DEFINITION OF TRENTON/BLACK RIVER PROSPECTS IN THE FINGER LAKES REGION, NEW YORK STATE

REVISED FINAL REPORT

NYSERDA AGREEMENT NO. 4877-ERTER-ER-99

February 15, 2003
April 23, 2003
June10, 2003

Submitted by:

Dr. Robert Jacobi, Project Director
UB Rock Fracture Group
Geology Department, 876 NSC
University at Buffalo
The State University of New York
Buffalo, NY 14060
(716) 645-6800, x2468
email:rdjacobi@geology.buffalo.edu

Mr. Stuart Loewenstein, President, Subcontractor
Quest Energy, Inc.
63 Kenmore Ave.
Amherst, NY 14226

Submitted to:

Dr. John Martin, NYSERDA Project Manager
NYS Energy Research and Development Authority
17 Columbia Circle
Albany, NY 12203-6399

NOTICE

ABSTRACT

Detailed surface structure data, Landsat lineaments, sparse well log data, and seismic reflection data were integrated order to demonstrate the existence and trends of Trenton/Black River faults in the Finger Lakes region of central New York State. This research project demonstrated the notable capabilities of this integrative methodology.

Four N-S seismic lines display high angle faults that offset the Precambrian basement. For many faults, the shallowest reflector with discernible offset is the Trenton reflector, indicating that the last major motion on these faults was in the Taconic Orogeny. A few faults extend higher in the stratigraphic section. Several of the faults form grabens in the Trenton/Black River section. These faults occur far east from the widely-known Trenton/Black River faults in the Keuka Lake region of the Glodes Corners Road Field and Muck Farm Field.

Lineaments coincident with the Trenton/Black River faults allow extension of the Trenton/Black River faults away from the seismic lines along the lineaments. Similarly, lineaments coincident with the shallow thrusts observed on the seismic lines also provide guides for extension of the shallow structure away from the seismic lines. In the study area, the research methodology can differentiate Landsat lineaments associated with Trenton/Black River faults from Landsat lineaments associated with relatively shallow thrusts and folds. The Trenton/Black River faults are characterized by ENE-trending Landsat lineaments, fracture intensification domains (FIDs), and aeromagnetic gradients, and the FIDs generally predate cross-strike fractures. In contrast, the previously mapped E-striking shallow structures are characterized by E-striking lineaments and FIDs that cross aeromagnetic trends, and many of the FIDs postdate the cross-strike fractures. East-northeast-and E-striking FIDs only occur in regions where faults were observed on the seismic lines or inferred from previous mapping. North-striking FIDs coincident with sharp excursions in the structure contours suggest N-striking cross-strike discontinuities. Sparse well log data are consistent with the interpretation that Trenton/Black River grabens occur through-out the Finger Lakes region.

KEY WORDS

Trenton/Black River faults, New York State, fractures, Appalachian Bin structure, lineament

ACKNOWLEDGMENTS

The authors are pleased to acknowledge the assistance by their able field crews for collection and analysis of structure and stratigraphic data. For structure data, the assistants included Courtney Lugert, Karen When, Fariha Islam, Rick Mayer, Fernanda Scuderi, and Jon Zybala. Dr. Gerald Smith assisted in the collection and analysis of stratigraphic data, and assisted in the final preparation of this report. For assistance at Quest Energy, the authors thank Brian Gates and Oliver Mohar. The authors also wish to acknowledge Dr. John Martin for his support and his viewpoints that added considerably to discussions concerning this research.

TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

SUMMARY

The importance of structural control on oil and gas reservoir quality, and in some cases, on even the presence of a play, is well known. However, delineation of detailed structure by conventional techniques, based on well logs and high resolution seismic data, is often prohibitively expensive, especially 3-D seismic or reconnaissance high resolution seismic. Further, in areas where exploration drilling has been minimal, well log analyses may yield little data concerning possible faults. A primary objective of the research was to demonstrate the validity of a rapid, relatively inexpensive method of determining target areas for more expensive technologies, such as seismic profiling or exploratory drilling. This approach integrates Landsat lineaments, fractures mapped at the surface, and limited seismic reflection profiles in order to identify the surface manifestations of deep structures. The research plan was to first test the integrated approach in an area where a seismic line indicated the presence of faults, and then apply the integrated technique, combined with sparse well log data, to identify additional deep structures.

The study area was east of prolific gas plays that occur along Trenton/Black River faults in the Finger Lakes region of central New York State (NYS). Subsurface structures of interest included grabens in the Trenton/Black River section that are controlled by faults that reach into the Precambrian basement. Other structures in the region included thrusts in the Siluro-Devonian section, and tear faults (or cross-strike discontinuities [CSDs]), that offset the trend of the thrusts and perhaps the Trenton/Black River faults.

The results of the study showed that integration of seismic lines with lineaments, surface structure and existing aeromagnetics is an extremely effective method for recognizing subsurface structure and mapping the patterns of these subsurface structures. The method is essentially a "poor-person's 3-D seismic".

Surface fracture studies were a powerful tool to groundtruth the lineaments. East-striking fracture intensification domains (FIDs) occur only in regions with E-striking lineaments, and only in regions above E-striking shallow thrust/fold structures that were either previously mapped at the surface and/or displayed in this report's seismic reflection data. Similarly, the ENE-striking FIDs occur only in regions with ENE-striking lineaments, and only in regions above Trenton/Black River faults observed on the limited seismic lines. The orientation and extent of the groundtruthed

lineaments yields a map view of the subsurface structures that are indicated by seismic data. Consistent with the differentiation of the source of the ENE- and E-striking lineaments, the ENE-striking lineaments (associated with deep faults that reach Precambrian basement) are parallel to aeromagnetic anomalies, whereas the E-striking lineaments (associated with shallow structures high in the sedimentary section) cross aeromagnetic anomalies.

The integrated approach confirmed the existence and location of Trenton/Black River faults east of the region where they had been previously recognized, and confirmed the existence of thrusts and CSDs previously known or suspected from well log data and surface stratigraphy.

OBJECTIVES OF THE RESEARCH PROJECT

The primary objectives of the research were twofold: 1) to develop and demonstrate a cost-effective methodology that can be used to recognize and map areas of high potential for Trenton/Black River plays in NYS, and 2) using this methodology, determine whether potential Trenton/Black River plays exist east of the Glodes Corners Road Field in the Finger Lakes region of central New York State. In order to accomplish these goals, the methodology must catalog all the structures in the area, and succesfully distinguish between potential Trenton/Black River faults and other faults that are restricted to higher levels of the stratigraphic section. The methodology integrated interpretations of reprocessed sesimic reflection profiles (Task 5) with well log analyses (Task 4), EarthSat (1997) lineaments (Task 6), and surface fracture and limited stratigraphic analyses (Task 7). The concept was to identify Trenton/Black River faults on the reprocessed seismic lines, and then extrapolate the faults away from the seismic lines on the basis of coincident lineaments, fracture intensification domains, and stratigraphic offsets of surface units.

For Task 4 (well log analysis), the specific objectives were to determine the regional structural trends. The lack of closely-spaced deep wells in the study area was assumed to preclude well logs as a general guide to Trenton/Black River faults. Well logs would also be used to confirm the reflector indentifications in the seismic reflection profiles.

For Task 5 (reprocessed sesimic reflection profiles), the specific objectives were to license and then reprocess four N-S sesimic lines. Following reprocessing, the seismic lines would be interpreted, resulting in line diagrams that portrayed prominent stratigraphic reflectors and faults.

For Task 6 (EarthSat [1997] lineaments), the specific objectives were to 1) determine if Landsat lineaments identified by Earthsat (1997) could be utilized as an aid for determining the location of Treton/Black River controlling structures, and 2) if so, to extend the Treton/Black River structures away from the sesimc lines along the lineaments. The validity of the lineaments as a predictor of deep structures was to be tested by observing whether the lineaments were coincident with deep structure displayed on sesimic reflection profiles, as well as coincident with fracture intensification domains, and structure inferred from well log analyses (if sufficient well density were available).

For Task 7a (Structural analyses), the specific objectives were to analyze fracture patterns observed in outcrops as an aid for delineation of deep structural trends. The locations and trends of fracture intensification domains (FIDs) would be compared to the EarthSat (1997) lineaments, to deep structure inferred from well logs and available seismic reflection profiles, and to shallow/surface structure recognized in surface stratigrahic data and in seismic reflection data. If FIDs were coincident with faults inferred from seismic reflection profiles, or coincident with previously recognized surface folds/faults, then similar FIDs could be regarded as indicators of faults in locations away from the seismic lines and previously mapped areas. Further, FIDs found to coincide with lineaments would confirm that the lineaments indicated faults.

For Task 7b (Stratigraphic analyses), marker beds would be identified and traced across areas where faults were suspected. Stratigraphic offsets across the suspected fault traces would confirm the presence of the fault, and assist in characterizing the unexposed fault.

BACKGROUND/APPROACH

The importance of structural control on oil and gas reservoir quality, and in some cases, on even the presence of a play, is well known. However, delineation of detailed structure by conventional techniques, based on well logs and high-resolution seismic data, is often prohibitively expensive. Similarly, high resolution seismic can be prohibitively expensive as a reconnaissance tool. An approach for delineating deep structure with much less expensive techniques has been developed, based on work over the past 15 years. This integrated approach has shown that deep structure in New York State has a surface expression that can be recognized by lineament and fracture analyses combined with soil gas surveys (e.g., Jacobi and Fountain, 1996, 2002; Fountain and Jacobi, 2000). Thus, characterization of the surface manifestations of deep-structures by lineaments, fractures, and soil gas anomalies can provide a rapid, relatively inexpensive method for determining the precise coordinates for the application of more expensive technologies, such as seismic profiling or exploratory drilling.

This study included primarily a proof-of-concept stage, wherein the new methodologies were tested along a reprocessed seismic line, and a minor application stage, wherein the new methodologies were used to map structures that may prove to be new potential exploration targets. In the proof-of-concept stage, the orientation, location and extent of subsurface structures deduced from lineament analysis, surface fracture analysis and well log analyses were tested against structure deduced from a reprocessed seismic line. The reprocessed seismic line trends north-south, across the major structures, and is located near the eastern shore of Seneca Lake in Seneca and Schuyler counties of central NYS, where extensive outcrops allowed detailed structural analyses to be tied to the seismic line (Figure 1). Additional seismic lines to the east and west were also interpreted (Figure 1).

The research project was accomplished by a partnership that included Quest Energy, Stuart Loewenstein, President, and Professor Robert Jacobi of the University at Buffalo Rock Fracture Group; two UB graduate students, Courtney Lugert and Karen Wehn also participated in the research. Stuart Loewenstein made the stratigraphic picks on the well logs; he contoured the various stratigraphic horizons and isopach maps using the program Geographix. Dr. Jacobi was in charge of the structure task; he and his graduate student, Courtney Lugert, collected and analyzed the structure data. This Final Report was written by Dr. Jacobi.

BASIS FOR PRESENT STUDY: NYSERDA-FUNDED PROJECTS

The rationale for the technical approach hinges primarily on the work Jacobi and Fountain performed for NYSERDA in Allegany County (Jacobi and Fountain, 1996; Jacobi and Fountain, 2002) and in Cattaraugus County (Jacobi et al., 2001a). They established that deep structures in the Appalachian Basin of western NYS have surface expressions that can be manifested by:

1. fracture intensification domains (FIDs);
2. lineaments observed on air photos, topographic maps, Landsat and SLAR images; and, in some cases,
3. soil gas anomalies.

These deep structures include reactivated fault systems, many of which are controlled by faults in the Precambrian basement, such as the Clarendon-Linden Fault System and cross-strike discontinuities (CSDs) in Allegany and Cattaraugus counties. In these and other areas, some Trenton/Black River faults also appear to be reactivated faults systems controlled by faults in the Precambrian basement (see Jacobi, 2002, for a review). Shallower structures (and surficial structures) also are typified by FIDs and lineaments, but some of these fault systems, such as the Alleghanian thrust fault in Allegany County, are not characterized by prolific soil gas.

FlDs are narrow, linear zones characterized by relatively closely-spaced fractures that define the trend and width of the FID. These fractures commonly are also the master fractures, even though in regions outside the FID this fracture set may characteristically abut other fracture sets. In many of the FIDs, fractures of sets other than the master set are reduced in number, compared to regions outside the FID. Fractal and geostatistical analyses of fractures within and outside of the FIDs show that FIDs have different fractal and geostatistical characteristics compared to fractures outside the FIDs (Jacobi et al., 2001b). FIDs generally coincide with faults both at the surface (faults observed in outcrop or inferred from stratigraphic offset between outcrops) and in the subsurface (faults observed on seismic reflection profiles or inferred from well log data).

In both Allegany County (Jacobi and Fountain, 1996, 2002), and Cattaraugus County (Jacobi et al., 2001a), remotely-sensed lineaments correlate spatially with FIDs (and subsurface structure). Thus, in regions where well and seismic control are relatively sparse, the FID and lineament tools can be integrated into the exploration package to better define where further, more conventional exploration techniques should be concentrated. Furthermore, in areas where some structure is known, these structures can be extended along the strike of the trends defined by these lineaments. Thus, the extension of known structures, or the recognition of new structure, based on this integrated approach can significantly improve the oil and gas potential for New York State.

PREVIOUSLY KNOWN STRUCTURE IN THE STUDY AREA

The study area is located in the Appalachian Plateau of NYS where primarily units of the Upper Devonian Catskill Delta Complex crop out. These units exhibit gentle folds, with dips reaching a maximum of 2^o, and are complexly fractured. Faults with significant stratigraphic offset (on the order of 30m) have been inferred, but never observed in outcrop.

Three prominent studies defined the regional structure in the area: Wedel (1932) mapped the surface folds; Bradley et al. (1941) refined the surface folds and recognized faults, and Murphy (1981) recognized several subsurface folds and faults in the area based on extensive well log analyses. Bradley et al. (1941) also inspected well log data, but the additional wells available to Murphy (1981) supercedes the Bradley et al. (1941) study for subsurface structure. None of the studies in this region had sufficient data to construct detailed structure contour maps on the Trenton/Black River units. However, Rickard (1973) suggested N-striking Ordovician-aged fault blocks to the northeast and northwest of the study area, based on anomalous data from a single well for each proposed fault block.

Wedel (1932) used transit level lines on large outcrops and elevations of marker units to determine dips of stratigraphic units in south-central NYS, including the present study area. He confirmed previously recognized folds (see Wedel, 1932, for references therein), and traced several folds across the present study area. In the study area Wedel (1932) portrayed the fold crestlines and troughs generally straight east-northeast between the Seneca and Cayuga lakeshores because most of his data came only from the two lakeshores. The most prominent surficial fold is the ENE-striking Firtree Anticline that crosses Seneca Lake at Firtree Point (Figure 2). On the Cayuga lakeshore, the Tully limestone provided a marker bed that indicated structural relief of approximately 150 ft (46 m). The Watkins Anticline was thought to trend east-northeast through Watkins Glen to Ithaca, and the structural relief was judged to be on the order of 40 ft (12 m).

Bradley et al. (1941) mapped several surface marker units with sufficient elevational control to construct a structure contour map that identifies folds in the detailed study area along the east side of Seneca Lake (Figure 2). They also measured the dip at a large number of outcrops in order to supplement the stratigraphic elevational data. They too found the prominent surficial fold, the Firtree Anticline; however their structure contours indicate that the anticline trace bears east (not east-northeast). The apparent east-northeast trend of the anticline proposed Wedel (1932) is a more general trend that resulted from offset of the E-striking anticline crestline along a N-striking fault inferred by Bradley et al. (1941). Farther to the north, a small E-striking anticline and two adjacent synclines also display the same apparent sense of map offset across the projected extension of the N-striking tear fault. Bradley et al. (1941) also found a NE-striking syncline with relatively steeply-dipping limbs near Ovid. The age of all these structures was assumed to be Alleghanian.

Bradley et al. (1941) also mapped four faults in the detailed study area, including the N-striking fault previously noted. Although they did not find this fault in outcrop, the anomalous elevation of stratigraphic markers led them to suggest the existence of the fault near the south end of Seneca Lake (Figure 2). The variable sense of inferred stratigraphic offset along the fault (from down-on-the-east in the south to down-on-the-west in the north) may indicate that the proposed fault trace is the locus of several lateral fault ramps with different senses of offset for different cross structures along the length of the composite structure. Alternatively, the variable offset may indicate that the fault is a scissors fault. This report suggests that the fault trend extends farther north along the east side of Seneca Lake and accounts for the deviations in the trends of the folds indicated by the structure contours (discussed above).

Bradley et al. (1941) believed they found evidence for three ENE-striking faults (Figure 2), but as detailed later in this report, the “faults” in outcrop are actually pop-ups with no discernible stratigraphic offset from one side of the structure to the other.

To the west of the detailed study area, Bradley et al. (1941) mapped a major NW-striking monocline that coincides with the more-recently recognized Lawrenceville-Attica lineament (see Jacobi, 2002, for discussion of this lineament). In this region, Bradley et al.’s (1941) surface structure contours indicate a total of 1200-1400 feet (366-426 m) of structural relief, down-on-the-southwest. The structure is not obvious in the structure contours because smaller scale faults and folds cross the monocline at a high angle, obscuring the more regional trend of the monocline. However, dips measured on many outcrops in the region of the monocline confirm the monoclinal dip indicated by the structure contours that were constructed from elevations of stratigraphic units in outcrop.

Murphy (1981) examined over 1800 well logs in south-central NYS and constructed a series of structure contour and isopach maps. The Onondaga structure contour map does not reveal folds between Seneca and Cayuga lakes, but does display an E-striking anticline south of Cayuga Lake that diminishes in structural relief to the west, where it is on strike with the Watkins Anticline of Wedel (1932). Murphy (1981) recognized the Seneca Lake Fault, which trends approximately N-S along the western side of Seneca Lake and extends south along lineaments to the NYS boundary. Evidence for the fault and its proposed 390 m of right-lateral offset came from salt exploration and mining (e.g., Jacoby and Dellwig, 1974). A similar N-striking, right-lateral strike slip fault, the Cayuga Lake Fault, was proposed by Murphy (1981) to extend south from the southeastern corner of Cayuga Lake to the NYS boundary. This proposed fault was based on well log analyses. Murphy (1981) believed that both faults were tear faults that separated different sections of thrust faults ramping up from decollement in the Silurian salt. He did not believe that these faults extended below the salt section, partly because the only structure contour map of a unit below the Silurian salt (the Lockport) showed only "smooth" contours, but this map was based on extremely sparse data.

To the west, Murphy's (1981) Onondaga structure contour map also shows the major NW-striking monocline along the Lawrenceville-Attica lineament. The amount of structural relief is variable, but reaches a maximum on the order of 1,000+ ft (304+ m), measured parallel to regional strike of the offset units.

The study area has a long history of surface fracture studies, spanning almost 100 years (see reviews in Engelder and Geiser, 1980; Engelder, 1985; Younes and Engelder, 1999). However, a confusing and often contradictory array of publications and opinions make deciphering the character of the fractures and fracturing history from the published literature extremely difficult. In general, three main systematic fracture sets were thought occur in the Appalachian Plateau of NYS: Set I is orthogonal to Alleghanian folds (cross-fold, or cross-strike, joints), Set II is approximately parallel to the Alleghanian folds (fold-parallel, or strike-parallel, joints) and Set III maintains an orientation of about 060^{o} across the Appalachian Plateau of NYS (e.g., Parker, 1942; Nickelsen and Hough, 1967; Engelder and Geiser, 1980). Set I consists of two fracture sets, Ia and Ib, with orientations less than 30^{o} apart. Set Ib fractures fan across NYS, generally orthogonal to the arc of Alleghanian fold traces (e.g., Engelder and Geiser, 1980). Although Engelder and Geiser (1980) believed that Set 1a fractures "show no evidence of...rotation [and] the strike of the joints maintains parallelism for 100 km before abruptly rotating about 20^{o} to the east" (p. 6334), Engelder and Geiser (1980) also stated that "in general, the mean orientations of... Ia rotate counterclockwise from east to west..."(p. 6323).

The proposed relationships between sets 1a and 1b have often appeared to be complicated and even contradictory. Parker (1942) believed that sets 1a and 1b were a conjugate shear pair, but Nickelsen and Hough (1967) suggested that sets Ia and Ib were *not* a conjugate shear pair because of a lack of evidence for shear and inconsistency in the fracture sets that form the conjugate pair. In 1980 Engelder and Geiser suggested that Set Ia formed during the Alleghanian Orogeny and Set Ib developed later during uplift, but that "residual strain" remaining from a deformation event that predated the development of Set Ia guided the later growth of Set Ib fractures; i.e., although Set Ib fractures propagated after Set Ia fractures, the Set Ib fractures developed in response to a residual strain from an earlier deformational event that had not been effective during the growth of Set Ia fractures.

By 1985, additional data led Engelder to revise the fracture history of Set I. In the deeper portions of the Devonian Catskill Delta Complex (east of the present study area), Engelder (1985) now believed that Set Ib fractures developed first, during the "Lackawanna Phase" of the Alleghanian Orogeny, followed by generation of Set Ia fractures and coeval cleavage surfaces during the Main Phase of the Alleghanian Orogeny. In contrast, a different story emerged for the stratigraphically higher portions of the Catskill Delta Complex (including the present study area). Engelder (1985) maintained that such a difference could be expected, given the different stress histories that resulted from deep burial vs. shallow burial of the Devonian section.

In the higher portions of the Catskill Delta Complex, Engelder (1985) found little evidence for determining the age relationship between sets Ia and Ib, since many outcrops did not display Set Ia fractures, and where both sets did occur, the sets were generally mutually intersecting, not abutting. At one outcrop in Taughannock Falls State Park (which is located on the southwest shore of Cayuga Lake), Set Ib fractures abutted Set Ia fractures, which suggested to Engelder (1985) that Set Ia fractures developed first, during the main Phase of the Alleghanian Orogeny, and that the Set Ib fractures therefore developed during post-Alleghanian uplift. However, in the same park, Bahat and Engelder (1984) also found Set Ib fractures in siltstones and Set Ia fractures in shales, indicating to Engelder (1985) that Set Ib fractures in the siltstone beds developed first during the Lackawanna Phase, and the Ia joints within the shale beds during the Main Phase. Engelder (1985) concluded that there must have been several times of Set Ib fracture generation (partly from assuming that Set Ia fractures had a consistent age across the basin).

The scenario described above for the generation of Set I fractures was superceded in 1997, when Zhao and Jacobi suggested that the two cross-strike fractures sets resulted from an arcuate stress field (in map view) migrating through the region during the Alleghanian Orogeny. In their model, as the stress field penetrated the Appalachian Basin, stress rotations with the opposite sense-of-rotation would occur at the opposite ends of the arc: counterclockwise in western NYS and clockwise in eastern NYS. Younes and Engelder (1999) used fringe cracks and twist hackles to affirm that in the region of the present study area (Seneca and Cayuga lakes), Set Ia generally postdates Set Ib, and that both developed during a rotation of the Alleghanian stress field (Engelder et al., 2001), as predicted by the Zhao and Jacobi (1997) model.

The strike-parallel fractures, Set II, also have had different explanations and proposed timings of development. Engelder and Geiser (1980) suggested that "the most likely time is during the development of folds while the upper beds are above a neutral fiber" (p. 6334). Engelder and Geiser (1980) placed the timing of the folding and fracturing after the generation of Set Ia fractures, but still during the Alleghanian Orogeny. Engelder (1985) suggested that the Set II fractures are release joints that developed during post-Alleghanian uplift, based on their shallow distribution in cored sections (generally < 500m), and that "they are not cut by Alleghanian structures" (p. 468). Although Younes and Engelder (1999) found twist hackles on an ENE-striking fracture set, the sense of rotation does not change across the Finger Lakes region. In contrast, the cross-strike fractures do display a change in the sense-of-rotation of the twist hackles across the Finger Lakes region. Thus, whether the ENE-striking fractures resulted from the same stress field as the cross-strike fractures is not clear, and the relation of the ENE-striking fractures to the Alleghanian Orogeny is obscure. Younes and Engelder (1999) do suggest that the fractures developed during tectonic relaxation after the Alleghanian Orogeny.

Set III fractures are difficult to distinguish from Set II fractures in the Finger Lakes region, since they have similar trends. Because the maximum horizontal compressive stress of the present stress field is oriented approximately colinearly with the strike of the fractures, Engelder (1982,

1985) believed that these fractures were neotectonic in origin. However, the offset of ENE-striking fractures along Set I fractures suggested to Engelder et al. (2001) that the Set III fractures are actually Acadian in age. To the west in Allegany County, Jacobi and Fountain (1996) found that FIDs oriented parallel to either Set II or Set III fractures generally predate the Alleghanian cross-strike Set I fractures.

METHODOLOGIES OF PRESENT STUDY

Task 4, Well Log Analyses

Well log analyses of 110 wells in the research area were used to construct structure contour and isopach maps for the study area. Formation boundary "picks" were made by Quest Energy, who followed the industry practice for recognizing each unit top; van Tyne and Foster's (1979) study illustrates such picks. Formation picks included the tops of the Devonian Onondaga, Silurian "Packer Shell" (Irondequoit), Ordovician Trenton and Black River units, as well as both bases and tops of the "E" and "F" salts. Structure contour maps for the tops of the Onondaga, "Packer Shell" (Irondequoit), Trenton, and Black River units were generated in Geographix by Quest Energy. Isopach maps, also constructed by Quest Energy on Geographix, include the Onondaga to "F" Salt interval, Onondaga to Irondequoit interval, Onondaga to Trenton interval, Irondequoit to Trenton interval, Trenton to Black River interval, the "F" Salt, the "E" Salt, and the composite "F" and "E" salt thickness. The maps were interpreted by Jacobi in a following section.

Task 5, Seismic Reflection Analyses

The subcontractor, Quest, licensed seismic lines EGI-004-00, SCNYRS1C, SCNYRS6, and SCNYRS7 (lines 1, 2, 3, and 4, respectively on Figure 1). The Geodata lines are 1980's vintage data. Data quality is good and the field acquisition parameters were as follows:

Source:

Type:	Vibroseis
Interval:	220 ft.
Pattern:	4 over 110'
Sweep:	21-110 Hz.
No. of Sweeps:	8

Instruments:

Recorder:	MDS-10
Gain:	48 Db
Filter:	18-128 Gate/Notch In
Record Length:	3 sec.
Sample Rate:	2 ms.

Receiver:

Geophone Type:	Mark L10B (8Hz)
Group Interval:	110 ft.
Pattern:	24 over 220 ft.
Coverage:	2400%
Spread: Trace:	1------------ 48 X 49 ------------96
	5720' 550' 550' 5720'

The Geodata lines were reprocessed by Elite Seismic Processing, Inc. in October, 2000.

Line EGI-004-00 was shot in January 2001 as part of a group shoot. The data quality is good and the field acquisition parameters were as follows:

Source:

Type:	Vibroseis
Interval:	220 ft.
Pattern:	2 over 110'
Sweep:	15-120 Hz.
No. of Sweeps:	8

Instruments:

Recorder:	OYO DAS-1
Filter:	Out/Notch Out
Record Length:	3 sec.
Sample Rate:	2 ms.

Receiver:

Geophone Type:	Mark L10A (10Hz)
Group Interval:	110 ft.
Pattern:	12 over 110 ft.
Coverage:	3000%
Spread: Trace:	1------------ 60 X 61 ------------120
	6655'' 165' 165' 6655'

Line EGI-004-00 was processed by Sterling Seismic Services, Ltd., in January, 2001.

Task 6, EarthSat's (1997) Lineaments

EarthSat (1997) interpreted Landsat images for all of the Appalachian Plateau of NYS, including the study area. The lineaments identified on the Landsat images were imported into the computer applications used by the UB Rock Fracture Group, including Arc/Info and Adobe Illustrator.

Task 7a, Structure Analyses

Jacobi and students (Courtney Lugert, Karen Wehn, Fariha Islam, Rick Mayer, Fernanda Scuderi, and Jon Zybala) used two different methods to collect structural data. During the first field season, Jacobi and associates collected structural data along scanlines. The scanlines were oriented on the outcrops such that the scanline crossed as many fracture sets at high angles as possible. Jacobi and associates collected nine attributes of every fracture that crossed the scanline, including:

1. Distance along the scanline where the fracture intersects
2. Strike and dip of the fracture
3. Exposed length of the fracture
4. Exposed height of the fracture
5. Abutting relationships (with other fractures)
6. Top and basal abutting relationships (primarily abutting some sedimentary unit)
7. Character of fracture trace (e.g., straight, curvy)
8. Decorations on the fracture face
9. Offset along the fracture

Jacobi and graduate students (Lugert and Wehn) used the orientation, character and abutting relationships to sort out the different fracture sets. After separating the fracture sets, they calculated the fracture frequency for each set from the fracture intercepts on the scanline. As most fractures are very steeply dipping (80^{o}+), modified rose diagrams can be used to portray the results. In these rose diagrams, fracture frequency is displayed in the top half of the diagram. Generally, three orders of magnitude are shown on the diagram as successively larger concentric circles, with the inner circle representing 0.1 fractures/m, the middle ring representing 1.0 fracture/m, and the outer ring representing 10 fractures/m. Thus, long petals indicate a relatively high number of fractures, as did the traditional rose diagrams. The advantage of this modified diagram is that it does not promulgate a potential sampling bias in cases where a scanline is parallel to a fracture set. In the traditional rose diagram, the raw number of fractures would be underrepresented for the set that paralleled the scanline.

The lower half of the modified rose diagram is used to indicate other features of the fracture sets, commonly abutting relationships (see Figure 3 [schematic diagram of fracture patterns in study area] and Figure 4 [legend for modified rose diagrams]). In general the longest petals in the lower half indicate the master fracture set; the next longest petals indicate the fracture set ("first abutting") that abuts the master fracture set, but that is itself master to still another fracture set, which is portrayed by even shorter petals ("second abutting"). Complications with this simple scheme arise from inconclusive or apparently contradictory abutting relationships and other factors, as detailed in Figure 4. These complications are indicated by different colored petals on the rose diagrams.

In the second field season, Jacobi and students used an abbreviated method to collect structure data at sites. Jacobi and students identified the fracture sets in the outcrop, and measured the spacing among a minimum of three fractures for each systematic fracture set. They also collected abutting and length/height information. These data were also portrayed on the same modified rose diagrams.

Task 7b, Stratigraphic Analyses

Jacobi and Smith used marker beds along the east side of Seneca Lake to determine anomalous regions of dip that might indicate faults either unexposed between outcrops or faults below the examined sections that resulted in monoclines at the surface.

RESULTS

DETAILED DISCUSSION OF RESULTS OF EACH METHODOLOGY

Task 4 Results: Well Log Analyses

The regional structure contours on the top of the Devonian Onondaga Formation (Figure 5) display a generally southward dip. Prominent structural features include the E-W trending structural high of the Wayne-Dundee Gas Field east of Keuka Lake, and the NW-trending apparent monocline in the western half of the map. The Wayne-Dundee Gas Field structural high is probably a westward, linked segment of the Firtree Anticline, and the NW-striking monocline corresponds spatially with the NW-striking Lawrenceville-Attica lineament (see Jacobi, 2002, and references therein). Both of these features are also evident in the Onondaga structure contour map of Murphy (1981). The stratigraphic offset across the monocline is on the order of 500 ft to 750 ft (152m to 229 m), calculated along regional E-W strike of the Onondaga. These numbers are less than the offset of the Devonian surface units, calculated from Bradley et al.'s (1941) structure contour map, but are of the same order as the stratigraphic offset of the Onondaga inferred from Murphy's (1981) structure contour map. Additional structure on the regional map occurs in northeasternmost Steuben County west of the Keuka Lake, where an E-trending structural low occurs above the Trenton/Black River Glodes Corners Road Field.

The more detailed view of the structure contours for the Onondaga is shown in Figure 6. The Wayne-Dundee Gas Field in the east-central part of the map is again prominent. The sparsity of well control between Seneca and Cayuga lakes results in fairly crude contours that do not allow definitive interpretation. However, the structural high in the northeast corner of Hector Township is most likely a manifestation of the E-trending Firtree Anticline. East- to ENE-trending grabens associated with the eastward extension of the Trenton/Black River Glodes Corners Road Field are not apparent in the sparse data set. However, the structural low in Lodi Township (and northernmost Hector Township) could be recontoured with an E-W trend that could reflect deeper structure of the Trenton/Black River grabens. An apparent NW-striking high at the southern end of Seneca Lake is also evident in Murphy's (1981) Onondaga structure contour map. He suggested that a right lateral strike-slip fault (or tear fault) in the Silurian and higher units bordered the western margin of the high. In this scenario an oblique slip with a down-on-the-west component is probable. However, both this structural high and the structural high to the southeast observed on the regional map (Figure 5) could be an effect of sparse well logs on an E-striking anticline that was recognized in the surface rocks by Bradley et al. (1941).

The regional structure contours on the top of the Silurian Irondequoit Formation (which is a distinctive well log marker below the Silurian salt section) are shown on Figure 7 and the more detailed view in Figure 8. The regional map (Figure 7) does not show as strong a trend for the Glodes Corners Road Field as the Onondaga structure contours (Figure 5). This lack of apparent major structure suggests that the Onondaga structures that appeared to be localized along the Trenton/Black River graben, were actually the result of salt tectonics, possibly localized by motion on the deeper Glodes Corners Road Field faults. The regional structure contours of the Silurian Irondequoit Formation differ from the Onondaga in another important point. The contours of the Silurian Irondequoit Formation strike fairly straight E-W across the western part of the map, implying that the NW-trending structure of the Attica-Lawrenceville lineament evident in the Onondaga structure contour map does not appear in the Irondequoit map. Thus, the major effect of the Attic/Lawrenceville lineament is most likely localized in the salt and overlying layers (see discussion below concerning isopachs).

Both the regional and detailed maps also indicate that the anticline of the Wayne-Dundee Gas Field east of Keuka Lake is restricted primarily to units above the salt, as the Irondequoit structure contour displays only a very subtle feature in this area. On the detailed figure (Figure 8), the structural lows east of Keuka Lake in Barrington Township and the (as contoured) larger low east of Seneca Lake in southern Lodi Township both are assumed to reflect effects the deeper structure of the Trenton/Black River grabens. Murphy's (1981) structure contour map on the top of the Silurian Lockport (a unit below the salt, as is the Irondequoit), does not indicate any structure in this area, but his well control was so sparse that no definitive conclusions can be drawn from the lack of structure.

The regional structure contours on the top of the Ordovician Trenton Group are shown on Figure 9 and the more detailed view in Figure 10. The regional map (Figure 9) shows the structural lows associated with the Glodes Corners Road Field (west of Keuka Lake), and the detailed view (Figure 10) displays a similar structural low on-strike east of Keuka Lake in Barrington Township, as well as another local low east of Seneca Lake in southern Lodi Township. Localized structural highs, perhaps associated with the flanks of the Trenton/Black River grabens, are observed between Seneca and Cayuga lakes in Hector and Enfield townships. A distinctive high east of northern Keuka Lake in Milo Township might be related to a NE-striking fault that

Murphy (1981) hypothesiszed extended northeast from the eastern side of Keuka Lake. Note that the Trenton structure contour map shows no structural effect for the Wayne-Dundee Gas Field east of Keuka Lake.

The regional structure contours on the top of the Ordovician Black River Group are shown on Figure 11 and the more detailed view on Figure 12. The regional map (Figure 11) shows the same structural elements as the Trenton structural contour map (compare Figures 9 and 11). Structural lows are associated with the Glodes Corners Road Field (west of Keuka Lake), as well as with a similar structural low on-strike east of Keuka Lake in Barrington Township (Figure 12) and another local low east of Seneca Lake in southern Lodi Township. The same localized structural highs as those in the Trenton data occur in the Black River data: east of northern Keuka Lake in Milo Township and between Seneca and Cayuga lakes in Hector and Enfield townships.

The regional isopach map for the Onondaga-“F” Salt interval is shown on Figure 13 and the more detailed view on Figure 14. The prominent thinning of the interval in northern Steuben County (Figure 13) reflects the NW-striking monocline (down-to-the-southwest along the Lawrenceville-Attica lineament) over the generally unaffected Irondequoit. On the detailed map (Figure 14), the localized anomalously thin zone in southernmost Lodi Township and the anomalously thick zone to the north in Lodi Township are probably related to drape folds over structure at the top of the salt because the anomalously thin zone occurs on the flank of the Firtree Anticline, and the thick zone occurs on an unnamed structural low (syncline). This syncline may be localized by the deep structure of the Trenton/Black River.

Isopach maps for the “E” and “F” salt intervals are shown on Figures 15 to 20. The isopach maps for the “F” salt (Figures 15 and 16) show an anomalously thick section in the core of the Firtree Anticline (on the west side of Cayuga Lake and a similar anomalously thick zone in part of the Wayne-Dundee Gas Field (NE corner of Tyrone Township). Because of the sparsity of well logs west of the “bulls-eye” west of Cayuga Lake, the “bulls-eye” could be recontoured as an approximately E-striking anomalously thick zone along the core of the Firtree Anticline. Another “bulls-eye” (an anomalously thick zone) located in Barrington Township on the east side of Keuka Lake occurs at a minor anticline on the southern flank of the Severne Point Anticline. That the salt is thicker in the cores of anticlines is consistent with the general model that the thrust ramps rise from the decollement in the Silurian salt, and that the salt is involved in the associated core on the western side of Cayuga Lake. The constant thickness beneath the Firtree Anticline suggests that the thrust ramp of the Firtree Anticline only involves the upper salt—the “F” Salt. However, slightly anomalous “E” Salt thicknesses are evident in both the Wayne-Dundee Gas Field and the “bulls-eye” in Barrington Township, although certainly not as prominent as in the “F” Salt. That the “E” Salt shows less thickness variation is consistent with the view that most of the decollement thrusting rode in the upper major salt in this area.

The regional isopach map for the “F” Salt displays most of the same features as the regional isopach map for the “E” and “F” salts interval (compare figures 15 and 19/20). The general pattern where the “F” Salt thickens (Figure 15) also matches the general isopach map for all salt intervals (combined) that was constructed by Murphy (1981). Both maps show that the thickest zone of salt, which occurs south of Seneca and Keuka lakes, has a NW-striking western boundary, and that a narrow zone of thick salt extends northwest along this boundary in central Steuben County. This boundary apparently accounts for the NW-striking monocline, observed in the Onondaga structure contour map, that is draped down-on-the-southwest across the thinning salt section (Jacobi, 2002; Figure 5). Jacobi (2002) suggested that the Lawrenceville-Attica lineament marks this monocline. The depositional edge of the main salt basin may have been controlled by deep faults along the Lawrenceville-Attica lineament, based on geopotential field anomalies concordant with both the Lawrenceville-Attica lineament and the NW-striking salt wedge, and the salt wedge may have in turn controlled the location of later faulting (Jacobi, 2002). Although structure contours on the top of the Irondequoit (which lies well below the salt section) do not indicate any significant effect of the hypothesized faults that, in this scenario, controlled deposition of the salt, the sparsity of well data combined with possible basin inversion may hide fault effects in the Irondequoit. Alternatively, the present NW-strike of the salt thickening may be due not to deposition but largely to vertical loading and consequent salt-wedge migration, as in the offshore Gulf Coast region.

The regional isopach map for the Onondaga-Irondequoit interval is shown on Figure 21 and the more detailed view on Figure 22. Both the Glodes Corners Road Field and the Muck Farm Field display a thinned section (west side of Keuka Lake in the northeastern corner of Steuben County). The thinned section reflects the contour pattern of the “F” Salt in the same region (compare Figure 15 with 21). The anomalous “bulls-eye” east of Keuka Lake (Figure 22) is also consistent with the thickened salt section in this locality (Figure 20). Only minor thickening occurs over the Wayne-Dundee Gas Field and the Firtree Anticline, compared to the major salt thickness Steuben increases observed in these folds. The lack of major thickening over the salt anticlines is surprising, and indicates that the units above the salt must thin significantly over the salt anticlines. For example, the Onondaga-Irondequoit interval thickens ~30 ft (9 m) in the region of the Firtree Anticline, whereas the "F" Salt alone thickens 140 ft (43 m) in the same area. Thus, the section above the salt must thin by more than 100 ft (30 m) over the anticline.

The regional isopach map for the Irondequoit-Trenton interval is shown on Figure 23 and the more detailed view on Figure 24. Both the Glodes Corners Road Field and especially the Muck Farm Field display a thickened section (west side of Keuka Lake in the northeastern corner of Steuben County). These anomalously thickened sections are consistent with grabens in the Trenton that do not extend significantly up to the Irondequoit. The anomalous "bulls-eye" east of Keuka Lake (Figure 24) probably results from a similar structure. Subtle thicker sections in the region occur between Seneca and Cayuga lakes; the thicker section in southern Lodi results from a structure similar to the Glodes Corners Road Field, and the anomalously thicker section west of southern Cayuga Lake may result from a similar feature. Similar features are observed in the isopach maps of the Onondaga to Trenton interval (Figures 25 and 26).

The regional isopach map for the Trenton-Black River interval is shown on Figure 27 and the more detailed view on Figure 28. The most prominent feature is an anomalously thick section that trends nominally NNE through the eastern finger of Keuka Lake. This trend is approximately coincident with Murphy's (1981) Keuka Lake Fault and a major aeromagnetic gradient that lies along the east side of Keuka Lake. Thus, this NNE-trending zone of thicker Trenton may be a syndepositional effect of Trenton-aged faulting that follows the major magnetic anomaly. The Glodes Corners Road Field shows a slight thinning (Figure 27), as would be expected from the dissolution/dolomitization and collapse in the graben. The thinning in southern Lodi Township is the result of a similar effect.

<u>Task 5 Results: Seismic Reflection Profiles</u>

The subcontractor, Stuart Loewenstein (President, Quest Energy) and Jacobi identified reflectors and faults on four reprocessed seismic lines that trend generally N-S (for locations, see Figure 1). Each of the lines displays Trenton/Black River faults associated with grabens. Seismic line 1 (Line EGI-004-00) is located west of Keuka Lake, and crosses over both the Glodes Corners Road Field and the Muck Farm Field. This seismic line is the standard for Trenton/Black River faults in NYS since the seismic line clearly displays the target structures in both the Glodes Corners Road Field and the Muck Farm Field. Figure 29 is an interpretation of part of Line EGI-

004-00 across the Glodes Corners Road Field. Faulting and grabens in the Trenton/Black River are evident; most of these faults do not significantly offset the underlying Knox Unconformity. This restriction of the Trenton/Black River faults to the section above the Knox suggests that these observed fault offsets are generally not a direct result of deep tectonic fault motion; rather, the fault offsets are primarily a manifestation of solution collapse grabens caused by carbonate dissolution and dolomitization. However, the vertical alignment of isolated fault segments from the Trenton to the basal Cambrian (?) reflectors (fault "#1" on Figure 29) may demand a more complicated explanation, if indeed these offsets are real and the alignment is not fortuitous. Reflectors between the fault segments of fault #1 are not offset (to the limits of seismic detection), but the top of the Trenton, top of the Black River, base of the Knox Unconformity and the basal Cambrian (?) appear to be offset. We suggest that a FID extending upsection from the fault in the Cambrian provided a dissolution pathway for limestones below the Knox Unconformity. A dissolution sag (similar to the Black River) with observable offset resulted, but by the end of Knox Unconformity time, differential deposition and corrasion had effectively reduced the structural relief to an unobservable minimum. A similar scenario is envisioned for a straight reflector with no observable offset that passes between the southern offsets of Trenton and Black River reflectors. Such a model suggests that mutiple times of dissolution occured in the Ordovician—at least three. The discontinuous "master" fault #1 extends down through the basal Cambrian(?) to intra-Grenvillian dipping reflectors. As with other Trenton/Black River faults, it appears that Grenvillian structure controlled the position of the Phanerozoic faulting.

The intra-Grenvillian dipping reflectors extend upward to positive relief on the basal Cambrian (?) reflector; this relief is interpreted to mark cuestas (hogbacks) of the intra-Grenvillian units at basal Cambrian (?) time. Both the basal Cambrian (?) reflector and an underlying weaker discontinuous reflector in the south display northward onlap of the hogbacks. Unlike intra-Grenvillian faults both to the east of Seneca Lake (this report), and to the west in Allegnay County (e.g., Jacobi and Fountain, 2002), these dipping intra-Grenvillian reflectors do not appear to have been growth faults during Iapetan rift development.

Figure 30 is an interpretation of part of Line EGI-004-00 across the Muck Farms Field. Faulting and grabens in the Trenton/Black River are also evident here. The "master" (northern) fault has a listric, growth fault geometry; it may not directly connect to a normal fault that offsets the Precambrian/Cambrian contact directly below the listric fault. This section exhibits a small southward-directed thrust that affects the Onondaga reflector. Because the thrust is located directly above the southern Trenton/Black River fault, it may be that the thrust developed in this location because upward migrating fractures from the Trenton/Black River fault provided a weak zone where a thrust ramp could develop, as proposed for Alleghanian thrusts in Pennsylvania by Scanlin and Engelder (in press).

Seismic Line 2 (SCNYRS1C, Figure 31) is located between Seneca and Cayuga lakes (Figure 1). Only three (15%) of the 19 deep faults on this line extend significantly above the Trenton reflector Thus, the last significant motion on most of the faults was in the Taconic Orogeny. A few of the faults appear to have been significantly active only during Iapetan opening times, since these faults affect the Precambrian/Cambrian contact, but are not recognized upsection (faults #12 and #13, Figure 31). Several of the faults are growth faults, such as #9, #10, and #14, with the largest offset on the Precambrian contact (Figure 31, Table 1). These faults with growth fault geometries, and the faults that only affect the Precambrian/Cambrian contact both suggest that most of these faults originated during the rifting stage of Iapetan ocean development (Jacobi, 2002). Grabens in the Trenton/Black River occur at faults #3, between the cluster of faults #4-#8, #14 and #18. In contrast to the Trenton-ages faults, fault #3 extends through the entire section, and may reach the surface. The variable offset upsection on fault #3 suggests multiple fault reactivations (and basin inversion) or a complex strike slip/scissoring fault system. Faults immediately to the south (faults #6 and #7) form grabens both in the Trenton/Black River section as well as higher in section—up to at least the Silurian salt section. This packet of faults, #3, #6, and #7, are the only faults on the seismic line that extend significantly upsection from the Trenton reflector, and the packet is located in the region of Valois where ENE-striking FIDs and lineaments occur (see Task 6 section). The E-striking Firtree anticline, and associated thrusts (S1-S5), are also imaged; these faults occur where E-striking FIDs and lineaments are located. The seismic character of fault #14 suggests that the trend of this fault may be close to the trend of the seismic line. Thus, although the fault appears to extend only as high as the Black River reflector (and perhaps the Trenton reflector), the fault could extend much higher out of the line-of-section. Such a possibility is consistent with the 1) N-striking Landsat lineaments (EarthSat, 1997), and 2) FIDs in the area of this fault, and 3) fault proposed by Bradley et al (1941).

Seismic line 3 (SCNYRS6, Figure 32) is located east of Cayuga Lake (Figure 1), and exhibits five faults that do not extend above the Trenton/Black River section. Small grabens in the Trenton/Black River are associated with some of these faults (e.g., those at “A” in Figure 3.5-3).

Like the faults imaged on Line 2, the growth fault geometries of several of the faults that offset the Precambrian contact suggest that these faults developed during Iapetan initial rifting and breakup, and were later reactivated during Taconic times.

Seismic line 4 (SCNYRS7, Figure 33) is located east of Line 3 (Figure 1). This seismic reflection line displays a prominent graben in the Trenton/Black River section, and the northern bounding fault of the graben extends upsection through at least the Tully reflector.

Task 6 Results: EarthSat's (1997) Landsat Lineaments

East of Keuka Lake, the Landsat lineaments identified by EarthSat (1997) have three general trends: northerly-striking (including NNE and NNW-striking), E-striking and ENE-striking (Figure 34). The NNE-striking lineaments along the eastern side of Keuka Lake are coincident with a major aeromagnetic gradient (Figure 34), indicating that the lineaments are probably related to major faults in the Precambrian basement. These lineaments also correspond to the Keuka Lake Fault that was recognized in well log data (Murphy, 1981; this study). The Keuka Lake Fault has a down-on-the-west stratigraphic offset (Murphy, 1981). Additional N-striking lineaments occur east of Seneca Lake; the N-striking lineament closest to Seneca Lake is located near the trace of an inferred fault (Bradley et al., 1941). Bradley et al.'s (1941) mapping suggests this fault is a tear fault that separates different portions of the E-striking Firtree Anticline (Figure 2). A more current views on tear faults might suggest that the fault actually marks a lateral ramp that separates thrust segments. The N-striking packet of lineaments east of Seneca Lake (including the lineament discussed above) occur where an ENE-striking positive aeromagnetic anomaly is truncated. Thus, these lineaments may be related to faults in the Precambrian basement that, when reactivated, guided the location the lateral ramp/"tear" faults.

On the west side of Seneca Lake, NNW-striking lineaments coincide with the Seneca Lake Fault, which Murphy (1981) suggested is a right-lateral tear fault. In contrast, Bradley et al., (1941) did not recognize a fault along this trend in surface stratigraphy and structure.

Between Seneca and Cayuga lakes are packets of ENE- and E-striking lineaments (Figure 34). The most promient set of ENE-striking lineaments extend from the southern tip of Keuka Lake, across the mid-section of Seneca Lake, and continues east-northeastward across Cauyga Lake. This set of lineaments is parallel to areomagnetic anomalies along much of its length, but the lineaments are displaced to the north of the aeromagnetic gradients. If these surface lineaments are related to the aeromagnetic gradients, then this displacement could indicate that the faults dip south between the aeromagnetic source and the surface. The ENE-striking packet of lineaments crosses seismic line #2 where the only group of faults (#3, #6, and #7) extend well above the Trenton reflector

The ENE-striking aeromagnetic high between Seneca and Cayuga lakes also is coincident with a less prominent set of ENE-striking Landsat lineaments along the southeast side of the aeromagnetic high. These lineaments may also indicate ENE-striking faults that intersect Precambrian basment and affect the Trenton/Black River section.

A packet of E-striking lineaments that passes across the southern portion of Cayuga Lake generally trends obliquely to the ENE-striking aeromagnetic anomaly (except for the region adjacent to Cayuga Lake). This oblique trend suggest that the lineaments are not related to faults in the Precambrian basement. Indeed, these lineaments are coincident with the mapped Firtree Anticline that affects surface rocks. As sesimc line 2 shows (Figure 31), the Firtree Anticline and associated thrusts are not rooted in Precambrian basement; rather, they sole out in the Silurian salt section.

Task 7a Results: Structure

Fracture Analyses Subtask. In the year 2000 field season Jacobi and associates measured nine characteristics of over 2300 fractures at 149 sites in the Seneca Lake transect; in the year 2001 field season they measured over 600 fractures at 61 sites. For this project, most of the fractures that Jacobi and associates measured were located on or near the eastern shore of Seneca Lake (Figure 35a). In Figure 35a, the fracture frequency of the systematic fracture sets and the intersection relationships among the fracture sets are displayed on modified rose diagrams. The sites were projected onto a N-S transect (Figure 35b) in order to compare fracture frequency variations of E- and ENE-striking fractures along the transect (Figure 35c).

Jacobi and associates found that the eastern shore of Seneca Lake can be divided into structural domains based on differences in fracture attributes. Although most regions share most fracture sets, changes in the fracture length, frequency and abutting characteristics define the different structural domains. The most common fracture sets include northerly- (“cross-strike”) and easterly- (“strike-parallel”) striking fracture sets with fairly wide spacings (for example, see Figure 36; for location, see Figure 37). However, each of the fracture sets also occurs as FIDs and some fractures display later motion (Figures 38-40). These variances, plus the abutting relationships, defined the structural domains discussed below.

Southern Structural Domain. In the area south of Hector (Figure 35c), the master fracture set generally strikes NNW (although some sites exhibit other master fractures, primarily N- to NNE-striking). Similarly, the NNW- and N-striking fractures typically form the FIDs in this structural domain. Examples of the master NNW-striking fractures are sites 5 and 71 (Figure 43), RDJ 73A (Figure 44), 19A (Figure 46), and 33 (Figure 47). (The locations of enlargement figures are indexed in Figure 41, and are numbered 42 to 53 from south to north.) In all of these examples, the fracture spacing of NNW-striking fractures is on the order of 1 fracture/meter. However, both the NNW-striking and N-striking fractures form narrow FIDs (N-striking at sites 17 [Figure 43] and 74 A+B [Figure 44], and NNW-striking at site 18 [Figure 43]). Rarely do other fracture sets form FIDs in this structural domain.

The NNW-striking master fractures are regarded as the Set Ib cross-strike fractures (e.g., Engelder and Geiser, 1980). Researchers (e.g., Engelder and Geiser, 1980; Zhao and Jacobi, 1997) suggested that this fracture set developed as a regional response to a far-field stress related to Alleghanian collisional tectonics. Although the cross-strike fractures typically are thought to be regularly spaced, Jacobi and Fountain (1996) identified cross-strike FIDs to the west in Allegany County, NYS. Jacobi and Fountain (1996) and Jacobi (2002) suggested that these FIDs indicate the location of cross-strike discontinuities (CSDs).

The relationship of the N-striking fractures to the NNW-striking fractures is complex. In the southern structural domain, the N-striking fractures either abut, or mutually intersect, or mutually abut the NNW-striking set. Rarely do the NNW-striking fractures abut the N-striking fractures. For example, at sites 1B and 4 (Figure 42), and RDJ 73A (Figure 44), N-striking fractures abut the NNW-striking set. However, at sites 3 (Figure 43), 74 A+B (Figure 44), 19 and 20 (Figure 46), N-striking and NNW-striking fractures are mutually intersecting. The N-striking fracture spacing is generally wider than (or equal to) the NNW-striking set. For example, at site 4 (Figure 42) the N-striking fractures are twice as widely-spaced as the NNW-striking set. In the Seneca Lake area, both twist hackles and fringe cracks suggest that the NNW-striking fractures developed first, followed by a clockwise stress rotation, during which the N-striking fractures developed (Younes and Engelder, 1999). Younes and Engelder's (1999) data agree with field observations made during this research project, and with observations made to the west in

Allegany County (Jacobi and Fountain, 1996; Zhao and Jacobi, 1997) for the relatively widely-spaced fractures. However, in both this detailed study area and in Allegany County N-striking FIDs occur that are master to the NNW-striking fractures. Thus, at least some N-striking FID development (and associated faulting) predated the NNW-striking fracture propagation.

East- and ENE-striking fracture sets occur in the structural domain, but are not the dominant fracture sets at most outcrops, and in several outcrops, the only systematic fracture set is northerly striking. Examples of the relatively widely-spaced fractures can be found in Figure 44, where the northerly striking fractures at each site have a higher frequency than the ENE- and WNW-striking fractures. At both RDJ 74 and RDJ 74A+B, the fracture frequency of the northerly-striking fracture sets is about an order of magnitude greater than that of the ENE-striking set. Similarly, at site 1B in Figure 42, the northerly-striking fractures have nearly an order of magnitude greater frequency that the easterly striking fractures.

The E-and ENE-striking fractures have been referred to as the strike-parallel (fold-parallel) fracture set (e.g., Engelder and Geiser, 1980). Typically, these fractures were thought to abut the NNW-striking set, and were therefore thought to be younger than the NNW-striking set (e.g., Engelder and Geiser, 1980). Origins proposed for these fractures include fracture development during uplift and denudation when "inherited Alleghanian stress" was released (e.g., Engelder, 1985). However, in Allegany County Jacobi and Fountain (1996) found that strike-parallel fractures can occur in FIDs that predate the cross-strike set; i.e., the strike-parallel fractures are master to (and older than) the cross-strike fractures in the FID. These FIDs appear to mark strike-parallel faults in other areas where sufficient data exist (e.g., Jacobi, 2002). Recently, Engelder et al. (2001) suggested that in the Finger Lakes region, ENE-striking fractures are faulted against northerly-striking fractures and therefore predate the Alleghanian cross-strike fractures. Thus, the ENE-striking fractures may be of late Acadian age (Engelder et al., 2001). This older age is consistent with Jacobi and Fountain's (1996) observations in Allegany County.

The significance of the orientation of the northerly-striking FIDs and master fractures typical of this structural domain is that the northerly trend matches the trend and general location of the Landsat lineaments of EarthSat (1997). Further, Bradley et al (1941) suggested that a N-striking fault existed in this same general area, based on stratigraphy. This fault is probably related to faults in the Precambrian, since the EarthSat (1997) lineaments truncate an ENE-striking aeromagnetic high. Thus, although this CSD may mark a lateral ramp ("tear" fault) for the ENE-

Alleghanian Firtree Anticline, the lateral ramp may have been guided by a deeper structure that reached Precambrian basement. Such structures may well affect the Trenton/Black River section.

Hector Structural Domain. The Hector Structural Domain is located in the region of Hector (Figure 35c), and is distinguished from the Southern Structural Domain by the spacing and abutting relationships of the E-striking fractures. To the south and north of Hector, the E-striking fractures generally are widely spaced and abut the northerly-striking fractures. In contrast, in the Hector structural domain, the E-striking fractures form FIDs with a fracture frequency as high as 30 fractures/meter (Figure 35c). Near Seneca Lake, the E-striking and northerly-striking fractures commonly mutually intersect, but to the east and north, the E-striking FIDs generally abut the NNW-striking fractures. The significance of the Hector Structural Domain is that this domain, characterized by E-striking fractures and FIDs, is coincident with E-striking Landsat lineaments (EarthSat, 1997) as well as the E-striking Firtree Anticline, which was mapped at the surface (e.g., Bradley et al., 1941, and see Figure 2).

Valois Structural Domain. The Valois Structural Domain is located in the region of Valois (Figure 35c), and is distinguished from the Southern and Hector structural domains by the spacing and abutting relationships of the ENE-striking fractures. To the south of Valois, the ENE-striking fractures are generally widely spaced and abut the northerly-striking fractures. In contrast, in the Valois structural domain, the ENE-striking fractures form FIDs with a fracture frequency in excess of 30 fractures/meter (Figure 35c). East-striking fractures also form FIDs in some of the same areas as the ENE-striking fractures (e.g., sites 8 and 9, Figure 48). In this domain the ENE-striking fractures commonly abut the northerly-striking fractures. For example, at site CML 3 (Figure 49) ENE-striking fractures abut NNW-striking fractures and at site 10 (Figure 48), the ENE-striking fractures both abut and intersect with the N-striking fractures. The Valois Structural Domain with prominent ENE-striking fractures and FIDs is coincident with ENE-striking Landsat lineaments (EarthSat, 1997) and with faults imaged on seismic reflection profiles that extend from Precambrian basement through most (if not all) of the Phanerozoic section.

Northern Structural Domain. The Northern Structural Domain is located north of Valois (Figure 35c), and consists of a conglomeration of sub-domains with varying ENE- and E-striking fracture spacing. For four kilometers immediately north of the Valois Structural Domain, wide spacing characterizes both the ENE- striking and the E-striking fracture sets, and in fact, the

Northern Structural Domain generally has wide E-striking fracture spacing similar to the Southern Structural Domain. From four kilometers northward, the domain is typified by variable ENE-striking fracture spacing, varying from background values of < 1 fracture/meter to 8+ fractures/meter (Figure 35c). In contrast, in this same region (four kilometers northward), the E-striking fractures have a uniformly low frequency of < 1.5 fracture/meter (with many values approaching zero), except in the area about 4 to 5 kilometers north of the Valois Structural Domain. There the average fracture spacing is about 7 fractures/meter (Figure 35c). The abutting relationships among the northerly and easterly trending fracture sets are as complicated (and similar to) those to the south. Although the NNW-striking fracture set can be observed as master to the ENE-striking set (e.g., sites RDJ-47 in Figure 50 and RDJ-54 and RDJ-59 in Figure 53), other relationships are also common. For example, the ENE-striking set and the NNW-striking set mutually abut (e.g., RDJ-58 in Figure 53), or mutually intersect (e.g., site 67 in Figure 51), or the ENE-striking set can be master to NNW-striking set (e.g., RDJ-51 in Figure 53). Similar situations exist for E-striking fracture intersections with NNW-striking fractures, and for ENE and E-striking fractures with N-striking fractures.

The N-striking set is not ubiquitous; rather it is found only in certain zones, some of which are FIDs (e.g., sites RDJ 22 in Figure 52, RDJ 49 and RDJ 55 in Figure 53). At several of the sites, the NNW- and N-striking fractures exhibited strike slip motion, displacing the ENE-striking fractures a few cm (e.g., sites RDJ 25 and RDJ 31, Figure 51). The N-striking fractures generally exhibit left-lateral strike slip and the NNW-striking fractures exhibit right lateral slip (e.g., sites RDJ 30A and 66, Figure 51). The most prominent NNW-striking fractures that display offset are at site 62 (Figure 51), where hydrocarbon and water seeps along observeable NNW-striking faults occur in a road cut. It is thus probable that in this area, northerly-striking faults, as well as easterly-striking faults occur at depth. The fact that the Alleghanian cross-strike fractures offset the ENE-striking fractures suggested to Engelder et al. (2001) that the ENE-striking fractures predate the Alleghanian fractures, and may be late Acadian in age.

Surface Faults Subtask.

Previously Proposed Faults Based on Surface Data. Bradley et al., (1941) suggested that three ENE-striking high angle faults occur between Valois and Ovid (Figure 2). The northernmost fault was identified on the basis of dipping beds ("drag" folding) and apparent stratigraphic offset. However, Jacobi and associates found that the exposures reveal a "pop-up" with no discernable stratigraphic offset between points on either side of the structure. Bradley et al. (1941) extended this proposed fault northeastward to Mill Creek where they observed dipping beds. However, the only structural feature here is also a pop-up. Thus, although the pop-ups may indicate a fault lower in the section (or in adjacent covered intervals), the surface geology does not demand a fault here. Bradley et al. (1941) stated that the middle ENE-striking fault is exposed in a small stream, but inspection of the stream by Jacobi and associates did not reveal any structural evidence for a fault.

The southern ENE-striking fault that Bradley et al. (1941) proposed was based on a locally excessively thick section of Cashaqua shale, which they hypothesized implied a tectonic (fault) thickening. However, neither Bradley et al. (1941) nor Jacobi and associates found structural evidence for the fault. Thus, there is no direct structural evidence for any of the ENE-striking faults portrayed in Bradley et al. (1941), and subsequently displayed on the NYS Geological Map (Fisher, 1980).

Bradley et al. (1941) inferred a N-striking fault along the eastern side of the southern part of Seneca Lake, based on stratigraphic relations. The N-striking FIDs that are common in the Southwern Structural Domain, and the N-striking lineaments support the fault inference. The presence of FIDs west of the inferred location may indicate that the fault is actually a series of smaller-offset faults. North-striking FIDs as far north as Ovid, as well as structure contour offsets in Bradley et al.'s data, suggest that the fault system should be extended north of Bradley et al.'s (1941) original estimate to at least Ovid. Stream lineaments north of Ovid (such as the N-S stream segments north of Box 53 in Figure 51) also suggest that the fault system may extend north of Ovid in the region of these lineaments.

Faults Discovered During This Investigation. Jacobi and associates found NE-striking, northwest-directed thrust faults in the far northern part of the study area near Ovid (Figures 54 and 55), where the Tully exhibits significant local northerly dips (see following section). The thrusts display minor offset (each on the order of a few cm or less). These thrusts indicate that the northward dipping limb of the Tully (see following section) is a fault-modified structure. The thrusts are consistent with a rollover fold/blind ramping thrust model for the locally northerly dip of the Tully.

The NE-strike is surprising, since the general easterly-striking structural trends in the region to the south strike either east or east-northeast. Thus, the NE-striking faults (and NE-striking FIDs and fracture set in the same area) may not be related to the ENE-striking strike-parallel fractures. Because none of the prominent magnetic gradients in the study area strikes 045^o, the orientation and location of the NE-striking faults, FIDs, and master fractures are probably not be controlled by significant fault systems in the Precambrian basement (unlike the ENE-striking FIDs to the south). The 045^o trend does agree, however, with the strike of bedding measured by Bradley et al (1941) in the same area. Possible explanations for the anomalous NE-strike of faults, FIDs, fractures, and bedding are that the strike represents:

1. part of a drag fold against a N-striking fault, or
2. part of a larger scale lateral ramp, or
3. an unrecognized NE-striking fault that does not significantly affect Precambrian basement.

None of these suggestions is very satisfying, since there are little data at present to examine and discriminate among the alternatives.

Northwest-striking fractures at some sites in the Highland Road region (Figure 52) exhibit fault motion. The most prominent are at site 62, where NNW-striking faults occur, along which hydrocarbon and water has seeped out of a road cut for the past 20+ years (according to local residents). Northwest-striking FIDs (e.g., site 66, Figure 52) also suggest NW-striking faults in this area.

Task 7b Results: Structure from Stratigraphic Analyses

In the northern part of the detailed study area the Tully Formation crops out, and forms a distinct marker that changes character relatively little compared to the turbidites. In the northernmost part of the study area, the Tully outcrops at distinctly higher elevations in the south than in the north. Because the entire Devonian section exhibits a regionally southward dip, the significantly higher elevations in the south are anomalous. In order to determine whether the anomalous elevations are the result of faulting or folding, and to determine the character and trend of the anomalous dips, Jacobi and Smith ran a survey line (scanline) along the Seneca lakeshore in the northern-most part of the study area (Figure 54). They located the Tully outcrops with respect to the distance along the scanline and then surveyed the elevation of the Tully with respect to the lake level (Figure 55). They also determined the dip of the Tully beds in outcrop with 48 in. (1.2 m) long levels and from elevation differences between the two ends of the outcrops.

The dip of the Tully measured in outcrops is sufficiently high to account for the most of the differences in observed elevation of the Tully (Figure 55). Thus, no major fault offset is necessary to explain the sharp elevation changes in the Tully. However, the dip could be an indication of a hammerhead (rollover) fold associated with a south-dipping (north-directed) ramping Alleghanian thrust. Alternatively, the northward dip is also consistent with a drape fold hypothesis wherein the southern boundary fault of a solution graben in the Trenton or salt section is located in the area. Only in the southernmost part of the cross-section (between sites RDJ-52 and RDJ-59) is the change in elevation higher than that predicted by the measured dips. Thus, in this area, a fault model is possible (Figure 55c). Note that even here, however, a fold is possible (Figure 55d).

The NE-striking FIDs and northwest-directed thrusts in the area of the Tully anomalous dips are consistent with either hypothesis, although the rollover fold/ramping thrust is possibly more compatible with the minor observed thrusts. In either case, the local thrusts do indicate that the fold/northward dip is a fault-modified structure.

DISCUSSION OF RESULTS OF INTEGRATED TECHNIQUES

The integration of Landsat (EarthSat, 1997) lineaments with fracture analyses, sesimic reflection profiles and aeromagnetics can provide a regional structural framework that indicates the regions where detailed Trenton/Black River exploration is warranted. This framework can discriminate between surface effects of deep Trenton/Black River structural features and those related to relatively shallow Alleghanian thrusts/folds. The capability of the integrative methodology is demonstrated in Figure 56. This figure displays an one-to-one correlation between:

1) E-striking FIDs and E-striking lineaments that are in turn coincident with the shallow-structure Firtree Anticline at Hector
2) ENE-striking FIDs and ENE-striking lineaments that are in turn coincident with Trenton/Black River faults that extend significantly above the Trenton reflector near Valois (unlike other Trenton/Black River faults to the south)

North-striking faults inferred from stratigraphic relationships (Bradley et al., 1941) are confirmed not only by N-striking FIDs and lineaments, but also by a fault that is inferred to be nearly tangent to N-S seismic line 2, based on the seismic character of the fault.

In regions where multiple lineament trends occur, by comparing the lineaments to aeromagnetic anomaly trends, the lineaments related to basement faults and deep Trenton/Black River faulting can be differentiated from shallow structures related to thrust ramps off of decollement in the Silurian salt section

Based on the relationships displayed in the Seneca Lake cross section, it is probable that the deep Trenton/Black River structures extend east from Seneca Lake along the general trend of the ENE-striking Landsat lineaments that pass through Valois. The seismic lines to the east confirm that deep Trenton/Black River structures do exist to the east of the Seneca Lake cross-section. North-striking faults may also affect the Trenton/Black River section, and may offset the ENE-trending Trenton/Black River structures. Although the deep wells in the Finger Lakes region are extremely sparse (except for the known Trenton/Black River fields), some of the few wells that do exist outside these fields have Trenton/Black River tops that are consistent with Trenton/Black River grabens in the region.

Relative timing of the development of ENE-striking and E-striking surface fractures can assist in deciphering the related faulting history. Although locally complicated, the general abutting relationships indicate that much of the fracturing associated with the E-striking Firtree Anticline developed after the cross-strike fractures of assumed Alleghanian age. In contrast, the ENE-striking FIDs developed before and peneconteporaneouisly with the cross-strike fractures of assumed Alleghanian age. This report suggests the ENE-striking FIDs are spatially associated with faults in the Trenton/Black River and Precambrian basement (and are presumed to be related). Thus, that the ENE-striking fractures and FIDs developed earlier than the Alleghanian cross-strike fractures indicates that these basement/Trenton/Black River faults were reactivated before the Alleghanian far-field stress developed sufficiently in the present surface rocks to rupture them. Such a time lag is consistent with the belief that the continental stress "carrier" is generally the Precambrian basement. The time lag is also consistent with the possibility that late Acadian adjustments on these basement faults preceeded growth of the Alleghanian cross-strike fractures. In either case, the main point is that these ENE-striking FIDs developed directly in response to deep basement fault reactivations, rather than directly to the far-field stress (as in the case of the cross-strike fractures).

It appears that two different mechanisms may have existed in this region for the development of fractures high in the sedimentary cover section. In the one case, reactivations of deep faults in response to stress loading (and perhaps plate flexure) can result in relatively early fracturing some time, far field stress can directly cause fracture development (e.g., Engelder and Geiser, 1980; Zhao and Jacobi, 1997), but this development can postdate the early fault adjustments. In terms of hydrocarbon migration along fractures, these two different mechanisms can provide quite different timing for potential migration.

For central NYS, the ability to differentiate the early, basement-fault related FIDs and related fractures from the later far-field stress-induced fractures and shallow-structure related fractures allows recognition and tracing of the basement faults. Because it is these basement faults that controlled the location and development of the Trenton/Black River porosity, the methodology of integrated aeromagnetics, lineaments, fracture analyses and limited seismic reflection lines provides a cost effective methodology for recognition of Trenton/Black River targets at the reconnaissance level.

CONCLUSIONS

This report demonstrates the usefulness of an integrative methodology for determining the existence, location, and trend of faults in the Trenton/Black River at the regional or reconnaissance level. Integration of surface structural data, Landsat lineaments, seismic reflection data and sparse well log data allows the general trend of the Trenton/Black River faults to be tracked across the Finger Lakes region. This report documents the existence of Trenton/Black River faults and grabens, observed in N-S seismic lines, far east of the well known Trenton/Black River faults of the Glodes Corners Road and Muck Farm fields. Perhaps just as importantly, however, this report demonstrates that in this region the general trend of the faults can be extrapolated away from the seismic lines because the groundtruthed Landsat lineaments can be discriminated with respect to structure that affects the Trenton/Black River vs. structure that is restricted to the Silurian salt section and higher units.

East-striking FIDs occur in regions of E-striking surface folds, and seismic data indicate thrust-cored anticlines above the Silurian salt layers in the region. Coincident with these structures are E-striking Landsat lineaments (EarthSat, 1997) that cross major aeromagnetic lineaments. In contrast, ENE-striking FIDs occur in regions where seismic data indicate faults of the Trenton/Black River section. Coincident with these structures are ENE-striking Landsat lineaments that parallel major aeromagnetic lineaments (these linear aeromagnetic gradients are assumed indicate faults in the Precambrian basement). Additional differences between the shallow and deep structures are that the E-striking shallow structures are generally younger than the ENE-striking deep structures, as determined from FID abutting relationships. The surface FIDs related to the Trenton/Black River structures may predate the development of Alleghanian cross-strike fractures, and so the timing of fracturing, and fracturing history, is different for the deep and shallow faults.

By using the integrative methodology tested in this research project, it is possible to discriminate deep structural (Trenton/Black River) trends from the structures restricted to the salt and higher sections. It is thus possible to map the general trends of the deep faults away from the seismic lines where they are observed. This report shows that the Trenton/Black River graben structures extend east across much of the Finger Lakes.

REFERENCES

Bahat, D., and Engelder, T., 1984, Surface morphology on cross-fold joints of the Appalachian Plateau, New York and Pennsylvania: Tectonophysics, v. 104, p. 299-313.

Bradley, W. H., Pepper, J. F. and Richardson, G. B., 1941, Geologic structure and occurrence of gas in part of southwestern New York: United States Geological Survey, Bulletin 899, 93 pp.

EarthSat (Earth Satellite Corporation), 1997, Remote sensing and fracture analysis for petroleum exploration of Ordovician to Devonian fractures reservoirs in New York State: *New York State Energy Research and Development Authority (Albany, New York), 35p.*

Engelder, T., 1982, Is there a genetic relationship between selected regional joints and contemporary stress within the lithosphere of North America?: Tectonics, v. 1, p. 161-177.

Engelder, T., 1985, Loading paths to joint propagation during a tectonic cycle: an example from the Appalachian Plateau, U.S.A.: *Journal of Structural Geology, 7, p. 459-476*.

Engelder, T., and Geiser, P.A., 1980, On the use of regional Joint sets as trajectories of paleo-stress fields during the development of the Appalachian Plateau, New York: *Journal of Geophysical Research, 85, p. 6319-6341.*

Engelder, Terry, Haith, Benjamin F., and Younes, Amgad, 2001, Horizontal slip along Alleghanian joints of the Appalachian plateau: evidence showing that mild penetrative strain does little to change the pristine appearance of early joints: Tectonophysics, v. 336, p.31-41.

Fisher, D. W., 1980, Bedrock geology of the central Mohawk Valley: New York State Museum Map & Chart No. 33, 44 p., 1 map.

Fountain, J.C., and Jacobi, R. D., 2000, Detection of buried faults and fractures using soil gas analyses: *Environmental and Engineering Geosciences, 6, p. 201-208.*

Jacobi, Robert D., 2002, Basement faults and seismicity in the Appalachian Basin of New York State, *in* Neotectonics and Seismicity in the Eastern Great Lakes Basin, R. H. Fakundiny, R. D. Jacobi, and C. F. M. Lewis (eds.): Tectonophysics, v. 353, p.75-113.

Jacobi, Robert and Fountain, John, 1996, Determination of the Seismic Potential of the Clarendon-Linden Fault System in Allegany County, Final Report: Presented 6/10/96 to NYSERDA, 2106 pp. & 31 oversized maps.

Jacobi, Robert D. and Fountain, John C, 2002, The character and reactivation history of the of the southern extension of the seismically active Clarendon-Linden Fault System, western

New York State, *in* Neotectonics and Seismicity in the Eastern Great Lakes Basin, R. H. Fakundiny, R. D. Jacobi, and C. F. M. Lewis (eds.): Tectonophysics, v. 353, p.215-262.

Jacobi, Robert, Fountain, John, and Loewenstein, Stuart 2001a, Demonstration of an exploration technique integrating Earthsat's Landsat lineaments, soil gas anomalies, and fracture intensification domains for the determination of subsurface structure in the Bass Island Trend, New York State, Draft Final Report: presented to NYSERDA (Albany NY) on 2/23/01, 181 p.

Jacobi, R. D., Eastler, T. E., and Xu, J., 2001b, Methodology for remote characterization of fracture systems in enemy bedrock underground facilities: in, Harmon, R., and Ehlen, J., (eds.), The Environmental Legacy of Military Operations: *Geological Society of America Engineering Geology Division, v. 14, p. 27-60.*

Jacobi, Robert D., Fountain, John C., Lugert, Courtney M., Wehn, Karen S., Nelson, Travis, Budney, Lucas, and Zybala, Jon G., 2002a, Fracture Intensification Domains, fracture flow, and Trenton-Black River faults in the Finger Lakes region, NYS: Geological Society of America, Abstracts with programs, v. 34, n. 1, p. A-11.

Jacobi, Robert D., Fountain, John C., Nelson, Travis, and Lugert, Courtney M., 2002b, Reactivated Precambrian faults in the Appalachian Basin of NYS: Geological Society of America, Abstracts with programs, v. 34, n. 6, p. 79.

Jacoby, C. H., and Dellwig, L. F., 1974, Appalachian foreland thrusting in Salina salt, Watkins Glen, New York: in Coogan, A.H., ed. Fourth Symposium on Salt: Northern Ohio Geological Society, p. 227-223.

Lugert, Courtney M., Jacobi, Robert D., When, Karen, S., and Fountain, John, 2001, Tracing deep structure: Fractures analysis in the Finger Lakes region of the Appalachian Plateau, NYS: Geological Society of America, Annual Meeting Program, v. 33, n. 6, A-394.

Lugert, Courtney M., Jacobi, Robert D., Wehn, Karen S., Fountain, John C., and Zybala, Jon G., 2002, Coincidence of fracture intensification domains with Trenton-Black River faulting in the Finger Lakes region, New York State: Part 1, Seneca Lake: Geological Society of America., Abstracts with programs, v. 34, n. 1, p. A-3.

Murphy, P. J., 1981, Detachment structures in south-central New York: Northeastern Geology, 3, 105-116.

Nickelsen, R. P., and Hough, V. D., 1967, Jointing in the Appalachian Plateau of Pennsylvania: Geological Society of America Bulletin, v. 78, p.609-630.

Parker, J. M., 1942, Regional systematic jointing in slightly deformed sedimentary rocks: Geological Society of America Bulletin, v. 53, p.381-408.

Rickard, Lawrence V., 1973, Stratigraphy and structure of the subsurface Cambrian and Ordovician carbonates of New York: New York State Museum and Science Service, map and chart series number 18, 26 pp. And 19 plates.

Scanlin, Michael A., and Engelder, Terry, in press, The basement versus the no-basement hypotheses for folding within the Appalachian Plateau detachment sheet: American Association of Petroleum Geologists, in press.

Van Tyne, A.M., and Foster, B. T., 1979, Inventory and analysis of the oil and gas resources of Allegheny and Cattaraugus counties, New York: Alfred Oil and Gas Office, Geological Survey, New York State Museum.

Younes, Amgad I., and Engelder, Terry, 1999, Fringe cracks: Key structures for the interpretation of the progressive Alleghanian deformation of the Appalachian plateau: Geological Society of America Bulletin, v. 111, p. 219-239.

Wedel, A. A., 1932, Geologic Structure of the Devonian Strata of South-Central New York: New York State Museum Bulletin, v. 294, 73 p.

Zhao, M., and Jacobi, R. D., 1997, Formation of cross-fold joints in the northern Appalachian Plateau: Journal of Structural Geology, 19, 817-834.

FIGURE CAPTIONS

FIGURE 1. General Location Map of Study Area. Seismic lines interpreted for this report are located randomly within the broad bands in order to preserve the proprietary nature of the seismic interpretation.

FIGURE 2. Structure Contour Map. Contours are on the base of the Devonian Rhinestreet Formation, which crops out in the study area. Contour interval = 25 ft. (7.6 m). After Bradley et al. (1941).

FIGURE 3. Schematic Diagram of Fracture Intersection Patterns. Lower half of rose diagrams illustrate how the accompanying fracture intersection pattern is indicated on modified rose diagrams (see legend for modified rose diagrams in Figure 4).

FIGURE 4. Legend for Modified Rose Diagrams. The top half of the modified rose diagram displays the fracture frequency for each fracture set, and the lower half of the diagram shows the abutting relationships of the fracture sets.

FIGURE 5. Regional Structure Contour Map: Top of Onondaga. Contour interval = 50 ft. (15 m). Red box in center indicates location of Figure 6. Figure 5 has the same location and extent as Figure 1.

FIGURE 6. Detailed Structure Contour Map: Top of Onondaga. Contour interval = 50 ft. (15 m). Red box in center of Figure 5 indicates location of Figure 6.

FIGURE 7. Regional Structure Contour Map: Top of Irondequoit. Contour interval = 50 ft. (15 m). Red box in center indicates location of Figure 8. Figure 7 has the same location and extent as Figure 1.

FIGURE 8. Detailed Structure Contour Map: Top of Irondequoit. Contour interval = 50 ft. (15 m). Red box in center of Figure 7 indicates location of Figure 8.

FIGURE 9. Regional Structure Contour Map: Top of Trenton. Contour interval = 50 ft. (15 m). Red box in center indicates location of Figure 10. Figure 9 has the same location and extent as Figure 1.

FIGURE 10. Detailed Structure Contour Map: Top of Trenton. Contour interval =50 ft. (15 m). Red box in center of Figure 9 indicates location of Figure 10.

FIGURE 11. Regional Structure Contour Map: Top of Black River. Contour interval = 50 ft. (15 m). Red box in center indicates location of Figure 12. Figure 11 has the same location and extent as Figure 1.

FIGURE 12. Detailed Structure Contour Map: Top of Black River. Contour interval = 50 ft. (15 m). Red box in center of Figure 11 indicates location of Figure 12.

FIGURE 26. Detailed Isopach Map: Onondaga to Trenton. Contour interval = 20 ft. (6 m). Red box in center of Figure 25 indicates location of Figure 26.

FIGURE 27. Regional Isopach Map: Trenton to Black River. Contour interval = 20 ft. (6 m). Red box in center indicates location of Figure 28. Figure 27 has the same location and extent as Figure 1.

FIGURE 28. Detailed Isopach Map: Trenton to Black River. Contour interval = 20 ft. (6 m). Red box in center of Figure 27 indicates location of Figure 28.

FIGURE 29. Interpretation of Part of Seismic Line #1 Across the Glodes Corners Road Field. Note the well-imaged grabens in the Trenton/Black River section. Arrows indicate selected paleo-cuestas (hogbacks) onlapped by the basal Cambrian (?) reflector. For location of seismic line, see Figure 1.

FIGURE 30. Interpretation of Part of Seismic Line #1 Across the Muck Farm Field. Note the well-imaged grabens in the Trenton/Black River section. For location of seismic line, see Figure 1.

FIGURE 31. Interpretation of Seismic Line #2. Reflector offsets on the various faults are compiled in Table 1. Note the well-imaged grabens in the Trenton/Black River section (e.g., between faults 5 and 7). Faults S1 to S5 are thrusts ramping up from the salt decollement, and they resulted in the Firtree Anticline that is observable in the Onondaga reflector. For location of seismic line, see Figure 1.

FIGURE 32. Interpretation of Seismic Line #3. A possible Trenton/Black River graben is located at “A”. For location of seismic line, see Figure 1.

FIGURE 33. Interpretation of Seismic Line #4. Note the well-imaged grabens in the Trenton/Black River section. For location of seismic line, see Figure 1.

FIGURE 34. Landsat Lineaments and Aeromagnetics. Landsat lineaments are from EarthSat (1997). The aeromagnetic field is high resolution, and reduced-to-pole; the data were procured and reduced by PRJ for a companion DOE-funded project.

FIGURE 35a. Modified Rose Diagrams of Fractures in the Detailed Study Area, East Side of Seneca Lake. Legend for modified rose diagrams in Figure 4. From Lugert et al. (2001, 2002) and Jacobi et al. (2002a, b).

FIGURE 35b. Location of N-S transect that is displayed in Figures 35c and 56. Sites were extrapolated to this transect in order to construct Figure 35c.

FIGURE 35c. N-S transect Displaying Fracture Frequency of ENE- and E-striking Fractures. Location of transect shown in Figure 35b. After Lugert et al. (2001, 2002) and from Jacobi et al. (2002a, b).

FIGURE 55d. Enlargement of the Southern Portion of the Transect, Fault Alternative. In this case the apparent dips for the cross section were rigorously applied, which can be used to infer a fault near site RDJ-59. See Figure 55a for location.

FIGURE 56. Summary Diagram. North-south transect along the east side of Seneca Lake (for location of transect, see Figure 35b). Soil gas profile from a companion project funded by DOE. The high frequency of E-striking fractures at Hector corresponds to location of E-striking Landsat lineaments, but not to a significant number of soil gas anomalies. The high frequency of ENE-striking fractures at Valois corresponds to location of ENE-striking lineaments, and to a significant number of soil gas anomalies. North of Valois, zones with high frequency of E-striking fractures correspond to regions with E-striking Landsat lineaments. From Jacobi et al. (2002a, b).

TABLE CAPTION

TABLE 1. Fault Offsets Observed on Seismic Line #2. Amount of offset is displayed for various reflectors on each fault that is observed on seismic line #1 (Fault #'s in the Table refer to numbered faults in Figure 31). The various reflectors are the Onondaga, Base of the Salt, Lockport, Trenton, Black River, Knox, and top of the Precambrian.

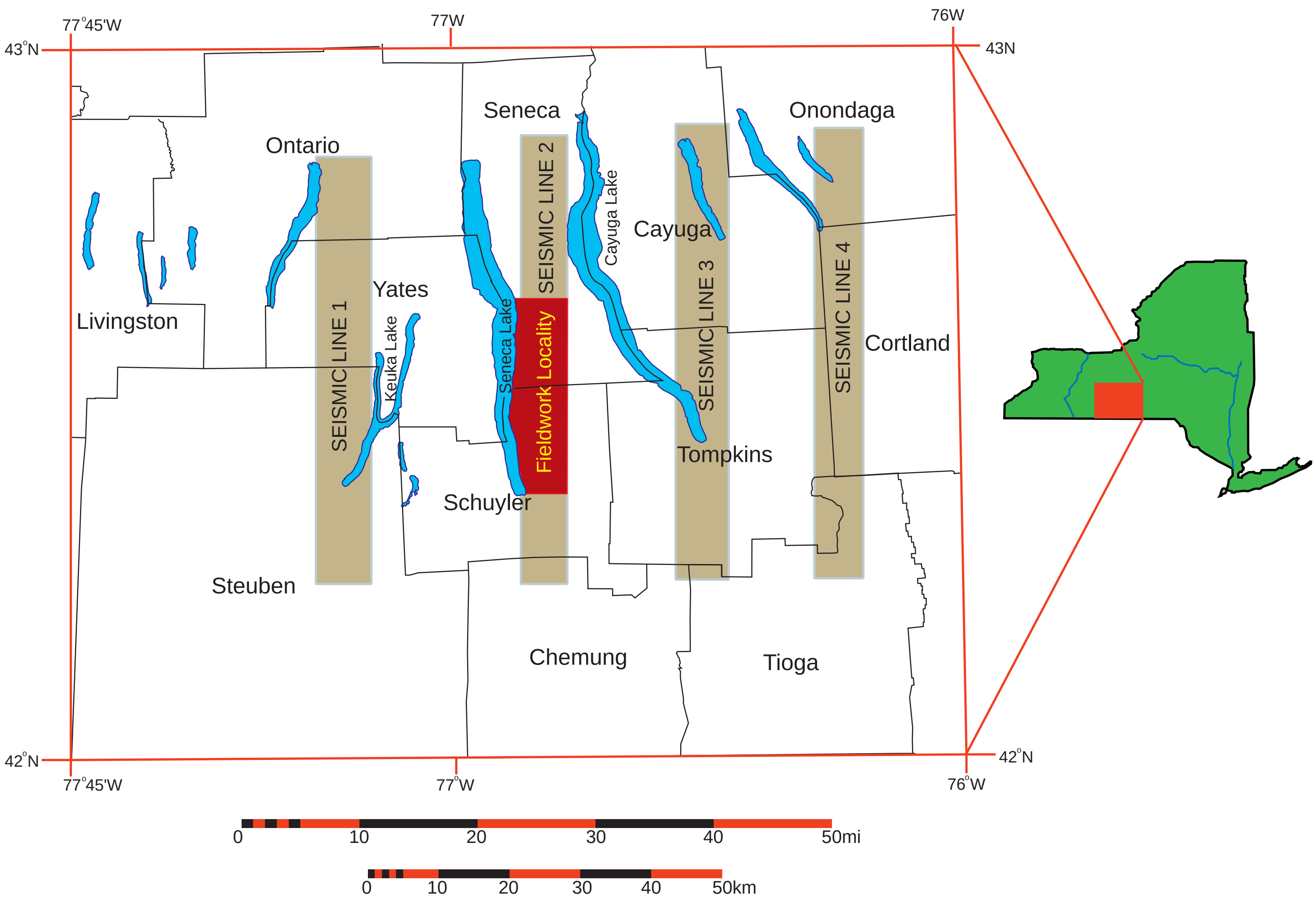

77°45'W
77W
76W
43°N
43N
42°N
42°N
77°45'W
77°W
76°W
Seneca
Onondaga
Ontario
Cayuga
Cayuga Lake
Yates
Livingston
Keuka Lake
Seneca Lake
Fieldwork Locality
SEISMIC LINE 1
SEISMIC LINE 2
SEISMIC LINE 3
SEISMIC LINE 4
Cortland
Tompkins
Schuyler
Steuben
Chemung
Tioga
0
10
20
30
40
50mi
0
10
20
30
40
50km

FIGURE 1

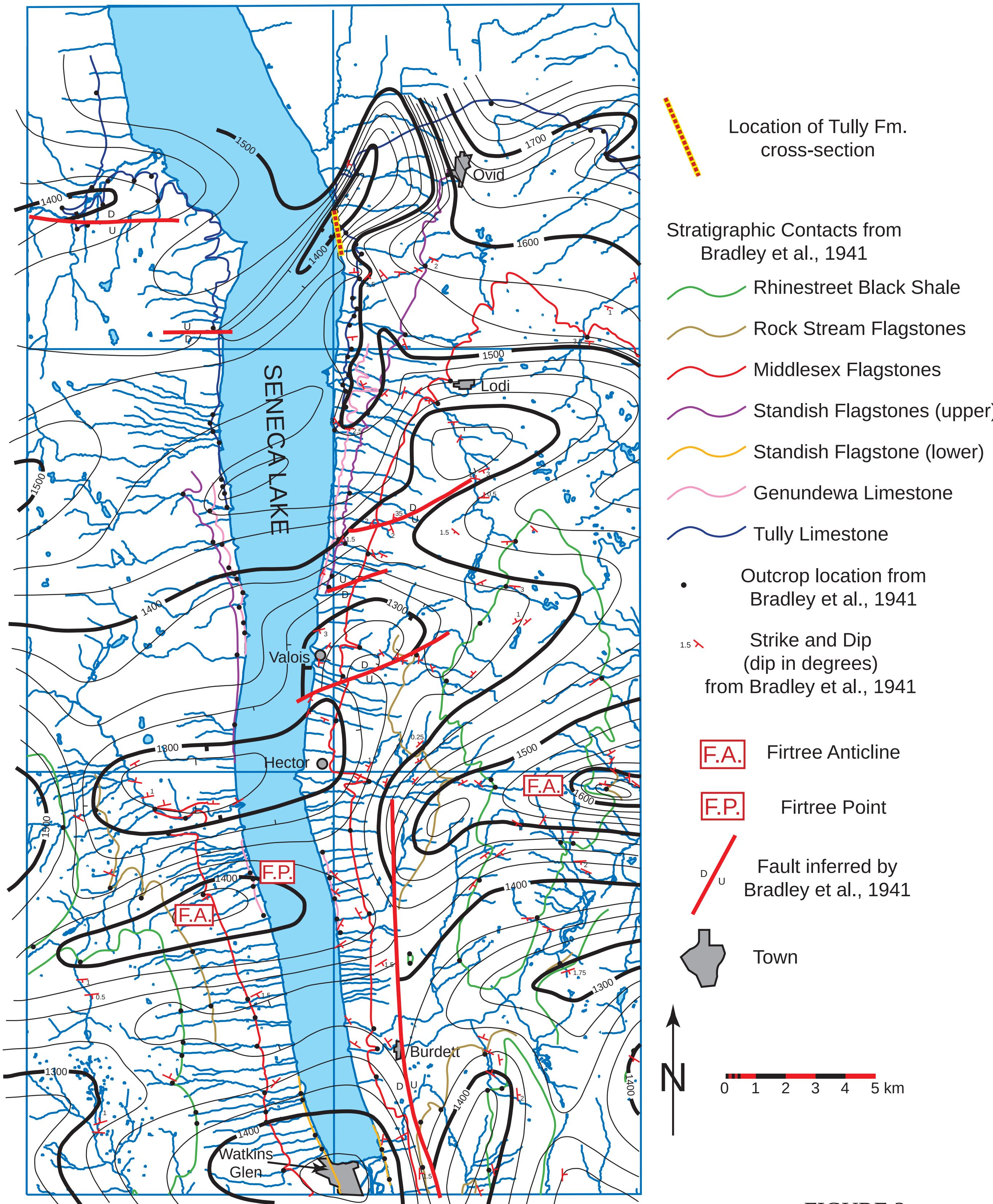

Location of Tully Fm. cross-section
Stratigraphic Contacts from Bradley et al., 1941
Rhinestreet Black Shale
Rock Stream Flagstones
Middlesex Flagstones
Standish Flagstones (upper)
Standish Flagstone (lower)
Genundewa Limestone
Tully Limestone
Outcrop location from Bradley et al., 1941
Strike and Dip (dip in degrees) from Bradley et al., 1941
F.A. Firtree Anticline
F.P. Firtree Point
Fault inferred by Bradley et al., 1941
Town
N
0 1 2 3 4 5 km
SENECA LAKE
Ovid
Lodi
Valois
Hector
Burdett
Watkins Glen
F.A.
F.P.

FIGURE 2

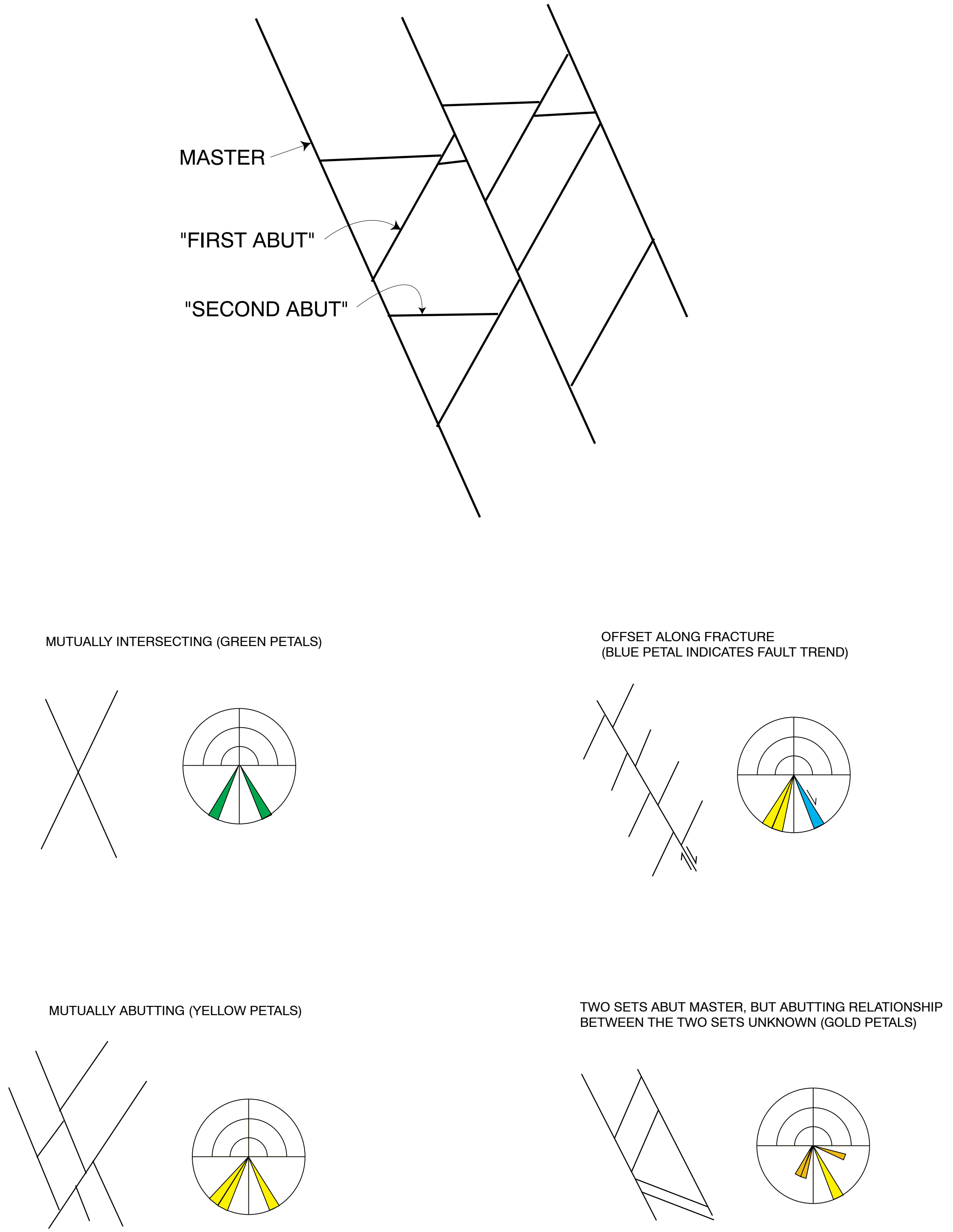

MASTER
"FIRST ABUT"
"SECOND ABUT"
MUTUALLY INTERSECTING (GREEN PETALS)
OFFSET ALONG FRACTURE
(BLUE PETAL INDICATES FAULT TREND)
MUTUALLY ABUTTING (YELLOW PETALS)
TWO SETS ABUT MASTER, BUT ABUTTING RELATIONSHIP
BETWEEN THE TWO SETS UNKNOWN (GOLD PETALS)

FIGURE 3

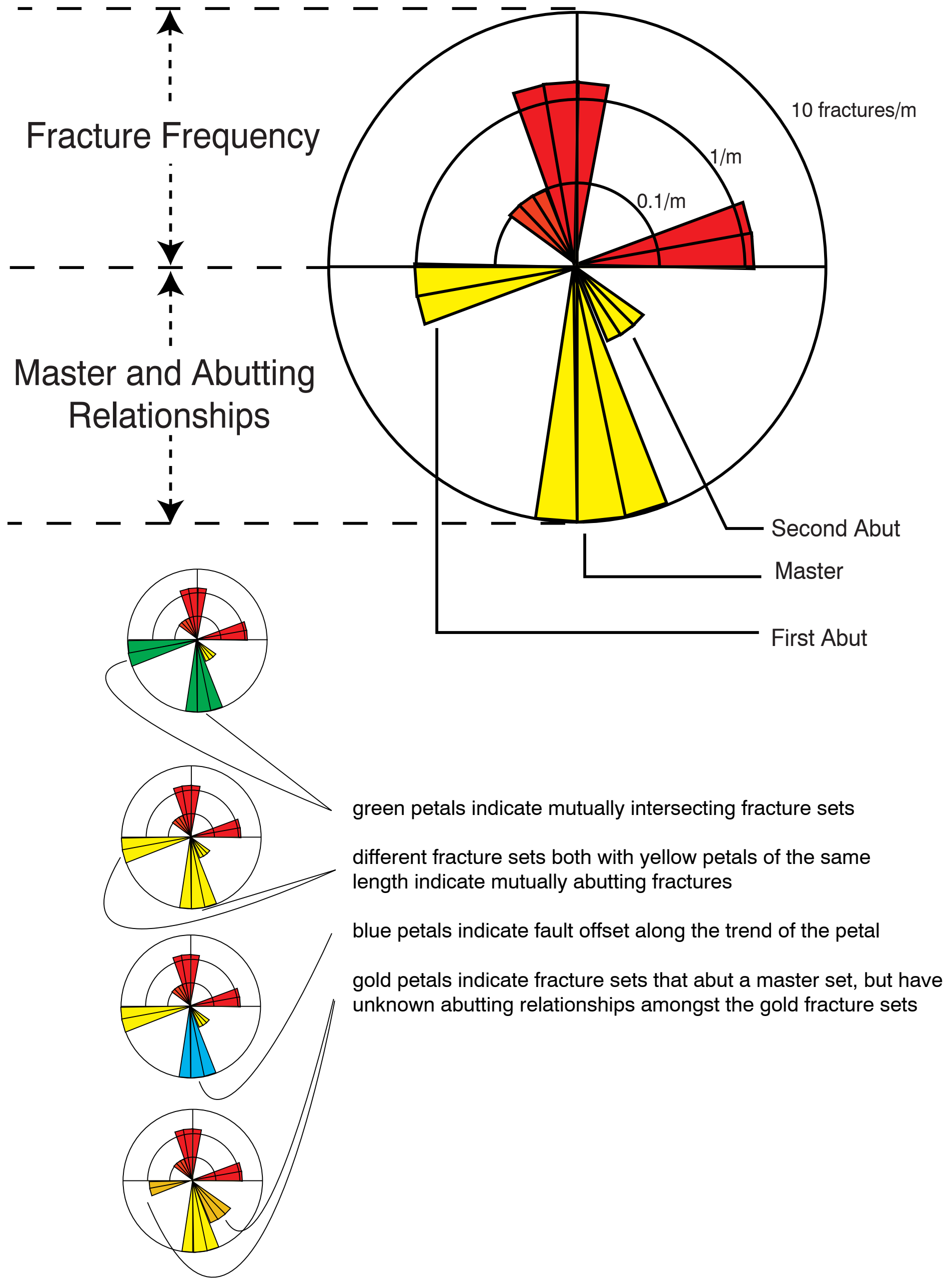
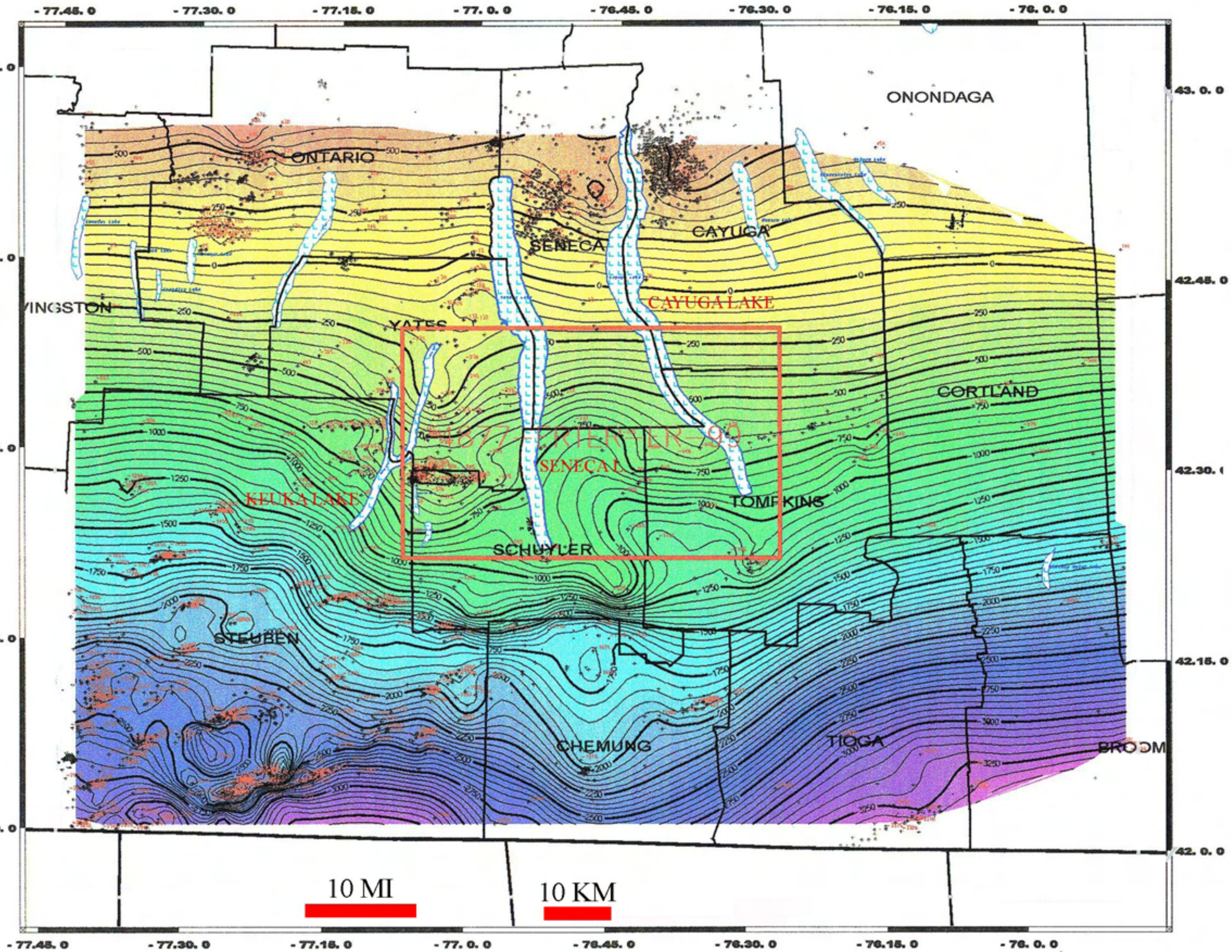

Fracture Frequency
Master and Abutting Relationships
10 fractures/m
1/m
0.1/m
Second Abut
Master
First Abut
green petals indicate mutually intersecting fracture sets
different fracture sets both with yellow petals of the same length indicate mutually abutting fractures
blue petals indicate fault offset along the trend of the petal
gold petals indicate fracture sets that abut a master set, but have unknown abutting relationships amongst the gold fracture sets

FIGURE 4



- 77.45. 0
- 77.30. 0
- 77.15. 0
- 77. 0. 0
- 76.45. 0
- 76.30. 0
- 76.15. 0
- 76. 0. 0
43. 0. 0
42.45. 0
42.30. 0
42.15. 0
42. 0. 0
ONONDAGA
ONTARIO
SENECA
CAYUGA
CAYUGA LAKE
VINGSTON
YATES
CORTLAND
SENECA L
KEUKA LAKE
TOMPKINS
SCHUYLER
STEUBEN
CHEMUNG
TIOGA
BROOM
10 MI
10 KM

FIGURE 5

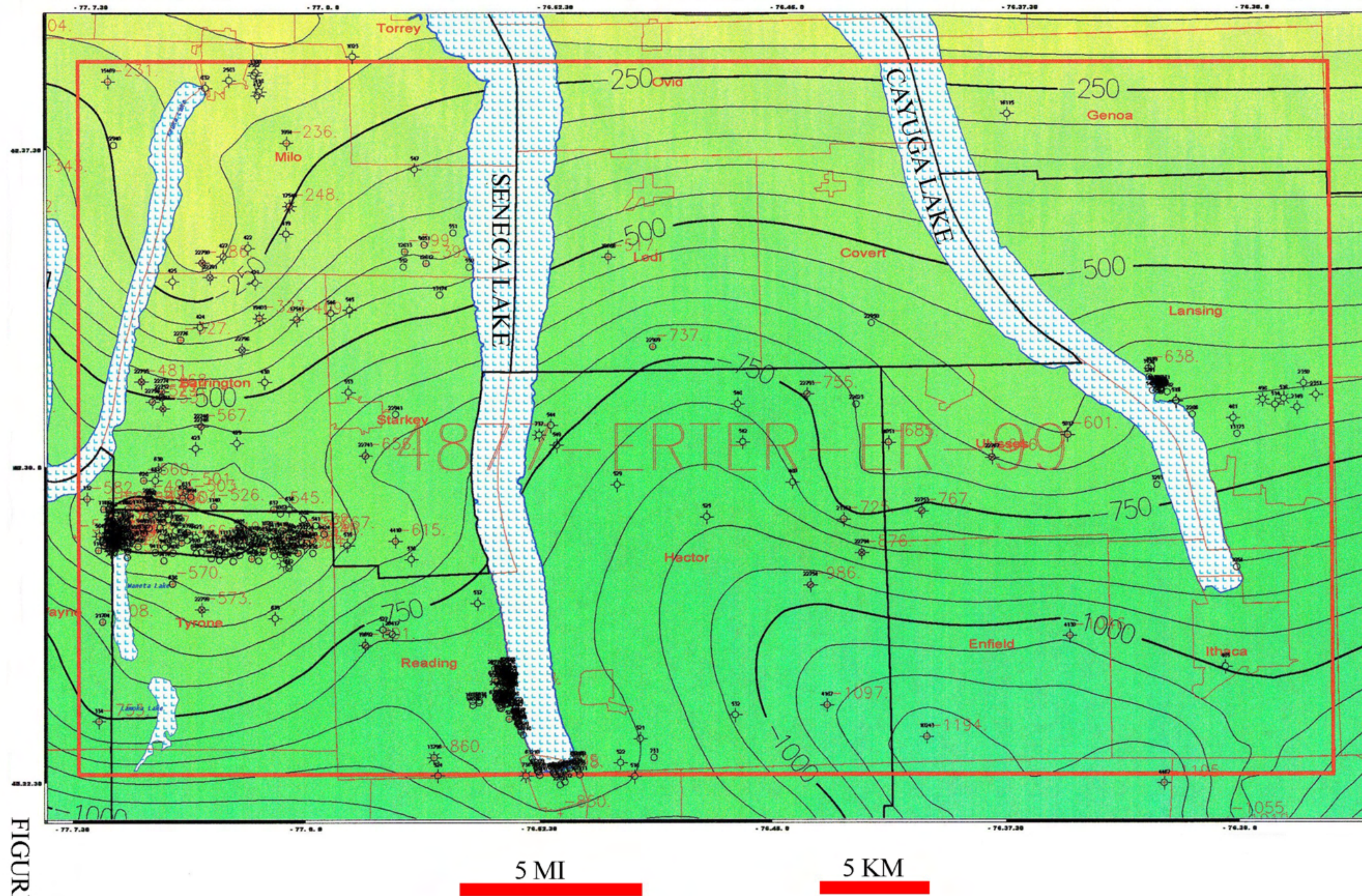

SENECA LAKE
CAYUGA LAKE
Torrey
Ovid
Genoa
Milo
Lodi
Covert
Lansing
Barrington
Starkey
Ulysses
Hector
Tyrone
Reading
Enfield
Ithaca
4877-ERTER-ER-99
250
500
750
1000
5 MI
5 KM

FIGURE 6

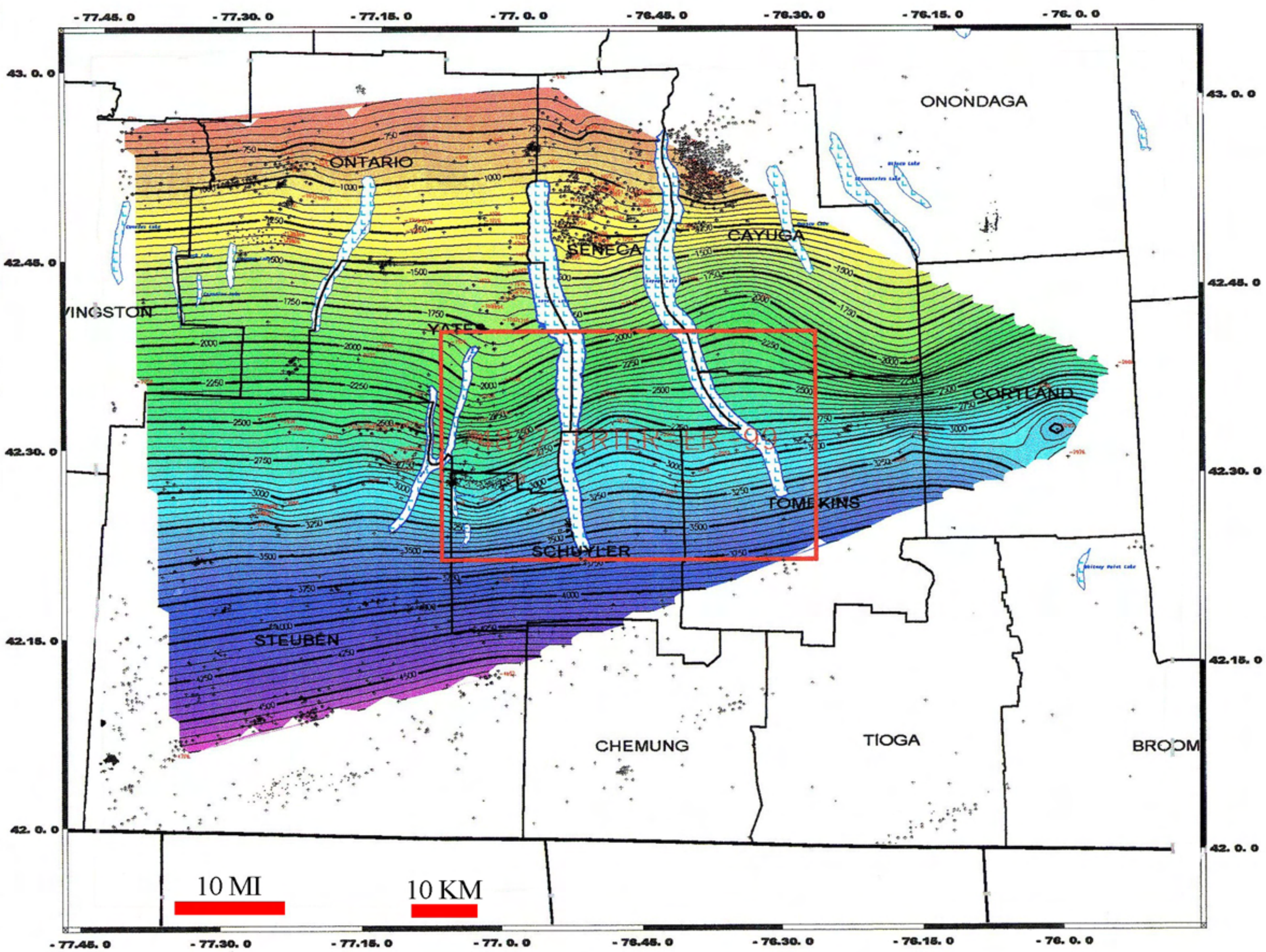
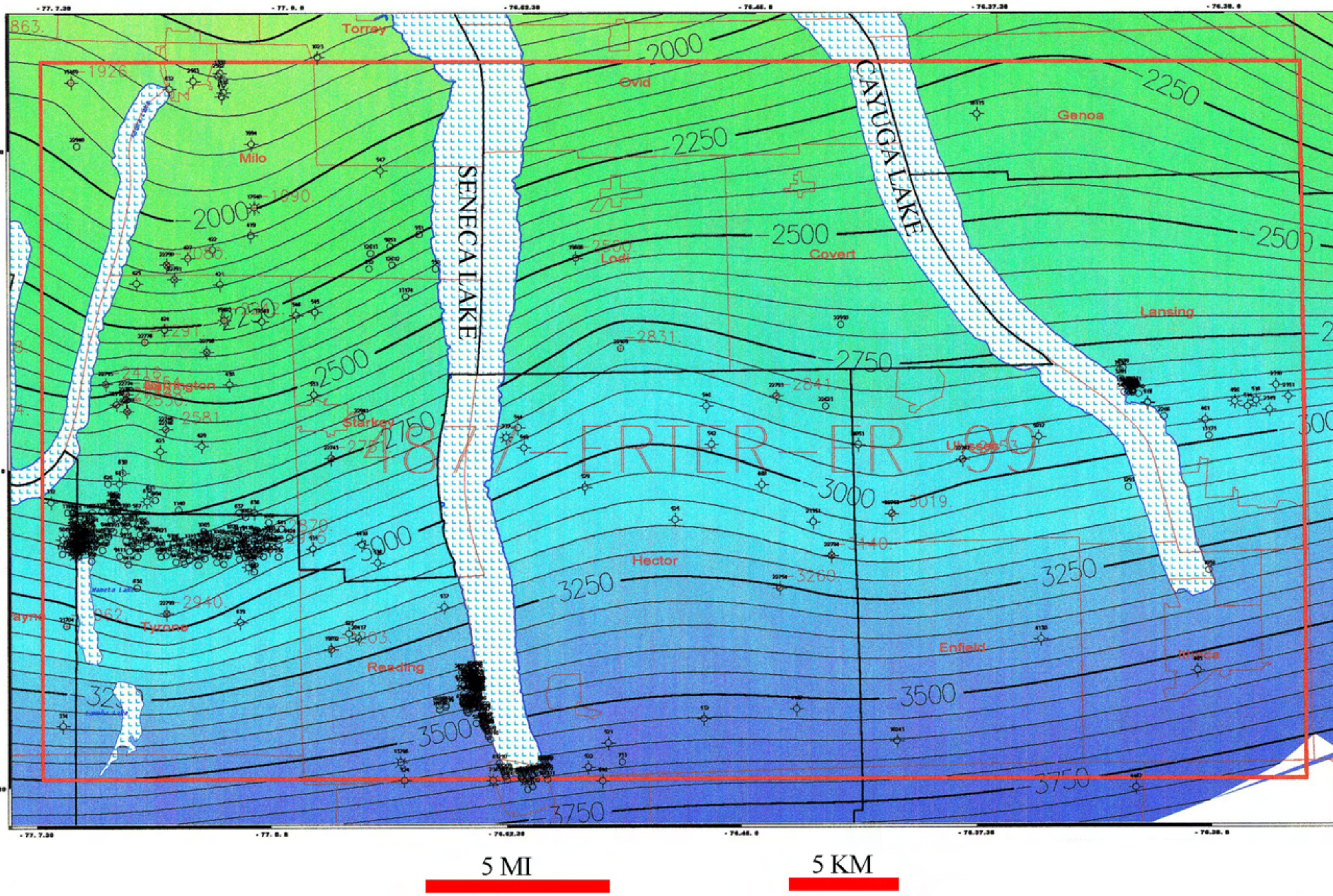
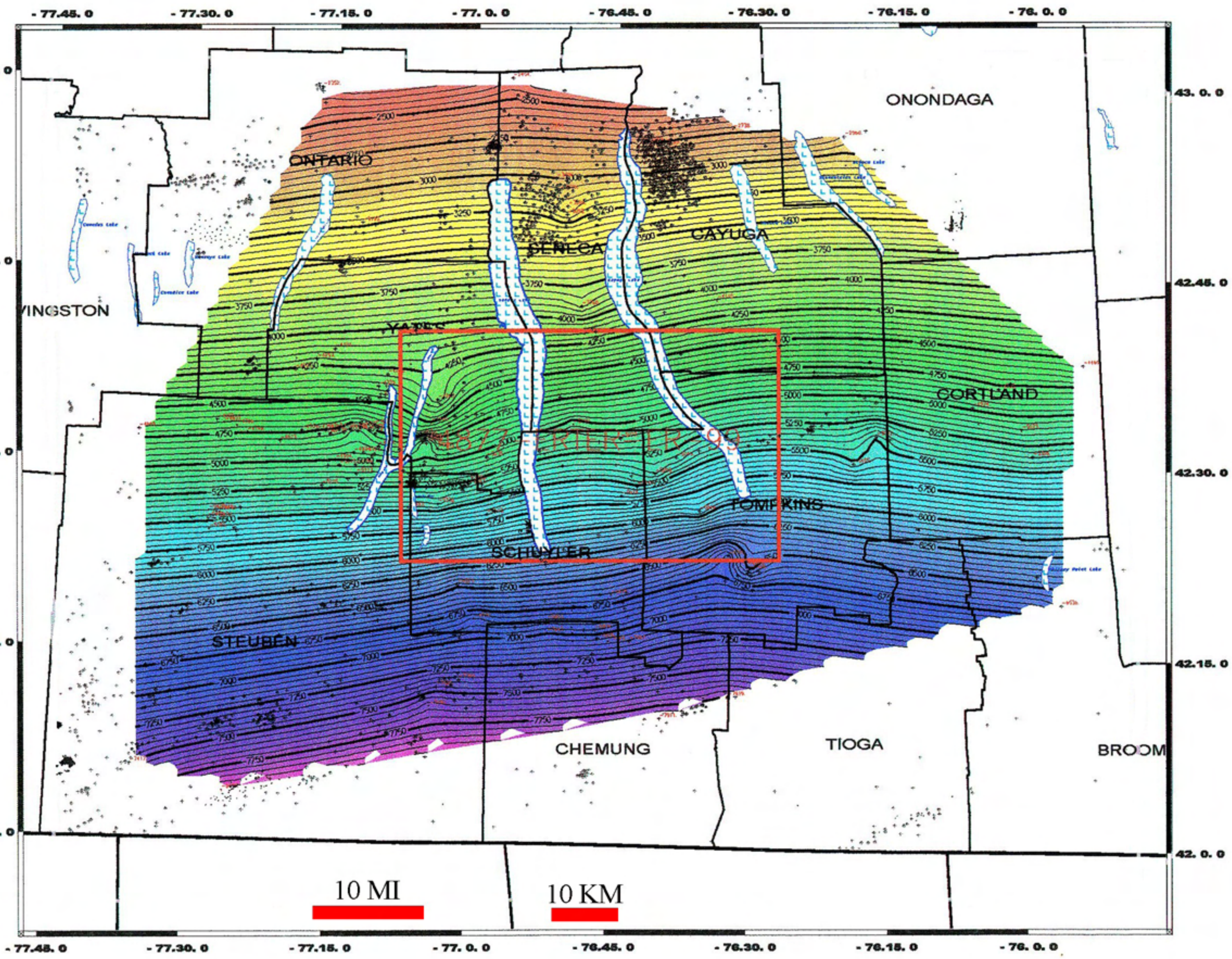

-77.45.0
-77.30.0
-77.15.0
-77.0.0
-76.45.0
-76.30.0
-76.15.0
-76.0.0
43.0.0
42.45.0
42.30.0
42.15.0
42.0.0
ONONDAGA
ONTARIO
CAYUGA
SENECA
VINGSTON
YATES
CORTLAND
TOMPKINS
SCHUYLER
STEUBEN
CHEMUNG
TIOGA
BROOM
10 MI
10 KM

FIGURE 7



SENECA LAKE
CAYUGA LAKE
Torrey
Ovid
Genoa
Milo
Lodi
Covert
Lansing
Barrington
Starkey
Ulysses
Hector
Tyrone
Reading
Enfield
Ithaca
2000
2250
2500
2750
3000
3250
3500
3750
5 MI
5 KM

FIGURE 8



- 77.45. 0
- 77.30. 0
- 77.15. 0
- 77. 0. 0
- 76.45. 0
- 76.30. 0
- 76.15. 0
- 76. 0. 0
43. 0. 0
42.45. 0
42.30. 0
42.15. 0
42. 0. 0
ONTARIO
ONONDAGA
SENECA
CAYUGA
VINGSTON
YATES
CORTLAND
TOMPKINS
SCHUYLER
STEUBEN
CHEMUNG
TIOGA
BROOM
10 MI
10 KM

FIGURE 9

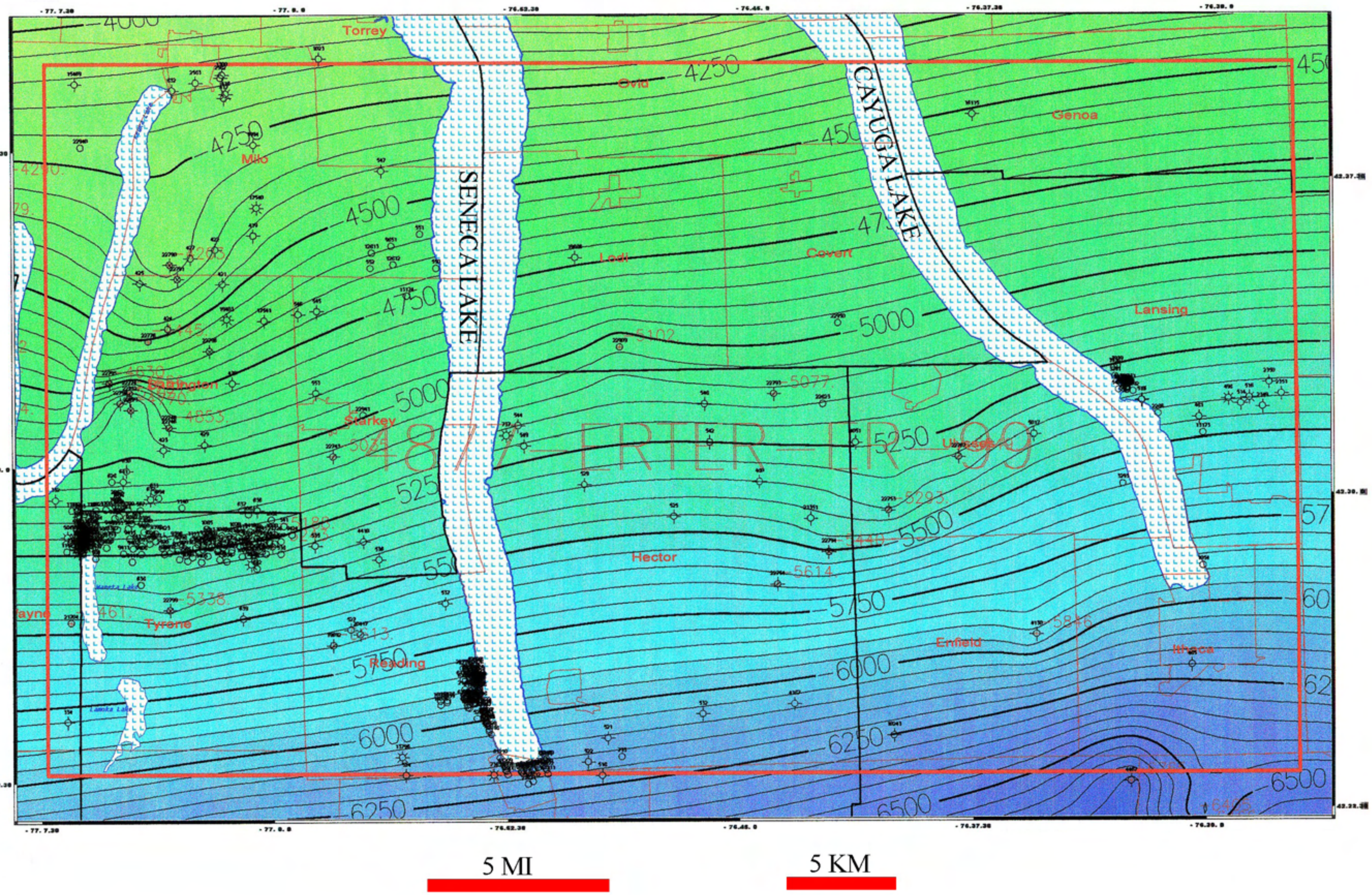

SENECA LAKE
CAYUGA LAKE
Torrey
Ovid
Genoa
Milo
Lodi
Covert
Lansing
Barrington
Starkey
Hector
Tyrone
Reading
Enfield
Ithaca
4250
4500
4750
5000
5250
5500
5750
6000
6250
6500
5 MI
5 KM

FIGURE 10

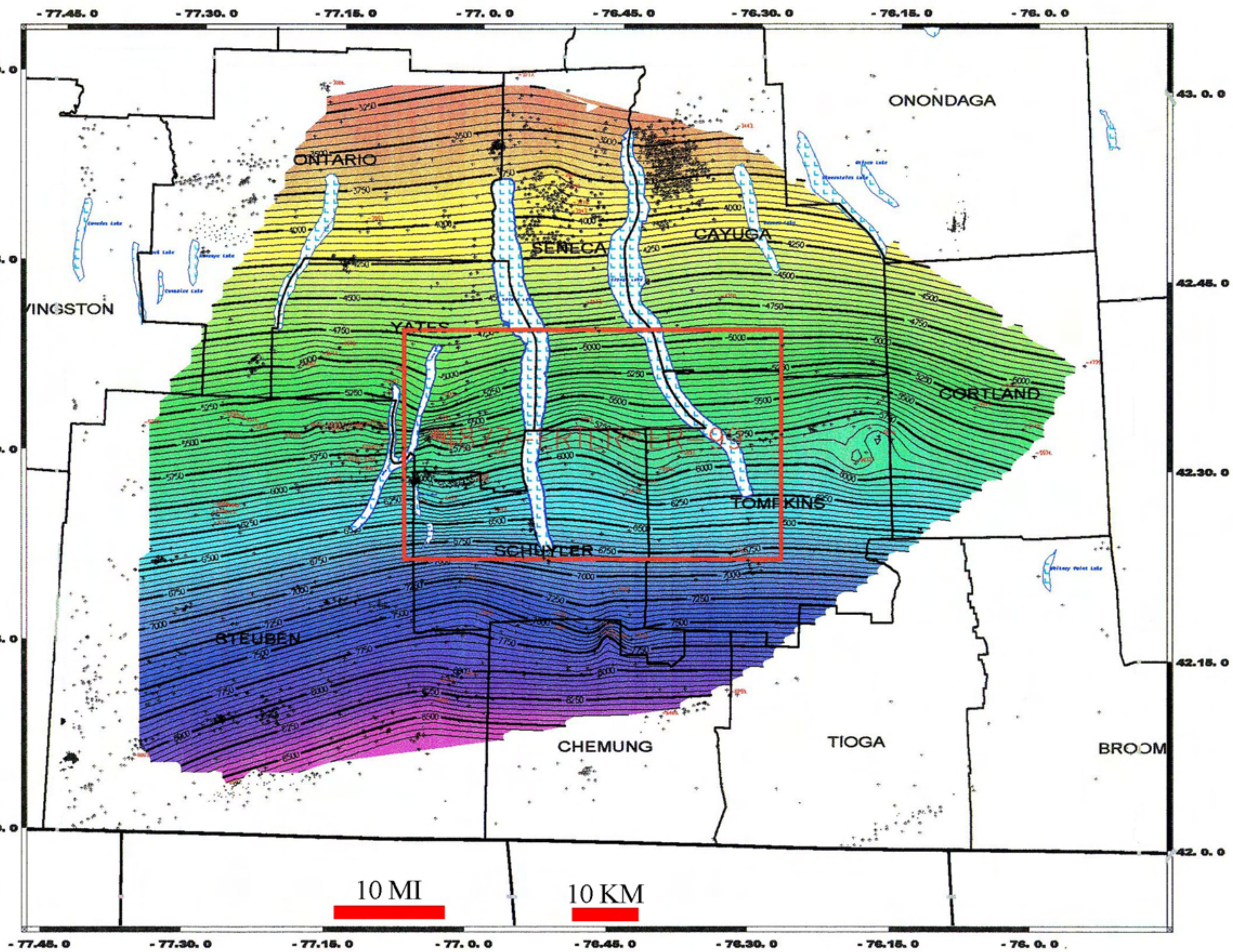

-77.45. 0
-77.30. 0
-77.15. 0
-77. 0. 0
-76.45. 0
-76.30. 0
-76.15. 0
-76. 0. 0
43. 0. 0
42.45. 0
42.30. 0
42.15. 0
42. 0. 0
ONONDAGA
ONTARIO
SENECA
CAYUGA
VINGSTON
YATES
CORTLAND
TOMPKINS
SCHUYLER
STEUBEN
CHEMUNG
TIOGA
BROOM
10 MI
10 KM

FIGURE 11

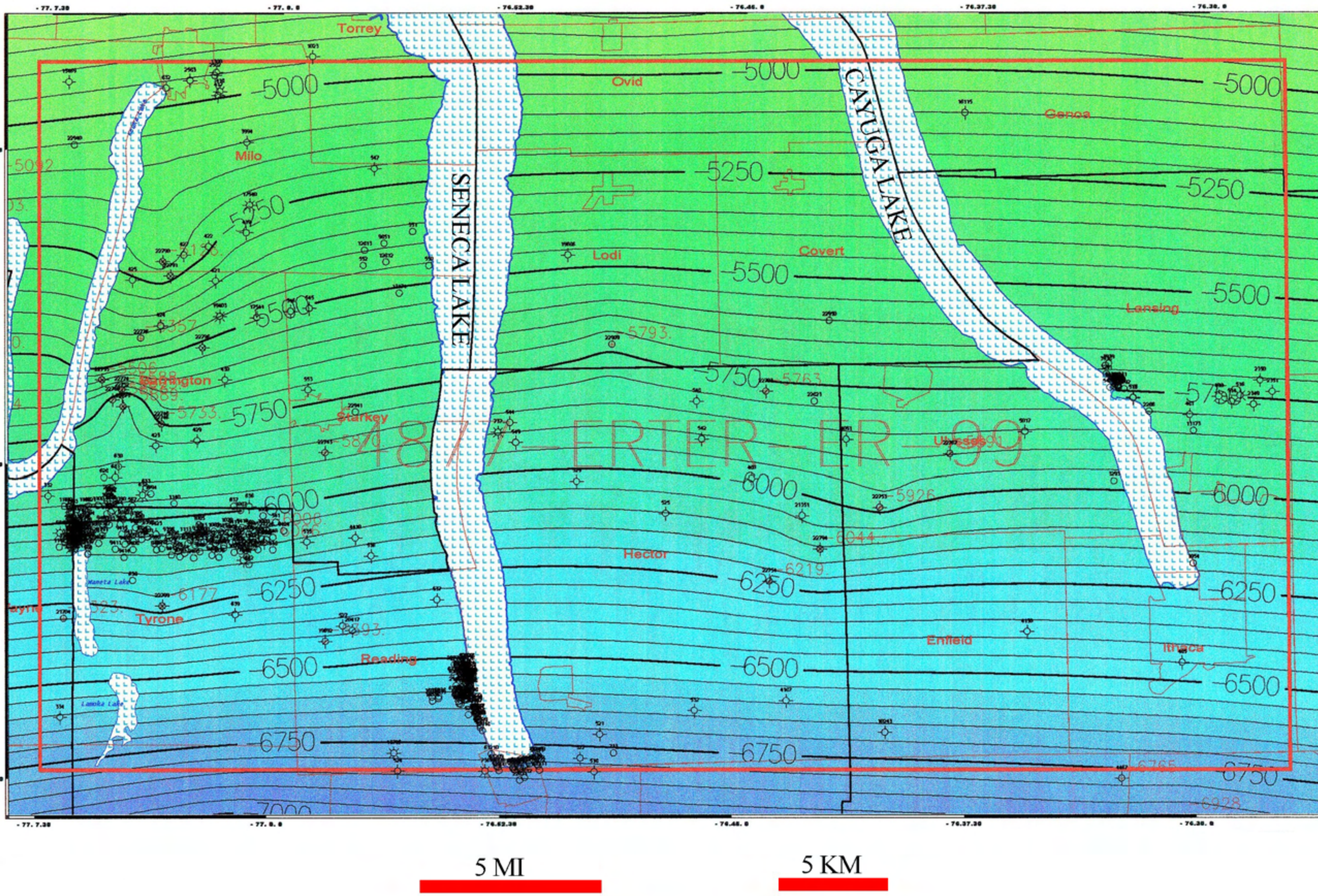
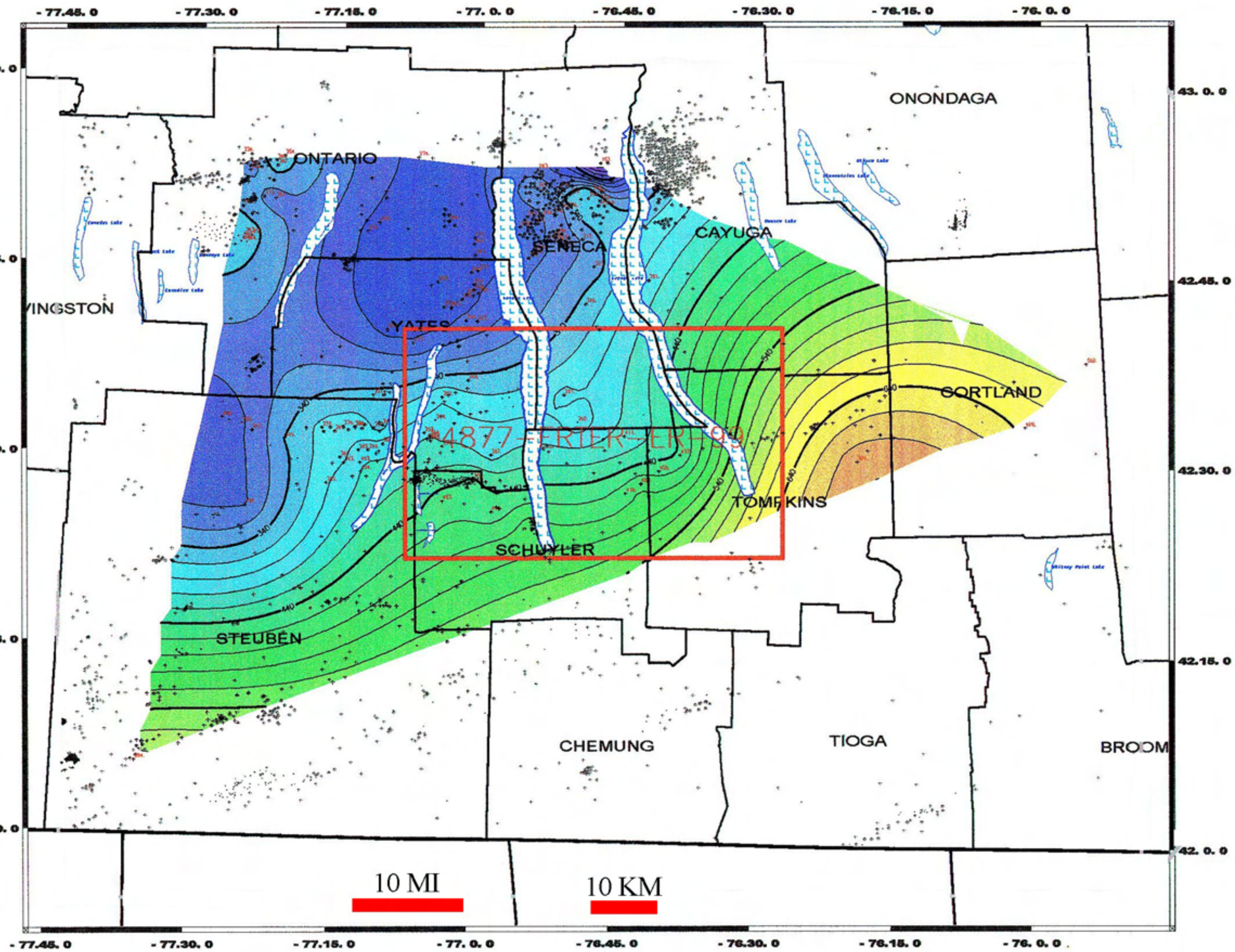

Torrey
Ovid
Genoa
Milo
Lodi
Covert
Lansing
Barrington
Starkey
Ulysses
Hector
Tyrone
Reading
Enfield
Ithaca
SENECA LAKE
CAYUGA LAKE
-5000
-5250
-5500
-5750
-6000
-6250
-6500
-6750
-7000
5 MI
5 KM

FIGURE 12



- 77.45. 0
- 77.30. 0
- 77.15. 0
- 77. 0. 0
- 76.45. 0
- 76.30. 0
- 76.15. 0
- 76. 0. 0
43. 0. 0
42.45. 0
42.30. 0
42.15. 0
42. 0. 0
ONONDAGA
ONTARIO
SENECA
CAYUGA
VINGSTON
YATES
CORTLAND
TOMPKINS
SCHUYLER
STEUBEN
CHEMUNG
TIOGA
BROOM
10 MI
10 KM

FIGURE 13

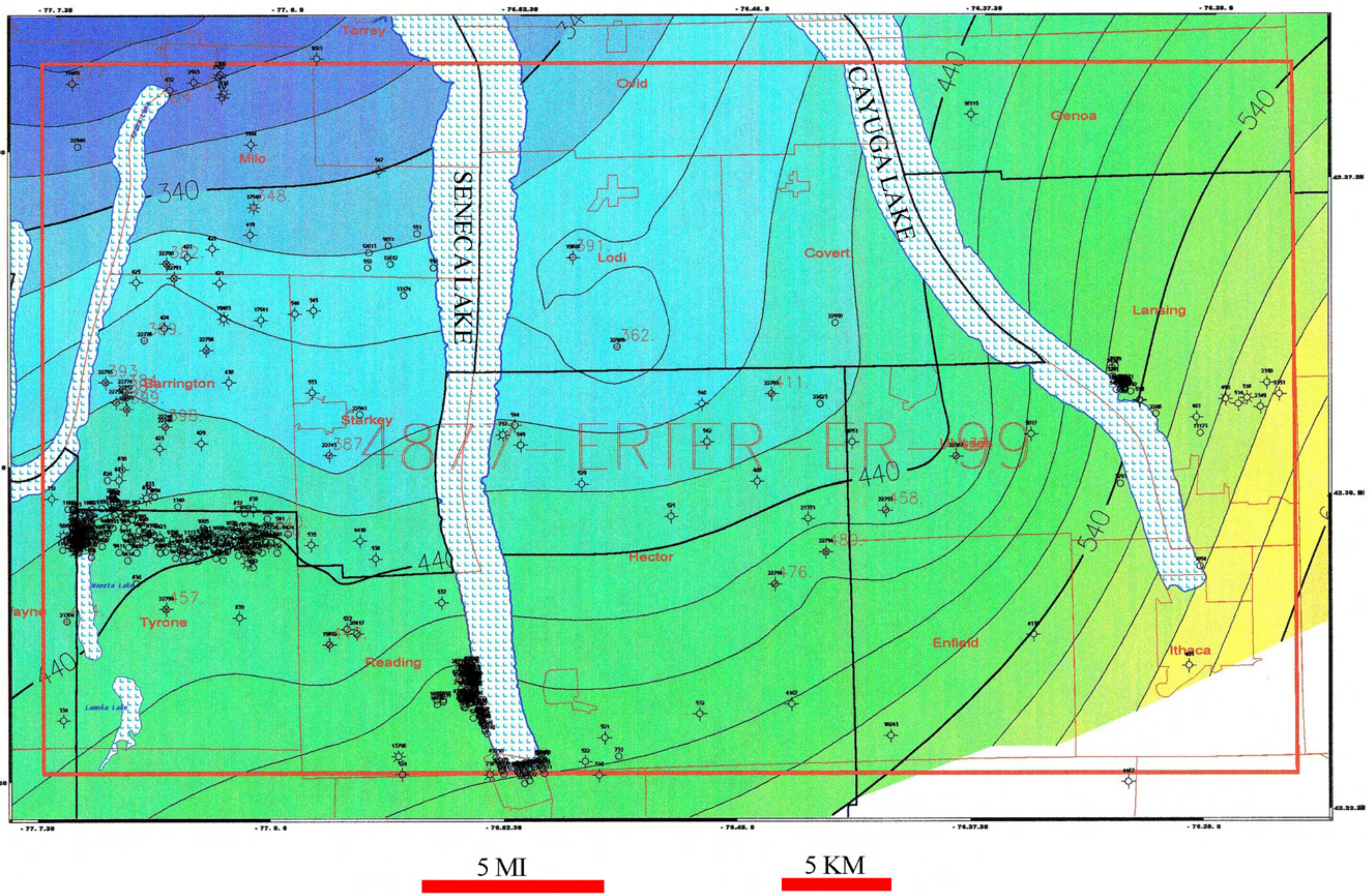

Torrey
Ovid
Genoa
Milo
SENECA LAKE
CAYUGA LAKE
Lodi
Covert
Lansing
Barrington
Starkey
Ulysses
Hector
Tyrone
Reading
Enfield
Ithaca
Waneta Lake
Lamoka Lake
340
440
540
5 MI
5 KM

FIGURE 14

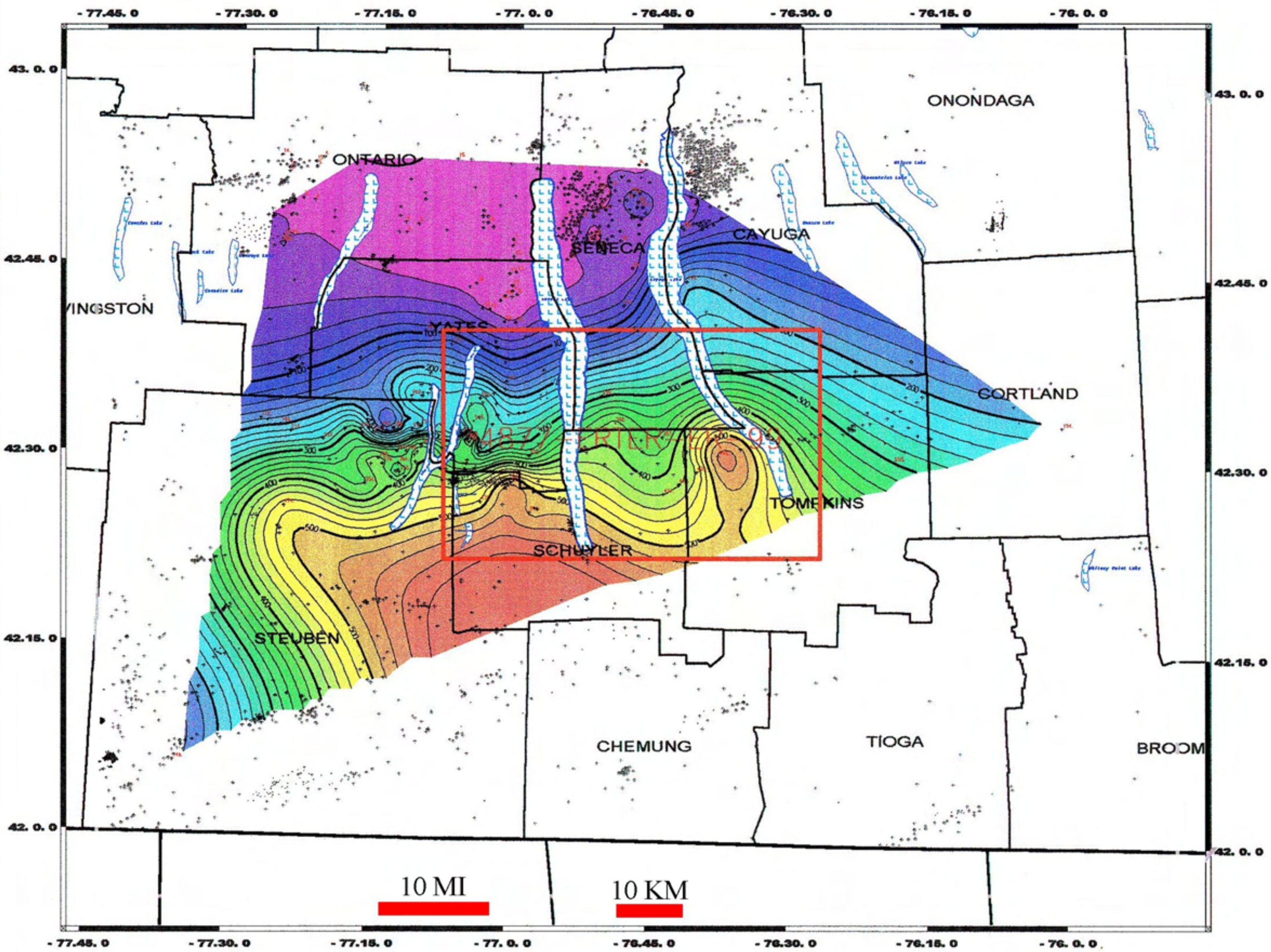

- 77.45. 0
- 77.30. 0
- 77.15. 0
- 77. 0. 0
- 76.45. 0
- 76.30. 0
- 76.15. 0
- 76. 0. 0
43. 0. 0
42.45. 0
42.30. 0
42.15. 0
42. 0. 0
ONONDAGA
ONTARIO
SENECA
CAYUGA
IVINGSTON
YATES
CORTLAND
TOMPKINS
SCHUYLER
STEUBEN
CHEMUNG
TIOGA
BROOM
10 MI
10 KM

FIGURE 15

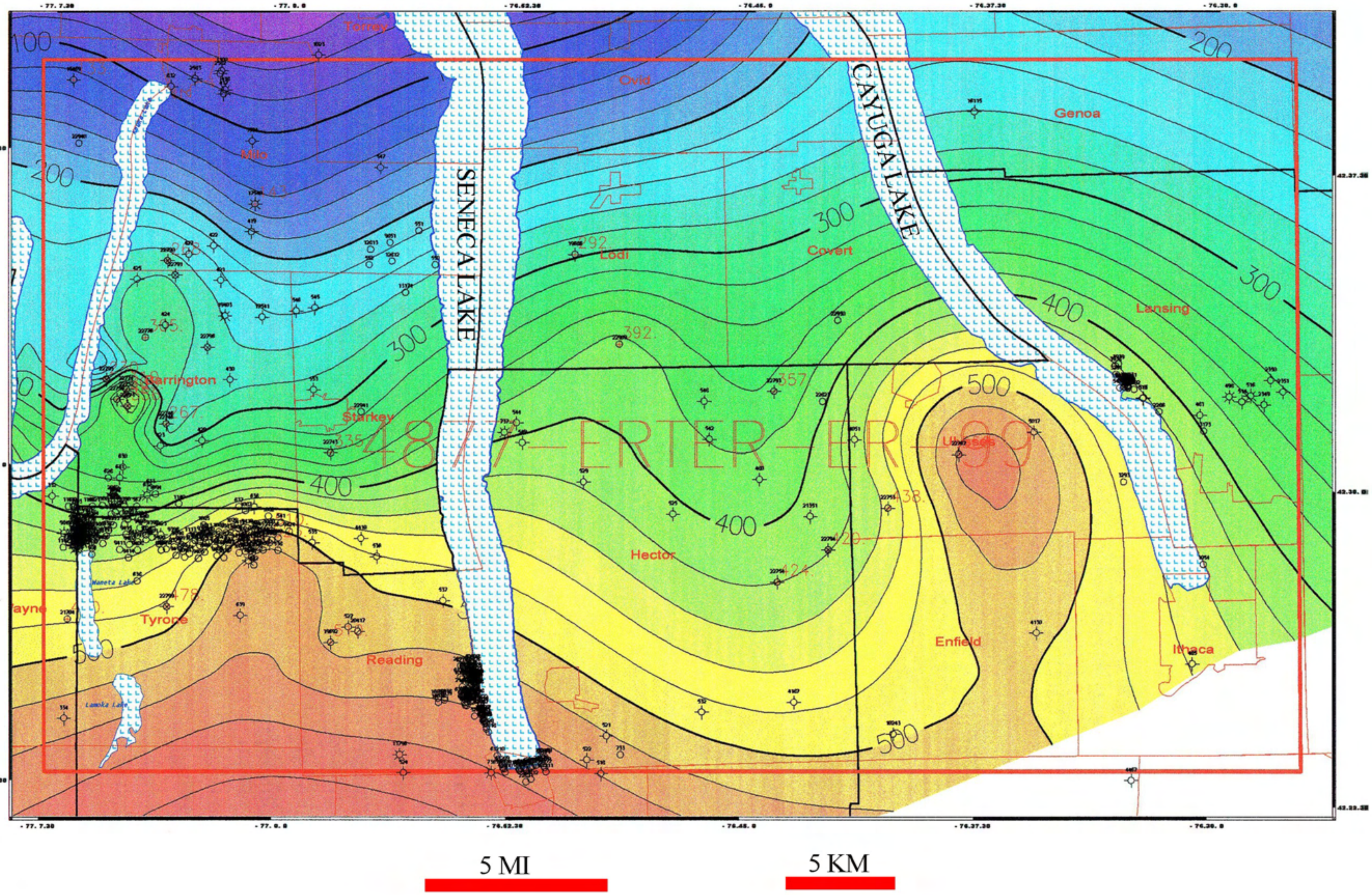
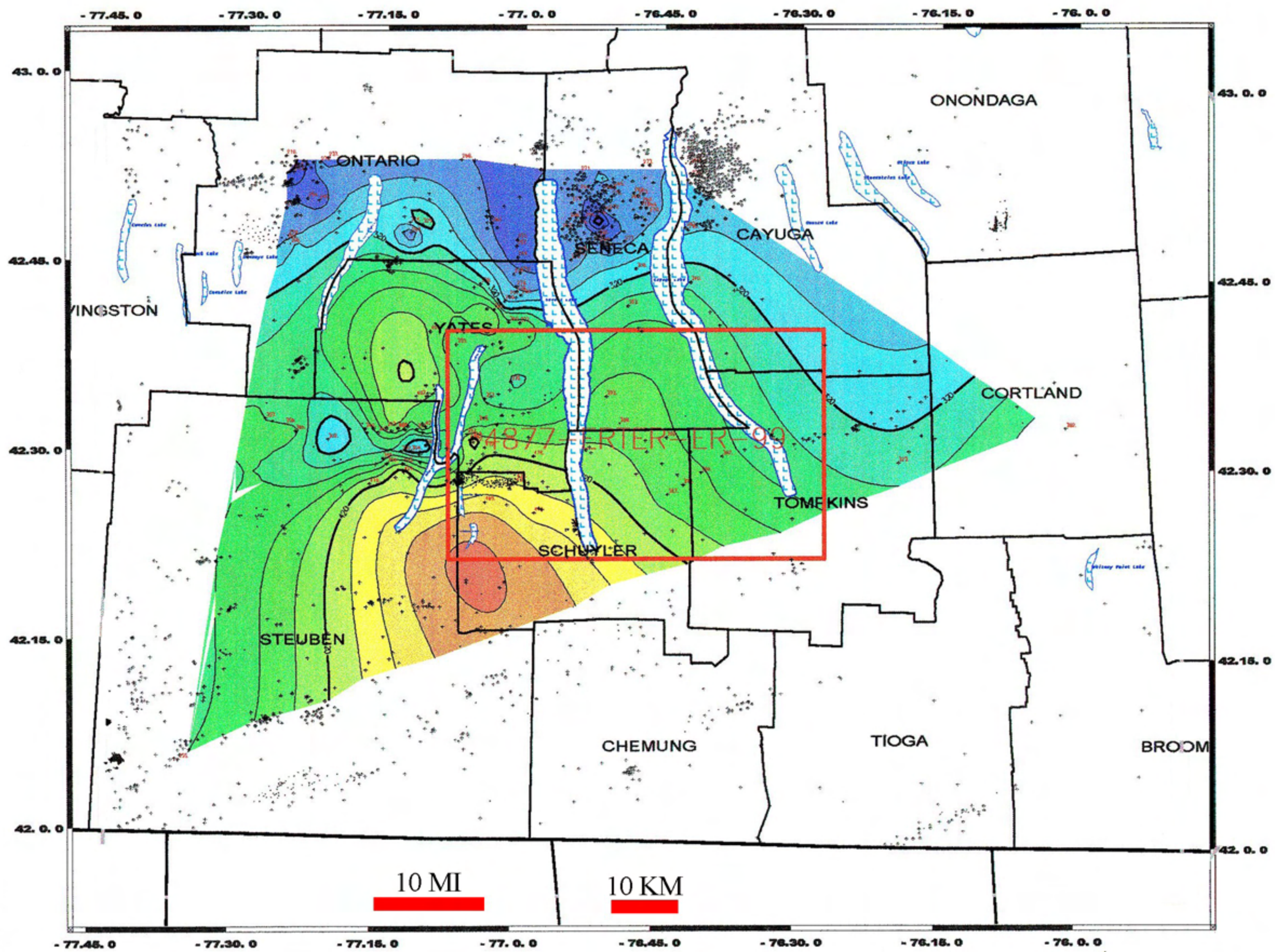

SENECA LAKE
CAYUGA LAKE
Torrey
Ovid
Milo
Genoa
Lodi
Covert
Lansing
Barrington
Starkey
Ulysses
Hector
Tyrone
Reading
Enfield
Ithaca
100
200
300
400
500
4877-ERTER-ER-99
5 MI
5 KM

FIGURE 16



- 77.45. 0
- 77.30. 0
- 77.15. 0
- 77. 0. 0
- 76.45. 0
- 76.30. 0
- 76.15. 0
- 76. 0. 0
43. 0. 0
42.45. 0
42.30. 0
42.15. 0
42. 0. 0
ONONDAGA
ONTARIO
SENECA
CAYUGA
VINGSTON
YATES
CORTLAND
TOMPKINS
SCHUYLER
STEUBEN
CHEMUNG
TIOGA
BROOM
10 MI
10 KM

FIGURE 17

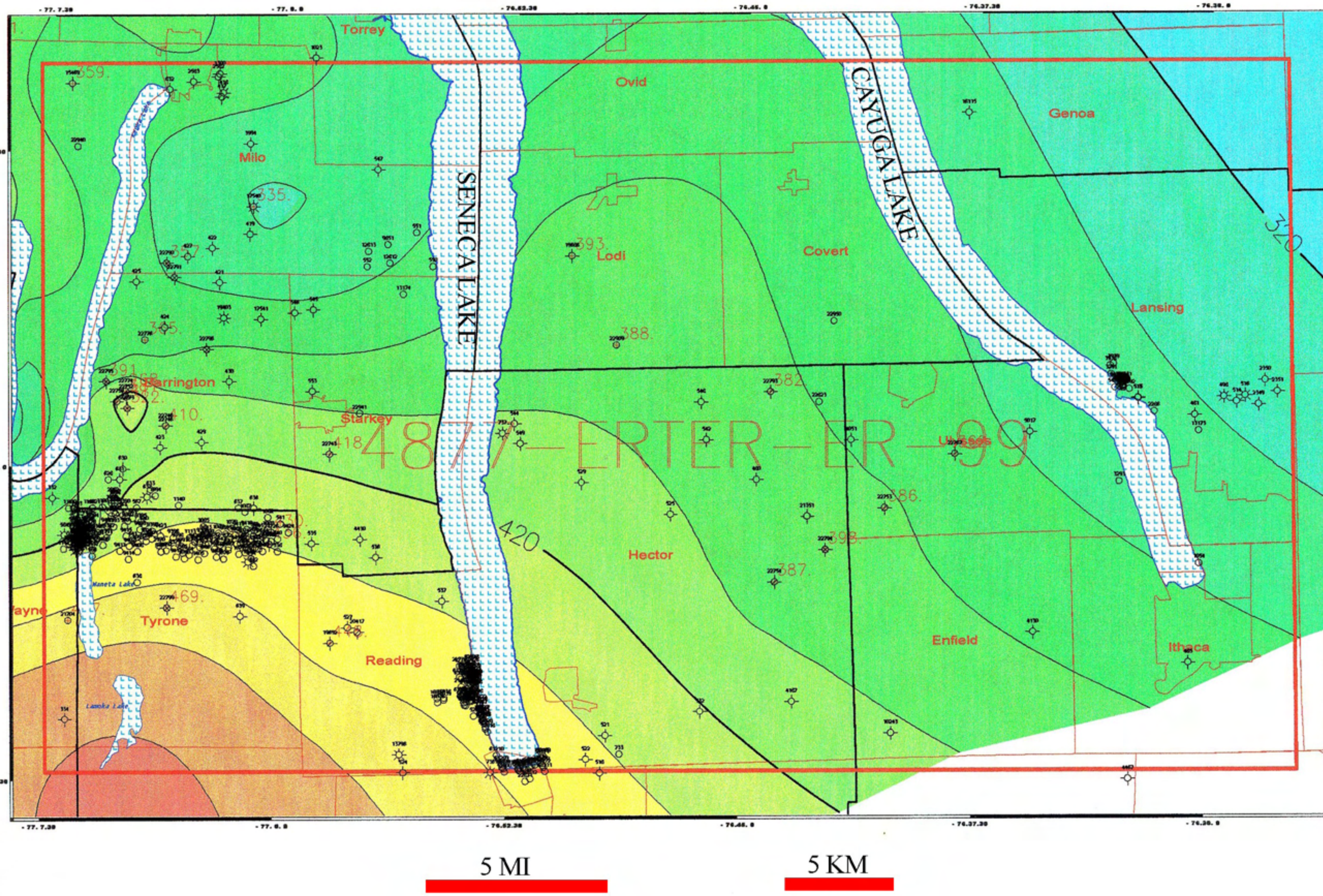
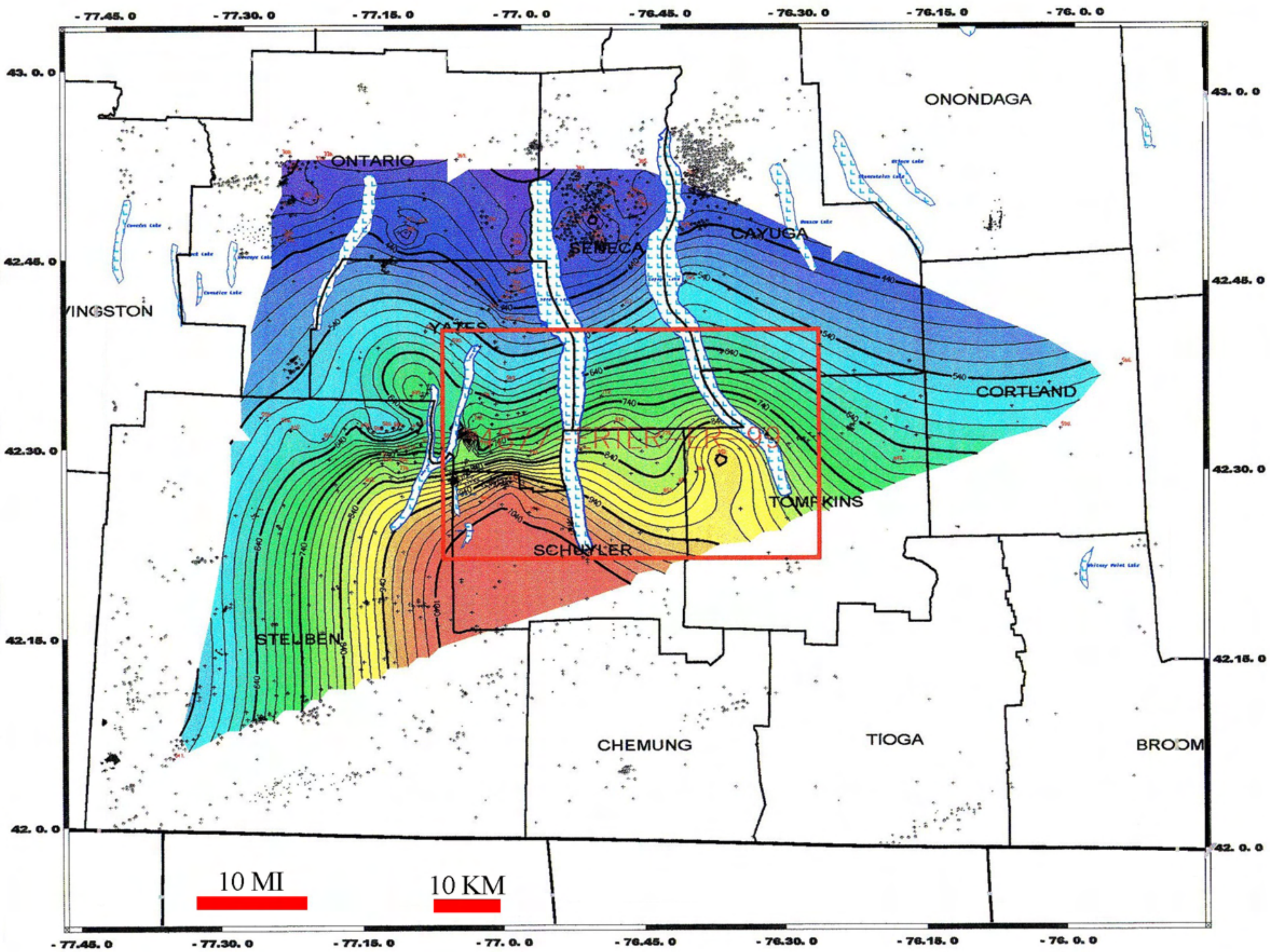

Torrey
Ovid
Genoa
Milo
SENECA LAKE
CAYUGA LAKE
Lodi
Covert
Lansing
Barrington
Starkey
4877-ERTER-ER-99
Hector
Enfield
Ithaca
Tyrone
Reading
320
420
5 MI
5 KM

FIGURE 18



- 77.45. 0
- 77.30. 0
- 77.15. 0
- 77. 0. 0
- 76.45. 0
- 76.30. 0
- 76.15. 0
- 76. 0. 0
43. 0. 0
42.45. 0
42.30. 0
42.15. 0
42. 0. 0
ONONDAGA
ONTARIO
SENECA
CAYUGA
VINGSTON
YATES
CORTLAND
TOMPKINS
SCHUYLER
STEUBEN
CHEMUNG
TIOGA
BROOM
10 MI
10 KM

FIGURE 19

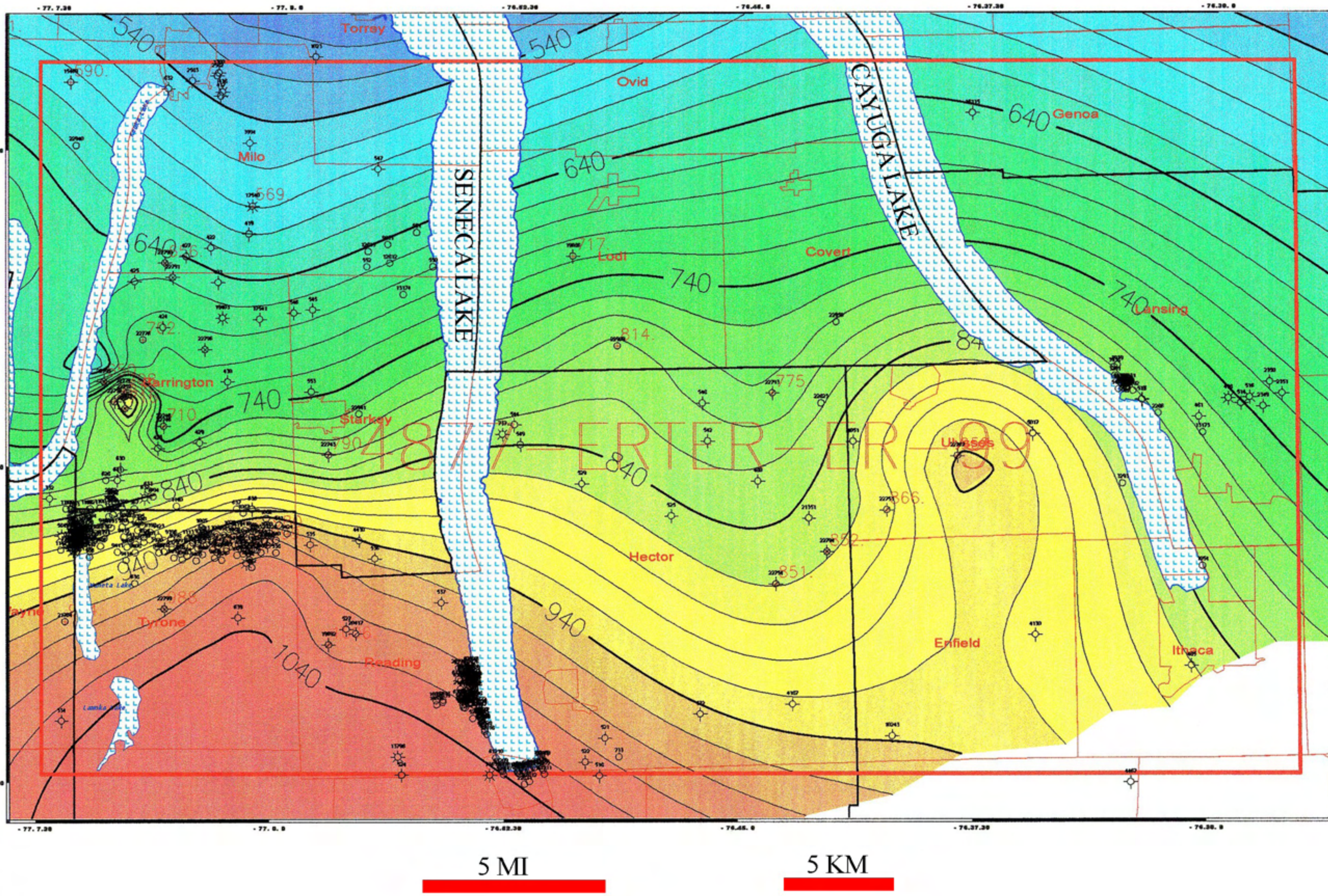
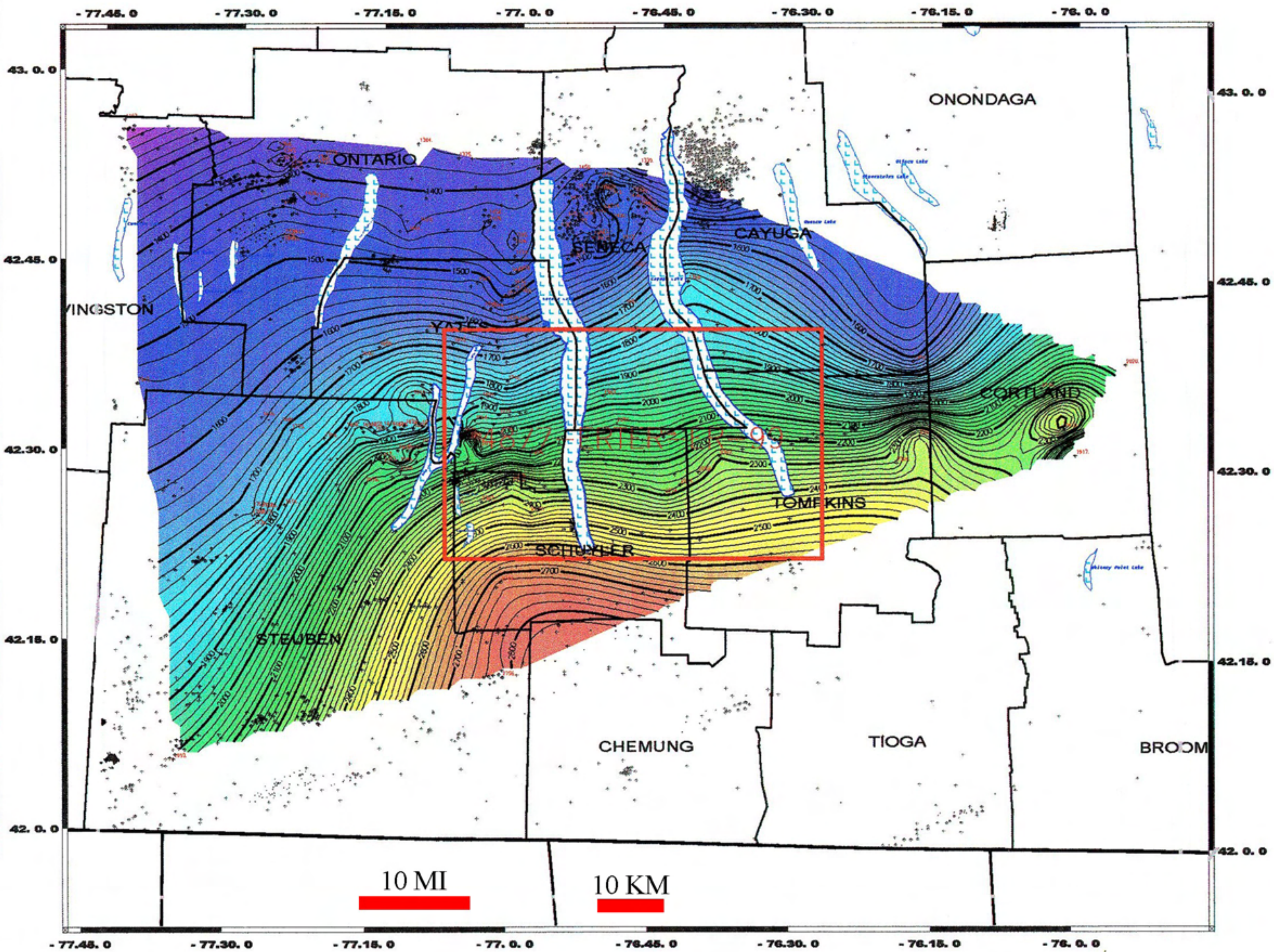

Torrey
Ovid
Genoa
Milo
Lodi
Covert
Lansing
Barrington
Starkey
Ulysses
Hector
Tyrone
Reading
Enfield
Ithaca
SENECA LAKE
CAYUGA LAKE
4877-ERTER-ER-99
540
640
740
840
940
1040
5 MI
5 KM

FIGURE 20



- 77.45. 0
- 77.30. 0
- 77.15. 0
- 77. 0. 0
- 76.45. 0
- 76.30. 0
- 76.15. 0
- 76. 0. 0
43. 0. 0
42.45. 0
42.30. 0
42.15. 0
42. 0. 0
ONONDAGA
ONTARIO
SENECA
CAYUGA
VINGSTON
YATES
CORTLAND
TOMPKINS
SCHUYLER
STEUBEN
CHEMUNG
TIOGA
BROOM
10 MI
10 KM

FIGURE 21

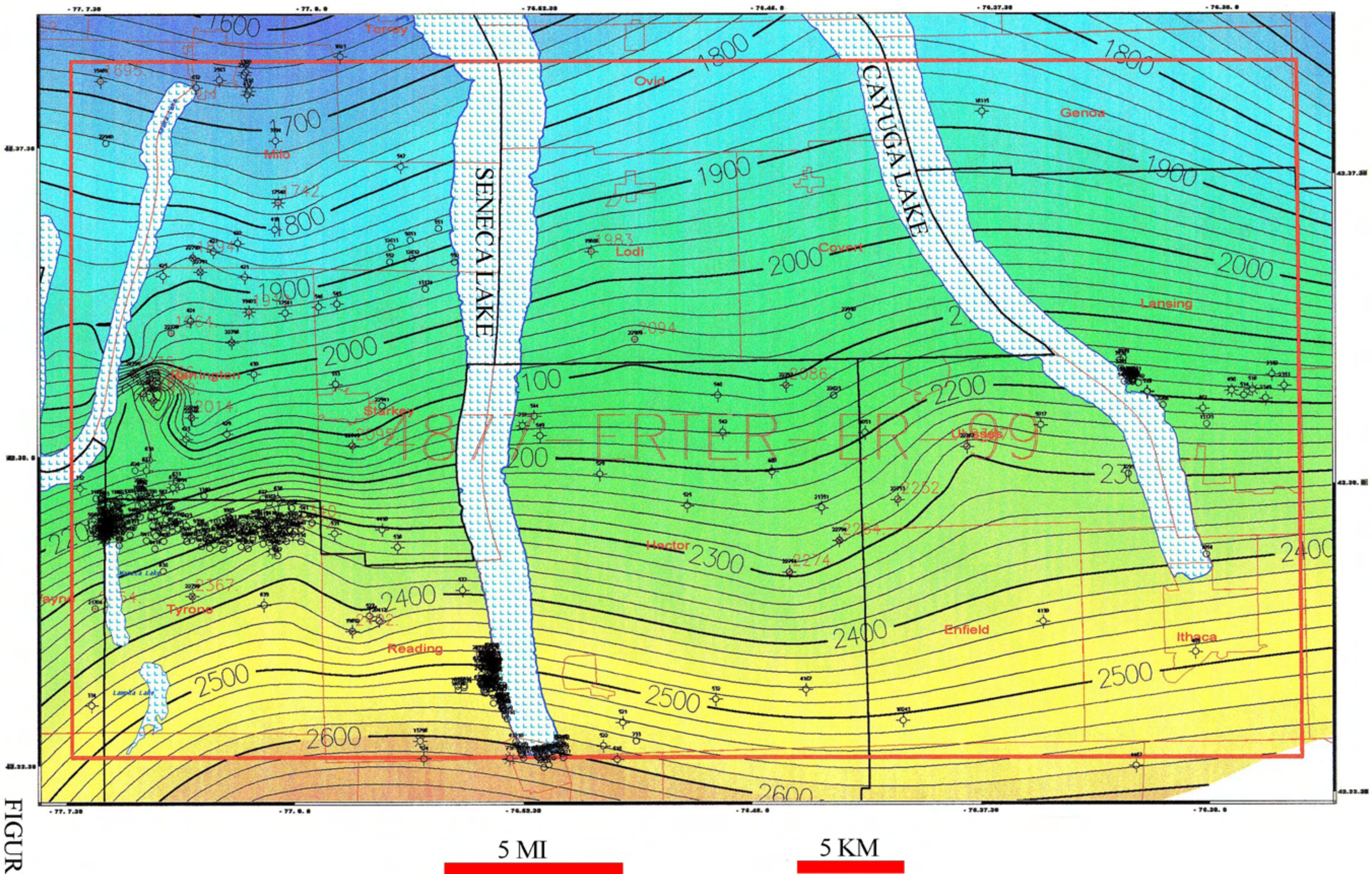

SENECA LAKE
CAYUGA LAKE
Torrey
Ovid
Genoa
Milo
Lodi
Covert
Lansing
Barrington
Starkey
Ulysses
Hector
Tyrone
Reading
Enfield
Ithaca
1600
1700
1800
1900
2000
2200
2300
2400
2500
2600
5 MI
5 KM

FIGURE 22

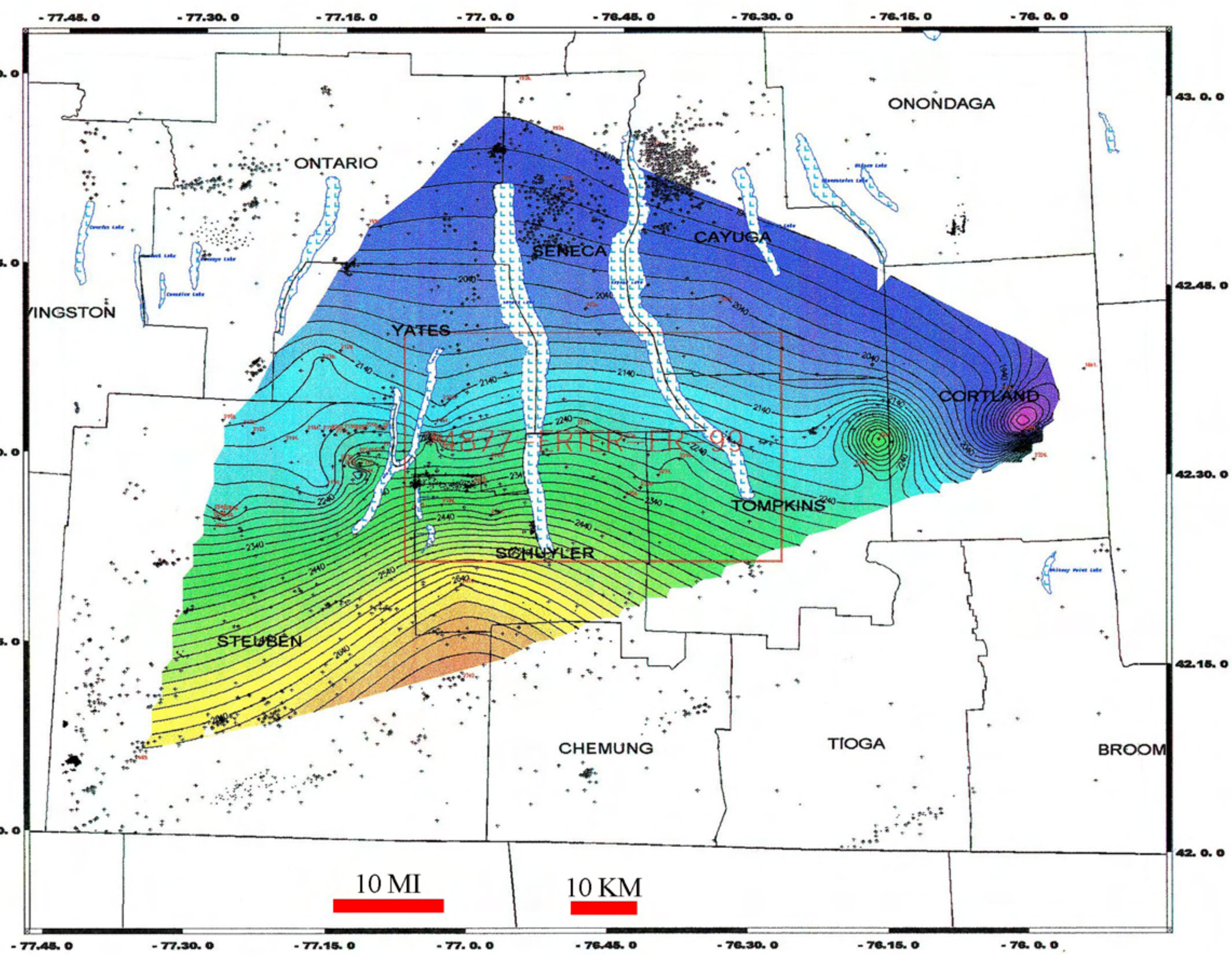

ONONDAGA
ONTARIO
SENECA
CAYUGA
YATES
CORTLAND
TOMPKINS
SCHUYLER
STEUBEN
CHEMUNG
TIOGA
BROOM
VINGSTON
10 MI
10 KM
- 77.45. 0
- 77.30. 0
- 77.15. 0
- 77. 0. 0
- 76.45. 0
- 76.30. 0
- 76.15. 0
- 76. 0. 0
43. 0. 0
42.45. 0
42.30. 0
42.15. 0
42. 0. 0

FIGURE 23

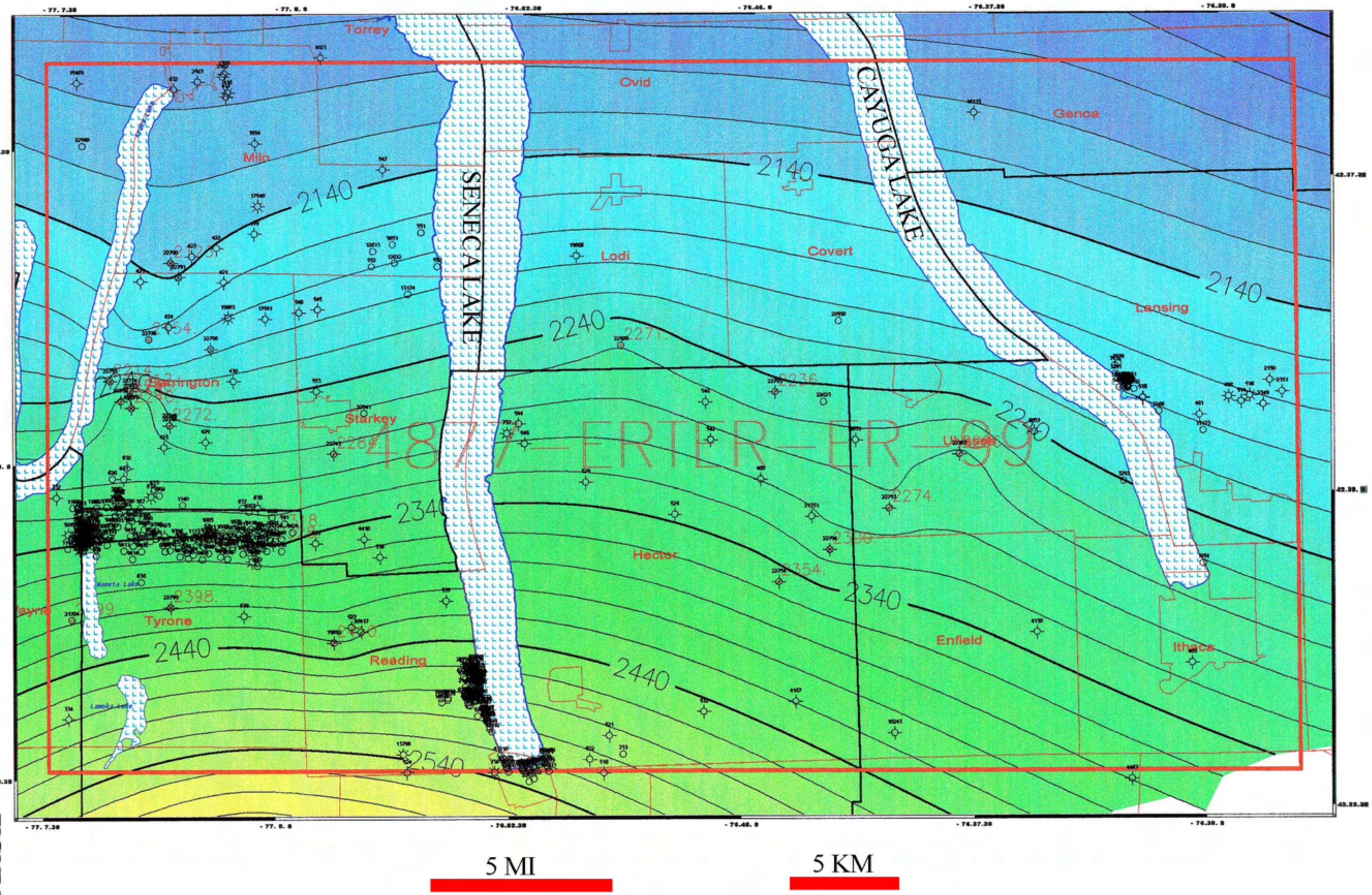

Torrey
Ovid
Genoa
Milo
SENECA LAKE
CAYUGA LAKE
Lodi
Covert
Lansing
Barrington
Starkey
Ulysses
Hector
Tyrone
Reading
Enfield
Ithaca
2140
2240
2340
2440
2540
5 MI
5 KM

FIGURE 24

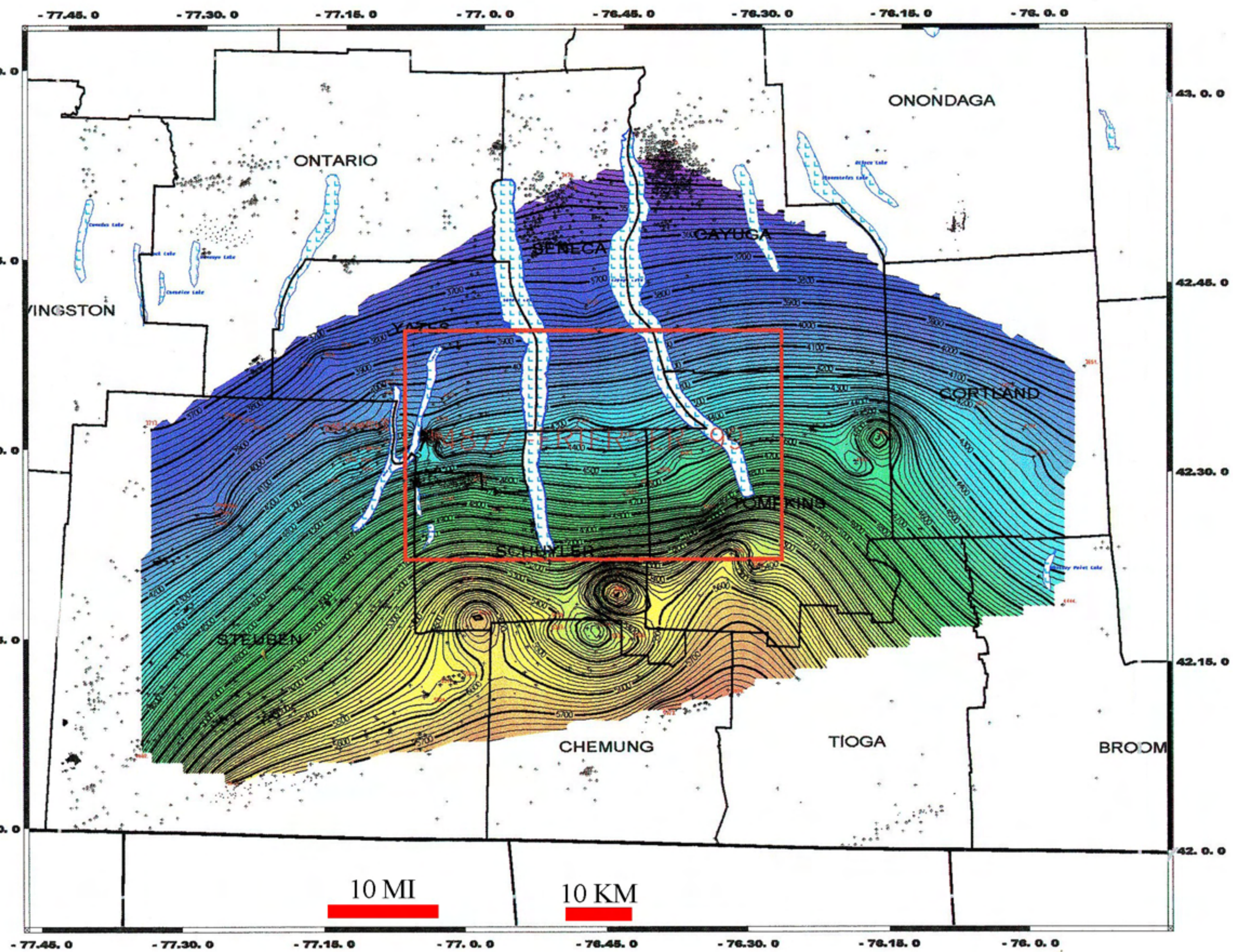
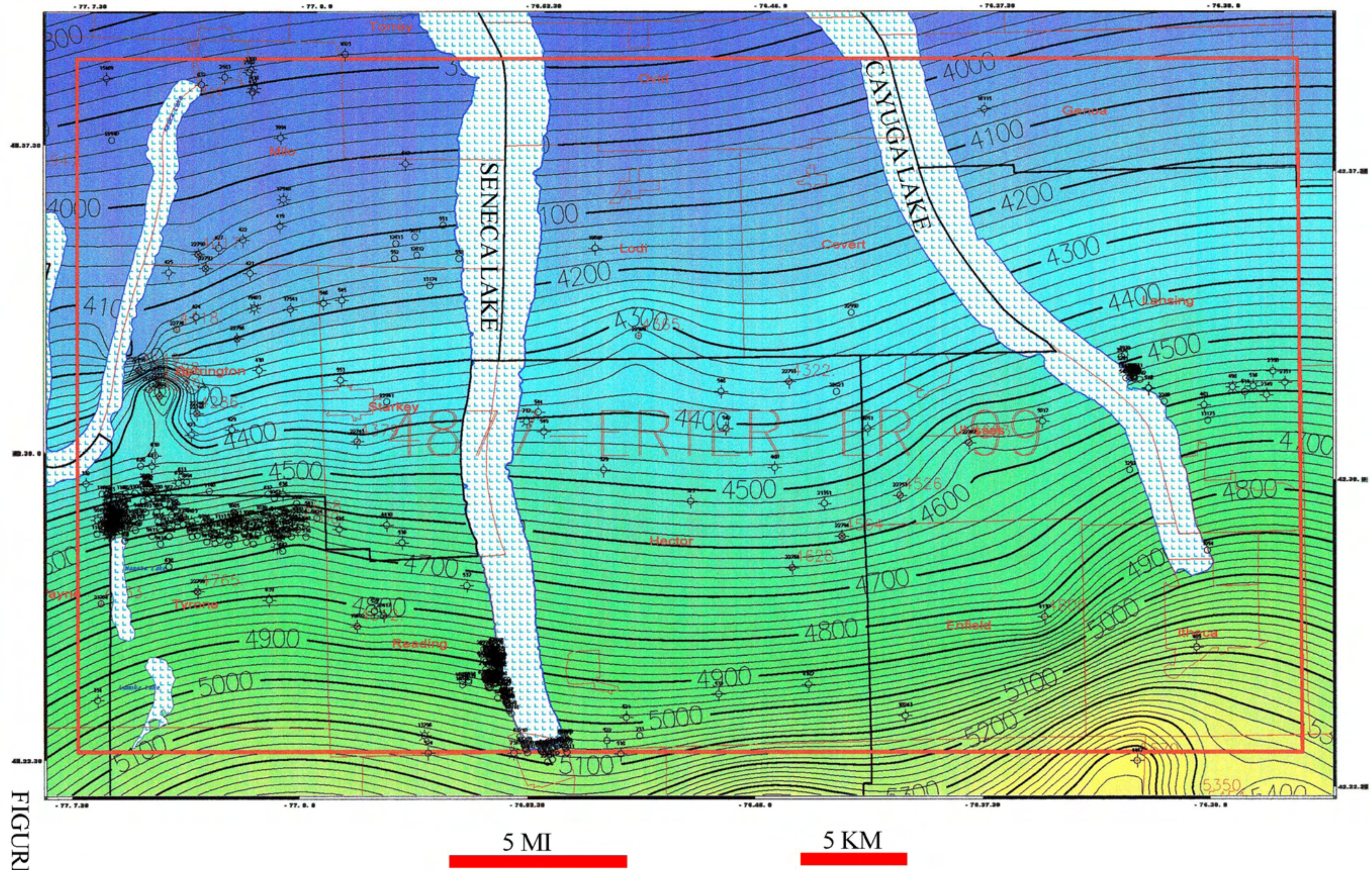

- 77.45. 0
- 77.30. 0
- 77.15. 0
- 77. 0. 0
- 76.45. 0
- 76.30. 0
- 76.15. 0
- 76. 0. 0
43. 0. 0
42.45. 0
42.30. 0
42.15. 0
42. 0. 0
ONONDAGA
ONTARIO
SENECA
CAYUGA
VINGSTON
YATES
CORTLAND
TOMPKINS
SCHUYLER
STEUBEN
CHEMUNG
TIOGA
BROOM
10 MI
10 KM

FIGURE 25



SENECA LAKE
CAYUGA LAKE
Torrey
Ovid
Genoa
Milo
Lodi
Covert
Lansing
Barrington
Starkey
Ulysses
Hector
Tyrone
Reading
Enfield
Ithaca
4000
4100
4200
4300
4400
4500
4600
4700
4800
4900
5000
5100
5200
5300
5350
5400
5 MI
5 KM

FIGURE 26

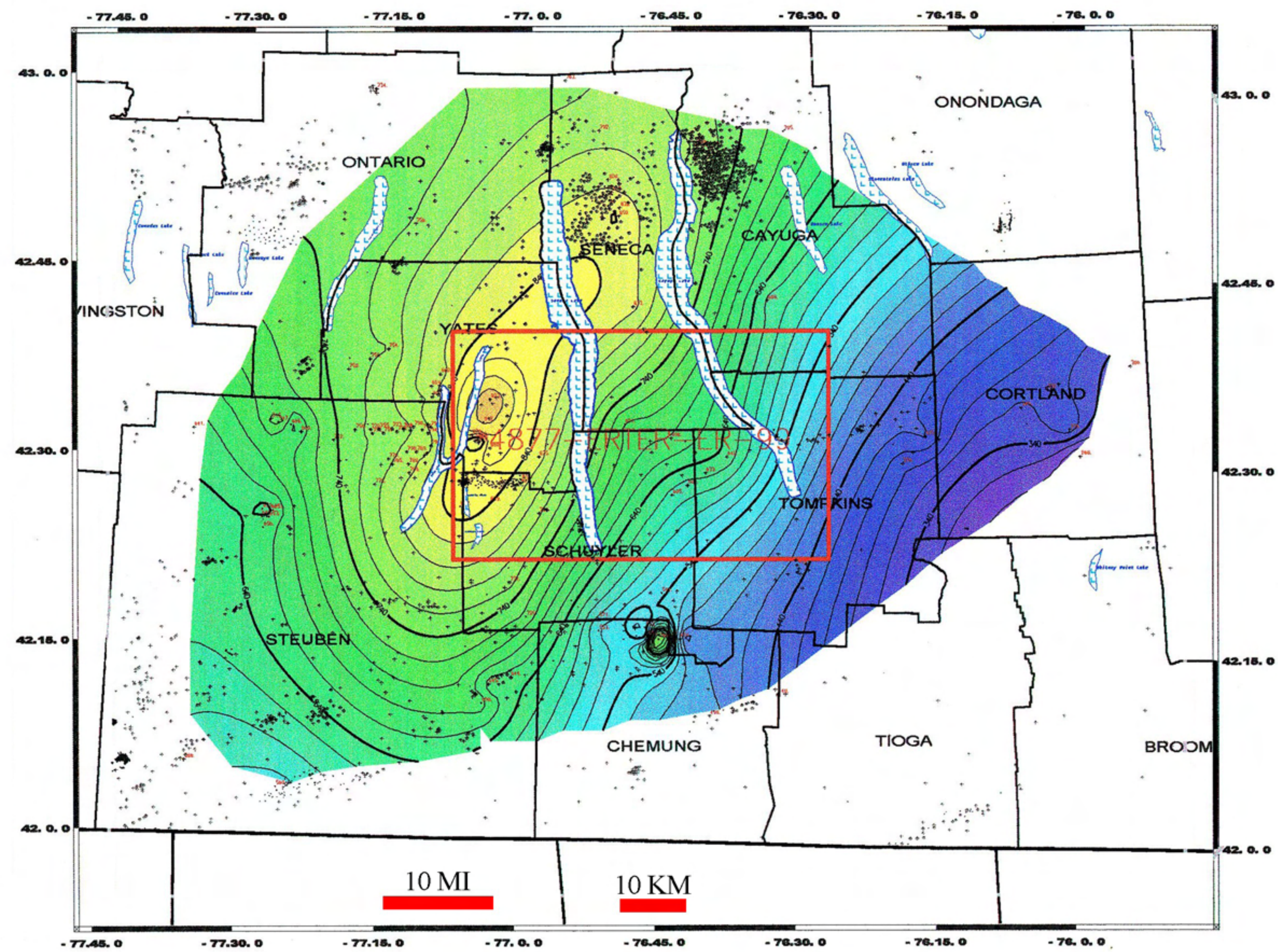

- 77.45. 0
- 77.30. 0
- 77.15. 0
- 77. 0. 0
- 76.45. 0
- 76.30. 0
- 76.15. 0
- 76. 0. 0
43. 0. 0
42.45. 0
42.30. 0
42.15. 0
42. 0. 0
ONONDAGA
ONTARIO
SENECA
CAYUGA
VINGSTON
YATES
CORTLAND
TOMPKINS
SCHUYLER
STEUBEN
CHEMUNG
TIOGA
BROOM
10 MI
10 KM

FIGURE 27

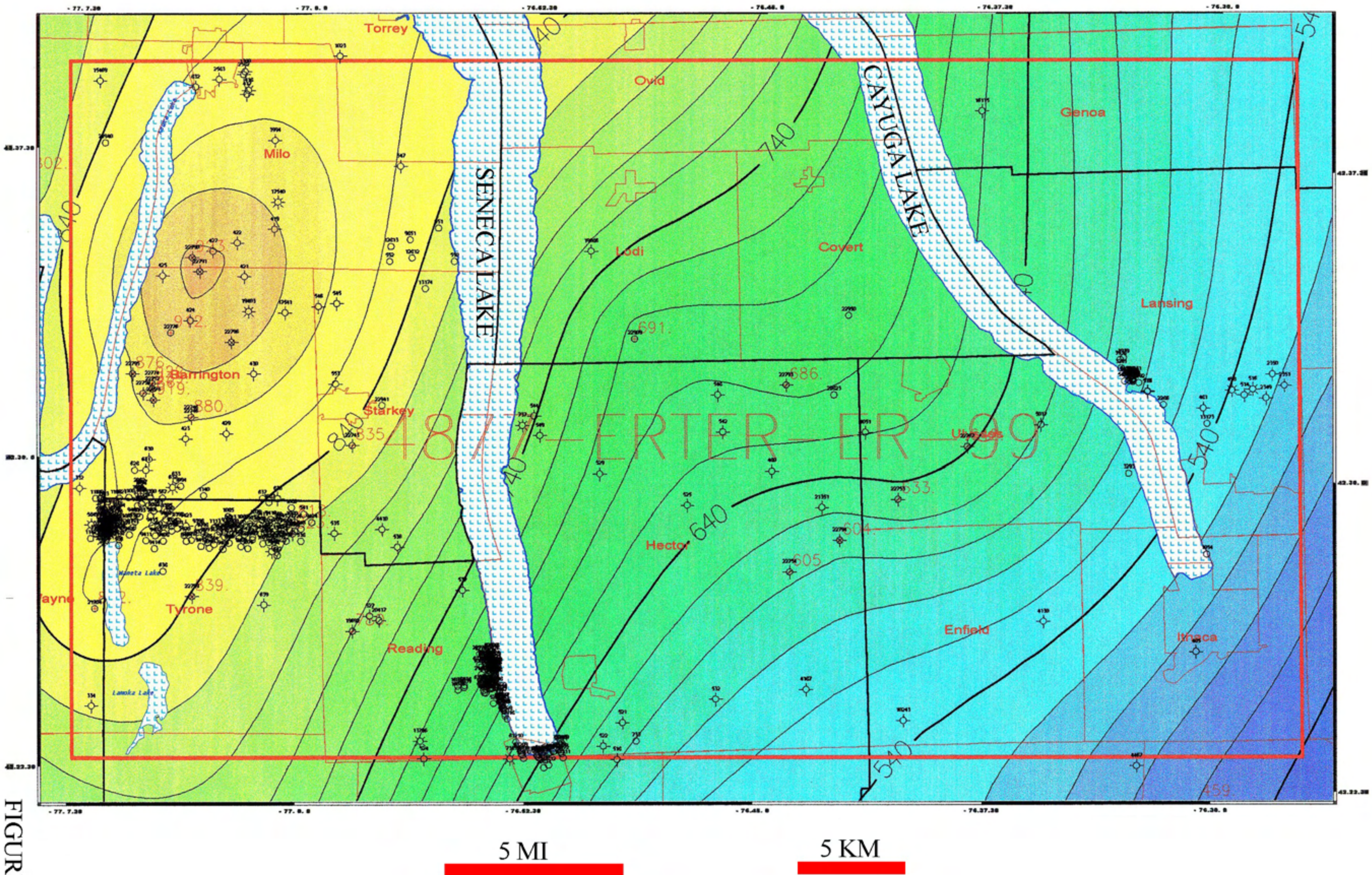

Torrey
Ovid
Genoa
Milo
SENECA LAKE
CAYUGA LAKE
Lodi
Covert
Lansing
Barrington
Starkey
Ulysses
Hector
Tyrone
Reading
Enfield
Ithaca
Waneta Lake
Lamoka Lake
740
640
540
840
5 MI
5 KM

FIGURE 28

GLODES CORNERS ROAD

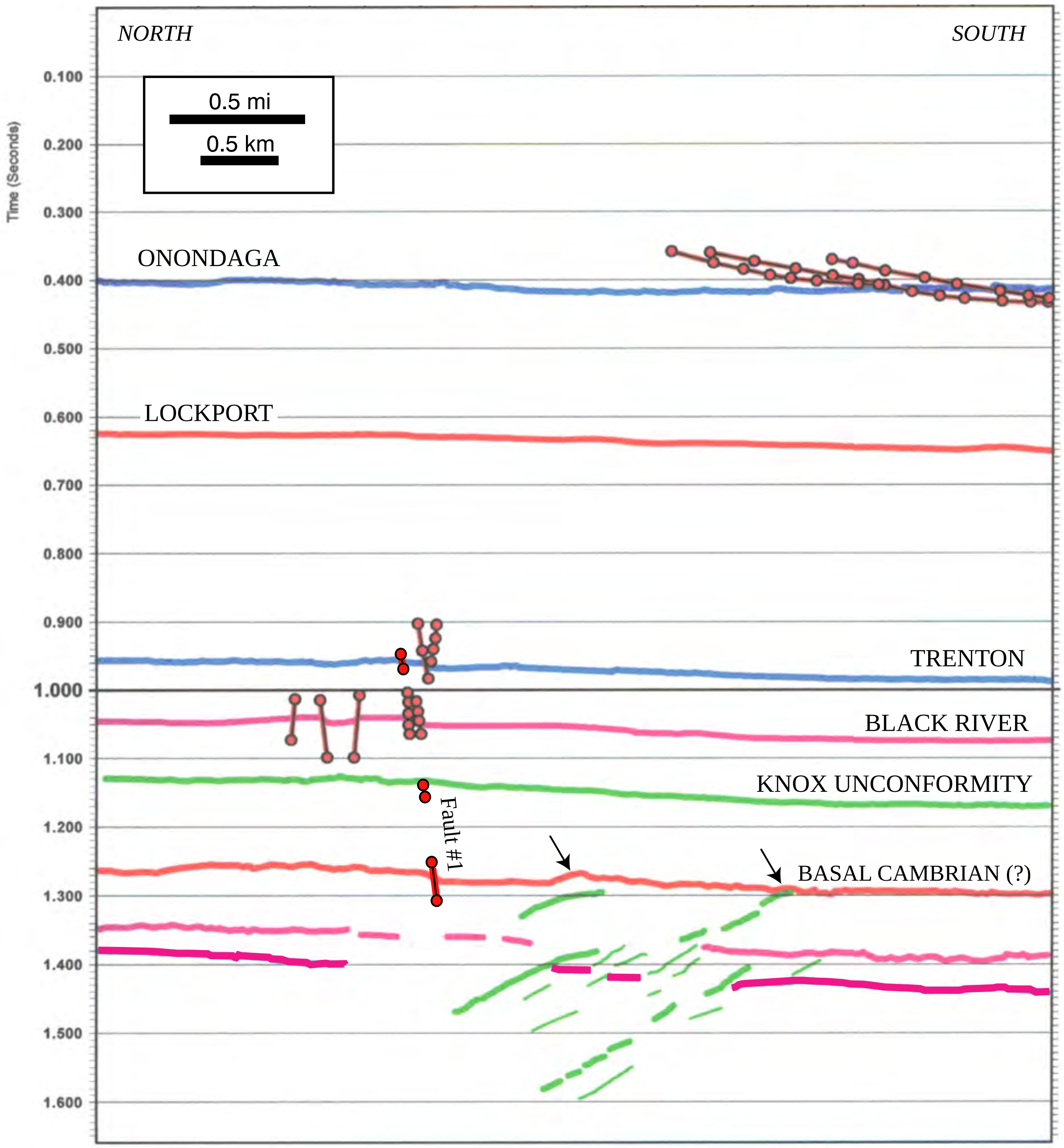


FIGURE 29

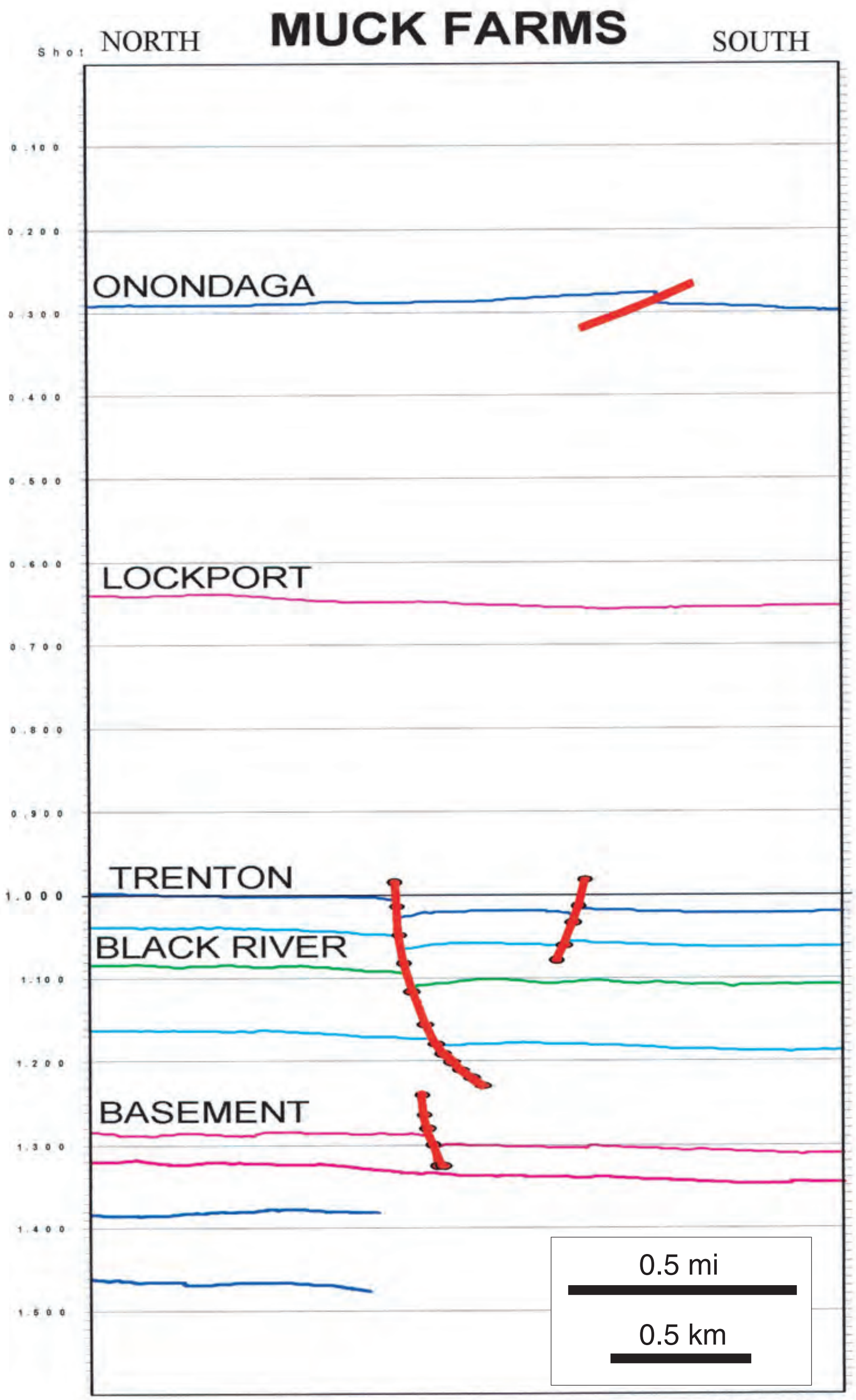
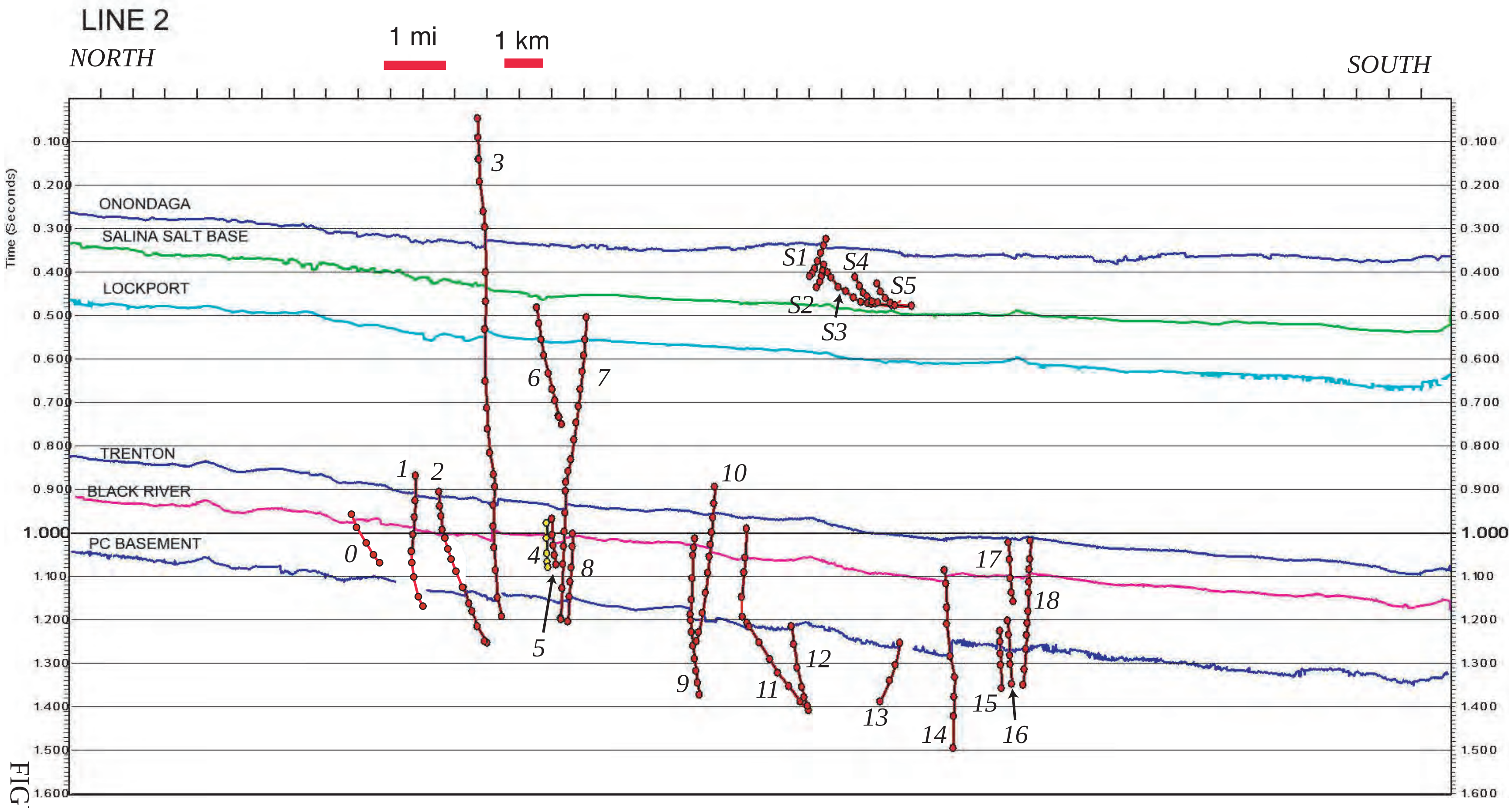

MUCK FARMS
Shot
NORTH
SOUTH
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000
1.100
1.200
1.300
1.400
1.500
ONONDAGA
LOCKPORT
TRENTON
BLACK RIVER
BASEMENT
0.5 mi
0.5 km

FIGURE 30



LINE 2
NORTH
SOUTH
1 mi
1 km
Time (Seconds)
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000
1.100
1.200
1.300
1.400
1.500
1.600
ONONDAGA
SALINA SALT BASE
LOCKPORT
TRENTON
BLACK RIVER
PC BASEMENT
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
S1
S2
S3
S4
S5

FIGURE 31

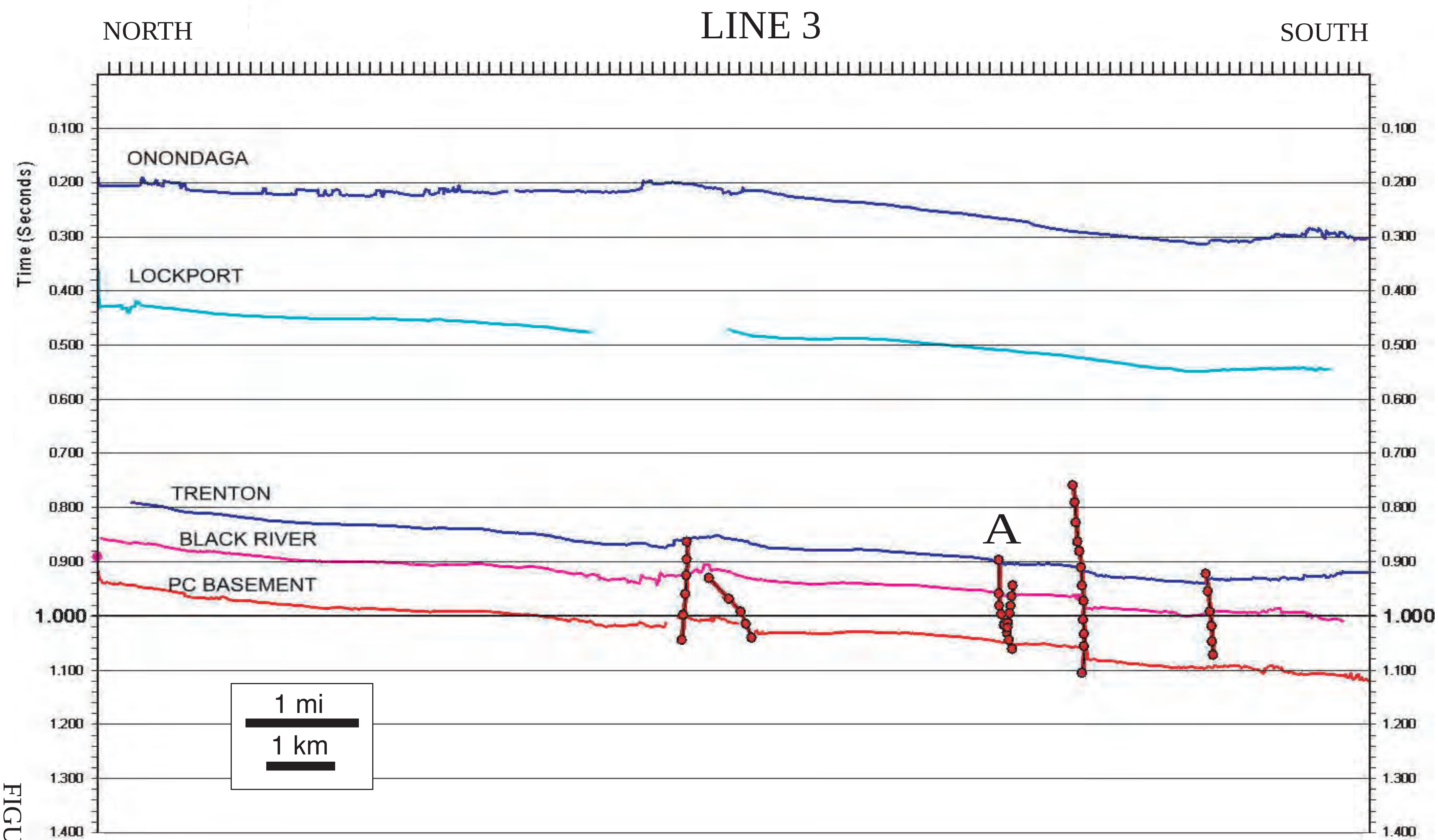

LINE 3
NORTH
SOUTH
Time (Seconds)
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000
1.100
1.200
1.300
1.400
ONONDAGA
LOCKPORT
TRENTON
BLACK RIVER
PC BASEMENT
A
1 mi
1 km

FIGURE 32

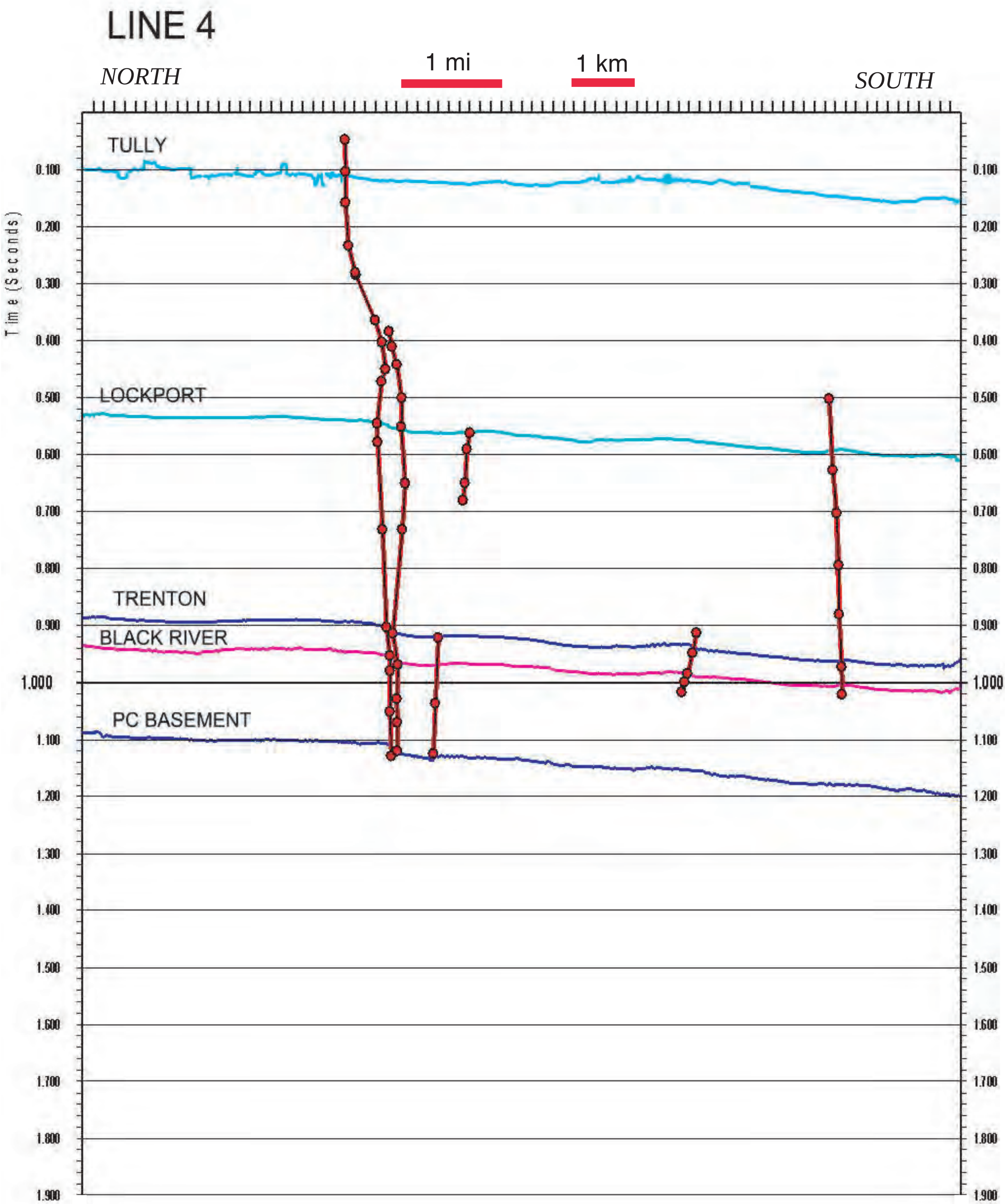

LINE 4
NORTH
1 mi
1 km
SOUTH
TULLY
LOCKPORT
TRENTON
BLACK RIVER
PC BASEMENT
Time (Seconds)
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000
1.100
1.200
1.300
1.400
1.500
1.600
1.700
1.800
1.900

FIGURE 33

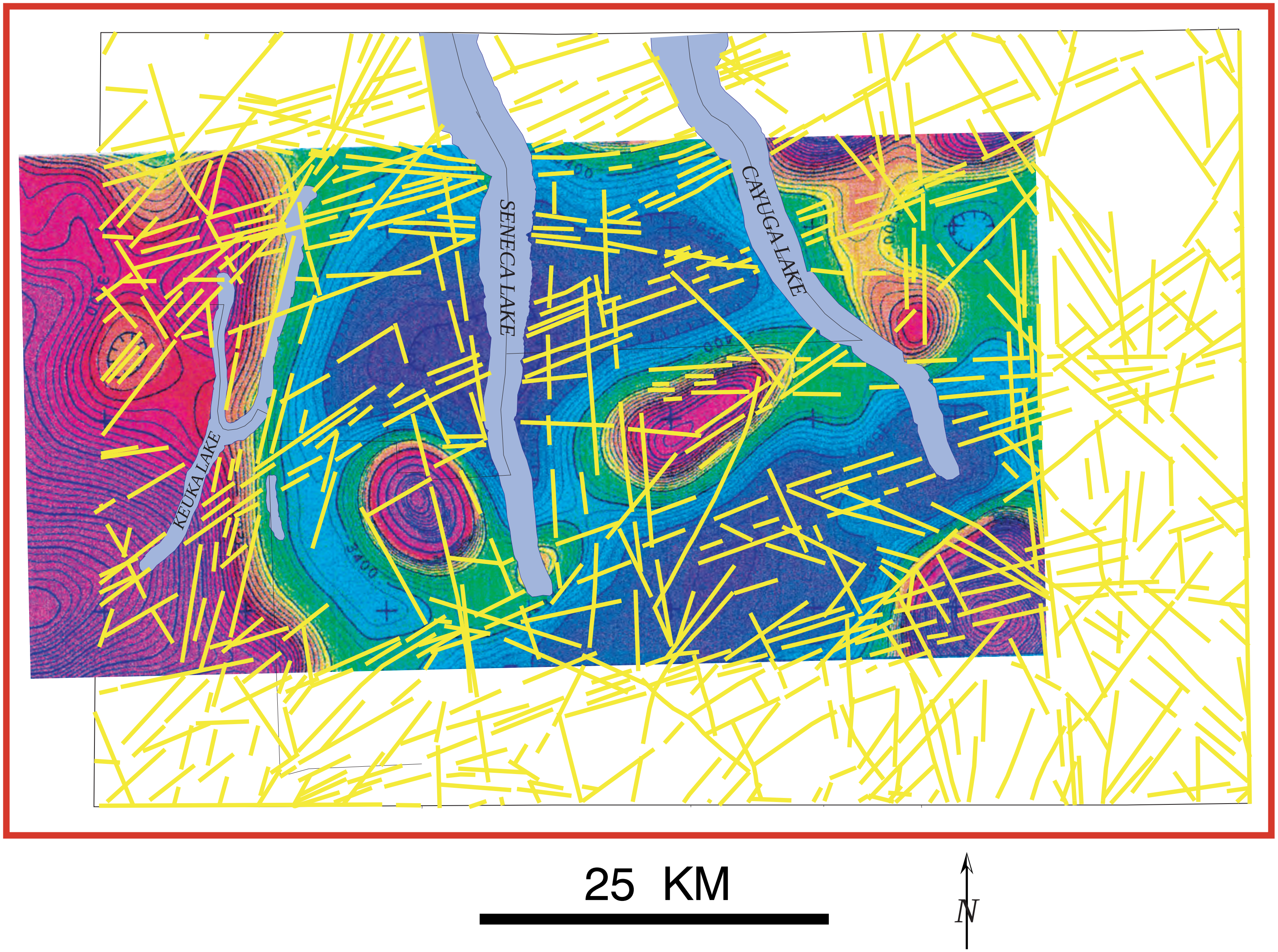


FIGURE 34

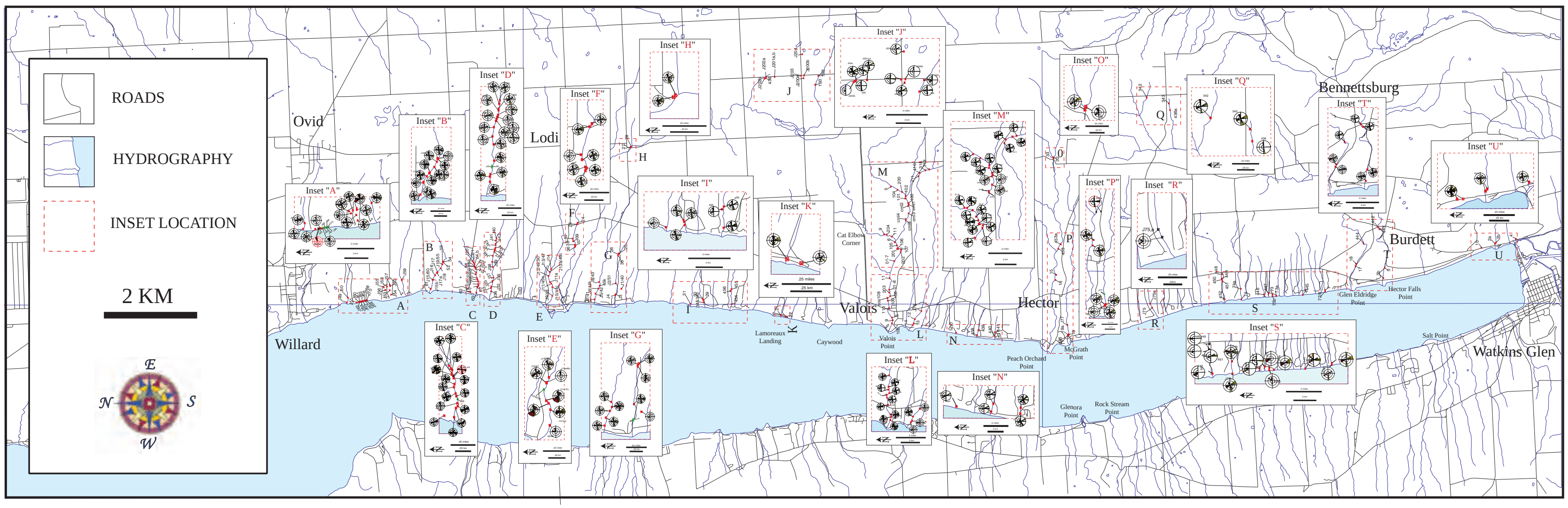

ROADS
HYDROGRAPHY
INSET LOCATION
2 KM
E
N
S
W
Ovid
Lodi
Willard
Valois
Hector
Bennettsburg
Burdett
Watkins Glen
Cat Elbow Corner
Lamoreaux Landing
Caywood
Valois Point
Peach Orchard Point
McGrath Point
Glenora Point
Rock Stream Point
Glen Eldridge Point
Hector Falls Point
Salt Point
Inset "A"
Inset "B"
Inset "C"
Inset "D"
Inset "E"
Inset "F"
Inset "G"
Inset "H"
Inset "I"
Inset "J"
Inset "K"
Inset "L"
Inset "M"
Inset "N"
Inset "O"
Inset "P"
Inset "Q"
Inset "R"
Inset "S"
Inset "T"
Inset "U"

FIGURE 35A

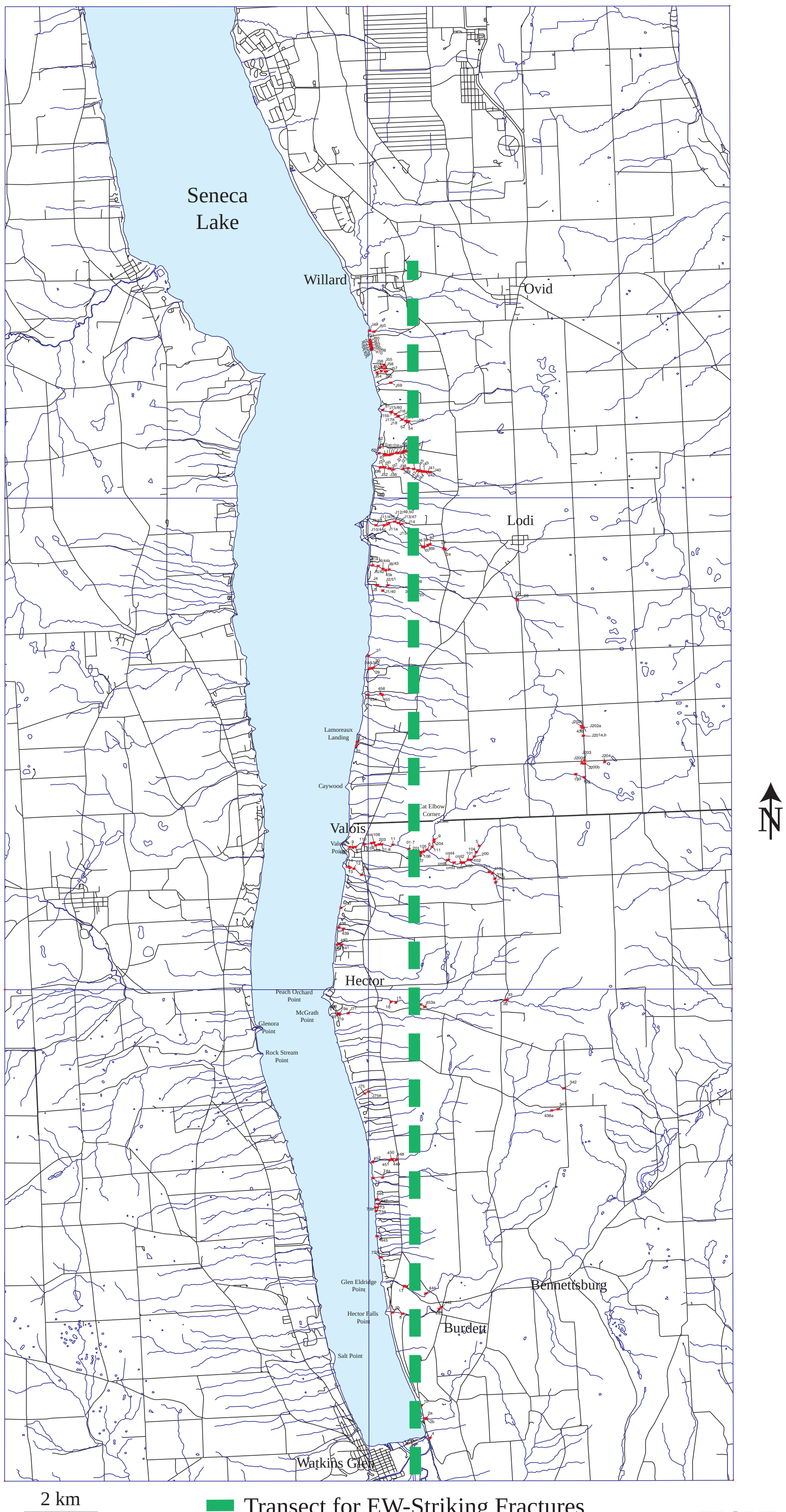

Seneca Lake
Willard
Ovid
Lodi
Lamoreaux Landing
Caywood
Cat Elbow Corner
Valois
Valois Point
Hector
Peach Orchard Point
McGrath Point
Glenora Point
Rock Stream Point
Glen Eldridge Point
Bennettsburg
Hector Falls Point
Burdett
Salt Point
Watkins Glen
N
2 km
Transect for EW-Striking Fractures

FIGURE 35B

E- AND ENE-STRIKING FRACTURE FREQUENCY

AT SITES EXTRAPOLATED TO A N-S TRANSECT

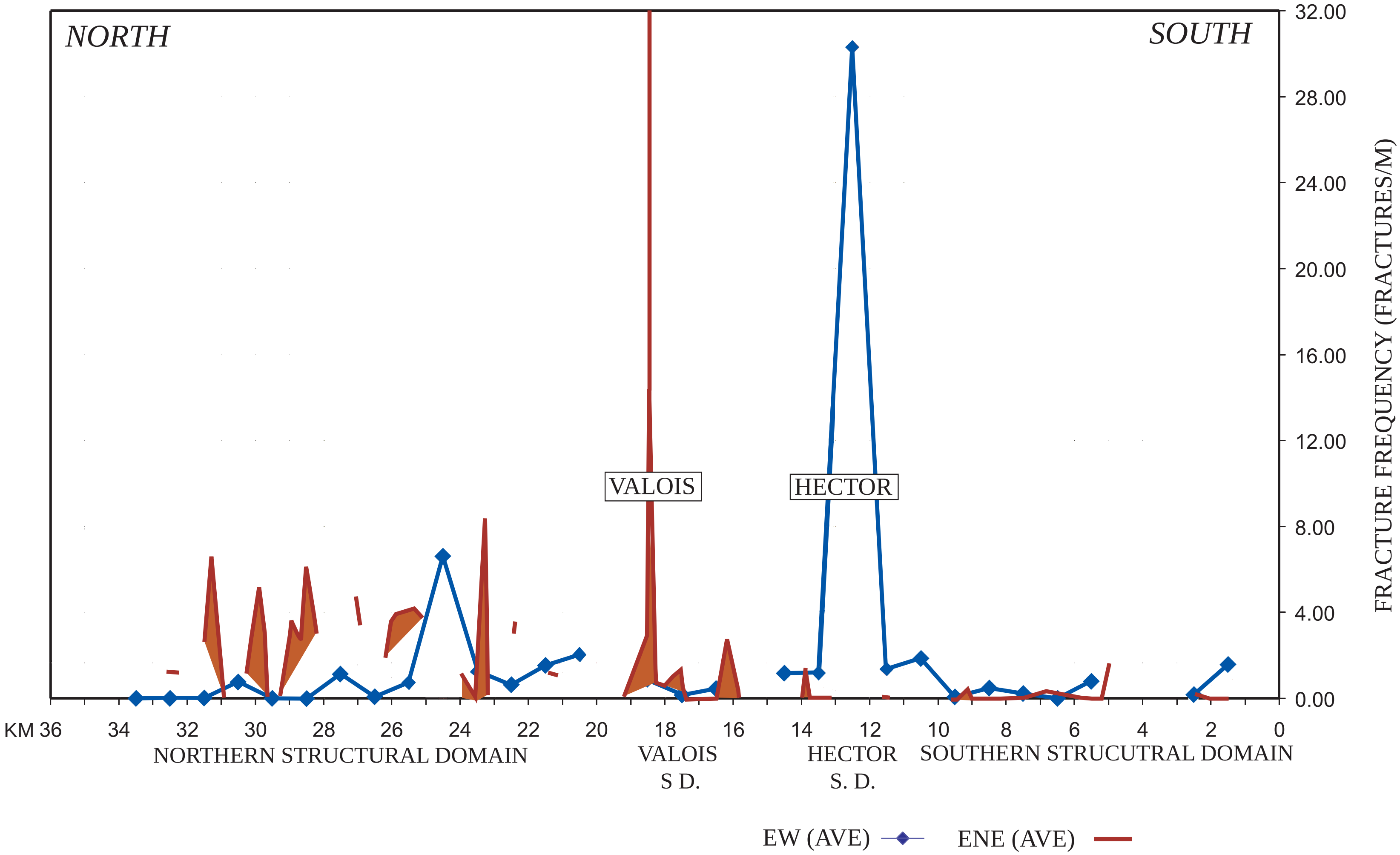
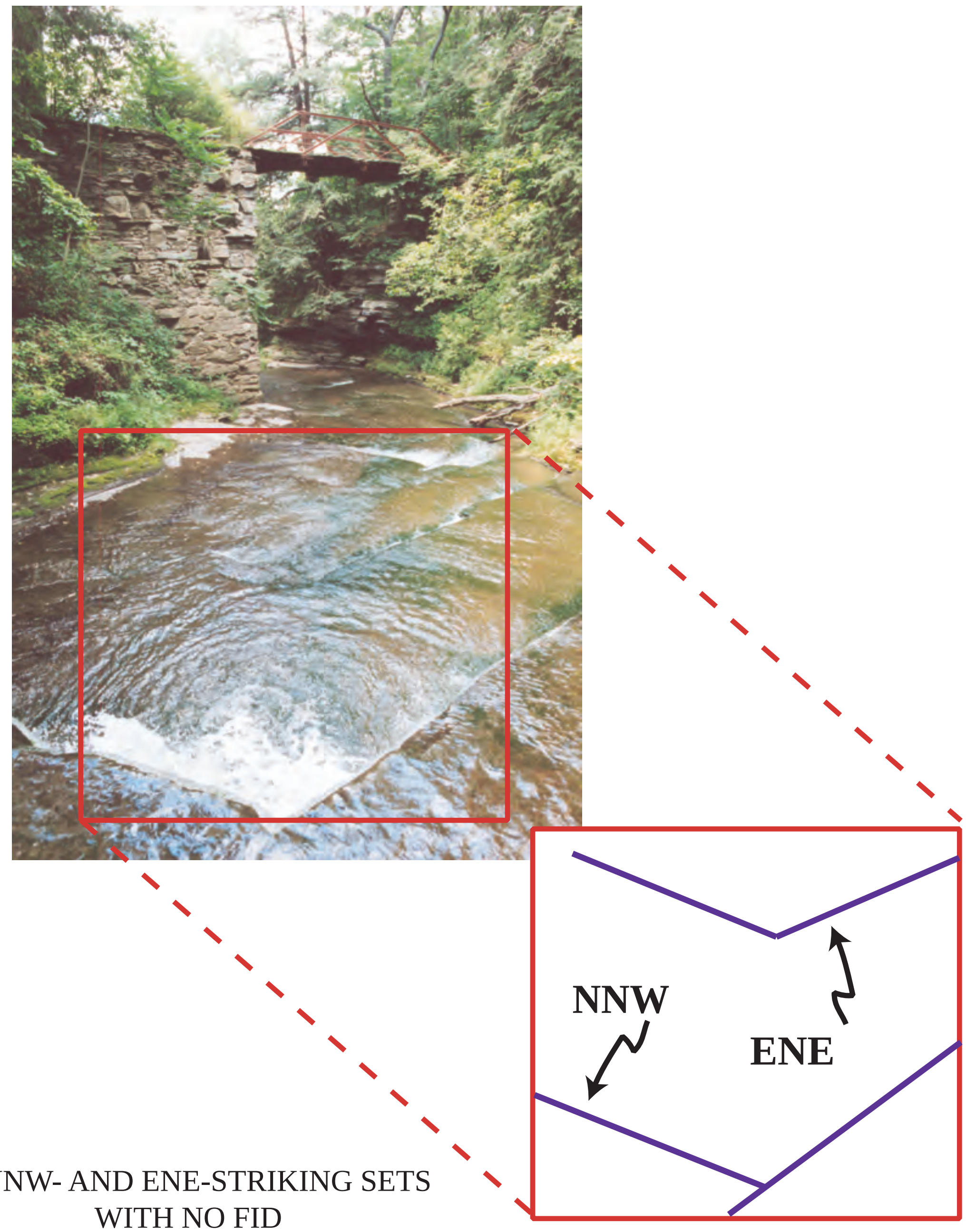


FIGURE 35C



NNW- AND ENE-STRIKING SETS
WITH NO FID
MIDDLE ROAD

FIGURE 36

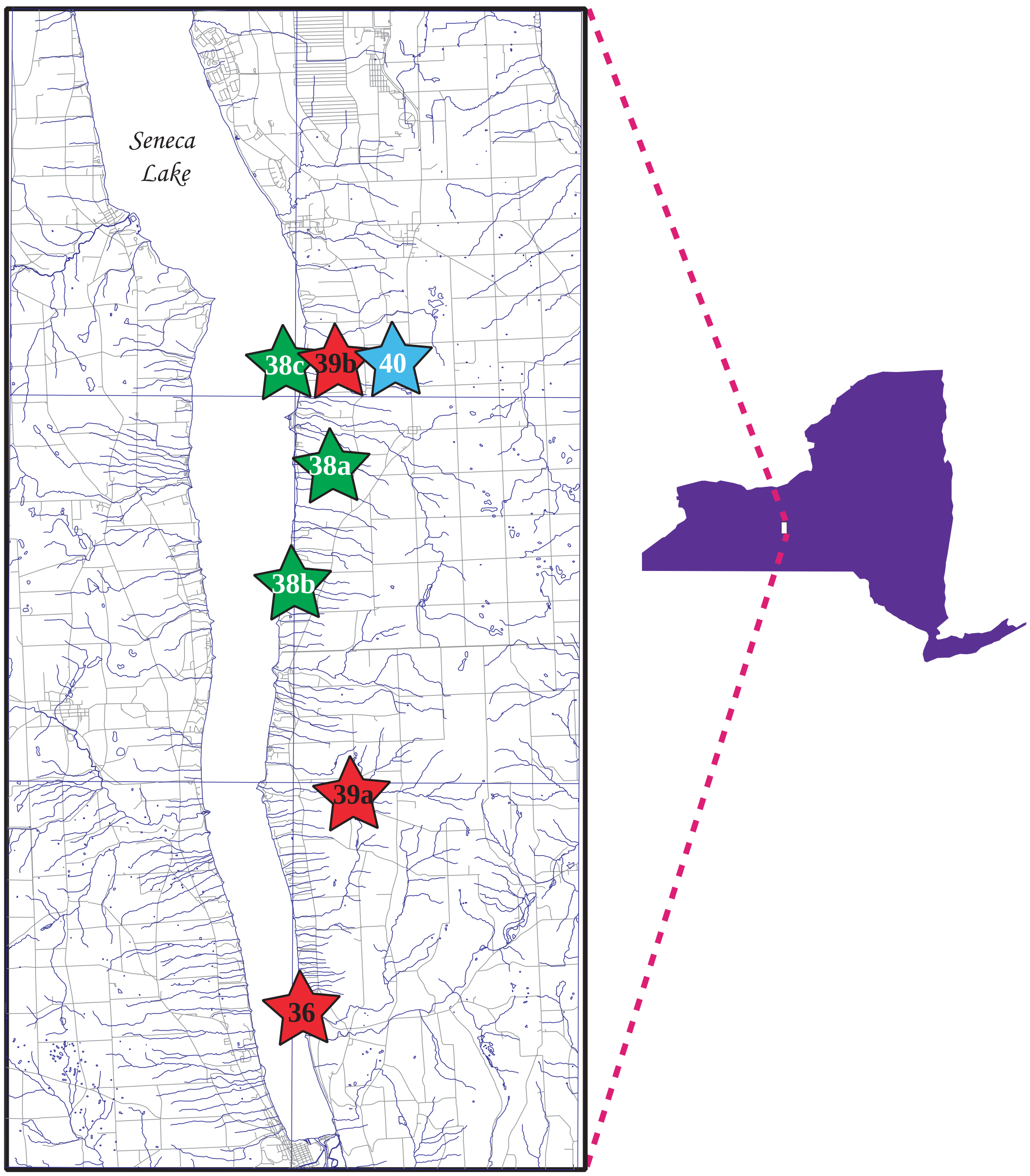


FIGURE 37

FIGURE 38

38a. ENE-STRIKING FID

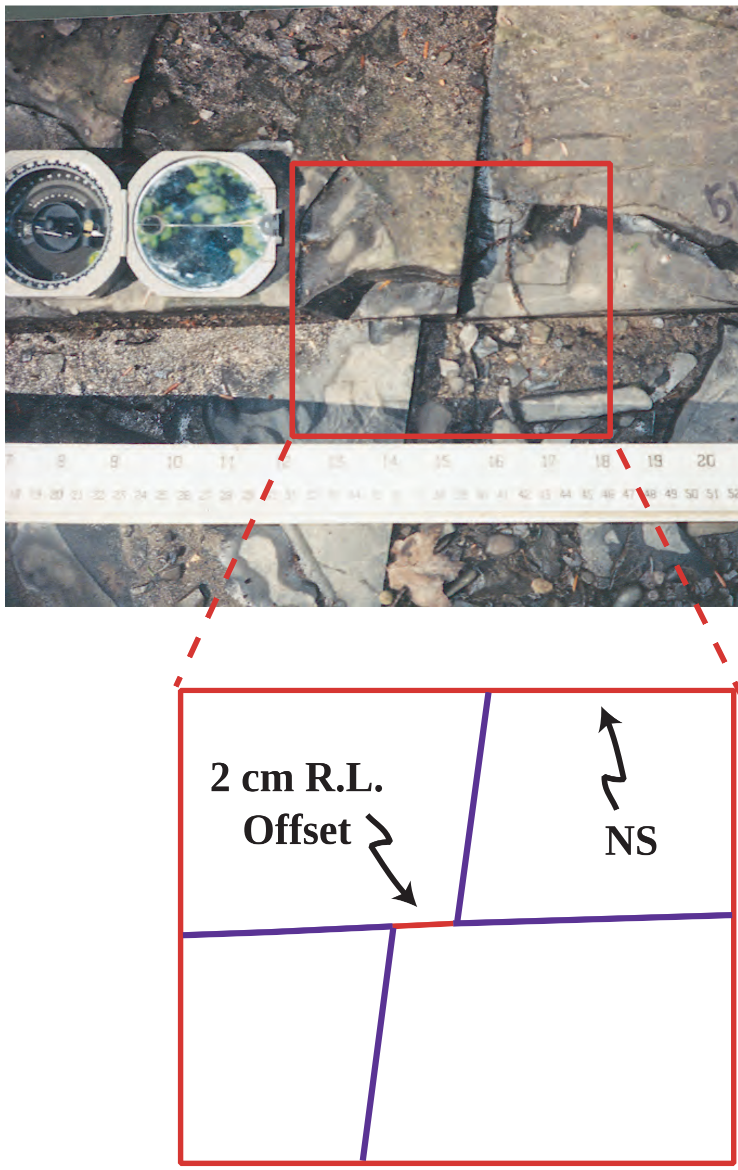
38b.. ENE-STRIKING FID

38c.. ENE-STRIKING FID

39a..   NNW-STRIKING FID

39b. NNW-STRIKING FID
SIXTEEN FALLS CREEK

FIGURE 39



40. N-STRKING FRACTURE
WITH DEXTRAL MOTION
SIXTEEN FALLS CREEK

FIGURE 40

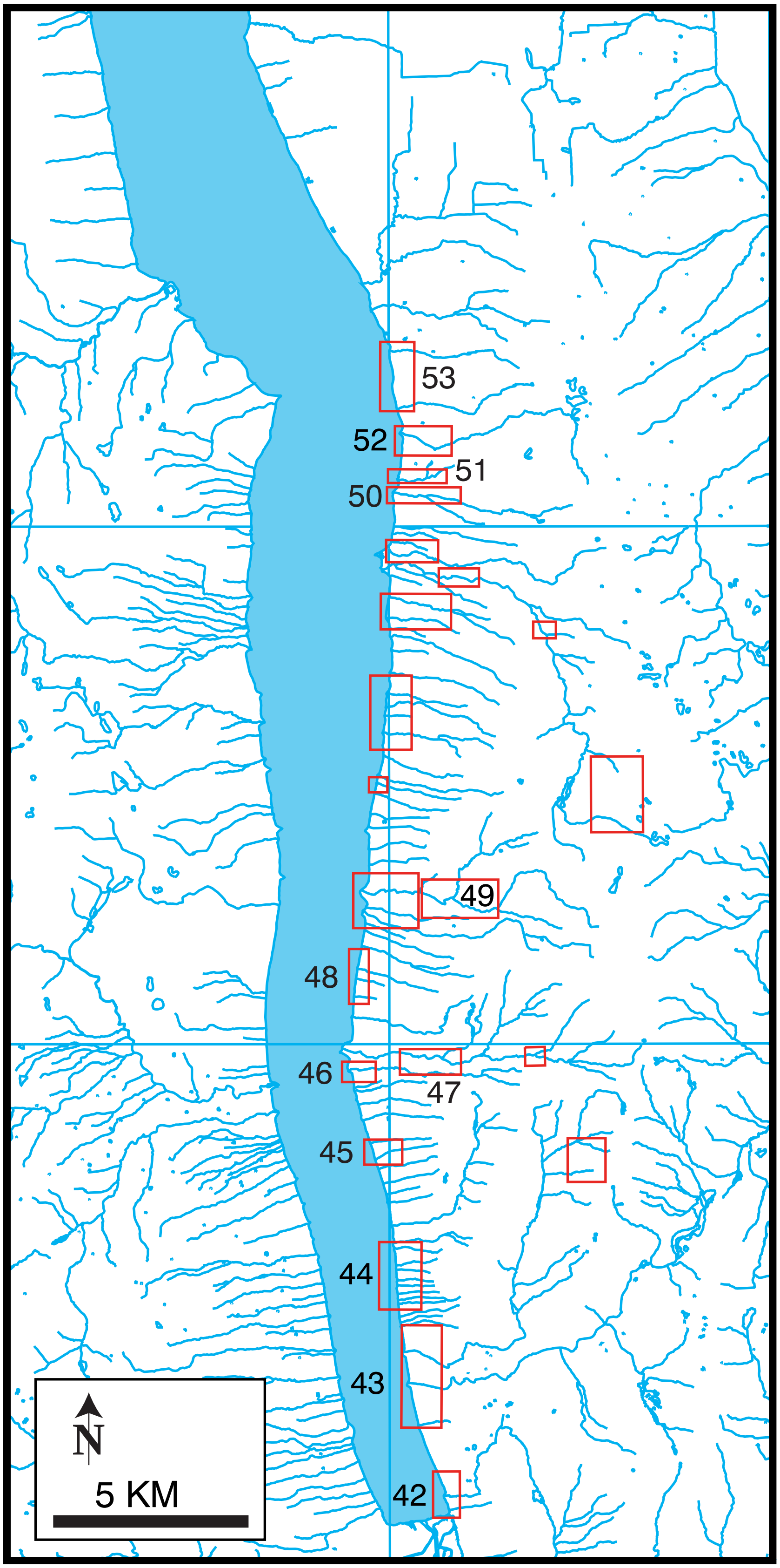


FIGURE 41

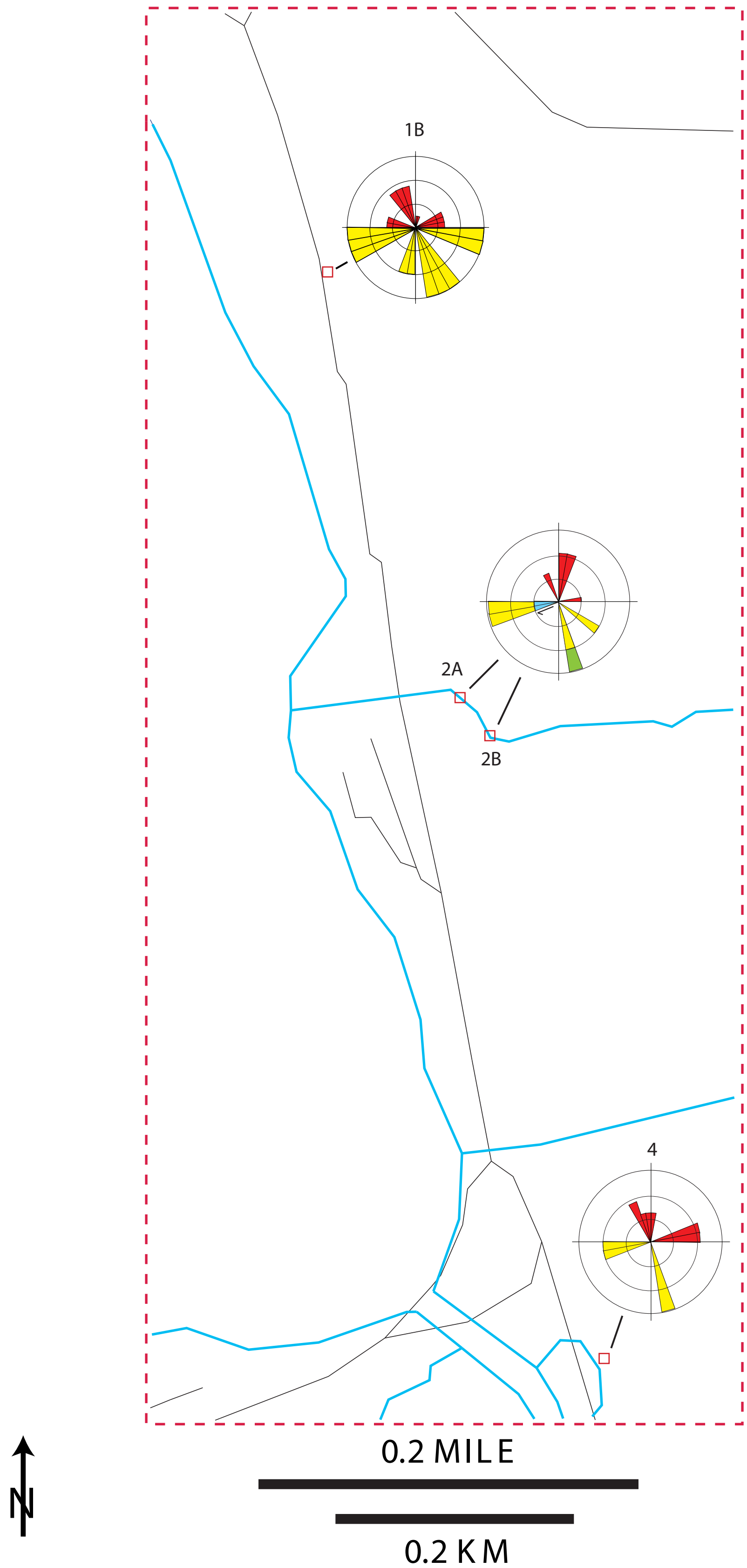


FIGURE 42

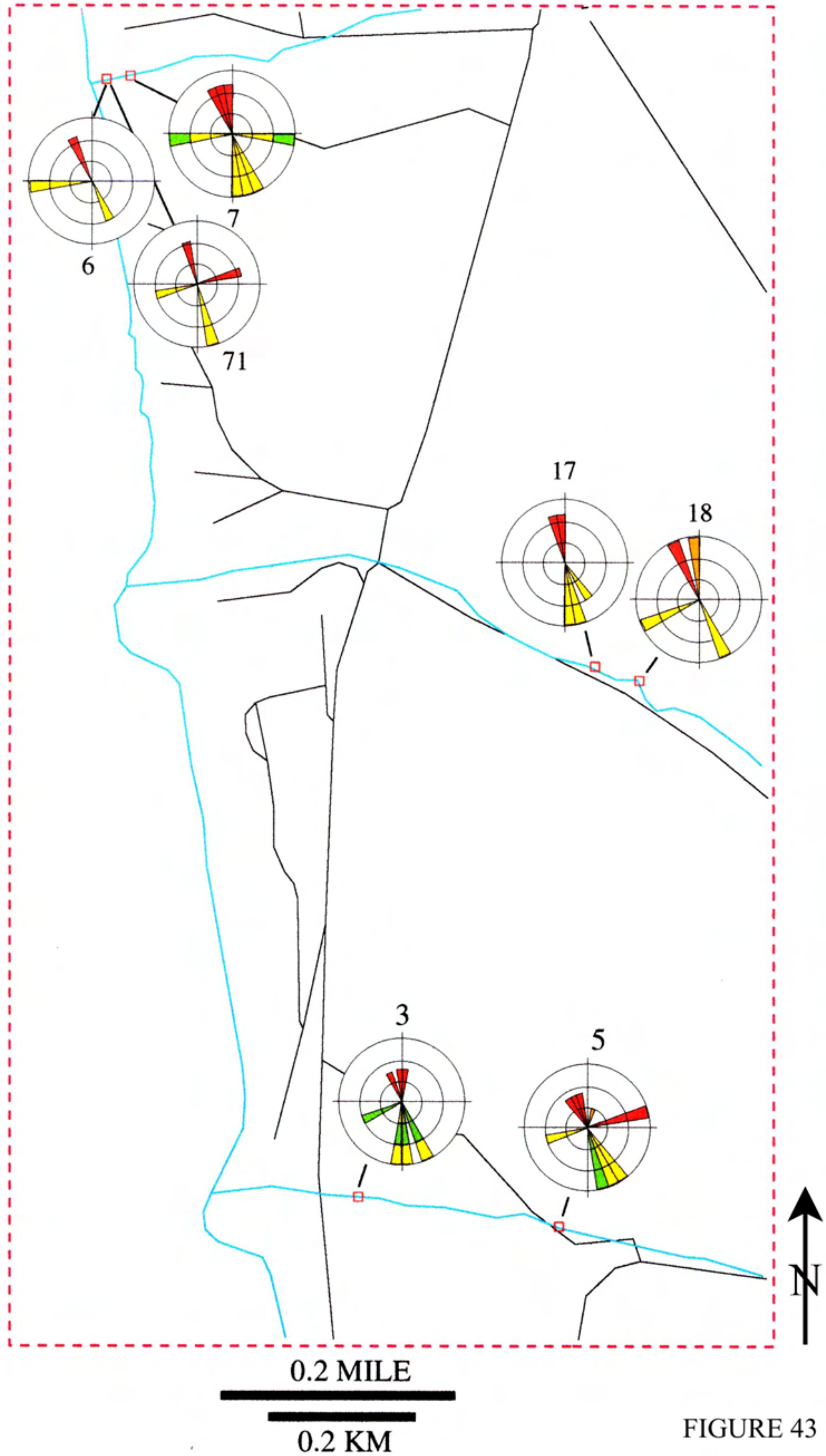


FIGURE 43

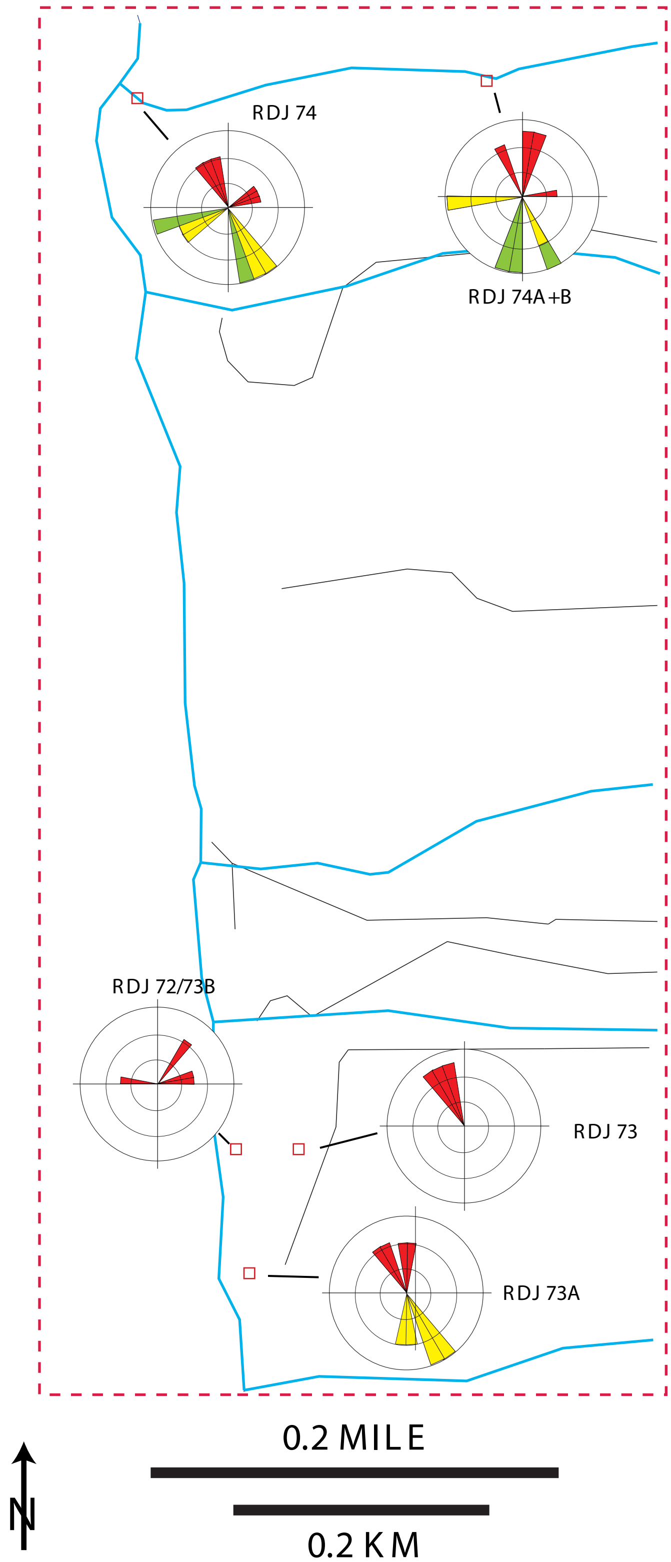


FIGURE 44

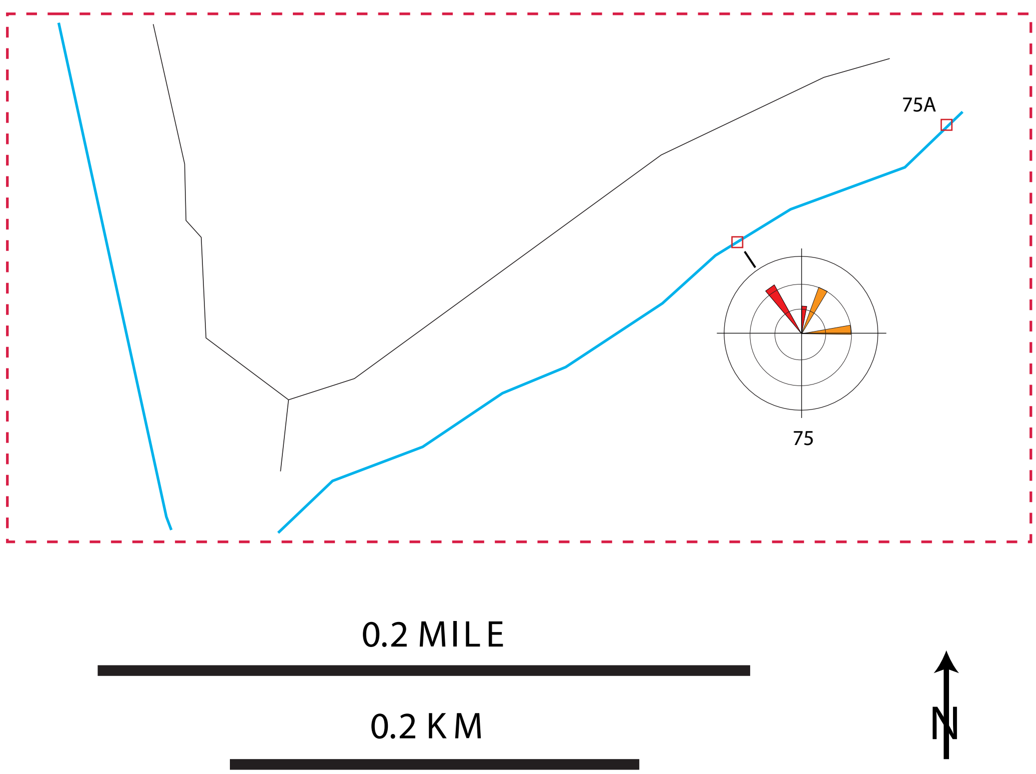


FIGURE 45

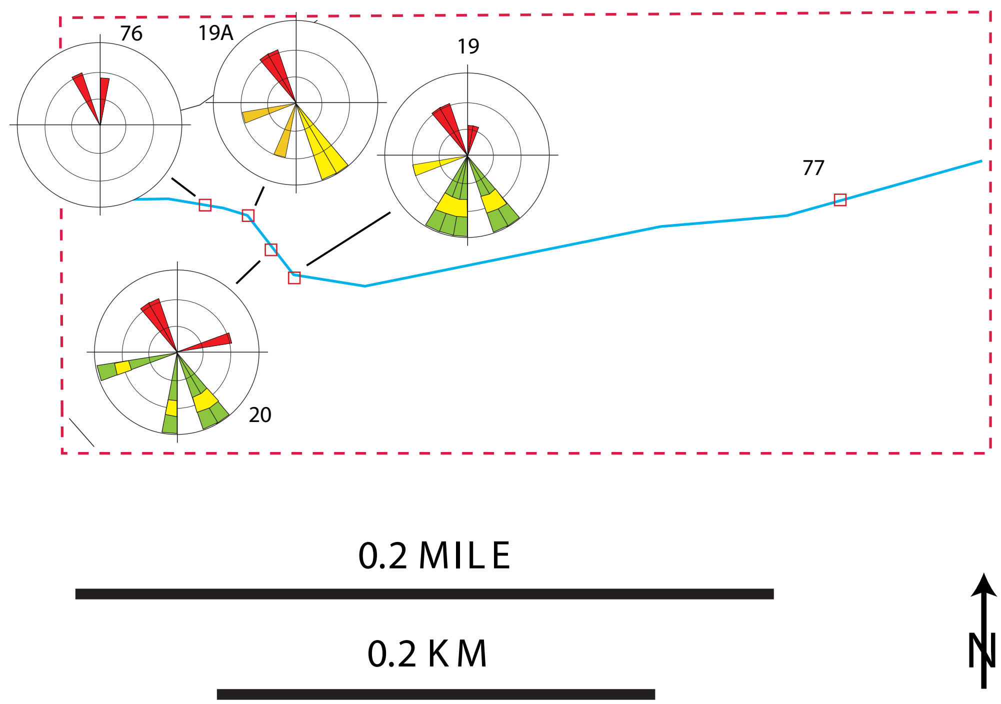


FIGURE 46

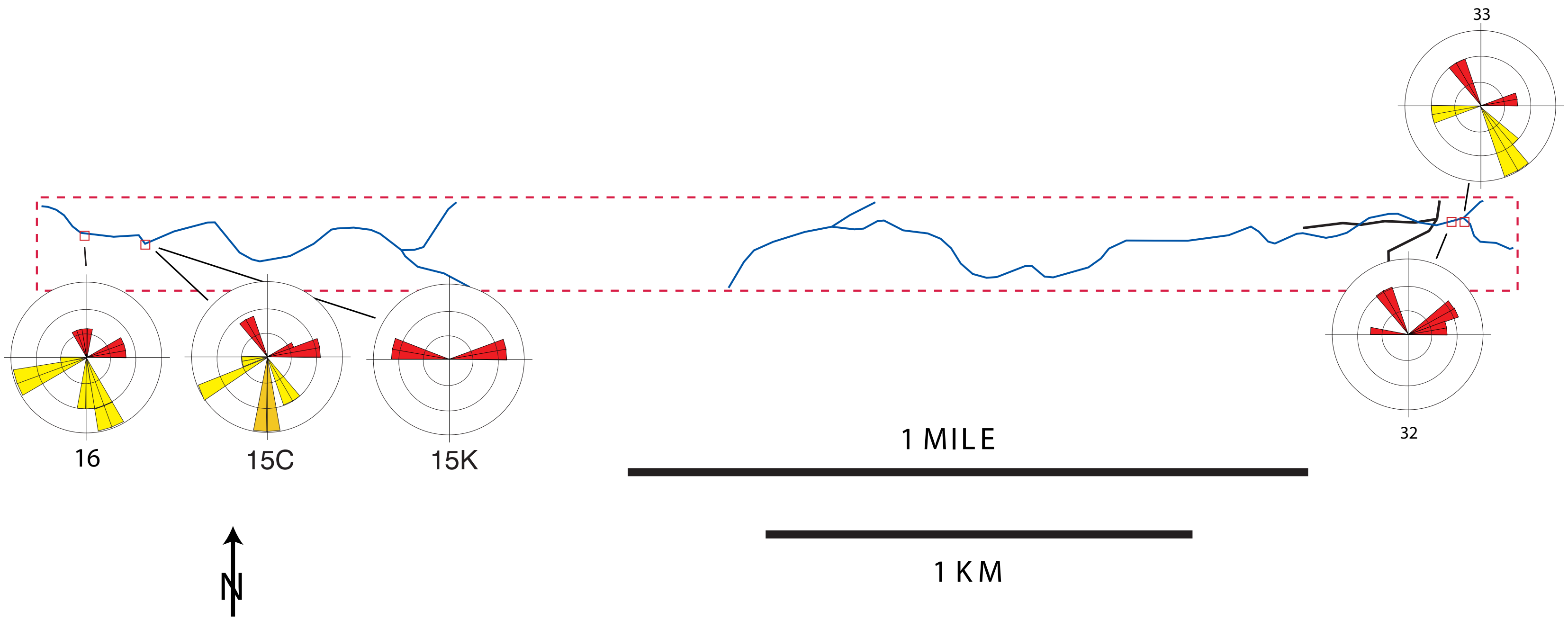


FIGURE 47

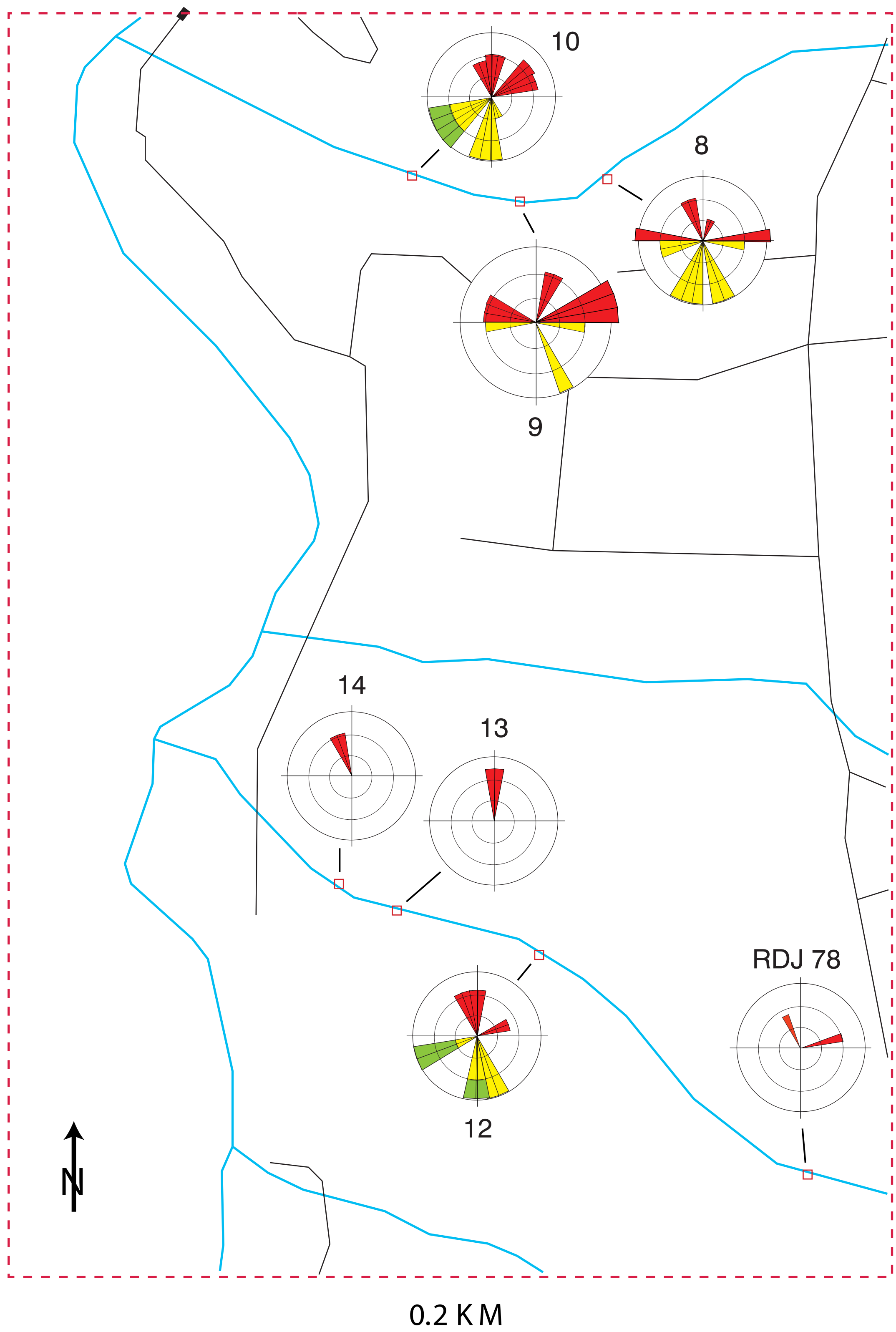


FIGURE 48

FIGURE 49

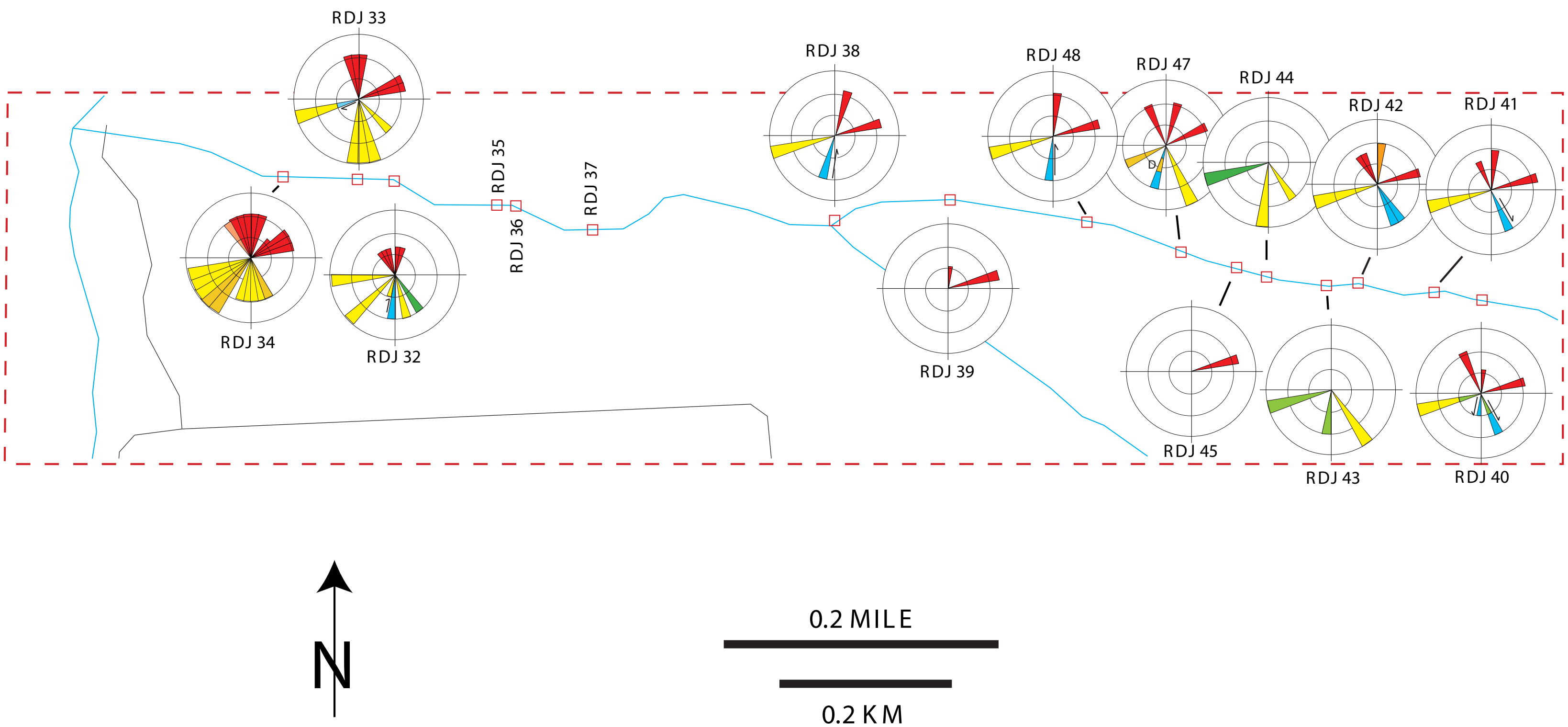

RDJ 33
RDJ 38
RDJ 48
RDJ 47
RDJ 44
RDJ 42
RDJ 41
RDJ 35
RDJ 36
RDJ 37
RDJ 34
RDJ 32
RDJ 39
RDJ 45
RDJ 43
RDJ 40
N
0.2 MILE
0.2 KM

FIGURE 50

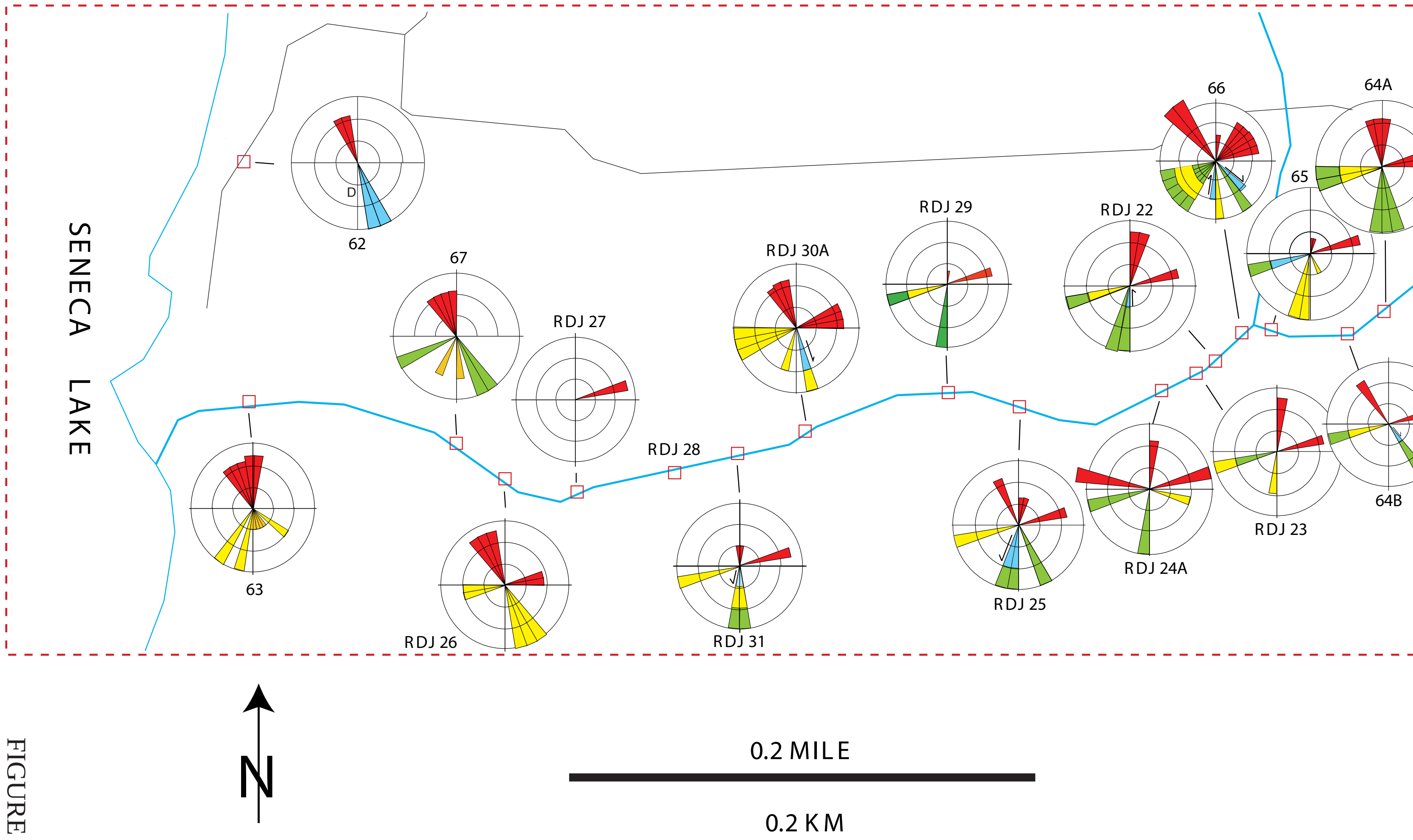

SENECA LAKE
62
67
RDJ 27
RDJ 30A
RDJ 29
RDJ 22
66
64A
65
63
RDJ 26
RDJ 28
RDJ 31
RDJ 25
RDJ 24A
RDJ 23
64B
N
0.2 MILE
0.2 KM

FIGURE 51

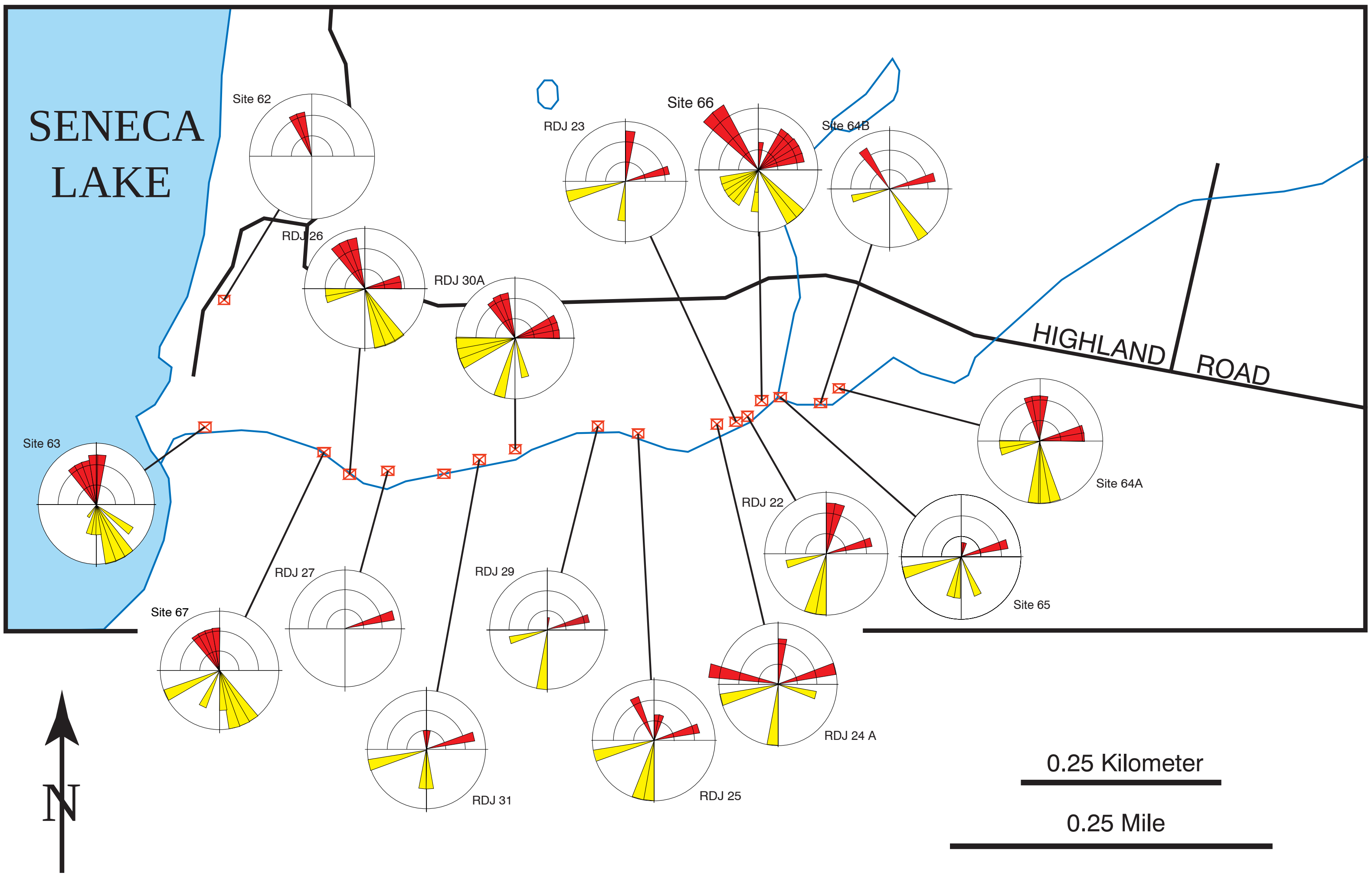

SENECA LAKE
Site 62
RDJ 26
RDJ 30A
RDJ 23
Site 66
Site 64B
HIGHLAND ROAD
Site 63
Site 64A
RDJ 22
Site 65
RDJ 27
RDJ 29
Site 67
RDJ 24 A
RDJ 31
RDJ 25
N
0.25 Kilometer
0.25 Mile

FIGURE 52

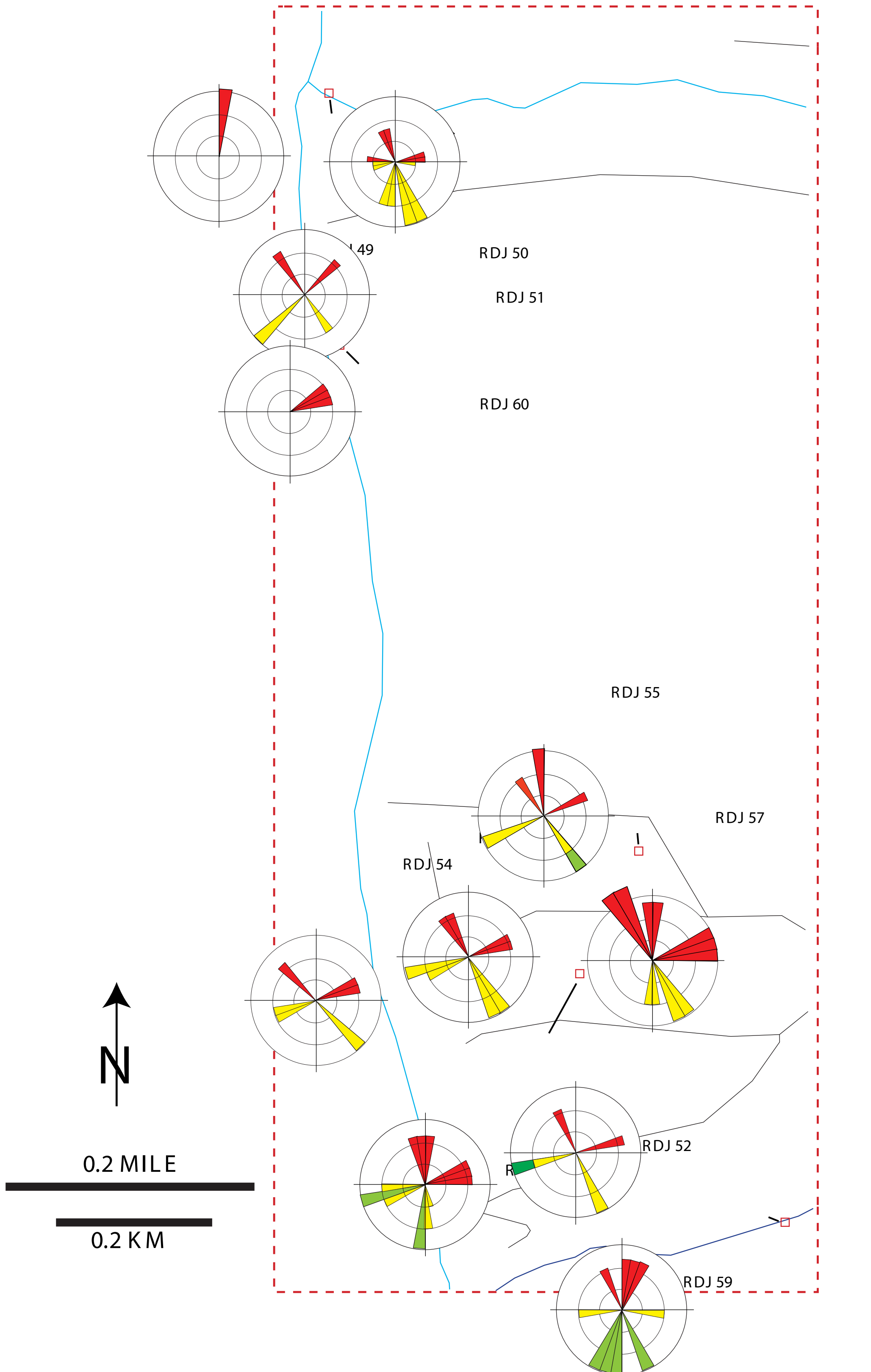

RDJ 50
RDJ 51
RDJ 60
RDJ 55
RDJ 57
RDJ 54
RDJ 52
RDJ 59
N
0.2 MILE
0.2 KM

FIGURE 53

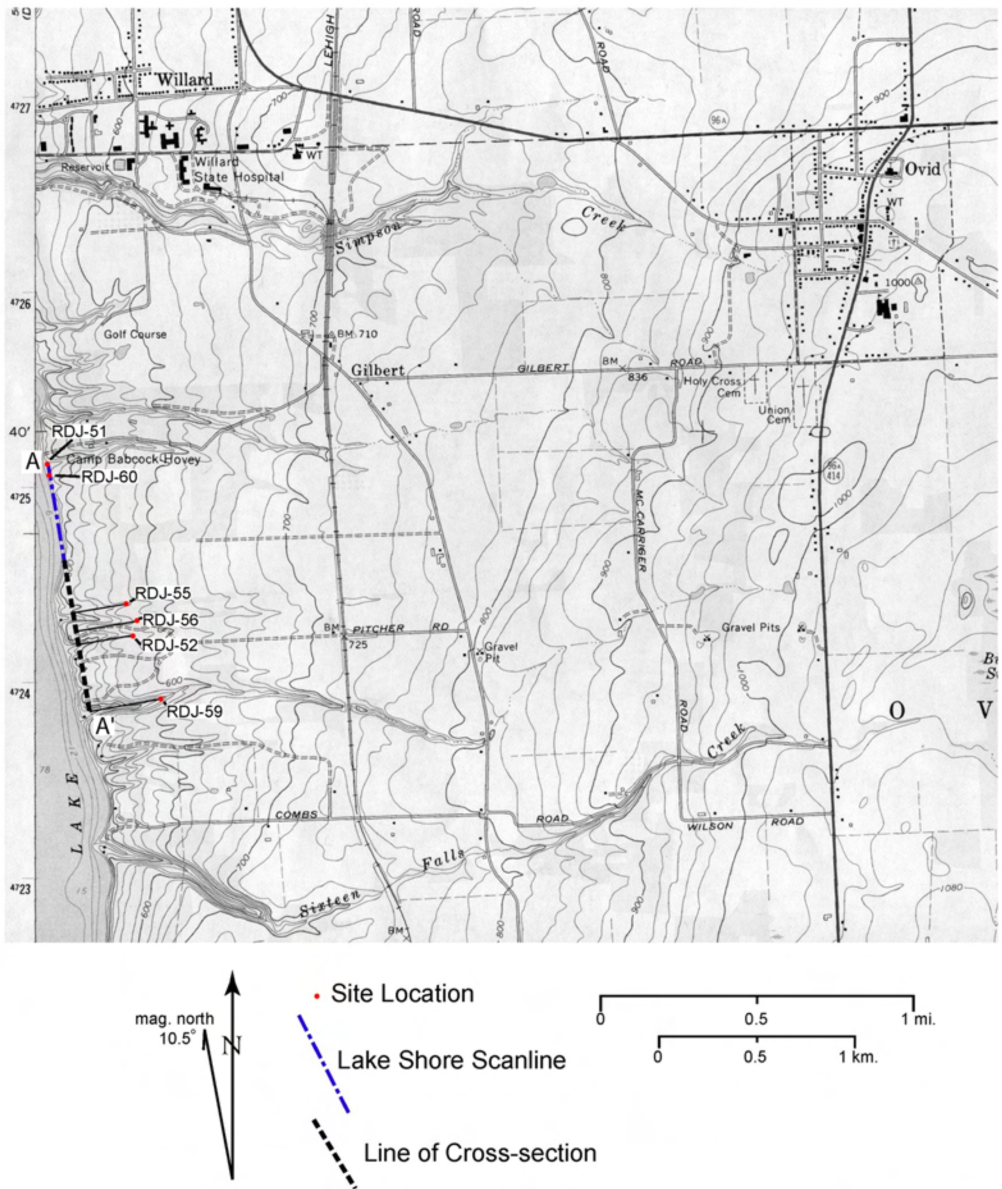

Willard
Willard State Hospital
Reservoir
Ovid
Simpson Creek
Golf Course
Gilbert
GILBERT ROAD
Holy Cross Cem
Union Cem
RDJ-51
A
Camp Babcock Hovey
RDJ-60
RDJ-55
RDJ-56
RDJ-52
RDJ-59
A'
PITCHER RD
Gravel Pit
Gravel Pits
MC CARRIGER ROAD
Creek
COMBS ROAD
WILSON ROAD
Sixteen Falls
LAKE
LEHIGH
Site Location
Lake Shore Scanline
Line of Cross-section
mag. north 10.5°
N
0 0.5 1 mi.
0 0.5 1 km.

FIGURE 54

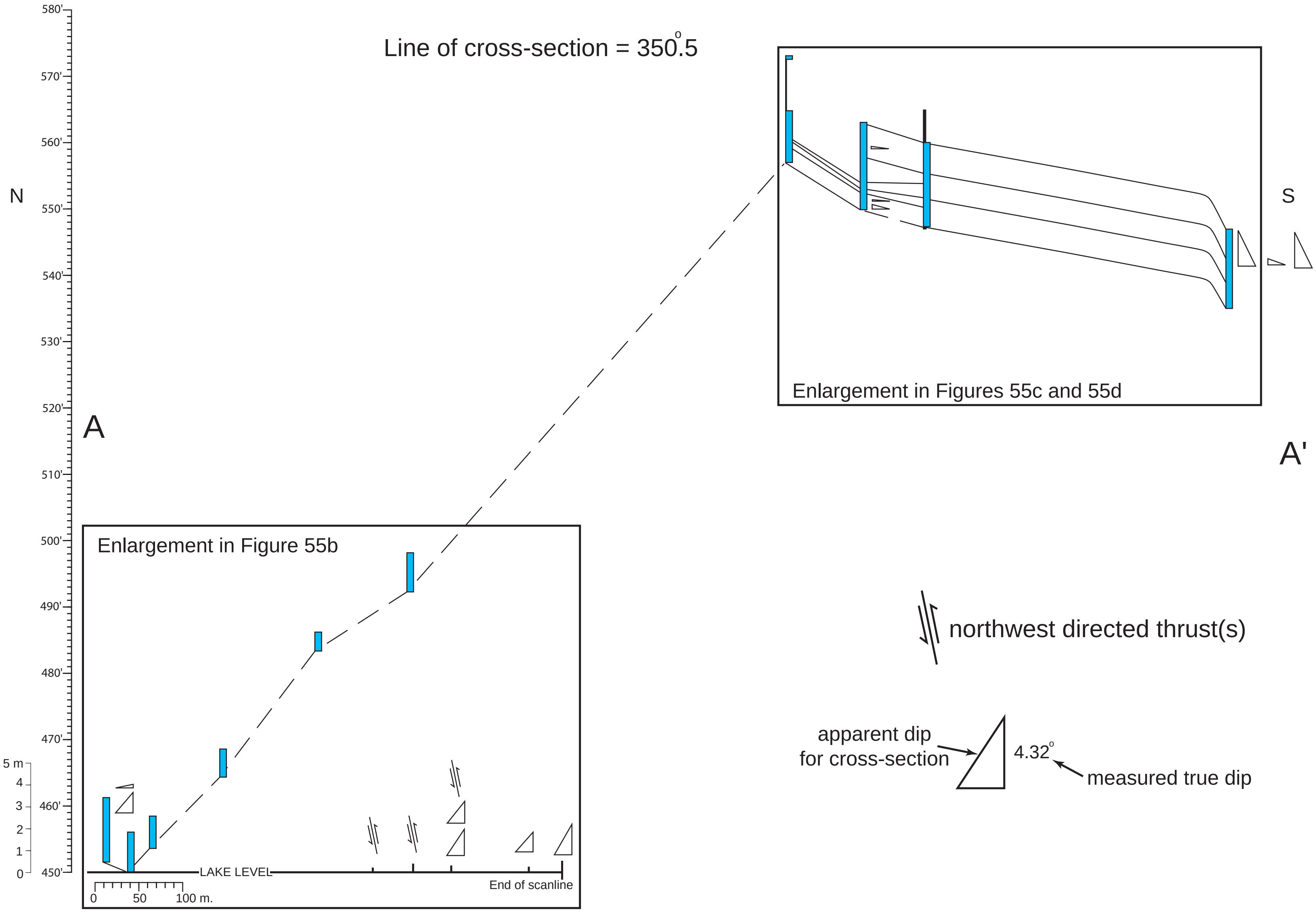

Line of cross-section = 350.5°
N
S
A
A'
Enlargement in Figures 55c and 55d
Enlargement in Figure 55b
LAKE LEVEL
End of scanline
0
50
100 m.
5 m
4
3
2
1
0
580'
570'
560'
550'
540'
530'
520'
510'
500'
490'
480'
470'
460'
450'
northwest directed thrust(s)
apparent dip
for cross-section
4.32°
measured true dip

FIGURE 55A

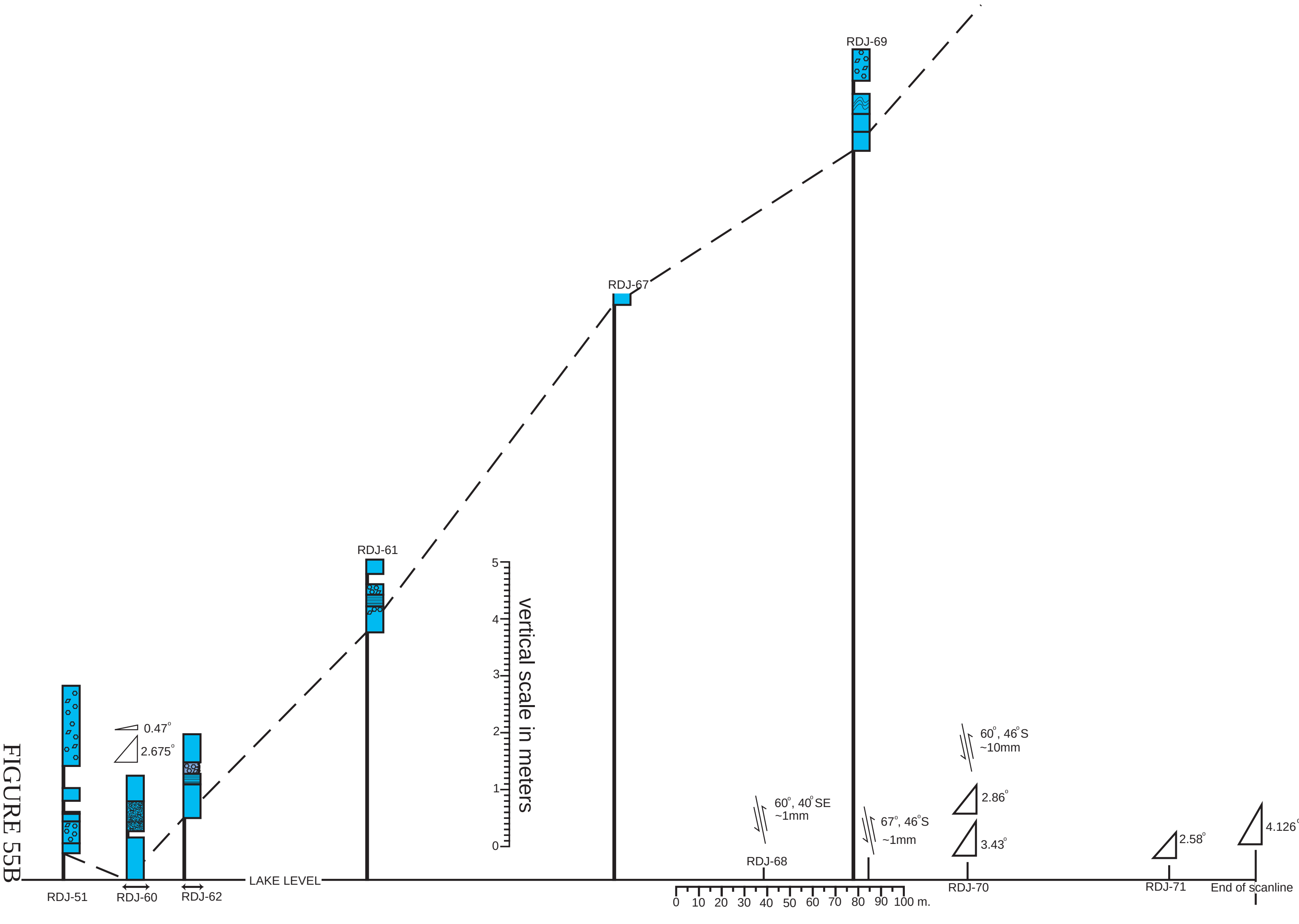

RDJ-69
RDJ-67
RDJ-61
vertical scale in meters
5
4
3
2
1
0
0.47°
2.675°
60°, 40°SE
~1mm
67°, 46°S
~1mm
60°, 46°S
~10mm
2.86°
3.43°
2.58°
4.126°
RDJ-68
LAKE LEVEL
RDJ-51
RDJ-60
RDJ-62
0 10 20 30 40 50 60 70 80 90 100 m.
RDJ-70
RDJ-71
End of scanline

FIGURE 55B

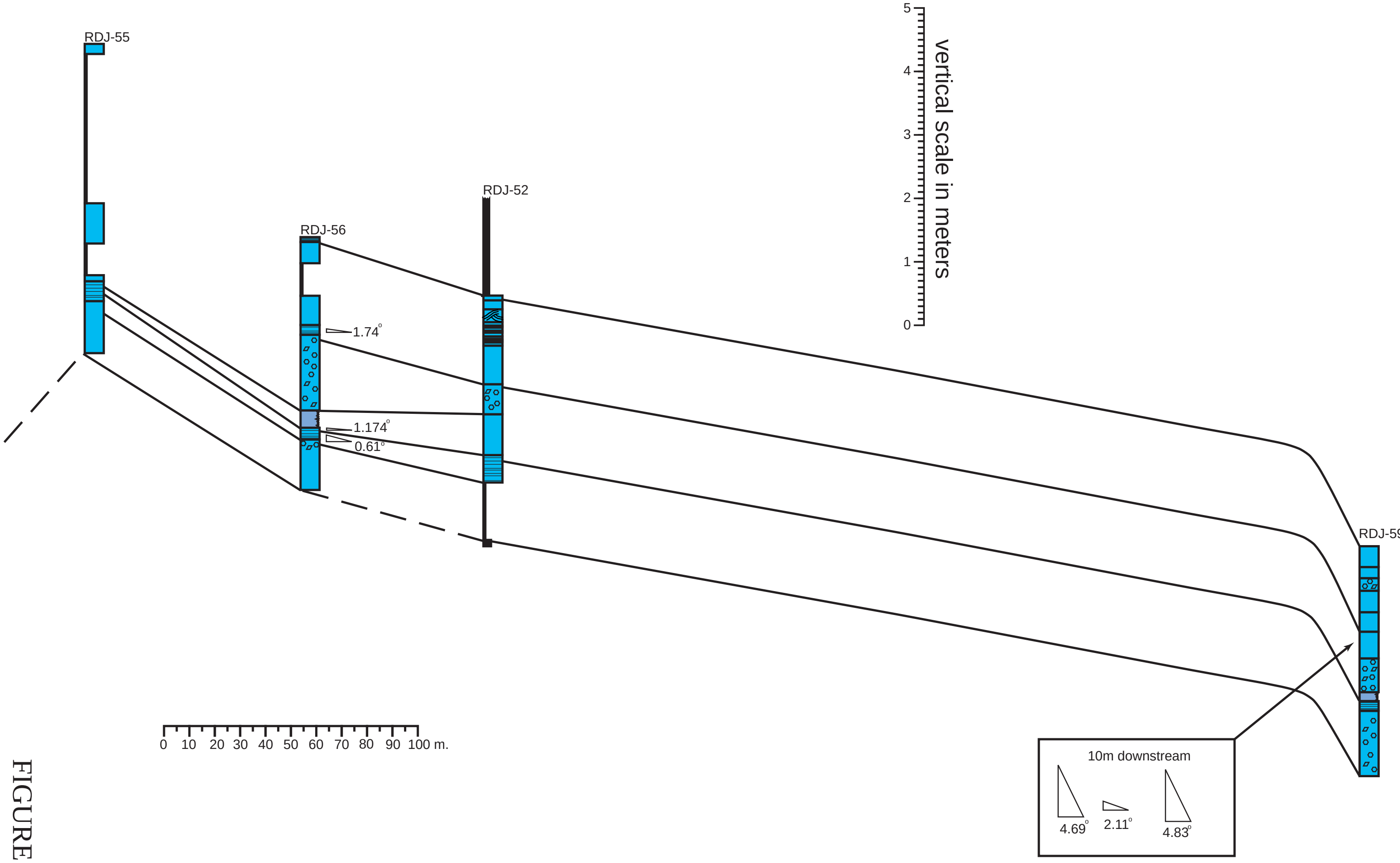
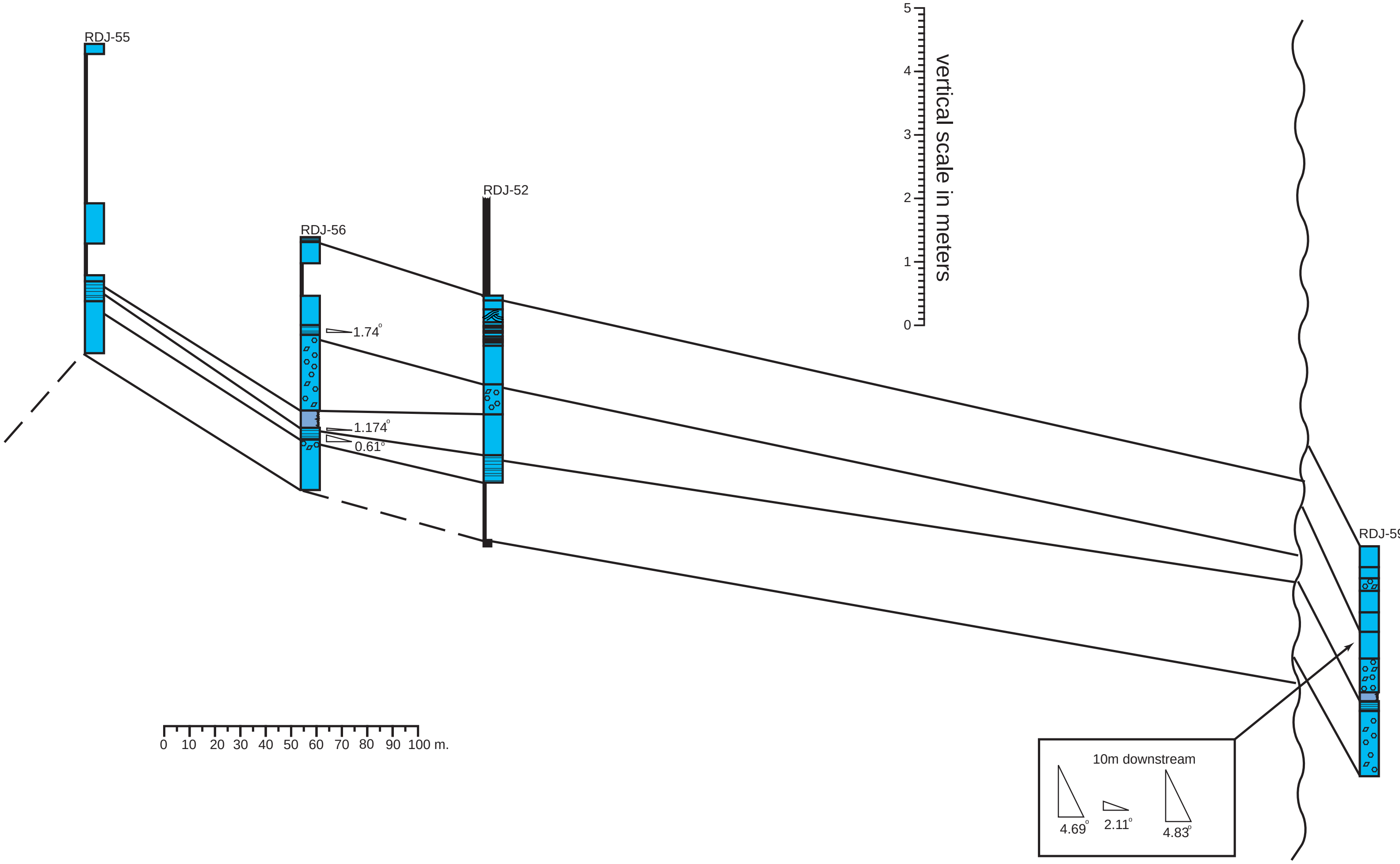

RDJ-55
RDJ-56
RDJ-52
RDJ-59
1.74°
1.174°
0.61°
5
4
3
2
1
0
vertical scale in meters
0 10 20 30 40 50 60 70 80 90 100 m.
10m downstream
4.69°
2.11°
4.83°

FIGURE 55C



RDJ-55
RDJ-56
RDJ-52
RDJ-59
1.74°
1.174°
0.61°
5
4
3
2
1
0
vertical scale in meters
0 10 20 30 40 50 60 70 80 90 100 m.
10m downstream
4.69°
2.11°
4.83°

FIGURE 55D

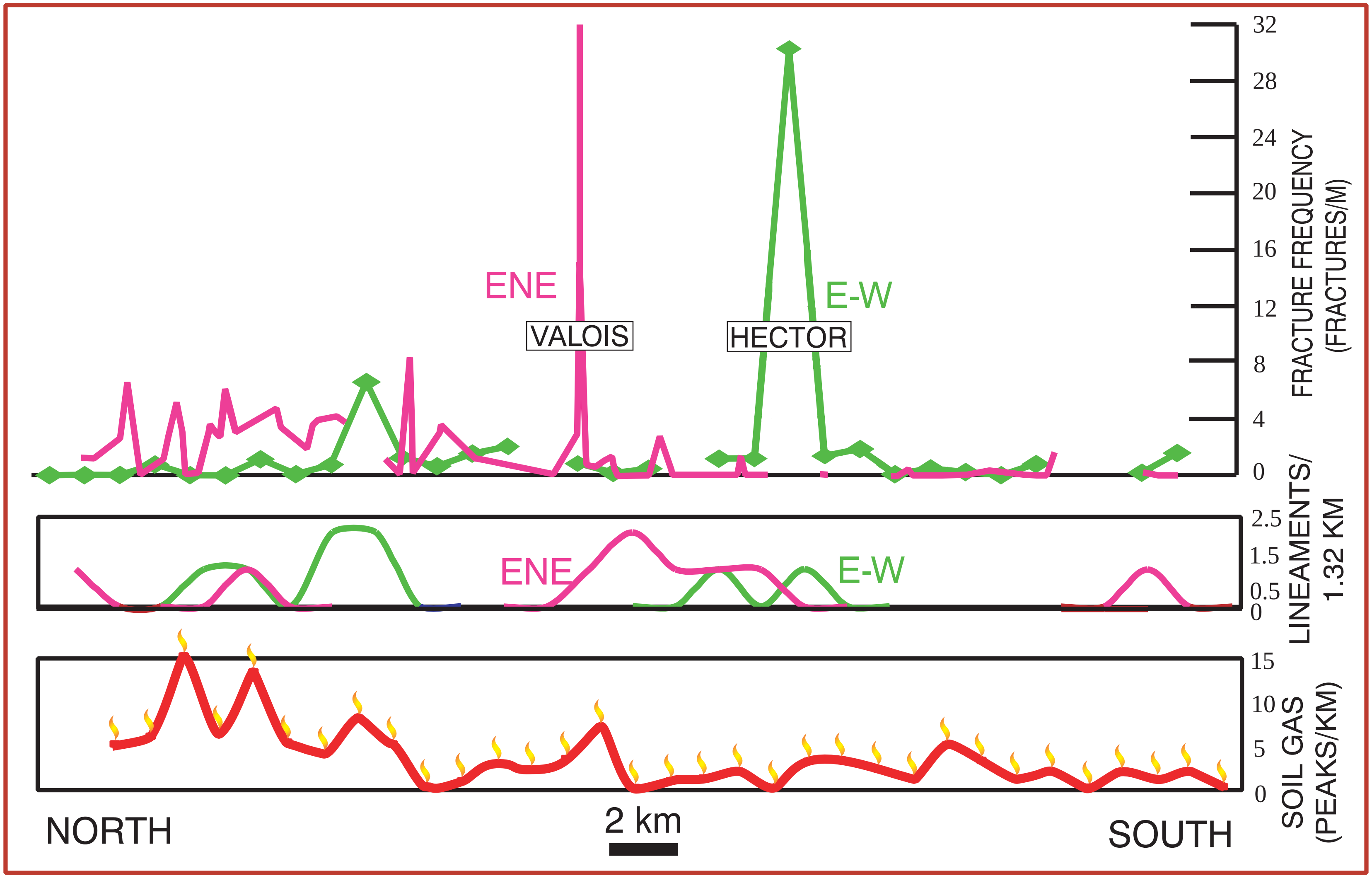

ENE
VALOIS
HECTOR
E-W
32
28
24
20
16
12
8
4
0
FRACTURE FREQUENCY
(FRACTURES/M)
ENE
E-W
2.5
1.5
0.5
0
LINEAMENTS/
1.32 KM
15
10
5
0
SOIL GAS
(PEAKS/KM)
NORTH
2 km
SOUTH

FIGURE 56

		Horizon SP - Shot Point | OS - Offset in milliseconds | DF - Downface of Fault ([N]orth, [S]outh, [T]hrus																				
		Onondaga			**Base Salt**			**Lockport**			**Trenton**			**Black River**			**Knox**			**Pre-Cambrian**		
	Fault Number	**SP**	**OS**	**DF**	**SP**	**OS**	**DF**	**SP**	**OS**	**DF**	**SP**	**OS**	**DF**	**SP**	**OS**	**DF**	**SP**	**OS**	**DF**	**SP**	**OS**	**DF**
NORTH	**1**										374	8	T	371	10	T						
	2										393	9	T	398	8	T	409	4	T	419	4	T
	3	428	13	T	430	8	S	430	18	T	437	18	T	437	30	T	437	22	T	442	?	T
	4													477	10	S						
	5													481	10	S						
	6							472	12	S												
	7							508	1	N	492	14	N	492	12	N	491	6	N	491	2	N
	8													498	1		496	6		495	6	
	9													595	2	T	594	2	T	593	?	T
	10										610	2	N	607	2	N	604	6	N	599	8	N
	11													635	6	N	632	6	N	647	4	N
	12																			673	12	T
	13																			760	6	T
	14													794	18	N	795	34	N	797	35	N
	15																			837	1	T
	16																			844	1	T
	17													846	4	S						
SOUTH	**18**													861	11	N	858	8	N	857	3	N