The 2nd South Asain Geoscience Conference and
Exhibition,GEOIndia2011,
12-14th Jan,2011,
Gearter Noida,New Delhi,India

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A Practical Review of Migration Issues and Solutions

Abstract

The two key steps in any imaging project are the model building and the migration. However, a confusing plethora of different techniques is available in the industry today, for both the model building and migration phases of a project. Here we will review the issues involved in imaging, and describe the various aspects that need to be addressed, showing examples of each for both the migration and model building phases.

Introduction

There are numerous migration schemes in widespread use which can be classified in two broad categories, both of which are numerical solutions to the wave equation. These two categories are the integral methods (including Kirchhoff and beam techniques), and the differential methods, which use wavefield extrapolation to solve the migration equations (these include reverse time migration (RTM) and wavefield extrapolation migration (WEM), also referred to by some as being ‘wave equation migration’, which is a bit misleading as all the methods attempt to solve the wave equation). Many of these migration techniques can in-turn be applied in various ‘domains’ on different input-data collections: e.g. time domain, frequency domain, and common shot, common azimuth, or common offset data, etc, and can also be solved with several different numerical techniques, such as finite difference (FD), phase shift, phase screen, etc. Current-day techniques solve what is called the acoustic wave equation: that is to say, they ignore all shear modes and mode conversion at interfaces: this is equivalent to treating all the rocks in the earth as liquids!.

It is also instructive to question what kind of pre-stack depth migration (preSDM) is required for a given geological environment. Once we have concluded that time migration may not be appropriate for the complexity of the problem in-hand, we still need to decide what kind of preSDM algorithm to use. Also, the method of velocity model building must be tailored to the type of depth migration algorithm we intend to use. We nowadays commonly have available Kirchhoff, beam, one-way ‘wave equation’ extrapolation (WEM), and two-way reverse-time migration (RTM) approaches to depth migration.

The ‘issues’ involved in selecting an algorithm primarily include: amplitude preservation; lateral velocity variation; dip response; algorithm noise; honouring the velocity field; multi-pathing; and two-way propagation. In this talk, we’ll consider some of these issues so as to familiarize the reader with some of the limitations of various migration algorithms, and the related effects in velocity model update. It should be noted that the algorithm we intend to use for producing the final image should ideally be linked in performance to how we build the velocity model. For example, if we have steep geological structures, and we correctly selected a migration algorithm with a good dip response for the final imaging step, then it would be inappropriate to use a model building route that was in some way dip limited, as it could not correctly represent the steep structures in the velocity model. Hence the subsequent migration would be in error, even though the migration algorithm itself had the potential to image the structures.

Amplitude preservation.

From a model building perspective (at least when using ray-based tomography), the least significant aspect is amplitude preservation. All migration algorithms in widespread use today give reasonably acceptable amplitudes in the images they create, and to a lesser extent, are also acceptable in terms of amplitude with offset or angle behaviour. In their simplest manifestations, ray-based techniques such as Kirchhoff and beam are kinematic. That is to say, they do not inherently consider amplitude, but only arrival times of events. They have to be modified with various correction schemes to introduce reasonable amplitude handling. The amplitude behaviour for a Kirchhoff preSTM is easier to control than a Kirchhoff preSDM, but this is primarily because of the gross simplifications underlying a time migration. Conversely, finite difference (FD) and other wavefield extrapolation schemes do inherently deal with amplitude behaviour, although the fidelity of this behaviour will depend on the order (hence computational cost) of the expansions used, and the type of imaging condition employed. It should still be kept in-mind however, that ***all*** the schemes in use within the industry today are solutions of the acoustic wave equation and most also ignore absorption (Q), hence for the most-part do not deal with mode conversion, transmission and reflection energy partitioning, or attenuation.

Lateral velocity variation

The issue of lateral velocity variation is very important, but is addressed for the most part by abandoning time migration and moving to a depth migration approach to the imaging problem. However, some depth migration schemes are themselves limited in the degree to which they can honour lateral velocity change. For example, a phase-shift technique has a very good dip response, so forms the basis of several migration techniques, but is only valid for a laterally invariant velocity field. To adapt this scheme to laterally varying media requires various interpolations between sets of individually laterally invariant results. Conversely, finite difference schemes are well able to handle lateral variation, but are in general more dip-limited (as they use a truncated series expansion for the square root terms in the migration operator). Kirchhoff and beam techniques handle lateral velocity variation very well, as long as the spatial wavelength of these changes is much longer than the seismic wavelength (and both have both a good dip response as well). However, for lateral velocity variation on a length scale similar to the seismic wavelengths, ray techniques are no longer appropriate.

Algorithm noise

All algorithms will create some kind of noise in the output image, as they are not perfect solutions of the wave equation. Mostly this created noise will be insignificant, but for some algorithms it will be worse than for others. For example, a Kirchhoff migration builds an image by copying a sample of input data out along the 3D impulse response curve for the velocity model associated with the corresponding part of the subsurface, and the sum of all such response build the output image. Some of the energy spread along this impulse response will interfere constructively if within the Fresnel zone of the actual reflector (i.e. the principle of stationary phase) to contribute to the output image but the remainder of this energy does not contribute, and the hope is that due to destructive interference, that it will simply cancel out and 'go away'. In practice, some of it remains in the output image as a form of steeply dipping (sometimes aliased) noise (figure 1). Wavefield extrapolation techniques will leave less noise, and a beam migration (although similar to Kirchhoff in that it uses ray tracing) will also have less noise, as the beam technique only computes a contribution to the output image in the vicinity of the post-migration Fresnel zone.

Honouring the velocity field

The issue of 'honouring the velocity field**'** is a subtle one. The velocity field we supply to the migration algorithm might be very detailed, and wavefield continuation algorithms will be capable of honouring that detail in the way they deal with the data. However, ray-based techniques do not use the velocity field directly. The most widely used ray-based technique is the single-arrival Kirchhoff integral migration, which usually is implemented in the time-space domain. In Kirchhoff migration, the migration process is separated into two stages: computation of the travel times along ray-paths through the velocity model, and summation of information associated with these travel paths. In practice, the travel time calculation is performed by considering a 2D surface acquisition position grid sampled at about 125m x 125m, representing both the source and receiver positions, and a 3D subsurface output volume sampled at about 75m x 75m x 50m. From each surface location on the 2D grid, we compute the one-way travel time to each of the nodes in the 3D subsurface volume. Given that an input trace's shot and receiver location will not generally lie on the surface nodes used for calculation, we must therefore read the travel time tables associated with the nearest neighbours and then interpolate. Also, given that the desired output samples will not lie on the 3D volume nodes, we must also interpolate those values between nearest neighbours. These interpolations introduce errors, and in addition if the ray spacing is too coarse, we could conceivably miss some detail from the velocity model. In addition, features which are of comparable size to the seismic wavelength cannot be represented with ray-based techniques. These aspects are demonstrated in the comparison shown in figure 2, data courtesy of ConocoPhillips Norway, where a Kirchhoff image over a gas leakage region gives a poorer image then A WEM result (both using the same input data and velocity model).

For beam migration, we can think of there being three stages in the process: 1) measurement of the time-dips present in the input data (related to the source and receiver surface emergence angles) for all shot and receiver locations for all locally coherent events present in the gathers, 2) using the current velocity model compute the surface location take-off (emergence) angles and via ray-tracing in conjunction with the travel times associated with these time dips, find the output locations of the associated image contributions, and 3) summation of information associated with these travel paths just within the post-migration Fresnel zone associated with the output location. In comparison with Kirchhoff migration, beam techniques have the advantages of dealing with multi-path arrivals and of keeping costs down by computing operators only in the vicinity of a narrow trajectory. However, depending on the beam scheme employed, this dip representation may be sparse (designed to characterize only the significant features of the data) and the ray tracing associated with the selected sub-set of events might not encompass all the detail in the velocity model.

Multipathing

Multipathing refers to the fact that energy can propagate from the surface to a reflecting element in the subsurface via several possible routes. A conventional Kirchhoff migration scheme computes only one possible ray path associated with the velocity model, hence is restricted in its ability to construct an accurate image in regions where multi-pathing occurs. This detail is also related to the mandatory coupling of migration algorithm and model building scheme. Below a salt body, a Kirchhoff migration is inappropriate as it will not capture all the required image energy, and part of the energy not correctly captured will appear in the gathers as a class of noise. Hence using these corrupt gathers as input to a model update scheme will yield an unreliable velocity model: the autopicking of these poorly behaved gathers will produce bizarre results, and the subsequent inversion will yield novel and unusual values of velocity!

Two-way propagation

Two-way propagation refers to ray paths that change direction either on their way from the shot down to the reflector, or coming back up from the reflector to the receiver (figure 3). Most migration algorithms that have been in commercial use over the past decades have been solutions of the 'one-way wave equation'. The wave equation has a square root term in it, and these algorithms only solve for one of the two possible roots: in effect this translates physically to only imaging upcoming energy. Solving the full (acoustic) two-wave equation, using for example RTM, could in principle image multiples and double bounce arrivals, if we have an accurate enough model to work with (and could deal with boundary conditions adequately). From a model building perspective, it would thus not make much sense to use RTM in a complex environment with a model built using one-way wave propagation assumptions. Also, a WEM image will have a class of noise in the image which results from two-way arrivals present in the input data being mispositioned in the one-way image. Figures 4 and 5 compare a WEM with an RTM (using the same input data and velocity model for comparison) from a West Africa deep water salt province.

Model Update Aspects

Ideally, the scale-length that we try to invert for in the model building should be tuned to the scale-length of feature of interest in the data, but within the limits of ray theory if we are using a ray-based tomography. For example, figure 6 shows an offshore India thin channel sand body associated with an erosional episode on an unconformity (data courtesy of Reliance Industries). Using tomographic inversion with a coarse cell size (500m*500m*100m) is unable to resolve the velocity associated with this feature. However, reducing the tomographic cell size to (200m*200m*20m) resolves the feature successfully (figure 7).

Discussion

Apart from the above technical aspects related to how algorithms function, there is also a difference in the way we need to work. Historically, when time migration was being used, the oil company interpreters would at best monitor the processing, and wait until the pre-processing was finished, the velocities picked, and the time migration run, before beginning the interpretation process. What was then passed-on to the interpreter was the final product from the view point of the geophysicist. Interpretations of layers from the time migrated volume would be made and later converted to depth using wells for calibration. Thus, the process was purely sequential. Conversely, depth imaging is an iterative multi-disciplinary effort, involving ongoing input from the oil company interpreter during several of perhaps many iterations of model update and (depth) migration. The interpretation may evolve during this process, as understanding of the prospect changes and is refined. Conversion from geophysical depth to geological depth may still need to be made (either on the interpreted depth horizons, or the depth volume), depending on whether we've been able to adequately address anisotropic effects, or localized heterogeneities.

Hence the complexity of the velocity model can evolve not simply because of the inversion update process being used, but also due to changes in any preconceptions that the interpreters might have, and additionally, their practical geological insight may also rule-out implausible inversion results. Due to the various limiting assumptions of the migration schemes available, it is important to couple the complexity of the algorithm to the complexity of the geological problem, and also to ensure that the velocity model building scheme is based on comparable (compatible) assumptions to the migration scheme.

As a final comment, we need to be aware that different migration algorithms make differing assumptions about the behaviour of the subsurface, and are based on varying mathematical simplifications of the acoustic wave equation. These limiting assumptions may have unacceptable consequences if we are using a given algorithm as part of the model update loop in an imaging project. We need to match the performance of the algorithm we select to the complexity of the subsurface model we expect to build, and image we hope to see.

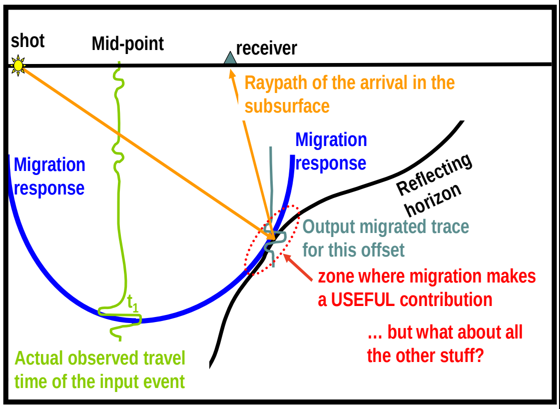

Figure 1: Kirchhoff migration copies energy from the input trace everywhere along the impulse response. However, only a small part of this contributes anything useful to the image: the rest can produce noise.

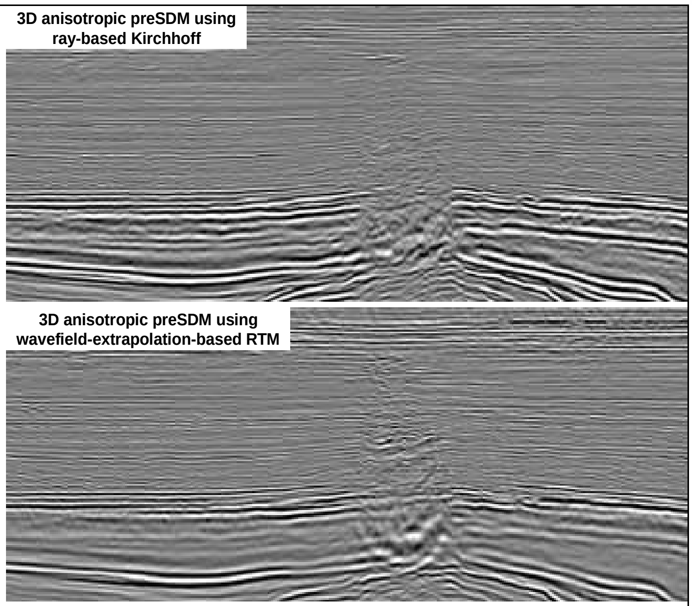

Figure 2: Kirchhoff migration compared to a wavefield extrapolation image over a gas leakage region (courtesy of ConocoPhillips Norway)

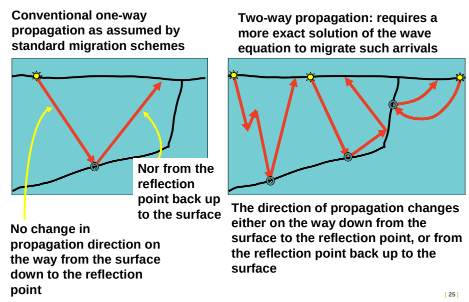

Figure 3: Two way travel paths

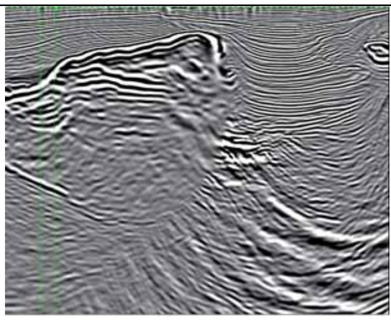

Figure 4: WEM image

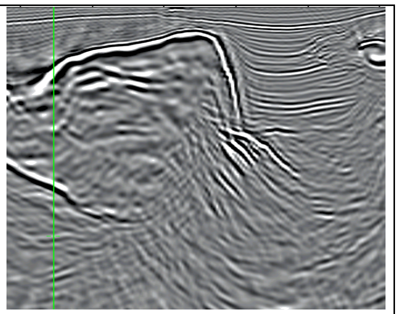

Figure 5: RTM image

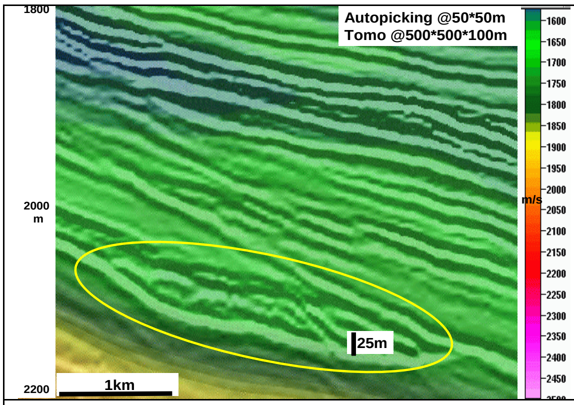

Figure 6: standard cell size tomography does not resolve the thin channel feature

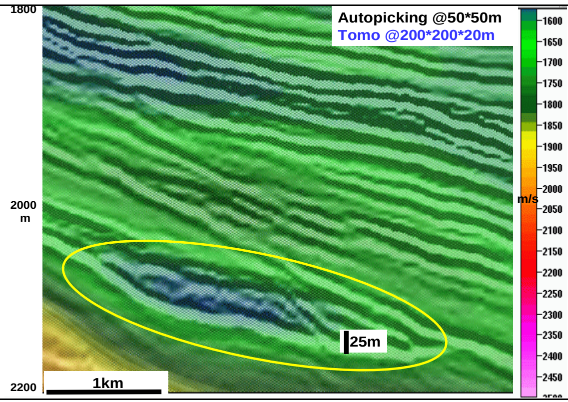

Figure 7: high-resolution cell size tomography resolves the channel feature