

## Wavefield driven reservoir analysis

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### Summary

Reservoir analysis of seismic data is performed on migrated seismic images, which represent the spatial variability of the medium's reflectivity. Intuitively, the process of migration rotates the wavelet so that it is normal to the imaged reflectors. Signal processing for reservoir analysis needs to follow the structure of the data in order to accurately estimate wavelet characteristics. The traditional 1D (vertical) convolutional approach does not honour this directivity. We introduce a wave equation based approach which provides an effective platform for structurally consistent reservoir analysis. This includes applications such as wavelet extraction, inversion, warping and 4D time-strain inversion.

### Introduction

A migrated seismic image represents the spatial variability of the earth's reflectivity. The process of migration effectively rotates the seismic wavelet so that it is normal to the imaged reflectors. In the presence of complex geologies and steep dips, the wavelet, when viewed vertically, is stretched according to the arc-cosine of the structural dip of the image.

Traditional reservoir analysis methods widely use a 1D convolutional model and typically evaluate wavelet characteristics vertically through the migrated image. In dipping and complex media, spectral variations are better evaluated in the direction normal to the reflectors (Cherrett, 2013; Khalil et al., 2015a; Lazaratos and David, 2009). The same logic holds for time-shifts and strains in time-lapse processing. This is demonstrated by Thore et al. (2012), Audebert and Agut (2014) and Khalil et al. (2015b).

We reintroduce the concept of seismic image waves, originally proposed by Hubral et al. (1996), to define an image domain wave equation. The wavefield solution of this equation allows us to perform kinematic and amplitude inversions of seismic data on dipping and complex structures. The method is applicable to pre- and post-stack 3D or 4D data and is easily combined with existing 1D analysis tools.

### Theory

Imaging algorithms (i.e. migration) map seismic energy recorded on the acquisition surface back to the subsurface locations which generated the reflections. The wavelet is then everywhere normal to the reflectors. Conceptually, pre-imaging, the wavelets are aligned with the time axis, while post-imaging they are orthogonal to the reflector and wavelets are stretched according to the dip when evaluated vertically.

Multiple attempts have been made to accommodate the effect of structural stretch on the imaged wavelet for different applications. In a colored inversion (Lancaster and Whitcombe, 2000) context, Lazaratos and David (2009) apply spectral shaping operators pre-imaging. More recently, Cherrett (2013) proposed a frequency-wavenumber approach for modelling and inversion using a constant velocity. Khalil et al. (2015a) includes variable velocity by introducing orthogonal displacements to the seismic image followed by a local depth-to-time conversion.

From a time-lapse perspective, as pointed out by Thore et al. (2012) and Audebert and Agut (2014), 4D changes

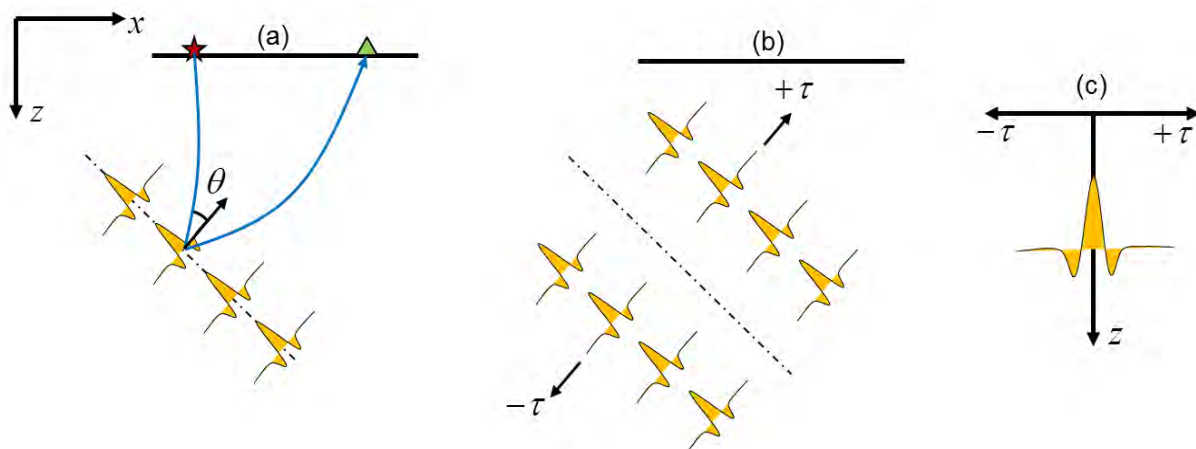


Figure 1 (a) A dipping reflector, the scattering angle and corresponding rays. (b) Forward and reverse wave-field propagation along the orthogonal time axis. (c) The corresponding gather along the orthogonal time axis.

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propagate in the direction normal to the reflectors. This limits the applicability of vertical analysis methods post-imaging, and points towards pre-imaging approaches such as time-lapse (4D) full waveform inversion (FWI), as proposed by Asnashaari et al. (2011). Wavefield inversion is computationally expensive and difficult to control, however, as it operates on pre-imaged data.

Our solution lies between the complex pre-imaging and simplistic post-imaging paradigms. We reintroduce the concept of a seismic image wave (Hubral et al., 1996), by positing that a seismic image follows a wave equation of the form (Khalil et al, 2015b)

$$\frac{1}{v^2(\mathbf{x})} \partial_\tau^2 I(\mathbf{x}; \tau) = \nabla^2 I(\mathbf{x}; \tau) \quad (1a)$$

and

$$v(\mathbf{x}) = \frac{1}{2} \frac{c(\mathbf{x})}{\cos(\theta)}, \quad (1b)$$

where  $\mathbf{x} = (x, y, z)$  is the space coordinate vector,  $\tau$  is a time-like coordinate,  $c(\mathbf{x})$  is the velocity of the medium,  $\theta$  is the scattering angle, and  $I(\mathbf{x}; \tau)$  is the seismic image wavefield associated with this reflection angle, i.e., a common-angle seismic image.

Equation 1 is derived using the cross-correlation imaging principle. This relationship is not new to the seismic literature; it has existed for a long time in different forms. Typically, the Fourier representation is used, for example in Sava and Fomel (2006). Mosher et al. (1996) derive a similar relation for a common-angle time migration scheme, and Zhang and Sun (2009) use it to remove low frequency artefacts from reverse-time migration in what is commonly known as the ‘Laplacian’ filtering process.

A wavefield solution to (1) is computed by defining initial and boundary conditions. In our implementation we set the zero time of the seismic image wavefield to the input seismic image  $I_o(\mathbf{x})$ ,

$$I(\mathbf{x}; \tau = 0) = I_o(\mathbf{x}). \quad (2)$$

Then we solve  $I(\mathbf{x}; \tau)$  for an arbitrary range of  $\tau$ , which can be done using finite-difference or pseudo-spectral methods.

Image variations on the  $\tau$  axis give the wavelet evaluated orthogonally to the dip of reflectors that are coherent in the

initial image. These variations capture wavelet characteristics in a structurally consistent way. This  $\tau$  axis serves as our domain of reservoir analysis, both from standalone and time-lapse perspectives. To emphasize the orthogonality property and to discriminate  $\tau$  from the vertical time, we refer to this axis as orthogonal time.

Figure 1 shows a cartoon demonstrating the concepts of the proposed method. Figure 2 demonstrates the wavelet stretch effect for a 45° dipping reflector. Kinematic or amplitude measurements performed in the orthogonal-time direction describe spectral characteristics of the seismic image more accurately than in vertical time.

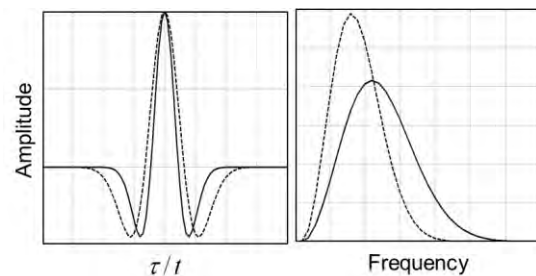


Figure 2: For a 45° dipping reflector, wavelets (left) and spectra (right) along the traditional vertical time (dashed lines) and along the orthogonal time (solid lines).

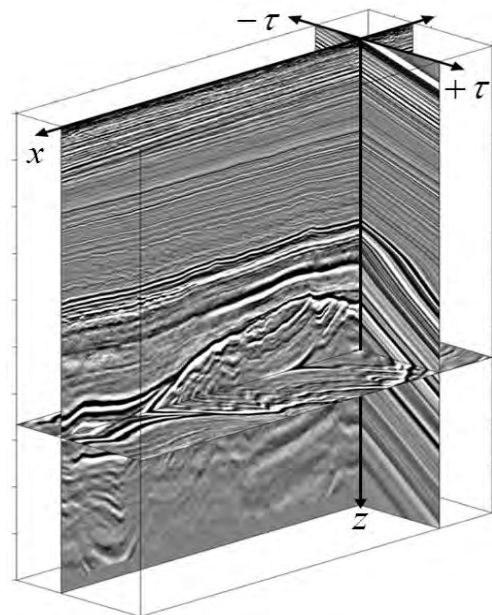


Figure 3: The wavefield solution for the seismic image used in the inversion example.

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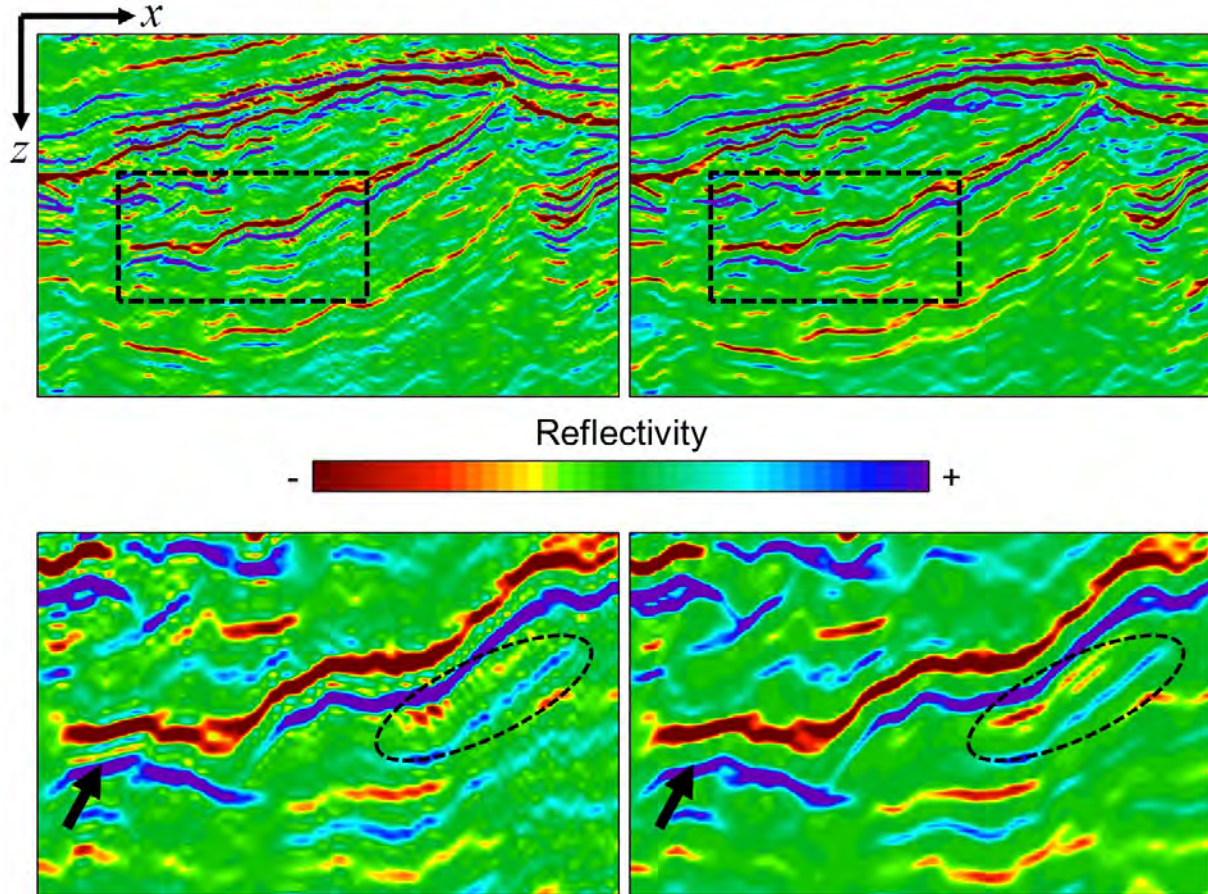


Figure 4: Acoustic inversion using the traditional time axis (left). Acoustic inversion using the orthogonal time axis (right). Both inversions are performed without spatial smoothing.

### Inversion

The success of an inversion method to estimate elastic parameters relies on its ability to deconvolve the wavelet from the seismic image. The stretching of the wavelet due to the structural dip thus may compromise the integrity of the process when performed using vertical-time convolutions.

This effect is demonstrated on a North Sea dataset. Figure 3 shows the constructed wavefield obtained by solving the image domain wave equation and setting the input seismic image as the initial condition. Figure 4 shows the estimated reflectivity from acoustic inversion using the traditional vertical time and the orthogonal time approaches. For the former, side lobes of the wavelet are not efficiently collapsed (black arrow), and the interference effect is not correctly resolved (dashed ellipse). Both issues are fixed by processing along the orthogonal time axis. Furthermore, residual migration noise is not amplified as in the

traditional 1D case and the results are more spatially coherent. The reason for this uplift is increased wavelet stationarity in the orthogonal time axis. Acoustic inversion using a vertically-derived wavelet is biased by the dip-induced spectral changes and the use of a single wavelet is not accurate for dipping reflectors.

### Time-shift and time-strain analysis

In Figure 5, we construct a demonstrative synthetic time-lapse test with four linear baseline dips. These are vertically shifted for the monitor. Shifts extracted along the orthogonal-time axis are correctly estimated, matching theoretical values equal to the vertical displacement multiplied by the cosine of the dip angle. The vertical shifts are in error by this cosine factor. Figure 6 shows a realistic (but synthetic) seismic example, where the monitor data incorporates a synthetic 4D velocity change, inducing a time-shift. The orthogonal time axis is then used for time-shift and -strain analysis on full stacks or pre-stack angle



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gathers. Figure 7 shows the estimated time-shifts evaluated in vertical time and orthogonal time. The differences in estimated time-shifts are more obvious when converted to time-strain, Figure 8. For the vertical case, the strain attribute indicates a false velocity change below deeper dipping events. The time-strain obtained along orthogonal time, by contrast, correctly identifies the location of the velocity change on the shallower (flat) event.

### Conclusions

In complex non-flat structures, imaging and reservoir analysis algorithms such as 3D and 4D inversions must honor the direction of energy propagation normal to the structural dip. Our wave-equation approach outputs image variations in orthogonal time and allows wavelet characteristics to be estimated without influence of the structural dip. Orthogonal-time imaging provides a way for existing 3D and 4D analysis and inversion techniques, pre- or post-stack, to more accurately characterize the data and with a higher level of wavelet stationarity. In orthogonal time, false wavelet characteristics generated by the image dip can be avoided more effectively. Orthogonal-time imaging is more direct than FWI as it operates in image domain. It is also more general than existing stationary techniques operating in frequency-wavenumber domain.

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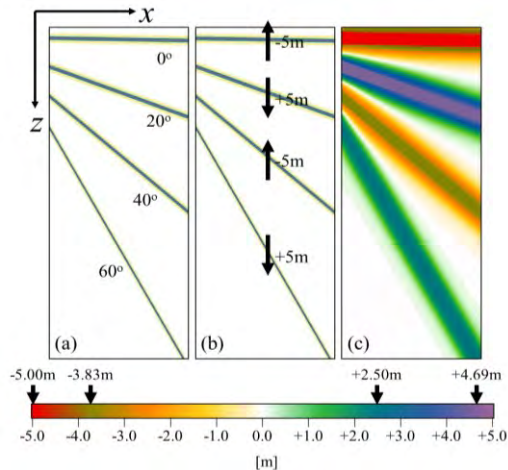


Figure 5: A synthetic dataset composed of four dipping layers. (a) The base dataset. (b) The monitor dataset, generated by applying positive and negative 5m shifts in the vertical direction. (c) The estimated normal displacements.

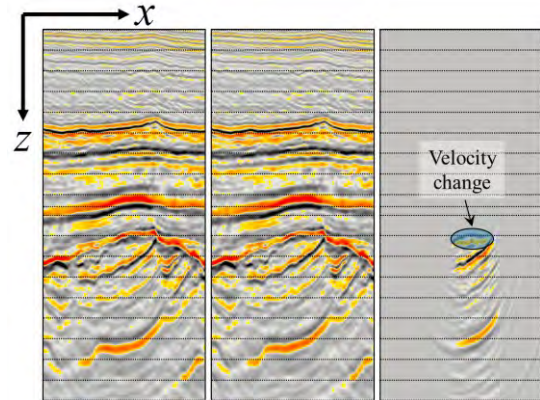


Figure 6: Base and monitor datasets (left and middle). The monitor dataset is generated by inducing a velocity change within the area of the oval to give the 4D difference on the right.

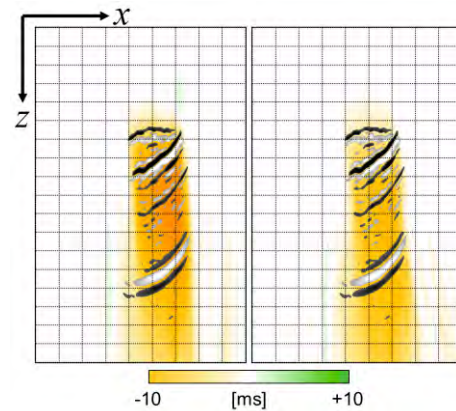


Figure 7: Estimated 4D time-shift, using the traditional vertical time (left) and using orthogonal time (right).

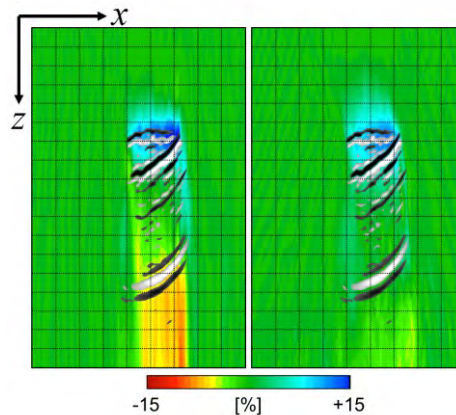


Figure 8: Estimated 4D time-strain, using the traditional vertical time (left) and using orthogonal time (right).

## EDITED REFERENCES

Note: This reference list is a copyedited version of the reference list submitted by the author. Reference lists for the 2015 SEG Technical Program Expanded Abstracts have been copyedited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

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