Distribution of Unminable Coals along the Eastern Margin of the Rome Trough in Central West Virginia with Considerations of Carbon Sequestration Potential and Risk

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Abstract

Successful carbon sequestration is gauged in terms of the likelihood of long term CO₂ retention and the potential CO₂ storage volume. Factors influencing long term reservoir integrity include coal seam continuity, coal seam depth, cap rock integrity, the presence of breaching faults and fracture zones, injection pressure and long term response of coal to CO₂ injection. We selected an area in central West Virginia for detailed assessment of coal sequestration potential. The area lies near the border between the southern and northern coal regions where detailed maps of the deeper coals have not been compiled. The study area also lies along the eastern margin of the Rome trough, a failed rift that developed primarily during the Cambrian and Ordovician periods but continued to accommodate minor displacements during the later Paleozoic. The structural complexity of the area incorporates the potential for detached structures since the area lies along the western limit of detached structures observed in the Appalachian foreland. An associated issue addressed in this study is whether shallow structures observed in the coal bearing section are associated with syndepositional reactivation of margin structures or result from post-depositional detachment. The study incorporates interpretation of conventional vibroseis and higher resolution weight-drop seismic data. Geophysical logs from over 100 wells are used to develop structure and isopach maps of low density and low gamma zones that may represent individual coal seams. Interpreted low density intervals and potential coals in this area are believed to be confined largely to the Kanawha Formation. Isopach maps reveal that these zones generally have pod-like distribution and would, in today’s terms, be considered unminable. The study also incorporates geomechanical simulations of surface displacements and pore pressure distributions resulting from hypothetical CO₂ injection efforts along with estimates of injection volume as a function of permeability. Optimal high permeability injection scenarios suggest that the coals in the section do not represent a sufficient sink for commercial scale sequestration efforts.

Background

The DOE NETL metric for storage permanence is 99% retention after 100 years (see Carbon Sequestration Technology Roadmap and Program Plan, 2006). This requires detection limits of less than 0.01%/year. Monitoring, mitigation, and verification (MMV) of the carbon sequestration process has been an essential component of carbon sequestration research since its inception (Wells et al., 2006). Geological and geophysical characterization activities play an important role in the MMV design process.

In this study we selected a hypothetical test site for assessment in central West Virginia between the northern and central coal regions (Figure 1). The area is located along the eastern margin of the Rome Trough. There is currently no mining or coal exploration activity in the area. Thus it is an area where minable and unminable coals likely exist and where some overlap in future mining and sequestration/enhanced coalbed methane recovery efforts could occur.

The area has been extensively drilled for oil from the lower Mississippian Big Injun sandstone. Several miles of seismic data over the field were available for this study (Figure 2). Available seismic data included 28 miles of conventional vibroseis data and 14 miles of higher resolution weight-drop data. Much of western West Virginia is underlain by an early Paleozoic failed rift complex. The failed rift complex develops to the west of the margin faults (Figure 3). The complex known as the Rome trough formed inboard from the main rift complex that developed during the opening of the early Paleozoic Iapetan Ocean (Thomas, 2005) during the breakup of Rodinia. Displacement along early Paleozoic extension faults within the trough was inverted in some areas during late Paleozoic orogenic loading (Wilson, 2000). Vibroseis Line 6 across the area (Figure 3) reveals the major structural elements underlying the study area. The combined offset across the deeper normal faults shown on Line 6 is approximately 2200 feet at the level of the Cambrian Eocambrian or acoustic basement interface. Note that there is considerable disharmony between basement and shallower structure
across these normal faults. The shallower reflection events (e.g. Keefer and Trenton) are structurally high over the northwestern-most basement block, indicating that this block moved upward following deposition of the shallow Mississippian and Lower Pennsylvanian strata. In addition to seismic data, 160 wells with $\gamma$ ray and density logs through the shallow section are used to map shallow structure and produce isopach maps of individual coal or low density intervals. Many of the wells in this area were drilled to produce oil from the Mississippian Big Injun Sandstone. Inverted basement structures produced structural highs into which oil accumulated. The oil was later forced down dip by gas as it came out of solution during post-Paleozoic erosional unloading (Shumaker et al. 1990). Structure on the Big Injun Sandstone (Figure 4a) reveals that the study area is located over a syncline that plunges northeastward. The structural rise in the Big Injun Sandstone observed along the western edge of the study area (Figure 4a) was produced by upward (reverse) movement of the fault block to the northwest (Figure 3) during the later Paleozoic. The growth of this structure during the late Paleozoic is also shown by coincident thinning of the middle Pennsylvanian through middle Mississippian strata along the structural rise to the west (Figure 4b).

**Figure 1**: Study area is located near the southern border of the Northern Appalachian Coal Region (from Rupert and Rice, 2001).
**Figure 2**: Seismic lines used in this study. Vibroseis line 6 extends roughly north to south through the area. Weight drop line 17 extends roughly east to west through the area.

**Figure 3**: Regional seismic line (Vibroseis Line 6) crossing through the assessment area.
While the influence of reactivated basement structures played an important role in localizing oil and gas accumulations in the area, the role, if any in coal formation and distribution is unknown. Since unminable coals in the basin may be possible candidates for future sequestration and enhanced coalbed methane recovery (ECBMR) efforts, mapping and understanding the origins of local structure along with an evaluation of coal continuity and thickness variation through the area are critical to accurate evaluation of carbon sequestration potential and leakage risk in unminable coals. Enhanced coalbed methane recovery in unminable coals represents a potential economical benefit of carbon sequestration activities. Justification for CO₂ credits however is likely to rely on ensured storage. If injected CO₂ leaks back into Earth’s atmosphere over the short term, the CO₂ credit may have limited value. Assessment of leakage potential will help justify the cost of long term carbon sequestration efforts.

**Syn- and Post-Depositional Deformation of Coal Bearing Strata**

Reactivation of the normal faults observed along the eastern edge of the Rome Trough (Figure 3) is associated with low relief drape folds in the overlying late Paleozoic section (Figure 4). Shallow normal faults can also be interpreted in the near surface (Figure 5). Reflections from the coal bearing strata are located roughly between 0.1 and 0.16 seconds. Shallow faults were mapped through small offsets and through zones of reduced coherence in the reflection seismic response along extensions of deeper faults into the near surface. The

**Figure 4:** a) Structure on the Mississippian Big Injun sandstone. b) Isopach map extending from the top of the lower Allegheny Fm sand to the top of the Mississippian Big Injun Sandstone.
influence on the shallower strata produced by syndepositional fault displacement is transferred up to the southeast. The eastward thickening of strata documented in the well-log derived isopach (Figure 4b) is also observed in the seismic as an increase in two-way travel time to the east (see figure 5 and 6) between the Big Injun and shallow coal reflection events. An isopach map of the Middle Pennsylvanian coal bearing strata (Figure 7) reveals a less distinct pattern of east-to-west thinning than that observed in the Middle Pennsylvanian through Middle Mississippian isopach (Figure 4b). However, the seismic and log derived variations along Line 17 are very consistent. The central part of Line 17 crosses a thickened area in the isopach map that is enhanced through and area with no well control by contour interpolation. While the overall 2 to 3km scale features in the isopach map can be attributed to the syndepositional movement of deeper basement blocks, the smaller lenses of thicker section cannot be attributed to syndepositional movements along these deeper faults. Some of these lenses are elongated in the NE to SW direction having an orientation similar to that of detached structures in the adjacent high plateau region to the SE. While inversion of movement along the basement fault would have occurred during deposition and have influenced local coal forming environments, shallow detached structures, if present, would have formed later during the Appalachian orogeny. The development of detached structures would not influence coal deposition; however, it would lead to localized enhancement of fracture systems in the Pennsylvanian section. Structural features on the top of the Salt Sands (Figure 8) suggest that these thickened regions result from erosional features on the surface of the Salt Sands – the basal surface used to construct Middle Pennsylvanian isopach. The analysis of data from the area does not suggest that detached structures are present. Nonetheless, the upward movement of the deeper basement block continued. The structural high over the basement block to the west persists through the shallower strata and is observable at the surface along a northeast extension of the Warfield anticline.

**Figure 5**: Shallow view of weight-drop Line 17. Intersection with Vibroseis Line 6 is shown.
Figure 6: Interval transit time variations between reflection events in the coal-bearing section along Line 17 suggest the presence of faults that may have been active during coal deposition.

Figure 7: Isopach map of the Middle Pennsylvanian section. Weight drop Line 17 is located along the yellow line.
The preceding structural analysis suggests that 1) some regional scale uplift occurred during deposition of the coals in the area and that 2) this deformation continues following deposition. Deformation following deposition can be expected to fracture the coal bearing strata.

**Coal Distribution**

Little is known concerning the details of subsurface coal distribution in the central West Virginia study area. Descriptions from scattered driller’s logs are presented by Hennen and Gawthrop (1917). The nearest wells in their study are located at distances of 6 to 7 miles to the NE and SE, respectively. These old wells also did not extend more than 300 feet or so beneath the surface. Thus the view of coal distribution in the area is limited to the near-surface coals in the Conemaugh Group and Allegheny Formation. Information on the coals in the deeper Kanawha, New River and Pocahontas formations considered in this study are generally inferred from map compilations to the southwest in Kanawha County along its border with Clay County. These maps are available online from the West Virginia Geological and Economic Survey Interactive Coal Bed Mapping Project (see http://www.wvgs.wvnet.edu/www/coal/cbmp/coalims.html).

Most of the coals or low-density zones observed in the logs compiled for this study appear to be concentrated in the Kanawha Formation. Coals are generally suggested by low density and low gamma ray log responses. These log responses, however, are not consistent throughout the

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**Figure 8**: Structure on the top of the Salt Sands.
database. In the absence of detailed core data from any wells in the area, the low density-low gamma zones were labeled sequentially as the Kanawha #3 through Kanawha #11 coal zones. The Kanawha #1 coal may be the Stockton Coal near the top of the Kanawha Formation. Coal maps to the southwest in Kanawha County suggest that the deeper Kanawha Formation coals beneath the Little Eagle (the Matewan, Gilbert and Douglas, for example) are not present in northwestern Clay County. Coals shown in cross section probably span the Stockton to Little Eagle (Blake, 2008, personal communication).

Isopach maps of interpreted Kanawha #3 and Kanawha #11 coals (Figures 9a and b, respectively) reveal considerable thickness variation over distances of a kilometer or so. The thickness of the shallow Kanawha #3 interval (Figure 9a) varies from 0 to over 8 feet in places. The deeper Kanawah #11 coal (Figure 9b) has a

![Isopach Map of the Kanawha #3 Coal Zone](image1)

![Isopach Map of the Kanawha #11 Coal Zone](image2)

**Figure 9:** a) Isopach map of the Kanawha #3 coal zone. Isopach map of the Kanawha #3 coal zone.
pronounced pod-like distribution. The aerial extent of individual pods varies from less than a kilometer to as much as 2 kilometers in places. Their thickness generally does not exceed 6 feet. Thickness variations suggest considerable variability in the local depositional environment. Some of this variability may also be due to erosion during deposition of overlying strata. Considerable thickness variation over small distances makes it unlikely that these coal zones could be easily mined. Most of the potential coals mapped in this area reveal considerable heterogeneity in distribution and can probably be classified as unminable in terms of present-day extraction technologies.

**Geomechanical Simulations**

Deformation of overburden strata in response to CO₂ injection was computed using finite element simulations. A detailed 73 layer mechanical model was developed of the subsurface based on full waveform and density log responses observed in one well. Density, shear wave and compressional wave sonic logs were used to estimate Young’s modulus as a function of depth (Figure 10). This model was further simplified into a 24 layer finite element model. Injection was modeled into a 2 meter thick coal buried at a depth of 480 meters. During the simulation the injection pressure was maintained at 8.27 MPa (1200 psi).

The coal permeability was limited to 1 md. Under those conditions, 515 tonnes of CO₂ were injected over a 365 day period. Surface deformation reached a maximum of 0.27 mm (Figure 11). The 8.27 MPa injection pressure is about 3.45 MPa (500 psi) above the hydrostatic pressure at this depth. The model results represent a relatively conservative scenario in which CO₂ injection volumes are limited by low matrix permeability (1md).

The presence of ground deformation, although small in this case, increases with depth to over 0.75 mm at the reservoir level and illustrates the possibility that overburden strata could be weakened in response to CO₂ injection and cause naturally-occurring fracture systems to open slightly. Extension could facilitate CO₂ escape, particularly when injection pressures exceed the hydrostatic pressure, as in this case.

The actual permeability of coals in this area is unknown. Matrix permeability of 1md represents a conservative estimate. Gas flows from lateral wells in other parts of the basin suggest that actual coal permeabilities may be much higher. Permeability is enhanced by coal cleat and fracture systems. As the permeability increases from 1 to 25 md, the injection amount increases from a little over 500 tonnes to more than 10,000 tonnes per year (Figure 12).

![Graph showing depth vs. permeability](image)

**Figure 10:** Isopach map of the Kanawha #3 coal zone.

**Figure 11:** Isopach map of the Kanawha #3 coal zone.
Figure 11: Variation of vertical displacement at the ground surface with time.

Figure 12: Computed injection amount versus permeability.
Conclusions

Analysis of log derived structure and isopach maps along with interpretations of seismic reflection travelt ime differences suggests that faults were active during deposition of the coal bearing strata. The persistence of basement controlled structure into the near surface reveals that the area continued to deform following deposition. Well log derived isopach maps of interpreted coal zones reveal that the coals in this area have pod-like discontinuous distribution. Reactivation following deposition is likely to have opened and extended fracture systems through coal seams and into the near-surface. The likelihood that overburden fracture systems are enhanced through late stage deformation and the presence of considerable heterogeneity and discontinuity in coal distribution, combined with overburden deformations produced by CO\textsubscript{2} injection translate into increased risk of leakage for any coalbed sequestration activities that might be conducted in this or similar areas of the basin. Even with higher permeabilities (~25 md) and injection into multiple seams, the storage capacity of these coals may be insufficient to accommodate deployment of commercial scale (1,000,000 tonnes per year) sequestration efforts.

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References


West Virginia Geological and Economic Survey Interactive Coal Bed Mapping Project (see http://www.wvgs.wvnet.edu/www/coal/cbmp/coalims.html)