Solutions for Deep Water Imaging

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GX Technology

SPG
GeoHorizons
January 2007
P8-22

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Introduction

Imaging in deep water environments poses a specific set of challenges, both in the data pre-conditioning and the imaging.

A prerequisite for any successful imaging project is the estimation of an accurate velocity field for the subsurface. For large scale industrial projects, this invariably implies the use of automatic pickers to assist in the velocity model building. A corollary of this assertion, is that the data going into the migration (and hence the autopicker) is free of noise and multiples, so that the autopicker can make reliable picks.

Consequently, best practise in imaging is inexorably linked to optimal pre-processing (the 'image-driven' concept).

In this paper, we will review several examples in current practise for addressing many of these issues involved in optimal imaging, concentrating our attention on multiple suppression, scattered noise attenuation, iterative velocity model building and depth imaging.

Deep Water Issues

The transition from the shallower coastal waters to the deep shelf often encounters significant topographical variation in the sea bed, which gives rise to numerous effects which must be dealt with by the processing geophysicist. These challenges include: deep channels, steep slopes, surface scatters (eg glacial scour, boulder fields), gas hydrates, cold-water column statics, etc.

Some areas also have a "hard" water bottom, resulting in high amplitude multiple reflections relative to primary energy. Scouring, channel formation and extreme rugosity can be common features of the outer slope. Diffracted and "out-of-plane" multiples present extreme challenges. Depending upon acquisition geometry, multiples are frequently aliased at far source-receiver offsets (Stewart, 2004).

Multiples: General Comments and Shallow Water Applications

It has become clear after extensive testing that "direct" multiples are best attenuated using the surface related multiple elimination (SRME) technique (Verschuur 1992). However, correct parameterization is critical for success. Predictive deconvolution (Peacock 1969), parabolic Radon (Hampson 1986) and tau-p deconvolution (Yilmaz 1987) all fail to adequately attenuate direct water bottom multiples.

Whilst SRME performs well on the "direct" water bottom multiples, tau-p deconvolution is the most effective in attenuating the "peg-leg" multiples. As before, good parameterization and data preparation are critical for success (e.g. here we show examples using the non iterative, high resolution transform of Sacchi, 1995).

One drawback with tau-p deconvolution, is that the entire ensemble passes through the transform. As a consequence, transform artefacts may be embedded in the data. Many multiple attenuation techniques (e.g. parabolic Radon and SRME) model the multiple and subtract from the original. This helps minimize process-induced artefact. A modified tau-p deconvolution method can also be used, which allows multiples to be modelled and subtracted, thus helping to minimize transform artefacts. Figure 1 shows an example of this, with use of an adaptive subtraction of the tau-p model, rather than a direct tau-p removal of the multiple. The input data (water period ~ 100ms twt) for offset 550m (hence the apparently 'deeper' water column) are shown in figure 1a, and the conventional tau-p result in 1b. Greater suppression is achieved in this case with an adaptive subtraction (1c).

Multiples: Deeper Water Applications

Traditionally, differential velocity based methods such as parabolic Radon have been used in deep water. These methods tend to fail on near offsets where locally there is little move-out difference between primaries and multiples. This problem becomes more serious with dip or where the multiple generators become more complex. Additionally, aliasing of the multiples on far offsets can lead to inadequate separation of primaries and multiples in transform space. This requires an additional de-alias step or a transform capable of handling aliased data. An alternative approach to interpolation for the de-aliassing is to perform the Radon transform in small overlapping windows within the CMP. Within each small sub-window in the CMP gather, the data 'appears' less aliased to the algorithm, as we a re not attempting to decompose the complete (parabolic) trajectory in one step. Figure 2 shows one such example: on the input deep water gathers (a) we see clear aliased multiples commencing at 2800ms. In 2b, we have a high resolution Radon demultiple result, and in 2c, the corresponding hi resolution Radon run in overlapping Gaussian tapered windows (referred to here as a 'beam' Radon).

In recent years, the SRME technique has become popular in deep water. Near offset multiples in particular, are better attenuated than those with Parabolic Radon. Cascading 2D SRME and Radon became an industry standard approach. However, the complexity of the multiple generator and "out-of-plane" effects can severely limit even this purely 2D combination. For this reason, a true 3D SRME solution was required.

However, prior to the full industrial availability of 3D SRME, various 2D emulations were developed to attenuate diffracted multiples and other 'shifted apex' CMP events (i.e. when viewed in common mid-point gathers, the apex of the multiple is observed, not at zero offset, but at an offset shifted towards the mid offset range). With this zero-offset apex restriction in-mind, we consider a variant on the Radon approach to handle shifted apex events on CMP gathers (referred to as Apex Shifted Multiple Attenuation: ASMA). Prior to the availability of 3D SRME, this was of great use for both diffracted multiples resulting from near surface 3D effects, and is still of use for some classes of industrial noise. Figures 3 & 4 show an application of ASMA to offshore east coast Canadian data. Here a corrugated sea bed gives rise to diffracted multiples that 2D SRME cannot handle, as the assumed 2D geometry is violated by out of plane events, such as multiples generated by sea floor off-line scatterers. In figure 3a, we see some CMP gathers after application of 2D SRME, the 'simple' well-bheaved elements of the multiples have been removed, leaving only those components which violate the geometrical assumptions of CMP geometry. Here we see hyperbolic events with their apex away from zero offset. Figure 3b shows the gathers following application of ASMA, and figure 3c shows the energy removed by the process. Figure 4 shows the stack before and after ASMA. It should be noted that although the stack itself may suppress some of the apex shifted energy, that for the purpose of velocity estimation, we need 'clean' gathers, so in this context, stacking does not help.

Over the past two years, these cascaded 2D approximations have been superseded by 3D SRME, which is more correct from a theoretical viewpoint. 3D SRME models the true 3D ray-paths associated with free surface bounces from ocean-bottom and buried scatterers, as well as with complexities in the multiple wavefield resulting from the topography of the generating surface. It can be shown that 2D SRME predicts multiple arrival times as being too great for out of plane scatterers. When the crossline dip exceeds about 10°, the 2D prediction will be too far removed from the actual arrival time for an adaptive subtraction to recover the error. In figure 5, we show the far-offset results of synthetic modelling of a shot with a single primary and its multiple, for an inline dip of 15° and crossline dip of 20°, and the corresponding position of the 2D SRME prediction of the multiple. The 3D SRME prediction gives correct arrival times.

Despite the issues related to acquisition and sampling, 3D SRME has proved to be a powerful new tool in the arsenal of multiple attenuation techniques, and has been particularly successful for shelf-break irregularities off the east coast of India, in deep-water sub-salt applications in the Gulf of Mexico, and on corrugated sea-bed multiples in Norwegian waters.

Figure 6 shows an example from Norwegian waters where a corrugated sea bed produces a complex multiple wavefield. In figure 6a we see an input near offset plane, whereas 6b and 6c compare the 2D SRME and 3D SRME results. Although the stacking process itself does suppress some of the multiple energy, this would not help us in the pre stack domain: namely on gathers which we need to work on for velocity estimation, and especially when we intend to use autopicker.

Continuing on the theme of preparing gathers for automatic picking for velocity estimation, we consider the gathers resulting from the SRME processes in figures 7, showing events near the first water bottom multiple (in a 1.4s window centred on 2.9s). Figure 7a shows the input CMP gather from the right of figure 6a. Figures 7b &c show the 2D and 3D SRME results respectively, and figure 7d is the 3D SRME results with a high resolution Radon to remove some of the remnant aliased energy. The latter two gathers are suitable input for automatic velocity estimation: a prerequisite for large volume complex imaging.

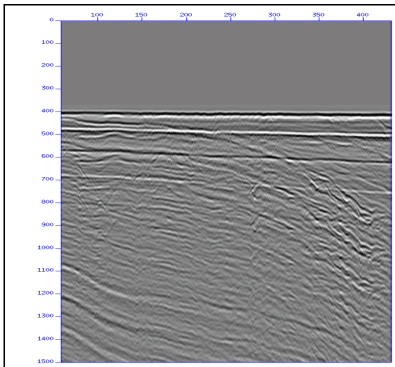	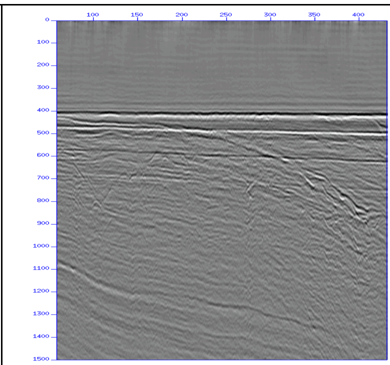	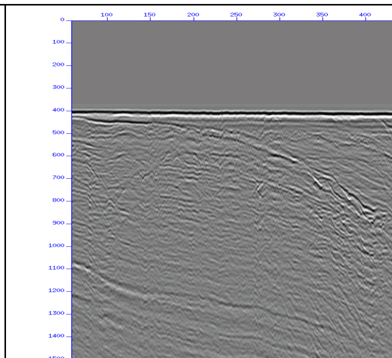
Fig 1a. shallow water mid offset	Fig 1b. conventional tau-p demultiple	Fig 1c. after adaptive tau-p demultiple

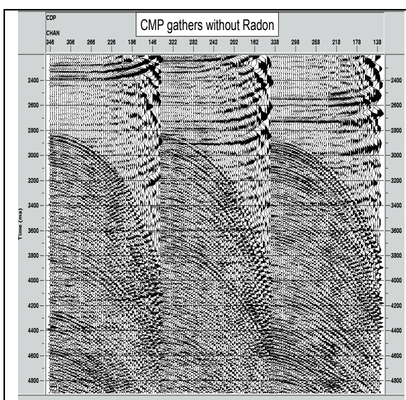	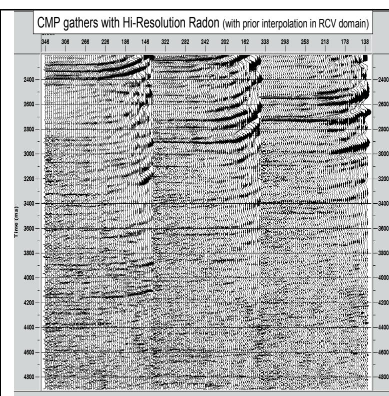	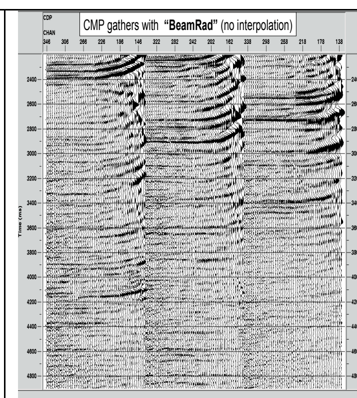
Fig 2a. aliassed deep water multiples on CMP gathers after 2nd order moveout correction	Fig 2b. high resolution Radon applied after receiver domain 2:1 interpolation	Fig 2c. 'Beam' Radon (no prior interpolation

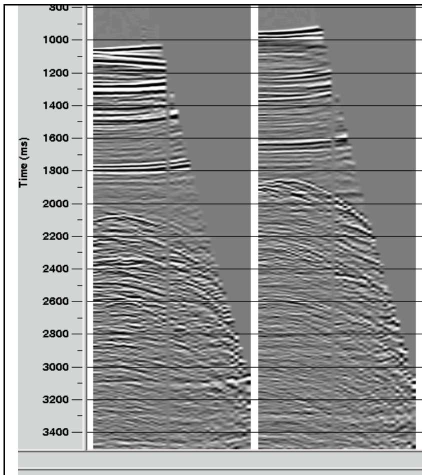

Fig 3a. Input CMP gathers after 2D SRME

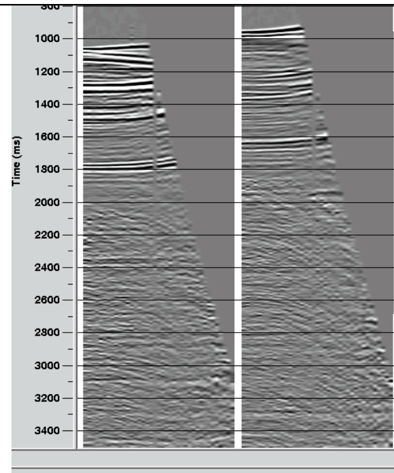

Fig 3b. CMP's following ASMA

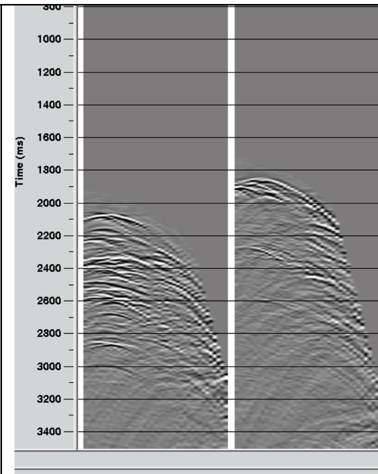

Fig 3c. ASMA model

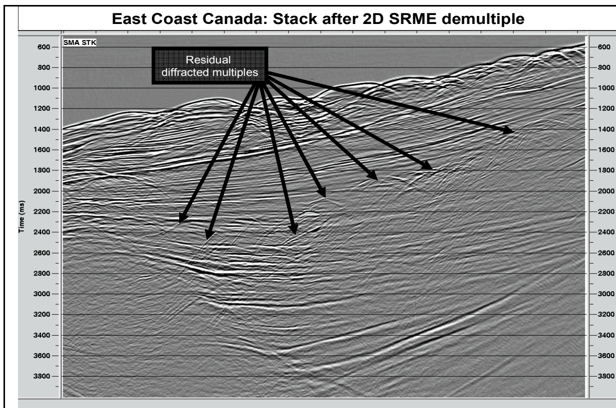

Fig 4a. Stack showing diffracted multiples

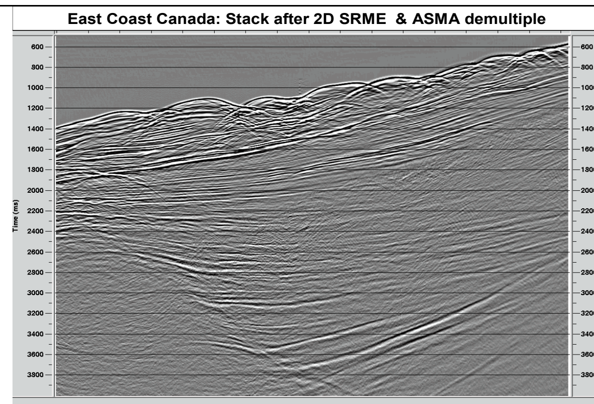

Fig 4b. Stack following ASMA

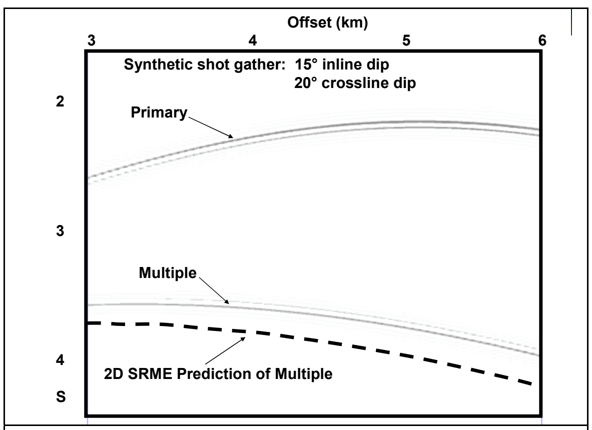

Fig 5. synthetic shot gather, showing primary and multiple, and the predicted position of the multiple from 2D SRME

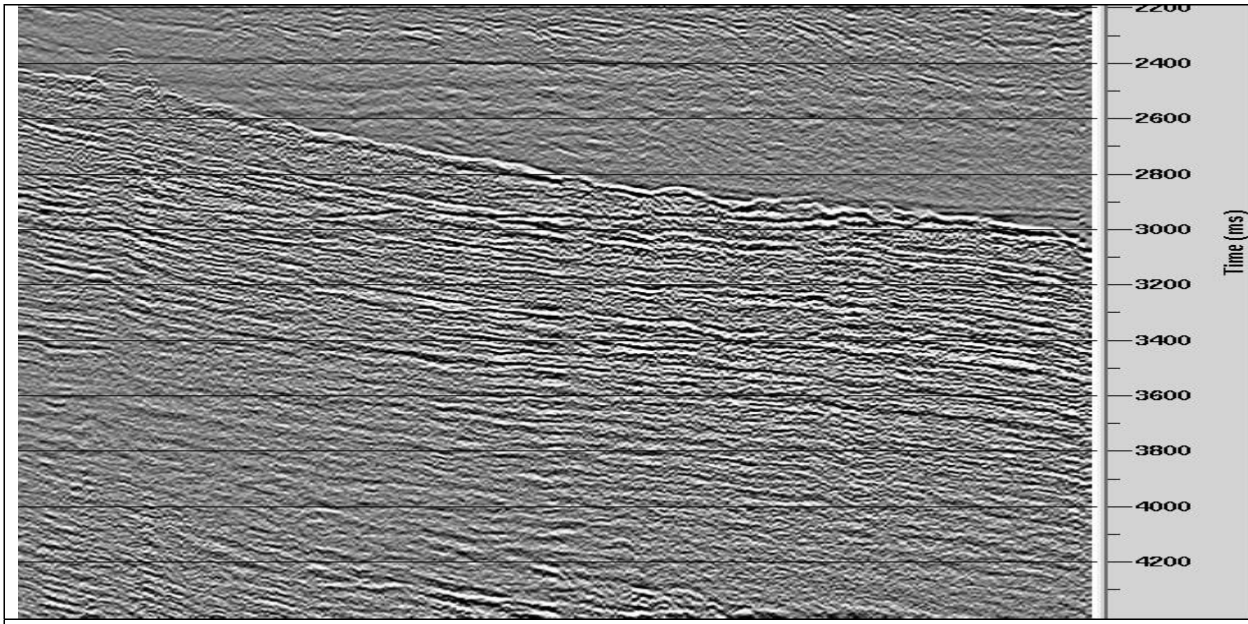

Fig 6a. near offset plane on input, showing deep multiple

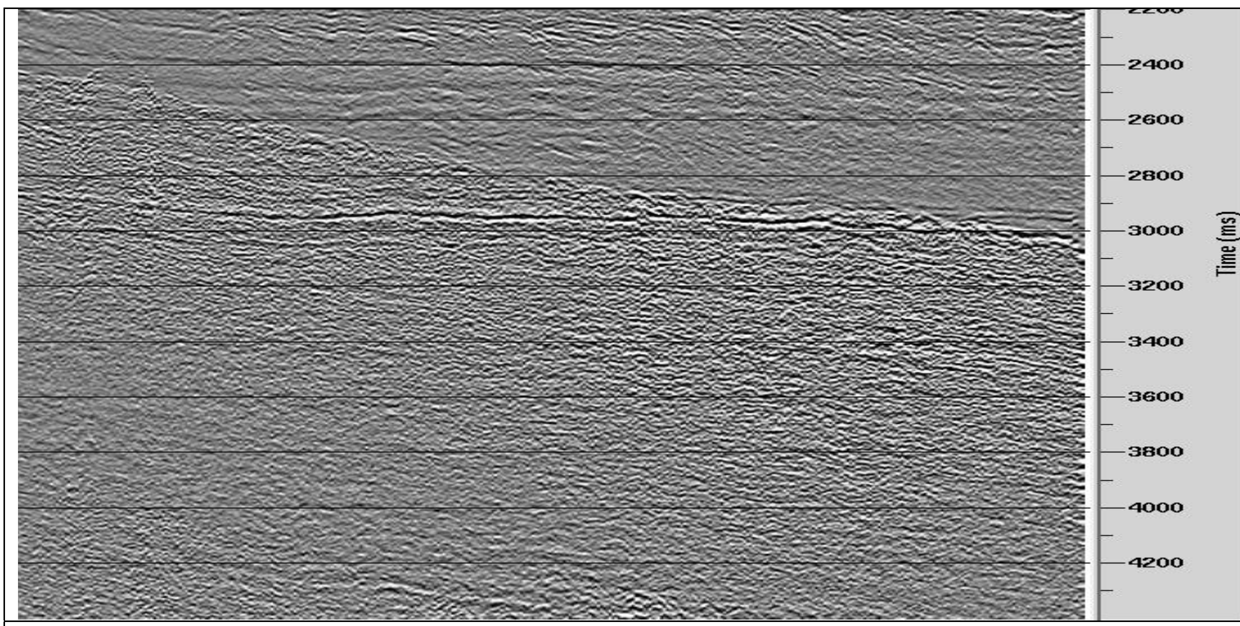

Fig 6b. near offset plane after 2D SRME: noise associated with the diffracted components of the multiple remain

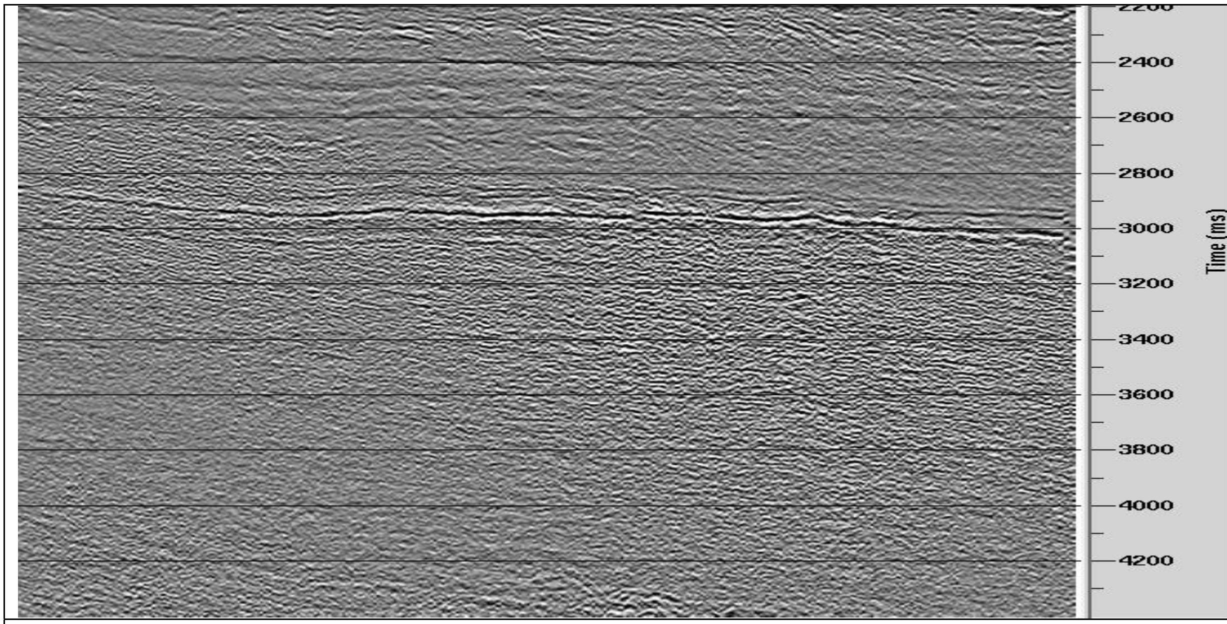

Fig 6c. result of 3D SRME, here much of the diffracted noise has been suppressed

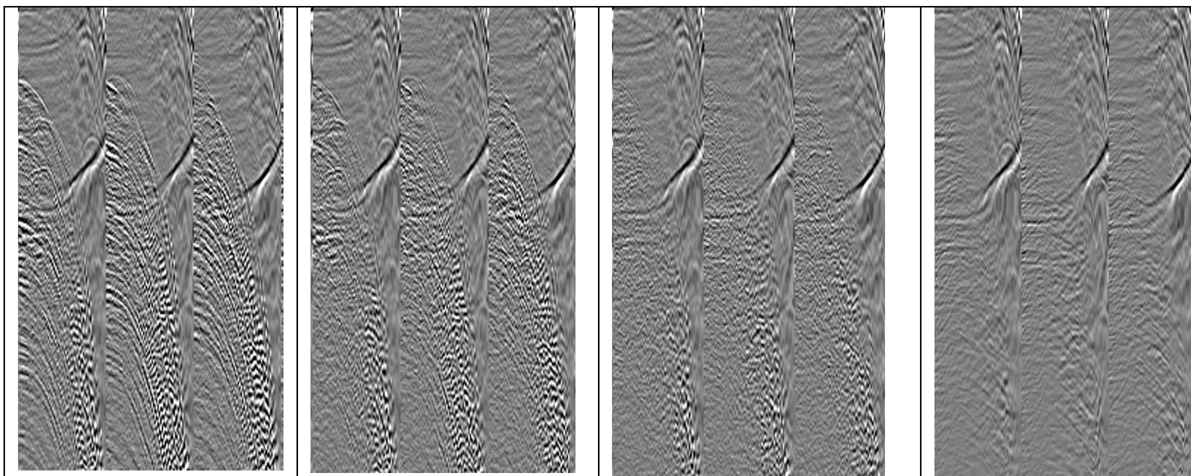

Fig 7a. input gathers | 7b. 2D SRME | 7c. 3D SRME | 7d. 3D SRME & Radon

Velocity Model Building & Pre-Stack Depth Migration

The debate over model representation has been underway for many years. Whether it is better to use a strictly layer based model or a pure gridded model are the two extremes of the argument (Jones, 2003). We prefer to keep our options open, and adopt a hybrid tomographic approach, where we combine the benefits of both schemes: the ability of a gridded route to capture the subtle lateral velocity variation inherent to some strata, whilst keeping the sharp vertical breaks occasionally present in the earth (such as at chalk and salt boundaries). If we have sufficient well control, then we can also incorporate anisotropy in the earth model (Thomsen, 1986, Alkhalifa & Tsvankin, 1995, Jones, et al, 2003). However, for deep water exploration projects we often lack such control, and resort to isotropic migration.

Styles of Layer Constraint for Hybrid Tomography

A hard constraint layer (such as at the sea bed, top and base chalk, or pickable near-surface channel), would result in the model being left unchanged in subsequent iterations ABOVE the picked layer. As such we move from a global tomography to a non-global tomography (but still use a gridded tomography with the layered constraint: i.e. the hybrid tomography, Jones et al, 2007)

A soft constraint layer would be used if the layer being picked was very uncertain, as is often the case for an ill-defined near-surface channel or the seismically transparent top-salt picks in the Zechstein sequence of the North Sea. In this latter case, we profit from having the salt velocity inserted in the model below the picked layer, which helps the convergence of the inversion, even though we allow the tomography to change both the velocity in the picked layer and the layer pick itself. In this case the model above the soft-constraint pick can change.

The initial depth interval velocity is often built from the time-stacking velocity (smoothed and converted to depth interval velocity). The water bottom is usually picked and gridded, and inserted in the initial model as an explicit layer (sometimes picked on a water-flood migration if the sea bed is rugose).

Following this step, several iterations of hybrid tomographic model update are performed as follows:

a) run 3D preSDM on a specified dense grid, outputting full offset gathers
b) run a plane-wave autopicker on all gathers, to determine dip, coherency, and residual gather-curvature (velocity error) fields
c) input autopicked data into tomography and update velocity field

For the strong vertical velocity contrasts (and when anisotropy is to be incorporated), horizons are picked as a constraint on the gridded tomography (the hybrid approach). In these iterations, an additional step is performed:

d). using the updated velocity from the previous tomographic update (c), run a new 3D preSDM outputting a restricted offset stack for the structural interpretation (on a 50m * 50m grid).

The autopicker is a proprietary GXT algorithm, based on plane-wave destructors (Claerbout, 1992; Hardy, 2003). A user-defined 3D probe containing trace portions for different CDP's and offsets is moved about the data. At each position, 2 slopes are computed (along the offset and CDP axis) which minimize the amplitude variation in a least square sense. The quality of this estimate is also computed. As a result of this picking, a 3D slope field and residual moveout estimate are determined.

As a by-product of the autopicking, we also obtain a residual move-out (RMO) corrected stack of the image. This is a good indication of whether the autopicker has found the correct residual moveout in preparation for the tomographic update (or if it has been say, incorrectly biased by residual multiples).

Following the autopicking, the tomography takes the RMO and dip field measurements in conjunction with weights based on the 'quality' of the autopicks, and generates a tomographic solution to minimize the residual moveout values (make the gathers flat and correctly position the data).

In figure 9 we see a stack after preSDM with the initial model, and the QC stack formed by applying an RMO correction with the velocity correction values determined by the autopicker. The final image shows a re-migration with the updated velocity field obtained after tomographic update of the RMO velocity picks.

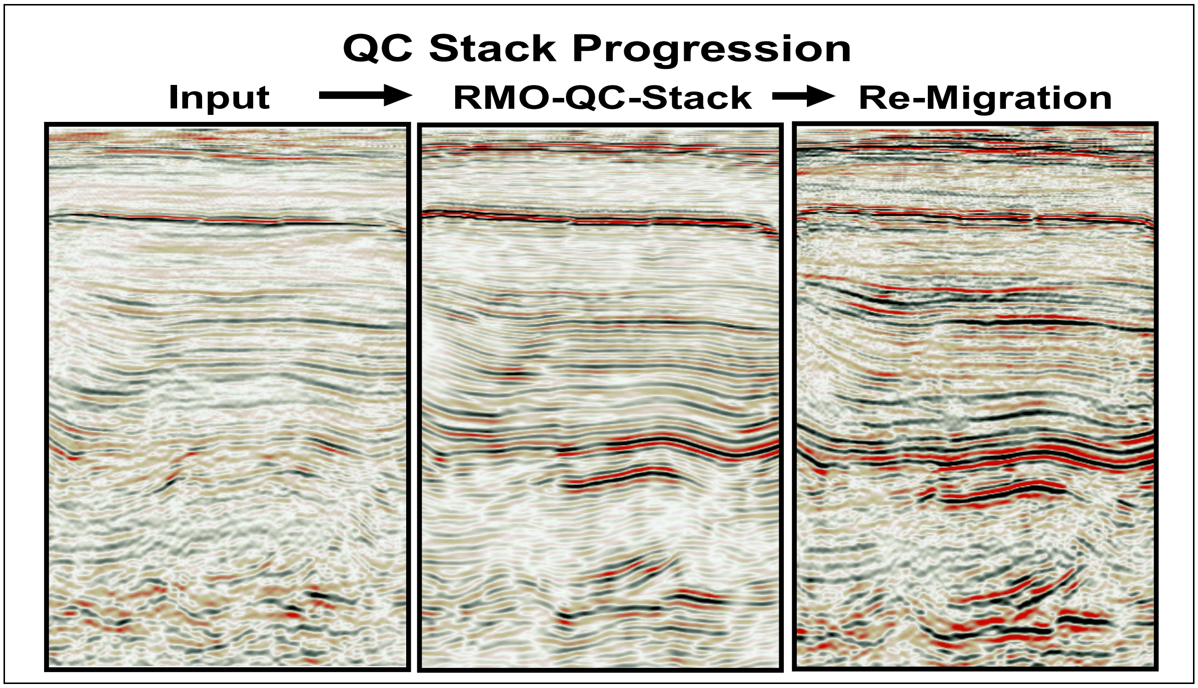

Figure 9: left: stack of CRP gathers from the current iteration. Centre: after the autopicking, an RMO correction is applied to these gathers using the picked residual curvature, thus improving the stack, but not producing movement in the events. Right: new image from re-migration after tomographic update of the velocity, based on the picked RMO residuals

Layered, Gridded, and Hybrid Comparisons.

In the first comparison (figures 10) we see results from a layer based versus gridded tomographic update on a section from a gas charged channel in deep water (offshore Norway). Away from the channel, where good picks of events can act as a geological constraint, the layer based tomographic update can yield good results, but were pick quality is unreliable (below the channel), the gridded approach can be better.

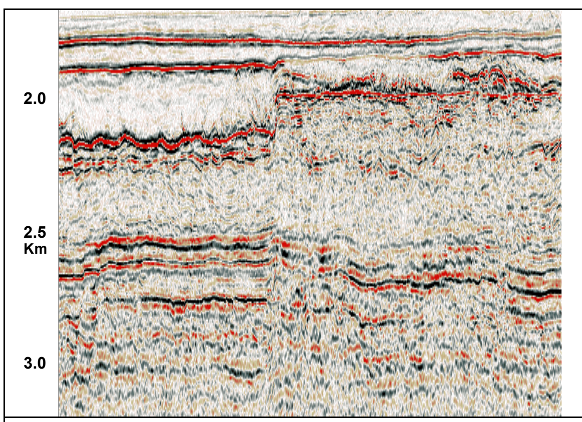

Fig. 10a preSDM image using a layered tomography model

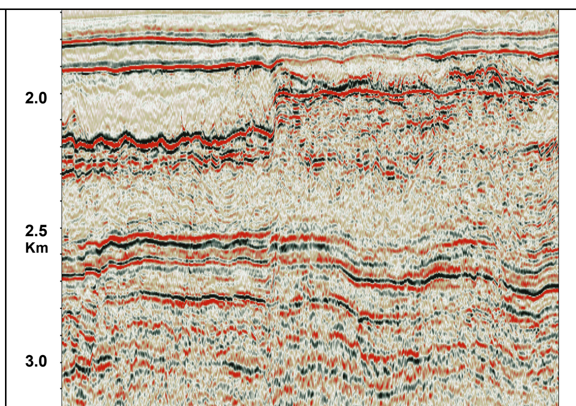

Fig. 10b preSDM image using purely gridded tomography model, with dense auto picking

The second example compares results from model building using purely gridded tomography, with a hybrid model, this time from the shallower waters of the southern North Sea. The first constraint layer picked was the top chalk. A portion of a possible salt withdrawal structure shows-up as ripples in vertical profile on the top chalk (figures 11 & 12). In the purely gridded model result, we can clearly see an imprint of the top chalk structure on the base chalk, and other events. Using the hybrid approach, where the top chalk is inserted in the model as a hard constraint, with a gridded velocity field both above and below, the imprint has been mostly removed, and the sub-chalk image improved.

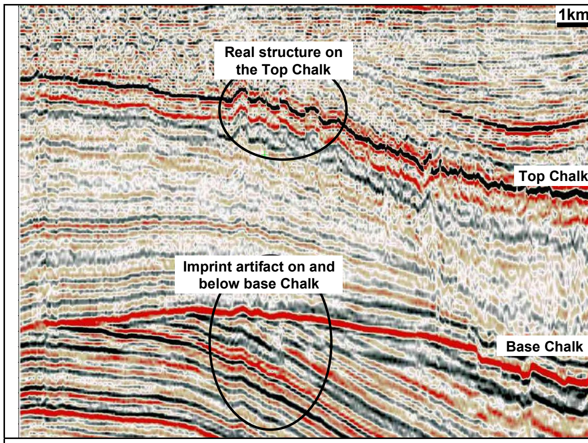

Figure 11: Inline depth section from the purely gridded tomographic model. The corrugations on the top chalk, associated with the crater-like feature are clearly visible. Below these corrugations, we see an imaging artifact resulting from velocity smearing through the top chalk.

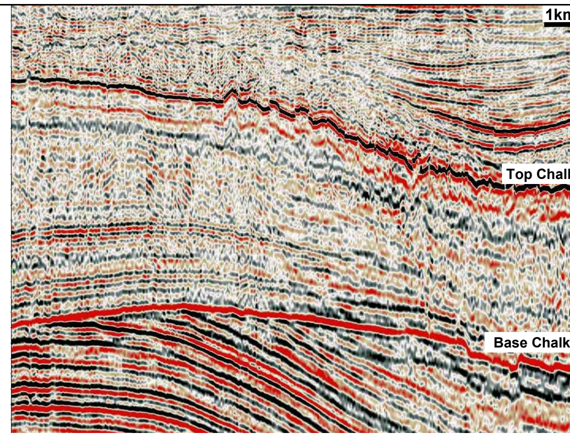

Figure 12: Inline depth section from the hybrid gridded model. The corrugations on the top chalk, associated with a crater-like feature are still clearly visible. However the imprint of these corrugations below the top chalk has been removed, producing a more reasonable image.

Imaging

Following completion of the model building, amplitude preserving 3D depth migration is performed usually using a Kirchhoff scheme for modest structural problems. A Kirchhoff scheme is suitable and adequate for most of the imaging problems we face, and has appeal due to its practicality, especially for iterative model building. For multi-pathing issues, as found below complex salt bodies, we use a Wavefield Extrapolation (WE) algorithm instead. This can be a one-way scheme, but more recently, full two-way solutions (suited for highly complex environments) such as reverse time migration (RTM) have become available (Farmer et al, 2006).

However, whichever imaging algorithm is most appropriate for our imaging problem, we must ensure that we strive to preserve the bandwidth and resolution inherent in the data and preserve any amplitude variation with offset (or angle) as required for subsequent attribute analysis.

Conclusion

For successful processing of seismic data, it is important to keep your options open. A diverse toolkit for noise and multiple attenuation, combined with a flexible model building system, and amplitude preserving imaging algorithms are necessary prerequisites to successfully accomplish this task.

It should also be kept in-mind, that as computer power and algorithmic developments make significant progress on a time scale of a few years, that it is worth considering re-processing vintage data periodically in order to extract maximum benefit from the acquisition effort.

The integration of client interpretational expertise in the model building stages of the process is invaluable. Such integration allows the interpreter to gain ongoing insight into the behaviour of the geology during the progress of the model building, such that additional effort can be targeted at areas of interest as required.

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