# 3-D Seismic-Based Definition of Fault-Related Porosity Development Trenton-Black River Interval, Saybrook, Ohio

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## Abstract

Oil and gas reservoirs of the Ordovician Trenton-Black River interval in the Appalachian Basin are commonly associated with fault-related hydrothermal dolomites. However, relationships between porosity development and fault geometry in these fields are poorly documented. In this paper we integrate 3-D seismic and wireline data from the Trenton-Black River interval at Saybrook Field in northeastern Ohio to study relationships between faulting and porosity development there. Faults were mapped using a combination of amplitude and coherency versions of the seismic data, and a 3-D porosity volume was generated for the Trenton-Black River interval by integrating attributes derived from the seismic data with log-based measures of porosity.

The productive trend in the Trenton-Black River interval at Saybrook is controlled by a 3.4mi (5.5 km) long, NW-SE oriented basement fault that was probably reactivated during the Taconic Orogeny (i.e., Late Ordovician). Strike-slip movement along the fault generated en echelon synthetic shear faults that branch at least 1350ft (411.5m) upward into the Trenton-Black River interval. The best porosity is developed in areas between overlapping synthetic shear

faults. Antithetic shear faults probably formed at these locations, and when combined with minor dip-slip movement created conduits for subsequent porosity generating fluids. Circular collapse structures associated with localized extension between overlapping shear faults are the primary drilling targets, and horizontal wells running parallel to the strike of the fault would have the best chances of intercepting good porosity development.

## Introduction

This paper integrates 3-dimensional (3-D) seismic-based structural interpretations and a 3-D seismic attribute study to examine the relationships between faulting and porosity development in a Trenton-Black River reservoir of the Appalachian Basin. Interest in the Ordovician Trenton-Black River interval has been growing because of continued drilling success in eastern North America and because of its potential as an analog for other reservoirs. In particular, the observed relationships between faulting, dolomitization and porosity development, combined with the presence of hydrothermal dolomites in at least some Trenton-Black River reservoirs (Smith et al., 2003; Jacobi et al., 2004), are similar to those observed in hydrothermal dolomite reservoirs elsewhere, for example the Ladyfern discovery of western Canada (Berger and Davies, 1999; Boreen and Colquhoun, 2003).

There are no published 3-D seismic-based structural studies of the Trenton-Black River interval. The prolific Albion-Scipio field in the Michigan Basin has been well studied (Hurley and Budros, 1990; Prouty, 1989), as have several Trenton-Black River fields in southern Ontario (Middleton et al, 1993;

Carter et al., 1996). However, most exploration and development of these areas was completed using two-dimensional (2-D) seismic data or log-based mapping, which may fail to capture the true structural complexity of these plays. In 2-D seismic profiles, Trenton-Black River targets have been associated with a combination of characteristics including structural sag along the horizon and dimming of reflection amplitudes in the area. These features have been interpreted as a response to faulting at depth and the resulting brecciation, dissolution collapse, and low velocity pull-down from the ensuing dolomitization.

Seismic attribute studies have been used successfully to predict the 3-D distribution of physical properties such as porosity (Russell et al., 1997; Scheulke and Quirein, 1998; Hampson et al., 2001; Leiphart and Hart, 2001; Tebo and Hart, 2005). Porosity in Trenton-Black River reservoirs is thought to be associated with dolomitization. Therefore, by using seismic attributes to image porosity, we sought to delineate the extent of the dolomitization, a possibility suggested by the results of Pearson and Hart (2004). Furthermore, by integrating the results of 3-D seismic-based structural mapping with an attribute-based porosity prediction, we sought to further constrain the controls on the development of the dolomite reservoir.

## GEOLOGICAL SETTING AND FIELD HISTORY

The Trenton-Black River interval has produced hydrocarbons in the Michigan and Appalachian Basins since 1884. The most productive fields include the 500 million barrel Lima-Indiana and the 290 million barrel Albion-Scipio Trends. Although some Trenton-Black River reservoirs in the

Appalachian Basin are associated with facies-related or fractured-enhanced limestone porosity, the most prolific fields produce from dolomites (Keith, 1989). There are two types of dolomite reservoir, those associated with regional dolomitization and localized fault-related dolomite. Regional dolomitization has been observed in the Michigan Basin (Wickstrom and Gray, 1989), but in Ohio, Ontario, New York and other areas exploration has focused on linear, fault-related trends that are exemplified by the Albion-Scipio Field.

Saybrook Field is located in northeastern Ohio, near the northwestern edge of the Appalachian Foreland Basin that covers much of the northeastern United States and parts of eastern Canada (Fig. 1a). There are a number of complex basement structures in the Ohio area, such as the Cambridge Arch that runs approximately north-south and is approximately 80mi (129km) to the southwest of Saybrook Field (Root, 1996). Another important feature is the Bowling Green Fault Zone that marks the western limit of the Grenville Province (Wickstrom and Gray, 1989). The Lima-Indiana Trenton-Black River Trend is on the Bowling Green Fault Zone, with fracture-related reservoirs in its vicinity accounting for up to 45% of the total 500 million barrels that have been produced there (Keith, 1989).

A simplified stratigraphic column for lower Paleozoic rocks in northeastern Ohio is shown in Figure 2. The Trenton-Black River interval was deposited during the Mid-Ordovician as shallow sub-tidal bioclastic shelf and platform carbonates (Wickstrom and Gray, 1989; Middleton et al., 1993). The Black River consists of shallow water muddy carbonates, whereas the Trenton carbonates were deposited in a deeper water setting with shale lamina and fossiliferous intervals throughout. In northwestern Ohio the Trenton-Black River interval generally consists of tan to gray, micritic to finely crystalline limestone. Shale and bentonite layers may can be used locally as log markers (Wickstrom and Gray, 1989). The Utica Shale sharply overlies the Trenton and the contact between these units has been interpreted as a submarine hardground (Keith, 1989; Budai and Wilson, 1991). This thick undifferentiated package of shale is considered to have been deposited in response to deepening of the basin and increased clastic influx resulting from erosion of the Taconic Mountains to the southeast.

The Saybrook discovery well, York UN #3, was drilled in 1997 based on exploration using 2-D seismic lines. Production at Saybrook began in 1997 and is from fractured, brecciated and vuggy dolomite of the Trenton-Black River interval that is laterally sealed by unaltered limestone and vertically sealed by the Utica Shale and/or unaltered limestone. Originally the structure of the field was interpreted to have formed from karsting related to Ordovician thrusting and subsequent subaerial exposure (MacKenzie and Grubuagh, 2000). Other producing intervals in the area include the Clinton and Rose Run sandstones (the latter unit included in the Trempealeau in Fig. 2). Trenton-Black River production peaked in 2001, and by the end of 2003 (the last year for which production data were available) seven wells had produced almost 5.3 BCF of gas.

A previous geophysical study of Saybrook was completed by Minken (2002). He unsuccessfully used various analyses such as amplitude variation with offset (AVO), model-based acoustic inversion and probabilistic neural networks in an attempt to characterize the productive trend. His study was completed using a limited suite of the available wells (only the 12 wells closest to the producing trend were included), and little consideration was given to the structural setting and its potential influence on the distribution of dolomite or porosity.

## DATABASE AND METHODOLOGY

The database for this study consisted of a 3-D seismic survey and well logs (Fig. 1b). The seismic survey was acquired with a dynamite source and covered an area of approximately 35mi$^2$ (56 km$^2$) with a bin size of 110ft (33.5m) by 110ft (33.5m).

We had digital logs for 27 wells within the 3-D survey area, although not all of the wells penetrated the entire Trenton-Black River interval. All of the wells had caliper, gamma ray, neutron porosity, density porosity, density, and photoelectric absorption logs. Acoustic logs were available for only two wells (Schoneman #1 and KR CAL UN #1). As such, “artificial” acoustic logs for other wells were created using multivariate regression to estimate the sonic log values from a combination of the other well logs. Details of this process are provided in Sagan (2004).

We picked stratigraphic markers in the well logs, then sonic and density logs were used to generate synthetic seismograms that were tied to the seismic data. This step allowed the log picks to be associated with seismic reflections that were then mapped in the seismic data using a combination of auto-tracking and handpicking – the latter being necessary in areas around faults. The major faults in the area were mapped using both amplitude and coherency versions of the seismic data. Horizon-based attributes such as dip angle, azimuth, and various measures of curvature (Roberts, 2001) were extracted from these horizons to look for subtle structures. Various visualization methods were used to analyze relationships between structural features.

A seismic attribute study was undertaken following the structural interpretation. We sought to create a porosity volume for the Trenton-Black River interval using the total average porosity (PHIA), which was generated from the average of the density porosity and neutron porosity logs. This type of log is an effective means of reducing the influence of lithology on the measured porosity (Hearst et al., 2000). We used the methodology of Hampson et al. (2001) to identify the best combination of seismic attributes for predicting PHIA. We then trained a neural network to convert the seismic amplitude data to a porosity volume for the Trenton-Black River interval, essentially replacing seismic traces with porosity logs in that interval. Finally, various visualization techniques were employed to examine relationships between porosity and structural features.

# RESULTS

## Stratigraphy

The Trenton-Black River interval at Saybrook averages 525ft (160m) in thickness and consists of relatively pure limestones with some minor interbedded shale and bentonite layers. It is sharply overlain by the ~1750ft (533m) thick Utica Shale (Figs. 3, 4). The Black River is marked by a somewhat cleaner, blockier gamma ray response than that of the Trenton (Figs. 3, 4).

Neutron-density cross plots and photoelectric factor logs indicate that the reservoir is in dolomite, either as thick dolomite (e.g. Downes #3; Figs. 3, 4) or in thin dolomite layers (as in Downes #1 and Mantell K #1; Fig. 4). Not all dolomite is porous, but significant porosity only occurs in the dolomitized zones (Fig. 3), with PHIA values ranging from 2% to 22%. The total dolomite thickness varies from 15ft (4.6m; Mantell K #1) to approximately 345ft (105m; Downes #3) and porous dolomite can be present anywhere from 22ft (6.7m) to 384ft (117m) below the top of the Trenton (i.e., throughout the Trenton-Black River interval). It is clear that the primary control on porosity development at Saybrook Field is not stratigraphgy. Many of the producing wells were not drilled all the way through the interval and so it is not possible to evaluate the true thickness of porous dolomite for these cases.

Synthetic seismograms were generated using a zero-phase statistical wavelet that was extracted from the data over an interval (600 – 900 ms TWT) that encompasses the Trenton-Black River. The synthetics were then tied to the seismic data with the primary aim of tying the interval below 600 ms. The correlation for the two wells with original sonic logs was excellent over the 600ms to 900ms interval (calculated correlation coefficients were .87 for Schoneman #1 and .82 for KR CAL UN #1; Fig. 5). In general the synthetics generated from "artificial" sonic logs also tied very well, with correlation coefficients that commonly ranged from 0.66 to 0.84. Sagan (2004) discussed the synthetics ties for all of the wells.

The seismic character of the principal stratigraphic horizons is illustrated in Figures 5-7. The top of the Trenton is a relatively high-amplitude peak at about 790ms in the seismic data whereas the top of the Black River corresponded to a zero crossing from trough to low-amplitude peak approximately 15ms below the Trenton. A high-amplitude peak at about 855ms corresponds to the top of the Trempealeau, although there were many thin beds in its vicinity that have might affected the seismic character of the Trempealeau on some of the well ties. A high-amplitude peak separating chaotic reflections below from stratified reflections above was chosen to represent the structure of the Basement Time-structure maps of the top of Basement, the Trenton and the Siluro-Devonian Big Lime unit are shown in Figure 8.

## Fault Mapping and Interpretation

### *Fault Mapping*

A combination of timeslices and vertical transects through coherency and amplitude versions of the seismic data was used to map faults. Saybrook Field overlays an approximately 3.4 mile-long (5.5km) basement fault that spans most of the seismic survey ("A" in Fig. 9). This fault is sinuous in plan view with a series of obvious bends across the survey. The overall strike of the main basement fault is approximately 122°-302°. There are also two smaller basement faults that are offset from the main trend, one striking 105°-285° to the northwest ("B" in Fig. 9) and another to the southwest ("C" in Fig. 9) that strikes 113°-293°. They both appear to extend past the survey limits, and are about 0.89mi (1.44km) and 1.06mi (1.7km) long respectively in the survey. The basement fault extends upward into the overlying Paleozoic section in a helicoidal (i.e., curved) manner (Figs. 10a, b, 11a). At its maximum, it cuts 1350ft (411.5m) into the overlying Utica Shale (where it dies out), and at the Trenton level the general strike is 118°-298°. In addition to this main fault, there are a series of five major en echelon faults at the Trenton-Black River level that trend obliquely to the basement fault (Fig. 11a). At various points they overlap to form concave-upward positive flower structures in cross-section, mainly in the center and the northwest parts of the survey (Figs. 6, 10a, b). The traces of these faults are somewhat sinuous, but on average their strike ranges from 097°-277° to 115°-295°. They vary in length from 0.28mi (0.45km) to 0.93mi (1.5km), and in height from approximately 1000ft (305m) to 300ft (91m).

Nineteen smaller faults were picked using coherency timeslices, although many appeared to be near the limit of seismic resolution. These features, only some of which are shown (in purple) in Fig. 11b, seem to be aligned in a slightly different orientation than the main en echelon trend, at about 090°-270° to 100°-280°. The faulted zone is about 1700ft (518m) wide in the middle of the survey, and up to about 2000ft (610m) wide in the north part of the survey where the previously noted offset basement faulting is present.

In addition to mapping the faults, surface attributes such as curvature, dip and azimuth were extracted from the horizons. These measures have aided in the detection of subtle faults that compartmentalize conventional reservoirs in the North Sea (Roberts, 2001) and in the identification of fracture-swarm sweet spots in tight-gas sandstones of New Mexico (Hart et al., 2002). The fault zone is clearly delineated in curvature displays of all horizons, exhibiting a general positive trend (i.e. convex-up) the length of the survey (Fig. 12a). The maximum curvature of the Trenton horizon was particularly effective in highlighting the areas along the main trend where there were depressions or “lows on the high”. These spots displayed negative curvature (concave-up) on the generally positive curvature trend of the structural high that corresponded to the main fault ridge. As indicated on Figure 12a, the ridges between the collapse structures are approximately parallel to one another, and have a trend of approximately 072°-252°, or 50° from the strike of the main basement fault.

*Interpretation*

Before examining the fault zone morphology, it is important to consider the conditions that lead to its formation. Although it has been suggested, based on the presence of aeromagnetic highs, that some Trenton-Black River reservoirs in southern Ontario and New York might overlie igneous bodies and associated fault networks (e.g., Carter et al., 1996), the slight positive magnetic values that are present in the Saybrook area (-75nT to 175nT) are insignificant when compared to values interpreted as plutons in western Ohio (<1000nT; von Frese et al., 1997). Additionally, not all of the Trenton pools in Ontario are directly associated with anomalies (Carter et al., 1996). The Basement faulting may have developed in response to events that occurred in relation to the Grenville orogeny and/or later Precambrian rifting. The strike of the Saybrook fault is similar to that of other Grenville-aged fault zones in northeastern Ohio, such as the Akron, Suffield, Smith Township and the Highlandtown and Middleburg faults that are oriented at 125°-305° (Root, 1996). Hart et al., (1996) used 3-D seismic data to map similar northwest-southeast striking faults affecting the Knox Unconformity (Fig. 2) in western New York. They concluded that these structures were produced by reactivation of a Grenville-aged structure.

Although we cannot unambiguously document lateral offset, the Saybrook fault geometry is consistent with a transpressional, left lateral strike-slip model. The elevated area around the faults suggests compression but, whereas reverse-fault displacement is present locally, normal fault offset dominates on vertical transects through most of the major faults. The upward-branching and helicoidal nature of the faults (Figs. 6, 10a,b) is typical of flower structures produced by strike-slip displacement (e.g., Naylor et al., 1986).

Using the nomenclature of Prouty (1989) the deformation above the main basement fault would be considered a shear fault zone, thus the faults in the area would be regarded as synthetic shear faults or antithetic shear faults depending upon their angular relationship to the basement fault (Mandl, 1988). The main synthetic shears change in orientation slightly from the level of the basement fault, as expected. The basement fault has a strike of 122°-302°; the extension of this fault at the Trenton-Black River is oriented at about 118°-298°, although it is somewhat sinuous. The other main synthetic shears at the Trenton-Black River level are oriented from 115°-295° to 097°-277° (7° to 25° from the basement fault). Where these synthetic shears overlap each other and meet at depth, they form the limbs of concave-up flower structures. If the primary stress is oriented at angles less than 45° from the basement fault, antithetic shears may form at angles of 48°-64° from the strike of the basement fault, although their presence would depend upon how evolved the system became (Mandl, 1999). Such values assume that the primary stress is mainly horizontal and depend upon the state of stress prior to shearing, as well as the internal friction angle of the faulted material (Fig. 12 b, c; Mandl, 1999; Ahlgren, 2001).

Although not imaged directly seismically, the ridges between the collapse structures were defined using curvature and their orientation (072°-252°) may attest to the presence of the antithetic shear faults. The smaller faults that were mentioned above also fit with the left-lateral shear model. Their orientations of 090°-270° to 100°-280°, on the order of 20°-30° off of the strike of the basement fault, indicate that they may have been precursors to the en echelon synthetic shear faults. As strike-slip systems evolve, the later-formed synthetic shears tend to become more in line with the movement of the underlying basement fault (Naylor et al., 1986; Ahlgren, 2001). Alternatively, some of the smaller faults may be accommodating displacement or space problems arising from the helicoidal nature of the main faults.

The faulting dies out in the overlying Utica Shale, and does not continue up into the Siluro-Devonian Big Lime (Figs. 6, 8), allowing for the timing of the main movement to be constrained to the Late Ordovician. This suggests that the faulting seen at Saybrook may be the result of far-field stresses from the Taconic Orogeny. Evidence of basement reactivation from this event has been recorded by Versical (1991) and Ettensohn et al. (2002) throughout the east-central United States, and other productive Trenton-Black River fields are associated with similar-age faulting (R. Bonnar, oral communication, 2005)

Figure 13 shows the location of Saybrook west of the New York Promontory, which according to Ettensohn et al. (2002) may have led to an increase in the lithospheric flexure that, in turn, caused basement reactivation in the area. The last and most intense activity of the Taconic Orogeny was on the northeastern edge of the New York Promontory, which would have been approximately east of the present location of the study area (Ettensohn et al, 2002). Versical (1991) used calcite twin strain analysis to establish the mean compression direction in Paleozoic strata of the Michigan Basin as SE-NW to approximately E-W. He also found that fault models that combined dip-slip movement and compression at angles of 20°-30° from a basement fault generated concave-up flower structures (as seen at Saybrook). Using the general strike-slip criteria that the primary stress is oriented at 45° to the direction of movement (122°-302°), the resulting primary stress at Saybrook would be oriented approximately 077°-257°, slightly north of east. However, given a zone of pre-existing weakness (i.e., a basement fault), reactivation may occur under a primary stress orientation that is less than 45° (as was measured by Versical (1991)). We conclude that the strike-slip faulting at Saybrook probably developed in response to approximately ESE-WNW compression during the later stages of the Taconic Orogeny.

It is important to recognize that the damage zone associated with the seismically imaged faults probably contains more small-scale faults and fractures than could be imaged seismically. The mapping of the main faults completed here should be considered a first order approximation of the true fault zone morphology.

## Attribute Study

After establishing the structural context and mapping the horizons, we sought to find and exploit an empirical relationship between log-based physical properties (porosity) and seismic attributes that would allow us to predict porosity in the 3-D seismic survey area away from well locations. An attribute is a derivative of the seismic data that may be extracted over an interval or along a horizon (Brown, 1996). The goal of the attribute study was to create a porosity volume for the Trenton-Black River interval. This result allowed us to examine the distribution of porosity in 3-D, an improvement over a porosity map in that we could look at 3-D relationships between porosity and faulting.

The target log was the average porosity log (PHIA), calculated as the average of neutron and density porosity, resampled to have a 2ms sample rate (i.e., the same as the seismic data). The interval of interest was defined from the top of the Trenton to the base of the Black River (identified as the Gull River) or

TD, whichever was the lowest level penetrated by the well. A subset of 18 out of the total 27 wells was used in the porosity prediction. These wells were selected largely based on their tie with the seismic data using the statistical wavelet. Non-producing wells having synthetics that tied with correlation coefficients greater than 0.75 and all producing wells (regardless of how they tied to the seismic data) were used. Two producing wells (York UN #3 and Strong UN #1) were not used because they were both deviated and they could not be adequately tied above the Trenton.

The porosity prediction was undertaken using methods proposed by Hampson et al.(2001) and used by Leiphart and Hart (2001) and Tebo and Hart (2005) amongst others. In essence, the method consists of identifying an empirical correlation function between seismic attributes and log-derived physical properties at well locations. Once the relationship has been established, it is used to predict physical properties in the seismic survey area away from wells. Multivariate regression, neural networks and geostatistics have all been used to first identify the nature of the empirical relationships (when present) and then use those relationships to predict physical properties. Neural networks, such as the one employed in this study, have proven to be more effective in some cases than multivariate regression in modeling the non-linear relationships that may exist between physical properties and seismic attributes (Leiphart and Hart, 2001; Hart and Chen, 2004).

Stepwise linear regression and validation testing indicated that a combination of six attributes most effectively predicted porosity (Sagan, 2004).

These attributes were the RMS (root-mean squared) amplitude, perigram, reflection strength, derivative of reflection strength, integrated trace and the cosine of instantaneous phase. When applied to the data, the resulting prediction (based on multiattribute linear regression) had a correlation coefficient of 0.73, with an average error of 1.36% (porosity units). These attributes were then used to train the neural network. The neural network had a training error of 0.96% (porosity units) and an overall correlation of 0.89 (Fig. 14a, b). This neural network was then applied to the entire seismic survey from the Trenton to the Trempealeau in order to predict the 3-D distribution of porosity for that interval. Representative vertical transects and stratal slices through the porosity volume are shown in Figures 15 and 16 respectively. Various interactive visualization technologies, including volume rendering of the porosity volume, were helpful for examining the 3-D distribution of porosity and relationships between faulting and porosity development. Unfortunately these results do not reproduce well in static 2-D images and so are not shown in this paper.

It is important to justify the use of the attributes used in the prediction in order to ensure that they are geologically valid (e.g., Schultz et al., 1994). The single best attribute to use was the RMS amplitude (calculated in a sliding window of 100ms), which has proven to be significant when tracking lithological changes (e.g., from limestone to dolomite) and amplitude anomalies (Chen and Sidney, 1997). The next two best attributes found by the prediction were perigram and reflection strength, which are interrelated. Perigram was first described by Gelchinsky et al. (1985) and is the low-frequency component of reflection strength that is then subtracted from the reflection strength such that it contains both positive and negative samples. The reflection strength is the amplitude independent of phase. Both perigram and reflection strength are useful for detecting phenomena such as thin-bed tuning effects, which may be useful in the Saybrook area given the variable thickness of the porous dolomite (15ft-345ft or 4.6m-105m), and both respond to changes in acoustic impedance, which in turn is directly influenced by lithological changes (as from limestone to dolomite) or other variations in physical properties (Chen and Sidney, 1997). The derivative of the reflection strength is a measure of the rate of change of that attribute. It conveys discontinuities in the amplitude, in contrast to changes in magnitude (as imaged by perigram and reflection strength), which may be caused by faulting or fractured rocks (Taner, 2001). The integrated trace is calculated performing integration such that the output trace is the sum of the original samples including the original sample. It shows contrasts in physical properties and can be considered a first-pass estimate of acoustic impedance, which is a function of lithology and porosity. Finally the cosine of instantaneous phase is commonly used as a measure of continuity that is independent of amplitude. As such it can be useful in delineating faulted zones and tuning effects (Chen and Sidney, 1997).

Some of the attributes that were found to be optimal predictors may appear to be somewhat redundant, such as perigram, reflection strength, and derivative of reflection strength. However, it can be proven mathematically that the step-wise regression methodology will only select attributes if they add information (Hampson et al., 2001). We conclude that the attributes all 'see' the porosity in slightly different ways.

A comparison of the predicted versus the actual porosity logs shows that in some of the wells, such as Dalin E UN #1 and Downes #1, the neural network under-predicted values at the base of the logs (Figure 14a). This is also evident in the cross plot of predicted versus actual values as those underpredicted values are well below the trend (Figure 14b). This effect is due to artifacts in the prediction for wells that terminate within the Trenton-Black River interval. Some higher porosity values were also predicted in the upper few milliseconds of the Trenton. The upper part of the Trenton limestone does tend to have slightly higher PHIA porosity (2-3% as at Rife #2 and Merilla L UN #5) than undolomitized rocks lower in the Trenton-Black River (which average 0-2%), although without core the reasons for this difference are unknown.

The prediction accurately illustrates the porosity especially in cases where the trend was just missed by drilling, as in the case of Downes #2 and Downes #3 (Fig. 15b). Although only 580ft (177m) separates these two wells (Fig. 1), Downes #3 contains porosity while Downes #2 does not. Unreasonably high porosity values around the edges of the survey, especially in the west and northwest, are most likely related to poor seismic data quality in those areas (c.f., Marrroquin and Hart, 2004).

## DISCUSSION

We focus our discussion on the relationship between faulting and porosity development. The regularity of the locations of the small collapse structures where the porosity is preferentially developed strongly suggests some structural control on the development of the porosity. Rotation of parallel antithetic shear faults can occur in an area of direct shear (Ahlgren, 2001). Discrete packages of rocks may form that rotate slightly in the opposite direction of the main shear (Figure 12a, b; Schreurs, 1994; Alhgren, 2001). With a left-lateral strike-slip system, antithetic rotation would occur in conjunction with north-south extension. This movement combined with minor dip-slip movement of the Saybrook fault system would create sag, and cause dilation along the faults, thus facilitating the upward migration of fluids. If Mg-rich fluids rose along these conduits, entered the formation and became concentrated in the structural highs, dolomitization could proceed (Warren, 2000). The associated brecciation and dissolution in these conduits could lead to the creation of the small collapse structures seen along the main ridge at Saybrook. This dolomitization may have been responsible for obliterating most of the direct evidence of antithetic movement. Furthermore, antithetic shear faults usually have little offset and are typically smaller in size than synthetic shear faults, making them more difficult to image seismically (Schreurs, 1994; Mandl, 1999; Ahlgren, 2001). Another factor to consider is that the amount of deformation along a fault is not constant (Ahlgren, 2001). Thus antithetic faults may have formed preferentially in areas where there was better development of the synthetic shears, as in the center of the main fault trend and in the northwest portion of the area. Cross-sections through the porosity volume show the relationship of the faults to the porosity in the vicinity of the wells. These cross-sections illustrate that the porosity is best developed in areas between the synthetic shear faults (i.e., the limbs of flower structures; Fig. 15a, b).

The highest porosity values are concentrated in the areas of intense faulting, especially where the synthetic shear faults overlap and meet at depth to create flower structures (Figs. 15a,b, 16). This may indicate that fluid migration pathways were better developed in these areas. Slices through the porosity volume (Fig. 16a-d) show that the porosity is more widespread near the top of the Trenton-Black River interval than near its base. This may be related to the fact that the faulted zone is smaller at the base of the flower structures in the Trenton-Black River, and thus the antithetic shear faults are not as well developed.

Because core or cuttings were unavailable for this study, it was not possible to determine the type of dolomite present or the temperature or other conditions at the time of its formation. However, high-temperature saddle dolomite (hydrothermal dolomite) is known from other Trenton-Black River fields in the region, for example in southwestern Ontario (Middleton et al., 1993), northern Indiana (Yoo et al., 2000) and central New York (Smith et al., 2003). The relationships demonstrated above between porosity, dolomite and faulting at Saybrook Field are consistent with a hydrothermal origin for at least some of the dolomite, but detailed geochemical analyses would be needed to test this hypothesis.

The source of the dolomitizing fluids remains enigmatic. For example, studies in the Michigan Basin and in southwestern Ontario have found that a

Silurian source is consistent with isotopic work done in the area (Granath, 1991; Middleton et al., 1993). Yoo et al. (2000) concluded that saddle dolomite in their area precipitated from basinal fluids emerging from the Michigan Basin. Activity related to Alleghanian deformation has likewise been proposed as a possible driver for fluid flow, moving the brines northward through the basin (Farquhar et al, 1987; Prouty, 1989; Hurley and Budros, 1990; Budai and Wilson, 1991). In the absence of geochemical analyses, we choose not to speculate about the origin of the dolomitizing fluids at Saybrook.

The non-uniform distribution of porosity along the structural trend (e.g., Fig. 16) has exploration and development implications. If a vertical well does not hit porosity, the chances of hitting reservoir-quality rock could be increased by sidetracking and drilling horizontally along the structural trend. This lesson could be used to reduce risk in areas without 3-D seismic data, providing that the structural trend could be adequately defined by 2-D seismic, aeromagnetic or some other form of data. However, those data sets will not be as useful for defining the structure as 3-D seismic data and cannot be used to generate porosity volumes. In other areas, such as Ontario and New York where Trenton-Black River form well-defined grabens, horizontal wells are typically drilled perpendicular to the axis of the grabens in an attempt to connect to graben-bounding fracture systems (R. Bonnar, pers. comm., 2005). If dolomitizing fluids preferentially migrate upward in extensional zones, then most places along the linear grabens of Ontario or New York could be sites of dolomitization, porosity development and open, extensional fractures. In a transpressive setting, such as at Saybrook, these conditions are only present locally where combinations of synthetic and antithetic shears generate localized extension. We conclude that proper characterization of the type of deformation will help operators to define the optimum drilling orientation for horizontal wells.

## CONCLUSIONS

This study established a relationship between a seismic attribute-based porosity prediction and the structural framework of a dolomitized Trenton-Black River gas field. This was accomplished through first mapping the faults in the area and then training a neural network to create a porosity volume of the Trenton-Black River interval. The neural network used six attributes identified through step-wise linear regression and was found to adequately predict the PHIA porosity of the wells included in the training set. The predicted trend closely followed that of the producing wells in the field.

The porosity prediction was used as a proxy for dolomite distribution given that, according to well logs, only dolomites contain significant porosity in the area. Reactivation of the basement fault that underlies the field appears to have created a ready network of fluid pathways that allowed the Mg-rich fluids to circulate and dolomitize the limestone host rocks. The interaction of synthetic, antithetic and dip-slip movement along the fault zone was responsible for creating these pathways. Seismic porosity imaging in which the best porosity appears to be developed in the areas between synthetic shears, where antithetic faults would be most likely to form, supports this hypothesis. This is especially apparent in areas where the synthetic shears form flower structures, indicating that these structures may have been more efficient fluid migration pathways.

The combined use of neural networks to predict porosity and fault mapping in 3-D shows that faulting is probably the key control on porosity development, and hence dolomite distribution at Saybrook. For plays similar to Saybrook in which the reservoir development is related to a strike-slip fault environment, detailed fault mapping combined with attribute-based porosity prediction should help to illuminate the impact of these structures.

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