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The seismic response to strong vertical velocity change

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Summary

Conventional seismic data processing, whether it be pre-stack data conditioning or migration, is designed with the theory of P-wave reflected energy in-mind, for travel paths involving only a single reflection. Any energy propagating with other modes or travel paths will not be dealt with appropriately during conventional seismic data processing. It is primarily for this reason that we spend so much time pre-conditioning seismic data, so as to meet the assumptions of the subsequent migration. In this study, looking at shallow-water marine data from high velocity- contrast environments (such as found with basalt or carbonates), I assess the behaviour of some other classes seismic energy, when subjected to conventional processing, so as to better understand the anomalous events appearing in migrated CRP gathers and images, due to contamination of the data with remnant refraction and mode-converted energy.

Keywords: *P-wave processing, artifact, mode-conversion, refraction*

Introduction

Due to the high velocity and density contrasts associated with basalt, chalk, or salt layers, and large vertical velocity gradients in the overlying sediments, we often record refraction and sometimes converted mode (PSSP, PSPP, PPSP) seismic arrivals. During conventional processing, these arrivals are dealt with ***as if*** it they were P energy, giving-rise to anomalous behaviour in the migrated data. Ideally, the data pre-conditioning steps (such as linear noise removal) should remove these events prior to velocity estimation and migration, but often spurious remnants of them remain.

Here I present a modelling study to assess behaviour of chalk-related seismic reflection and refraction events on a shallow-water marine survey (Jones, 2013b). Diving rays and refractions resulting from large vertical compaction velocity gradients are also addressed, as remnant energy from these events impinges on the underlying chalk reflections. The study attempts to qualitatively highlight some of these effects, so as to give insight into the nature of the observed results on real data associated with unusual behaviour observed in gathers during velocity model building and images after migration.

Modelling study

The P-wave velocities were derived from the high resolution tomographic preSDM model derived on a commercial preSDM project over a region in the North Sea (using a tomographic inversion cell size of 50m * 50m * 50m in the chalk to resolve thin intra-chalk layering). This was verified and calibrated using available well sonic logs. Density was estimated using a modified Gardner relationship, calibrated to the available density logs, with ‘reasonable’ values used in the shallow section (which was not logged). In addition, some literature was reviewed to determine a range of realistic shear-wave velocity and density values near the sea bed (e.g. Carbone et al., 1998; Muyzert 2006; Shillington et al., 2008).

2D modelling was performed using both finite difference (FD) and ray-trace techniques, both acoustically and elastically. All modelling was isotropic, and for investigation of post-critical phase change, attenuation was turned-off so as not to further change the wavelet’s phase. The modelling was performed primarily using GXII, but also in ProMax. For the ray-trace part of the study, a layered model was constructed, and for the detailed analysis of elastic events, a locally flat model analog was made to remove any structural bias.

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The study concentrated on a single representative inline, and four nearby wells. A depth migrated seismic section with superimposition of these wells shows that we have at least three high velocity bands within the chalk and a strong compaction gradient above it (Figure 1).

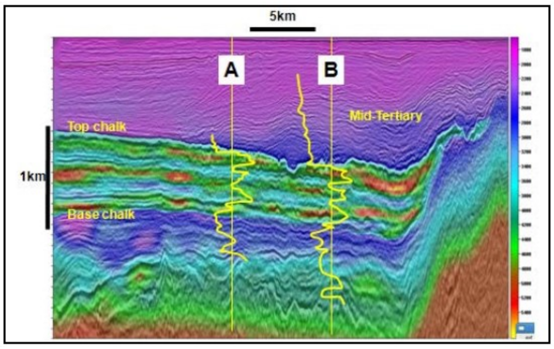

Figure 1: smoothed interval velocity logs superimposed on the preSDM image, with tomographic velocity colour overlay. The wells are from nearby locations, so do not tie the line perfectly. The locations of the top and base chalk, and mid-tertiary reflector are also indicated.

Figure 2 shows the elastically modeled FD synthetic data (created with the model shown in Figure 1) after preSDM using the correct model (that used to create the synthetic data). Real 3D preSDM data, from an intermediate stage in the production project (not final gathers) are shown in Figure 3: these gathers exhibit many of the features seen in the modelled data.

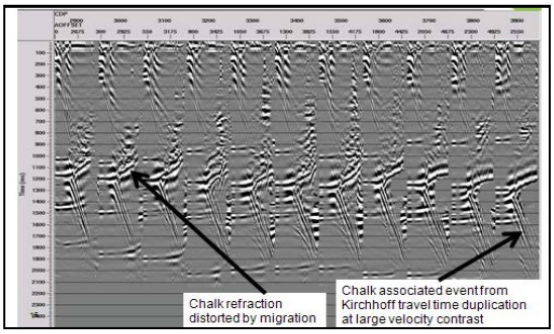

Figure 2, preSDM of the FD modelled gathers (using the correct velocity model), converted to time. The refracted energy looks anomalous, as migration is not designed to handle refracted events

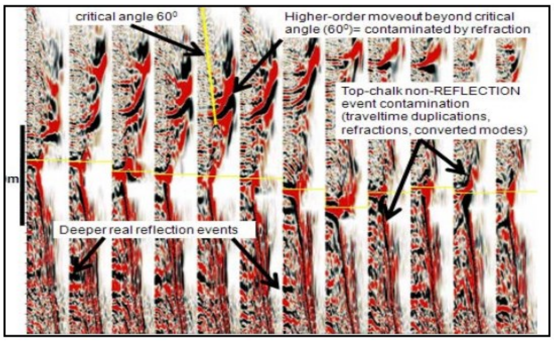

Figure 3, real data from near the seismic preSDM section shown in Figure 1. Many of the features seen in the modelled data (Figure 2) are also present here. Maximum offset 5.2km.

Simplified modelling to help understand complex arrivals

The moveout behaviour observed in the modelling performed using finite differencing with the complex velocity model does indeed produce results resembling the observed data. However, to better understand the nature of the observed events, I'll commence the analysis by first considering a grossly simplified set of models, and then move on to introducing converted modes in the modelling by using elastic rather than acoustic modelling.

Before considering more complex multi-layered models lets first look at the behaviour of a half-space (that is, a model with two solid regions, with a reflecting boundary at some depth between them). Figure 4 shows FD acoustic modelling of a half-space with reflection and refraction events for a 'top chalk' reflector model, with upper medium velocity = 2700m/s and lower region chalk velocity = 4800m/s. Visible are the direct wave arrival, the top chalk reflection, and commencing at the critical-angle offset, a refraction event can be seen slightly above the post critical reflection trajectory.

Figure 5 shows a more complex model with several layers, and Figure 6 shows these data after application of NMO with the corresponding RMS velocity. The chalk event is flattened, the refracted head wave curls upwards (resembling anisotropic reflection behaviour), and elements of the chalk reflector are distorted into a linear downward trending event by the NMO process.

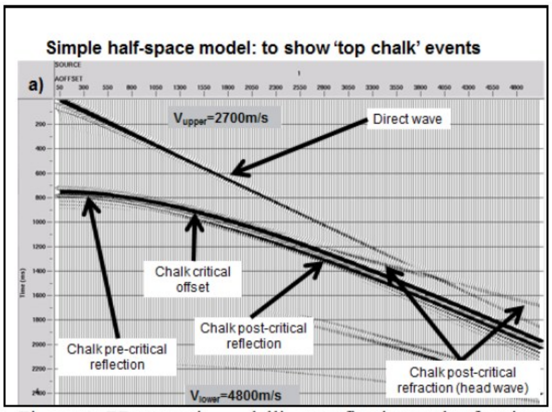

Figure 4: FD acoustic modelling. reflection and refraction events for a 'top chalk' half-space reflector model

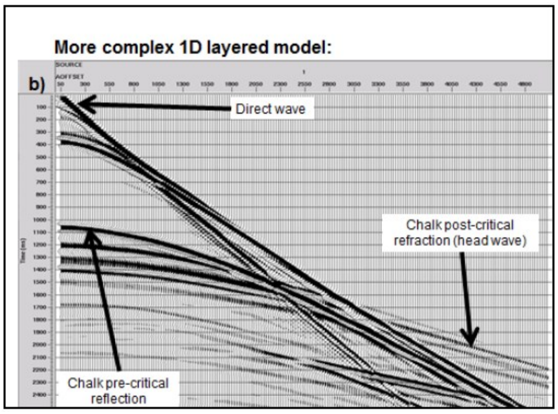

Figure 5: FD acoustic modelling of more complex 1D model.

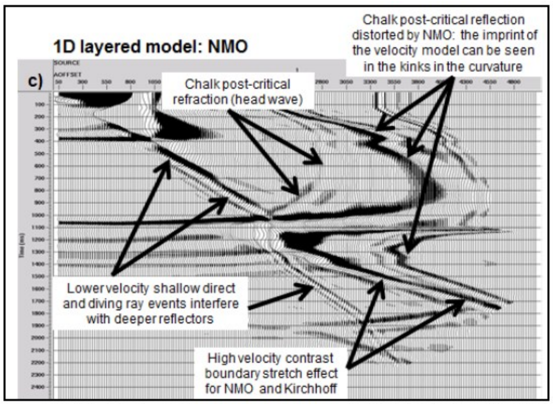

Figure 6: FD acoustic modelling. NMO of the data in Figure 5 produces various kinds of distortion: the downward trending NMO high-velocity contrast boundary artefact is visible, and other non-P reflection events are distorted by the NMO function.

Converted mode arrivals

For the synthetic modelling performed, converted modes are associated with the mid-tertiary and top chalk reflectors, but for the purposes of demonstration, I'll discus only those related to the top-chalk event, as this was present across the entire region. For the various converted modes seen, the conversion takes place at the sea bed for transmitted events and at the high velocity-contrast interfaces for reflected events.

In Figure 7 I show the elastic ray-trace modelled data for the 1D model, showing the input and NMO'd CMP but just for the top-chalk reflection and associated mode-converted arrivals. Conversion is occurring at the sea bed for transmission and at the top chalk for reflection, so we are seeing PSPP, PSSP, and PPSP arrivals, as well as the usual PPPP arrival (the PSPP and PPSP events are coincident as their arrival times are the same for the 1D model). On the right is shown the full FD elastic modelled result for all events in the 1D model result for comparison. In the full FD modelling, we see mode-converted energy from both the tertiary and top chalk events. Amplitudes will differ between the ray-traced and FD modelled data, as ray tracing primarily delivers reasonable kinematics, whereas FD modelling should also produce reasonable dynamics.

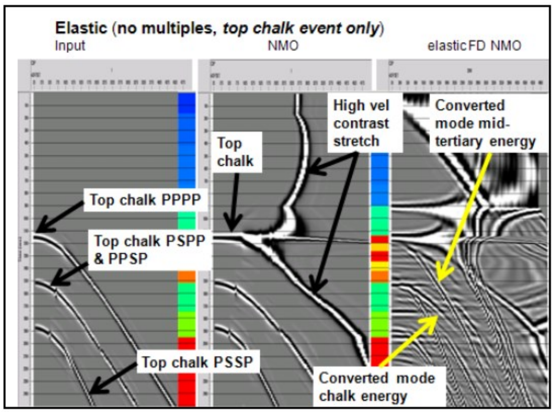

Figure 7: elastic ray-trace modelled data with 18Hz peak frequency for the chalk layer 1D model, showing the input, and NMO'd CMP, for the top-chalk reflection and associated mode-converted arrivals .On the right is shown the FD elastic result for comparison. We see mode- converted energy from both the tertiary and top chalk events, as well as the strong travel time bifurcation related event.

Comparison with Real data.

In Figure 8, I show the synthetic FD data where the moveout trajectories of the converted mode events have been picked on the migrated CRP gather (yellow dotted lines), and then also superimposed on the real data shown in Figure 9. The real data shown in the left panel of Figure 9 are those used as input to the migration (with various linear noise and some demultiple processing). Both after NMO (centre panel) and after preSDM (right panel), the data still show some remnant noise associated with the converted mode energy. The downward (and upward) dipping linear noise from the chalk refractions can be partly removed using a Radon filter.

These classes of remnant energy are still quite persistent even after significant pre-processing efforts. They could indeed be further attenuated, but this would most likely require more 'heavy-handed' pre-processing that would probably also damage the underlying desired signal. Their presence after the pre-processing leads to misleading events in the CRP gathers, and can thereby especially hamper velocity model building, as the quasi-linear trends and abrupt amplitude anomalies can degrade the performance of the various transforms used in velocity analysis (Jones, 2013a). They are less of a problem in the final image, as they tend to stack-out.

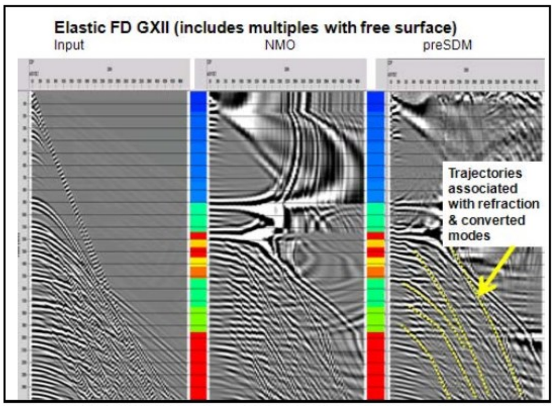

Figure 8: FD elastically modelled data with all multiples, showing raw data, after NMO correction, after preSDM. Superimposed on the migrated gather are show manual picks of the moveout trajectories of the converted and refracted events (yellow dotted lines)

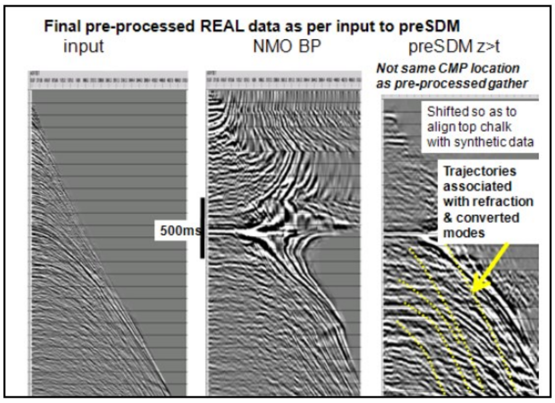

Figure 9: real data at with pre-processing as input to final migration, showing input data, after NMO correction, after 3D preSDM. The yellow trajectories on the preSDM are the refractions and modelled converted modes from the tertiary and top-chalk as picked on the modelled data migrated gathers. It can be seen that remnant noise in the real data does appear to correspond with the modelled residual refraction and converted mode events.

Conclusions

Refraction and mode-converted energy is not correctly handled by conventional P-wave single reflection processing, and hence should ideally be removed prior to migration. However, remnant energy from such events invariably remains in the data after pre-processing, and contaminates the resultant CRP gathers and images. Here I have tried to demonstrate the nature and behaviour of this remnant energy, so as to give some insight into what detail we should be focusing on and what we should be ignoring in resultant gathers and images.

Acknowledgements

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