INNOVATIVE METHODOLOGY FOR DETECTION
OF
FRACTURE-CONTROLLED SWEET SPOTS
IN THE
NORTHERN APPALACHIAN BASIN

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FINAL TECHNICAL PROGRESS REPORT

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DISCLAIMER

ABSTRACT

For two consecutive years, 2004 and 2005, the largest natural gas well (in terms of gas flow/day) drilled onshore USA targeted the Ordovician Trenton/Black River (T/BR) play in the Appalachian Basin of New York State (NYS). Yet, little data were available concerning the characteristics of the play, or how to recognize and track T/BR prospects across the region. Traditional exploration techniques for entry into a hot play were of limited use here, since existing deep well logs and public domain seismic were almost non-existent. To help mitigate this problem, this research project was conceived with two objectives: 1) to demonstrate that integrative traditional and innovative techniques could be used as a cost-effective reconnaissance exploration methodology in this, and other, areas where existing data in targeted fracture-play horizons are almost non-existent, and 2) determine critical characteristics of the T/BR fields. The research region between Seneca and Cayuga lakes (in the Finger Lakes of NYS) is on strike and east of the discovery fields, and the southern boundary of the field area is about 8 km north of more recently discovered T/BR fields.

Phase I, completed in 2004, consisted of integrating detailed outcrop fracture analyses with detailed soil gas analyses, lineaments, stratigraphy, seismic reflection data, well log data, and aeromagnetics. In the Seneca Lake region, Landsat lineaments (EarthSat, 1997) were coincident with fracture intensification domains (FIDs) and minor faults observed in outcrop and inferred from stratigraphy. Soil gas anomalies corresponded to ENE-trending lineaments and FIDs. N- and ENE-trending lineaments were parallel to aeromagnetic anomalies, whereas E-trending lineaments crossed aeromagnetic trends. 2-D seismic reflection data confirmed that the E-trending lineaments and FIDs occur where shallow level Alleghanian salt-cored thrust-faulted anticlines occur. In contrast, the ENE-trending FIDs and lineaments occur where Iapetan rift faults have been episodically reactivated, and a few of these faults extend through the entire stratigraphic section. The ENE-trending faults and N-striking transfer zones controlled the development of the T/BR grabens.

In both the Seneca Lake and Cayuga Lake regions, we found more FIDs than Landsat lineaments, both in terms of individual FIDs and trends of FIDs. Our fused Landsat/ASTER image provided more lineaments, but the structural framework inferred from these lineaments is incomplete even for the fused image. Individual lineaments may not predict surface FIDs (within 500m). However, an individual lineament that has been groundtruthed by outcrop FIDs can be used as a proxy for the trend of intense fracturing.

Aeromagnetics and seismic reflection data across the discovery fields west of Keuka Lake demonstrate that the fields terminate on the east against northerly-striking faults that extend from Precambrian basement to, in some cases, the surface; the fields terminate in the west at N- and NW-striking faults. Seismic and well log data show that the fields must be compartmentalized, since different parts of the same field show different histories of development. T/BR fields south of the research area also terminate (on the east) against northerly-trending lineaments which we suggest mark faults.

Phase II, completed in 2006, consisted of collection and analysis of an oriented, horizontal core retrieved from one of the T/BR fields in a graben south of the field area. The field is located

along ENE-trending EarthSat (1997) lineaments, similar to that hypothesized for the study area. The horizontal core shows much evidence for reactivation along the ENE-trending faults, with multiple events of vein development and both horizontal and vertical stylolite growth. Horizontal veins that post- and pre-date other vein sets indicate that at least two orogenic phases (separated by unloading) affected vein development. Many of the veins and releasing bend features (rhombochasms) are consistent with strike-slip motion (oblique) along ENE-striking faults as a result of Taconic peripheral bulge and later collisional stresses. Later orogenic effects from possibly the Acadian, and certainly the Alleghanian, are also present. Although the core does not exhibit significant zones of high porosity, rubble zones and fault zones observed on an accompanying FMI log were apparently the sources of gas production that resulted in this well being a good producer in spite of the low matrix porosity.

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TABLE 2.8-2. Observed Breaks in Reassembled Core.

EXECUTIVE SUMMARY

The objectives for this research project were to demonstrate the effectiveness of integrated techniques in order to determine the presence and trend of deep fracture plays, specifically the Ordovician Trenton/Black River (T/BR) grabens in the Finger Lakes region of New York State. In so doing, the second objective was to define characteristics of the structure in the region of inertest. The rationale for focusing on the T/BR in NYS is that the T/BR is presently the hottest play in the Appalachian Basin, and in fact the largest gas wells drilled onshore USA in 2004 and 2005 were drilled in the T/BR fields of NYS. The integrated techniques demonstrated in this research project included lineament identification, detailed fracture analysis to confirm the lineaments and understand the structure of the study area, soil gas analyses to confirm the lineament trends, seismic reflection analyses to determine whether faults do exist below the lineaments, advanced seismic analyses to determine if the faults and units associated with the T/BR grabens exhibit enhanced porosity, outcrop stratigraphy and well log analyses to recognize possible fault trends, and aeromagnetic and gravity analyses to determine regional trends and test whether the lineaments follow basement features (assumed to be the case for T/BR features).

The Seneca Lake Swath clearly demonstrated the value of our integrative techniques. Landsat lineaments (EarthSat, 1997) are oriented in three directions within the swath: East, East-northeast, and North. N-and ENE-trending lineaments are parallel to aeromagnetic gradients; these lineaments thus probably represent structure systems that extend from Precambrian basement to the surface. In contrast, an E-trending lineament bundle crosses an aeromagnetic anomaly; this set of lineaments is therefore thought to represent shallower structure that is not related to Precambrian basement. This analysis alone suggests that the deep T/BR grabens would be oriented along the bundle of ENE-trending lineaments, whereas the shallow structural level reservoirs of the Alleghanian anticlines would be located along the E-trending lineaments in the study area. The ENE-trend is confirmed by more recently developed T/BR fields to the south which are located along ENE-trending bundles of EarthSat (1997) lineaments.

Fracture analysis of detailed outcrop structure data confirmed the lineaments in the Seneca Lake Swath. On the Seneca Lake Transect (which is about 32 km long) ENE-trending fracture intensification domains (FIDs) were found only in regions where the ENE-trending lineament bundles occur. Similarly, where E-striking FIDs occur is exactly where the E-trending lineament bundle passes through the swath. Soil gas analyses were also consistent with the fracture and lineament analyses. The number of ethane “spikes” along the Seneca Lake Transect more than doubled in the regions of the ENE-trending lineaments and ENE-striking FIDs. In the study area soil gas also can be used to differentiate ENE-striking structure from E-striking shallow structures which do not exhibit a significant number of soil gas spikes.

A 2-D seismic reflection profile along the Seneca Lake Transect confirmed the inferences gained from the integrative techniques discussed above. First, the E-striking FIDs and lineaments are located above the high structural-level Alleghanian Firtree Anticline. The ENE-trending lineaments and FIDs are located above faults that extend from Precambrian basement up into the Siluro-Devonian section. These faults have T/BR grabens developed along them. Additional faults observed on the seismic line have an array of last fault-motion timings: Iapetan rifting only, Black River, Trenton and post-Trenton Taconic times.

Surface stratigraphic mapping showed that surface structures coincide exactly with the EarthSat (1997) Landsat lineaments. That all data sets from the Seneca Lake Swath provided consonant data is noteworthy; there are no conflicting data for the Seneca Lake Swath.

In the Cayuga Lake Swath the correlation between lineaments and FIDs is less compelling than the Seneca Lake Swath. There are many more FIDs and FID trends than lineaments and lineament trends. Thus, lineament analysis can provide a (partial) view of the structural framework, but the lack of a certain lineament may not indicate the lack of a similarly oriented FID. Some lineaments may be relatively distant from sites with appropriately oriented FIDs. Thus, a particular lineament should not be assumed to represent the exact location of a FID or fault (within 250-500m), unless the lineament can be groundtruthed by one of the techniques demonstrated here.

Advanced seismic analyses showed standard seismic processing packages can be utilized to significantly enhance the understanding of the seismic reflection data. For example, the advanced seismic analysis showed that a dry hole in the study area did penetrate the target area (a T/BR fault zone and graben), but that this target area was relatively dense (low porosity), unlike other fault zones.

The data for this study also provided insights on the structure of the T/BR fields. The eastern termination of the discovery fields (Glodes Corners Road and Muck Farm fields) is along a northerly-trending reactivated Precambrian fault. Similarly, the T/BR grabens in the study may have transfer zones along northerly striking faults, such as the fault along the east side of Seneca Lake. The more recently developed T/BR fields south of the study area also terminate on the east along a northerly trending bundle of EarthSat (1997) lineaments that probably represent a fault system. The western termination of the discovery fields were originally at both N- and NW-trending structures, but extensions of the fields now both terminate on NW-trending structures. The seismic line across the Glodes Corners Road Field shows little offset in the Trenton, but the model from Beardsley (1999) showed significant offset on the Trenton. We suggest that this difference is a reflection of compartmentalization within the field, and that at least some of the transfer zones across the segments were localized by preexisting basement fault system.

The horizontal oriented core retrieved in Phase II from one of the grabens to the south shows much evidence for reactivation along the ENE-trending faults, with multiple events of vein development and stylolite growth. Horizontal veins that post- and pre-date other vein sets indicate that at least two orogenic times (separated by unloading) affected vein development. Many of the veins and releasing bend features (rhombochasm) are consistent with strike slip motion (oblique) along ENE-striking faults as a result of Taconic peripheral bulge and later collisional stresses. Later orogenic effects from possibly the Acadian, and certainly the Alleghanian, are also present. Although the core does not exhibit significant zones of high porosity, rubble zones and fault zones observed on an accompanying FMI log were apparently the sources of gas production that resulted in this well being a good producer in spite of the low matrix porosity.

1.0 INTRODUCTION

1.1 GENERAL INTRODUCTION AND OBJECTIVES

3-D seismic analysis is unquestionably one of the premier methods for obtaining information concerning deep structure, including predictions of enhanced fracture porosity in reservoirs. However, the high cost of 3-D seismic makes it economically unfeasible in many basins with *perceived* marginal gas reserves. However, without some advanced technology like 3-D seismic, the deep structure in many basins (like the Appalachian Basin of New York State) cannot be critically evaluated because available seismic reflection profiles and deep well logs provide insufficient control.

This research project demonstrates a cost-effective alternative to 3-D seismic for exploration purposes. The project demonstration is a combination of low-cost, innovative technologies that, when integrated, yield near-3-D quality on a regional scale for identification of fractured reservoir prospects. The study area covers about 1,970 km^2 (760 sq. miles), an area that would cost considerably in excess of $60 million for 3-D seismic coverage alone; in contrast, our research expense is a fraction of that cost.

The basic premise is that highly productive zones in tight reservoirs are associated with discrete zones of intense fracturing, termed “fracture intensification domains” (FIDs, Jacobi and Fountain, 1996, Jacobi and Xu, 1998; Jacobi, 2002). These zones can be identified by integration of surface geology, lineaments, well log data, seismic data and soil gas anomalies. FIDs in the northern Appalachian Basin have been shown to be indicative of fault zones at depth. Thus, by identifying and tracing FIDs, we can predict the location of zones of increased fractures in the subsurface.

Large gas discoveries have been made recently in the Ordovician Trenton/Black River (T/BR) along fault zones in the New York State portion of the Appalachian Basin. In fact in 2004 the largest gas well drilled in onshore USA was in the T/BR of New York State, based on a flow rate of over 40 mmcf/d (Anonymous, 2005). For 2005, the largest well drilled was again reputed to be in the New York State T/BR play. The larger wells in the T/BR fields in 2005 produced more than 6 bcf/y (Anonymous, 2006); the range was from considerably less than 1 bcf/y (0.15 bcf/y) to greater than 6 bcf/y, and the average was on the order of 2 bcf/y (Anonymous, 2006). The anomalously high flow rates of these wells make it critically important to be able to recognize faults and associated FIDs. However, because of vegetation and surficial deposits, FIDs cannot be recognized and traced continuously in outcrop. In order to recognize and trace the FIDs, we have developed an integrated program that involves:

1) surface structure,
2) soil gas analyses,
3) remotely-sensed lineaments,
4) existing (2-D) seismic data, and
5) aeromagnetics.

Structural studies on outcrops allow identification of FIDs; then lineaments from aeromagnetic data and remotely-sensed images are used to trace the FIDs between outcrops. Soil gas anomalies can confirm that the lineaments are associated with fracturing. Existing well log and seismic data are used to substantiate the interpretations. Aeromagnetics and, to a lesser extent, gravity are useful because many of the fault systems in the Phanerozoic section of the northern Appalachian Basin can be traced along aeromagnetic (and gravity) gradients; these fault systems are the multiply-reactivated Phanerozoic components of Precambrian and Iapetan rift faults that affect Precambrian (magnetic) basement.

The objectives of this research were two-fold:

1) To demonstrate that the integrated techniques utilized in this study are a cost-effective methodology to determine critical structural elements in an exploration program, and
2) To determine the structure of the region to serve as a model for exploration for gas fracture-reservoirs, including the T/BR.

In order to procure and analyze the data necessary for the demonstration project, the integrated research project was divided into seven tasks. These tasks included:

1) Traditional and innovative analyses of fractures (Jacobi),
2) Lineaments (Jacobi),
3) Soil Gas Analyses (Fountain),
4) Seismic Data Acquisition and Interpretation (Jacobi and Loewenstein),
5) Advanced Seismic Analyses (Hart),
6) Stratigraphy/well log analyses (Jacobi and Loewenstein),
7) Aeromagnetic Survey and Analyses (deRidder).

The study area is located in the northern Appalachian Basin in the Finger Lakes region of central New York State, primarily between Seneca and Cayuga lakes (Figure 1.1-1, Topical Report #1 [TR #1]). The target is the Ordovician Trenton/Black River groups, although fractured tight sands and black shales above the Trenton, as well as fractured carbonate and sandstone below the Black River, also occur in the area, and could be potential targets in the future.

The discovery field of the most prolific gas play in New York State (and the Appalachian Basin) is the Glodes Corners Road Field, which is an Ordovician Trenton/Black River (T/BR) play that is located west of Keuka Lake. This field was developed by Columbia Natural Resources (CNR), who estimated that the yield/well is 1.3 bcf. The Glodes Corners Road Field is located above faults that are probably reactivated structures related to the Iapetan rift faults (e.g., Beardsley, 1999, 2001; Jacobi et al., 1999; Jacobi, 2002). Well logs from the Glodes Corners Road Field indicate a narrow graben that increases in stratigraphic offset upsection in the Ordovician Black River and overlying Trenton, increasing to 6 m in the Trenton. On seismic reflection profiles, the T/BR fields occur along fault zones that appear as narrow (~ 0.61 km [2000 ft.]) grabens with negligible regional offset. These grabens are thought to be a result of a combination of

1) solution collapse,
2) reverse flower structures (along strike-slip faults).

The present study area is due east of the discovery field, essentially along strike from the discovery field. The study area is also north of the more recently developed large T/BR fields such as the Quackenbush Field.

1.2 PREVIOUSLY KNOWN STRUCTURE IN THE STUDY AREA

1.2.1 Introduction

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 30+ m) have been inferred, but never observed in outcrop.

1.2.2 Folds and Faults

Three prominent studies defined the shallow 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) superceded 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 1.2-1 [TR #1]). On the Cayuga lakeshore, the Tully limestone provided a marker bed that indicated structural relief of approximately 46 m (150 ft). 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 12 m (40 ft).

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 on the east side of Seneca Lake (Figure 1.2-1 [TR #1]). 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 (Figure 1.2-1 [TR #1]). Although they did not find this fault in outcrop, the anomalous elevation of stratigraphic markers among widely-spaced outcrops led them to suggest the existence of the fault near the south end of Seneca Lake (Figure 1.2-1 [TR #1]). 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 fault follows N-striking Landsat lineaments identified by Isachsen and McKendree (1977) and by EarthSat (1997). The present report suggests that the fault 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 1.2-1 [TR #1]), 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 366-426 m (1200-1400 ft) 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 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).

Another N-striking, right-lateral strike slip fault, the Cayuga Lake Fault, was inferred from well logs by Murphy (1981); the fault extends south from the southeastern corner of Cayuga Lake to the NYS boundary along a prominent topographic lineament (Murphy, 1981) and an EarthSat (1997) lineament. Murphy (1981) believed that both the Seneca and Cayuga Lake 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.

Approximately N-striking faults were also hypothesized for the north end of Keuka Lake (the Keuka Lake Fault, Jacobi, 2002) on the basis of well log and field data (Bergin, 1964; Murphy, 1981). From structure contours Murphy (1981) inferred that Alleghanian (?) slip on the fault was down-on-the-west and dextral. Jacobi (2002) suggested that these faults probably are associated with faults in the Precambrian basement because the Keuka Lake Fault coincides with a prominent gravity gradient and aeromagnetic gradient. The fault is also coincident with EarthSat (1997) lineaments.

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 304+ m (1,000+ ft), measured parallel to regional strike of the offset units.

At the north end of Cayuga and Owasco lakes Rickard (1973) proposed an Ordovician N-striking horst and graben, based on growth-fault geometries inferred from sparse well logs. However, Saroff (1977) believed that the primary structural trend in the Auburn gas field (located northeast of northern Cayuga Lake) is northeast, based on structure contours, magnetic lineaments and the distribution of wells with interpreted high fracture porosity. Consistent with Saroff’s (1977) proposed NE-striking faults is a prominent magnetic high that trends northeast from Auburn to west of Oneida Lake (Jacobi, 2002).

In 2002 Jacobi integrated 1) EarthSat (1997) lineaments, 2) aeromagnetic gradients, 3) gravity gradients, and 4) outcrop fracture data across the Appalachian Basin in New York State in order to identify probable fault systems (Figure 1.2-2 [TR #1]). In the study area this data integration corroborated the faults discussed above.

Jacobi (2002) also proposed additional northerly striking, E- and ENE-striking, and NW-striking faults. Jacobi (2002) proposed that Murphy’s (1981) Keuka Lake Fault extends north-northeast to Lake Ontario along EarthSat (1997) lineaments. Like the Keuka Lake Fault, the proposed north-northeast extension follows a gravity gradient south of Lake Ontario. The Keuka Lake Fault Extension tracks the western margin of the Romulus Trough (or sag), a Middle Devonian local depositional basin (e.g., Mayer et al., 1994), and is the locus of facies changes in Middle Devonian units (Mayer et al., 1994). It thus appears that this fault was a control for Middle Devonian basinal deposition. Jacobi (2002) also proposed that a splay of the Keuka Lake Fault extends south-southwest from Keuka Lake to the New York State border along a prominent EarthSat (1997) lineament and an aeromagnetic gradient. The aeromagnetic gradient suggests that the fault affected Precambrian basement.

The Glodes Corners Road Field was the Trenton/Black River (T/BR) discovery field in New York State. The basic structure of the field was first revealed when Beardsley (1999, 2001) showed that the field consisted of a narrow, E-striking graben with increasing offset upsection (Figure 1.2-3 [TR #1]). Beardsley (1999) suggested that the offset was compatible with a solution collapse. Hydrothermal fluids, migrating along preexisitng faults (perhaps Iapetan rift faults) had first dissovled the limestone and then precipitated dolomite in vugs, along fractures, and in intergranular porosity. The age of initial porosity devlopement must have been Taconic, since Silurian seismic reflectors do not deflect across many of the T/BR grabens. It is probable that fault activity related to the Taconic collision promoted fluid migration through "seismic pumping". The age of hydrocarbon migration and trapping is yet unkonwn, but Jacobi et al. (2006) suggested that the initial age could have been relatively early (Late Taconic), with later stages (perhaps more signficant in terms of volume) ocuring during the later orogenies, the Salinic, Acadian and Alleghanian. Each of these orogenies probably caused fluid migration, but whether hydrocarbon accompanied all stages is not yet known. For extended reviews of the fields in New York State, see Smith (2006) and Jacobi et al. (2006).

1.2.3 Fractures

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 most outcrops examined 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.

Continued detailed fracture studies across western NYS since the time of the Zhao and Jacobi (1997) model (e.g., Baudo and Jacobi, 2000; Tober and Jacobi, R. D., 2000) revealed relationships between Set Ia and Ib fractures that conflict with the general Zhao and Jacobi (1997) model. The sense of rotation between Set Ia and Ib is opposite to the general model, and is commonly inconsistent among local areas. Based on these ubiquitous inconsistencies, Jacobi et al. (2002) suggested that many of the observed cross-strike fracture rotations are the not the result of far field regional Alleghanian stress rotations; rather, they are the result of local stress rotations that developed in response to newly recognized major fault systems--fault systems that extend into the Precambrian basement. Such local stress rotations could have resulted from faults that were “open” after a stress release or, as suggested by Rawnsley et al. (1998), from perturbations resulting from points of convergence along the fault.

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) did 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 collinearly with the strike of the fractures, Engelder (1982, 1985) and Gross and Engelder (1991) 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, and were caused by "high fluid pressure developed during the burial of the Catskill Delta before the onset of the Alleghanian Orogeny" (p. 40). Lash et al. (2004) concurred with an Acadian age, based on abutting relationships that suggested that the ENE-striking fractures were the oldest, and predated the Alleghanian cross strike fractures. More recently, Engelder and Whitaker (2006) suggested that Set III fractures first began to develop in Late Pennsylvanian time in coal, and Late Pennsylvanian to Permian time in Devonian black shale and other clastics in the Finger Lakes region. To the west in Allegany County, Jacobi and Fountain (1996) found that ENE-striking FIDs (oriented parallel to either Set II or Set III fractures) generally predate the Alleghanian cross-strike Set I fractures.

2.0 EXPERIMENTAL (METHODOLOGY)

2.1 FRACTURE ANALYSES

The design of the fracture analyses task was to collect fracture data from outcrops as follows:

1) first along a N-S swath along the east shore of Seneca Lake (Figure 2.1-1 [TR #1]),
2) second, a swath along the west shore of Cayuga Lake (Figure 2.1-1 [TR #1]),
3) third, the region between the two shoreline swaths (Figure 2.1-1 [TR #1]).

These generally N-S swaths would reveal effects of suspected easterly-trending structures, such as easterly-striking FIDs. Soil gas analyses and a N-S seismic line in the same swaths allowed full integration of the various methodologies

Jacobi and assistants (Courtney Lugert, Karen Wehn, Fariha Islam, Rick Mayer, Fernanda Scuderi, Phil Stokes, Josh Stroup, and Jon Zybala) used two different methods to collect outcrop structural data during the first field season. They collected most of the structural data along scanlines and a relatively small amount by an abbreviated methodology described below.

In the scanline methodology, which was detailed in Jacobi and Zhao (1996a, b) and Jacobi and Fountain (1996), Jacobi and assistants laid out the scanline in a direction to "capture" as many fractures as possible. They then constructed a sketch map in their field notebooks that showed the location of the scanline and the nail marking the end of the scanline in relation to the pertinent geographical features. They indicated the general site location in the field by tying an annotated ribbon to an overhead tree. The sketch map of the site also includes sufficient geographical markers to be able to identify the site location on the topographic base map. They annotated the site of the scanline on the enlarged topographic map base. Jacobi and students then measured the orientation of the scanline and collected data on 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, and
9) Offset along the fracture.

Jacobi and assistants entered all the site data and the fractures data in Excel data spreadsheets. For each site, the next step was to separate the fractures into different fracture sets on the basis of the orientation, character and abutting relationships of the individual fractures. After separating the fracture sets, they calculated the fracture frequency for each set from the fracture intercepts on the scanline. Since most fractures dip steeply (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 (Figure 2.1-2 [TR #1]). Three orders of magnitude on the diagram are shown as successively larger concentric circles, with the inner circle representing 0.1 fractures/m, the middle ring representing 1.0 fractures/m, and the outer ring representing 10 fractures/m. Thus, long petals indicate a relatively high number of fractures per meter, as did the traditional rose diagrams. The advantage of this modified diagram is that it does not promulgate a potential sampling bias that arises if a scanline is parallel to one fracture set and orthogonal to another fracture set. In the traditional rose diagrams, 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 either abutting relationships, or length (which is a proxy for abutting relationships). Examples of modified rose diagrams with different lower semicircles patterns are portrayed in Figure 2.1-2 [TR #1]. Figure 2.1-3 [TR #1] shows several representative fracture patterns in the study area with a modified rose diagram that represents each particular fracture pattern. In general the longest petals in the lower half indicate the master fracture set; the next longest petals indicate the fracture set that abuts the master fracture set ("first abutting"), but that set 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, some of which are displayed in Figures 2.1-2 [TR #1] and 2.1-3 [TR #1]. These complications are indicated by different colored petals on the rose diagrams.

Jacobi and assistants also used an abbreviated method to collect structure data at some sites in the first year of data collection, and used this abbreviated method for most of the data collection in the following three field seasons. In this method, Jacobi and assistants identified the fracture sets at the outcrop, and measured at the outcrop 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.

The base maps for the rose diagram displays were constructed in ARC/INFO. Streams were from the COUGIR website, and were found to match the streams on USGS 7.5' topographic maps generally quite well (with less than a 7.5' topographic map line-width error anywhere in the quadrangle when displayed at full scale). In contrast, the roads from the county transportation maps at the same website were very poorly digitized. We have modified the more severe problems. After digitizing the sites in ARC/INFO, we transferred the maps to Adobe Illustrator in order to paste the rose diagrams on the base maps. Additionally, we redigitized all the site locations in order to have accurate UTM coordinates for each.

In order to display the variations in E and ENE-striking fracture frequencies along the shore of Seneca Lake, and to compare these variations to variations in the number of soil gas anomalies and EarthSat (1997) lineaments, Jacobi and assistant Lugert constructed a N-striking transect along Seneca Lake (location shown in Figure 2.1-4 [TR #1]). For determining the ENE-striking fracture frequency along the transect, they extrapolated all the sites, using an ENE bearing, to the N-striking transect. They then calculated the average fracture frequency in a 1 km window from all sites in that 1 km window. For the E-striking fracture frequency along Seneca Lake, Jacobi and assistant used the same N-S transect that they used for projected ENE-striking fracture frequencies. They extrapolated all the sites to this transect using both an ENE bearing and an E-W bearing. By extrapolating, on an ENE-bearing, the sites to the transect for the E-W striking fracture frequencies, the sites match (spatially) for both the ENE-striking fractures and the E-W striking fractures (Figure 2.1-5 [TR #1]). Comparison between the fracture frequency for both ENE and EW fractures at the same locale on the transect is thus possible (Figure 2.1-5 [TR #1]). In contrast, if the sites are projected to the transect on an E-W-strike for the E-W striking fractures, a mismatch on the transect occurs between site locations used for the E-W-striking fractures and the (same) sites used for ENE-striking fractures. (Figure 2.1-6 [TR #1]). However, the E-W extrapolation provides a more rigorous base for examination of the E-W fractures alone, with respect to deeper structure.

Comparison of Figures 2.1-5 [TR #1] and 2.1-6 [TR #1] shows that the different bearings for projecting the individual sites to the N-S transect do result in slightly different curves of ENE-striking fracture frequency on the transect. Although the largest spike is located between 12 and 13 km on both figures (2.1-5 [TR #1] and 2.1-6 [TR #1]), the other large spikes have different magnitudes on the two figures and one spike has a different position on the two different transects (compare the spikes between 24 and 28 km on figures 2.1-5 [TR #1] and 2.1-6 [TR #1]). Nevertheless, the three spikes do show the same general curves along the transect.

For the western shore of Cayuga Lake, a similar operation was performed to construct a transect to portray the variations in fracture frequency of the ENE- and E-striking fractures (for location of transect, see Figure 2.1-7 [TR #1]). For the Cayuga Lake Transect, the sites were projected to the transect on an ENE bearing for ENE-striking fractures and the sites were projected to the transect on an East bearing for E-striking fractures.

2.2 LINEAMENTS SUBTASK

Our basic lineament data set is from EarthSat (1997), who identified lineaments on Landsat Thematic Mapper ™ images across the Appalachian Basin in New York State. After resampling and enhancing TM bands 2, 4, and 7, EarthSat (1997) recognized tonal and stereoscopic (topographic) lineaments on the enhanced images by “eye”. Jacobi (2002) then bundled the lineaments that were relatively long and/or closely-spaced. Both the bundled lineaments and the individual lineaments are utilized in the analyses of this report.

Jacobi and associate (Lugert) analyzed the topography of the study area in order to identity lineaments quantitatively by examining both the magnitude and the orientation of the topographic slopes in a DEM of the study area. The program used is a subroutine in ARC/VIEW that calculated the aspects of the slope (direction and magnitude).

Jacobi and associate (Drechsel) enhanced satellite images using various algorithms to accentuate the visibility of lineaments. The images were processed using routine correction subroutines and principle component analyses in ENVI. This processing included noise and atmospheric corrections, enhancements such as gray level thresholding, principal component analysis, and contrast stretching, all standard routines available in the computer program ENVI.

Jacobi and associate (Drechsel) identified lineaments on three different images: 1) a principal component analysis of an ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) image, 2) a combination of ASTER and Landsat bands that have the least correlation (fused L&A image), and 3) a Landsat TM image (7,4,2) from the older EarthSat (1997) study.

ASTER is a sensor that has high band sensitivity and spectral resolution, which makes it particularly sensitive to small wavelength changes. In terms of spectral resolution, ASTER has one data point per 0.01 m, which makes it an order of magnitude better spectral resolution than Landsat TM, which has one data point per 0.27 m. ASTER also has a higher spatial resolution in the Visible and Near Infrared: 15 m compared to 30 m for Landsat. These factors make the ASTER sensor potentially more powerful than Landsat for lineament identification. Fusing the ASTER image with the Landsat image has the potential to produce an even greater pixel contrast, compared to either separate image. A vegetation analysis was also completed using Normalize Difference Vegetation Index to determine if the identified lineaments correlate with stressed vegetation.

Lineaments were identified on the satellite images in regions of existing detailed structural field data from the UB Rock Fracture Group. We then tested statistically, using Weights-of-Evidence, which lineament technique best agreed with fractures measured in outcrops in the same area.

The variables tested were:

1) each lineament orientation
2) each type of lineament (EarthSat, 1997; new ASTER; new fused ASTER with Landsat) ,
3) different lengths of lineaments, and
4) different fracture frequencies for each orientation.

In the Weights of Evidence method the greater the contrast value calculated, the better the correlation is between structural field data and satellite-identified lineaments. Contrast values were calculated for each lineament orientation and for several different threshold fracture frequencies of the same orientation as the lineament. The results of these tests revealed which lineament methodology is optimum for which orientation and fracture.

In addition, Jacobi compared EarthSat's (1997) Landsat lineaments to other data sets (aeromagnetics, gravity, seismic reflection profiles, and soil gas anomalies, as well as fracture frequency) in order to determine which lineaments might reflect structure. Where spatial coincidence occurred among lineaments and the other data sets, especially FIDs observed in outcrop, the inferred structures were extended along the lineaments from the field site. For example, if an outcrop with a NNE-tending FID is coincident with a NNE-striking EarthSat (1997) lineament, then the fault inferred from the FID potentially can be extended along the trace of the lineament. In this way, a map of potential faults can be constructed, even in regions with no outcrop and no seismic reflection data.

2.3 SOIL GAS ANALYSES

Soil gas surveys were conducted along primarily north-south profiles, following existing seismic lines. The operations followed the general techniques and rationale of Jacobi and Fountain (1996) and Fountain and Jacobi (2000). In this research project, traverses were conducted primarily along the edge of roads and samples were collected at a distance of 3 to 10 meters from the road, depending on road construction, to avoid the roadbed fill material.

Fountain and associates initially obtained samples by driving a stainless steel probe to a depth of 60 cm using a hand-held sledge hammer. In 2001, Fountain modified the procedure by using an electric impact hammer rather than hand-sledges, and he constructed special extraction tools to automate probe extraction.

Twenty cubic centimeters of air, slightly more than one probe volume, was withdrawn from the probe and discarded with an air-tight syringe to purge atmospheric air from the probe. An additional 60 cc of air was then withdrawn with the syringe and injected directly into a gas chromatograph (GC) equipped with a flame ionization detector for analysis (a Century OVA 128 GC). Gas enters the soil gas probe through an array of holes approximately 5 cm above the tip; the holes are covered by a loose sliding collar that minimizes plugging during insertion in the ground.

Samples were collected at 10 m intervals. This distance is somewhat arbitrary; however, the results of over 10,000 analyses established that most anomalies are more than 10 m wide (Fountain and Jacobi, 2000), confirming that a 10 m spacing will detect most anomalies. Linear response of the gas chromatograph was determined by analysis of standard gasses at the start of each day, after four hours of analyses, and at the end of each day. Samples were analyzed in duplicate every 10 samples.

All samples with 10 ppm or greater total organic vapor content were returned to the laboratory for analysis on a laboratory gas chromatograph (GC) to determine ethane/methane ratios. The GC was calibrated daily for response and elution times using standard gas mixtures.

2.4 SEISMIC DATA ACQUISITION, REPROCESSING, AND INTERPRETATION

Loewenstein (Quest Energy) purchased four N-S seismic lines and subcontracted with seismic processors to reprocess the records (see Figure 2.4-1 [TR #1] for general location of the proprietary seismic lines). Loewenstein and Jacobi interpreted the seismic lines for prominent stratigraphic reflectors and faults. Where recognizable, they picked reflectors that represent the Tully, Onondaga, Trenton, Black River and Precambrian/Cambrian contacts. They used accepted industry practices for the reflector recognition (e.g., Jacobi and Fountain, 1996; Jacobi et al., 2000). The interpretation of the 2-D seismic are displayed along the seismic line in the results section.

2.5 ADVANCED SEISMIC ANALYSES

The seismic expression of faults is a function of several variables, including seismic reflector offset and the frequency content of the seismic data. On migrated seismic lines, faults are most easily recognized by reflection offsets, changes in dip, changes in amplitude, etc. Subtle faults are most easily detected in 3-D seismic volumes by deriving and analyzing “horizon” attributes, such as dip, edge detection and azimuth, or “coherency” attributes (e.g., Hart et al., 1996). Additionally, complex trace attributes (e.g., instantaneous frequency, reflection strength) can be useful for fault detection. Hart analyze critical sections of the seismic profiles procured in the preceding subtask in the manner described above.

2.6 STRATIGRAPHY/WELL LOG ANALYSES

Jacobi and Loewenstein constructed subsurface structure contour maps based on distinctive units identified in well logs. These maps aid in determining fault locations and fault offset. The contouring was accomplished by a subroutine package in Geographix. The stratigraphic tops picked from well logs followed industry practice for recognition of each unit top; van Tyne and

Foster's (1979) study illustrates such picks. The production of these maps was partly funded by a NYSERDA grant.

Jacobi and Smith provided geological cross-sections across prominent surface structure where a prominent marker unit, the Tully Formation, outcropped. The elevations of the marker units were determined from topographic maps and from surveying the sites in from lake level.

2.7 AEROMAGNETIC SURVEY AND ANALYSES

Aeromagnetic prospecting is a powerful methodology that can define the basement fault block patterns with detail on a basinal scale. Pearson, deRidder and Johnson, Inc. acquired, processed, and interpreted an aeromagnetic survey of the study area. Using both widely available techniques and proprietary methods, Pearson, deRidder and Johnson, Inc. and Jacobi delineated basement-related structural elements that serve as bounding structures on intra-basement lithology blocks, supra-basement structural relief, and zones of faulting

Contract specifications for the aeromagnetic survey were as follows:

Survey area:	710 square miles
Line spacing:	1/3- mile N-S x 1-mile E-W
Line mileage:	3,600 line miles
Ground clearance:	500' above ground level, or as to be decided
Acquisition subcontractor:	Airmag Surveys, Inc., Philadelphia, PA

As detailed in the Results section, the actual line spacing was better than that specified—the NS line spacing was ¼ mile. The data were processed using an equivalent source method, which compensates for elevation differences at line intersections, taking into account anomalous vertical magnetic gradients. Both profile and grid based interpretation methodologies were employed to derive the maximum information content of the data set. The resulting maps can be used to infer lineaments related to faults in the basement, and can, in some cases, be used to determine approximate amount of offset on basement.

2.8 PHASE II: VERIFICATION-HORIZONTAL CORE

Jacobi spent nearly four years negotiating with various entities in order to obtain an oriented horizontal core in one of the T/BR fields in NYS. In 2006 the core was retrieved in a T/BR graben that is located along ENE-trending EarthSat (1997) lineaments, similar to those that this study suggests are related to structures associated with T/BR grabens.

The horizontal core retrieved for Phase II was oriented in the hole by two techniques: a three-prong scribe ahead of the core barrel and a "magnetic core orientation" tool behind the core barrel. The plan was that the single scribe ["lead" or top] was oriented "up[1]" (vertical) at the start of coring and the double scribe (with scribes spaced about 3.8 cm [1.5 in.] apart) was on the

[1] Note that in this horizontal coring operation, "up" and "down" do *not* refer to up hole and down hole.

bottom of the horizontal core at the start of coring (the bisectrix of the double scribe was 180º away from the lead scribe, and pointed "down"). However, as the coring operation progressed, the core barrel assembly, including the scribes rifled (or spiraled), as is common. The scribe marks on the core rotate down-core on complete sections of core. Thus, the scribe alone is useful for matching core sections that may not have other distinguishing architectures at their ends, but cannot be used for detailed absolute orientations.

Talisman/Fortuna also contracted with Multi-Shot Surveyors Inc. (MSI) and the coring company, Corion, for a "magnetic core orientation" tool that records the absolute orientation of the core assembly (including the scribes) at a location 15.5 m (51 ft) behind the bit. This tool records the orientation of the core barrel (as indicated by the lead, or top, scribe) every 0.3 m (1 ft) as coring proceeds, and took "stationary" surveys of the orientation every 1.5 m (5 ft). Talisman and MSI personnel first oriented the core in Calgary by reorienting the lead scribe with respect to the measurements of the magnetic core orientation tool. This preliminary orientation did not benefit from the core reassembly that Jacobi and graduate student Agle (J & A) performed later, and did not benefit from detailed analyses of the orientation data. J&A, with assistance from Talisman and MSI personnel, completed a detailed reorientation of the lead scribe with respect to the measurements of the magnetic core orientation tool; J & A integrated and averaged the MSI orientations taken every 0.3 m (1 ft) with what was "up" based on the continuous nature of the reassembled core over distances of several magnetic core orientation measurements.

There were 9 locations where the core rotated more than 10º (Table 2.8-1 [TR #9]). J&A used these depths to calibrate the depths of the 15 measurements from the magnetic core orientation tool with the (different) nominal depths of the core. Most of the core rotations (including the major rotation zones) inferred from the "magnetic core orientation" correlated with locations in the core where either a spin could be observed on the end of the core section, or the two adjacent core sections did not match, or where the core was essentially rubble (compare Table 2.8-1 [TR #9] to Table 2.8-2 [TR #9]).

J &A then attempted to correlate the core to the FMI log run in the horizontal hole in order to 1) correlate features in the core with features on the log, so that the FMI log could be better interpreted in regions where no core was taken, and 2) assist in estimating the amount of gap between core sections where the core has only rubble or where there is an observed core spin. Talisman personnel had suggested, based on a porosity spike, that the nominal depths of the core that were assigned at the drill site were incorrect with respect to the log suite. They suggested that the core depths were from 2,973 m to ~ 2,984 m (9754 ft to ~9791 ft), rather than from the driller's depths of 2,975 m to 2,987 m (9762 ft to 9799 ft). The core initiation point is clear within a meter (a few feet) on the FMI log, because the decision to core was made immediately after a gas show, and between 2,971.3 m to 2973.3 m to possibly 2,974 m (9748.5 ft and 9755 to possibly 9757.5 ft) feet the FMI log suggests a gas-charged fault zone. Based on a nearly horizontal, distinctive stylolite observed on both the FMI log and the core, and a vertical fracture partially filled with white baroque dolomite crystals, J & A estimated that the core begins at about 2974.2 m to perhaps 2974.8 m (9758 ft to perhaps 9760 ft) relative to the FMI log.

During the initial correlation between the core and the FMI log, a problem arose. The apparent bedding in the core reversed below a major core spin at 2.28 m (7.49 ft) (below the top of the core). The amount of core spin is based on the MSI/Corion magnetic core orientations and the physical core spin is observed on the core end. However, the FMI log did not show such a change in dip. Thus, it was determined that the central part of the core, between 2.28 m and 6.17 m (7.49 and 20.24 ft) was upside down. Talisman then contracted with Core Labs to take 360º pictures of the cores, and these photographs were compared digitally to the FMI log at the same scale by HEF Petrophysical. Using this side-by-side comparison, the consulting company was able to match up distinctive features that appeared on both images to gain depth control and rotation control.

This side-by-side comparison finally located the core depth with respect to the FMI log. Using this method, it was determined that the core began at 2,976.4 m (9,765 ft), compared to 2,975.4 m (9,762 ft) from driller's log, 2973.0 m (9,754 ft) from petrophysical logs, and 2974.8 m (9,760 ft) from J & A's preliminary correlation with the FMI log. With depth control established, J & A were able to find distinct features that could be recognized on both the FMI log and the 360º photos. J & A found that a few of the rotations made by the consulting company were not physically possible, since the core in those areas was solid with no breaks. J & A rotated the core to be internally registered to the up line on the FMI log. This was accomplished by identifying shallow to intermediately dipping features on both images and utilizing the geometries of the curves to determine the amount the core must be rotated over each complete segment. On the FMI log, the point where the up-line and the image of the feature cross on the FMI log was assumed to be true vertical for the feature. Once the true vertical was established for each feature, the same part of the feature (at true vertical) could be assigned as vertical on the 360º core photos. Once J & A knew where vertical should be on the core photos, it was a simple matter to determine how much each core segment needed to be rotated. Runs 1 and 4 were determined to be the correct orientation and the FMI log was too fuzzy for a definitive interpretation for Run 5. As predicted, features identified on Runs 2 and 3 (which are actually one solid segment separated by a large mineralized zone) yielded rotations of 168º, 203º, 125º, 176º, and 166º. These discrepancies were caused by "rifling" of the core barrel as described above. Since these two runs were one continuous cylinder of core, this entire run was rotated 168º (the average of all the features).

Jacobi and Agle measured each feature observed on the core twice—once on the full diameter core before slabbing, and again, after the core had been slabbed. Features that were measured and described include:

1) horizontal and vertical stylolites,
2) veins,
3) crystal growth orientation with respect to vein walls
4) rhombochasms orientation with respect to associated vein
5) vugs,
6) dolomitization fronts,
7) intergranular porosity,
8) other bedding features.

The data that were collected during J & A's second trip to Calgary were rotated to be consistent with the final determined rotations for each core segment.

3.0 RESULTS AND DISCUSSION

3.1 FRACTURE ANALYSES

3.1.1 Introduction

In the 2000 field season Jacobi and associates measured nine characteristics of over 2300 fractures at 149 sites on the east shore of Seneca Lake. In the 2001 field season they measured over 3000 fractures at 276 sites along Seneca Lake and the west shore of Cayuga Lake. In the 2002 field season they completed field work on the west side of Cayuga Lake, filled in data gaps along the eastern shore of Seneca Lake, and collected data between Seneca and Cayuga lakes in order to trace structural trends between the two N-S swaths. Figure 3.1-1 [TR #1] shows the location of the sites and modified rose diagrams for the Seneca Lake Swath.

Jacobi and associates found that the eastern shore of Seneca Lake and the western shore of Cayuga 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. In other words, different fracture sets predominate in different regions, and these fracture sets change character across the field area. The most common fracture sets include northerly- (“cross-strike”) and easterly- (“strike-parallel”) striking fracture sets with fairly wide spacings (for example, see Figure 3.1-2 [TR #1]; for location, see Figure 3.1-3 [TR #1]). However, each of the fracture sets also occurs as a FID and some fractures display later motion (Figures 3.1-4 to 3.1-6 [TR #1]). These variances, plus the abutting relationships, defined the structural domains discussed below.

3.1.2 Seneca Lake Data Analyses

3.1.2.1 Southern Structural Domain

In the area south of Hector (Figures 3.1-7, 3.1-8 [TR #1]), the master fracture set generally strikes NNW (although some sites exhibit other master fractures, primarily N- to NNE-striking). Examples of the master NNW-striking fractures are sites 4 (Figure 3.1-9 [TR #1]), 5, 71 (Figure 3.1-10 [TR #1]), RDJ 73A (Figure 3.1-11 [TR #1]), 19A (Figure 3.1-13 [TR #1]), and 33 (Figure 3.1-14 [TR #1]). In all of these examples of master fractures, 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 in the Southern Structural Domain. For example, N-striking FIDs occur at sites 17 (Figure 3.1-10 [TR #1]) and 74 A+B (Figure 3.1-11 [TR #1]), and a NNW-striking FID outcrops at site 18 (Figure 3.1-10 [TR #1]). At these sites (e.g., 74, 74A+B [TR #1]) the fracture frequency of the northerly-striking fracture sets is about an order of magnitude greater than that of the NNW-striking fractures outside the FID (such as sites 5 and 7, Figure 3.1-10 [TR #1]) and of the ENE-striking set outside the FID. Rarely do other fracture sets form FIDs in this structural domain.

Inspection of the rose diagrams in Enlarged Area Figure 3.1.9 [TR #1] reveals that at most sites, the northerly striking fractures have a higher frequency than the ENE and WNW striking fractures. Similarly, in Enlarged Area Figure 3.1-11 [TR #1], the northerly-striking fractures have nearly an order of magnitude greater frequency that the easterly striking fractures at site 1B.

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 only abut the N-striking fractures at an outcrop. For example, at sites 1B and 4 (Figure 3.1-9 [TR #1]), and RDJ 73A (Figure 3.1-11 [TR #1]), N-striking fractures abut the NNW-striking set. However, at sites 3 (Figure 3.1-10 [TR #1]), 74 A+B (Figure 3.1-11 [TR #1]), 19 and 20 (Figure 3.1-13 [TR #1]), 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 3.1-9 [TR #1]) 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 3.1-11 [TR #1], 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 3.1-9 [TR #1], 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) or early Alleghanian (e.g., Engelder and Whitaker, 2006). These older ages are 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 northerly-trending 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 easterly-trending 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.

3.1.2.2 Hector Structural Domain

The Hector Structural Domain is located in the region of Hector (Figures 3.1-7 [TR #1], 3.1-8 [TR #1]), 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 3.1-8 [TR #1]). 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 1.2-1 [TR #1]). In Enlarged Area Figure 3.1-15 [TR #1] at sites 8 and 9 the easterly striking fractures have an order of magnitude higher frequency than do the northerly striking fractures, even though the master set is northerly striking.

3.1.2.3 Valois Structural Domain

The Valois Structural Domain is located in the region of Valois (Figures 3.1-7 [TR #1], 3.1-8 [TR #1]), and is distinguished from the Southern and Hector structural domains by the spacing and abutting relationships of the ENE-striking fractures. South of Valois, 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 3.1-8 [TR #1]), and at some sites the ENE-striking fractures predate the northerly striking fractures—the ENE-striking fractures are either master to northerly trending fractures or are offset along northerly striking fractures (e.g., Figure 3.1-17 [TR #1]).

East-striking fractures also form FIDs in some of the same areas as the ENE-striking fractures (e.g., sites 8 and 9, Figure 3.1-15 [TR #1]). In this domain the ENE-striking fractures commonly abut the northerly-striking fractures. For example, at site CML 3 (Figure 3.1-16 [TR #1]) ENE-striking fractures abut NNW-striking fractures and at site 10 (Figure 3.1-15 [TR #1]), 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. T/BR grabens developed along some of these faults.

3.1.2.4. Northern Structural Domain

The Northern Structural Domain is located north of Valois (Figures 3.1-7 [TR #1], 3.1-8 [TR #1]), 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 3.1-8 [TR #1]). 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 3.1-8 [TR #1]).

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 3.1-17 [TR #1] and RDJ-54 and RDJ-59 in Figure 3.1-20 [TR #1]), other relationships are also common. For example, the ENE-striking set and the NNW-striking set mutually abut (e.g., RDJ-58 in Figure 3.1-20 [TR #1]), or mutually intersect (e.g., site 67 in Figure 3.1-18 [TR #1]), or the ENE-striking set can be master to NNW-striking set (e.g., RDJ-51 in Figure 3.1-20 [TR #1]). ENE-striking FIDs are master to NNW-striking fractures at several sites (site RDJ 31 in Figure 3.1-18 [TR #1]). Similar complicated relationships 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 3.1-19 [TR #1], RDJ 49 and RDJ 55 in Figure 3.1-20 [TR #1]). 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 3.1-18 [TR #1]). 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 3.1-18 [TR #1]). The most prominent NNW-striking fractures that display offset are at site 62 (Figure 3.1-18 [TR #1]), where hydrocarbon and water seeps along observeable NNW-striking faults occur in a road cut.

It is probable, based on the ENE-and northerly strking FIDs that in this strcuutral domain northerly-striking faults, as well as easterly-striking faults occur at depth. That the Alleghanian cross-strike fractures offset the ENE-striking fractures suggests that the ENE-striking fractures predate the Alleghanian fractures, and may be late Acadian in age (Engelder et al., 2001) or early Alleghanian (e.g., Engelder and Whitaker, 2006).

3.1.2.5. Seneca Lake Transect

Figure 3.1-8 [TR #1] displays the N-S transect along the eastern shore of Seneca Lake (see Figure 2.1-4 [TR #1] for location of transect). This transect summarizes the variations in frequency of ENE-and E-striking fractures in the Seneca Lake swath.

The highest frequency for EW-striking fractures occurs near Hector, where the frequency reaches about 30 fractures/meter. In contrast, ENE-trending fractures are nearly non-existent in this locale. As discussed in the Integration and Discussion Section (3.9), this high frequency at Hector corresponds spatially to the E-striking Firtree Anticline, an anticline mapped at the surface and from well logs (Figure 1.2-1 [TR #1]; e.g. Bradley et al., 1941; Murphy, 1981). The seismic section also confirms the structure as ramping thrusts from a salt decollement that resulted in the anticline.

South of Hector in the Southern Structural Domain and north of Hector in the Valois Structural Domain, the frequency of E-striking fractures generally is nearly zero. In the Northern Structural Domain the frequency generally varies from near-zero to 1 fracture/m, except for a higher frequency zone at 24.5 km on the transect that reaches about 7 fractures/m. This second high frequency zone corresponds to a region (near Lodi) where Bradley et al.'s (1941) structure contours strike E-W.

The frequency of ENE-striking fractures averaged over a kilometer window is generally less than 1 fracture/meter south of Valois, and many sites have a fracture frequency of essentially zero. In contrast, much higher maximum frequencies characterize the region in Valois and regions to the north; 4-6 fractures per meter are common, and frequencies reach a maximum of 34 fractures/m in the region of Valois. As discussed in the Integration and Discussion Section (3.9), this high fracture frequency coincides with a high number of EarthSat (1997) lineaments and soil gas spikes. Faults with T/BR grabens also are observed on seismic line #2 in this precise region; one of faults north of the well-developed T/BR graben may extend to near ground-surface. The Northern Structural Domain is characterized by variable frequencies of ENE-striking fractures, from near-zero to five zones with 5+ fractures/m frequency. The higher frequency zone at 28 km on the transect coincides with EarthSat (1997) ENE-trending lineaments, and the higher frequency zone at 23.5 km on the transect coincides with ENE-striking structure contours south of Lodi and an ENE-striking structure in the same area (a popup that was originally mapped as a normal fault, see following section, Figure 1.2-1 [TR #1]).

3.1.3 Surface Faults East of Seneca Lake

3.1.3.1 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 1.2-1 [TR #1]). 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 60 years later the stream did not reveal any structural evidence for a fault to Jacobi and associates (either the fault outcrop is presently covered or eroded away, or the "fault" was a misinterpretation).

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 Southern 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 (1941) data, suggest that the fault system should be extended north of Bradley et al.'s (1941) original estimate to at least Ovid. N-trending stream lineaments west-northwest of Ovid also suggest that the fault system may extend north of Ovid in the region of these lineaments (these N-S lineaments can be found as stream segments north of Inset 20 in Figure 3.1-7 [TR #1], and also seen in Figure 1.2-1 [TR #1] as the same stream lineament north of the Tully cross section).

3.1.3.2 Faults Discovered During This Investigation

In the Highland Road region (Figure 3.1-19 [TR #1]) several fracture trends indicate local faulting. At several of the sites, the N-striking fractures exhibited right lateral strike slip motion, displacing the ENE-striking fractures a few cm. The N-striking fracture set is not ubiquitous in the region; rather it is found only in certain zones. NNW- to NW-striking fractures at some sites also exhibit fault motion. The most prominent is at site 62, where hydrocarbon and water has seeped out of NNW-striking faults in a road cut for the past 20+ years (ever since the road cut was blasted out, according to local residents). It is thus probable that in this area, N- and NW-striking faults occur at depth (as well as ENE-striking faults). Northwest-striking FIDs (e.g., site 66, Figure 3.1-19 [TR #1]) also suggest NW-striking faults in this area. The N-striking faults are probably part of the proposed fault system along the eastern side of Seneca Lake from Watkins Glen to north of Ovid (see discussion in previous sections). The NNW-striking faults could be fractures that were reactivated as a result of motion on the N-striking fault system.

Jacobi and associates found NE-striking, northwest-directed thrust faults in the far northern part of the study area near Ovid (Figures 3.1-21 [TR #1] and 3.1-22 [TR #1]), 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 Engelder and Geiser (1980) showed generally ENE-striking “strike-parallel” fractures in the region, and to the south E- to ENE-striking structures are the norm for easterly trends. 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 related to a far-field Alleghanian stress field. It may be that the orientation and location of the NE-striking faults, FIDs, and master fractures are controlled by significant NE-striking fault systems in the Precambrian basement. However, none of the prominent aeromagnetic gradients in the immediate vicinity of Ovid strikes 045^o, although some of magnetic gradients to the south in the study area strike 045^o (see Aeromagnetic Section, 3.7). 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 these features represent:

1) part of a fracture/fault/fold/riedal shear system along a N-striking left-lateral fault, or
2) part of a larger scale lateral ramp, or
3) an unrecognized NE-striking fault that does not significantly affect Precambrian basement.

Discrimination among these alternatives is dificult because there are little data at present, but the N-striking fault system along the Seneca Lake east shore is certainly probable. As examined in the Discussion Section, all the data are consistent with a N-strking tear fault. However, at the northern end of Cayuga Lake, NE-striking faults that affect the Phanerozoic and Precambrian have been propsoed (see Introduction). Thus, althought we believe the NE-striking faults at Seneca Lake may be related to a N-striking tear fault, the alternative of NE-striking basement control cannot be rejected.

3.1.3 Cayuga Lake Data Analyses

3.1.3.1 Introduction

Sites for the 2001 and 2002 fracture data along the west side of Cayuga Lake are displayed in Figure 3.1-23 [TR #1]. Locations of enlargements that present rose diagrams constructed from the 2001 and 2002 fracture data are displayed on Figure 3.1-23 [TR #1]. Modified rose diagrams are presented in the detailed maps of the enlargement areas in Figures 3.1-24 [TR #1] to 3.1-43 [TR #1].

3.1.3.2 Maps of FIDs Combined with EarthSat (1997) Lineaments

3.1.3.2.1 Introduction. In order to better ascertain possible spatial relations between fracture intensification domains (FIDs) and Landsat lineaments (as portrayed by EarthSat, 1997), we analyzed each site for the presence of FIDs (defined as > 4 fractures/ m) in the Cayuga Lake area (Figure 3.1-44 [TR #1]). After eliminating sites without FIDs, rose diagrams displaying only FID data for each site and EarthSat (1997) lineaments were displayed on the Northern, Central, and Southern Combined maps (“Combined Maps”, Figs. 3.1-45 [TR #1] to 3.1-47 [TR #1]), as well as in detail in the Insets (Figs. 3.1-48 [TR #1] to 3.1-67 [TR #1]).

For a more rigorous test (groundtruth) of the lineaments with respect to outcrop data, we used a statistical measure of fit, the weights-of-evidence" method. The results of this test are discussed in the lineament section of this report.

3.1.3.2.2 Northern Combined Map In the Northern Combined map (Figure 3.1-45 [TR #1]), the predominate FID trend is NNW, although EarthSat (1997) recognized no NNW-striking Landsat lineaments in that area. In contrast, our analyses of DEMs for the region, as well as traditional topographic map inspection, show prominent NNW trends. For example, the shoreline of Cayuga Lake parallels the FIDs. These FIDs generally intersect other fracture sets, but at some sites the FIDs are the master to other fracture trends (e.g., in Insets A and E, Figures 3.1-41 [TR #1] and 3.1-52 [TR #1], respectively). The character of these fractures (including trend and master/abutting relationships) are similar to the Alleghanian cross-strike fractures of Engelder and Geiser (1980). We therefore suggest that these FIDs developed during the Alleghanian Orogeny, and most were not initially release fractures caused by modern processes such as glacial stress removal after carving of the valley. If these FIDs consisted of joints that were younger than Alleghanian, i.e., the FID joints abutted other fractures sets such as the strike-parallel fractures, we would then judge these fractures to be candidates for release fractures.

A second trend of FIDs not reflected in EarthSat (1997) lineaments for the Northern Combined map area is a N-S trend. In insets C, E, F, and G, (Figures 3.1-50 [TR #1], 3.1-52 [TR #1], 3.1-53 [TR #1], and 3.1-54 [TR #1], respectively) multiple sites with N-striking FIDs occur. In Inset C the N-striking FID in the north-central area of the Inset C can be followed 0.25 km across two creeks. Like the NNW-striking FIDs, the N-striking FIDs also intersect or are master to other fracture sets. For example, the N-striking FID in the north-central area of the Inset C intersects an E-striking FID. In the southeast corner of Inset C, the N-striking FID is master to a NNW-striking FID.

The predominate Landsat lineament trend is ENE in the Northern Combined map (Figure 3.1-45 [TR #1]). In Inset A on the Northern Combined map, lineament L1 is coincident with sites that display ENE-striking FIDs (Figure 3.1-45 [TR #1]). Similarly, ENE-striking Landsat lineament L3 in Inset E and L5 in Inset F are coincident with ENE-striking FIDs. However, we found eight additional zones of ENE-striking FIDs in the Northern Combined map that do not correspond to EarthSat (1997) lineaments (Figure 3.1-45 [TR #1]). These additional FID zones suggest that the Landsat lineaments of EarthSat (1997), though indicating the structural trends, cannot be used as a precise one-to-one indicator for the expected locations of FIDs.

The fracture interactions between ENE-striking fractures and cross strike fractures in the Northern Combined map are complicated. For example in Inset E (Figure 3.1-52 [TR #1]) at many sites the ENE–striking fractures are both master to, and intersect, the cross-strike (NNW-striking) fractures, but the FIDs only intersect the cross-strike fractures. The inference is that some ENE–striking fractures predate the cross-strike fractures, while other ENE-striking fractures may be contemporaneous with the cross-strike fractures and FIDs (or may have developed when the cross-strike fractures were "tight"). In other regions, the ENE-striking FIDs postdate the cross-strike fractures (in Inset F, Figure 3.1-53 [TR #1]). This range of relative ages is consistent with the observations on seismic lines that some of the Trenton/Black River faults have been multiply-reactivated.

The Northern Combined map also includes one EarthSat (1997) lineament that trends approximately E-W, L4. This lineament does not have a counterpart in outcrop FIDs, although it passes near sites in Inset E and is on-strike with sites in Inset F (Figure 3.1-53 [TR #1]). The relatively low number of E-striking EarthSat (1997) lineaments in the Northern Combined map is consistent, however, with the relatively low number of E-striking FIDs. Only three unequivocal E-striking FIDs were recognized in the Northern Combined map area. Thus, although again the specific E-striking FIDs in outcrop are not reflected in specific EarthSat (1997) lineaments (and vice versa), the regional structural grain indicated by the lineaments (e.g., few E-W trends in the Northern Combined map) is corroborated by the outcrop data.

3.1.3.2.3 Central Combined Map. The same FID trends that are found in the Northern Combined Map also occur in the Central Combined map (Figure 3.1-46 [TR #1]). Like the Northern Combined Map, the NNW-striking FIDs have no counterpart in EarthSat (1997) lineaments. One NNW-striking FID displayed dextral offset of ENE-striking FIDs (Inset I, Figure 3.1-14 [TR #1]). Several N-striking FIDs occur, none of which are indicated by EarthSat (1997) lineaments. In Inset H (Figure 3.1-55 [TR #1]), the N-striking FIDs occur on strike in two creeks 0.5 km apart. Additional N-striking FIDs were identified in insets I, J, K, L, and M (Figures 3.1-56 [TR #1] to 3.1-60 [TR #1], respectively). In inset M (Figure 3.1-60 [TR #1]), the N-striking FIDs are master to E-striking FIDs and intersect or abut ENE- and NNW-striking FIDs. The FIDs in Inset M are approximately on-strike with N-striking Landsat and topographic lineaments that extend north of Cayuga Lake. This zone of lineaments and FIDs may indicate a N-striking fault.

In the Central Combined Map (Figure 3.1-46 [TR #1]), two Landsat lineament trends predominate: ENE to NE, and EW. Lineaments L7 and L8 trend ENE and cross several sites in insets K, L, and J. No sites contain FIDs striking ENE. These lineaments are thus unsupported by groundtruthing. Lineament L6 strikes about NE; this lineament also crosses sites in insets K and H. None of these sites displays a NE-striking FID. This specific lineament is also therefore unsupported by structure data. However, about 0.5 km to the southeast in Inset K, two sites do have NE-striking FIDs, the only NE-striking FIDs in the Central Combined map. This relatively close association between Lineament L6 and the NE-striking FIDs may indicate that a NE-striking structure does pass through the area, but slightly to the Southeast of that proposed by the EarthSat (1997) lineaments.

In contrast to the unsupported NE-striking lineaments in the Central Combined Map, some of the E-striking lineaments in the Central Combined Map occur where outcrop data confirm the trends (Figure 3.1-46 [TR #1]). The southern packet of E-striking lineaments (including L12) is located in a region where three outcrops display E-striking FIDs in insets M and O, with the closest E-striking FID about 0.15 km from the lineament in Inset M. Lineaments in the northern E-striking packet (including L9 and L10) do not pass directly across sites with E-striking FIDs. However, E-striking FIDs in insets J and K are located 0.3 km away from E-trending EarthSat (1997) lineaments. Thus, like the area to the north, the specific locations of the E-striking lineaments are not confirmed by FIDs in outcrop, but the regional E-striking structural grain in this area is confirmed by both lineaments and FIDs. In all three sites with E-striking FIDs in Inset M, the E-striking FIDs post-date the Alleghanian cross-strike fractures. The E-striking FIDs in this region are spatially associated the Alleghanian Firtree anticline. If the FIDs resulted from buckling of the anticline, then the anticlinal growth post-dates the development of the cross-strike fractures.

3.1.3.2.4 Southern Combined Map. In the Southern Combined Map area, the dominant FID trend is again NNW (Figure 3.1-47 [TR #1]). Every inset displays NNW-striking FIDs which are either master to other fracture sets (e.g. in Inset R), or intersect other sets (e.g., Inset S). NNW-striking FIDs in insets P, Q, R, and S have no EarthSat (1997) counterpart (like the regions to the north). However, in Inset T, a NNW-striking lineament, L4, passes across a site that includes a NNW-striking FID. Other NNW-striking FIDs in Inset T indicate that even here, more FIDs occur in outcrop than indicated from Landsat lineaments.

A relatively minimal number of N-striking FIDs were measured in the Southern Combined Map, compared to the Central Combined Map. N-striking FIDs were found in Insets P, Q and R (Figures 3.1-63 [TR #1], 3.1-64 [TR #1], and 3.1-65 [TR #1], respectively); no N-striking FIDs occur in inset T (Figure 3.1-67 [TR #1]). The N-striking FIDs may consist of relatively short segments in this area, since none of the FIDs were recognized on-strike in neighboring streams. No N-striking EarthSat (1997) lineaments are located in the Southern Combined map area.

ENE-striking FIDs occur in insets P and Q (Figures 3.1-63 [TR #1] and 3.1-64 [TR #1], respectively); the southern ENE-striking FID in the northern part of Inset Q is approximately on trend with ENE-striking EarthSat (1997) lineament L13 (Figure 3.1-47 [TR #1]). ENE-trending lineament L14 does not cross any sites, and so cannot be confirmed or denied, but lineament L15 passes across a site which does exhibit an ENE-striking FID in Inset R. Additional ENE-striking FIDs were recognized in Inset S (Figures 3.1-47 [TR #1], 3.1-66 [TR #1]), where no Landsat lineaments were identified (EarthSat, 1997).

E-striking FIDs occur in the southern half of Inset P (Figure 3.1-63), and in the center of Inset Q (Figure 3.1-64 [TR #1]). In inset R (Figure 3.1-65 [TR #1]), E-striking FIDs were recognized on strike in outcrops about 0.5 km apart. Several E-striking FIDs occur in Inset T (Figure 3.1-67 [TR #1]). None of these E-striking FIDs is represented by E-striking EarthSat (1997) lineaments (as had been noted in previous reports, based on the 2-D transect).

3.1.3.2.5 Combined Map Summary. The greatest number of FIDs trend NNW, parallel to the general Cayuga lakeshore (except where the lakeshore bends in the Central Combined Map area). Only one EarthSat (1997) NNW-striking lineament was proposed in this region. The ubiquity of the NNW-striking FIDs may indicate that the general lake outline follows a NNW-striking fault system. N-striking FIDs also occur in the Cayuga area, and are prevalent in the Central Combined Map area. Although no N-striking EarthSat (1997) lineaments were recognized in the Cayuga area, the N-striking FIDs in the eastern part of the Central Combined Map are on strike with EarthSat (1997) lineaments and topographic/stream lineaments. Probable N-striking faults are indicated.

E-striking and ENE-striking FIDs occur in structural domains of the Cayuga Lake study area. In the Northern and Southern Combined Map areas, ENE-striking FIDs are coincident with ENE-trending EarthSat (1997) lineaments. However, at least eight additional FIDs were discovered that are not associated with an ENE-striking EarthSat (1997) lineament. A similar situation exists with the E-striking FIDs and lineaments. The EarthSat (1997) E-striking lineaments generally are confirmed by coincident E-striking FIDs, but additional E-striking FIDs suggest a higher number of E-striking faults. The E-striking lineaments and FIDs in the Central Combined Map are related to the E-striking Firtree Anticline, and the ENE-striking lineaments may be related to older Iapetan rift fault trends that were reactivated.

3.1.3.2 NNW-Trending Cayuga Lake Transect

3.1.3.2.1 E-striking fractures and FIDs. The 2001 and 2002 data were projected to a NNW-SSE transect along the western shore of Cayuga Lake (for transect location, see Figure 2.1-7 [TR #1]); the data were averaged in 1 km windows along the transect (Figures 3.1-68 [TR #1] and 3.1-69). In the southern half of the NNW-SSE Cayuga Lake transect (Figure 3.1-68 [TR #1]), a number of zones with closely-spaced fractures (FIDs) that strike east occur between 8 and 16 km. East-striking Landsat lineaments (EarthSat, 1997) also occur in this same area. To the west, this same packet of E-trending lineaments is located on the previously recognized E-striking, Alleghanian Firtree Anticline. Although an exact one-to-one correlation between lineaments and E-striking FIDs is not observed for the Firtree Anticline at Cayuga Lake (Figure 3.1-68 [TR #1]), lineaments related to the anticline do occur in the same region as E-striking FIDs with fracture frequencies greater than 10 fractures/meter (for E-striking fractures). On Inset J (Figure 3.1-33 [TR #1]), Site 1-157 has a very high fracture frequency for E-striking fractures, and this site is approximately on-strike with a set of discontinuous E-striking lineaments to the west of Inset J (Figure 3.1-46 [TR #1]). Although Inset K covers a region that includes these E-striking lineaments, we have no outcrops in the specific areas of the lineaments in Inset K. Another E-striking lineament passes through Inset M (Figure 3.1-46 [TR #1]). In Inset M site 253 (Figure 3.1-36 [TR #1]), which has a high E-striking fracture frequency (about 10 fractures/m), occurs in the region where the E-striking lineament was recognized by EarthSat (1997). Farther north in Inset M (Figure 3.1-36 [TR #1]), site 1-249 also exhibited a high E-striking fracture frequency. In all three sites, the high frequency E-striking fractures post-date the Alleghanian cross-strike fractures; i.e., the fracturing associated with the Alleghanian Firtree anticline post date the development of the cross-strike fractures.

The southern-most series of E-striking FIDs with fracture frequencies of greater than 5/meter does not correspond to recognized Landsat lineaments. Between this zone of FIDs and the Firtree Anticline lineaments/FIDs, another zone of E-striking FIDs occurs (at 5.5 km to 6.5 km on the transect; Figure 3.1-68 [TR #1]). This FID zone also does not coincide with any Landsat lineaments, but the number of sites with high fracture frequencies suggests that there is an E-striking Alleghanian structure (fault) in this region.

The northern half of the NNW-SSE transect is characterized by generally low E-striking fracture frequencies. Only at 27 km on the transect (Figure 3.1-68 [TR #1]) and northward do fracture frequencies approach 5/m (or greater). No Landsat lineaments were recognized in this region by EarthSat (1997). The only E-striking Landsat lineament in the northern half of the transect occurs in a region where no sites show any evidence of E-striking FIDs (between 21 and 24 km on the transect; Fig 3.1-68 [TR #1]). This lineament passes through Insets E and F (Figure 3.1-45 [TR #1]), where no E-striking FIDs were found (Figs. 3.1-28 [TR #1] and 3.1-39 [TR #1]), and in fact, only one site displays any E-striking fractures (at 1 fracture/m). The lack of fractures to support the lineament, and the lack of coinciding topographic lineaments, suggests that this lineament may not reflect important subsurface features in this region. Both the lack of support for this lineament, and the lack of lineaments where we do have high frequency fractures, point up the need for verification of the Landsat lineaments, and the usefulness of fracture studies as a means of verification, as well as an indicator of structure not recognized in the Landsat data.

3.1.3.2.2 ENE-striking fractures and FIDs. The distribution of ENE-striking FIDs and Landsat lineaments on the NNW-SSE transect is shown in Figure 3.1-69 [TR #1]. The two northern packets of ENE-striking lineaments (between 21 and 16 km and between 28 km and the end of the transect, Figure 3.1-69 [TR #1]) both correspond to regions where ENE-striking FIDs occur. These ENE-striking lineaments and FIDs are thought to reflect the Trenton/Black River structures, since they are coincident with reactivated Trenton/Black River structures observed on a seismic line along the Seneca Lake transect (discussed in Section 3.9). In Inset A (Figure 3.1-24 [TR #1]), an ENE-striking FID observed at Site 1-307 is coincident with an ENE-trending Landsat lineament (compare Figure 3.1-24 [TR #1] with 3.1-45 [TR #1]) and with a stream.

The fracture intersections between ENE-striking fractures and cross strike fractures in this region are complicated. For example in Inset E (Figure 3.1-28 [TR #1]) at many sites the ENE–striking fractures and FIDs are master to the cross-strike (NNW-striking) fractures (e. g., sites 1-279, 1-286). However, they also intersect the cross-strike fractures (same sites). The inference is that some ENE–striking fractures and FIDs predate the cross-strike fractures, whereas other ENE-striking fractures may be contemporaneous with the cross-strike fractures (or may have developed when the cross-strike fractures were "tight"). In some regions, the ENE-striking FIDs postdate the cross-strike fractures (e.g., Site 1-233A in Inset F, Figure 3.1-29 [TR #1]). This range of relative ages is consistent with the observations on seismic lines that some of the Trenton/Black River faults have been multiply-reactivated.

The central packet of NE to ENE-striking lineaments passes through Insets I, J, K, and L (Figure 3.1-46 [TR #1]) and corresponds to high fracture frequency in ENE-striking fractures (Figure 3.1-69 [TR #1]) as well as NE-striking fractures (e.g. site 1-226 in Inset I, Figure 3.1-32 [TR #1]). The same range of intersection relationships is observed here as to the north. The southern zone of ENE-trending lineaments pass through insets Q and R (Figure 3.1-47 [TR #1]). Sites 1-188 and 1-297 in Inset R (Figure 3.1-41 [TR #1]) exhibit ENE-striking FIDs that coincide with the location of a Landsat lineament (compare Figure 3.1-4 [TR #1] with Figure 3.1-41 [TR #1]). At this area, the ENE-striking fractures both predate and postdate the Alleghanian cross-strike fractures.

3.2 LINEAMENTS

A slope aspect analysis of the DEM in the Seneca Lake region is shown in Figure 3.2-1 [TR #2]. This figure shows prominent approximately N-striking lineaments in the southern part of the study area east of Seneca Lake, where a relatively high number of N-striking fractures and FIDs occur (see Section 3.1). In the central part of the study area at Hector and Valois, prominent E-trending lineaments occur on both sides of Seneca Lake, and ENE- and NE-trending lineaments form a zone from Hector to north of Valois (Figure 3.2.1 [TR #2]). These ENE- and NE-striking topographic elements on the east side of Seneca Lake correspond to the zones where we found a concentration of ENE- and NE-striking fractures and FIDs (see Section 3.1). In fact, as shown on the standard deviation-of-the-slope map, the only prominent ENE-striking anomalous topographic gradient in the study area east of the lake occurs east of Valois (at yellow arrow in Figure 3.2-2). The ENE trend is parallel to the gradient in an aeromagnetic anomaly to the south (see discussion in Section 3.7) and is located where prominent ENE-striking FIDs and ENE-trending EarthSat (1997) lineaments occur.

On the standard deviation-of-the-slope map (Figure 3.2-2 [TR #2]), the narrow anomalous slopes form an inverted V-pattern (pointing northerly); this pattern results from slope breaks related to more resistant weathering units combined (on the east side) with glacially-accentuated features.

The EarthSat (1997) lineaments for the study area are shown in Figure 3.2-3 [TR #2]. There are four dominant trends of lineaments and lineaments "bundles" in the study area: northerly-, E-, ENE-, and NE-striking. Northerly-trending lineament "bundles" are located along Keuka Lake, Seneca Lake, and Cayuga Lake. As discussed in detail in the Aeromagnetic Section (3.7), the lineament bundle along the East Branch of Keuka Lake is coincident with prominent aeromagnetic and gravity gradients. Well logs indicate a fault along the east shore (Murphy, 1981, this report, Section 3.6). Similarly, the northerly-trending lineaments along the east side of Seneca Lake also mark a fault system, as evidenced by outcrop stratigraphy (Bradley et al., 1941), N-striking FIDs (Section 3.1), and a truncation of aeromagnetic anomalies (Section 3.7). The two northerly-trending lineament bundles east of Cayuga Lake also probably represent fault systems.

The E-trending lineament bundle in the central part of the study area that extends from the eastern border of the study area to west of Seneca Lake is coincident with the Alleghanian Firtree Anticline. Note that in the Seneca Lake region the lineament bundle is offset by N-striking lineaments. Jacobi (2002) suggested that these N-striking zones are tear/transfer/lateral ramps of the thrusts associated with the Firtree Anticline, and that these N-striking zones are localized by deeper structures of similar trend. For the region east of Seneca Lake, the relationship between E-striking lineaments and E-striking fractures are discussed in Fracture Section 3.1.2.2 and the Discussion Section (3.9); for the region west of Cayuga Lake, the relationship between E-striking lineaments and E-striking fractures is discussed in Fracture Sections 3.1.3.2 and Discussion Section (3.9).

The ENE-striking lineament bundles are sub parallel to aeromagnetic gradients, and have been proposed by Jacobi et al. (2004 a-d, 2005a-d, 2006a-c) to represent Iapetan rift faults that have been multiply-reactivated, including T/BR times. For the region east of Seneca Lake, the relation of ENE-striking lineaments to ENE-striking fractures are discussed in the Fracture Section 3.1.2.3 and the Discussion Section (3.9); for the region west of Cayuga Lake, the relation is discussed in Fracture Section 3.1.3.2.

Few EarthSat (1997) NNW- and NW-lineaments were recognized in the study area. This lack does not appear to represent the actual structural fabric. As discussed below (in this section), as well as in the Cayuga Swath structure section (3.1.3.2) and in the Aeromagnetic Section (3.7), the study area does exhibit northwesterly trending FIDs and gravity gradients, which probably indicate faults with northwesterly trends.

Neither the Glodes Corners Road Field nor the Muck Farm Field has EarthSat (1997) lineaments associated directly with the field. However, re-evaluation of a newer Landsat image by Everett, Staskowski, Jacobi and Drechsel (EarthSat and UB personnel; Everett et al., 2003, 2004; Staskowski et al., 2003; Drechsel et al., 2004; Cruz et al., 2005) showed that a weak easterly-trending lineament does pass over the Glodes Corners Road Field. Additionally, the Muck Farm extension (Figure 3.2-4 [TR #2]) is nearly coincident with easterly-trending lineaments, and the original northeasterly trend of the Muck Farm Field is parallel to lineaments immediately south of the field. Nevertheless, the EarthSat (1997) lineaments did not predict the Glodes Corners Road and the Muck Farm fields, unlike the ENE-striking lineament bundles to the south that are along trend of the T/BR fields to the south (Figure 3.2-4 [TR #2]). As discussed in detail in the Aeromagnetic Section (3.7), the fields terminate primarily against northerly-trending lineaments and northwesterly-trending lineaments (Figure 3.2-4 [TR #2])

The false-color ASTER principal component image on which we identified lineaments in the study area is shown in Figure 3.2.5a [TR #2]. We identified lineaments on three different magnifications of the image. Figure 3.2-5b [TR #2] shows an example of lineament identification in the study area on the ASTER principal component image. The higher spatial resolution (about an order of magnitude better than Landsat), coupled with the higher number of spectral bands, allow a much better definition of lineaments. Additionally, the higher spatial resolution of the image allows a better discrimination between cultural and natural lineaments. Our analysis demonstrates similar trends as those found in earlier data sets (EarthSat, 1997, and our DEM analyses), but a much higher number of individual lineaments were recognized.

Figure 3.2-6a [TR #3] shows the fused ASTER and Landsat image—a combination of ASTER and Landsat bands that have the least correlation ("fused L&A image"). Lineaments identified on this image are shown in Figure 3.2-6b [TR #3].

The results of the Weights of Evidence method show that for the Seneca Lake region, NE- and ENE-striking lineaments from the fused L&A image are marginally better at predicting FIDs (>4 fractures/m) than lineaments from the ASTER (alone) Principal Component (PC) analysis (Figure 3.2-7 [TR #3]), but both are significantly better than EarthSat (1997) lineaments at predicting appropriately-oriented FIDs. The lineaments from the fused L&A image are also better at predicting NW and NS-trending FIDs (Figure 3.2-7 [TR #3]). In contrast, E- and NNW-striking FIDs are better predicted by lineaments from the ASTER (alone) PC analysis (Figure 3.2-7 [TR #3]). For all sites in the Seneca Lake region with fracture frequencies greater than 2 fractures/m, lineaments from the fused L&A image better predicted fractures trending NE, ENE, NW, NNW, and NS (Figure 3.2-7 [TR #3]). Only EW fractures are better represented by the ASTER (alone) PC analysis. In both the fracture frequencies > 4 fractures/m chart and the FID chart (Figure 3.2-7 [TR #3]), the EarthSat (1997) lineaments successfully predicted only N-S trending fractures and FIDs (i.e., the contrast values for these trends was above the significance threshold of 0.25.

The images from which we identified the "best[1]" lineaments for each orientation for the Cayuga Lake area are different from those in the Seneca Lake region. Lineaments from the fused L&A image best predict FIDs that trend NW and NNW (Figure 3.2-8 [TR #3]). For NE-, ENE- and EW- striking FIDs, the ASTER (alone) PC analysis results in more coincident lineaments than the lineaments from the fused L&A image (Figure 3.2-8 [TR #3]). In the Cayuga Lake region, the EarthSat (1997) lineaments best predicted ENE-striking FIDs. For all sites with fracture frequencies greater than 2 fractures/m, no image successfully predicted NE-striking fractures (Figure 3.2-8 [TR #3]). Like the FIDs at Seneca Lake, lineaments from the fused L&A image best predict FIDs that trend NW and NNW (Figure 3.2-8 [TR #3]). The ASTER (alone) PC analysis results in more coincident lineaments than the lineaments from the fused L&A image for ENE- and EW-trending fractures. The "best" type of lineament for each fracture trend and each fracture frequency are displayed schematically in Figures 3.3-9a [TR #3] and 3.3-9b [TR #3].

The conclusion is that no single image processing methodology provides an optimum image for identifying all lineament trends that correspond to FIDs and lesser fracture spacing. The interesting thing is that the "best" methodology is not constant across the region for the same lineament trend. General ground slope with respect to look angle and sun angle may play a role in this difference across the region. We do not believe that regional vegetation type is critical in this difference, based on our NDVI analysis. Finally, much of the difference for ENE-trending EarthSat (1997) lineaments may be an artifact of the manner in which weights of evidence contrast values are calculated. We are in the process of evaluating this factor, but no "glitch" in the calculations can account for the lack of lineaments in certain orientations, even though FIDs are common in those directions (e.g., NW-trending FIDs with no comparable EarthSat [1997] lineaments).

3.3 SOIL GAS ANALYSES

In the summer of 2000, Fountain and associates collected soil gas samples every ~9.3 m along an 11.3 km (7 mi.) N-S traverse east of Seneca Lake (Figures 3.3-1 [TR #3] and 3.3-2 [TR #3]). Fountain had planned to extend the traverse south to the Watkins Glen area, but soggy ground from continual rain prevented completion of the traverse. In the summer of 2001 Fountain acquired 5836 soil gas samples along more than 32 km of traverse. The traverses completed the planned north-south transect from Ovid to Watkins Glen. Figure 3.3-3 [TR #3] displays the average number of soil gas spikes on the transect. Additional lines included completion of a survey box around a recently drilled T/BR test well and offsets of the main traverse near Ovid and near Lodi, where extensive contamination from dense housing had made the main road non-viable. In the summer of 2002 Fountain and associates measured 3,034 samples in the field and performed over 230 lab analyses. Fountain and associates collected 51.9 km (19.96 mi.) of traverses at a sample spacing of 10m. The traverses were intended to determine if the soil gas anomalies observed on the main N-S traverse could be recognized farther east. Detailed soil gas surveys were also performed in the region of T/BR test wells, Campion #1 and Ziefle #1 (Figures 3.3-4 [TR #3], 3.3-5 [TR #3], and 3.3-6 [TR #3]), since these wells were Trenton/Black River

[1] Here "best" lineaments indicates the set of lineaments from a particular processed image that passes over more outcrops with appropriately oriented fractures than similarly oriented lineaments from any other processed image

tests drilled into Trenton/Black River grabens (Figures 3.4-4 [TR #3] to 3.4-21 [TR #3]). The survey boxes were planned to determine the orientation of the soil gas anomalies (if linear).

Soil gas results from the N-S traverse along Seneca Lake are shown in Figure 3.3-2 [TR #3]. A large number of ethane-charged soil gas anomalies occur in the northern half of the traverse between Ovid and just south of Lodi (Figure 3.3-2 [TR #3]). South of Skinner Rd. the number of spikes decreases significantly. The soil gas anomalies on the N-S traverse show a strong coincidence with ENE-trending lineaments (Figure 3.3-3 [TR #3]), but not with the E-W trending lineaments.

The E-trending lineaments are related to the high-structural level Alleghanian Firtree Anticline (as discussed in the Discussion Section 3.9). The lack of gas spikes across the anticline suggests that the structures associated with the anticline either:

1) do not tap sufficient gas-charged reservoirs (compared to the ENE-striking fractures, or
2) the E-W trend is sufficiently oblique to the present horizontal principal compressive stress (S_H) to tighten the fractures to impede gas migration, or
3) the form of the E-striking and the ENE-striking fractures differ.

Since the Silurian salt blanket is encountered immediately below the E-striking Fir Tree Point Anticline, it seems probable that the surficial ENE-striking fractures do not extend deeper in the section than the E-striking Fir Tree Point Anticline fractures. Thus, it seems unlikely that the ENE-trending fractures could tap more (deeper) reservoirs than the E-striking fractures (unless additional reservoirs occur along ENE-trending fracture systems above the salt —a remote possibility). We suggest that the ENE-trending fractures and the ENE-striking fractures pass through the same number of gas reservoirs above the Silurian salt section.

The second alternative is possible but may not be probable because the oblique angle between the E-W fractures and the ENE-trending S_H is small (on the order of 18^o-20^o maximum). It is also remotely possible, but not probable, that the ENE-striking fractures associated with the anticline have already drained the reservoirs in the vicinity of the fractures.

The remaining, third alternative explanation is a possibility. In such a case, the ENE-striking fractures would have considerable individual heights, and would be FIDs through the entire section above the salt, joining multiple reservoirs with the surface. In contrast, the E-striking fractures may have formed under less differential stress, and have less individual height, with intervening ductile zones where fracturing is less pervasive, with the result that the reservoirs are not all connected to the surface.

No matter which model ultimately is found to be correct, it appears that the number of gas spikes correlate well with the ENE-striking EarthSat (1997) lineaments. As discussed in Section 3.9, the ENE-striking lineaments coincide with ENE-striking FIDs, and with faults observed on seismic reflection data. Note in particular that relatively few soil gas anomalies (spikes) occur south of Valois, mimicking the lack of ENE-trending lineaments and ENE-trending fractures with high-frequencies (FIDs) (Figure 3.3-3 [TR #3]). The coincidence of ENE-striking lineaments, FIDs, and faults on seismic confirms our contention that the soil gas anomalies correspond with structural features. Note that the detailed locations provided by soil gas anomalies provide more precise information than lineament analysis

Combining the soil gas data from the N-S traverse with additional traverses to the east, it is apparent that a zone of soil gas anomalies extends from the N-S traverse to numerous soil gas spikes near the gas well in the east (Figures 3.3-4 [TR #3], 3.3-5 [TR #3], and 3.3-6 [TR #3]). The southern boundary of this zone corresponds to the southern boundary faults of a Trenton/Black River graben.

The index maps for traverses that display detailed soil gas data integrated with topographic profiles, streams, and EarthSat's (1997) lineaments from Landsat are shown in Figures 3.3-5 [TR #3] and 3.3-6 [TR #3]. Figures 3.3-7 [TR #3] to 3.3-19 [TR #3] display individual soil gas analyses along traverses, as well as topographic profiles and lineament locations on the same traverses. Figure 3.3-20 [TR #3] is a detailed index map of a T/BR test, Campion #1, area that shows soil gas anomalies, fracture rose diagrams, lineaments from EarthSat (1997), and topography/stream network. Traverses surrounding the Campion #1 well are shown in Figures 3.3-21 [TR #3] to 3.3-24 [TR #3]). Figures 3.4-7 [TR #3] to 3.4-24 [TR #3] show detailed soil gas surveys in the region of T/BR test wells Campion #1 well and the Ziefle #1 wells (location of wells in Figure 3.4-6 [TR #3]). Inspection of these profiles reveals the following:

1) Individual large-magnitude soil gas anomalies (spikes) are rarely wider than 50 m (e.g., Figures. 3.3-7[TR #3] to 3.3-19 [TR #3]), and most have very narrow peaks than constitute a single sample (sample spacing is 10 m). Even clusters of soil gas spikes (such as those between 720 m and 950 m on Traverse 2002-2 (Figure 3.3-8 [TR #3]) are relatively narrow—on the order of 200-250 m. Thus, widely-spaced sampling will not necessarily represent the actual number and location of soil gas seeps, and correlating between soil gas spikes in widely-spaced samples on parallel traverses could lead to incorrect inferred trends. The narrowness of the anomalies suggests that the seeps result from single fractures or narrow fracture intensification domains (FIDs).
2) Because most of the soil gas spikes analyzed for ethane do have an ethane content, these spikes record thermal gas (rather than biogenic or "swamp" gas). A few spikes do not show any ethane, suggesting that these spikes are biogenic (e.g., the spike at approximately 1520m on Traverse 2002-2; Figure 3.3-8 [TR #3]).
3) Many of the lineaments from EarthSat (1997) and straight stream segments coincide with, or are very close to, soil gas spikes. For example, in Figure 3.3-7 [TR #3], the ENE-striking EarthSat (1997) lineament at about 85 m is close to the isolated soil gas spike at about 55 m. Similarly, on Traverse 2002-2 (Figure 3.3-8 [TR #3]) the E-striking stream at 280 m and associated valley is coincident with a series of soil gas spikes, as is the NNW-striking stream and valley at about 2,000 m.
4) We recognized many more soil gas spikes than lineaments (either EarthSat's, 1997, or stream lineaments). For example, in Figure 3.3-8 [TR #3], there are 6 soil gas spikes and no lineaments.
5) The number of spikes on the sides of the traverse boxes precludes a simple correlation of spikes along a single trend. However, among traverses 2002-7 and 2002-13, 2002-11 (Figures 3.3-13 [TR #3] and 3.3-16 [TR #3], 3.3-17 [TR #3], respectively; see Figure 3.3-6 [TR #3] for locations), an ENE-striking trend can be passed through soil

gas spikes on these traverses. This trend may extend farther east, where it intersects NNW-trending lineaments (stream and EarthSat, 1997) and soil gas spikes at the intersection of traverses 2002-3 and 2002-4. This ENE-striking trend is, however, about 10^{o} away from the nearby EarthSat (1997) trend.

6) A soil gas trend may exist along a NNW-striking EarthSat (1997) lineament and stream. Unfortunately, the lineament passes through the intersection of two sides of each survey box, so the trend cannot be established with certainty (intersections 2002-2 and 2002-5; 2002-4 and 2002-3; Figure 3.3-6 [TR #3]).

In the immediate region surrounding the Campion well (the western Trenton/Black River well, Figures 3.3-5 [TR #3] and 3.3-20 [TR #3]), soil gas anomalies were recorded just north of the well. These soil gas spikes could correspond to the ENE-striking EarthSat (1997) lineament that passes through the immediate area, but the Campion well was drilled on the intersection of a NNE-striking topographic lineament and an ENE-striking lineament. Thus, the soil gas spikes may also reflect the NNE-striking lineament. In the Campion well area, outcrops with E-striking fractures (see Figure 3.3-20 [TR #3] for rose diagrams) occur in the vicinity of the ENE-trending lineament (intersection of Traverse 2001-B1 and 2001-B2). The lack of ENE-striking fractures here suggests that the ENE-striking lineament does not extend this far east, and may end east of the Campion well where the stream changes direction (Figure 3.3-20 [TR #3]). Figure 3.3-20 [TR #3] also shows that there is little correlation between the ENE-striking lineaments and soil gas spikes in this area.

3.4 SEISMIC DATA ACQUISITION, REPROCESSING, AND INTERPRETATION

3.4.1 Acquisition and Reprocessing

The subcontractor, Quest, licensed four N-S seismic reflection lines, three of which are from Geodata (Figure 2.4-1 [TR #1]). The fourth line (Line #1) was shot in January 2001 as part of a group shoot. The Geodata lines are 1980s vintage data. Data quality is good and the field acquisition parameters were as described below. The Geodata lines were reprocessed by Elite Seismic Processing, Inc. in October, 2000, and were interpreted by Stu Loewenstein (Quest) and Jacobi in 2000-2001. The parameters for the Geodata lines are listed below.

Source:		
	Type:	Vibroseis
	Interval:	220 ft. (67 m)
	Pattern:	4 over 110 ft (33.5 m)
	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. (33.5 m)
Pattern:	24 over 220 ft. (67 m)
Coverage:	2400%
Spread: Trace:	1------------ 48 X 49 ------------96
	5720’ 550’ 550’ 5720’
	1743 m 167.6 m 167.6 m 1743 m

The data quality for Line #1 is good and the field acquisition parameters were as described below. This line was processed by Sterling Seismic Services, Ltd., in January, 2001, and was interpreted by Stu Loewenstein (Quest) and Jacobi in 2001. The parameters for Line #1 are listed below.

Source:

Type:	Vibroseis
Interval:	220 ft. (67 m)
Pattern:	2 over 110 ft (33.5 m)
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. (33.5 m)
Pattern:	12 over 110 ft. (33.5 m)
Coverage:	3000%
Spread: Trace:	1------------ 60 X 61 ------------120
	6655’ 165’ 165’ 6655’
	2028.4 m 50.3 m 50.3 m 2028.4 m

3.4.2 Interpretation

Each of the four seismic lines displays Trenton/Black River faults associated with grabens. Seismic line 1 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 3.4-1 [TR #3] is an interpretation of part of Line 1 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 could suggest that these observed fault offsets are primarily a manifestation of solution collapse grabens caused by carbonate dissolution, rather than a direct result of deep tectonic fault motion. However, the vertical alignment of isolated fault segments from the Trenton to the basal Cambrian (?) reflectors (fault “#1” on Figure 3.4-1 [TR #3]) 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. Possibly a FID extending upsection from the fault in the Cambrian provided a dissolution pathway for limestones below the Knox Unconformity. A dissolution/fault sag (similar to the Black River) with observable offset would be the result, 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 multiple times of dissolution occurred 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.

A second possibility for the lack of deep penetration of the northern boundary fault of the graben is that the fault is a riedel shear controlled by a deeper segment of fault #1. Similar scenarios can be envisaged for other “rootless” faults observed on single 2-D seismic lines. In either the fault model or solution collapse model, it appears that most of the activity where the seismic line crosses the Glodes Corners Road Filed ended in Trenton time, since the Trenton reflector is minimally offset on the southern boundary fault, and not offset at all across the northern boundary fault.

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 Allegany County (e.g., Jacobi and Fountain, 2002), these dipping intra-Grenvillian reflectors do not appear to have been significant growth faults during Iapetan rift development.

Figure 3.4-2 [TR #3] is an interpretation of part of Line 1 across the Muck Farm Field. Faulting and grabens in the Trenton/Black River are also evident here. The “master” (northern) fault has a listric fault geometry with increasing offset upsection. This fault may not directly connect to a normal fault that offsets the Precambrian/Cambrian contact directly below the “listric” fault. Alternatively, the “listric” fault could be part of reverse flower structure. 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.

Seismic Line 2 (Figure 3.4-3 [TR #3]) is located between Seneca and Cayuga lakes (Figure 2.4-1). 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 3.4-3 [TR #3]). Several of the faults are growth faults, such as #9, #10, and #14, with the largest offset on the Precambrian contact (Figure 3.4-3 [TR #3]). 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. The E-striking Firtree anticline, and associated thrusts (S1-S5 on Figure 3.4-3 [TR #3]), 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 (Figure 3.4-4 [TR #3]) is located east of Cayuga Lake (Figure 2.4-1 [TR #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 3.4-4 [TR #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. The anticlinal structure in the center of the line that significantly affects the T/BR may be a positive flower structure. If that model is correct, then these (ENE-striking?) faults were tear faults during Taconic times. Their orientation is favorable for such an interpretation (e.g., Jacobi et al., 2004a-d).

Seismic line 4 (Figure 3.4-5 [TR #3]) is located east of Line 3 (Figure 2.4-1 [TR #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. The character of the northern fault suggests that it also experience strike slip motion.

3.5 ADVANCED SEISMIC ANALYSES

3.5.1 Introduction

The seismic expression of faults is a function of several variables, including the fault offset and the frequency content of the seismic data. On migrated seismic lines, faults are most easily recognized by reflection offsets, changes in dip, changes in amplitude, etc. Subtle faults are most easily detected in 3-D seismic volumes by deriving and analyzing "horizon" attributes, such as dip, edge detection and azimuth, or "coherency" attributes (e.g., Hart et al., 1996). Additionally, complex trace attributes (e.g., instantaneous frequency, reflection strength) can be useful for fault detection. In the manner described above, Dr. Hart (McGill University) analyzed critical sections of the seismic profiles procured in the preceding subtask.

In 2002 work by Dr. Hart (McGill University) focused on using seismic attribute displays to refine structural and stratigraphic interpretations. The seismic lines were interpreted using Geographix SeisVision software. Seven seismic markers were picked and validated on four seismic lines:

1. Top Onondaga (Devonian)
2. Top Salina (Silurian)
3. Top Lockport (Silurian)
4. Top-of-Trenton (Ordovician)
5. Top-of-Black River (Ordovician)
6. Knox Unconformity
7. Top-of-basement

The Trenton seismic horizon has a regional strong amplitude character while other markers manifested wide seismic amplitude variations in time and space. The validation of stratigraphy has been implemented via seismic signature correlation for above-basement sequences and correlation polygon confirmation.

3.5.2 Interpretation

The interpretation focused on the interval Top-of-Trenton to Basement and defined a series of major horsts and grabens, 13 blocks on Line 1, 15 blocks on Line 2, 6 blocks on Line 3, and 3 on the Line 4. The majority of these faults show vertical to highly dipping faults. Most of these faults can be extended to the basement with a few extending upward to shallow near-surface depths. Almost all the tectonic failure surfaces are intimately related to basement tectonics; however, seismic data quality and resolution limitation do not permit detailed interpretation of basement faults.

The interpretation shows that Trenton/Black River carbonate sequence has undergone heavy faulting and fault-associated fracturing. Interesting rollover folds defining possible low amplitude structural closures have been observed at 8 locations on the Line 1; one of them is associated with the Glodes Corners Road Pool. The positive closures have been interpreted at top-of-Trenton and can be detected on the lower series as well. Eastward, a major fault-bounded rollover structure has been interpreted at the northern part of the Line 2. Additional intensive faulting with rollovers, as well as a northward sedimentary series thinning, has been interpreted on the line too.

The interpretation of the Line 3 and the Line 4 indicated a much lower tectonic deformation level. The basement dip in considerably lower and the sedimentary series show less deformation.

An interesting fault-associated closed structure has been identified at the central part of the Line 3. The tectonic framework in the east of the region defines a lower frequency, step-like faulting.

Further processing related to complex seismic trace attribute analyses provided a better understanding and provided criteria for fracture and other possible seismic anomaly associations within the area. The following complex trace attributes were derived for the four seismic sections:

- ✓ Instantaneous Amplitude
- ✓ Instantaneous Frequency
- ✓ Instantaneous Phase

Visible instantaneous amplitude variations have been observed on the top-of-Trenton marker near fault zones. Amplitude dimming characterizes the collapsed and fault bounded blocks. This can be attributed to a possible change in petrophysical characteristics of Trenton carbonates due to faulting, fracturing and probably further diagenic modifications. This criterion was confirmed by seismic inversion. Other intermediate markers between top-of-Trenton and top-of-Black River also show strong amplitude variations and in some areas complete dimming.

Instantaneous frequency is lower within fault-collapsed zones as well as in rollover sections. This lowering can be attributed to stronger seismic wavelet attenuation within these areas. Instantaneous phase shows visible changes and inversion in fault bounded graben areas. Seismic phase changes can be considered as evidence of fracture-dominated zones.

3.5.3 Seismic Attributes, Inversion, and Associated Well Log Analyses

3.5.3.1 Introduction

Kamal Al Atroshi and Bruce Hart of the McGill Seismic Research Group (MSRG, McGill University) refined the stratigraphic and structural analyses of the seismic data in 2002-2003. They inverted one of the seismic lines near wireline log data that had become available to directly image physical properties of the productive fault zones on that line. MSRG undertook structural and attribute analyses of the seismic data, and log analysis in support of the inversion work. MSRG's objectives were: a) to use advanced analyses to identify and interpret faults, and b) to integrate the seismic data with log data to distinguish the hydrothermal dolomite systems from the surrounding limestones. MSRG compared inversion results on Line 2 with those from Line 1.

3.5.3.2 Available data

- Seismic data of the Line 2 (time migrated)
- Well log data from a Black River test well, including GR (gamma ray), CALI (caliper), SP (spontaneous potential), RXO (flushed-zone resistivity), HLLD (deep resistivity), HLLS (shallow resistivity), HART (computed true resistivity), NPHI (neutron porosity), SPHI (sonic porosity), DPHI (density porosity), PEF (photoelectric factor).
- Fluid shows and test data.

3.5.3.3 Seismic Markers

Seismic interpretation of the North-South oriented Line 2 utilized the following markers (Figures 3.5-1&2 [TR #3]);

1) Top-of-Trenton (Yellow marker); represents a high amplitude, continuous reflection peak.
2) Top-of-Black River (Green marker); represents a zero crossing +/- peak to trough reflection.
3) Knox Unconformity (Blue marker); represents a reflection peak. The marker shows variable reflection amplitude and continuity from south to north. No phase change has been observed along the marker except at structural deformation zones, where some phase distortion can be identified.
4) Crystalline Basement (Violet marker); represents a reflection peak, the top-of-basement shows lateral variations in reflection amplitude and continuity

A reflection strength display clearly shows the seismic character variations among the major picked four markers (Figure 3.5-3 [TR #3]).

3.5.3.4 Seismic Marker Flattening

Marker flattening was helpful in studying the time thickness variation of three main seismic packages bounded by the four main markers. Upon flattening on the Basement marker (Figure 3.5-4 [TR #3]), the Basement/Knox interval (composed of 6 relatively concordant, continuous, variable amplitude reflectors) shows visible thinning at the north and south, whereas maximum thickness occurs in the central part. This variation can either be attributed to accommodation variations provided by basement blocks, or can as well be due to erosional truncation at the Knox level.

Flattening on the Knox reflector (Figure 3.5-5 [TR #3]) shows significant time thinning of the Black River section from south to north. Additional thinning occurs at seven grabens bounded by closely spaced normal faults. Regional section thinning seems to be gradual and starts immediately north of a major fault. The seven collapse zones could be considered as potential targets, at least from a structural perspective. Seismically, the Black River interval is composed of a sequence of low amplitude, low frequency and discontinuous reflections that become chaotic at the central part of the sequence.

Upon flattening the Black River marker (Fig-3.5-6 [TR #3]), the overlying Trenton sequence shows a more regular time thickness variation than the Black River interval. Trenton time thickness is greatest at the north and in the central portions of the line. A significant time thickness reduction occurs within two wide grabens.

3.5.3.5 Structural Interpretation

Structurally, the area has undergone a significant extension, possibly accompanied by wrenching (Figures. 3.5-7 [TR #3], 3.5-8 [TR #3], 3.5- 9 [TR #3]**),** giving rise to a sequence of structural grabens and horsts of different sizes. Twenty-two faults have been interpreted in the sequence extending from the basement to the top of the Trenton. These faults show variable dips and throws. Fault frequency increases at the northern segment with visible rollover events near fault shoulders. Seven small grabens associated with thickness reductions in the Black River section have been interpreted. Those collapse structures dominate the structurally higher northern sector of the area.

3.5.3.6 Seismic Attribute Analyses

In order to identify possible fault-associated fractures systems, as well as other subtle variations, seismic data were processed in order to extract complex (analytic) trace attributes via sample-by-sample computation.

<u>*3.5.3.6.1 Instantaneous Amplitude Processing (Figures 3.5-10, 3.5-11, 3.5-12 [all TR #3]).*</u> This attribute, also known as reflection strength, is amplitude that is independent of phase. It is proportional to the total energy of the seismic signal at each instant in time. The instantaneous amplitude is the envelope function of the seismic trace. The envelope reflects low frequency filtering of the amplitude variations with time. Values are always greater than, or equal to, zero. The mathematical expression is:

$$e(t) = [r^2(t) + q^2(t)]^{1/2}$$

Where:

- e(t) = energy envelope,
- r(t) = real seismic trace, and
- q(t) = quadrature seismic trace or the imaginary part of the seismic trace.

Strong energy reflections can be associated with major lithologic changes as well as, in some settings, oil and gas accumulations. Lateral energy variations can quantify changes in acoustic rock properties and bed thickness. Seismic Line 2 shows significant lateral variations in the instantaneous amplitude attribute; reflectivity dimming occurs at the top-of-Black River within some of the faulted and collapsed graben shaped units. This dimming can be attributed to possible fracturing or higher secondary porosities at the upper Black River level.

<u>*3.5.3.6.2 Instantaneous Phase (Figures. 3-5-13, 3.5-14 [all TR #3]).*</u> This attribute shows phase (that is independent of amplitude). It is a measure of continuity of events on a seismic profile. The output relates to the phase component of the wave propagation. Instantaneous phase is mathematically defined as:

$$p(t) = \tan^{-1}[q(t)/r(t)],$$

Where:

- p(t) = instantaneous phase trace,
- q(t) = quadrature seismic trace, and
- r(t) = real seismic trace.

The top-of-Black River marker shows a lateral phase change with phase inversion at some positions. These phase distortions occur near and within the faulted and collapsed top-of-Black River.

<u>*3.5.3.6.3 Instantaneous frequency (Figures 3.5-15, 3.5-16, 3.5-17 [all TR #3]).*</u> Instantaneous frequency is the rate of change of instantaneous phase. This attribute corresponds to the average frequency of the amplitude spectrum of the seismic wavelet and can be an indicator of fracture

zones dominated by lower frequencies. Mathematically, instantaneous frequency can be defined by:

$$dp(t) / d(t)$$

Where:
p(t) = instantaneous phase trace

The southern part of the line shows no instantaneous frequency anomalies, however, the crestal part at the north shows a significant low frequency anomaly zone immediately beneath the top of the Black River where instantaneous amplitudes also dim. Structurally, this unit has not undergone any visible faulting; therefore, the anomaly may be attributed to localized fracturing or hydrothermal alteration effects. Seismic inversion (see below) could be used in order to confirm the validity of this interpretation. Other anomalies have also been interpreted along some major faults. However, some of these anomalies extend upward into the Trenton; therefore, no possible Trenton seal can be provided for the Black River.

3.5.3.6.4 Seismic Coherency Processing (Figure 3.5-18 [all TR #3]). Coherency is a geometrical attribute that is useful for detecting faults and other seismic event terminations. The processing was been carried out on Line 2. However, results were not encouraging, since this processing was developed for 3-D data rather than 2-D (results are commonly looked at in time slices). Nevertheless, results were helpful in confirming some of the interpreted faults.

3.5.3.7 Well log Analyses from a Black River Test well (Figures 3.5-19, 3.5-20, 3.5-21, 3.5-22, and 3.5-23[all TR #3]).

MSRG undertook log analyses in order to help establish the relationships between seismic-derived and log-derived physical properties. Two composite logs have been prepared covering the Trenton and Black River intervals. Logs used were; NPHI, SPHI, DPHI, PEF, RXO, HLLD, HLLS, HART, GR, SP and Caliper.

3.5.3.7.1. Log Response Analyses

1) The Upper Black River interval, 39.6 m (130 ft) thick, defines a clean and porous (vuggy) dolomitic interval; a 5.8 m (19 ft) zone 7.9 m (26 ft) below the top of the interval shows signs of hole over-gauging. No signs of shale can be detected from the FMI and GR logs. The interval shows high deep and shallow resistivities, therefore no indication of filtrate invasion. An average of 14% NPHI & 3% DPHI has been recorded at the over-gauged section which can probably be related to intensive dolomitization. No gas shows were recorded during drilling. Three possible gas bearing units have been detected via NPHI & DPHI log signatures; these units are 1.8 m (6 ft), 1.2 m (4 ft) and 1.2 ft (4 ft) thick (Figure 3.5-21 [TR #3]).

2) The Middle Black River interval (39.6 m [130 ft] thick**)** is more argillaceous and shows lower RXO & HLLD resistivities. Average NPHI level is 10%; the interval shows two log gas signatures (Figure 3.5-23 [TR #3]) as well as a gas kick recorded near the base of the Middle Black River interval (Figure 3.5-20 [TR #3]).

3) Lower Black River (77.7+ m [255+ ft.] thick (to TD) is composed of three clean compact intervals separated by shale barriers (labeled “SH” in Figure 3.5-20 [TR #3]). The dolomitic intervals show high deep resistivity but lower RXO values indicating high filtrate invasion. Three gas signatures were observed (Figure 3.5-20

[TR #3]). Seismic inversion results (discussed below) did not support any possible reservoir quality within this interval.

3.5.3.7.2. Facies characterization & Cross-Plot Analyses

1) NPHI & SPHI Plot (Figure 3.5-24 [TR #3]). This plot identified a cluster for Trenton (blue envelope) that shows a linear relationship and four different clusters for the Black River interval. The Trenton cluster (blue envelope) shows a linear relationship. The most prevalent Black River facies is the cluster outlined by the red envelope, which is characterized by a low sonic porosity and a variable neutron. The red envelope defines the clean dolomitic Black River intervals. Recorded gas kicks as well as log gas signatures occurred within these facies. The second-most dominant facies (violet envelope) defines a similar characteristic trend, but with a higher average sonic porosity. A third, minor facies (dark blue envelope) marks the more shaly dolomites. The fourth, blue envelope identifies shale barriers within the Black River unit.

2) NPHI& DPHI Plot (Figure 3.5-25 [TR #3]). This plot defines two major distinct clusters, the light blue envelope with red and blue points for Black River and a violet envelope with blue points for Trenton. Black River facies show a NPHI range from 0.4% to 14%, including gas kick and gas log signature zones (red points) and variable density porosities. Figure 3.5-26 [TR #3] shows an association of porosity, resistivity and GR & caliper logs with a NPHI vs. DPHI cross-plot for the upper and middle Black River. The discrimination of the gas log response zones within the interval indicates an anomaly cluster (colored points) with an average NPHI of 0.09 to 0.12 corresponding to variable DPHI values up to 0.23. Figure 3.5-27 [TR #3] shows a gas signature of a compact dolomite unit. The FMI log has been incorporated with the facies discrimination analyses in Figure 3.5-28 [TR #3]. The thick, porous upper dolomite unit has proven to be dry; however, some thinner and probably less porous lower intervals have proven to be gas bearing from drilling and log analyses results. The lower Black River interval shows two gas signatures in a dolomitic unit within a thick shaly section of the lowermost clean dolomite (Figure 3.5-29 [TR #3]).

3) NPHI & True Resistivity Plot (Figure 3.5-30 [TR #3]). Two major facies cluster trends are identified that show inverse relationships (negative slopes). The Black River facies tend to be more resistive and mark some possible gas bearing zones (green points and green intervals). This interval marks higher resistivities and lower NPHI values.

4) True Resistivity (Hart) & RXO plot (Figures 3.5-31, 3.5-32 [all TR #3]). These plots incorporate the FMI composite log. The discrimination objective is to identify porous zones marked by considerable divergences between deep and shallow resistivity logs. These divergence intervals within the Black River section indicate filtrate invasion zones in dolomites and indicate the units of best porosities.

5) GR & True Resistivity Plot (Figure 3.5-33 [TR #3]). Both Trenton facies (light blue) and Black River facies (red) show inverse relationships in terms of GR and true Resistivity. The Black River facies cluster (violet envelope) indicates clean and

resistive facies at the upper and middle part of the formation. Shale intervals (green cluster envelope) can be discriminated in the lower part of the formation.

6) Caliper & GR Plot (Figure 3.5-34 [TR #3]). The caliper/GR relationship defines three different clusters within the Black River; the violet envelope defines the upper and part of middle Black River sections with an over-gauged hole that is characterized by low shale content. The red cluster defines the cleanest gauged Black River section whereas the blue cluster is related to shale units. Hole over-gauging in this well occurs at the clean dolomitized zones of the Black River, and may indicate intensive fracturing near a fault.

3.5.3.8. Seismic Inversion

In order to proceed with the seismic inversions, MSRG needed to transfer seismic picks (top-of-Trenton, top-of-Black River, Knox U, and the top-of-basement) on Line 2 from GeoGraphix to the Hampson-Russell software (Figure 3.5-35 [TR #3])**.** Log-to-seismic calibration as well as the generation of synthetic traces marked a reasonable (but not high) correlation coefficient of 64% and the composite log showed an acceptable match. A P-wave impedance log was generated from sonic and density logs of a Black River test well. The impedance log was then correlated with the synthetic traces as well as with the remainder of the logs (Figure 3.5-36 [TR #3]). This log was used as the basis for calculating the impedance model utilized for the later seismic inversion process (Figure 3.5-37 [TR #3])**.** The computed acoustic impedance log shows three main AI sequences; the upper sequence marks top-of-Black River. The anomalously low impedances represent the intra-Black River shale dominated intervals. The upper and lowermost intervals represent the clean dolomites; the middle interval is a shalier dolomitic facies.

Prior to seismic inversion, an attempt was made to use the integrated absolute amplitude attribute processing in order to study the seismic amplitude behavior at the zone of interest (Figures 3.5-38 [TR #3], 3.5-39 [TR #3], 3.5-40 [TR #3]). This attribute refers to a continuous trend calculation of seismic instantaneous amplitudes in time and space. It is sometimes known as a “band limited” (or recursive) inversion. The results seem very helpful in checking for zones of structural and/or stratigraphic anomalies. The results supported the location of the T/BR test well within the low amplitude trend. Moreover, four other graben-related zones of interests are observed on the section**.** At the T/BR test well projected location, the amplitude attribute anomaly extends upward within the Trenton section, which might mean that the reservoir seal is absent, thus supporting the dry results of the well. However, south of the projected location of the T/BR test well, another anomaly indicates good seal conditions that could be tested by drilling.

Seismic inversion results (Figures 3.5- 41 [TR #3], 3.5-42 [TR #3], 3.5-43 [TR #3]) show that the T/BR test well effectively penetrated the near-fault collapse (but relatively tight) zone (light blue interval) with an AI range of 56,000-57,000 ft/s*g/cc. This high AI level extends laterally to the north and south of the well. These results are consistent with the poor results obtained from the well: although the well penetrated an otherwise seismically attractive target, no porous dolomite facies (that would be associated with a low AI values from the inversion) were developed there. Results of inversion work on Line 1 clearly showed that productive (low AI) zones at the Muck Farms and Glodes Corners fields may be recognized using seismic inversion.

Inversion has shown a second possible target (green spot with AI 47,000 ft/s*g/cc) south of the test well (Figure 3.5-43 [TR #3]), which was previously indicated as an anomaly during the seismic attribute analysis. This target is interesting in terms of acoustic impedance values and its confined nature. Moreover, results indicate the existence of an excellent seal facies. Other near top-of-Black River AI anomalies has been identified, with similar characteristics, including two to the south of the possible target and one two the north (Figure 3.5-43 [TR #3]).

A second inversion was ran that was based on a model using impedance values generated from a modified and corrected density log, as well as a generated sonic log from the inverse Gardner equation (Figure 3.5-44 [TR #3]). This step was undertaken because inversion of Line 1 in the first year of this project needed to be accomplished without a measured sonic log. Density log modification was conducted to remove "spikes" associated with bad hole conditions. The new inversion slightly enhanced the resolution of inverted data, but did not significantly modify conclusions derived the previous inversion results at the top-of-Black River.

In order to calibrate the seismic inversion data with FMI images and porosities, as well as with downhole lithofacies, the (e-log) impedance data in TWT and depth were calibrated with the FMI log from one of the T/BR test wells in the region (Figures 3.5-45 [TR #3] and 3.5-46 [TR #3]). Results show that the upper Black River dolomitized and porous interval falls within a 2 ms TWT time window. This window matches a relatively tight zone according to the inversion results (Figure 3.5-47 [TR #3]).

A third seismic inversion was carried out using an impedance model based on impedance values generated from a corrected density log and the original sonic log from one of the T/BR test wells in the region (Figure 3.5-48 [TR #3]). Inversion results improved inversion resolution and added more details to the upper Black River interval, especially at the test well site. The AI log was used to calibrate the FMI log in time and depth for both the upper porous and middle shaly intervals (Figures 3.5-49 [TR #3] and 3.5-50 [TR #3]). The upper time-calibrated unit was then projected on the inverted data. Inversion results indicated that the porous interval is located in a tight zone that shows an AI range of 56,000 ft/s*g/cc (Figure 3.5-51 [TR #3]). The same procedure was applied to the middle Black River shaly interval (Figure 3.5-52 [TR #3]).

3.5.3.9. Interpretation of Seismic Lines 3 & 4

The integrated absolute amplitude processing, as well as structural interpretation, was applied to the two remaining seismic lines 3 and 4. Anomaly trends are observed on both lines; these anomalies are fault associated. However, no thickness reduction can be identified within the Black River section. Therefore, these are considered to be risky drilling targets.

3.6 STRATIGRAPHY/WELL LOG ANALYSES

3.6.1 Introduction: Structure Contour and Isopach Maps

In 2001-2002 the subcontractor, Quest Energy, collected all available well log and completion information for Trenton and deeper wells from regional offices of the New York State Department of Environmental Conservation. Log picks were entered into a Geographix database from which structural and isopach contours were generated. Any anomalous values were checked and corrected as needed.

In 2001-2002 the subcontractor, Quest Energy, constructed structure contour and isopach maps, based on all deep well logs in the Geographix database. The results were a series of maps contoured on Geographix that are displayed in Figures 3.6-1 [TR #4] to 3.6-24 [TR #7]and that Jacobi interpreted (following sections). From the maps it is readily apparent that for "deep" structure (i.e., structure below the Silurian salt), the general sparsity of available deep well data in 2001-2002 prohibited well log analyses as an exploration tool in the northern Appalachian Basin. The general lack of close deep wells means that small-scale (local) structure, such as the T/BR grabens, generally cannot be recognized. Only in a few areas, primarily where known T/BR fields exist, are there sufficient deep wells to define local structure.

3.6.2 Structure Contour Maps

*3.6.2.1 Top-of-Onondag*a *(Devonian)*

Figure 3.6-1 [TR #4] shows the regional structure contours of the top of the Devonian Onondaga Formation and Figure 3.6-2 [TR #4] displays a more detailed view of the structure contours for the Onondaga in the area of interest. Prominent structural features include the following:

1) E-trending high of the Wayne-Dundee Gas Field east of Keuka Lake in Tyrone Township (especially well exhibited in Figure 3.6-2 [TR #4]). The Wayne-Dundee Gas Field structural high is probably a westward, linked segment of the E-trending Alleghanian Firtree Anticline. This feature is also evident in the Onondaga structure contour map of Murphy (1981).
2) NW-trending monocline in the western half of the regional map (Figure 3.6-1 [TR #4]). This monocline corresponds spatially with the Lawrenceville-Attica lineament (see Jacobi, 2002, and references therein). The stratigraphic offset across the monocline is on the order of 500 ft to 750 ft (152 m 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.
3) E-trending structural low evident west of Keuka Lake in northeastern-most Steuben County (Figure 3.6-1 [TR #4]). This low is located above the Trenton/Black River Glodes Corners Road Field. However, seismic reflection profile #1 (Figure 3.4-1 [TR #3]) demonstrates that the structural low is not restricted to the narrow Trenton/Black River graben, but extends to both the north and south of the graben. Further, the structure contour map of the Silurian reflectors underlying the Onondaga (Lockport and underlying Irondequoit Formation), discussed below, generally do not exhibit a prominent structural low. Thus, this Onondaga structural low is restricted to the Silurian salt and shallower horizons. The low suggests that dissolution and faulting are not restricted to the Trenton/Black River horizon, but also occur higher in the section; in this case the low is probably related to salt tectonics (flowage) away from the present low toward the associated E-trending Alleghanian anticline to the south, as proposed for other Alleghanian salt-cored anticlines to the south (e.g., Frey, 1973; Wiltschko and Chapple, 1977). Consistent with the salt flowage interpretation, the isopach for combined "E" and "F" Salina salt units displays an anomalously thin zone

over the region of the Glodes Corners Road Field (Figure 3.4-1 [TR #3]). That the Alleghanian folds are here parallel to the T/BR fields is probably not a coincidence. Scanlin and Engelder (2003) and Jacobi et al. (2003; 2004a-d, 2005a-d, 2006a-c) have proposed that reactivation of the deep structure controlled, in part, the shallow Alleghanian fold locations.

4) The sparsity of well control between Seneca and Cayuga lakes results in crude, generalized contours that do not accurately portray the actual structure (Figure 3.6-2 [TR #4]). For example, the structural high in the NE corner of Hector Township is most likely a manifestation of the E-W trending Firtree Anticline. Similarly, the structural low in Lodi Township (and northern-most Hector Township) could be re-contoured with an E-W trend that would reflect the Alleghanian folds.
5) An apparent NW-striking high at the southern end of Seneca Lake (Figure 3.6-2 [TR #4]) 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 structural 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 3.6-1 [TR #4]) could also be an inaccurate portrayal, caused by sparse well logs, of an E-striking anticline that was recognized in the surface rocks by Bradley et al. (1941).
6) The northerly-striking structural high at the northern end of Keuka Lake (East Branch) (Figure 3.6-2 [TR #4]) could also be re-contoured to reflect an easterly-trending, short Alleghanian anticline. We have insufficient data points to determine the trend. However, the lack of a similar structure in the underlying Silurian Irondequoit suggest that the structure is salt related. Alternatively, the salt-cored structure could trend northerly along a major fault proposed from lineaments, aeromagnetics and gravity (see Aeromagnetic section).
7) South of the Finger Lakes, outside of the area of interest, structural highs and lows are prominent (Figure 3.6-1 [TR #4]); these features are related to easterly-striking Alleghanian folds, but are poorly expressed in the contours because we chose to use subroutines in the Geographix mechanical contouring program that do not impose any bias to the data (such as an ENE-"grain" in the contouring). For example, the structural high at the south end of Seneca Lake with a northerly trend represent structural relief related to E-trending Alleghanian folds (compare Figure 3.6-1 [TR #4] to 1.2-1 [TR #1]).

3.6.2.2 Top-of-Irondequoit Formation (Silurian).

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 3.6-3 [TR #4] and the more detailed view is shown on Figure 3.6-4 [TR #4]. The regional map (Figure 3.6-3 [TR #4]) does not show as strong a trend for the Glodes Corners Road Field as the Onondaga structure contours (Figure 3.6-1 [TR #4]). This lack of apparent major structure suggests that the Onondaga structures were localized along the Trenton/Black River graben, but are actually the result of salt tectonics localized by motion on the deeper Glodes Corners Road Field faults. The regional structure contours differ from the Onondaga in another important point: the contours strike straight E-W across the western part of the map, i.e., 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 effects of the Attica/Lawrenceville lineament in the shallow part of the stratigraphic section are most likely localized in and above the salt layers (see discussion below concerning isopachs). Comparison of both maps also shows that the Wayne-Dundee Gas Field fold east of Keuka Lake is also restricted primarily to units above the salt, since the Irondequoit structure contour indicates only a very subtle feature. On the detailed figure (Figure 3.6-4 [TR #4]), the structural lows east of Keuka Lake in Barrington Township and the (as contoured) larger low east of Seneca Lake on southern Lodi Township both may reflect effects the deeper structure of the Trenton/Black River grabens.

3.6.2.3 Top-of-Trenton Group (Ordovician)
The regional structure contours on the top of the Ordovician Trenton Group are shown on Figure 3.6-5 and the more detailed view on Figure 3.6-6 [TR #4]. The regional map (Figure 3.6-5 [TR #4]) reveals the structural lows associated with the Glodes Corners Road Field (west of Keuka Lake). A similar structural low east of Keuka Lake in Barrington Township is about on-strike with the Glodes Corners Road and Muck Farm fields, and may represent a T/BR graben (Figure 3.6-6 [TR #4]). The lack of well control precludes determination of the trend of the graben; the graben could trend easterly, similar to the fields west of Keuka Lake, or it could be localized along the northerly striking fault system on the east side of Keuka Lake (see discussion of the East Branch Keuka Lake Fault in the Aeromagnetic section). Another local structural low east of Seneca Lake in southern Lodi Township is more likely related to a T/BR graben. Localized structural highs, perhaps associated with the flanks of Trenton/Black River grabens, are observed east of the northern part of Keuka Lake in Milo Township and between Seneca and Cayuga lakes in Hector and Enfield townships. The structural high in Milo Township was hypothesized by Murphy (1981) to be related to a NE-striking fault that extended northeast from the eastern side of Keuka Lake.

3.6.2.4 Top-of-Black River Group (Ordovician)
The regional structure contours on the top of the Ordovician Black River Group are shown on Figure 3.6-7 [TR #5] and the more detailed view on Figure 3.6-8 [TR #5]. The regional map (Figure 3.6-7 [TR #5]) shows the same structural elements as the Trenton structural contour map (compare Figures 3.6-5 [TR #4] and 3.6-7 [TR #5]), although most features have subdued structural relief compared to the Trenton map. This lower structural relief is consistent with the Glodes Corners Road Field model of Beardsley (1999, 2001), wherein the amount of offset on the faults increases up-section through the Black River-Trenton units (Figure 1.2-3 [TR #1]). A very segmented structural low is associated with the Glodes Corners Road Field (west of Keuka Lake). A similar structural low east of Keuka Lake in Barrington Township is about on-strike with the Glodes Corners Road and Muck Farm fields, and may represent a T/BR graben (Figure 3.6-6 [TR #4]). As discussed in the Trenton Group section, the trend of this graben is not known. Another local low east of Seneca Lake in southern Lodi Township is related to an easterly trending graben (see discussion section). 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 well log control west and southwest of the southern tip of Keuka Lake is extremely sparse, but both the Trenton and Black River tops do not demonstrate significant regional offset on the Lawrenceville-Attica lineament. Thus, the amount of Ordovician offset must be localized, and relatively minimal, compared to the structural relief above the Silurian salt.

3.6.3 Isopach maps

3.6.3.1.Devonian Onondaga-to-Silurian "F" Salt Interval

The regional isopach map for the Onondaga to "F" Salt interval is shown on Figure 3.6-9 [TR #5] and the more detailed view on Figure 3.6-10 [TR #5]. The prominent thinning of the interval in central and northern Steuben County (Figure 3.6-9 [TR #5]) is the result of the NW-striking Onondaga monocline (dipping down-to-the-southwest along the Lawrenceville-Attica lineament) over the regionally unaffected Irondequoit and deeper units. On the detailed map (Figure 3.6-10 [TR #5]), the localized anomalously thin zone in southernmost Lodi Township occurs at an unnamed ENE-striking syncline mapped from outcrops by Bradley et al. (1941). The syncline may have been localized by reactivated deep structures that controlled the Trenton/Black River grabens.

Anomalously thin zones are observed east of Keuka Lake both in central and northern Barrington Township. These zones could be continuous, forming a NNE-trending anomalously thin zone that is coincident with the East Branch Keuka Lake Fault. Alternatively, the sparse well log data also allows a different interpretation: short-segmented E-trending Alleghanian structures, similar to that proposed for the anomalous thin zone east of Seneca Lake. The prominent N-trending contours in the Cayuga Lake region (Figure 3.6-10 [TR #5]) are partly an artifact of contouring sparse data; the sharp turn in contours west of Cayuga Lake in Ulysses Township is the result of a thickened section in the core of the Firtree Anticline, and little data to the north. However, the regional map (Figure 3.6-9 [TR #5]) shows that a thicker section does exist to the east; the section appears to thicken along northerly striking faults, proposed in the Aeromagnetic and lineament sections.

3.6.3.2. Silurian Salt Intervals

Isopach maps for the salt intervals are shown on Figure 3.6-11 [TR #5] to Figure 3.6-16 [TR #6]. The isopach maps for the "F" salt (Figures 3.6-11 [TR #5] and 3.6-12 [TR #5]) show a prominent anomalously thick section in the core of the Firtree Anticline (on the west side of southern Cayuga Lake and an anomalously thick zone in part of the Wayne-Dundee Gas Field (NE corner of Tyrone Township). 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 folds (e.g., Frey, 1973; Wiltschko, and Chapple, 1977). The 'bulls-eye" anomalously thick zone in Barrington Township (on the east side of Keuka Lake) is located at a minor E-striking anticline on the southern flank of the Severne Point Anticline. However, the thick zone could also be indicative of a northerly trending anomalous zone, similar to that in the Onondaga to "F" salt isopach map (see discussion above).

The lower "E"-Salt (Figures 3.6-13 [TR #6] and 3.6-14[TR #6]) does not exhibit the thickening in the Firtree anticline core on the western side of Cayuga Lake, suggesting that most of the salt flowage/thrusting in the Firtree Anticline in this area was accomplished within the "F" salt. However, both the Wayne-Dundee Gas Field and the "bulls-eye" in Barrington Township do display anomalously thick sections, although not as prominent as in the "F" salt. The "E"-Salt thick zone in the Wayne-Dundee Gas Field is west of the thick zone in the "F" salt, suggesting that thrust ramps and salt flowage affected different units along the length of anticline (with transfer zones/cross faults/lateral ramps joining the segmented thrusts). The Barrington Township anomalously thick zone is also apparent on the "E" salt isopach; like the "F" salt, the trend is not definitive, but may be east, and related to Alleghanian folding/thrusting. However, the more regional view shows that the isopach contours trend generally NNE along the branches of Keuka Lake, coincident with the proposed East Branch Keuka Lake Fault (see discussion in Aeromagnetic section). As discussed above (in the Onondaga structure contour section), an E-striking anomalously thin zone is located west of Keuka Lake, and is presumed to be related to salt flowage toward the Alleghanian anticline directly to the south. That the "E" salt overall shows less thickness variation is consistent with the view that much of the decollement thrusting here rides in the upper salt.

3.6.3.3.Devonian Onondaga-to-Silurian Irondequoit Interval

The regional isopach map for the Onondaga-Irondequoit interval is shown on Figure 3.6-17[TR #6] and the more detailed view on Figure 3.6-18[TR #6]. This interval is traditionally used to determine the total affect of Alleghanian thrusting and folding above the Silurian salt and associated flowage of the salt. The anomalously thin zone above the E-trending Glodes Corners Road Field (west side of Keuka Lake in the northeastern corner of Steuben County) is, as discussed above, consistent with the salt withdrawal model. The anomalous "bulls-eye" east of Keuka Lake (Figure 3.6-18[TR #6]) is consistent with the thickened salt section in this locality (Figure 3.6-16[TR #6]).

The Wayne-Dundee Gas Field and the Firtree Anticline only exhibit minor thickening, compared to the structural relief of these folds. The structural relief is on the order of 30 – 122 m (100-400 ft) (Figure 1.2-1[TR #1], Bradley et al, 1941), yet the apparent thickness increases on the isopach map are about 15 m (50 ft). This discrepancy is, at least partly, an artifact of contouring in areas of (cross-strike) sparse well log data, with the result that smoothed contours do not reveal the actual local closure and structural relief. Secondly, if the wells are not on the axis of the fold, then the isopach should be a lower amount than the structural relief. Finally, some of the folds do exhibit smaller structural relief. In addition, however, the structure contour map for the Irondequoit (discussion in section 3.6.2., and see Figures 3.6-3[TR #4] and 3.6-4[TR #4]) does show slight variations along fold axis that correspond to changes in Onondaga-Irondequoit interval thickness. For example, the Irondequoit is higher in the western end of the Wayne Dundee Field, where the Onondaga-Irondequoit interval thickness is less than the east end. Conversely, the Irondequoit is lower at the Barrington Township anomaly, where the Onondaga-Irondequoit interval thickness is considerably thicker than normal.

3.6.3.4. Silurian Irondequoit-to-Ordovician Trenton Interval

The regional isopach map for the Irondequoit-Trenton interval is shown on Figure 3.6-19 [TR #7] and the more detailed view on Figure 3.6-20 [TR #7]. 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 were filled by Irondequoit time; the grabens do not extend up to the Irondequoit (as evidenced in the seismic data). The anomalous "bulls-eye" east of Keuka Lake (Figure 3.6-20 [TR #7]) is 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 Onondaga to Trenton interval isopach maps (Figures 3.6-21 [TR #7] and 3.6-22 [TR #7]).

3.6.3.5. Ordovician Trenton-to-Black River Interval

The regional isopach map for the Trenton-Black River interval is shown on Figure 3.6-23 [TR #7] and the more detailed view on Figure 3.6-24 [TR #7]. The most prominent feature is an anomalously thick section that trends nominally NNE along the East Branch of Keuka Lake. This trend is approximately coincident with the East Branch Keuka Lake Fault, proposed on the basis of a major aeromagnetic gradient (discussed in Section 3.7) that lies along the east side of Keuka Lake. We suggest, therefore, that this depositional effect is the result of Trenton-aged faulting that follows the major magnetic anomaly. Note that the Glodes Corners Road Field and Muck Farm Field show a slight thinning (Figure 3.6-23 [TR #7]), 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.

3.6.4 Outcrop Structure Inferred from Stratigraphy

Jacobi and Smith identified and measured the stratigraphy and elevations of stratigraphic markers in Upper Devonian outcrops in a N-S transect along the eastern shore region of Seneca Lake. Although they attempted a detailed stratigraphy in the turbidities, they found that the individual sandstones, and even the sandstone packets, appear to lens and change character locally from south to north. The consequent lack of recognition of markers over relatively long distances precluded detailed structural control from detailed stratigraphic correlations in the southern part of the transect. Jacobi and Smith did measure the dip of turbidite beds exposed in extensive outcrops, especially along the lakeshore, where outcrops of 50 m or more are not uncommon.

In the northern part of the transect the Tully Formation crops out, and forms a distinct marker with constant character relative to the turbidites. In this 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 higher elevations to 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 constructed a survey line (scanline) along the Seneca lakeshore in the northern-most part of the transect (Figures 3.1-21 [TR #1] and 3.1-22 [TR #1]). They located the Tully outcrops with respect to the distance on the scanline and then surveyed the elevation of the Tully with respect to the lake level (Figure 3.1-22 [TR #1]). They also measured the dip of the Tully beds in outcrop with both 1.21 m (48 in.) long levels and with elevation differences between the two ends of the outcrops.

From Figure 3.1-22 [TR #1] it appears that the dip of the Tully measured in outcrops is sufficiently high to account for the entire elevation difference observed on the scanline and in regions to the south. 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 graben (e.g., a solution/faulted graben in the Trenton or Lockport or salt section or Onondaga) is located in the area. Only in the southernmost part of the cross-section (between sites RDJ-52 and RDJ-59) is the observed dip in outcrops distinctly lower than that needed to account for the observed elevation change; in this area a fault model is probable (Figure 3.1-22c). Note that even here, however, a fold with higher dips than those observed could account for the observed elevation change (Figure 3.1-22d [TR #1]).

Detailed inspection of the outcrops in the area of the Tully anomalous dip also revealed NE-striking FIDs and northwestward-directed thrusts (Figure 3.1-22) with minor offset (each on the order of a few cm or less). These thrusts are consistent with either hypothesis (fold or fault) 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.

3.7 AEROMAGNETIC SURVEY AND ANALYSES

3.7.1 Introduction

University at Buffalo Rock Fracture Group (UBRFG) subcontracted with Pearson, deRidder and Johnson, Inc. (PRJ) to acquire and process a high-resolution aeromagnetic survey of the study area. The N-S flight line spacing was 0.4 km (¼ mi.) and the E-W tie line spacing was 1.6 km (1 mi), as detailed in the Appendix. The survey was flown with GPS navigation during September and October, 2000.

As detailed in the Appendix, the 1995 IGRF formula, diurnal variations, and various other corrections were applied to the data to construct the Total Magnetic Intensity map (Figure 3.7-1 [TR #8]). PRJ further processed the data to produce:

1) Total Magnetic Intensity, Reduced to Pole (RTP, Figure 3.7-2 [TR #8])
2) Horizontal Gradient of RTP Aeromagnetics (HG, Figure 3.7-3 [TR #8])
3) Vertical gradient of RTP Aeromagnetics (VG, Figure 3.7-4 [TR #8])
4) Second Vertical Derivative of RTP Aeromagnetics (SVD, Figure 3.7-5 [TR #8])
5) Linear Feature Analyses of RTP Aeromagnetics (LFA, Figure 3.7-6 [TR #8])

PRJ's interpretations of the aeromagnetic anomalies are presented in the Appendix, and the aeromagnetic features are delineated in Figure 3.7-7 [TR #8]. Anomalies critical to determining the fault framework in study area and in developing T/BR reservoirs are discussed below; these discussions are based in part on PRJ's interpretations. The RTP map (Figure 3.7-2 [TR #8]) shifts anomalies as much as 2 km northward compared to the Total Magnetic Intensity map (Figure 3.7-1 [TR #8]), but the major anomaly trends are recognizable in both data sets. The magnetic gradients displayed in these two maps are prominent, and are in agreement in general with older data sets.

Included in the aeromagnetic section is a short review of the regional Bouguer gravity in the study area. This review is focused on the relation of the gravity gradients to the aeromagnetic gradients.

3.7.2 Northerly-striking Gradients

3.7.2.1 East Branch Keuka Lake Magnetic Gradient
3.7.2.1.1 Description. The Horizontal Gradient Map (Figure 3.7-3 [TR #8]) shows a distinctive northerly trending gradient in the western part of the overflight region that separates magnetic high anomalies to the west from interspersed magnetic lows and highs to the east (Figure 3.7-2). The primary NNE-striking, steep gradient, the East Branch Keuka Lake gradient; extends from about 42^o 22'30''N to 42^o 37'30'N, and is the longest continuous gradient in the overflight area. Shorter relatively steep gradients parallel (on both sides) the East Branch Keuka Lake gradient in the north; the western parallel gradient is named here the West Branch Keuka Lake gradient (Figure 3.7-3 [TR #8]). All three steep gradients are also precisely defined in the Vertical Gradient Map, the Second Vertical Derivative, and the Linear Feature Analysis maps (Figures 3.7-4 [TR #8], 3.7-5 [TR #8], and 3.7-6a [TR #8], respectively). Considered together, the NNE-striking gradients on the HG map have a slight left-step en echelon pattern.

The East Branch Keuka Lake gradient is particularly well displayed in the LFA and SVD maps (Figures 3.7-6 [TR #8], 3.7-5 [TR #8], respectively), where the gradient has an extremely straight strike, and appears to truncate gradients that trend NE and NW. The extremely small (map-view) curvature of the strike of the gradient indicates that this gradient represents a fault that separates Precambrian basement terranes with strikingly different magnetic susceptibilities—high on the west-such as a mafic igneous complex. This fault in the Precambrian basement probably extends to the surface in some form, based on coincident topographic and remote sensing anomalies (discussed in Section 3.9).

3.7.2.1.2 Relation to T/BR and Other Fields. Both the discovery field, Glodes Corners Road Filed, and the Muck farm Field, are located in the only magnetic low west of the East Branch Keuka Lake Magnetic Gradient (Figure 3.7-8 [TR #8]). The eastern termination of both easterly-trending fields is the West Branch of Keuka Lake, which also lies along the East Branch Keuka Lake magnetic trend. This termination is particularly well-displayed in the LFA map, Figure 3.7-6b [TR #8]. The western termination of the Wayne-Dundee field (which is located along an Alleghanian anticline) also is the East Branch Keuka Lake gradient. Thus, it appears that the northerly–striking fault in the Precambrian basement was later reactivated in the Ordovician as a cross-fault controlling easterly-striking fault development in the T/BR fields and was reactivated still later in the Alleghanian as a cross fault for the development of eastern trending structures associated with the Wayne-Dundee field (the Firtree Anticline).

3.7.2.2 Other NNE-striking Magnetic Gradients
3.7.2.2.1. Northwestern region, Description. Two other northerly trending gradients lie west of the East and West Branch Keuka Lake gradients (Figure 3.7-7 [TR #8]). The longer gradient, the East Italy Gradient, extends from about 42^o 30'N to 42^o 35'N, where the gradient terminates against a WNW-trending gradient (Figures 3.7-3 [TR #8] and 3.7-7 [TR #8]). With a slight jog across the WNW-trending gradient, the East Italy Gradient may continue north to the northern limit of the overflight region (Figure 3.7-7 [TR #8]). In the same region, the West Yatesville Gradient also trends NNE from about 42^o 35'N northward (Figures 3.7-3 [TR #8] and 3.7-7 [TR #8]).

3.7.2.2.2. Relation to T/BR. The western termination of the Glodes Corners Road Field in 2001 was located at the East Italy Gradient (Figure 6b), but the field has been extended in a southwesterly direction since that time. The join between the southwesterly and westerly trending parts of the field is located near the East Italy Gradient (Figure 3.7-6c). The westerly-trending portion of the Glodes Corners Road Field crosses several low amplitude northerly trending gradients (Figure 3.7-6b [TR #8]).
3.7.2.2.3. Central Region, Description. Northerly-trending gradients border a long section of Seneca Lake from near the northern border of the overflight area south to about 42 ^{o} 27'N (Figures 3.7-3 [TR #8] and 3.7-6b [TR #8]). Another small amplitude gradient is located in the center of the lake from about 42 ^{o} 30'N northward (Figures 3.7-3 [TR #8] and 3.7-6b [TR #8]). The small amplitude of these gradients led PRJ to suggest that these gradients are related to sources in the Paleozoic and glacial cover sequence (see Appendix). Additionally, however, as discussed in Section 3.1, a cross fault follows these gradients, primarily along eastern Seneca Lake gradient; the Alleghanian Fir Tree Point Anticline exhibits a jog across this cross fault.
3.7.2.2.4. South-central and Southeastern Region, Description. Several relatively short and low amplitude gradients occur in the region near the southern border of the overflight region from about 76^{o} 49'W to 76^{o} 30'W (Figures 3.7-3 [TR #8], 3.7-4 [TR #8] and 3.7-7 [TR #8]). None of these has known affects on any structures.

3.7.3 ENE/NE-trending Aeromagnetic Gradients

3.7.3.1 Description

The dominate linear gradients east of the East Branch Keuka Lake gradient trend ENE/NE and NW. The longest northeasterly trending gradient separates an aeromagnetic low anomaly to the south from a series of magnetic highs, including the Burdett, Searsburg and Myers anomalies, to the north (Figures 3.7-2 [TR #8] and 3.7-7 [TR #8]). This gradient is well displayed in the HG, VG, and LFA maps (Figures 3.5-3 [TR #8], 3.5-4 [TR #8], and 3.5-6 [TR #8], respectively). The gradient displays a jog along northwesterly trending gradients near Cayuga Lake (Figures 3.7-2 [TR #8], 3.7-3 [TR #8], 3.7-4 [TR #8], and 3.7-7 [TR #8]), and appears to be interrupted by the NW-trending gradients associated with Cayuga Lake. A shorter ENE- trending gradient occurs on the north side of the Searsburg Anomaly. The amplitude of the gradients, and the fairly straight nature of the gradients, suggest that the gradient marks faults in the Precambrian basement that separate terranes of differing magnetic susceptibility.

Other ENE/NE trending gradients occur in the northwestern corner of the overflight region (the King Ferry gradients; short, small amplitude ENE/NE trending gradients are located in the two major ENE-trending magnetic lows (e.g., along the Enfield anomalies). In the southwestern corner of the overflight area, nearly NE-striking gradients are truncated by the NNE-striking East Branch Keuka Lake gradient (e.g., Figures 3.7-3 [TR #8] and 3.7-6 [TR #8]). One of the NE-striking anomalies curves into the trend of the East Branch Keuka Lake gradient, whereas the other is truncated by the East Branch Keuka Lake gradient.

3.7.3.2 Relation to T/BR Fields

Although no T/BR fields are presently located along these ENE/NE striking gradients, to the south the T/BR fields (such as Quackenbush) are localized along ENE-striking Landsat lineaments (EarthSat, 1997) that Jacobi (2002) suggested represented faults; these faults are most likely Iapetan-opening rift faults that were reactivated several times (Jacobi et al., 2003, 2004a-d, 2005a-d, 2006a-c). In this study area, we have no 3-D seismic, but integration of fracture, soil gas, 2-D seismic, and lineament data suggest that faults along these aeromagnetic gradients are also reactivated Iapetan opening rift faults, some of which form the border faults for T/BR grabens.

3.7.4 NW-trending Aeromagnetic Gradients

3.7.4.1 Description

In the eastern part of the overflight area, a long, fairly continuous, high amplitude, NW-striking gradient occurs, the Cayuga Lake Structure Zone (Figure 3.7-7 [TR #8]). This set of NW-striking gradients is well displayed on the HG, VG, and LFA maps (Figures 3.7-3 [TR #8], 3.7-4 [TR #8], and 3.7-6 [TR #8], respectively). In all three maps, it appears that the NW-trending gradients truncate the ENE/NE-striking gradients.

In the western part of the overflight area, several NW-striking gradients are observed. A prominent NW-striking gradient extends northwesterly from the southern border of the overflight region and forms the northern boundary of the Bradford Anomaly (Figures 3.7-2 [TR #8], 3.7-3 [TR #8], 3.7-4 [TR #8], and 3.7-6 [TR #8]). The NNE-trending East Branch Keuka Lake gradient truncates the NW-trending anomaly.

On the west side of the East Branch Keuka Lake gradient, several NW-striking anomalies occur, including the Rheims Anomaly. A possible continuation of the Bradford Anomaly Gradient forms the northeastern border of the Rheims Anomaly (Figures 3.7-2 [TR #8], 3.7-6 [TR #8], and 3.7-7 [TR #8]); the Rheims NW trend extends to the NNE-striking Italy Anomaly, which appears to truncate the NW-trending gradient (Figures 3.7-2 [TR #8], 3.7-6 [TR #8], and 3.7-7 [TR #8]). North of the Rheims gradient, a NW-trending gradient truncates the NNE-striking Italy and Yatesville anomalies, and may contribute to the left steps in the NNE-striking Keuka Lake gradients (Figures 3.7-2 [TR #8], 3.7-6 [TR #8], and 3.7-7 [TR #8]).

3.7.4.2 Relation to T/BR Fields

The western termination of the Muck Farm Field in 2001 was near the Rheims NW-trending gradient (Figure 3.7-6b), and the western end the Muck Farm extension may also terminate along the Rheims NW-striking gradient (Figure 3.7-6c [TR #8]). Both terminations of the 2001 Glodes Corners Road field are located along NNE-striking gradients, but the western extension of the Glodes Corners Road Field is presently located along the Rheims NW-trending gradient.

3.7.5 Circular and Low-amplitude Aeromagnetic Anomalies (from the PRJ Report, Appendix)

The Reading Center anomaly (Figures 3.7-3 [TR #8] and 3.7-7 [TR #8]) was considered by PRJ to be related to an intrusive source body with significant depth extent and with an upper surface approximately 1.7 km (5600 ft) below sea level (essentially at the Precambrian/Cambrian contact). PRJ proposed a very high susceptibility contrast relative to the host rock and suggested that the intrusion is a mafic body. Such a mafic body is consistent with the circular positive gravity anomaly in the region of the Reading Center aeromagnetic anomaly (see following Bouguer Gravity Section, 3.7.6). A negative magnetic zone of smaller amplitude, the Wayne area, surrounds the Reading Center intrusion. Locally different basement lithologies, or the effect of the deep extension of the intrusive body, may be associated with the observed magnetic anomaly pattern.

A semi-circular lithology block represented by the Buttermilk Falls anomaly is located in the extreme southeastern corner of the survey area. The block is bounded on the north by a linear magnetic gradient. PRJ proposed an intrusive origin for the source body at a depth of about 2.7 km (9000 ft) below sea level.

A positive, circular anomaly about 50 nT overlies a similarly shaped area of till moraine and kame deposits south of Applegate Corner in the southeastern part of the survey area (near the Enfield Anomalies, Figure 3.7-7 [TR #8]). Additional low amplitude, high frequency magnetic anomalies that trend northerly to northeasterly occur in the areas both west and east of the south end of Seneca Lake where numerous glacial deposits are mapped. These anomalies are clearly delineated on both the Vertical Gradient and the Linear Feature Analysis maps (Figures 3.7-4 [TR #8] and 3.7-6 [TR #8], respectively). PRJ noted that numerous other high frequency magnetic responses, which locally show a relation to mapped glacial deposits, are present in the data. PRJ suggested that the aeromagnetic anomalies with amplitudes of up to 50 nT that appear to be spatially related to the glacial deposits must indicate that a significant susceptibility contrast and/or thickness is associated with these surficial sediments. These anomalies have, in places, hampered the delineation of broader, basement-related responses.

3.7.6 Bouguer Gravity

The Bouguer gravity anomaly map (Figure 3.7-9 [TR #8]) displays a NNE-striking gradient that is coincident with the East Branch Keuka Lake magnetic gradient. However, the Bouguer gravity is relatively low over the aeromagnetic high. Such a relationship (aeromagnetic high coupled with a gravity low) does not have a simple explanation—igneous rocks with a higher magnetic susceptibility are generally mafic—but mafic rocks have a higher density than silicic igneous and sedimentary rocks. A contribution to the gravity low from less dense salt is also not probable, since the contours of salt thickness do not follow the NNE-trending gradient. The Romulus Trough (or sag), a Middle Devonian local depositional basin (e.g., Mayer et al., 1994) lies to the east of the northern extension of the gravity gradient. Thus, the Middle Devonian sag also is counter to the gravity anomaly, with the gravity high over the sag. It appears that the long-wavelength NNE-trending gravity high in the center of the study area may have a strong contribution from a source other than the Phanerozoic section, and other than the source of the magnetic anomalies. (It is true, of course, that some relatively low density granites and gneisses can have a high magnetic susceptibility, but such a situation is relatively rare. If, however, the primary source that contributes to the aeromagnetic anomaly is different from that which gives rise to the gravity anomaly, it remains probable that deep counterparts of the East Branch Keuka Lake Fault System controls the boundary of both sources (located along Keuka Lake), since the gravity and aeromagnetic trends are coincident along the Keuka Lake trend.

The NE-striking gravity gradient in the southeastern part of the study area (Figure 3.7-9 has a trend parallel to the aeromagnetic gradients in the same area. The gradient (low to the southeast) is part of a large NE-trending gravity low that may reflect a northeastward, buried extension of the Rome Trough (Harper, 1989; Jacobi, 2002). Conversely, the gravity low is parallel and immediately adjacent to the Scranton Gravity High, which may have a mantle source (e.g., Jacobi et al., 2005a-c). Short wavelength deviations of the general gradient trends across Seneca and Cayuga lakes are most likely the result of glacial-filled valleys, with lower density glacial sediment in the glacial fill than in the surrounding hills. The semi-circular positive gravity anomaly west of the southern part of Seneca Lake probably results from the mafic intrusion in the same area proposed from a circular aeromagnetic positive anomaly, the Reading Center anomaly (see Aeromagnetic section, 3.7.5, above)

3.8 PHASE II: VERIFICATION-HORIZONTAL CORE

3.8.1 Introduction

Fortuna retrieved 11.18 m (36.67 ft) of horizontal core from the Trenton/Black River in the "hottest" play in the Appalachian Basin in central New York State. The core was cut on a 120º azimuth, oblique to the trend of a Trenton/Black River field that extends along an EarthSat (1997) ENE-trending lineament south of the study area[1]. In Phase I of this research project, we determined that ENE-trending lineaments in the study area reflect deep faults that initiated as Iapetan Opening/Rome Trough extensional faults, and were reactivated during several tectonic phases. East-northeast-trending EarthSat (1997) lineament bundles south of the study area have also been proposed to represent reactivated fracture systems that initially developed as Iapetan Opening/Rome Trough extensional faults (e.g., Jacobi, 2002). The orientation of these ENE-striking faults would have been suitable for reactivation with a strong strike-slip component during the Taconic and Acadian orogenies (e.g., Jacobi et al., 2004a-d). The strike-slip motion would have reversed as the orogeny progressed. At the drilling site, the general ENE-strike of the field has a small jog. The extent to which the structural features and their orientations were influenced by this small jog is not known. The reassembled core, with "up" based on the correlation to the FMI log (as described in Section 2.8), is shown in Figure 3.8-1 [TR #9].

3.8.2 General Core Description

The core consists of a fairly dense dolomite. Common features observed include veins (generally dolomitic) and stylolites (both horizontal and steeply dipping), but also includes vugs, bedding, and dolomitization fronts. A few beds with significant intergranular porosity were observed; large vugs are present, but not in abundance.

3.8.3 Full Core Porosity/Permeability Tests

The core was cut for porosity and permeability tests on full-diameter core segments. Twenty-six samples were taken from throughout the core at intervals selected to isolate desired features. Porosities range from less than 1% to nearly 9%. Permeabilities range from 0.01 to nearly 0.7 md. The sampled intervals were chosen to isolate the influence of specific features on fluid dynamics. In many cases, stylolites can provide barriers to fluid flow, but the test results (Figure 3.8-2 [TR #9]) show that some of the larger stylolites yield the best permeabilities in the core.

[1] For proprietary considerations, we are not at liberty to indicate the exact location of the core site.

There was very little vuggy porosity in this core and the highest porosity was reached in a "bedding" interval containing interstitial void space.

3.8.4 Structure in Core

3.8.4.1 Introduction

J & A characterized and measured 397 geological features on the core, including the orientation of 211 veins and 81 stylolites. Of these totals, 99 veins were measured on the full (pre-slabbed) core (Figure 3.8-3 [TR #9]), and 43 stylolites were measured on the full (pre-slabbed) core (Figure 3.8-4 [TR #9]). The dominant trends of veins are N, NNE, NE, ENE, and WNW (Figure 3.8-3c [TR #9]). The N-striking veins have an intermediate dip to the west. The NNE-striking veins have intermediate to steep dips to both the NW and SE. NE-trending veins dip steeply toward the southeast. The ENE-striking veins dip steeply to the NW. The WNW-striking veins have two dip populations: steeply (near vertical), and moderately to very shallowly to the north. The stylolites have two orientation populations: NE- and WNW- striking (Figure 3.8-4c [TR #9]). The NE-striking stylolites dip steeply to the SE, and the WNW-trending stylolites generally dip very shallowly NE.

3.8.4.2 Kinematic Indicators

The cross-cutting/abutting relationships of every observed vein and stylolites, where determinable, are shown in Figure 3.8-5 [TR #9]. Seven rhombochasm kinematic indicators were observed before slabbing of the core (Figure 3.8-6 [TR #9]), and eight additional kinematic indicators were found after slabbing (Figure 3.8-7 [TR #9]). Admittedly, a larger population of kinematic indicators would be advantageous, but these few features do assist in constructing a possible tectonic model.

We observed one ENE-striking vein with a rhombochasm that may indicate the sense of motion on the ENE-striking graben faults. The sense of motion inferred from the ENE vein with a rhombochasm (feature 112, Figures 3.8-6 [TR #9] and 3.8-7 [TR #9]) indicates a left-lateral sense of motion. Such a sense of motion is opposite to the expected motion associated with an east-west directed maximum principal compressive stress acting upon the ENE-trending Iapetan Opening faults. An east-west directed σ_1 might result from late collision during the Taconic or Acadian orogenies. A northerly directed σ_1 would have been set up in earlier Taconic times during the passage of the continental plate over the peripheral bulge (e.g., Jacobi et al, 2003, 2004a-d, 2005a-d, 2006a-d). Consistent with this interpretation are the three NW-striking veins (feature 66 in Figure 3.8-6 [TR #9] and features B and C in Figure 3.8-7 [TR #9]) with rhombochasms that indicate right-lateral motion. An alternative explanation for the left-lateral ENE-striking vein is that the vein developed during the Main phase of the Alleghanian Orogeny, a time when Engelder and Geiser (1980) and Engelder (1985) proposed that σ_1 was oriented N-S in central and southeastern NYS. However, master-abutting considerations discussed below suggest that the ENE-striking vein developed very early in the history of the unit—in early Taconic times.

The six northerly-trending veins with rhombochasms indicate three left lateral (features 9 and 24/25 in Figure 3.8-6 [TR #9] and feature D in Figure 3.8-7 [TR #9]) and three right lateral motions (feature 2 in Figure 3.8-6 [TR #9] and features A and E in Figure 3.8-7 [TR #9]). These opposite inferred sense-of-motions probably indicate multiple phases of vein development—one during a time of southwesterly-directed maximum principal compressive stress (for features 2, A, and E), and a time of NW-directed maximum principal compressive stress (for features 9, 24/25, and D). The northwesterly-directed S_H is compatible with the far-field stress Engelder and Geiser's (1980) and Engelder's (1985) proposed for the "Lackawanna" Phase (early phase) of the Alleghanian Orogeny.

The two slip directions inferred from the northerly-trending veins are both compatible with Hatcher's (2002) more recent of Alleghanian "zipper tectonics". In this model, Hatcher's geology map of thrust transport (his Figure 1) suggests the later Main Phase of the Alleghanian Orogeny in the central and southern Appalachians was NW-directed, rather than "westward – directed", as stated in his text (p. 203,. It is thus not clear in the zipper tectonic model whether the Main Phase and/or the Lackawanna Phase had a NW-directed S_H. However, in the simplest model with an early reversal of slip on the orogen (sub) parallel faults (Hatcher, 2002), left lateral faulting (with an inferred northerly to northwesterly directed S_H) was followed by right lateral faulting (with an inferred SW-directed S_H). These Alleghanian S_H orientations are consistent with the veins in the core, but could the inferred slip directions from the veins also be appropriate for other orogenies, including the Blountian Phase of the Taconic, the Taconic, Salinic, or Acadian?

The northwesterly-directed σ_H is also compatible with compression associated with the Blountian Phase of the Taconic Orogeny, but, as discussed below, the Blountian Phase was over, or nearly over, by the time of Black River deposition. The southwesterly-directed (range of SSW to WSW-directed) S_H (for features 2, A, and E) could be Taconic or Acadian (if WSW-directed), but the NW-directed S_H is not easily reconciled with simplistic Taconic or Acadian tectonic models for eastern NYS.

We have no good knowledge concerning the kinematics of the Silurian Salinic Orogeny. From well logs, seismic reflection data, and outcrop patterns, we know that this orogeny reactivated the faults in NYS (Jacobi and Smith, 2000; Jacobi et al., 2006d), but the exact motion sustained by the faults is not yet known. That lack of data, plus the vagueness in the tectonic models for the Salinic in New England, do not allow a definitive proposal for the stress field. Thus, we cannot with assurance indicate which vein trends are consistent with a Salinic stress field. However, it is probable that an easterly extensional stress (S_h) was exerted in the Appalachian Basin of NYS during the salt basin development. Such a stress field orientation would be similar to the stress field orientation during times when the peripheral bulge was affecting the continent, and the northerly-trending veins should have been primarily extensional.

In all the preceding discussions concerning stress orientation of a particular orogeny, it is assumed that the inferred slip directions are the result of the far-field (regional) stress. However, stress release along the pre-existing deep faults in the region may have controlled the local stress fields (Jacobi et al., 2002), or, as Rawnsley et al. (1998) suggested, the points of convergence along fault may have caused local stress reorientations. In either of these cases, the NW- and SW-directed σ_H could also represent local reorientations of the far-field E-W Taconic compression after an earthquake on the graben-bounding faults. A locally more complicated stress pattern at the core site might also have developed since the core site is near a jog in the graben, which may indicate a transfer/cross-strike zone. Shear that is divergent to the main (deeper) fault trend is also commonly ascribed to riedal shears. In the case of the northerly-striking veins with rhombochasms, however, the orientation of these veins is not consistent with either R or R' riedel shears developed in a west-directed compression on ENE faults. However, faults associated with the jog in the ENE-trending graben near the core site might have reoriented the local stress sufficiently to promote northerly-striking riedel shears on northerly trends. From this discussion it is apparent that local stress fields may have episodically existed in the core site and therefore could negate the inferences drawn from a simplistic model of far-field stress control for the development of individual veins and associated rhombochasms. However, it is clear that the northerly-striking veins with rhombochasms are not easily explained by riedel shears in a west-directed σ_1 that would have characterized the later stages of collision of the Taconic (main phase).

3.8.4.3 Sequence of veins and stylolites

The relative sequence of vein and stylolite development can be ascertained from master-abutting relationships at intersections. In the case of veins and stylolites, the master (i.e., through-going or "cutting" feature) is younger than the abutting feature—opposite to that of fractures. In Figure 3.8-5 [TR #9], J & A plotted the master abutting relationships with respect to vein and stylolite strike. The shallow-dipping WNW-trending stylolites are cut by most features in the core. However, a few veins are cut by the horizontal stylolites: four veins that strike WNW, one that strikes ENE and one that strikes NNE. Horizontal stylolites can form at relatively shallow depths, implying that they can form early in the burial history of the carbonate units. For example, estimates of burial depths for stylolite genesis in carbonates range from 90 m (Bushinsky, 1961; Schlanger, 1964) to 600 to 900 m (Dunnungton, 1967). Thus, the WNW-, ENE-, and NNE- striking veins cut by stylolites developed very early. It is probable that the horizontal stylolites developed first during Taconic burial, perhaps even during Trenton time, since the Trenton is about 189 m (620 ft) thick in the central part of the research area (based on a T/BR test well), about 183 m (600 ft) thick east of Cayuga Lake (Rickard, 1973), and as much as 244 m (800+ ft) thick at the northern end of Seneca Lake (Rickard, 1973). If the stylolites in the underlying Black River are indeed Trenton (or Utica) aged (Taconic), then the vertical veins cut by the horizontal stylolites must also be certainly Taconic, probably early Taconic, based on the following consideration. The ENE-striking vein has a rhombochasm (#112) that suggests left-lateral slip. This slip direction, and inferred northerly-directed σ_H is consistent with the model of earlier Taconic times when the continent flexed over the peripheral bulge before final collision. The ENE strike is probably controlled by the deep ENE-striking faults. The strike of the NNE-trending vein might reflect fault activity along the northerly striking faults that terminate some of the T/BR fields (discussed in section 3.9, among others). The WNW strike of the other early veins is also parallel to cross-strike features (as inferred from aeromagnetics in the Muck Farm Field). The NNE trend is also sufficiently divergent from the ENE graben fault trend to be about parallel to r' riedel shear orientations (i.e., these shears would be antithetic riedel shears). We have no data to discriminate between a riedel shear model and cross-strike fault model for these NNE-striking veins. The Blountian Phase of the Taconic Orogeny may have had a northwesterly-directed σ_H. Since the Blountian Phase predates much of the classic New England "Taconic" Orogeny, could this "early" Taconic have also caused the development of the some (or all) of the early veins discussed above that predate Taconic burial? Especially, could the WNW veins be riedel shears generated by the NW-directed $\sigma_1$of the Blountian Phase? The end of Blountian

Phase is about the time of the Deicke-Millbrig volcanic ash layers ("K-bentonite layers"); these ash layers pass through the top of the clastic wash off the Blountian Phase orogen (Mitchell et al., 2006). However, these same ash layers are commonly at, or very close, to the well log pick of the top of the Black River, and the core was retrieved from the upper section of the Black River. Thus, there is only a remote probability that the majority of the "early" veins resulted from the Blountian Phase rather than from the main New England Taconic Phase. Certainly the horizontal stylolites could not have resulted from the Blountian Phase.

Is there evidence from other orogens that horizontal stylolites can postdate earlier vertical fractures that must have developed in the same orogeny? In Mexico Cretaceous carbonates record early near-vertical veins that were later cut (and dissolved) by sub-horizontal stylolites (Ferket et al., 2004), and in the Oman Foredeep, horizontal stylolites cut veins that Buruss et al. (1983) proposed developed during (peripheral bulge) uplift.

Vertical stylolites were observed in the core, and trend generally NE to NNE, and cut most of the veins. Steeply dipping stylolites indicate a period of layer-parallel shortening caused by a sub-horizontal (tectonic) maximum principal compressive stress directed NW to WNW. As discussed for the veins above, a northwesterly-directed σ_1 is compatible with the "Lackawanna" Phase of the Alleghanian Orogeny (Engelder and Geiser, 1980; Engelder, 1985). However, as also discussed above, a NW-directed σ_1 could also represent a local redirection of the far-field E-W Taconic compression. Such a reorientation could develop along open graben-bounding faults.

One vertical stylolite cuts a nearly horizontal stylolite; thus, the layer-parallel shortening of the vertical stylolites postdates the vertical loading indicated by the horizontal stylolites. Such a timing relationship suggests: tectonic horizontal loading postdates probable sedimentary deposition loading.

One vertical stylolite also cuts the only horizontal vein we observed in the core. Horizontal veins imply vertical unloading, which typically occurs (on the craton) the during the relaxation phase of an orogeny. If this assumption is correct (based on only one horizontal vein), then the vertical stylolites are probably not Taconic in age, since they post-date the relaxation phase. Thus, the NE- to NNE-striking vertical stylolites are more likely Alleghanian in age. The Acadian is considered a less likely alternative since we assume far-field σ_1 was oriented E-W, based on structures east of the Catskills. (However, divergent orientations from local late Acadian stress fields could be possible, as could be inferred from structures in Devonian units with divergent trends south of the Mohawk Valley (Jacobi and Smith, 2000). Similarly, the Salinic Orogeny is a remote possibility for the NW-directed σ_1, since the stress fields for that orogeny are yet to be determined.

Steeply dipping stylolites are cut by stylolites dipping 55º. Thus, the sequence for stylolite development is sub-horizontal followed by near vertical followed by steeply dipping stylolites (55º).

Several veins cut the vertical NE-striking stylolites, including one NNE-striking vein, two NE-to ENE-striking veins, and one WNW-striking vein. The NNE to NE striking veins are the youngest veins observed in the core. One of the NE to ENE-striking veins has a rhombochasm which implies right-lateral strike-slip motion. A westerly-directed σ_1 is inferred from the rhombochasm. This westerly-directed σ_1 postdates the NW-directed σ_1 that resulted in the vertical stylolite and therefore postdates the Lackawanna Phase (Engelder and Geiser, 1980; Engelder, 1985) of the Alleghanian Orogeny. Such a sequence is consistent with the Alleghanian zipper tectonic model of Hatcher (2002) (NW-directed followed by west-directed σ_1), but is not compatible with the older Alleghanian models (e.g., Engelder and Geiser, 1980) of NW-directed followed by north-directed σ_1 in this region.

The time window that is bracketed by the horizontal and later vertical stylolites is characterized by the development of several sets of veins. ENE-trending veins cut the horizontal stylolites, but they are themselves cut by all subsequent features (veins and vertical stylolites) in the core. The ENE-striking veins parallel the graben axis and are likely related to continued graben development. Cross-cutting relationships show that the WNW-striking veins postdate the ENE-striking veins. Like the earlier WNW-striking veins, these veins may be related to cross-strike discontinuities or to riedel shears.

Thick accumulations of anthraxolite characterize the horizontal stylolites, and suggest that hydrocarbon migration occurred along these stylolites. A similar early migration of hydrocarbon in the Oman Foredeep that predated horizontal stylolite growth was proposed by Buruss et al (1983) based on fluid inclusions trapped in veins. Jacobi et al. (2006d) suggested that porosity development for potential hydrocarbon migration and reservoir development in carbonates of the northern Appalachian Basin could have occurred several times, related to each orogeny, and that the initial porosity developed relatively early in the geologic history of each unit. The timing of hydrocarbon migration is more difficult to ascertain, although we have initiated a cooperative program to date anthraxolite. A past assumption has been that major hydrocarbon generation and migration occurred only during the Alleghanian Orogeny (see review in Jacobi et al., 2006d), but episodic migration during Taconic and perhaps later orogenic phases may have also contributed to the present hydrocarbon reservoirs (Jacobi et al., 2006d).

3.9 INTEGRATION AND DISCUSSION

3.9.1 Seneca Lake Swath and Transect

3.9.1.1 N-striking Fault (CSD) on the Seneca Lake Swath and its relation to T/BR grabens

The variations in abundance of fractures, both in terms of fracture frequency and in orientation, record the history of local stress variations. For example, on the southeastern-most shore of Seneca Lake, N-striking FIDs are most common, and no ENE- or E-striking FIDs are found. N-striking lineaments from Landsat and a DEM were identified in this same area. Impressively, one of the EarthSat (1997) Landsat N-striking lineaments near Burdett is nearly coincident with an inferred N-striking fault that Bradley et al. (1941) proposed based on outcrop stratigraphy (Figure 3.9-1 [TR #9]). The seismic reflection line in the same area (Line 2) also exhibited a fault with seismic characteristics consistent with a fault orientation nearly parallel to the seismic line (which is oriented N-S). Finally, a northerly-trending aeromagnetic gradient is located in the same general area. Thus, all these disparate data sets point to the same structure—a N-striking fault that is located along the southeastern shore of Seneca Lake. The groundtruthing in this case is the fractures—DEM, Landsat, ASTER and aeromagnetic lineaments all indicate a structure in the region, but are not in themselves definitive. The 2-D seismic line is, of course, another groundtruth, but it does not yield definitive answers for possible faults with offsets less than about (optimistically) ½ to ¼ the dominant wavelength (18 m to 35 m, 58 ft to 115 ft), nor is it known for definitive recognition of structure close to the trend of the seismic line, and of course in processed 2-D, we cannot determine the trend of the structures.

This northerly-trending fault not only affects the Devonian section that outcrops, but also affects Precambrian basement, based on sub parallel aeromagnetic gradients, and a fault observed on seismic reflection data that may be the fault in question. Bradley et al.'s (1941) surface mapping and Murphy's (1981) map showed that the E-trending Alleghanian Firtree Anticline is offset along this N-striking fault. We assume that the offset is original, and that the pre-existing, reactivated N-striking fault controlled the site of a linkage (lateral ramp or transfer zone) between independently developing segments of the Firtree Anticline. The N-striking fault can be thought of as a cross-strike discontinuity (CSD).

We have no data that definitively demonstrate that this fault offsets the T/BR grabens observed on the seismic Line #2. However, the fault(s) on seismic Line #2 that may represent the deeper component of Bradley et al.'s (1941) surface fault do offset the Black River (e.g., fault #14 on Figure 3.4-3 [TR #3]) and (to a lesser extent) the Trenton. Furthermore, both the Glodes Corners Road and Muck Farm fields terminate against the similarly-trending Keuka Lake Fault System. Seismic reflection data across the N-striking Clarendon-Linden Fault System ("CLF", located farther west; e.g., Jacobi and Fountain, 2002) also show that the CLF was significantly active during Taconic times; early extension was followed by thrusting. Thus, if the CLF is analogous to the N-striking fault along Seneca Lake, it is probable that the N-striking fault at Seneca Lake was active in Trenton times and did control the lateral extent of T/BR graben segments. If the structures represented by the Devonian structure contours and the outcropping ENE-trending popups/faults (Bradley et al., 1941) follow deeper T/BR structures, then the T/BR grabens continue into the N-striking fault system.

We proposed that this N-striking fault extends North beyond the map area in the Ovid/Willard area. The N-striking narrow structural high west of Lodi in Bradley et al.'s (1941) structure contours fault system may indicate the northward continuation of this fault system (Figure 3.9-1 [TR #9]). The NE-striking structures localized on the eastern shore of Seneca Lake from Valois to Ovid could represent compressional structures related to left lateral shear on the fault system.

3.9.1.2 N-trending Seneca Lake Transect: E- and ENE-trending FIDs, T/BR grabens and Alleghanian Structures

On the Seneca Lake transect, a startling spatial coincidence is found among the fracture frequencies of ENE and E-striking fractures, Landsat (EarthSat, 1997) lineaments, and soil gas anomalies (Figure 3.3-3 [TR #3]). The ENE-striking fractures have a tight spacing (high frequency) at Valois, where E-striking fractures have near-zero fracture frequencies. This frequency spike of ENE-striking fractures coincides with a "spike" in the number of soil gas anomalies/kilometer (Figure 3.3-3 [TR #9]). The Valois high frequency in ENE-striking fractures also coincides with a bundle of ENE-striking EarthSat (1997) lineaments. The Valois zone of ENE-trending lineaments are remarkably coincident with the strike of surface structure mapped by Bradley et al (1941; Figure 3.9-1 [TR #9]). Considering the east shore of Seneca

Lake from Watkins Glen to north of Lodi, the structure contours and popup strikes only strike ENE in the area of the ENE-striking lineaments (Figure 3.9-1 [TR #9]). These lineaments are also parallel to a major aeromagnetic anomaly located directly to the south. On seismic Line #2, this region corresponds to faults bordering a T/BR graben (Figure 3.4-3 [TR #3]). One of these faults extends from basement to near ground-surface. That the faults affect Precambrian basement is consistent with the aeromagnetic interpretation. Thus, we suggest that this ENE-striking high frequency fracture zone, coupled with lineaments and soil gas anomalies, all indicate that the master faults for the T/BR grabens here trend ENE.

Directly south at Hector, E-striking fractures exhibit a high frequency, whereas the ENE-striking fractures have near-zero frequencies. This high frequency zone of E-striking fractures coincides with a bundle of E-trending EarthSat (1997) lineaments, which are coincident with the Firtree Anticline (Figure 3.9-1 [TR #9]), as mapped at the surface by Bradley et al., (1941). Seismic Line #2 confirms the surface mapping, and displays thrust ramps in the salt-cored anticline (Figure 3.4-3 [TR #3]). Why the number of soil gas spikes at this fracture frequency spike do not increase, unlike the increase observed at the ENE-striking fracture spike (at Valois), is unclear. As discussed in the Soil Gas Section (3.3), possible explanations include:

1) the ENE-striking fractures are parallel to the present S_H in central and western New York State, with the result that the ENE-striking fractures are open more than the E-striking fractures, and/or
2) the ENE –striking high frequency fracture zones represent FIDs that may have significantly more height than the E-striking FIDs. The significance of the fracture height is that the high (“tall”) FIDs allow rapid gas migration up single FIDs without reaching a ‘top abut” that forces the gas horizontally along less permeable paths before the gas encounters the next vertical FID (see Jacobi and Fountain, 2002, for more details)

North of Valois, both ENE and E-striking fractures display zones with elevated frequencies. The E-striking high frequency at about 24.5 km on the Seneca Lake transect coincides with EarthSat (1997) lineaments and E-striking structure contours on outcropping Devonian units (Bradley et al., 1941). The high frequency ENE-striking fractures at the north end of the transect also correspond to EarthSat (1997) lineaments, structure contours (Bradley et al., 1941) and the high number of soil gas spikes.

3.9.2 Lineaments and FIDs: Coincidence and Groundtruthing in Seneca Lake Swath vs. the Cayuga Lake Swath

On the Seneca Lake Transect, high frequency ENE and E-striking fractures coincide remarkably well with Landsat (EarthSat, 1997) lineaments and soil gas anomalies (Figure 3.3-3 [TR #3]). Additionally, the Landsat lineaments appear to reflect the surface structure that was portrayed by the field mapping of Bradley et al. (1941, Figure 3.9-1 [TR #9]). Yet the more rigorous weights-of-evidence showed that EarthSat (1997) ENE- and E-trending lineaments do not correlate particularly well with FIDs in the Seneca Lake swath, whereas lineaments from other images do correlate with FIDs. Furthermore, analyses of individual sites with FIDs on the west side of Cayuga Lake showed that many ENE- and E-striking lineaments did not coincide exactly with field sites with appropriately trending FIDs.

Why does the weights-of-evidence statistical technique not confirm the apparent good correlation in the Seneca Lake swath between FIDs (E- and ENE-striking) and appropriately-oriented EarthSat (1997) lineaments? And, what is the cause of the apparent discrepancy between the lineaments in the Seneca Lake region versus those in the Cayuga Lake region? Although the potential factors discussed below may be important in some cases, we believe the single most significant factor contributing to the inability of the weights of evidence to confirm the apparent good correlation between EarthSat ENE- and E-striking lineaments and appropriately oriented FIDs is the method in which weights of evidence calculates contrast values. Two factors are important here: the length of the lineament and the density of sites versus the number of lineaments. The Landsat E- and ENE-striking lineaments from EarthSat (1997) tend to be long, longer than the width of the Seneca Lake swath in which most of the sites on the Seneca Lake side occur. Thus, much of the lineament cannot be overlapped by buffers of individual sites. Consequently, that area of the buffered lineament area with no site overlap will function as a negative toward contrast value (the test of coincidence) between sites and lineaments. In contrast, the ASTER lineaments are shorter, and so do not contribute such large unconfirmed buffered areas. Second, although in general we had more sites on the Seneca Lake swath than the Cayuga lake swath, in the region where the ASTER image overlaps the Cayuga lake swath, we have a significantly higher density of sites compared the Seneca Lake swath. Thus, for many lineaments, there is a better chance that some site, or set of sites, falls within the lineament buffer. The result is that the Cayuga Lake swath should have a better contrast values, for all lineaments, but especially for the relatively short ASTER lineaments. We are presently modifying the weights-of-evidence methodology to account for these problems.

Another factor may play a role in the inconsistency between EarthSat (1997 and weights of evidence. We found many more fracture FIDs than lineaments. The conclusion we reached was that perhaps many faults at depth are represented at this high stratigraphic horizon by a series of parallel, small-offset FID systems. In Allegany County such series of step fault were observed in outcrop for each of the major fault orientations (N, NE and NW; e.g., Jacobi and Fountain, 2002). Similar features could occur in the Finger Lakes. Thus, the lineament may follow one fault splay, but the fractures in outcrop may be on a parallel, relatively distant fault splay. In Allegany County, in fact, swamps and drainage systems characterized the main faults, with nearly no outcrops along these faults (which would result in a poor weights-of-evidence contrast value.

The combination of these factors, we believe, yields the apparent disparity between the excellent correlation of FIDs and lineaments observed on the Seneca Lake transect vs. the mediocre correlation determined by weights of evidence, and difference in correlation on the two lake swaths.

3.9.2 Lineaments and Aeromagnetics

Figure 3.9-2 [TR #9] shows the RTP aeromagnetic field in the overflight region overlain by the EarthSat (1997) lineaments and T/BR gas fields (Figure 3.9-2a [TR #9]), as well as lineament bundles (Figure 3.9-2b [TR #9]). The coincidence of NNE-trending EarthSat lineaments and the East Branch Keuka Lake aeromagnetic gradient is unmistakable. Based on the coincidence between the Precambrian-sourced aeromagnetic anomaly and the surface-based EarthSat (1997) lineaments, it is clear that fractures along the East Branch of Keuka Lake extend from Precambrian basement to the surface, where they apparently controlled the erosional development of the East Branch of Keuka Lake. The fractures in the Precambrian basement must represent a significant fault system since they delineate such a major aeromagnetic gradient. The amount of offset at the ground surface is unknown, but Murphy (1981) found minor offset (< 10 m, down-on-the west)) at the Onondaga level. The well on the east side of Keuka Lake with anomalous elevations for tops (about 10 m too deep for Trenton/Black River compared to surrounding wells), may indicate the amount of offset on blocks in the fault zone (although this offset could also be related to an easterly-trending T/BR graben).

The ENE-trending lineaments in the central part of the overflight area (between Seneca and Cayuga lakes) also are parallel to major aeromagnetic anomalies, but are spatially displaced from the major ENE-trending gradients. That the lineaments are parallel suggests that they too represent fracture systems that extend into Precambrian basement. However, because the lineaments are not located along the major aeromagnetic lineaments, the offsets in the Precambrian are relatively minor or the faults have shallow dips to reach the surface 5+ km north of the major gradient. Because the seismic Line #2 shows that most of the faults that reach higher stratigraphic horizons are relative steeply dipping, the first alternative is more probable. Certainly, the proposed ENE-striking faults on Seismic Line #2 exhibit relatively small offsets at the Precambrian/Cambrian contact.

In contrast to the northerly and ENE-trending lineaments that are parallel to aeromagnetic anomalies, some of the E-trending lineaments cross the trends of the aeromagnetic anomalies. This relationship is best seen in the central part of the overflight area east of Seneca Lake. Here the E-trending EarthSat (1997) lineaments cross the ENE-striking aeromagnetic anomaly. This disparity in trend suggests that the E-striking lineaments are not related to basement features, and are instead related to high-structural level features. As discussed above, these E-trending lineaments (at Hector) are related to the Firtree Anticline, which on Seismic Line #2 is shown to be a Silurian-salt-cored, thrust-faulted anticline of Alleghanian age, with little, if any, deeper structure directly associated with the anticline.

These considerations, as discussed below, demonstrate that it is possible to determine some of the characteristics of the fault systems represented by the EarthSat (1997) (and other) lineaments by comparing trends and coincidence of the lineaments to the aeromagnetic gradients.

3.9.3 Lineaments: Groundtruthing and Recommendations

A disconcerting feature of the T/BR discovery fields, the Glodes Corners Road and the Muck Farm fields, is that neither one was located on EarthSat (1997) lineaments. Such is not the case with the T/BR fields to south, which are located on ENE-striking lineament bundles (Figures 3.2-4 [TR #2] and 3.9-3; e.g., Jacobi et al. 2004a-c). Re-analysis of Landsat images and ASTER images do indicate very subtle lineaments along the fields (Everett et al., 2003), but these lineaments might not have been identified if the field locations had not been already known by the image analysis operators (Everett et al., 2003). Thus, the lack of prominent EarthSat (1997) lineaments does not definitively indicate the lack of T/BR fields, but prominent, groundtruthed lineaments can indicate the trend and potential along-strike length of the fields.

In both the weights of evidence and in the Cayuga Lake detailed analyses of individual FIDs vs. lineaments, it became clear that

1) Many more FIDs exist than lineaments recognized in remotely-sensed data, and
2) EarthSat (1997) are particularly poor at recognizing N- and NNW-striking FIDs in this region.

The conclusion to be reached is: lineaments from remotely-sensed data sets (DEM and satellite imagery) can reveal some of the general structural fabric of an area, but the lineaments may not depict all the trends and exact FIDs. However, if an outcrop with an FID is located along a particular lineament, then it is appropriate to extend the FID along the length of that lineament. However, several lineaments in the Cayuga Lake swath had outcrops directly on the lineament that did not display an appropriately-oriented FID. We conclude from such incongruities that some lineaments are either misidentified, or are longer than warranted by actual fracture data. Thus, without groundtruthing, it appears inappropriate to use a particular lineament as an *exact* locator of a fault.

It is clear that most exploration companies lack the personnel to rigorously field check the lineaments with an outcrop fracture analyses. Are lineaments then superfluous for most exploration programs? We do not believe so, based on 15 years of satellite and other imagery analyses in the northern Appalachian Basin. One alternative is to contract out the structural and/or soil gas groundtruthing work. Another alternative is to perform spot checks on lineaments of interest; a third alternative is to assume that "bundles" of lineaments all trending the same direction do indicate some structural feature in the general area of the bundle. This assumption is valid for the ENE-trending T/BR fields south of the study area, where all three main fields (Figure 3.9-2 [TR #9] and 3.9-3 [TR #9]) are aligned along bundles of lineaments that Jacobi (2002) suggested were fault systems (that manuscript was written before any drilling was known from those regions). A fourth alternative is to test whether the lineaments from satellite imagery are coincident with other geophysical/geological gradients or with structure observed on seismic reflection data. For example, coincident aeromagnetic gradients probably indicate basement involvement in a fault system (assuming the target area is the northern Appalachian Basin). This technique has been demonstrated in the present research, as well as in earlier studies of the ENE-trending lineaments. For example, Jacobi (2002) suggested that the ENE-trending lineaments with parallel aeromagnetic gradients probably represented ENE-faults that affected Precambrian basement.

In summary, lineaments and lineament bundles can be used to identify structural fabric, and to trace specific structures, if the exploration program has appropriate fracture data, soil gas data, or a seismic line with faults in the vicinity of the lineaments. In contrast, single lineaments without groundtruthing can be used more as a guide to the structural fabric, rather than a specific target (within 500m). By integrating aeromagnetics, it is clear that many of the lineament bundles can be verified as fault systems in basement. Of course, the ultimate is to use fracture, soil gas, and seismic reflection analyses to verify the lineament or lineament bundle. In terms of satellite imagery, it appears from the present study that targets of different orientations demand different image processing techniques for maximum lineament recognition (as detailed in the lineament section). For ENE-striking FIDs that represent fault systems and targets in central New York State, Landsat (EarthSat 1997) and a fused Landsat and ASTER image provide the best images for lineament identification, but for E-striking FIDs, ASTER alone provides the best image for lineament identification. For N-striking cross fault recognition, the fused Landsat and ASTER image provides the best image, whereas for NNW-striking FIDs, the ASTER image alone is the best image.

3.9.4 Faults and the T/BR discovery fields, Glodes Corners Road and Muck Farm Fields

Although the T/BR Glodes Corners Road Field and the Muck Farm Field were not the focus of present research, the data sets of some of the techniques used in this study extend to these fields (aeromagnetics, gravity, EarthSat [1997] lineaments, and seismic reflection data). Integration and examination of these data sets in the region of the known T/BR fields increases our ability to define the fault systems that promoted the development of these two T/BR fields.

The fault systems that controlled the development of the T/BR Glodes Corners Road Field and the Muck Farm Field have been debated since the fields were discovered. Beardsley (1999, 2001) suggested that the location of the Glodes Corners Road Field was controlled by easterly-trending Iapetan rift faults. Smith (Smith and Nyahay, 2003, 2005; Smith et al., 2003, 2004) maintained that the two fields developed as riedel shears between two NW-striking tear faults. The seismic reflection interpretations in the present study, coupled with aeromagnetics, gravity, and lineaments from remotely sensed imagery, resolve some of these issues.

The eastern termination of both the Glodes Corners Road Field and the Muck Farm Field is a major NNE-striking fault system, the Keuka Lake Fault System. This system has several parallel branches, including the West and East Branch Keuka Lake faults. These faults are inferred from extremely linear aeromagnetic gradients and a coincident gravity gradient. EarthSat (1997) lineaments are also coincident with the proposed fault, and Murphy (1981), in a well log analysis, recognized the fault in Devonian units. The aeromagnetic gradient implies that this fault extends into Precambrian basement.

The possible faults controlling the western termination of the two fields demand a more complicated interpretation. The western termination of the Glodes Corners Road Field in 2001 was at another NNE-trending aeromagnetic gradient. However, the western extent of the Muck Farm Field in 2001 was not this NNE-trending gradient, but a WNW-trending gradient. Since that time, the fields were extended westward; the trends of the fields changed, and the western terminations of both fields now occur outside the overflight area for the aeromagnetic survey. Taken together, however, the western terminations form a WNW trend (Figures 3.7-6 [TR #9] and 3.7-8 [TR #9]). Older magnetic data (see Jacobi, 2002) indicate that the present western terminations occur where both NNE and NW-striking aeromagnetic gradients occur, as well as similarly trending Landsat lineaments (EarthSat, 1997).

The seismic reflection interpretation across the Glodes Corners Road Field shows that at the location of the seismic shot line, most of the T/BR graben offset is in the Black River; the overlying Trenton (top) shows minimal offset. However, the model of the Glodes Corners Road

Field based on well logs and presented by Beardsley (1999, 2001) clearly shows that at the location of the wells, the graben extends up through the Trenton, and in fact the Trenton (top) shows more offset than the underlying Black River. This contrast in structural styles along strike argues strongly for compartmentalization within the overall Glodes Corners Road Field. Such compartmentalization could indicate small-scale riedel shears with rhombochasms at an (low) oblique angle to the general E-strike of the Glodes Corners Road Field. It could also indicate that the E-striking graben is highly segmented from initial linked fault segments, with the link locations controlled by pre-existing cross-structure, as suggested by the NNE-trending aeromagnetic gradients that cross the field (e.g., Figures 3.7-3 [TR #8] and 3.7-6a [TR #8]). What seems unlikely is the model that the east trend itself is a riedel shear between two northwesterly trending faults. The data presented here indicates that the east ends of both fields terminate against a NNE-striking fault system, and the west terminations are variously against NNE-and NW-trending features.

3.9.4 Seismic Interpretation and Taconic Fault Trends

The four seismic lines we reprocessed, as well as additional proprietary lines in the region, all showed T/BR structures. On all four lines, obvious T/BR grabens were observed. Many of the border faults for the T/BR grabens extend into Precambrian basement, and show growth fault geometries at the top of the Precambrian. These faults were Iapetan rift faults that were episodically reactivated, including during Taconic (T/BR) times. Some grabens do not show a direct connection to faults in the basement, and show decreased offset downsection, such as the Glodes Corners Road Field and Muck Farm Field. The down-section decrease in fault offset and the lack of an observed fault at depth are consistent with solution collapse features, but an alternative explanation of solution guided by high-level riedel shears above a master fault cannot be rejected by our 2-D seismic line. Based on the parallel EarthSat (1997) lineaments, aeromagnetic gradients and FIDs that all trend ENE in the region of T/BR grabens and reactivated faults, we suggest that the master faults for the grabens trend ENE in the Valois region.

Several faulted anticlines that involve the T/BR, but not overlying Lockport, suggest Taconic compressional shear (transpressional) structures (wrench faulting). These structures may have a different trend than the T/BR grabens, but multiple-oriented lineaments cross the seismic line where these features occur. We are therefore not certain of the trends of these features.

Northerly trending (N to NNE) faults in the region (e.g., the Keuka Lake Fault System and the fault system along the East shore of Seneca Lake) also were active during Taconic times. From the Keuka Lake Fault System, it appears that these cross-strike discontinuities (CSDs) controlled the termination of the T/BR grabens as well as the much higher structural level Alleghanian anticlines. NW-striking faults may also control T/BR terminations (as proposed for the western termination of the Muck Farm Field). The conclusion is that a gridwork of faults was active during the Taconic. Jacobi et al. (2004 a-d) proposed that these multiply-oriented fault systems would behave differently during the various stages of the Taconic Orogeny. For example, the northerly trending faults would be extensional as the continent experienced stress associated with the peripheral bulge, but would be compressional during final collision. The reversal of motion is also proposed for the strike slip faults—the strike slip component along NW-striking faults, for example, would be dextral during peripheral bulge and sinistral during final collision. Thus, the faults comprising the gridwork were probably all active during most of the Taconic, but with reversing senses of motion.

3.9.5 Advanced Seismic Processing

Two T/BR grabens were drilled in the immediate study area; one of these grabens was imaged on one of the presented seismic lines. Both holes were dry, despite angled (deviated) holes (none was drilled horizontally, however). The structures that were drilled were “typical” T/BR grabens, and other experts who have examined the original seismic reflection data have said they would have drilled there also. But the holes were dry. How can one guard against drilling a dry hole in a T/BR graben? One answer is that horizontal drilling obviously assists in this endeavor, since the grabens are so heterogeneous in porosity and dolomitization (as shown in the horizontal core and associated FMI logs in Phase II of this project). Another method is to perform more advanced analyses of the seismic data in the regions of the grabens. As demonstrated by the seismic attribute analyses in this project, the graben where the dry hole was drilled does not show positive seismic attributes for a big T/BR producer. For example, the seismic inversion results show that the dry hole effectively penetrated the near-fault collapse zone, but that the zone was relatively tight, with an AI range of 56,000-57,000 ft/s*g/cc. This high AI level extends laterally to the north and south of the well. These results are consistent with the poor results obtained from the well: no significantly porous dolomite facies (that would be associated with a low AI values from the inversion) were developed there. This type of advanced seismic study may be used to differentiate potentially good T/BR targets from those that have a poor chance of producing.

3.9.6 Soil Gas Analyses

Soil gas analyses at closely spaced intervals show that this technique can be used in an integrative battery of methodologies to separate fracture systems and lineament systems of different origins. The ENE-lineaments and fractures (presumably related to reactivations of Iapetan rift faults that involved Precambrian basement) have a strong soil gas signature, whereas the high structural level features related to an Alleghanian anticline do not. It is apparent from this work and earlier work (e.g., Jacobi and Fountain, 1996) that soil gas anomalies can be used to confirm lineament trends, and to differentiate the different lineament and fracture sets. However, weather plays a critical role in collecting soil gas data. Ground that is saturated from weeks of rain, or conversely, ground that is particularly dry from weeks of draught cannot be used, since in either case the soil gas cannot be measured by the present system. Further, it was planned that soil gas analyses would be collected in small box patterns where it was necessary to determine the trend of a soil gas spike. In the past, these boxes included fallow fields at the side of the road where undisturbed soil could be sampled. However, in the present study area, most fields were tilled, and so the soil gas box patterns could not be accomplished.

3.9.7 Stratigraphy/Structure Contours from Well Logs

When we conducted the well log analyses in 2001, deep well log data were sparse. Consequently, our efforts at structure contours and isopach maps illustrate the slim value of well logs as a major exploration tool in an unexplored region: the well log sparsity essentially precluded well log use as an effective exploration tool. As detailed in the stratigraphy section, the lack of deep wells meant that subtle structure could not be differentiated from general trends, except in already developed fields (e.g., Glodes Corners Road Field). This inability to differentiate is especially true for the T/BR fields, since the total maximum offset can be on the order of 17 m (50 ft) or less—a value that is easily within the "noise" of regional trends if the wells are sparse. However, well log analysis could be used to indicate regions where additional work should be carried out, if wells with dolomitized Black River of Trenton are flagged.

Regional trends in the structure contours and isopach maps of the study area did reveal important structures, but detailed structure in most areas was lacking, and the poor well control commonly resulted in misleading contours in regions where, from other data sets, we knew the actual trend of the structures. We were able to ascertain that the NW-trending major monocline in the Devonian section (that controls the outcrop pattern in central New York State) is a high-structural level feature, restricted to the Silurian salt horizons and above. However, gravity and aeromagnetic anomalies suggest that the monocline is controlled by faults that affect Precambrian basement. These faults must have little regional stratigraphic offset, since the widely spaced wells do not indicate significant regional offset in Ordovician units across the zone where the deep faults must occur.

A well on the east side of Keuka Lake is characterized by anomalous depths to unit tops, including the T/BR. If the anomalous depths are correct, then these depths could indicate an easterly-oriented T/BR graben or NNE-striking fault blocks in the East Branch Keuka Lake fault.

3.9.8 Oriented Horizontal Core

The problems with orienting the core were detailed in Section 2.8. The present orientation of each core section yields a more consistent view of the veins and stylolites than the original orientations. Although there is a remote possibility that we still have the sections mis-oriented, the fact that bedding dip now remains fairly constant throughout the core is satisfying, since bedding dip does not change significantly in the accompanying FMI log for the section of the well where the core was taken. That, plus the consistency of vein and stylolite orientations, makes us fairly confident that the orientations we report here are correct. The second problem is that the core is too short to have a statistical representation of each vein and stylolite set. For example, we only observed one horizontal vein, one intersection between a vertical stylolite and the horizontal vein, and one ENE-striking vein with a rhombochasm (from which to infer relative motion). These low numbers of samples mean that the history we deduced from the core should not be viewed as a precise and exact account; rather, it is probable that this approximation will incur significant revision if more core data become available.

Although the details concerning tying the events observed in the core to a particular origin and orogenic event may change for some of the features as more data become available, the general views provided by this one core are, we believe, fairly robust. First, veins developed early in the unit's history, before horizontal stylolites were generated. Since horizontal stylolites form during early loading, these early veins, some of which trend ENE, indicate that the Black River was being tectonized during peripheral bulge time—i.e., the graben boundary fault was active during (and soon after) the deposition of the Trenton/Black River. Further, sense-of-motion inferred from the rhombochasm along the ENE-trending vein is consistent with a peripheral bulge stress field proposed by Jacobi et al (2003, 2004 a-d; Fig. 3.9-4 [TR #9]), and unlike that proposed for later Taconic closure (Fig. 3.9-5 [TR #9]). The syndepositional faulting is also consistent with the growth fault geometry observed in the seismic data for this interval and in the outcrop data from the Mohawk Valley (e.g., Jacobi and Mitchell, 2002).

Vertical stylolites cut both horizontal stylolites and a horizontal vein. Because a horizontal vein indicates a period of unloading, the vertical stylolites probably formed during a later orogenic phase. The strike of the vertical stylolites (NE to ENE) suggests a northwesterly-directed $\sigma_{\square}$, probably related to the Alleghanian orogeny, but other explanations cannot be totally dismissed such as a local reorientation of the stress field, which would mean that the stylolites may have developed during other orogenies (Salinic, Acadian). Additional ENE- and WNW-striking veins formed both before and after the formation of the vertical stylolites (and after the horizontal stylolites).

Some of the vein sets have a very long history. For example, the ENE- and WNW-striking veins formed before the horizontal stylolites, after the horizontal and before the vertical stylolites, and after the vertical stylolites. The same orientation of veins formed during two, possibly three or more orogenic phases. This repeating pattern dramatically illustrates the importance of the reactivation along these faults—every orogenic phase reactivated some of the faults, as confirmed in the seismic data.

Thick anthraxolite in the horizontal stylolites may suggest these stylolites were migration pathways for maturing hydrocarbon. If the anthraxolite is not entirely *in situ* (as we believe, based on the volume of the material in some of the stylolites), then the migration of the hydrocarbon must postdate the stylolite formation (since $\sigma_{\square}$ would have been vertical, and the forming stylolite would have closed), and most likely have occurred during a time of local unloading, when the horizontal stylolite could be open. Although this seems counterintuitive, since the hydrocarbon is being heated in most models by burial, two alternatives are possible. The hydrocarbon migrated updip from a site of burial to this region that was already uplifting, or the hydrothermal fluids locally matured the hydrocarbons.

4.0 CONCLUSIONS

The objectives for this research project were to demonstrate the efficacy of integrated techniques in order to determine the presence and trend of deep fracture plays. The research project was specifically aimed at the T/BR grabens in the New York State portion of the Appalachian Basin, where the largest gas wells drilled in 2004 and 2005 onshore USA are located**.** However, the methodology tested here can well be applied to similar plays in other basins. By developing this demonstration project, the second objective of the project was realized: to define characteristics of the structure in the study region.

The Seneca Lake Swath and Transect clearly demonstrated the value of our integrative techniques. Landsat lineaments (EarthSat, 1997) are oriented in three directions in the swath, East, East-northeast, and North. By integrating aeromagnetics with the lineaments, it is apparent that the N-trending and especially the ENE-trending Landsat lineaments are parallel and, in some cases, coincident with aeromagnetic gradients. These Landsat lineaments thus probably represent structure that extends from Precambrian basement to the surface. In contrast, an E-trending Landsat lineament bundle crosses an aeromagnetic anomaly at an oblique angle. This set of lineaments is therefore thought to represent structure that is not related directly to Precambrian basement. In terms of T/BR deep reservoirs and Alleghanian anticlinal shallow reservoirs, this analysis alone suggests that T/BR grabens would be oriented along the bundle of ENE-trending lineaments, whereas the shallow structural level reservoirs of the Alleghanian anticlines would be located along the E-trending lineaments. The ENE-trend of T/BR fields in the study area is confirmed by more recently developed T/BR fields 8 km to 16 km (5-10 mi) south of the study area. There grabens are located along ENE-trending bundles of EarthSat (1997) lineaments.

Fracture analysis of detailed outcrop structure data confirmed the lineaments. The only regions on the Seneca Lake Transect (which is about 32 km long) that exhibited ENE-tending FIDs are where the ENE-trending Landsat lineament bundles occur. Similarly, where E-striking FIDs occur is exactly where an E-trending Landsat lineament bundle passes through the swath. The fracture analyses showed that the two directions have different histories. The ENE-striking fractures have a reactivation history—some developed before the main Alleghanian northerly-directed stress in this area (that resulted in cross-strike fractures), whereas other ENE-striking fractures developed after that time. The multiple-aged ENE-striking fractures are consistent with the multiple reactivations of presumed ENE-striking faults observed in seismic reflection data. In contrast to the ENE-striking fractures, the E-striking FIDs postdate the Alleghanian development of the cross-strike fractures. Finally, the swath also exhibits N-striking FIDs along its length, and these N-striking FIDs are consistent with N-trending Landsat lineaments and with faults proposed from surface stratigraphy and from seismic data. All three lineament trends were also confirmed, both in trend and location, by structure contours constructed on outcropping Devonian units by Bradley et al. (1941).

Soil gas analyses were also consistent with the fracture and lineament analyses. The number of ethane "spikes" on the Seneca Lake Transect coincided with ENE-striking FIDs and EarthSat's (1997) ENE-trending Landsat lineament bundle. Soil gas can be used in areas without outcrop to confirm that a particular lineament is related to structure, and here, at least, can be used to differentiate E- from ENE-striking structures.

A 2-D seismic reflection profile in the Seneca Lake swath confirmed the inferences gained from the integrative techniques discussed above. First, the E-striking FIDs and Landsat lineaments occur above the Alleghanian Firtree Anticline, a well known, well mapped E-striking anticline located in the swath. The ENE-trending lineaments and FIDs are located above faults that extend from Precambrian basement up into the Siluro-Devonian section. These faults have T/BR grabens developed along them. Additional faults are observed on the seismic line with an array of fault timings. Some are Iapetan rift faults only, others were active through Black River time, whereas others were active through Trenton and post Trenton Taconic times. There are many more faults on the seismic line than lineaments; we assume that the ENE-striking lineament bundle reflects the faults and fractures that extend up high into the section, and do not necessarily represent the deepest faults with no significant shallower counterpart (as observed on the seismic reflection line). The 2-D seismic line also crossed a fault that may be almost parallel to the seismic line. This fault could be the N-striking fault hypothesized from the stratigraphic offset and N-striking FIDs, Landsat lineaments and aeromagnetic gradients.

Finally, surface stratigraphy mapping by us and others showed that surface structures trend in exactly the same orientations and locations as the EarthSat (1997) lineaments. That all data sets from the Seneca Lake Swath and Transect provided consonant data is noteworthy; there are no conflicting data for the Seneca Lake Swath.

The Cayuga Lake Swath and Transect confirmed the general conclusions from the Seneca Lake Swath, but revealed serious qualifications. For example, NNW- to NW-trending lineaments are almost non-existent in the EarthSat (1997) data set, whereas FIDs in those directions are common. Lineament analysis on images from different satellite platforms and different processing techniques found that different images can promote better lineament identification (including NW- and NNW-trending lineaments) than the Landsat images used by EarthSat (1997). Detailed analyses of fracture FIDs and lineaments in the Cayuga Lake Swath showed 1) that EarthSat (1997) lineaments may not be close (within 250-500m) to outcrops with appropriate FIDs, and 2) that there are many more FIDs than lineaments. Thus, the EarthSat (1997) lineament analysis can provide a view of the general structural framework, but the lack of certain lineaments may not indicate the lack of similarly oriented FIDs. Both the surface structure and the seismic line showed more faults and more FIDs than lineaments.

In summary, although the EarthSat (1997) lineaments on the Seneca Lake Swath are exceptionally consistent with surface structure, the Cayuga Lake Swath shows that lineaments may be relatively distant from sites with appropriately oriented FIDs. Thus, a particular lineament should not be assumed to represent the exact location of a FID or fault (within 250-500 m), unless the lineament can be groundtruthed by one of the techniques demonstrated here. Nevertheless, lineament patterns, especially those from the more recent satellite platforms and processing techniques (as demonstrated herein) can describe the fracture FIDs necessary for fracture play development, and if a particular lineament is groundtruthed, it can reveal the exact trend and maximum along-strike extent of the fracture trend (as seen on the Seneca Lake transect).

The advanced seismic analyses showed that standard seismic processing packages can be utilized to significantly enhance the understanding of the seismic reflection data. Traditional interpretation of seismic lines can easily identify T/BR grabens that are potential reservoirs, but the techniques demonstrated in this project show that advanced analysis can be used to predict the porosity in the structure. For example, a dry hole was drilled in one of the grabens identified on the Seneca Lake Swath. The seismic analysis showed that although the hole did penetrate the target (fault zone and graben), this target had low porosity, unlike other fault zones.

In addition to demonstrating the effectiveness of these integrated techniques in defining probable trends of fracture plays, including the T/BR, the data also provided insights on the structure of the T/BR fields. For example, we found that the discovery fields are terminated on the east at a northerly trending Precambrian fault system that was episodically reactivated, and now extends up through at least the Devonian Onondaga, and perhaps to the surface. Similarly, the T/BR grabens in the study may transfer along northerly-striking faults, such as the fault along the east side of Seneca Lake. Similarly, the newer T/BR fields south of the study area also terminate on the east along a northerly-trending bundle of EarthSat (1997) lineaments that probably represent a fault system. The western terminations of the discovery fields were originally at N and NW-trending structures, but extensions of the fields now terminate on NW-trending structures. The seismic line across the Glodes Corners Road Field shows little offset in the Trenton, but the model from Beardsley (1999) shows significant offset on the Trenton. We suggest that this difference is a reflection of compartmentalization within the field, and that at least some of the transfer zones across the segments were localized by pre-existing basement fault systems that can be inferred from aeromagnetic gradients.

Phase II of the research project was intended to verify that the integrated methodologies could actually predict the location of a T/BR graben. Bundles of ENE-trending EarthSat (1997) lineaments occur south of the study area, similar to those in the study area that we propose indicate the trend of T/BR grabens. The ENE-trending lineaments south of the study area mark recently developed T/BR fields. We retrieved a horizontal, oriented core from the Black River in one of these fields that extend along Landsat lineaments. Proprietary seismic data showed that the core was taken in a T/BR graben. We characterized and measured 397 geological features in the oriented horizontal core, including 211 veins and 81 stylolites. The cross-cutting/abutting relationships of the veins and stylolites were established, as were the slip directions along veins from 15 rhombochasm kinematic indicators. These data established that the dolomitic Black River unit has undergone several episodes of reactivation, with multiple times of vein development and stylolite growth during multiple orogenic phases and/or orogenies.

Veins developed early in the history of the Black River, before horizontal stylolites were generated. Since horizontal stylolites form during early loading, these early veins, some of which trend ENE parallel to the general lineament and graben orientation, indicate that the Black River was being tectonized during the Laurentian continental response to peripheral bulge stresses—i.e., the graben boundary fault was active during (and soon after) the deposition of the Trenton/Black River. The sense-of-motion along the ENE-trending vein is consistent with a peripheral bulge stress field.

A horizontal vein indicates that vertical unloading separates sets of veins, and suggests that at least two orogenic times have promoted vein development. Vertical stylolites cut both the horizontal vein and the early horizontal stylolites. Because the horizontal vein indicates a period of unloading, the vertical stylolites formed during a later orogenic phase. The strike of the vertical stylolites (NE to ENE) suggests a northwesterly-directed $\sigma_{\square}$, perhaps the Lackawanna Phase of the Alleghanian orogeny. A less likely, but possible scenario, is that the Salinic or Acadian stress field was locally reoriented into a NW trend.

Some of the vein sets have a very long history. For example, the ENE- and WNW-striking veins formed before the horizontal stylolites, after the horizontal stylolites and before the vertical stylolites, and after the vertical stylolites. Thus, the same orientation of veins formed during two, possibly three or more orogenic phases. This repeating pattern dramatically illustrates the importance of the reactivation along these faults—every orogenic phase reactivated some of the faults, as confirmed in the seismic data. The NNE-, N-, and WNW-striking veins may reflect cross-strike structural features (e.g., transfer zones) or in some cases riedel shears along the general graben trend.

Although the core does not exhibit significant zones of high porosity, rubble zones and fault zones observed on an accompanying FMI log suggest that the gas that made this well a good producer was sourced in the fault zones, not in matrix porosity. These fault zones do not exhibit significant veining on any of the rubble clasts. Thick anthraxolite in the horizontal stylolites may suggest these stylolites were a migration pathway for maturing hydrocarbon. If the anthraxolite is not entirely *in situ*, then the migration of the hydrocarbon must postdate the stylolite formation, and most likely have occurred during a time of local unloading. We suggest episodic hydrocarbon migration during several orogenies may have also contributed to the present hydrocarbon reservoirs.

In summary, out techniques identified and mapped both deep and shallow structure, partly because the deep structures have been episodically reactivated so that fractures associated with the structures extend (near) to the surface. A test of our techniques predicts a T/BR field from which we retrieved a Black River core that displays several periods of vein development.
The methodology employed here are easily transportable to other fracture prospective targets both in the Appalachian Basin and other basins worldwide.

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FIGURE CAPTIONS

FIGURE 1.1-1a. **General Location Map of Study Area on a Structure Contour Map of Top of Precambrian in the Appalachian Basin**

White shaded area in central New York indicates location of Figure 1.1-1B. Structure contours after Shumaker (1996).

FIGURE 1.1-1b. **General Location Map of Study Area.**

Four proprietary seismic lines and aeromagnetics were interpreted for this project within the yellow box. In order to preserve the proprietary nature of the seismic interpretation, the actual shot point locations of the seismic lines are not shown. Location of map shown in Figure 1.1-1A.

FIGURE 1.2-1. **Structure Contour Map in Seneca Lake Region.**
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 1.2-2. **Proposed Faults in the Northern Appalachian Basin of New York State.**
Figure after Jacobi (2002).

FIGURE 1.2-3. **Cross Section of the Glodes Corners Road Field.**
Section is based on well logs. After Beardsley (1999, 2001), from Jacobi et al. (2006d).

FIGURE 2.1-1. **Field Areas (Swaths) for Fracture Study.**
Larger font text indicates names of 7.5' topographic quadrangles, whereas boxes with smaller font text indicate place names.

FIGURE 2.1-2. **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 2.1-3. **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 2.1-4. **Location of N-S Seneca Lake Transect for ENE- and E-Striking Fractures.**
Transect displayed in Figure 3.1-8. Sites were extrapolated to this transect in order to construct Figure 3.1-8.

FIGURE 2.1-5. **E- and ENE-Striking Fracture Frequency at Sites Extrapolated (on an ENE-Strike) to a N-S Seneca Lake Transect**.

FIGURE 2.1-6. **E-Striking Fracture Frequency at Sites Extrapolated (on an E-Strike) to a N-S Seneca Lake Transect**.

FIGURE 2.1-7. **Cayuga Lake Transect Location Map.**
Orange line indicates location of Cayuga Lake Transect shown in Figures 3.1-68 and 69. Small numbers indicate outcrop locations. Red boxes are inserts that are enlarged in figures 3.1-24 to 3.1-43. Green lines are Landsat lineaments from EarthSat (1997).

FIGURE 2.4-1. **Location Map of Interpreted Seismic Lines.**
One proprietary seismic line is located in each of the four swaths. In order to preserve the proprietary nature of the seismic interpretation, the exact shot point locations of the seismic lines are not shown

FIGURE 3.1-1. **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. (2002) and Jacobi et al. (2002a, b).

FIGURE 3.1-2. **Widely-Spaced NNW- and NNE-Striking Fractures.**
One-lane bridge in background provides approximate scale. Location of Figure 3.1-2 shown in Figure 3.1-3. From Lugert et al. (2002) and Jacobi et al. (2002a, b).

FIGURE 3.1-3. **Index Map Showing Locations of Figures With Photographs.**

FIGURE 3.1-4. **ENE-Striking FIDs.**
Locations shown in Figure 3.1-3. After Lugert et al. (2002) and Jacobi et al. (2002a, b).

FIGURE 3.1-5**. NNW-Striking FIDs. Locations shown in Figure 3.1-3.**
After Lugert et al. (2002) and Jacobi et al. (2002a, b).

FIGURE 3.1-6. **N-Striking Fracture With Dextral Motion.**

To discriminate between strike slip offset and a normal abutting relationship of the E-striking fracture, an arbitrary standard was set that three “abutting” fractures had to show equal (or nearly equal) offset across the “master” fracture in order for the “master” fracture to be considered a fracture along which strike-slip motion had occurred. Thus, in this case, at least two more fractures adjacent to the one shown displayed the same magnitude and sense of offset as the one in the photograph. Location shown in Figure 3.1-3. From Lugert et al. (2002) and Jacobi et al. (2002a, b).

FIGURE 3.1-7. **Index Map Showing Locations of Map Enlargements East of Seneca Lake for Modified Rose Diagrams.** Labeled boxes are shown in figures 3.1-9 to 3.1-20. After Lugert et al. (2002) and Jacobi et al. (2002a, b).

FIGURE 3.1-8. **N-S Seneca Lake Transect Displaying Fracture Frequency of ENE- and E-Striking Fractures.**
Location of transect shown in Figure 2.1-4. Values are averaged in a 1 km window along the transect from all projected sites. After Lugert et al. (2002) and from Jacobi et al. (2002a, b).

FIGURE 3.1-9. **Enlargement #9 East of Seneca Lake with Modified Rose Diagrams.** Explanation for modified rose diagrams in Figure 2.1-2. Map location shown in Figure 3.1-7. After Lugert et al. (2002) and Jacobi et al. (2002a, b).

FIGURE 3.1-10. **Enlargement #10 East of Seneca Lake with Modified Rose Diagrams.** Explanation for modified rose diagrams in Figure 2.1-2. Map location shown in Figure 3.1-7. After Lugert et al. (2002) and Jacobi et al. (2002a, b).

FIGURE 3.1-11. **Enlargement #11 East of Seneca Lake with Modified Rose Diagrams.** Explanation for modified rose diagrams in Figure 2.1-2. Map location shown in Figure 3.1-7. After Lugert et al. (2002) and Jacobi et al. (2002a, b).

FIGURE 3.1-12. **Enlargement #12 East of Seneca Lake with Modified Rose Diagrams.** Explanation for modified rose diagrams in Figure 2.1-2. Map location shown in Figure 3.1-7. After Lugert et al. (2002) and Jacobi et al. (2002a, b).

FIGURE 3.1-13. **Enlargement #13 East of Seneca Lake with Modified Rose Diagrams.** Explanation for modified rose diagrams in Figure 2.1-2. Map location shown in Figure 3.1-7. After Lugert et al. (2002) and Jacobi et al. (2002a, b).

FIGURE 3.1-14. **Enlargement #14 East of Seneca Lake with Modified Rose Diagrams.** Explanation for modified rose diagrams in Figure 2.1-2. Map location shown in Figure 3.1-7. After Lugert et al. (2002) and Jacobi et al. (2002a, b).

FIGURE 3.1-15. **Enlargement #15 East of Seneca Lake with Modified Rose Diagrams.** Explanation for modified rose diagrams in Figure 2.1-2. Map location shown in Figure 3.1-7. After Lugert et al. (2002) and Jacobi et al. (2002a, b).

FIGURE 3.1-16. **Enlargement #16 East of Seneca Lake with Modified Rose Diagrams.** Explanation for modified rose diagrams in Figure 2.1-2. Map location shown in Figure 3.1-7. After Lugert et al. (2002) and Jacobi et al. (2002a, b).

FIGURE 3.1-17. **Enlargement #17 East of Seneca Lake with Modified Rose Diagrams.** Explanation for modified rose diagrams in Figure 2.1-2. Map location shown in Figure 3.1-7. After Lugert et al. (2002) and Jacobi et al. (2002a, b).

FIGURE 3.1-18. **Enlargement #18 East of Seneca Lake with Modified Rose Diagrams.** Explanation for modified rose diagrams in Figure 2.1-2. Map location shown in Figure 3.1-7. After Lugert et al. (2002) and Jacobi et al. (2002a, b).

FIGURE 3.1-19. **Enlargement #19 East of Seneca Lake with Modified Rose Diagrams.** Explanation for modified rose diagrams in Figure 2.1-2. Map location shown in Figure 3.1-7. After Lugert et al. (2002) and Jacobi et al. (2002a, b).

FIGURE 3.1-20. **Enlargement #20 with Modified Rose Diagrams.** Explanation for modified rose diagrams in Figure 2.1-2. Map location shown in Figure 3.1-7. After Lugert et al. (2002) and Jacobi et al. (2002a, b).

FIGURE 3.1-21. **Location of Tully Transect Along Seneca Lake in Figure 3.1-22.** Geological cross-section along the transect shown in Figure 3.1-22. Transect location also shown in Figure 1.2-1.

FIGURE 3.1-22a. **Geological Cross-section of the Tully Formation.** Location shown in Figure 3.1-21.

FIGURE 3.1-22b. **Enlargement of the Northern Portion of the Tully Transect Along Seneca Lake.** Note that the apparent dips for the cross-section that were measured from outcrops are consistent with the general dip inferred from correlations among the outcrops. Thus, a fault is not necessary in this part of the transect to explain the large differences in site elevations of the Tully. See Figure 3.1-22a for location.

FIGURE 3.1-22c. **Enlargement of the Southern Portion of the Tully Transect Along Seneca Lake, Fold Alternative**. Note that the apparent dips for the cross-section that were measured from outcrops are consistent with the general dip inferred from correlations among the outcrops. Thus, a fault is also not necessary in this part of the transect to explain the large differences in site elevations of the Tully. See Figure 3.1-22a for location.

FIGURE 3.1-22d. **Enlargement of the Southern Portion of the Tully Transect Along Seneca Lake, 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 3.1-22a for location.

FIGURE 3.1-23. **Location Map for Field Sites and Insets that Display Modified Rose Diagrams of the Cayuga Lake Swath.** Green lineaments are Landsat lineaments from EarthSat (1997).

FIGURE 3.1-24. **Inset A with Modified Rose Diagrams of the Cayuga Lake Swath.**

For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-25. **Inset B with Modified Rose Diagrams of the Cayuga Lake Swath.** For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-26. **Inset C with Modified Rose Diagrams of the Cayuga Lake Swath.** For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-27. **Inset D with Modified Rose Diagrams of the Cayuga Lake Swath.** For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-28. **Inset E with Modified Rose Diagrams of the Cayuga Lake Swath.** For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-29. **Inset F with Modified Rose Diagrams of the Cayuga Lake Swath.** For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-30. **Inset G with Modified Rose Diagrams of the Cayuga Lake Swath.** For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-31. **Inset H with Modified Rose Diagrams of the Cayuga Lake Swath.** For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-32. **Inset I with Modified Rose Diagrams of the Cayuga Lake Swath.** For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-33. **Inset J with Modified Rose Diagrams of the Cayuga Lake Swath.**

For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-34. **Inset K with Modified Rose Diagrams of the Cayuga Lake Swath.** For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-35. **Inset L with Modified Rose Diagrams of the Cayuga Lake Swath.** For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-36. **Inset M with Modified Rose Diagrams of the Cayuga Lake Swath.** For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-37. **Inset N with Modified Rose Diagrams of the Cayuga Lake Swath.** For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-38. **Inset O with Modified Rose Diagrams of the Cayuga Lake Swath.** For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-39. **Inset P with Modified Rose Diagrams of the Cayuga Lake Swath.** For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-40. **Inset Q with Modified Rose Diagrams of the Cayuga Lake Swath.** For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-41. **Inset R with Modified Rose Diagrams of the Cayuga Lake Swath.** For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-42. **Inset S with Modified Rose Diagrams of the Cayuga Lake Swath.**

For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-43. **Inset T with Modified Rose Diagrams of the Cayuga Lake Swath.**
For location, see Figure 3.1-23. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half (see Figure 2.1-2).

FIGURE 3.1-44. **Location Map for Field Sites and Combined Data Maps in the Cayuga Lake Swath**.
Green lineaments are Landsat lineaments from EarthSat (1997). The Northern, Central, and Southern map areas are shown in figures 3.1-45, 3.1-46, and 3.1-47, respectively.

FIGURE 3.1-45. **Northern Combined Map in the Cayuga Lake Swath.**
Although all sites are shown, the map displays rose diagrams for only fracture intensification domains (FIDs). See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams. Solid green lineaments are Landsat lineaments from EarthSat (1997) that are confirmed by nearby FIDs. See Figure 3.1-44 for location of figure.

FIGURE 3.1-46. **Central Combined Map in the Cayuga Lake Swath.**
Although all sites are shown, the map displays rose diagrams for only fracture intensification domains (FIDs). See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams. Solid green lineaments are Landsat lineaments from EarthSat (1997) that are confirmed by nearby FIDs. See Figure 3.1-44 for location of figure.

FIGURE 3.1-47. **Southern Combined Map in the Cayuga Lake Swath.**
Although all sites are shown, the map displays rose diagrams for only fracture intensification domains (FIDs). See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams. Solid green lineaments are Landsat lineaments from EarthSat (1997) that are confirmed by nearby FIDs. See Figure 3.1-44 for location of figure.

FIGURE 3.1-48. **Inset A Display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-45. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-49. **Inset B Display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-45. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the

lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-50. **Inset C display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-45. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-51. **Inset D Display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-45. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-52. **Inset E Display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-45. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-53. **Inset F Display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-45. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-54. **Inset G Display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-45. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-55. **Inset H Display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-46. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-56. **Inset I Display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-46. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-57. **Inset J Display of FIDs in the Cayuga Lake Swath.**

For location, see Figures 3.1-44 and 3.1-46. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-58. **Inset K Display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-46. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-59. **Inset L Display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-46. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-60. **Inset M Display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-46. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-61. **Inset N Display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-46. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-62. **Inset O Display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-46. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-63. **Inset P Display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-47. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-64. **Inset Q Display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-47. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-65. **Inset R Display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-47. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-66. **Inset S Display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-47. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-67. **Inset T Display of FIDs in the Cayuga Lake Swath.**
For location, see Figures 3.1-44 and 3.1-47. Modified rose diagrams show fracture frequency in the upper half and fracture intersection relationships in the lower half. See Figure 2.1-2 for explanation of the lower semi-circle on the rose diagrams.

FIGURE 3.1-68. **Transect on West Side of Cayuga Lake that Compares E-striking Fracture Frequency to E-striking Landsat Lineaments from EarthSat (1997).**
For location of transect, see Figure 2.1-7.

FIGURE 3.1-69. **Transect on the West Side of Cayuga Lake that Compares ENE-Striking Fracture Frequency to ENE-Striking Landsat Lineaments from Earthsat (1997).**
For location of transect, see Figure 2.1-7.

FIGURE 3.2-1. **Aspect of Topographic Slopes from DEM in the Seneca Lake Region.**
Pixel resolution is 10m. (Flat gray region in central part of figure is Seneca Lake)

FIGURE 3.2-2. **Standard Deviation of Topographic Slopes from DEM.**
Region overlaps northern part of Figure 3.2-1. Seneca Lake is shown in grey at the extreme upper left. Arrow indicates ENE-trending lineament. Pixel resolution is 10m.

FIGURE 3.2-3. **EarthSat (1997) Landsat Lineaments.**
Green box and green lineaments are in the aeromagnetic study area; these lineaments are discussed in the text.

FIGURE 3.2-4. **EarthSat (1997) Landsat Lineaments with T/BR Fields.**
Easterly trending red blobs indicate the extent of T/BR fields in 2001 (GC= Glodes Corners Road Field; MF = Muck Farm Field). Purple blobs represent selected T/BR fields in 2004.

FIGURE 3.2-5a. **ASTER Principal Component Image.**
Region surrounds Seneca Lake (on left) and Cayuga Lake (on right). After Drechsel et al. (2004) and Cruz et al. (2005).

FIGURE 3.2-5b. **ASTER Principal Component Image with Identified Lineaments (in white).**
Region same as Figure 3.2-5a. After Drechsel et al. (2004) and Cruz et al. (2005).

FIGURE 3.2-6a. **Fused ASTER and Landsat Image.**
After Drechsel et al. (2004) and Cruz et al. (2005).

FIGURE 3.2-6b. **Fused ASTER and Landsat Image with Lineaments.**
After Drechsel et al. (2004) and Cruz et al. (2005).

FIGURE 3.2-7. **Seneca Lake Contrast Values for all Fracture Frequency Groups and all Lineament Groups.**
After Drechsel et al. (2004) and Cruz et al. (2005).

FIGURE 3.2-8. **Cayuga Lake Contrast Values for all Fracture Frequency Groups and all Lineament Groups.**
After Drechsel et al. (2004) and Cruz et al. (2005).

FIGURE 3.2-9a. **Cartoon Indicating which Satellite Image and Processing Technique Resulted in the Peak Contrast Value for each Orientation and Fracture Frequency in the Seneca Lake Swath.**
After Drechsel et al. (2004) and Cruz et al. (2005).

FIGURE 3.2-9b. **Cartoon Indicating which Satellite Image and Processing Technique Resulted in the Peak Contrast Value for each Orientation and Fracture Frequency in the Cayuga Lake Swath.**
After Drechsel et al. (2004) and Cruz et al. (2005).

FIGURE 3.3-1. **Location Map for the Soil Gas Analyses in Figure 3.3-2.**
Note Ovid in the upper part of Figure.

FIGURE 3.3-2. **Soil Gas Analyses Along the N-S Seneca Lake Traverse.**
Soil gas samples were collected and analyzed every 10 m. Anomalous concentrations of soil gas are shown as spikes along the traverse. Spike length is proportional to the soil gas concentration measured at that location. High concentrations show up as bars orthogonal to the traverse. Location shown in figure 3.3-1.

FIGURE 3.3-3. **Seneca Lake N-S Transect.**
In the upper panel, averaged (1 km window) fracture frequency is displayed for E- and ENE-striking fractures. In the middle panel the

number lineaments that trend E and ENE are averaged over 1.32 km. In the lower panel the number of soil gas significant anomalies ("spikes") are averaged over a 1 km window. For location of the transect, see Figure 2.1-4.

FIGURE 3.3-4. **General Location Map for Soil Gas Box Surveys.**

FIGURE 3.3-5. **Location Map for Soil Gas Box Surveys in the Vicinity of Trenton/Black River Wells.**
Location of map shown by the large rectangle in Figure 3.3-4.

FIGURE 3.3-6. **Detailed Inset Displaying the 2002 Soil Gas Surveys in the Vicinity of Trenton/Black River Wells.**
Inset location shown by large rectangle in 3.3-4.

FIGURE 3.3-7. **Soil Gas Traverse 2002-1 (Lodi Center Road).**
Green topographic profile after Delorme. For location of profile, see Figure 3.3-6.

FIGURE 3.3-8. **Soil Gas Traverse 2002-2 (Arden Road).**
Green topographic profile after Delorme. For location of profile, see Figure 3.3-6.

FIGURE 3.3-9. **Soil Gas Traverse 2002-3 (County Rte. 142).**
Green topographic profile after Delorme. For location of profile, see Figure 3.3-6.

FIGURE 3.3-10. **Soil Gas Traverse 2002-4 (West Covert Road).**
Green topographic profile after Delorme. For location of profile, see Figure 3.3-6.

FIGURE 3.3-11. **Soil Gas Traverse 2002-5 (West Bates Road).**
Green topographic profile after Delorme. For location of profile, see Figure 3.3-6.

FIGURE 3.3-12. **Soil Gas Traverse 2002-6 (Arden Road).**
Green topographic profile after Delorme. For location of profile, see Figure 3.3-6.

FIGURE 3.3-13. **Soil Gas Traverse 2002-7 (Lodi Covert Townline Road).**
Green topographic profile after Delorme. For location of profile, see Figure 3.3-6.

FIGURE 3.3-14. **Soil Gas Traverse 2002-8 (Stout Road).**
Green topographic profile after Delorme. For location of profile, see Figure 3.3-6.

FIGURE 3.3-15. **Soil Gas Traverse 2002-9 (West Covert Road).**
Green topographic profile after Delorme. For location of profile, see Figure 3.3-6.

FIGURE 3.3-16. **Soil Gas Traverse 2002-10 (ATV Trail).**
Green topographic profile after Delorme. For location of profile, see Figure 3.3-6.

FIGURE 3.3-17. **Soil Gas Traverse 2002-11 (Case and Townsend Roads).**

Green topographic profile after Delorme. For location of profile, see Figure 3.3-6.

FIGURE 3.3-18. **Soil Gas Traverse 2002-12 (Burdick Road).**
Green topographic profile after Delorme. For location of profile, see Figure 3.3-6.

FIGURE 3.3-19. **Soil Gas Traverse 2002-13 (Burdick Road Ext.).**
Green topographic profile after Delorme. For location of profile, see Figure 3.3-6.

FIGURE 3.3-20. **Detailed Inset of Lodi Center Area Displaying Soil Gas Surveys and Modified Rose Diagrams of Fractures in the Vicinity of the Campion Trenton/Black River Test Well.**
Inset location shown by square in Figure 3.3-5.

FIGURE 3.3-21. **Soil Gas Traverse 2001-B1 (Wilkins Road).**
Green topographic profile after Delorme. For location of profile, see Figure 3.3-20.

FIGURE 3.3-22. **Soil Gas Traverse 2001-B2 (ATV trail**).
Green topographic profile after Delorme. For location of profile, see Figure 3.3-20.

FIGURE 3.3-23. **Soil Gas Traverse 2001-B3 (Seneca Road).**
Green topographic profile after Delorme. For location of profile, see Figure 3.3-20.

FIGURE 3.3-24a. **Soil Gas Traverse FOU-1 (Lodi Center Road).**
Green topographic profile after Delorme. For location of profile, see Figure 3.3-20.

FIGURE 3.3-24b. **Soil Gas Traverse FLO1-1 (E-W Segment-Seneca Road).**
Green topographic profile after Delorme. For location of profile, see Figure 3.3-20.

FIGURE 3.3-24c. **Soil Gas Traverse FLO1-1 (N-S Segment-Bishop Corners Road).** Green topographic profile after Delorme. For location of profile, see Figure 3.3-20.

FIGURE 3.4-1. **Interpretation of Part of Seismic Line #1 Across the Glodes Corners Road Field.**
Note the well-imaged graben in the Trenton/Black River section. Arrows indicate selected paleo-cuestas (hogbacks) onlapped by the basal Cambrian (?) reflector. G indicates Glodes Corners Road graben. For approximate location of seismic line, see Figure 2.4-1 (exact location not revealed to preserve the proprietary nature of the data).

FIGURE 3.4-2. **Interpretation of Part of Seismic Line #1 Across the Muck Farm Field.**

Note the well-imaged graben in the Trenton/Black River section. For approximate location of seismic line, see Figure 2.4-1 (exact location not revealed to preserve the proprietary nature of the data).

FIGURE 3.4-3. **Interpretation of Seismic Line #2.**
Reflector offsets on the various faults are compiled in Table 1 [TR #9]. Note the well-imaged grabens in the Trenton/Black River section (e.g., between faults 5 and 7). Faults S1 to S5 are thrusts in the Firtree Anticline that ramp up from the salt decollement; the salt-cored anticline is observable in the Onondaga reflector. For approximate location of seismic line, see Figure 2.4-1 (exact location not revealed to preserve the proprietary nature of the data).

FIGURE 3.4-4. **Interpretation of Seismic Line #3.**
A possible Trenton/Black River graben is located at "A". For approximate location of seismic line, see Figure 2.4-1 (exact location not revealed to preserve the proprietary nature of the data).

FIGURE 3.4-5. **Interpretation of Seismic Line #4.**
Note the well-imaged grabens in the Trenton/Black River section. For approximate location of seismic line, see Figure 2.4-1 (exact location not revealed to preserve the proprietary nature of the data).

FIGURE 3.5-1. **Sample of Part of Seismic Line 2, Interpreted.**
Line overlaps with Figure 3.5-2. Complete seismic line with shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

FIGURE 3.5-2. **Sample of Part of Seismic Line 2, Interpreted.**
Line overlaps with Figure 3.5-1. Complete seismic line with shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

FIGURE 3.5-3. **Sample of Reflection Strength (Instantaneous Amplitude) Version of Seismic Line 2.**
Complete seismic line with shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

FIGURE 3.5-4. **Sample of Line 2 Flattened at Basement Horizon.**
This flattening emphasizes Paleozoic thickness trends. Complete seismic line with shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

FIGURE 3.5-5. **Sample of Seismic Line 2 Flattened on the Knox Unconformity.**
Complete seismic line with shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

FIGURE 3.5-6. **Sample of Seismic Line 2 Flattened on the Black River.**
Complete seismic line with shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

FIGURE 3.5-7. **Sample of Fault Interpretations Along Seismic Line 2 Superimposed on Reflection Strength Display of Line 2.**
Complete seismic line with shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

FIGURE 3.5-8. **Close-up of a Small Graben Feature, Line 2.**
Shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

FIGURE 3.5-9. **Close-up of a Small Graben Feature, Line 2.**
Shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

FIGURE 3.5-10. **Sample of Reflection Strength Display, Line 2.**
Alternate color display. Complete seismic line with shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

FIGURE 3.5-11. **Close-up, Reflection Strength Display, Line 2**.
Shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

FIGURE 3.5-12. **Close-up Showing Dimming and Thickness Reduction of Black River Horizon, Line 2.**
Shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

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Shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

FIGURE 3.5-14. **Instantaneous Phase Display, Part of Line 2**.
Shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

FIGURE 3.5-15. **Instantaneous Frequency Display, Line 2.**
Shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

FIGURE 3.5-16. **Close-up, Instantaneous Frequency Display, Line 2**.
Shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

FIGURE 3.5-17. **Close-up, Instantaneous Frequency Display, Line 2.**
Shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

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Shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

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Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-21. **Comparison of Logs with Borehole Imagery for the Upper Black River.**
Data from a Black River test well in the study region. Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-22. **Comparison of Well Logs Including Borehole Imagery (FMI Log, Right) with Driller's Log (Left) in a Black River Test Well in the Study Region.**
Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-23. **Comparison of Conventional Well Logs and Image Log in the Middle Black River.**
Data from a Black River test well in the study region. Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-24. **Crossplot of Neutron Porosity Versus Sonic Porosity.**
Data from a Black River test well in the study region. Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-25. **Density Porosity Versus Neutron Porosity**
Data from a Black River test well in the study region. Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-26. **Log Response for the Middle and Upper Black River.**
Data from a Black River test well in the study region. Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-27. **Two Gas Signatures for the Lower Black River.**
Data from a Black River test well in the study region. Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-28. **Gas Signatures Crossplot (Figure 3.5-29) and Image Log of Primarily the Upper Black River.**
Data from a Black River test well in the study region. Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-29. **Gas Signatures in Shaly Section, Lower Black River**.
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FIGURE 3.5-30. **Neutron Porosity Versus True Resistivity for the Trenton and Black River.**
Data from a Black River test well in the study region. Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-31. **Flushed Zone Resistivity (RXO) Versus True Resistivity (HART).**
Data from a Black River test well in the study region. Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-32. **Flushed Zone Resistivity Versus True Resistivity.**
Data from a Black River test well in the study region. Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-33. **Gamma Ray Versus True Resistivity.**
Data from a Black River test well in the study region. Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-34. **Caliper Versus Gamma Ray Plot.**
Data from a Black River test well in the study region. Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-35. **Sample of Line 2, Imported into Hampson-Russell Software**.
Shot point numbers and depths not shown in order to preserve the proprietary nature of the seismic line.

FIGURE 3.5-36. **Synthetic Seismogram Display for a Black River Test Well in the Study Region.**
Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-37. **Initial Acoustic Impedance Model.**
Model based on logs from a Black River test well in the study region, and seismic picks, used for inversion of seismic line 2. Shot points and depths not shown in order to preserve the proprietary nature of the data.

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Shot points and depths and shot points not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-39. **Close-up of Integrated Absolute Amplitude Processing for Part of Seismic Line 2.**
Depths and shot points not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-40. **Close-up of Integrated Absolute Amplitude Processing, Calibrated with Computed Impedance, for Part of Seismic Line 2.**
Depths and shot points not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-41. **Close-up of Inversion Results on Part of Seismic Line 2.**
Data near a Black River test well and to the south. See Figure 3.5-43 for color scale. Depths and shot points not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-42. **Close-up of Inversion Results on Part of Seismic Line 2.**
Data near a Black River test well and to the north. See Figure 3.5-43 for color scale. Depths and shot points not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-43. **Flattened Inversion Results for Part of Seismic Line 2.**
Depths and shot points not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-44. **Inversion Results for Part of Seismic Line 2.**
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FIGURE 3.5-45. **Comparison of Borehole Image Log and Acoustic Impedance Log.**
Data collected at a T/BR test well in the region. Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-46. **Comparison of Borehole Image Log and Acoustic Impedance Log.**
Data from a T/BR test well in the region. Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-47. **Close-up of Inversion Results for Part of Seismic Line 2.**
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FIGURE 3.5-48. **Inversion Results for Part of Seismic Line 2.**

Inversion derived using edited density log. Shot points and depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-49. **Time-Depth Calibration, Acoustic Impedance and Borehole Image Logs, Upper Black River Section.**
Data from one of the T/BR test wells in the region. Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-50. **Time-Depth Calibration, Acoustic Impedance and Borehole Image Logs, Middle Shaly Black River Section.**
Data from one of the T/BR test wells in the region. Depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-51. **Close-up of Inversion Results for Part of Seismic Line 2 with FMI Log and AI overlay.**
Focus is on the porous interval. This part of seismic line 2 is shown in Figure 3.5-48. Shot points and depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.5-52. **Close-up of Inversion Results for Part of Seismic Line 2.**
Log overlay focuses on the middle Black River shaly interval. This part of seismic line 2 is shown in Figure 3.5-48. Shot points and depths not shown in order to preserve the proprietary nature of the data.

FIGURE 3.6-1. **Regional Structure Contour Map: Top of Onondaga**.
Contour interval = 50 ft. (15 m). Red box in center indicates location of Figure 3.6-2.

FIGURE 3.6-2. **Detailed Structure Contour Map: Top of Onondaga.**
Contour interval = 50 ft. (15 m). Location shown as red box in Figure 3.6-1.

FIGURE 3.6-3. **Regional Structure Contour Map: Top of Irondequoit.**
Contour interval = 50 ft. (15 m). Red box in center indicates location of Figure 3.6-4

FIGURE 3.6-4. **Detailed Structure Contour Map: Top of Irondequoit.**
Contour interval = 50 ft. (15 m). Location shown as red box in Figure 3.6-3.

FIGURE 3.6-5. **Regional Structure Contour Map: Top of Trenton.**
Contour interval = 50 ft. (15 m). Red box in center indicates location of Figure 3.6-6.

FIGURE 3.6-6. **Detailed Structure Contour Map: Top of Trenton.**
Contour interval =50 ft. (15 m). Location shown as red box in Figure 3.6-5.

FIGURE 3.6-7. **Regional Structure Contour Map: Top of Black River**.

Contour interval = 50 ft. (15 m). Red box in center indicates location of Figure 3.6-8.

FIGURE 3.6-8. **Detailed Structure Contour Map: Top of Black River.**
Contour interval = 50 ft. (15 m). Location shown as red box in Figure 3.6-7.

FIGURE 3.6-9. **Regional Isopach Map: Onondaga to "F" Salt.**
Contour interval = 20 ft. (6 m). Red box in center indicates location of Figure 3.6-10.

FIGURE 3.6-10. **Detailed Isopach Map: Onondaga to "F" Salt.**
Contour interval = 20 ft. (6 m). Location shown as red box in Figure 3.6-9.

FIGURE 3.6-11. **Regional Isopach Map: "F" Salt.**
Contour interval = 20 ft. (6 m). Red box in center indicates location of Figure 3.6-12.

FIGURE 3.6-12. **Detailed Isopach Map: "F" Salt.**
Contour interval = 20 ft. (6 m). Location shown as red box in Figure 3.6-11.

FIGURE 3.6-13 **Regional Isopach Map: "E" Salt.**
Contour interval = 20 ft. (6 m). Red box in center indicates location of Figure 3.6-14.

FIGURE 3.6-14. **Detailed Isopach Map: "E" Salt.**
Contour interval = 20 ft. (6 m). Location shown as red box in Figure 3.6-13.

FIGURE 3.6-15. **Regional Isopach Map: "E" and "F" Salts.**
Contour interval = 20 ft. (6 m). Red box in center indicates location of Figure 3.6-16.

FIGURE 3.6-16. **Detailed Isopach Map: "E" and "F" Salts.**
Contour interval = 20 ft. (6 m). Location shown as red box in Figure 3.6-15.

FIGURE 3.6-17. **Regional Isopach Map: Onondaga to Irondequoit.**
Contour interval = 20 ft. (6 m). Red box in center indicates location of Figure 3.6-18.

FIGURE 3.6-18. **Detailed Isopach Map: Onondaga to Irondequoit.**
Contour interval = 20 ft. (6 m). Location shown as red box in Figure 3.6-17.

FIGURE 3.6-19. **Regional Isopach Map: Irondequoit to Trenton.**
Contour interval = 20 ft. (6 m). Red box in center indicates location of Figure 3.6-20

FIGURE 3.6-20. **Detailed Isopach Map: Irondequoit to Trenton.**

Contour interval = 20 ft. (6 m). Location shown as red box in Figure 3.6-19.

FIGURE 3.6-21. **Regional Isopach Map: Onondaga to Trenton.**
Contour interval = 20 ft. (6 m). Red box in center indicates location of Figure 3.6-22.

FIGURE 3.6-22. **Detailed Isopach Map: Onondaga to Trenton.**
Contour interval = 20 ft. (6 m). Location shown as red box in Figure 3.6-21.

FIGURE 3.6-23. **Regional Isopach Map: Trenton to Black River.**
Contour interval = 20 ft. (6 m). Red box in center indicates location of Figure 3.6-24.

FIGURE 3.6-24. **Detailed Isopach Map: Trenton to Black River.**
Contour interval = 20 ft. (6 m). Location shown as red box in Figure 3.6-23.

FIGURE 3.7-1. **Total Magnetic Intensity Map.**
Map produced by PRJ

FIGURE 3.7-2. **Reduced to Pole (RTP) Magnetic Map.**
Produced by PRJ

FIGURE 3.7-3. **Horizontal Gradient of RTP Magnetics (HG).**
Produced by PRJ. EBKL = East Branch Keuka Lake gradient.

FIGURE 3.7-4. **Vertical Gradient of RTP Magnetics (VG).**
Produced by PRJ

FIGURE 3.7-5. **Second Vertical Derivative of RTP Aeromagnetics (SVD).**
Produced by PRJ

FIGURE 3.7-6a. **Linear Feature Analyses of RTP Aeromagnetics (LFA).**
Produced by PRJ

FIGURE 3.7-6b. **Linear Feature Analyses of RTP Aeromagnetics (LFA) with Lakes and Selected Gas Fields.**
T/BR fields are the Glodes Corners Road Field (GC) and the Muck Farm Field (MF). Extent of the gas fields is that for 2001. Wayne-Dundee is related to an Alleghanian anticline.

FIGURE 3.7-6c. **Linear Feature Analyses of RTP Aeromagnetics (LFA) with Lakes and Selected Gas Fields.**
T/BR fields are the Glodes Corners Road Field (GC) and the Muck Farm Field (MF). Purple blob indicates the extent of T/BR fields in 2004.

FIGURE 3.7-7. **PRJ Interpretation of Gradients in the Aeromagnetic Field**

FIGURE 3.7-8. **RTP Magnetics and Gas Fields.**
Gas fields are the same as in Figure 3.7-6b and 3.7-6c.

FIGURE 3.7-9a. **Bouguer Gravity and T/Br Fields.**
Gravity contour interval = 5 mgal. Blues are relatively low. T/BR fields same as in Figure 3.7-6b and 3.7-6c. Gravity from Jacobi (2002).

FIGURE 3.7-9b. **Bouguer Gravity, RTP Magnetics and T/Br Fields.**
Gravity contour interval = 5 mgal. Blue contours are relatively low. T/BR fields same as in Figure 3.7-6b and 3.7-6c. Gravity from Jacobi (2002).

FIGURE 3.8-1. **Reassembled, Oriented, Horizontal Core from the Black River in Central New York State.**
Rotation of individual core segments were rotated to match FMI log.

FIGURE 3.8-2. **Porosity and Permeability Determinations of Full Core Segments**.
The upper panel shows porosity measurement, and the lowest panel shows permeability values. The middle panel indicates the type of feature tested, stylolite, porous bedding, vugs, and normal (dense) bedding.

FIGURE 3.8-3. **Orientations of Veins Measured on the Full Core (Before Slabbing).**
Stereonets in upper panels display orientations of veins. Histogram of vein orientations in the lower panel defines the boundaries of the orientation sets (e.g., NE-trending veins strike between 45^0 and 65^0); boundaries of sets based on natural distribution breaks and vein characteristics (e.g., intersection relationships).

FIGURE 3.8-4. **Orientations of Stylolites Measured on the Full Core (Before Slabbing).**
Stereonets in upper panels display orientations of stylolites. Histogram of stylolites orientations in the lower panel defines the boundaries of the orientation.

FIGURE 3.8-5. **Cross-Cutting Plot for all Stylolites and Veins Collected from Full-Diameter Core and Slab.**
The X-axis is the strike of a feature observed to cut another feature and therefore is younger. The Y-axis is the strike of a feature seen to be cut by another feature and therefore older. The symbols show which type of feature is cut and being cut. Clusters defined in the upper left (red and green outlines) wherein the cutting veins trend between 25^0 and 50^0 do not have well defined inverse relationships (wherein the cut features trend between 25^0 and 50^0).

FIGURE 3.8-6. **Sketches of Kinematic Indicators from the Full Core.**
Lines within the rhombochasm indicate crystal growth direction. All features shown here are releasing bends (transtensional rhombochasms). The photo is of feature #112 and shows the geometry of these types of features. The stick diagram in the lower right shows a composite of the sense of offsets observed on

all veins of varying orientation. The red feature is youngest, followed by green, and blue is the oldest. The black features in this composite are of undetermined relative age.

FIGURE 3.8-7. **Sketches of Additional Kinematic Indicators from the Slabbed Core.** Lines within the rhombochasm indicate crystal growth direction. Features A and 9 are restraining bends (zones of transpression) as shown in the upper photo of feature A. The offsets of features B, C, and D were determined by consistent twists as shown in the middle photo of feature B. Feature 112 is a transtensional rhombochasm as illustrated in the lower photo. The offsets of features 14 and E were determined by crystal growth orientations oblique to the vein opening direction. The sketch in the lower right shows a composite of the sense of offsets observed on all veins of varying orientation. Double arrows indicate two features showing the same slip. The red feature is youngest, followed by green, and blue is the oldest. The black features in this composite are of undetermined relative age.

FIGURE 3.9-1. **Structure Contour Map on the Devonian Rhinestreet and Landsat Lineaments.**
Structure from Bradley et al. (1941) and Lineaments from EarthSat (1997).

FIGURE 3.9-2. **Aeromagnetics (RTP), EarthSat (1997) Lineaments and Selected T/BR Gas Fields.**
A) Map shows individual lineaments (in white) and T/BR discovery fields in red (original extent) and more recent extent (purple). B) Map shows overlay of lineament bundles (yellow zones) that probably mark fault systems.

FIGURE 3.9-3. **Landsat Lineaments and Selected Trenton/Black River Fields. Lineaments from EarthSat (1997).**

FIGURE 3.9-4. **Orientation of Structural Features During "Middle" Taconic Times (Before the Laurentian Plate had Jammed the Subduction Zone).**
A) Potential extensional features (normal faults and Mode I fractures) are highlighted that could have formed, or been reactivated, under the stress conditions of continental plate flexure over the peripheral bulge and into the trench. Dashed features are oriented less favorably, but would also have been active if they were pre-existing.
B) Potential strike-slip features (strike slip faults and Mode II fractures) are highlighted that could have formed, or been reactivated, under the stress conditions of continental plate flexure over the peripheral bulge and into the trench. Dashed features are oriented less favorably, but would also have been active if they were pre-existing. Right lateral, NW-striking faults are gray, compared to the bold black of the left lateral faults. The strike slip faults probably experienced oblique slip with a down-to-the-east component of slip. In both cases "A" and "B", the inexact orientation of the trench and the relative convergence between the plates makes these diagrams primarily schematic. CLF = Clarendon-

Linden Fault System, D = Dolgeville Fault, E = Ephrata Fault, EFBZ = Elzevir-Frontenac Boundary Zone, ESA = East Stone Arabia Fault, GL = Galway Lake Fault, HE = Herkimer Fault, HO = Hoffmans Fault, LF = Little Falls Fault, MC = Mother Creek Fault, N = Noses Fault. P = Prospect Fault, S = Sprakers Fault, W = West Stone Arabia Fault After Jacobi et al. 2003. (Block diagram after Bradley and Kidd, 1991)

FIGURE 3.9-5. **Orientation of Structural Features During "Late" Taconic Times (During the Laurentian Plate Jamming the Subduction Zone).**
A) Potential extensional features (Mode I fractures) are highlighted that could have formed, or been reactivated, under the stress conditions during final jamming. Dashed features are oriented less favorably, but would also have been active if they were pre-existing.
B) Potential strike-slip features (strike slip faults and Mode II fractures) are highlighted that could have formed, or been reactivated, under the stress conditions of continental plate flexure over the peripheral bulge and into the trench. Dashed features are oriented less favorably, but would also have been active if they were pre-existing. Right lateral, NE-striking faults are gray, compared to the bold black of the left lateral faults. The strike slip faults probably experienced oblique slip with a down-to-the-east component of slip. In both cases "A" and "B", the inexact orientation of the trench and the relative convergence between the plates makes these diagrams primarily schematic. Abbreviations same as in Figure 3.9-4. After Jacobi et al. (2003). (Block diagram after Bradley and Kidd, 1991).

TABLE CAPTIONS

TABLE 2.8-1. **Core Rotations.**

TABLE 2.8-2. **Observed Breaks in Reassembled Core**.

LIST OF ABBREVIATIONS

AI = acoustic impedance (log)

ASTER = Advanced Spaceborne Thermal Emission and Reflection Radiometer, a satellite-acquired image

Bcf = billion cubic feet

CALI = caliper log

CLF = Clarendon-Linden Fault System

CSD = cross-strike discontinuity

CNR = Columbia Natural Resources

DEM = digital elevation model

DPHI = density porosity

e(t) = energy envelope,

E = East

ENE = East-northeast

ENVI = remote sensing computer program

FID = fracture intensification domain

FMI = formation microimage (well log)

GC = gas chromatograph

GPS = ground-positioning system

GR = gamma ray

HART = computed true resistivity (log)

HG = Horizontal Gradient of RTP Aeromagnetics

HLLD = deep resistivity (log)

HLLS = shallow resistivity (log)

Hz = Herz

IGRF = International geomagnetic reference field

J & A = Jacobi and Agle

L & A = Landsat and ASTER

Landsat TM = Landsat is a series of unmanned earth-orbiting satellites that acquire images, TM = thematic mapper

LFA = Linear Feature Analyses of RTP Aeromagnetics

km = kilometer

m = meter

mi = mile

md = millidarcies

ms = millisecond

MSI = Multi-Shot Surveyors Inc.

MSRG = McGill Seismic Research Group

NPHI = neutron porosity

nT = nanotassels SP???????????

NYS = New York State

md. = millidarcies

p(t) = instantaneous phase trace

PC = Principal Component

PEF = photoelectric factor (log)

PRJ = Pearson, deRidder and Johnson, Inc.

q(t) = quadrature seismic trace or the imaginary part of the seismic trace.

r(t) = real seismic trace

RTP = reduced-to-pole aeromagnetics

RXO = flushed-zone resistivity (log)

S_H = maximum principal compressive horizontal stress

□□□= maximum principal compressive horizontal stress

□□ = maximum principal compressive stress

SP = spontaneous potential (log)

SPHI = sonic porosity (log)

sq. = square

SVD = Second Vertical Derivative of RTP Aeromagnetics

T/BR = Trenton/Black River

TD = touchdown (base of hole)

TWT = two-way travel time

2-D = two-dimensional

UBRFG = University at Buffalo Rock Fracture Group

UK = United Kingdom

VG = Vertical gradient of RTP Aeromagnetics

W = West

X’ = x minutes of latitude or longitude

APPENDIX

AN AEROMAGNETIC INTERPRETATION OF THE FINGER LAKES AREA SOUTH-CENTRAL NEW YORK WITH A NORTHWESTERN EXTENSION

for:
The State University of New York
Buffalo, New York
Subcontract SUNY R93742
DOE/NETL PRDA No DE-RA26-99FT40191

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I. INTRODUCTION

During the period September 1999 to January 2000, Pearson, deRidder and Johnson, Inc. of Lakewood, Colorado, in cooperation with Airmag Surveys Inc. of Philadelphia, Pennsylvania, undertook the acquisition, processing, and interpretation of an aeromagnetic data set over the Finger Lakes area in south-central New York. The project was undertaken by PRJ under a subcontract No. R93742 to the State University of New York at Buffalo as part of a Department of Energy contract DOE/NETL PRDA No. DE-RA26-99FT40191.

The scope of the study included a comprehensive interpretation of the aeromagnetic data of the Finger Lakes survey in both profile and map form to delineate a basement-related, structural framework of the survey area. The delineation of basement-related structural elements as bounding structures on intrabasement lithology blocks and their association with possible basement relief and faulting was the main purpose of the data analysis. The interpretation results were compared with available digital elevation models from the public domain data sets.

The study was extended by the inclusion of a regional aeromagnetic data set to the north and northwest of the Finger Lakes Survey. This data set was purchased by PRJ on behalf of the State University of New York at Buffalo from the Geologic Survey of Canada and is subject to the terms and conditions of the GSC. A regional analysis of both the merged magnetic data and digital elevation models for the larger area was undertaken. As part of the project the development of a map-based Lineament Interpretation Method was undertaken to derive an interpretation tool for improved models of magnetic lineaments. The results of this development, as applied to both the detailed and regional data sets, are included in the study.

This report discusses the data acquisition, processing parameters, and interpretation results obtained and was undertaken under ***PRJ*** job number 0030/2000.

II. SURVEY SPECIFICATION AND DATA PROCESSING

The detailed survey is located in south-central New York State and covers parts of Cayuga, Seneca, Yates, Thompkins, Schuyler and Steuben Counties.

Data acquisition was undertaken by Airmag Surveys Inc. of Philadelphia, Pennsylvania, during the period from September 19, 2000, to October 2, 2000. The survey base of operations was located in Binghamton, New York. Turbulent conditions were a factor during data acquisition, and field operations consisted of 10 flying days and 4 stand-by days. Operations consisted primarily of early morning and late afternoon data acquisition. The survey pilot logs are provided in Exhibit A hereto.

The data were acquired to the following specifications:

Flight line spacing:	¼-mile
Flight line direction:	N-S
Tie line spacing:	1 mile
Tie line direction:	E-W
Ground clearance:	500 ft agl
Sampling rate:	0.25 second (nominally 45 feet)
Line mileage:	
as per survey lay-out:	3,600 miles
as acquired:	3,949 miles

Instrumentation (Air)

Aircraft:	Cessna 320
Magnetometer:	Geometrics G823A Cesium Vapor
Radar altimeter:	Honeywell 8508
Barometric altimeter:	Rosemont 800E18
GPS - system:	Motorola DGPS - Receiver Trimble 2000 AE
Video system:	Panasonic

Instrumentation (Ground)

Base magnetometer:	Scintrex Cesium Vapor
GPS - base:	Motorola DGPS
Acquisition System:	WWV - monitor Hewlett Packard Data Acquisition System

The magnetic and ancillary data were processed according to the following specifications.

a. Navigation data

Motorola GPS data acquired during acquisition were post-flight differentially corrected with the GPS-base station and preliminary flight path maps produced. Final processed DGPS data were merged with the raw acquired data traces.

b. Pre-processing

All merged data traces were edited for completeness and data spikes. The IGRF-correction, based on the 1995 IGRF formula, was applied to the magnetic data trace based on sensor elevation and location for each data point. Diurnal data were IGRF-corrected, based on diurnal station location and elevation. A high-cut filter (< 6 min) was applied to the diurnal data, and the low pass diurnal applied to the IGRF-corrected magnetics as a diurnal correction.

A significant amount of culture-related magnetic responses were present on the data set. Large amplitude anomalies were observed related to built-up areas, such as over the town of Ithaca and, in the southern parts of the survey area radio transmitters are present which produced numerous, spurious high frequency anomalies.

De-culturing of the data was undertaken on a profile by profile basis, and large amplitude, culture-related anomalies, in excess of 10 nT or more, were manually removed from the data and the resulting data gap interpolated by splining.

c. Data leveling

The final, IGRF- and diurnally corrected magnetic data trace was profile- leveled using a DC-level shift which was applied to the profile data to minimize intersection mis-ties. Only minor "herring - boning" was present in the data after this step.

d. Gridding and mapping

The profile-oriented magnetic data derived above was gridded and mapped using the Equivalent Source Gridding methods developed by PRJ. The method employs the computation of a magnetic layer consisting of data points below each profile observation value relative to the elevation of that point. The values of the magnetic layer are determined by iteration to reproduce the observed magnetic values and once this is done, new values can be calculated using the equivalent layer at any desired elevation and grid spacing.

III. DATA SETS OF THE FINGER LAKES SURVEY

The Total Magnetic Intensity map and various derivative maps are part of this report. The following section presents a summary discussion of these maps and their intended uses.

Flight Line Locations

This proprietary data set, overlain on a topographic base map, shows the flight line locations, with line identifiers and fiducials (time-marks) along the profile. Line spacing and locationing were generally well maintained for the survey. Some 10 tie lines and one flight line were flown in segments due to local fog problems. Sufficient overlap between these line segments exists so that no problems during data processing were experienced. Line-end run-in and run-out outside the survey block averaged some 1.5 km, and no short lines are present.

Total Magnetic Intensity (TMI) Maps

The data set is presented as a color contour map with a contour interval of 5 nT and shows a magnetic relief of some 1000 nT across the survey area. The large range of responses is inferred to be indicative of major lithology changes within basement, with strongly positive responses indicative of areas locally containing high susceptibility Precambrian rocks. A dominant area of such positive anomaly patterns is located in the western part of the survey area.

Locally dominant anomaly alignments seem to be areally confined, with NNE-, ENE- and NNW-trending responses prevalent in the western, central and eastern parts of the survey respectively. Noticeable is the presence of a number of high amplitude, circular or semi-circular anomalies throughout the survey block. Most are strongly positive anomalies, up to 860 nT, and it is possible that major intrusions are associated with Precambrian basement. The presence of Cretaceous-Jurassic kimberlites locally in outcrop in the survey area may indicate that some of the intrusive activity may be post-depositional in origin.

Reduced-to-Pole (RTP) Maps of Total Magnetic Intensity

Unlike gravity anomalies that are primarily located over their causative bodies, magnetic anomalies are dependent upon their directions of magnetization and on the direction of the earth’s regional field. Reduction-to-the-Pole filtering removes the directional dependency of the earth’s field and transforms an anomaly into the one that would be observed with vertical magnetization. As a result, reduction to the pole filtering removes asymmetries caused by the non-vertical inducing field and places the anomalies move directly over their causative bodies, thus facilitating the interpretation of the magnetic data set. The Reduction-to-the-Pole operator has shifted the larger magnetic responses northwards as much as 2 km. Additionally, linear features and contacts are better defined. For this study, the earth’s principal magnetic elements that are accounted for in the Reduction-to-Pole filter are:

Total Intensity:	55,221 nT
Declination:	-12.62 W

Inclination: 70 N

The Reduced-to-Pole magnetic data set shows a similar regional magnetic pattern as the Total Magnetic Intensity map. All subsequent data analysis and interpretation procedures were completed on the Reduced-to-Pole data.

Horizontal Gradient (HG) Maps of RTP Magnetics

After the Reduction-to-Pole correction, a magnetic body is spatially more directly associated with the related magnetic response. The maximum gradient of the anomaly slope is located near, or over the body edge. That is, the horizontal gradient operator in map form produces maximum ridges over edges of magnetic basement blocks and faults. In addition, the horizontal gradient highlights linear features, related to contacts, in the data set.

The Horizontal Gradient map is presented with this report both as a color contour map and as two shadowgraphs with NE and NW illumination. Analysis of this data set indicates that very strong gradient anomalies are associated with the many circular or semi-circular magnetic responses, indicative of well-defined susceptibility contacts and the gradient responses related to these contacts dominate the data set. Additionally, differences in anomaly alignment in the various parts of the map are well delineated.

All gradient operators act to some extent as a high-pass filter and the Horizontal Gradient is no exception. In this respect the method is sensitive to shallow or near-surface sources as well as to minor noise-levels in the grids. It is noted that a series of subtle gradient anomalies are present in the southern and central parts of the survey.

Vertical Gradient (VG) Map of RTP Magnetics

The Vertical Gradient (VG), or fall-off rate, of an anomaly is related to the depth and geometry of the causative body. The VG operator attenuates broad, more regional anomalies and enhances local, more subtle magnetic responses, and as such is very sensitive to shallow magnetic source-bodies and contacts.

In the VG maps presented with this report as a color contour map, the large, regional magnetic gradients observed in the RTP map have been effectively attenuated, and individual magnetic responses superimposed upon these gradients are now well delineated. An alignment of anomalies, trending north-northeast in the central part of the survey area, is indicated. The minor Horizontal Gradient anomalies in the southern part of the survey discussed above have also been emphasized in this data set.

Second Vertical Derivative (SVD) of RTP Magnetics

The Second-Vertical-Derivative (SVD), or rate of change of the fall-off rate of an anomaly, primarily emphasizes near-surface or surficial magnetic sources, or any remaining noise-level in the RTP data set. A number of the well-defined circular or semi-circular anomalies outlined on the RTP and VG maps are starting to break up into separate responses and an inordinate number of linear anomalies are seen in the SVD map.

Further analysis of these data indicate that few, if any flight line or tie line oriented anomalies are present, and that the noise-level in the original RTP grid is probably minimal. Comparison of the SVD data set with the topography of the survey area indicates a striking correlation of the SVD anomalies with topographic features in the survey block. This correlation includes the alignment of the anomalies with the larger lakes, as well as responses overlying many of the smaller topographic features in the southern and central parts of the study area. An inescapable conclusion seems to indicate that a measurable magnetic susceptibility contrast is associated with surficial features within the study block.

Linear Feature Analysis (LFA) Map of the RTP Magnetics

As part of the study presented in this report, PRJ undertook the development of a lineament interpretation method for improved models of magnetic lineaments. The methodology of this development will be more fully reported upon in a report and publication as part of the Technology Transfer requirements of the project. The results of the development are presented with this interpretation as a color contour map of the delineated linear features.

Examination of the data sets indicates that the dominating effects of the larger susceptibility contrasts evident in the Horizontal Gradient data have been largely attenuated and many of the more subtle responses on the HG data are now clearly shown. As the technology emphasizes the linearity of gradient changes, a correspondence with most, but not all of the anomalies on the SVD data set is evident.

Many of the conclusions and correlations derived above under the discussions of the various gradient maps can be corroborated from an analysis of the LFA map, but most striking is the disruptive effect of some of the north-easterly-aligned cross trends on the anomaly patterns.

IV. PROFILE ANALYSIS AND DEPTH DETERMINATIONS

A quantitative analysis of the detailed Finger Lakes survey data set, based on the Total Magnetic Intensity profiles and gridded data, was undertaken. A series of profile depth estimates were completed on selected profiles of the Total Magnetic Intensity data across the survey area, followed by local modeling of individual anomalies. Where considered relevant, this information is indicated on the interpretation overlay. Due to anomaly overlap problems, and the presence of numerous high-frequency anomalies related to surficial source bodies, only a limited number of useable depth estimates were obtained. Individual anomaly interpretation results are discussed in the interpretation section hereunder. At best, depth estimates without geological constraints are judged to be accurate to ±15 percent.

V. FINGER LAKES SURVEY INTERPRETATION RESULTS

A. Introduction

For any magnetic survey in a basin setting, a large number of magnetic responses are generally observed. Some of these anomalies can directly be related to surficial sources, such as topography, surficial geology or cultural effects, and generally serve only as a "geologic noise-level," masking some of the underlying source bodies. Other anomalies may conceivably arise from within the sedimentary section and may reflect structure on slightly magnetic sediments, such as volcaniclastic or conglomeratic sediments. These anomalies are generally very subtle, and it is not known if any such intrasedimentary sources are present within this part of the Appalachian Basin.

Traditionally, the use of magnetic surveys in oil and gas exploration has primarily centered around the determination and interpretation of basement-related responses to derive a structural framework applicable to the depositional environment. The geologic premise for this approach is the assumption that basement, and associated structure, has played an active role during and after sediment deposition, and that some of this activity is reflected in the sedimentary section.

Within this context, three main groups of interpretational elements can be distinguished:

> Intrabasement sources, which reflect susceptibility contrasts or lithologic differences within basement. Source body size spans the full range of basement lithologic changes, and associated magnetic anomalies can range from small to extremely large.
>
> Suprabasement sources, which are related to relief on the basement surface, and are either of paleotopographic or structural origin. Associated magnetic responses are generally very subtle with low amplitudes.
>
> Basement lineaments, which reflect detectable basement structural or tectonic elements. They may be reflected by zones of magnetic discontinuity in anomaly patterns and are generally determined from a qualitative analysis of the data set and its derivatives.

An intimate interrelationship between these interpretational elements exists, and even where interpreted with some degree of certainty, their effect upon the overlying sedimentary section remains the most important question to be addressed by an interpreter.

Additionally, magnetic interpretation results have to be evaluated in terms of the pre-, syn- or post-depositional structural history of the basins to highlight those interpretational elements relevant in the exploration evaluation of a basin.

B. Surficial Magnetic Sources

Analysis of both the profile data and the derived gridded data, such as the gradient maps, has shown that significant responses are associated with surficial magnetic sources, which are in most cases directly related to mapped glacial deposits (Surficial Geologic map of New York, Finger Lakes sheet, NY State Geologic Survey, 1986). In view of their effects in locally obscuring, or distorting the basement-related magnetic responses, a more detailed discussion of the more noticeable surficial magnetic sources is presented hereunder.

1. *Anomalies Associated with the Lakes*

Three lakes, Keuka, Seneca, and Cayuga, are located within the survey area and each of the lakes is characterized by well-defined, linear magnetic responses, with amplitudes locally in excess of 35 nT. Lake Keuka shows a strongly positive response over its southern arm, which increases in amplitude southwards into the drainage pattern of the Lake Salubria area. In the latter area the anomaly overlies mapped morainal and outwash deposits. In a northerly direction the anomaly follows the bifurcation of the lake an extends further northwards from the West Branch of Lake Keuka into the Sugar Creek drainage. Lakes Cayuga and Seneca, being wider than Keuka Lake, show a characteristic bimodal arrangement of anomalies with a central positive and flanking negative responses.

It is considered that the observed magnetic responses reflect possibly considerable thicknesses of glacial material in the lakes. The development of a bimodal anomaly over the wider lakes may be related to the combined effect of the lake bottom sediments and the plate-edge anomaly over the lake shore with locally mapped tills and morainal deposits.

2. *Drainage-related Anomalies*

Well-defined anomalies are associated with many of the drainage patterns in the survey area. The observed responses range from strongly positive such as over Boltar Creek draining into Cayuga Lake, to strongly negative, such as over the Cayuga Inlet drainage. Other noticeable anomalies are associated with Salmon Creek and Five Mile Creek in the eastern and western parts of the survey block.

Mapped sections of glacial and lacustrine deposits, which may locally reach significant thicknesses, are inferred to be associated with the mapped positive and negative anomalies respectively.

3. *Anomalies Related to Mapped Glacial Deposits*

A strongly positive, circular anomaly of some 50 nT directly overlies a similarly shaped area of Till Moraine and Kame deposits south of Applegate Corner in the south-eastern part of the survey block. Additionally, in the areas both west and east of the south end of Seneca Lake, numerous glacial deposits are mapped which trend northerly to north-easterly. These areas are characterized by a parallel alignment of high frequency magnetic anomalies. These anomalies are clearly delineated on both the Vertical Gradient and the Linear Feature Analysis maps. Numerous other, high frequency magnetic responses, which locally show a relation to mapped glacial deposits, are present in the data.

4. *Discussion*

The amplitudes of up to 50 nT of the observed magnetic responses related to the glacial deposits indicates that a significant susceptibility contrast and/or thickness is associated with these surficial sediments. These anomalies have, in places, hampered the delineation of broader, basement-related responses.

The wavelength of the anomalies is highly variable, and the full wavelength (trough to peak to trough) ranges from a few thousand feet over the linear morainal deposits to some 18,000 feet over the larger deposits mapped. This apparent lower frequency response is undoubtedly related to the probable lensoid nature of many of the glacial deposits. Within the range of postulated basement depth in the study area, at some 8,000 feet below surface, some anomaly overlap between the responses from the surficial deposits and those associated with basement surface-related magnetic sources must be expected.

As part of the interpretive process, the Surficial Geology map of New York was enlarged to a map scale of 1:100,000, and magnetic features, such as gradient anomalies and derived contacts, identified which are considered directly related to known glacial deposits. Major features in this category are shown as such on the Interpretation Overlay.

C. Discussion of the Basement Interpretation Presented

1. *Features Shown on the Interpretation Overlay*

Major features shown on the Interpretation Overlay include shallow or surficial source bodies and lineaments, as derived from the discussion under B. above, as well as inferred deeper-seated, basement-related lithology blocks, their bounding structures and cross trending lineaments. A more detailed discussion of the characteristic areas outlined is presented hereunder.

2.*High Susceptibility Basement Lithology Blocks*

a.Prattsburg area

Along the western flank of the survey, this zone of strongly positive responses is interpreted as a high susceptibility basement lithology block. The block is bounded by a strong, NNE-trending lineament zone and minor parallel lineaments in the northern half of the zone indicate a local width of up to 8 kilometers for the main structural feature.

Internal to the area, individual lithology blocks show both a NNE-trending alignment, such as for the Italy source body, as well as a more NE-trending alignment, such as for the very high susceptibility body associated with the Rheims anomaly. Minor NNW-trending basement blocks and structures are indicated for the Yatesville anomaly and for the area north of the Italy response.

Cross lineaments in the area are dominated by NE-trending alignments, which seem to control the widening of the NNE-trending, en-echelon structures along the northeastern flank of the main bounding structural zone. Northwesterly directed linear features have been derived for two zones in the northern and southern parts of the area, with the latter structures extending south-eastwards into the Bradford anomaly area.

b. Reading Center-Burnett-Searsburg anomaly zone

A NE-oriented zone of basement source bodies is inferred to be present in the south-central part of the study area and this lithology zone is bounded by well-developed, flanking lineaments. NW- to NNW-trending cross structures are indicated.

The Reading Center anomaly is considered to be related to an intrusive source body with great depth extent and with an upper surface approximately 5600 feet below sea level. A very high susceptibility contrast of some 7500 mcgs-units, relative to the host rock is interpreted and the intrusion may be a very mafic body.

c.Kings Ferry-Myers anomaly block

This basement lithology block is located in the north-eastern part of the survey and is bounded by a major, NNW-trending belt of lineaments, the Cayuga Lake structure zone. The area consists of a number of lithology blocks with dominant NE- and NW-directed alignments. It is noted that many of the NE-trending lineaments seem to terminate against the Cayuga Lake structures.

d. Buttermilk Falls anomaly

A semi-circular lithology block is partly delineated in the extreme south-eastern corner of the survey. The block is bounded on the north by a strong, linear magnetic feature. An intrusive origin for the source body, at a depth of some 9000 feet below sea level, is inferred.

3.*Low Susceptibility Basement Lithology Blocks*

Three areas on the magnetic data set are characterized by major, intensely negative magnetic responses and are shown on the Interpretation Overlay as the ENE- to NE-trending East and West Kelly Corners areas and the Odessa area. The amplitude of the observed negative responses is very large and is considered to be primarily due to major lithology differences within basement, rather than structural effects alone. A highly silicic, possibly granitic or meta-sedimentary composition of basement may be inferred.

A negative magnetic zone of smaller amplitude, the Wayne area, surrounds the Reading Center intrusion. Locally different basement lithologies, or the effect of the deep extension of the intrusive body, may be associated with the observed magnetic anomaly pattern.

4.*Weakly Anomalous Zones*

Two areas with weakly positive responses have been delineated. The first zone, in the northern part of the study, consist of the northerly-trending Himrod, Dresden and Lodi anomalies. Flanking structural control for the associated source bodies is inferred, and anomalies and structures seem to terminate against the ENE-trending structure zone characterizing the Kelly Corner areas.

The second area, consisting of the moderately positive Enfield anomalies in the south-eastern part of the survey, is located in a NE-trending structure zone. The inferred deeper-seated linear features defining the Enfield zone are parallel to the basement structures bounding the Searsburg and Buttermilk Falls anomalies to the north and south respectively and the Enfield structural zone may have a similar basement association.

At least one of the anomalies in the Enfield zone is related to surficial glacial deposits and other shallow lineaments in the area show a correlation with the general strike of the zone. It is considered likely that this basement feature may have a surface expression.

5.*Discussion of Structural Framework*

Very noticeable in the interpretation presented with this report is the preferential occurrence of lineament directions in areally restricted parts of the detailed survey block. The absence of magnetic responses does not necessarily preclude the existence of geologic structures, as negative proof is not a readily acceptable commodity. The observed concentration of delineated lineaments in certain areas of the survey block may, however, represent real geologic zones with different structural regimes and history. Within this context, the following structural framework is presented.

a.NNE-trending features

This lineament direction is conspicuously concentrated within the Prattsburg area and as major flanking structural control to this basement lithology block. A second area of concentration of these lineaments is located north of the Kelly Corners areas and abuts against an ENE-trending lineament zone. Minor, partly delineated structures are noted in the south-eastern part of the survey.

Rickard (1973) on his structure contour map on Precambrian basement in New York presents a series of NNE-trending horsts and grabens along the northern basin flank in Wyoming, Ontario, Otsego, and Schoharie Counties. It is interpreted that similar features may be present in the survey area and therefore extend much deeper into the basin than indicated. A tensional structural environment may thus be associated with this NNE-trending lineament group.

b. NE-trending features

This direction reflects the most strongly developed group of lineaments in the survey area. The features form bounding structural control on the Buttermilk Falls, Burnett-Searsburg, southern Rheims and King Ferry-Myers high susceptibility basement blocks. A correlation between this direction and surficial magnetic sources in the Enfield anomaly zone is inferred and NE-trending structures form the dominant cross cutting direction in the DEM data set for the survey area.

The presence of this direction as bounding control on basement lithology blocks, coupled with the observed topographic correlations may define older, pre-existing basement structural control that has been re-activated in later times.

This direction is limited to a single contact delineated along the northern flank of the Rheims anomaly. Some eight, easterly-trending “anticlinal” features are shown on an insert to the

Geologic Map of New York and some five of these structures cross the survey area. No correlation to the limited interpreted E-trending structural elements in the magnetic data was observed.

d. ENE-trending features

This direction, slightly offset from the NE-aligned trends discussed above, is considered to be restricted to the northern part of the survey. The lineaments are in evidence in the Kelly Corners areas as the southern termination of anomalies and structures to the north, and as subtle lineaments related to surficial sources. The zone extends into the central part of the Prattsburg lithology block.

Although no direct topographic correlation is evident, the ENE-trending lineaments may be related to, or associated with the more dominant NE-aligned features.

e.NW-trending features

This direction is confined to two major structural zones in the Prattsburg area and may reflect the different structural regime that has characterized this basement block.

f.NNW-trending features

A major lineament direction in the study area is shown by these features and is delineated most prominently by the Cayuga Lake structure zone, which terminates and possibly offsets a series of NE-trending structures to the east. This lineament alignment is additionally observed as cross cutting features in the Searsburg and Burnett anomaly zones and as flanking structures on the Reading Center intrusion.

A relation between this direction and the interpreted intrusion of the Reading Center anomaly and possibly the Buttermilk Falls source body seems to exist. Mapped Cretaceous-Jurassic intrusions in the survey area generally trend NNW and may show a crude spatial association with the Cayuga Lake structure zone. It is considered likely that this structural direction was active during Cretaceous-Jurassic times and may have a significant structural component extending into the sedimentary section.