Final Report
Assessing the Contribution of Satellite Hyperspectral Data To Petroleum Exploration

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Introduction

Originally, this project was designed by Earth Satellite Corporation (EarthSat) to compare the measurements and results of a previously acquired, airborne hyperspectral survey with measurements and results obtained using satellite hyperspectral (ASTER) data. As often happens in research, the original project design had to be modified. All of the available ASTER satellite data directly over the airborne survey area were cloud covered and unusable. Consequently, with the approval of the NYSERDA contract manager, the focus and perspective of the study changed and the ASTER data were evaluated using different techniques and by comparison to several alternate data sets. This change in approach led to interesting, potentially economical, and important results.

In short, this study shows that fracture zones can be mapped on the ASTER data, that the analysis of the orientation of these ASTER fracture zones in terms of stress history and thermal history allows prediction of the open directions through time, and that spectral anomalies observed on the ASTER data appear to correlate with hydrocarbon micro-seepage along these fracture zones. In addition, as with other fracture zones mapped on Landsat satellite data (EarthSat, 1997), many of the fracture zones mapped on the ASTER data coincide with subsurface structural features that are potentially seismically active (Jacobi, 2002).

Specific results include:

1. Field work verified that fracture zones mapped on the ASTER satellite image coincide with fracture zones on the ground.
2. Fracture zones mapped on the ASTER satellite images coincide with soil gas anomalies mapped in the field.
3. Producing wells are located in fracture zones mapped on the ASTER satellite images.
4. Field work verified that there are oil seeps located along some of the fracture zones mapped on the ASTER satellite data.
5. Many of the ASTER spectral anomalies and fracture zones coincided with changes in vegetation. In turn the differences in vegetation are consistent with (but not necessarily unique to) the presence of hydrocarbons.
6. Based on the results recorded above (1-5), ASTER spectral anomalies along fracture zones appear to be related to the seepage of hydrocarbons.
7. Many of the fracture zones mapped on the ASTER data coincide with Jacobi's (2002) potentially seismically active zones.
8. This work, coupled with fracture density analysis and an analysis of the orientation of fracture zones in terms of stress history and thermal history, can provide powerful guides to exploration and delineate areas with potential seismic hazards.

Background

The focus of the work was on fractured rock reservoirs, both the Devonian shales that EarthSat's previous work addressed (EarthSat, 1997), and the Ordovician Trenton-Black River fractured carbonate reservoirs. Fractured reservoirs are notoriously difficult to explore for and problematic to develop. Fractured carbonate reservoirs (sometimes named "hydrothermal dolomite") are particularly complex by virtue of: 1) multiple cycles of fracturing, dissolution and mineralization, 2) the anisotropic non-homogenous distribution of porosity and permeability within the reservoir, and 3) the relative insensitivity (until recently) of conventional tools such as seismic data and wireline logs to critical elements of the reservoir. Like fractured carbonate fields elsewhere, (e.g. Albion-Scipio in Michigan), those in New York have dry holes "on-trend" with some of the most prolific producers in the Finger Lakes region. Production is confined to narrow zones, and the controlling structures are very difficult to image on regional seismic lines.

Fractured carbonate fields like the Trenton-Black River Glodes Corners Road field, New York and the Stony Point and Albion-Scipio fields, Michigan, are end members of a continuum with Mississippi Valley type (MVT) lead-zinc deposits at one extreme, and oil and gas fields at the other extreme. Both the oil fields and MVT deposits involve: 1) the movement of large volumes of relatively low temperature fluids (70°C to perhaps a maximum of 200°C – most are in the range of 70°C to 150°C) and 2) fractured carbonate rocks that have undergone a substantial amount of solution, dolomitization, and mineralization (PbS, ZnS, CaF_2) with porosity and permeability are confined to solution enhanced fracture systems and dolomitized wall rock immediately adjacent to the fracture system. Interestingly, the 70°C to 200°C temperature range is also associated with temperature required for the generation and expulsion of hydrocarbons from a source rock (Barker, 1979, and Tissot, et.al., 1974).

At one end of the continuum are the prolific MVT lead-zinc districts like Pine Point Northwest Territories, Canada; the Tri-State district of Missouri, Kansas and Oklahoma; Burkeville, Kentucky; and the Illinois lead-zinc district. All of these MVT deposits also contain minute traces of dead hydrocarbons (bitumen, gilsonite, asphaltite, etc.). At the other end of the spectrum are oil and gas fields like the prolific Albion-Scipio and Stony Point trends of Michigan, the Electra field of Ontario, and the Trenton-Black River fields of New York, Kentucky, and West Virginia, which have large volumes of hydrocarbons and economically paltry amounts of galena and sphalerite. In a sense, fractured carbonate hydrocarbon reservoirs and Mississippi Valley Type deposits constitute a time sequence. The oil and gas fields represent an early stage with active movement of large volumes of fluid with concomitant solution, dolomitization and mineralization. The MVT deposits represent an end phase after generation, expulsion, migration, and deposition when the bulk of the hydrocarbons and associated fluids have escaped as evidenced by the fact that most MVT deposits contain remnant inclusions of oil.

Methodology

This study used ASTER hyperspectral satellite data, which measures 14 segments (or bands) of the electromagnetic spectrum. Three of the bands are in the visible near-infrared (VNIR) portion of the spectrum, six bands are in the Short Wavelength Infrared (SWIR) portion of the spectrum, and five bands are in the Thermal Infrared (TIR) portion of the spectrum. These bands have 15 meter resolution (VNIR), 30 meter resolution (SWIR), and 90 meter resolution (TIR). The spectral bands on the ASTER system were designed for mineral exploration, consequently it is also very useful for detecting the subtle minerologic and vegetation change effects often associated with the seepage of hydrocarbons.

The ASTER VNIR & SWIR bands were processed using several algorithms. The Minimum Noise Fraction (or MNF) transform proved to be the most useful. To improve the radiometric enhancement of the data, clouds and cloud shadows were removed (or masked-out) during this processing. Consequently, on the ASTER images, clouds and cloud shadows appear as black patches.

The ASTER images were then interpreted to delineate fracture zones and any indication of spectral anomalies that might be related to hydrocarbon microseepage. This step was done interactively by projecting the processed image on-screen and having four investigators use laser pointers to guide the digitizing of the interpretation directly into a GIS layer.

The mapping focused on delineating fracture zones. There is a high degree of agreement between fracture zones mapped on Landsat data in an earlier study (EarthSat, 1997) and those mapped using the ASTER data. The higher spatial resolution (15 m vs. 30 m) and larger effective scale of mapping (1:100,000 vs. 1:250,000) of the ASTER data permitted more precise location of fracture zones and eliminated cultural confusion. More importantly, the spectral power of the ASTER data added considerably to the recognition of fracture zones. Some of the fracture zones were mapped using obvious geomorphic evidence (straight stream valleys, topographic scarps, etc.), but subtle spectral differences observable in the ASTER data also made detection and mapping of many fracture zones much more obvious than on the Landsat data.

Interpretation

Comparison of the fractures mapped on the ASTER data to previous geologic field mapping (Jacobi, 2002), additional field work, soil gas geochemical surveys, and known or suspected faults demonstrated that there was a strong correlation between fractures mapped on the ASTER data and important geologic phenomena.

In the fracture analysis, there are two fracture orientations that are very prominent: east-northeast and north-northwest. These fracture maxima tend to change orientation across southern New York State. In the eastern study area near Keuka Lake (Figure 1), the fracture maxima are almost due east and due north. In the western study area along the Bass Island trend (Figure 1), the fracture maxima are northeast to east-northeast and northwest to west-northwest.

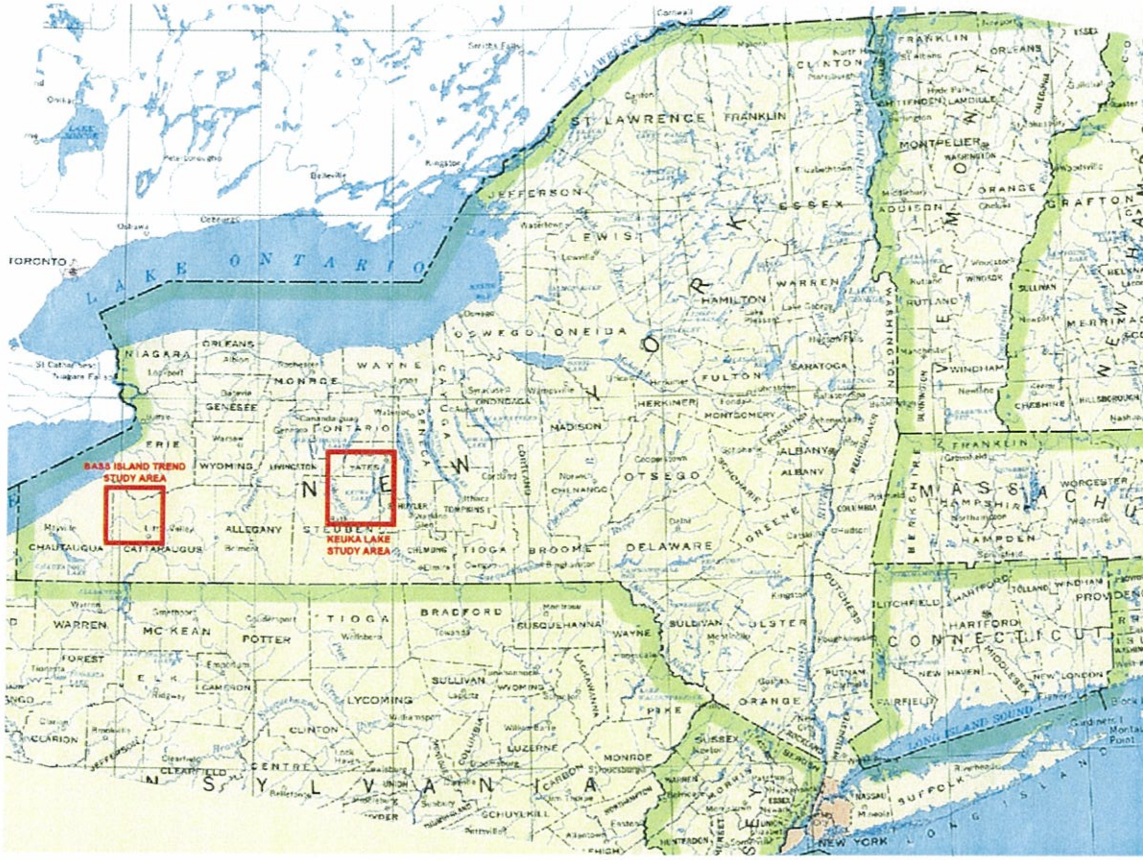

Figure 1: Location of the Bass Island Trend and Keuka Lake / Glodes Corners Road Study Areas.

The fractures mapped on the ASTER data closely match known and postulated faults (Jacobi, 2002) and fracture intensity domains (Nelson, 2002). Particularly striking are the east-northeast faults that control the Bass Island trend (Van Tyne and Foster, 1979; Beinkafner, 1983), the Clarendon-Linden fault zone (Chadwick, 1920; Van Tyne, 1975; Falkundiny, et.al., 1978; Jacobi and Fountain, 1993, 1996, and 2002), the north-northeast striking faults near Keuka Lake (Murphy, 1981), and the essentially east-trending fracture zone that controls Glodes Corner Road field.

Many other fractures mapped on the ASTER data coincide with fracture intensity domains (FID) defined by Jacobi and Fountain (1993, 1996, and 1999). Jacobi and Fountain noted that many of these FID contain anomalously high amounts of methane soil gas (10 to 250 times background). These workers have documented in the field the correspondence of FID's and fracture zones mapped on satellite data.

This close correspondence of features seen in the ASTER data and known faults and fracture zones is of scientific interest and has at least two major economic implications:

1. Jacobi (2002) has shown that there is a relationship between these structural boundaries and seismicity, and

2. In New York State, a substantial portion of hydrocarbon production comes from reservoirs where fracturing profoundly influences, if not controls, producibility (e.g. Devonian, brown shale fields, Bass Island trend, Trenton-Black River fractured dolomite fields, etc.)

Field checking the eastern study area around Keuka Lake revealed that the fractures visible in the ASTER data are also visible on air photos, and correspond with a variety of features on the ground and on topographic maps (gullys, small streams, vegetation alignments, etc.) as shown in Figures 2, 3, and 4.

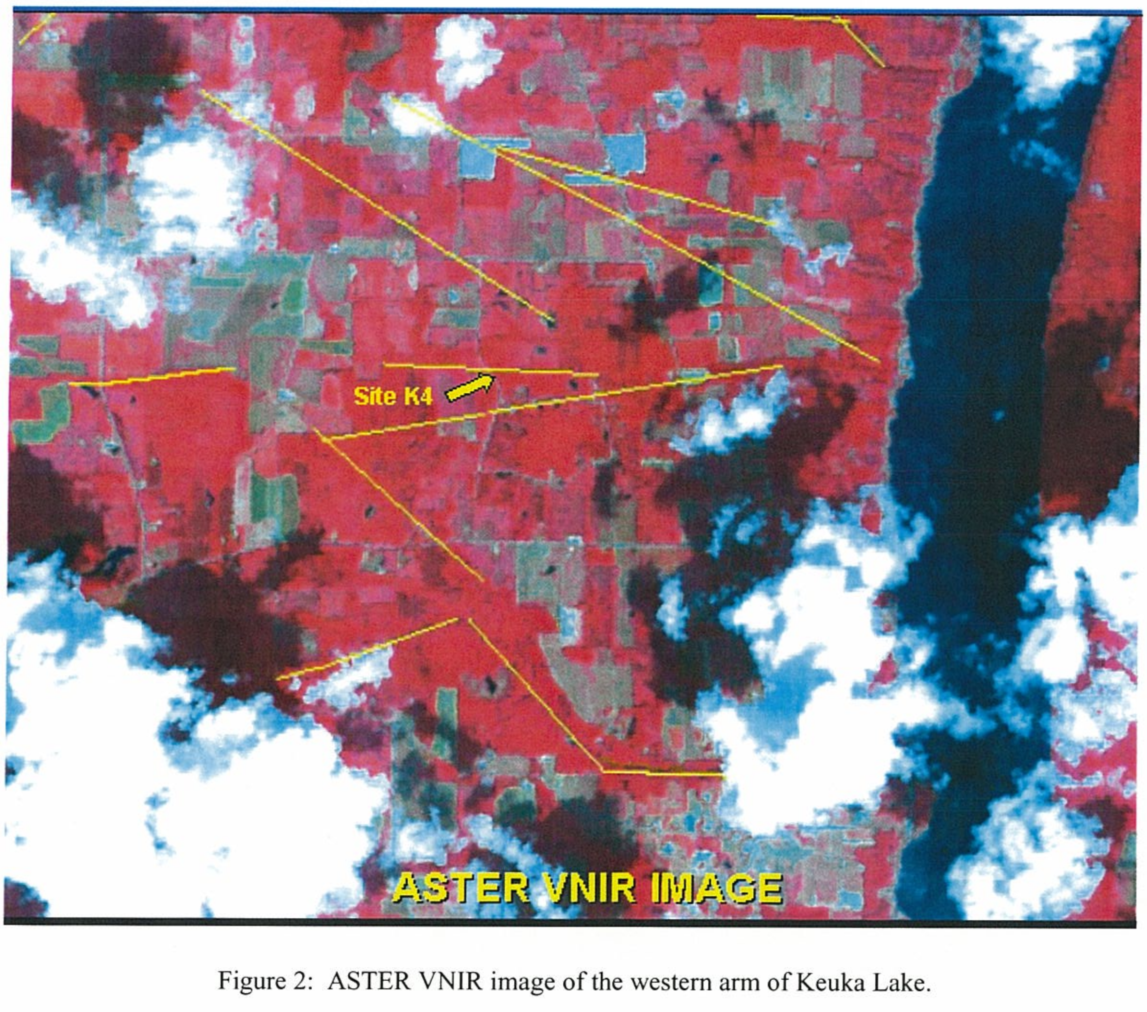

Figure 2: ASTER VNIR image of the western arm of Keuka Lake.

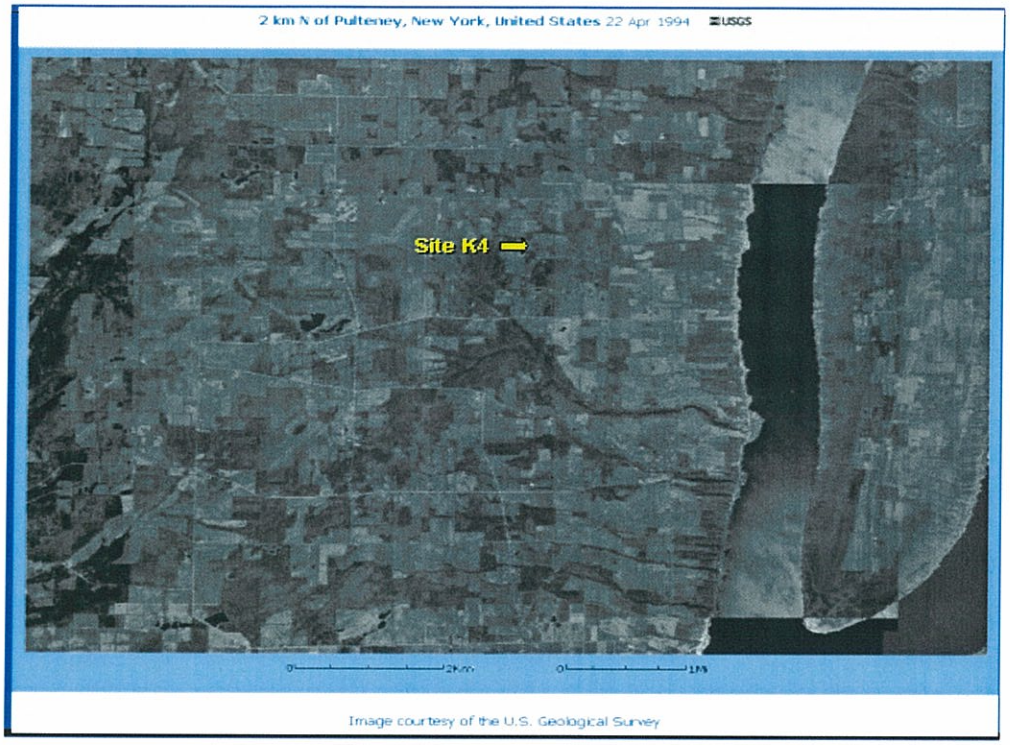

Figure 3: Air photo of the western arm of Keuka Lake

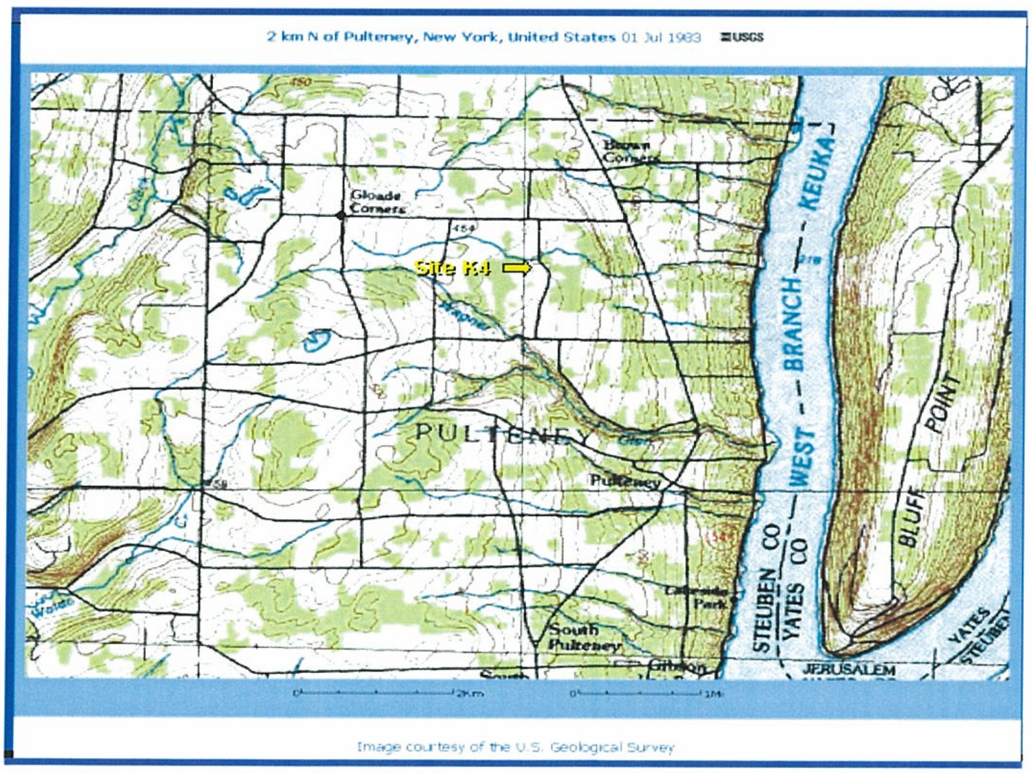

Figure 4: Topographic map of the western arm of Keuka Lake

Figure 5 shows a fracture in the ASTER data at Site K4. On an air photo (Figure 6), it appears as a dark alignment in the woods. On the ground, the dark area is a very small stream (Figure 7). As seen from the road (Figure 8), there is a profound difference in vegetation inside and outside the fracture zone.

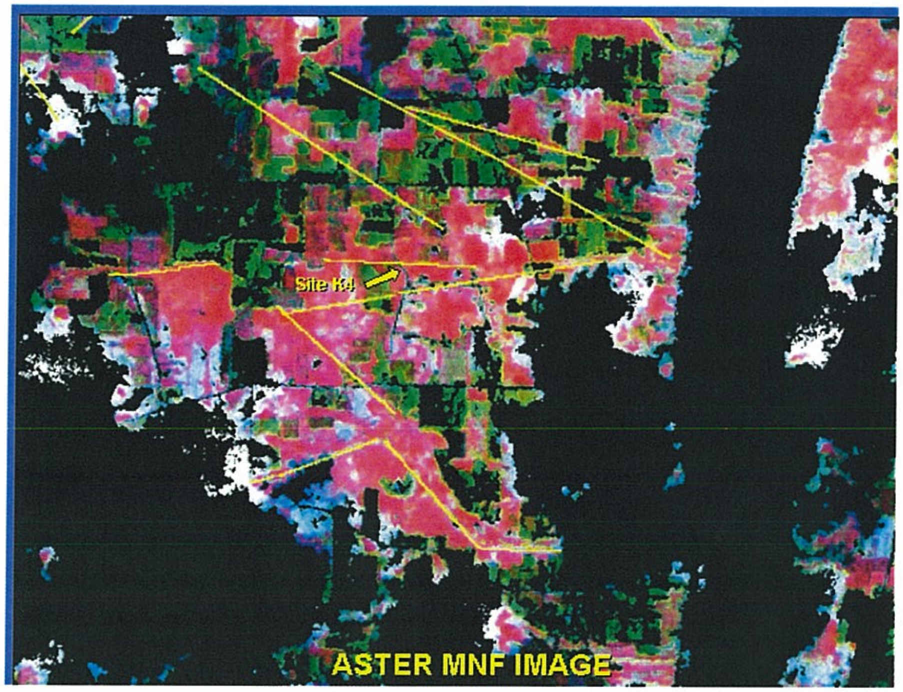

Figure 5: ASTER MNF image of Site K4.

Figure 6: Air photo of Site K4.

Figure 7: Ground photo of Site K4.

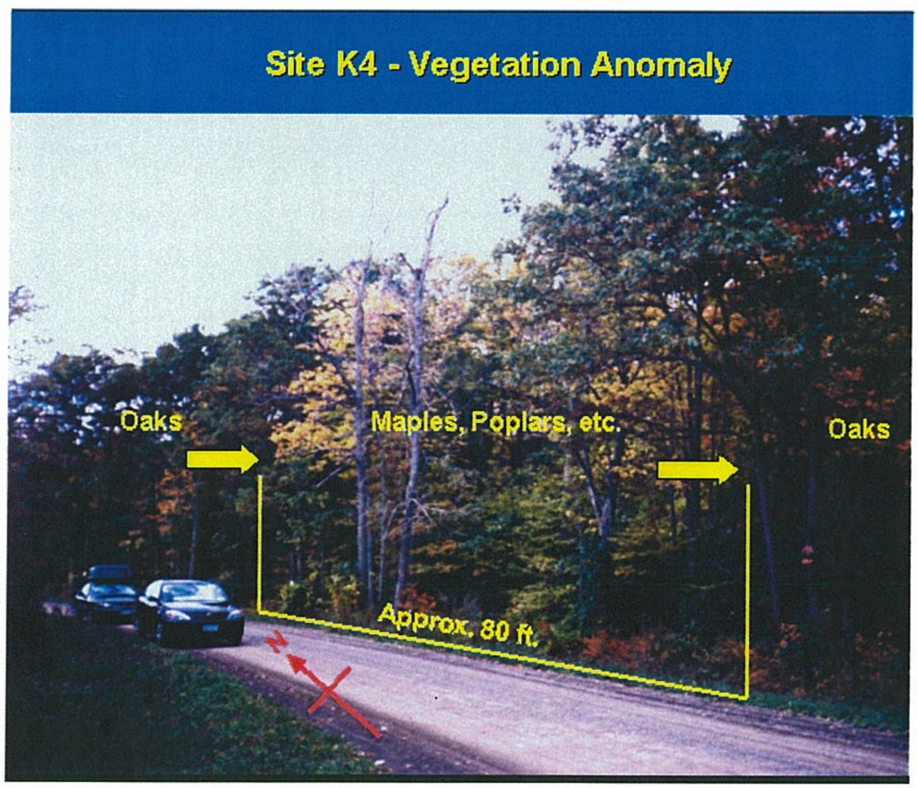

Figure 8: Vegetation anomaly at Site K4.

In the fracture zone there are maples, poplars, green ash and basswood; immediately outside of the fracture zone oaks are the predominant species. In the fall when the photograph was taken (Figure 8), the differences in vegetation are obvious because of leaf color changes. However, the ASTER data were acquired in the summer when there were no obvious leaf color differences.

In the Geosat Report (1985), Barry Rock noted the same type of anomalous vegetation associated with the Lost River gas field in West Virginia. The explanation is that mycorrhizal fungi have a symbiotic relationship with the trees. The fungi are crucial to the uptake of nutrients for the trees. In oaks, these fungi are in external nodes on the roots. In poplars, green ash, basswood, and some maples, the fungi are internal to the root structure. The oaks are less tolerant to water-saturated or gas-saturated soils. Consequently, where there is an absence of oaks or an abundance of poplar/maples away from water-saturated areas, one might suspect the presence of hydrocarbons in the soil. This appears to be the situation at Site K4. At this site there is a small, dry stream bed but the maple/poplar community covers a much wider area than the stream bed or the adjacent area. Site K4 is on-trend with Glodes Corner Road field. Similar types of spectral anomalies and vegetation patterns are present throughout the area.

Immediately to the west (Figure 9) and on trend with the K4 fracture and vegetation anomaly is Site K8. This site lies on a very small east-northeast-trending creek. There is an oil well at the point indicated where the green and red colors meet. The well is in the Glodes Corners Road field.

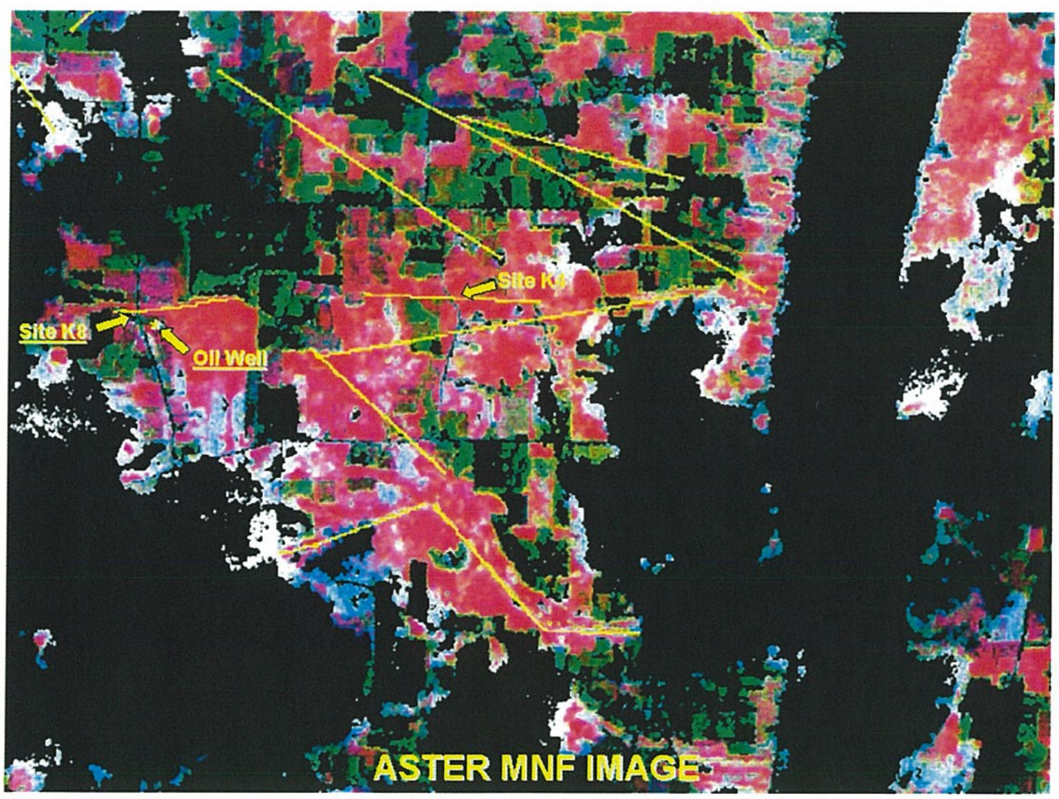

Figure 9: ASTER MNF image of Site K8.

At Site K8 there is a hydrocarbon seep in the creek bed (Figure 10). The picture was taken looking straight down at the creek bed where the creek passes under the west side of the road. East-northeast-trending fractures are visible in the creek bed.

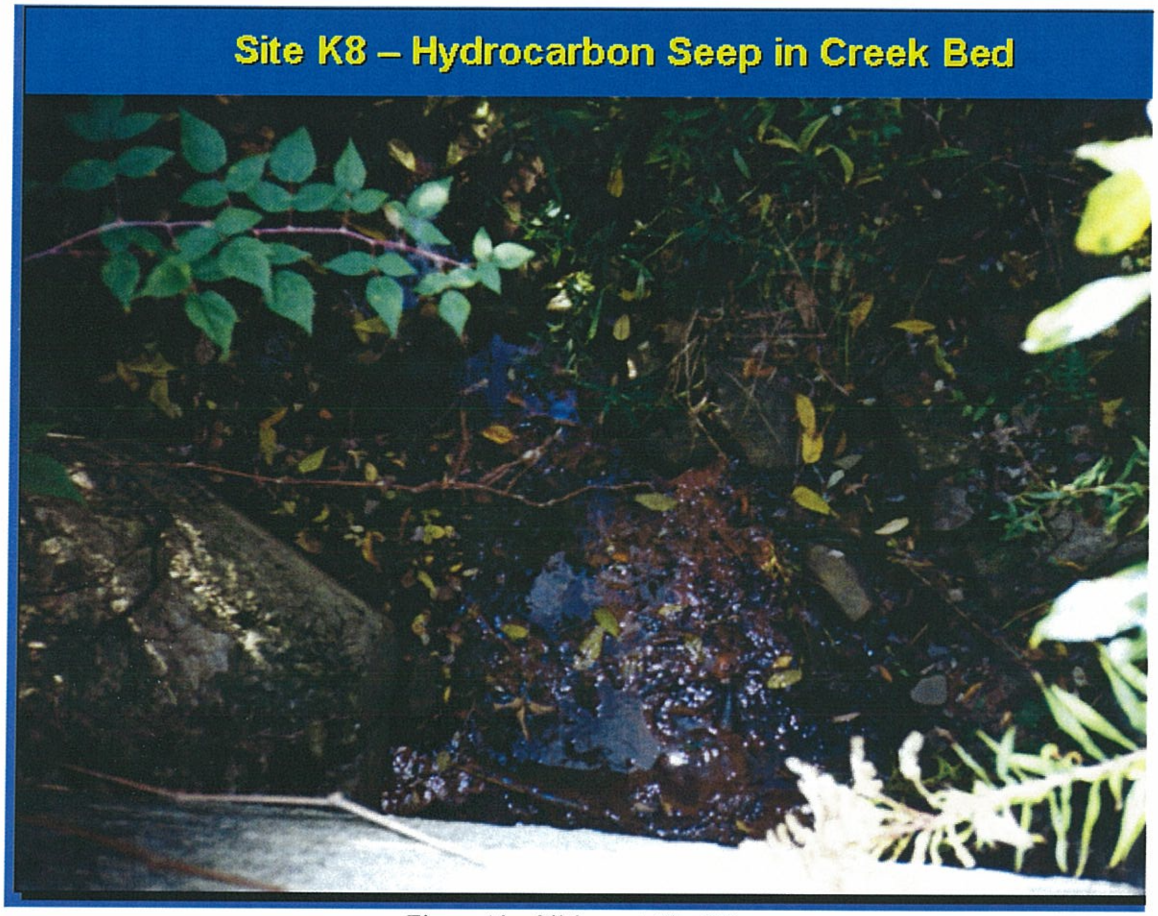

Figure 10: Oil Seep at Site K8.

In the Wagener Glen area (western shore of Keuka Lake; Figure 11), joints control the straight stretch of the stream. The east-west joints are parallel to Alleghenian fold axes and were the open-standing fractures at that time. An air photo of the area (Figure 12) shows the east-west-trending, Wagener Glen. Joints appear to control many of the glens in the vicinity of Wagener Glen.

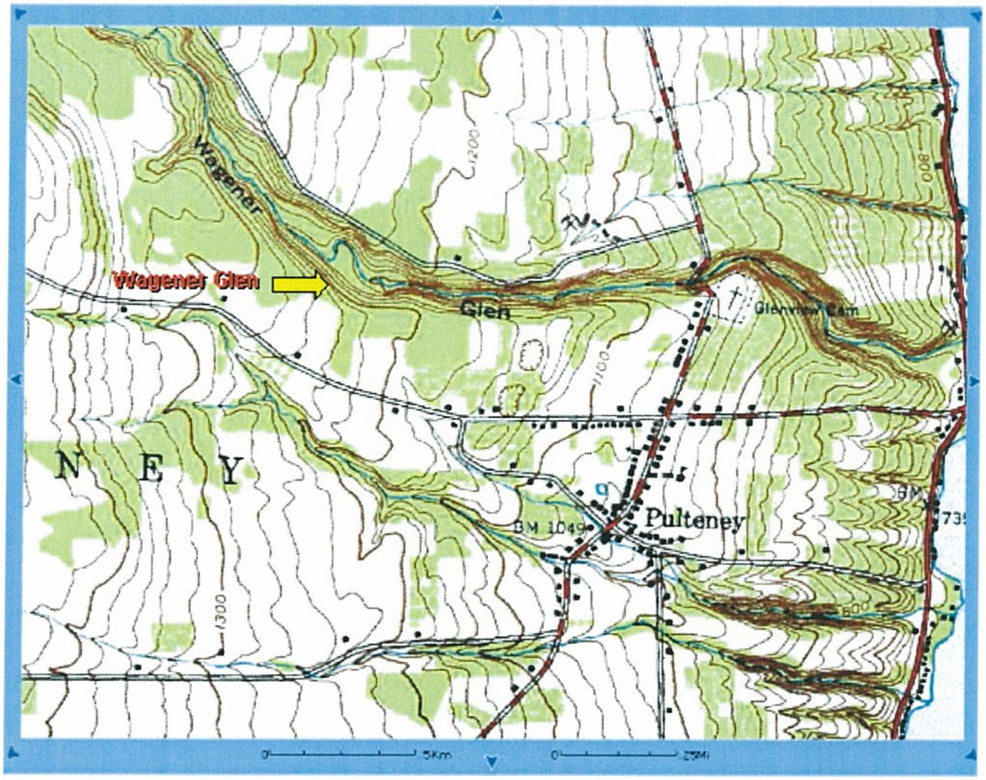

Figure 11: Topographic map of the Wagener Glen area.

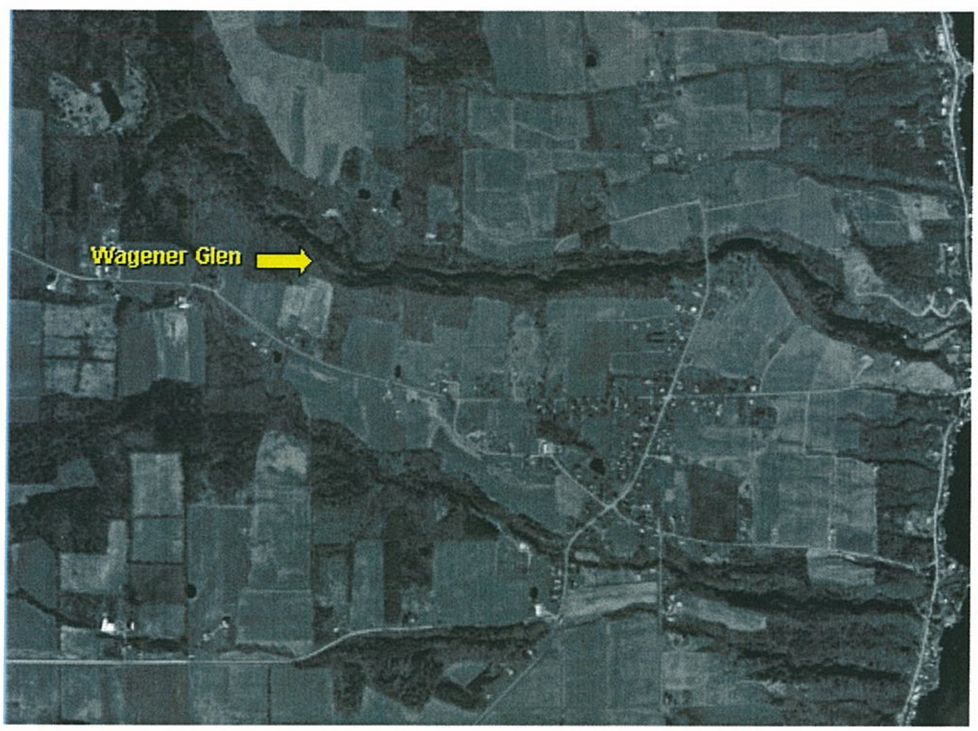

Figure 12: Air photo of the Wagener Glen area.

On the Minimum Noise Fraction image (Figure 13) there is a bold, light colored spectral anomaly that marks the anomalous vegetation along the stream and on the uplands adjacent to the glen. The unusual vegetation is mostly on the upland area adjacent to, and 150 to 200 feet above the stream, rather than right in the stream. Consequently, water saturation does not explain the anomaly. The anomaly does not include all of the forested area on the uplands, but is confined to a narrow, fracture-parallel zone.

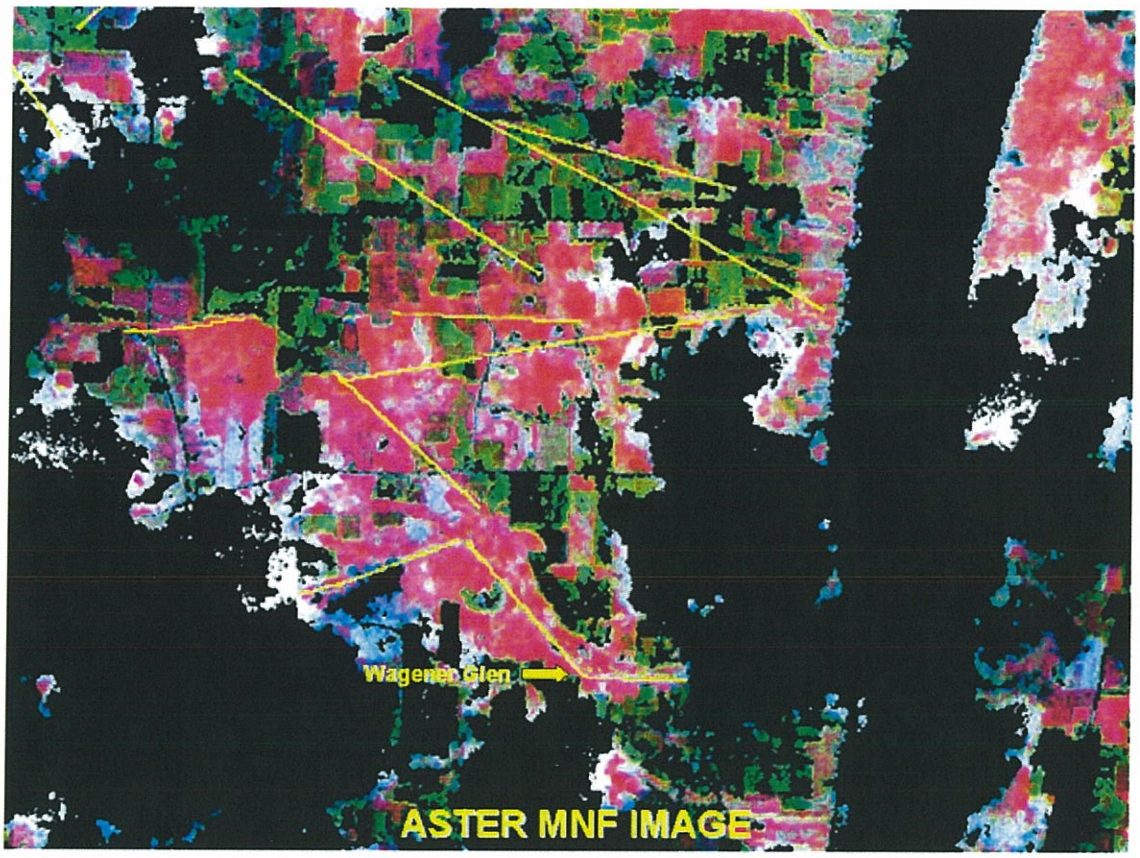

Figure 13: ASTER MNF image of the Wagener Glen area.

Figure 14 shows the joints that control the stream valley at Wagener Glen. Note the straight fracture surfaces. The stream controlling joints strike N85°E as does the fracture zone mapped on the ASTER image. Looking upstream (Figure 15), the N85°E joint set is clear. It also is visible in the stream bank where the stream turns. In addition, there are steps in the stream bed which are joints that strike N18°W.

Figure 14 N85ºE joints controlling Wagener Glen stream bed (view looking downstream).

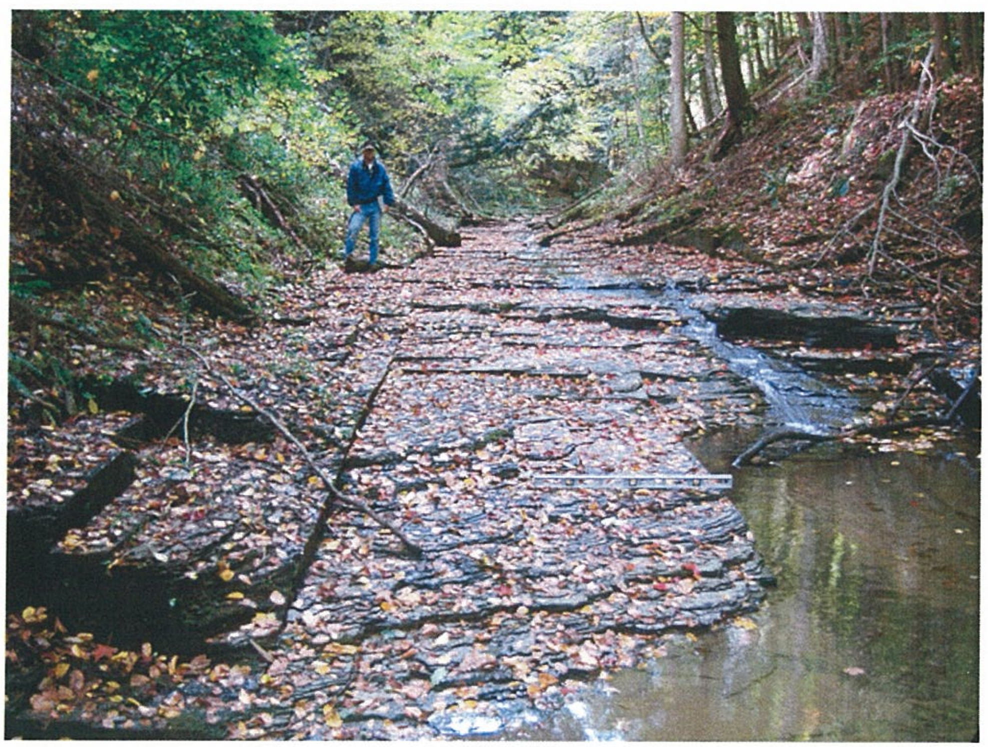

Figure 15: N85ºE joints controlling Wagener Glen stream bed (view looking upstream).

Figure 16 shows the jointing in the stream bed in detail. Notice that the east-northeast joint set (N85°E) either abuts the N18°W set or that the two sets offset each other. This suggests the east-northeast set is younger, but there has been some contemporaneous movement of both sets.

Figure 16: Detailed view of the jointing in Wagener Glen.

Thus, there is a relationship between fracture zones, ASTER spectral anomalies, and vegetation changes. Furthermore, the types of vegetation changes observed in the field are consistent with the presence of hydrocarbons. More importantly, Glodes Corners Road field lies on the east-northeast-trending fracture zones mapped on the ASTER imagery, there are ASTER spectral anomalies along these fracture zones, and there are indications of hydrocarbon seepage along these fracture zones.

To the west of the Keuka Lake study area in the Bass Island trend of western NY, the fractures mapped on the ASTER data (Figure 17 - red lines) were compared to previous Landsat fracture mapping (EarthSat, 1997 - white lines), field work, production data, cross-strike discontinuities, and soil gas transects reported by Nelson, et. al., 2002.

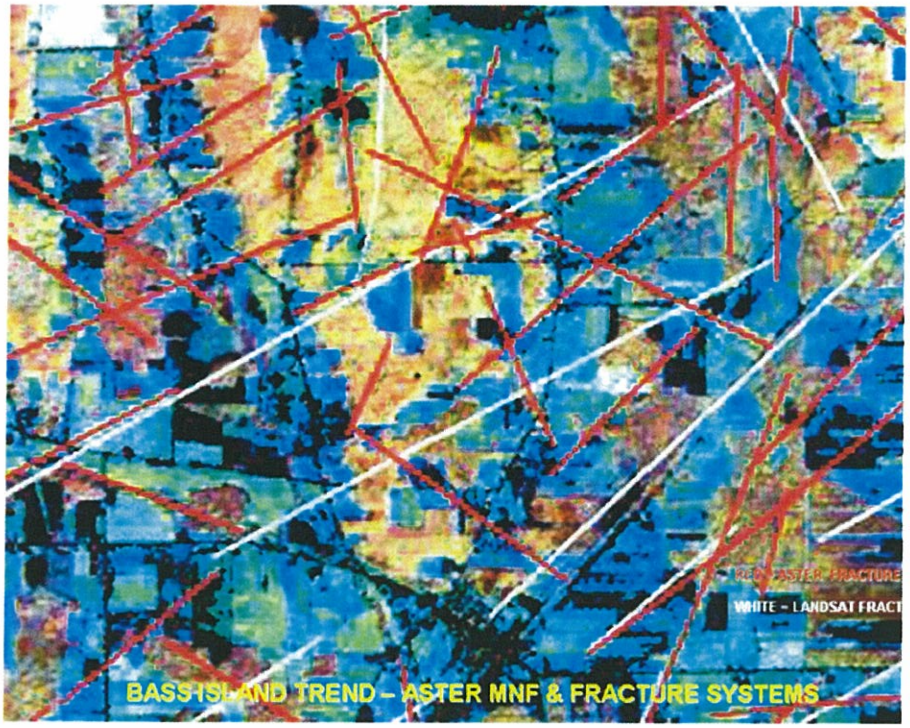

Figure 17: ASTER MNF image with fracture analysis.

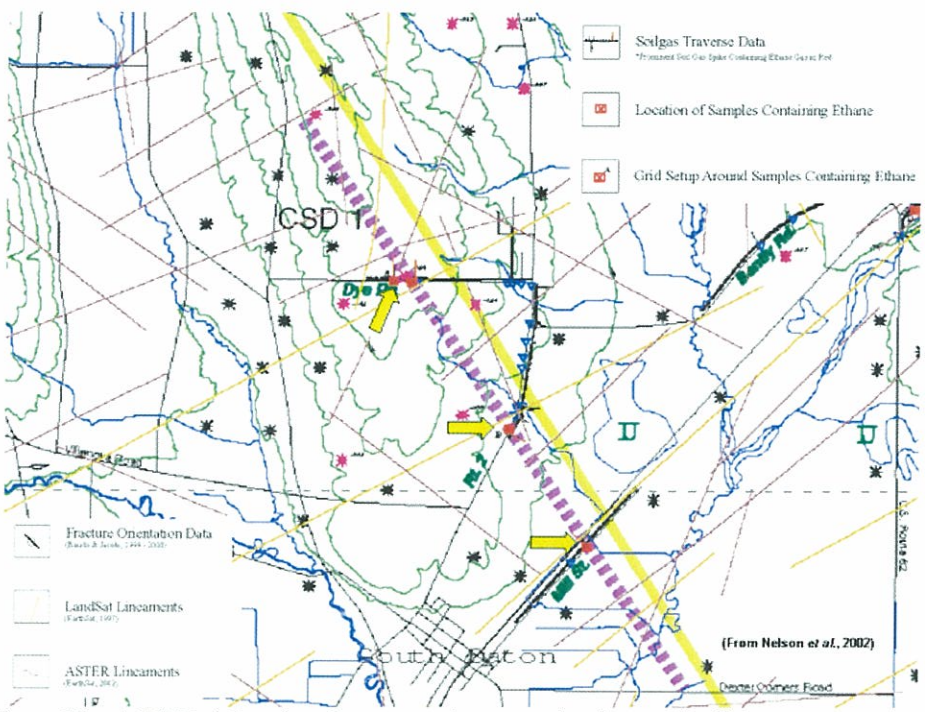

Figure 18.: ASTER & Landsat fracture analyses, production, and soil gas transects along CSD 1.

The gold lines in Figure 18 are fractures mapped in 1997 using Landsat TM imagery, the brown lines are fractures mapped on the ASTER images, the thick yellow lines are fracture intensification domains mapped by Jacobi and his colleagues, and the purple dashed lines are cross-strike structural discontinuities (Nelson et al., 2002). Nelson et al. (2002) ran soil gas transects along these cross-strike discontinuities. The red boxes on the cross-strike structural discontinuities mark anomalously high soil gas sample readings that include ethane. Nelson's map shows several producing wells that lie along or on-trend with the fractures mapped on the satellite images. All the soil gas/ethane highs occur where the soil gas transects cross fracture zones mapped on the satellite imagery.

Figure 19 shows an area slightly to the east of the previous area. The same relationships hold. The soil gas highs (red boxes) occur on fractures mapped from the satellite imagery and seem to be associated with either northeast or north-northwest-trending fractures.

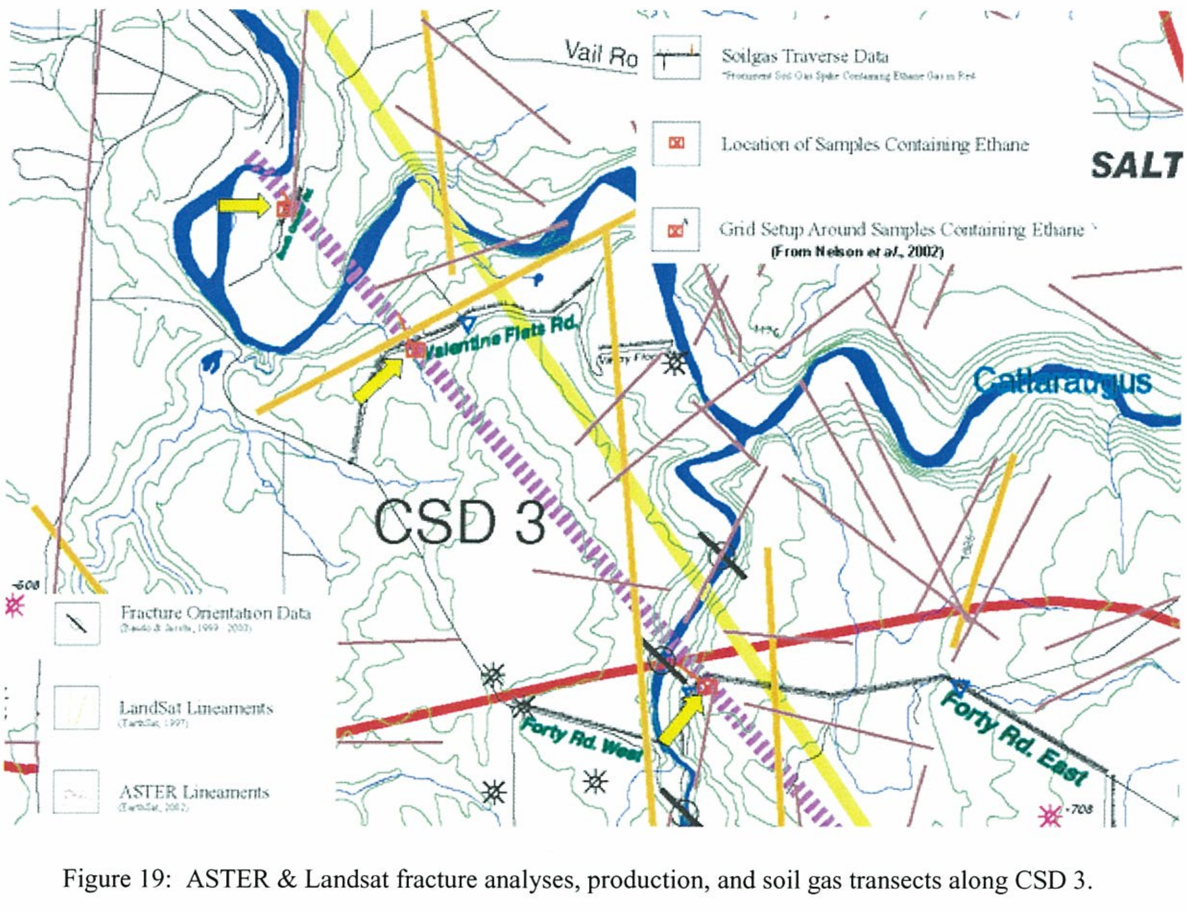

Figure 19: ASTER & Landsat fracture analyses, production, and soil gas transects along CSD 3.

Jacobi and his co-workers noticed that on a regional basis, the northeast-trending fracture system becomes more nearly east-west as one travels to the east. Fracture analysis on the Landsat and ASTER data reinforces this observation. This change in trend of the fracture system mimics the change in strike of the Alleghenian fold axes shown here on a tectonic map of the state (Figure 20). Keuka Lake and the Bass Island trend serve as points of reference. The fold axes swing from northeast in the west, to east-northeast near Keuka Lake.

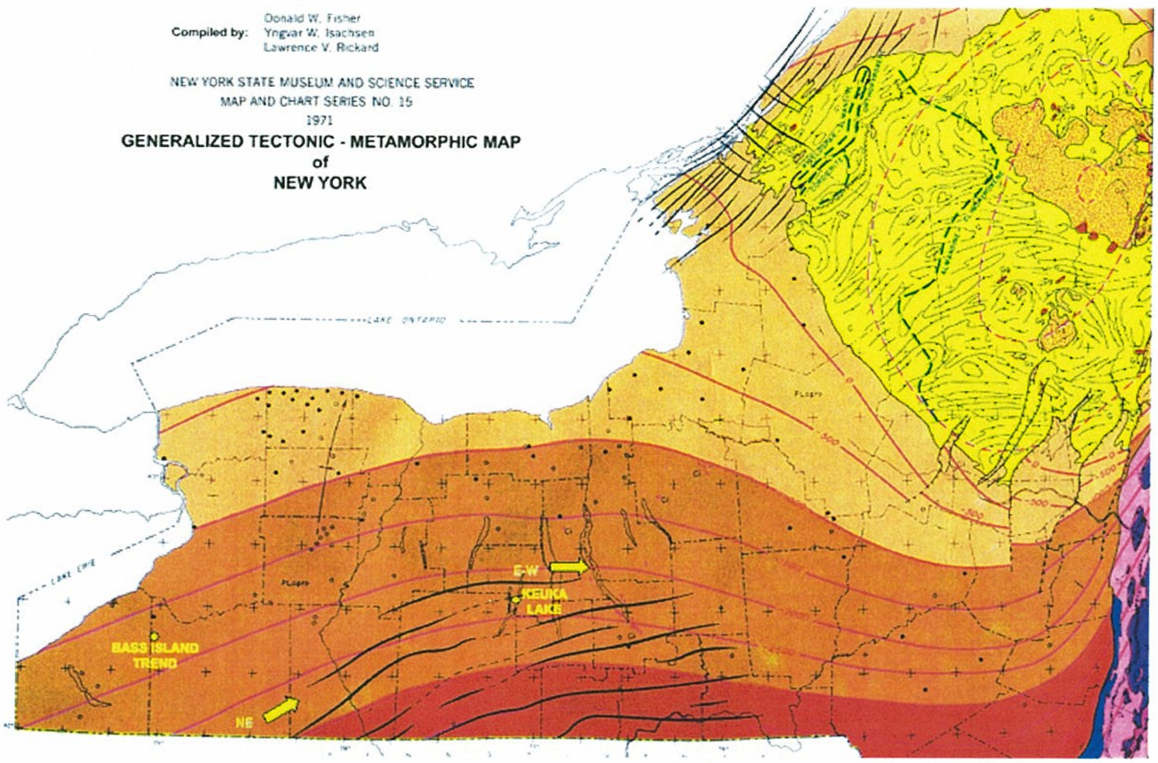

Figure 20: Map of New York showing the change in trend of the Alleghenian fold axes.

Timing of Fracturing Relative to Generation of Hydrocarbons

In pursuing fractured reservoirs, it is important to determine which fracture system is the open (or extensional) fracture direction. In many reservoirs, it is the fracture zone perpendicular to the least compressive stress, or parallel to the maximum horizontal stress (Figure 21). Over much of eastern North America today, the maximum horizontal compressive stress trends east-northeast to northeast. Thus, the open fractures parallel that trend. Many of the Devonian shale fields lie on fracture density highs of this orientation (EarthSat, 1997).

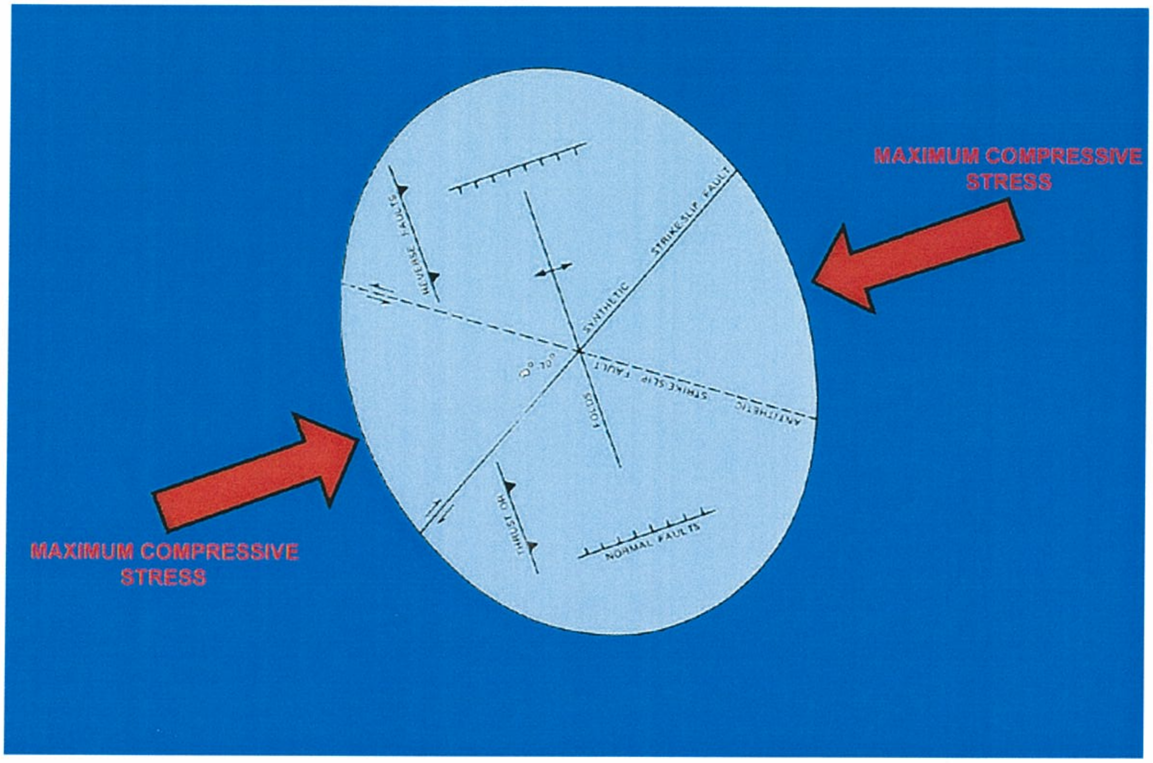

Figure 21: Stress ellipsoid showing the current Maximum Compressive Stress direction in eastern North America.

However, with rocks that are susceptible to solution, dolomitization, or mineralization, one needs to consider both the stress history and the thermal history of maturation/ generation/ and expulsion of the source rocks as well as the current state of stress. This is so because the early expulsed fluids from source rocks are highly corrosive and can greatly enhance the porosity and permeability of fractures through which they pass by virtue of solution and dolomitization. Conversely, the orientation of the fractures used for initial migration or the orientation fractures created by autohydrofracing related to the overpressuring associated with the conversion of kerogen to hydrocarbon is determined by the stress field at that time.

In central and western New York State, the maximum principal compressive stress was oriented northwest to west-northwest during the Taconic, Acadian and Alleghenian orogenies. Thus, northwest to north-northwest fractures would have been open (Figure 22) at those times. Folds and thrusts from all three orogenies would strike northeast. The folding and thrusting produced an abundance of fractures parallel to fold axes or thrusts.

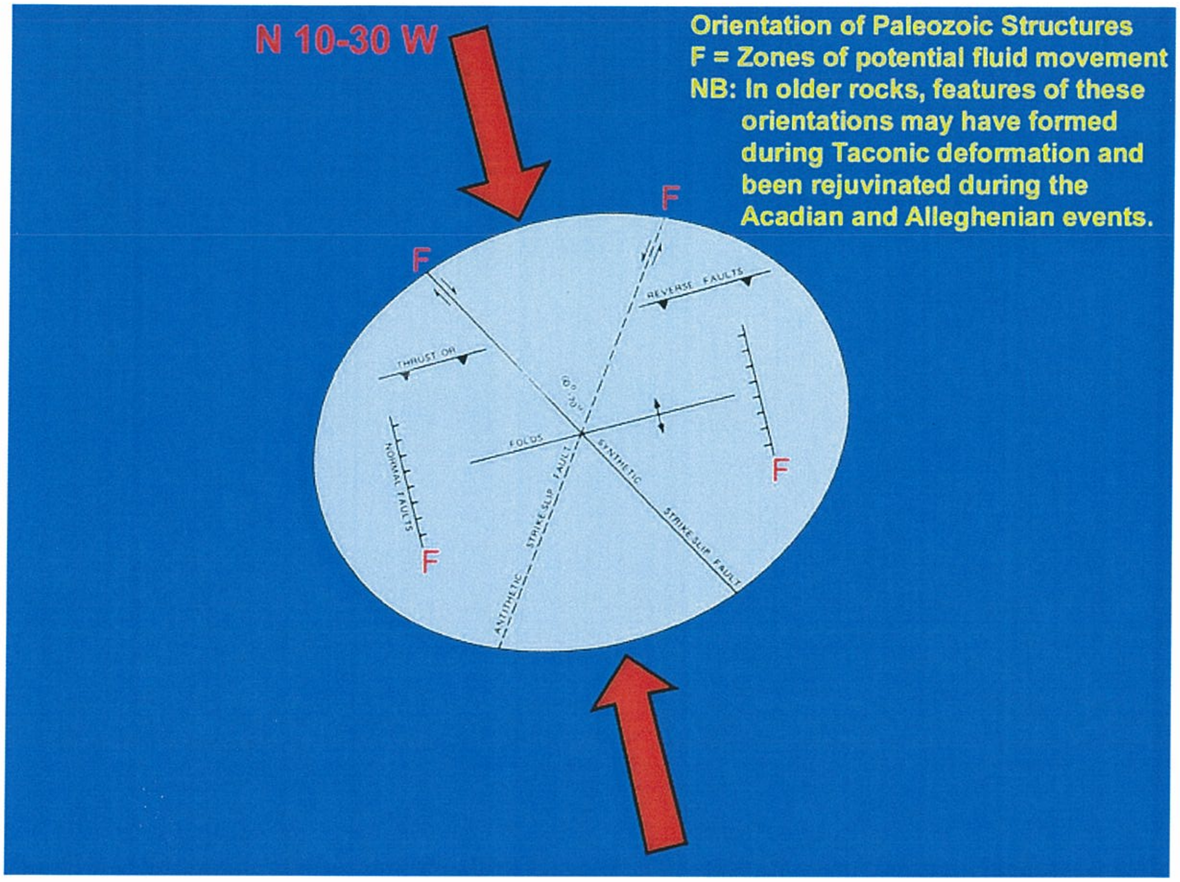

Figure 22: Stress ellipsoid for central and western New York during Paleozoic time.

Generation and expulsion may have begun by Acadian, but was certainly underway by Alleghenian time. Consequently, the porosity and permeability of north-northwest fracture systems may have been enhanced and preserved (once a surface is wetted with hydrocarbons, secondary mineral growth is unlikely).

Figure 23 shows fractures that may have served as fluid migration pathways. Considering the tectonic and hydrocarbon generation history in this area, one might expect good production rates from Trenton-Black River reservoirs along north-northwest (fracture C) or east-northeast-trending fracture systems (fracture A). For Devonian reservoirs, the east-northeast fractures (fracture A) would be the first choice as a target.

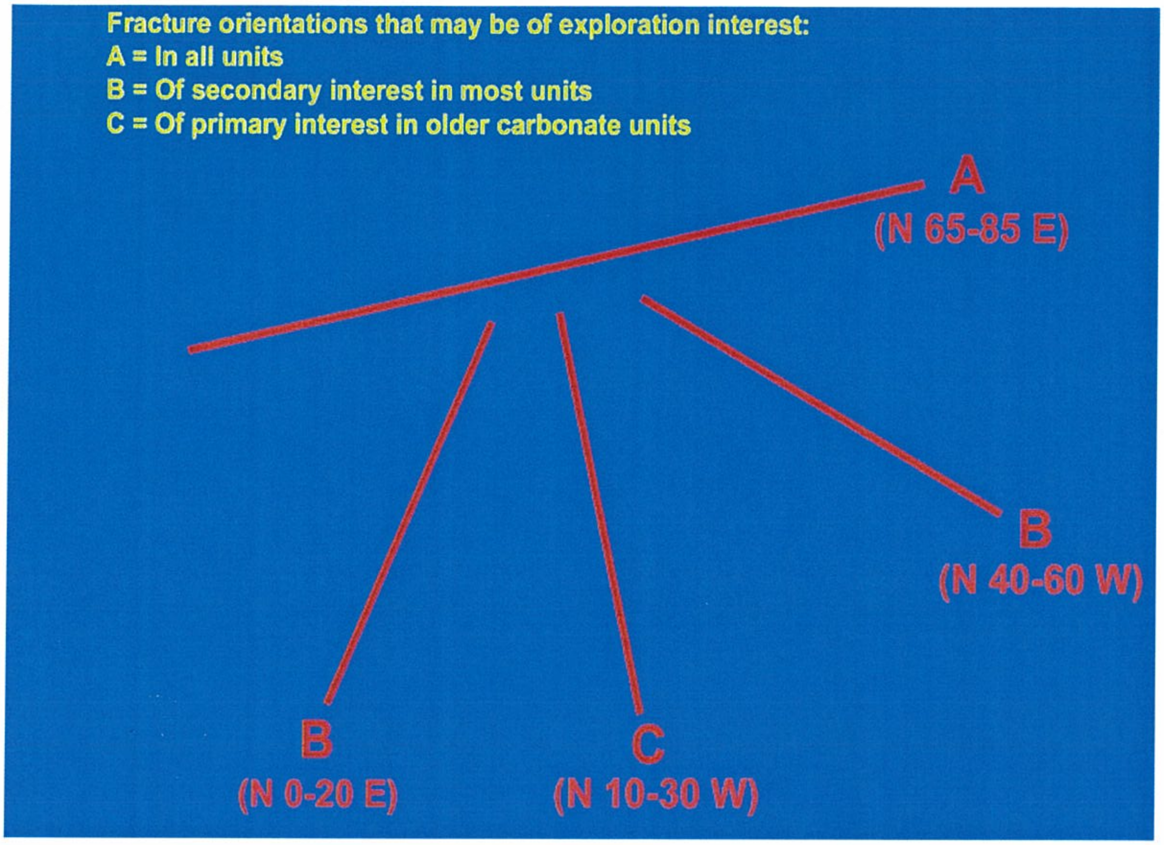

Figure 23: Fracture orientations of exploration interest in central and western New York.

Summary and Conclusions

- ASTER hyperspectral data highlight a number of fracture zones verified in the field and by comparison to other data sets and previous work. Spectral signatures mark many of these zones.
- Fractures mapped from the ASTER data coincide with known and postulated faults, fracture intensification domains, and cross-strike discontinuities.
- Some of these fracture zones appear to mark the edges of structural blocks.
- The spectral anomalies appear to be related to changes in vegetation. The changes in vegetation are those that one would expect from the presence of hydrocarbons.
- Soil gas anomalies, seeps, and production are associated with some of the east-northeast and north-northwest–trending fractures.

The economic consequences of these observations may be extensive. First, Jacobi (2002) has shown the relationship between faults and fractures mapped on satellite data in New York State and seismicity. This has important implications from construction of several types of civil works, and the burial and storage of toxic wastes.

These observations also suggest that combining the fracture interpretation of ASTER hyperspectral data, and a knowledge of the stress history and thermal history of an area may prove to be a useful exploration tool for fractured carbonate reservoirs. Because of the low cost of these data, they constitute an excellent guide to the use of more expensive techniques such as geochemical sampling, seismic surveys, and drilling.

Thus, exploitation of these data could greatly accelerate the exploration for fractured reservoirs including: Devonian brown shales, fractured quartzite and fractured carbonates (hydrothermal dolomite).

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