REMOTE SENSING AND FRACTURE ANALYSIS FOR PETROLEUM EXPLORATION OF ORDOVICIAN TO DEVONIAN FRACTURED RESERVOIRS IN NEW YORK STATE

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1.0 EXECUTIVE SUMMARY

The goal of this project was to create a series of interpretative and analytical geologic tools in electronic format to assist in the assessment of large portions of New York State for the prospect of fractured-reservoir, hydrocarbon production.

The base for this assessment was a detailed (1:250,000 scale) geologic interpretation of ten digitally-enhanced, Landsat Thematic Mapper (TM) images covering all of New York State except for New York City and Long Island. In addition to this analysis, the ten images were digitally mosaicked into a single picture of New York State (1:500,000 scale) to provide a coherent view of the entire area, and the digital mosaic was divided into four 1:250,000 scale image map sheets based on USGS 1:250,000 scale topographic maps, for ease in data integration with other data sets. The geologic interpretation focused on the interpretation of fractures and structures that may indicate fracture reservoir conditions and any tonal or vegetation anomalies that may indicate the seepage of hydrocarbons. Integration of this interpretation with a careful synthesis of the literature and other existing data produced additional data layers and insights critical to basin wide evaluation of the potential for fractured reservoir production. Some of the items of information that were particularly useful for this basin-wide analysis were the distribution and depth of source/reservoir rocks as derived from well logs, oil and gas field production statistics, well location maps, the ambient state of stress and stress history, and the history of thermogenic generation and maturation of hydrocarbons.

The geologic interpretation was digitized and fracture density contour maps and rose diagrams were created for the entire study area and each of the four mapsheets. The combination and integration of all of the data sets in an ARC/INFO Geographic Information System (GIS) lead to the selection of twenty-one exploration fairways of high exploration potential for fractured reservoir production. All of the data layers (including the Landsat TM images and mosaic) were delivered in both hard-copy and digital formats.

2.0 INTRODUCTION

2.1 Study Area

The study area includes the New York portion of the Appalachian basin as defined by the outcrop of the base of the Upper Ordovician Utica Shale and the New York portion of the St. Lawrence Lowlands covered by non-igneous rock. This study is concerned with the development of fractured-rock hydrocarbon reservoirs, therefore, only the clastic portion of the section mentioned above has been studied.

2.2 Objective

The objective of this project is to provide a data set that will assist in the evaluation of, exploration for, and exploitation of fractured-rock hydrocarbon reservoirs in the state of New York. The work is based on the interpretation of remotely sensed data and the study is presented in both hard-copy and digital formats.

The study is designed to provide tools and information that are practical and useful at the basin level of exploration for commercial, fractured-reservoir accumulations of oil and gas. To make the information interpreted from the remotely sensed data more useful, an examination of the stress history of the region has been undertaken in relation to the onset of maturation and generation of hydrocarbons. In most situations, the extensional fractures, that is those lying parallel to the ambient Maximum Principal Compressive Stress (MPCS) direction, are the most open-standing fractures, and consequently constitute the best reservoirs for hydrocarbon. However, there are areas where the onset of generation and migration occurred under stress conditions different than those now present. In these areas the open standing fractures at the time of generation may constitute good reservoirs either because they were enhanced by solution at the time of first migration or that wetting by hydrocarbons has prevented cementation. In order to know which fracture systems or which portions of a given fracture system are potential targets, one needs to know the distribution and depth of potential reservoir rocks. This study focused on the organic-rich, black and brown shales of Ordovician to Devonian age and the closely associated sandstones and siltstones. Rocks of equivalent age and composition are prolific producers from fractured reservoirs in the Michigan basin and the area to the south in Ohio and Indiana and in the Devonian shale basin further south in the Appalachian basin.

2.3 Deliverable Products

In addition to this report, the following products are delivered with this study:

- One copy each of the ten, geocoded, Landsat Thematic Mapper, TM Band 7,4,2 (R,G,B) color-composite images at 1:250,000 scale.
- One copy of the geocoded, ten-scene, Landsat Thematic Mapper, TM Band 7,4,2 (R,G,B) color-composite mosaic of Upstate New York at 1:500,000 scale.
- One copy of each of the four geocoded Landsat TM image maps of New York at 1:250,000 scale.
- One copy of the Geologic Interpretation at 1:250,000 scale for each of the four image maps of New York presented as a color plot.
- One copy of the Fracture Density Analysis at 1:250,000 scale for each of the four image maps of New York presented as a color overlay.
- One copy of the Exploration Fairway Maps at 1:250,000 scale for each of the four image maps of New York presented as a color overlay.
- One 8mm Tape of the ARC/INFO Files in UNIX TAR, ARC/INFO Export format for each of the above mentioned interpretations, analyses, and maps.
- One 8mm Tape of the geocoded image files UNIX TAR format for each of the above mentioned Landsat TM images, image maps, and mosaics.

3.0 METHODOLOGY

3.1 Landsat Thematic Mapper Data and Processing

The Landsat 5 satellite orbits the earth in a sun-synchronous, polar orbit at an altitude of approximately 700 kilometers. The Thematic Mapper (TM) sensor on board the satellite records solar radiation reflected or emitted from the earth's surface in seven spectral bands. The recorded data are telemetered to ground receiving stations where the data are radiometrically corrected, destriped, and geometrically corrected before being distributed or stored. The radiometric corrections adjust for instrument noise and atmospheric distortions. The destriping algorithm equalizes scan-line response imbalances prevalent in the satellite systems at the time of data collection. The geometric corrections compensate for distortions due to variations in orbital altitude, satellite orientation, and earth rotation.

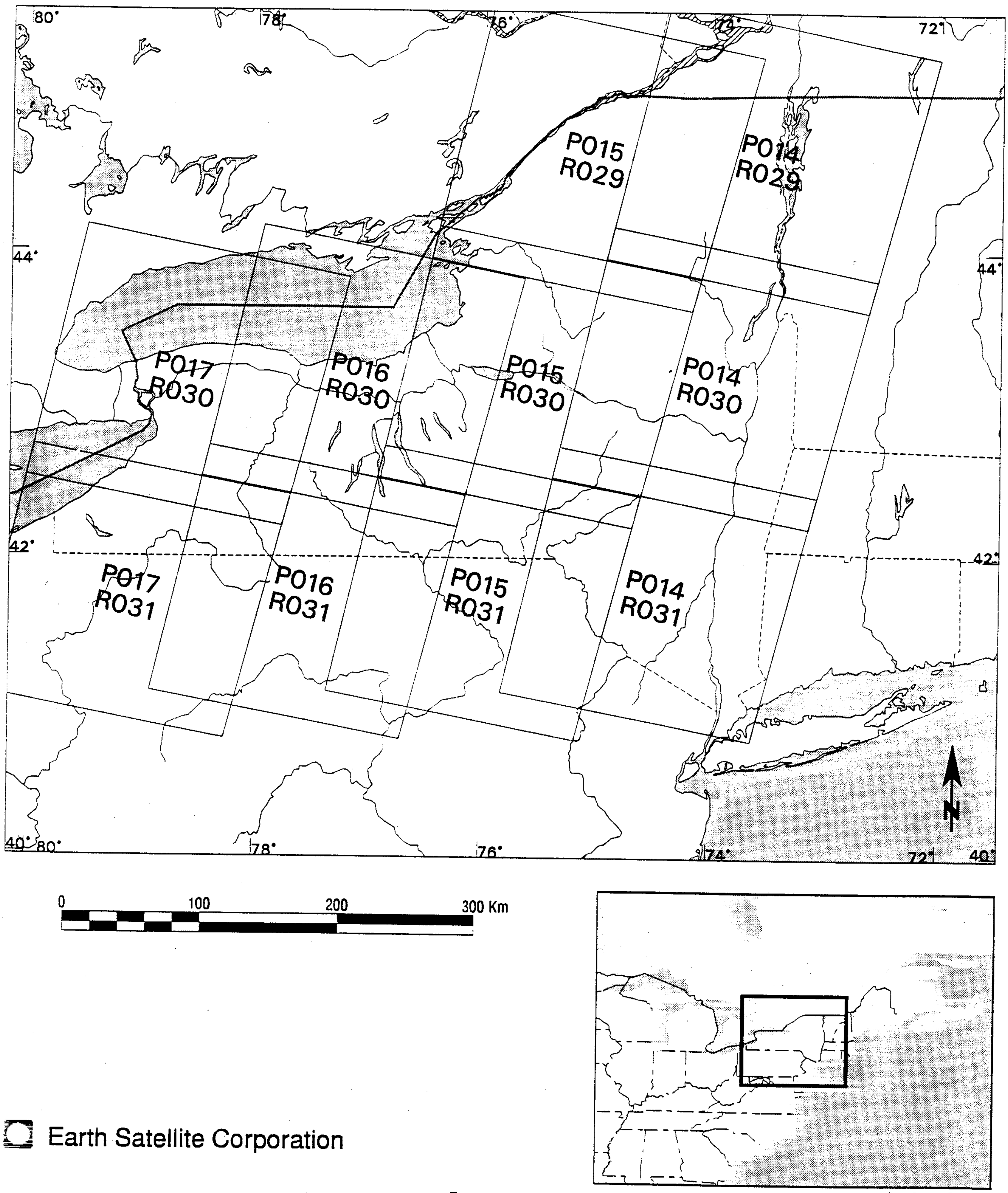
Landsat TM data have a spatial resolution of 28.5 meters in the six visible (VIS), near-infrared (NIR), and short wave infrared (SWIR) bands and a spatial resolution of 120 meters in the thermal infrared (TIR) band. Each band can be used individually to produce a single-band image, or two or more bands can be color-composited to produce a false-color image.

A total of 10 Landsat TM scenes have been used for this project (Figure 1):

Path / Row	Date	Path / Row	Date
14/29	6/17/84	15/31	5/13/86
14/30	8/26/86	16/30	4/18/86
14/31	10/26/85	16/31	4/18/86
15/29	5/13/86	17/30	5/11/86
15/30	5/13/86	17/31	5/11/86

Upon receipt of the digital data from the ground receiving station, EarthSat's Image Processing Division geocodes the Landsat TM data used for this study (TM Band 2, TM Band 4, and TM Band 7) using ground control points selected from the most appropriate map source (USGS 1:250,000 scale, 1° x 2° topographic maps of New York State), resamples the data using a cubic convolution algorithm, edge enhances the data using a modified LaPlacian filter, color-balances the

Figure 1: Landsat TM scene coverage used in the study.



individual scenes to eachother, mosaics the data, and divides the processed imagery into the four Landsat TM Band 7,4,2 (R,G,B) color composite mapsheets provided with this study (Figure 2). The four Landsat TM mapsheets have exactly the same geometry as the USGS 1° x 2° 1:250,000 quadrangle maps; this allows for precise location of any mapped features by overlaying the features to the 1° x 2° maps. The processed data are film recorded on a laser film recorder and printed in Earthsat's Photographic Lab.

For this study, all of the Landsat TM scenes, mosaics, and mapsheets have been processed to a Transverse Mercator Projection, UTM Zone 18, and NAD 27.

The digitally processed imagery is produced both as individual scenes as well as a digital mosaic and map sheets. Having the individual scenes has two significant advantages. Each scene can be enhanced specifically for that scene without having to compromise in order to match adjacent scenes in a mosaic and the overlap areas between scenes of adjacent paths provide two independent looks at an area giving stereo reinforcement which assists interpretation.

The individual images are photographically enlarged to 1:250,000 scale. This provides an excellent interpretation base for basin-wide fracture analysis. This scale, based on experience, provides an excellent balance between synoptic coverage and high resolution.

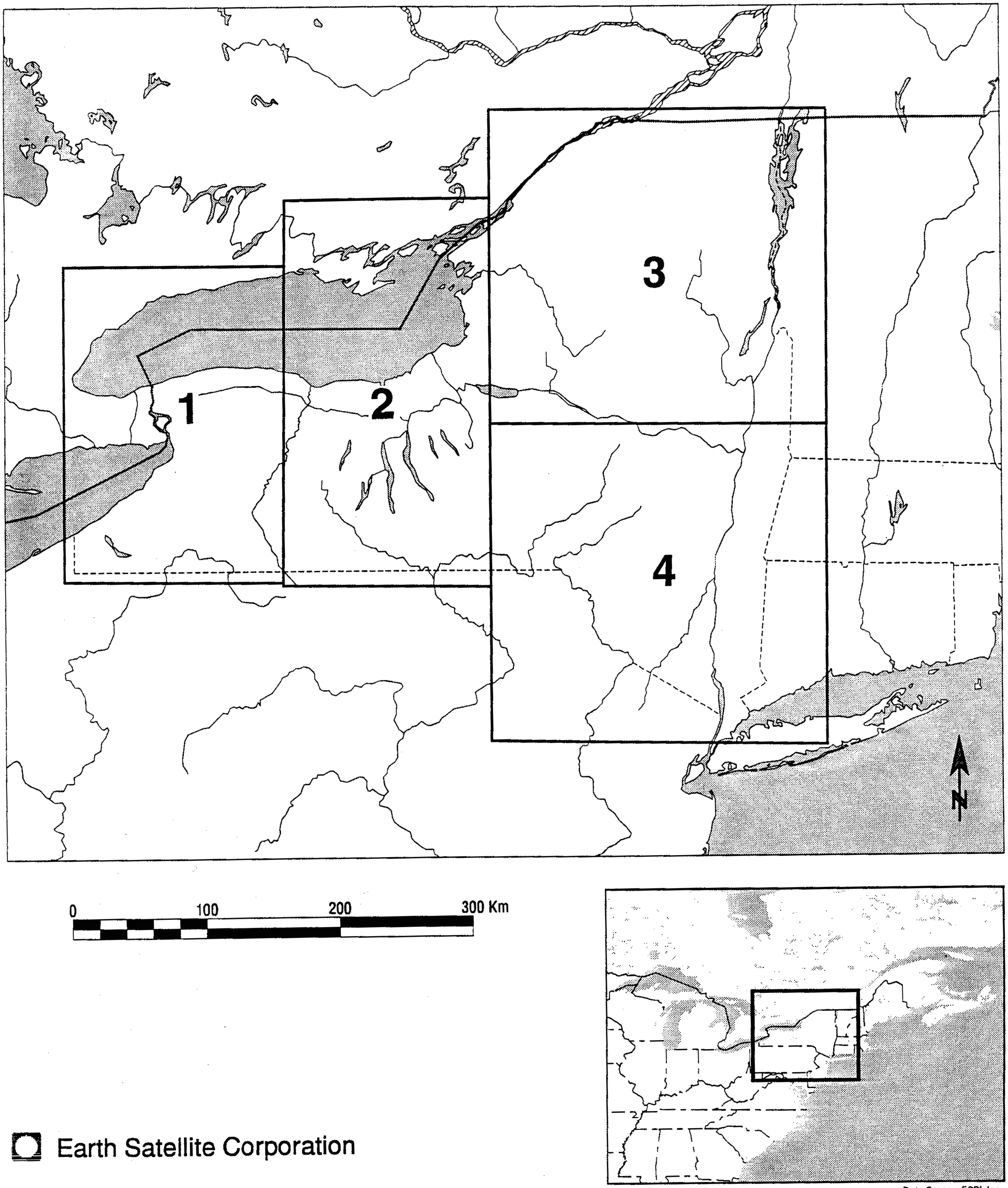
3.2 Literature Review

At the same time the imagery is being ordered and processed, a review of the literature is conducted at the USGS National Center Library in Reston, VA and at the New York State Geological Survey in Albany, New York for additional information. Information of interest included: location of known faults and structures in the region; distribution, thickness, depth of burial, and organic content of Ordovician and Devonian "black" shale units; basin location, tectonic deformation, and maturation history of these units; oil and gas field production statistics; well log data; and gravity and magnetic anomaly maps.

3.3 Interpretation Methodology

The methodology of satellite imagery interpretation for petroleum exploration relies heavily upon standard photointerpretation techniques (Philipson, 1997; Mollard and Janes, 1984; Lillesand and Kiefer, 1979; Colwell, 1960; Lueder, 1959), plus a solid foundation in structural geology and

Figure 2: The four image mapsheets created for the study.



tectonics. The interpretation of the imagery is aided by published maps, available literature, geophysical data, and well data.

The geologic interpretations are drawn directly on clearfilm mylar overlays to the individual 1:250,000 scale images with permanent ink pens using Dietzgen and Lietz mirror stereoscopes in the overlap areas for stereo reinforcement. The published maps are used as a guide to lithologic identification and general lithologic distribution but the interpretation and mapping of the various lithologic boundaries and structure is based solely on the Landsat imagery. Areas of unusual or anomalous vegetation (perhaps associated with hydrocarbon microseepage) are also mapped at this stage.

The 1:500,000 scale mosaic is used during the interpretation process to assist in evaluation of the regional tectonic features and elements that are not as obvious or continuous on the larger scale 1:250,000 imagery. Regional tectonic features (basins, basin boundaries, uplifts and major fault/fracture zones) are defined after the preliminary interpretation is complete. These large features are meant to reflect regional trends and are not necessarily related to a single structural feature or a particular rock outcrop. Once completed, the individual 1:250,000 scale interpretive overlays are edge matched to the adjacent images for structural and stratigraphic continuity.

The 1:250,000 scale interpretations are cartographically reproduced in two stages. In the first stage, the 1:250,000 scale hand-drawn interpretations are hand-digitized and the vector files are annotated using an ARC/INFO Geographic Information System (GIS). These digitized versions are then plotted on a Versatec electrostatic plotter to produce check-plots of the interpretations. The check-plots are compared to the hand-drawn interpretations to check the accuracy and precision of the data transfer. The check-plots are also overlain on the Landsat mapsheets to verify registration. The second stage consists of making the necessary edits as identified during stage one and compiling the map collar information and layout for the overlays. Once all of the edits have been made, a final master plot for each 1:250,000 map sheet (Figure 3) is generated on clearfilm overlay material and checked for accuracy and overall appearance. Upon approval, multiple copies are generated for delivery. As a last step, all of the finalized, digitized data are compiled on an 8mm tape in UNIX TAR, ARC/INFO Export format for delivery.

The Fracture Density Analysis (Figure 4) is accomplished in the ARC/INFO GIS by moving

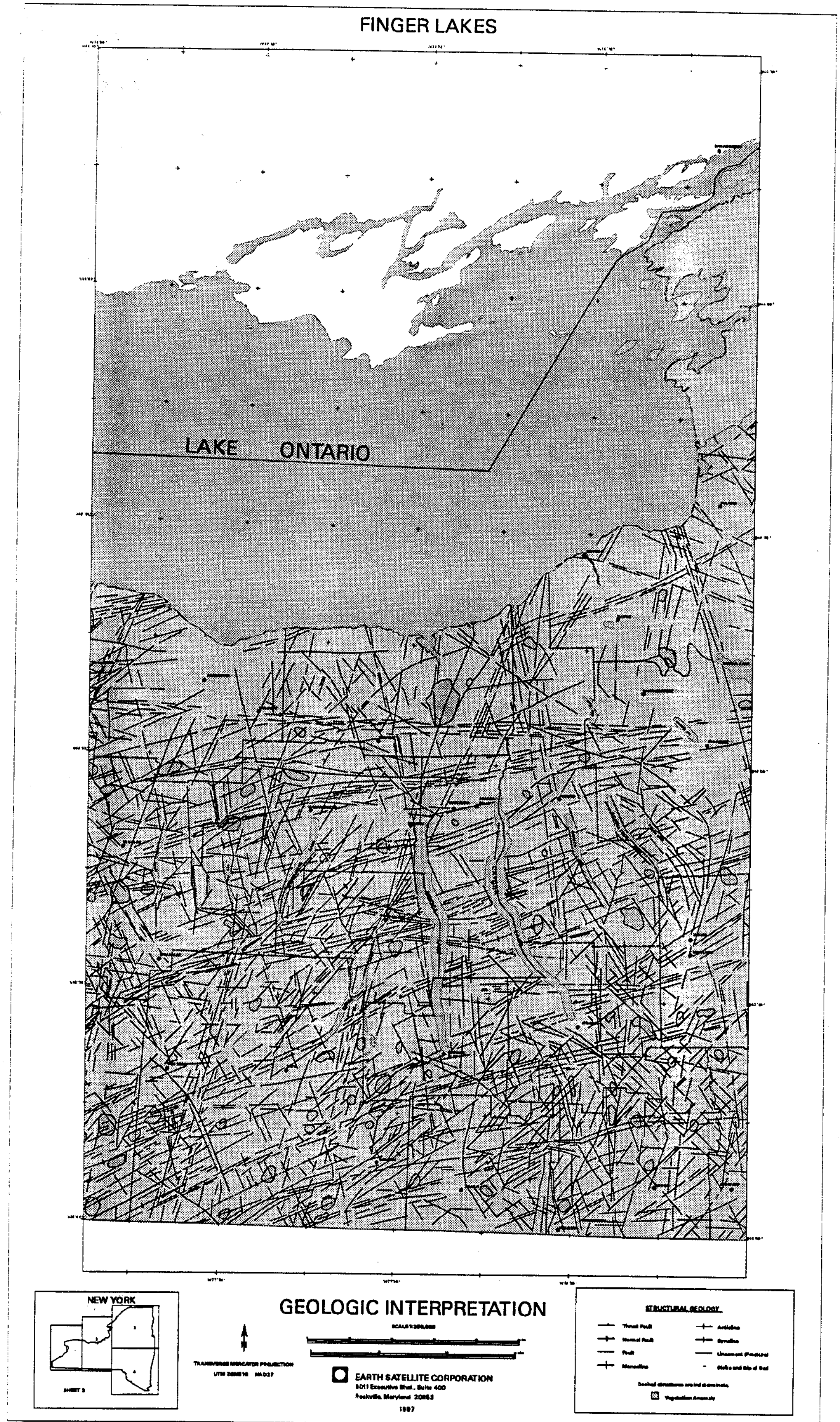


Figure 3: Geologic Interpretation for the Finger Lakes Mapsheet.

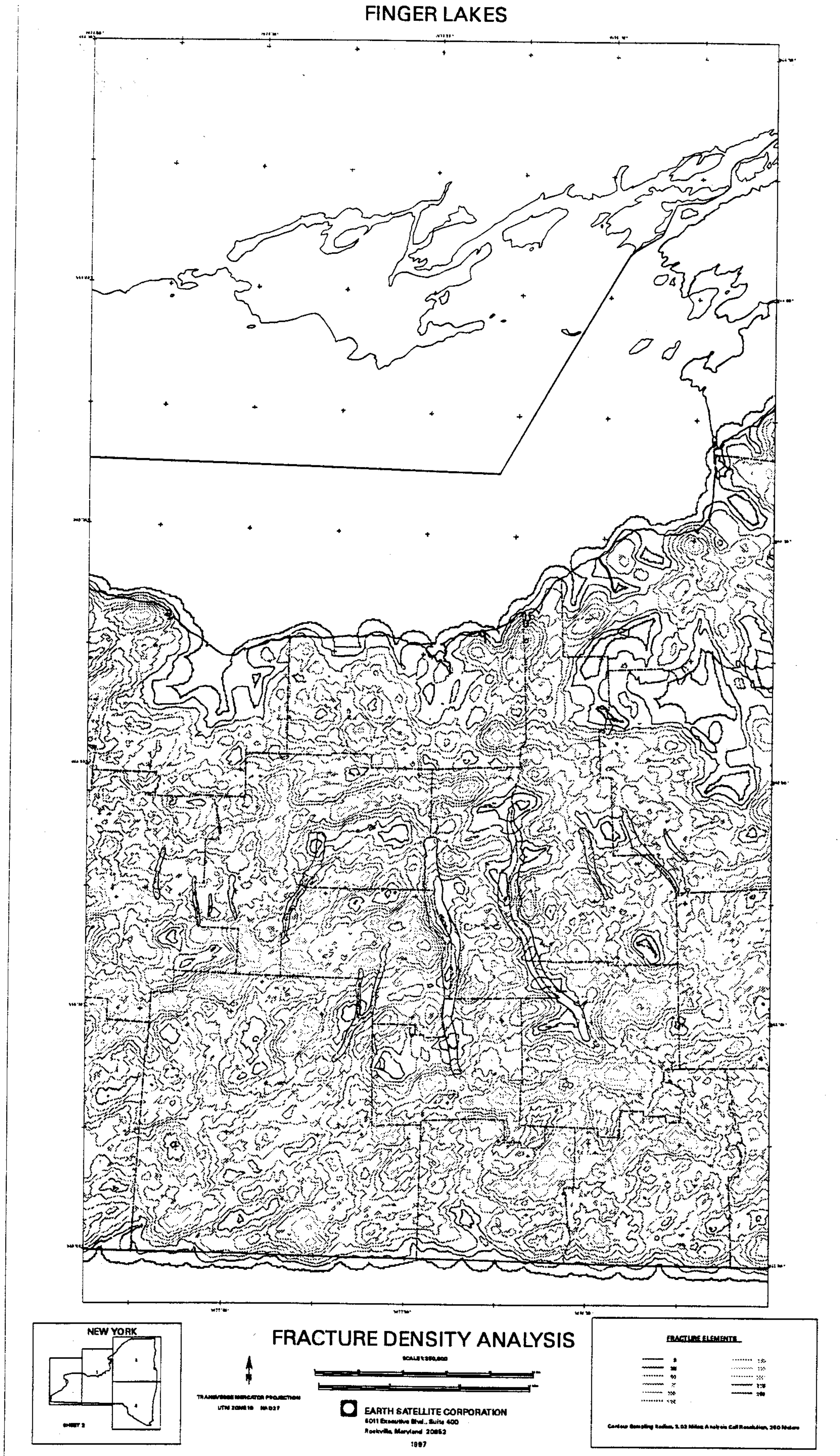


Figure 4: Fracture Density Analysis for the Finger Lakes Mapsheet.

a sampling kernal, 2.02 miles in radius and having cell resolution of 250 meters, through the digital geologic analysis and recording a value in each of the cells of the number and orientation of the fractures in the given cell. These cell values are then digitally contoured to reflect the number and orientation of the fracture elements mapped in the study. Areas of high fracture density consequently have high values and area of low fracture density have low values. The contours are color ramped so that high fracture density contours show up in reds, oranges, and yellows, while low fracture density contours show up in blues and violets.

The digital geologic analysis is also used to create rose diagrams of fracture length versus orientation for all of the study area and each of the four mapsheets (Figure 5).

3.4 Data Analysis and Integration

All of the well information, production statistics, interpretations, analyses, and data are integrated in the ARC/INFO GIS to identify, characterize, and highlight those fracture zones, orientations of fractures, or specific areas that are of particular interest for fracture reservoir hydrocarbon exploration. The tectonic history; ambient states of stress in the upper crust; hydrocarbon generation, maturation, and migration history; oil and gas show data; and knowledge of existing fracture-related production are also used in selecting the exploration fairways. Once the exploration fairways are delineated, the exploration fairways; the Devonian and Ordovician oil and gas field and well location data; the zero edge of the Silurian Salt; and the oil and gas show data are made into an "Exploration Fairways" data set and plotted for each of the four mapsheets (Figure 6).

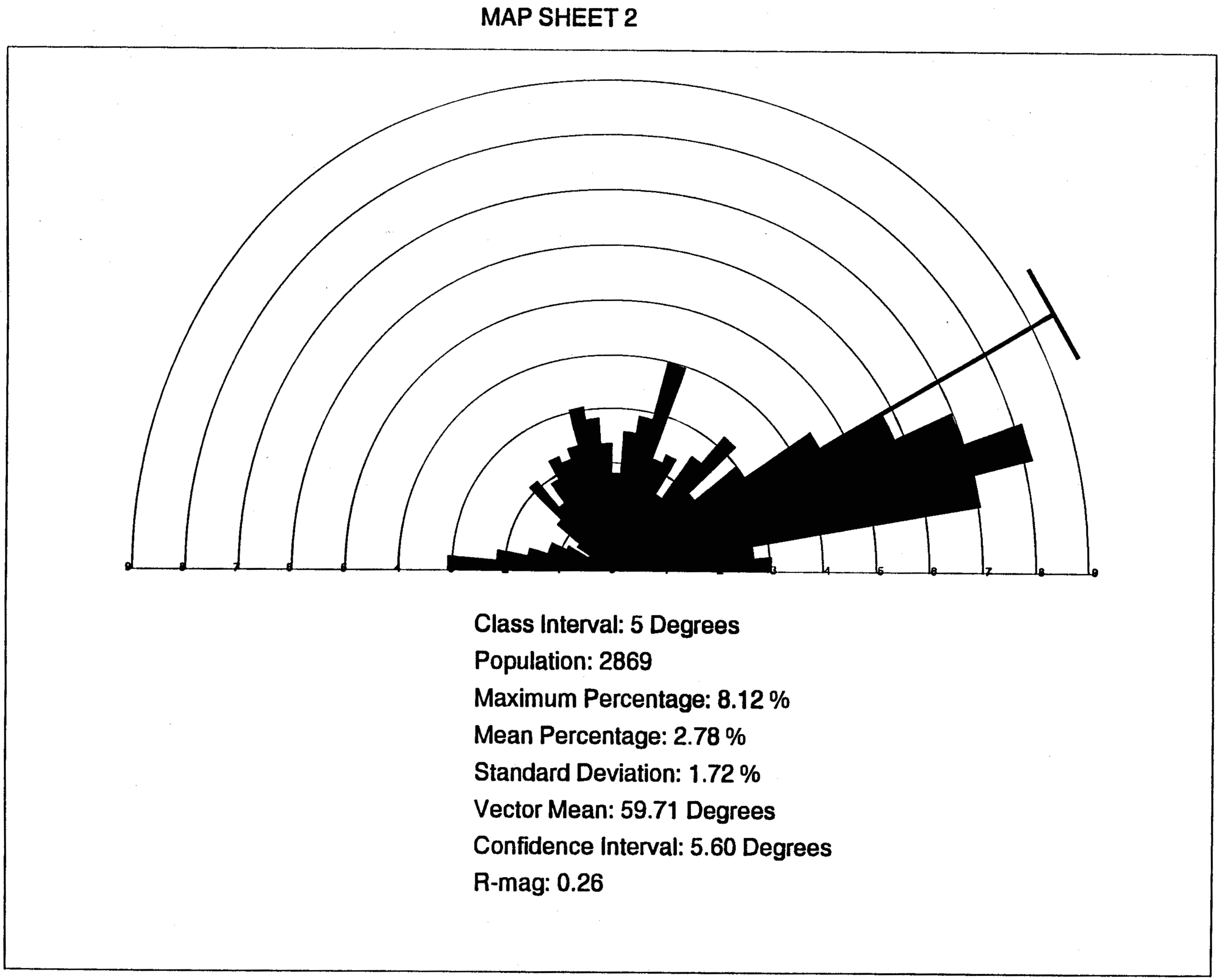


Figure 5: **Rose diagram for the Finger Lakes Mapsheet.**

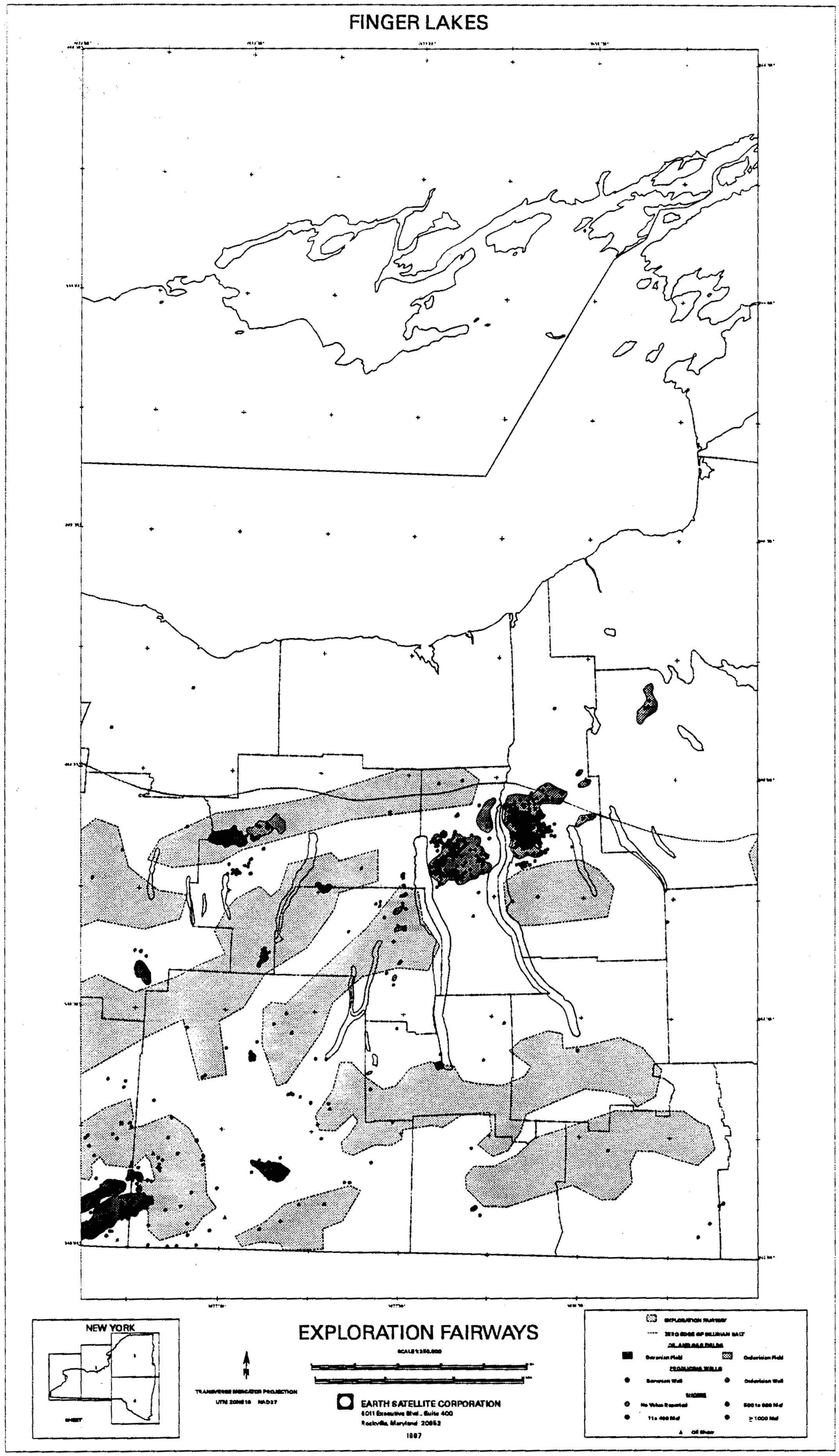


Figure 6: **Exploration Fairways map for the Finger Lakes Mapheet.**

4.0 RESULTS

4.1 Rose Diagrams

The rose diagrams of total fracture length versus fracture orientation for the entire study area and each of the four mapsheets are shown in Figures 7 through 11. As shown on Figure 7, the predominant fracture orientations for the entire study area trend N60°-65°E, with other major fracture zones at N45°-60°E, N65°-80°E, N35°-40°E, N25°-30°E, N10°-20°E, N5°-15°W, N30°-45°W, and E-W. For Mapsheet 1 (Niagara), the predominant fracture directions trend N60°-65°E, N65°-70°E, N55°-60°E, N25°-30°E, N5°-10°E, N20°-25°W, N30°-40°W, and E-W. In Mapsheet 2 (Finger Lakes), the predominant fracture orientations turn more easterly to N70°-75°E, N65°-70°E, N75°-80°E, N55°-65°E, N15°-20°E, N5°-15°W, and E-W. For Mapsheet 3 (Adirondack), the wide variation in fracture directions is indicative of the fact that this sheet contains both the northeastern-most portion (mostly Ordovician section) of the Appalachian basin and the St. Lawrence Lowlands portion of the study; the predominant fracture directions trend N60°-70°E, N50°-55°E, N20°-30°E, N10°-20°W, N30°-45°W, and N55°-65°W. In Mapsheet 4 (Hudson) the effect of basement reactivation of trends associated with the Taconic orogeny (N5°-20°E and N5°-20°W trends) and the trends associated with the eastern-most portion of the Appalachian basin (N45°-55°W, N25°-40°E, and N45°-60°E trends) are evident.

4.2 Exploration Fairway Selection

The selection of the exploration fairways (Figure 12) is the culmination of this phase of the remote sensing portion of the NYSERDA fractured reservoir study. As mentioned in Section 3.4 above, the exploration fairways were selected using a combination and integration of satellite-derived information (fracture zone location and orientation, fracture density, vegetation anomalies) and well information on Ordovician and Devonian oil and gas fields, wells and shows. The twenty-one exploration fairways are very large, angular, and in some instances contain existing production or abandoned wells and fields. The exploration fairways are meant to be an initial, broad, state-wide delineation of areas of high fractured-reservoir potential and are not meant to delineate specific drill-sites or all areas of fracture-related potential. Additionally, the selection of the exploration fairways

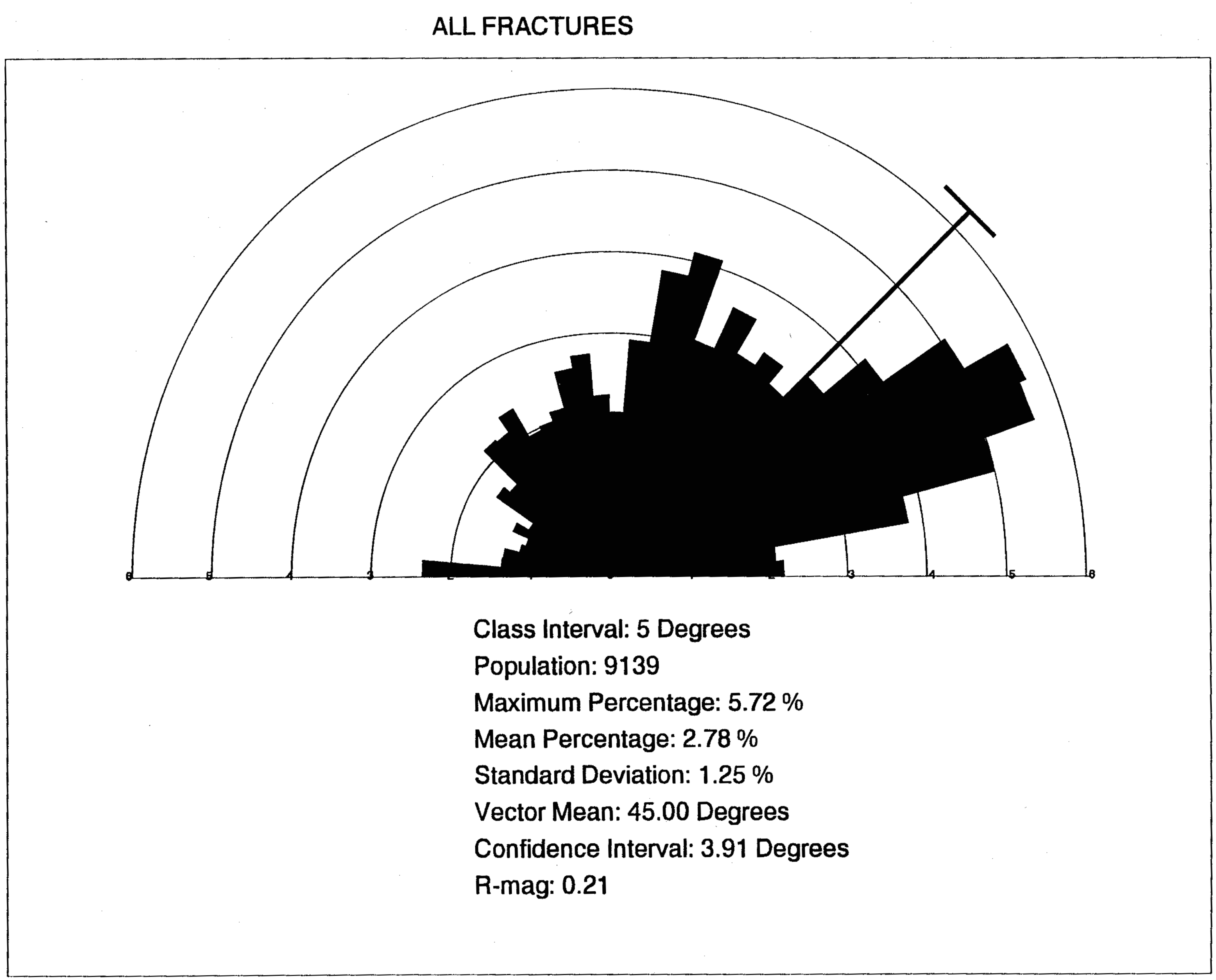
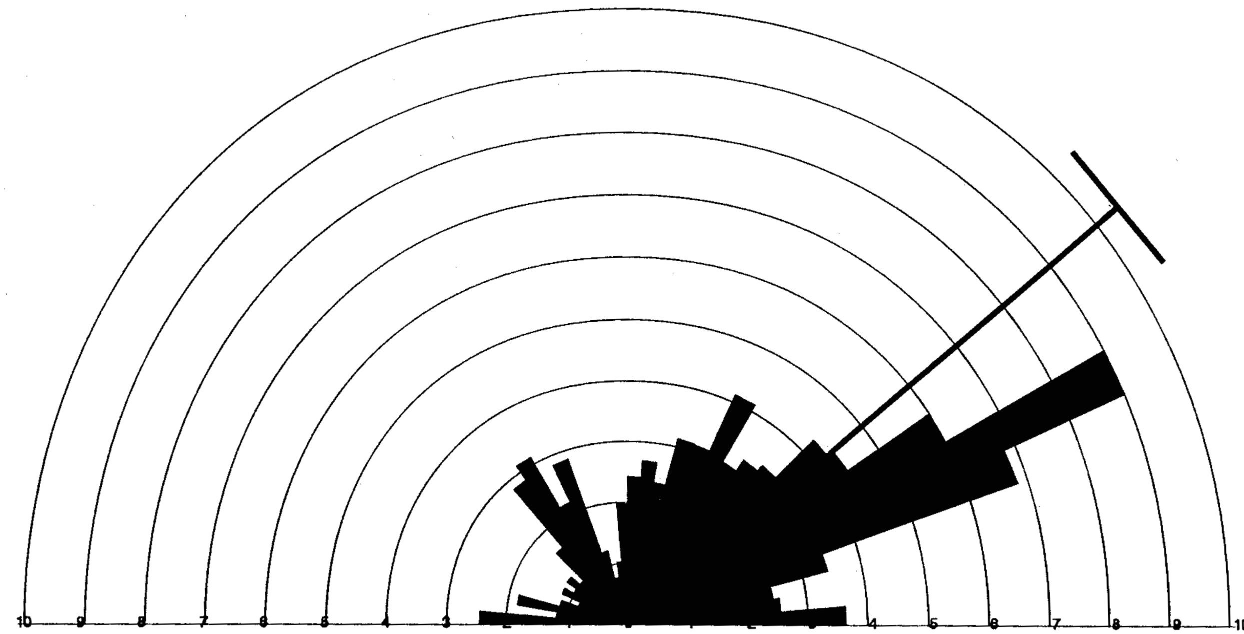


Figure 7: Rose diagram for the entire study area.

MAP SHEET 1



Class Interval: 5 Degrees
Population: 1966
Maximum Percentage: 9.01 %
Mean Percentage: 2.78 %
Standard Deviation: 1.74 %
Vector Mean: 49.63 Degrees
Confidence Interval: 6.27 Degrees
R-mag: 0.28

Figure 8: **Rose diagram for Mapsheet 1 (Niagara).**

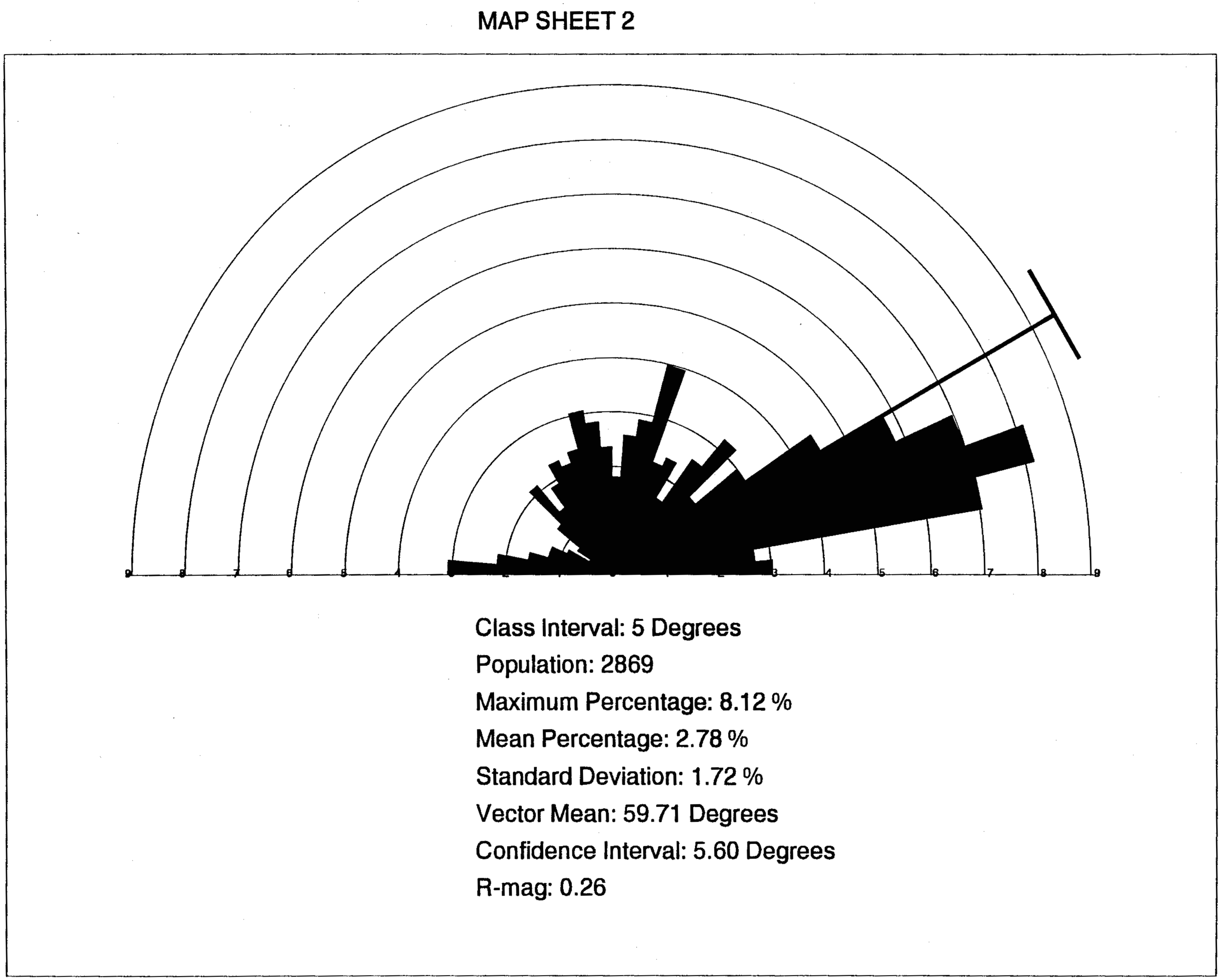
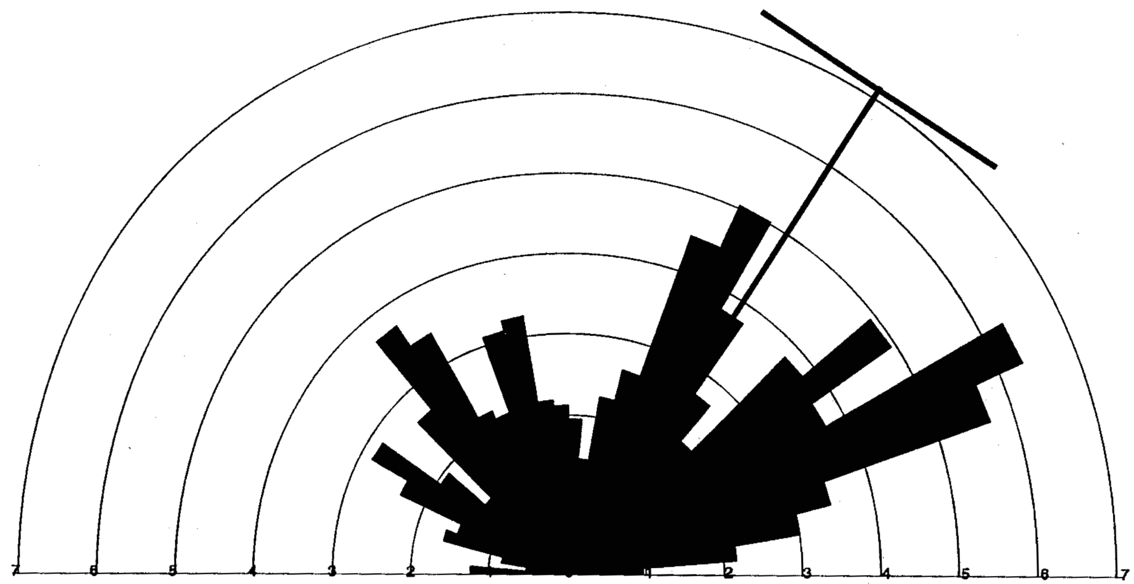


Figure 9: **Rose diagram for Mapsheet 2 (Finger Lakes).**

MAP SHEET 3



Class Interval: 5 Degrees
Population: 1466
Maximum Percentage: 6.32 %
Mean Percentage: 2.78 %
Standard Deviation: 1.35 %
Vector Mean: 32.82 Degrees
Confidence Interval: 13.75 Degrees
R-mag: 0.15

Figure 10: **Rose diagram for Mapsheet 3 (Adirondack).**

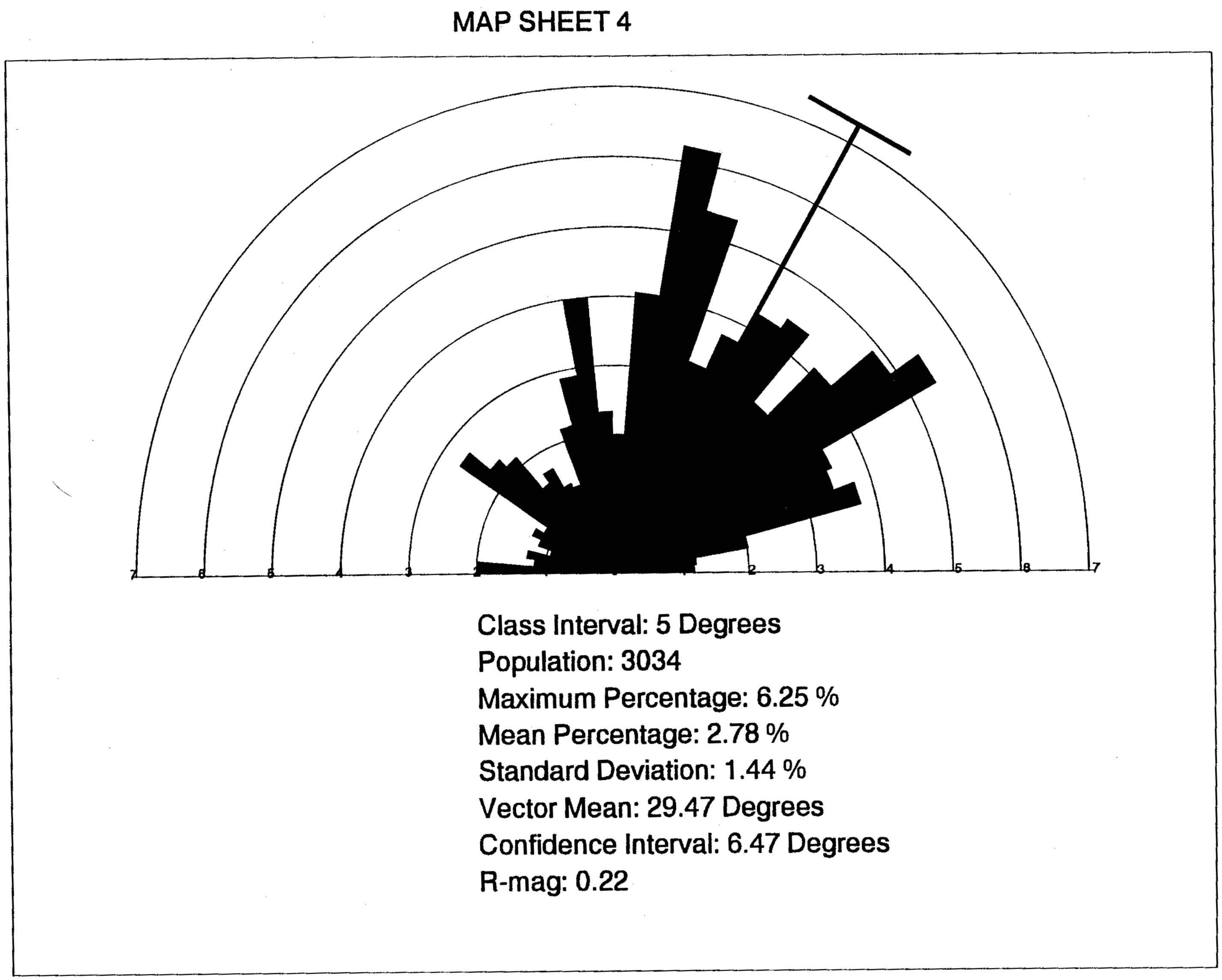


Figure 11: Rose diagram for Mapsheet 4 (Hudson).

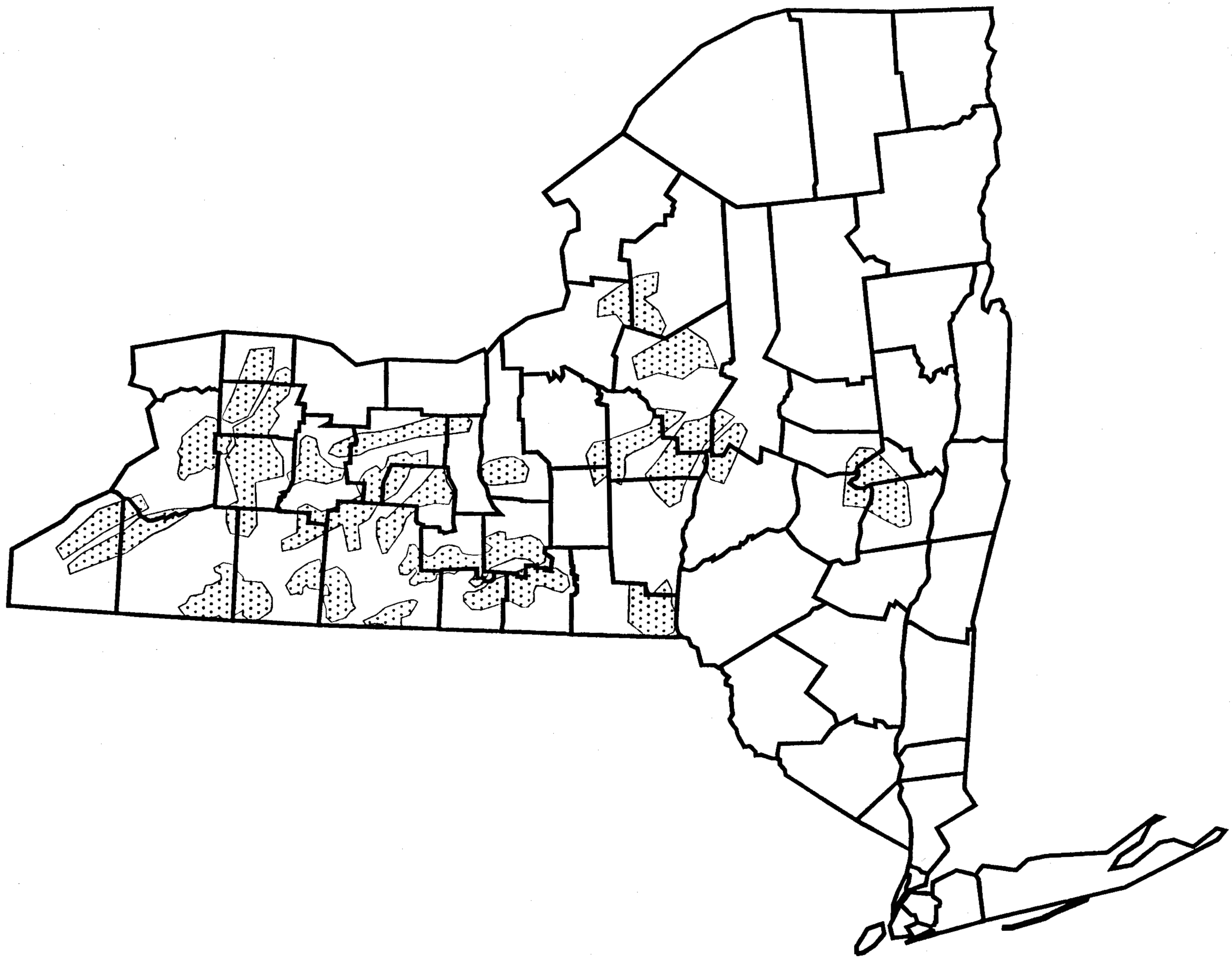


Figure 12: Devonian and Ordovician Exploration Fairways for New York State.

was not limited to the Devonian outcrop (or sufficiently-mature subcrop) as originally planned because so many of the fairways continued structurally beyond these boundaries. Instead, both Devonian and Ordovician outcrop and subcrop and all geological parameters were taken into account in the selection of the exploration fairways. Consequently, once the Devonian outcrop is reached, the target horizons for fractured-reservoir potential become the Ordovician Queenston Sandstone and Utica Shale horizons.

The Ordovician fairways have a different overall trend than those of the Devonian section. This is not surprising in that the Ordovician sequences are more profoundly influenced by: pre-existing basement structure; the Taconic orogeny and related structural grain; and lay under a very extensive stress transfer horizon (the Salina Salts) that would have served to translate almost all the stress from subsequent tectonism to the overlying sequences and result in a muted effect in the underlying Ordovician rocks. Also, movement in the Ordovician strata during subsequent tectonism and deformation would have occurred preferentially along pre-existing planes of weakness rather than creating new fractures. With this as background, the model that emerges from the integration of all the data is that the fractured reservoirs in the Utica Shale through Queenston Sandstone of the Ordovician contain dominant open fracture systems with a north-south orientation whereas the Devonian fractured reservoirs contain a dominant open fracture system with a east-northeast orientation. It is these two trends that are of primary concern in the exploration for fractured reservoirs in the Ordovician and Devonian strata of New York. At the time of deposition and during the subsequent deformation of these units, the east-west trend in the Ordovician strata and the north-northwest trend in the Devonian strata would have acted as zones of fluid migration, diagenesis, and alteration and may, consequently, remain prospective trends as well. The Devonian orientations reflect the effects of the Allegheny orogeny. While the Valley and Ridge Province of the central Appalachians does not extend into New York State, the associated fracture systems and parallel structural orientations are reflected throughout the New York portion of the Appalachian basin. In fact, features suggesting that this area was part of the Alleghenian Foreland include fracture patterns indicative of those found in the frontal regions of major thrust faults in other petroleum provinces as well as evidence of inversion features.

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