TTI Wave-equation Migration of A 3-D Canadian Foothills Dataset

Richard Bale*
CGGVeritas, Calgary, AB
Richard.Bale@CGGVeritas.com

and

Samuel Gray
CGGVeritas, Calgary, AB, Canada

Summary

In this paper, we demonstrate application of a 3-D TTI wave-equation migration (WEM) on a dataset from the Canadian Foothills. The migration uses a modifiedax phase-shift plus interpolation (PSPI) algorithm in which spatial variation of velocity, anisotropy and orientation of the symmetry axis are all accounted for by a suitable choice of reference operators. When compared with a TTI Kirchhoff migration on the same data, we find that the wave-equation method has some advantages in terms of imaging complex structure and of illumination. In particular there are less obvious "shadow zones" than when Kirchhoff is applied. While the Kirchhoff method is more flexible, can easily generate gathers suitable for post-migration processing, and can be economically run to a higher frequency, WEM is becoming a valuable tool in the quest for improved imaging of Foothills data.

Introduction

Wave-equation migration (WEM) has become the de facto standard for imaging in many offshore exploration areas such as the Gulf of Mexico. The application of WEM to onshore data has been hampered by issues such as topography and irregular acquisition geometries. For the Canadian Foothills this is further complicated by the presence of steeply dipping sedimentary layers which give rise to tilted transverse isotropy (TTI). While isotropic and VTI algorithms for WEM have been in widespread use for some time, it is only in the last couple of years that any serious effort has been addressed to the implementation of TTI WEM algorithms. In contrast, Kirchhoff and other ray-based methods such as Gaussian Beam migration have for some time been able to handle TTI ray-paths, and have been extensively used in the Canadian Foothills. Nevertheless, the structural complexity encountered in these areas suggests that application of WEM could offer improvements in image quality and illumination, when compared to ray-based methods.

Our TTI WEM algorithm is based on a phase-shift plus interpolation approach. The theory was presented last year and was illustrated using 2-D examples (Bale et al., 2007). In the current paper we briefly describe how the method is extended to 3-D, and we present an application of the method on a 3-D Foothills dataset. In order to provide well sampled shot-records for migration, the data were first regularized using the 5-D interpolation/regularization method introduced by Trad (2007).

Theory

The TTI operator used is based on the acoustic TI approximation (Alkhalifah, 1998), formulated as a phase shift operator. The phase shift must be computed as the solution to a quartic equation, involving the two horizontal wavenumbers k_x and k_y, as well as five medium parameters: V_0, the velocity parallel to the symmetry axis; the Thomsen parameters ε and δ; θ, the tilt of the symmetry axis with respect to the vertical, and; ϕ, the azimuth of the symmetry axis. An example of the operator impulse response is shown in Figure 1. Note that the crossline and inline (black lines on the depth slice) intersect at the zero offset location of the impulse. The asymmetry of the impulse response arises from the TTI medium itself.
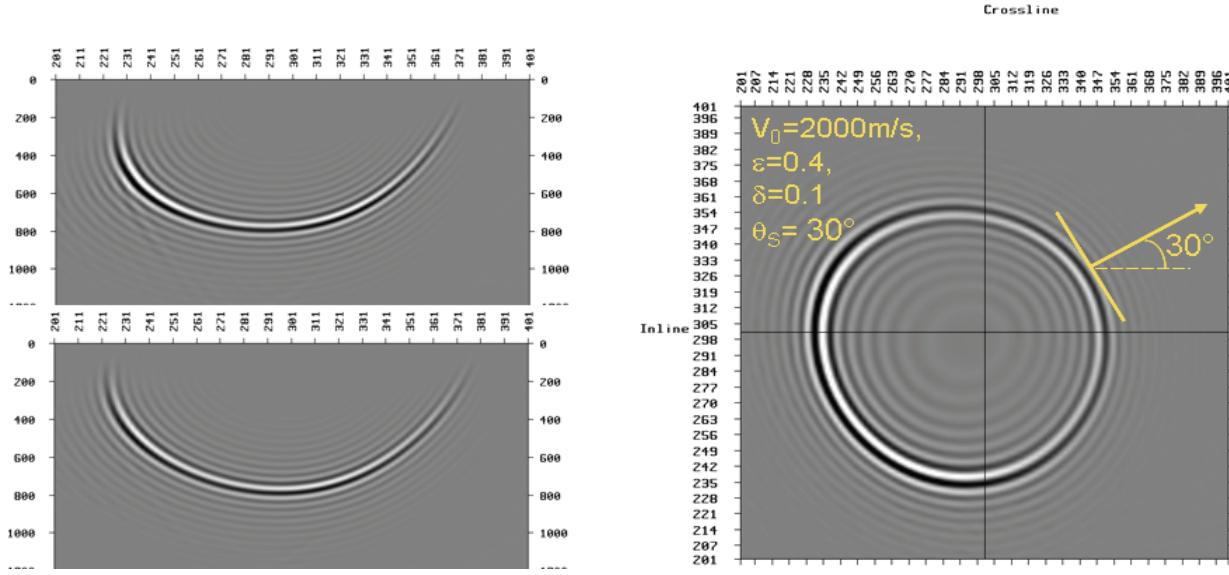

Figure1: Inline profile (top), crossline profile (bottom), and depth slice at 500m through a zero offset impulse response in a homogeneous medium, with V_0=2000m/s, Thomsen parameters ε=0.4, δ=0.1, symmetry axis tilt 30° from vertical and azimuth 30° from inline direction. The horizontal and vertical lines on the depth slice show the position of the inline and crossline profiles.

As described in Bale et al. (2007), the lateral variations of the medium are accommodated by using a PSPI method, in which the extrapolation is applied for a number of reference operators, then the results interpolated in the spatial domain. The reference operators depend on the combination of medium parameters, and these must be sampled sufficiently well to represent variations in the medium for each depth step. On the other hand, the number of reference operators should be kept minimal to reduce cost of the algorithm. These competing goals are achieved in part by exploiting correlations between medium parameters, and in part by using an adaptive phase-error criterion for choosing the reference values for symmetry axis tilt - since the number of reference tilts needed depends on the strength of anisotropy (e.g. only one is needed for extremely weak anisotropy).

For 3-D, a similar line of reasoning allows us to adaptively select the number of reference azimuths used for the tilt axis. Clearly if the tilt is vertical or near vertical, we only need one (arbitrary) azimuth. As the tilt angle increases, the number of reference azimuths also must increase, for example to distinguish between parts of the medium tilted in the northwest direction from those in the northeast. The azimuth sampling needed also depends on the strength of anisotropy. To simplify selection, we always choose an azimuth increment which divides evenly into 360°.

Field Data Example

The Copton Foothills 3D seismic survey covers complex Alberta Foothills geology between the Smoky and Narraway rivers, approximately 15 kilometers northwest of Grande Cache. We have chosen a subset of the survey in the south consisting of 34 shot lines, and 32 receiver lines covering an area of approximately 400 sq. km to run our migration tests. The input data were first regularized with respect to receivers using the technique described in Trad (2007), so that each shot record has a properly sampled receiver domain. The original receiver locations and the regularized receiver locations prepared for migration are shown in Figure 2. The shot locations were not regularized.
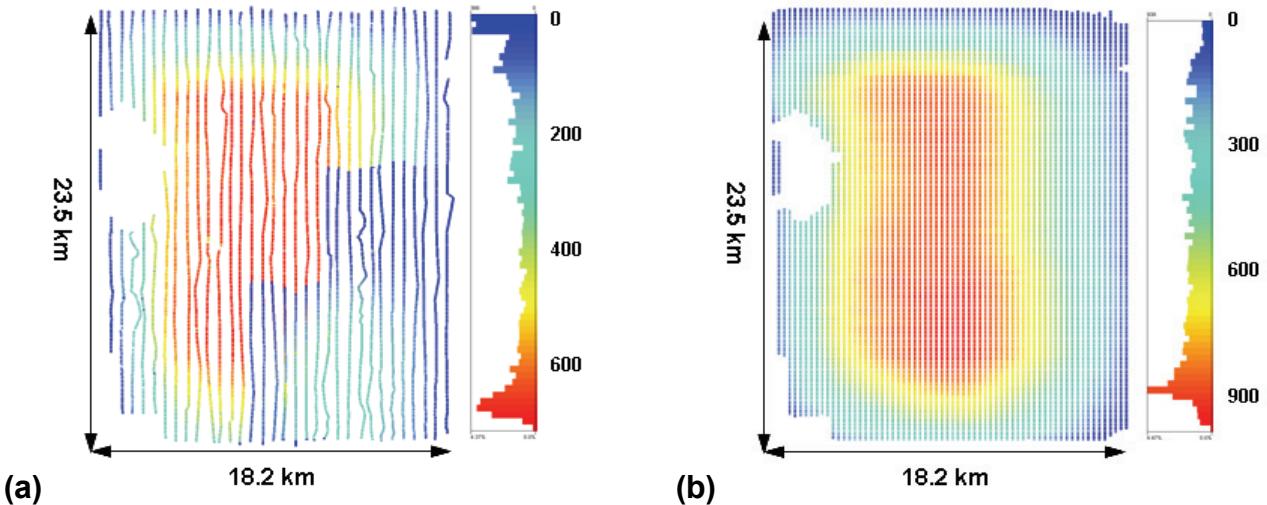

Figure 2: Receiver locations and receiver fold (colour) for (a) original receivers, and (b) regularized receivers.

The data were migrated using the TTI WEM algorithm and a TTI Kirchhoff algorithm for comparison. The results on one crossline (parallel to receiver lines) are shown in Figure 3. The TTI model which was used for both migrations contains significant tilt of the symmetry axis of up to 67°, and has constant Thomsen parameters $\varepsilon=0.12$ and $\delta=0.03$ in the overburden, above the Nordegg. Below the Nordegg, the model is isotropic. Output bin sizes were 70m x 35m.

The Kirchhoff migration included frequencies up to 80Hz, whereas the WEM was restricted to 40Hz. The cost of WEM increases at least quadratically as the frequency range increases, whereas the cost of Kirchhoff increases linearly. Furthermore, it is straightforward to generate common image gathers for Kirchhoff migration, whereas this is possible but more costly for WEM. In this example the WEM result was directly imaged without any post-migration mutes applied, while some image gather mutes where applied to the Kirchhoff image. For these reasons, the Kirchhoff migration produces a better imaged result for the shallow regions. However, the WEM result deeper in the section show some advantages over the Kirchhoff, as indicated in the solid ellipses. Generally it is expected that WEM illuminates structurally complicated areas better than Kirchhoff, since it uses the full wavefield, whereas Kirchhoff migration relies upon ray-paths which may have "shadows" (i.e. areas the rays don't reach). This expectation seems to be borne out by the example shown here.

Conclusions

We have applied TTI wave-equation migration on a 3-D dataset in a complex structural area from the Canadian foothills. The data were regularized first to provide uniformly sampled receiver locations. Kirchhoff migration on the same data provided a clearer image of the shallow data, but deeper in the section the wave-equation migration reveals the structure more clearly. We suggest that both approaches are valuable in imaging the complex structures of the Foothills.

Acknowledgements

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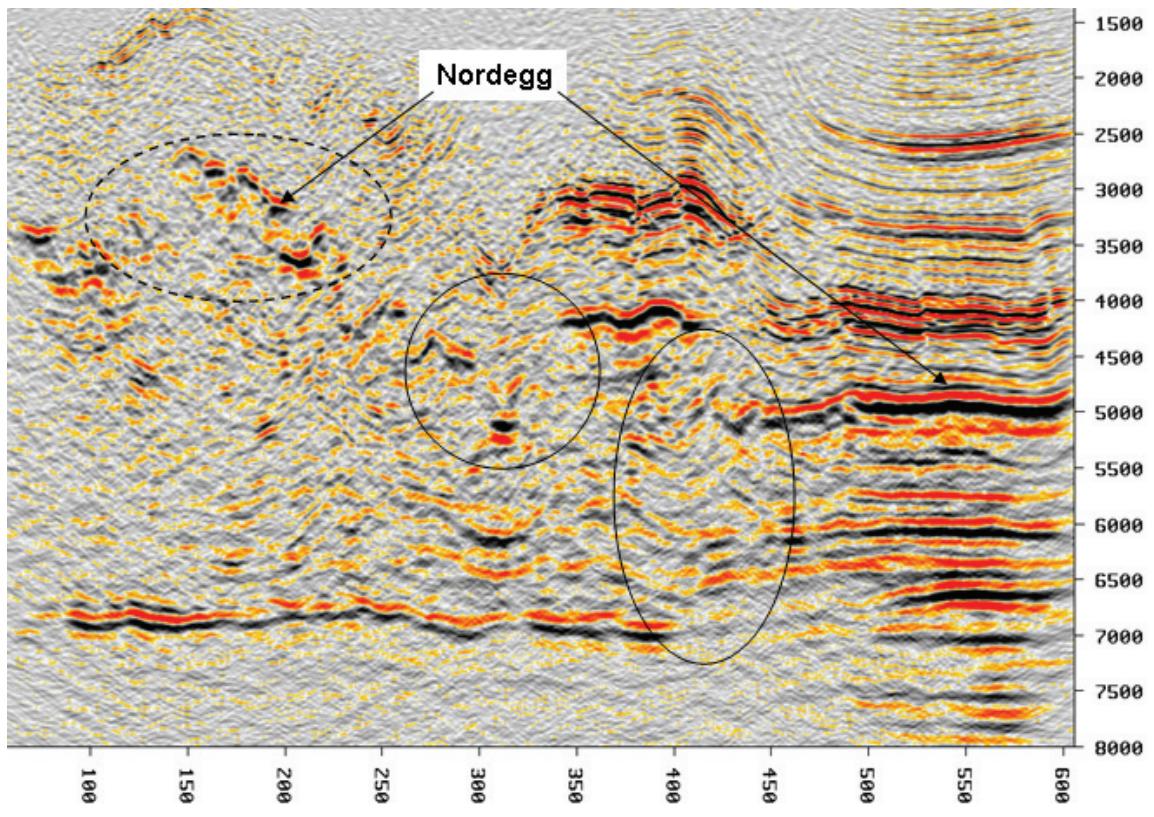
(a)
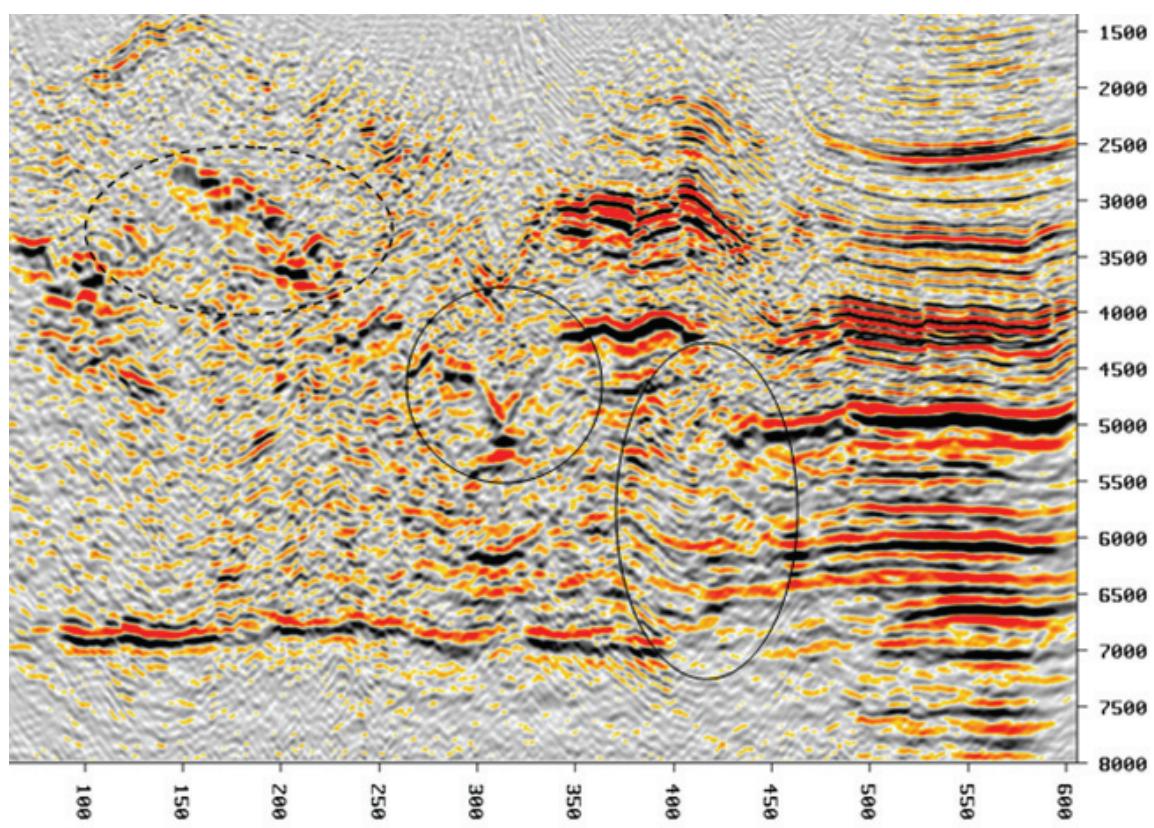
(b)

Figure 3: A cross-line from the 3-D Copton survey, showing a comparison of (a) TTI Kirchhoff migration; with (b) TTI wave-equation migration. The Kirchhoff migration included frequencies up to 80Hz, whereas the WEM was migrated up to 40Hz. Solid black ellipses indicate areas where WEM appears superior to Kirchhoff. Dashed ellipse shows an example where Kirchhoff is superior.