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

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ABSTRACT

In this study we analyze data on fractures and possible faults in the surface, primary seal and cover strata to evaluate site integrity and the viability of long term CO$_2$ retention for the Southwest Regional Partnership on Carbon Sequestration’s San Juan Basin Fruitland Coal pilot test. The project is funded by the U.S. Department of Energy and is managed by the National Energy Technology Laboratory.

Near-surface shear wave anisotropy and drilling induced breakouts support the interpretation that retained tectonic stress anisotropy influences the development of near-surface fracture systems. Shear wave anisotropy in the vicinity of the borehole is characterized by an average fast-shear direction of N36E along the length of the borehole. Drilling induced breakout trends are tightly clustered with mean orientation of N57W. Open fractures observed in general have random distribution. Aperture distribution is significantly log normal. Attribute analysis of 3D seismic reveals the presence of narrow field scale zones of discontinuity in time slice view that have pronounced NE trending mode. Additional post-stack processing reveals discontinuities in profile view that are interpreted as minor faults and fracture zones.

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 the sealing strata.

**BACKGROUND**

**San Juan Basin Pilot Site** - Analysis of fracture systems is undertaken in the area surrounding the Southwest Regional Partnership (SWP) on Carbon Sequestration’s 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 CO$_2$ sequestration in deep, unmineable coal seams. The SWP conducted the pilot in the high permeability Upper Cretaceous Fruitland coals in the 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 (5.5 to 9 meters) distributed over a 200 foot (61 meter) thick interval in the Fruitland Formation (Figure 3).

Fassett (1991) notes that coalbed methane production from the Fruitland coals began in the 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 with shut-in casing pressure of 56psi (B. Akwari, personal communication, 2010).

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, in general, 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 might 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 Fruitland, 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 acquisition and analysis of fracture detection logs (the Schlumberger FMI log). In-situ stress orientations were estimated from 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. Surface fracture mapping
was complimented by analysis of high resolution (60 centimeter (2 foot) pixel size) QuickBird imagery of the area.

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 (see Carbon Sequestration Technology Roadmap and Program Plan, 2007, available at http://www.netl.doe.gov/technologies/carbon_seq/refshelf/project%20portfolio/2007/2007Roadmap.pdf). CO\textsubscript{2} injection began July 30th of 2008 and continued through August 14th of 2009. During the 12 month injection period, approximately 319 MMCF, equivalent to nearly 18,407 short tons of CO\textsubscript{2}, were injected into the Fruitland coals. Leakage of 0.01% per year corresponds to leakage of 1.5 tons of CO\textsubscript{2} per year. This amount, when distributed uniformly over the 1.5 square kilometer (0.58 square mile) site corresponds roughly to about 0.001 kilograms per square meter per year (0.0002 lbs/ft\textsuperscript{2} per year). In a previous study of the West Pearl Queen pilot site located in southeastern New Mexico, 2090 tons of CO\textsubscript{2} 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 CO\textsubscript{2} along the injection well bore. Well bores in the vicinity of carbon sequestration sites are considered among the most likely sources of significant short term leakage (e.g. Nordbotten et al., 2009). 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 particularly if injection pressures and swelling induced strains were to open fractures in the seal.
Fracture Systems and Coalbed Methane Production – Fracture systems produced by late stage deformation might produce penetrative (reservoir-to-surface) deformation of the 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 compiled by Taylor and Huffman (1998) suggest the basin is underlain by a system of approximately N30-40E and N50-60W trending basement faults. Nine square miles of proprietary 3D seismic were 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 presented by Marroquin and Hart (2004) revealed a relationship between areas of high curvature and high producing Fruitland coalbed methane production wells in an area about 15 miles (24 km) east-northeast of the pilot site. 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 (Ambrose and Ayers, 1991).

**Site layout and characterization** – The Southwest Regional Partnership and National Energy Technology Laboratory conducted a variety of monitoring activities on the pilot site (Figure 4). These included 1) surface monitoring for perfluorocarbon tracers injected into the CO$_2$ stream by NETL; 2) soil gas monitoring (NETL); 3) time-lapse vertical seismic profiling (Schlumberger); 4) continuous monitoring of CO$_2$ concentration at three offset production wells (New Mexico Tech.); 5) periodic sampling to determine total production gas stream composition on eleven offset production wells (ConocoPhilips); 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 5) 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 southwest (Figure 5) 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 including the Ojo Alamo and Nacimiento reflection events. The Kirtland through Nacimiento intervals include about 1600 feet (488 meters) of the cover strata. These subtle structures may produce zones of enhanced fracture intensity.

**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 (approximately 12 miles (20 km) to the west-northwest). 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 and that results of image analysis should be examined for consistency with surface mapping and subsurface data.

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 (497 meters) beneath the surface at the site. The gamma ray and density logs from the injection well indicate that the upper 500 feet (152 meters) consist predominantly of sandstone with shale interbeds that vary in thickness from a few feet to 20 feet (6 meters) or so. The shale intervals thicken with depth to 50 to 100 feet (15 to 30.5 meters). 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 6).
**Statistical Analysis** – We use the Rayleigh Test (e.g. Davis, 2002) to evaluate whether distributions of fracture trends are significantly non random by comparing the vector mean resultant, \( \overline{R} \), to the critical value of \( \overline{R} \) for a given sample. The value of \( \overline{R} \) is calculated as

\[
\frac{R}{n} = \sqrt{\frac{\left( \sum_{i=1}^{n} \cos \theta_i \right)^2 + \left( \sum_{i=1}^{n} \sin \theta_i \right)^2}{n}}
\]

(1)

where \( n \) is the number of observations and \( \theta_i \) is the fracture strike (see Davis, 2002). A table of critical values is used to determine the probability that a value of \( \overline{R} \) could be obtained through random 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 orientations are rotated into the same quadrant or adjacent quadrants to produce a continuous distribution of angles. For example fractures with strike of N200E would be rotated 180 degrees and assigned a value of N20E. If the Rayleigh test indicates that a preferred orientation exists then the standard error of the mean can be computed as

\[
s_e = \frac{1}{\sqrt{nR\kappa}}.
\]

(2)

where \( \overline{R} \) is the mean vector resultant of the fracture trends, and \( \kappa \) is a maximum likelihood estimate of the concentration parameter (Davis, 2002). The 95% confidence interval about the mean is calculated as \( 1.96 \, s_e \) (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 primarily as a conservative measure of whether preferred orientations may exist within any given distribution.
FRACTURE CHARACTERIZATION

Surface fracture systems were mapped using high resolution QuickBird imagery (from DigitalGlobe) along with complimentary surface fracture mapping. The QuickBird image has a 0.6 meter (2 foot) ground cell resolution so that larger fractures along the edges of the mesas in the area are visible in the image (Figure 7). 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 8). QuickBird interpretations were divided into those within and along the rim of the west canyon (area A in Figure 8), those along a small bluff, also west of the injection well (area B in Figure 8) and in and along the rim of the south canyon (area C in Figure 8). 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 sandstone interval capping the mesa. Length-weighted rose diagrams of the QuickBird lineaments from areas A, B, and C (Figure 8) contain modes with orientations that vary with position along the mesa rim.

Along the west rim of the site mesa (Figure 8, area A) a N34W set dominates the rose plot (Figure 9A). Smaller NS and N50E sets are also present. Along the central bluff (Figure 8, area B) a prominent N37W mode is present with a much smaller N45E mode (Figure 9B). QuickBird interpreted fractures in the south canyon (Figure 8, 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 Rayleigh test indicates fracture
distributions are non random at \( \alpha \) levels of 0.025 and less. 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.

Field based observations also suggest the presence of separate modes or sets of
fractures (Figure 10, 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 mean N60E trend. A
larger mode with a mean of N78E stands out in the distribution. Orientations observed at
different locations on the mesa (A through C) are significantly non-random at \( \alpha \) less than
0.01. However, the Rayleigh test indicates that the cumulative surface-mapped fracture
distribution (Figure 10D) is not statistically different from a random or uniform
distribution. Local modes 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 residual tectonic strain.
A similar study was conducted on an adjacent mesa about 1.5 kilometers southwest of the present injection well. This study suggests that sampling a greater range of outcrop and valley wall orientations will influence the outcome of the analysis. Fracture orientations were measured along the mesa rim and ridge locations that nearly encircle the mesa-top (see locations a through g on Figure 11). In the analysis of orientation data in the vicinity of the injection well, the sample locations were limited primarily to nearly north-south and northeast-southwest trending mesa rims (Figures 8). QuickBird- and surface-mapped fracture trends in this area are much less scattered (Figure 12a through g). The cumulative rose diagram of QuickBird-mapped fractures (Figure 12h) is characterized by two prominent modes: one with N45W vector mean and the other, N40E. The analysis incorporates a total of 479 QuickBird mapped fractures. Surface mapped fractures are, likewise, less scattered (Figure 13). The cumulative rose diagram (Figure 13h) has two prominent modes with mean trend of N48W and N30E. A total of 383 surface-mapped fractures are incorporated in this analysis. The QuickBird-mapped fractures (Figure 12h) are significantly non-random at \( \alpha = 0.01 \); the surface-mapped fracture trends are considered marginally non-random with an \( \alpha = 0.1 \).

Pronounced modes in the QuickBird-mapped cumulative distribution (Figure 12h) occur at vector mean azimuths of N41E and N45W with 95% confidence limits of 3 and 4.5 degrees, respectively. Modes in the cumulative field-mapped fracture distribution (Figure 13h) occur at N30E and N48W with 95% confidence limits of 5 and 6 degrees, respectively.

The strike of the basin in the vicinity of the pilot site 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 (Figures 9D and 12h) are interpreted to have developed in response to
the principal compressive stress direction in the region associated with the Laramide
Orogeny.

The surface-mapped fracture distributions are marginally non-random at best. The
modes observed in the cumulative rose diagram in the area to the southwest of the pilot
site (Figure 13h) although pronounced, could be drawn at random from a uniform
distribution with a probability of 0.1. Based on surface mapping alone, we cannot argue
that residual in-situ stress associated with basin formation and geometry control surface
fracture orientation. However, the distributions of QuickBird image-mapped fractures are
significantly non-random in both areas where detailed analysis was undertaken. The
satellite view may filter out a lot of the smaller cross joints leaving a better view of the
master joint systems exposed at the surface. In the following discussions we present
observations of shear wave anisotropy and drilling induced fracture orientations observed
within a couple hundred feet of the surface. These data suggest that significant near-
surface deviatoric stress is present.
The injection well was drilled and logged in two stages. The hole was initially drilled to a depth of 2944 feet (897 meters), a depth just above the major Fruitland coal section (Figure 3). The hole was filled with fluid and then logged. The hole was then cased and cemented and an additional 226 feet (69 meters) of hole were drilled through the Fruitland coal section. FMI log coverage was limited to the upper section of the borehole (324’ to 2943’ (99m to 897m)). Two separate sonic scanner runs provided coverage from 285’ to 3156’ (87m to 962m). The top of the Fruitland Formation was encountered at a depth of 2826 feet (861 meters) 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 (903 meters) subsurface (Figure 3).

The Sonic Scanner is a wireline tool that provides monopole and dipole measurements of acoustic wave travel times. The tool has 13 receiver stations, each containing 8 radial receiver elements. The receiver stations are distributed along the length of the service sonde at half-foot (0.15 meters) intervals. The tool contains three sonic transmitters including a cylindrical ceramic monopole transmitter and two directional dipole shaker transmitters. The sources are located approximately 12 feet (3.66 meters) from the center of the receiver array. The Sonic Scanner provides accurate measurements of compressional, fast-shear, slow-shear and Stonely wave slowness. These observations are transformed into radial and axial measurements of stress-depandant properties of rocks near the wellbore. The tool was used in this study primarily to identify the orientation of the maximum compressive principal stress direction. This direction corresponds to the fast shear azimuth measured by the Sonic Scanner.
details on the Sonic Scanner may be obtained at the Schlumberger website (http://www.slb.com/content/services/evaluation/petrophysics/acoustic/sonic_scanner.asp).

The Schlumberger FMI, Fullbore Formation MicroImager, is a wireline microresistivity tool that provides oriented borehole images in wells drilled with water-based muds. The individual measurements from 192 electrodes arrayed on eight pads deployed circumferentially from the logging tool are merged into a false-color resistivity image. Clearly visible features include bedding, natural fractures both open and healed, drilling induced fractures and borehole breakout as well as textures such as burrows.

Other uses include vugular porosity characterization and the precise localization of previously taken side-wall cores. The image is oriented by the tool’s on-board magnetometers and accelerometers. Planer features, such as bedding or fracture planes, intersecting the cylindrical borehole produce a sinusoid that is traced by an interpreter. Interpretation software then calculates the dip and dip-direction of the best fit plane to the interpreter’s picks. The apertures of open natural fractures can be quantified down to as small as ~1 micron (Luthi and Souhaite, 1990; Faivre, 1993). In this paper we also present natural fracture and borehole breakout orientation data and fracture aperture data derived from the FMI log.

Further description of the FMI and a case study in the use of image logs for reservoir characterization can be found in Utah Geological Survey Open-File Report 458 (Koepsell and Longman, 2005). Technical details on the FMI log may be obtained from the Schlumberger website (http://www.slb.com/content/services/evaluation/geology/fmi.asp).
Fast Shear Azimuth – The distribution of fast shear directions measured by the Sonic Scanner along the length of the borehole has a pronounced peak in the northeast quadrant with a vector mean orientation of N36E (Figure 14A). The distribution is significantly non-random at $\alpha < 0.01$ and has 95% confidence limit about the mean of approximately $\pm 2.2$ degrees. Very small modes in the northwest and northeast quadrants have vector mean orientation of N53W, N16W and N14E (Figure 14A). Within the upper Fruitland Formation (2826 to 2943 feet subsurface (861 to 897 meters)) the fast shear azimuths (Figure 14B) are significantly non-random at $\alpha < 0.01$. Fast shear modes in the distribution have mean orientations of N38W, N6E and N45E. In the lower coal bearing Fruitland Formation (2943 to 3132 feet subsurface (897 to 955 meters)) the fast-shear directions are also non-random in distribution ($\alpha < 0.01$) with mean orientation of N10E (Figure 14C). The 95% confidence limit about the mean fast-shear direction in the Lower Fruitland is $\pm 4.8$ degrees. Fast-shear azimuths in the strata overlying the Fruitland Formation have mean orientation of N43E with 95% confidence limit of $\pm 1.8$ degrees (rose diagram not shown but similar to Figure 14A).

An F test was used to determine whether the mean fast-shear azimuth (N43E) observed in intervals overlying the Fruitland Formation is significantly different from that in the lower Fruitland coal section (N10E). The F-test statistic is calculated as follows (Davis, 2002):

$$F_{1,n-2} = \left(1 + \frac{3}{8\kappa}\right) \frac{(n-2)(R_1 + R_2 - R_n)}{(n - R_1 - R_2)}$$

In this equation $\kappa$ (the concentration parameter) is computed from the mean resultant ($\overline{R_p}$) of the two samples. Equation 3) is used in the case where $\kappa$ is greater than 2 but less...
than 10. The total number of values in the pooled sample is \( n \) (1810). \( R_1, R_2 \) and \( R_p \) (Equation 3) are resultant vector lengths computed from samples 1 and 2 and the pooled sample. The degrees of freedom used in this test are \( n-1 \) and 1808 \( (n-2) \). The critical value of \( F \) calculated for an \( \alpha \) level of 0.01 is about 6.66. \( F \) calculated from Equation 3) is 695. The calculated value of \( F \) greatly exceeds the critical value and allows us to conclude that the mean orientation of the fast-shear directions observed in strata overlying the Fruitland Formation is significantly different from the mean fast-shear direction measured in the Fruitland coal section.

**Drilling induced breakouts** - Drilling induced breakouts observed in the FMI log have mean orientation of N57W (Figure 15A) with 95% confidence limit of 3.6 degrees. A total of 97 drilling induced breakouts were interpreted in the FMI log. Only 5 breakouts were observed in the upper Fruitland (2826 to 2943 feet subsurface (861 to 897 meters)). This small subset also has mean trend of N57W (Figure 15B) with a 95% confidence limit of 10 degrees. Breakout orientation is generally consistent along the entire length of the borehole. The shallowest breakout was interpreted at 329 feet (100 meters) and the deepest observation made at 2936 feet (895 meters). The drilling induced breakouts and fast shear direction provide independent measures of the maximum compressive stresses in the logged strata. The breakouts form normal to the present-day in-situ maximum compressive stress. The N57W breakout trend implies a maximum compressive stress \( (\sigma_H) \) orientation of N33E. This is close to the fast-shear azimuth of N36E (95% confidence limits of \( \pm \) 2.2 degrees) averaged over the logged interval (285 to 3132 feet subsurface (87 to 955 meters)).
In contrast, the fast-shear direction observed in the Fruitland coal section has a more northerly (N10E) trend. The orientations of coal face cleats observed in the Gas Research Institute (GRI) Northeast Blanco Unit (NEBU) well about 7 miles east of the pilot site 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 16A). The Rayleigh test reveals this distribution is significantly non-random. Modes with mean orientation of N63W, N01E and N67E are present. From an interpretive perspective, preferred orientations appear to be forming in the distribution, but the number of observations is too low to suggest significant geological relationships. The orientations of open fractures in the Kirtland Shale (Figure 16B) are statistically random in distribution. A limited number of open fractures (N=5) observed in the FMI log in the upper Fruitland Formation have vector mean strike of N11E. This small subset of fractures is significantly non-random with $\alpha$ level of 0.01 and 95% confidence interval of $\pm$19 degrees. The N11E orientation is similar to the fast-shear orientation inferred from the sonic scanner through the upper Fruitland (~N13E, Figure 14B). The top of the Upper Fruitland Coal is reported at 2963 feet (903 meters). The FMI log provides fracture interpretations only down to about 2943 feet (897 meters), 20 feet (6.1 meters) above the Upper Fruitland Coal. As noted earlier, the average fast-shear direction of N10E in the underlying Fruitland coal section differs statistically from the
fast shear direction in the strata above the Fruitland. The result suggests possible rotation in the residual stress field within the Fruitland Formation.

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 17) particularly for the total set of open fractures and those observed in the Kirtland Shale (Figures 17 A and B). The set of open fractures observed in the upper Fruitland reveals they are general within about 35 degrees of vertical with one exception (Figure 17C).

Lorenz and Cooper (2003) report the presence of extensive north-south to north northeast-south southwest striking vertical extension fractures in exposures of the deeper Late Cretaceous MesaVerde Group and Dakota Sandstone. The northerly trend of vertical extension fractures reported by Lorenz and Cooper is consistent with the small set of open fractures observed in the FMI logs through the uppermost Fruitland (Figure 16C).

The fast-shear direction in the Fruitland also has the more northerly, north northeast-south southwest trend (Figure 14C). Although open fractures in the formations overlying the Fruitland do not reveal statistically significant trend, the fast-shear and breakout orientations observed in the sealing strata suggest that maximum compressive principal stress in these formations has shifted to the northeast. The maximum compressive stress orientation in the overlying sealing strata shifts from approximately N10E to between N33E (inferred from breakout orientations) and N43E (inferred from the fast-shear azimuths). Present day in-situ stress in the sealing strata may be decoupled from that in the underlying Fruitland and deeper formations.
**Fracture Aperture** - Schlumberger’s FMI log analysis includes computation of the hydraulic electrical apertures. Fracture aperture distribution is an important fracture property critical to flow simulation. We prefer to use the mean aperture as opposed to the hydraulic aperture. Hydraulic aperture is in itself a simulation of flow, with the assumption that the liquid is water. Running the reservoir simulation using the physical (electrical) aperture is better than using the hydraulic aperture. The electrical aperture (Figure 18A) is a calculated mean aperture along the fracture trace interpreted in the FMI log. The mean aperture of that largest fracture is 0.31 inches (0.79 centimeters). This is a continuous fracture that cuts across a borehole breakout. As the aperture calculation goes along the sinusoid and crosses the broken-out area the aperture “blooms” out into the conductive breakout. This yields an anomalously high calculated mean aperture. The influence of these anomalously high apertures is compounded when they are cubed to obtain hydraulic aperture (Figure 18B). Another outlying fracture is complicated by breakout along its trace. The hydraulic aperture distribution contains several fractures with apertures larger than 0.3 inches (0.76 centimeters). The largest electrical aperture is about 0.31 inches (0.79 centimeters) and considerably less than the equivalent hydraulic aperture of 0.76 inches (1.9 centimeters). The average hydraulic aperture is 0.137 inches (0.35 centimeters) compared to an average of 0.084 inches (0.21 centimeters) for the electrical aperture. The frequency distributions of electrical and hydraulic aperture are both positively skewed. The electrical aperture distribution is more compact. The standard deviation of electrical apertures is ±0.06 inches (±0.15 centimeters) compared to a standard deviation of ±0.14 inches (±0.36 centimeters) for the hydraulic apertures.
We also examine aperture distribution for log normal behavior. Log normal aperture distributions were reported by Bianchi (1968) in outcrop and Snow (1970) (also see Barton and Stephansson, 1990). Electrical and hydraulic aperture distributions observed in the injection well are plotted on logarithmic scale (Figure 18 C and D) for comparison. Results from the chi-square test for goodness of fit to the normal distribution indicate that the distributions of log apertures (both electrical and hydraulic) do not differ significantly from the normal distribution. The chi-square test also indicates that both log electrical and log hydraulic aperture do not differ significantly from each other. The mean log electrical aperture is -1.21 with standard deviation of $\pm 0.39$. The mean hydraulic aperture is -1.06 with a standard deviation of $\pm 0.43$.

**Healed Fractures** - A total of 57 healed fractures were identified in the FMI log interpretation. They were encountered from depths of 370 feet (113 meters) to 2925 feet (892 meters) subsurface. The orientations of healed fractures appear to be more widely scattered (Figure 19A) than the open fractures (Figure 16A) penetrated by the wellbore. As with the open fractures, the $\bar{R}$-value is low and these differences are largely attributed to random scatter. The orientations of healed fractures interpreted in the Kirtland Shale (Figure 19B) 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 (113 meters) to the top of the Fruitland Formation at 2826 feet (861 meters) subsurface. A relatively large number of healed fractures (14 or about 25%) were observed in the upper 100 feet (30.5 meters) of the Fruitland Formation (Figure 19C). The $\bar{R}$-value for these fractures taken separately is also quite low, again suggesting that the orientations
are effectively random in distribution. 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 19A)
occur at N53W, N14E and N59E. Peaks in the rose diagram of healed fractures in the
upper Fruitland (Figure 19C) occur at N66W, N03W, and N50E, with confidence limits
of 11 degrees, 14 degrees and 21 degrees, respectively. With exception of healed
fractures in the Kirtland shale (Figure 19B), modes observed in these distributions could
arise at random.

3D SEISMIC INTERPRETATION AND ATTRIBUTE ANALYSIS

Several seismic attributes were calculated and examined to determine if additional
insights could be gained from the seismic data regarding the structural and stratigraphic
integrity of the reservoir and overlying strata. Post-stack processing and seismic
interpretation was concentrated on enhancement and identification of seismic features
that might be associated with fracture zones and faults. Evidence of pervasive fracturing
of the overburden strata is presented in the preceding sections. The 3D seismic data from
the site provide observations that may reveal the presence of potential larger scale
fracture zones in the reservoir and cover strata. The likelihood that fracture systems
observed in the borehole may have extensive interconnections that could facilitate escape
of injected CO$_2$ into near-surface aquifers or back into Earth’s atmosphere is of critical
importance to the long term viability of the sequestration effort. The seismic
interpretation helps upscale the borehole results to site scale.
The absolute value of the derivative of seismic amplitude was calculated to help unveil potential fracture zones extending vertically through the section. A 20Hz to 90Hz bandpass filter was initially applied to the post-stack data to reduce high frequency noise in the final migrated stack. An automatic gain control was also applied to the derivative to normalize amplitude variations over short (75 millisecond) time windows. The processed data (Figure 20) reveal numerous continuous linear zones that crosscut reflection events. While reservoir-to-surface faults are not observed in the 3D seismic data, linear alignments of features cross-cutting reflection events extend continuously 500 feet (152.4 meters) to 700 feet (213.4 meters) from the upper Fruitland through Kirtland reflection events. Mapping of these zones through the 3D seismic volume reveals they trend roughly between N20 to 35W. The interpretation suggests fracturing and minor faulting of the cover strata may be more pervasive than previously anticipated.

A closeup view (Figure 21) along this same dip line reveals some subtle disruptions of amplitude within the Kirtland Shale to the southwest near one of the producing wells (the COM A 300). Between the Fruitland top and base (Figure 21) there are some subtle features that may be associated with vertically juxtaposed stratigraphic pinchouts or internal faults. 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.

Subtle seismic indications of fracturing within the Fruitland sequence are present
in places (e.g. Figure 21); 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 (patented Schlumberger process) reveals a regular system of
discontinuities interpreted to be fracture zones or small faults within the Fruitland
Formation and overlying strata. The Ant Track algorithm is accessed using
Schlumberger’s Petrel Seismic-to-Simulation software. Rose diagrams of ant-tracks
reveal pronounced NE trending modes throughout the Fruitland sequence (Figure 22).
Less pronounced NW trending modes are infrequently observed. The NE trend is also
very pronounced in the overlying Kirtland Shale (Figure 23). The $\bar{R}$ value in all cases
suggests that these distributions are non-random for $\alpha$ level of 0.01.

Directional analysis of edge discontinuities reveals prominent N55 to 58E trends
in frequency-weighted rose diagrams through the Fruitland (Figure 22). All distributions
are significantly non-random at $\alpha$ level of 0.01. Multiple modes are observed in all these
directional plots, but are most pronounced near the top of the Fruitland sequence around
530 milliseconds. Modes with mean trend of N56E and N54W have 95% 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 23). Ant-track trends remain fairly regular throughout. The $\bar{R}$ values
suggest ant-track orientations are non-random with $\alpha$ of 0.01 (in the upper and middle Kirtland) to 0.05 (in the Nacimiento). The ant tracks are characterized generally by pronounced modes in the northeast quadrant of the rose diagrams. Mode means in the northeast quadrant are N55E for the middle Kirtland; N51E for the upper Kirtland; and N53E for the Nacimiento. Smaller modes also occur in the northwest quadrant with means of N45W, N45W, and N40W, respectively.

**SUMMARY AND CONCLUSIONS**

This study focuses on acquisition and analysis of natural fracture and stress orientation data to provide a detailed interpretation of potential fracture systems and faults within the cover strata and injection zone of the Southwest Regional Partnership’s Fruitland coal carbon sequestration pilot test in the San Juan Basin of New Mexico. The results of the study provide information about potential flow pathways 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 sealing strata were characterized using a variety of remote sensing and geophysical data.

The presence of tectonic influence on near-surface fracture development is supported by the presence of significant residual tectonic stress in near-surface strata. The N33E shallow fast-shear trend and the N23E trend inferred from the shallow breakouts are not significantly different. Since in-situ stress within the near-surface is sufficient to fracture the borehole wall, it may exert some influence on development of surface fracture systems.
Sonic Scanner observations, unlike those from the FMI log, were available through the injection zone. Average fast-shear directions in the sealing strata of N36E are statistically different from the N10E trend within the coal section. The N10E trend observed in the coal bearing intervals is similar to the north-northeast south-southwest fracture trends observed by Lorenz and Cooper (2003) in outcrops of the underlying Mesaverde Formation and Dakota Sandstone. Observations reveal a significant shift in the orientation of present-day in-situ stress from the north-northeast in the lower Fruitland to more northeasterly trend within the cover strata.

Open fractures in the upper Fruitland have significantly non-random distribution with mean trend of N11E. The mean trend of these open fractures is similar to the mean fast-shear directions in the upper and lower Fruitland (N13E and N10E, respectively). Electrical and hydraulic aperture distributions obtained for open fractures from FMI log analysis have log normal distribution.

We also interpreted proprietary 3D seismic data provided for this study by the Southwest Regional Partnership for Carbon Sequestration. Post-stack processing reveals discontinuities in seismic profile and timeslice view. Use of the Schlumberger Petrel Ant Tracking edge enhancement process reveals the presence of numerous reflection discontinuities with mean orientation of N55 to 58E. Ant-track trends in the cover strata have prominent northeast trending modes with mean trends between N51 to 55E. Discontinuities observed in post-stack enhanced profile view suggest the presence of considerable fracturing and minor faulting within the Kirtland Shale caprock. These zones are less common within the Fruitland sequence.
Overall, the analysis presented in this study suggests the presence of extensive fracture systems within the sealing strata. Interpreted fracture systems could increase the probability of long-term CO\textsubscript{2} leakage. 3D seismic interpretation suggests these small faults and fracture zones have limited vertical extent. Major penetrative faults are not evident in the 3D seismic; however, the presence of numerous open fractures in the sealing strata with variable trend suggests vertical migration of injected CO\textsubscript{2} is possible. Open fractures are encountered from depths of 1000 feet (305 meters) subsurface within the San Jose Formation to 2900 feet (884 meters) within the upper Fruitland Formation. The distribution of open fractures has modes with NW, N and NE trend. Given that these open fractures are encountered locally within the injection well it seems likely that arbitrarily located wellbores would penetrate open fractures with similar frequency. A similar frequency of open fracture systems throughout the site could facilitate interconnection and long-term upward migration of CO\textsubscript{2} through more penetrative fracture zones interpreted in the 3D seismic. The fracture analysis presented in this paper provides the basis for development of a discrete fracture network that could be used in flow simulations. Models that incorporate discrete fracture networks with properties identified in this study could be used to assess the range of possible leakage rates that might occur through overburden strata.
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FIGURE CAPTIONS

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 (from Heath, 2010).

Figure 2: Local structure on the top of the upper Fruitland Coal. The approximate location of the injection well is highlighted by the red circle near the center of section 32 (31N/8W). Modified from Henthorn et al. (2007).

Figure 3: Stratigraphic column showing selected wireline logs and interpretation for the injection well ConocoPhillips EPNG Com A Inj 1). The injection zone extended through the thick Fruitland coals starting at a depth of approximately 2,940 feet subsurface. (from Heath, 2010).

Figure 4: 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 5: Northeast-southwest line through the injection well (middle of section) 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.

Figure 6: The edge of the mesa is bordered by a series of three rugged cliffs formed in separate sandstone layers. The steps or breaks between bluffs coincide with shale
intervals. The point of observation is located about 400 meters south of the injection well and the view is to the southwest.

Figure 7: 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 8: 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.

Figure 9: 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.

Figure 10: 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.

Figure 11: 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.

Figure 12: Rose diagrams of QuickBird-mapped fracture traces on the mesa southwest of the pilot site. Areas sampled to compile rose diagrams a through g are shown in Figure 10. 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 13: Rose diagrams of surface-mapped fracture traces on the mesa southwest of the pilot site. Areas a through g are located on Figure 10. 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).

Figure 14: 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 mode in the northeast quadrant with mean orientation of N42E degrees (N=1314). Smaller peaks are observed at approximately N53W (N=87), N16W (N=116) and N14E (N=299). B) Mean direction in the upper part of the Fruitland Formation is N12.6E (N=236); C) In the coal bearing section the average fast shear direction is N10E (N=379).

Figure 15: 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).

Figure 16: 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.
Figure 17: Equal area (Schmidt Net) projections of poles to open fracture planes. A) Al open fractures; B) open fractures observed in the Kirtland Shale; and C) open fractures observed in the upper Fruitland Fm.

Figure 18: A) Electrical fracture aperture distribution; B) hydraulic fracture aperture distributions; C) log of electrical and D) log hydraulic aperture distributions.

Figure 19: 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.

Figure 20: 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. Arrows point to the tips of linear features cross-cutting reflection events.

Figure 21: 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.

Figure 22: 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 23: Ant-track discontinuities mapped in the middle (A) and upper (B) Kirtland shale and Nacimiento Formation C).
Figure 3
Figure 6

Figure 7
Figure 8
Figure 13

Figure 14
Figure 15

Figure 16
Figure 17

A) 

B) 

C) 

D) 

Figure 18
Figure 19

Figure 20
Figure 21
Figure 22

Figure 23