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Imaging Using Mining Machinery as a Source

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SUMMARY

A mine is a difficult geophysical environment to work in because of the presence of large amounts of noise. For seismic techniques in particular, the presence of drilling, blasting, shearers cutting rock, pumping and other activities leads to high levels of background seismic noise. But this seismic noise interacts with the rock in the same way as energy from an active seismic source would do, so it could, in principle, be used to image the rock.

Most sources of noise -- drills, shearers, pumps -- are continuous, so there is no well defined "shot time" and no well-defined direct or reflected arrivals in measured traces. However, a process of coherence-weighted cross-correlation across an array of sensors can produce a set of relative travel times, which can be used for tomographic imaging.

Experiments have been done in a number of coal mines, using a coal shearer as a source of energy, and recording the signal on arrays of geophones, installed either in roadways underground, or on the ground surface above the mine. This data has been processed using various techniques to try to extract velocity and attenuation information. Results indicate that the technique is successful in extracting relative arrival times across an array from continuous noise.

Key words: seismic imaging, passive seismics, mining

INTRODUCTION

Mining seismic surveys are potentially useful for orebody delineation and the mapping of faults and other structural features that could impact mining. In addition, seismic imaging can in principle yield more-direct geotechnical information: the effects of rock stress and fracturing on seismic propagation imply that these geotechnical properties, can be imaged using seismic waves. At the least, changes in stress and fracture state ought to be detectable using time-lapse techniques.

Mines are seismically noisy environments; drilling and blasting in hard rock, or rock cutting or shearing in soft-rock environments, produce significant seismic energy, which, although complicating standard seismic surveys, could in principle be used as a source of energy for seismic imaging. This paper looks at the use of continuous sources of noise, such as shearers or drilling, for seismic imaging. These types of sources, unlike a standard seismic shot, do not have a well-defined origin time; and unlike a vibroseis source, their waveform is uncontrolled and unknown.

Examples are presented here of tomographic images produced using a coal-shearer as a seismic source, with arrays of geophones installed either underground in the roof of roadways, or on the surface above the mine. It is shown that changes in stress caused by the mining process produce large changes in rock velocity which can be detected using the shearer to generate a tomographic image.

TRAVELTIME TOMOGRAPHY

Since seismic velocity and attenuation are affected by the stress and fracture state of the rock, tomographic images of velocity and attenuation will provide information about stress and fracturing. In order to avoid having to untangle the effects of varying geology on seismic propagation, time-lapse images, which only show changes in rock properties, are the appropriate tool to use. This section deals with the problem of generating a velocity image using traveltime data from a mining machinery source.

A continuous source does not have a well-defined origin time, so one cannot pick arrival times on sensor traces, as one would if a shot had been fired. In principle, an accelerometer could be attached to the source to make a source signal, synchronised with the receiver traces, available for cross-correlation or deconvolution processing as is done with vibroseis. In practice, however, this is extremely difficult because of the harshness of the underground mine environment, and because of safety considerations, such as the possible presence of explosive gasses in coal mines requiring intrinsically safe electronic equipment. So processing of this passive data has to be done without any direct measurement of the source.

For the traveltime tomography problem, the lack of knowledge of the source waveform is dealt with by determining relative arrival times of the source waveforms across the array. A source time (or, equivalently, the travel time to a reference sensor) is then included as one of the unknowns to be solved. Relative travel times can be determined by cross-correlating pairs of traces to get inter-trace delay values. This results in a set of equations relating unknown travel times to delays between traces,

$$t_j - t_k = \Delta_{jk}$$

where t_k is the unknown travel time to the k'th geophone, and Δ_{jk} is the lag determined from cross correlation. This can be written as a matrix equation

$$\mathbf{A}\,\mathbf{t} = \mathbf{\Delta}$$

$$\begin{bmatrix} 0 & \cdots & \cdots & \cdots & 0 \\ \cdots & +1 & \cdots & -1 & \cdots \\ 0 & \cdots & \cdots & \cdots & 0 \end{bmatrix} \begin{bmatrix} \cdots \\ t_j \\ \cdots \\ t_k \\ \cdots \end{bmatrix} = \begin{bmatrix} \cdots \\ \Delta_{jk} \\ \cdots \end{bmatrix}$$

This matrix is singular (there is not enough information to determine all the travel times), but this is resolved by setting one of the times to zero (making travel times relative to that reference geophone) resulting in that column being removed from the matrix. The result is an over-determined system, which can be solved in a least-squares sense.

The pseudo-periodic nature of the drill or shearer source results in multiple maxima in the cross correlation between two recorded traces. The presence of noise, as well as potential complexities due to multipath effects and reverberation, means that one cannot simply assume that the cross-correlation peak will yield the correct time delay between the two signals. In fact, a naïve cross-correlation yields rather poor results, with cycle skipping often evident in the trace-to-trace match.

An improved estimate of the delay time between two traces can be achieved using two techniques: First, prior information about expected travel times given reasonable estimates of the velocity can be used to mitigate the cycle-skipping problem somewhat. Secondly, by computing the inter-trace lag in the frequency domain via a cross-spectral phase-slope, one can use the spectral coherence between the traces as an implicit filter to weight the coherent frequencies more strongly (Carter 1987).

LONGWALL-PANEL TOMOGRAPHY

The first example uses the technique to produce an image of velocity variation across a coal longwall mining panel using the shearer as a source. As the shearer moves across the face, it illuminates the rock from multiple directions.

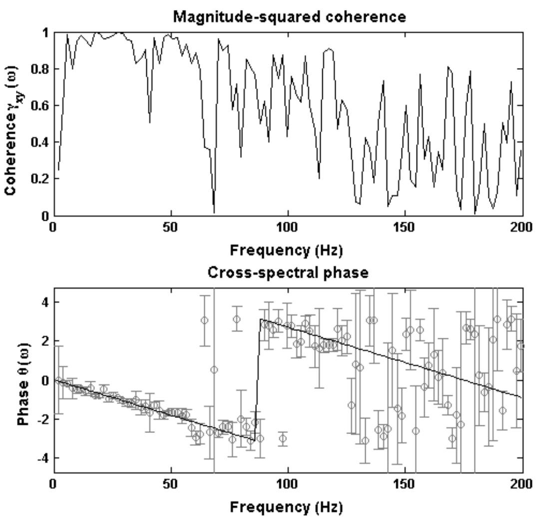

Figure 1. Example straight-line fit to cross-spectral phase (with 2π phase jump) with frequencies weighted by coherence.

Figure 1 shows an example straight-line fit to a cross-spectral phase spectrum, where the fit is weighted by coherence. The larger coherence values can be seen to correspond to regions of lower noise. The resulting set of aligned traces is shown in figure 2. Notice how the waveform shapes change across the array, partly due to local geological effects. It is these changes in waveform shape that make the coherence-based methods necessary.

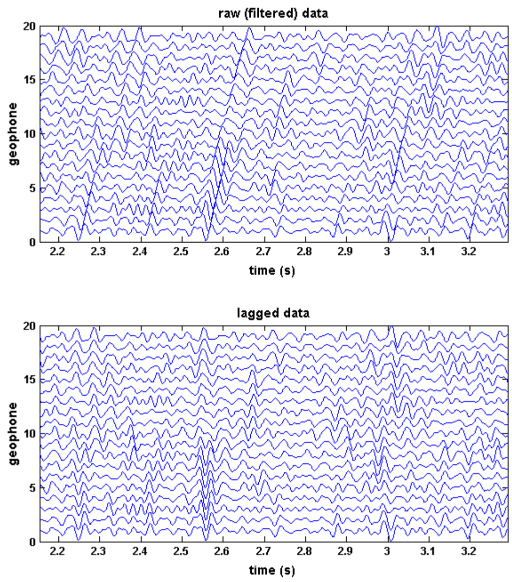

Figure 2. Low-pass filtered data (top) from the coal shearer, and (bottom) data shifted to align after solving for relative travel times.

An example tomography result from a coal mine in New South Wales is shown in figure 3. The sensor locations were restricted to being in fresh air and at least 100m away from the face, resulting in a less-than-optimal array geometry. The results are nonetheless plausible, with high velocities corresponding to high stress zones in front of the face and a sandstone channel through the geophone array. This kind of result proves the concept sufficiently to spur development of the intrinsically-safe sensors that would be needed to achieve better array geometries.

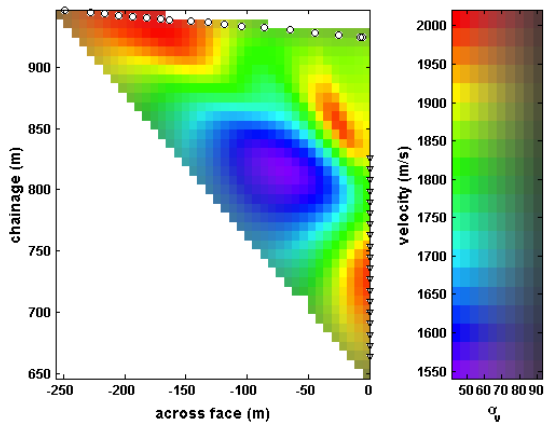

Figure 3. An example tomogram showing a plan view of velocity variation across a longwall panel. Circles show the shearer locations across the face for the data windows used, triangles show the line of geophones installed in a roadway roof.

MINING-INDUCED VELOCITY CHANGES

The second example shows a large change in velocity associated with mining from a dataset acquired in a coal mine in New Mexico (King 2011). An array of geophones was laid out in an L-shape on the surface above the mine (Figure 4) and energy from the shearer, at a depth of 200m, was recorded. Relative arrival times were then computed from 30-second-long windows of data.

Assuming that the signal originated at the known shearer location, indicated in Figure 4, the relative travel times are plotted against known shearer-geophone distances in figure 5. The points are plotted in colours matching the geophone locations in figure 4. There is a striking separation into two clusters with different apparent velocities given by the slopes of best-fit straight lines through the points. The group showing low velocities are all from geophones lying behind the face, presumably because the seismic energy has traversed the destressed and fractured rock above the mined-out section of the panel behind the face.

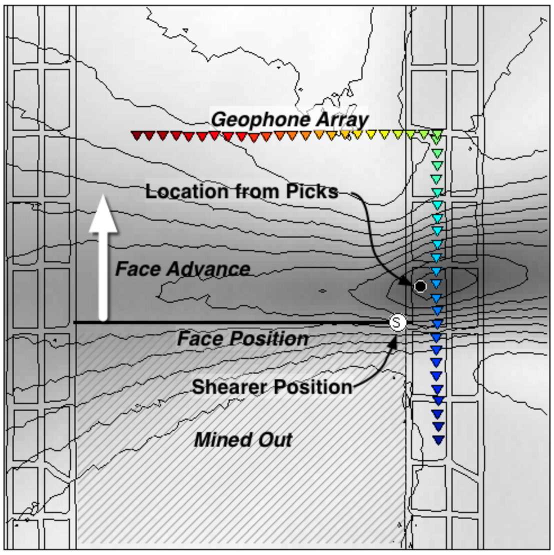

Figure 4. Plan view showing the geophone array location relative to the mine gateroads. The location and direction of advance of the mining face is shown, along with the shearer position. The source location determined from arrival-time delays across the array is shown as a black circle; the grey-scale image shows the location estimate derived from reverse-time migration. Both locations use a layered-earth velocity model that ignores mining-induced velocity changes.

In order to rule out the possibility that the velocity change is an artefact caused by incorrect source location, for example energy that comes from a seismic fracturing event rather than from the shearer, the source was located in two different ways, both using a layered-earth velocity model. First, standard earthquake-location techniques (Gibowicz & Kijko 1994) were applied to the relative arrival times, resulting in the location shown in figure 5 as a black dot. Second, a "migrated energy image," shown as a grey-scale contoured background in figure 4, was produced by migrating a much-longer window of the traces to a horizontal plane at the mining depth and then summing over time to form an energy image, similar to the source-scanning algorithm of (Kao & Shan 2004). Both methods yield similar locations. The locations do not correspond to the known shearer position, because mining-induced velocity changes were ignored.

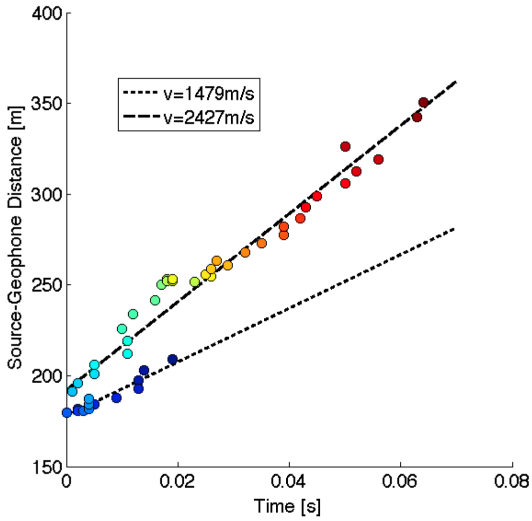

Figure 5. Shearer-geophone distances plotted against relative travel times. Colours match the geophone locations in figure 4. Two clusters of events are seen with different velocities given by the straight-line-fit slopes. The velocity

One of the unknowns in a longwall coal mine is the shape of the caved zone which develops above the mined-out panel, the region where rock has collapsed into the void created by mining. The geometry of this cave, and of the intact, weight-bearing rock above and around it, determines the stress that must be carried by pillars on either side of the mined-out panel, so is an important piece of geotechnical information. This large change in velocity associated with the mining progress implies that it might be possible to image the cave zone and determine its geometry seismically.

Although the geometry of a longwall mine means that the shearer can be used to generate images of velocity variation on a horizontal plane. (King & Luo 2009), generating a 3D picture, or even a vertical section is more difficult. The data from the shearer was therefore augmented by multiply-stacked sledgehammer shots along a gateroad underground, parallel to the direction of face advance. In addition, weight-drop shots were fired into the array from multiple locations on the surface, in order to provide some constraints in vertical velocity variation using refracted arrivals. A fast-marching method (Sethian & Popovici 1999) was used to compute the curved ray paths required for these large velocity changes.

The resulting vertical section velocity image is shown in figure 6. Three anomalous regions are visible: (1) a low-velocity near-surface layer; (2) a low-velocity region behind the face (at ~110m) corresponding to the collapsed rock and overlying fractured rock generated by the mining; and (3) a high-velocity region above the face generated by high stresses. Ray paths shown in the figure demonstrate that the resolution is quite low. Although the velocity changes associated with mining are shown to be large and easily detectable, it is difficult to achieve the kind of array density and geometry that would be required to provide useful information from mining-equipment sources alone. The most promising approach would be to use mining-induced microseismic events as sources. A typical mine generates many thousands of these per day, and they are widely dispersed spatially.

CONCLUSIONS

Mining machinery can be used as a source for seismic imaging, even when the signal is continuous, random and unknown, and so no definite start time can be picked. The arrival time lag between two sensors can be determined using the slope of the phase of their cross spectrum. The presence of noise from other sources, and of changes in waveform shape due to propagation effects can be dealt with by using the coherence spectrum between the two traces to weight the phase points, and by including prior information in the form of expected arrival times from an estimated background velocity model.

The motion of a coal longwall shearer back and forth across the face means that, for each pass of the shearer across the face, a whole line of sources can be generated. This means that a horizontal planar tomography image can be computed given sensors installed in gate roads. This kind of image could be useful for detecting anomalous regions ahead of the face, related to geology or stress, thereby allowing the mine to take proactive precautions if they are deemed hazardous.

A vertical section was generated to test the idea of trying to determine the geometry of the caved zone behind the face. The geometry of the shearer movement is less helpful in this case, and extra shots underground and on surface were required to get any image at all. The addition of information from mining-induced fracture events, many thousands of which are produced each day by the average mine, is likely to provide the required extra data, so this is proposed as the most promising way forward.

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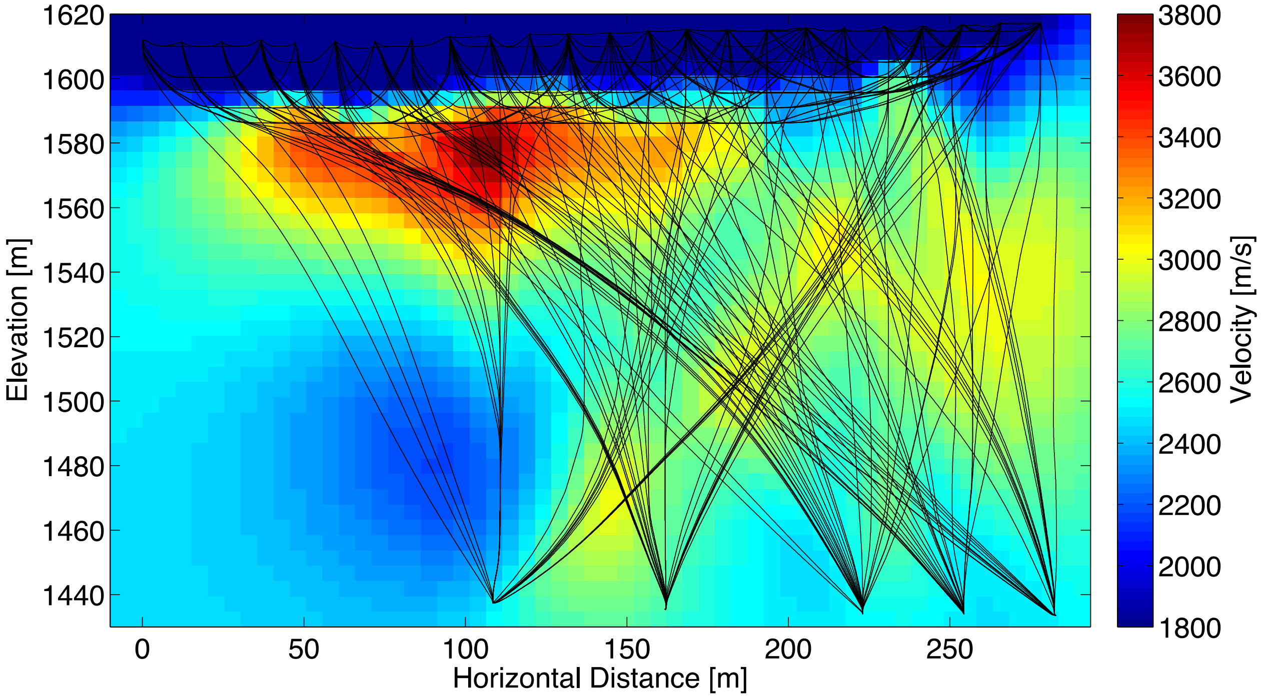

Figure 6. Vertical velocity section generated by the shearer at 110m, sledgehammer shots underground, and weight-drop shots at surface. Three anomalous zones are seen: (1) a low-velocity zone at surface; (2) the low velocity region behind the face associated with the caved zone; (3) a high-velocity zone associated with stress above the face.