Efficient Beam Velocity Model Building with Tomography Designed to Accept 3d Residuals Aligning Depth Offset Gathers

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SUMMARY

This novel Velocity Model Building (VMB) system addresses issues of Economics, Turn-Around-Time, Quality, Resolution, Stability and Ease-of-Use.

Seismic data is decomposed into wavelets, each with important, invariant attributes, particularly traveltime and dip at source and receiver locations. This wavelet representation is independent of the VM and provides the input to all subsequent PreSDM, VMB and quality control (QC) operations.

Ray tracing through a VM provides a mapping of each wavelet to its migrated spatial location and is very efficient for generating PreSDM common image point gathers (CIP) for VMB QC. The method enables the rapid estimation of a 3D spatial shift for each wavelet that produces high quality alignment of the CIP offset gathers. An efficient consistent tomography module inverts these 3D residuals into a high resolution, stable update to the current VM. The steps in this paragraph are iterated.

Workflows exploit the power of these already efficient individual processes, facilitate visualization of the QC products, ease the burden on data processing personnel, and provide rapid, flexible VMB. Examples illustrate the quality of this system.

Introduction

There are several preferred pre-stack depth migration (PreSDM) algorithms available but they are typically computationally intensive and require a previously determined quality velocity model (VM). The determination of the VM is often the most critical step in the seismic processing chain prior to final depth imaging. Efficient, stable, flexible, high quality VM building (VMB) is particularly necessary to minimize the elapse time between seismic data acquisition and seismic interpretation. This paper extends the Beam PreSDM technique described by Sherwood *et al.* (2009) to provide such a VMB system, this achieved by workflows including a novel module to estimate 3D residual move out (3DRMO) and a tomography module for consistent conversion of the 3DRMO values to a VM update. This VMB system covers land and marine, NAZ, MAZ, WAZ, FAZ acquisitions.

Method and Results

Sherwood *et al.* (2009) detail three main modules for Beam PreSDM. For clarity in this paper these are described briefly here. They will be followed by more detailed accounts of the two additional modules required for VMB.

1. Decomposition

Sensibly pre-processed seismic data is decomposed into a regular basis of time wavelets, each with important invariant attributes, particularly traveltime and dip with respect to time at its source (S) and receiver (R) locations.

2. Migration

Ray tracing through a current VM provides a mapping of each wavelet to its migrated spatial location, together with other attributes including reflector dip.

3. Reconstruction

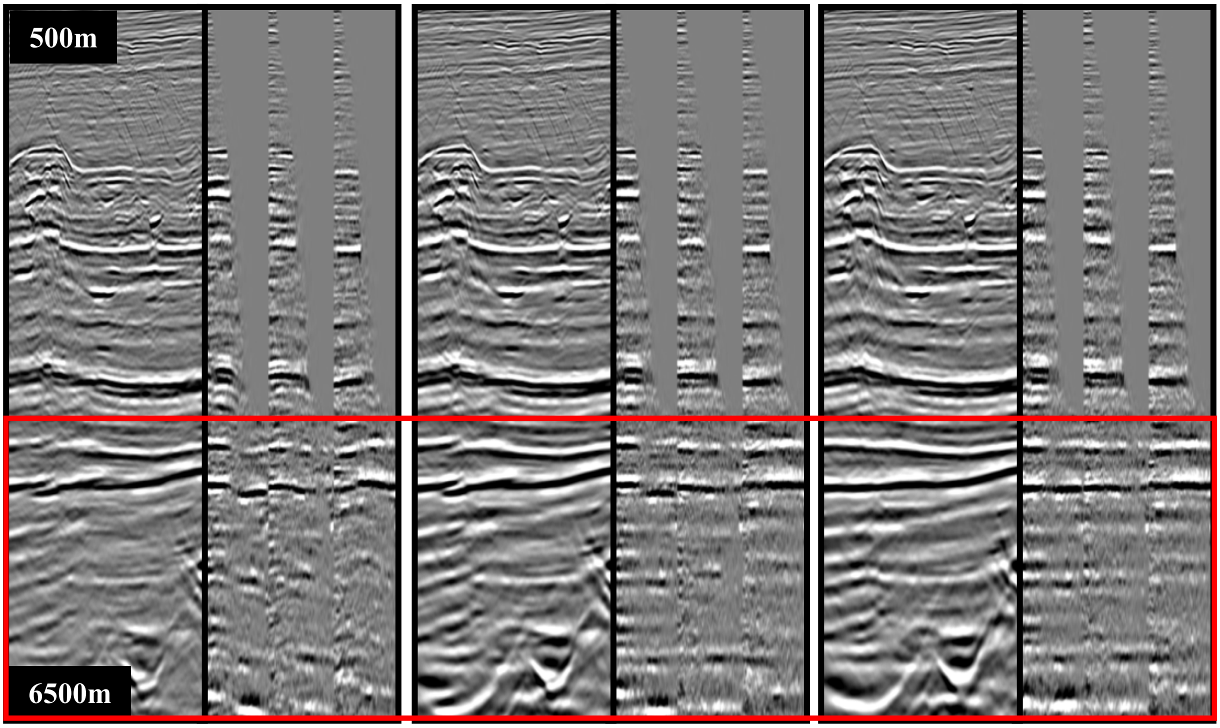
Migrated offset common image point (CIP) gathers result from reconstructing each wavelet in migrated space using knowledge of its attributes. An actual example is shown in Figure 1a, together with a corresponding stack section.

4. 3DRMO

This module uses correlation functions between wavelets in order to estimate a residual traveltime shift for each wavelet that will align it with neighbouring migrated wavelets. Note that this time shift is effectively equivalent to a 3D spatial shift of the migrated location of the wavelet perpendicular to its corresponding reflector dip, the relationship being controlled by the phase velocity specified by the current VM and the incident and reflected ray directions at the reflector. This facilitates a reconstruction (item 3) of CIP gathers, and their stack, corrected for the estimated 3DRMO shifts, as shown in Figure 1b.

If necessary, this 3DRMO procedure can be iterated and typically converges adequately within about 5 iterations. An extreme result for 10 iterations is shown in Figure 1c. Comparison with Figure 1a clearly illustrates the ability of the iterated 3DRMO shifts to align CIP gathers exhibiting complex residual move out. It seems physically significant that this quality of alignment can be achieved with the limited freedom associated with a single time shift for each wavelet. It is of obvious potential value for AVO analysis.

An important detail is the need to place a magnitude limit on the 3DRMO time shifts in order to avoid possible ‘cycle skipping’ within the corrected gathers. This limit is related to the dominant period of the time data and is typically about 12 ms to 48 ms for shallow to deep data, respectively. In the early stages of VMB the S to R offsets, or the angle of incidence at the reflector, can be restricted so that actual residual errors are within the limit imposed to avoid ‘cycle skipping’.



1a. Migrated Stack / Gather **1b. 1 iteration of 3DRMO** **1c. 10 iterations of 3DRMO**

Figure 1: *Example of the effectiveness of iterative 3DRMO for aligning beam migrated gathers.*

The iterative 3DRMO time shift for a wavelet must not be construed as the actual shift along its ray path. Due to its estimation using correlation functions, it is actually referenced to some average of the shifts for its neighbours in migrated space. Thus a stack corrected for 3DRMO will be somewhat smoothed across faults and blur them. This throws interpreters into panic mode! But, not to worry, this simply becomes an important consistency issue to address in the following tomography step. There, a wavelet’s incremental traveltime associated with an arbitrary VM perturbation must also be referenced to neighbouring wavelets approximating the neighbours used in 3DRMO. Images associated with a velocity update from a tomography consistent with 3DRMO will blur faults no more than other tomographic methods.

5. Tomography

The 3DRMO traveltime residuals are ideally suited for input to traveltime tomography. First and foremost is the high quality and density of the residuals, evidenced in corrected gathers and associated QC displays. Secondly, each wavelet is associated with a specific S and R location and has known ray directions there, together with an image point determined from depth migration with the current VM. This enables fast, direct re-computation of the migration ray path, this being required for the determination of the coefficients of a linear equation relating model slowness perturbations to a traveltime change for the wavelet. As noted earlier, this traveltime change must then be referenced to some local spatial average in order to relate to actual 3DRMO shifts.

5a. Inversion mode of the Tomography module

The tomography module broadly follows an excellent formulation outlined by Zhou *et al*. (2003), whose notation will be used here, and also incorporates some of the TTI anisotropy details discussed by Zhou *et al.* (2011). The basic tomography equation becomes

$$\mathbf{LCFR}s' = \mathbf{L}(d + e); \qquad s = \mathbf{R}s'$$

The rectangular matrix **F** maps model slowness perturbations, s, into ray path traveltime changes, square matrix **C** causes each of these to be referenced to some local spatial average, d is the 3DRMO time shift data and e is error. **L** is a left preconditioning operator, typically a data weight mask used to select the 3DRMO shifts. **R** is a right preconditioning operator that regularizes and stabilizes the solution and accelerates convergence. It is actually implemented here as

$$\mathbf{R} = \mathbf{M}\,\mathbf{S}\,\mathbf{M}$$

M is a diagonal matrix weight mask representing the square root of the magnitude of the expected slowness perturbations and **S** is a varying spatial smoothing operator. An important use is the provision of diagonal elements of **M** equal to zero in spatial regions where it is desired to not update the VM.

The system of linear tomography equations is solved for a slowness update, s, using the iterative conjugate gradient algorithm defined by Zhou *et al*. (2003) in order to minimize the square error norm $||\mathbf{L}e||$. As an example, 20 iterations might be performed with an update to the VM being output following every 4th iteration, thereby allowing selection of a preferred update. The obvious way to proceed is to return to step 3 and re-migrate with the updated VM. However, additional flexibility and efficiency are achieved by extending this step 5 to include the following 'Modelling mode'.

5b. Modelling mode of the Tomography module

A ray path traveltime change attribute is directly evaluated as **F**s, where s is a slowness update equivalent to the current VM update. As stated earlier, under item 4, this traveltime update converts to a 3D spatial shift. Inclusion of this in a subsequent reconstruction (item 3) forms residually migrated CIP gathers consistent with the VM update. The convenience becomes obvious with the observation of a compute elapse time of about 3 minutes for a residual migration as opposed to about 1 hour for conventional beam migration.

Steps 5a and 5b are iterated to increment the VM update, possibly changing some tomography inversion parameters, typically the model mask, **M,** or the smoothing parameters, **S.** Accuracy of residual migration obviously decreases with increasing magnitude of the current VM update and it becomes sensible to return to step 2 for a conventional migration and continued iteration, if deemed desirable. Figure 2 is an example from offshore Norway of a final VM overlain with the PreSDM. Note the resolution in the VM and the consistency of the VM details with the structure exhibited on the seismic.

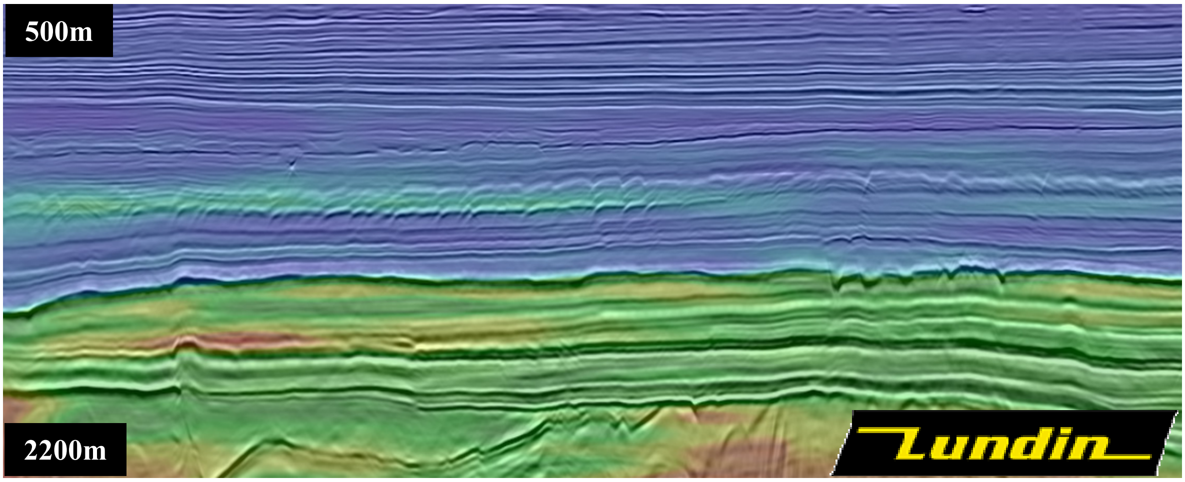


Figure 2: *Example of a final VM overlain with PreSDM. VMB was not provided with horizons.*

Figure 3 is extracted from a 25,000 km^2 survey from offshore West Africa. It shows the total tomographic update to a simple initial VM overlain with the final PreSDM. The water bottom and top salt horizons were provided in order to avoid velocity updates in the water and beneath top salt.

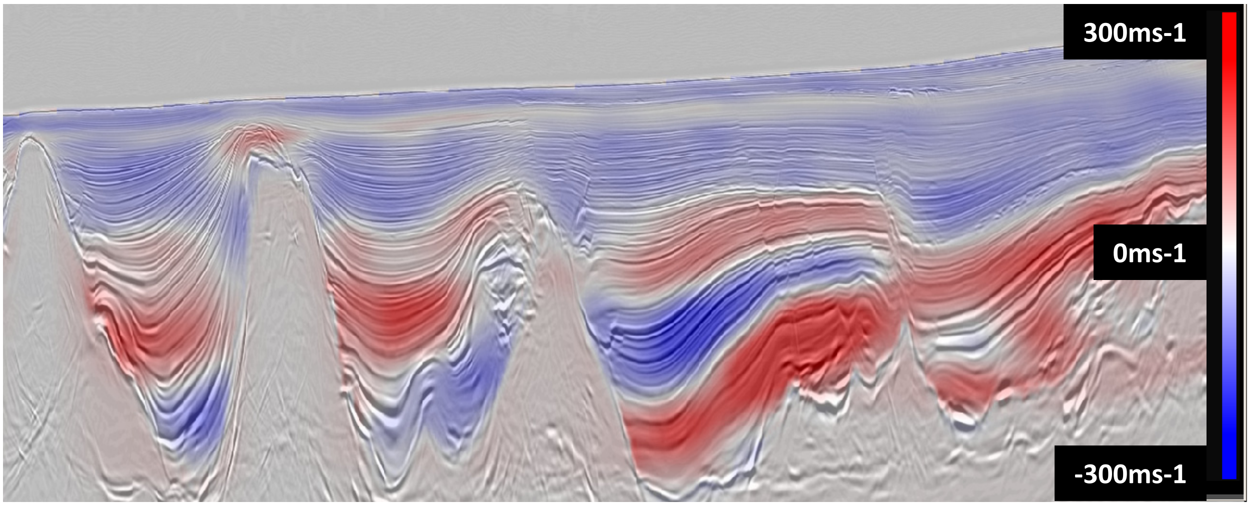


Figure 3: *Example from offshore West Africa of a tomograpic velocity update and its consistency with structural seismic detail. Only the water bottom and the top of salt horizons were provided in the VMB.*

Conclusions

A decomposition of conventionally pre-processed seismic data into a basis of wavelets and their attributes is described in a previously published implementation of beam PreSDM. This wavelet set enables particularly efficient, high quality VMB. Two necessary additional modules are 3DRMO for estimating high quality residual corrections to CIP gathers, and a consistent tomography for inversion to a VM update. Workflows exploit the power of these already efficient modules, facilitate rapid visualization of the QC products, ease the burden on data processing personnel, and minimize turn-around-time. The rapid acceptance of this VMB system for production use attests to its effectiveness.

Acknowledgements

The authors thank PGS for permission to publish this paper and Lundin for making Figure 2 available.

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