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

SEMI-ANNUAL TECHNICAL PROGRESS REPORT

January 1, 2005 - June 30, 2005

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October 12, 2005

DE-AC26-00NT40698

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# ABSTRACT

The primary goal was to enter Phase 2 by analyzing geophysical logs and sidewall cores from a verification well drilled into the Trenton/Black River section along lineaments. However, the well has not yet been drilled; Phase 2 has therefore not been accomplished. We have switched oil and gas exploration and production companies, and are now in continued negotiations with Fortuna concerning a plan to retrieve 18 m of horizontal core across a gas-charged zone in the Trenton/Black River in central New York State, the “hottest” play in the Appalachian Basin.

We completed analysis of remote sensing images to determine, by using the weights-of-evidence method, which images and processing techniques result in lineaments that best reflect the fractures found in outcrop. The conclusions do not differ from the preliminary conclusions reported in the previous progress report. These data continue to demonstrate that integration of aeromagnetic and remote sensing lineaments, surface structure, and soil gas and seismic allows us to extrapolate Trenton-Black River trends away from confirmatory seismic lines.

EXECUTIVE SUMMARY

The primary goal for this reporting period was to enter Phase 2 by analyzing geophysical logs and sidewall cores from a verification well drilled into the Trenton/Black River section along lineaments. However, the well has not yet been drilled; Phase 2 has therefore not been accomplished. We have switched oil and gas exploration and production companies, and are now in continued negotiations with Fortuna concerning a plan to retrieve 18 m of horizontal core across a gas-charged zone in the Trenton/Black River in central New York State, the "hottest" play in the Appalachian Basin.

All secondary goals (except lineament analysis), not dependent upon well drilling, were completed the previous reporting periods.

We completed analysis of remote sensing images to determine, by using the weights-of-evidence method, which images and processing techniques result in lineaments that best reflect the fractures found in outcrop. The conclusions do not differ from the preliminary conclusions reported in the previous progress report. These data continue to demonstrate that integration of aeromagnetic and remote sensing lineaments, surface structure, soil gas and seismic allows us to extrapolate Trenton-Black River trends away from confirmatory seismic lines.

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# LIST OF GRAPHICAL MATERIALS

(none)

# 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. 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 students used an abbreviated methodology to collect outcrop structural data during the second and later field seasons. 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 students entered all the site data and the fracture data in Excel data spreadsheets. For each site, the next step is to calculate the fracture frequency for each set. As most fractures are very steeply dipping ($80^{o}$+), modified rose diagrams can be used to portray the results. In these rose diagrams, fracture frequency is displayed in the top half of the diagram. 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.

## 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 sledgehammer. Twenty cubic centimeters of air, slightly more than one probe volume, is withdrawn from the probe and discarded with an airtight 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 a10 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.

## 2.8 DRILLING AND TESTING OF VERIFICATION WELL

If at the Decision Point, it is determined to all parties' satisfaction that the project will continue to Task 2.8, the subcontractor, Loewenstein, shall 1) drill an exploratory well at the site judged most likely to exhibit FIDs at depth, and 2) conduct a logging program that shall determine the nature of the intersected fractures. The offeror (Jacobi), subcontractor (Loewenstein), and the Government shall select the drill site, based on all the integrated maps that portray the FIDs in the study area (including outcrop FIDs integrated with topographic and magnetic lineaments, soil gas anomalies and fracture systems suspected from the reprocessed seismic data). The offeror (Jacobi), subcontractor (Loewenstein), and the Government shall locate the drill site along a east-northeast trending FID. If north-striking FIDs are found to intersect the east-northeast FIDs, after discussion with the Government at the Decision Point, the offeror (Jacobi) and subcontractor (Loewenstein may choose the intersection point as the optimal drill site.)

The subcontractor (Loewenstein), shall conduct the following logging program

- Mud Logging – Sample description and gas detection information that identifies mineralogies indicative of healed and partially healed fractures, as well as detection of gas entry points in the well bore at the time of drilling that might indicated fractured zones.
- Temperature and Acoustic Logs – Identify gas entry points in the well bore to correlate with other logging information.
- Formation imaging (Schlumberger Formation Micro Scanner) – "Direct" detection of fractured zones.
- Combinable Magnetic Resonance Logging – Identify zones of higher permeability and movable fluids.

The subcontractor (Loewenstein) shall be responsible for selective coring in the target. The subcontractor (Loewenstein) shall be responsible for obtaining sidewall cores for fracture and reservoir characterization. The offeror (Jacobi) shall digitally image the cores and characterize the fracture spacing, intersections and form (e.g., styolitic) for each set that occurs in the cored interval.

# 3.0 RESULTS AND DISCUSSION

## 3.1 FRACTURE ANALYSES SUBTASK

The results were reported in previous progress reports.

## 3.2 STRATIGRAPHY/WELL LOG ANALYSES SUBTASK

The results were reported in previous progress reports.

## 3.3 LINEAMENTS SUBTASK

Satellite images were enhanced using various algorithms to accentuate the visibility of lineaments. This processing included noise and atmospheric corrections, enhancements such as gray level thresholding, principal component analysis, and contrast stretching. We identified lineaments on three different images: 1) a principal component analysis of the ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) data, 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 an older study (EarthSat, 1997). ASTER is a sensor that has high band sensitivity and spectral resolution, which makes it particularly sensitive to small wavelength changes. 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.

Lineaments were identified on the satellite images in regions of existing detailed structural field data from the UB Rock Fracture Group. We then utilized the Weights of Evidence method in order to 1) groundtruth the lineaments from the three different image processing methodologies, and to 2) determine which methodology results in the most lineaments that are coincident with fractures of the same trend (including Fracture Intensification Domains [FIDs]). This analysis determined which data set is optimal for selecting lineaments related to structure. The final results of the Weights of Evidence method do not differ from the preliminary results reported in the previous Progress Report (and summarized in the Table 1 on the following page).

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. Regional ground slope with respect to look angle and sun angle may play a strong role in this difference across the region. We are not convinced that regional vegetation type is critical in this difference, based on our NDVI analysis.

TABLE 1. OPTIMAL LINEAMENT IDENTFICATION METHOD FOR VARIOUS ORIENTATIONS (as tested against fracture frequency at sites)

| | | | | | | |
|---|---|---|---|---|---|---|
| | **SENECA LAKE (WEST-FACING REGIONAL SLOPE)** | | | | | |
| | NE-striking | ENE-striking | EW-striking | NS-striking | NNW-striking | NW-striking |
| FIDs (> 4 fractures/m) | fused L&A | fused L&A | ASTER PC | fused L&A | ASTER PC | fused L&A |
| all sites w/ frac.> 2/m | fused L&A | fused L&A | ASTER PC | fused L&A | fused L&A | fused L&A |
| | **CAYUGA LAKE (EAST-FACING REGIONAL SLOPE)** | | | | | |
| | NE-striking | ENE-striking | EW-striking | NS-striking | NNW-striking | NW-striking |
| FIDs (> 4 fractures/m) | ASTER PC | EARTHSAT* | ASTER PC | ** | fused L&A | fused L&A |
| all sites w/ frac.> 2/m | *** | ASTER PC | ASTER PC | ** | fused L&A | fused L&A |

* = EarthSat (1997) lineaments from Landsat images
**= not a sufficient number of lineaments
*** = lineaments from the various images did not predict NE-striking fracture sites

## 3.4 SOIL GAS ANALYSES

The initial results were reported in previous progress reports.

## 3.5 SEISMIC DATA ACQUISITION, REPROCESSING, AND INTERPRETATION

The results were reported in previous progress reports.

## 3.6 ADVANCED SEISMIC ANALYSES

The results were reported in previous progress reports.

## 3.7 AEROMAGNETIC SURVEY AND ANALYSES

The results were reported in previous progress reports.

## 3.8 DRILLING AND TESTING OF VERIFICATION WELL

Jacobi is negotiating with Fortuna who is planning to drill a well that will pass through the Trenton/Black River along a set of lineaments in the "hottest" play in New York State. When this well is drilled, all the geophysical tools and coring planned for Phase 2 will be accomplished. At present, DOE funds associated with the verification phase have not been expended.

## 4.0 CONCLUSIONS

The primary goal was to enter Phase 2 by analyzing geophysical logs and sidewall cores from a verification well drilled into the Trenton/Black River section along lineaments. However, the well has not yet been drilled; Phase 2 has therefore not been accomplished. We have switched oil and gas exploration and production companies, and are now in continued negotiations with Fortuna concerning a plan to retrieve 18 m of horizontal core across a gas-charged zone in the Trenton/Black River in central New York State, the “hottest” play in the Appalachian Basin.

All secondary goals (except lineament analysis), not dependent upon well drilling, were completed in the previous reporting periods. We completed analysis of remote sensing images to determine, by using the weights-of-evidence method, which images and processing techniques result in lineaments that best reflect the fractures found in outcrop. The final conclusions do not differ from the preliminary conclusions reported in the previous progress report. No single image processing methodology provides an optimum image for identifying all lineament trends that correspond to FIDs and lesser fracture spacing. However, as a general statement, for lineaments in various orientations on regionally west-facing slopes, fused L & A images provide a better correspondence between lineaments and FIDs, as well as trends with > 2/fractures/m, than images developed from the ASTER PC method, but significant variations do occur (as detailed in Table 1). For regionally east-facing slopes, no one method provides the best correspondence between lineaments and FIDs/trends with > 2 fractures/m. These data continue to demonstrate that integration of aeromagnetic and remote sensing lineaments, surface structure, soil gas and seismic allows us to extrapolate Trenton-Black River trends away from confirmatory seismic lines.

FIGURE CAPTIONS

(none)