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INNOVATIVE METHODOLOGY FOR DETECTION
OF
FRACTURE-CONTROLLED SWEET SPOTS
IN THE
NORTHERN APPALACHIAN BASIN
SEMI-ANNUAL TECHNICAL PROGRESS REPORT
(AND PHASE I FINAL REPORT)

January 1, 2002-May 31, 2002

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June 30, 2002

DE-AC26-00NT40698

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ABSTRACT

In the structure task, for this reporting period, we also edited and revised the map that displays the modified rose diagrams for the data we collected and reduced along the east side of Seneca Lake. We also revised the N-S transect that displays the frequency of ENE-striking fractures, and constructed a new N-S transect that shows the frequency of E-striking fractures. This transect compliments the earlier transect we constructed for fracture frequency of ENE-striking fractures. Significantly, the fracture frequency transect for E-W fractures shows a spike in fracture frequency in the region of the E-striking Firtree anticline that is observed on seismic reflection sections. The ENE fracture set does not exhibit an unusually high fracture frequency in this area. In contrast, the fracture frequency of the ENE-striking set is anomalously high in the region of the Trenton/Black River grabens.

We have nearly completed reducing the data we collected from a NNW-SSE transect on the west side of Cayuga Lake and we have constructed modified rose diagrams for most sites. Structure contour maps and isopach maps have been revised based on additional well log analyses. Except for the Glodes Corners Field, the well spacing generally remains insufficient to identify faults or their precise locations. However, relatively sharp elevational changes east of Keuka Lake support the contention that faults occur along the east side of Keuka Lake. Similarly, a single well east of Seneca Lake shows that the Trenton there is low compared to distant wells, based on an assumed regional slope. This same area is where one of the Trenton grabens occurs.

We have completed the interpretation of the reprocessed data that Quest licensed and had reprocessed. Several grabens observed in the Trenton and Black River reflectors are consistent with surface structure, soil gas, and aeromagnetic anomalies. In this report we display all four interpreted seismic lines.

These data indicate that integration of aeromagnetic and topographic lineaments, surface structure, soil gas with seismic and well logs allows us to extrapolate Trenton-Black River trends away from confirmatory seismic lines.

TABLE OF CONTENTS

	page
DISCLAIMER	1
ABSTRACT	2
LIST OF GRAPHICAL MATERIALS	4
1.0 INTRODUCTION	6
2.0 EXPERIMENTAL	8
2.1 FRACTURE ANALYSES SUBTASK	8
2.2 STRATIGRAPHY/WELL LOG ANALYSES SUBTASK	9
2.3 LINEAMENTS SUBTASK	9
2.4 SOIL GAS ANALYSES	9
2.5 SEISMIC DATA ACQUISITION, REPROCESSING, AND INTERPRETATION	10
2.6 ADVANCED SEISMIC ANALYSES	10
2.7 AEROMAGNETIC SURVEY AND ANALYSES	11
3.0 RESULTS AND DISCUSSION	11
3.1 FRACTURE ANALYSES SUBTASK	11
3.2 STRATIGRAPHY/WELL LOG ANALYSES SUBTASK	13
3.3 LINEAMENTS SUBTASK	16
3.4 SOIL GAS ANALYSES	16
3.5 SEISMIC DATA ACQUISITION, REPROCESSING, AND INTERPRETATION	16
3.6 ADVANCED SEISMIC ANALYSES	16
3.7 AEROMAGNETIC SURVEY AND ANALYSES	23
4.0 CONCLUSIONS	23

LIST OF GRAPHICAL MATERIALS

- Figure 3.1-1 Regional study area, 2000-2002
Figure 3.1-2 Transect location for ENE and E-W striking fractures
Figure 3.1-3 revised rose diagrams for the eastern side of Seneca Lake
Figure 3.1-4 E-striking fracture frequency at sites extrapolated (on an ENE-strike) to a N-S transect
Figure 3.1-5 E-and ENE-striking fracture frequency at sites extrapolated (on an ENE-strike) to a N-S transect
Figure 3.1-6 E-striking fracture frequency at sites extrapolated (on an E-strike) to a N-S transect
Figure 3.1-7 Cayuga Lake location map for insets
Figure 3.1-8 Inset A
Figure 3.1-9 Inset B
Figure 3.1-10 Inset C
Figure 3.1-11 Inset D
Figure 3.1-12 Inset E
Figure 3.1-13 Inset F
Figure 3.1-14 Inset G
Figure 3.1-15 Inset H
Figure 3.1-16 Inset I
Figure 3.1-17 Inset J
Figure 3.1-18 Inset K
Figure 3.1-19 Inset L
Figure 3.1-20 Inset M
Figure 3.1-21 Inset N
Figure 3.1-22 Inset O
Figure 3.1-23 Inset P
Figure 3.1-24 Inset Q
Figure 3.1-25 Legend for modified rose diagram
Figure 3.2-1 Regional structure contour map: top of Onondaga
Figure 3.2-2 Detailed structure contour map: top of Onondaga
Figure 3.2-3 Regional structure contour map: top of Irondequoit
Figure 3.2-4 Detailed structure contour map: top of Irondequoit
Figure 3.2-5 Regional structure contour map: top of Trenton
Figure 3.2-6 Detailed structure contour map: top of Trenton
Figure 3.2-7 Regional structure contour map: top of Black River
Figure 3.2-8 Detailed structure contour map: top of Black River
Figure 3.2-9 Regional isopach contour map: Onondaga to "F" Salt
Figure 3.2-10 Detailed isopach contour map: Onondaga to "F" Salt
Figure 3.2-11 Regional isopach contour map: "F" Salt
Figure 3.2-12 Detailed isopach contour map: "F" Salt
Figure 3.2-13 Regional isopach contour map: "E" Salt
Figure 3.2-14 Detailed isopach contour map: "E" Salt
Figure 3.2-15 Regional isopach contour map: "E" and "F" Salt
Figure 3.2-16 Detailed isopach contour map: "E" and "F" Salt

Figure 3.2-17 Regional isopach contour map: Onondaga to Irondequoit
 Figure 3.2-18 Detailed isopach contour map: Onondaga to Irondequoit
 Figure 3.2-19 Regional isopach contour map: Irondequoit to Trenton
 Figure 3.2-20 Detailed isopach contour map: Irondequoit to Trenton
 Figure 3.2-21 Regional isopach contour map: Onondaga to Trenton
 Figure 3.2-22 Detailed isopach contour map: Onondaga to Trenton
 Figure 3.2-23 Regional isopach contour map: Trenton to Black River
 Figure 3.2-24 Detailed isopach contour map: Trenton to Black River
 Figure 3.5-1 Preliminary mapping seismic line locations
 Figure 3.5-2 Interpreted seismic line 2
 Figure 3.5-3 Interpreted seismic line 3
 Figure 3.5-4 Interpreted seismic line 4
 Figure 3.6-1 Structural & Stratigraphic Interpretation of Line 1
 Figure 3.6-2 Structural & Stratigraphic Interpretation of Line 2
 Figure 3.6-3 Structural & Stratigraphic Interpretation of Line 3
 Figure 3.6-4 Structural & Stratigraphic Interpretation of Line 4
 Figure 3.6-5 Line 2 flattened on Knox U. horizon
 Figure 3.6-6 Instantaneous amplitude showing variation at top Trenton and within the faulted blocks. High values in red. Line 1
 Figure 3.6-7 Instantaneous amplitude (high in red) - Line 2
 Figure 3.6-8 Instantaneous amplitude (high in red) - Line 3
 Figure 3.6-9 Instantaneous amplitude (high in red) - Line 4
 Figure 3.6-10 Integrated absolute amplitude - Line 1
 Figure 3.6-11 Instantaneous Phase - Line 4
 Figure 3.6-12 Instantaneous Phase - Line 1
 Figure 3.6-13 Amplitude weighted cosine phase - Line 1
 Figure 3.6-14 Apparent Reflection Polarity - Line 1
 Figure 3.6-15 Logs for Well 21592 Glodes Corner Road Pool (Gas Pay Zone; Upper Black River)
 Figure 3.6-16 Logs for Well 22745 Muck Farms Pool (Gas Pay Zone; Upper Black River)
 Figure 3.6-17 Logs for Well 22765 Muck Farms (Dry Hole)
 Figure 3.6-18 Synthetic seismogram for Well 21592 showing tie to seismic data
 Figure 3.6-19 Seismic line overlain by computed Impedance logs - Line 1
 Figure 3.6-20 Well 21592 Glodes Corner Road
 Figure 3.6-21 Line 1 - Impedance model based on logs from two wells (stars)
 Figure 3.6-22 Model-based seismic inversion, Line 1, using two wells (see Fig. 3.6-21)
 Figure 3.6-23 Final seismic inversion with single well
 Figure 3.6-24 Selected amplitude spectra for Top Black River
 Figure 3.6-25 Average amplitude versus average frequency attributes for upper 20ms of Black River

1.0 INTRODUCTION

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. 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 760 sq. miles, an area that would cost about \$22 million for 3-D seismic coverage alone; our proposal 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). 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 (Jacobi and Fountain, 1996, Jacobi and Xu, 1998). Thus, by identifying and tracing FIDs, we can predict the location of zones of increased fractures in the subsurface.

Because large gas discoveries (estimated 3 bcf/well) have been made recently along fault zones in the New York State portion of the Appalachian Basin, it is important to be able to recognize FIDs. Because of vegetation and surficial deposits, the FIDs cannot be traced continuously in outcrop. In order to 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) seismics, and
5. aeromagnetics.

Structural studies on outcrops allow identification of FIDs; then lineaments from aeromagnetic and remotely-sensed data 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 confirm the interpretations. Many of the fault systems in the northern Appalachian basin can be traced with aeromagnetics because the surface faults are reactivated deep faults that are located in the Precambrian basement.

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). The target is the

Ordovician Trenton/Black River groups, although fractured tight sands above the Trenton also occur in this area. The most prolific gas play in New York State today is the Glodes Corners Road Field, an Ordovician Trenton/Black River play that is located west of Keuka Lake. This field was developed by Columbia Natural Resources (CNR), who estimates that the yield/well is 1.3 bcf. The east-northeast trend of the Glodes Corners Road Field suggests that the Glodes Corners Road Field is located along faults that are reactivated structures related to the older Cambrian Rome Trough, which is assumed to trend approximately east-northeast in regions south of the play (Jacobi et al., 1999). Well logs from the Glodes Corners Road Field indicate a narrow fault zone that increases in stratigraphic offset upsection, increasing to 6 m in the Trenton.

On seismic reflection profiles, the Trenton plays occur along fault zones that appear as narrow (~2000') grabens with small regional offset. These grabens are thought to be a result of a combination of

- ◆ solution collapse,
- ◆ reverse flower structures (along strike-slip faults), and
- ◆ seismic pull-down from the lower velocities associated with dissolution and fault brecciation.

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

- ◆ Traditional and innovative analyses of fractures (Jacobi),
- ◆ Stratigraphy/well log analyses (Jacobi and Loewenstein),
- ◆ Lineaments (Jacobi),
- ◆ Soil Gas Analyses (Fountain),
- ◆ Seismic Data Acquisition and Interpretation (Loewenstein and Jacobi),
- ◆ Advanced Seismic Analyses (Hart), and
- ◆ Aeromagnetic Survey and Analyses (deRidder).

During the third reporting period, we made significant progress, as outlined in the "Results and Discussion" section.

2.0 EXPERIMENTAL

2.1 FRACTURE ANALYSES SUBTASK

Jacobi and graduate students (Lugert and Wehn) used an abbreviated methodology to collect outcrop structural data during the second field season. In the abbreviated methodology, Jacobi and assistants identified the fracture sets in the outcrop, and measured the spacing among a minimum of three fractures for each systematic fracture set. They also measured the strike and dip of the fractures, and collected information concerning the abutting relationships, length/height, character of fracture trace (e.g., straight, curvy), and offset along the fracture. They constructed a sketch map in their field notebooks that showed the location of the outcrop and a sketch map of the fracture traces on the outcrop. 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. They annotated the site of the outcrop on the enlarged topographic map base.

Jacobi and graduate students (Lugert and Wehn) entered all the site data and the fractures data in Excel data spreadsheets (Appendix 1 for sites, Appendix 2 for fracture data). For each site, the next step is to calculate the fracture frequency for each set. As most fractures are very steeply dipping ($80^{\circ}+$), 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. We generally show three orders of magnitude on the diagram as successively larger concentric circles, with the inner circle representing 0.01 fractures/m, the middle ring representing 0.1 fracture/m, and the outer ring representing 1 fracture/m. Thus, long petals indicate a relatively high number of fractures, as did the old rose diagrams. The advantage of this modified diagram is that it is compatible with scanline data that we collected the first year. We use the lower half of the rose diagram to indicate other features of the fracture sets, commonly either abutting relationships, or length (which is a proxy for abutting relationships). The longest petals in the lower half indicate the master set; the next longest petals indicate the set that abuts the master set, but that is itself master to another fracture set, which is portrayed by even shorter petals.

Advanced analysis techniques, including fractal analysis and geostatistics (see Jacobi et al., 2001, for a review) will be carried out where these techniques will add to the understanding of the fracture development and significance of fractures for identifying deep structure. However, from the first two field seasons, the fracture data look to be very robust, so these techniques may not be necessary. The extent of outcrop was far greater than we had expected, and so the need for these special techniques that we developed especially for areas with limited outcrop, may not be necessary.

We had previously calculated the fracture frequency for all the fracture sets at each site, constructed modified rose diagrams for all the sites, and constructed a preliminary N-S transect that displayed the frequency of ENE-striking fractures.

2.2 STRATIGRAPHY/WELL LOG ANALYSES SUBTASK

Jacobi and Loewenstein will provide the project with 1) structure contours on bedrock marker beds that outcrop in the study area, and 2) subsurface structure contour maps based on distinctive units identified in well logs. Such maps shall aid in determining fault locations and offset. The construction of these maps is funded by an ongoing NYSERDA project. The contouring will be accomplished by a subroutine package in Geographix. The stratigraphic tops picked from well logs will follow the industry practice for recognizing each unit top; van Tyne and Foster's (1979) study illustrates such picks.

Jacobi and assistants will provide geological cross-sections across prominent surface structure where outcrops of marker units allow such constructions. The elevations of the marker units will be determined from topographic maps, and/or from altimeters, and/or from surveying from a known elevation.

2.3 LINEAMENTS SUBTASK

Jacobi and Loewenstein will combine lineaments recognized in Landsat images and in 7.5' topographic quadrangle maps. They will integrate Earthsat's (1997) pick of Landsat lineaments in the demonstration area with a reanalyzed Landsat data set. They will also analyze 7.5' topographic maps for lineaments following Jacobi and Fountain's (1996) methodology.

Jacobi will contribute an analysis of digital elevation data available from USGS for the study area. This analysis will include edited topography, a high-pass of the topography, and a horizontal gradient of the high-pass of the topography. We will compare lineaments observed in these gradient maps to those lineaments observed on the Landsat and 7.5' quadrangle maps.

The resulting series of maps of the demonstration area will include 1) Earthsat's Landsat lineament map, 2) our interpretation of lineaments from the Landsat data, 3) lineaments from 7.5' topographic quadrangle maps, 4) lineaments from gradient maps of Pearson, deRidder and Johnson, Inc. and 5) a map integrating all 4 data sets. We will compare the lineaments with the preliminary FID map. Where coincidence occurs between lineaments and FIDs observed in outcrop, we will extend the observed FID along the lineament. After the first iteration, we will compare the lineament/FID map with the soil gas analyses discussed below.

2.4 SOIL GAS ANALYSES

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

Samples are obtained by driving a stainless steel probe to a depth of 60 cm using a hand-held sledge hammer. Twenty cubic centimeters of air, slightly more than one probe volume, is withdrawn from the probe and discarded with an air tight syringe to purge atmospheric air from the probe. An additional 60 cc of air is 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 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.

Samples are 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 is 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 are analyzed in duplicate every 10 samples.

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

2.5 SEISMIC DATA ACQUISITION, REPROCESSING, AND INTERPRETATION

Loewenstein will purchase available seismic lines and subcontract with seismic processors to reprocess the records where necessary. He will evaluate the reprocessing effort and be especially cognizant of statics problems. If such problems appear to exist, he will request that the processor reprocess any section that may exhibit such problems. Loewenstein and Jacobi will interpret the seismic lines for prominent stratigraphic reflectors and faults. Where recognizable, they will pick the reflectors that represent the Tully, Onondaga, Trenton, Black River and Precambrian/Cambrian contacts. They will use accepted industry practices for the reflector recognition (e.g., Jacobi and Fountain, 1996; Jacobi et al., 2000). The interpretation of the 2-D seismic will be displayed along the seismic line in depth (time) sections that show potential faults. These depth displays will be integrated with the surficial FID/soil gas/lineament maps in two ways: 1) the location of surficial FIDs/soil gas anomalies and lineaments will be shown above the depth section for ease in spatial correlation, and 2) the locations of deep structure (faults) as interpreted from the seismic line, will be entered in Geographix so that their locations can be compared in map view with the locations of the surficial FIDs/soil gas anomalies and lineaments.

2.6 ADVANCED SEISMIC ANALYSES

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, Hart will analyze critical sections of the seismic profiles procured in the preceding subtask.

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. will acquire, process, and interpret an aeromagnetic survey of the study area. Using both widely available techniques and proprietary methods, Pearson, deRidder and Johnson, Inc. and Jacobi will delineate basement-related structural elements that serve as bounding structures on intra-basement lithology blocks, supra-basement structural relief, and zones of strike-slip faulting that may be associated with fracture swarm development. In addition, the proprietary profile data interpretation tool, STARMAG, licensed by Texaco exclusively to Pearson, deRidder and Johnson, Inc., will be amended, using local constraints, to allow for improved models of magnetic lineaments related to fracture swarms.

Specifications shall be 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

The data will be 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 will be 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. Jacobi and Loewenstein will integrate the aeromagnetic lineaments with the FID/lineament/soil gas maps and seismic attribute studies. Spatial coincidence among aeromagnetic lineaments and the FID/lineament/soil gas/seismic line fractures (seismic attribute) maps will be taken as defining probable fault systems that affected the entire sedimentary section, including the Ordovician targets.

3.0 RESULTS AND DISCUSSION

3.1 FRACTURE ANALYSES SUBTASK

The study areas are shown in Figure 3.1-1. We had three objectives for this reporting period: 1) edit and revise the map displaying rose diagrams along the east side of Seneca Lake 2) complete

a N-S transect for data along the east side of Seneca Lake that shows the frequency of E-W-striking fractures at all sites (Figure 3.1-2 shows the transect location), and 3) complete the analyses of the summer 2001 data, including constructing a map displaying rose diagrams along the west side of Cayuga Lake. For the first objective Jacobi and graduate student (Lugert) revised the existing rose diagram map, adding new data, and editing the drafting mistakes that were apparent in the first version. The new map is shown in Figure 3.1-3

For the second objective (E-W-fracture frequency along Seneca Lake) Jacobi and graduate student (Lugert) used the same N-S line of section that they used for the transect that considers ENE-striking fractures. They extrapolated all the sites to the transect both using an ENE bearing and an E-W bearing. They then calculated the average frequency in a 1 km window from all sites in that 1 km window. By extrapolating, on an ENE-bearing, the sites to the transect for the E-W striking fractures, the sites match (spatially) for both the ENE-striking fractures and the E-W striking fractures (Fig. 3.1-4). Jacobi and Lugert thus were able to compare the fracture frequency for both ENE and EW fractures at the same locale on the transect (Fig. 3.1-5). In contrast, extrapolating (on an E-W-strike) sites to the transect for the E-W striking fractures (Fig. 3.1-6) produces a mismatch of site locations on the transect between the sites used for the E-W-striking fractures and the (same) sites used for ENE-striking fractures. However, the E-W extrapolation is provides a more rigorous base for examination of the E-W fractures alone, with respect to deeper structure.

Comparison of Figures 3.1-4 and 3.1-6 shows that the different bearings for extrapolating the individual sites to the N-S transect does result in slightly different curves on the transect. Although the largest spike is located between 12 and 13 km on both Figures (3.1-4 and 3.1-6), the other large spikes have different values on the two figures and one has different positions on the two different transects (compare the spikes between 24 and 28 km on figures 3.1-4 and 3.1-6). Nevertheless, the three spikes do show the same general curves along the transect.

Figure 3.1-5 shows that the ENE and the EW-striking fractures do not exhibit the same frequencies along the transects. The largest spike for EW-striking fractures occurs near Hector, where the ENE-trending fractures are nearly non-existent. This spike corresponds spatially to the Firtree Anticline, an anticline mapped at the surface and from well logs as an E-W trending structure. The seismic section also confirms the structure as ramping thrusts from a salt decollement that resulted in fault bend folds. That the high frequency of EW fractures occurs where the known EW-striking fold occurs confirms the usefulness of fractures as predictors of structure. In contrast to the EW-striking fractures, the ENE-striking fractures have high frequency in Valois and to the north (Fig. 3.1-5). This area is where significant Trenton/Black River faults are found on the seismic line. Thus, it appears that in along Seneca Lake, where the deep structure is not hidden by shallower structures, we can recognize and discriminate the trends of both the shallow structures (Firtree Anticline) and the deeper structures (Trenton/Black River).

We have nearly realized the third objective, to complete the analyses of data along the west side of Cayuga Lake. Personnel problems prevented the completion of this objective, but we will be

finished by the next reporting period. Figure 3.1-7 displays the location of the insets, in which much of the data are compiled as modified rose diagrams (Figs. 3.1-8 to 3.1-24; see Fig. 3.1-7 for a rose diagram explanation). In some inset areas (B, F, L, and N; Figs. 3.1-9, 3.1-13, 3.1-19, and 3.1-21, respectively), no significant fracture intensification domains (FIDs) are observed. However, in other inset areas, FIDs were discovered. In the northern insets, NNW-striking FIDs are prevalent (insets A, C, D, and E); these FIDs are parallel to the general trend of Cayuga Lake in this area. N-striking FID also occur in B, D, and E. a few ENE-striking FIDs occur in insets A, C, and D, but this trend in this area is the least prominent in terms of FIDs. In the central cluster of insets (F, G, H, I, J), NNW-striking FIDs were observed in insets G, I, and J. N-striking FIDs are less prominent than to the north, only inset G as a significant N-striking FID. Inspection of Figure 3.1-7 reveals that in the central area, the NW-striking stream lineaments to the north are interrupted by a long set of NE-striking lineaments. Significantly, unlike like the northern region, the central region has prominent NE-striking FIDs, as well as ENE-striking FIDs. In the southern region (insets K-Q), more N-striking FIDs occur (insets K, O, and P), several NNW-striking FIDs occur in insets O, P, and Q. One NW-striking FID (parallel to the lake shore,) is located in inset K. E-W and ENE-striking FIDs occur in M, Q and P. The FIDs suggest faults parallel to the lake shore, and parallel to the strong NW-striking lineaments west of the lake. Additionally, the central area appears to have several fault trends, including NE, EW and ENE. These trends are consistent with stream lineaments and aeromagnetics.

3.2 STRATIGRAPHY/WELL LOG ANALYSES SUBTASK

The subcontractor, Quest Energy, has revised earlier structure contour and isopach maps, based on 20 additional deep well logs. The results are a series of maps contoured on Geographix that are displayed in Figures 3.2-1 to 3.2-24 and that are interpreted below by Jacobi. Figure 3.2-1 show the regional structure contours to the top of the Devonian Onondaga Formation. Prominent features include the E-W trending high of the Wayne- Dundee gas Field east of Keuka Lake, and the NW-trending monocline in the western half of the map. This monocline corresponds spatially with the Lawrenceville-Attica lineament. Additionally, the E-W trending structural low of the Trenton/Black River Glodes Corners Road Field is evident west of the Keuka Lake in northeasternmost Steuben County. The more detailed view of the structure contours for the Onondaga is shown in Figure 3.2-2. The Wayne-Dundee Gas Field in the east central part of the map is again prominent. The sparsity of well control between Seneca and Cayuga lakes results in fairly crude contours that do not reveal simple structure. However, the structural high in the NE corner of Hector Township is most likely a manifestation of the E-W trending Firtree Anticline. E-W to ENE-trending grabens associated with the eastward extension of the Trenton/Black River Glodes Corners Road Field are not apparent in the sparse data set. However, the structural low in Lodi Township (and northernmost Hector Township) could be recontoured with an E-W trend that would reflect deeper structure of the Trenton/Black River grabens.

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 3.2-3 and the more detailed view on figure 3.2-4. The regional map (Fig. 3.2-3) does not show as strong a

trend for the Glodes Corners Road Field as the Onondaga structure contours (Fig. 3.2-1). 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 Filed 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 effect of the Attic/Lawrenceville lineament is most likely localized in the salt layers (see discussion below concerning isopachs). Both maps show that the Wayne-Dundee Gas Field fold east of Keuka Lake is also restricted primarily to units above the salt, as the Irondequoit structure contour indicates only a very subtle feature. On the detailed figure (Fig. 3.2-4), 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 are assumed to reflect effects the deeper structure of the Trenton/Black River grabens.

The regional structure contours on the top of the Ordovician Trenton Group are shown on Figure 3.2-5 and the more detailed view on figure 3.2-6. The regional map (Fig. 3.2-5) does show the structural lows associated with the Glodes Corners Road Field (west of Keuka Lake), as well as a similar structural low on-strike east of Keuka Lake in Barrington Township (Fig. 3.2-6) and another local low east of Seneca Lake in southern Lodi Township. Localized structural highs, perhaps associated with the flanks of Trenton/Black River grabens, are observed east of northern Keuka Lake in Milo Township and between Seneca and Cayuga lakes in Hector and Enfield townships.

The regional structure contours on the top of the Ordovician Black River Group are shown on Figure 3.2-7 and the more detailed view on figure 3.2-8. The regional map (Fig. 3.2-7) shows the same structural elements as the Trenton structural contour map (compare Figs. 3.2-5 and 3.2-7). Structural lows are associated with the Glodes Corners Road Field (west of Keuka Lake), as well as with a similar structural low on-strike east of Keuka Lake in Barrington Township (Fig. 3.2-6) and another local low east of Seneca Lake in southern Lodi Township. The same localized structural highs as those in the Trenton data occur in the Black River data: east of northern Keuka Lake in Milo Township and between Seneca and Cayuga lakes in Hector and Enfield townships.

The regional isopach map for the Onondaga-"F" Salt interval is shown on Figure 3.2-9 and the more detailed view on figure 3.2-10. The prominent thinning of the interval in northern Steuben County (Fig. 3.2-9) is the result of the NW-striking Onondaga monocline (down-to-the-southwest) over the generally unaffected Irondequoit. On the detailed map (Fig. 3.2-10), the localized anomalously thin zone in southernmost Lodi township and the anomalously thick zone to the north in Lodi Township suggest drape folds over structure on the top of the salt because the thin zone occurs on the (flank of) the Firtree Anticline, and the thick zone occurs on an unnamed structural low (syncline). This syncline may be localized by the deep structure of the Trenton/Black River.

Isopach maps for the salt intervals are shown on Figure 3.2-11 to Figure 3.2-16. The isopach for the "F" salt (Figs. 3.2-11 and 3.2-12) show anomalously thick section in the core of the Firtree Anticline (on the west side of Cayuga Lake and a similar anomalously thick zone in the Wayne-Dundee Gas Field (NE corner of Tyrone Township). The 'bulls-eye' anomalously thick zone in Barrington Township (on the east side of Keuka Lake) is located at a minor anticline on the southern flank of the Severne Point Anticline. That the salt is thicker in the cores of anticlines is consistent with the general model that the thrust ramps rise from the decollement in the Silurian salt, and that the salt is involved in the associated folds. The lower "E"-Salt (Figs. 3.2-13 and 3.2-14) does not exhibit the thickening in the Firtree anticline core on the western side of Cayuga Lake, but both the Wayne-Dundee gas Field and the "bulls-eye" in Barrington township are evident, although not as strong as in the "F" salt. That the "E" salt shows less thickness variation is consistent with the view that much of the decollement thrusting rides in the upper salt.

The regional isopach map for the Onondaga-Irondequoit interval is shown on Figure 3.2-17 and the more detailed view on figure 3.2-18. Both the Glodes Corners Road Field and the Muck Farm Field display a thinned section (west side of Keuka Lake in the northeastern corner of Steuben County). The anomalous "bulls-eye" east of Keuka Lake (Fig. 3.2-18) is consistent with the thickened salt section in this locality (Fig. 3.2-16). The Wayne-Dundee Gas Field and the Firtree Anticline only exhibit minor thickening, compared to the salt thickness increases in these folds.

The regional isopach map for the Irondequoit-Trenton interval is shown on Figure 3.2-19 and the more detailed view on figure 3.2-20. Both the Glodes Corners Road Field and especially the Muck Farm Field display a thickened section (west side of Keuka Lake in the northeastern corner of Steuben County). These anomalously thickened sections are consistent with grabens in the Trenton that do not extend significantly up to the Irondequoit. The anomalous "bulls-eye" east of Keuka Lake (Fig. 3.2-20) 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 (Figs. 3.2-21 and 3.2-22).

The regional isopach map for the Trenton-Black River interval is shown on Figure 3.2-23 and the more detailed view on figure 3.2-24. The most prominent feature is an anomalously thick section that trends nominally NNE through the eastern finger of Keuka Lake. This trend is approximately coincident with a major aeromagnetic gradient 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 shows a slight thinning (Fig. 3.2-23), 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.

3.3 LINEAMENTS SUBTASK

The results were reported in previous progress reports. Aspect calculations of topographic slopes from DEMs show the prominent approximately N-striking lineaments in the southern part of the study area east of Seneca Lake, where we have a relative preponderance of N-striking fractures and FIDs. Similarly, in the central part of the study area on the east side of Seneca Lake, a zone of ENE and NE-striking topographic elements corresponds to the zone where we found a concentration of ENE and NE-striking fractures and FIDs.

3.4 SOIL GAS ANALYSES

Fountain and his assistants completed data analyses for the first two field years, and the results were reported in a previous progress report.

3.5 SEISMIC DATA ACQUISITION, REPROCESSING, AND INTERPRETATION

The subcontractor, Quest, and Jacobi have completed their analyses of the four generally N-S seismic lines. Each of the lines displays Trenton/Black River faults associated with grabens. Seismic line 1 is located west of Keuka Lake (for locations, see Fig. 3.5-1), and crosses over both the Glodes Corners Road Field and the Muck Farm Field. Preliminary interpretations of grabens associated with these fields were presented in a previous progress report. Seismic line 2 (Fig. 3.5-2) is located between Seneca and Cayuga lakes (Fig. 3.5-1) where it crosses several faults. Several faults are identified in the Trenton/Black river (and deeper) reflector packet that do not extend much above the Trenton. In contrast, the fault at "A" on Figure 3.5-2 extends through the entire section, and may reach the surface. Faults immediately to the south (at "B" on Figure 3.5-2) form grabens both in the Trenton/Black River section and higher in section-up to at least the salt section. These faults occur in an area where strong ENE-striking FIDs and soil gas anomalies occur. The E-striking Firtree Anticline, and associated thrusts, are imaged at "C" on Figure 3.5-2. These faults occur where E-striking FIDs are located. Seismic line 3 (Fig. 3.5-3) exhibits five faults that do not extend above the in the Trenton/Black river section. Some, (e.g., those at "A" on Fig. 3.5-3) form small grabens. Seismic line 4 (Fig. 3.5-4) displays a prominent graben in the Trenton/Black River, and the northern bounding fault of the graben extends upsection through at least the Tully.

3.6 ADVANCED SEISMIC ANALYSES

The Advanced Seismic Analysis task continued to refine stratigraphic and structural analyses of the seismic data in 2001-2002. Participants include Kamal Al Atroshi and Bruce Hart of the McGill Seismic Research Group (McGill University, Montreal, QC, CANADA H3A 2A7). Additionally, Atroshi and Hart inverted one of the seismic lines (the only line with necessary log data) to directly image physical properties of the productive fault zones. Atroshi and Hart'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.

1- Marker Picking and validation:

Seven seismic markers have been picked on the four seismic lines:

- a- Top Onondaga (Devonian)
- b- Top Salina (Silurian)
- c- Top Lockport (Silurian)
- d- Top Trenton (Ordovician)
- e- Top Black River (Ordovician)
- f- Knox Unconformity
- g- Top Basement

Figures 3.6-1 to 3.6-4 show seismic picks for the Trenton, Black River, Knox Unconformity and Basement horizons on the four seismic lines. In these and subsequent figures, colors have been manipulated to maximize certain interpretive aspects of the images.

2- Target markers reflection character:

On a normal polarity display, the top Trenton horizon is a strong and reflection peak (positive amplitude). Reflection continuity interruption is mainly due to faulting with some reflection amplitude dimming observed within downthrown graben areas. The Trenton seismic sequence is composed of parallel high-amplitude concordant reflections. The sequence doesn't show major isochron ("thickness") change over the 4 lines.

The top Black River horizon was picked at the transition of a positive to a negative reflection. The reflection cycle below the marker shows lateral amplitude variations with amplitude reinforcement observed within graben areas. The Black River seismic sequence shows time isopach variations. Thinning occurs above basement structural high in the North, on lines 1 and 2. The thinning is especially evident on sections that have been flattened on the Knox Unconformity (e.g., Fig. 3.6-5). The top Black River marker shows reflection truncation of some underlying reflectors.

3- Structural Interpretation of seismic data:

Our (Atroshi and Hart's) interpretation focused on the interval between Top Trenton to Basement. We used various attributes, in particular reflection strength, to better highlight faults in the area. The structural framework represents a series of horsts and grabens within an

extensional tectonic setting. Some of the major faults can be extended into the basement (Figs. 3.6-1 to 3.6-4). Rollover and horizon tilting are observed at the faulted and collapsed areas affecting both Trenton and Black River sections.

The Black River sequence shows a clear time thickness reduction within some fault bounded, fractured and collapsed areas; this shrinkage can probably be attributed to diagenetic, post faulting deformation processes. These units are:

- Line 1- CDP 230, CDP 380, CDP 480
- Line 2-CDP 233, CDP 315, CDP 490, CDP 600
- Line 3- Interval; CDP 390 to CDP 413
- Line 4- Interval; CDP 260-280, and Interval; 325-370

4- Seismic attribute analyses:

We (Atroschi and Hart) continued seismic attribute analyses, begun in Year 1, to help identify seismic response anomalies associated with fractures, faults, dolomitization or and any other variations in petrophysical properties that might be related to acoustic impedance.

- Instantaneous amplitude (Reflection strength):

Both top Trenton and near top Black River show lateral amplitude variations. Amplitude dimming occurs within faulted units (Figs. 3.6-6 to 3.6-9).

- Integrated absolute amplitude:

This attribute has been calculated on the line 1 for the interval 900- 1500 ms including Trenton and Black River sequences. The objective is to compare the total amplitude responses within each sequence and to identify zones of integrated amplitude weakness. Anomalous low values have been observed within the Black River sequence at fault zone boundaries. These blue zones on Figure 3.6-10 appear related to fractured and higher porosity intervals at various vertical extents.

- Instantaneous phase and amplitude weighted cosine phase:

Seismic phase criteria are frequently used for fracture zone delineation. Instantaneous phase attribute and an amplitude weighted cosine phase displays for line 1 show clear phase changes at the upper part of Black River near faulted areas, within both Glodes Corner Pool and Muck Farms fields (Figs. 3.6-11 to 3.6-13).

- Apparent reflection polarity attribute:

The use of this attribute is limited to reflectors with high to moderate seismic continuities. The first continuous marker related to top Black River shows a visible polarity inversion. The inversion occurs clearly at faulted and fractured areas near the wells 21592, 22745, and 22765. Further polarity inversion is observed at CDP 716 and CDP 370 (Fig. 3.6-14).

5- Well Data:

We examined three wells for the inversion project due to their proximity to seismic line 1. We digitized the calliper, gamma ray, density, neutron porosity, and photo- electric factor logs and loaded them into Hampson-Russell's *Geoview* in order to produce a composite log as well as to achieve the log- to- seismic tie. Gardner's relationship was used in order to derive a P-wave log from the density log. This formula creates a sonic log by applying an exponential transform to input Density log.

$$P\text{-wave} = C1 * \text{Density}^{**4}$$

The P-wave and density logs were then used to derive an acoustic impedance log (Fig. 3.6-15) and subsequently a synthetic seismogram.

Well 21592. ID Charles Grayet #21625, Glodes Corner Road Pool near CDP 225.

Structurally, the well is located in a graben or sinkhole at the Black River level. The well penetrated 218 feet of the target Black River interval. The density log shows little variation throughout the Trenton-Black River interval, although the Black River tends to have somewhat higher density (Fig. 3.6-15). Some decreases in density are associated with washout zones (visible on the calliper log) at the top of the Trenton and the Black River formations. The photoelectric factor log suggests that the uppermost part of the Black River could be dolomite (PEF ~3) rather than limestone (PEF ~ 5).

Well 22745. ID Faber #23285, Muck Farms Pool near CDP 355.

Structurally, the well is located on a rollover structural high of a major south dipping normal fault at CDP 378, on a vertical projection at Black River level. The well penetrated 684 feet of the target formation. The upper 29 feet of that formation were perforated and tested gas (Fig. 3.6-16). P-wave log, synthetic seismic traces and impedance logs were derived from the density log. The upper approximately 5 feet of the Black River is characterized by abruptly higher density, and hence velocity and impedance, values. The photoelectric factor and gamma ray logs suggest dolomite (perhaps shaly) for this interval. The calliper log shows borehole enlargement throughout most of the Black River.

Well 22765. ID Wise #23520, Muck Farms pool near CDP 400.

The well is located on a rollover structure, south of a major structural collapse area (CDP 380 – 395) on Black River's level (see Fig. 3.6-1). This well penetrated 489 ft of Black River formation, which tested dry (Fig. 3.6-17). The density log readings show an extremely erratic response, when compared with logs from the other two wells, in the lower Trenton and Black River intervals. Examination of the caliper log indicates borehole washout at this level, suggesting logging problems. Therefore the well's impedance response has not been considered during later stages of analyses regarding seismic inversion.

6- Well - Seismic tie and calibration- Line 1:

The generation of a sonic log from density permitted us to convert all available log data sets from depth into seismic two way time, therefore, formation tops as well as all other geological units have been calibrated to their corresponding seismic response by the use of synthetic seismograms (e.g., Fig. 3.6-18).

We (Atroschi and Hart) tried extracting statistical wavelets from line 1 for use in our synthetic seismograms. However, the best correlation coefficients between real seismic data and synthetic traces was obtained by the use of a zero phase, 200 ms long, low-cut 5/10 Hz, high-cut 50/60 Hz wavelet.

The synthetic shown in Figure 3.6-18 suggests the top Trenton should be picked as a trough, and the Black River should be picked as the transition from a negative to a positive reflection. The correlation coefficient between the seismic data and our synthetic is relatively poor however. We attribute the relatively low correlation coefficients between the seismic data and the synthetics to the logging problems previously discussed. As such, we based our stratigraphic picks on those provided by Quest (see above). Figure 3.6-19 shows Line 1 with acoustic impedance log overlays.

7- Density versus Neutron Porosity cross plots:

In the absence of core or cutting descriptions, Atroschi and Hart used cross-plots in an attempt to identify lithology and to characterize how changes in lithology correspond to changes in physical properties. Figure 3.6-20 shows a sample density-neutron porosity crossplot for the well 21592. The interval analyzed (7160-7440) ft covers the lower Trenton and all Black River section. A few primary clusters have been identified.

- A relatively dense (averaging 0.7-0.75 gm/cc), low porosity facies cluster comprising the majority of the Black River (red cluster). The photoelectric factor log and crossplot overlays (not shown) indicate that these are tight limestones.
- Low-density, somewhat higher porosity facies cluster (dark blue) of the upper Black River. These rocks may be recognized as dolomites on this crossplot.
- Very low density and relatively high porosity units (green cluster) probably associated with bad logging conditions (?fractures ?washouts) in the dolomitic units.
- The cyan grouping of the lower Trenton appears to consist of limestones with slightly higher porosity than the limestones of the Black River.
- The magenta cluster is associated with dolomites and dolomitic limestones (from the PEF log) that appear to have anomalously low density and high porosity. Whether this is a gas effect or due to borehole conditions remains unclear.

From these analyses, we conclude that dolomites could potentially have either higher acoustic impedance (blue cluster) than unaltered limestone (as predicted) or lower impedance (magenta cluster). The effects of borehole conditions on the calculated impedance values remains questionable.

8-Seismic Inversion:

Atroshi and Hart sought to invert the seismic data in order to see whether it is possible to distinguish dolomites (associated with fractures) from tight limestones. Using the Hampson-

Russell software, we first needed to create an impedance model from well logs to be a basic framework for seismic trace inversion. Line 1 was the only seismic line with wells either on the line or close enough to the line that it was possible to use the inversion software.

Atroshi and Hart created three inversion models using calibrated impedances of the wells 21592, 22745, and 22765. Atroshi and Hart found that they could not use all of the wells to create the impedance model because of erroneous density readings (and hence velocity values derived from the density log) due to poor borehole conditions (see above). Figure 3.6-21 shows abrupt lateral impedance changes in the Trenton and upper Black River half way between the two wells marked with a star. These differences result from erroneous density readings in one of the wells, and the software's algorithm for interpolating impedance values between existing control points. The model-based inversion result based on this model (Fig. 3.6-22) shows a geologically implausible abrupt change in acoustic impedance at the same location. The impedance model built using all 3 wells (not shown) was even more improbable.

Because of these problems, Atroshi and Hart chose to build an impedance model using log data from a single well, the 22745, Muck Farms Pool. The inversion result for the Line 1 was derived with the following options:

- Zero phase, 200 ms wavelet of 5/10-50/60 Hz band pass and a sampling rate of 2 ms.
- Domain; from 900 ms to 1.5 sec.
- Model used the highest possible resolution from the processed well logs.
- All geological/seismic horizons are incorporated

Three different inversion techniques, Neural Network Inversion, Linear Programming Sparse Spike Inversion, and Model Based Inversion, were applied. The best result, the only result illustrated and described here) was obtained using the model-based inversion. Inversion results were imported from Hampson-Russell into GeoGraphix (fault interpretation is not possible in the Hampson-Russell software) and incorporated with the existing structural interpretation of the line 1.

Figure 3.6-23 shows the inversion results with interpreted faults. Relatively high impedance values are shown in red, relatively low impedance values are shown in blue. In general, the Trenton interval has lower impedance than the Black River. A relatively high impedance layer (orange colors) is present at the top of the Black River. Note however that the impedance appears to decrease within, or adjacent to, fault blocks (transition from orange to yellow or green) as marked by the red arrows. We suggest that these lower impedances are associated with fractured dolomites, such as those present in the well logs. Although dolomite typically has a

higher impedance than limestone (see above), the presence of fractures, vugs and/or gas in the dolomites appears to be lowering the impedance at the seismic scale of investigation.

9- Other analyses:

The seismic inversion result indicates great promise as a possible means of identifying fractured dolomite zones in the Trenton/Black River interval, but results are obtained only where digital logs are available. Accordingly, Atroshi and Hart began to investigate two other approaches to fracture/fault detection that do not rely on the presence of wells on the seismic line. Atroshi and Hart's hope is that these approaches would be useful on "exploration" seismic lines, i.e., those without well control.

Spectral analyses can be considered as a helpful tool for delineating some intensively fractured zones. This technique has been applied to the seismic line 1, on top and near top Black River interval as a complementary argument to seismic amplitude inversion. Eleven analyses locations on the marker were chosen according to their basic seismic response on the migrated section as well as to their position with respect to the interpreted faults, collapse sinkholes and drilled wells. Analyses results (Fig. 3.6-24) gave interesting indications on the existence of wide lateral variation of this attribute. Near and within tectonically deformed zones, a spectral deformation has been observed and mainly the loss of high frequency components response, which can be attributed to a heavily fractured medium.

Complex trace attributes extracted from the top of the Black River may also show trends that can be associated with fractures. In Figure 3.6-25 Atroshi and Hart show a crossplot of average amplitude versus average frequency for a 20 ms window near the top of the Black River. Note the presence of distinct clusters; the red points appear to be associated with faulted zones. Further work will be necessary to test and build upon these results.

10 - Conclusions and recommendations:

Geophysical and geological data have been successfully integrated in the course of this project. The use of various seismic attributes and geophysical analyses has proven useful to help delineate faults and fracture domains within upper Black River Group. Despite the difficulties related to density logs for two of the three wells, inversion results have successfully identified low-impedance zones that correspond to the productive fractured dolomites.

Atroshi and Hart suggest the following work for the final year of the project:

- 1) Inversion can be applied on the other existing lines, like lines 2, 3 and 4, if viable well data are obtained. A new well, with excellent quality log data, is available for at least one of these additional seismic lines.
- 2) The inversion of Line 1 could potentially be "fine-tuned", to look at details of the impedance structure in the area of existing fields.
- 3) Variations in complex trace attributes, alone or in combination, along the productive Black River horizon could be used to help identify fracture zones on "exploration" seismic lines

lacking well data needed for inversion. The approach will be developed for line 1, then tested on the other lines available to us.

4) In order to achieve a higher control on fractured zone detection in the area, we propose to do detailed trace spectral analyses of CDP gathers on prestack data. This technique is considered as one of the key parameters for fracture detection protocols.

3.7 AEROMAGNETIC SURVEY AND ANALYSES

Pearson, deRidder and Johnson, Inc. completed their task, and the final results were reported in a previous progress report.

4.0 CONCLUSIONS

During the third reporting period, we collected data necessary to keep the project on schedule. In structure, we completed a N-S transect west of Cayuga Lake that indicates NE and ENE-trending FIDs and faults approximately on strike with the ENE-striking FIDs along the east shore of Seneca lake (north of Valois). The NE-striking FIDs and faults are thought to be controlled by basement faults. Soil gas data displayed a number of ethane-charged soil gas "spikes" on a N-S transect from Ovid south to near Valois. The soil gas team found a larger number of spikes in the northern half of the survey, suggesting more open fractures (and faults) in the northern half of the survey. Seismic data have been purchased and reprocessed. Several grabens observed in the Trenton reflector are consistent with surface structure, soil gas, and aeromagnetic anomalies. The aeromagnetic survey is completed and the data are processed. Prominent magnetic anomalies suggest that faults in the Precambrian basement are located beneath regions where grabens in the Trenton are located.

Regional Study Area, 2000 - 2002

- ☐ 7.5' Topographic Quadrangles for Field Campaign 2001
- ☐ Area of Study

Figure 3.1-1

FIGURE 3.1-2

5 km

FIGURE 3.1-3. Rose diagrams for sites along eastern side of Seneca Lake

E-STRIKING FRACTURE FREQUENCY AT SITES EXTRAPOLATED (ON AN ENE-STRIKE) TO A N-S TRANSECT

FIGURE 3.1-4

E- AND ENE-STRIKING FRACTURE FREQUENCY AT SITES EXTRAPOLATED (ON AN ENE-STRIKE) TO A N-S TRANSECT

FIGURE 3.1-5

E-STRIKING FRACTURE FREQUENCY AT SITES EXTRAPOLATED (ON AN E-STRIKE) TO A N-S TRANSECT

FIGURE 3.1-6

CAYUGA LAKE LOCATION MAP FOR INSETS

FIGURE 3.1-7

Figure 3.1-8 Inset A

Figure 3.1-9 Inset B

0.2 km

Figure 3.-10 Inset C

Figure 3.1-11 Inset D

Figure 3.1-12 Inset E

Figure 3.1-13 Inset F

Figure 3.1-14 Inset G

Figure 3.-15 Inset H

Figure 3.1-16 Inset I

Figure 3.1-17 Inset J

Figure 3.1-18 Inset K

Figure 3.1-19 Inset L

Figure 3.1-20 Inset M

Figure 3.1-21 Inset N

Figure 3.1-22 Inset O

Figure 3.1-23 Inset P

Figure 3.1-24 Inset Q

FIGURE 3.1-25 Legend for Modified Rose Diagrams. The upper portion represents the fracture frequency, while the bottom portion illustrates the master and abutting relationship.

Figure 3.2-1 Regional structure contour map: top of Onondaga

Figure 3.2-2 Detailed structure contour map: top of Onondaga

Figure 3.2-4 Detailed structure contour map: top of Irondequoit

Figure 3.2-5 Regional structure contour map: top of Trenton

Figure 3.2-6 Detailed structure contour map: top of Trenton

Figure 3.2-7 Regional structure contour map: top of Black River

Figure 3.2-8 Detailed structure contour map: top of Black River

Figure 3.2-9 Regional isopach contour map: Onondaga to "F" Salt

Figure 3.2-10 Detailed isopach contour map: Onondaga to "F" Salt

Figure 3.2-11 Regional isopach contour map: "F" Salt

Figure 3.2-12 Detailed isopach contour map: "F" Salt

Figure 3.2-13 Regional isopach contour map: "E" Salt

Figure 3.2-14 Detailed isopach contour map: "E" Salt

Figure 3.2-15 Regional isopach contour map: "E" and "F" Salt

Figure 3.2-16 Detailed isopach contour map: "E" and "F" Salt

Figure 3.2-17 Regional isopach contour map: Onondaga to Irondequoit

Figure 3.2-18 Detailed isopach contour map: Onondaga to Irondequoit

Figure 3.2-19 Regional isopach contour map: Irondequoit to Trenton

Figure 3.2-20 Detailed isopach contour map: Irondequoit to Trenton

Figure 3.2-21 Regional isopach contour map: Onondaga to Trenton

Figure 3.2-22 Detailed isopach contour map: Onondaga to Trenton

Figure 3.2-23 Regional isopach contour map: Trenton to Black River

Figure 3.2-24 Detailed isopach contour map: Trenton to Black River

Figure 3.5-1 Approximate location of seismic lines

Interpreted seismic line 2. approximate location shown in Figure 3.5-1

Figure 3.5-2

LINE 3

1 mi 1 km

Interpretation of seismic line 3. For approximate location of line, see Figure 3.5-1

Figure 3.5-3

LINE 4

Interpreted seismic line 4. See Figure 3.5-1 for approximate location

Figure 3.5-4

Figure 3.6-1 Structural & Stratigraphic Interpretation of Line 1

Figure 3.6-2 Structural & Stratigraphic Interpretation of Line 2

Figure 3.6-3 Structural & Stratigraphic Interpretation of Line 3

Figure 3.6-4 Structural & Stratigraphic Interpretation of Line 4

Figure 3.6-5 Line 2 flattened on Knox U. horizon

Figure 3.6-6 Instantaneous amplitude showing variation at top Trenton and within the faulted blocks.
High values in red. Line 1

Figure 3.6-7 Instantaneous amplitude (high in red) - Line 2

Figure 3.6-8 Instantaneous amplitude (high in red) - Line 3

Figure 3.6-9 Instantaneous amplitude (high in red) - Line 4

Figure 3.6-10 Integrated absolute amplitude - Line 1

Figure 3.6-11 Instantaneous Phase - Line 4

Figure 3.6-12 Instantaneous Phase - Line 1

Figure 3.6-13 Amplitude weighted cosine phase - Line 1

Figure 3.6-14 Apparent Reflection Polarity - Line 1

Figure 3.6-15 Logs for Well 21592 Glodes Corner Road Pool (Gas Pay Zone; Upper Black River)

Figure 3.6-16 Logs for Well 22745 Muck Farms Pool (Gas Pay Zone; Upper Black River)

Figure 3.6-17 Logs for Well 22765 Muck Farms (Dry Hole)

Figure 3.6-18 Synthetic seismogram for Well 21592 showing tie to seismic data

Figure 3.6-19 Seismic line overlay by computed Impedance logs - Line 1

Figure 3.6-20 Well 21592 Glodes Corner Road

Figure 3.6-21 Line 1 - Impedance model based on logs from two wells (stars)

Figure 3.6-22 Model-based seismic inversion, Line 1, using two wells (see Fig. 3.6-21)

Figure 3.6-24 Selected amplitude spectra for Top Black River

Figure 3.6-25 Average amplitude versus average frequency attributes for upper 20ms of Black River