Dip constrained non-linear slope tomography: an application to shallow channels characterization

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Abstract

Ray based migration velocity analysis from pre-stack seismic reflection data is based on the characterization of the migrated reflected events by their position, dips and residual move-out. Such approaches update the depth velocity model through an optimization process, where the residual move-out of the picked migrated events is minimized while obeying some regularization constraints related to the depth or the shape of some horizons or the smoothness or structural conformity of the velocity field. We propose to introduce an additional term in the cost function involving the dip of kinematically migrated locally coherent events. The velocity is then updated to match the expected dip of the re-migrated events. We develop here the theoretical aspects of this approach within the frame of non-linear slope tomography and present a first application to the characterization of very shallow channels creating pull-up and pull-down effects in deeper parts of the migrated image. Due to the very limited offset range these effects could not be solved by residual move-out based tomography, but we demonstrate that the introduction of the dip inversion allows correcting for these pull-up and pull-down effects, resulting in improved depth imaging.

Introduction

Velocity model building aims at computing an accurate velocity model for seismic imaging. As the inverse problem is non-linear and ill-posed it requires both a non-linear optimization process and the introduction of relevant constraints. Among the non-linear tomography tools those based on non-linear slope tomography (Lambaré, 2008) have proven to be the basis of efficient industrial solutions able to cope with dense volumetric picking (Guillaume et al., 2008; Tieman et al., 2009). We will focus on them here. A wide diversity of constraints have been proposed, involving smoothness or structural constraints on the velocity model or positioning or structural constraints on the reflectors (Delprat-Jannaud and Lailly, 1993; Sinoquet, 1993; Jin, 1999, Adler et al., 2008).

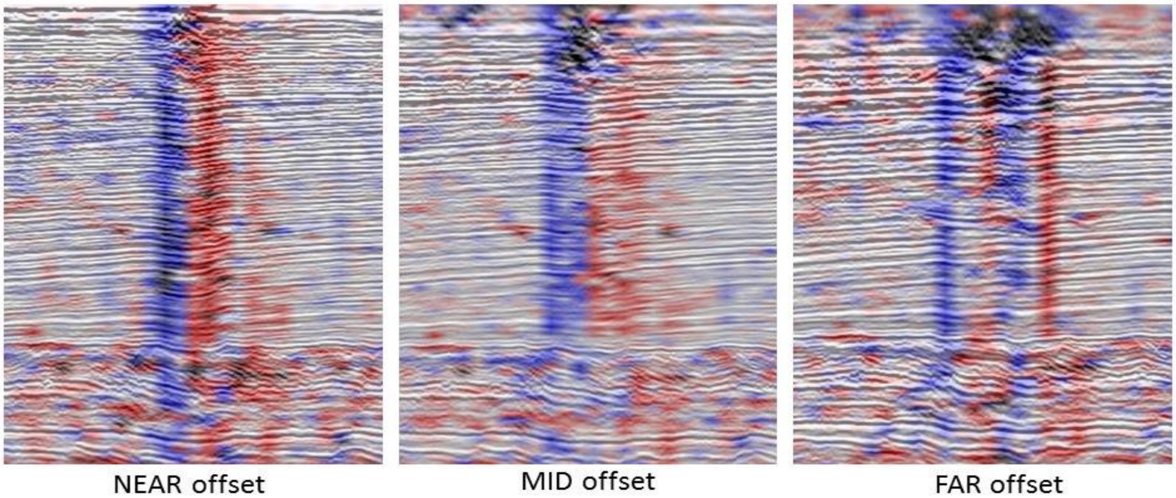

Figure 1: Pull down and pull up effects associated to very shallow channels as measured in offset stacks 0-400m, 400-800m and 800-1200m. The colour indicates the dip error with respect to a smooth dip model. This type of configuration is particularly adapted for dip constrained non-linear slope tomography.

Structural constraints can be introduced as soon as we have some structural knowledge about the expected image. In particular distortions in imaging associated to shallow heterogeneities, channels, faults, gas clouds, rough topography, or flat spot may all be corrected by proper structural constraints. So far the introduction of structural constraints on reflectors has been limited to horizons (Delprat-Jannaud and Lailly, 1993; Sexton and Williamson, 1998) and not extended to locally coherent events as considered in non-linear slope tomography. We propose to introduce in the non-linear slope tomography (Guillaume et al., 2008) an additional structural constraint under the form of a dip constraint. An extra term is introduced in the cost function for minimizing the misfit between the dip of the re-migrated events and an expected dip (e.g. the average dip). We first present this original spatial dip constraint and derive the expression of the associated Fréchet derivatives allowing the introduction of this component in the non-linear optimization scheme used by the non-linear slope tomography. We then present a first application involving very shallow channels. In this case, RMO cannot be picked with sufficient precision but clear pull-up and pull-down effects can be measured (Figure 1).

Dip constrained non-linear slope tomography

The inversion data in the non-linear slope tomography consist of a set of locally coherent events defined in the un-migrated time domain by their shot and receiver position, their two-way travel time and their slopes in all the dimensions of the acquisition geometry (x, y and vector offset) (Lambaré et al., 2008) (Figure 2).

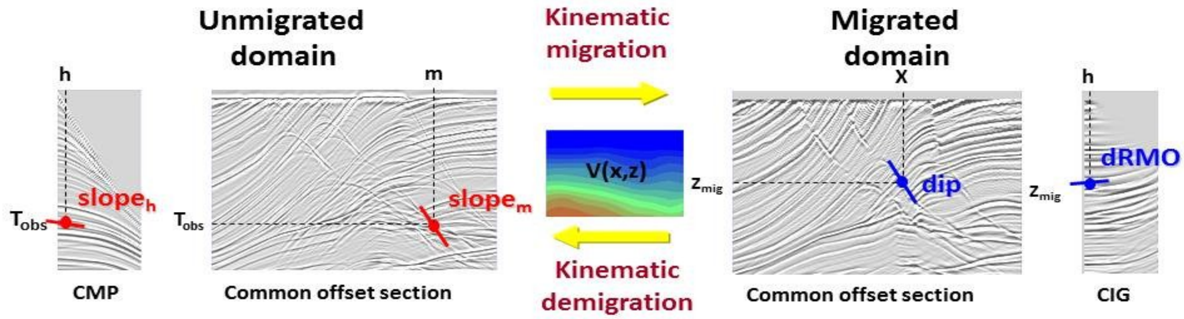

Figure 2: Kinematic invariants (left) and migrated facet (right) in 2D non-linear slope tomography (m denotes for mid-point position, and h for offset). Non-linear slope tomography aims at flattening gathers minimizing δRMO. Our proposed dip constraint introduces an additional term in the cost function involving the misfit between the dip of the migrated facet and an expected dip model.

These data are generally obtained by kinematic de-migration and because they do not depend on the initial velocity model they are called kinematic invariants (Guillaume et al., 2001). Each locally coherent event is kinematically re-migrated in the velocity model to update and for each of them we compute the derivative of residual move out (RMO) curve in offset δRMO (Chauris et al, 2002) (Figure 2). The non-linear slope tomography finds a velocity model, *m*, that minimizes the cost function *C(m)*:

$$C(m)=\sum_{events}\alpha\left\|\delta RMO\right\|^2+R(m)\ , \qquad (1)$$

where *R(m)* denotes some regularization terms on the velocity model parameters and α denotes the weighting factors associated to picked events. The non-linear slope tomography uses a non-linear iterative local optimization scheme for updating the velocity model. Fréchet derivatives of δRMO with respect to velocity model parameters can be computed thanks to paraxial ray theory (Chauris et al., 2002).

Let's consider now that we have extra information on the common offset dip of some events (Figure 2). This information consists of an expected dip value $dip_{expected}$. For example in the case of the pull-up and pull-down distortions observed on figure 1 we expect the spatial dip to follow the general trend of the structure. The offset dependent spatial dip distortions that are measured below localised velocity anomalies can be introduced in the cost function for delineating and quantifying those velocity anomalies. We then propose the extended cost function:

$$C(m)=\sum_{events}\alpha\left\|\delta RMO\right\|^2+\sum_{events}\beta\left\|dip-dip_{\mathrm{expected}}\right\|^2+R(m)\ , \qquad (2)$$

The additional term containing the misfit between the migrated and expected dips (β denotes the weight associated to each event). Dip constrained non-linear slope tomography consists in minimizing the new cost function (2) using again a non-linear iterative local optimization scheme, with Fréchet derivatives for the dip term computed using paraxial ray theory.

A shallow channel example

Due to the sparseness of picked data but also to intrinsic limitations in terms of resolution, migration velocity analysis often fail to identify velocity variations caused by very shallow channels (Figure 1). These unresolved velocity anomalies result after depth migration into distortions, e.g. so-called pull-up or pull-down effects that affect in particular the shape and the position of the migrated seismic reflectors in the deeper parts of the subsurface. Several approaches have been proposed for removing these distortions. For example the geometry of channels can be fixed while the best channel-fill interval velocity is determined by a time consuming migration velocity scan (Jones, 2010), or by migration of horizons (Robein, 2003) with a lack of accuracy and flexibility, due to the limited number of picked horizons. Introducing the dip constraint can lead to much more accurate and flexible workflows and we test it here on a typical case study from North Sea.

Figure 1 shows the pull-down and pull-up effects observed on various PreSDM partial offset stacks for a velocity model obtained by a conventional RMO tomography. The lack of RMO picks in the very shallow layers leads to poorly resolved velocities. The expected dip model is estimated from a smoothed version of the dip model. Figure 1 shows the discrepancies between the measured (offset dependent) dip and the expected dip model. A dense set of dip and RMO picks is computed by dense volumetric picking in the depth range [0, 1250 m]. It is inverted for updating the velocity in the shallow layers in [0,300 m] depth range by dip constrained non-linear slope tomography. In a final step, a conventional non-linear slope tomography is performed while freezing the velocity in the shallow layers. Figure 3 shows a depth slice at 100 m depth where the localised shallow velocity structures have been revealed by the dip constrained tomography. We see that they nicely conform to geological structures and also remove pull-down effects (Figure 4).

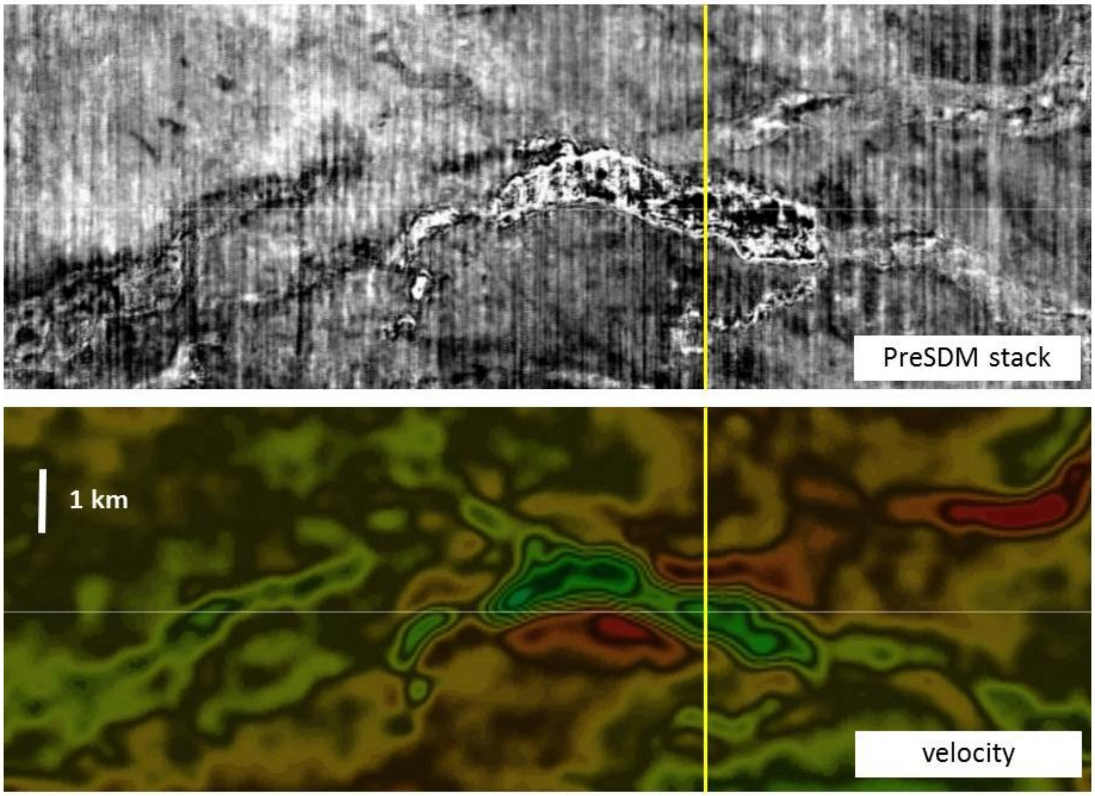

Figure 3: Shallow slice at 100 m depth of the PreSDM stack and of the corresponding velocity model obtained by dip constrained non-linear slope tomography.

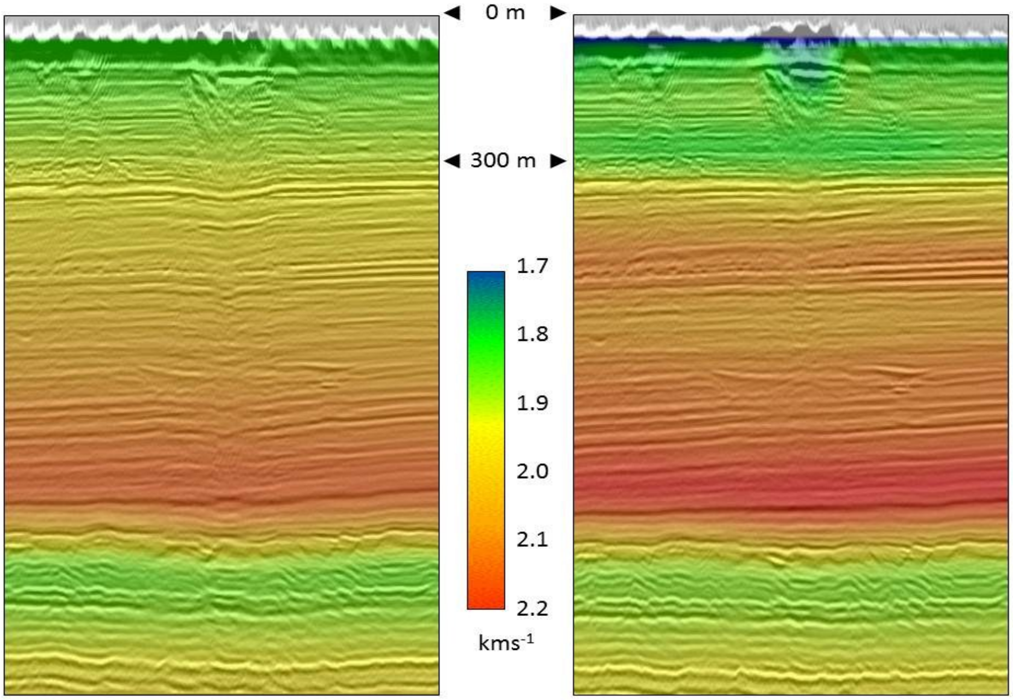

Figure 4: Vertical section of PreSDM stack and velocity model across a channel before (left) and after (right) dip constrained non-linear slope tomography. The location of the vertical section is indicated on Figure 3 by a yellow line.

Conclusions

We have shown that introducing a dip constraint in the non-linear slope tomography can improve the accuracy and the flexibility of the tool. Note that the dip constraint is a structural constraint that does not constrain the position. Used together with the RMO, it insures an optimum 3D correction to match the expected structures. As such it can correct for imaging distortions in a rather automated way. We see a wide set of potential applications for this approach that can be applied as soon as offset dependent dip observations can be made, e.g. pull-up, pull-down effects or any distortions in imaging associated to shallow heterogeneities, channels, volcanic intrusions, faults (Birdus, 2007), rough topography (Birdus 2008), flat spot, base of salt, etc.

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