The advantage and significance of prestack migration

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Introduction

In Western Canada there is only a small percentage of seismic data processed with prestack migration. With recent increases in computational power and new developments in prestack migration software, the prestack migration should be included in routine processing of seismic data in my opinion. I will discuss the advantage and significance of prestack migration in this paper.

Accuracy for dipping events

Poststack migration itself can be very accurate. The problem is how to obtain an accurate zero-offset time section. Usually we use a stacked time section approximating a zero-offset section, because we assume lateral velocity changes are relatively small and events are flat. This is not always true. Even for "flat" data, lateral velocity changes may be relatively small, but events are not always flat; anomalies we are interested in always contain dipping components. If we assume velocity is constant and assume a dipping event has the same dip angle and is endless, we might find the images of stack + poststack migration and prestack migration are very close. Actually, things are not so good. If dipping events were not endless, the significant differences would be found at the ends. In addition, even if the velocity only changes with depth, extra errors would be found. A simple calculation can prove the former, and the latter can be easily explained.

In Fig. 1, *S* indicates a shot location, R indicates a receiver location, and *G* is the location of reflector at depth *d*. The migration distance from midpoint *M* is *h*. The difference of time ($\Delta\tau$) between the images of stack + poststack and prestack migrations can be found as:

$$\Delta\tau = \tau_{post} - \tau_{pre} = \sqrt{t_G - (x/v)^2 - (2h/v)^2} - 2d/v \qquad (1)$$

where *v* is velocity, *x* is offset between shot and receiver, and two-way recording time

$$t_G = \{\sqrt{d^2 + (x/2 + h)^2} + \sqrt{d^2 + (x/2 - h)^2}\}/v$$

The corresponding dipping angle θ can be found from the following equation:

$$\theta = \frac{1}{2}\tan^{-1}\left[\frac{2h/d}{1 - (h/d)^2 + ((x/2)/d)^2}\right] \qquad (2)$$

It is not difficult to prove $\Delta\tau \leq 0$. If *h=0*, i.e. dip = 0 or offset *x=0*, we have $\Delta\tau$=0. |$\Delta\tau$| increases with the ratio *x/d* and *h/d*. For 3-D data sets, there are usually a lack of near offset traces, so the error $\Delta\tau$ would be larger compared to 2-D data sets. If depth *d=1000m*, offset *x=1000m*, migration distance *h=500m*, velocity *v=2500m/s* (the corresponding dip angle θ=22.5 degree) for example, we have $\Delta\tau$=-17.3ms. This is a significant difference between stack + poststack migration and prestack migration.

If velocity changes with depth, *v=v(z)* or *v=v(τ)*, the stack + poststack migration would create an extra error due to the vertical velocity changes. If we have reflector G at depth *d*, with the corresponding time τ_G, only the velocity above τ_G should be applied in imaging as prestack migration does. However in the stack + poststack migration procedure, we incorrectly use RMS velocity at τ_0 ($\tau_0 = \sqrt{\tau_G^2 + (2h/v)^2} \geq \tau_G$) or velocity distribution above τ_0 to do NMO. Usually velocity increases with depth. In this case, fortunately the extra error has an opposite sign with above-mentioned $\Delta\tau$. Unfortunately the extra error has the same sign as $\Delta\tau$, if there is a low velocity layer between τ_G and τ_0.

Higher signal/noise ratio

If we assume that input data contains only two parts: signal (SI) and random noise (RNI) and assume that velocity is accurate, the output migrated image would have three parts: signal (SO), random noise (RNO) coming from RNI and migration noise background (MNB). Usually signal/noise ratio after migration [SO/(RNO+MNB)] is higher than the ratio before the migration (SI/RNI), because migration much reduces the input random noise. We expect and often find the signal/noise ratio of prestack migrated image is higher than that of poststack migrated image. The reasons can be summarized as follows:

Figure 2

surface

circle

ellipse

Flat event

I

Figure 1

surface

circle

ellipse

$\Delta\tau$

G

h

S   M   R
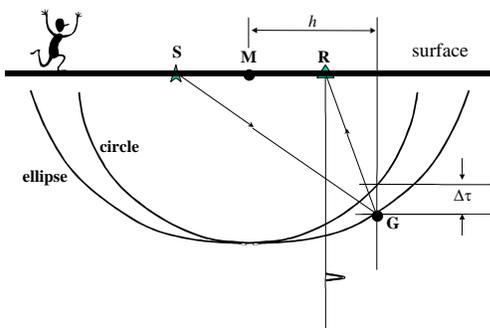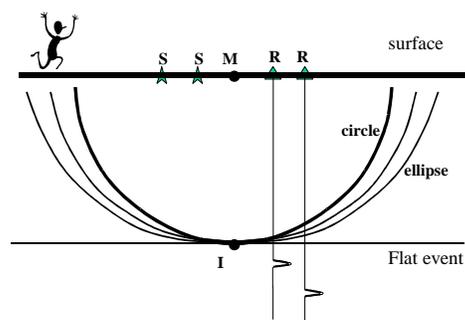
(1) The error in stack + poststack migration, mentioned in above section, would weaken the signal.

(2) The MNB comes from incomplete cancellation in migration. However the cancellation is more complete in prestack migration than in stack + poststack migration. This can be seen in Fig. 2. There are two traces with different offsets in one CDP gather. If we assume that there is only one flat reflector and velocity is constant, then the reflector point is located just under midpoint, the poststack migrated image should be two coincident circles and the prestack migrated image would be two ellipses with different focal distances. Only the amplitudes near reflector point *I* contribute to signal, and others would cancel out with the contributions from other input traces. Such cancellation always leaves migration noise background. Obviously the distribution of the prestack migrated output is more even than that of poststack migrated output. This leads to more complete cancellation in a prestack migrated image compared to that of a poststack migrated image. The prestack migration suppresses input random noise more efficiently, based on the same explanation.

The high signal/noise ratio of prestack migrated images would be useful to improve AVO results. More discussion on this will be included in my further papers about AVO.

Particular benefits of converted wave migration
In converted wave processing, the CDP point is a function of depth (or time) even for flat events and 1-D velocity. Stacking the converted wave data always introduces extra errors, but with prestack migration it is easy to handle the converted wave data accurately with two velocity models (P-wave velocity and S-wave velocity). There are no additional errors compared to P-wave data migration.

Risk reduction with prestack migration
The procedure of prestack migration or stack + poststack migration can be represented by a general summation:

$$IMAGE(x, y, z) = \sum_{record} \sum_{trace} \sum_{time} W * A(x_s, y_s, x_r y_r, t) \qquad (3)$$

Here *A* is amplitude of input traces and *W* is a very complicated weighting function. Obviously *W* is a function of velocity model, the locations of shots and receivers, and location of image points. Using different methods and choosing different parameters would change the weighting function, and change the image. Testing by different methods and different parameters is often used to find the best image and to check the reliability of the results. However the best image would often be found with prestack migration, because prestack migration is more accurate in principle. The best method to check the reliability may be the comparison of the images of prestack and stack + poststack procedures, because the procedures and the weighting function in (3) of the two procedures are so different. For flat data we have often found that the prestack migrated image does not change the interpretation. This is quite normal, because the stack + poststack migration procedure is often a good approximation. The consistency of the interpretations with both procedures would increase the reliability of the results and reduce drilling risks. If the prestack migrated image changes the interpretation significantly for flat data, more investigations may be necessary to find the reasons for the changes. If the procedure includes scaling (e. g. scaling is usually done between stack and poststack migration), there is no such simple linear relationship (3). However this does not change the above conclusions.

Possible problem in shallow layer image

In principle the prestack migrated image should be better than the poststack migrated image, but we may find this is not true for some areas, especially in shallow layers. In the shallow, the prestack migrated image may be noisier than poststack migrated image. This may be acceptable. I explain the possible reason here. Migration is based on a strengthen and cancellation procedure. Proper scaling is very important for migrations. The folds of CDPs are distributed unevenly, especially in shallow layers. This makes scaling difficult in prestack migration and there is no equivalent difficulty for scaling in poststack migration. As well, we may find that prestack migration or poststack Kirchhoff migration for 3-D datasets incorrectly images the events in the shallow layers. This is not acceptable. It may deter exploration geophysicists from using 3-D prestack migrations. This comes from underdeveloped software, but can be solved with software progress.

If we accept the exploding reflector concept, an accurate poststack wave equation migration is almost perfect. An accurate Kirchhoff poststack migration can reach almost the same image. However prestack migration includes both functions of stacking and poststack migration. Stacking is not a physical procedure, so the prestack wave-equation migration is no longer perfect like poststack migration. Thus, in my opinion, the wave-equation methods are no longer in an advantageous position compared to ray theory methods (e. g. Kirchhoff method) for prestack migration, especially for 3-D data.

Real data examples

The poststack and prestack migrated images for a small 3-D dataset are shown in Fig. 3 – 5. Comparing the images in Fig. 3 and Fig. 4, improvements in the prestack migrated image can be found (e. g. events 2 and 3). However some shallow events in Fig. 4 (e. g. event 1) may not be imaged as good as in poststack migrated image, as I explained in above section. In Fig. 5, I show the prestack migrated image with underdeveloped software. Obviously, it is not as good as the image in Fig. 4 with the newly developed software, especially in the shallow layers. The shallow events in Fig. 5 are incorrectly imaged. For example there is a strong artificial event just under event 1 in Fig. 5. For such software the image in the shallow zone may be quite sensitive to image control or mute, which shouldn't be. Developing accurate and efficient prestack migration software may still be a challenge.
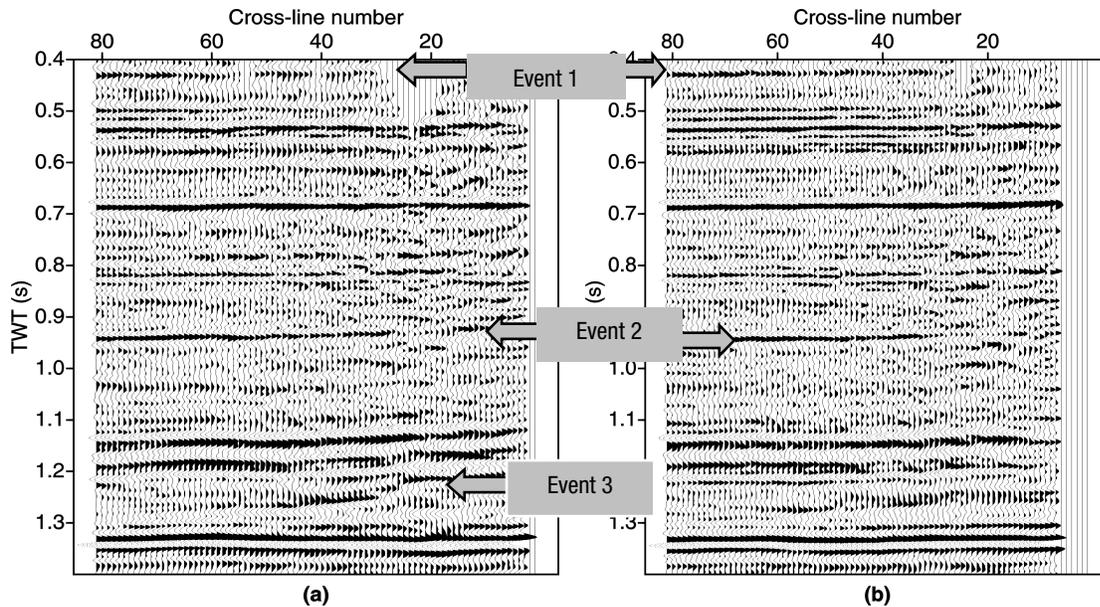
Fig. 3. Poststack migrated image: (a) inline 37 and (b) inline 55.

Conclusions

Compared to stack + poststack migration procedure, prestack migration procedure is more accurate and has higher signal/noise ratio, particularly for 3-D data sets and/or converted wave data sets. The prestack migration focuses energy at the right position for dipping events and non-zero offset traces. The prestack migration distributes non-focal energy more evenly, leaving weaker noise in the background. Both of these effects would increase the signal/noise ratio of the image, even for flat data. If the approximation made in stack + poststack migration procedure is accurate enough, the prestack migration procedure would not change the interpretation. Agreement between prestack and poststack migration interpretations is a good indicator of reliability. With increases in computational power and development of prestack migration software, I predict prestack migration will become a routine procedure in seismic data processing in the future, just as poststack migration did many years ago.

Acknowledgements
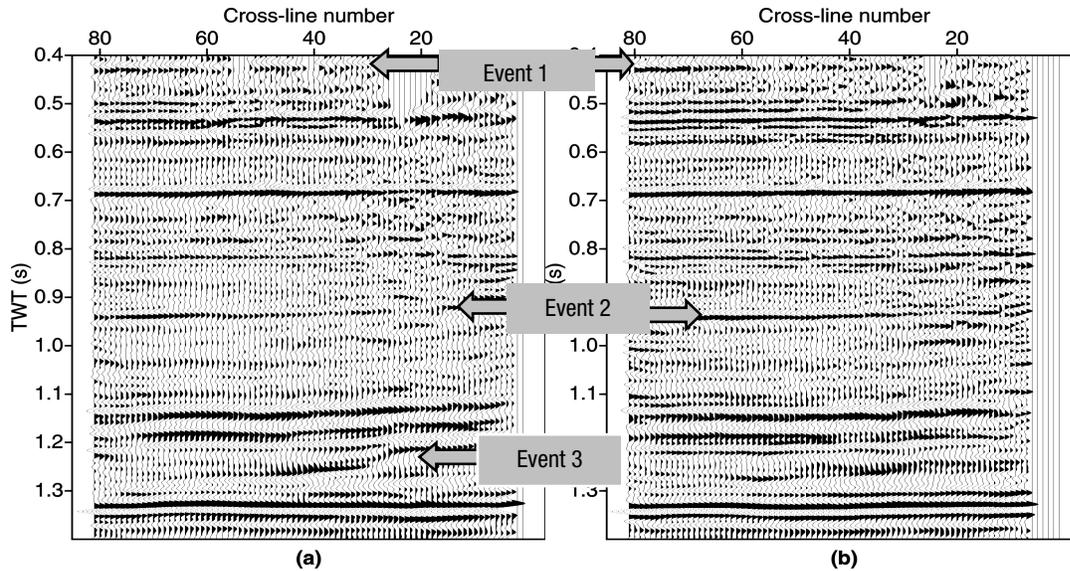
Fig. 4. Prestack migrated image with newly developed software.

Fig. 5. Prestack migrated image with underdeveloped software.