Complete Wavefield Imaging Using Broadband Dual-sensor Streamer Data

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SUMMARY

When considering shallow water towed streamer data, developing an accurate velocity model using primary reflections alone is challenging and often only allows an average velocity of the near surface interval to be defined. For robust reservoir imaging, it is essential to resolve near surface velocity heterogeneity, thus the conventional VMB approach, which uses data acquired with standard streamers, is compromised.

A methodology for VMB utilising the complete wavefield has been presented. The foundation of the method is dual-sensor towed streamer data which allows separation of the recorded wavefield and is thus the technology enabler for an advanced imaging workflow. Complete wavefield imaging delivers a high-resolution velocity model of the near surface which in a conventional approach typically remains unresolved. The more accurate near surface velocity model and subsequent imaging improves the accuracy and confidence of the imaging at reservoir levels.

Introduction

Here we present a new and innovative method for robust velocity model building (VMB) in shallow water environments. The majority of marine datasets are acquired with towed streamers where only the primary reflections are conditioned for VMB using a tomographic solution. This conventional approach suffers from a very limited offset range at shallow depths resulting in poor angular illumination. Limited angular/offset illumination leads to poorly constrained velocity updates from reflection tomography alone. In regimes where the near surface structure is laterally variable, the lack of detailed velocity control in the shallow section often leads to compromised and ambiguous imaging at reservoir intervals.

To overcome the challenges of VMB in shallow water and improve imaging accuracy at reservoir intervals, we propose a methodology which incorporates analysis of the complete wavefield including refractions and multiples not just the primary reflections (Figure 1). This approach provides increased illumination of the near surface and hence greater velocity control. The method is made possible by wavefield separation of dual-sensor towed streamer data and leverages wavelet-shift tomography, full-waveform inversion (FWI) and separated wavefield imaging (SWIM) technologies within an integrated workflow. A case study using field data is presented where the study area exhibits a complex subsurface below the water bottom at 150m depth. Work on this data remains ongoing.

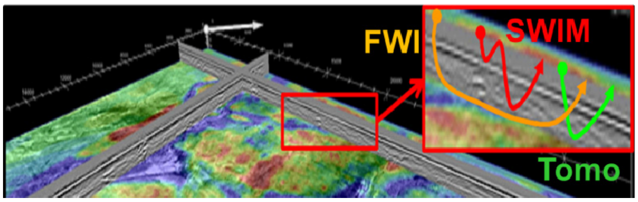

Figure 1 *Sketch of the different wave types and technologies employed in complete wavefield imaging.*

Methodology

Imaging with multiples to establish a near surface velocity trend

The first stage of the method consists of building a good initial model for the subsequent FWI updates; the model needs to be sufficiently accurate to prevent cycle skipping. This is achieved by using reflection tomography, but due to the shallow water environment, this becomes challenging in the very near surface. With conventional techniques it is possible to obtain a good estimate of the average velocity down to a depth where the angular illumination is sufficient for reflection tomography to function robustly, however the correct near surface gradient (*k)* of the velocity field is difficult to assess. We propose to perform migration scans of different velocity gradients, utilising the SWIM technique (Whitmore *et al*., 2010) to assess the optimal gradient in a long wavelength sense.

The top panel of Figure 2 shows offset gathers from traditional imaging of the field data where the initial model was constructed from available well information. For this model two shallow gradients of k=1 and k=3 were scanned, keeping the average velocity constant at a depth of z=350m, which is at a depth where enough offset illumination is available to make an assessment of gather flatness. The effect of the gradient remains difficult to assess above this level due to the very limited offset range. SWIM enables us to develop a more robust image of the shallow subsurface with well-sampled angle gathers where residual moveout can be assessed (Figure 2, bottom).

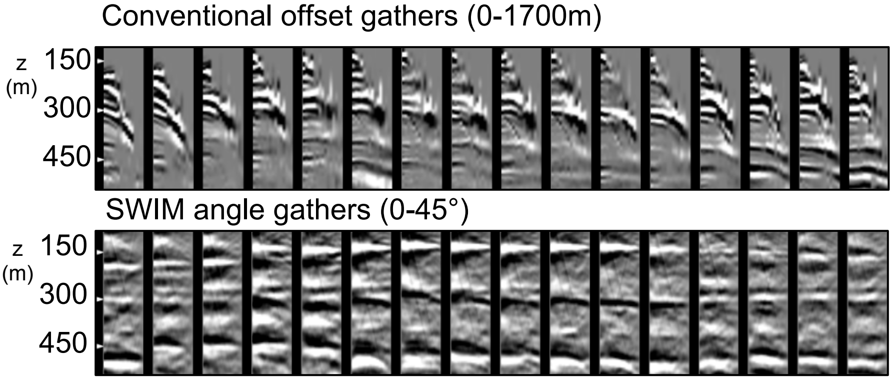

Figure 2 *Offset gathers in depth from conventional imaging for a velocity gradient k=3, with confirmation angle gathers from SWIM using the multiple wavefield to give greater illumination.*

In conventional hydrophone streamers, the down-going wavefield after reflection from the sea surface interferes with the primary up-going wavefield as the receiver-side ghost. However, utilizing a dual-sensor streamer, it is possible to separate these interfering wavefields into up-going and down-going components without interference. Therefore, as the down-going wavefield passes through the receiver array, this energy becomes effectively a new source within the field experiment. Each receiver becomes a new source position which delivers improved sub-surface illumination. This is illustrated with the field data in Figure 3, which compares a very shallow depth slice at z=170m obtained from conventional imaging and SWIM. The conventional image suffers from poor cross-line coverage associated with the acquisition sail line spacing while the SWIM image has much enhanced coverage and spatial resolution.

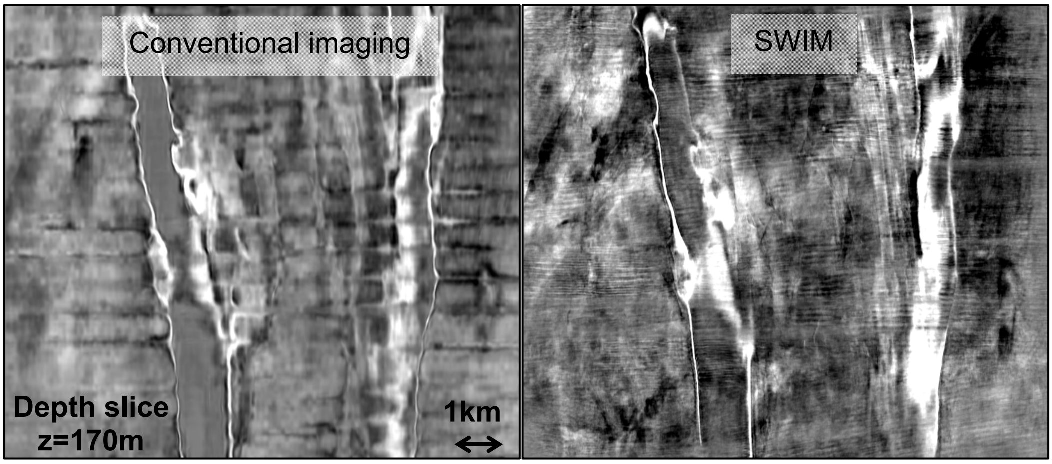

Figure 3 *Shallow depth slice at z=170m from conventional imaging (left) and SWIM (right). Note the better spatial illumination and increased detail from SWIM.*

Shallow model refinement with FWI

Having validated the near surface velocity gradient using SWIM, the velocity model is further refined using an FWI approach. The FWI technique updates the velocity model driven by data residuals, where within an iterative loop, we minimize the differences between the observed data and modelled data.

Figure 4 shows an example of a recorded and modelled shot gather from the field data. FWI does use the complete wave field but the updates are mainly driven by refractions and diving waves in shallow environments. To ensure convergence, the inversion process starts with the lowest possible frequency in the data containing coherent energy, typically around 2Hz. In this example, the data are rich in low frequencies due to the deep towing configuration which is typical when using dual-sensor streamers

(Zhou *et al.*, 2013). Higher frequencies are added to the data bandwidth as the inversion progresses, adding spatial resolution to the velocity updates. Figure 5 shows the velocity difference from an early FWI iteration run on a swath of sail lines, the structural conformability with the main channel feature is evident.

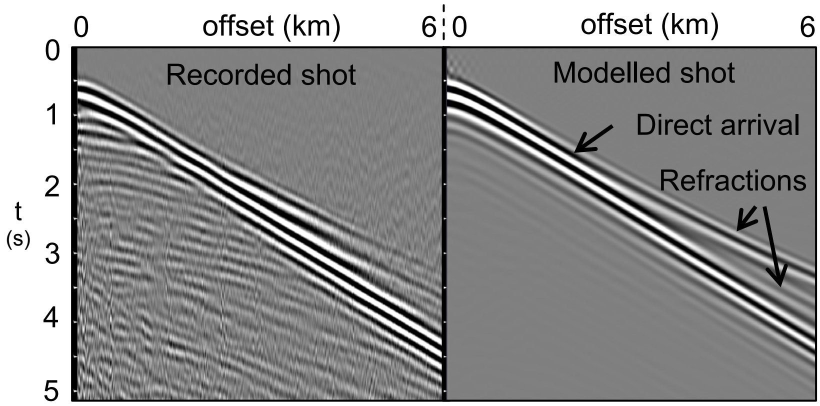

Figure 4 *Input and modelled shot gathers from FWI up to 6Hz.*

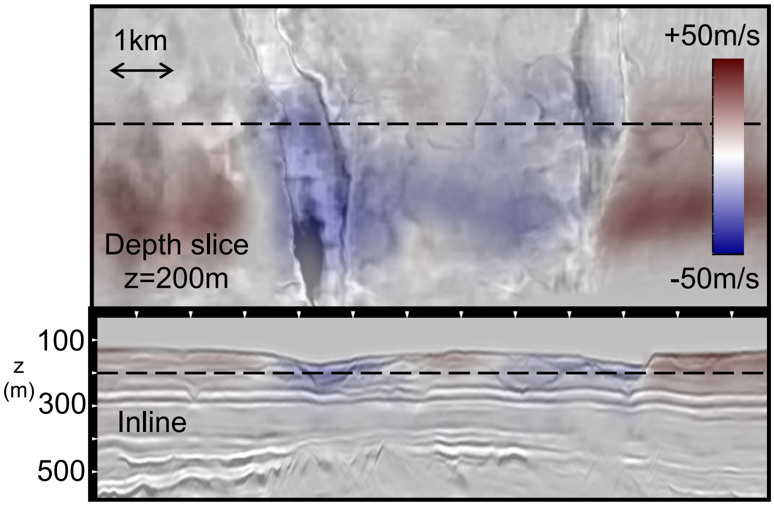

Figure 5 *FWI update (early stage) difference along 200m depth slice and inline. Note conformability with the channel structures.*

Deeper model build with wavelet shift tomography

Once the complexity in the shallow overburden is resolved the model building is completed by applying wavelet-shift tomography using primary reflections. The process consists of decomposing the recorded data into beam-derived wavelets, migration mapping of the wavelets to the depth domain followed by reconstruction into an image. Subsequent tomographic slowness updates of the model may be performed utilising back projection of 3D travel-time residuals combined with other wavelet attributes (Sherwood *et al.*, 2011). The velocity model produced with wavelet shift tomography is well conditioned as all data used within the image are employed to drive the tomographic updates. This produces geologically consistent models of very high spatial resolution.

Conclusions

When considering shallow water towed streamer data, developing an accurate velocity model using primary reflections alone is challenging and often only allows an average velocity of the near surface interval to be defined. For robust reservoir imaging, it is essential to resolve near surface velocity heterogeneity, thus the conventional VMB approach, which uses data acquired with standard streamers, is compromised.

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