Equivalent offset migration: the implementation and application update

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INTRODUCTION

We have some improvements about equivalent offset migration (EOM) method. In 1996, we presented a new algorithm to implement the construction of CSP gathers, which is more accurate and also faster than the old algorithm used in the 1995 version ProMAX code (CSP Gathers). As a result of our investigation about the amplitude distribution and scaling during EOM process, we found out several ways to improve the quality of the CSP gathers, as well as the final image sections. Most of them have been implemented in the new code in ProMAX as different options, such as

- Amplitude scaling;
- Migration aperture limitation;
- Asymptotic solution;
- Trace fold division;
- Double sided CSP gather;
- Output the CSP trace fold gather.

In addition, a simple 45 degree phase shift (RJW filter) module is developed independently for the migration phase correction. It can be used before or after CSP gather construction, or even apply this filter on the final image section.

Practical applications of this new version of “CSP Gather” give better results. The most evident improvements are

- the quality of CSP gather,
- the migration velocity analysis on CSP gathers,
- the final image section, and
- providing better model data for CSP statics analysis.

The ProMAX module is now ready for 2D data processing. The 3D version is a later work.

SOME CONCEPTS ABOUT EOM METHOD

We would like to review some concepts about EOM method, they are closely related to the improvements. The first aspects we want to mention is a different approach of the definition of equivalent offset, it shows that the equivalent offset concept is introduced naturally from the kinematics of pre-stack Kirchhoff time migration. The CSP gather construction is considered as a pre-stack partial migration, which only distributes seismic sample energy in space direction. The time direction distribution is left as a second step when we can obtain better migration velocity information. The first step, i.e., the CSP construction process, indeed provides very accurate migration velocity. The second, we will give some kinematics and model data examples to show how the energy of hyperbolic events on CMP gathers is distributed to a CSP gather.

What is a scatter point?

Kirchhoff depth migration is based on an energy-scattering model. This model assume that the earth subsurface consists of scatterers. The scatterers reflect incoming energy back to any direction. Kirchhoff time migration method is basically based on the same model, but the scatter point is usually not the physical subsurface location, instead, it can be considered as a point on the time image section. For constant velocity case, it is exactly equivalent to depth migration scatter point. But for variant velocity structure, the time migration "scatter point" location has very complex relation with the real energy scatterers in the earth. This problem has been discussed by many authors, such as Hubral, P. (1977). Practically, we regard each location on the time image section (x, T_0) as a scatter point.

Another essential aspect for this time domain scatter point model is the velocity information. For each scatter point (x, T_0), we assume that it has a velocity value (isotropic P-wave only) which is independent to the source and the receiver locations, and also independent to all the other scatter points. The RMS velocity for layered model is an example (approximate) of this kind of velocity.

Thus, the final model for our discussion is a triplet (x,T_0,V). For a given scatter point, the travel time response can be expressed as

$$T = \sqrt{\left(\frac{x-h}{V}\right)^2 + \left(\frac{T_0}{2}\right)^2} + \sqrt{\left(\frac{x+h}{V}\right)^2 + \left(\frac{T_0}{2}\right)^2}. \tag{1}$$

Some kinematics based on scatter point model

Migration process can be considered as an inverse operation of the seismic experiments. Migration is the method to find out where the energy, which is recorded as seismic samples**,** come from, and then distribute the energy back to the places. For a sample with arrive time T and a source-receiver half offset h, equation (1) expresses a relation between the image time T_0 and the migration distance x**.** Usually, this relation is expressed as an ellipse equation with the source and receiver as the foci. Here, we prefer an expression as following:

$$T_0^2 = T^2 - \frac{4}{V^2}h^2 - \frac{4}{V^2}x^2 + \frac{4}{V^2}\frac{4x^2h^2}{V^2T^2}. \qquad (2)$$

This equation tells us more than just the migration elliptic response. First, consider the first two terms on the right hand side, we introduce a new time T_N as

$$T_N^2 = T^2 - \frac{4}{V^2}h^2. \qquad (3)$$

This is exactly what normal moveout (NMO) correction does on this sample. This means after NMO (or equivalently see, on stacked section without dip moveout (DMO)), the desired migration response can be expresses as

$$T_0^2 = T_N^2 - \frac{4x^2}{V^2}\left(1 - \frac{4h^2}{V^2T^2}\right). \qquad \mathbf{(4)}$$

Post-stack migration is a process to distribute the energy of the sample to the samples along a curve in (T_0, x) coordinates which is close to the migration response expressed by equation (2). The T_0 to x relation for post stack migration is

$$T_0^2 = T_N^2 - \frac{4x^2}{V^2} \qquad (5)$$

The difference between (4) and (5) tells us the inaccuracy of post-stack migration. DMO is a process that is designed to minimize this difference.

It is important to mention that, migration is a process that moves the sample energy in both time direction (from T to T_0) and space direction (from 0 to x). The post-stack migration process tries to simplify the whole migration by moving the energy only in time direction (NMO equation (3)), then move the energy in space direction with some time direction compensation (equation (5)). This simplification reduces the computation cost of migration enormously, and this is maybe the only advantage of post-stack migration.

Are there other ways to split the two-directional migration process and make it more efficient? Equivalent offset migration (EOM) is such a solution.

EOM: a two-step migration technique

Start from equation (2), re-arrange it by separating the time-direction term and space-direction term as

$$T_0^2 = T^2 - \frac{4}{V^2}\left(h^2 - x^2 + \frac{4x^2h^2}{V^2T^2}\right), \qquad (6)$$

and introduce the concept of equivalent offset h_e as

$$h_e^2 = h^2 - x^2 + \frac{4x^2h^2}{V^2T^2}. \tag{7}$$

Then equation (2) becomes a space-direction free NMO equation

$$T_0^2 = T^2 - \frac{4h_e^2}{V^2}. \tag{8}$$

Equation (7) is a relation between equivalent offset h_e and the migration distance x. for each distance x, this relation assigns a new offset to the input sample. Actually, if we consider the offset domain is also a direction related to migration energy distribution, then equivalent offset migration method move the energy in space and offset directions, while NMO and stack is a energy distribution in time and offset directions.

The introduction of equivalent offset needs a new binning process in both space coordinate and equivalent offset coordinate. When all the input energy of samples is distributed by equation (7), a new data volume sorted in common scatter point (CSP) surface locations, equivalent offset bins is constructed. A 2-D gathering of this volume at a given CSP location is called a CSP gather. CSP gathers provide a powerful tool to obtain migration velocity filed because the validity of equation (8). The construction of CSP gathers is the first step of EOM method, and, NMO correction (equation (8)) and conventional CDP stack give the final pre-stack time migrated section.

What is on a CSP gather?

CSP gather construction is an intermediate step for the entire EOM procedure, the CSP gathers can be considered as normal CDP gathers. This means we can do signal analysis, velocity analysis and even filter processing on the gathers before we applying NMO and CDP stacking for the final imaging.

The quality of CSP gathers is essential to the migration velocity analysis and the final migration results. At first, we use a synthetic model (as shown in Figure 1) to obtain a set of seismic data. Then we form a CSP gather as shown in Figure 2. The CSP location for the gather is at the middle of the seismic line, and the gather looks very different from normal CMP gathers, which should only contain two hyperbolic events for this model.

In Figure 2, the two events also correspond to the two interfaces of the model. Unlike the hyperbolic shape of the reflection events from linear interfaces, they have some “side effects”.

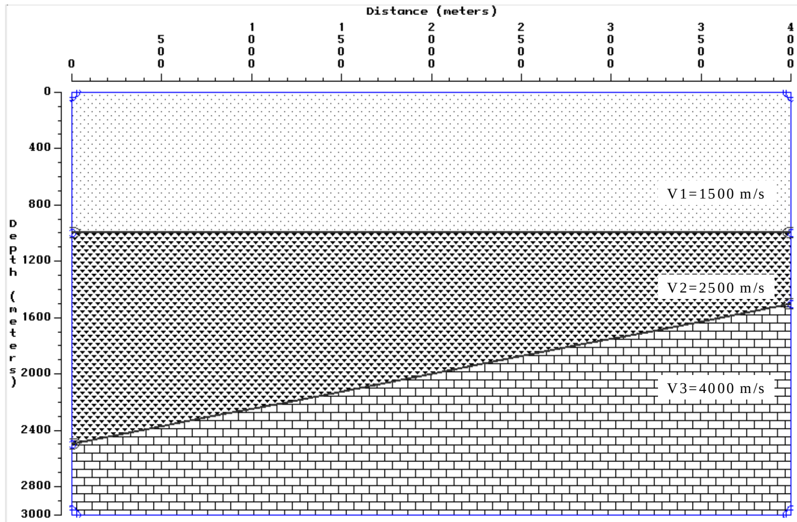

Figure 1: A simple synthetic model

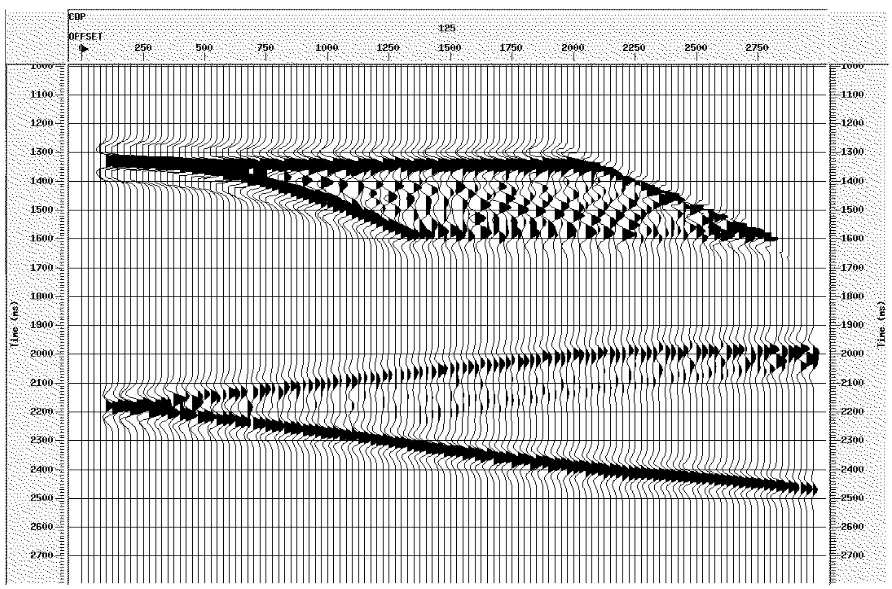

Figure 2: A CSP gather located at the middle of the line with the whole seismic data as the input. This gather is constructed without amplitude scaling, but use the fold division for amplitude balancing on the gather.

These side effects have different appearances for horizontal interface and dipping interface. For horizontal reflector, there is a strong flat "event" tangent to a hyperbolic curve at the zero offset trace. As described by Bancroft (1997), this flat effect refers to an event on the zero-offset section. For the dipping reflector, there is a dipping "event" start from the zero-offset trace, and this refers to a dipping event on the zero-offset section

From CMP to CSP: a new viewpoint to understand EOM

How do these "side-effects" on the CSP gather happen? Lets see how the energy is distributed from CMP gathers the CSP gather.

Re-write the equivalent offset equation (7) to

$$h_e^2 = x^2 + h^2 \cdot \left(1 - \frac{4x^2}{V^2 T^2} \right). \tag{9}$$

h_e is a function of half source-receiver offset h with a "shift" and a "re-scale" determined by the CSP location and the migration distance. The events on a CMP gather will be shifted to larger offsets and squeezed to a smaller offset range. The shifting is determined by the migration distance x, while the squeezing size depends on all the factors involved.

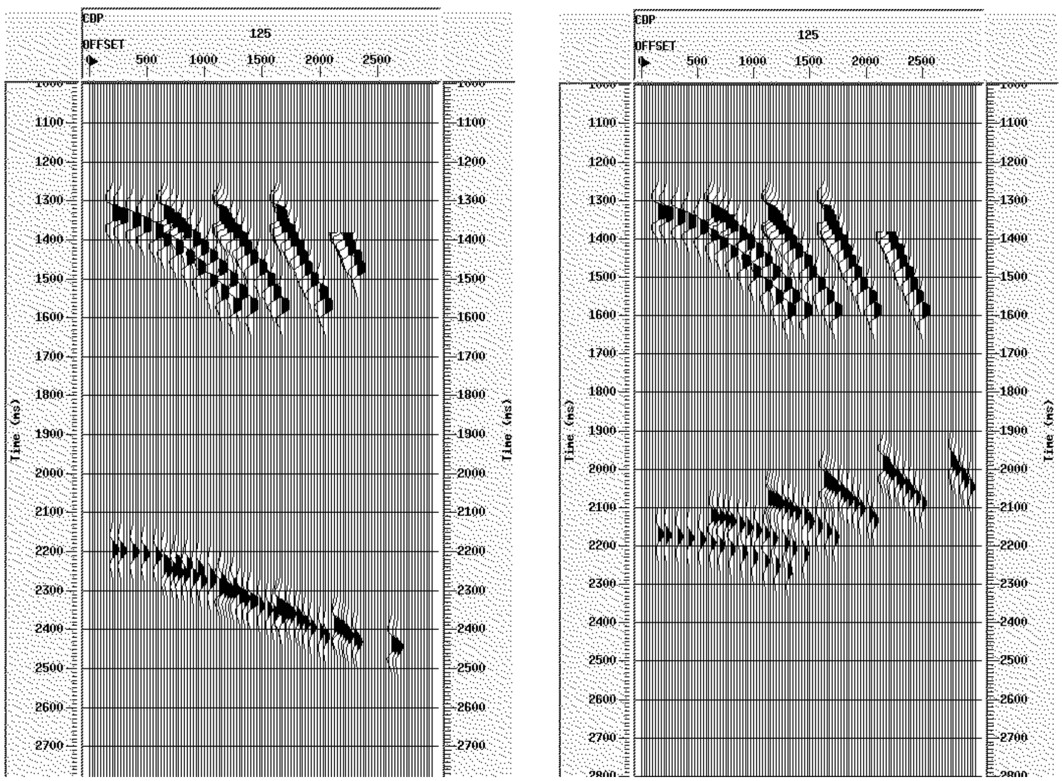

Figure 3: The energy distribution from CMP gathers to a CSP gather. The two gathers are partially formed CSP gather located at the same location as the gather in Figure 2. The left gather is formed by only 5 CMP gathers located all at the left side of the CSP location, while the right side gather is formed from 5 CMP gathers located at the right side of the CSP location.

Figure 3 provides two partially formed CSP gathers for analyzing the individual behavior of each CMP gather contributing to the CSP gather. The two CSP gathers are all located at the same location as the gather shown in Figure 2. while these two gathers only have the contribution from 5 different CMP gathers (totally we have 246 CMP gathers in the synthetic data).

The difference between the two gathers in Figure 3 is: the left one has the contribution from 5 CMP gathers all located at the left side of the CSP location, while the right side gather contains the contribution from 5 CMP gathers all located at the right side of the CSP location. Compare these two gathers, there are following points we would like to mention:

- The appearances for the flat event and the dipping event are different. In both CSP gathers, the upper event has no evident difference, while the lower one has very different appearances.
- The CMP gather located farther from the CSP location (it means bigger ***x***) will be shifted farther and squeezed more.
- The constructive and destructive behavior of the CSP gather will cancel most of the contributions but those distributed at the boundaries of the "plow" shape (Bancroft and Geiger, 1996). That's why there is a strong flat effect in the CSP gather shown in Figure 2, while other places has much lower amplitude.
- Flat event has almost the same shape on both the two partial CSP gathers, because flat subsurface is symmetric to the CSP location. While for the dipping event, it has different appearances on the two gathers.
- The flat and dipping effects may influence the quality of the CSP gathers for velocity analysis and final imaging. We have to consider some amplitude behavior during the CSP construction.

Figure 4 is the CSP gather with some amplitude scaling (detail in next section), the flat and dipping effects are ver well attenuated.

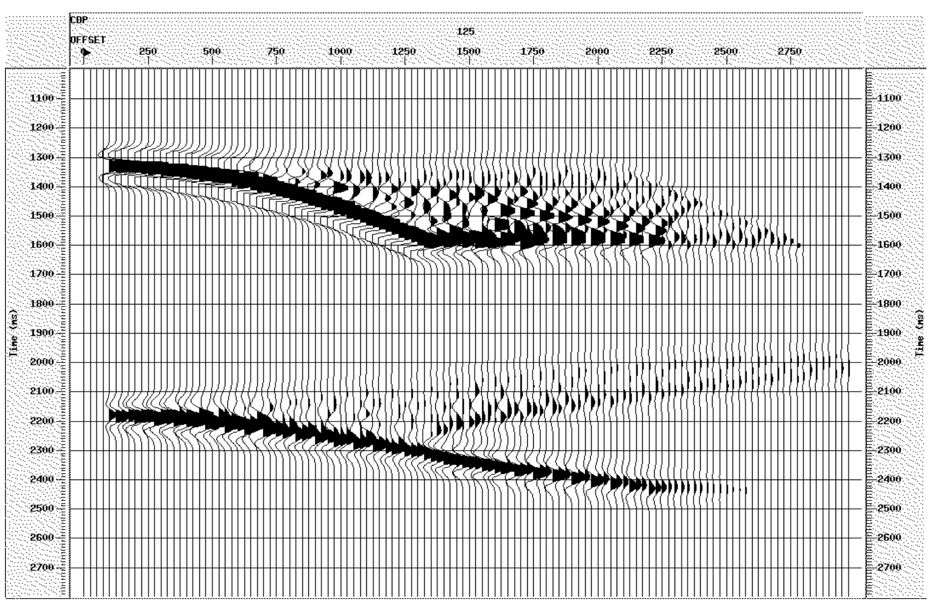

Figure 4: The CSP gather located at the same location of the gather shown in Figure 2 with some amplitude scaling during the construction process.

DESCRIPTION OF THE IMPROVEMENTS

As previously listed in the introduction section, we have some more options in the new version of the “CSP Gather” module in ProMAX. This section will give some short descriptions and some practical considerations.

Amplitude scaling

Our amplitude scaling is based on the ratio of $\boldsymbol{x}$ to $\boldsymbol{h_e}$, which can not be greater than 1 because of the definition of equivalent offset. Two options can be used as

$$\boldsymbol{scale1} = \boldsymbol{1} - \frac{\boldsymbol{x}}{\boldsymbol{h_e}} \text{ or } \boldsymbol{scale2} = \boldsymbol{1} - \left(\frac{\boldsymbol{x}}{\boldsymbol{h_e}}\right)^{\boldsymbol{2}}.$$

With same source-receiver offset, these scales reduce the amplitude from farther migration distance more than near migration distance. This is the migration scaling essential feature. In other words, all the traces in a CMP gather have same migration distance to a given CSP gather but with different source-receiver offsets, for nearer offset traces in the CMP gather, the equivalent offset $\boldsymbol{h_e}$ are smaller, then these scales are smaller. This means farther offset traces have more contributions to the CSP gather than the nearer offset traces. In this way, the scaling attenuates the zero offset effects shown in Figure 2.

These scales are related to the migration aperture, which is determined by the earth subsurface structure. Usually, the steeper the reflectors are, the bigger the aperture is (with same velocity). If there is steep dip, our scales here should be used carefully to make sure the energy from large distance is properly collected.

CSP gather construction with amplitude scaling will take longer time than without any scaling, but the whole EOM process is still very fast.

One possible future work is to find more accurate amplitude scaling function.

Migration aperture limitation

As mention above, if the subsurface does not have steep dips, the migration aperture can be smaller, so when we form CSP gathers, it is unnecessary to collect the energy from very far CMP gathers. Set a limit on the migration aperture thus reduce the computation cost efficiently. It also attenuates some zero-offset side effects at large equivalent offset traces.

This aperture limitation can be implemented with some edge tapering. It also can be designed to be independent limit values for different migration directions (azimuths).

Asymptotic Solution

The equivalent offset is usually time variant and velocity dependent, but a simplified solution is also very useful. Define a asymptotic equivalent offset as

$$h_e^2 = x^2 + h^2, \tag{10}$$

which is totally velocity free and time invariant. The computation will be much faster, and also, this asymptotic solution can form a set of psuedo-CSP gathers which provide good velocity information. It is a quick way to take a look at the CSP gathers and even the “imaging” section.

This asymptotic solution is used very efficiently for our residual statics analysis method (see Li and Bancroft, 1997).

CSP trace fold division

Trace fold division is used also in the old ProMAX code, but it is limited to integer, so it is not proper for fold division with amplitude scaling.

The fold of the traces in CSP gathers has very wide range of variance, usually from zero to several thousands. Fold division is a directly way to keep the trace balance on the CSP gathers.

Double-sided CSP gathers

Usually we just create one-side CSP gathers, i.e., only use positive equivalent offset value. But the structures under the surface are not always simple, we leave a chance to see how the contributions from different azimuths differ from each other. Actually, the two psuedo CSP gathers shown in Figure 3 give a example whay the two sided CSP gathers are useful.

Output CSP trace fold

The trace fold division should be always used during the construction of CSP gathers. But it is usually unnecessary to save the fold information. NMO is part of the EOM process, for better final imaging,. CSP trace fold can also be used to do a second round trace balancing on NMO corrected CSP gathers. The NMO corrected data amplitude scaling is also a future work.

RJW filter

RJW filer is a 45 degree phase shift which is also part of conventional Kirchhoff migration. EOM splits Kirchhoff migration into mainly two steps which include CSP gather construction, NMO correction and CDP stacking. We developed the code separately from CSP gather construction process is because this filter can be used at any stage of the EOM process.

FINAL IMAGING RESULTS

All the improvements mentioned above have already been implemented, we would like to show some final imaging results from Blackfoot 2D P-P data. The sand channel is clearly imaged.

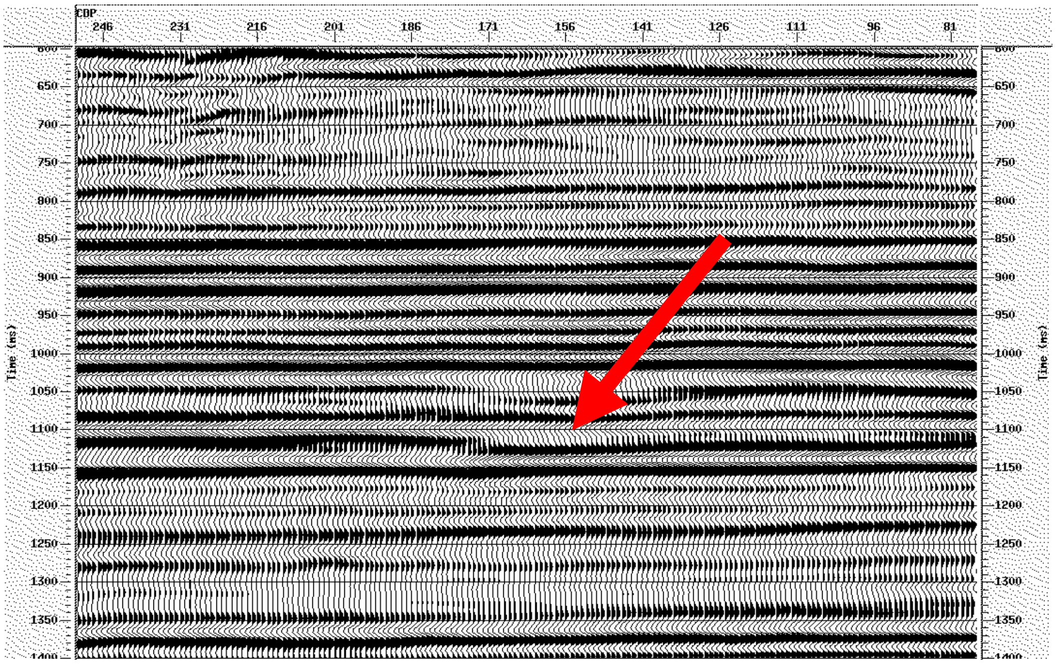

Fig 5. Equivalent offset migration of Blackfoot 10 Hz vertical component data set. The Glauconitic is shown by the arrows

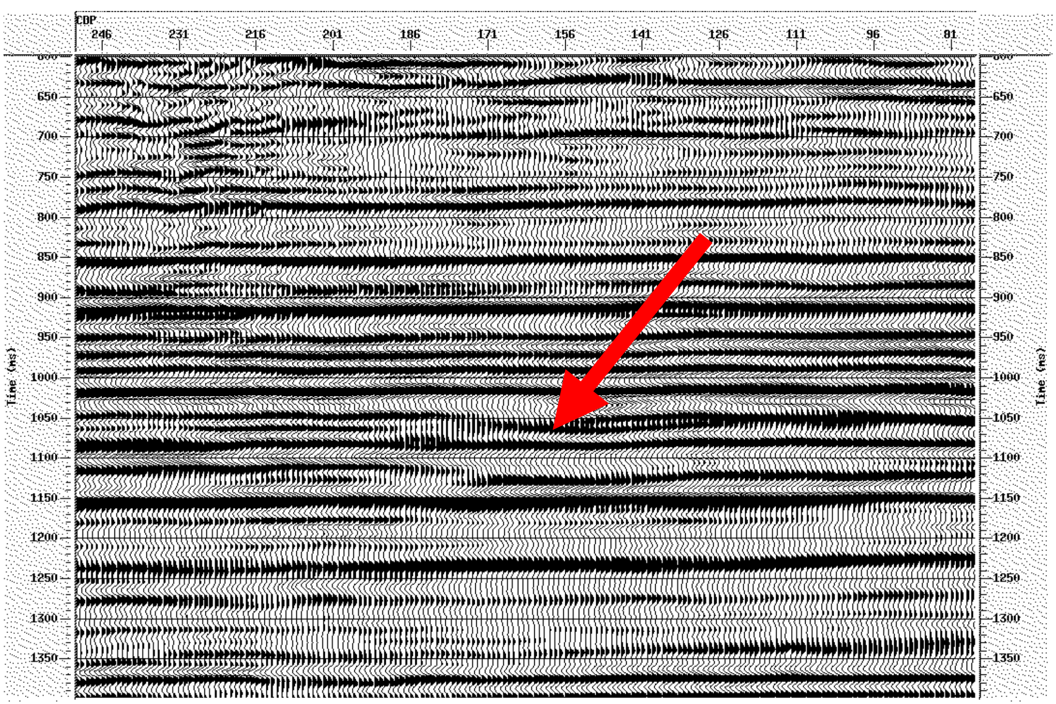

Figure 6: Deconvolutaion of the data in Figure 5.

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