Seismic tests at Southern Ute Nation coal fire site

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ABSTRACT

We conducted a near surface seismic test at the Southern Ute Nation coal fire site near Durango, CO. The goal was to characterize and image the coal fire and to help plan any future surveys. We collected data along two transects. Data from Line 1, which overlies unburned coal, shows useful frequency content above 100 Hz and a reflection that we interpret to originate at approximately 11 m depth. Data from Line 2, which crosses the burn front and many fissures, is of lower quality, with predominantly jumbled arrivals and some evidence of reflected energy at one or two shot points. It seems that neither refractions nor reflections image down to the coal layer; in part this is attributed to the presence of unexpected high-velocity layers overlying the coal. The consequence is that possible information about the coal is hidden behind the events from shallow layers. Based on these data, we suggest that further seismic work at the site is unlikely to successfully characterize the coal fire zone of interest.

INTRODUCTION

In March 2009 personnel from Stanford University, the U.S. Geological Survey and the Southern Ute Department of Energy collected compressional (P) wave near surface seismic data along two transects at the site of a coal fire on Southern Ute Nation lands. The objective of this effort was to determine the utility of seismic methods for imaging the coal and ash layers of interest at the site, and to assist with planning any future data acquisition efforts.

The field site is generally open terrain with a gently dipping ($\sim10^\circ$) ground surface. The shallowest geology consists of sandstone (highly fractured and fissured in many places); the sandstone is overlain by a thin layer of soil, of about .5 m, throughout much of the site. Abundant well data show the coal layer to be about 8 m thick and to be dipping in the same direction, but a slightly higher angle ($\sim20^\circ$) than the ground surface. The top is approximately 5 m deep at the up-slope (up-dip) edge of the site (to the northwest) and up to 16 m deep in the down-slope part of the site. Open fissures with red-hot rock clearly visible 0.5 m below the ground surface are one clear indication of the shallow fire. Noxious gases coming from the vents are another indication.

Numerical simulations of seismic experiments at the site indicated that imaging the unburned coal could be possible with sufficiently high-frequency source energy if the impacts of fissures and layering above the coal were minimal (de Ridder and Haines, 2008). A short site visit enabled the collection of a simple data set. A basic data processing analysis was performed to assess data quality and identify arrivals. For line 1, located above unburned coal where no fissures have been mapped, data quality is good and reflections assumed to be from the sandstone layer that underlies the coal are visible. For line 2, crossing the burn front and numerous mapped fissures, data quality is reduced. The reflection might be visible for one shot point. Velocity estimation indicates that neither refractions nor reflections image as deep as the coal layer. Two main reasons for the differences between simulations and field test is the presence of high-velocities layers above the coal, and a shallow reflector.

SEISMIC DATA

We collected P-wave seismic data along two transects, using conventional hammer-plate-seismic techniques. The recording arrays consisted of a Geometrics Geode with 24 live channels and 30 Hz vertical geophones at 3 m spacings. In order to create shot gathers with a greater number of traces at a narrower spacing, four shots were closely-spaced at each shot location. By placing these shots at a 0.75-m spacing, and then interleaving the resulting four 24-channel shot gathers, a 96 channel array was simulated, illustrated schematically in Figure 1. This approach is a variation on the "walk-away" testing that is commonly used for acquiring data at a new field site. The interleaving technique assumes that geology does not vary too rapidly along the transect. Any lateral geological variation would violate this assumption, and cause artifacts in the shot gathers.

Five or six shot locations were recorded along each line, rather than a shot between each pair of geophones. The shot locations are evenly distributed along the line, with one shot point off the end of each line to observe longer-offset arrivals. Each shot gather is the result of stacking approximately 5 hammer impacts, after manual data checking for trigger errors and other problems. It should be noted that for most data in these surveys, the noise reduction benefits of stacking are minimal; data quality for each individual hammer impact is good.

Line 1: Unburned coal and no fissures

The first transect was recorded along a line running approximately NE-SW in an area thought to overlie purely unburned coal (based on boreholes at each end of the line). Being oriented roughly along the geologic strike, the topography along the line is generally flat and nearly horizontal. No fissures have been mapped in the area of this line. An averaged, normalized frequency spectrum of data recorded at Line 1 is shown in Figure 3. A frequency wave-number spectrum of the shot recorded at position 72 m along Line 1, at the southwestern end 10 m SW of well #11, is shown in Figure 4.

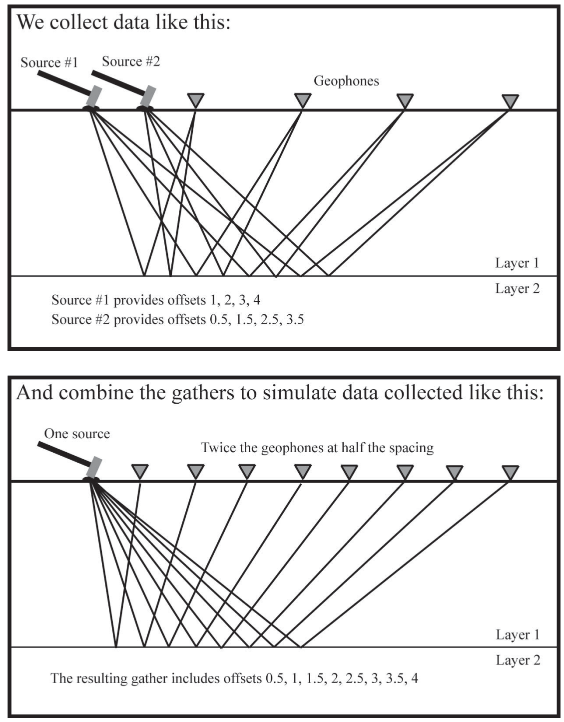

Figure 1: Sketch of interleaving approach. With Y geophones, at a spacing X, and using N shots at a spacing of X/N, the interleave technique results in a shot gathers with $N \times Y$ traces and a spacing of X/N. Geology is assumed to be fairly constant in the lateral direction. [**NR**]

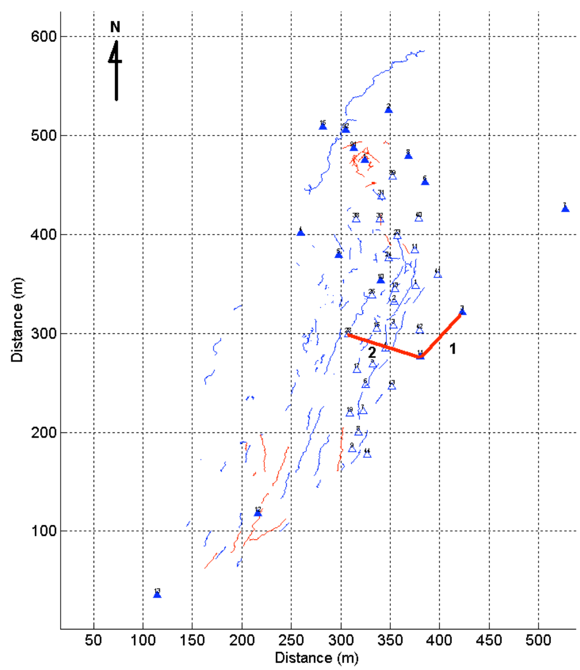

Figure 2: Site map with fissures (thin lines), wells (full triangles), thermocouples (open triangles) and seismic lines (thick lines). Courtesy of Taku Ide. [**NR**]

Figures 5(a)-5(f) and 6(a)-6(d) show shot gathers from shots at approximately 0 m, 18 m, 48 m, 72 m and 80 m, along Line 1. For each shot the figures contain a raw data section and a 80-500Hz bandpassed gain controlled section. In general, data quality is good, and strong energy is recorded to at least 100 Hz. In some shot gathers, a reflection can be observed. Energy propagates well to the farthest recorded offsets. For all of these line 1 data plots, NE is to the left. The interleaving technique for interpolation worked best for the shot gather in Figure 6(c). The shot in Figure 5(c) was recorded on a sandstone outcrop on the road, the data is ringy and the interleaving technique is less successful than for other shots along this line.

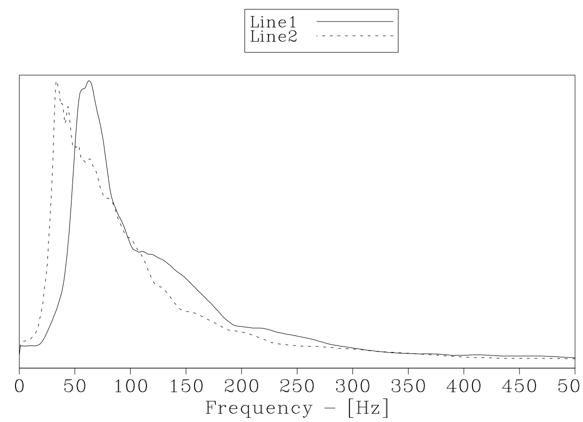

Figure 3: Averaged, normalized spectra of surveys at line 1 and line 2. [**ER**]

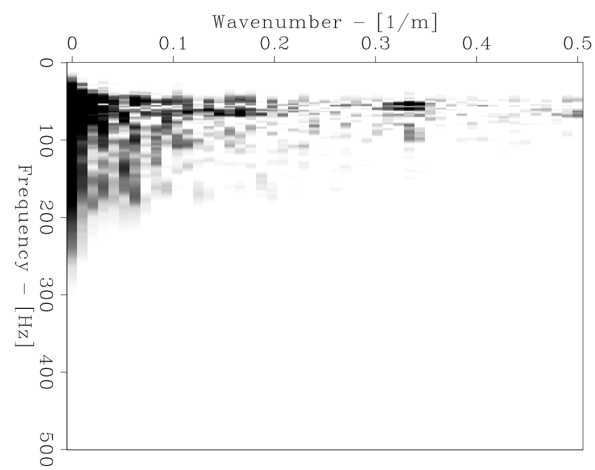

Figure 4: Frequency wave-number spectrum of the shot recorded at Line 1, at 72 m (see also Figure 6(b) below). [**ER**]

Line 2: Across the burn front and many fissures

The second transect was recorded along a line running approximately NW-SE. The NW end of the line is within an area above burned coal and the SE end is in an area thought to be above unburned coal. The line crosses many mapped fissures, particularly toward the NW end of the line.

Figures 7(a)-8(b) and 8(a)-8(f) show shot gathers from shots at approximately 0 m, 12 m, 24 m, 50 m, 72 m and 77 m, along Line 2. An averaged and normalized

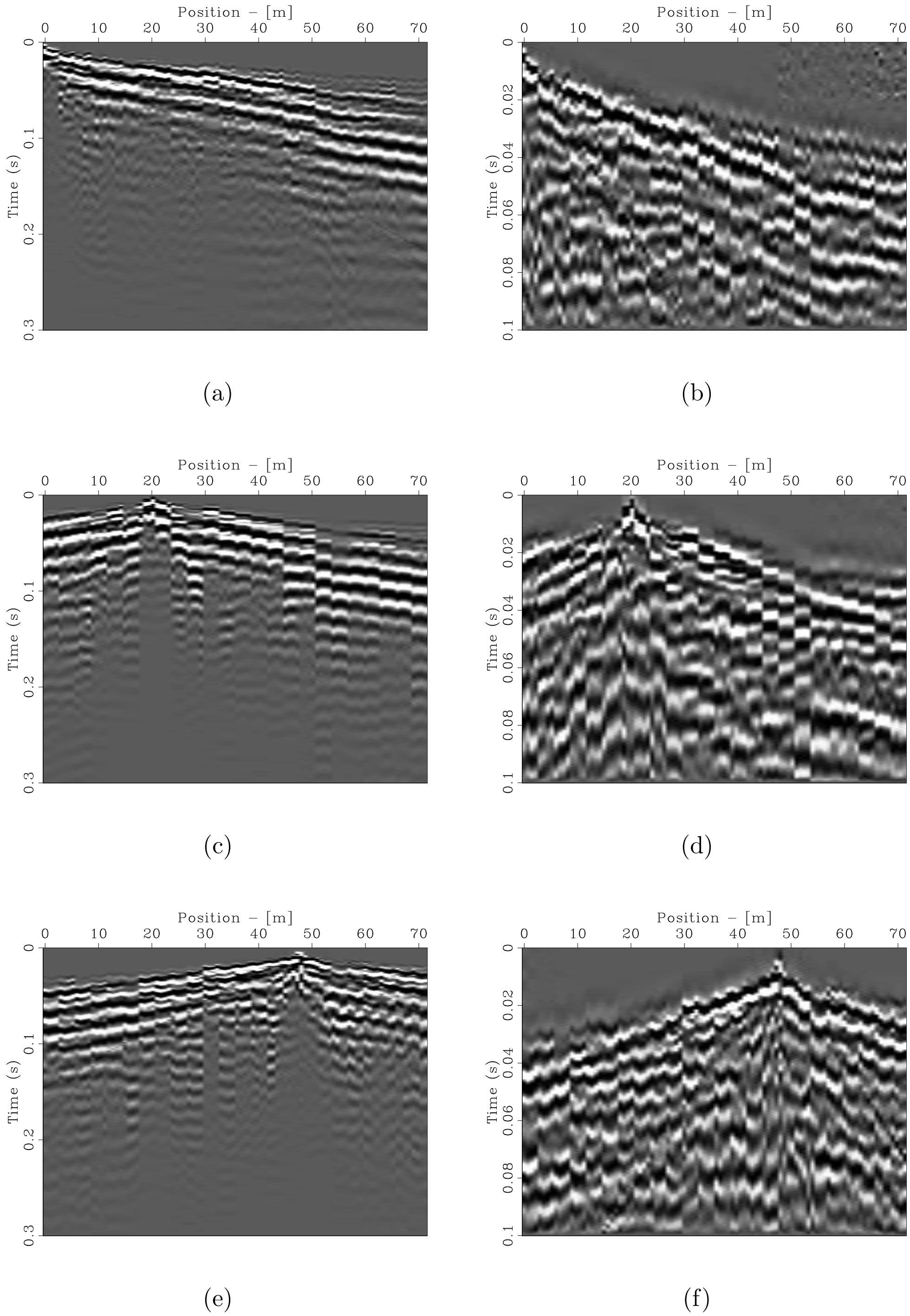

Figure 5: Line 1 shot gathers: a) Raw shot at 0 m, b) shot from (a) 80-500Hz bandpass and AGC and zoom; c) raw shot at 18 m, d) shot from (c) 80-500Hz bandpass and AGC and zoom; e) raw shot at 48 m, f) shot from (e) 80-500Hz bandpass and AGC and zoom. [**ER**]

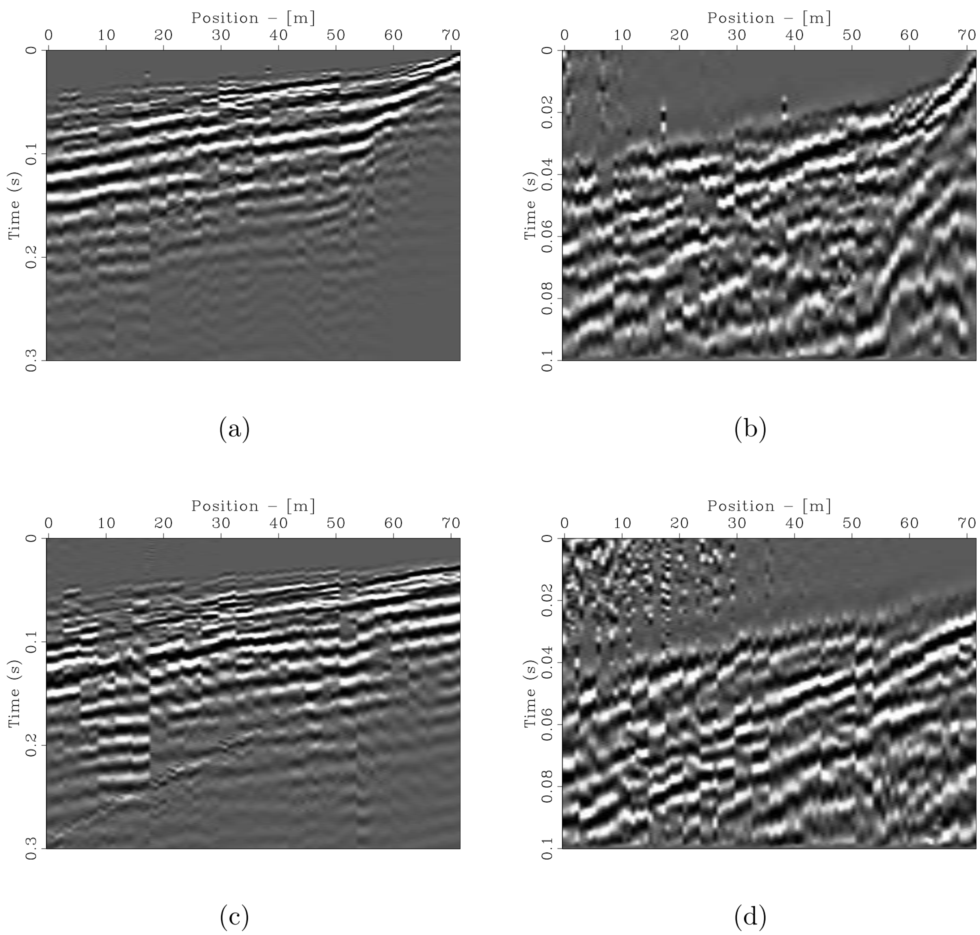

Figure 6: Line 1 shot gathers: a) Raw shot at 72 m, b) shot from (a) 80-500Hz bandpass and AGC and zoom; c) raw shot at 72 m, d) shot from (c) 80-500Hz bandpass and AGC and zoom. [**ER**]

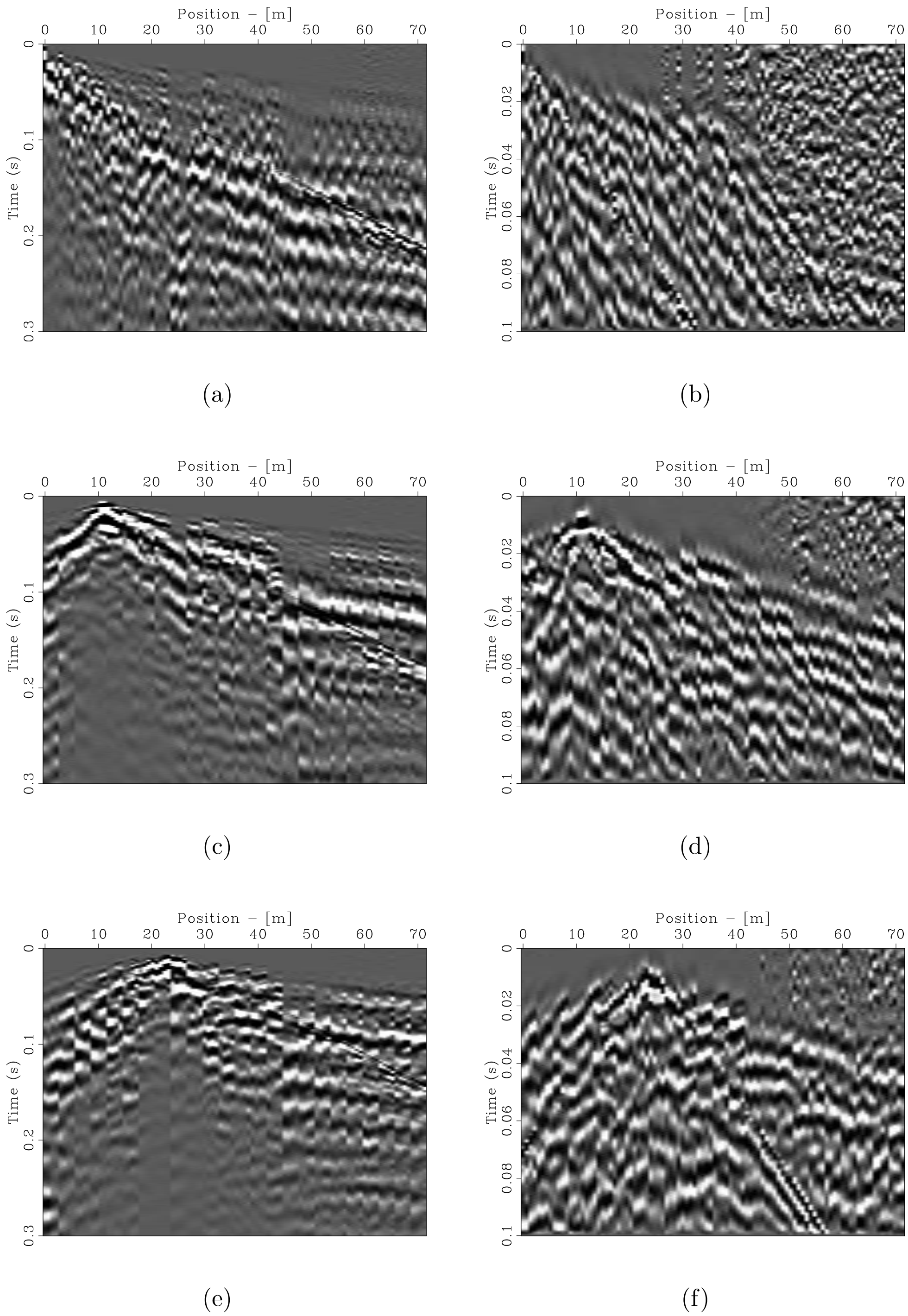

Figure 7: Line 2 shot gathers: a) Raw shot at 0 m, b) shot from (a) 80-500Hz bandpass and AGC and zoom; c) raw shot at 12 m, d) shot from (c) 80-500Hz bandpass and AGC and zoom; e) raw shot at 24 m, f) shot from (e) 80-500Hz bandpass and AGC and zoom. [**ER**]

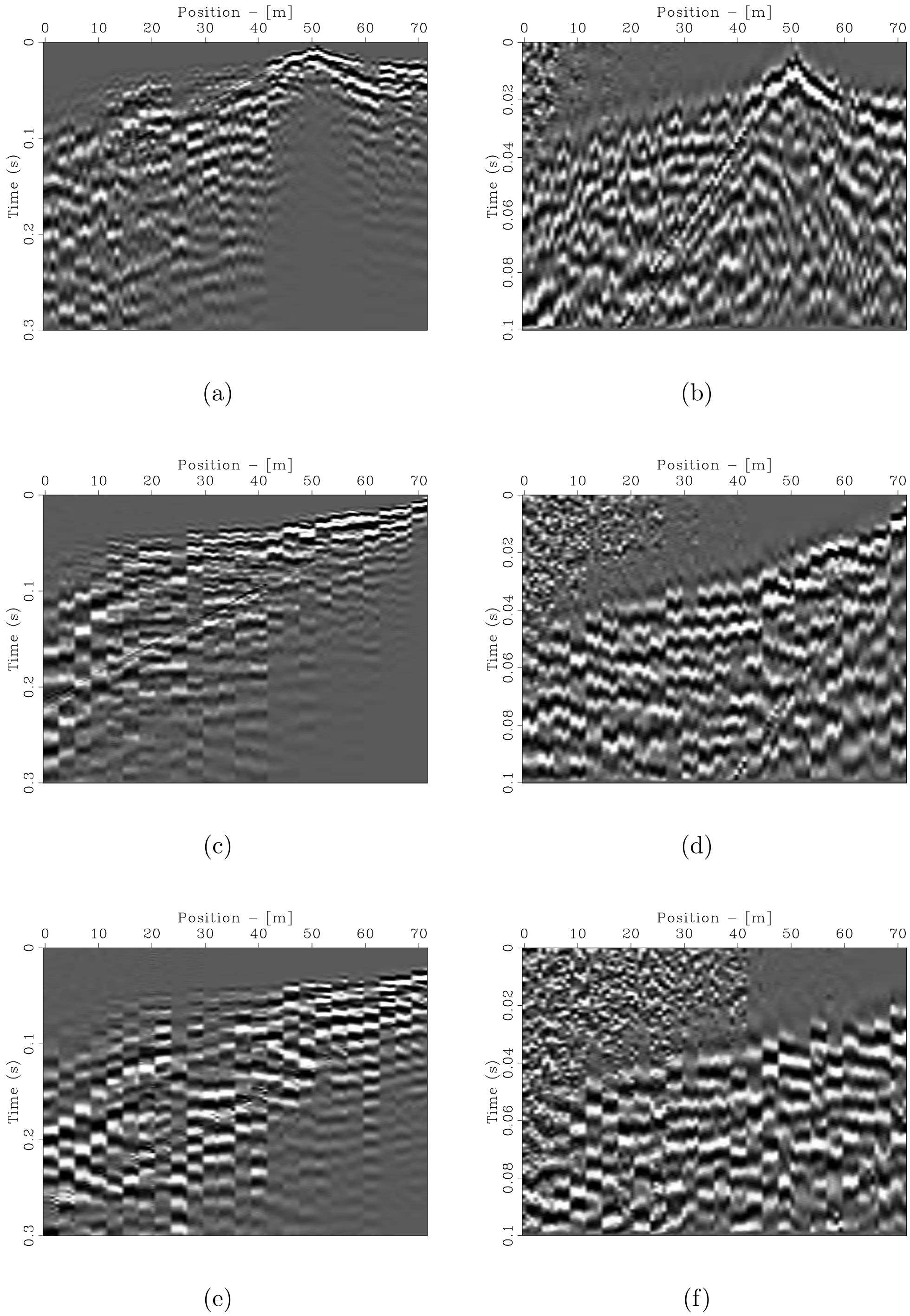

Figure 8: Line 2 shot gathers: a) Raw shot at 50 m, b) shot from (a) 80-500Hz bandpass and AGC and zoom; c) raw shot at 72 m, d) shot from (c) 80-500Hz bandpass and AGC and zoom; e) raw shot at 77 m, f) shot from (e) 80-500Hz bandpass and AGC and zoom. [**ER**]

frequency spectrum of data recorded at Line 2 is shown in Figure 3. The data of the shot gather in Figure 7(a) is rather jumbled due to nearby fissures, the interleaving technique is not so effective. Data quality is generally worse than for line 1, and is particularly poor for the NW end of the line. At the SE end of the line, the data more closely resemble those for line 1, and the previously mentioned reflection may be visible between position 45 m to 60 m in Figure 8(d). The interleaving technique falls apart for these data due to strongly heterogeneous wave propagation, larger topographical variations, and the many fissures. There is a high frequency event visible in almost all shot gathers; this is the air wave. Note how the interleaving technique works quite well for that event, as the event is neither jumbled nor aliased. For all of these line 2 data plots, NW is to the left.

INTERPRETATION

In two of the better quality shot gathers, Figures 6(b) and 6(d), four different events can be distinguished. 2 refracted wave events are observed: a direct P wave event and a reflected wave event. These are annotated in Figures 9 and 10. The interpreted reflection is also visible at positions greater than about 55 m in Figure 6(d). At small offsets we see very slow and dispersive ground roll, annotated G.

We performed simple refraction analyses to estimate a velocity profile (Stein and Wysession, 2003). The direct P-wave and two refractions' slopes indicate three velocities: $v_1 = 480$ m/s, $v_2 = 1400$ m/s and $v_3 = 3000$ m/s. These are relatively consistent for both figures, although errors in the range of 30% are possible. The intersection times in Figure 9 indicate two layer thicknesses of $h_0 = 1.2$ m and $h_1 = 5.8$ m. The intersection times in Figure 9 indicate two layer thicknesses of $h_0 = 0.9$ m and $h_1 = 9.1$ m. These differences are due both to estimation error and lateral variation of the geology and topography. However, they suggest two positive velocity discontinuities at approximately 1 m and $8 - 10$ m. Comparing these depths to the log shown in Figure 11 (depth indicated in feet), suggests that they are not as deep as the coal and could be associated with the top of the thick sandstone bed. Perhaps the thin sandstone bed in the shale, or a positive velocity gradient in the shale, is the reflector. The intersection time of the reflection is approximately 0.02 s, using a estimated velocity of 1400 m/s. This would indicate a reflector at approximately 14 m depth.

The frequency wave-number spectrum in Figure 4 shows significant high wave-number noise. This is partly due to the interleaving technique. The energy associated with reflections, refractions and surface waves is all located and mixed together below wave-numbers of .15 m^{-1} and frequencies below 25 Hz. This offers little opportunity to filter the refractions and surface waves from the reflection. Applying Normal Move Out (NMO) to flatten the reflector on the shot gather of Figure 6(b) was consistent with the velocity estimates.

The shot gather after NMO with three different velocities is shown in Figure 12.

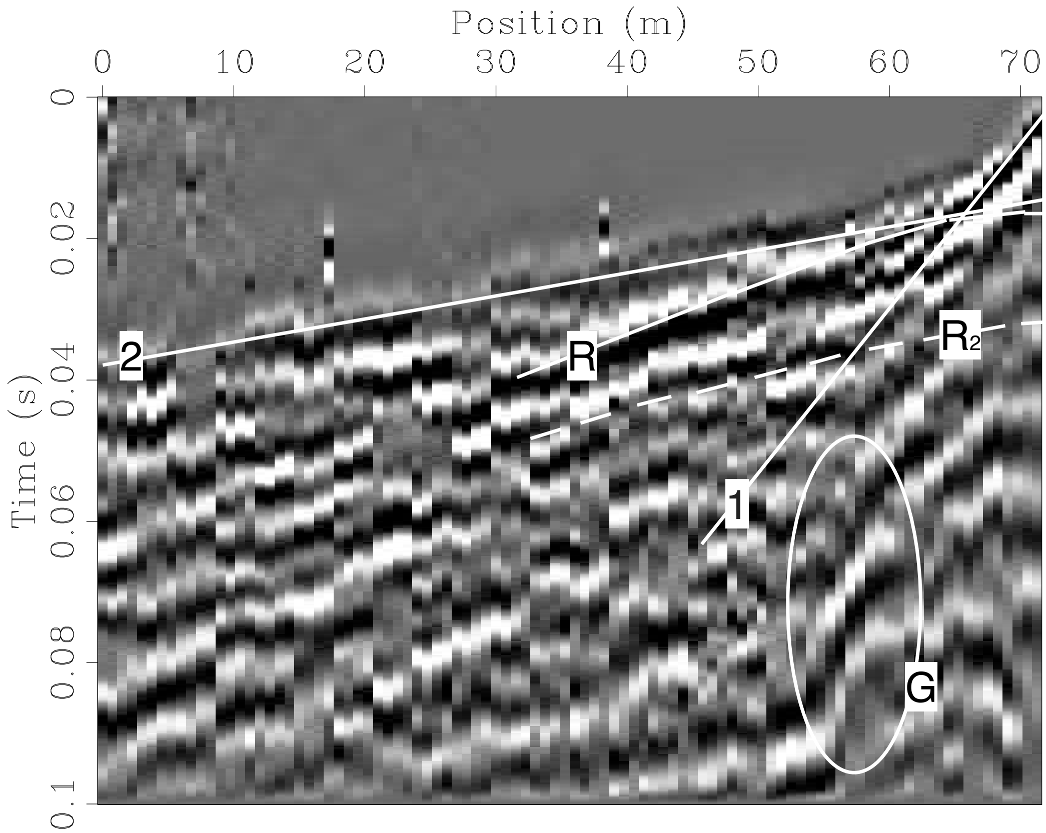

Figure 9: Line 1, shot at southwestern end, 10 m SW of well #11. A possible reflection, annotated R, appears between positions 30 to 55 m. A direct P-wave is annotated 1, and two refracted waves are annotated 2 and 3. A possibly hidden reflected event is annotated R_2. Dispersive ground roll G. [**NR**]

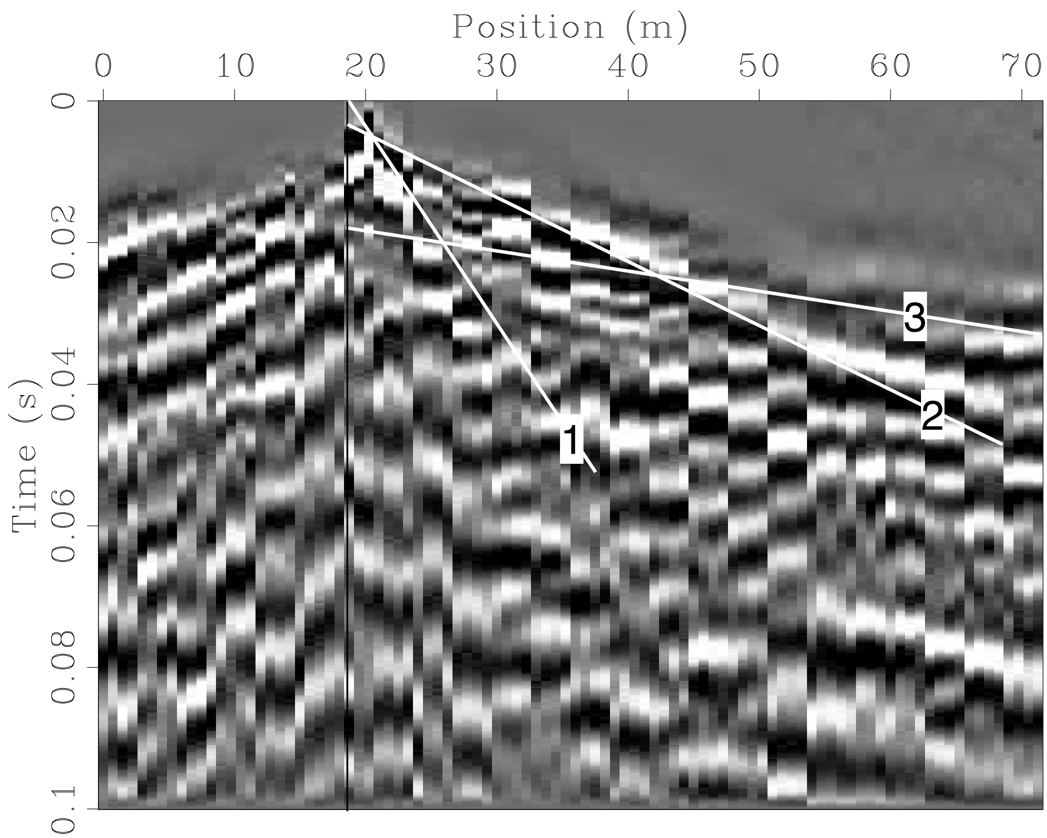

Figure 10: Line 1, shot on sandstone outcrop, in the road. A direct P-wave event annotated 1, two refracted waves annotated 2 and 3. [**NR**]

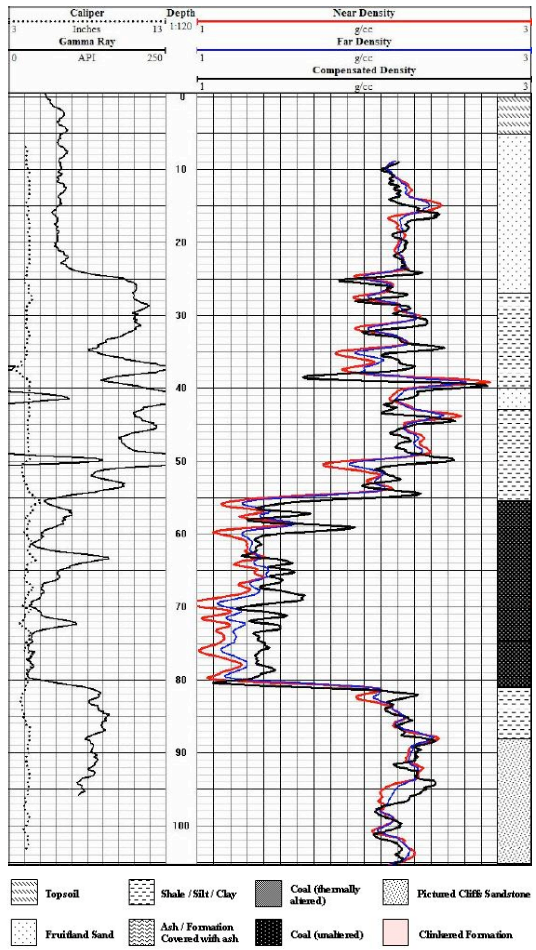

Figure 11: Well log at well #3. Lithology is indicated below, with depth indicated in feet. A 9 m thick coal layer is located at approximately 16 m depth. [**NR**]

A NMO velocity of 1150 m/s seems optimal to flatten the flanks of the interpreted reflector. This NMO velocity was tested for consistency with the velocities coming from refraction. Various stacking velocities, v_s, and normal incidence travel times, τ, were tested for their equivalent interval velocity, v_i, and layer thicknesses, h.

$$
\begin{array}{llll}
v_s = 480,\ 1150 & \tau = 0.0055,\ 0.02 & h = 1.32,\ 9.55446 & v = 480,\ 1317.86 \\
v_s = 450,\ 1150 & \tau = 0.005,\ 0.02 & h = 1.125,\ 9.76681 & v = 450,\ 1302.24 \\
v_s = 500,\ 1150 & \tau = 0.0055,\ 0.018 & h = 1.375,\ 8.3722 & v = 500,\ 1339.55 \\
v_s = 480,\ 1150 & \tau = 0.0075,\ 0.02 & h = 1.8,\ 8.78955 & v = 480,\ 1406.33
\end{array}
\qquad (1)
$$

Most combinations are fairly sensible, but pushing the lower velocity to 1400 m/s also pushes the slow top layer to 2 m thick. This result is unrealistic considering our data and field observations. Regardless of exact numbers, it appears that the reflection originates at a depth of approximately 11 m. Revisiting Figure 9, note a weaker event, R_2, that is possibly a reflection hidden behind the interpreted reflection R. These estimates are rough, but error is unlikely to exceed 30 %.

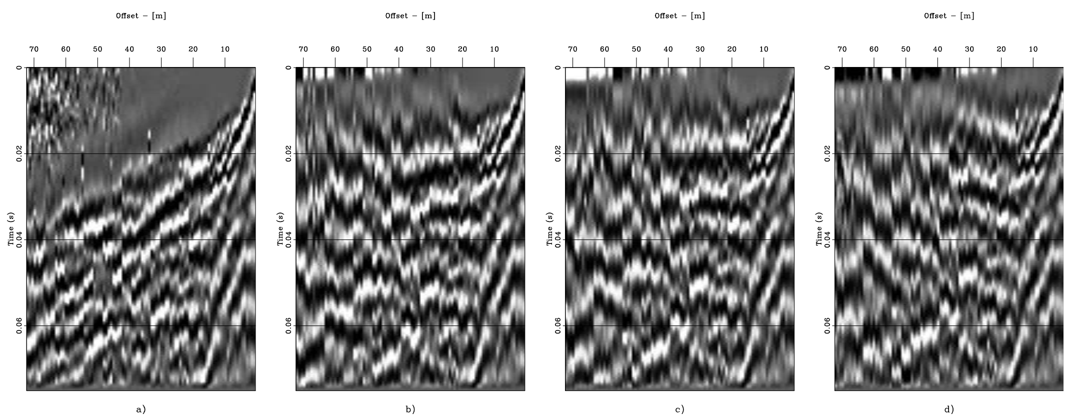

Figure 12: Line 1, shot at southwestern end, 10 m SW of well #11. a) No NMO, b) NMO with v_s = 1300, c) v_s = 1150, d) v_s = 1000. Note that 1150 m/s seems to be the correct NMO velocity. [**ER**]

CONCLUSIONS

We conducted a seismic test at the Southern Ute Nation coal fire site using minimal equipment. Data quality is at the high end of what can be expected for sledgehammer-source data. The recorded frequency content is strong up to 100 Hz. The test shots were interpreted to contain several refracted events and a reflection event.

The refraction and reflection events are interpreted for a subsurface velocity profile. The velocities were higher than anticipated by a previous modeling effort (de Ridder and Haines, 2008). The fast layers that are interpreted to overlie the coal pose a difficulty to any seismic surveying because they are an impediment to deeper wave propagation. As we expected, the fissures present a major impediment to wave propagation and substantially degrade data quality. In addition, the test shots indicate highly dispersive ground roll and strong statics in the area.

Refraction and reflection analyses suggest a meter-thick layer of a little less than 500 m/s on top, and a layer of about 9-10 meters of a velocity of about $1300 - 1400$ m/s overlying a lower layer with a velocity as high as 3000 m/s. The reflection event is originating at a depth of approximately 11 m, which is well above the coal layer. It might hide possible reflections from the coal layer.

There are no distinguishable events deep enough to adequately characterize the coal layer. The major difficulty is unexpected fast layers above the coal, as well as a relatively strong reflection event from a layer above the coal. It is conceivable that the depth estimates are inaccurate and the reflection event is from the top of the coal, but this is unlikely. Even if the reflection happens to be from the top of the coal, it is only clearly visible on only a few shot gathers. Thus we must conclude that further seismic work at the site is unlikely to be successful at imaging the targeted coal or ash layer.

ACKNOWLEDGMENTS

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