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Summary

Mapping reservoir architecture (geobody size, shape, and stacking patterns) in the subsurface is critical for exploring and producing hydrocarbons, CO₂ storage, and geothermal resource development since it can define connectivity or compartmentalization of flow zones (Meirovitz et al. 2020). However, our capacity to interpret depositional system architecture is limited by seismic resolution. In addition to limited bandwidth, the resolution of discrete geologic features mapped by seismic attributes can be mixed through the vertical analysis window. In this work, we use synthetic seismic data derived from an outcrop analogue to better understand how seismic bandwidth affects the vertical and areal resolution of stacked stratigraphic features. We studied five synthetic seismic volumes from low to high-frequency bandwidths of 15 Hz, 30 Hz, 60 Hz, 90 Hz, and 180 Hz from a deepwater channelized slope system in the Magallanes Basin, Chile. We analyze the effect of different seismic attributes: coherence, dip magnitude, dip azimuth, root mean square amplitude, and Laplacian filters on our different bandwidth data to understand how much “mixing” of stratigraphic features there is by comparing with the true geological model. We explore how the attributes' parametrization affects the imaging of differently sized features by modifying the analysis window in each case from +/-2ms to +/- 100 ms.

Results show that the “mixing” occurs as a result of 1) the seismic bandwidth, 2) the algorithm used for each seismic attribute calculation, and 3) the attribute analysis window. Broad band, higher frequency data and small analysis windows provide clear images of the stacked channels. In contrast, low-frequency data and larger analysis windows result in more mixing or “composite” appearance, affecting interpretations and NTG estimates. The Laplacian filter's use proves to enhance the distinction of the different channel architectures providing high-resolution edge detection even for the lower frequency data.

Introduction

Imaging and interpretation of different sized stratigraphic architectures in the subsurface using seismic reflection data is often compromised due to limits in seismic resolution. Insufficient resolution and tuning effects can influence volumetric interpretations and gross rock volume calculations (Pemberton et al., 2018). Seismic attributes provide a means to enhance vertical and lateral changes in reflectivity, thickness, continuity, and orientation. The delineation of such features is often frequency dependent, (Chopra and Marfurt, 2020). For instance, Lyu et al., (2020) found that discontinuities in thin-beds were better illuminated near their tuning frequency, where the signal-to-noise ratio was higher. The analysis of spectral components is one of the most effective ways to map lateral changes in stratigraphic thickness and infill, where one can either animate through all the components, use the peak spectral frequency and peak magnitude, or center three appropriate spectral components against RGB (Partyka, 1999; Marfurt and Kirlin, 2001; Castagna and Sun, 2006, Leppard, 2010).

Figure 1: A representative vertical slice through the 3D stratigraphic model showing (a) a detailed cross section of a single channel element, (b) the stacked channel system, and acoustic impedance model and (c) the high frequency, high bandwidth synthetic seismic section (modified from Langenkamp et al., 2020).

Recent developments in multi-spectral coherence (Li et al., 2018; Lyu et al., 2020) address some of the limits to lateral resolution due to waveform interference. In this paper, we
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Figure 2: The seismic response to the stratigraphic model created from outcrop analysis for three different source wavelets (in red, blue and green) and corresponding spectra. d indicates the dominant (or average frequency), b indicates the bandwidth (modified after Langenkamp et al., 2020).

Whether based on crosscorrelation, semblance/variance, eigenstructure analysis, or the gradient structure tensor, all coherence algorithms use a vertical and lateral analysis window. For good quality data, Marfurt et al. (1998) found it best to analyze stratigraphic features using a narrow temporal analysis window as possible, determined by the highest frequency in the input (or the 3rd frequency corner in the Ormsby wavelets in Figure 2). For poor quality data, a larger window approximating the dominant period of the data provides improved results with minimal stratigraphic mixing. Jones and Roden (2012) and Chopra and Marfurt (2020) show volumetric dip estimates can also be frequency dependent.

We evaluate the seismic attribute sensitivity to frequency content changes and analysis window size, comparing dip magnitude, dip azimuth, coherence, RMS amplitude, and Laplacians, indicating the degree of stratigraphic mixing for each scenario. As synthetic 3D data on this scale is not often readily available, this study demonstrates the effectiveness of the workflow with an unambiguous dataset.

Geological model description

The geological model used as the parent of our synthetic seismic data represents a sandstone-rich deepwater channel system along a progradational slope system (Hubbard et al., 2010). These deepwater deposits from the cretaceous Tres Pasos Formation were exposed on about 3 km long outcrops in the Laguna Figueroa, Magallanes basin, Chile (Macauley and Hubbard, 2013; Hubbard et al., 2014). The high quality of the stacked channel systems was used to construct a 3D geological model of the system (Jackson et al., 2018; Langenkamp et al., 2020). In Figure 1a, we show the geological model, which consists of five facies: 1) channel element axis in yellow 2) channel element off axis in orange 3) channel element margin in brown, 4) homogeneous shale in gray, and 5) background shale (inner and outer levee facies) in white. The facies fill single channel elements (400 m wide and 25 m thick; Figure 1a) which stacked into a hierarchical channel complex system (2 km wide and 265 m thick; Figure 1b). The amplitude of the higher frequency volume is also shown in Figure 1c.

Data source

The dataset used in this paper consists of five synthetic seismic models of 15 Hz, 30 Hz, 60 Hz, 90 Hz, and 180 Hz (Chile Slope System research consortium; Langenkamp et al., 2020). A detailed bed- to field-scale 3D architecture outcrop-based model of the slope channels of the Tres Pasos Formation at Laguna Figueroa outcrop was used as the foundation for forward seismic reflection modeling (Jackson et al., 2018; Ruetten, 2021). The forward seismic models were built using a series of zero-phase Ormsby wavelets and 1D convolution (Langenkamp et al., 2021). Figure 2 shows a vertical slice in the 180 Hz, 30 Hz and 15 Hz respectively. Facies-based rock properties (Figure 1b; adopted from Stright et al., 2014) show an increase in acoustic impedance is represented by amplitude peaks, whereas troughs depict a decrease in acoustic impedance. The synthetic volumes have a vertical window of 500 ms. For the study purposes, we have cropped the volume from 175 ms to 320 s to avoid dead zones in the reflectivity and focus on the target channel systems.

Methodology

For the analysis of the effect of bandwidth on vertical and lateral resolution, or what we call “stratigraphic event mixing,” we followed the steps depicted in Figure 3. First, we did an exploratory data analysis to define a vertical window of interest constrained to the objective of the study: 175 ms and 320 ms from our five volumes of synthetic seismic data. After cropping the 15 Hz, 30 Hz, 60 Hz, 90 Hz, and 180 Hz dominant frequency volumes, we calculated dip magnitude, dip azimuth, coherence (energy ratio similarity), and broadband Laplacians. For each case, we defined a suite of 3-trace by 3-trace analysis windows with various heights from 2 ms to 100 ms. For visualization and interpretation purposes, we used co-rendering techniques. Finally, analysis of results was performed comparing: 1) the response on the
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same attribute and analysis window in the different bandwidth volumes, 2) the effect of changing the window of analysis size for the same seismic attribute, and 3) the impact of changing the analysis window for different seismic attributes. All cases were compared with the initial true data/model.

Seismic attribute sensitivity on synthetic seismic

Resolution, sampling and frequency content of seismic data
By definition, the vertical resolution of seismic data is a $\frac{1}{4}$ of the wavelength ($\lambda$), where the $\lambda$ is determined by dividing the average velocity by the dominant frequency. This resolution refers to the vertical dimensions (therefore, stratigraphic features) that the seismic data can resolve. Sampling refers to the interval at which seismic is recorded. This sampling interval is usually 2 ms or 4 ms (Stright et al., 2009) and is linked to the data’s dominant frequency.

The vertical resolution of seismic data is $\frac{1}{4}$ the wavelength where $\lambda = \frac{v}{f}$, the higher frequency $f$ is, the lower the vertical resolution of seismic data will be. Stratigraphic mixing occurs when using a large analysis window.

Figure 5 shows coherence results, allowing the detection of edges, especially in time slices. We noticed, however, stratigraphic mixing in the vertical slices when using a large analysis window.

Laplacian applied to the seismic data
Chopra and Marfurt (2012) described the Laplacian filter as mean amplitude curvature. It highlights regions of rapid change in the sum of the inline and crossline amplitude second derivatives. Laplacian filters are commonly used to enhance the edges seen in photographic images. For seismic data, we apply the Laplacian filter defined as

$$L_{\text{RMS—amplitude—weighted}} = \sqrt{\frac{\partial^2 v^{(1)}(x,y)}{\partial x^2} + \frac{\partial^2 v^{(1)}(x,y)}{\partial y^2}} (2)$$

along structural dip, where $v^{(1)}(x,y)$ and $\lambda_1$ are the first eigenvector and eigenvalue that best represents the lateral amplitude variation in the analysis window.

Discussion of results and future work

After comparing all the scenarios: different bandwidth data from low to high frequencies, over multiple geometric and amplitude derived seismic attributes and the evaluation of different parametrizations in the algorithms, especially the variation of the window of analysis in each case vs the true data (the geological model) resulted in the following observations: As expected, broad band, higher frequency data (e.g. 90 and 180 Hz) combined with a short analysis window (e.g. 2 ms, 20 ms) minimized stratigraphic mixing (Figure 4). In contrast, lower frequency data that were analyzed using a large vertical analysis window (Figure 5) resulted in poor imaging of the channel complexes, vertically mixing geological features at different stratigraphic levels. This affects the temporal evaluation of features, that show an overlap of individual architectures in the system in consecutive time slices, or in other words, a vertical offset from the known position of sedimentary units (also shown by Pemberton et al, 2018). This observation warns of potential interpretation pitfalls in applying such attributes to real seismic data. Stratigraphic mixing can hinder the correct temporal and spatial representation of individual elements, as well as mapping and estimating the volume of the reservoir units of interest. Future work will determine if animating up and down through the system can better localize the actual geologic features of interest.

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Figure 4: Seismic attribute sensitivity analysis showing some results varying frequency input small, medium and high, and the effect of window size increase from ±2 ms to ±50 ms. Same vertical and horizontal slices are displayed to better compare. High frequency data with a small analysis window provides the most suitable representation of the true model. In RMS amplitude the most accurate facies depiction is given by high frequencies and small window combination, imaging channel base and inner and outer levee facies.

Figure 5: Comparison of energy ratio similarities, with frequency and analysis windows variations; (A) 90 Hz data and a window equal to the dominant period of ±5 ms; (B) 15 Hz data and a short window of ±5 ms; (C) 15 Hz data and a window equal to the dominant period of ±33 ms. Note how large analysis windows vertically smear the response, while smaller windows provide less vertical smearing of stratigraphy, looking narrower on (B) than in (A).
REFERENCES


