3-D slant stacks and elliptical moveout of passive seismic data

Dave Nichols

ABSTRACT

If passive seismic data recorded over a stack of plane layers is 3-D slant stacked the slant stack traces should obey the Kunetz-Claerbout relations. We use this property to estimate a slant stacked reflection seismogram from passive data. The events in the estimated slant stacked reflection seismogram should show elliptical moveout. We can therefore perform elliptical moveout scans in a similar manner to NMO scans to try to determine the velocity structure of the subsurface. Applying this simple processing sequence to the SEP passive seismic dataset does not produce clear results. A more sophisticated model of the data is needed to estimate velocities successfully from the ambient wavefield.

INTRODUCTION

The SEP passive seismic dataset has energy that arrives at steep angles (Nichols et al., 1989), a compressional wave traveling near vertically should lose little energy to S-wave conversions. In this case the Kunetz-Claerbout (Claerbout, 1968) relations for waves vertically incident on a stack of plane layers should be applicable to constant (p_x, p_y) traces.

If the passive data is converted to the (p_x, p_y, τ) domain by a 3-D slant stack we can then autocorrelate the slant stacked traces to obtain an estimate of a slant stacked reflection seismogram, under the assumption of propagation through a stack of plane layers. Events on the estimated slant stacked reflection seismogram should show elliptical moveout if they are reflections from plane layers (Phinney et al., 1981). We can therefore perform a semblance scan over elliptical trajectories to obtain an estimate of the subsurface velocity.

The first results from this processing sequence do not look promising. Most of the events on the estimated reflection seismogram do not show elliptical moveout and the velocity scans show no clear evidence of strongly correlated elliptical events. I discuss possible improvements in the model and the possibility that the geology of the experiment site may not be suited to this estimation procedure.

CONVERSION TO REFLECTION SEISMOGRAM

3-D slant stack

The passive data is transformed into traces of constant (p_x, p_y) by a 3-D slant stack, this is just a summation over planes in the x,y domain.

$$P(p_x, p_y, \tau) = \sum_x \sum_y P(x,\ y,\ \tau + p_x x + p_y y)$$

where p_x is the horizontal slowness in the x-direction, p_y is the horizontal slowness in the y-direction and τ is the intercept time of the summation trajectory at zero offset. Figure 1 shows an example of the slant stacked data. The left hand panel is a slice through the 3-D slant stacked dataset along the $p_y = 0$ axis and the right hand panel is a slice along the $p_x = 0$ axis.

Estimation of the slant stacked reflection seismogram

The data $P(\omega, p_x, p_y)$ is assumed to be the convolution of a random source $W(\omega, p_x, p_y)$ with the generalized transmission function $X(\omega, p_x, p_y)$ which is the wavefield measured at a free surface when an impulsive plane wave is transmitted through the stack of layers.

$$P(\omega, p_x, p_y) = X(\omega, p_x, p_y) W(\omega, p_x, p_y)$$

We know from the Kunetz-Claerbout relations for normal incidence that the reflection seismogram, $R(z)$, is related to the transmission function by,

$$1 + R(z) + R(1/z) = C X(1/z) X(z).$$

We should be able to obtain a reflection seismogram by taking one side of the auto-correlation of the transmission function.

This theory is based on a model of plane waves vertically incident on a stack of plane layers that have unit delay time between layers. If there is no conversion from the compressional wave to other modes this theory is also valid for plane waves at any angle. The arbitrary layer boundaries used in the model are merely changed to preserve the unit delay time property. If there is conversion to other modes the theory is not valid as the result depends on the fact that the energy flux in all the layers is the same. This is not the case if some of the energy is converted to other wavetypes.

Since the source is assumed to be white we have

$$\tilde{P}(\omega, p_x, p_y) P(\omega, p_x, p_y) = \tilde{X}(\omega, p_x, p_y) X(\omega, p_x, p_y).$$

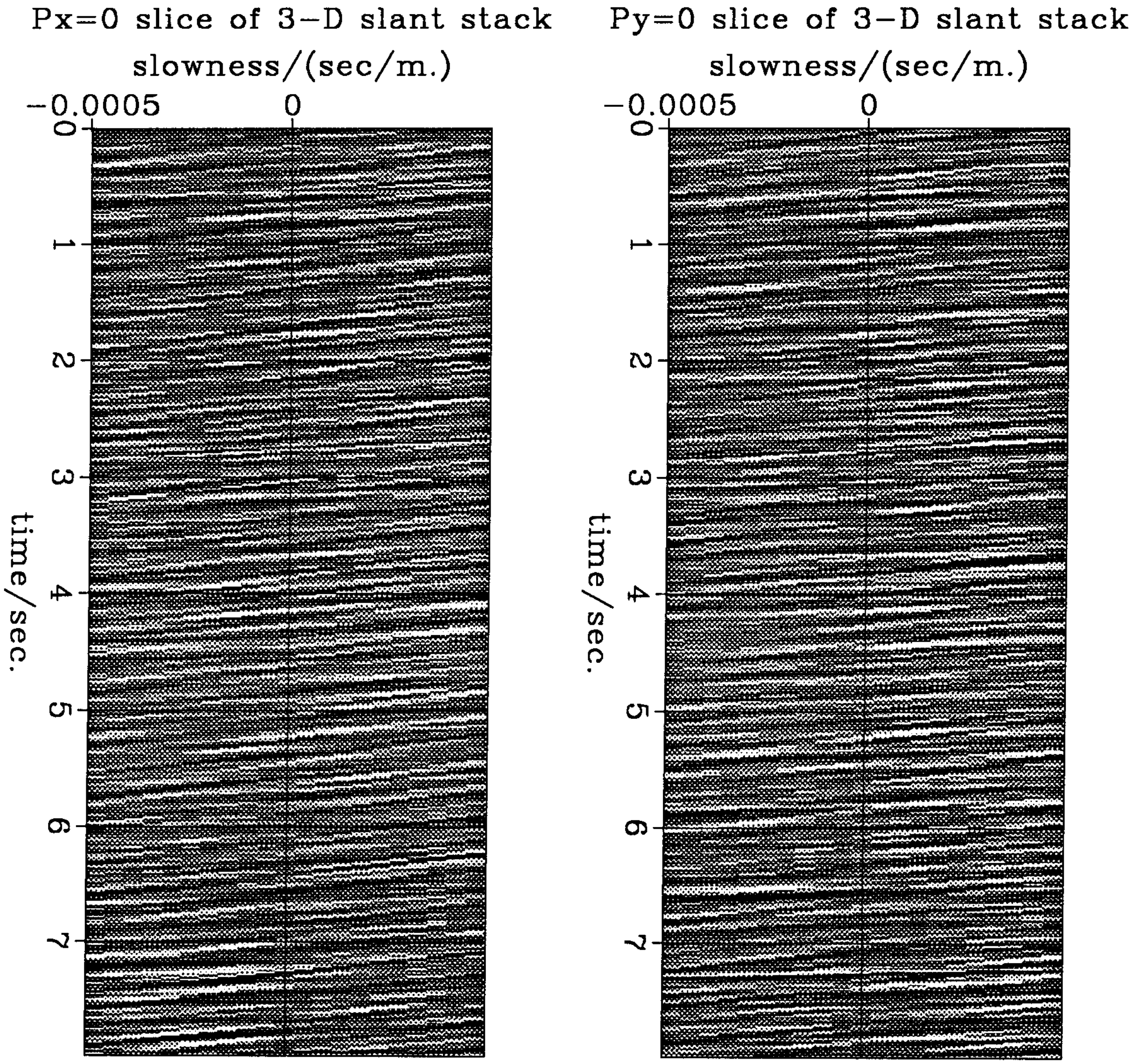

FIG. 1. Two slices through a 3-D slant stack of a passive record. On the left is the $p_y = 0$ slice, on the right is the $p_x = 0$ slice.

We can therefore obtain an estimate of the slant stack of the reflection seismogram by autocorrelating the slant stacked traces of the passive data, taking only one side of the autocorrelation and subtracting one from the zero lag sample. If the source is not white some further processing is needed to separate the effects of the source and the reverberation in the stack of plane layers. Lin Zhang suggests a way to do this in this report (Zhang, 1989).

When we apply this processing to the passive seismic data we get results like those shown in figure 2. There are high amplitudes at small lags, this is due to the band limited nature of our data, we do not have a truly white signal. Most of the later energy appears as linear events with no moveout across the gather.

Figure 3 shows the $p_y = 0$ slice from five separate records and the stack of the five records. If all correlations are random other than those caused by reverberations in the layers the stacking should provide an improved estimate of the slant stacked reflection seismogram. There seem to be several consistent flat events on these records. If an event is flat it means there was the same correlation lag for all values of p_x. This is not the behavior we expect for reverberations in a stack of plane layers. In the next section I discuss the sort of moveout we would expect on events that are generated by reflections in the earth.

ELLIPTICAL MOVEOUT

A 3-D slant stack of a reflection seismogram recorded over a stack of plane layers should show elliptical moveout. The travel time of reflection for small p obeys the equation,

$$\tau = \tau_0(1 - p_x^2 v^2 - p_y^2 v^2)^{1/2}$$

where v is the R.M.S. velocity to the reflector.

We can look at semblance as a function of time along ellipses parameterized by different velocities in a similar manner to conventional hyperbolic velocity analysis. Figure 4 shows elliptical moveout scans for five of the passive records and the stack of the five records. There is only one significant peak on the semblance plots, it is at a time of 1.25 seconds and a velocity of 6300m/s. This peak is consistently present on all the individual records and is clearer on the velocity analysis of the stack of the records. This velocity might seem higher than would be normally encountered but it is within the range of normal velocities for basalt or limestone. There is known to be basalt and limestone present in the geology of the area. Although the velocity analysis gives consistent results it has a very low semblance, the maximum is about 0.2, and it is not possible to see elliptical moveout clearly on the slant stacked and autocorrelated data. This is not a satisfactory situation and more investigation into the causes of the non-elliptical events on the slant stacked data is required.

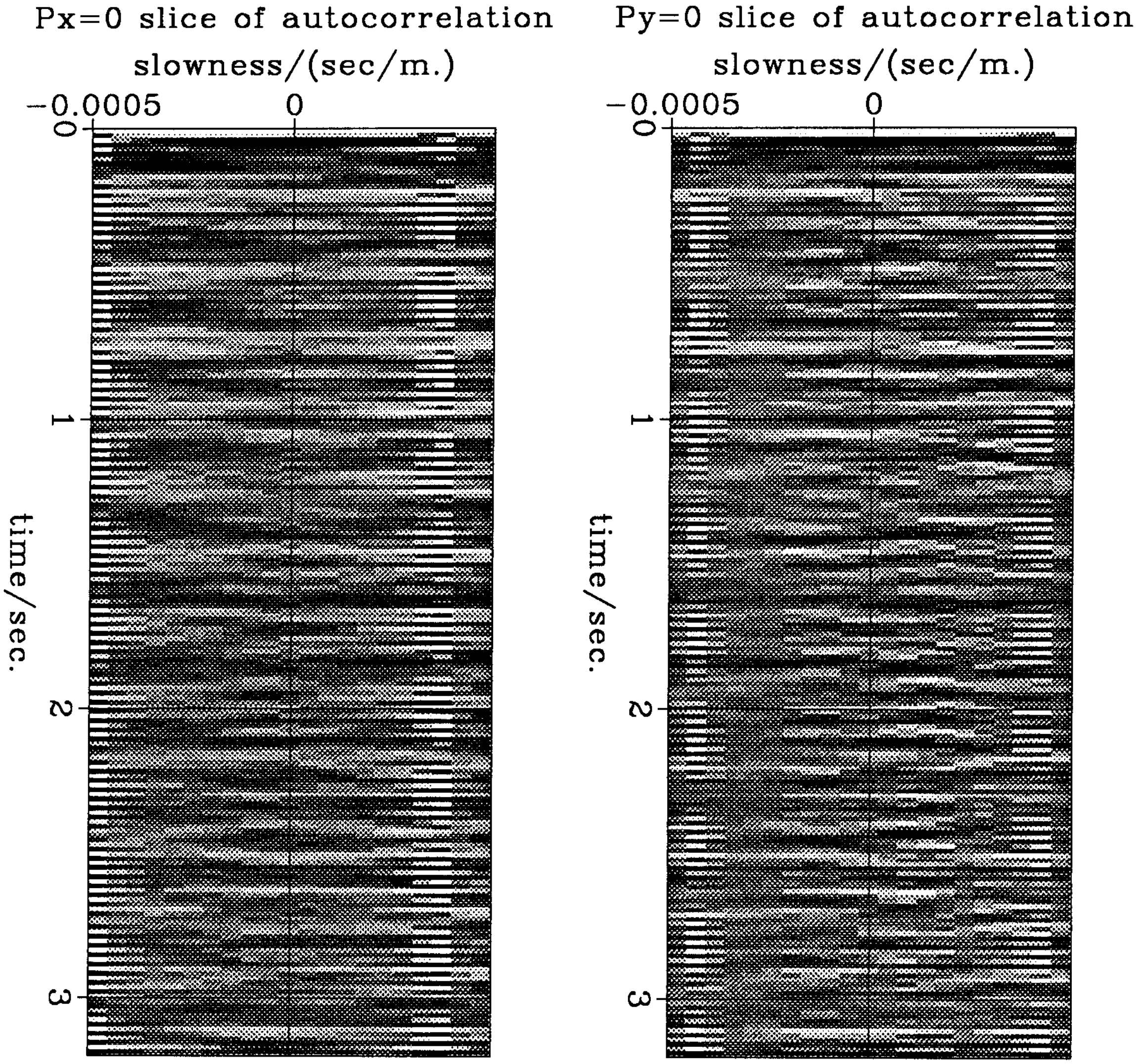

FIG. 2. Two slices through the autocorrelation of the slant stacked data shown previously. On the left is the $p_y = 0$ slice, on the right is the $p_x = 0$ slice.

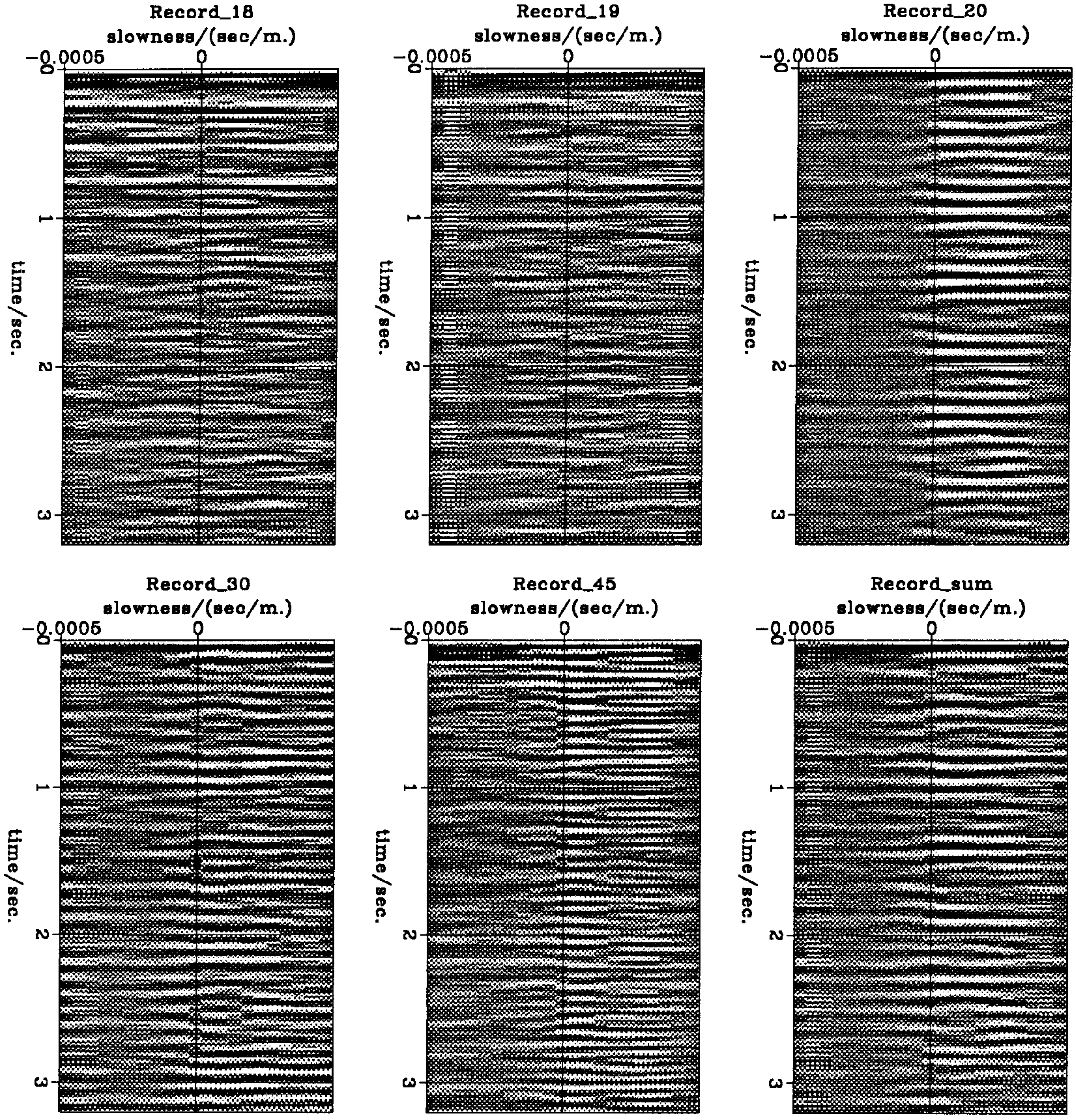

FIG. 3. The $p_y = 0$ slice through the autocorrelation of the slant stacked data for five different passive records. The sixth panel (bottom right) is the stack of the five records.

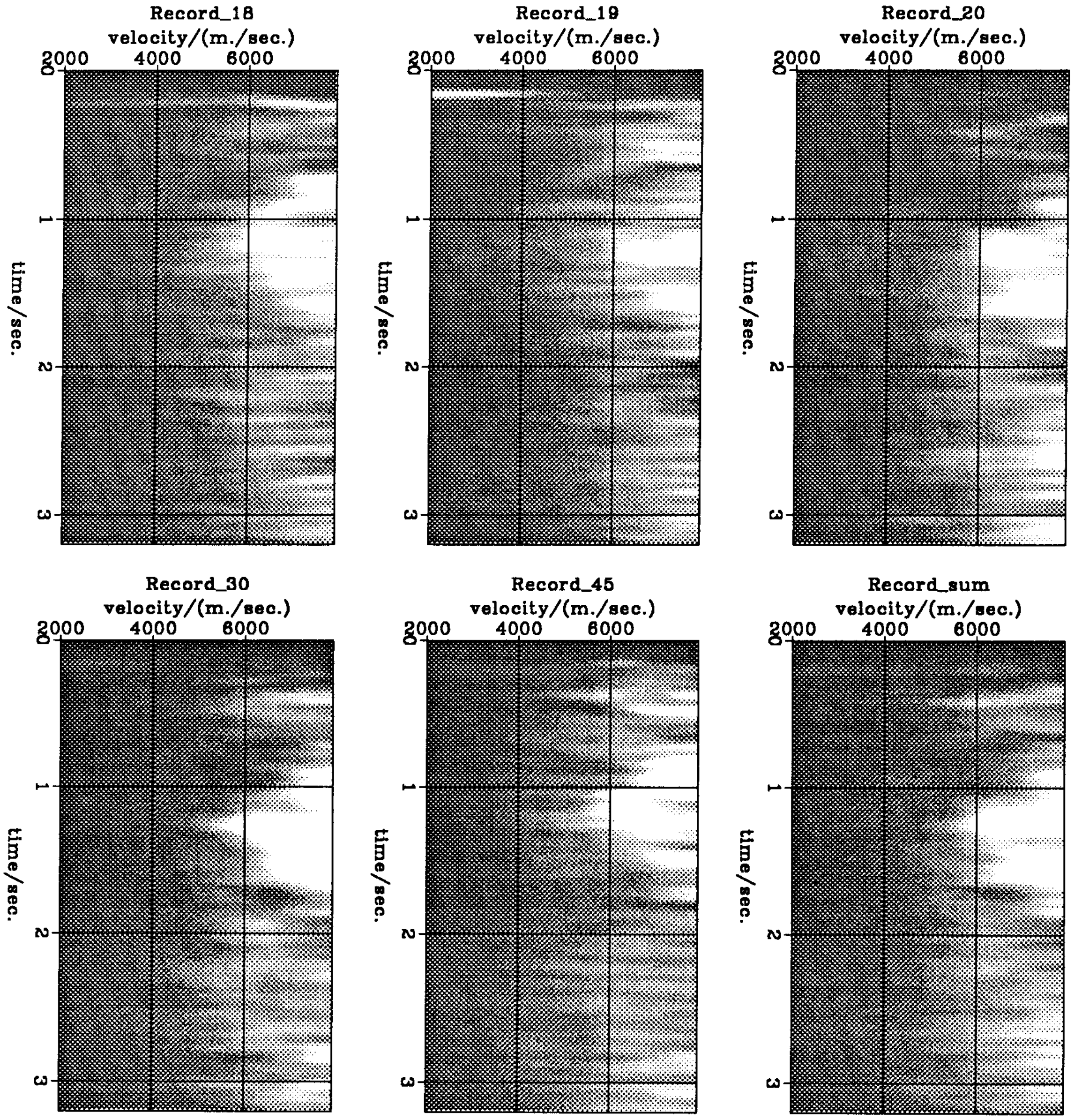

FIG. 4. Velocity analysis panels showing semblance along elliptical trajectories in the autocorrelated-slant stacked data. The first five panels show the results for five records, the sixth panel (bottom right) is the same analysis performed on the stack of the five records.

CONCLUSIONS

The processing sequence does not produce clear results. There is some hope that averaging more records will improve the quality of the elliptical moveout scans but there are some fundamental problems with the method. More effort is needed to identify the causes of and remove the linear events on the 3-D slant stacked dataset. The model used is flawed because it does not allow for artifacts in the slant stack produced by anomalously high amplitude events and missing traces due to equipment failures. The known geology of the experimental area is not a stack of plane layers. A more sophisticated model might overcome the first two problems but if the geology is too irregular the method might still fail.

REFERENCES

Claerbout, J.F., 1968, Synthesis of a layered medium from its acoustic transmission response: Geophysics, **35**, 264-269.

Nichols, D., Cole, S., and Zhang, L., 1989, An introduction to the SEP passive seismic dataset: This report.

Kunetz, G., 1964, Generalization des opérateurs d'antirésonance a un nombre quelconque de reflécteurs: Geophysical Prospecting **12**, 283-289.

Phinney, R.A., Chowdhury, K.R., and Frazer, L.N., 1981, Transformation and analysis of record sections: Journal of Geophysical Research, **86**, 359-377.

Zhang, L., 1989, Reflectivity estimation from passive seismic data: This report.