Stanford Exploration Project, Report 112, November 11, 2002, pages 141–151

Flattening without picking

Jesse Lomask and Jon Claerbout[1]

ABSTRACT

We introduce an analytical method for integrating dip information to flatten uninterpreted seismic data. First, dips are calculated over the entire seismic volume. The dip is then integrated in the Fourier domain, returning for each sample a time shift to a flat datum. Then each sample is shifted in the seismic data to remove all structural folding deformation in a single non-interpretive step. Using the Fourier domain makes it a quick process but requires that the boundaries are periodic. This method does not yet properly handle faults because of their discontinuous nature, but is presently very effective at removing warping and folding.

INTRODUCTION

A commonly used interpretation technique is to flatten data on horizons. This removes structure and allows the interpreter to see geological features as they were laid down. For instance, after flattening the seismic data, an interpreter can see an entire flood plain complete with meandering channels in one image.

Previously, in order to flatten seismic data, a horizon needed to be interpreted. If the structure was changing then many horizons needed to be interpreted. Here we propose a method for automatically flattening entire 3D seismic cubes without any interpretation at all. Our method involves first calculating dips everywhere in the data using a dip estimation technique described in Claerbout (1992). The local dips are resolved into a local travel time via a least squares problem that we solve in the Fourier domain. Then the data is shifted according to the travel times to output a flattened volume.

In this paper, we review the method for calculating dips and describe, in detail, the dip integration method. Then we show the results of several test cases. The first test case is a 3D synthetic data set with planes dipping at a single dip everywhere. The second test case is also a 3D synthetic data set, but has curved horizons. Finally, we apply this method to flatten horizons warped by a salt piercement in a real 3D seismic data set from the Gulf of Mexico.

This method successfully flattens the synthetic test data sets and removes a lot of deformation from the real test data set. These results are encouraging and invite more testing with more complicated models. The ability of this method to flatten data with faults still needs further development.

[1]**email:** lomask@sep.Stanford.EDU,jon@sep.Stanford.EDU

METHODOLOGY

First we calculate the dip. Dip can be easily calculated using a plane-wave destructor as described in Claerbout (1992).

For the dip in the x direction of a seismic cube with a wave field represented by $u(x,y,t)$, at each sample we calculate:

$$p_x = -\frac{x' * t'}{t' * t'} \tag{1}$$

where x' is the $\partial u/\partial x$ taken on a mesh in (x,t) and t' is $\partial u/\partial t$. Because we are calculating a different dip at each sample, it is necessary to smooth the dips. We apply a triangle filter to both the numerator and denominator of equation (1). Presently, in calculating p_x, we smooth along the x-axis and t-axis. However, a more robust approach would be to smooth along the x-axis, t-axis, and y-axis.

Our main objective is to find an absolute time (t) at each sample in the seismic data cube. Because the dip can be thought of as the gradient (∇), the dip in the x direction (p_x) is the x component of the gradient. Similarly, the dip in the y direction (p_y) is the y component of the gradient. Using our integration method described below, we first apply the divergence (∇') to the gradient. Then we convert to Fourier space where we integrate twice by dividing by the Laplacian. Then we convert back to the time domain. The resulting t can be thought of as the absolute time for each point in the data.

Beginning with our input dip data:

$$\nabla t \quad = \quad \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial t}\right) t \tag{2}$$

where $\frac{\partial}{\partial x} = p_x$, $\frac{\partial}{\partial y} = p_y$, and $\frac{\partial}{\partial t}$ is all ones for smoothness in time (explained below).

The analytical solution is found with:

$$t \quad \approx \quad FFT^{-1}\left[\frac{FFT\left[\nabla'\nabla t\right]}{-Z_x^{-1} - Z_y^{-1} - Z_t^{-1} + 6 - Z_x - Z_y - Z_t}\right] \tag{3}$$

where $Z_x = e^{iw\Delta x}$, $\mathrm{Z_y = e^{iw\Delta y}}$, $\mathrm{Z_t = e^{iw\Delta t}}$ and FFT is the 3D Fourier transform.

The denominator is the Z-transform of the 3D Laplacian. The zero frequency term of the Z-transform of the denominator is neglected. This means that the resulting surface in space will have an unknown constant shift applied to it. However, by adding the t dimension and assuming the gradient in the t direction to be all ones, we are insuring that the integrated time varies smoothly in the t direction.

Integrating in three dimensions enforces vertical smoothness. The dip in the t direction is all ones. This can be thought of intuitively as imagining that the dip in the x direction is the derivative of x with respect to t. So dip in the t direction is the derivative of t with respect to t, therefore it is always one. By integrating in 3D, we prevent our method from swapping sample positions in time.

Boundaries

Artifacts were created by this method when the boundaries of the result of the divergence were not periodic. One way to solve this problem is to make mirror images of the input dip data. Mirroring, which is basically replicating and time reversing data, requires increasing the data size by a factor of four in 2D and a factor of eight in 3D. Another way that requires less memory, is to define a new gradient operator that is periodic.

A periodic gradient operator can most easily be explained with a one dimensional example. A non-periodic gradient operator differences all of the samples in a one dimensional array. The periodic gradient operator does the same but also it differences the first and last samples. In equation (3), the application of the divergence (∇') with a periodic gradient operator outputs a periodic result that when Fourier transformed will better match the periodic denominator.

If we were to use the periodic gradient operator without mirrors in our formulation then in calculating the dip, we would need to know the dip from one side of the image to the other. This eliminates the periodic gradient as a solution to our problem in the x and y directions but not the t direction. In the t direction, where the gradient is one everywhere, we know the gradient from one end to the other. It is equal to the total time. As a result, we are using the periodic gradient operator in all three dimensions but only need mirrors in the x and y dimensions. This increases our data size by a factor of only four, rather than eight, even though it is in 3D.

TEST CASES

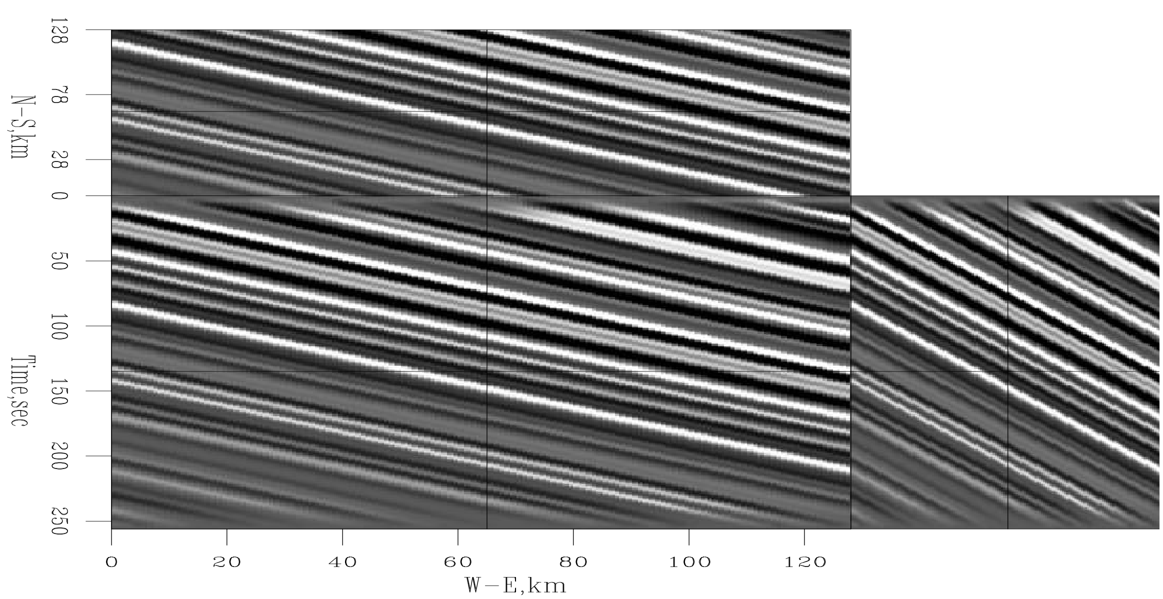

Figure 1: Test case 1. Dipping planes. jesse1-plane3D [ER]

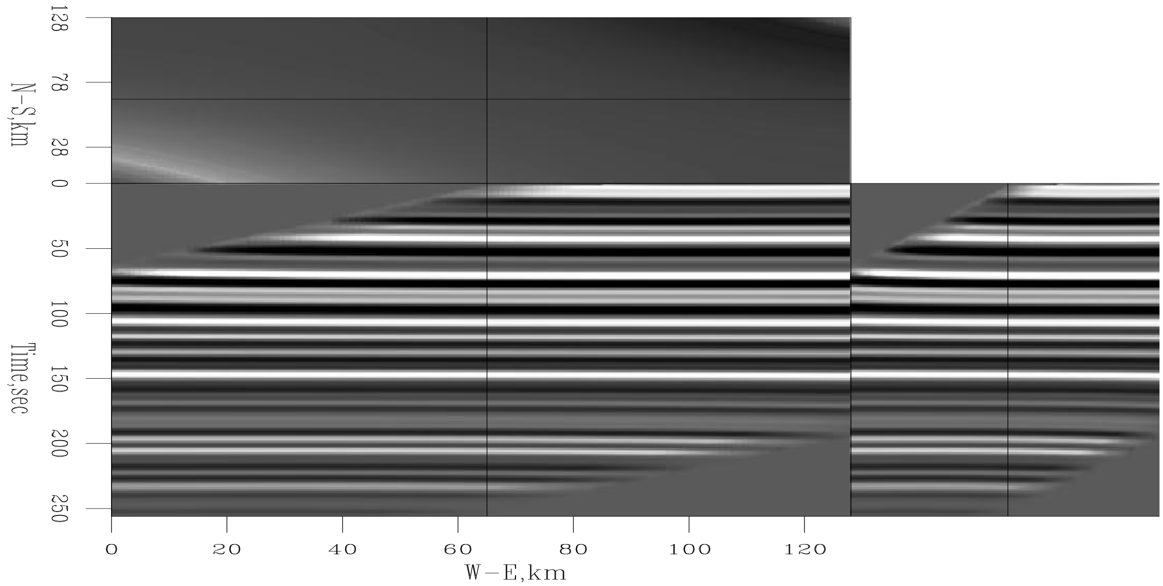

Figure 2: Result of flattening data in Figure 1. jesse1-plane3D.3Dflat [ER]

Dipping planes

The 3D synthetic data set in Figure 1 consists of a single synthetic seismic trace that is replicated and delayed so that the dip in both the x and y directions is unity. Running a dip estimator as in equation (1) will ideally result in dips of one in each direction.

The results of the flattening method of the data in Figure 1 are shown in Figure 2. Notice that the dipping planes are now flat and that the time slice on top is all one gray tone, indicating that it is flat.

Curved horizons

Figure 3 shows our next test case. The surfaces are curved upwards along the x-axis. The results of the flattening are shown in Figure 4. The method has successfully flattened the data. The slight undulations that look like interpolation errors are present in the original model in Figure 3.

Real 3D data

Figure 5 is a real 3D data cube from the Gulf of Mexico provided by Chevron. It consists of almost flat horizons that have been warped up around a salt piercement. Numerous channels can be seen in time slices. In the time slice at the top of Figure 5 a channel can be seen snaking across along the south side.

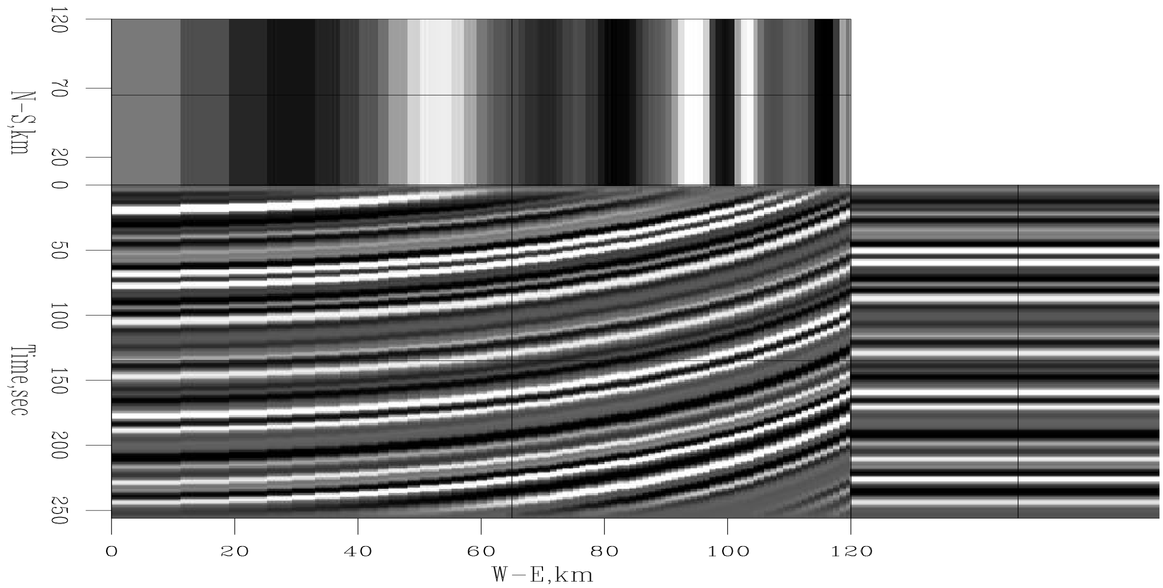

Figure 3: Test case 2. Curved horizons. jesse1-ski_jmp [ER]

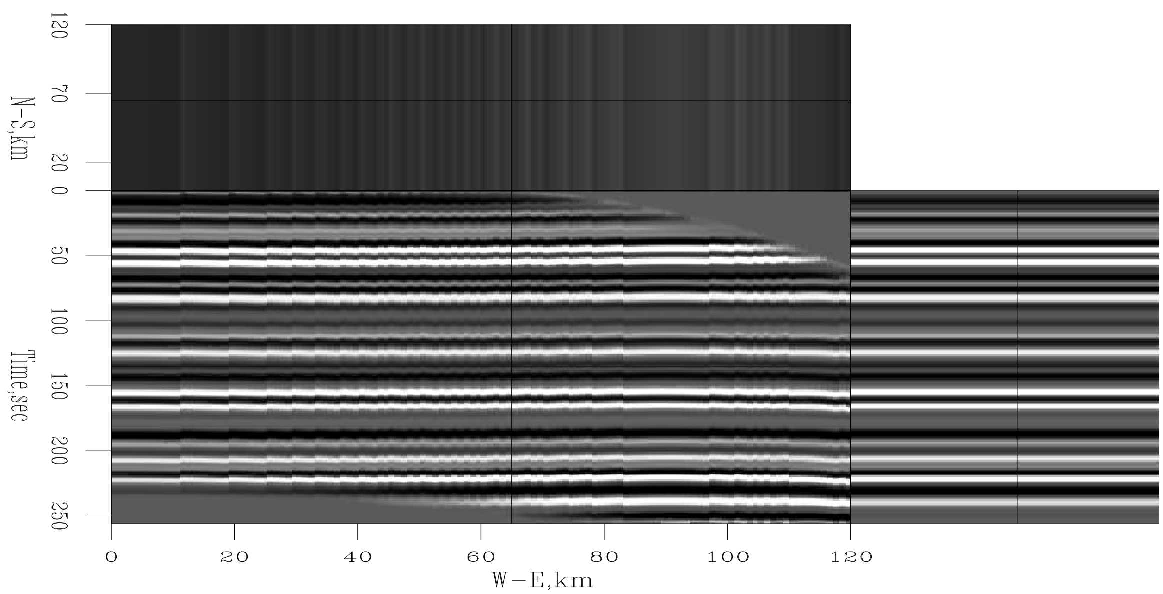

Figure 4: Result of flattening data in Figure 3. jesse1-ski_jmp.3Dflat [ER]

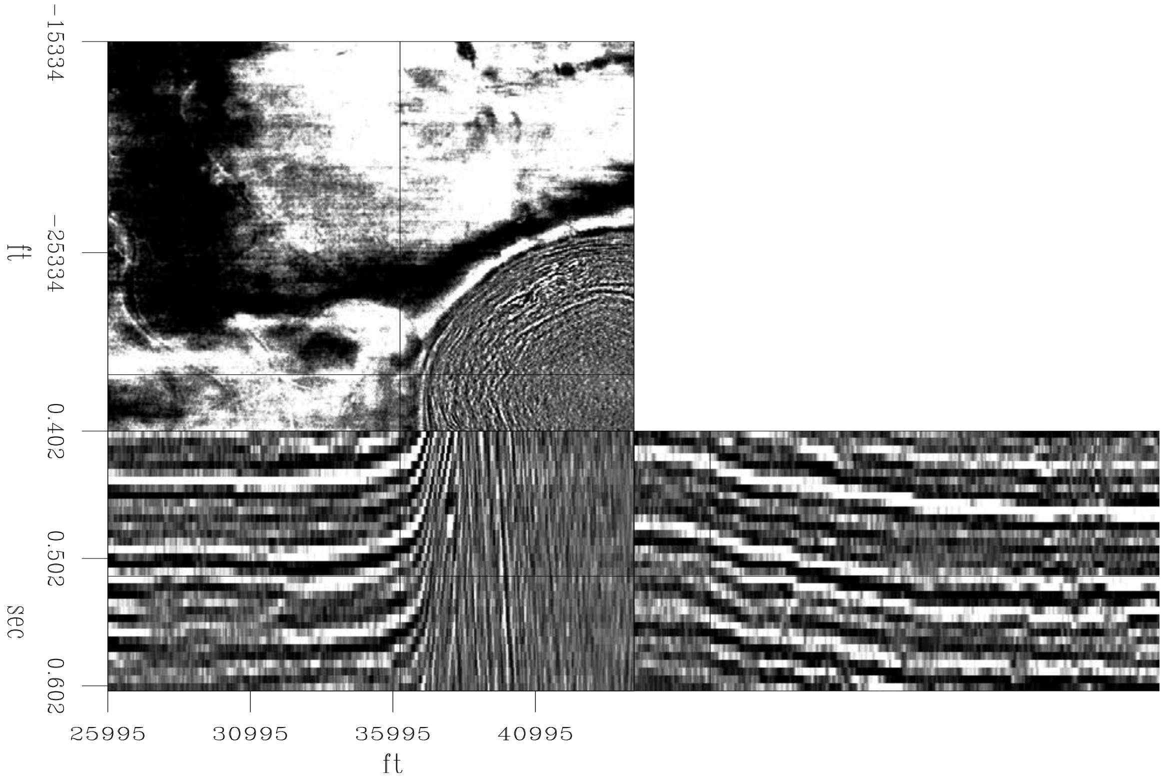

Figure 5: Test case 3. Chevron Gulf of Mexico data. jesse1-chev [ER]

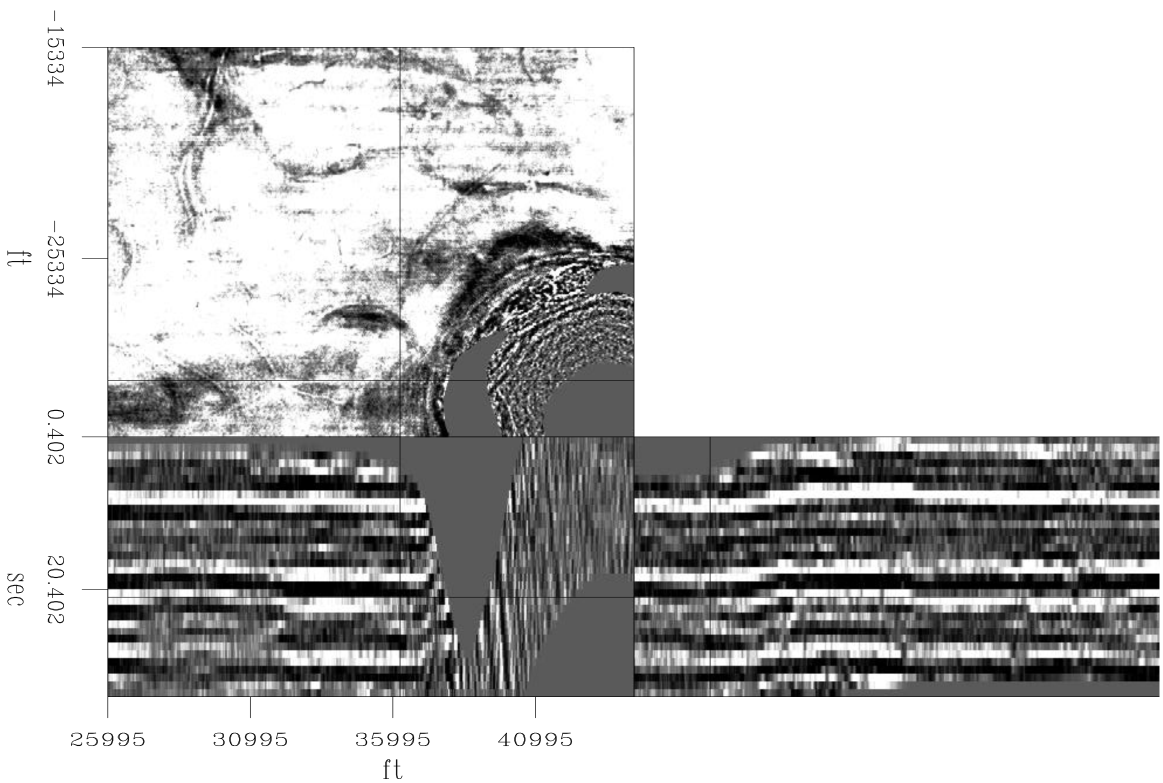

Figure 6: Result of flattening data in Figure 5. jesse1-chev.3Dflat [ER]

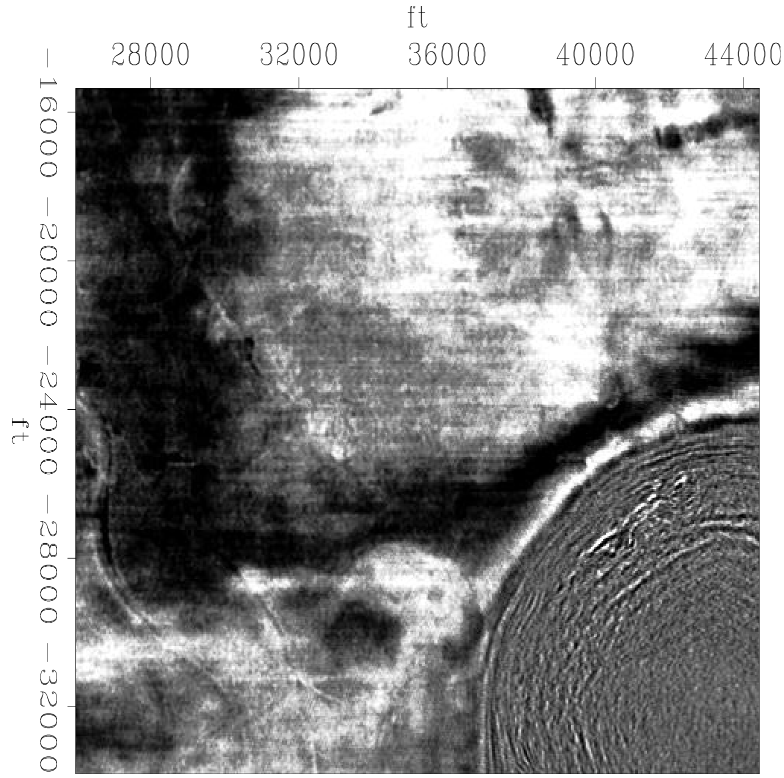

Figure 7: Time slice from Unflattened Chevron Gulf of Mexico data. jesse1-chev_ts [ER]

Figure 6 shows the flatted output of the Chevron data. Notice that the horizons are flatter than those of Figure 5.

Figure 7 is an unflattened time slice from the Chevron data and Figure 8 is a flattened time slice (horizon slice) from approximately the same place in the data. Notice Figure 8 does not have the low frequency banding that Figure 7 has. Also notice that the salt dome appears to be smaller in Figure 8. This indicates that the layers warped up by the salt have been made flatter.

Figure 9 compares an east-west section from the Chevron data to its flattened counterpart. The left side of the flattened section is clearly flatter that the input above. However, notice that the flattened image doesn't do a great job where the beds are dipping up steeply. This could be a result of poor dip estimation and definitely warrants further investigation.

CONCLUSIONS

Our method of resolving local dips into time shifts has effectively flattened seismic in our test cases.

Our use of the 3D Fourier transform may not be necessary. We maybe able to integrate the dips in 2D. This would make this method capable of handling large data sets easily. As

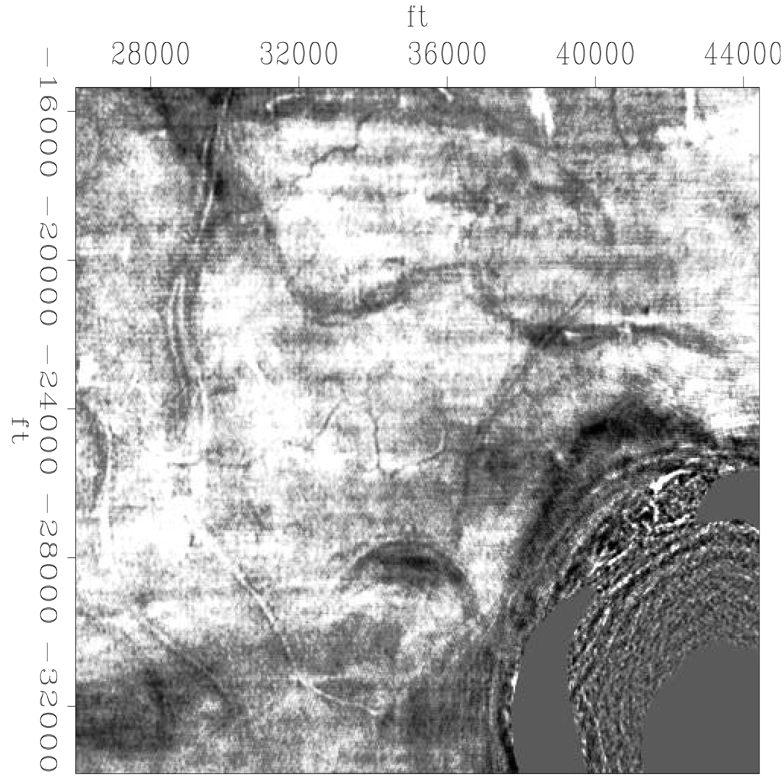

Figure 8: Time slice from Flattened Chevron Gulf of Mexico data. jesse1-chev.3Dflat_ts [ER]

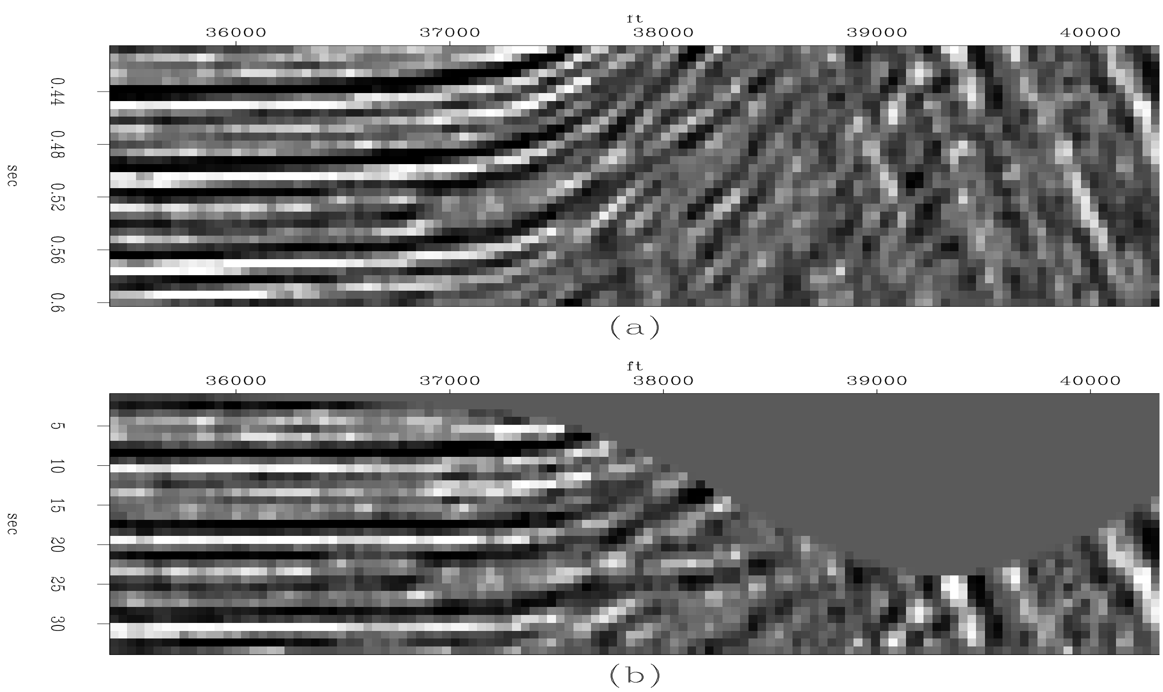

Figure 9: East west sections from Chevron data. (a) Unflattened. (b) Flattened. jesse1-chev.section [ER]

mentioned earlier, we can smooth both the numerator and denominator of the dip calculation in equation (1) along all three axis. This could possibly eliminate the need for integrating in the t direction by properly smoothing the dip calculation.

The ability of this method to work with data that has pinch outs and faults still needs to be looked at. A local dip estimator will estimate incorrect dips at faults. Compounding the problem, our dip integration method will try to honor those incorrect dips. Once in the Fourier domain, it will be very hard to correct this problem.

Overall, the results of this method are very encouraging. The ability to flatten data could be a powerful tool in automating interpretation in general. There could be many processing applications as well, such as flattening gathers.

ACKNOWLEDGMENTS

We would like to thank ChevronTexaco for the Gulf of Mexico data.

REFERENCES

Claerbout, J. F., 1992, Earth Soundings Analysis: Processing Versus Inversion: Blackwell Scientific Publications.