PS Sequence Stratigraphic Boundary Delineation Based on Adaptive Seismic Decomposition*

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Abstract

While sequence stratigraphic boundaries are commonly observed and mapped on vertical slices through amplitude volumes, they are often masked by noise and artifacts from seismic acquisition and processing. “Signal decomposition” techniques can reveal hidden features in the seismic data. Traditionally, most seismic decomposition methods have been constrained by interpreter parameters such as spectral components. However, the subsurface has been built over geologic time through deposition, deformation, erosion, and diagenesis, which can lead to a conflict between the “actual” features and human defined expressions. For this reason, a data-driven decomposition such as used in the SETI project might be more appropriate than an interpreter-defined decomposition method using predefined parameters. We apply a data-adaptive signal decomposition method named variational mode decomposition (VMD) on both synthetic and 3D field data with the objective of mapping sequence boundaries. Unlike time domain decomposition methods, the VMD decomposes seismic signal in the frequency domain, which makes it more robust and optimal. Without any priori knowledge, it separates the intrinsic frequency components buried in the data based on their spectral responses. Though it doesn't enhance high frequencies, the VMD improves the ability to recognize stratigraphic boundaries on different components by suppressing interference from other less representative components. In the synthetic examples, we build four deposition cycle models: normal, inverse, inverse-normal, and normal-inverse models. The first intrinsic mode functions (IMF-1) calculated using VMD exhibits the pattern of gamma ray curve, which can be predicted theoretically. In order to validate this observation, we examine gamma ray logs acquired through Marble Falls Limestone in the Fort Worth Basin and find a high correlation with IMF-1 computed from the seismic data. To determine if these correlations are general, we compute IMFs from seismic data volume acquired over a clastic delta in the Dutch Sector of the North Sea. Because of the data quality, the sequence boundaries of the delta facies are not very clear on the seismic amplitude data. In contrast, the different IMFs from VMD highlight onlaps, toplaps, downlaps, and flooding surfaces more clearly, as well as the transgression and regression features. From the examples, VMD shows promises in seismic stratigraphy interpretation and potentials for assisting facies analysis.

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Summary

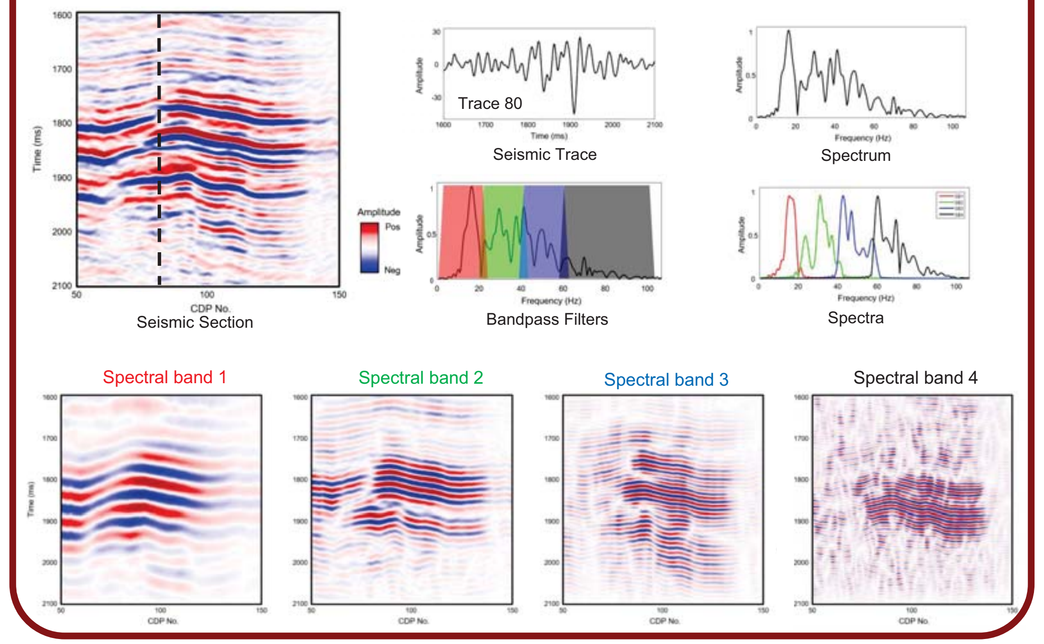
While sequence stratigraphic boundaries are commonly observed and mapped on seismic amplitude volumes, they are often masked by noise and artifacts from seismic acquisition and processing. "Signal decomposition" techniques can reveal hidden features in the seismic data. Traditionally, most seismic decomposition methods have been constrained by interpreter parameters such as spectral components. However, the subsurface has been built over geologic time through deposition, deformation, erosion, and diagenesis, which can lead to a conflict between the "actual" features and human defined expressions. For this reason, a data-driven decomposition might be more appropriate than an interpreter-defined decomposition method using predefined parameters.

In this work, we apply a data-adaptive signal decomposition method named variational mode decomposition (VMD) on both synthetic and 3D field data with the objective of mapping sequence boundaries. Unlike time domain decomposition methods, the VMD decomposes seismic signal in the frequency domain, which makes it more robust and optimal. Without any priori knowledge, it separates the intrinsic frequency components buried in the data based on their spectral responses. Though it doesn't enhance high frequencies, the VMD improves the ability to recognize stratigraphic boundaries on different components by suppressing interference from other less representative components.

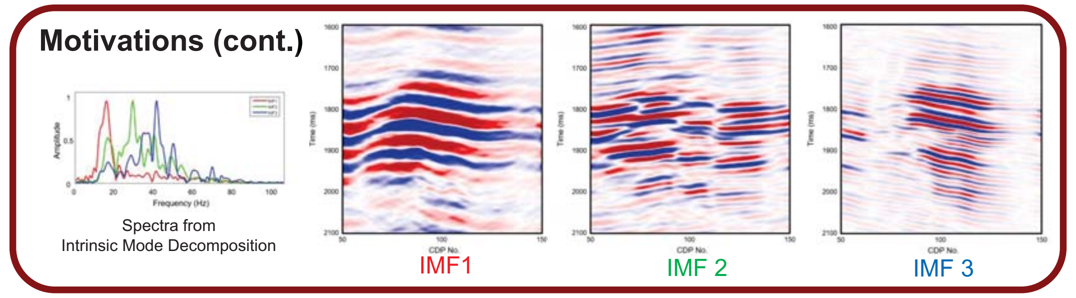
Motivations

- Adaptively highlight subtle information from seismic data.
- Assist seismic stratigraphy analysis.
- Improve automatic facies analysis with stratigraphic constraint.

Here, we show an example to demonstrate the differences between data-driven decomposition and bandpass filter.



Motivations (cont.)



Variational Mode Decomposition

VMD decomposes an input signal into a number of modes that have specific sparsity properties. Each **intrinsic mode function (IMF)** has a localized frequency component, which represents certain hidden information. VMD is achieved by solving the following optimization problem:

$$\min_{\{u_k,\,\omega_k\}} \left\{ \sum_k \left\| \partial_t \left[\left(\delta(t) + \frac{j}{\pi t} \right) * u_k(t) \right] e^{-j\omega_k t} \right\|_2^2 \right\}$$

$$s.\,t. \quad \sum_k u_k(t) = s(t)$$

where u_k and ω_k are modes and their center frequencies, respectively. $s(t)$ is the signal to be decomposed. $\delta(t)$ is the Dirac function.

Geology

The field data set is from the Southern North Sea Basin. After complex multiple stages of orogeny, rift and subsidence that occurred during Paleozoic and Mesozoic time, the Southern North Sea Basin experienced an inversion during the Tertiary. High sediment influx from neighbouring highlands that uplifted in late Miocene filled the basin, resulting in a prograding fluvio-deltaic system. This system (part of the giant Eridanos delta) constitutes the siliciclastic shelf deposits within the Pliocene interval, the thickness is from 350 m to 430m in study area (Overeem et al., 2001). Several localized unconformities were formed during the deposition process (Sales, 1992; Ghazi, 1992; Gautier, 2003).

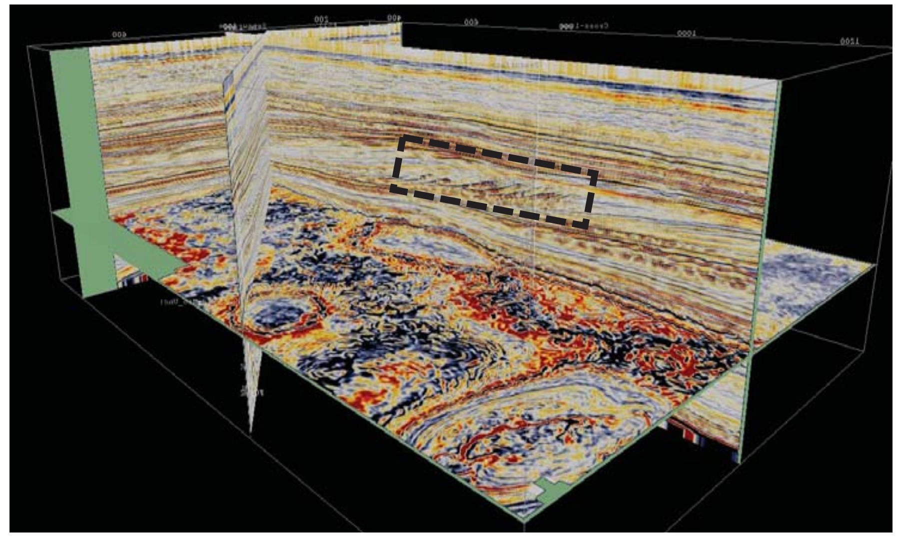


Figure 1: 3D seismic data and the target horizon highlighted.

Synthetic Depositional Sequence Characterization

Besides seismic reflection analysis, sequence stratigraphy interpretation can be made based on rock composition, grain size characteristics, spontaneous potential, and Gamma Ray log shapes (Rider, 1999). The transgressive/regressive facies recognition is the key for the stratigraphic sequence division. Well logging, which is usually the source of the geology information, is limited to discrete and widely spaced sampling points within a survey area. For this reason, we wish to determine the sedimentary and depositional environment for most areas of interest from the seismic data. Following Rider (1999) and Martins-Neto and Catuneanu (2009), we build a single cycle of a delta progradational model. The percentage of sandstone increases upward, grain size changes from fine to coarse, with the sandstone interbedded with similar thick shale layers.

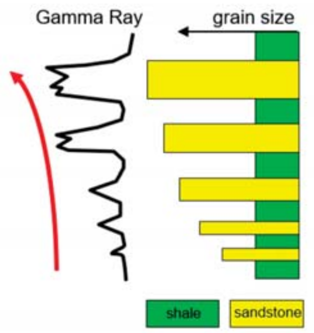


Figure 2: Gamma Ray log shape and depositional setting of deltaic progradational depositional trends. The sandstone is coarsening upward, and its thickness is also increasing upward interbeded with similar thick shale.

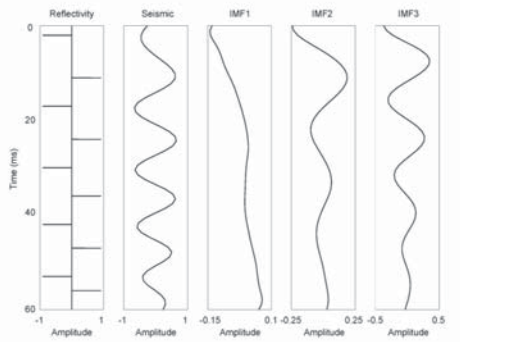


Figure 3: Reflectivity series, corresponding seismic trace, and IMF-1, IMF-2 and IMF-3 of the delta progradational model in Figure 2. Note that the amplitude of IMF-1 decreases upward like the Gamma Ray log in Figure 2.

We apply VMD to the synthetic seismic data, and obtain IMF-1, IMF-2, and IMF-3, shown in Figure 3. Note the IMF-1 exhibits the same trend as the Gamma Ray log in Figure 2. IMF-2 and IMF-3 display other high frequency information.

Field Applications

The deltaic cycles in the Dutch sector range from a river-dominated to wave-tide dominated stages. These cycles exhibit classic clinoform geometries prograding towards the basin (Petruno et al., 2015). Figure 5 shows our sequence stratigraphy interpretation. Based on the recognition of seismic reflection termination patterns (toplap, onlap, downlap and truncation, shown in Figure 5), five regional and local subaerial unconformities, two maximum regressive surface, two maximum flooding surface and three basal surface of forced regression are defined using a seismic sequence stratigraphic interpretation workflow (Vail et al.,1977,1987; Mitchum et al. 1977; and Posamentier et al.,1999). According to sequence boundaries, position and parasequence stacking pattern, the Pliocene strata of study area can be divided into four third- order sequences. Furthermore, a complete depositional sequence is divided into four system tracks: Lowstand Systems Tracts (LST), Transgressive Systems Tracts (TST), Highstand Systems Tract (HST) and Falling Stage Systems Tract (FSST), on the basis of the principles of quadripartite division for sea level cycle (Hunt and Tucker,1992, 1995; Plint and Nummedal, 2000), such as SQ-1 and SQ-2 in Figure 5. Because of the erosion when relative sea level dropped, SQ-3 and SQ-4 form incomplete depositional records. The delta system that prograded across the continental shelf during the FSST stage deposited thick sandstone. In the base level rising stage (TST and HST), nonuniform thickness mudstone draped over the delta sandstone.

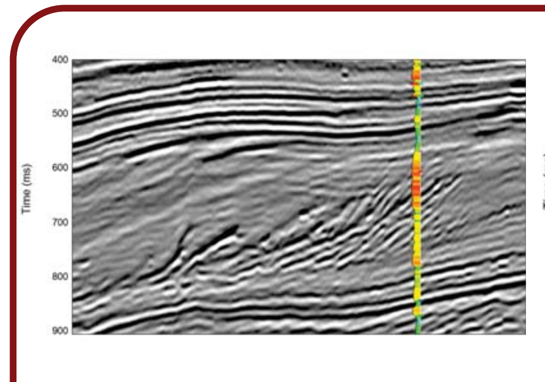


Figure 4: A vertical well with posted Gamma Ray log, and a vertical slice through the seismic amplitude volume without interpretation. The stratigraphy interpretation is in Figure 5.

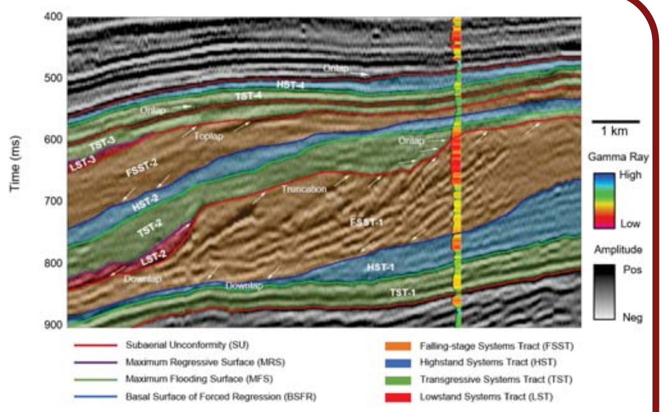


Figure 5: The Pliocene strata are divided into four third-order sequences (SQ). One complete base level cycle is divided into four stages, LST, TST, HST, and FSST. SQ-1 and SQ-2 contain relative complete system tracts, SQ-3 and SQ-4 only retain the strata records of base level rising because of regional erosion.

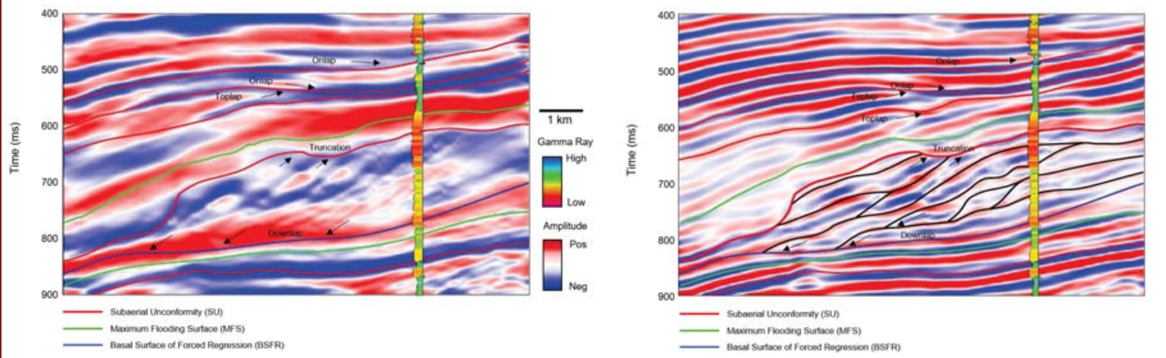


Figure 6: The high amplitudes on IMF 1 (left) highlight SUs, MFSs and BSFR. Stratigraphy terminations are clear in both IMF 1 and IMF 2, with the clinoform more clearly imaged by IMF 2 (right).

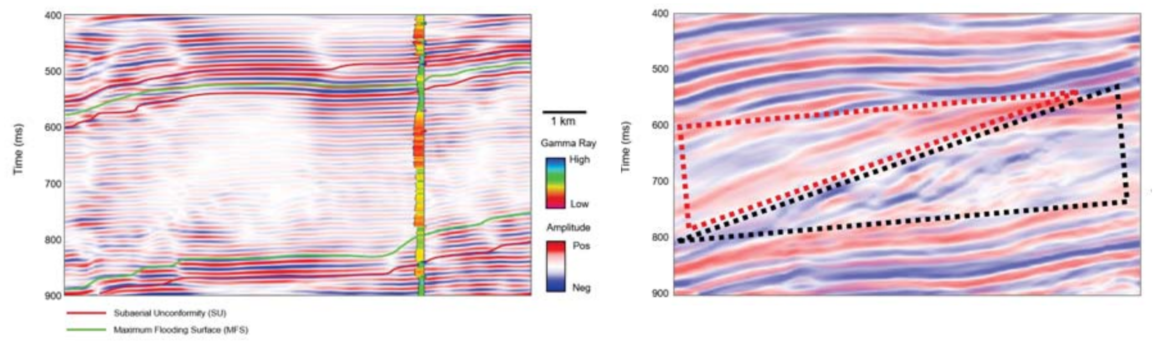


Figure 7: The SUs and MFSs exhibit high amplitudes on IMF 3 (left), but the stratigraphy details seen in IMF 1 and IMF 2 are not clear. In general, the components needed to generate a sequence stratigraphic interpretation are more clearly imaged on IMFs than in the broad band input seismic data. By blending addition IMF 1 and IMF 2 (right), one can delineate the two depositional sequences, SQ-1 and SQ-2 (dotted triangle).

Conclusions

Using the seismic data and a limited number of well logs, we evaluate the use of VMD in the identification of the depositional sequences, which provides images amenable to detailed sequence stratigraphic interpretation, providing components that are easier to interpret than either the broad band input data, or more commonly used band-pass filtered (spectral voices) versions of the data.

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