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Coalbed methane: a 3-D reservoir seismic data set

David E. Lumley[1]

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ABSTRACT

Coalbed methane reservoirs are becoming an increasingly interesting prospect to some major oil and gas companies. The rapid spatial heterogeneity of coal physical properties, methane saturation levels, and coal fracture systems and flowpaths makes these targets a challenging prospect for reservoir characterization research in general, and 3-D prestack seismic impedance inversion in particular. I briefly present some examples of a comprehensive 3-D land seismic data set made available to SEP by Amoco Research, and point out some interesting features, problems and prospects in the data with respect to my inversion goals. The data are characterized by a strong AVO response on the coalbed target at 0.5 seconds, and a weaker basement reflection at 1.3 seconds. The swaths are contaminated by spatially aliased air-wave noise, ground roll, and trapped surface modes, and contain apparent source-receiver amplitude and residual statics variations.

INTRODUCTION

Coalbed methane reservoirs are relatively new production opportunities, and much of the current knowledge and expertise has been pioneered by Amoco. Previously, methane has been produced from coalbeds by injecting water to create a pressure gradient across the reservoir. As water flows from an injection to a producing well, it desorbs methane gas from coal pore surfaces. The liberated methane flows along coal cleats, into coal fracture systems, and along to the producing wells. Recently, new production technology has been tested by injecting nitrogen to lower the partial pressure of coalbed methane. The liberated methane is driven below the bubble point, and is more efficiently produced as a liquid hydrocarbon rather than a gas.

The success of coalbed-methane production depends critically on understanding the in situ spatial properties of coal, the reservoir coal fracture systems, the macro

[1]**email:** not available

flow patterns and permeabilities of the reservoir, and the ability to detect and monitor the spatial distribution of injected and produced gas. Amoco have donated data to my thesis project on the basis that they hope 3-D seismic impedance estimates may help clarify the spatial heterogeneity and production rates of their coalbed reservoirs.

In the remainder of this brief paper, I discuss my research goals for the data set, show some examples from the 3-D $\grave{P}\acute{P}$ land data, and point out some interesting features, problems and prospects in the data with respect to my inversion goals.

RESEARCH GOALS

I propose to use the comprehensive 3-D Amoco data set to estimate reservoir mechanical properties and their spatial variation in a true 3-D sense. This procedure will require sequential data processing steps involving: (1) P and S velocity analysis from 3-D $\grave{P}\acute{P}$ and 2-D $\grave{P}\acute{S}$ reflection data, (2) 3-D prestack migration images of reservoir structure, stratigraphy and fault geometry, (3) 3-D simultaneous prestack inversion of the $\grave{P}\acute{P}$ and $\grave{P}\acute{S}$ reflection data for P and S relative impedance contrasts within the reservoir zone, and (4) integration of the P and S velocity and impedance contrast information to make estimates of the P and S impedances I_P and I_S, in a 3-D spatial volume encompassing the reservoir block.

The most significant portion of this research effort is directed at the problem of estimating impedance contrasts from seismic reflection data. I will approach this problem in the following manner. Using a reliable estimate of the P and S migration velocity models resulting from the velocity analysis step (1), multiple constant offset elastic migrations will be performed for each of the $\grave{P}\acute{P}$ and $\grave{P}\acute{S}$ data sets. This procedure will result in four sequences of maps: $R_{PP}(\mathbf{x};\mathbf{x}_h)$, $\Theta_{PP}(\mathbf{x};\mathbf{x}_h)$, $R_{PS}(\mathbf{x};\mathbf{x}_h)$ and $\Theta_{PS}(\mathbf{x};\mathbf{x}_h)$, where R represents the angle-dependent elastic reflectivity estimate, and Θ represents the reflection angle estimate. The R and Θ values make a direct mapping to $\grave{P}\acute{P}$ and $\grave{P}\acute{S}$ reflectivity as a function of reflection angle, which can subsequently be inverted for P and S impedance contrasts, using the Zoeppritz plane-wave response, as a function of subsurface position. The theory for making these reflectivity and angle estimates will be based on elastic Kirchhoff integrals and ray-theoretic WKBJ Green's functions (Lumley and Beydoun, 1991; and Lumley 1992, 1993a and 1993b.)

Once the impedance contrasts are estimated, they can be linearly combined with the P and S velocity estimates to make broadband impedance estimates. Spatial variations in I_P and I_S are useful in that they have physical correlations with: presence and saturation of gas in pore space (I_P low, I_S normal to high), fractured high permeability zones (both I_P and I_S are low), and can be combined to estimate 3-D variations in Poisson's Ratio, which can be a good discriminator of lithology (e.g., sandstone vs. shale vs. coal). I propose to correlate my I_P and I_S results with Amoco borehole, rock physics, and production engineering data. This correlation will be at the very least a qualitative integration of these multi-disciplinary data types, and may possibly extended to a quantitative integration using existing Markov-Bayes methods of spatial geostatistics.

THE 3-D DATA

Amoco have collected a complete spectrum of seismic data over the 3-D reservoir survey area. The Amoco Research seismic crew have recently shot a 3-D $\grave{P}\acute{P}$ survey, a 2-D $\grave{P}\acute{S}$ survey, some 9-component profiles, a multicomponent VSP, an "AVO" VSP, a dipole sonic (anisotropy mode), a full suite of logs, and cores. There is a good chance that the 3-D $\grave{P}\acute{P}$ survey will be repeated in the near future to monitor a nitrogen injection pilot which is currently underway.

The project is a joint effort between Amoco research geophysicists and production engineers, and the engineers can provide detailed information regarding anisotropic permeability and sorption properties in the coals, constraints on stress-dependent permeability, production history matching tailored specifically to coalbeds, and detailed information regarding brittle failure in coal.

The 3-D $\grave{P}\acute{P}$ data are correlated Vibroseis, recorded on frozen ground and packed snow surface conditions. Here are a few acquisition details about the 3-D $\grave{P}\acute{P}$ dataset:

- Correlated Vibroseis data.
- Total area covered = 2.6 sq. km.
- Number of shots = 96 per swath * 14 swaths = 1344.
- Traces per shot = slightly less than 600.
- Sample interval = 2 ms.
- Data storage size = 2 GB.
- CMP bin spacing = 7.6 m inline, 15.2 m crossline.
- CMP fold = 20 to 50.
- RMS velocity of principal target = 4.0 km/s
- Depth of target is at 1 km, or 0.5 seconds.
- Dips are shallow everywhere in the area ($\leq$ 5 degrees).

Figure **??** shows a representative receiver line from the 3-D survey, after gaining by a t^2 factor. The coalbed methane reservoir is the bright reflection at 0.5 seconds. Note the strong AVO character, and the possible polarity reversal (from positive to negative) at the far offsets. The very weak and low frequency basement reflection is barely discernible at 1.3 seconds. There is strong airwave contamination in the lower left corner of the panel, which is severely aliased. Fortunately, it does not cut across the target reflector. However, the Rayleigh waves at about 1.5 km/s and the near-surface trapped mode waves (snow + soil?) at about 750 m/s do somewhat contaminate the near offsets of the target reflector. Additionally, there are some noise bursts on some traces, and some degree of static variation.

Figure **??** shows a muted version of the raw gather. I show this because the mute pattern cuts across the far offsets of the target reflector, destroying a significant portion of that apparent AVO polarity reversal! Originally, before the mute, there is about 40 degrees worth of aperture illumination on the coalbed reservoir. After the mute, there is effectively only about 30-35 degrees remaining. This has an impact on the ability to accurately estimate shear impedance contrasts in the prestack inversion process: the more angle coverage the better the shear impedance contrast estimate reliability. Perhaps some new work can be done on a frequency and dip-dependent mute algorithm to preserve as much of the coal AVO as possible, yet suppress the critical refraction energy.

Figure **??** shows the spectrum of the raw muted data averaged over the receiver line. Figure **??** shows a small experiment in reducing the surface wave noise. An 18 Hz notch filter was applied after examining the data spectrum and correlating an 18 Hz spectral peak to the surface waves. The notched spectrum is displayed in Figure **??**. As seen, the simple notch did a pretty effective job at suppressing the surface waves. However, it also appears to have changed the phase on the coalbed reflector, and introduced a lot of spurious (?) ringiness, perhaps due to the narrowing of bandwidth. A second coal interval at 1.0 seconds seems to have come in clearer though. But, the basement reflector at 1.3 seconds has all but vanished. This is an important reflector to preserve in order to anchor the variations in the upper coalbed level at the final interpretation stage.

Figure **??** shows a $\tau - p$ slant stack of the receiver line. Most of the aliased airwave and low-velocity surface waves are well isolated in this spectrum. In particular, the coal reflection at 0.5 seconds is well separated at a fairly high moveout ray parameter of about 0.1 s/km. This appears to be a good domain in which to try an amplitude-preserving coherent noise suppression by least-squares inverse slant-stacks.

Figure **??** shows a simple NMO velocity semblance spectrum. The coalbed target reflection comes in strong at about 4.0 km/s rms velocity. There appears to be a fairly linear rms velocity gradient starting at about 3.5 km/s near-surface to about 4.5 km/s at the 1.3 second basement reflection. The airwave and surface waves are off the scale of this plot at the low velocities of 0.35 to 1.5 km/s. The velocity domain may be another good place to try a true-amplitude noise suppression, since the reflection energy is at such high rms velocities compared to the coherent noise. This would involve 3-D least-squares hyperbolic inverse stacks if attempted.

Finally, using the linear rms velocity gradient model, I did a quick stack of the receiver line to see a preliminary stack quality. I merely replicated the stacked trace eight times to give it a nice visual effect. The coal reflection at 0.5 seconds stacks in very well, and has a nice Klauder wavelet zerophase shape (this is Vibroseis data recorded on frozen ground). There seems to be coherent reflection energy at 0.7, 0.9, 0.95, 1.0, 1.1 and 1.3 seconds. The basement reflection at 1.3 seconds is very ringy and probably requires a tighter velocity specification, and definitely some redundancy to enhance the signal.

CONCLUSION

Currently, I am working on sorting out the 3-D coordinate geometries of the data set to be able to do some pre-processing. The idea will be to develop some "true" 3-D preprocessing algorithms using the Connection Machine and/or the Cray YMP/8 and C90. I also insist that these processes be as *true-amplitude* as possible, because I am ultimately interested in preserving the raw AVO character in order to subsequently apply my prestack impedance inversion techniques.

ACKNOWLEDGMENT

Craig Jarchow (Amoco Research) was very helpful in arranging the procurement of the Amoco 3-D coalbed methane reservoir data set.

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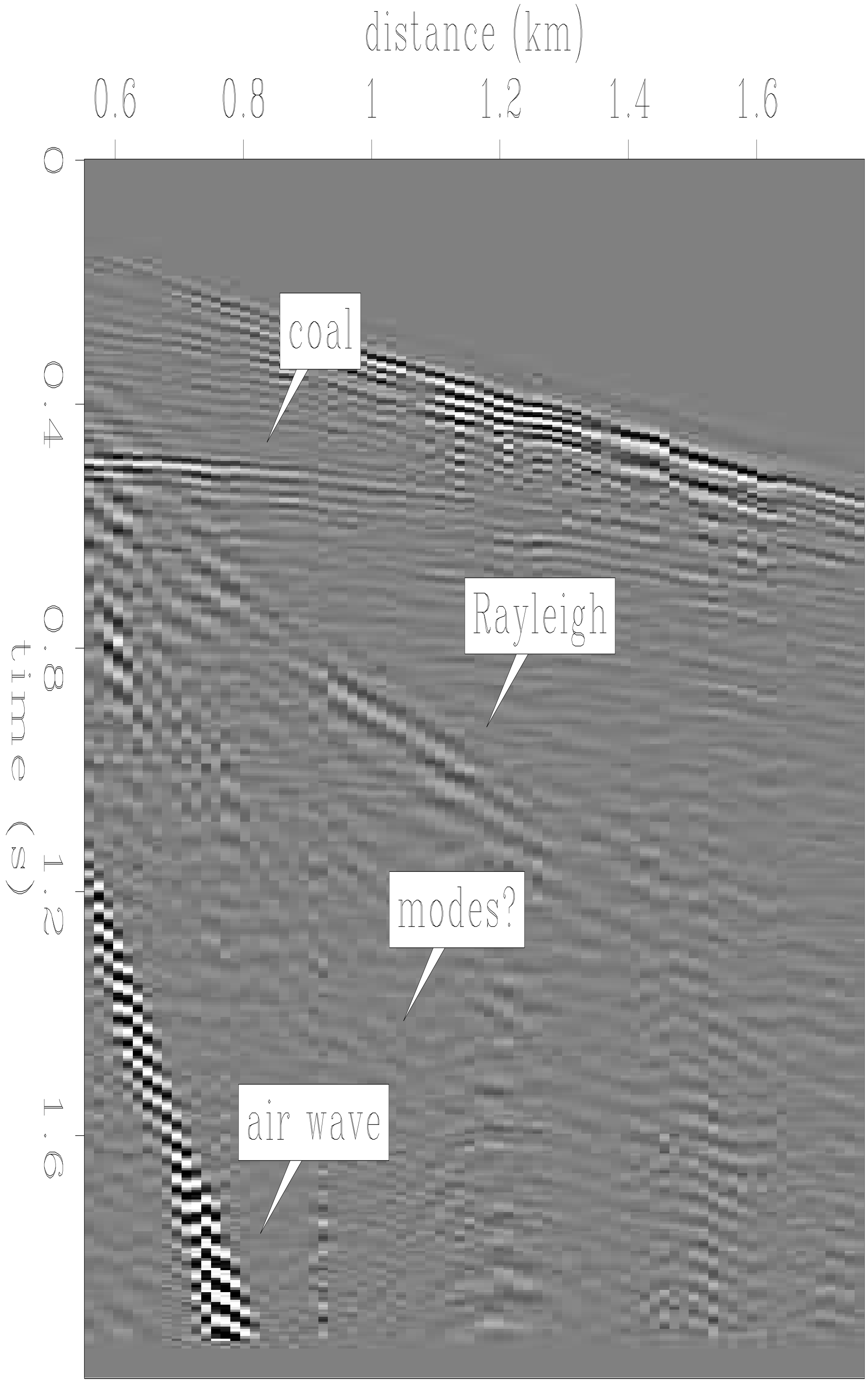

Figure 1: Raw receiver line from the 3-D coalbed methane data set. Gained by a factor of t^2. The coal is the bright reflection at 0.5 seconds, with a possible AVO polarity reversal at far offsets. Basement is the weak reflection at 1.3 seconds. Note the strong surface waves and aliased airwave. david4-tpow-ann [ER]

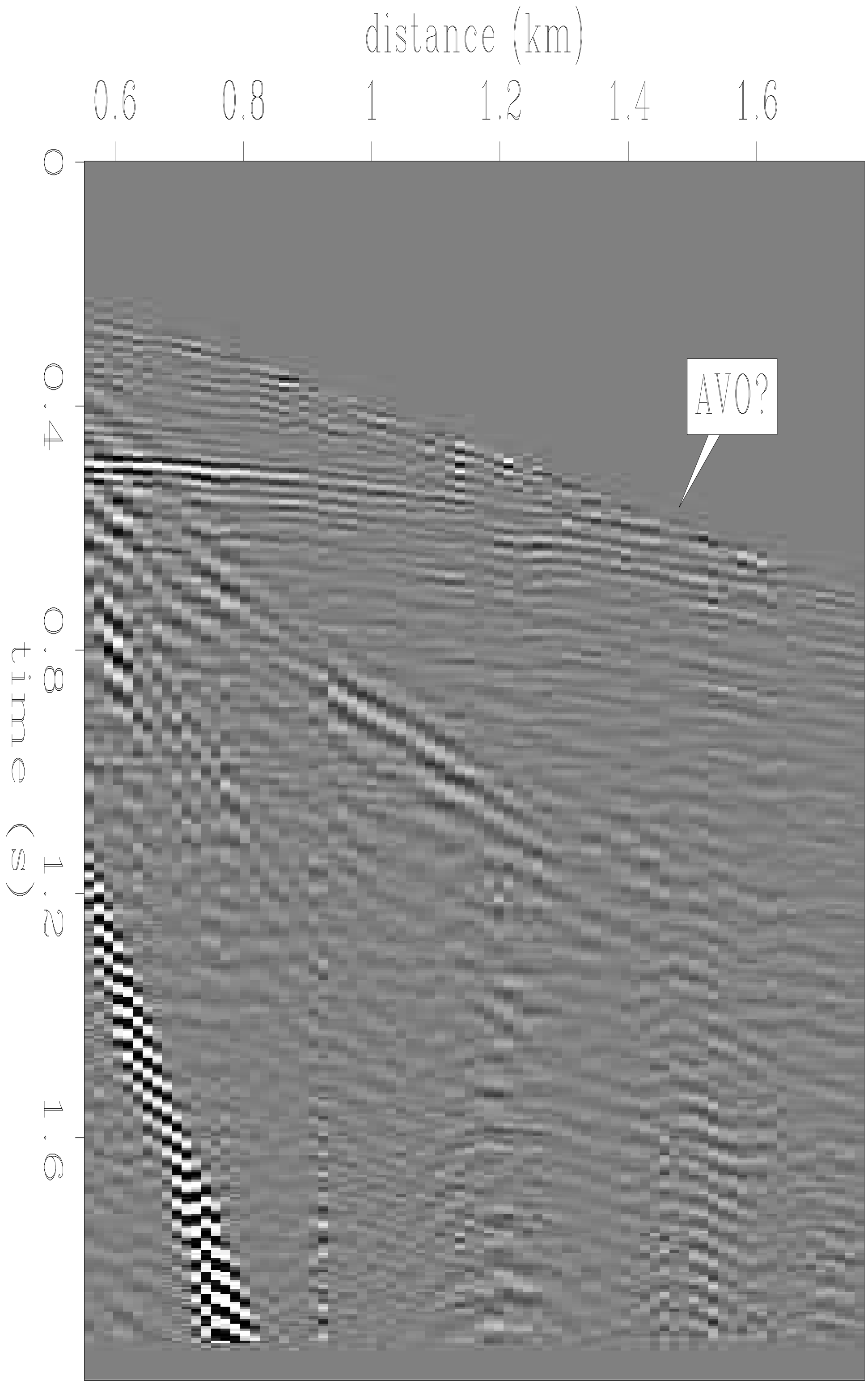

Figure 2: Muted version of the raw receiver line. Note that the mute has truncated the AVO aperture on the coal reflection from about 40 degrees to about 30-35 degrees. This will have an adverse impact on ultimate shear impedance contrast resolution in the final prestack impedance inversions. david4-mute-ann [ER]

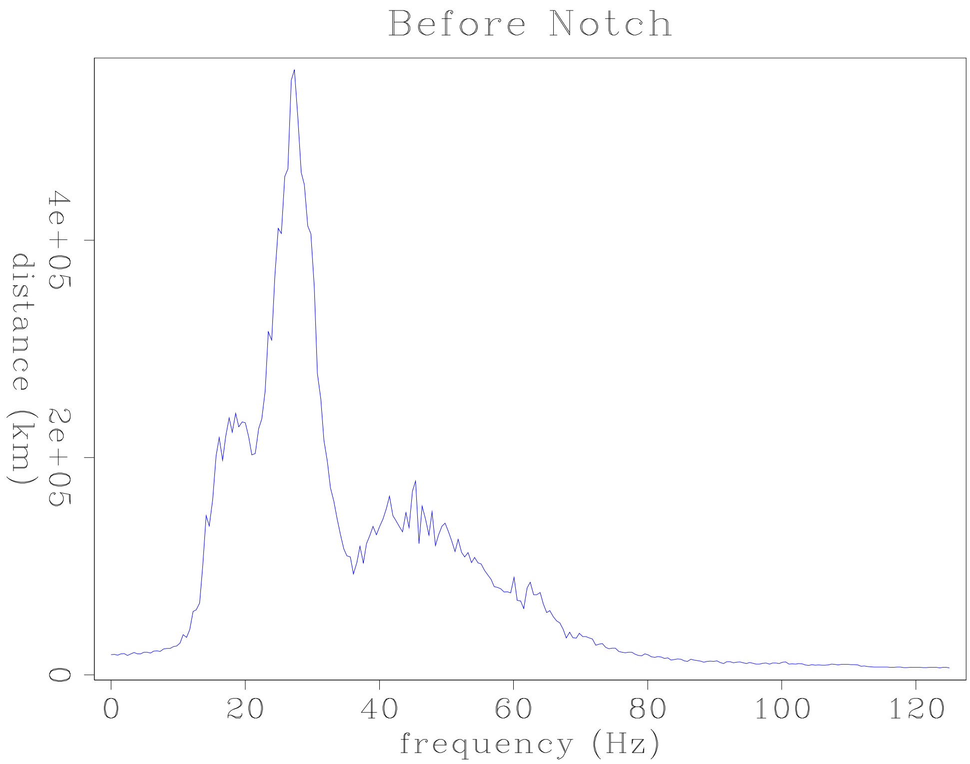

Figure 3: Raw data average spectrum before notch filter. Peak at 18 Hz is interpreted as surface wave noise . david4-spectrum1 [ER]

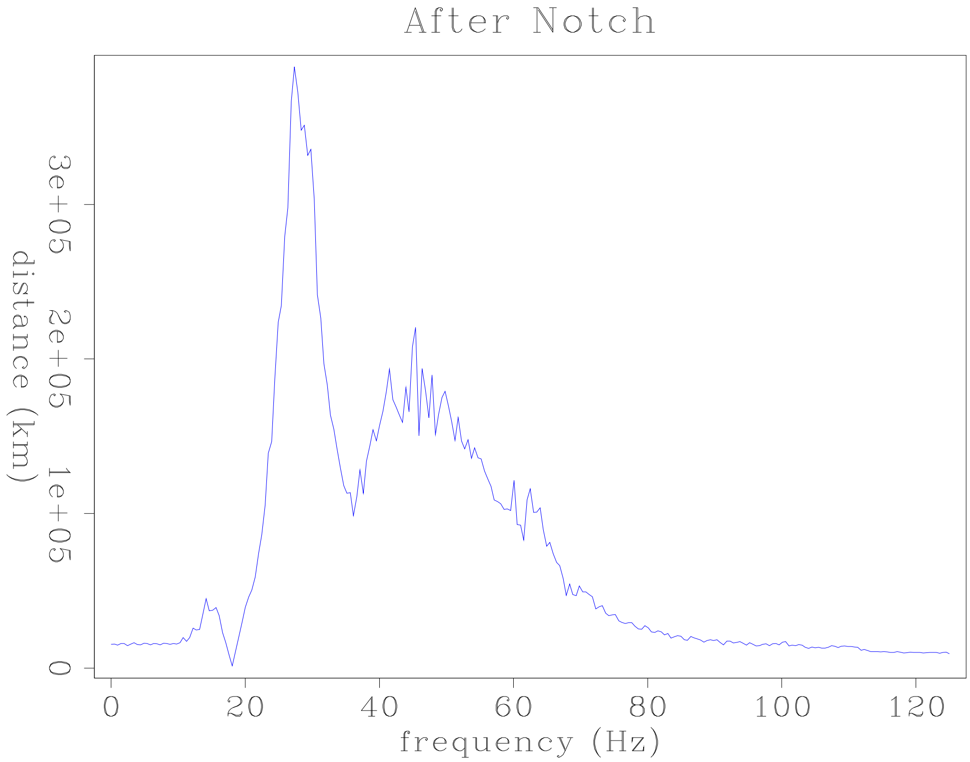

Figure 4: Average data spectrum after 18 Hz notch filtering. david4-spectrum2 [ER]

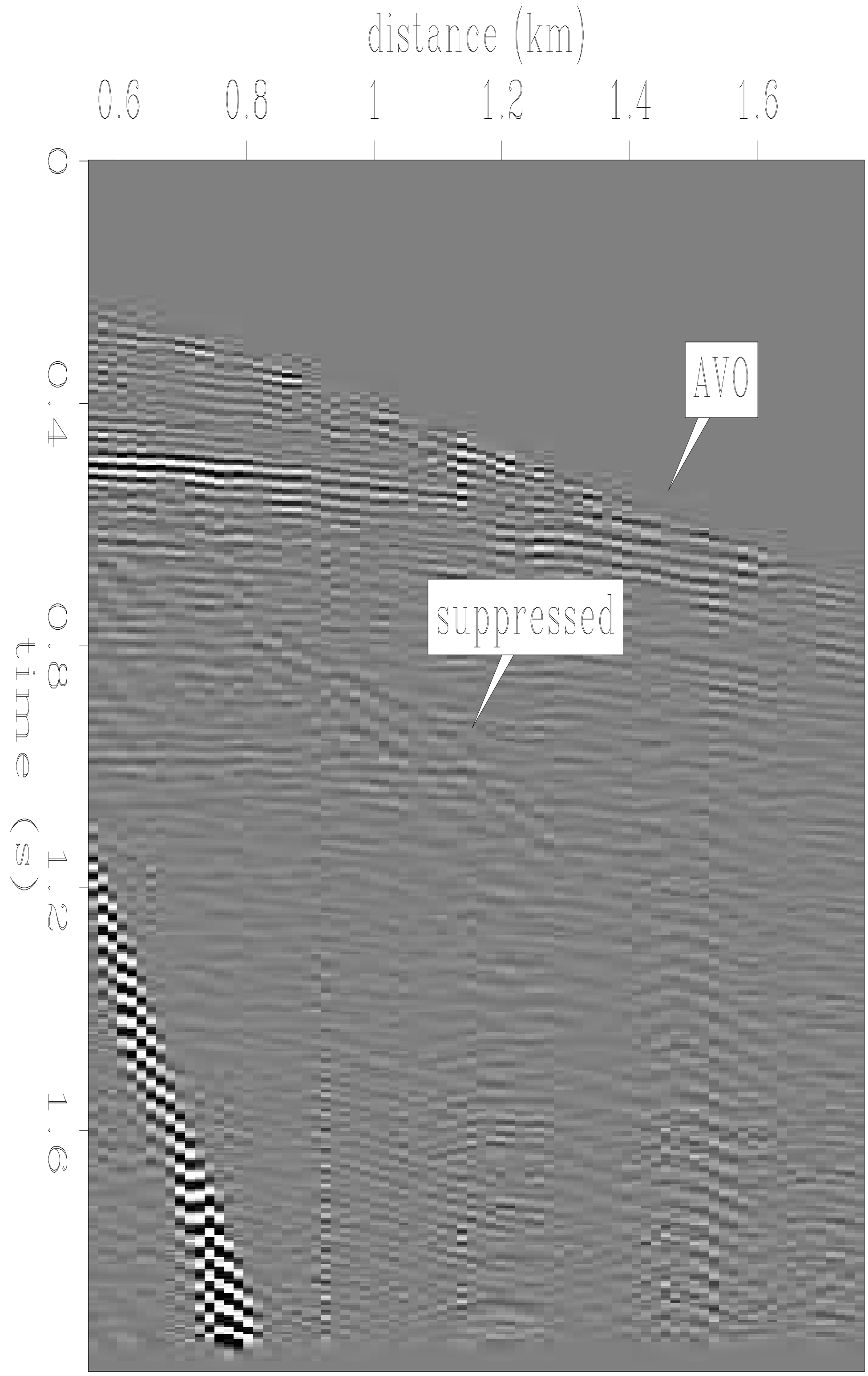

Figure 5: Receiver line data after 18 Hz notch filtering. Most of the surface wave noise has been suppressed. The aliased airwave remains. The notch also has changed the phase on the coal reflection, and eliminated the basement reflection. david4-notch-ann [ER]

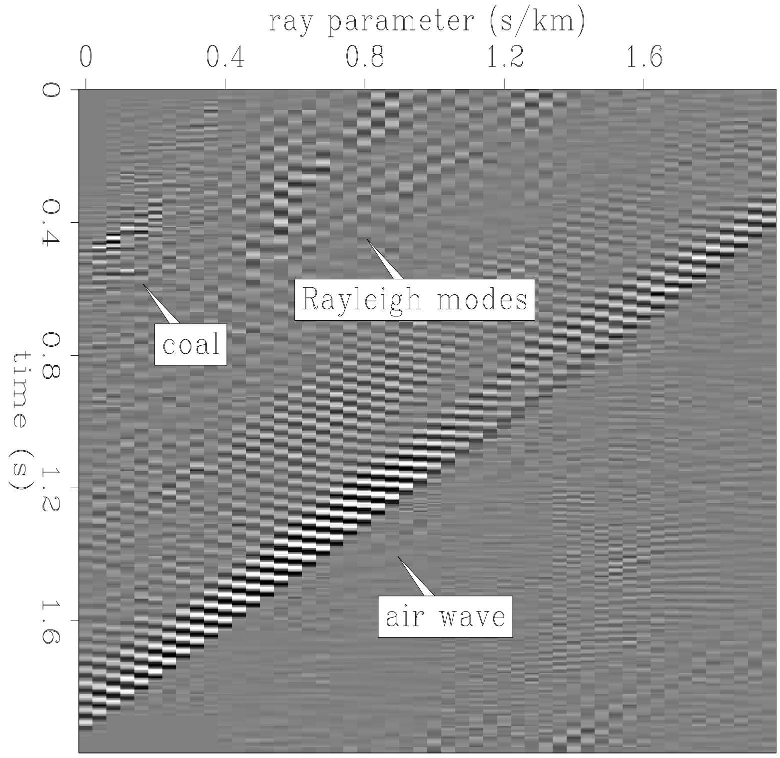

Figure 6: $\tau - p$ slant stack transform. The surface wave noise and coal reflections seem well separated in this space. $\boxed{\text{david4-vslan-ann}}$ [ER]

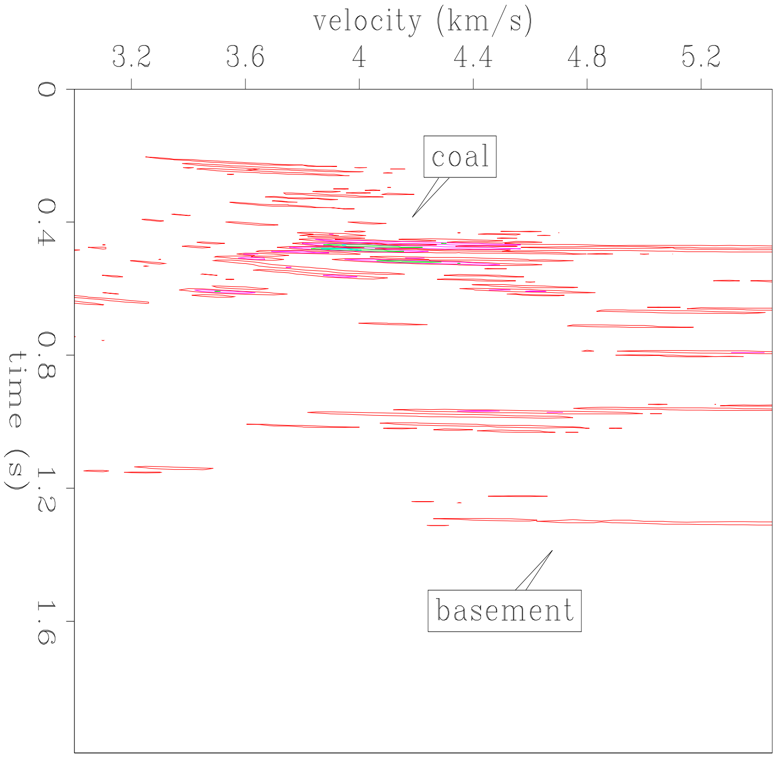

Figure 7: NMO velocity semblance scan. The coal reflection has an rms velocity of about 4.0 km/s. david4-vstack-ann [ER]

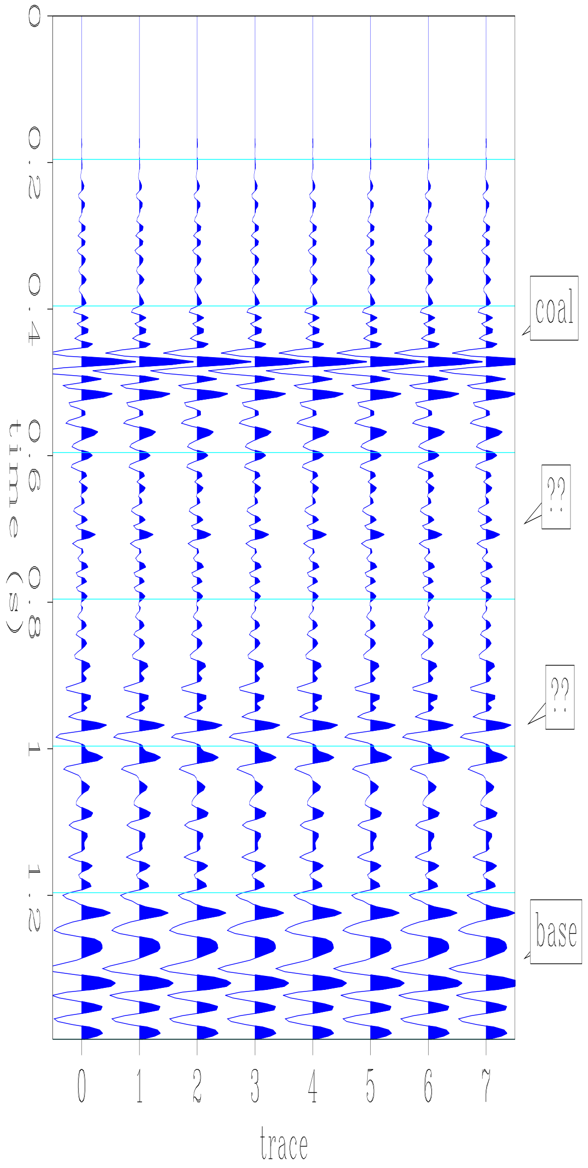

Figure 8: Receiver line stack, replicated eight times for visual effect. The coal target reflection appears at 0.5 seconds, and basement at 1.3 seconds. david4-stack-ann [ER]