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Data parallel wave equation datuming

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ABSTRACT

Seismic data gathered on land is distorted by irregular acquisition topography. Seismic imaging algorithms are generally applied to data which is redatumed to a planar surface. In regions of mild topography where the near surface velocity is much slower than the subsurface velocity, a static shift is adequate for the transformation. However, when the necessary shift increases in magnitude and when the near surface velocity is comparable to the subsurface velocity, the static approximation becomes inadequate. Under these circumstances, a static shift distorts the wave field and degrades the velocity analysis and imaging. In this case wave equation datuming is more appropriate than static shift.
Wave equation datuming is much more computationally intensive than static shift and is therefore seldom applied. Furthermore, redatuming may involve multiple applications of the datuming routine to estimate the near surface velocity structure. I implement a data parallel wave equation datuming algorithm which can be applied to land data as an alternative to static shift in order to improve velocity analysis and imaging and to estimate near surface velocity structure. The Kirchhoff algorithm is efficiently implemented on a Connection Machine CM5 and makes wave equation datuming practical.

INTRODUCTION

The effect of irregular acquisition topography is that it distorts seismic data. This is a serious problem in mountainous regions where there is extreme topographic relief along seismic lines. Wave equation datuming provides a useful method of transforming data to a planar datum and determining the near surface velocity structure. This eliminates the distortion caused by the topography and allows standard processing methods such as velocity analysis, DMO, and migration to be efficiently applied (Bevc, 1992b).

Several authors have shown that wave equation datuming is better than statics for continuing data through known velocity structures (Wiggins, 1984; Shtivelman and

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Canning, 1988; Reshef, 1991). These authors do not discuss the determination of the velocity to be used in the datuming process. In order for these methods to work, the near surface velocity must be known. I address the more general situation for which the near surface velocity structure is unknown.

When the near surface velocity is unknown there are different ways to proceed depending on the nature of the seismic data. One approach is to upward continue the data to some planar datum above the topography with a fictitious extrapolation velocity. This should unravel the distortions caused by the irregular acquisition topography and allow standard imaging techniques to be applied to the data (Bevc, 1992b,?; Payne and Marcoux, 1992). Another approach is to downward continue the data through the near surface with many estimates of the actual velocity. When the correct velocity is used, wave based processing procedures such as velocity analysis are optimized. This concept forms the basis for a near surface velocity inversion scheme.

Both these schemes are computationally intensive, especially the second one which requires multiple applications of the datuming algorithm. To tackle such problems I developed an efficient data parallel Kirchhoff datuming algorithm on the Connection Machine. I describe the implementation of the algorithm and apply it to prestack land data from the Wyoming overthrust belt.

IMPLEMENTATION

Kirchhoff Datuming

The irregular geometries of land data acquired in rugged terrain make a datuming algorithm based on the Kirchhoff integral convenient. Berryhill (1979) gives the following expression for the upward continuation of a scalar wave field:

$$U(0,z,t) = \frac{1}{\pi}\int_{-\infty}^{\infty} dx \frac{z}{c}\frac{1}{r_x} U(t - \frac{r_x}{c}), \tag{1}$$

where $U(0,z,t)$ is one trace of the upward continued wave field at datum elevation z and lateral position $x = 0$. The function $U(t - \frac{r_x}{c})$ is a time delayed filtered version of the input traces on the original datum. The assumptions that go into the derivation of this equation are locally valid for non-planar datums and two dimensional wave fields.

For a wave field transformation from one datum to another, the discretized form of equation (1) is a summation where each input trace U_i is weighted and time shifted. Each output trace is calculated by performing a sum of the form:

$$U_j(t) = \sum_i \cos\theta_i A_i U_i(t - t_i) \tag{2}$$

where $U_i(t - t_i)$ is a filtered input trace recorded at location i along the lower datum and delayed by travel time t_i. The effect of the filtering operation is to compensate for the Hankel tail. A_i is an amplitude term incorporating spherical divergence and geometric terms, θ_i is the angle between the normal to the input surface and the straight line travel time path connecting input location i and output location j, t_i is the time shift corresponding to the travel time between the input and output locations.

Figure 1 illustrates the impulse response of upward continuation and downward continuation for three diffractors at three different depths. The energy from each diffractor is distributed along a hyperbolic trajectory. The trajectory is the same for all depths. It is natural and convenient to do the calculation in the frequency domain because each input trace is shifted by a time invariant amount. The algorithm is cast in $\omega - x$ domain so that each individual output trace is calculated by performing a sum of the form:

$$U_j(\omega) = \sum_i \cos\theta_i A_i e^{i\omega t_i} U_i(\omega). \tag{3}$$

Because the time shift is performed in the frequency domain, there is no need to interpolate. Anti-aliasing is easily handled by filtering the input traces as necessary. Another advantage of performing the computation in the frequency domain is that a half-order differential operator is easily applied to compensate for the Hankel tail.

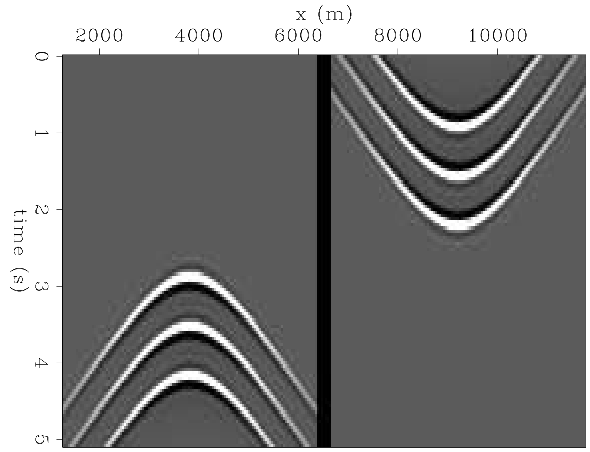

Figure 1: Impulse response of three diffractors at three different depths for upward continuation and downward continuation. If you have the electronic version of this document, you can press the button to see a movie of the impulse response for diffractors at different depths. dimitri1-updnimp1 [CR]

Kirchhoff datuming is typically implemented in a serial fashion by looping over the input traces as indicated by equations (2) and (3). The algorithm can be applied to zero-offset data or to shot and receiver gathers. Pre-stack datuming is done by extrapolating the shots and the geophones separately using equation (3) (Berryhill, 1984). The extension to three dimensions is straight forward and has the same algorithmic form. Equations (1) through (3) are for upward continuation. For downward continuation the conjugate transpose process is used.

Data Parallel Implementation

Since wave equation datuming is computationally intensive, I implement the algorithm on the Connection Machine CM5 (TMC, 1992). In order to maximize the performance of the CM5 it is necessary to map the data into the processors in such a way as to minimize communication and maximize computation. To achieve this optimization, I map the time/frequency axis serially in-processor and map offset in parallel (Figure 2). The geometric information that goes into calculating the $\cos\theta_i$, A_i, and t_i terms are also mapped in parallel. These are the horizontal vectors labeled as headers in Figure 2. For pre-stack two or three dimensional data the connection machine is filled in a third parallel direction that represents shot and/or receiver gathers.

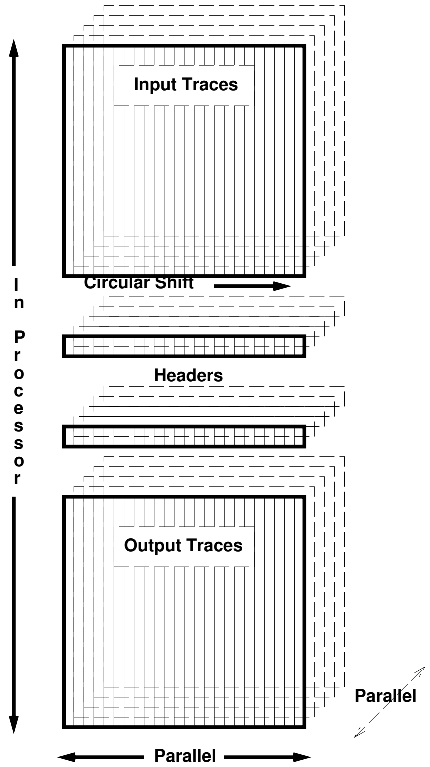

Figure 2: Data mapping for the parallel Kirchhoff datuming algorithm. The vertical direction is in-processor, horizontal and depth directions are parallel. Each plane in the first parallel direction represents one shot or receiver gather. All computations are performed in-processor. The input traces and input headers are circularly shifted in the parallel direction as indicated by the arrow. dimitri1-cmmap [NR]

With this data mapping, each virtual processor contains one input trace, one output trace, and the geometrical parameters which determine trace shift and weighting in local memory. The program executes by summing the weighted and shifted input traces into their output locations in parallel. The input traces are then passed to the next processor and the sequence is repeated. This trace passing is indicated by the circular shift in Figure 2. Both the input traces and the input headers are shifted in the same way. By organizing the algorithm and data in this way, all computations are performed in-processor with the only inter-processor communication being the nearest-neighbor circular shift operation.

REDATUMING LAND DATA

The most common form of datuming is to perform static shifts of data traces. This is adequate for regions where the near surface raypaths are nearly vertical and where the shifts are small. The static shift method is commonly applied to correct for near surface velocity variations due to weathering layers and for topographic effects. When static shifts are large and the assumption of vertical raypaths is not valid, the wave field is distorted by the static shift so that velocity analysis, migration and any other wave equation based processing is severely degraded (Bevc, 1992). The problem with many land data sets is that the topography distorts the data so much that it is not possible to pick coherent reflection events or to estimate velocity. In these situations wave equation datuming is necessary.

A shot gather from the Wyoming overthrust data set is shown in Figure 3. This data suffers from statics problems due to lateral variations in the near surface low velocity layer and due to topography. On the right side of the gather, the first arrivals form a straight line and the reflections are nearly hyperbolic. The left side of the gather is distorted by the topography and the near-surface velocity structure.

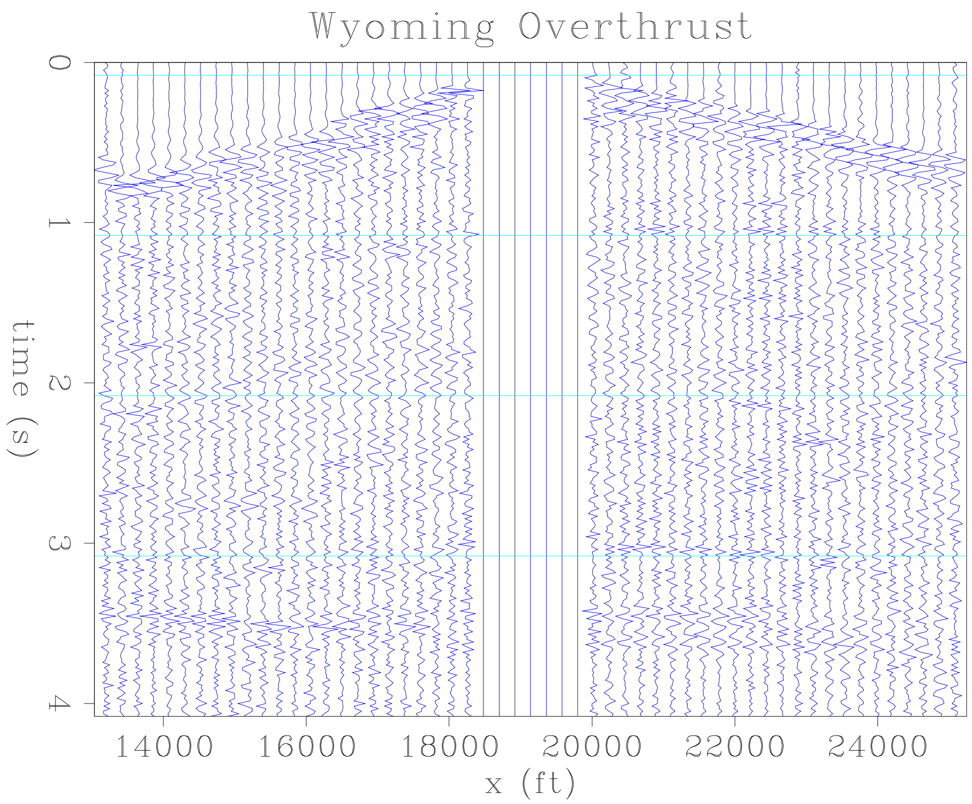

Figure 3: A shot gather from the Conoco Wyoming overthrust data set. There is a prominent reflection event at about 3.5 seconds. The right side of this event displays hyperbolic moveout but the left side is distorted. $\boxed{\text{dimitri1-CWin}}$ [CR]

The topography along the shot profile is displayed in Figure 4. The first arrivals are delayed in the region with lower topography. This region must therefore have a thick low velocity near surface layer. The portion of the gather with higher elevation corresponds to faster near surface velocity.

If the near surface velocity structure is known, data can be downward continued

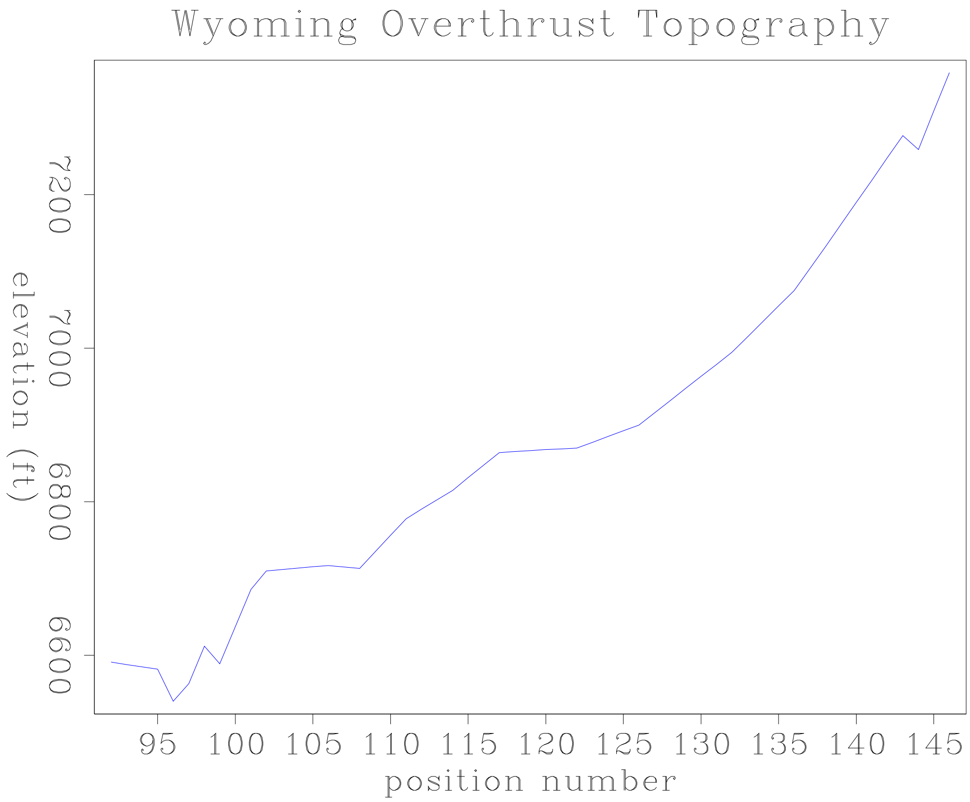

Figure 4: Topographic profile along the Wyoming overthrust shot gather. dimitri1-topog [NR]

through the near surface velocity structure to some lower datum. For most land data, the near surface velocity is not known. One method of eliminating distortions due to topography is to upward continue the data to an arbitrary datum above the highest topography. This is analogous to upward continuing marine data from the water bottom back to the original acquisition surface in marine layer replacement applications. The proper velocity to use for upward continuation should be close to the near surface velocity. Once the data have been upward continued to a higher datum, conventional velocity analysis can be performed. The result of velocity analysis, stacking, and migration after wave equation datuming should be superior to the result after static shift.

The result of upward continuing the shot of Figure 3 is shown in Figures 5 and 6. Many different velocities were used for the upward continuation but only four panels of the resulting data cube are shown here.

In Figure 5 the data are upward continued with relatively low velocities of $2000 ft/s$ and $5733 ft/s$. Evidently these velocities are too low because the left and right side of the gather are not symmetric: The first arrivals on the left side are delayed more than they were in the original data (Figure 3). The datuming velocity of $2000 ft/s$ is certainly to slow since the reflection event which was originally at $3.5s$ has been delayed substantially in Figure 5a.

The gather looks more symmetric when higher datuming velocities of $10,000 ft/s$ and $20,000 ft/s$ are used (Figure 6). These higher velocities are close to the medium velocity for the portion of the gather which is recorded at the higher elevations. The deep reflector which was initially at $3.5s$ is unraveled when the data are redatumed with the higher velocities. There are also other events at earlier times which become visible as coherent reflections with hyperbolic trajectories. These are especially evident in the last frame of the movie where the data have been extrapolated upward with a velocity of $20,000 ft/s$ (Figure 6b).

Although only one shot gather is datumed here, the results are promising, since the algorithm has the desired effect of unraveling the effects of irregular topography. Because wave equation datuming is superior to static shift when near surface raypaths are not vertical, upward continuing all the shot and receiver gathers should result in an improved processing flow for data with severe topography and statics.

CONCLUSION

The efficient implementation of the Kirchhoff datuming algorithm on a parallel computer makes wave equation datuming a feasible alternative to conventional static shift. In regions of large topographic relief, the subsurface velocity structure is difficult to determine; therefore it may not always be possible to continue the data to some lower datum directly. With the fast and efficient wave equation datuming algorithm presented here, it is possible to estimate near surface velocity structure iteratively. The

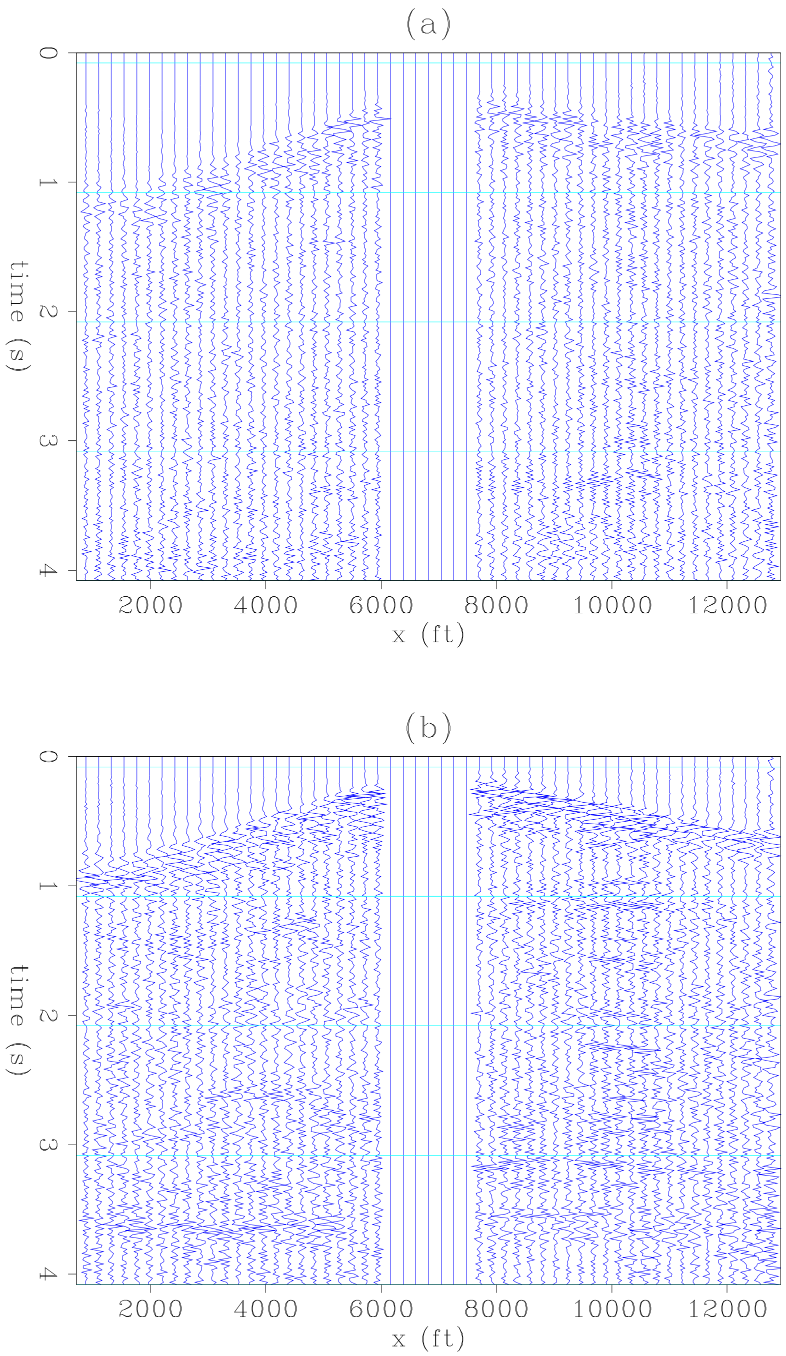

Figure 5: A shot gather from the Wyoming overthrust data redatumed with velocities of (a) $2000 ft/s$ and (b) $5733 ft/s$. If you have the electronic version of this document, you can press the button to see a movie of the shot gather redatumed with a range of extrapolation velocities between $2000 ft/s$ and $10,000 ft/s$. dimitri1-CWmovie1 [CR]

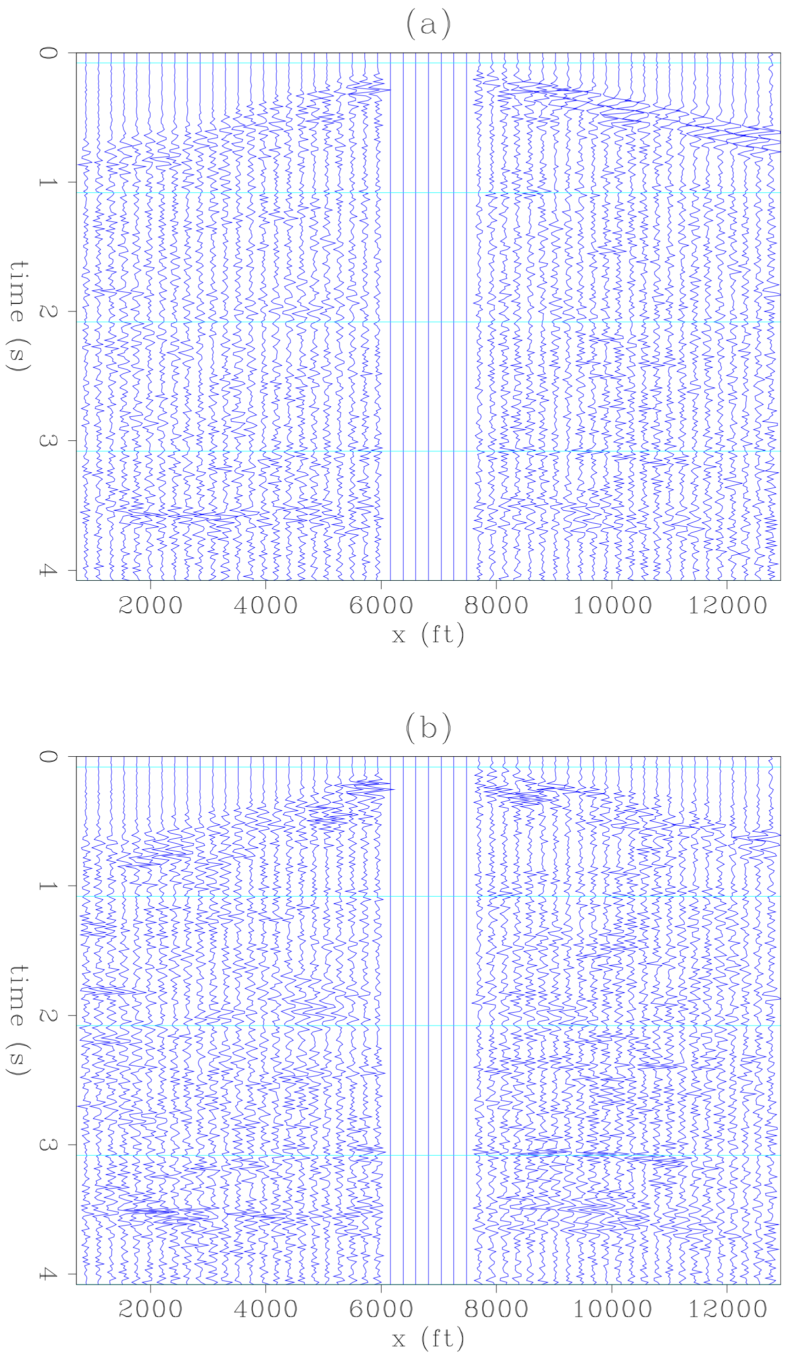

Figure 6: The same shot gather from the Wyoming overthrust data redatumed with velocities of (a) $10,000 ft/s$ and (b) $20,000 ft/s$. If you have the electronic version of this document, you can press the button to see a movie of the shot gather redatumed with a range of extrapolation velocities between $4000 ft/s$ and $20,000 ft/s$. dimitri1-CWmovie2 [CR]

datuming algorithm can also be used to continue data upwards and perform wave equation based processing at a flat datum.

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