Limitations of the exploding reflector model in sub-salt imaging

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Summary

The exploding reflector model has been the basis for wave equation post stack migration. It enables imaging of zero offset data with one downward continuation step, as opposed to the multiple downward continuation steps required in pre-stack migration. However, the exploding reflector model does not account for reflections for which the corresponding down-going ray path differs from the up-going ray path.

By means of a synthetic example which includes a high velocity inclusion, different alternatives for imaging of zero offset data are tested. The results show that the restriction to identical down-going and up-going ray paths causes discontinuities in the image of reflectors in regions beneath the high velocity inclusion.

The limitations of the exploding reflector can be overcome by using multi arrival Kirchhoff migration, or for wave equation imaging, using pre-stack migration algorithms for the imaging of post-stack data. Both alternatives require an economic price.

Introduction

The exploding reflector model (Lowenthal et al, 1977) has been most important in the imaging of post-stack seismic data. According to this model, a zero offset seismic section can be produced by a single experiment, where all the seismic reflectors "explode" simultaneously at time zero, and subsequently the data is recorded at the surface. In order to produce correct travel times with this concept, all the velocities in the subsurface need to be halved with respect to their actual values. The exploding reflector model allows performing wave equation post stack imaging with a single downward continuation calculation, as opposed to the multiple downward continuations which are required in pre-stack imaging.

The exploding reflector model is closely related to normal incidence ray tracing, in which rays are initiated at right angles to the reflecting horizons and are traced upwards to the surface. The travel times produced from this type of ray tracing closely match the arrival times of events obtained from wave equation exploding reflector modeling. Inherently normal incidence ray tracing is restricted to single arrivals, where the down-going ray path of a reflection event is identical to the up-going ray path.

In most cases, migration based on the exploding reflector model will reproduce all the horizons which created events on the corresponding zero offset time section. An exception occurs when the normal incidence ray fails to reach the surface, while there is an alternative ray path which produces a zero offset reflection (Fig 1). This situation can occur in sub-salt imaging of sediments, where the normal incidence ray hits the salt body at an angle beyond the critical angle (Fig 1). Failure to include the non-normal incidence arrival can degrade the results of post stack migration.

The exploding reflector concept is not essential in Kirchhoff migration which images the data from separate shot-receiver pairs. However, when the Kirchhoff migration uses only a single arrival for each subsurface location, intrinsically the imaging occurs from specular rays which are at right angles to the reflectors. Single arrival Kirchhoff migration of zero offset data therefore corresponds to normal incidence reflection.

In the following, we examine depth imaging of zero offset data from a synthetic model using different imaging algorithms. Kirchhoff single arrival migration, Kirchhoff multi arrival migration, wave equation exploding reflector migration and common shot wave equation migration are compared.

Synthetic example

For this study, we use a synthetic model of a high velocity body embedded in a horizontally layered medium. The geometrical configuration and the material parameters of this model are shown in Fig 1. The cmp spacing in this example was 25m and each of the simulated shot gathers contained 30 offsets in the range 0 to 2900 meters respectively. This model can be considered as an idealization of salt structures with steep salt-sediment interfaces.

Fig 2 shows a simulated zero offset section which was obtained for this model. The section was calculated using common shot wave equation modeling, after muting all the output traces, except for the zero offset trace. This section was used as input data for the migration tests.

Fig 3 shows a depth section which was obtained by first arrival Kirchhoff migration of the input data using the first three offsets (range 0-200m). From a practical viewpoint this section resembles closely a zero offset migrated section. In this figure, the high velocity body was imaged quite well. The horizontal interfaces of the model were also imaged well, except for the regions below the steeply dipping lower boundaries of the high velocity inclusion. This failure can be understood by examining the zero offset ray paths shown in Fig 1, which reflect from a point on the first interface (point A). At this point the normal incidence ray fails to reach the surface within the boundaries of the survey. The zero offset arrival within the model results from non normal incidence reflection, where the down going ray path follows a different trajectory than the up going ray path. Conversely, the horizontal interfaces are imaged well in regions where the normal incidence ray path reaches the surface within the survey aperture (e.g. point B in Fig 1). Figure 3 contains some spurious events around the inclusion. These events stack out when multi offset migration is used.

Fig 4 is a depth section obtained by Kirchhoff migration, using maximum energy arrivals. This image is similar to the image obtained with first arrivals (Fig 3), except in the region below the steep interfaces where it is slightly better. However, the horizontal reflectors are still truncated there. This is not surprising, since any single arrival Kirchhoff imaging method for zero offset data allows only normal incidence specular rays to form the image.

Fig 5 is a depth section obtained by Kirchhoff migration using simultaneously first arrivals and maximum energy arrivals. In this case, each image point can be formed by up to four arrivals, namely, 1. Down going first arrival (FA), and up going (FA); 2. Down going maximum energy (ME), and up going ME; 3. Down going FA, and up going ME; and 4. Down going ME, and up going FA. In the case of zero offset data the times for events 3. and 4. are identical. The horizontal reflectors in Fig 5 are continuous across the model, suggesting that the image was formed according to Fig 1 with different down-going and up-going respective ray paths. There remain, however, in Fig 5 artifacts outside of the model similarly to the previous figures.

Fig 6 shows a depth section which was obtained by wave equation exploding reflector imaging of the data in Fig 2. The image of the horizontal reflectors in this figure is comparable to the images in Fig 3 and Fig 4 from single arrival Kirchhoff migration. This is because this type of migration, although inherently multi-arrival, can only produce images which correspond to normal incidence rays (e.g. events 1. and 2. above) This image contains less artifacts than images produced by Kirchhoff migration.

Fig 7 is a depth section which was obtained by common shot pre-stack depth migration, using only the first three offset traces in each input shot gather. The images of all the reflectors in this model are continuous and the section has the least artifacts of all the sections presented. This shows that in certain locations, data that was recorded on the surface at zero offset, becomes non zero offset during the downward continuation process, until the imaging step when it becomes again zero offset.

For the sake of comparison Fig. 8 is a depth section obtained by pre-stack common shot migration using all offsets in the shot gathers. This section shows fewer artifacts and is superior to Fig. 7. This indicates that with multiple offset data there is better specular ray coverage of the reflectors which translates to better imaging.

Conclusions

This work has shown the limitations of the exploding reflector concept in the imaging of complex structures. Inclusion of multi arrival paths in both Kirchhoff migration and wave equation imaging (indirectly by using common shot migration) significantly improved the continuity of the image of the reflectors. It therefore appears that the advantage of pre-stack migration over post stack migration is not only in multi-offset redundancy, but also in allowing non-normal incidence reflections to form the image.
From a practical viewpoint, this work suggests that with complicated structures, multi arrival Kirchhoff migration may produce better imaging of post stack data than wave equation migration which is based on the exploding reflector concept.

This study has also shown that common shot wave equation migration of zero offset data is superior to wave equation migration based on the exploding reflector model. However this approach requires almost the same amount of computer resources as full pre -tack wave equation migration and is therefore impractical.

References

Loewenthal, D., Lu, L., Roberson R., and Sherwood J., 1976. The wave equation applied to migration: Geophys. Prosp., 24, 380-399.

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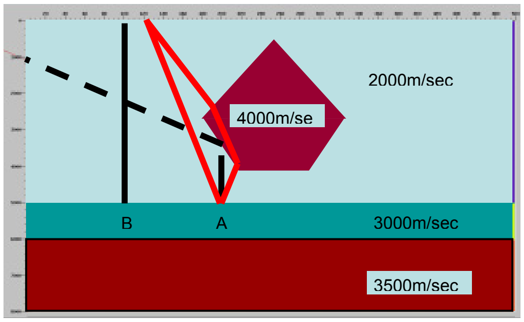

Figure 1: Subsurface model configuration and zero offset ray paths

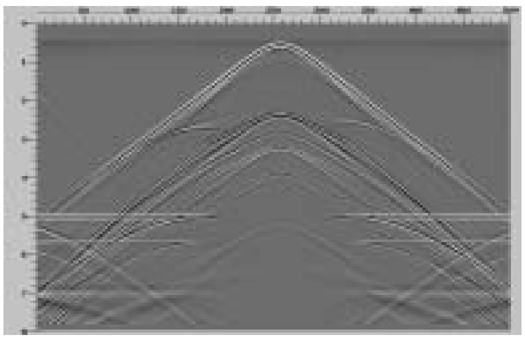
Figure 2: Zero offset synthetic time section

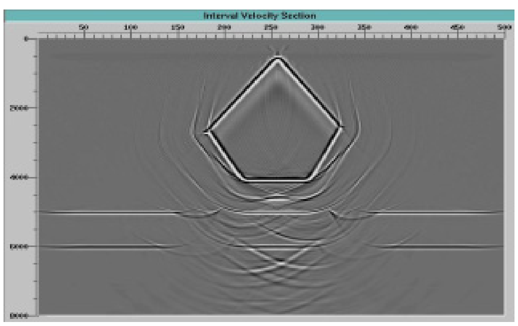

Figure 3: Kirchhoff first arrival depth migrated section.

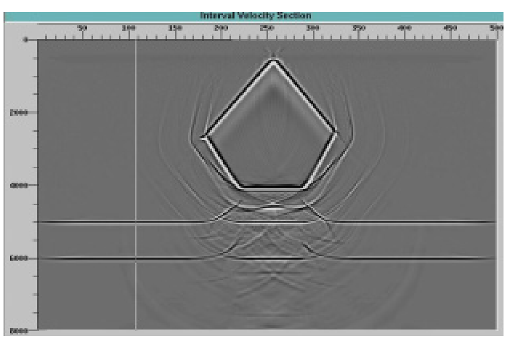

Figure 4: Kirchhoff maximum energy depth migrated section

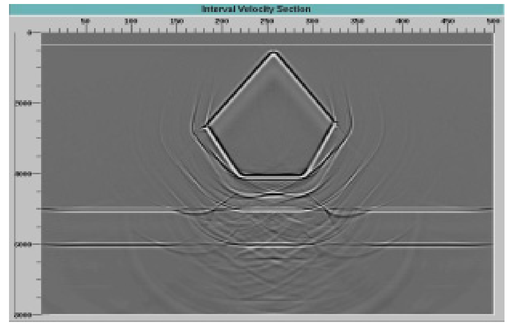

Figure 5: Kirchhoff multi arrival depth migrated section

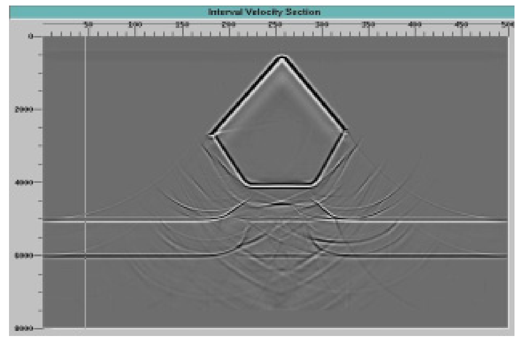

Figure 6: Exploding reflector wave equation migrated section

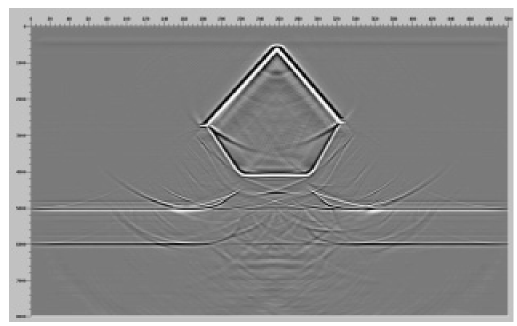
Figure 7: Wave equation 3 offsets migrated secftion.

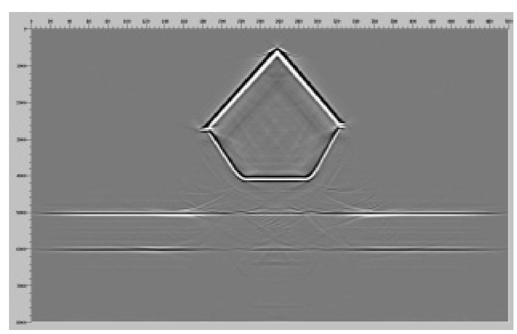
Figure 8: Wave equation all offsets migrated section.