Seismic Evaluation of the Fruitland Formation with Implications on Leakage Potential of Injected CO₂

Tom Wilson¹², Art Wells¹ and George Koperna³

Abstract
Subsurface characterization activities undertaken in collaboration with the Southwest Regional Carbon Sequestration Partnership on their San Juan Basin pilot test include acquisition of geophysical logs, time lapse VSP and analysis of 3D seismic data from the site. The project is funded by the U.S. Department of Energy and is managed by the National Energy Technology Laboratory. CO₂ injection began in late July of 2008 and appears it will continue at least into early August of 2009. Total CO₂ injection volume to date (mid July, 2009) is approximately 300MMcf. Subsurface characterization activities are critical to the evaluation of reservoir integrity and the potential that leakage of injected CO₂ might occur.

Work discussed in this presentation focuses primarily on the analysis of 3D seismic from the area. 3D seismic interpretation reveals that the Late Cretaceous Fruitland Formation forms a well defined seismic sequence bounded by high amplitude reflection events at its top and base. The pattern of internal reflection events is parallel and conformable near the top and base of the sequence. The 3D seismic view of the Fruitland Formation shows considerable detail not inferred from well log correlations in the area. The pattern of internal reflection events is marked by significant internal discontinuity. Fruitland coal reflection events reveal the presence of local fold-like structures with wavelengths of 1 km to 3.5km accompanied by relief of 6 feet to 60 feet. The origin of these structures is uncertain. Some of the structures observed in the Fruitland are present in overlying Paleocene and Late Cretaceous intervals.

Post-stack processing of the 3D seismic is undertaken to enhance subtle discontinuity in the data that might be indicative of small faults or fracture zones that could jeopardize reservoir integrity. 3D seismic from the area is processed using edge enhancement, event similarity and spectral decomposition algorithms. Additional seismic attributes are also evaluated for evidence of faults or fracture zones. The analysis raises questions concerning local variations in Fruitland coal depositional systems, the influence of differential compaction within the Fruitland coal section, and local structure of possible tectonic origin. The vertical extension of larger wavelength structures into shallower strata suggests that local deformation of the area continued through the Paleocene and may include minor deformation of Eocene strata exposed at the surface in the areas surrounding the pilot site. Extensive tracer monitoring at the surface for evidence of CO₂ escape ensures that escape very small amounts of CO₂ should that occur, will be detected.

Introduction
Seismic analysis undertaken in this study consists primarily of post stack attribute analysis. Attribute analysis refers to an extensive collection of processes designed to enhance features of interest in subsurface interpretation. Attributes calculated and evaluated in this study included a variety of edge and discontinuity enhancement algorithms. The motivation for this analysis is to identify potential fracture zones and faults that may breach the injection zone and lead to migration of injected CO₂ into overlying strata. The project is funded by the U.S. Department of Energy and is managed by the National Energy Technology Laboratory.

In the following discussion, an example of the 3D post-stack seismic processing efforts is illustrated. An ongoing more comprehensive study incorporates application of edge enhancement and event similarity prediction algorithms, along with calculation and evaluation of tuning cubes and Ant Tracking. The example presented in this proceedings paper illustrates the benefit of looking at attributes other than seismic amplitude. Overall, the analysis suggests the possibility for internal compartmentalization of the Fruitland coals through this area accompanied by fairly extensive system of fracture networks.

Seismic analysis presented here suggests that the subsurface geology is quite complex at the scale of the pilot site. Amplitude anomalies are numerous in the vicinity of the injection well in addition to kilometer

¹ National Energy Technology Laboratory, ² West Virginia University, ³ Advanced Resources International
wavelength structures. Regional studies by Fassett (1997), Wray (2000), reveal the presence of considerable heterogeneity within the Fruitland Formation and individual seams. The detailed study of Ayers and Zellers (1994) conducted near the pilot site reveals considerable complexity in the Fruitland Fm depositional systems. In a schematic sense, Wray (2000) represents the variety of heterogeneity that can be encountered in the Fruitland coals (Figure 1). Fassett (1997) indicates that continuity of subsurface coals over distances of a mile is speculative, at best. Pinchouts, local fault truncations, channel scour and facies changes are all encountered in the Fruitland coals. Seismic analysis provides a glimpse of some of this heterogeneity.

Site monitoring activities undertaken through the Southwest Regional Partnership include 1) surface monitoring for perfluorocarbon tracers injected into the CO₂ stream by NETL; 2) continuous monitoring of CO₂ concentration at three offset production wells; 3) periodic sampling to determine total production gas stream composition on eleven offset production wells; 4) monitoring of surface tilt (Pinnacle); and 5) time-lapse vertical seismic profiling (Schlumberger). 3D seismic interpretations will aid interpretation of monitoring observations. The seismic analysis may also help guide modifications to existing reservoir flow models if needed.

**Seismic Interpretation**

A black and white variable area wiggly trace display (Figure 2) illustrates basic features associated with the seismic response of the Fruitland sequence.
In this 2D seismic display, locally steepened dips are evident across the area. This line trends northeast-southwest. Considerable internal discontinuity of reflection events is evident throughout.

Figure 2: In this 2D seismic display, locally steepened dips are evident across the area. This line trends northeast-southwest. Considerable internal discontinuity of reflection events is evident throughout.

3D seismic interpretation reveals that 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. This discontinuity appears to be associated primarily with the upper and middle Fruitland coals. The 3D seismic view of the Fruitland Formation is considerably different than that inferred from well log cross sections. The seismic reveals significant discontinuity as noted, whereas the coal intervals shown in well log cross sections often suggest continuity which may, in fact, not be the case. These are problems related to sparse sampling that we are all familiar with. Seismic interpretation also reveals the presence of local fold-like structures (Figures 2 and 3) with wavelengths ranging from 1 km to 3.5 km accompanied by relief of 6 feet to 60 feet.

The origin(s) of these structures is uncertain. In some cases, time-structural rise across the top of the Fruitland is accompanied by a drop across the base. This suggests that apparent structure across the base may result from added travel time through the relatively lower velocity Fruitland Formation. However, the relationship is not consistent. 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 appear to have some hint of continuation into intervals overlying the Kirtland.

Other possible influences to consider include detachment within the coals and differential compaction associated with lateral variations of net compressibility associated with variations in depositional environments and lithologic heterogeneity within the Fruitland Fm. Although regional face cleat trend in the area has NE-SW trend, Ayers and Zellers (1994) note that compaction folding of coals above and below channel sandstones could produce localized areas of enhanced
fracture density. Their cross sections reveal coal splitting associated with fluvial channel systems within the Fruitland Fm. Compaction induced coal fracture systems are discussed by Donaldson (1979) and Tyler et al. (1991). Internal reflection patterns observed in the 3D seismic from the area (figures 2 and 3) suggest the presence of some channeling.

**Figure 3:** This northwest-southeast line illustrates a similar level of reflection discontinuity along the axis of the basin. Local structural features are also evident in the display.

**Figure 4:** Shallower reflection events associated with the upper Kirtland Shale, the Ojo Alamo Sandstone and Nacimiento Fm.
Seismic displays (Figures 3 and 4) suggest thinning to the southeast. A regional view of the Fruitland isochore map (Figure 5) covers approximately a 9 square mile area. The isochore map shows areas of thinning (orange and red areas, Figure 5) that stretch to the southeast along the axis of the basin. The morphology of these patterns is not clearly associated with specific depositional environments. Sandstone deposits in the Fruitland formation generally flowed northeastward onto coastal areas of the Western Interior Seaway. While there appear to be channel-like features in some vertical displays, we do not see the dip-elongate (northeast oriented) pattern of sandstone bodies expected in the Fruitland (Ayers and Zellers, 1994). The isochore might reveal depositional patterns if they are accompanied by differential compaction. The change in travel time through the Fruitland sequence encountered in the vicinity of the injection and production wells is at most 8 milliseconds. Using an average interval velocity of 10,600 feet per second for the Fruitland, this corresponds approximately to thickness changes on the order of 42 feet.

Reflection events arising from the lower Fruitland coal are continuous and well defined throughout the area. Travel time changes from these continuous internal reflections in the vicinity of the injection well and surrounding production wells correspond to thickness variations on the order of 2 to 3 feet, or so (Figure 6). This estimate assumes a constant velocity of about 7,700 feet/second in this coal interval. The reflection event from the top of the coal appears to be closer to the overlying zero crossing (Figure 7). The following negative cycle was used due to its continuity. While the events interpreted to be associated with the lower Fruitland coal do not coincide with the actual top and base of the lower Fruitland seam, they do provide a measure of the internal thickness variations and structure of this lower coal zone.

![Figure 5: Isochore map of the interpreted Fruitland Formation seismic sequence.](image-url)
Figure 6: Isochore map of the interpreted lower Fruitland coal zone.

Figure 7: A detailed view of reflection events associated with the lower Fruitland coal.
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 CO₂. Thus we are interested in identifying possible fracture zones and faults that might facilitate the escape of injected CO₂ into overlying formations and possibly to the surface.

An example of this analysis (Figure 8) illustrates how additional information can be extracted regarding the presence of possible fracture zones and fault systems. The absolute value of the derivative of seismic amplitude was calculated. An AGC was applied to the derivative to normalize amplitude variations. Between the Fruitland top and base (Figure 8) there are some subtle features that may be associated with vertically juxtaposed stratigraphic pinchouts or internal faults. Some of these 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 to the surface might be facilitated by these fracture systems.

A closeup view (Figure 9) 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

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Figure 9: Close up view of finite difference attribute along the dip line shown in Figure 8. This line passes through the COM A 300 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.

coincident with this high are observed in the underlying Pictured Cliffs Sandstone. The Fruitland isochore (Figure 5) reveals a northwest trending zone of thinning in the Fruitland sequence. Thinning correlates to the presence of reflection terminations against the lower Fruitland sequence boundary. These reflection patterns are interpreted to be associated with northwest trending shoreline sands in the Pictured Cliffs Sandstone. We speculate that sequence thinning is related to differential compaction over a shoreline sand body. We also speculate 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 8), however, the finite difference computations do not provide clear evidence of local faults within the Fruitland Fm. The results obtained from analysis of additional seismic attributes will be presented at the meeting. One of these attributes (Ant Tracking) reveals a regular system of discontinuities interpreted to be fracture zones or small faults within the Fruitland Fm. Rose diagrams of Ant Tracks reveal pronounced clusters with N50-55E trend throughout the Fruitland (e.g. Figure 10A). Less pronounced NW trending clusters are infrequently observed. The NE trend is also very pronounced in the overlying Kirtland Shale (e.g. Figure 10B), Ojo Alamo Sandstone and Nacimiento Formation.
Conclusions

The Southwest Regional Partnership’s San Juan Basin carbon sequestration pilot site lies about 10 miles southwest of the axis of the San Juan Basin. CO₂ was injected into the Fruitland Formation over depths ranging between 2,940 to 3,150 feet subsurface. During the course of a year, nearly 18,000 tons of CO₂ were injected into the Fruitland Formation. Subsurface characterization activities were undertaken in this study to help assess site integrity and provide a framework for interpretation of NETL’s perfluorocarbon tracer and soil gas observations at the site.

Seismic interpretation of about 9 square miles of 3D seismic data centered around the injection well reveals that the late Cretaceous Fruitland Formation forms a well defined seismic sequence with high amplitude reflections marking the top and base of the sequence. Internal reflection patterns suggest considerable stratigraphic complexity in the Fruitland Formation depositional systems. The lower Fruitland coal reflection events are fairly continuous across the site whereas the middle and upper Fruitland coal events are fairly discontinuous and difficult to correlate through the surrounding area. The detailed seismic view also reveals considerable local structural complexity not generally observed in well log derived cross sections. The overlying Kirtland Shale is considered to represent the effective caprock for Fruitland Formation reservoirs. Variable area wiggly trace displays illustrate the stratigraphic and structural complexity of the Fruitland sequence. Isochore (travel time difference) maps of the Fruitland sequence and lower Fruitland coal intervals reveal considerable variability of thickness throughout the area. Thinning of the Fruitland sequence occurs along a NW-SE trend through the pilot site that coincides with a high in the base of the sequence. Stratigraphic buildup and pinchout are observed in the upper Pictured Cliffs seismic sequence.

We speculate that thinning of the Fruitland sequence observed along the NW-SE trend is associated with differential compaction over northwest trending shoreline sand bodies in the upper Pictured Cliffs Sandstone and that differential compaction of the Fruitland may enhance local fracture intensity along this NW-SE trend.

Post-stack processing of the 3D seismic was undertaken to help enhance seismic indicators of fracturing and faulting. The output from specific post stack processing steps is generally defined as a seismic attribute. There are a multitude of seismic attributes including instantaneous phase, instantaneous frequency, envelope, energy, etc. In this study we explored the potential use of a less common attribute consisting of the absolute value of the derivative of the seismic amplitudes. An automatic gain control (AGC) was applied to the output to help equalize attribute amplitude over short time windows. The result of this simple process suggests the presence of considerable fracturing and minor faulting within the Kirtland Shale caprock. Indicators for extensive fracturing and faulting within the Fruitland sequence are much less apparent.
The Schlumberger Ant Tracking process however does delineate subtle zones of reflection discontinuity that form clusters with approximate N50-55E trend. Similar patterns of discontinuity are observed in the Kirtland and overlying Tertiary intervals (interpreted Ojo Alamo and Nacimiento seismic sequences).

3D seismic coverage is critical to the assessment of site integrity. In this study, 3D seismic analysis reveals numerous details about internal reservoir stratigraphic and structural framework which we are unable to infer from limited borehole correlations. Seismic attribute analysis can be used effectively to enhance subtle features in the seismic response that may be indicative of fracture zones and faults that could jeopardize reservoir integrity. The results of the analysis suggest that several small faults and fracture zones disrupt overlying intervals and to less extent, the reservoir interval. However, interpreted faults and fracture zones have limited vertical extent and major penetrative faults have not been observed at the site.

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The seismic data used in this evaluation are proprietary and provided through the Southwest Regional Partnership.

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References


