Fracture evaluation of the Southwest Regional Partnership’s San Juan Basin Fruitland coal carbon sequestration pilot site, New Mexico

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Abstract

Geological and geophysical characterization of carbon sequestration reservoir and capping strata are essential to evaluate site integrity and viability for long term retention of CO₂. In this study we analyze data on fractures and possible faults in the surface, primary seal and cover strata at the Southwest Regional Partnership on Carbon Sequestration’s San Juan Basin Fruitland Coal pilot test. We use QuickBird image-mapped fracture interpretations, surface-mapped fractures, FMI log based fracture interpretations, fast-shear directions measured using the Sonic Scanner, and attribute analysis of 3D seismic data to determine if fracture systems are present, their directional properties and whether they present risk of vertical migration through the sealing strata. The pilot test was performed in the High Rate Fruitland coal production fairway in the north-central part of the San Juan Basin. The project is funded by the U.S. Department of Energy and is managed by the National Energy Technology Laboratory.

Directional analysis of QuickBird-mapped fracture systems reveals statistically significant NE and NW trending fracture sets that are consistent with local basin geometry. Surface-mapped fracture distributions are less systematic. Near-surface shear wave anisotropy and drilling induced breakouts support interpretation of a direct relationship between near-surface fracture systems and retained tectonic stress anisotropy. Shear wave anisotropy in the vicinity of the borehole is characterized by an average fast-shear direction of N37E along the length of the borehole from 286 to 3132
feet subsurface. Drilling induced breakouts are tightly clustered with mean orientation of N57W. Attribute analysis of 3D seismic generally reveals the presence of field scale discontinuities that form NE trending clusters (average trend of N58E). Linear discontinuities with average N50W to N61W trend are also observed in some timeslices. Attribute processing also reveals discontinuities in profile view that are interpreted as minor faults and fracture zones. The injection well FMI log reveals numerous open fractures with variable trend. Aperture distribution is positively skewed with mode of 0.08 inches. The results of the analysis suggest that fractures, fracture zones and possible faults may disrupt the reservoir and primary sealing strata. Interpreted faults and fracture zones have limited vertical extent and major penetrative faults are not observed in the 3D seismic interpretations. The results provide the basis for developing discrete fracture networks for use in flow simulation to evaluate the potential for significant long term leakage through sealing strata.
Background

San Juan Basin Pilot Site - Analysis of fracture systems is undertaken in the area surrounding the Southwest Regional Partnership on Carbon Sequestration’s (SWP) coalbed methane carbon sequestration pilot site located in the north-central part of the San Juan Basin of northwestern New Mexico (Figure 1). The pilot test was undertaken in collaboration with ConocoPhillips as a joint enhanced coalbed methane recovery test and demonstration of CO₂ sequestration in deep, unmineable coal seams. The SWP conducted the pilot in the high permeability Upper Cretaceous Fruitland coals in High Rate Fruitland production fairway southwest of the northwest trending basin hinge (Figures 1 and 2). The Fruitland coals in the area consist of three prominent seams between 18 and 30 feet thick distributed over a 200 foot thick interval in the Fruitland Formation.

Figure 1: Structure contours on the top of the Pictured Cliffs Sandstone at the base of the Fruitland Formation. The pilot site is located southwest of the northwest trending basin hinge (Taken from Lorenz and Cooper, 2003).
Fassett (1991) notes that coalbed methane production from the Fruitland coals began in mid-1970s. Fruitland production is partitioned into four type-producing areas (Meek and Levine, 2006) and the pilot site is located in what was originally an over pressured area referred to as the High Rate Fairway, a giant unconventional methane gas play (Ayers, 2003). The High Rate Fairway lies in the north central part of the basin and wells in the fairway originally produced with flow rates greater than 10 MMCF per day. Meek and Levine (2006) noted that 11.4 Tcf of gas had been produced from the Fruitland through 2004. Wells in the High Rate Fairway typically come on line with initial production rates of about 1 MMCF per day and within a year increase to peak production rates of about 3.7 MMCF per day. After 12 years, the typical well will have produced about 13 BCF (Meek and Levine, 2006). Fassett (2000) reported that the Fruitland coals
contained nearly 50 TCF of gas. The pressure within the Fruitland coals at the pilot site prior to injection was very low at approximately 50psi.

The Southwest Regional Partnership pilot test is part of the U. S. Department of Energy’s Phase II regional partnership efforts that are designed to test procedures and approaches for intermediate scale CO$_2$ sequestration (Litynski et al., 2006). The test also evaluates the potential for CO$_2$ enhanced coalbed methane recovery from the depleted Fruitland coals in the area. CO$_2$ molecules are preferentially adsorbed to the coal matrix and displace methane molecules in approximately 2:1 proportions. While these returns make the process attractive for its potential to flush out residual methane from the coal matrix, the CO$_2$ molecules also take up more space than the methane molecules they displace and produce coal swelling that reduces reservoir permeability (Palmer and Mansoori, 1998).

Reservoir Integrity - Reservoir integrity is an issue of primary concern to all geologic sequestration efforts. Significant leakage of injected CO$_2$, if it were to occur, could nullify the investment of time and money spent in carbon capture and sequestration efforts and would pose impacts to environmental health and safety (Oldenburg, 2008). The present study is part of a broader series of studies undertaken on the San Juan Basin pilot site to monitor the site for leakage and to verify that long term storage is achieved. Monitoring activities include deployment and continuous monitoring of surface deformation in response to CO$_2$ injection using tiltmeters, and time-lapse offset vertical seismic profiles. Soil gas and tracer monitoring efforts were also undertaken at the site. The National Energy Technology Laboratory (NETL) injected small amounts of perfluorocarbon tracers and deployed an array of capillary adsorption tube samplers to detect
tracer leakage should it occur (Wells et al., 2007). In conjunction with the tracer monitoring effort, NETL has also undertaken extensive soil gas testing in an array surrounding the injection well. Background tracer and soil gas measurements were collected for more than a year preceding injection and continued on a regular basis during the injection period. In addition, core from the upper and lower Kirtland Formation, the major regional aquitard and seal overlying the Frutiland, was collected for analysis of the Kirtland’s sealing properties.

Acquisition and analysis of data to define the nature of fracture systems in the reservoir and sealing strata are important to the characterization of carbon sequestration sites. Fracture systems often facilitate fluid and gas migration. Extensive fracture characterization efforts were planned as part of our collaborative efforts with the SWP to document the presence and extent of fractures in the primary seal and cover strata. Fracture characterization of cover strata incorporated use of fracture detection logs (the Schlumberger FMI log) and measurements of in-situ stresses using borehole measurements of the fast shear wave propagation direction and drilling induced fracture orientations. The fast-shear direction provides a measure of the principal compressive stress orientation in the vicinity of the well bore. We also mapped surface fracture orientations throughout the area surrounding the site.

The DOE NETL metric for secure storage is 99% retention after 100 years, which requires that leakage remain at less than 0.01 % per year. The SWP originally planned to inject 75,000 tons of CO$_2$ into the Fruitland coals. Viable long term storage requires that leakage during the first year not exceed 7.5 tons. (Update with actual data – to date only 300 MMCF ). Spread roughly over approximately 1.5 square kilometers uniform leakage at 7.5 tons per year corresponds roughly to about 0.005 kilograms per square meter. In a
previous study of the West Pearl Queen pilot site located in southeastern New Mexico, 2090 tons of CO₂ were injected into a depleted oil reservoir. Monitoring of the site for perfluorocarbon tracers revealed leakage rates of 0.0085% per year (Wells et al., 2007). In the case of the West Pearl Queen site, leakage was attributed largely to vertical migration of CO₂ in the vicinity along the well bore. Well bores in the vicinity of carbon sequestration sites are considered among the most likely sources of significant short term leakage. Considerable effort is taken to locate and monitor all abandoned and actively producing wells in the vicinity of a pilot site. Significant long term leakage through the primary seal(s) could also be facilitated through interconnected open fracture networks. Although CO₂ storage in coal is primarily through CO₂ adsorption into the coal matrix, significant fracture permeability in the overlying strata could facilitate CO₂ leakage.

Fracture Systems and Coalbed Methane Production – Fracture systems presenting the greatest risk for leakage are those produced by late stage deformation that might have deformed reservoir and cover strata. Structure on the top of the upper Fruitland coal in the vicinity of the site (Figure 2) dips less than a degree to the northeast toward the basin axis. Regional seismic interpretations presented by Taylor and Huffman (1998) suggest the basin is underlain by a system of approximately N30E and N60W trending basement faults. Nine square miles of proprietary 3D seismic was provided to the Partnership. Seismic interpretation reveals the presence of small structures that have wavelengths of a couple thousand feet or so; however, major faults are not observed in the seismic data (Wilson et al., 2009). Fassett (2002) notes that the present-day structure of the San Juan Basin developed primarily during mid-Paleocene through Eocene time. The lower Eocene Cuba Mesa member of the San Jose Formation is exposed at the
surface across the site. The relatively sparse distribution of wells in the area provides no evidence for the presence of faults in the vicinity of the pilot site.

Lorenz and Cooper (2003) describe the complex tectonic interrelationships that existed during the Laramide orogeny and the development of the San Juan Basin. They conducted an extensive study of fracture systems in the Mesaverde and Dakota sandstones. Their study reveals the presence of pervasive north to north-northeast oriented extension fractures in exposures located primarily in the northern half of the basin including the pilot site. Fractures within coal seams play an important role in coal bed methane production and could have adverse effects on long-term CO$_2$ storage.

Ambrose and Ayers (1991), in their study of the geologic controls on occurrence and productivity of methane from the Fruitland Formation in the Cedar Hills area of the San Juan basin, note that maximum daily production rates are greatest where coal beds have been folded along a synclinal axis. They note that fractures associated with these folds may increase permeability and therefore enhance production. Tremain et al. (1991) also note that orientation, spacing, and mineralization of coal cleats create permeability anisotropy that influences methane production potential in the San Juan basin. Curvature analysis of 3D seismic data undertaken by Marroquin and Hart (2004) revealed a relationship between areas of high curvature and high producing Fruitland coalbed methane production wells. Although the structures along the axis of the San Juan basin are subtle associated fracture systems exert notable influence on coalbed methane production in the region.

**Site layout and characterization** - The pilot site (Figure 3) is covered by a variety of monitoring activities. Monitoring efforts undertaken through the SWP include
1) surface monitoring for perfluorocarbon tracers injected into the CO₂ stream by NETL; 
2) soil gas monitoring (NETL); 3) time-lapse vertical seismic profiling (Schlumberger); 
4) continuous monitoring of CO₂ concentration at three offset production wells; 5) 
periodic sampling to determine total production gas stream composition on eleven offset 
production wells; and 6) monitoring of surface tilt (Pinnacle).

Site characterization efforts incorporated in this study include 3D seismic 
coverage of the area provided to the SWP by industry. A black and white variable area 
wiggly trace display from the 3D survey over the site (Figure 4) illustrates basic 
characteristics of the reflection seismic response from the Fruitland Formation and 
overlying strata. The Late Cretaceous Fruitland Formation forms a well defined seismic 
sequence with high amplitude reflection events marking the top and base of the sequence. 
The pattern of internal reflection events is generally parallel and conformable near the top 
and base of the sequence. However, considerable internal reflection discontinuity is 
present in the upper and middle Fruitland coals. Some aspects of the structure observed in 
the Fruitland carry upwards through overlying Paleocene and Late Cretaceous intervals. 
For example, to the northwest (Figure 4) there is a gentle structural rise in both the upper 
Fruitland and the Kirtland and adjacent reflection events. On the southeast end of this line 
small folds in the upper and Middle Fruitland have minor continuation into intervals 
overlying the Kirtland and through Nacimiento reflection events.
Figure 3: High resolution QuickBird image showing locations of local wells (red dots), CO₂ injection well (center), vertical seismic profile source points, and perfluorocarbon tracer and soil gas sample locations.
Figure 4: Northeast-southwest line illustrates seismic events associated with the Fruitland Fm, Kirtland Shale, the Ojo Alamo Sandstone and Nacimiento Fm. Internal reflection discontinuity is evident in the Fruitland and shallower seismic sequences. Local structural features are also evident in the display.

**Image-mapped fractures and lineaments** - Analysis of aerial photographs and satellite imagery is often employed to identify potential fracture zones. The San Juan basin area has been the focus of numerous fracture and lineament studies. Photolineaments were mapped in a 1969 study (Kelley and Clinton 1960). Knepper (1982) mapped lineaments from Landsat imagery and made an important distinction in his work by associating certain lineaments with gravity and magnetic anomalies and dike swarms. Decker and others (1989) analyzed Landsat and aerial photography in the Cedar Hills area (refer to location nw so many miles). They reported that linear features observed in imagery were parallel to the coal cleat directions and sub parallel to open fractures in core from a well in the Cedar Hills, New Mexico area. Work by Wandrey (1989) incorporated field checking and revealed that some aerial photographic trends corresponded to joints on larger scale photos. Analysis of a variety of black and white,
color infrared, and Landsat TM (bands 7, 4 and 2) of the Cedar Hills area was undertaken. The area has been thoroughly studied using a variety of imagery; however, Baumgardner (1991), in his attempts to integrate observations from the various studies found little agreement between the various image-mapped lineament distributions. More than 95% of the lineaments mapped in four separate studies did not coincide. The results emphasize that analysis of image-mapped lineaments may lead to conflicting conclusions. The results of image analysis should be examined for consistency with surface mapping and subsurface data.

In this study we examine QuickBird imagery (e.g. Figure 3) to identify potential near-surface fracture zones. Image analysis in this study focuses on the use of the QuickBird imagery as a proxy for field mapping of fracture systems. QuickBird image-mapped fractures and lineaments are compared to field observations of fracture orientation and length. The relationship of image- and surface-mapped fracture systems to subsurface fracture systems is also evaluated. The study incorporates analysis of 2600 feet of FMI log from the CO$_2$ injection well. Natural and drilling induced fracture orientations are also compared to fast shear azimuths obtained using Schlumberger’s Sonic Scanner tool.

**Near Surface Geology and Fracture Systems**

Surface geology at the site consists of a sequence of flat lying interbedded sandstones and shales of the Eocene age Cuba Mesa member of the San Jose Formation. The Cuba Mesa is the lower-most member of the San Jose Fm. The mud log from the injection well indicates that the San Jose Formation extends an additional 1630 feet beneath the surface
at the site. The gamma ray and density logs from the injection well indicate that the upper 500 feet consist predominantly of sandstone with shale interbeds that vary in thickness from a few feet to 20 feet or so. The shale intervals thicken with depth including predominantly shale intervals 50 to 100 feet thick. The near-surface stratigraphy throughout the region is characterized by canyon cut mesas whose edges consist of a series of sandstone steps and benches (Figure 5).

Figure 5: The edge of the mesa is bordered by a series of three rugged cliffs associated with separate sandstone layers. The steps or breaks between bluffs coincide with shale intervals. Canyon wall exposures in this photo lie about 400 meters south of the injection well.

**Statistical Analysis** – We evaluate directional data collected at individual locations for significant non-random clustering by comparing the vector mean resultant, $\bar{R}$, to the critical value of $\bar{R}$ for a given sample. The test is known as the Rayleigh Test. A table of critical values is used to determine the probability that a value of $\bar{R}$ could occur through sampling of a uniform distribution of fracture orientations. Fracture trends are assumed
to have a von Mises distribution, the circular equivalent of the normal distribution (e.g. Davis, 2002; Mardia and Jupp, 2000). All cluster orientations are rotated into the same quadrant or adjacent quadrants to produce a continuous distribution of angles. The standard error of the mean is computed as

\[
se = \frac{1}{\sqrt{nR\kappa}},
\]

where \(\bar{R}\) is the mean vector resultant of the fractures in a given cluster, and \(\kappa\) is the concentration parameter. The 95% confidence interval about the mean is calculated as 1.96 \(se\) (e.g. Davis, 2002). Many of the directional distributions presented in the following study are polymodal and do not have von Mises distribution; however, the test results are cited as a conservative measure of whether preferred orientations may exist.

**Fracture Characterization**

Surface fracture systems were mapped using high resolution QuickBird imagery (reference) along with complimentary surface fracture mapping. The QuickBird image has a 0.6 meter ground cell resolution so that the larger fractures along the edges of the mesas in the area are visible in the imagery (Figure 6). Interpreted fracture traces were digitized and plotted in rose diagrams for directional analysis. The canyons bounding the pilot site to the south and west of the injection well are visible in the QuickBird image of the larger area (Figure 7). QuickBird interpretations were divided into those within and along the rim of west canyon (area A in Figure 7), those along a small bluff, also west of the injection well (area B in Figure 7) and in and along the rim of the south canyon (area C in Figure 7). Fracture interpretations in the QuickBird image are restricted largely to linear features observed in the sandstone exposures along the mesa edge and canyon.
walls. Limited fracture development is observed in sandstone exposures on the interior of the mesa. It appears that the majority of fractures form in response to extension along the eroded edges of the massive sandstones. Length-weighted rose diagrams of the QuickBird lineaments from areas A, B, and C (Figure 8) contain clusters with orientations that vary with position on the mesa.

Figure 6: QuickBird view showing fractures in the Cuba Mesa Sandstone exposed at the surface along the edge of the mesa south of the injection well.
Figure 7: QuickBird image covering the mesa southwest of the injection well. Mapped fracture traces are highlighted. Area A corresponds to the west canyon, B, to the central bluff, and C, to the southeast or south canyon.
Along the west rim of the site mesa (Figure 7, area A) a N34W set dominates the rose plot (Figure 8A). Smaller NS and N50E sets are also present. Along the central bluff (Figure 7, area B) a prominent N37W cluster is present with a much smaller N45 E cluster (Figure 8B). QuickBird interpreted fractures in the south canyon (Figure 7, area C) are more variable in orientation and can be divided into 3 modes or sets: smaller NS and EW mode with a more pronounced N43E mode. The distributions of fracture orientation are non random at $\alpha$ levels of 0.025 and less, where the value of $\alpha$ refers to the probability that this distribution of orientations could actually be uniform. A cumulative rose diagram reveals the presence of four modes: N35W, NS, N45E and EW. The cumulative distribution is also non random at $\alpha$ less than 0.025. The NE and NW trending sets are most pronounced. These sets are sub-orthogonal (80 degree separation in mean trend). The mean trends for the NE and NW modes have closer to 90 degree separation.

![Figure 8: Length weighted rose diagrams of QuickBird-mapped fracture traces: A) mesa rim and canyon west of the injection well; B) central exposures; C) mesa rim and canyon to the south; D) cumulative rose diagram.](image)

Field based observations also suggest the presence of separate modes or sets of fractures (Figure 9, A through C). Along the rim of the mesa bordering the west canyon,
the mean fracture trend including all fractures is N16W. The mean orientation obtained using only those fractures between N5W and N55W is approximately N30W. In the interior of the mesa near the central bluff the mean is approximately N40W. Along the rim of the south canyon, fractures are scattered roughly about a N60E trend; however, a majority of fractures in the northeast quadrant of the rose diagram form a mode with a mean of N78E. Orientations observed at different locations on the mesa (A through C) are significantly non-random at $\alpha$ less than 0.01. However, the cumulative frequency-weighted rose diagram of the surface-mapped fractures (Figure 9D) suggests that fractures at the site have random orientation. Local clusters are lost in the variability associated with the site as a whole.

The results suggest that the majority of the fractures observed in the sandstones exposed in this area formed after they were exposed at the surface. Fractures appear to have developed in response to release stresses developed along the rim of the mesa. These fractures are referred to as valley-wall fractures (Lorenz et al. 2006) and their formation is generally believed to be unrelated to tectonic residual tectonic strain.

Figure 9: A) Surface-mapped fracture trace orientations measured along the west canyon rim. B) central bluff; C) south canyon; D) cumulative rose diagram. Rose diagrams of surface-mapped fractures are not length weighted.
Although fracture orientations tend to parallel valley walls, the canyons and eroded canyon walls in this area form clusters whose orientations are consistent with basin geometry. Directional analysis of drainage pathways extracted from DEM data over the area (Figure 11) reveals well defined peaks in the distribution of drainage paths in the area surrounding the injection well (Figure 12A). Directional analysis of drainage pathways over the mesa southwest of the injection well yields similar results (Figure 12B). Despite the appearance of peaks in the distribution, drainage pathways around the injection well do not differ statistically from a random or uniform circular distribution. The drainage pathways surrounding the area southwest have marginally non-random distribution with \( \alpha \) level of 0.1.

Figure 11: Drainage pathways extracted from DEM data in the vicinity of the pilot site. Drainage paths extracted in the vicinity of the injection well are shown in dark blue; those from the area to the southwest are shown in light blue. The injection well is located by the red dot (upper right). NETL tracer sample locations are shown as light green dots.
Drainage pathways around the injection well fall into 4 clusters with orientations of N04W (N=27), N42E (N=33), EW (N=25) and N47W (N=40). In the area to the southwest (Figure 12B) clusters have mean trend of N03E (N=26), N45E (N=37), N85E (N=33) and N48W (N=57). The 95% confidence interval on drainage pathway clusters averages between 5 and 6 degrees in all cases. In the area to the southwest where fracture orientations exhibit some preference for clustering, the larger clusters form at N48W and N45E, coincident with those observed in the vicinity of the pilot site.

A)

B)

Figure 12: Length-weighted rose diagrams of drainage path orientations extracted from DEM data over A) the area surrounding the injection well and B) the area southwest of the injection well.

A preliminary study conducted on an adjacent mesa located about 1.5 kilometers southwest of the present injection well (see Figure 11) highlights the importance of sampling a range of outcrop (i.e. valley wall) orientations. Fracture orientations were made along mesa rim and ridge locations that nearly encircle the mesa-top (see locations a through g on Figure 13). Sample locations in the vicinity of the injection well are limited primarily to nearly north-south and northeast-southwest trending mesa rims (Figures 7 and 13). QuickBird- and surface-mapped fracture trends in this area are much less scattered (Figure 14 a through g). The cumulative rose diagram of QuickBird-
mapped fractures (Figure 14h) is characterized by two prominent clusters: one with N45W vector mean and the other, N40E. The analysis incorporates a total of 479 QuickBird mapped fractures. Surface mapped fractures are, likewise, more clustered (Figure 15). The cumulative frequency-weighted rose diagram (Figure 15h) has two prominent clusters with mean trend of N48W and N30E. A total of 383 surface-mapped fractures are incorporated in this analysis. The QuickBird-mapped fractures (Figure 14h) are significantly non-random at $\alpha = 0.01$; the surface-mapped fracture trends are marginally non-random at the larger value of $\alpha = 0.1$.

Figure 13: Topographic map showing the location of the injection well and subdivisions A to C on the site mesa and a to g on the adjacent mesa to the southwest where additional fracture studies were conducted.
Pronounced clusters in the QuickBird-mapped distribution occur at vector mean azimuths of N41E and N45W with 95% confidence limits of 3 and 4.5 degrees, respectively. Major clusters in the field-mapped fracture data occur at N30E and N48W with 95% confidence limits of 5 and 6 degrees, respectively.

Figure 14: Rose diagrams of QuickBird-mapped fracture traces on the mesa southwest of the pilot site. Rose diagrams a through g are located in Figure 11. They circle the mesa counter clockwise from the west rim (a) around the perimeter of the mesa to the ridge north of the mesa (g). Rose diagram h is a length-weighted cumulative rose diagram (N=479).
Figure 15: Rose diagrams of surface-mapped fracture traces on the mesa southwest of the pilot site. Rose diagrams a through g are located in Figure 9. They circle the mesa counter clockwise from the west rim (a) to the ridge north of the mesa (g). Rose diagram h is a frequency-weighted cumulative rose diagram (N=383).

The strike of the basin in this area inferred from regional structure contours (e.g. Figure 1) is approximately N45W. Strike is locally quite variable in these shallow dipping strata (Figure 2, see also Fassett, 2000). The NE QuickBird trending fractures (Figure 9D and 12h) are assumed to be associated with the principal compressive stress direction in the region inferred from face cleat orientations observed in core from the nearby GRI NEBU well (Mavor and Close, 1989).

The systematic occurrence of fracture systems in the area suggests that fracture origin is largely controlled by anisotropic in-situ stress associated with basin formation and geometry. Shear wave anisotropy and drilling induced fractures observed within a couple hundred feet of the surface indicate the presence of significant near-surface deviatoric stress.
Sonic Scanner and FMI Log Observations

The injection well was drilled and logged in two stages. The hole was initially drilled to a depth of 2944 feet, a depth just above the major Fruitland coal section. The hole was filled with fluid and logged. The hole was then cased and cemented and an additional 226 feet of hole was drilled through the Fruitland coal section. FMI log coverage was limited to the upper section of the hole (324’ to 2943’). Two separate sonic scanner runs provided coverage from 285’ to 3156’. The top of the Fruitland Formation was encountered at a depth of 2826 feet subsurface. FMI log observations provide information on fracturing to within a few feet of the Upper Fruitland Coal, which was encountered at a depth of 2963 feet subsurface.

Describe sonic scanner?

Fast Shear Azimuth - Fast shear directions measured by the sonic scanner along the entire length of the borehole reveal a major peak in the northeast quadrant with a vector mean orientation of N37E (Figure 16A). The 95% confidence limit about the mean is approximately 1 degree. Secondary peaks in the northwest and northeast quadrants have vector mean orientation of N57W and N14E, respectively (Figure 16A). Within the upper part of the Fruitland Formation logged in the first drilling run (2826 to 2943) the fast shear directions form two clusters (Figure 16B) with mean trends of N64W and N08E. In the lower coal bearing Fruitland Formation (2943 to 3132 feet) logged in the second run, the fast shear direction has little variability about a mean orientation of N14E (Figure 16C). The fast shear direction appears to be fairly weak and variable through the upper Fruitland where it drifts from NW to N and then NE directions down the hole. All distributions are significantly non-random at an $\alpha$-level of 0.001. The 95% confidence
limit on the mean fast-shear azimuth in the lower Fruitland coal section is less than 1 degree.

Figure 16: A) The fast shear direction determined from the Schlumberger sonic scanner over the entire length of the hole (275 to 3132 feet) is dominated by a cluster in the northeast quadrant with mean orientation of N43E degrees (N=4567). Smaller peaks are observed at approximately N14E (N=1061) and N57W (N=500). B) Within the upper part of the Fruitland Formation, peaks are observed at N64W (N=115) and N08E (N=118); C) In the coal bearing section the average fast shear direction is N14E (N=379).

**Drilling induced breakouts** - Drilling induced breakouts observed in the FMI log through the upper Fruitland from 2826 to 2943 feet (N=5) have a vector mean orientation of N57W (Figure 17) and 95% confidence limit of 10 degrees. The vector mean orientation of all breakouts identified in the FMI log (N=97) is also N57W (95% confidence limit of 3.6 degrees). Breakout orientation is generally consistent along the entire length of the borehole. The shallowest breakout was interpreted at 329 feet and the deepest observation made at 2936 feet. The drilling induced breakouts and fast shear direction provide independent measures of the maximum compressive stresses in the rock. The breakouts form normal to the present-day in-situ maximum compressive stress. The N57W breakout trend implies a maximum compressive stress ($\sigma_H$) of N33E. The fast-shear azimuth generally lies parallel to the present day maximum compressive stress.
and its value of N37E (95% confidence limits of ± 1 degree) is similar to the N33E (95% confidence limits of ± 3.6 degrees) value inferred from the breakout orientations.

Figure 17: Drilling induced breakouts observed in the FMI logged interval (324 to 2943 feet) have mean trend of N57W (N=97). Those within the upper part of the Fruitland (2826 to 2943 feet) also have mean trend of N57W (N=5).

In contrast, the fast-shear direction observed in the Fruitland coal section, taken by itself, has a more northerly (N14E) trend. The orientations of coal face cleats observed in the GRI NEBU well about 7 miles east of the injection well have approximately N35E trend (Mavor and Close, 1989). The breakout orientations and fast shear directions in the strata overlying the Fruitland Formation are consistent with that trend; however, the rotation of the fast-shear direction to the NE within the lower coal bearing section suggests some possibility that the face cleats may have more northerly trend at the pilot site.
Open fractures – A total of 48 open fractures were interpreted in the FMI log (Figure 18A). Although three clusters appear in the open fracture trends: N63W, N01E and N67E; the low value of $\bar{R}$ suggests randomness in distribution. From an interpretive perspective, preferred orientations appear to be forming in the distribution, but the number of observations is too low to suggest definitive geological relationships.

![Figure 18](image)

Figure 18: A) Open fracture trends interpreted in the FMI log from 1000 to 2905 feet in the borehole (N=48); B) open fractures in the Kirtland Shale primary seal (N=21); C) a limited number of open fractures (N=5) in the upper Fruitland (2830 to 2905) have mean orientation of about N11E.

The orientations of open fractures in the Kirtland Shale are not statistically different from a random distribution; however, a mode appears to begin taking form with approximate N65E trend. A limited number of open fractures (N=5) observed in the FMI log in the upper Fruitland Formation have vector mean strike of N11E similar to the fast shear orientation inferred from the sonic scanner in the Fruitland Formation. Taken separately from the total, this subdivision of fractures is significantly non-random with $\alpha$ level of 0.01 and a 95% confidence interval of 19 degrees. The top of the Upper Fruitland Coal is reported at 2963 feet; however, a significant coal fraction is encountered at
approximately 2948 feet where the density drops to about 1.8 gm/cm$^3$. The FMI log provides fracture interpretations only down to about 2943 feet, 20 feet above the Upper Fruitland Coal. The fast-shear direction rotates to N14E in the Fruitland coal section and suggests possibility of a rotation in the residual stress field within the Fruitland Formation. Instability in the fast-shear measurements in the upper 100 feet of the Fruitland Formation suggests transition in residual stress from N37E to the N14E. We speculate that the open fractures observed in the well may have formed in response to late-stage Laramide compression. The late-stage compression may have produced some detachment in the coal section.

Equal area projections of open fractures observed in the injection well reveal almost random distribution of poles as suggested in the analysis of fracture strike (Figure 19) particularly for the total set of open fractures and those observed in the Kirtland Shale (Figures 19 A and B). The set of open fractures observed in the upper Fruitland is small and in this case also supportive of a northeasterly preferred trend (Figure 19C).

Figure 19: Equal area (Schmidt Net) projections of poles to open fracture planes. A) All open fractures; B) open fractures observed in the Kirtland Shale; and C) open fractures observed in the upper Fruitland Fm.
Schlumberger’s FMI log analysis includes computation of the hydraulic electrical apertures. Fracture aperture distribution is an important fracture property critical to flow simulation. The open fractures penetrated in this well provide a general view of aperture distribution in the cover strata at the site (Figure 20). The frequency distribution is positively skewed with mode of 0.08 inches.

![Fracture Aperture Distribution](image)

**Figure 20:** Hydraulic electrical fracture aperture distribution. N=48.

**Healed Fractures** - The orientations of healed fractures appear to be more widely scattered (Figure 21A) than the open fractures (Figure 18A) penetrated by the wellbore. However, as with the open fractures, the $R$-value is low; these differences are attributed to random scatter. A total of 57 healed fractures were mapped in the FMI log interpretation. The orientations of healed fractures in the Kirtland Shale show some tendency for preferred orientation at $\alpha = 0.1$. A mode with approximate N45W trend emerges from the background. Healed fractures along the length of the borehole were distributed with
similar frequency from depths of 370 feet to the top of the Fruitland Formation at 2826 feet subsurface. A relatively large number of healed fractures (14 or about 25%) were observed in the upper 100 feet of the Fruitland Formation (Figure 21C). The $R$-value for these fractures taken separately is also quite low, suggesting the orientations are effectively random in distribution. However, modes appear to emerge along trends consistent with tectonic in-situ strains inferred from the drilling induced breakouts and fast-shear directions. Mean azimuths of the three modes observed in the full sample (Figure 21A) occur at N53W, N14E and N59E. The confidence limits on the mean orientations of each cluster are 13 degrees, 13 degrees and 9 degrees, respectively. Peaks in the rose diagram of healed fractures in the upper Fruitland occur at N66W, N03W, and N50E, with confidence limits of 11 degrees, 14 degrees and 21 degrees, respectively.

Figure 21: A) Healed fracture trends interpreted in the FMI log from 370 to 2925 feet in the borehole (N=57); B) Healed fractures observed in the Kirtland Shale (N=17); C) Healed fractures (N=14) in the upper Fruitland Formation.
3D Seismic Interpretation and Attribute analysis

Several seismic attributes have been calculated and examined to determine if additional insights can be gained from the seismic data regarding the structural and stratigraphic integrity of the reservoir and overlying strata. Our main objective is to assess the potential for vertical leakage of injected CO\textsubscript{2}. Thus we are interested in identifying possible fracture zones and faults that might facilitate the escape of injected CO\textsubscript{2} into overlying formations and possibly to the surface. Evidence of pervasive fracturing of the overburden strata is presented in the preceding sections. The likelihood that these fracture systems may have extensive interconnections that might facilitate escape of injected CO\textsubscript{2} into near-surface aquifers or back into Earth’s atmosphere is of critical importance to the long term viability of the sequestration effort.

The absolute value of the derivative of seismic amplitude helped unveil potential fracture zones extending vertically through the section. A 20Hz to 90Hz bandpass filter was applied to reduce migration noise in the final migrated stack. An automatic gain control was also applied to the derivative to normalize amplitude variations. Between the Fruitland top and base (Figure 22) there are some subtle features that may be associated with vertically juxtaposed stratigraphic pinchouts or internal faults. Some of these features occur near the periphery of the pilot area as defined by the production wells. Considerable evidence of fracturing and minor faulting is observed in the Kirtland Shale. While large penetrative faults are not present in the strata overlying the Fruitland Fm., considerable fracturing of overlying intervals is suggested by the data. If the integrity of the reservoir is compromised, eventual escape into overlying strata might be facilitated by these fracture systems.
Figure 22: Gain adjusted absolute value of the finite seismic amplitude difference reveals vertically continuous amplitude disruptions that cut through laterally coherent reflection events. This line is about 3.4 miles in length and oriented in the NE-SW dip direction through the injection well (center green vertical line). Neighboring wells are located about 1500 feet from the injection well.

A closeup view (Figure 23) along this same dip line reveals some subtle disruptions of amplitude within the Kirtland Shale to the southwest near one of the producing wells (COM A 300). The injection well sits on top of a subtle structure in the lower Fruitland. Stratigraphic pinchouts coincident with this high are observed in the underlying Pictured Cliffs Sandstone along a northwest trending zone of thinning in the Fruitland sequence. Thinning correlates with the presence of reflection terminations against the lower Fruitland sequence boundary (Wilson et al., 2009). These reflection patterns are interpreted to be associated with northwest trending shoreline sands in the Pictured Cliffs Sandstone (Wilson et al., 2009). They speculate that sequence thinning is related to differential compaction over a shoreline sand body and that differential
compaction could enhance fracture intensity along this northwest trend, particularly in the lower part of the sequence where interpreted differential compaction is more pronounced.

Figure 23: Close up view of finite difference attribute along the dip line shown in Figure 8. This line passes through the injection well (center) and the COM A 300 producing well about 1200 feet southwest of the injection well. Local structure in the Fruitland coal, stratigraphic pinchouts and amplitude disruptions are present in the vicinity of the injection well.

Subtle seismic indications of fracturing within the Fruitland sequence are present in places (e.g. Figure 23); however, the finite difference computations do not provide clear evidence of local faults within the Fruitland Fm. Additional attribute analysis referred to as Ant Tracking reveals a regular system of discontinuities interpreted to be fracture zones or small faults within the Fruitland Fm. This algorithm is accessed using Schlumberger’s Petrel Seismic-to-Simulation software. Rose diagrams of ant-tracks reveal pronounced NE trending clusters throughout the Fruitland sequence (Figure 24).
Less pronounced NW trending clusters are infrequently observed. The NE trend is also very pronounced in the overlying Kirtland Shale (Figure 24). The $\bar{R}$ value in all cases suggests that these distributions are non-random at an $\alpha$ level of 0.01.

Directional analysis of edge discontinuities reveals prominent N55-58E trends in frequency-weighted rose diagrams through the Fruitland (Figure 24). All distributions are significantly non-random at a $\alpha$ level of 0.01. Multiple clusters begin to emerge in all these directional plots, but are most pronounced near the top of the Fruitland sequence around 530 milliseconds. Clusters with distinct NE and NW trend have mean trends of N56E and N54W. These clusters have confidence levels of 11 degrees and 10 degrees respectively.

The density of discontinuities increases in the middle Kirtland and shallower reflection events associated with the middle and upper Kirtland shale and Nacimiento Formation (Figure 25). Ant-track trends are fairly regular throughout. The $\bar{R}$ values suggest ant-track orientations are non-random with an $\alpha$ level of 0.01 (upper and middle Kirtland) or 0.05 (Nacimiento). The ant tracks are characterized generally by a pronounced cluster in the northeast quadrant of the rose diagrams. Cluster means in the northeast quadrant are N55E for the middle Kirtland; N51E for the upper Kirtland; and N53E for the Nacimiento. Smaller clusters also occur in the northwest quadrant with means of N45W, N45W, and N40W, respectively.
Figure 24: Ant track maps and rose diagrams of ant-track trends. Maps of ant-track discontinuities were generated at 30 millisecond intervals from the base of the Fruitland sequence at approximately 630 milliseconds (A) to top at approximately 540 milliseconds (D).

Figure 25: Ant track discontinuities mapped in the middle (A) and upper (B) Kirtland shale and Nacimiento Formation C).
Summary and Conclusions

This study focuses on characterization of natural fracture systems that might influence the long term fate of CO_2 injected into the Fruitland coals as part of the SWP’s carbon sequestration pilot test. Natural fracture systems present in the Upper Cretaceous Fruitland coal reservoir and overlying Cretaceous and Tertiary cover strata were characterized using a variety of remote sensing and geophysical data. Interpretations of surface fracture systems were undertaken using high resolution QuickBird imagery and surface mapping. Information about fracture systems extending from within 300 feet of the surface down to the top of the Fruitland coal section is extracted from Schlumberger’s FMI and Sonic Scanner logs. Information about possible fracture orientations within the Fruitland coal section is inferred indirectly from the average fast azimuth direction measured by the Sonic Scanner. 3D seismic interpretation and post stack attribute analysis highlight discontinuities in reflection events present in the reservoir and overlying strata. These discontinuities, interpreted as small offset faults or fracture zones, provide additional perspectives on potential field-scale fracturing within the reservoir and overburden strata.

The majority of fractures mapped in the vicinity of the pilot site developed along valley walls. QuickBird image-mapped fractures on the site mesa and an adjacent mesa southwest of the site reveal the presence of preferred orientations of N45E and N35W (site mesa) and N40E and N45W (southwest mesa). Smaller NS and EW trending fracture sets are also observed on the site mesa. Less distinct NS and EW sets are present in the area to the southwest. Surface mapped fractures around the site mesa have random orientation, while those mapped on the mesa to the southwest are non-random with peak
trends of N30E and N48W. Although the majority of fractures develop along valley and ridge rims in response to tension release, analysis of drainage pathways extracted from DEM data suggests, with marginal statistical significance, that valleys in the area follow tectonic trends consistent with basin geometry in the area. On the site mesa, valley rim and ridge exposures are limited to northwest and northeast trends. This introduces a bias in the results toward those orientations. Bias can be minimized by sampling valley rim and ridge exposures that encircle the study area as they did to the southwest. Overall, the analysis of image- and surface-mapped fractures supports the conclusion that surface fracture systems have preferred orientations and develop in response to residual tectonic stress.

The presence of significant residual tectonic stress in the near-surface is confirmed by Schlumberger’s borehole Sonic Scanner and FMI log observations. Measurements of fast-shear azimuth obtained from the Sonic Scanner log through depths of 286 to 386 feet subsurface have N31E trend with 95% confidence limit of ±3 degrees. Drilling induced wellbore breakouts are observed in the FMI log from 329 feet in the near-surface down to a depth of 2936 feet. Mean breakout orientation along the length of the wellbore is consistently N57W. Over the near-surface interval, for example, the breakouts have mean trend of N57W with 95% confidence interval of ±5 degrees. Near surface in-situ stress within 329 feet of the surface is sufficient to fracture the borehole wall. This 329 foot borehole depth corresponds roughly to a depth of about 100 feet below the surrounding valley floors in the vicinity of the site.

Schlumberger Sonic Scanner and FMI log observations helped us extend our understanding of residual stress and fracture distribution from the near-surface down
through strata overlying the Fruitland coal injection zone. Sonic Scanner observations, unlike those from the FMI log, were available through the injection zone. Drilling induced breakout orientations of N57W along the length of the borehole suggest invariant in-situ principal compressive stress direction of N33E. The average fast-shear direction obtained from Sonic Scanner measurements over the entire length of the borehole is N43E. The fast-shear direction is associated with stress induced or fracture induced stress anisotropy. The fast-shear direction refers to the shear wave vibration direction. Fracture induced intrinsic anisotropy arises through birefringence of the shear wave into a fast-shear vibration component that parallels the maximum principal compressive stress direction (or the dominant fracture trend) in strata surrounding the borehole; the slow-shear direction is orthogonal to the fast-shear direction. Stress induced anisotropy results from in-situ stress. When the fast-shear direction is evaluated over local intervals above and within the Fruitland coal section, a transition occurs from the average N43E trend to a N14E trend within the coal section. We speculate that this N14E trend observed through the coal bearing intervals may be related to fracture induced anisotropy and also imply a face cleat orientation of N14E.

A variety of open and healed fracture trends are penetrated between subsurface depths of 370 feet to 2925 feet within the upper Fruitland Fm. The distributions are marginally non-random at best. A small set of open fractures in the upper Fruitland (N=5) are significantly non-random with mean trend of N11E with 95% confidence interval of 19 degrees. The occurrence of these open fractures in the transition zone observed in the fast-shear orientations within the upper Fruitland supports speculation that open fractures and face cleats in the underlying Fruitland coal section may have more northerly trend.
We also interpreted proprietary 3D seismic data provided for this study from the SWP. The seismic coverage provides a regional scale (9 square mile or 23 square kilometer) view of discontinuities in reflection seismic data that may be associated with fracture zones and small faults. Attribute analysis revealed discontinuities in seismic profile views and also in timeslice view. Use of the Schlumberger Petrel ant-tracking edge enhancement process reveals the presence of numerous reflection discontinuities that are organized into a pattern of northeast and northwest trending zones. On the regional scale the dominant clusters in the northeast quadrant of the rose diagrams have fairly uniform mean orientation of N55E to N58E. A cluster in the northwest quadrant emerges near the top of the Fruitland coal section. It has a mean orientation of N54W. The 95% confidence levels on the mean vary between ±8 and ±12 degrees.

Ant-track trends in the overlying Kirtland and Nacimiento intervals have prominent northeast trending clusters with mean trend between N51E and N55E. Northwest trending clusters have mean trends between N40W and N45W. The 95% confidence levels on mean trend vary between ±6 and ±12 degrees. Discontinuities observed in profile view suggest the presence of considerable fracturing and minor faulting within the Kirtland Shale caprock. Indicators for extensive fracturing and faulting within the Fruitland sequence are present but much less apparent.

Overall, the analysis presented in this study suggests that existing fracture systems could increase the probability of long-term CO$_2$ leakage. Although post stack attribute processing reveals seismic features interpreted as small faults and fracture zones that disrupt overlying strata and to less extent, the reservoir interval, interpreted seismic faults and fracture zones have limited vertical extent. Major penetrative faults are not evident in
the 3D seismic. Although there is no suggestion in the seismic interpretation that
uninterrupted migration pathways extend from the reservoir to surface, the presence of
open fractures with variable trend suggests vertical migration of injected CO₂ is possible.
Open fractures are encountered from depths of 1000 feet subsurface within the San Jose
Formation to 2900 feet within the upper Fruitland Formation. The distribution of open
fractures has modes with NW, N and NE trend. The aperture distribution is positively
skewed with a mode of 0.08 inches. Flow simulations using models that incorporate
discrete fracture networks with properties identified in this study are needed to assess the
range of possible leakage rates that might occur through overburden strata at this and
similar sites.
Acknowledgements (incomplete)

This technical effort was performed in support of the National Energy Technology Laboratory’s on-going research in carbon sequestration under the RDS contract DE-AC26-04NT41817-60604000. We’d like to thank Dave Wildman and Donald Martello, our DOE-NETL project managers, and George Koperna and Scott Reeves, Advanced Resources International, for their support and advice on these efforts; Brian McPherson and Reid Grigg of the Southwest Regional Partnership for their help in facilitating our involvement in their San Juan Basin pilot test; and Ryan Frost, Tom Cochrane and Bill Akwari of Conoco Phillips for their help to facilitate many of the activities on the site. We’d also like to thank Bill O’Dowd, the DOE-NETL project manager for the Southwest Regional Partnership, for his support and advice on these efforts and for his review comments.

Discussions with Dwight Peters, Schlumberger, were critical to the design of logging operations conducted in the injection well. The processing and analysis of FMI log and Sonic Scanner data by Andrew Mioduchowski and Gabriela Martinez of Schlumberger were essential to this effort. The seismic data used in this evaluation are proprietary and provided through the Southwest Regional Partnership. Comments on the manuscript provided by Jason Heath and Scott Cooper helped improve the content and focus of the paper.

Tom Wilson is an Institute Fellows working with NETL under the Institute for Advanced Energy Solutions (IAES) and appreciates the opportunity to work jointly with research staff in the Office of Research and Development at NETL.
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