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Image Enhacement After Migration

John C. Bancroft*, CREWES – Department of Geoscience, University of Calgary, Alberta, Canada
bancroft@ucalgary.ca
and
Thais Guirigay and Helen Isaac, CREWES – Department of Geoscience, University of Calgary, Alberta, Canada

Summary

Substantial improvements in the resolution of seismic data can be achieved after a conventional seismic migration is followed by deconvolution. The migration process should produce this higher resolution, but it is typically not applied during the migration process. We present two arguments to validate this proposition and illustrate the improved resolution that can be achieved.

Introduction

There is considerable opposition to applying deconvolution after migration. One reason is that migration lowers the frequency content of dipping events to prevent aliasing, and a deconvolution would increase the frequency of the wavelet and introduce aliasing. This reason is valid for highly structured data, and a special deconvolution algorithm should be used. However, data that is not highly structured will benefit from a simple algorithm such as spiking deconvolution.

Another reason given for not deconvolving after migration is that deconvolution introduces artifacts that result from poor migration algorithms. An example is a downward continuation algorithm that cut and pastes the downward steps and then smoothes the steps with a filter: a deconvolution may reveal the transition steps. This is the result of a poor algorithm.

A third reason is that deconvolution will increase the noise.

Seismic data before migration should be limited to a range of dips from 0 to 45^o. Migration changes those dips range from 0 to 90^o. Energy on pre-migration data from 45 to 90^o is noise and should be removed by the migration. However, some algorithms deliberately retain the noise to make a section appear more interpretable, i.e. to reduce the "worminess". Other routines are not able to reduce the noise that should be removed. At the very least, this noise could be removed by dip filters before migration.

Two reasons why deconvolution should be used after migration (Bancroft et al 2011) are:

- migration should lower the noise contend that allows the signal to noise ratio (SNR) to be extended to a higher frequency, and
- migration is a transpose process that approximates inversion. A true inversion includes the deconvolution as part of the algorithm.

Theory

Deconvolution essentially tries to flatten the amplitude spectrum to a maximum frequency where the SNR > 1. Energy with a SNR < 1 is considered to be noise and removed with a high cut filter. This is illustrated in Figure 1 which contains an exaggerated cartoon sketch of the amplitude spectrum of seismic data and three levels of noise. The first noise level represents the noise level in the raw data with a maximum bandwidth (BW) *Fr*, the second is the reduced noise after stacking and or noise removal processes to give a BW *Fs*, and the third is the noise level after migration where the BW is now *Fm*. Each time we reduce noise, we increase the maximum frequency where the SNR > 1.

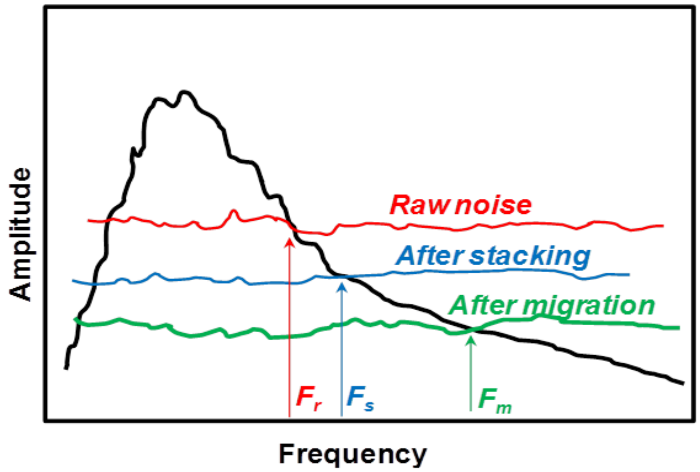


Figure 1: Cartoon illustrating the increase bandwidth as the noise level is reduce after stacking and then after migration..

Deconvolution after migration should extend the bandwidth to *Fm*, which increases the bandwidth of the data.

The second reason for deconvolution after migration is provide by Least Squares Migration (LSM). LSM provides a true inversion of the imaging process in comparison to a migration that only performs a transpose approximation to inversion. We use Kirchhoff migration to illustrate this concept, however it applies to all "wave-equation" migrations.

Consider the forward process of modelling with linear algebra as

$$\mathbf{Dr} = \mathbf{s}\,, \tag{1}$$

where $\mathbf{D}$ is a diffraction matrix, $\mathbf{r}$ a reflectivity structure and $\mathbf{s}$ the modelled seismic section. A true inversion to recover the reflectivity would be

$$\mathbf{r} = \mathbf{D}^{-1}\mathbf{s}\,, \tag{2}$$

providing $\mathbf{D}$ is invertable. $\mathbf{D}$ is usually not invertible so we make use of LSM to get an estimate of the reflectivity from

$$\breve{\mathbf{r}} = \left(\mathbf{D}^{\mathrm{T}}\mathbf{D}\right)^{-1}\mathbf{D}^{\mathrm{T}}\mathbf{s}\,. \tag{3}$$

We assuming the $\mathbf{D}^{\mathrm{T}}\mathbf{D}$ matrix is diagonally dominant, and in migration approximate it with the identity matrix $\mathbf{I}$, which has the convenient inverse that equals $\mathbf{I}$, i.e.,

$$\left(\mathbf{D}^{\mathrm{T}}\mathbf{D}\right)^{-1} \approx \left(\mathbf{I}\right)^{-1} = \mathbf{I}\,. \tag{4}$$

This allows us to write an alternate estimate for the reflectivity as

$$\tilde{\mathbf{r}} = \mathbf{D}^{\mathrm{T}}\mathbf{s}\,, \tag{5}$$

which is the transpose process that we call migration. (Claerbout (1992) described a long time ago that many processes in exploration geophysics that we think they are inverse processes are really transpose processes.)

What have we lost by dropping the $\mathbf{D}^{\mathrm{T}}\mathbf{D}$ part of the inversion? That is the part that recovers the bandwidth of the data.

Let us now include a wavelet matrix $\mathbf{W}$ that can be multiplied with the diffraction matrix $\mathbf{D}$ to put wavelets on the diffractions, i.e.,

$$\mathbf{WDr} = \mathbf{s}\,. \tag{6}$$

Now our reflectivity matrix $\boldsymbol{r}$ can really be a high frequency representation of the true reflectivity and we have the wavelet with the diffraction as it should be. The least squares solution is now

$$\breve{\mathbf{r}} = \left(\mathbf{D}^{\mathbf{T}}\mathbf{W}^{\mathbf{T}}\mathbf{W}\mathbf{D}\right)^{-1}\mathbf{D}^{\mathbf{T}}\mathbf{W}^{\mathbf{T}}\mathbf{s}\,. \quad (7)$$

Removing the inversion part and going back to the transpose solution we get

$$\tilde{\mathbf{r}} = \mathbf{D}^{\mathbf{T}}\mathbf{W}^{\mathbf{T}}\mathbf{s}\,. \quad (8)$$

This implies that we need to "correlate" with the wavelet, but that sounds like lowering the frequency. That is correct, and if we did do that, we would end up with a zero-phase wavelet, typical of a true matched filter that lowers the noise, but reduces the bandwidth. If we ignore the wavelet matrix, as in equation (5) then we do have a higher frequency migration but with more noise.

Lets include the inversion part again in equation (7), but in a form of dimensional analysis, i.e.,

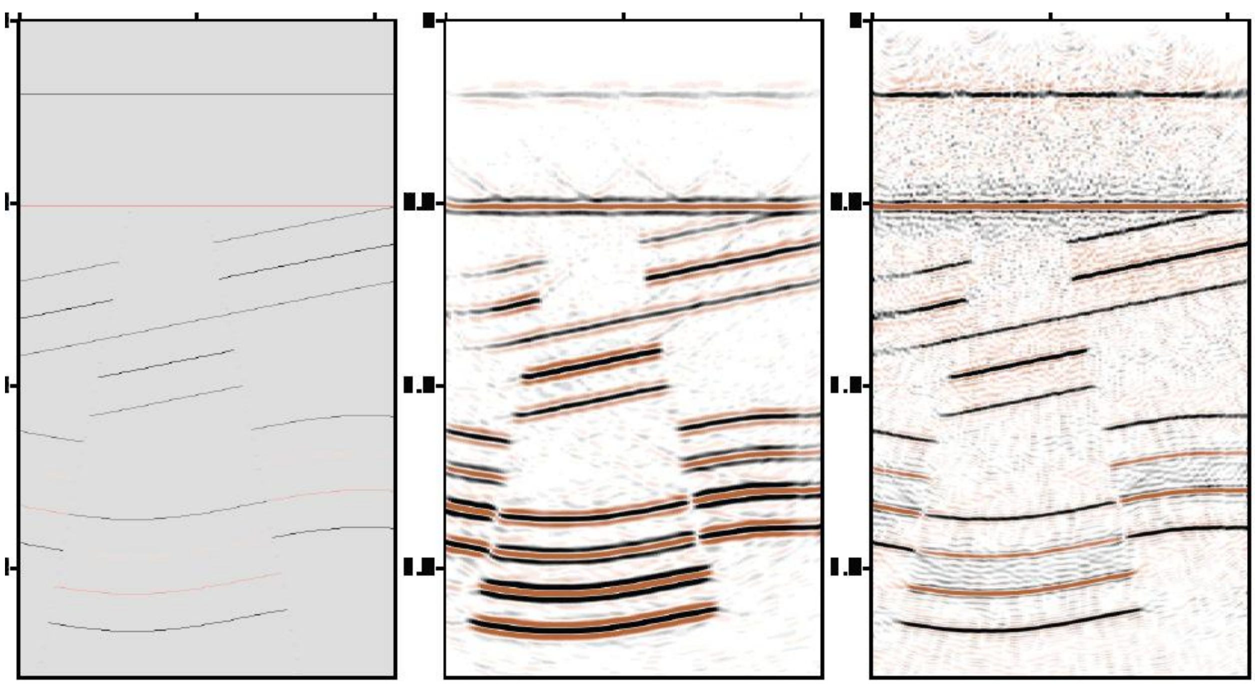
$$\mathbf{r} = \frac{D^T W^T s}{D^T W^T W D} = \frac{s}{WD} \approx \frac{D^T s}{W}\,, \quad (9)$$

where, on the left, we have two wavelets in the numerator and denominator. We end up with our conventional migration $\boldsymbol{D^T s}$ on the right, which still requires some inverse action with the wavelet, i.e. deconvolution to recover the reflectivity.

We illustrate with this concept with a true inversion that uses a LSM that is computationally intensive and usually only simple models are used, as shown in Figure 2. We show a reflectivity structure (a), a migration from seismic data modelled on the structure (b), and a corresponding least LSM (c). Notice the wavelet remains with the migration, but has been substantially removed in the LSM.

These results look and are impressive, but the modelling and inversion process did not contain noise, which enabled the high frequency content of the wavelet to reconstruct the reflectivity. We contend that the same resolution in Figure 3c could have been achieved with a deconvolution to the migrated section in Figure 3b. LSM is still very expensive to run and is not used in general processing.

LSM can be approximated with a conventional migration followed by a deconvolution, especially in areas with shallow dips. A more complex dip respecting deconvolution is required for highly structured data.

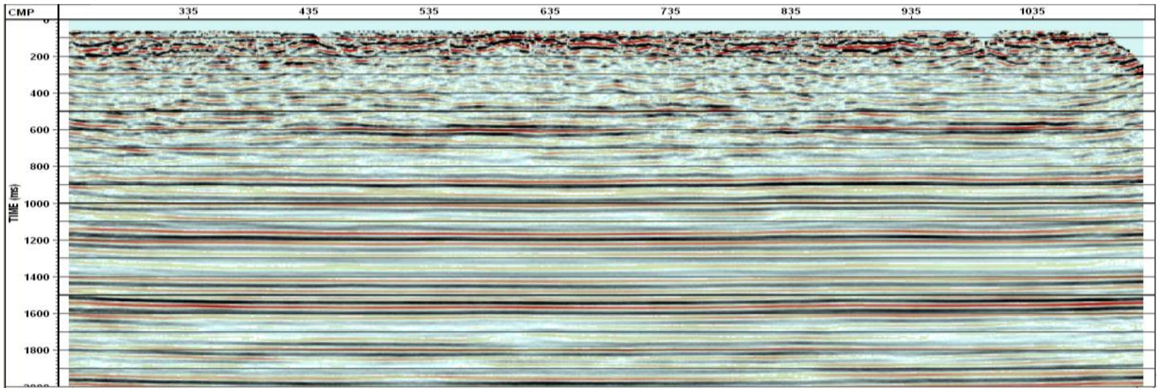


a) b) c)

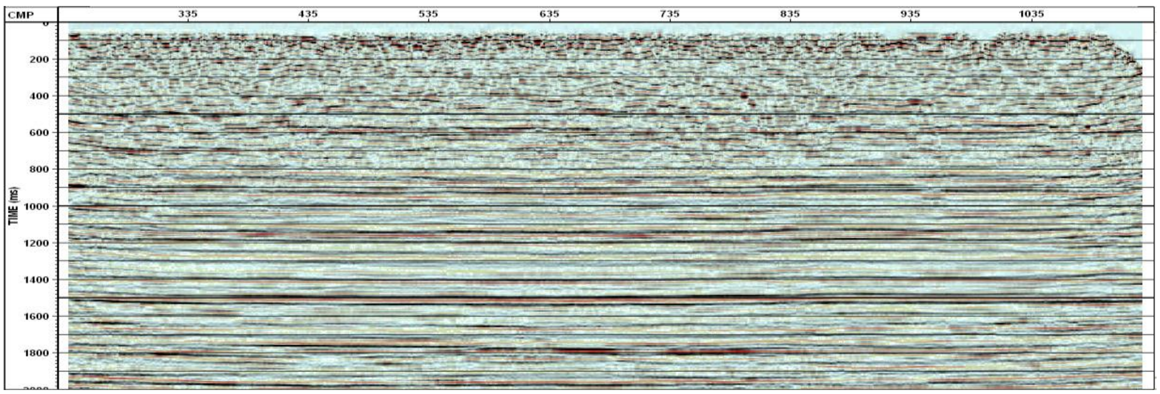
FIG. 2 Illustration of a) a reflectivity structure, b) a migration, and c) a least squares migration.

Examples

2D was acquired in the Hussar, Alberta area in 2011. A low-dell data set was processed with a prestack Kirchhoff migration using the EOM method and shown in Figure 3a. A deconvolution was applied to this data and is shown in part (b). Note the improved resolution of the deconvolved data.



a)



b)

FIG. 2 Hussar data showing a) the prestack migration, and b) the deconvolved section after migration.

Comments and Conclusions

The value of applying deconvolution after a prestack migration is presented and discussed. Deconvolution should be applied based on the spectral envelope of signal and noise, and on the concept of least squares migration.

Data before a prestack migration does not have the advantage of a poststack migration that has deconvolution applied to the stacked section before migration. Deconvolution after a prestack migration becomes even more important.

The higher frequencies obtained with deconvolution after migration may require re-evaluation of the trace interval used in acquiring seismic data.

A special deconvolution may be required for highly structured 2D or 3D data.

Acknowledgements

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References

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