Seismic investigation of natural coal fires: A pre-fieldwork synthetic feasibility study.

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ABSTRACT

Natural underground coal fires are a world-wide concern, emitting carbon dioxide and other pollutant gasses into the atmosphere; one such coal fire is located at Durango, Colorado. We carried out elastic modeling in order to investigate the potential of applying P-wave seismic methods to the problem of differentiating between burned and unburned coal in the upper $\sim$30 m of the subsurface at the site near Durango. This is a challenging problem for any geophysical method, but preliminary modeling results show that the problem is tractable under certain circumstances. Our highly simplified model suggests that imaging the coal layer can potentially be accomplished with adequately high frequencies (source center frequency $>$ 125 Hz); imaging the actual burned zone would be more difficult. The model neglects the major near-surface heterogeneity known to exist at the site; features such as fissures would surely result in diffractions and reflections that could obscure much of the desired signal.

INTRODUCTION

Ongoing research at a site outside Durango, Colorado, is focused on characterizing and modeling a coal bed that has been burning underground for a number of years. The goal is to develop an understanding of how coal fires burn for the purpose of designing optimum solutions for extinguishing coal fires around the world. The unique aspect of this particular fire is that it is small-scale and easily accessible. We were asked whether seismic methods could potentially provide useful information at the site, ideally as a way to map the burned and unburned coal. Any related information would be useful, such as mapping only the unburned coal, and/or locating fissures and other subsidence features that might not reach the surface.

We conducted elastic modeling to simulate a P-wave seismic survey at the site, to assess the likelihood of successfully applying seismic methods to this problem, and to determine optimal parameters for any field data acquisition. The model is highly simplified given that it neglects the fissures and other overburden heterogeneity. The main target is the partially burned coal layer.

The site is roughly 300m by 100m. Researchers of the Global Climate & Energy Project at Stanford University (GCEP, 2008) have been studying the site using a number of different approaches to understand the progression of the fire over time and try to predict its likely future trends. One approach has been the mapping of surface anomalies across the site – mainly fissures resulting from the compaction of the ash as the coal burns. Researchers have also drilled a total of 14 wells across the site, in areas where they know the coal has burned, where they think the burn front is located, and in unburned areas. A 100 ft core was recovered from one of these wells. Five wells have geophysical logs (caliper, gamma and density), and rock cutting samples were taken at 5-ft intervals in all the wells.

The coal bed is approximately 5 m thick where it is unburned and closer to 2-4 m thick where it has burned. It outcrops northwest of the site and dips to the southeast. In the area of the site itself, the coal bed ranges from approximately 10 m depth to approximately 30 m. Wells showing ash are predominantly in the northwest (up-dip) end of the site, with unburned coal located down-dip. The coal bed is embedded within a sandstone formation that also includes some shale layers. A thin unconsolidated layer composed of rocky soil up to approximately 1.5 m thick overlies parts of the site.

We present specifics of our elastic model, and then present the resulting synthetic data. We examine the data in various domains, and show a brute stack of the data set. Finally, we discuss our findings in relation to the original question, and consider the impacts of neglected aspects of the modeling.

ELASTIC MODELING

We have used the code e3d, described by Larsen and Grieger (1998), to simulate a seismic survey at the coal fire field site. E3d is an explicit 2D/3D elastic finite-difference wave-propagation code that is widely used (e.g., Martin et al., 2006). It is accurate to fourth order in space and second order accurate in time.

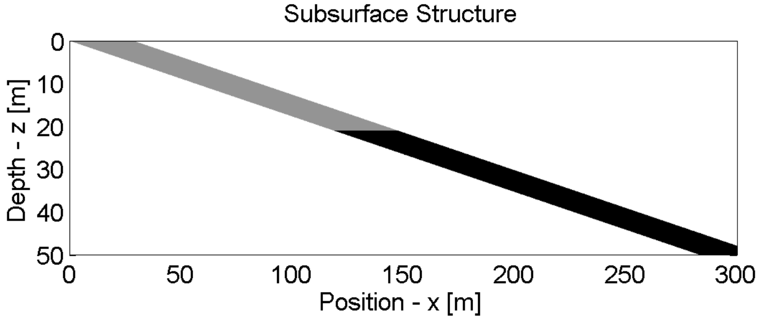


Figure 1: Subsurface structure; a dipping, partially burned (grey) coal (black) layer. P and S wave velocities are given in Table 1. [**NR**]

Figure 1 shows the layout of our 2D model space, with layer properties shown in Table 1. A 5m thick layer of coal, half burned, dips 10° across a background of sandstone. We synthesized a seismic survey across the model with shots and receivers at 1-m spacings. The source is a vertical force with the waveform of a 125-Hz Ricker wavelet. This is intended to simulate a better-than-average sledgehammer impact. The frequency of a real sledgehammer impact is likely to be considerably lower and the waveform completely dependant on the local conditions. The receivers record both vertical, V_z, and horizontal, V_x, (in-plane) components of particle velocity. In this report we focus on the vertical (PP) component but include the horizontal component for interested readers. The model neglects the major near-surface heterogeneity like soil layer, shale layers and fissures known to exist at the site.

Table 1: Seismic P and S wave velocities and velocity gradients.

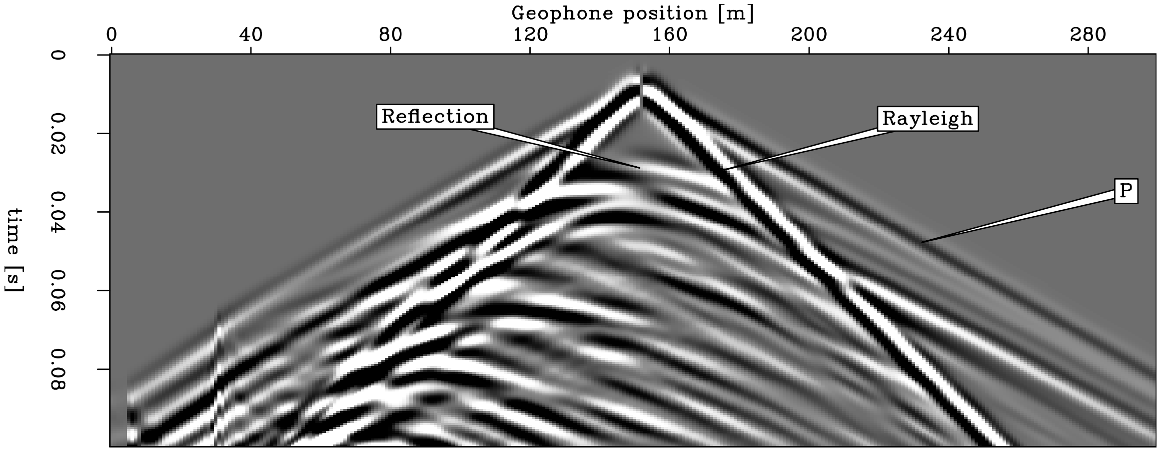
Unit	V_p [m/s]	$\partial_z V_p[1/s]$	V_s [m/s]	$\partial_z V_s[1/s]$
Sandstone	2000	.2	1200	.154
Coal	1200	0.0	800	0.0
Ash	300	0.0	200	0.0

DATA

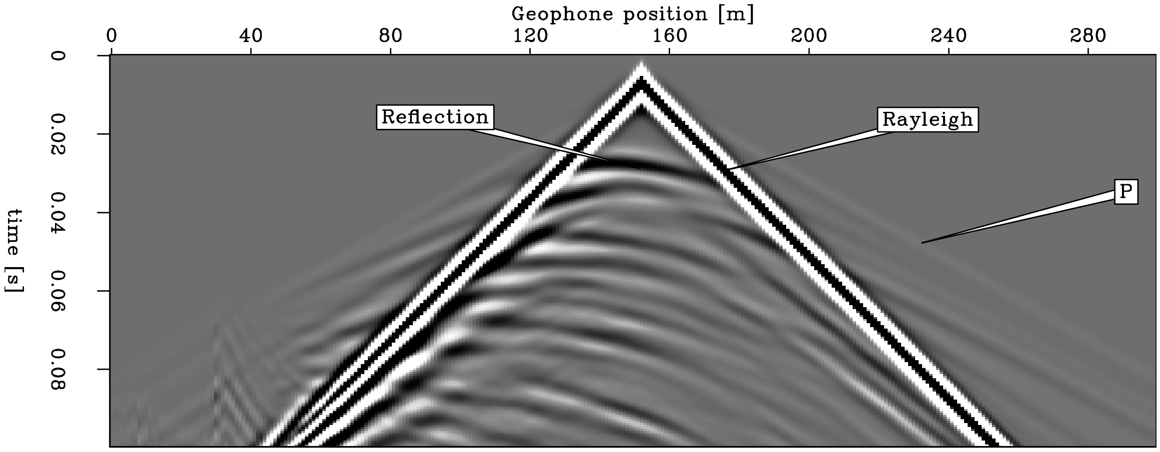
Figure 2 shows a pair of shot gathers for a shot at position 150 m, directly over the end of the burn front. The reflection arriving at ∼0.03 s at zero offset is the reflection from the top of the coal seam. The reflection from the base of the coal very closely follows the reflection from the top, and the two interfere. Multiples dominate the remainder of the record. In the common-offset domain (Figure 3) we see clear, though faint, diffractions from the end of the coal and note that the reflection from the base of the coal/ash layer is difficult to discern here as well. To the right of 150 m, the reflections from the top and bottom of the coal combine to create the observed pattern of interfering surface and reflected waves. To the left of 150 m, the basal reflection is obscured by the multiples. At 150 m, we can just see the basal reflection diving away due to velocity pull-down. The jumbled patterns at the left end of the shot gather and common-offset gather are observed where the ash layer crops out at the surface.

A quick processing flow (f-k filter with high-cut of $\frac{\omega}{k_x} = 1250$ m/s for surface waves, and with NMO correction but no DMO or migration) yields the stacked section in Figure 4. The reflection from the top of the coal/ash layer is clearly observed. The slight lateral change observed at position 150 m is due to the change from ash to coal, and represents the velocity pull-down of the basal reflection where low-velocity ash exists. Left of 150 m the observed reflection is due only to the top of the coal/ash layer. Right of 150 m the reflection is due to both the top and bottom of the coal.

Figure 5 shows a stacked section low-pass filtered with 100 Hz, to show what we might see for a lower source bandwidth. It is important to note that 100 Hz is still at the high end of what can reliably be expected with a sledgehammer (e.g., Miller et al., 1992; Miller et al., 1994). The reflections for the top and bottom of the coal



Horizontal component of particle velocity



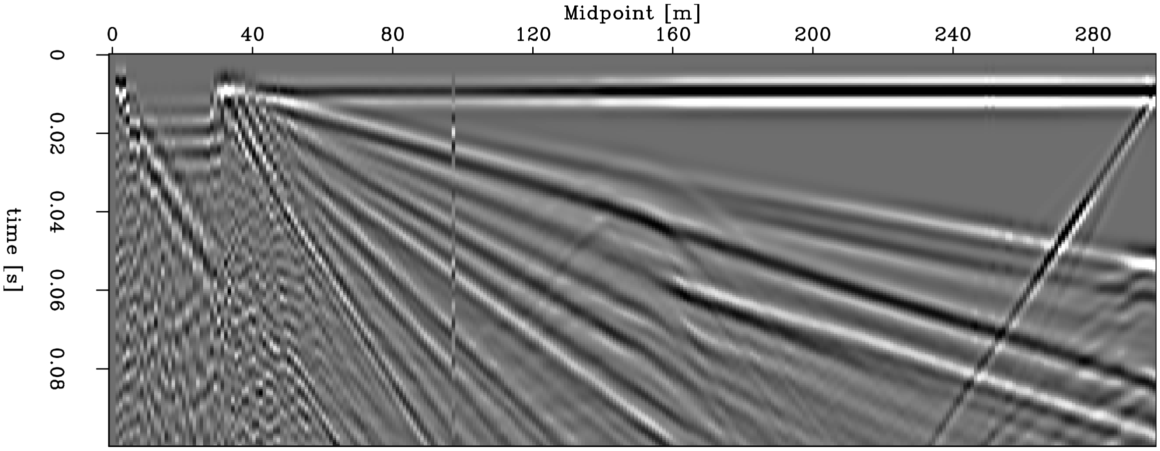
Vertical component of particle velocity

Figure 2: Shot gather for a shot at 150m. In the horizontal component, we can distinguish both the S and P surface wave. In the vertical component, we can only distinguish the Rayleigh wave. At $t = 0.03$ we see the reflections from the top of the coal layer. **[CR]**

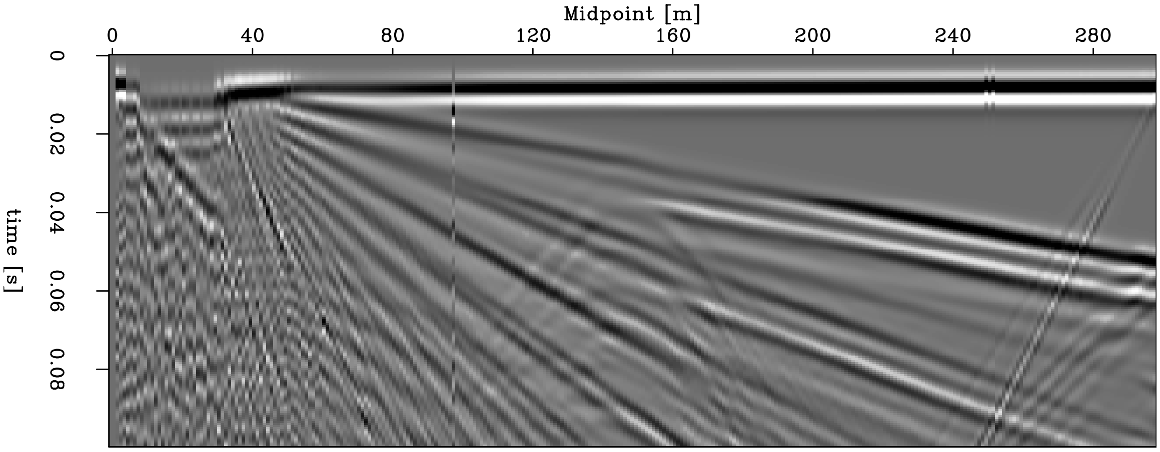
are much more difficult to resolve from each other, and would be very difficult to interpret.

DISCUSSION

Our modeling suggests that, with a suitably high-frequency source and optimal field conditions, useful information can be gained from seismic surveys at the Durango coal fire site. We could realistically hope to discern changes across the burn front such as diffractions; these would be difficult to interpret because fissures would produce other, possibly stronger, diffractions. Separately imaging the top and bottom of the coal would be much more useful and would require frequencies at least as high as



Horizontal component of particle velocity

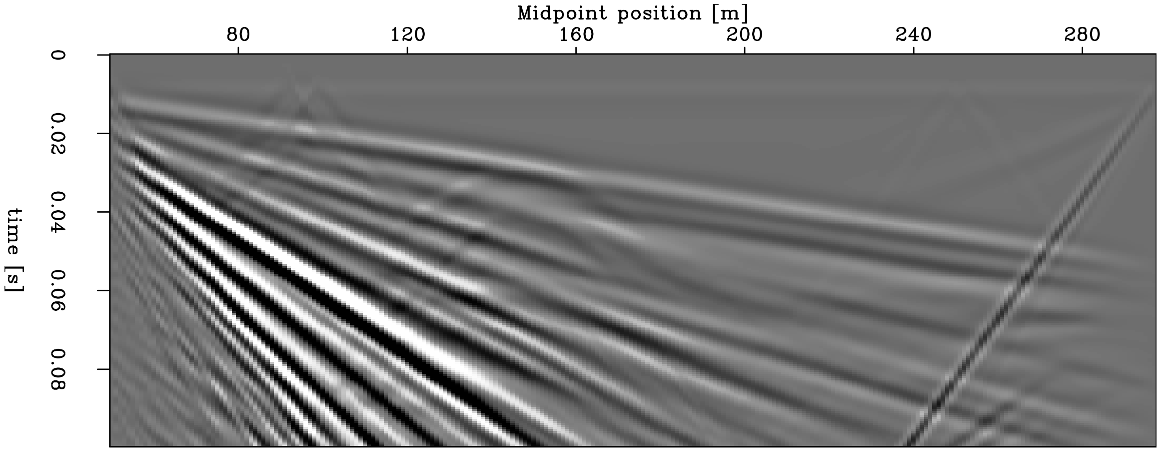


Vertical component of particle velocity

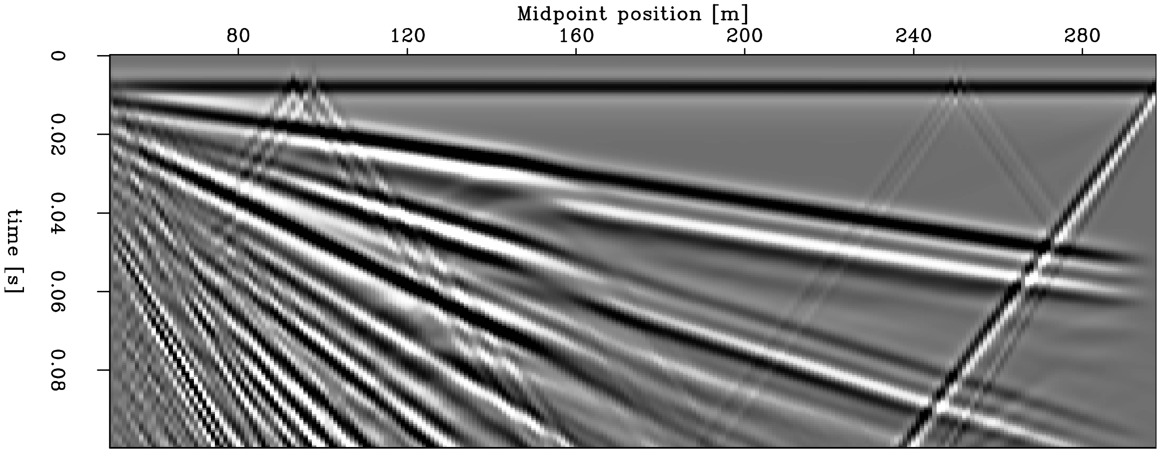
Figure 3: Zero offset gather. Clearly visible is the reflection from the top of the coal/ash layer. Less clearly and almost unseparated is the reflection from the bottom of the coal layer, the bottom of the ash layer is not visible. Weak diffractions from the ash-edge are visible. [**CR**]

those used in the model. A lower source bandwidth would be inadequate.

Attaining frequencies even as high as those in the model (125 Hz) is difficult in practice. With sandstone at the surface, coupling of sources and geophones should be good and attenuation reasonably low. But in areas where dry rocky soil overlies the sandstone, coupling issues and attenuation would almost certainly filter the higher frequencies in addition to significantly impacting the propagating wavefront. A successful survey would require working directly on bare rock (likely gluing geophones into drilled holes) and quite possibly a high frequency source such as a small vibrator. The application of either of those, would significantly increase the field-work effort. Attaining sufficiently high-frequency energy with a hammer is not impossible at this site, but certainly challenging.



Horizontal component of particle velocity

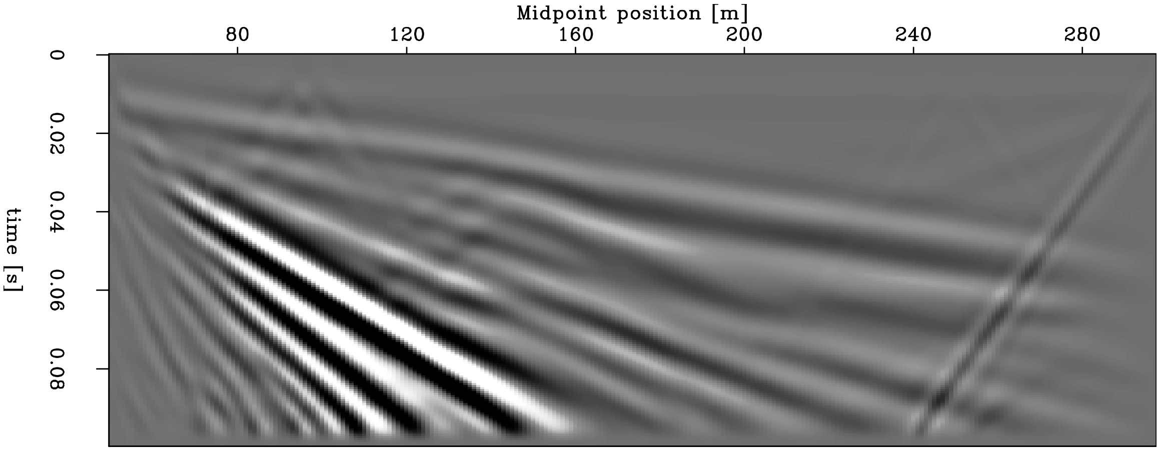


Vertical component of particle velocity

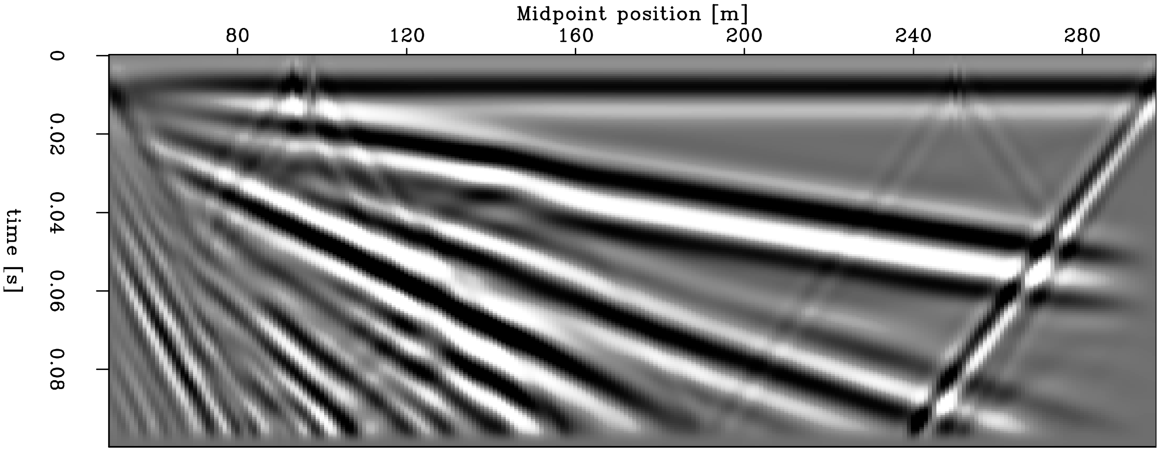
Figure 4: Stacked section, after surface wave removal and NMO correction. The bottom of the coal layer is visible, but clearly overlaps with the reflection from the top of the coal layer. [**CR**]

The model omits very important known heterogeneity at the site, a key problem that would surely impact the quality of any acquired data. The fissures extending from the burned zones to the surface would undoubtedly have a major impact on propagating wave fields, quite possibly masking the reflections from subsurface features in the burned areas. These fissures are less common (absent?) above the unburned coal, so we are more confident in the validity of our results in that part of the model. But shale layers exist throughout the sandstone in the field area, and could also cause reverberations and spurious reflections in the data. Thus even under ideal circumstances, where source and receiver coupling are optimal and source frequencies exceed 100 or even 200 Hz, the recorded waveforms might be very difficult to interpret.

In addition to the missing fissures, other aspects of the model may be wrong. For



Horizontal component of particle velocity



Vertical component of particle velocity

Figure 5: Stacked section, after surface wave removal and NMO correction. Data are bandpass-filtered to 100 Hz to more accurately represent possible data. The bottom of the coal layer, and the difference between coal and ash, is no longer visible. [**CR**]

instance, we do not really know what parameters are reasonable for the burned coal; we simply divided the coal properties by four. But the ash might be better modeled as a void, which would make a major difference. We could expect stronger diffractions from the edge of the burned zone. But because the reflection from the coal is already quite strong, not much difference is expected between the reflections of the burned and not unburned parts of the coal seam. In any case, the known subsidence and rock changes that exist above the burned zone at this site and observed at other such sites (e.g., Wolf, 2006) would surely impact both wave propagation above, and within, the burned zone. The absence of this heterogeneity in the model is a major simplification of the real case.

We have not simulated an SH-wave survey at the site, an option that should be considered in any near-surface application. Being strongly sensitive to voids, shear waves might prove useful in this case. Their lower propagation speed would lead to shorter wavelength and better resolution for a given frequency, but generation of high frequency sources is even harder for SH-wave sources than it is for P-wave sources. In addition, the jumbled nature of the fissured sandstone would likely lead to many spurious S-P conversions that would complicate interpretation of the observed wave field. Accurately simulating the complexities of an SH-wave survey at the site would be difficult.

CONCLUSIONS

Our modeling results provide important insights into the feasibility of conducting seismic studies at the Durango coal fire site. The modeling results suggest that under ideal circumstances, P-wave reflection could successfully image the unburned coal and could help to constrain the burned zone. Successful data acquisition would likley require thorough planning and seismic source selection, very careful field procedures including working directly on the rock surface (not on any soil), and great care to ensure high frequencies. A key unknown is the impact that fissures and other near-surface uncertainty would have on the data; these features might completely corrupt the wavefield and render useless data collected even under the most careful procedures.

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