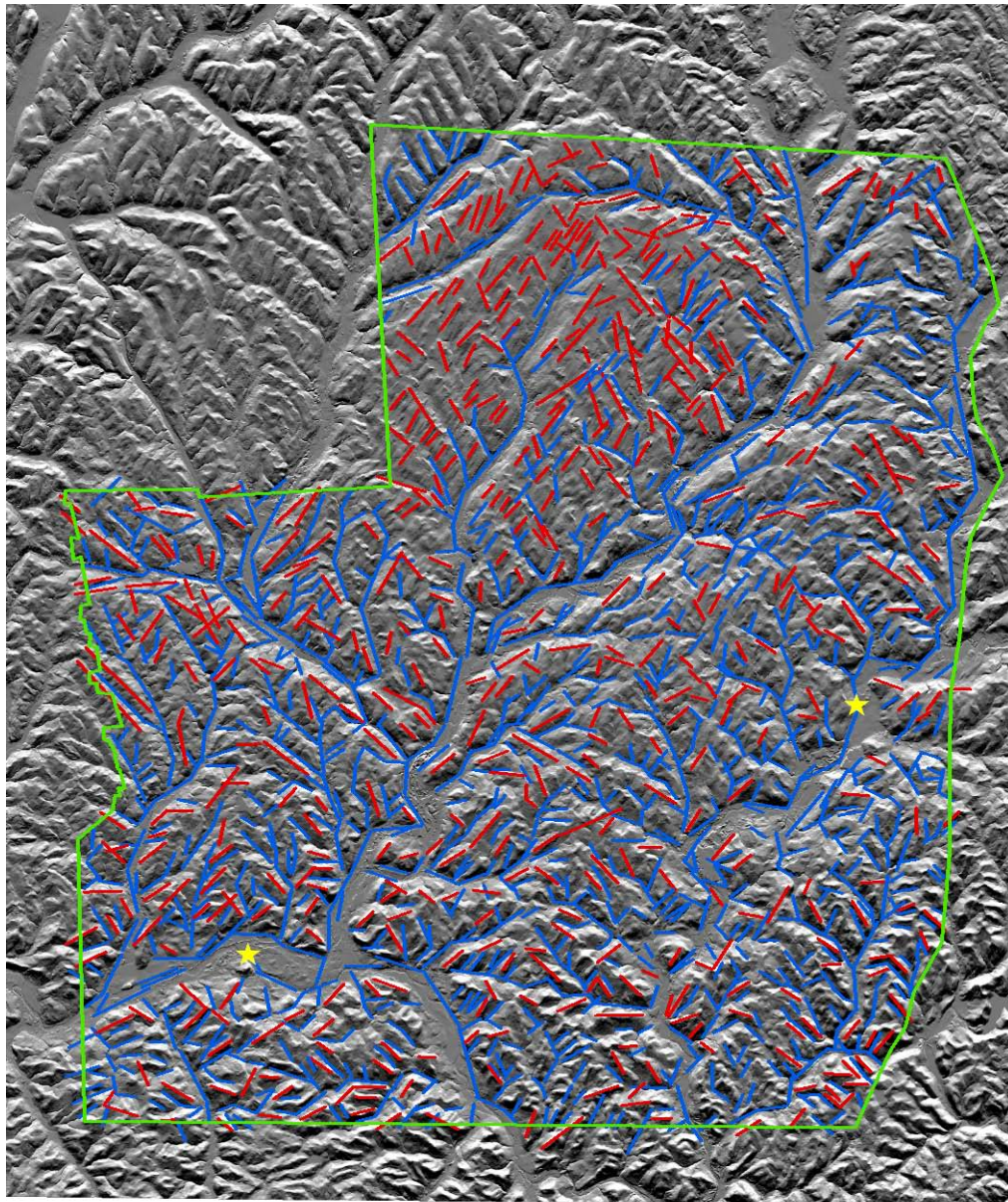


Figure: S5.6 – Phase II – DEM shaded relief representation with digitized lineaments for project area (eastern focus area shown)

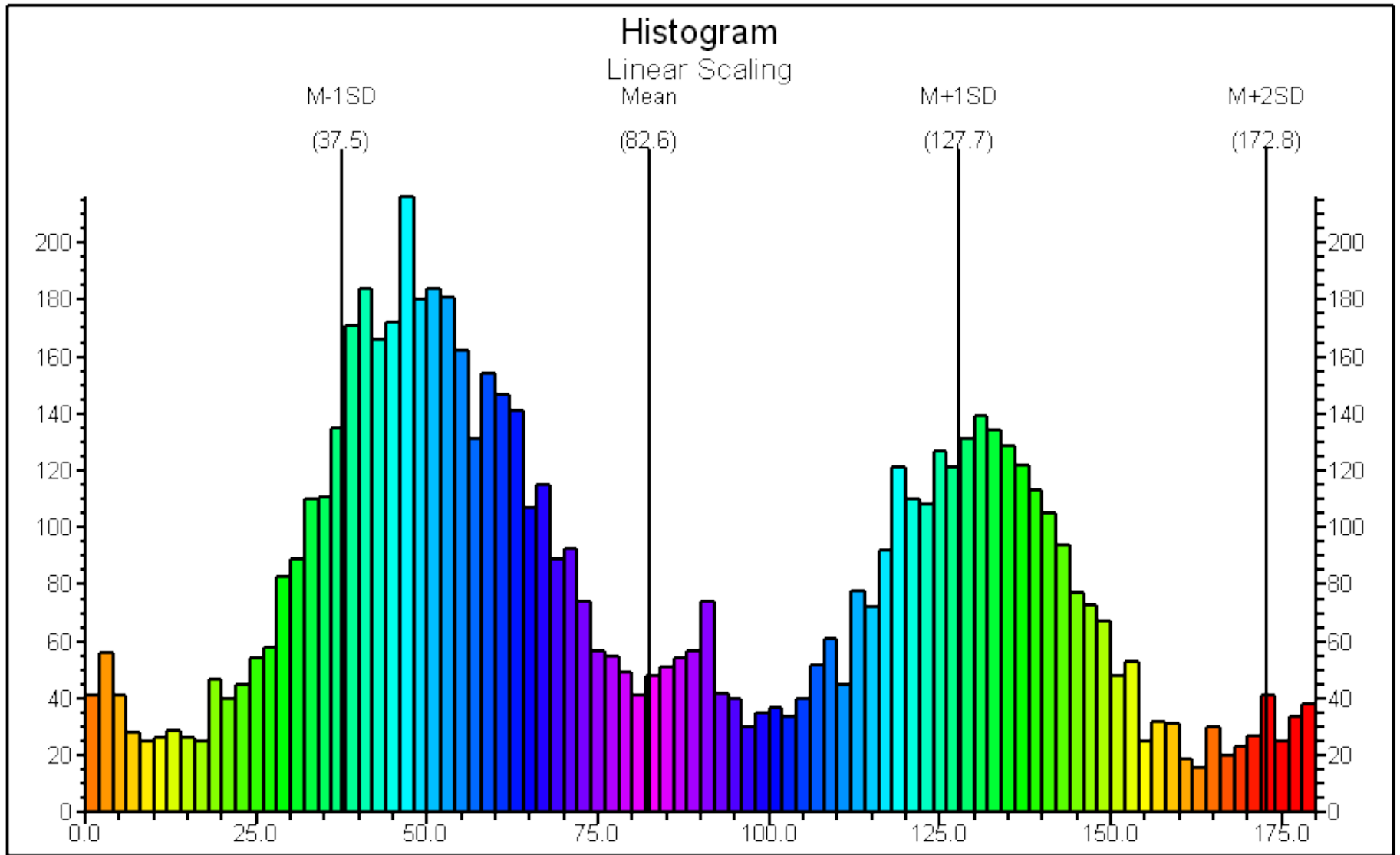


Figure: S5.7 – Histogram of ASTER digitized lineaments for the Project Area with a bin size of 2°

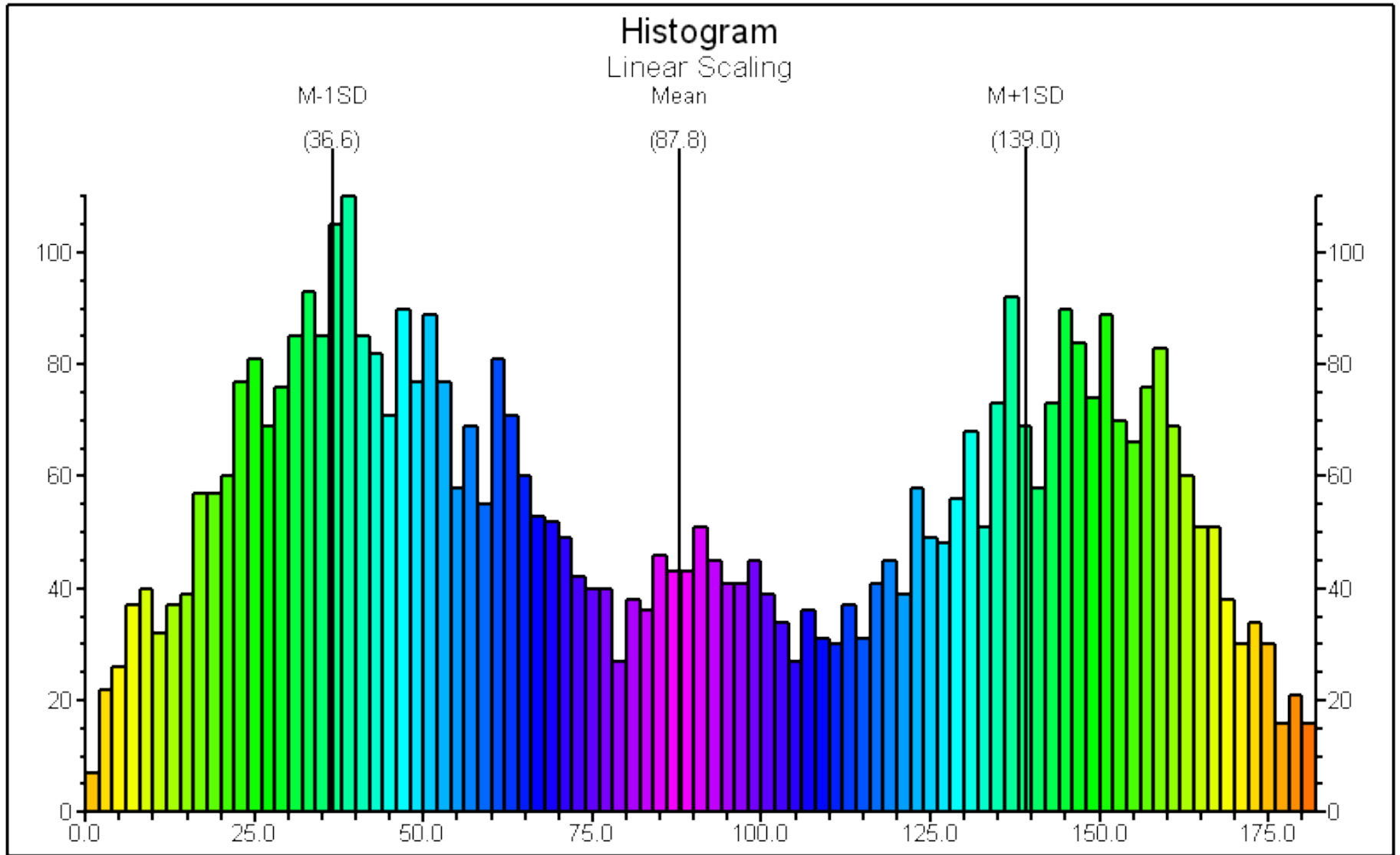


Figure: S5.8 – Histogram of DEM digitized lineaments for the Project Area with a bin size of 2°

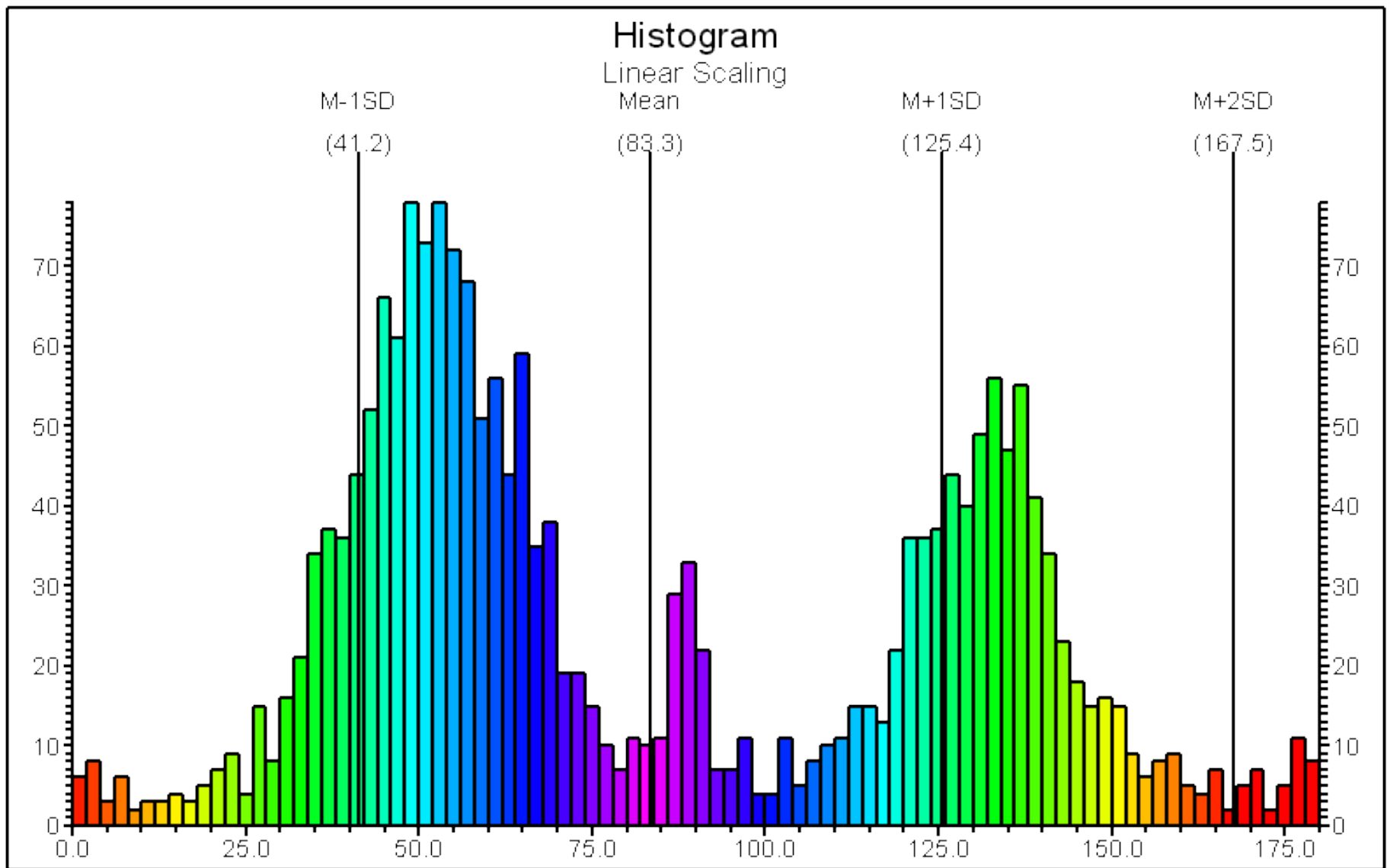


Figure: S5.9 –Histogram of ASTER digitized lineaments for the Cayuga Subset with bin size of 2°

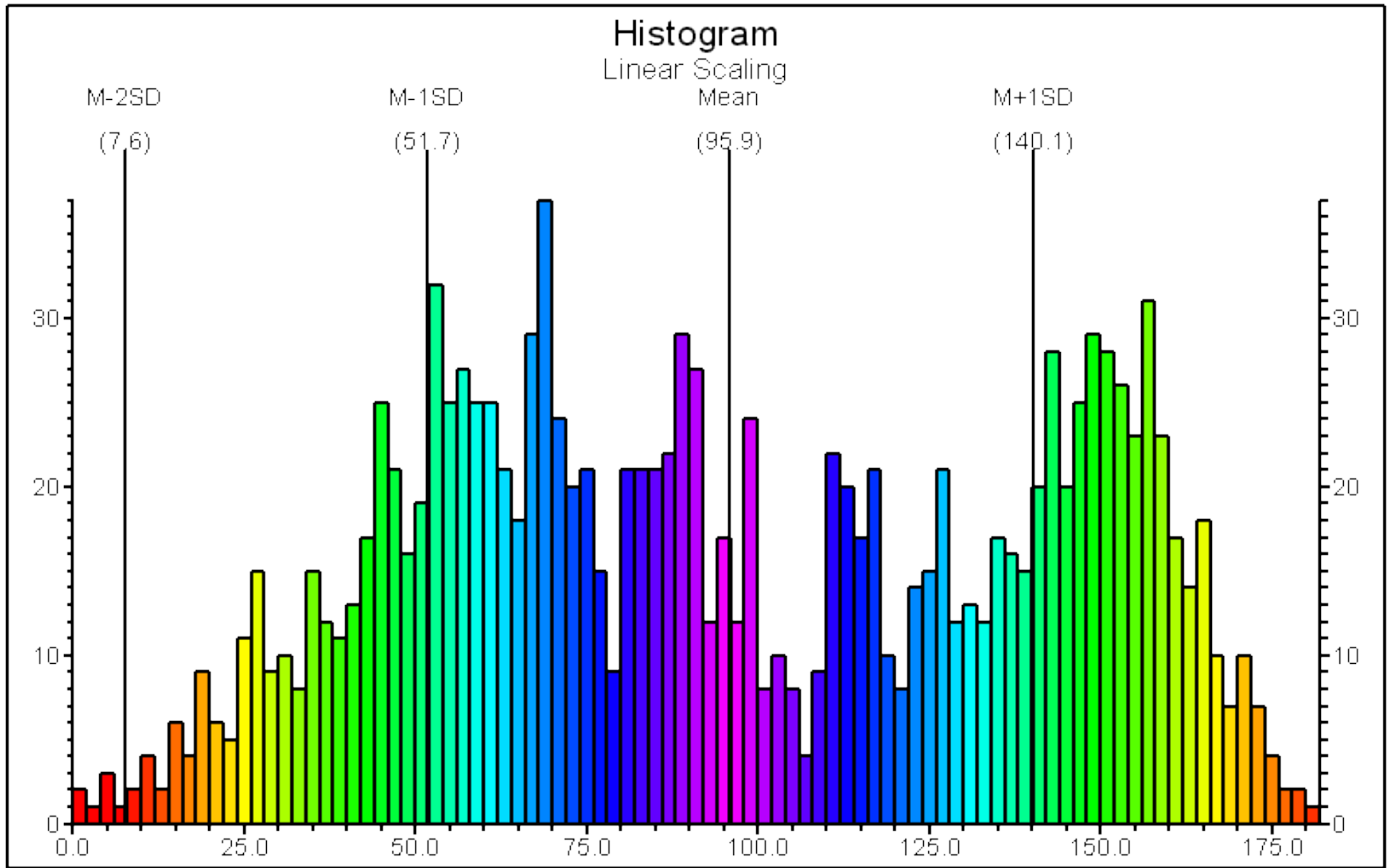


Figure: S5.10 – Histogram of DEM digitized lineaments for the Cayuga Subset with bin size of 2°

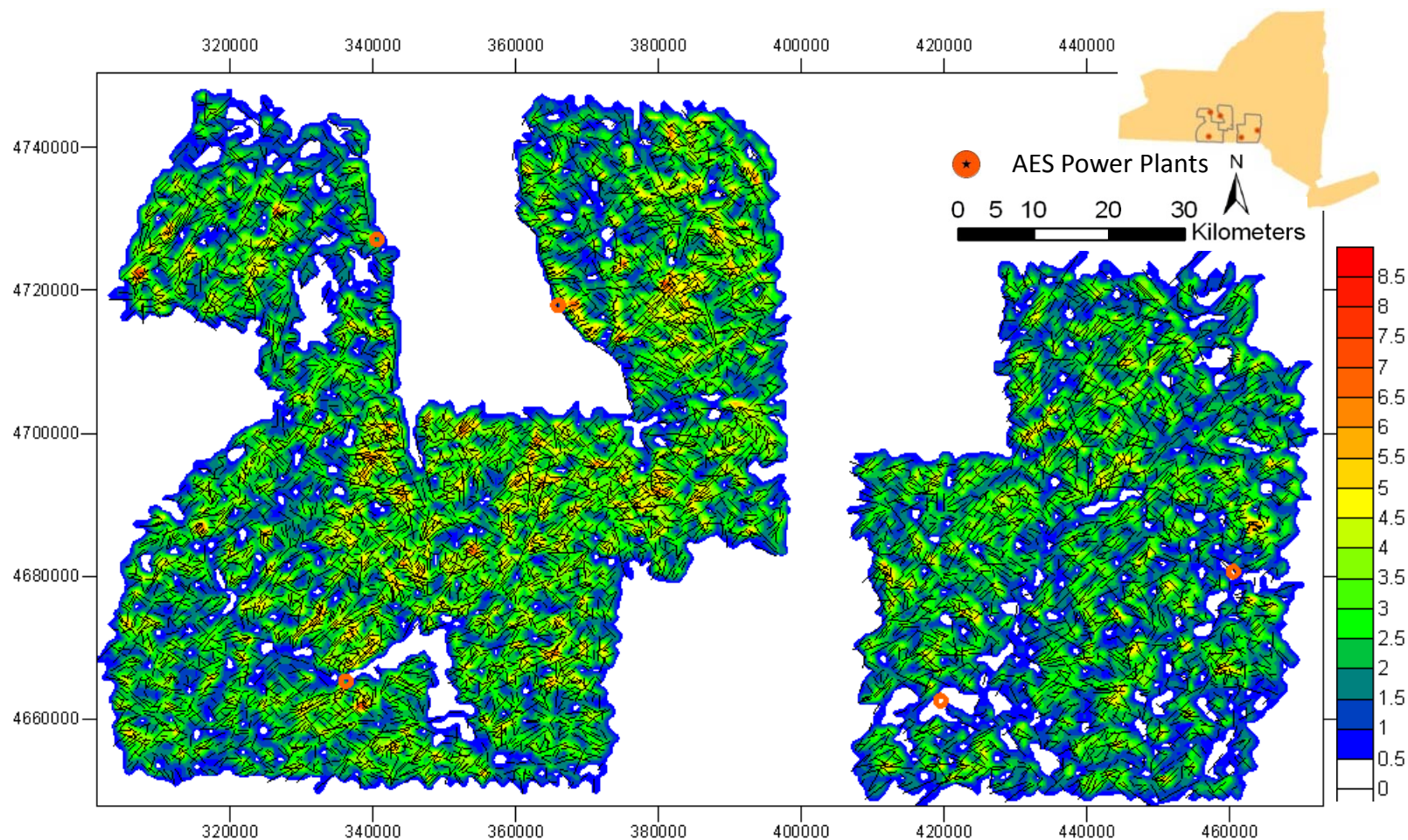


Figure: S5.11- Lineament density map from all ASTER lineaments with lineaments overlaid, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meter in UTM (N18) projection system, Phase II, entire project area

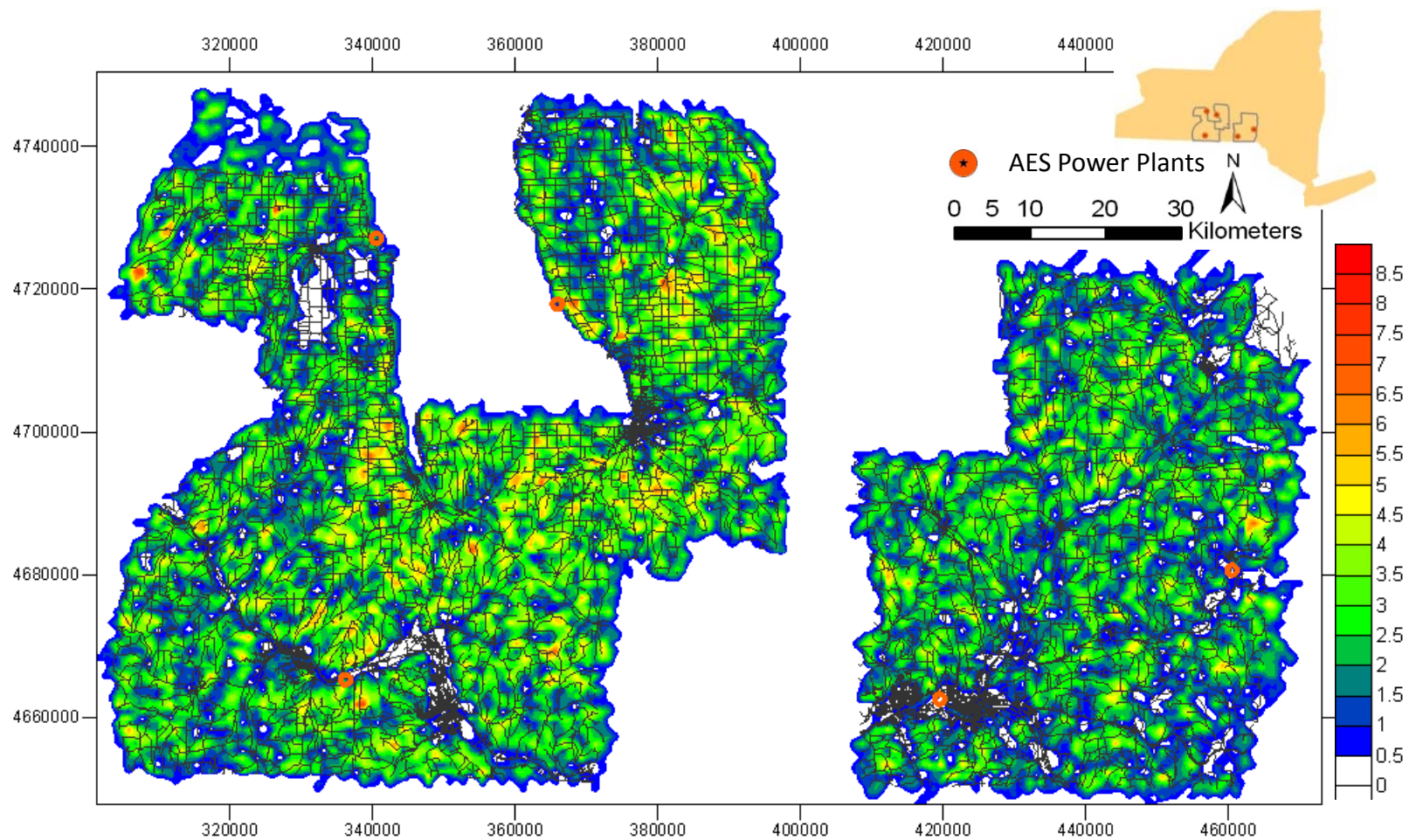


Figure: S5.12 - Lineament density map from all ASTER lineaments with roads overlaid, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meter in UTM (N18) projection system, Phase II, entire project area

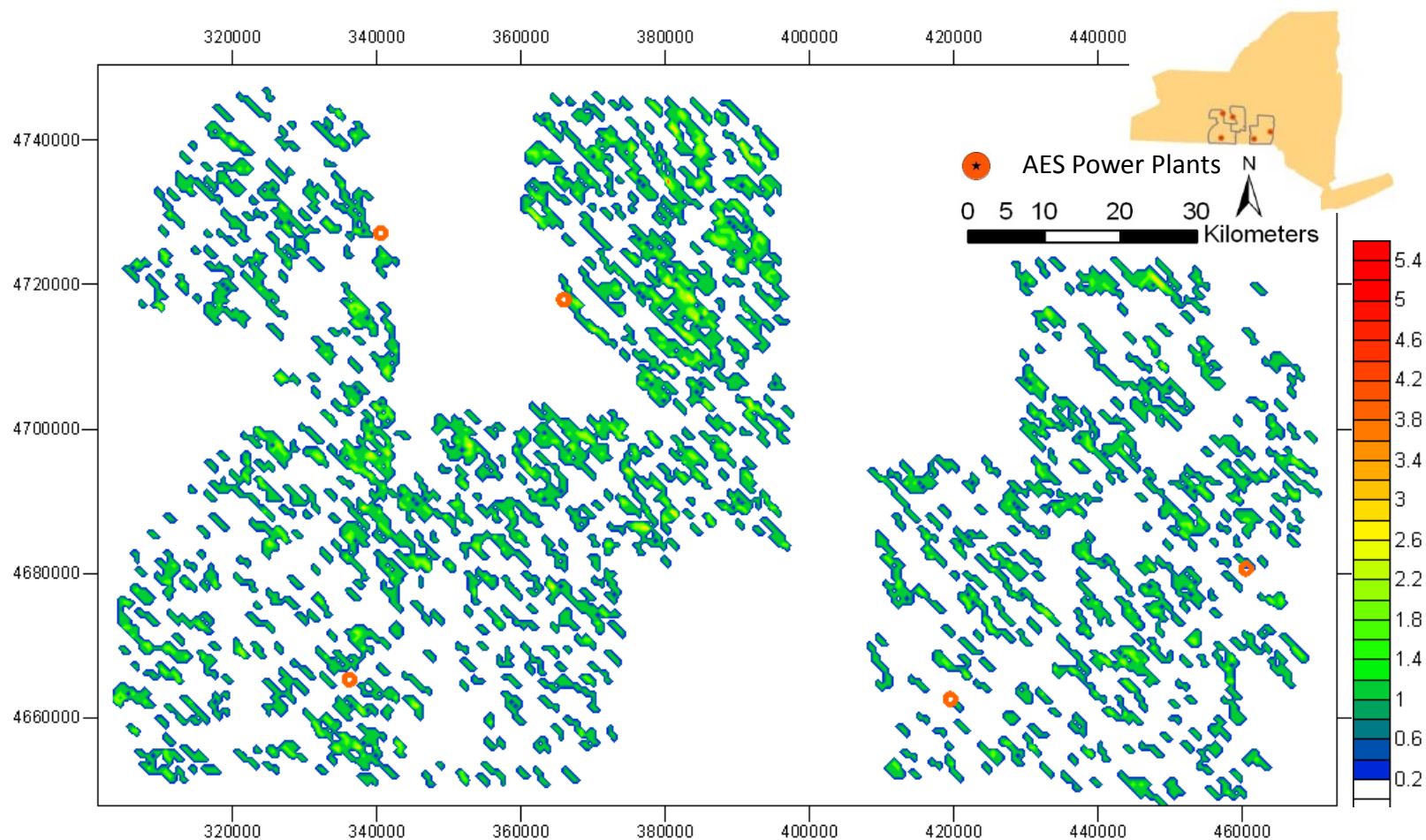


Figure: S5.13 - Lineament density map from NW ASTER lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meter in UTM (N18) projection system, Phase II, entire project area

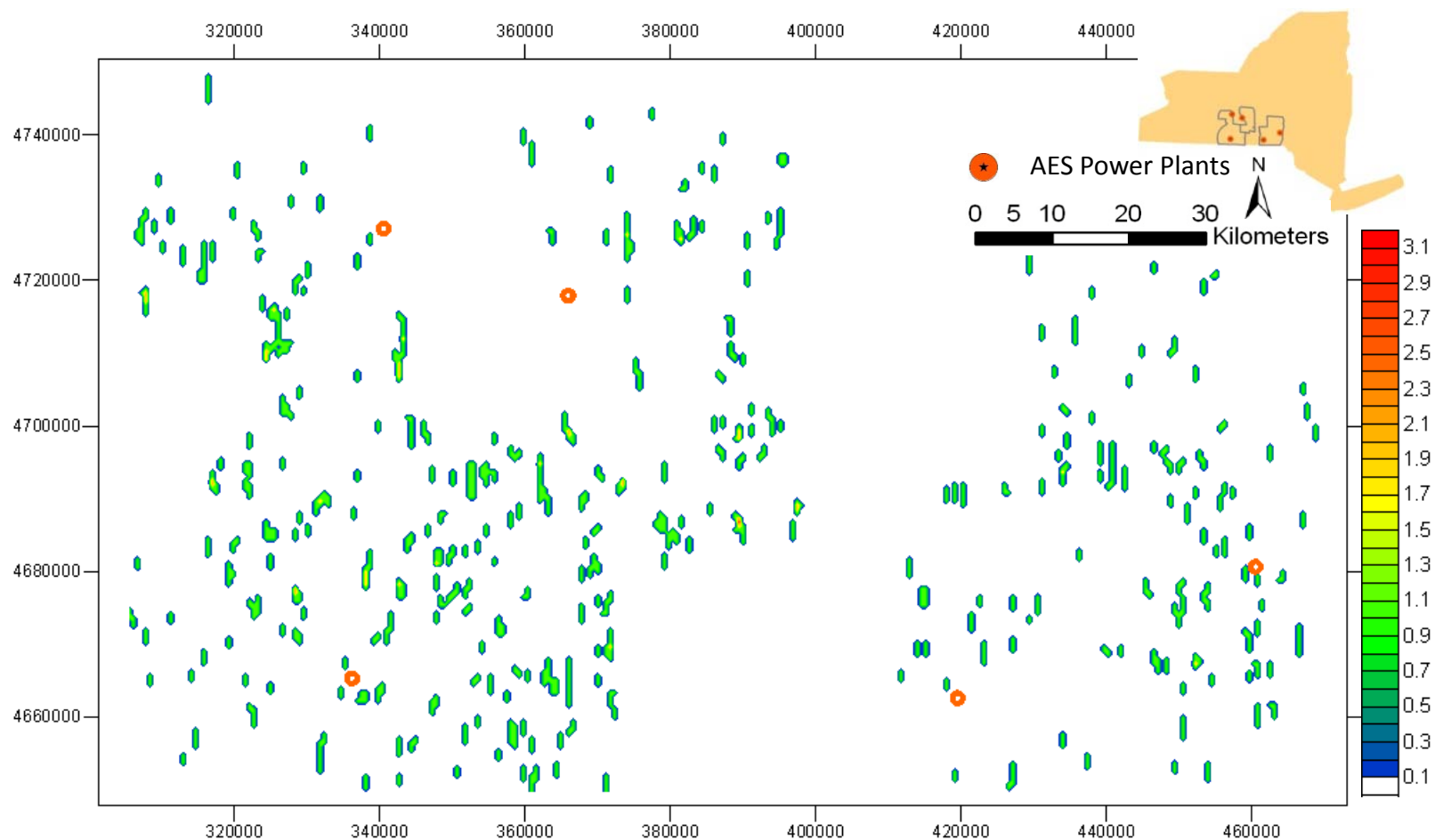


Figure: S5.14 - Lineament density map from NS ASTER lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meter in UTM (N18) projection system, Phase II, entire project area

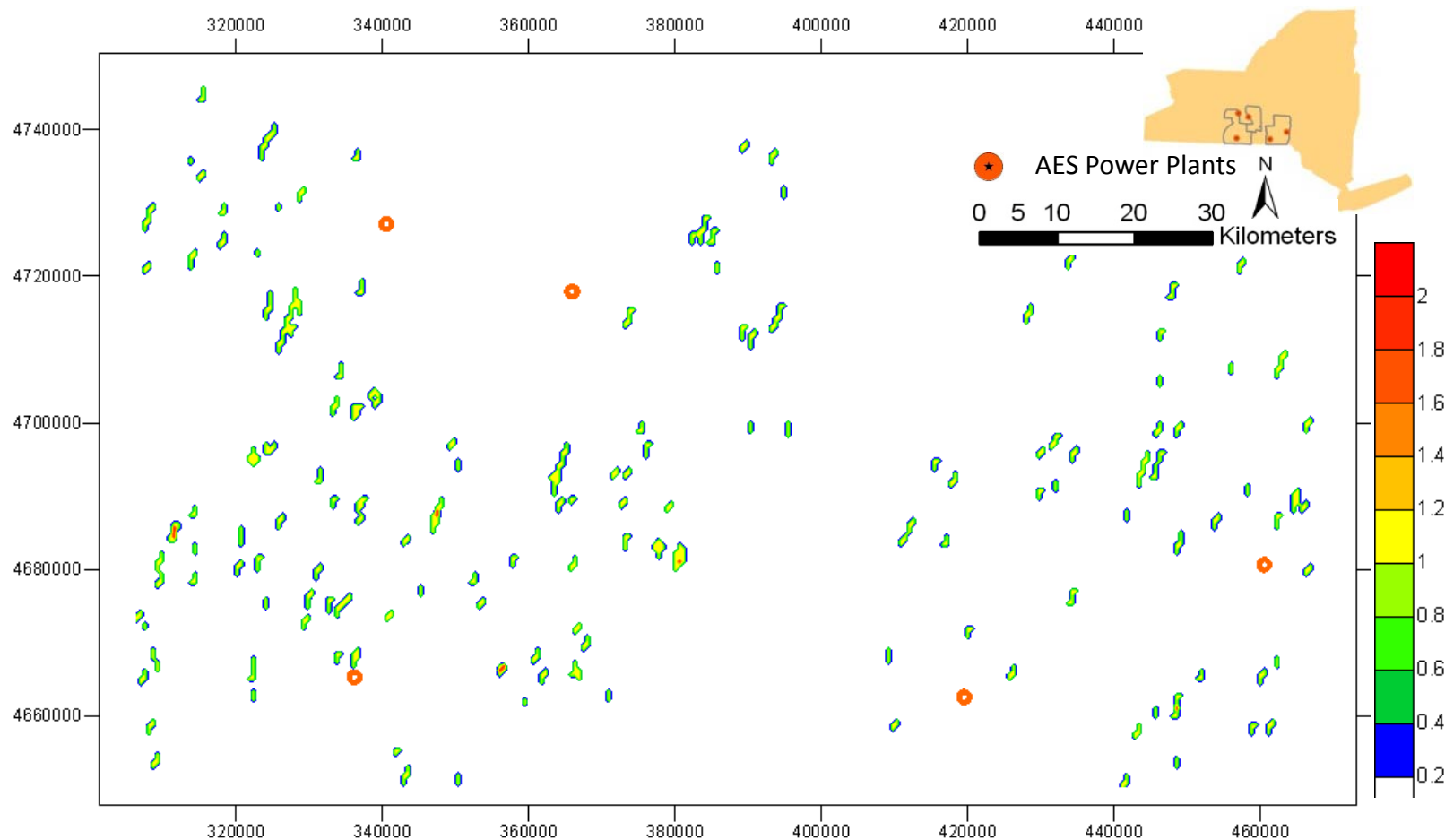


Figure: S5.15 - Lineament density map from NNE ASTER lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meter in UTM (N18) projection system, Phase II, entire project area

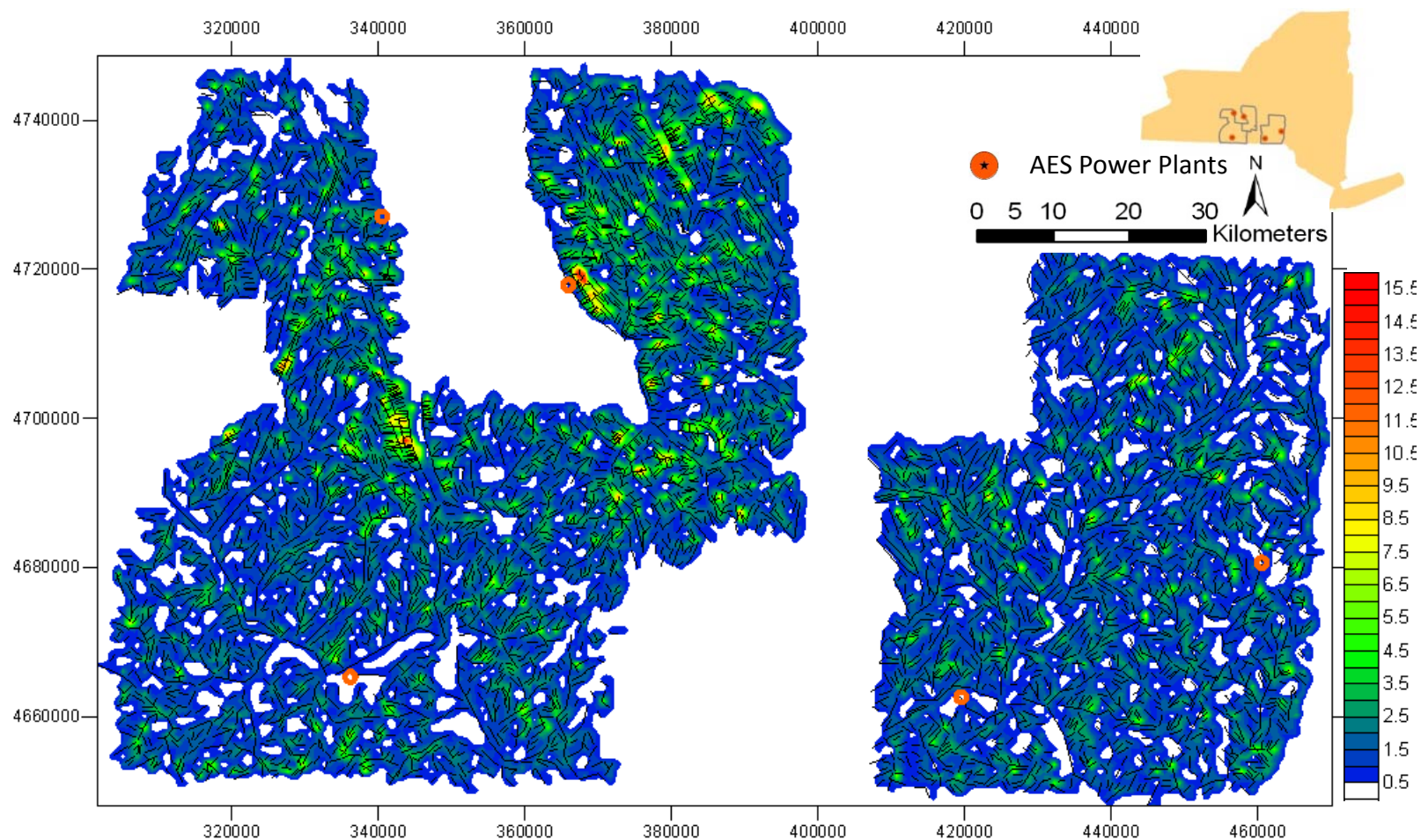


Figure: S5.16 - Lineament density map from all DEM lineaments with lineaments overlaid, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meter in UTM (N18) projection system, Phase II, entire project area

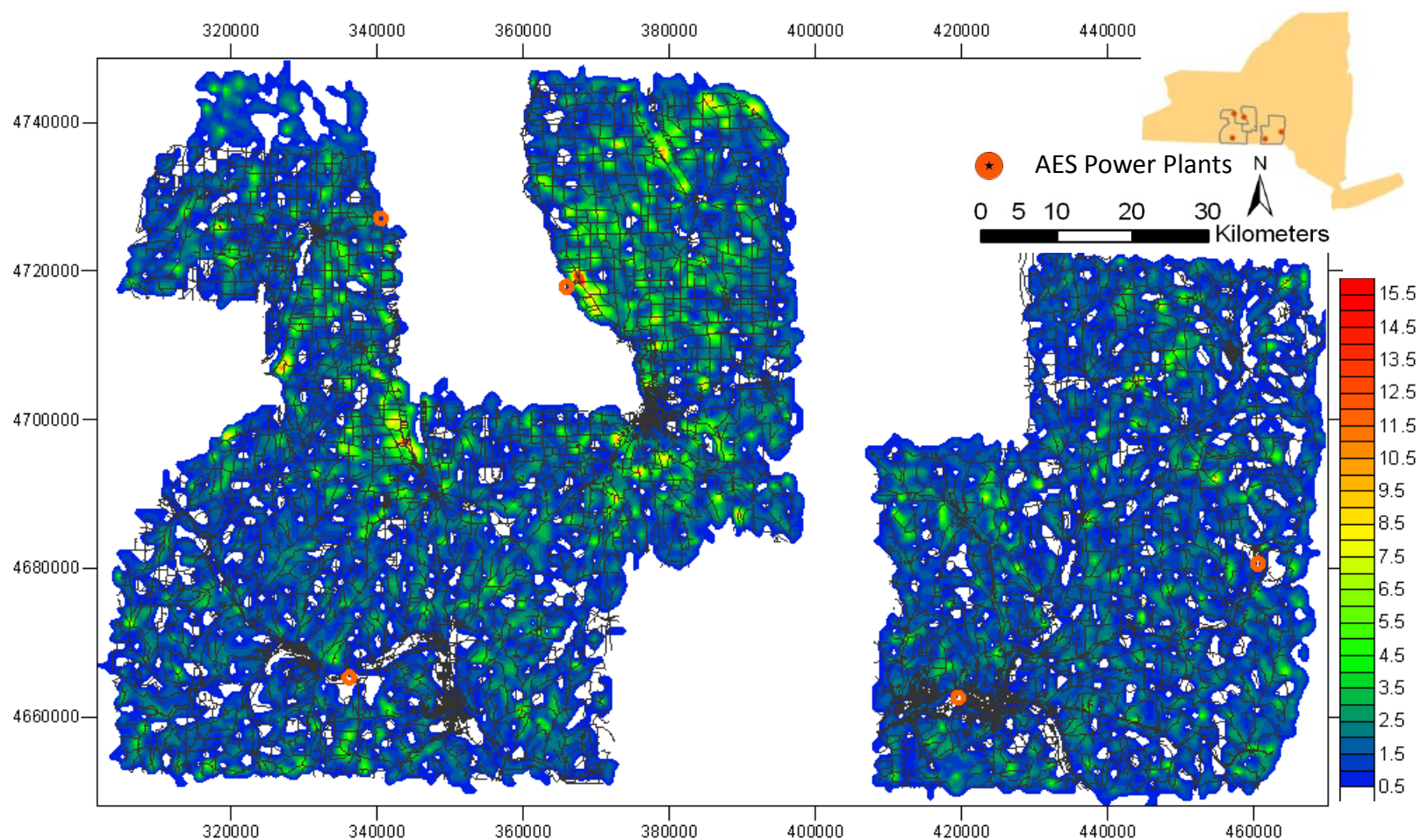


Figure: S5.17 - Lineament density map from all DEM lineaments with roads overlaid, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meter in UTM (N18) projection system, Phase II, entire project area

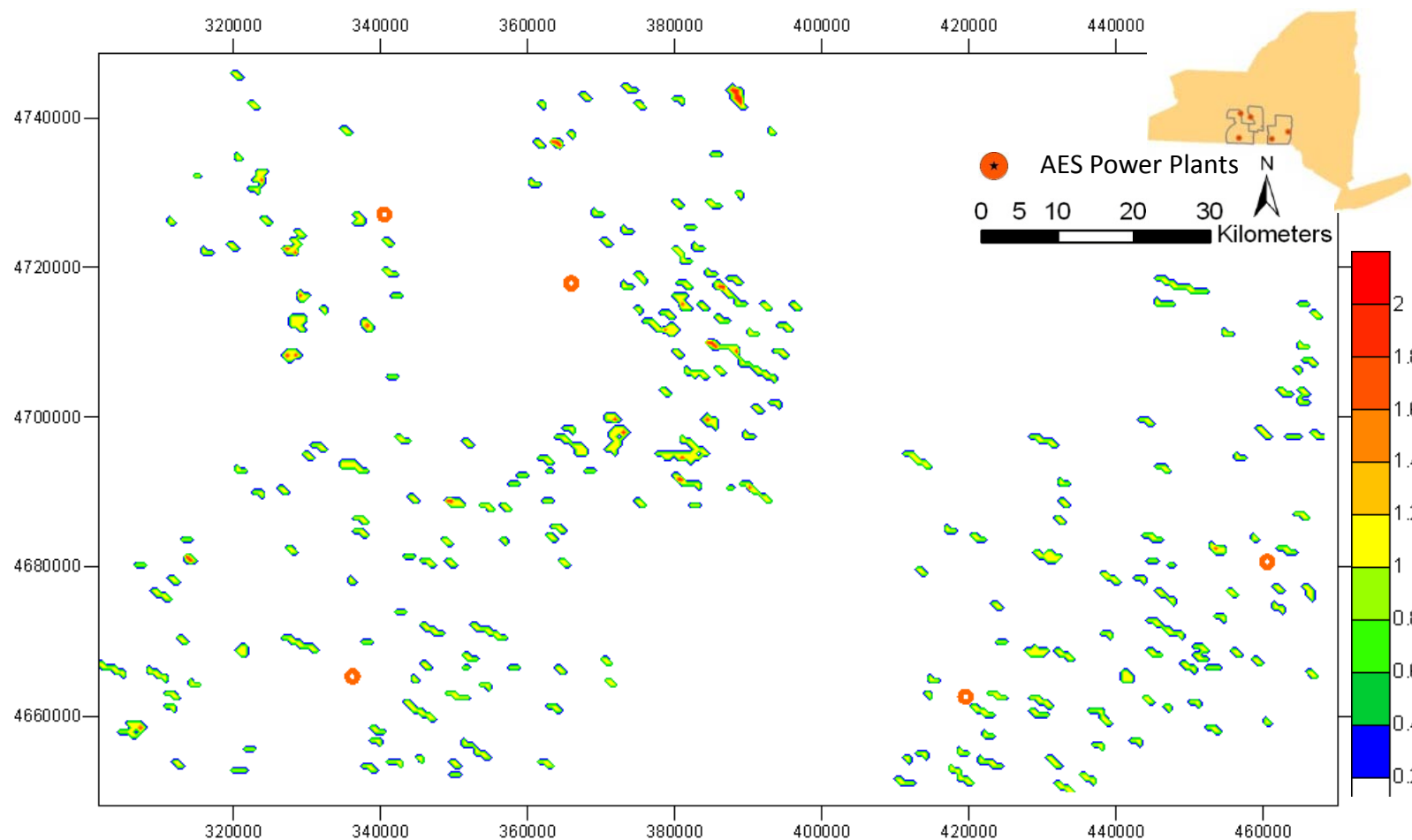


Figure: S5.18 - Lineament density map from WNW DEM lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meter in UTM (N18) projection system, Phase II, entire project area

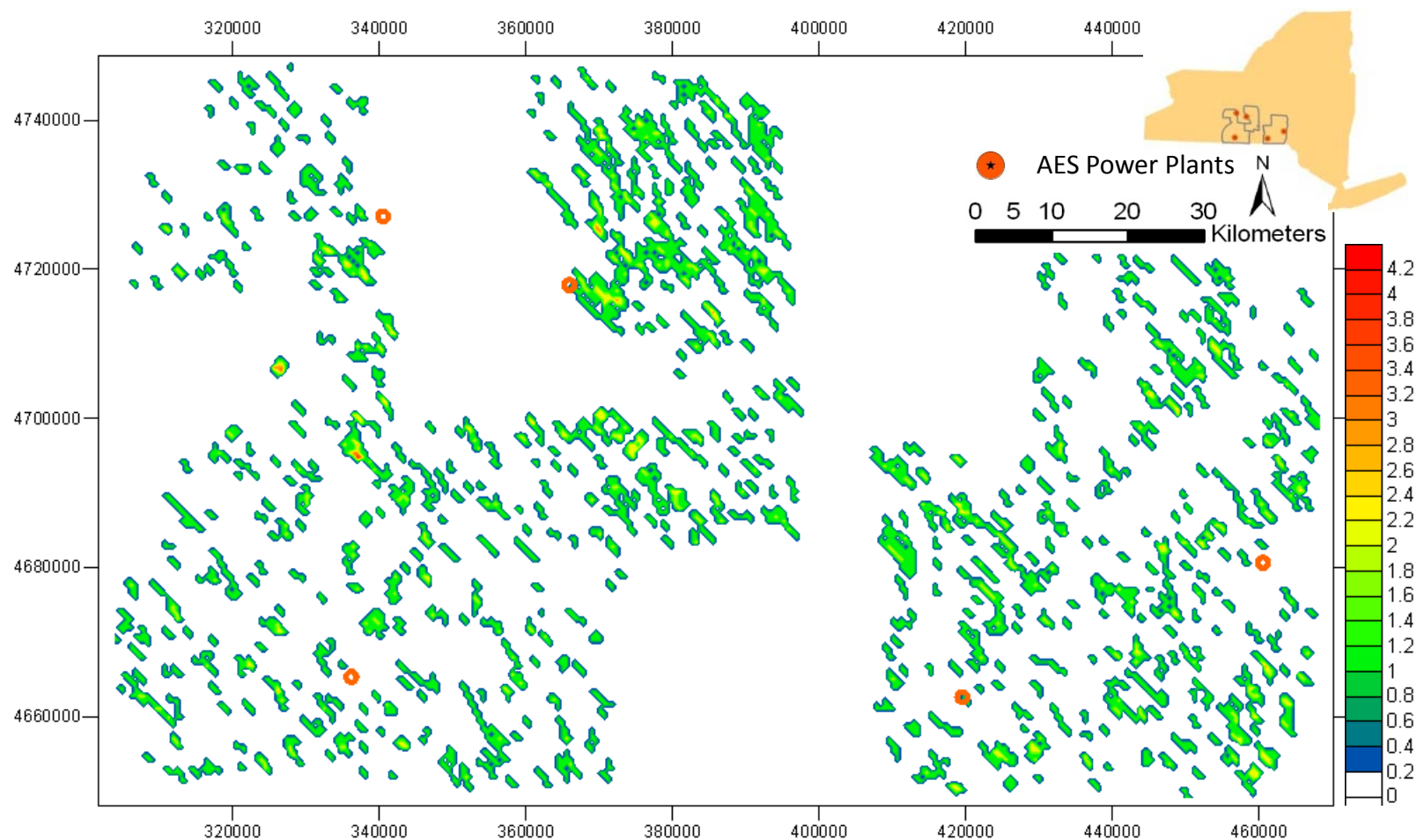


Figure: S5.19 - Lineament density map from NW DEM lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meter in UTM (N18) projection system, Phase II, entire project area

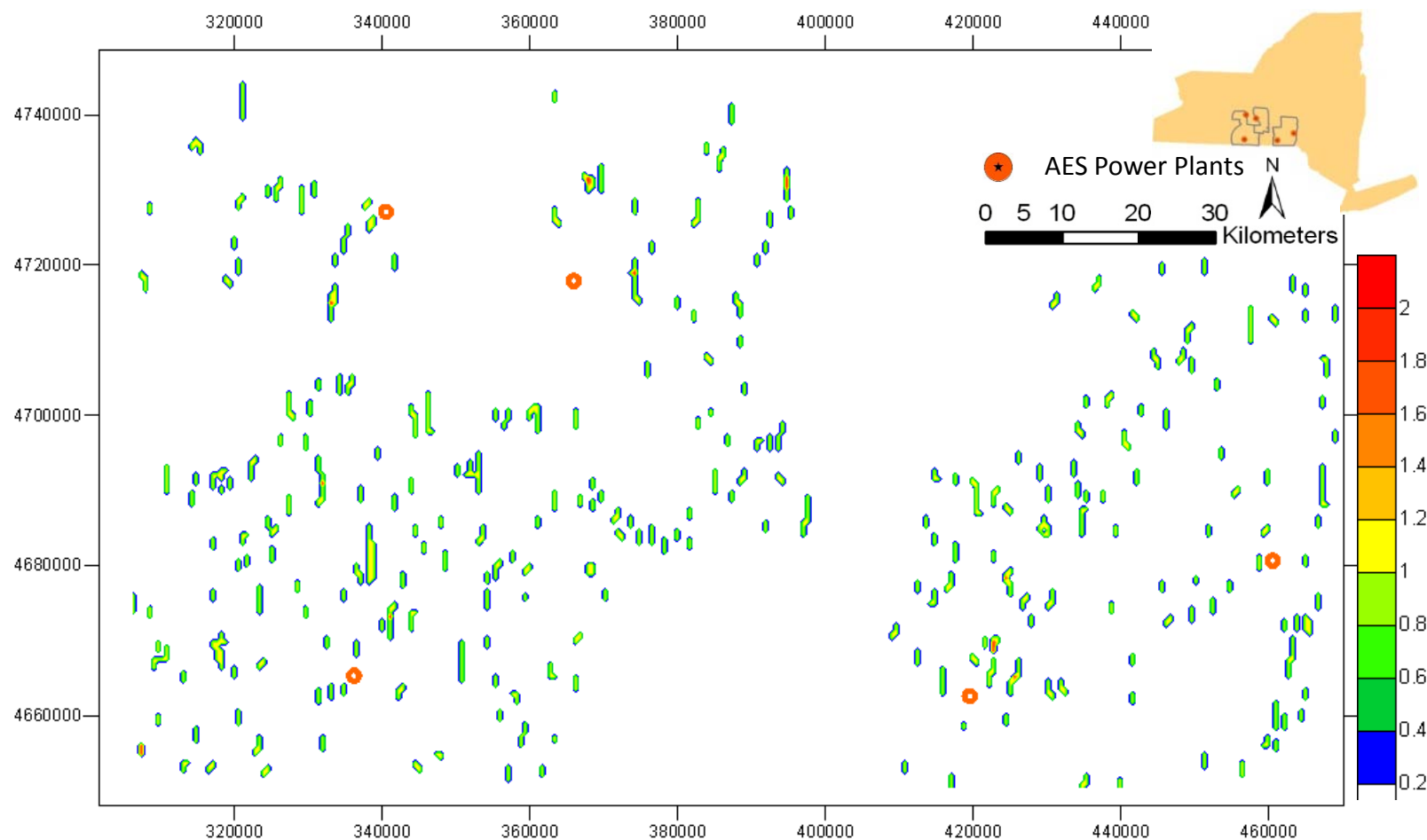


Figure: S5.20 - Lineament density map from NS DEM lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meter in UTM (N18) projection system, Phase II, entire project area

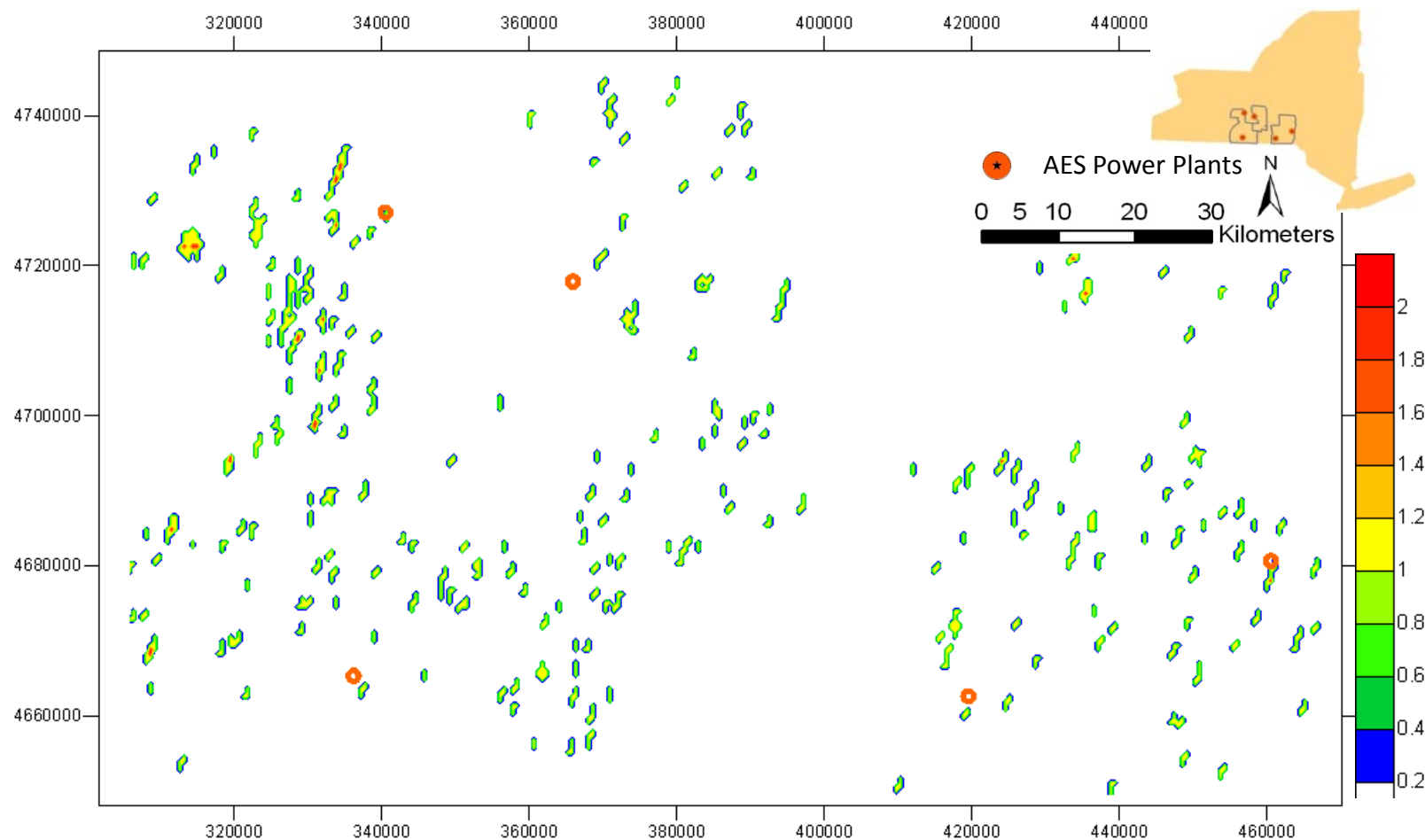


Figure: S5.21 - Lineament density map from NNE DEM lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meter in UTM (N18) projection system, Phase II, entire project area

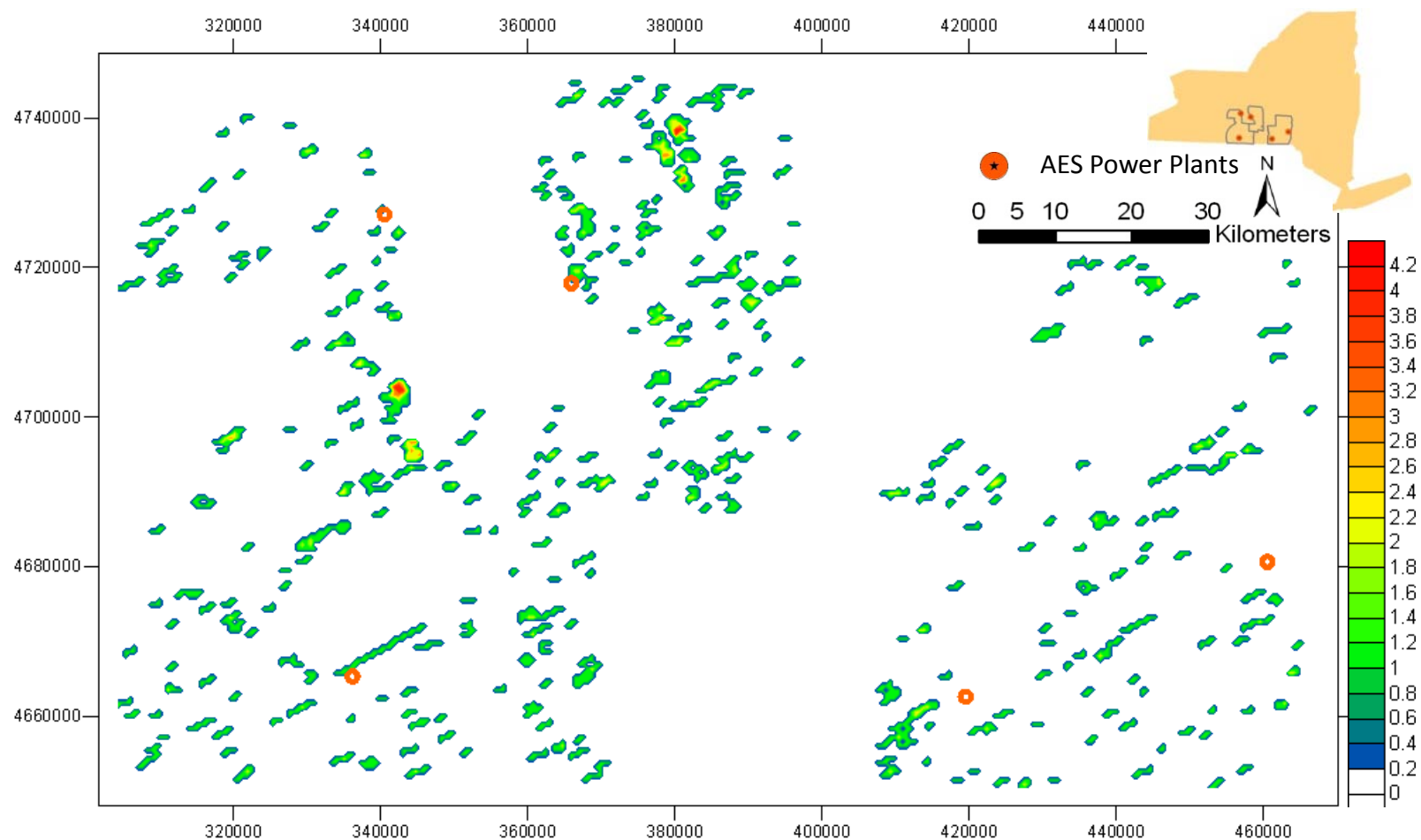


Figure: S5.22 - Lineament density map from ENE DEM lineaments, colors show lineament density in counts per 0.333 square miles. Coordinates are given in meter in UTM (N18) projection system, Phase II, entire project area

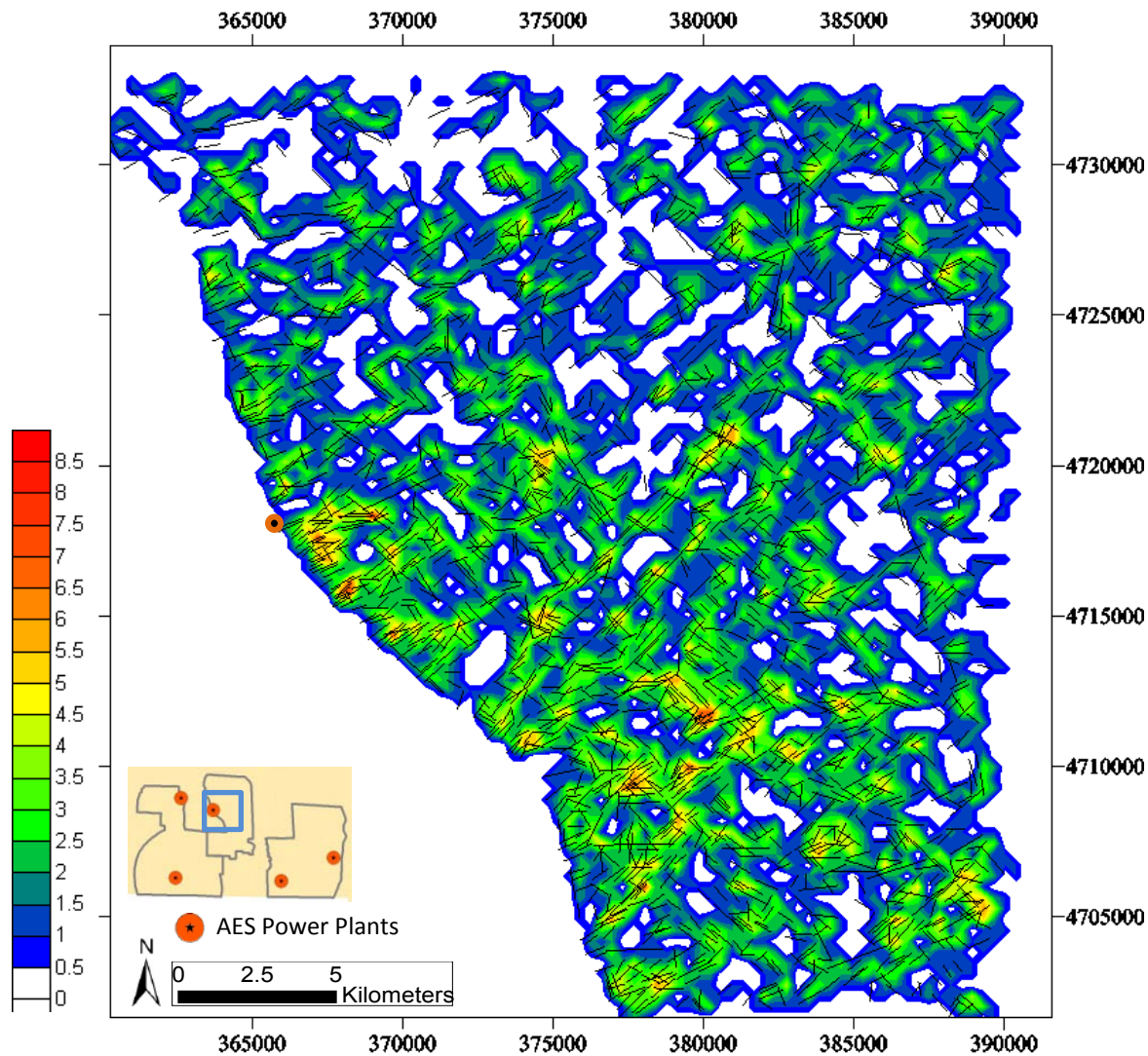


Figure: S5.23 - Lineament density map from All ASTER lineaments with lineaments overlaid, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

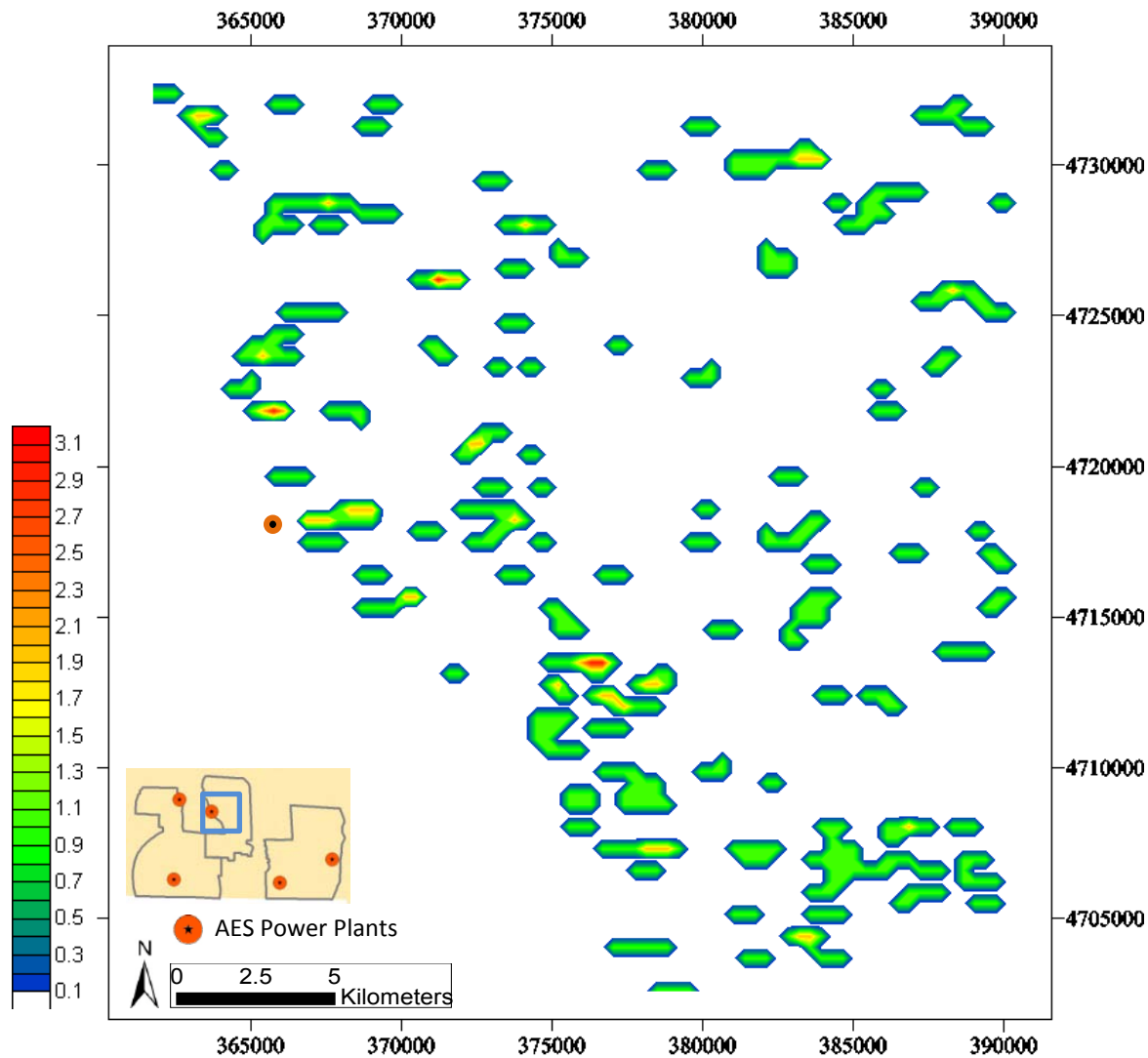


Figure: S5.24 - Lineament density map from EW ASTER lineaments, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

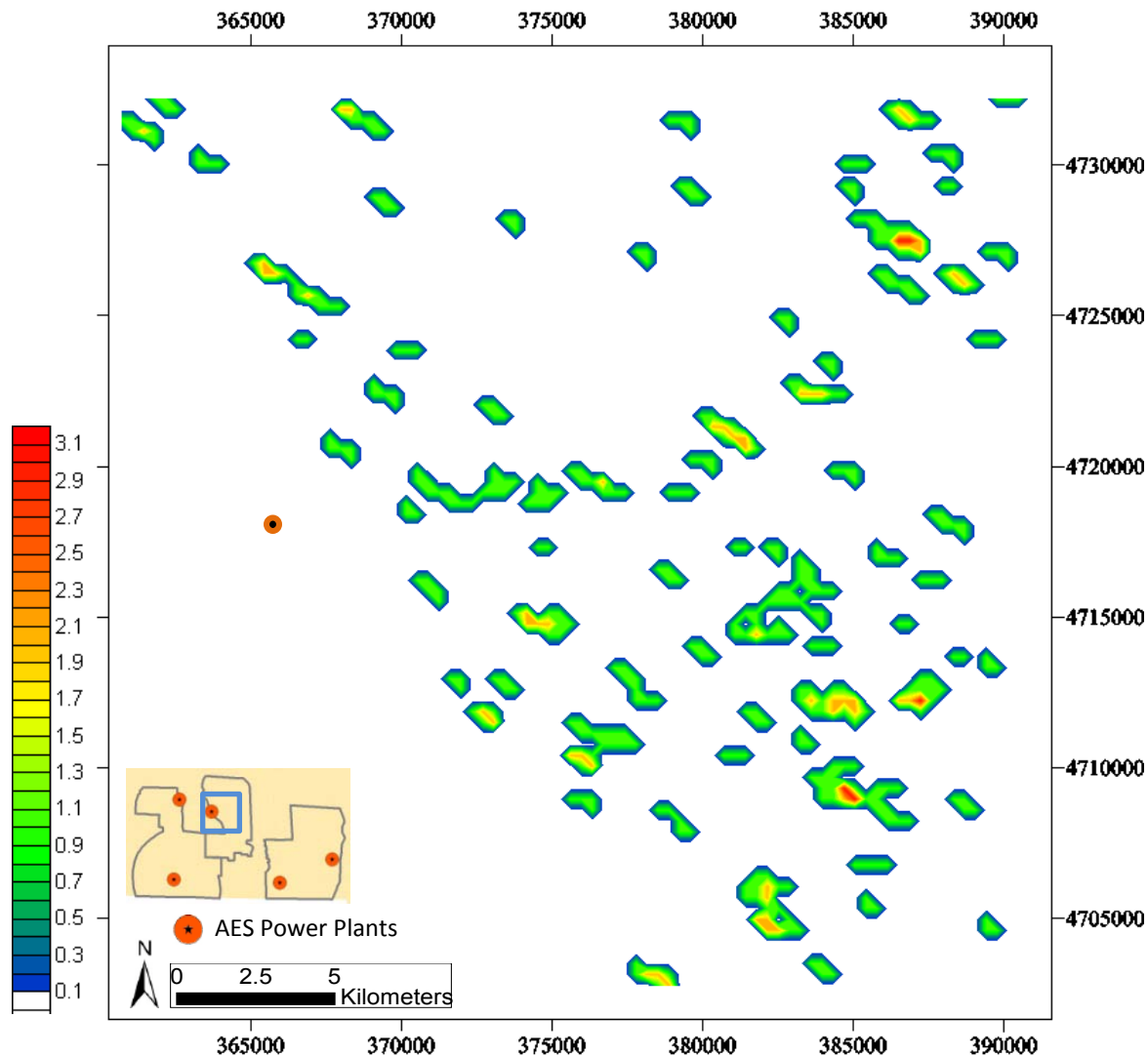


Figure: S5.25 - Lineament density map from WNW ASTER lineaments, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

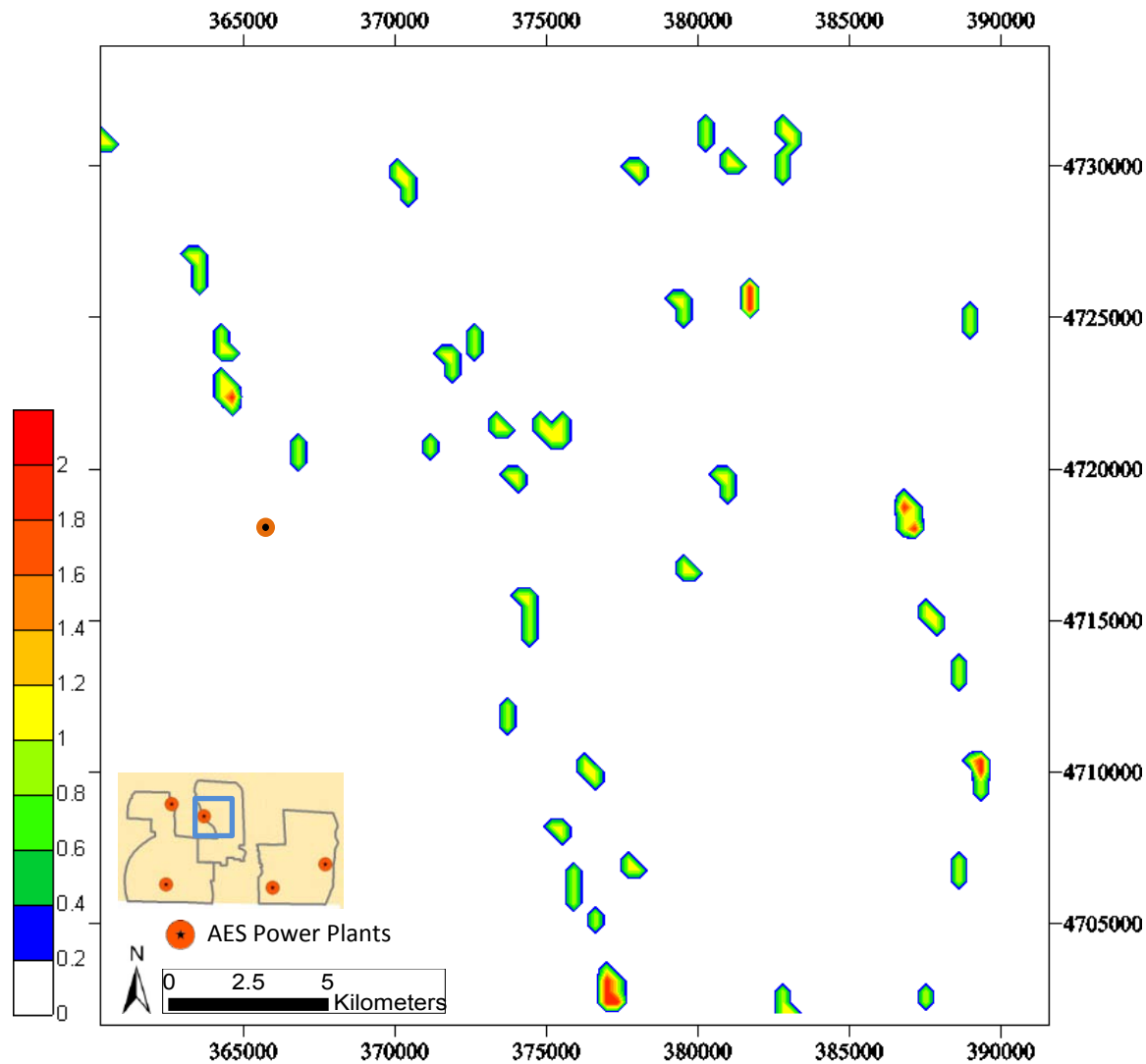


Figure: S5.26 - Lineament density map from NNW ASTER lineaments, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

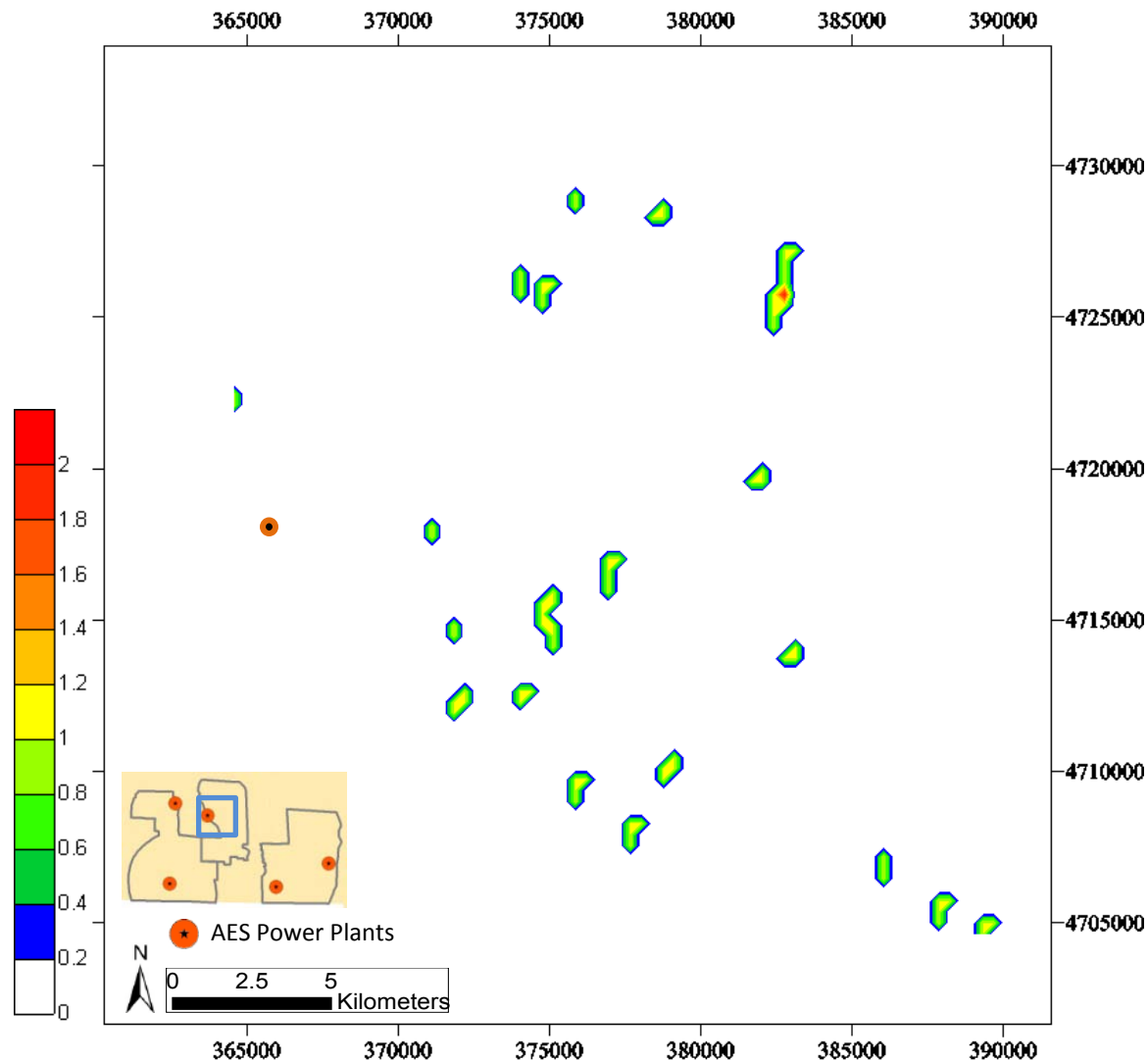


Figure: S5.27 - Lineament density map from NNE ASTER lineaments, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

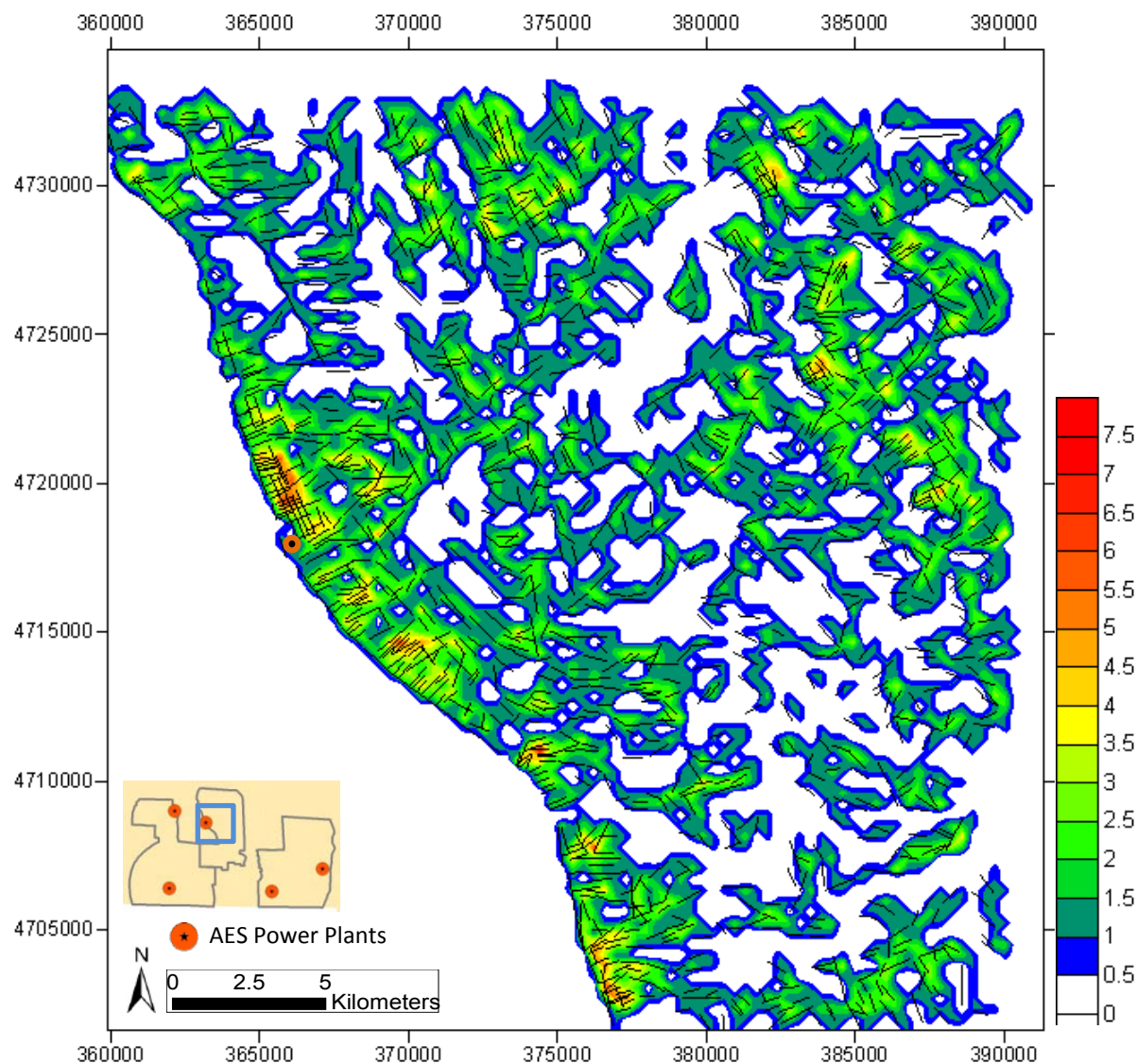


Figure: S5.28- Lineament density map from All DEM lineaments with lineaments overlaid, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

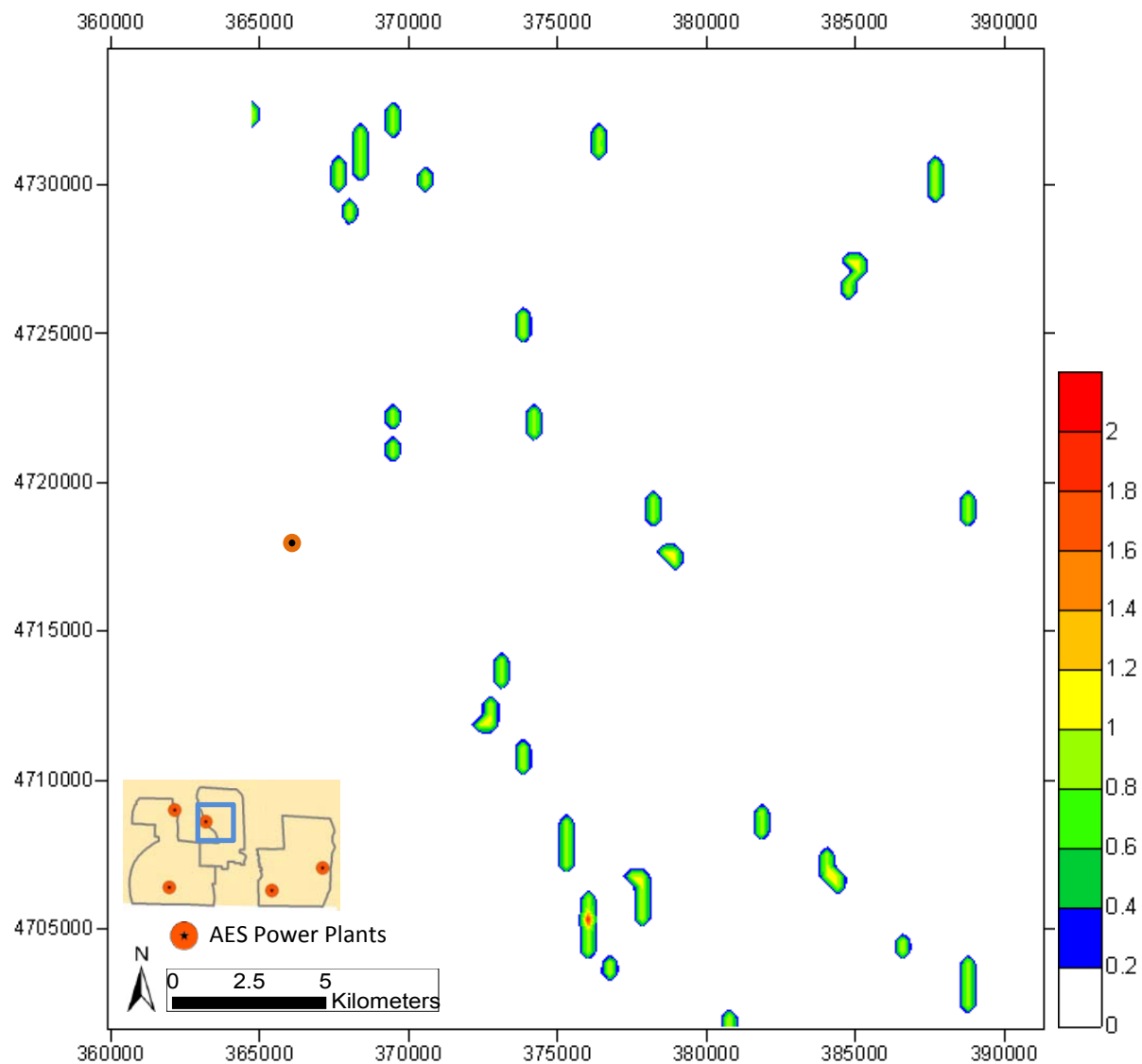


Figure: S5.29 - Lineament density map from NS DEM lineaments, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

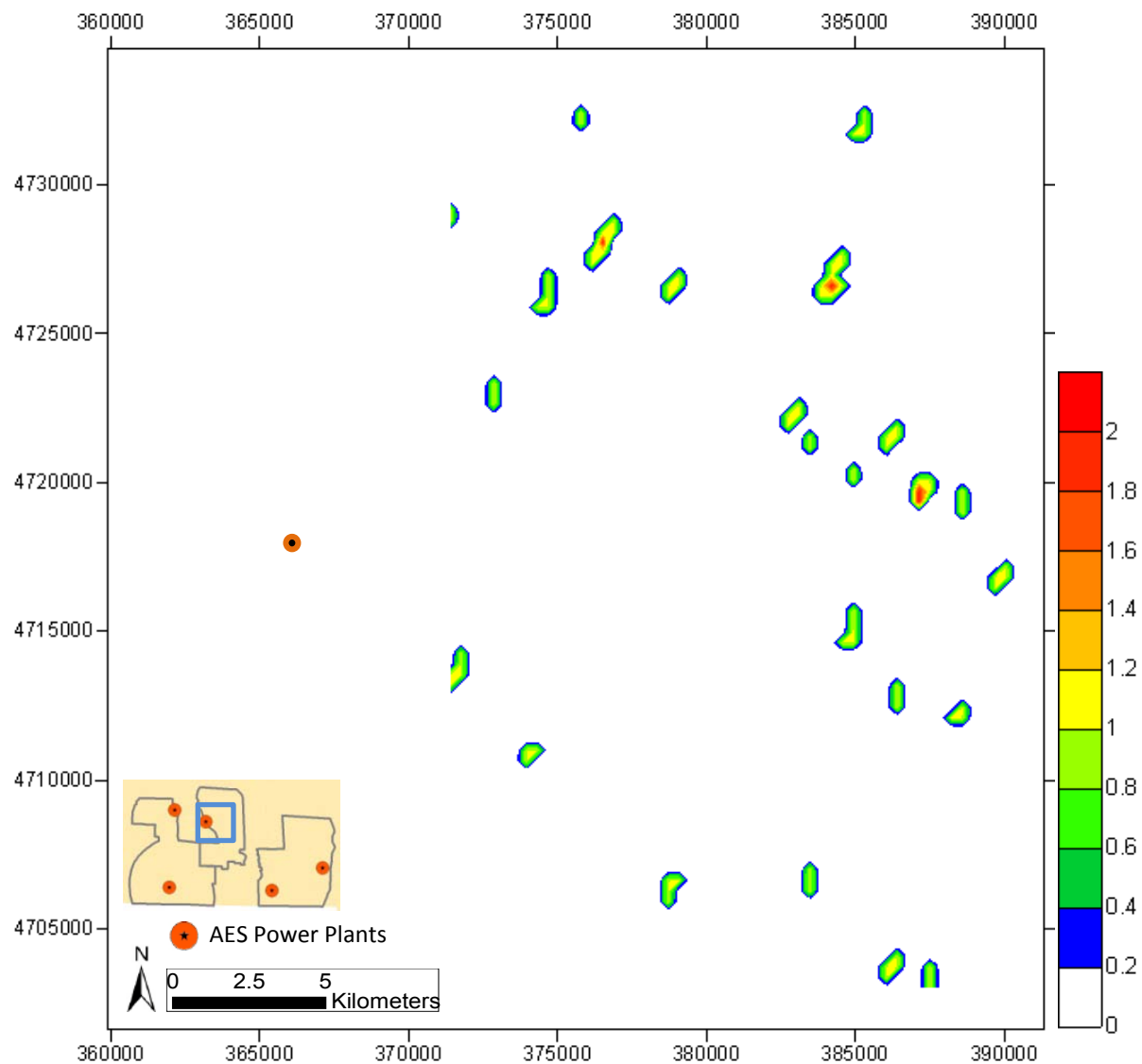


Figure: S5.30 - Lineament density map from NNE DEM lineaments, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

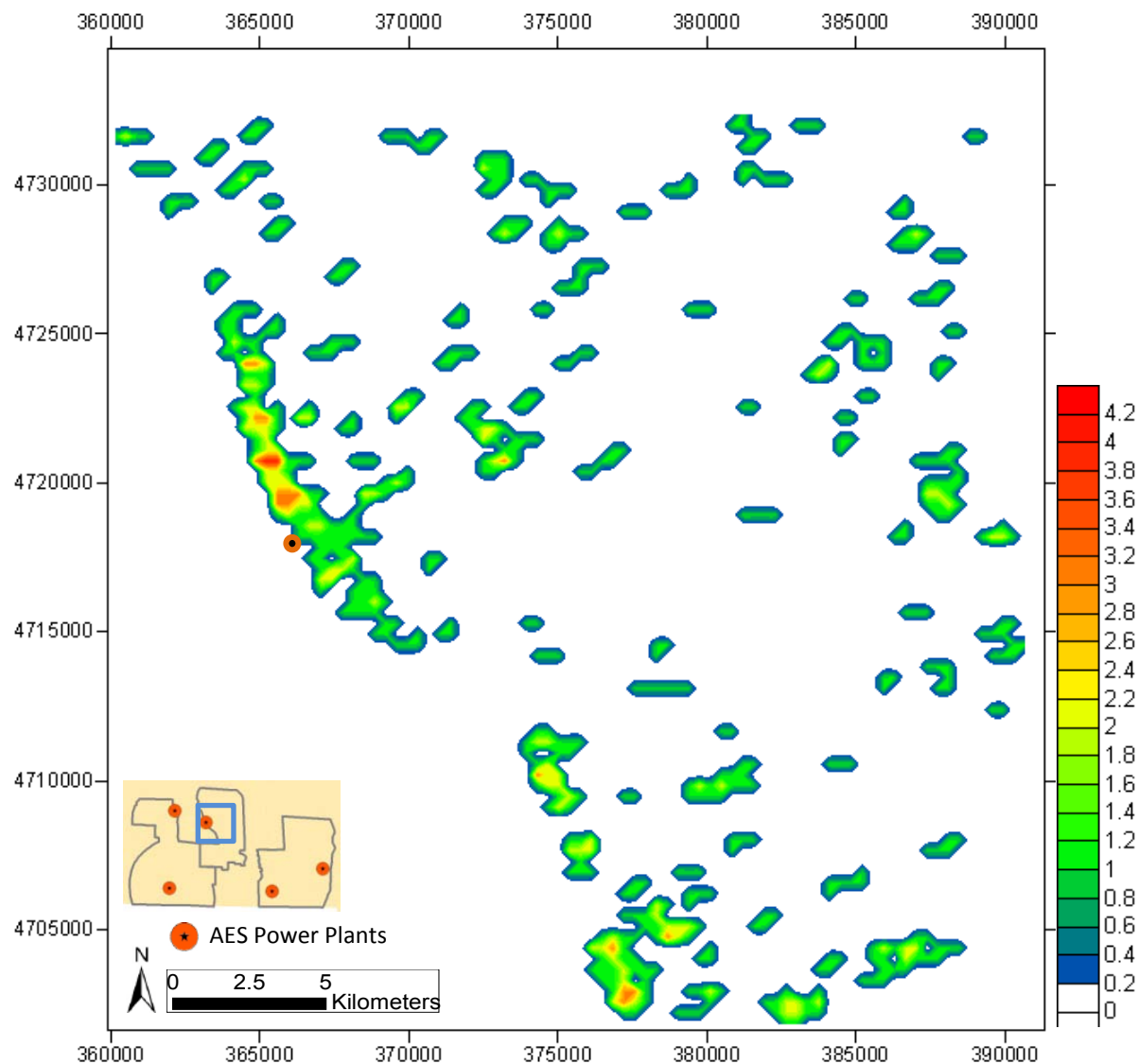


Figure: S5.31 - Lineament density map from ENE DEM lineaments, colors show lineament density in counts per 0.05 square miles. Coordinates are given in meters in UTM (N18) projection system, Phase III, Cayuga subset

Appendix I

Supplemental Figures

Chapter 6

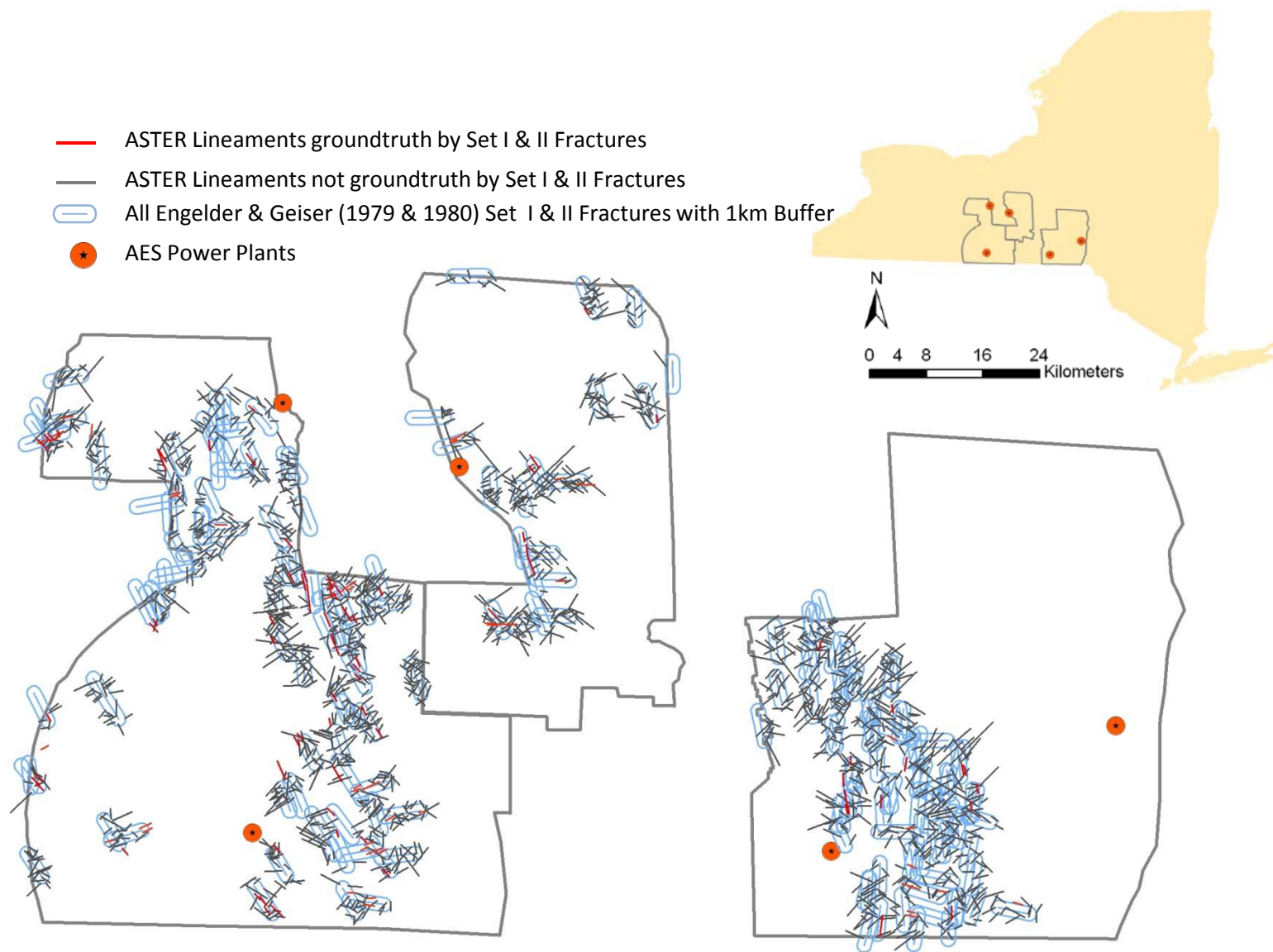


Figure: S6.1 - Map of project area with all ASTER lineaments within the 1km buffer of Engelder & Geiser (1979 & 1980) set I & II fractures

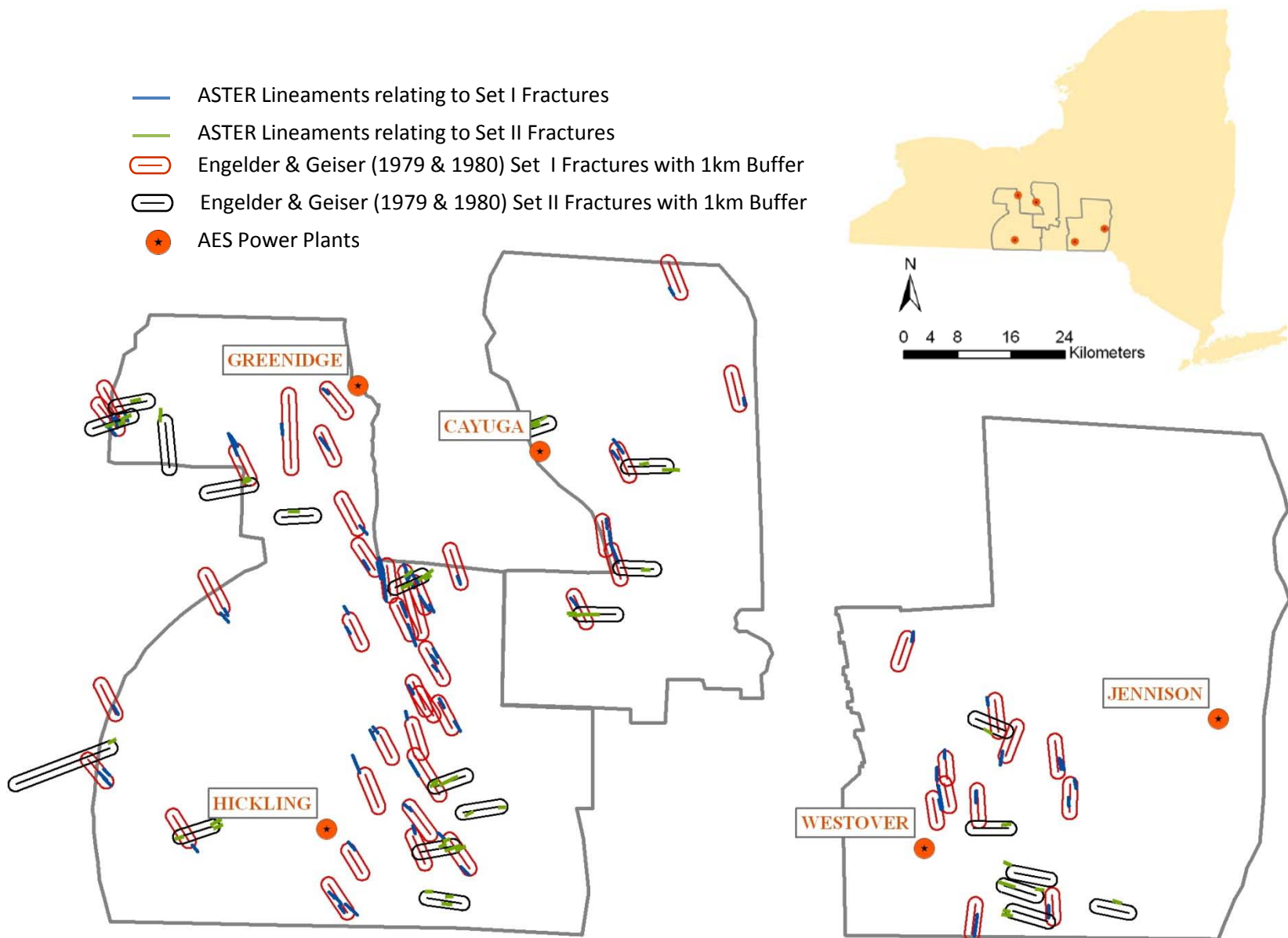


Figure: S6.2 - Map of the project area with selected Engelder & Geiser (1979 & 1980) set I & II fractures with 1km buffer and selected ASTER lineaments within the buffer

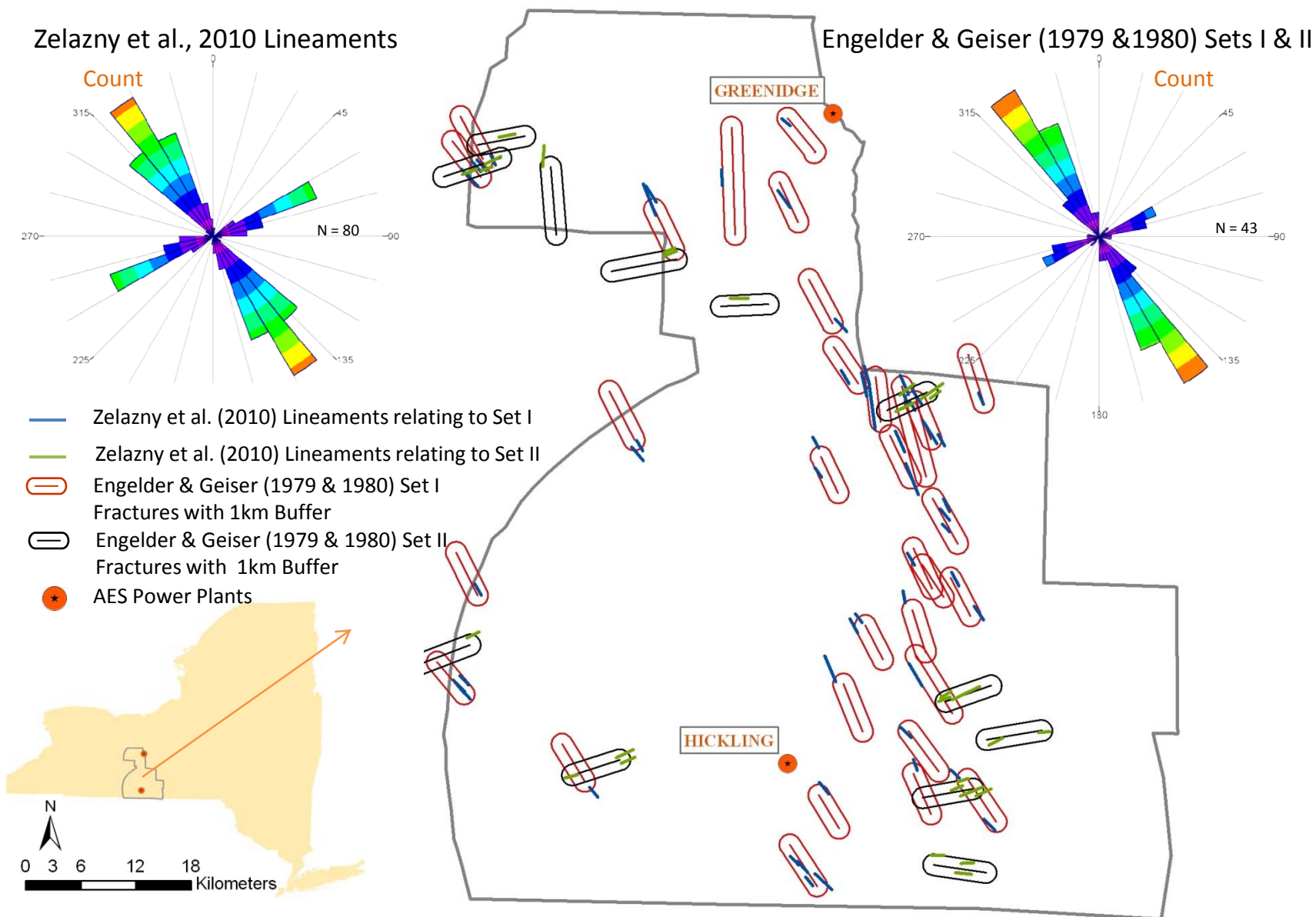


Figure: S6.3 - Map of the Western Focus Area with selected Engelder & Geiser (1979 & 1980) Set I & II Fractures with 1km Buffer with selected Zelazny et al. (2010) Lineaments within the buffer and Rose Diagrams based on Count

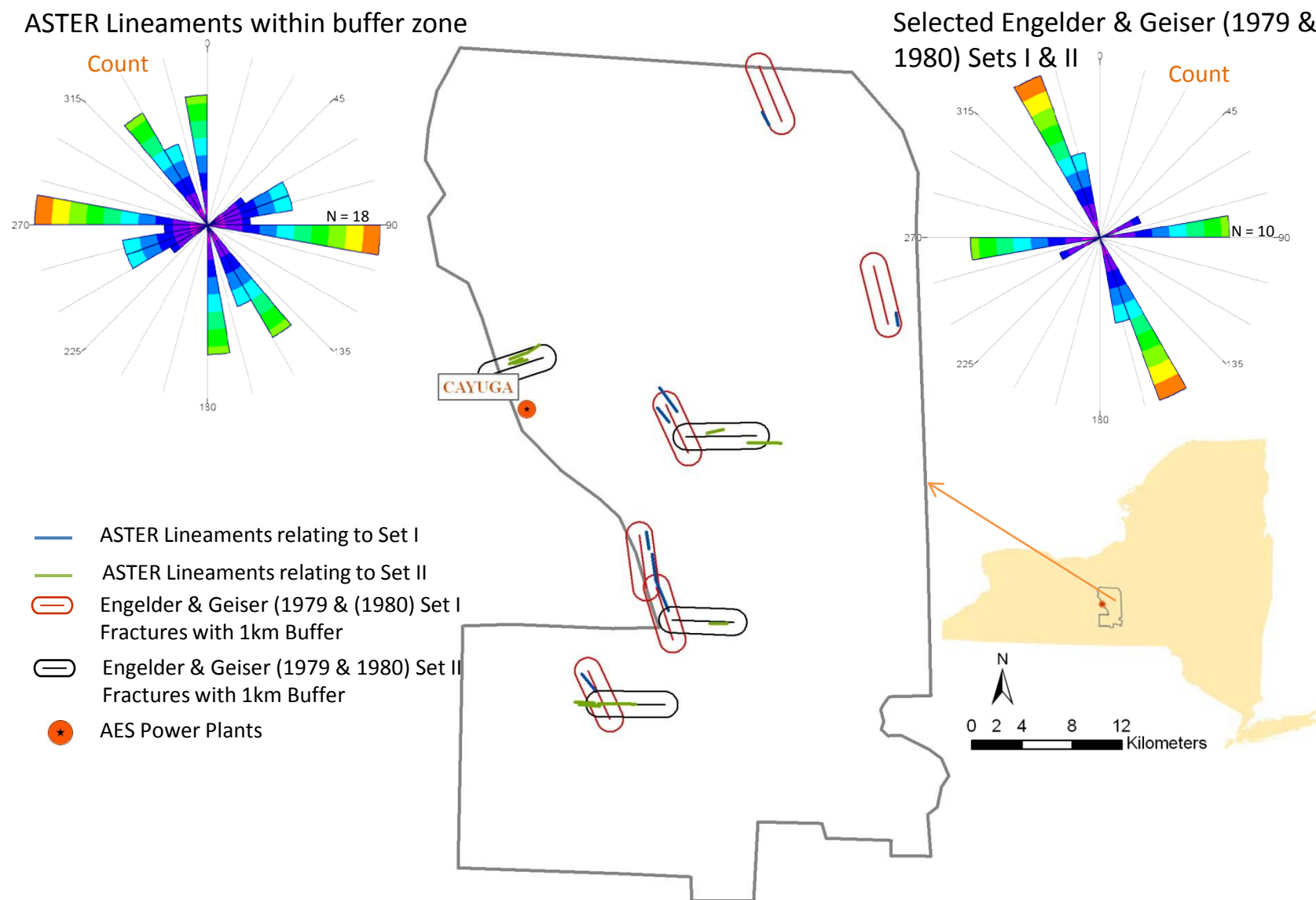


Figure: S6.4 - Map of the central focus area with selected Engelder & Geiser (1979 & 1980) set I & II fractures with 1km buffer with selected ASTER lineaments within the buffer and rose diagrams based on count

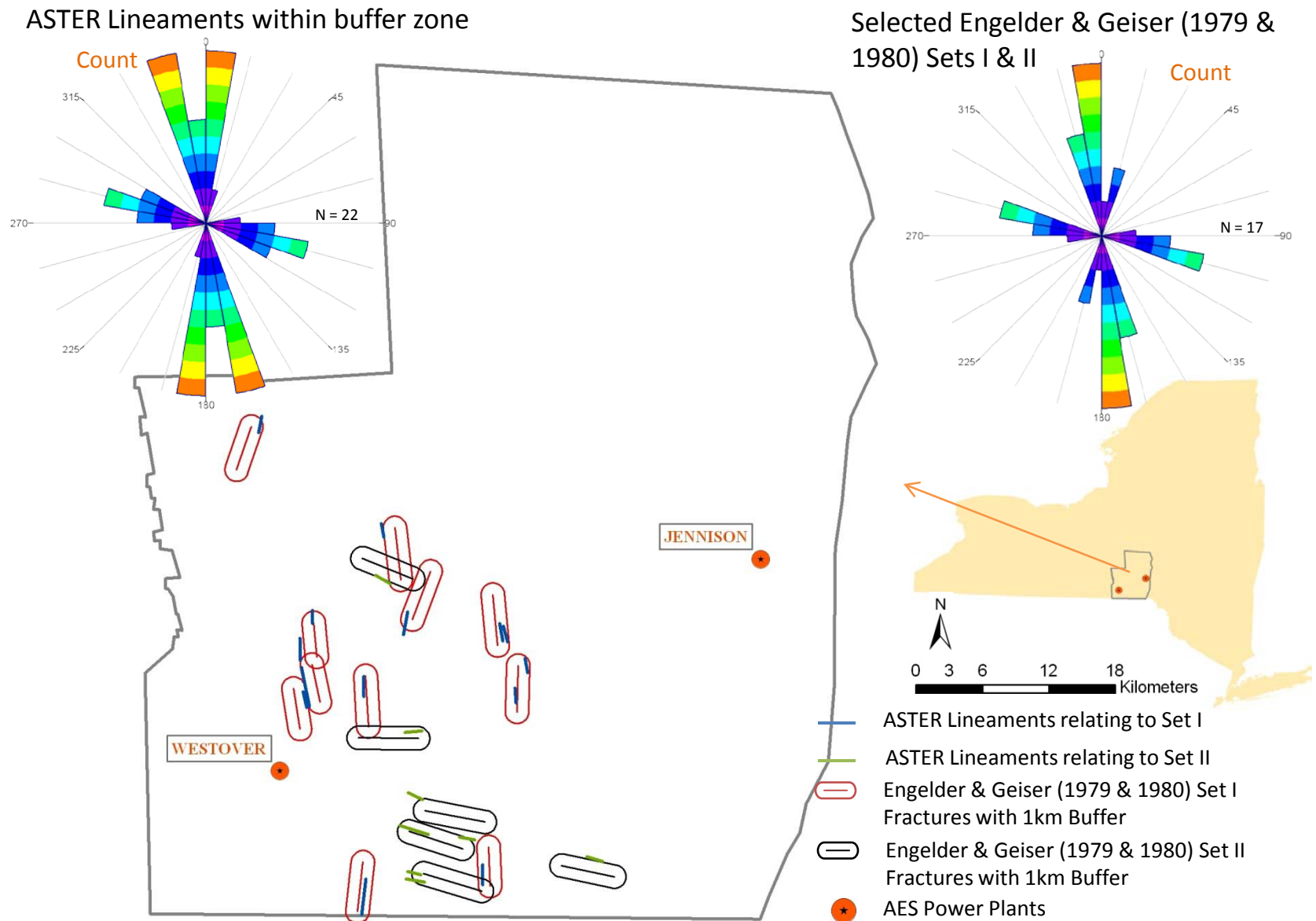


Figure: S6.5 - Map of the eastern focus area with selected Engelder & Geiser (1979 & 1980) set I & II fractures with 1km buffer with selected ASTER lineaments within the buffer and rose diagrams based on count

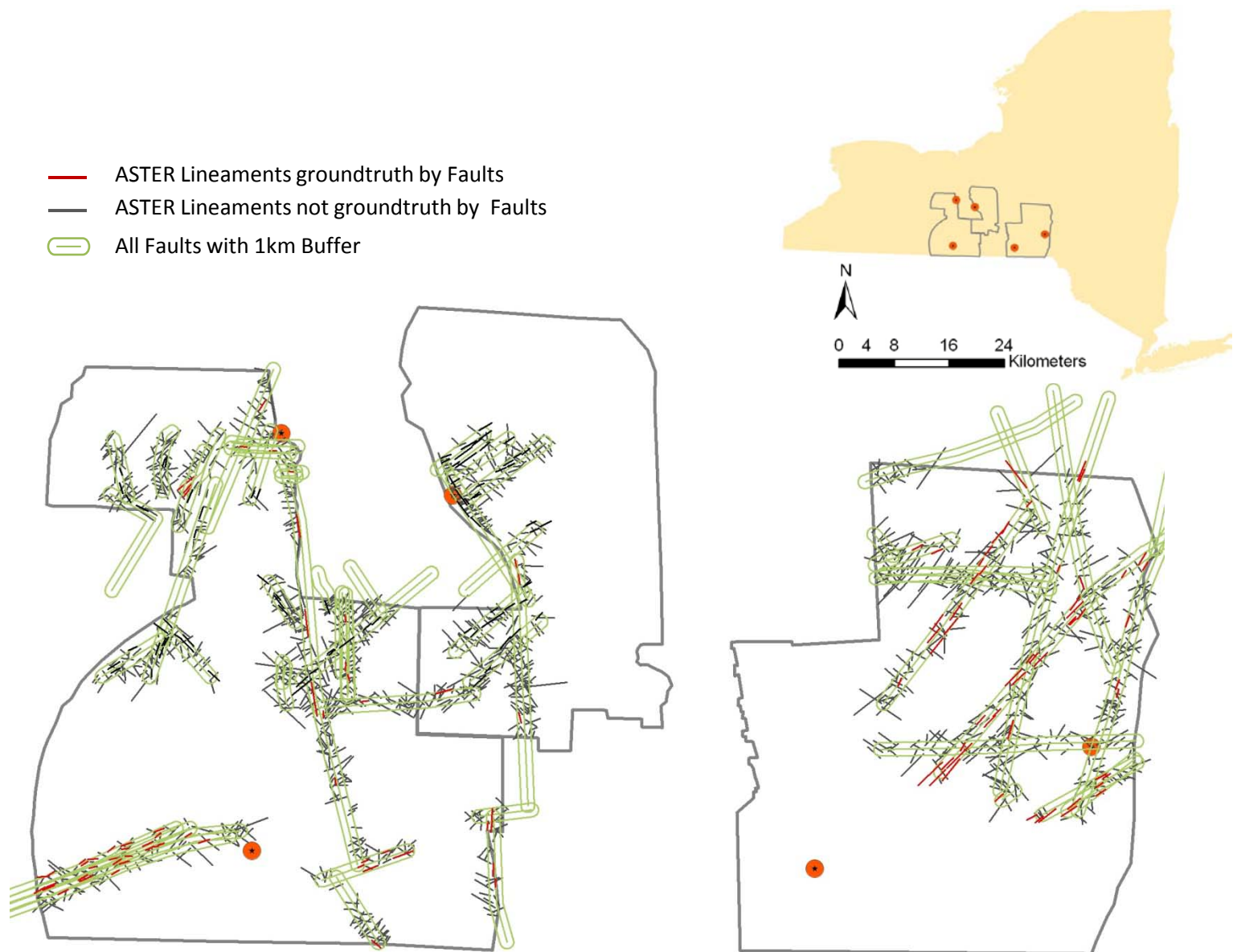


Figure: S6.6 - Map of project area with all ASTER lineaments within the 1km buffer of fault data

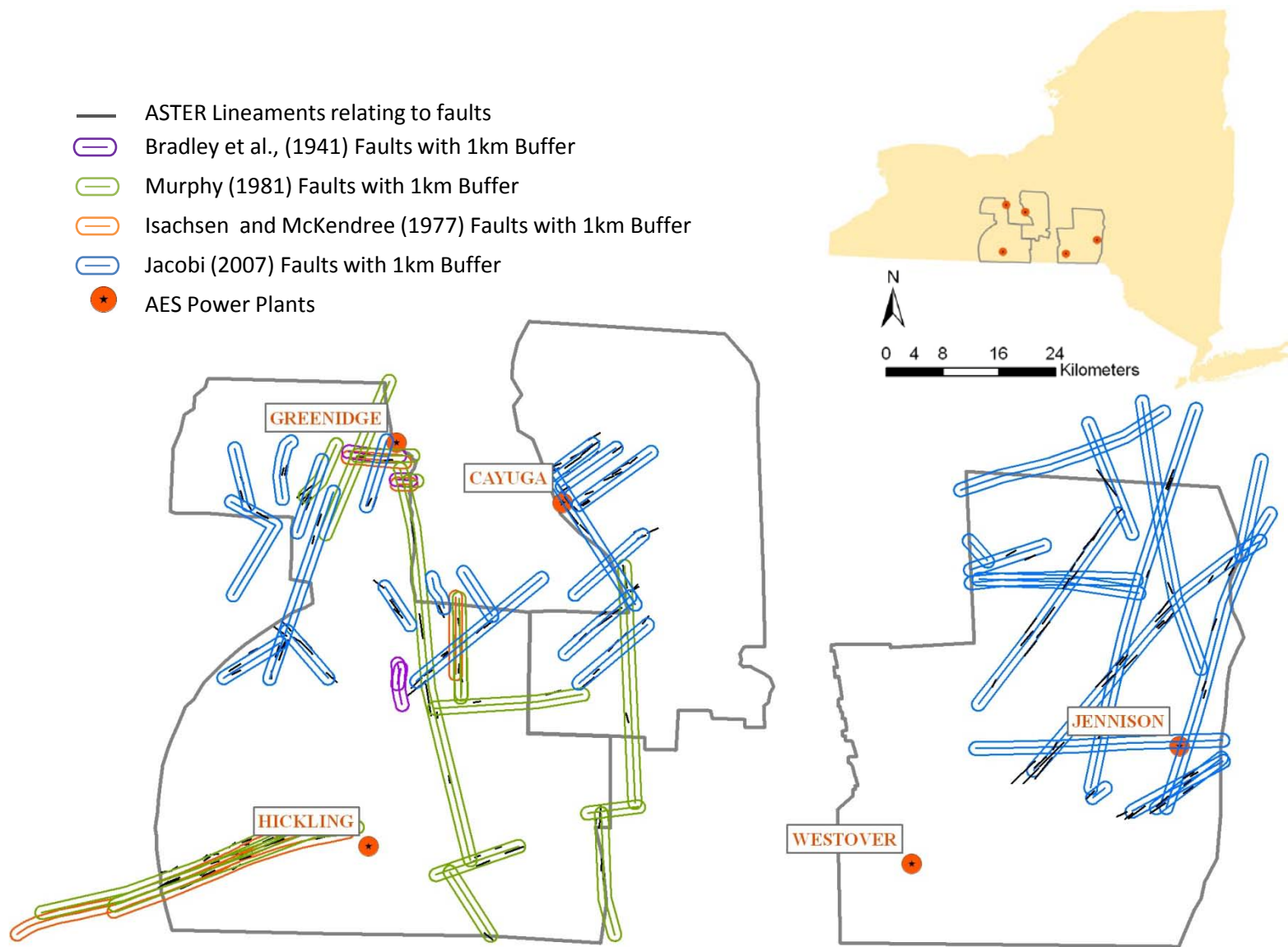


Figure: S6.7 - Map of the project area with selected faults from Bradley et al., (1941), Murphy (1981), Isachsen and McKendree (1977), and Jacobi (2007) and selected ASTER lineaments within a 1 km buffer

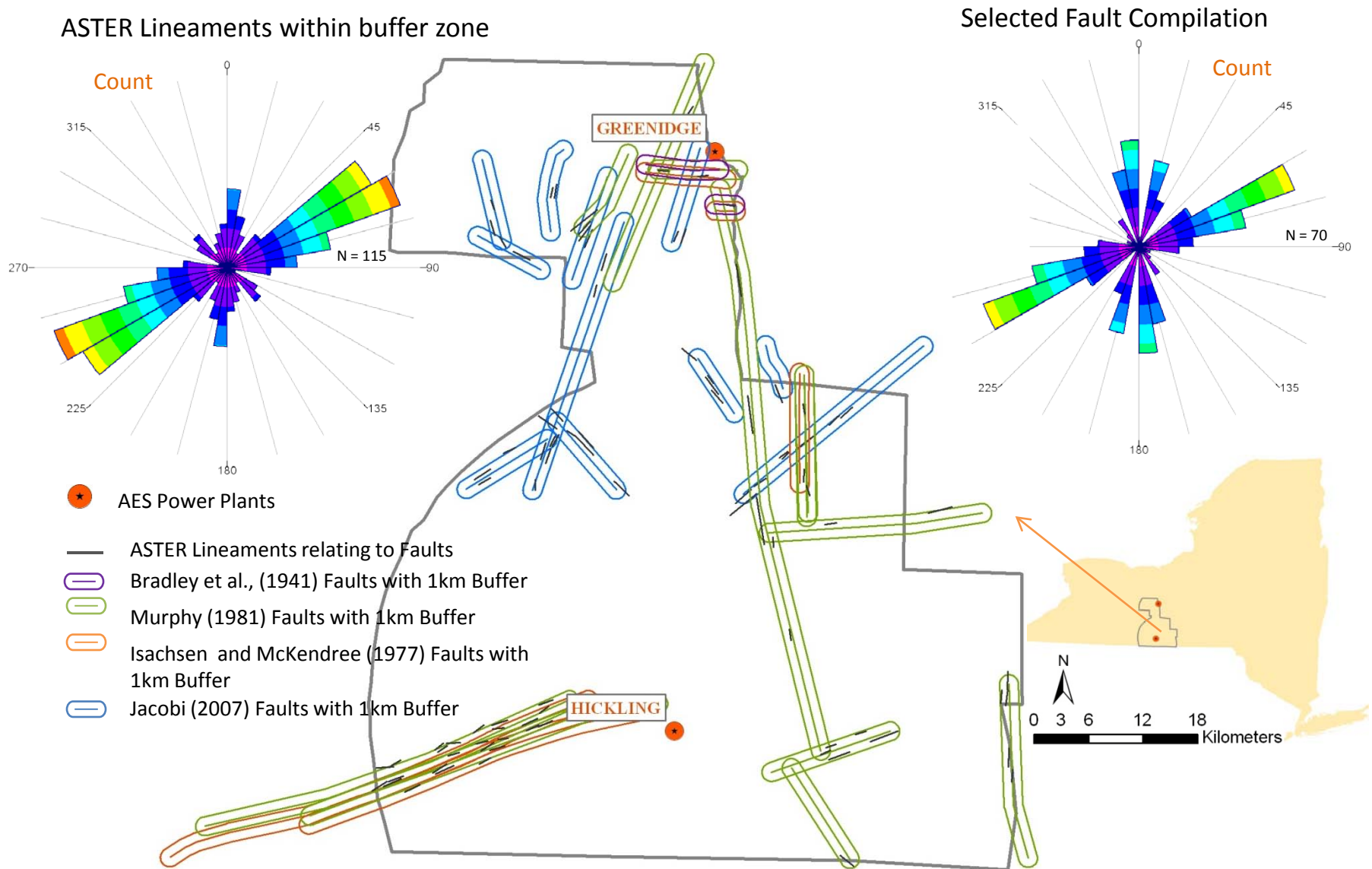


Figure: S6.8 - Map of the western focus area with selected faults from Bradley et al., (1941), Murphy (1981), Isachsen and McKendree (1977), and Jacobi (2007) and selected ASTER lineaments within a 1 km buffer; rose diagrams based on count

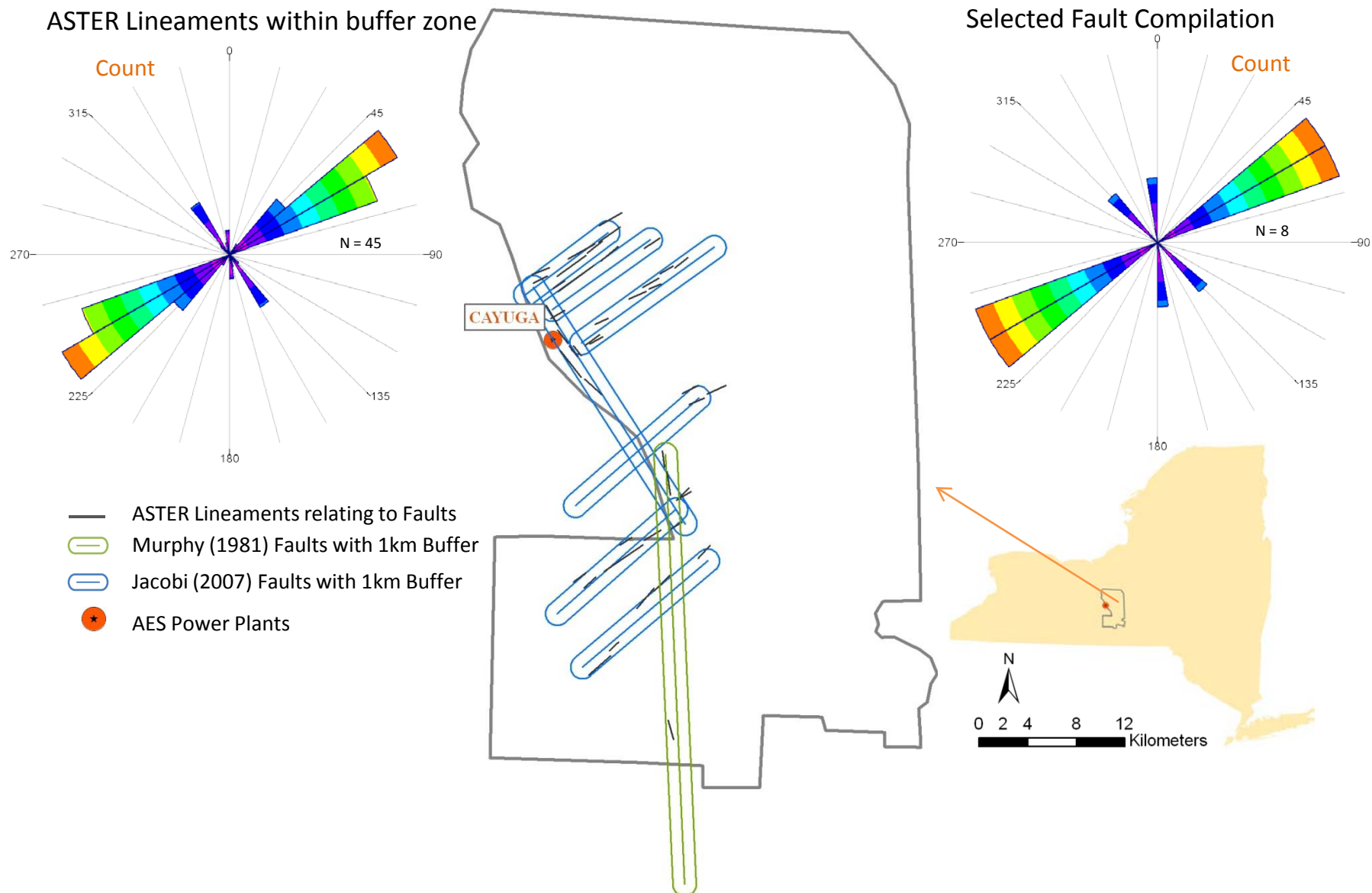


Figure: S6.9 - Map of the central focus area with selected faults, Murphy (1981) and Jacobi (2007) and selected ASTER lineaments within a 1 km buffer; rose diagrams based on count

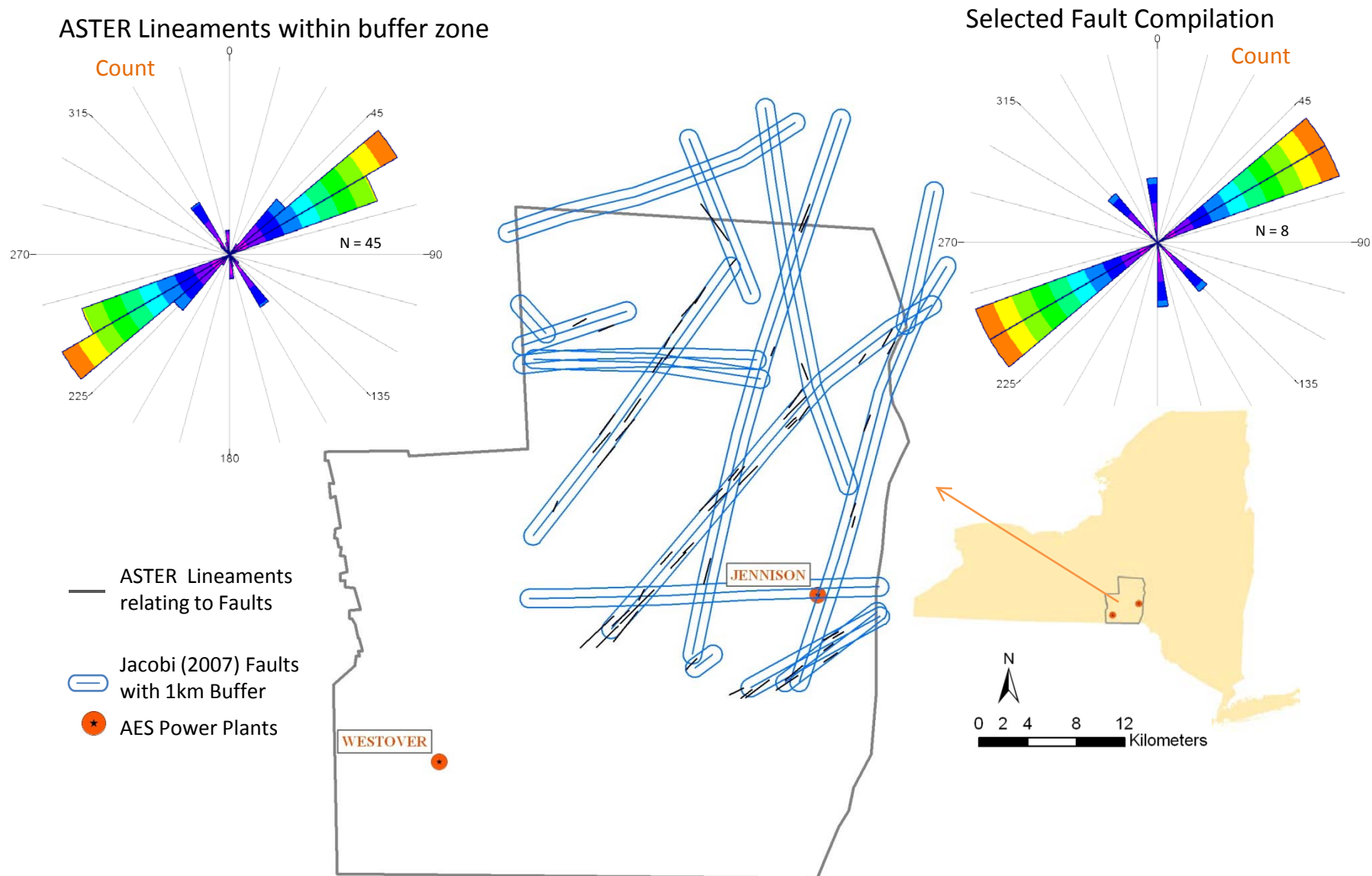


Figure: S6.10 - Map of the eastern focus area with selected faults from Jacobi (2007) and selected ASTER lineaments within a 1 km buffer; rose diagrams based on count

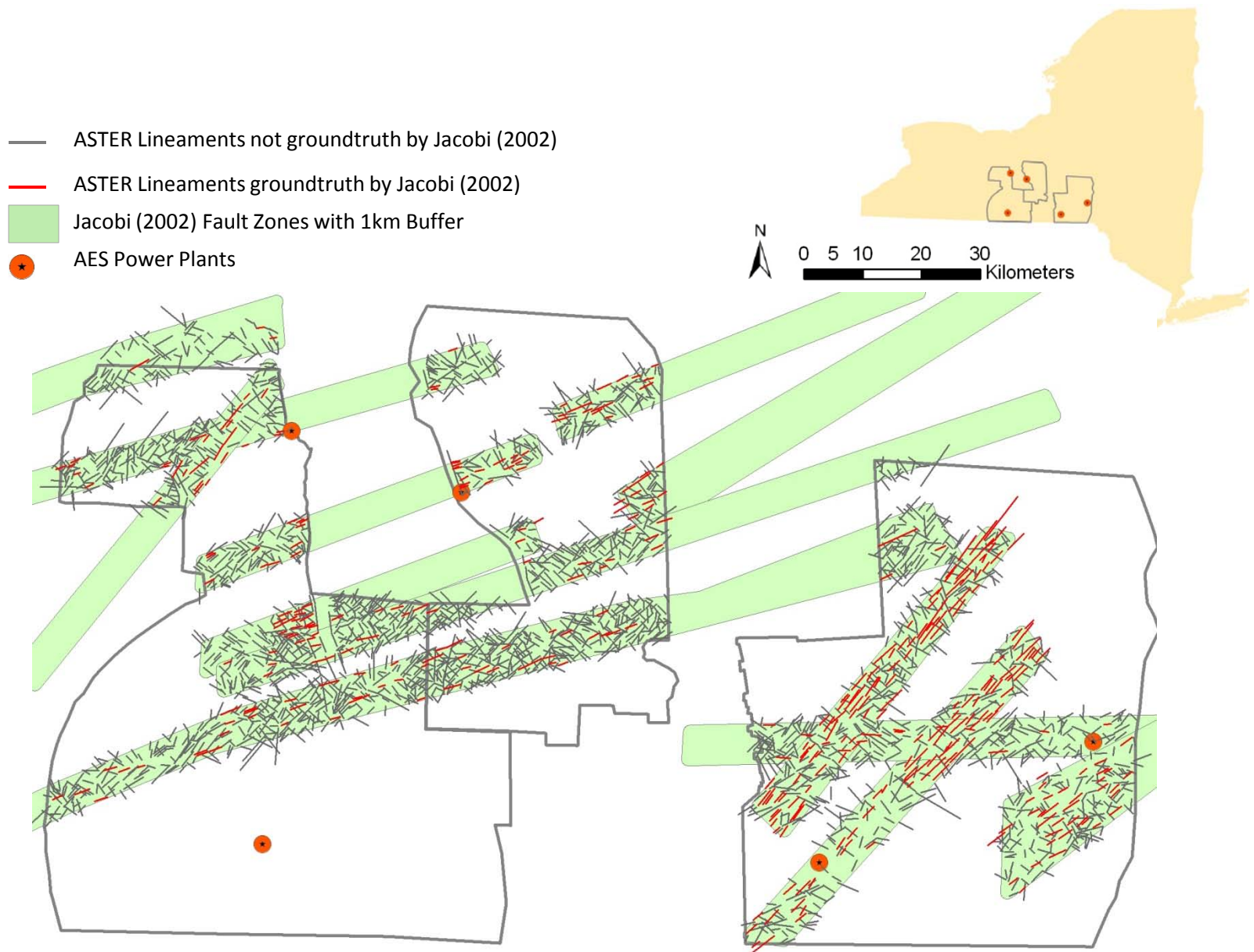


Figure: S6.11 - Map of project area with all ASTER lineaments within the 1km buffer of fault zone data

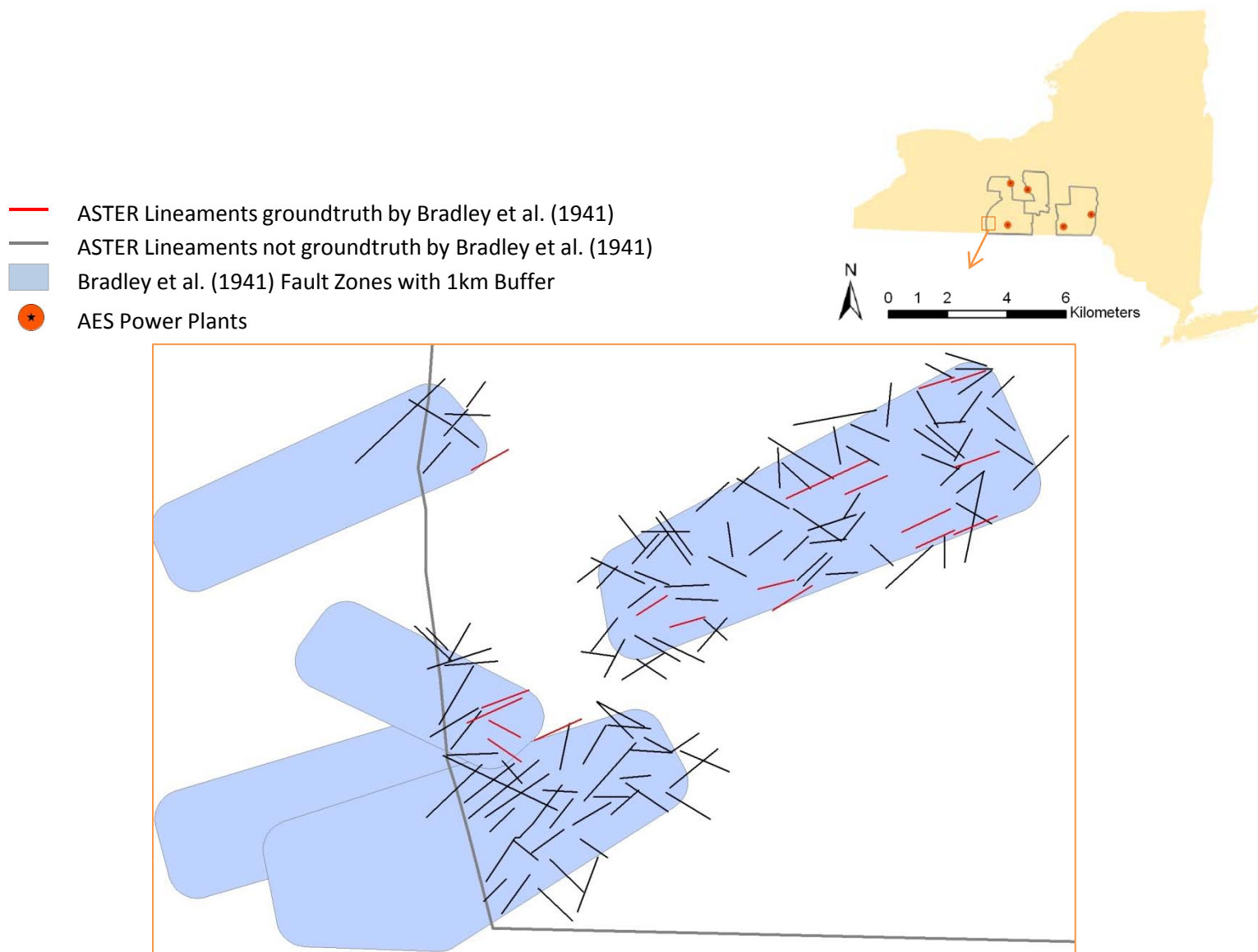


Figure: S6.12 - Map of zoomed in region of project area with all ASTER lineaments within the 1km buffer of fault zone data

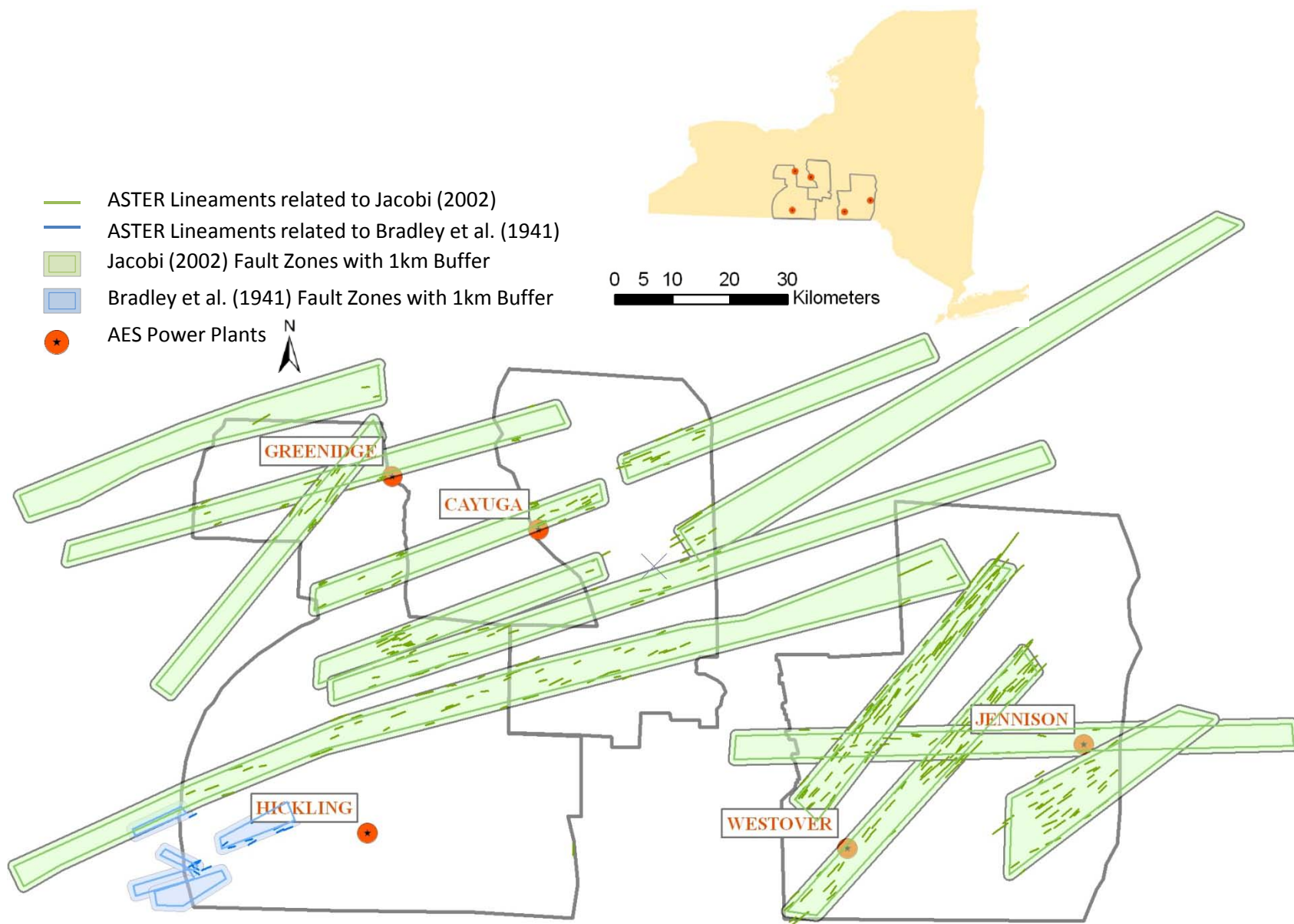


Figure: S6.13 - Map of the project area with selected Bradley et al. (1941) fault zones, Jacobi (2002) fault zones (all with 1 km Buffer) and selected ASTER lineaments within the buffer

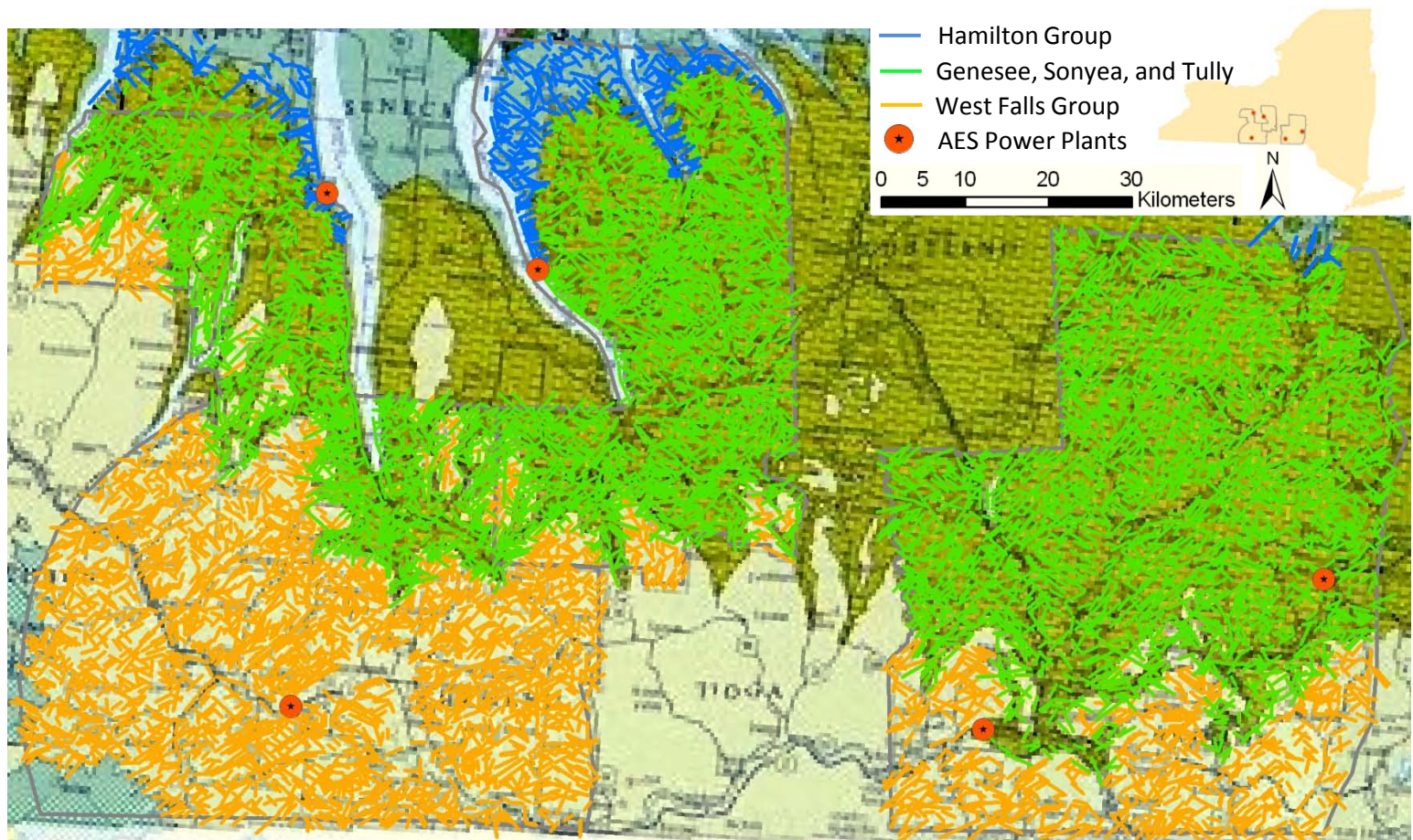


Figure: S6.14 - Map of the project area with ASTER lineaments selected based on geologic units with base map

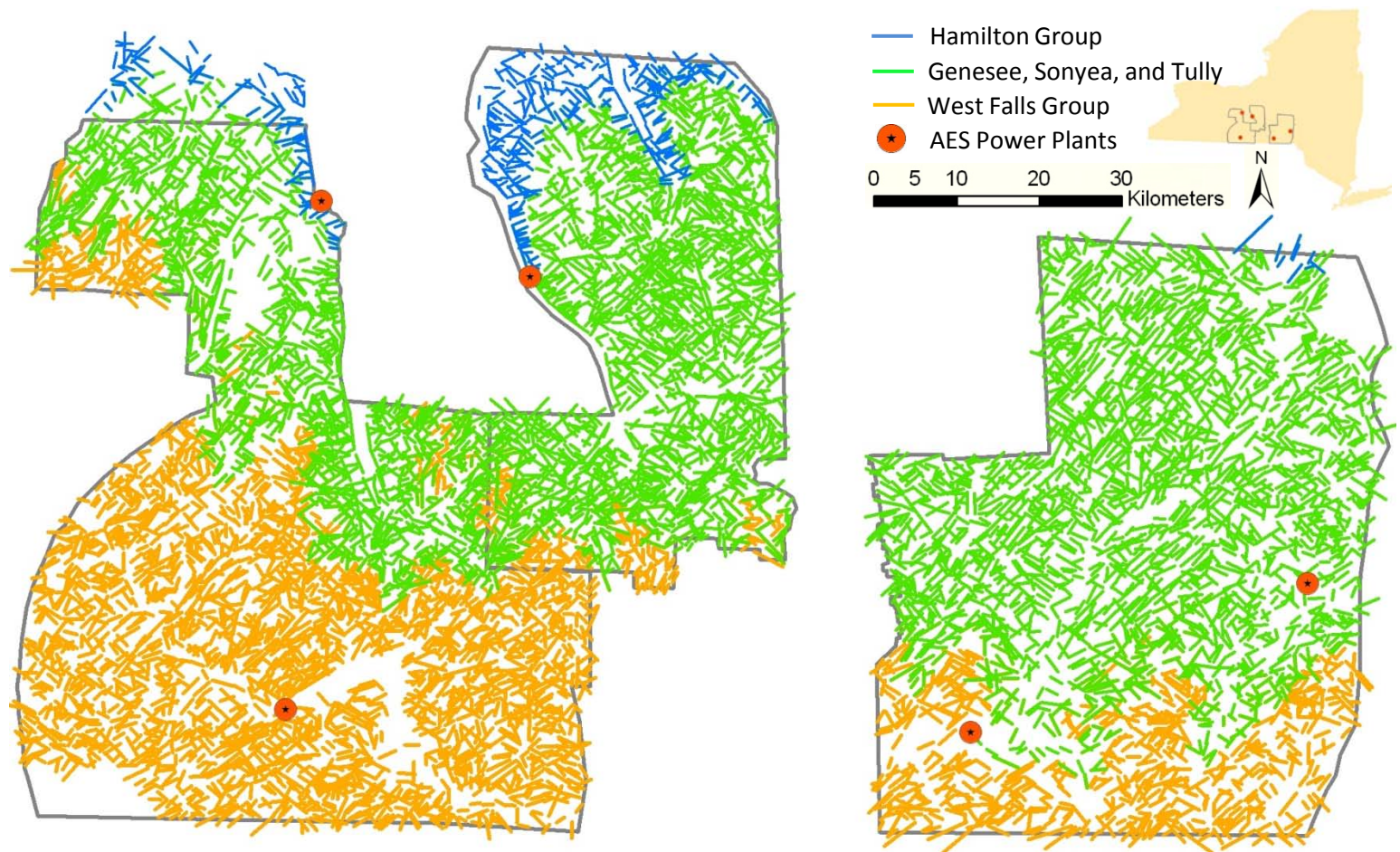


Figure: S6.15 - Map of the project area with ASTER lineaments selected based on geologic units

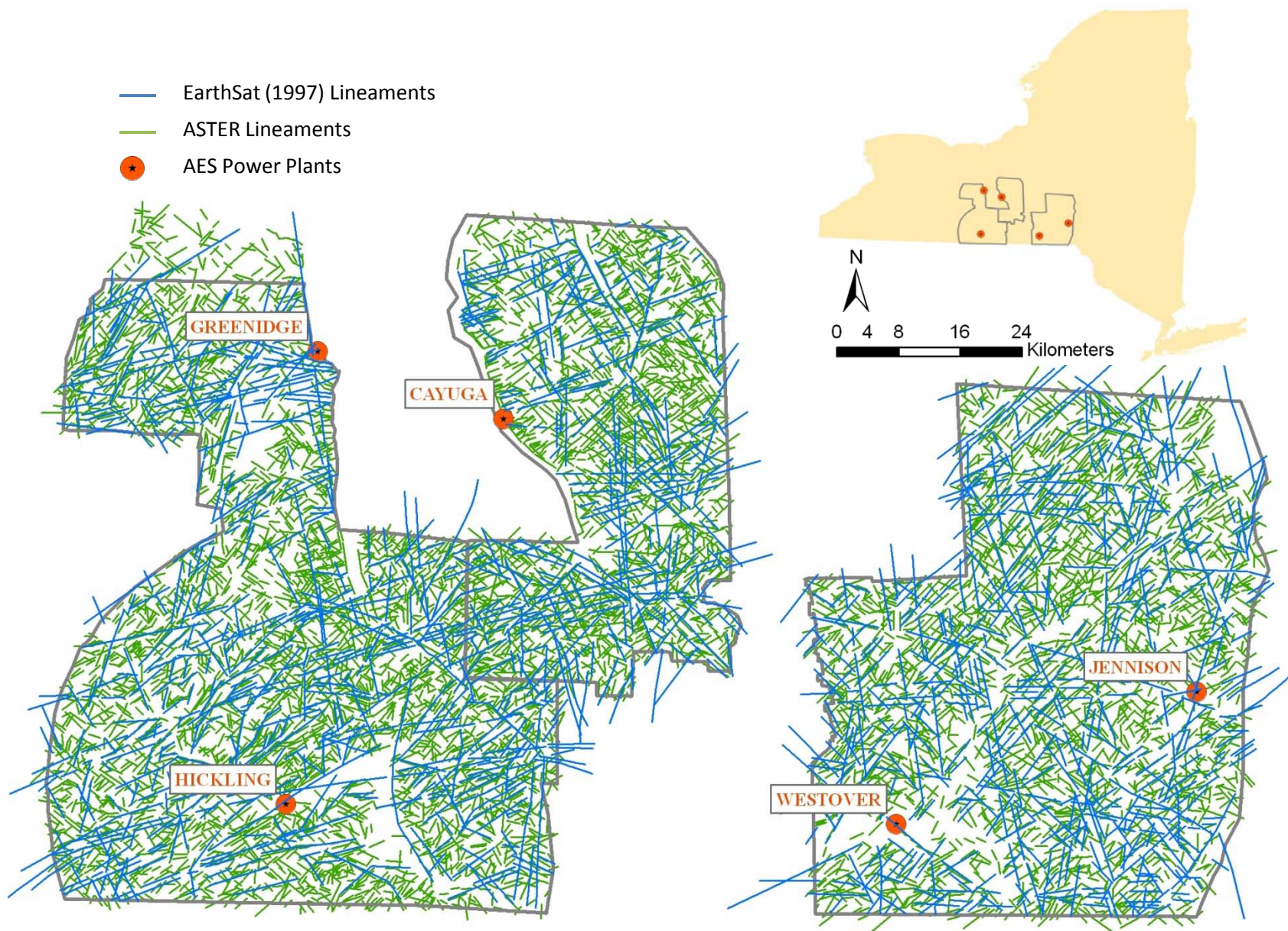


Figure: S6.16 - Map of the project area with all EarthSat (1997) lineaments and all ASTER lineaments

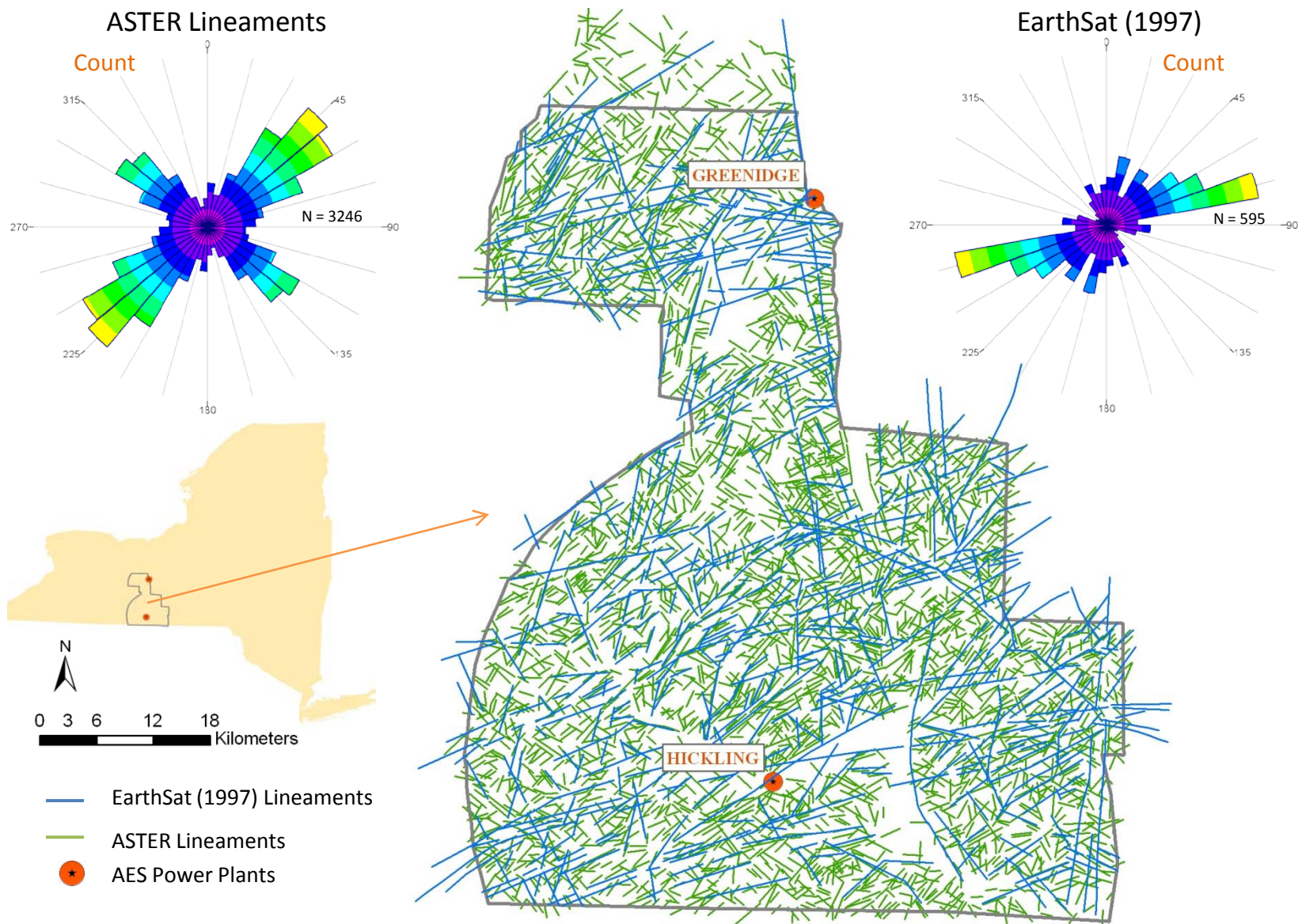


Figure: S6.17 - Map of the western focus area with all EarthSat (1997) lineaments, all ASTER lineaments and rose diagrams based on count

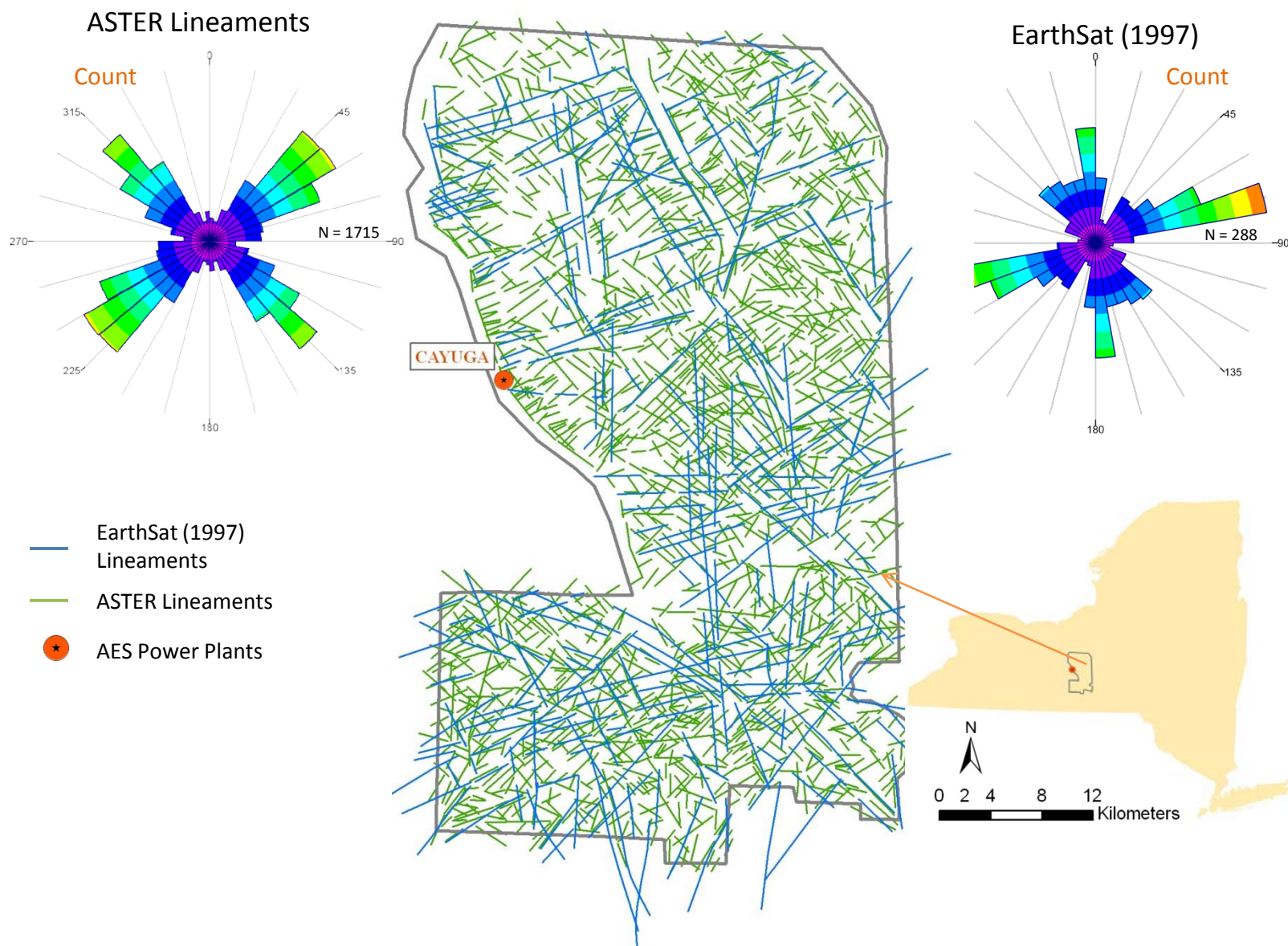


Figure: S6.18 - Map of the central focus area with all EarthSat (1997) lineaments, all ASTER lineaments and rose diagrams based on count

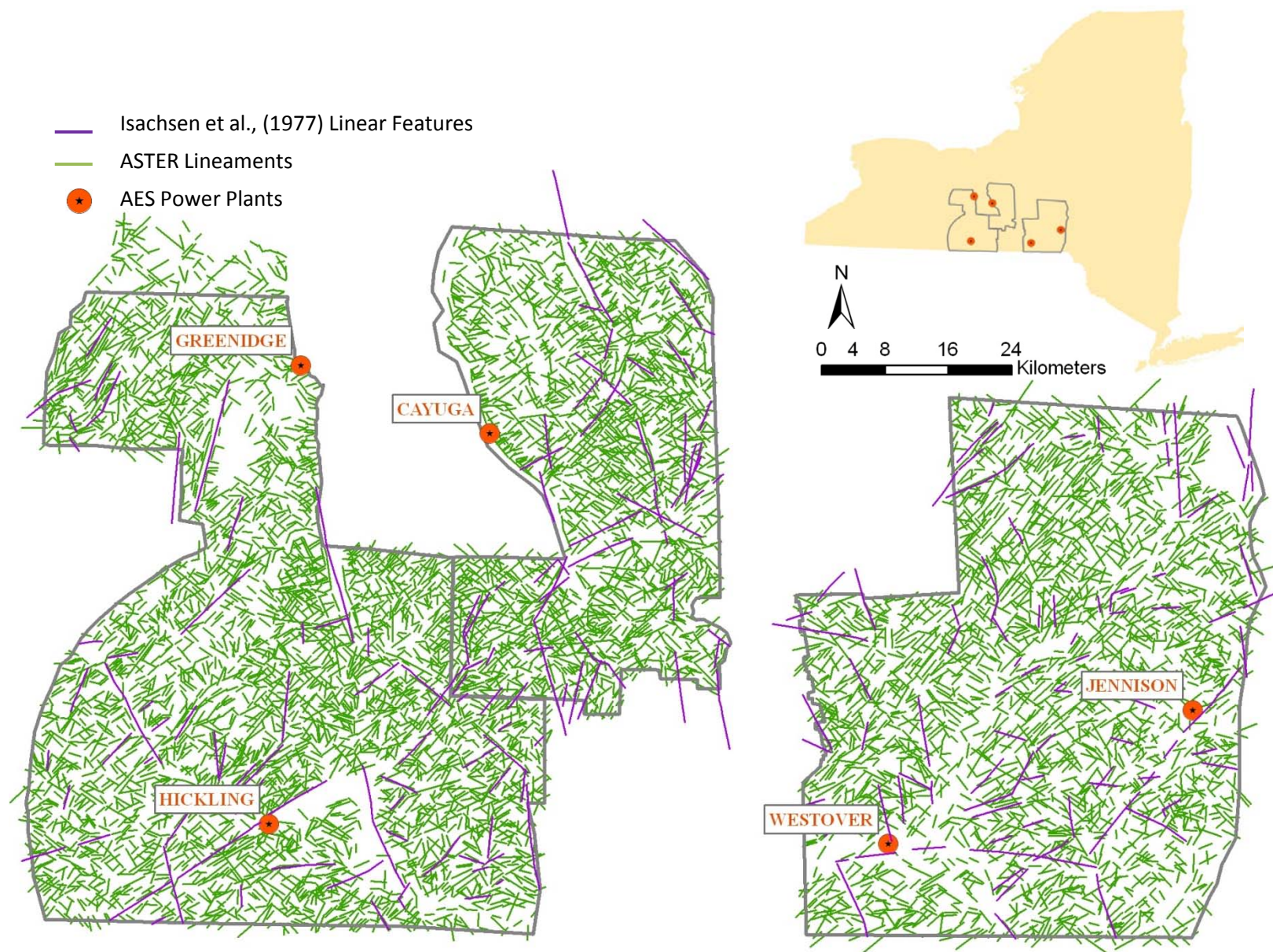


Figure: S6.19 - Map of the project area with all Isachsen et al., (1977) linear features and all ASTER lineaments

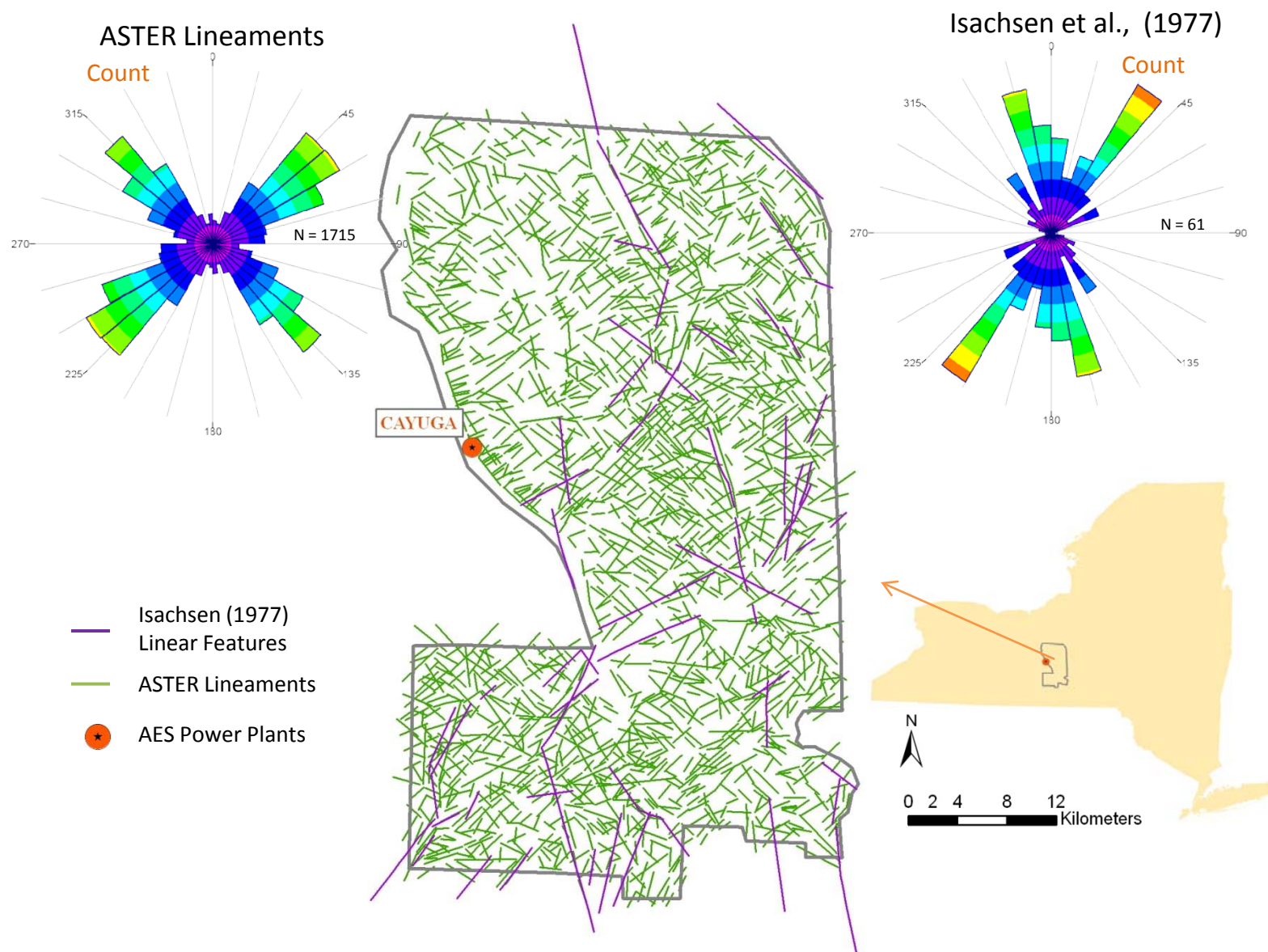


Figure: S6.20 - Map of the central focus area with all Isachsen et al., (1977) linear features, ASTER lineaments and rose diagrams based on count

Appendix II

Project Details

A. Image Processing

1. Experimental – Never used for lineament identification

Band Combination R(4) G(5) B(3) – Landsat

Band Combination R(5) G(3) B(4) – Landsat

Principal Component – R(PC2) G(PC1) B(PC1) – ASTER

Principal Component – R(PC2) G(PC1) B(PC3) – ASTER

Convolution Processing - 45° - Side-looking Airborne Radar (SLAR)

2. Images used during phase I, II and III for lineament identification

True-color Band Combination - R(3) G(2) B(1) – Landsat

False-color Band Combination- R(7) G(4) B(2) – Landsat

Principal Component – R(PC1) G(PC2) B(PC3) – Landsat

Band Combination R(2) G(3N) B(1) – ASTER

Principal Component – R(PC2) G(PC1) B(PC3) – ASTER

DEM Shaded Relief representation – sun illumination angle 0°

DEM Shaded Relief representation – sun illumination angle 45°

DEM Shaded Relief representation – sun illumination angle 90°

DEM Shaded Relief representation – sun illumination angle 315°

3. Principal Component Analysis

Principle component is a multi-image manipulation digital image processing technique commonly used to reduce the redundancy in multispectral data by compressing the image into a less number of bands (Lillesand, Kiefer et al. 2004). Principal Component Analysis (PCA) is a mathematical operation that transforms all channel-DN values linearly onto statistically defined orthogonal axes from which new spectral channels are formed (Adams and Gillespie, 2006). The new PC bands are linear combinations of the original data multiplied by transformation coefficients that are statistical quantities of eigenvectors on a pixel by pixel basis (Lillesand, Kiefer et al. 2004). The new bands have an increase in noise with increasing numbers; as a result, typically only the first three bands are utilized (Adams and Gillespie, 2006). The PC1 band shows the largest degree of variability, PC2 shows the second largest variation, and PC3 is the third (Jensen, 2005).

B. What worked/ What did not work /What worked well

1. Image Processing

The principal component analysis worked best for enhancing images and providing the best color variation to identify the lineaments. False-Color and True-Color composites provided good results for lineament identification but did not provide the highest color variation. The other color composite experiments did not perform well and therefore were not used for lineament identification. Shaded relief DEMs were suitable for lineament identification. Using a 25° sun elevation angle rather than 45° made lineament identification easier. All sun azimuths provided good results and each had the potential to identify unique lineaments. Using a color shaded relief DEM with multiple

illumination directions would have been the optimum choice for Phase II but was not considered until the end of the project.

2. Lineament Identification/Digitizing

The lineament identification process and chosen categories were well suited to for the project and were used consistently. The overlay of the road data on the lineament map may have hindered the ability to identify NS and EW lineaments, since lineaments coinciding with roads were not digitized. However, this prevented roads being mistaken for lineaments and was therefore a necessary overlay. Variations in land use and land cover hindered the lineament identification in areas with a lot of agriculture and high population. The process of quality control with weekly comparisons, checks and lineament identification was ideal; it was also consistent throughout the project. The scales used for this project were the following: 1:65,000 during Phase I, 1:125,000 during Phase II and 1:25,000 during Phase III. These all provided good results for the project. I would include a fourth phase to digitize lineaments at a scale of 1:250,000 to capture the longer lineaments digitized by EarthSat (1997) and Isachsen and McKendree (1977).

3. Lineament Analyses

The rose diagrams and basic statistics allowed for good comparisons and were consistent throughout the project; they facilitated the identification of the primary and secondary trends of the lineaments – a process that made it easy to compare lineament distributions. The density maps were of great help for the project, particularly the filtered lineament density maps. The grid rose diagram analysis applied for the project area and

the Cayuga subset, while helpful, did not show drastic differences in rose diagrams. This made it difficult but not impossible to identify relationships between lineaments and the regional geologic changes across the project area - changes related to tectonic variations. The fabric analysis was successful in identifying some relationships between field data and lineaments and worked well as a means of ground-truthing the lineaments. The stratigraphic analysis was also helpful as a technique but did not provide a better understanding of the project area because of the uniformity of the lithology and tectonics within the strata of the project area.

Appendix – III

How I calculated the azimuth or orientation of the lineaments in ArcGIS.

The following script was downloaded from <http://www.ian-ko.com/>

```
On Error Resume Next
Dim pMxDoc As IMxDocument
Dim pMap As IMap
Dim pCurve As ICurve
Dim pPoint1 As IPoint, pPoint2 As IPoint
Dim dDistance1 As Double, dDistance2 As Double
Dim bAsRatio1 As Boolean
Dim pVector As IVector3D
Dim dAzimuth As Double
Dim dDelta As Double
Dim Pi As Double
Dim bSrefFromMap As Boolean
'=====
'adjust the parameters below
'bSrefFromMap = True ==> the length will be calculated in the projection of the Map
'bSrefFromMap = False ==> the length will be calculated in the projection of the data
'bSrefFromMap needs to be True only if a real distance in Map units will be used - bAsRatio =
False
bSrefFromMap = False
dDistance1 = 0# 'Indicates the start point of the line. Change the value to perform calculations
for a different point.
bAsRatio = True ' the distance above will be used as a ratio from the total length. Change to false
to input an absolute distance.
dDelta = 0.000001 'A small tolerance - no change of direction expected within this tolerance
'=====
dDistance2 = dDistance1 + dDelta
```

```

Pi = 4 * Atn(1)
If (Not IsNull([Shape])) Then
  Set pCurve = [Shape]
  If (Not pCurve.IsEmpty) Then
    If (bSrefFromMap) Then
      Set pMxDoc = ThisDocument
      Set pMap = pMxDoc.FocusMap
      pCurve.Project pMap.SpatialReference
    End If
    Set pPoint1 = New Point
    pCurve.QueryPoint 0, dDistance1, bAsRatio, pPoint1
    Set pPoint2 = New Point
    pCurve.QueryPoint 0, dDistance2, bAsRatio, pPoint2
    Set pVector = New Vector3D
    pVector.ConstructDifference pPoint2, pPoint1
    dAzimuth = pVector.Azimuth
    dAzimuth = dAzimuth * 360 / (2 * Pi)
  End If
End If

```

In the test= box type: dAzimuth

The procedure:

In the attribute table of the lineament feature add a new field with type (double), and then right click to calculate values (work outside of edit session). Click on the new field name, select advance and copy and paste the script above into the *Pre-Logic VBA Script Code* box and “dAzimuth” in the *test=* box finally click OK.

How I calculated the length of the lineaments in ArcGIS.

The following script was downloaded from <http://www.ian-ko.com/>


```

'=====
'shape_Return_Length.cal
'Author: Ianko Tchoukanski
'http://www.ian-ko.com
'=====

On Error Resume Next
Dim pMxDoc As IMxDocument
Dim pMap As IMap
Dim pGeometry As IGeometry
Dim pCurve As ICurve
Dim dLength As Double
Dim bSrefFromMap As Boolean
'=====

'Adjust the parameter below
'True ==> the length will be calculated in the projection of the Map
'False ==> the length will be calculated in the projection of the data
bSrefFromMap = True
'=====

If (IsNull([Shape])) Then
    dLength = -1
Else
    Set pGeometry = [Shape]
    If (pGeometry.IsEmpty) Then
        dLength = -1
    Else
        If (bSrefFromMap) Then
            Set pMxDoc = ThisDocument
            Set pMap = pMxDoc.FocusMap
            pGeometry.Project pMap.SpatialReference
        End If
        Set pCurve = pGeometry
    End If
End If

```

```
dLength = pCurve.Length  
End If  
End If
```

```
__esri_field_calculator_splitter__  
dLength
```

The procedure:

In the attribute table of the lineament feature add a new field with type (double), and then right click to calculate values (work outside of edit session). Click on the new field name, select advance and copy and paste the script above into the *Pre-Logic VBA Script Code* box and “dLength” in the *test=* box finally click OK.

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