Non-linear scanning tomography for velocity model building in seismic-obscured areas

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Summary

Non-linear slope tomography offers numerous effective solutions for velocity model building in complex geologies. One of its great advantages is the possibility to merge picks coming from common image gathers (CIGs) obtained on different velocity model. Here a new workflow of integrating selected CIG picking from different migration velocity for non-linear slope tomography is put forward to resolve large velocity errors associated with complex geology which can cause poor imaging or migration artifacts. We propose to first create a series of trial velocities from the initial velocity by varying its values inside poor imaging zones. Migrations are then applied using these trial velocities. The second stage involves CIG picking on these migrated gathers with tight constraints to ensure reliable picks. Following the process of non-linear slope tomography these CIG picks are then de-migrated to kinematic invariants with their corresponding trial velocities. The final stage is a joint tomographic inversion using all the invariants combined. The new workflow can bring more reliable information to the tomography inside complex geology where the S/N ratio is low and/or the initial velocity has large deviation from true velocity. As a result, it can give more reliable and robust velocity updates.

Introduction

Imaging through Seismic-Obscured Areas (SOA) is a long-standing challenge in seismic processing. One of the major problems is to get a high resolution velocity update within such areas. This problem is caused by the lack of sufficient reliable reflector residual moveout (RMO) information that can be used for tomographic inversion, especially when the starting velocity is far from correct and large amounts of migration artifact are generated. If this complex geology resides in shallow areas, a good solution is diving wave Full Waveform Inversion (FWI). However, deep structures are beyond diving wave FWI penetration, and reflection FWI suffers from the lack of clear reflectors and/or cycle skipping issues. The standard approach to this problem is tomography or manual updates with input from geological interpretation. Tomography suffers from unreliable CIG picks or even no picks at all due to low quality gathers when the velocity error is large. Manual updating using geological interpretation sometimes gives better results, but is subjective. We propose a new tomography-based and scanning-based workflow to resolve this issue. A similar scanning approach, called Common Reflection Point (CRP) scan, was mentioned in traditional non-linear tomography (Guillaume, 2003; Audebert *et al.*, 1996). This technique was used to select one velocity that gives the smallest overall RMO for the starting migration. Thus, only one set of picks from this single migration is used in the tomographic inversion. Our new approach uses multiple sets of picks instead of one, giving tomography more reliable information to resolve complex velocity. A similar scanning-based tomography method was presented by Wang *et al.* (2006), specifically to resolve velocity below salt bodies. This method picks only on migrated stacks generated from different perturbed velocities and de-migrates the picks to the bottom of salt (BOS). This method requires a clear and accurate BOS to be present in the seismic. Our proposed approach is not limited by this constraint, so it can be used for all complex geology including salt bodies.

Traditional non-linear tomography

Before introducing the new method, we present a simple review of traditional non-linear tomography. The first step of a standard tomography is to migrate the data D with initial velocity V_0:

$$G_0 = L(V_0)[D] \tag{1}$$

where G_0 denotes the migration gathers in the image domain, $L(V_0)$ denotes the migration operator with velocity V_0. Stack S_0 is obtaned by stacking on the gathers G_0. V_0 can be obtained from previous time/depth processing. CIG picking is then performed on migrated stack and gathers:

$$C_0 = P(S_0, G_0) \tag{2}$$

where C_0 denotes CIG picks obtained from the picking process P with stack S_0 and gathers G_0. Kinematic de-migration of CIG picks generates invariant I which is independent of migration velocity:

$$I_0 = L_K^T(V_0)[C_0] \tag{3}$$

where L_K^T denotes kinematic de-migration (Guillaume *et al.*, 2008). Tomography updates velocity using this invariant and original migration velocity:

$$V' = T(V_0, I_0), \tag{4}$$

where T denotes tomographic inversion.

Proposed non-linear scanning tomography

Our proposed approach starts with creating a series of trial velocities by varying the values inside the area of complex geology while keeping the velocity values elsewhere unchanged:

$$V_0 \rightarrow V_i \qquad i = 1,2,3\cdots,n \tag{5}$$

These trial velocities serve as prior estimations of the true velocity, such that some events may appear to be flat and coherent when migrated with one of these trial velocities. Migrating data with all these trial velocities gives multiple stacks S_i and gathers G_i which are available for CIG picking.

$$G_i = L(V_i)[D] \tag{6}$$

Individual CIG picking is then performed on each stack and gather combination to form CIG pick subsets.

$$C_i = P(S_i, G_i, f) \tag{7}$$

Here we apply a tight constraint, f, to ensure picking of only the primary events. Since the trial velocity may deviate far from the true velocity, we pick only flat and strong events with user-defined gamma control, where gamma is defined as the ratio between the true velocity and current migration velocity. Cross correlation between picks and corresponding events on gathers can also be used to further remove unreliable picks. Each stack and gather combination from one trial velocity is associated with one subset of picks. Individual subsets of these picks may not cover the whole seismic-obscured area, but combining all subsets often gives decent coverage, allowing a good tomographic update. De-migrating the high-graded picks with their corresponding trial velocity gives a series of invariant sets (Guillaume *et al.*, 2008).

$$I_i = L_K^T(V_i)[C_i] \tag{8}$$

These invariants can be combined into one set. Then the updated velocity can be obtained from tomography inversion starting at initial velocity with combined invariants.

$$V' = T(V_0, I_{1,2,\cdots,n}) \tag{9}$$

Compared to traditional tomographic workflows, this approach provides reliable picks for inversion by perturbing the velocity, allowing robust velocity updates without the need of human interpretation, even when the starting velocity is far from the actual. The updated velocity will be more objective and closer to the true velocity. This is particularly suitable for deep gas cloud velocity updates, since usually the starting seismic velocity is far larger than the true gas velocity due to strong absorption which causes notorious SOA underneath.

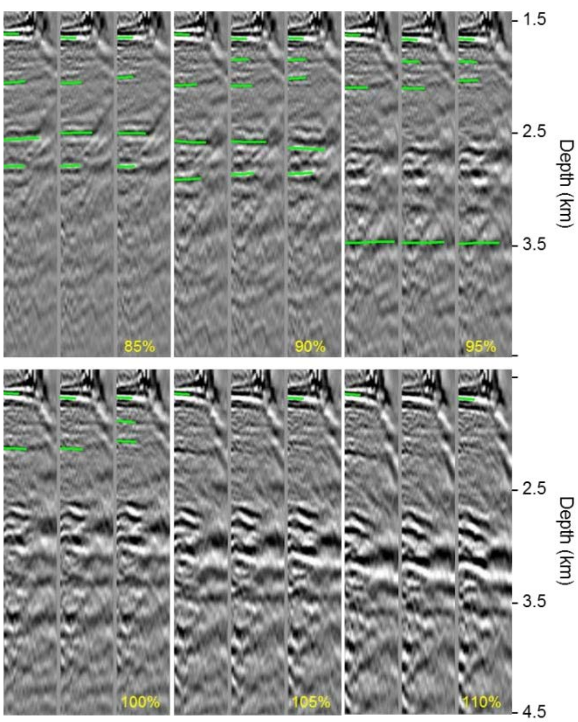

Figure 1: CIG picks (green) on migrated gathers created with different trial velocities.

Field data example

Non-linear scanning tomography was applied to 3D streamer data offshore Brunei where complex gas clouds pose serious imaging problems. The data had been

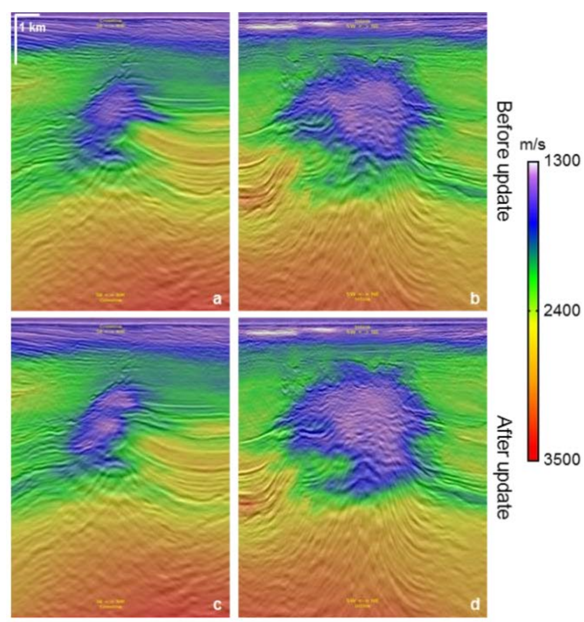

Figure 2: Velocity overlaid on seismic full stack (unchanged) before (upper) and after (lower) non-linear scanning tomography

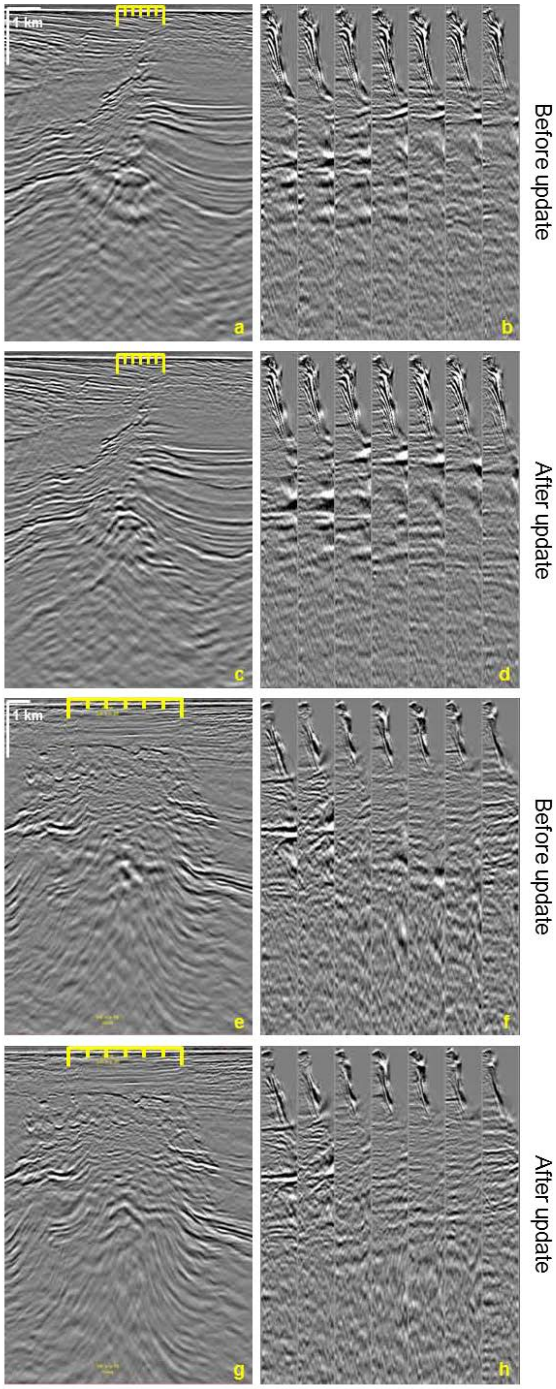

Figure 4: Q TTI Kirchhoff migration stacks and CIG results before and after non-linear scanning tomography. The locations of the CIG's are indicated by the ticks on stack sections. Panels a-d correspond to the area shown in Figure 2a. Panels e-h correspond to the area shown in Figure 2b.

processed earlier (Lin *et al.*, 2016) using the following advanced processing flow. Refraction FWI (Warner *et al.*, 2013) was used to resolve shallow gas clouds followed by FWI-guided Q tomography to compensate amplitude dimming and phase distortion in the deep gas clouds (Zhou *et al.*, 2014). To further improve the velocity in the deep, geologically-guided scenario testing was implemented to build the deep gas velocity model. Finally, Q TTI Reverse Time Migration (RTM) was selected to further improve imaging quality (Xie *et al.*, 2015; Ratcliffe *et al.*, 2014). With these technologies in place, the final seismic image showed great improvement over the 1993 result. However, the image under deep gas clouds was still obscured due to large velocity errors.

Starting from this velocity model, dual azimuth tomography was used to further improve the image. This improved the images outside the gas clouds, while improvements inside the gas clouds were limited. Our new approach was then utilized together with dual azimuth tomography. The first step of our approach scans the velocity inside the gas cloud while keeping the velocity outside unchanged, allowing more picks to be generated inside the deep gas clouds for tomographic inversion. Figure 1 shows 6 sets of CIG picks, associated with 6 trial velocities, overlaid on migrated gathers inside one deep gas cloud at around 2.2 km to 4 km depth. The initial velocity is denoted as 100%. At 100% to 110% velocities, the events in the deep gas zone on migrated gather are broken, misshaped, or severely curving down. CIG picks at these velocities are not reliable. At 85% and 95% velocities, corresponding events appear to be coherent and close to flat, making them more reliable. The reliable picks were de-migrated, combined and input to non-linear tomography.

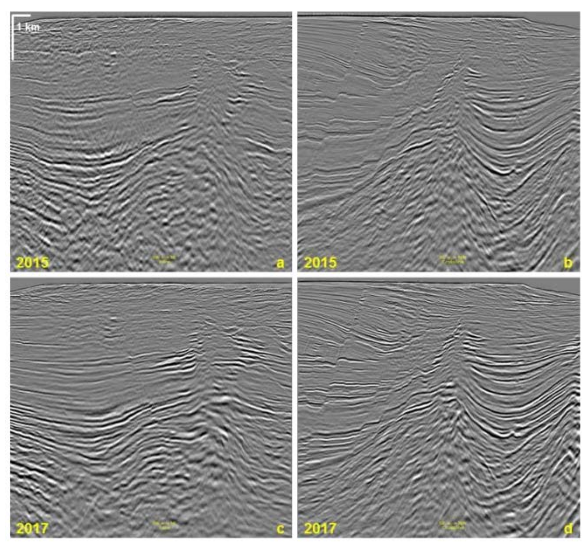

Figure 3: Final Q TTI RTM full stack comparison. Upper: 2015 processing; Lower: 2017 re-processing.

Figure 2 shows the updated velocity obtained using our new approach. Compared to the initial velocity (Figure 2a, b), the updated velocity is lower inside the gas clouds, consistent with our expectation. Specifically, our new

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approach resolved two small gas bodies shown in Figure 2c which were previously interpreted as one (Figure 2a). Q TTI Kirchhoff migration results show flatter and more continuous gathers with less noise, and more coherent, focused and geological events in the full stack (Figure 3).

To further improve the final image, we adopted not only Q TTI RTM as in the 2015 processing, but also Multi-Azimuth stack (MAZ stack). By combining data from two azimuths, we have improved illumination in the SOA, providing more continuous and focused events. The final Q TTI RTM result comparison (Figure 4) shows significant uplift. Some complex structures inside and under the mega gas cloud, unclear or not present in the previous data, are clearly imaged with non-linear scanning tomography. In particular, Figure 4b and 4d demonstrate that our new approach works not only on the gas clouds but also under the fault above the gas clouds (fault shadow problem).

Conclusions

A new picking workflow for a non-linear slope tomography-based velocity model building approach is presented for resolving large velocity errors in seismic-obscured areas associated with complex geology. Local velocity scans provide a suitable environment for increasing the success of CIG picking. One set of CIG picks associated with a single initial velocity field provides limited information for tomography in these complex areas. However, the combination of all available sets of CIG picks from various scans exhibits a sufficient degree of accuracy and density for non-linear tomography to succesfully update the velocity model. This new approach has been tested on extremely challenging field data offshore Brunei, and has proven to be highly effective. Our approach is not limited to gas clouds, and can be applied to any data which suffers from large velocity errors due to complex geology.

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