Advanced self-organizing map facies analysis with stratigraphic constraint
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Summary
As a powerful and the most popular seismic facies analysis method, self-organizing map (SOM) projects multiple attributes into a lower dimensional (usually 2D) latent space. Because of lacking geological time information, the seismic facies classification results sometimes are problematic or unreliable. In this study, we briefly introduce a stratigraphic constraint derived from seismic decomposition method into SOM facies analysis. After describing the principal method, we show an example of an improved SOM using information of sedimentary cycle, which is derived from variational mode decomposition (VMD) on seismic amplitude data. On an unconventional shale application, we observe that the constrained SOM facies map shows layers that are easily overlooked on traditional unconstrained SOM facies map.

Introduction
SOM is an excellent seismic facies analysis/classification tool that captures the information residing in (multiple) input seismic attributes by reorganizing data samples based on their topological relation. Examples of the very first applications of SOM on seismic facies analysis include Strecker and Uden (2002), in which the authors used multiattribute input and performed SOM classification volumetrically using a 2D SOM latent space, and Coleou et al. (2003) used both seismic amplitudes (waveform classification) and seismic attributes as inputs for SOM. To overcome the issue that the distance information in the input attribute space is lost once projected into the 2D SOM latent space, Zhao et al. (2016) adopted a distance-preserving step in SOM, constraining the SOM facies to better reflect the degree of diversity in input attribute space. However, till now all the SOM applications are spatially (and temporally, for time domain seismic data) unaware, because seismic data are sorted into “attribute space” (each dimension is one seismic attribute) before feeding into a classification technique like SOM.

One of the side effects of such spatial unawareness is the lack of explicitly defined geologic time involved when performing SOM seismic facies analysis. That is to say, the patterns of facies on an SOM map could only follow patterns presented in input attributes. Adding information of sedimentary cycle, which provides spatial (or temporal) constraint on the vertical axis, may help define layers that are otherwise not well defined on seismic attributes. Liu et al. (2015) used empirical mode decomposition (EMD) (Huang et al., 1998) to decompose the seismic signal into different modes to analyze sedimentary cycle. However, being a recursive model decomposition method, EMD is sensitive to noise and sampling and therefore not so robust. To overcome such issues, Dragomiretskiy and Zosso (2014) proposed a novel mode decomposition method, VMD, which decomposes a signal concurrently and is robust to noise and sampling. Li et al. (2016) applied VMD method on deriving a sedimentary cycle model from seismic amplitude data.

In this study we follow the workflow described in Li et al. (2016), adopting the VMD method to decompose the seismic amplitude signal into a user-defined number of modes, and select one of the modes as an indicator of the sedimentary cycle by calibrating with well logs. By adding such sedimentary cycle constraint in SOM facies analysis, we identify some layers are better represented comparing to the traditional unconstrained SOM facies analysis.

Methodology
In traditional SOM seismic facies analysis, the distance used to find the best matching unit (BMU) for a given multiattribute data sample vector is calculated using only attribute values. As motioned above, there is no geological time constraint, which sometimes leads to unreasonable classification results.

In this study, we constrain this distance by adding a term defined by the gradient of a mode calculated using VMD. The modified distance metric is:

\[ d = (1 - \alpha) \sum_{i=1}^{N} ||A_i - A_{PV_i}|| + \alpha ||V_{grad} - V_{PVgrad}|| \]  

where \(d\) is the weighted distance between a multiattribute sample vector and a prototype vector; \(N\) is the number of attributes; \(A\) and \(A_{PV}\) are the attribute values of a sample vector and a prototype vector, respectively; \(V_{grad}\) and \(V_{PVgrad}\) are the gradient of a mode from VMD for a sample vector and a prototype vector, respectively; and \(\alpha\) is a weight between 0 and 1. In practice, we find an \(\alpha\) of 0.6 – 0.7 provides reasonable result. The complete workflow of the modified SOM facies analysis is shown in Figure 1.

Geologic Setting
We apply the proposed workflow on a seismic data set acquired over the Fort Worth Basin, United States. In the study area, interbedded limestone and shale layers are presented, with the Upper and Lower Barnett Shales being the dominant shale reservoirs. A general stratigraphic chart
showing the shale reservoir formations in the Fort Worth Basin is given in Figure 2.

Application

To constrain the SOM analysis using VMD derived mode, we first use VMD to decompose the seismic signals into three independent modes, which represents long, medium, and short sedimentary cycles. Figure 3 shows the decomposed three modes of a trace adjacent to well A. By comparing the gradient of the three modes with the Gamma Ray log on well A, we find the gradient of VMD 3 matches the pattern of the Gamma Ray log the best (Figure 4), which means the gradient of VMD 3 is an appropriate representation of the sedimentary cycle at this area. Therefore, we use the gradient of VMD 3 as the constraint in the subsequent SOM analysis.
We use P-impedance, S-impedance, Mu/Lambda, and Poisson’s Ratio as input attributes to feed into the SOM algorithm. These input attributes are selected to represent the variation in lithology caused by sedimentation. We use SOM to project these four attributes into a 2D latent space with a 2D colorbar (Matos et al., 2009), which helps to define facies that are not easily identified on these attributes. Figure 5 gives the SOM facies maps with and without VMD constraint at \( t = 1.28 \) s. In this figure we observe the map with VMD constraint has more details, but the meaning of colors remains vague. To better compare the results, we take vertical sections at AA’ (Figure 6) and BB’ (Figure 7), on which different formations are better presented.

**Figure 5.** SOM facies maps generated (a) without VMD constraint and (b) with VMD constraint at \( t = 1.28 \) s. A 2D colorbar is used for visualization.

In Figure 6, we can clearly observe that different formations are delineated with more distinct colors when a VMD constraint is added. More specifically, a thin layer between Marble Falls Limestone and Upper Barnett Limestone presents in Figure 6b cannot be traced in Figure 6a (black ovals in Figure 6). This thin layer behaves high Gamma Ray on the well log at well A, while the Marble Falls Limestone and Upper Barnett Limestone are of low Gamma Ray. Such response on Gamma Ray log has verified the extra layer identified on the SOM facies map with VMD constraint.

Figure 7 gives vertical sections of SOM facies maps without and with VMD constraint at line BB’. Similar to Figure 6, we can also identify a higher contrast of color in Figure 7b comparing to Figure 7a, which means the facies are more distinct. In the Upper Barnett Shale formation, a layer that is not precisely defined in Figure 7a is now presented much more clearly (black ovals), and we observe lateral variation within this layer, represented by variation of colors. Figure 8 gives a close look at trace \( X_1 \) and \( X_1’ \), with overlaying trace display. Comparing to trace \( X_1 \), the difference between two adjacent formations is more dramatic in \( X_1’ \), which results in a better separation between different layers. To further understand the geologic meaning of the layer picked out by SOM with VMD constraint, we use the \( \frac{V_p}{V_s} \) ratio at line BB’ to look for evidence of this layer (Figure 9). There is obviously a layer of high \( \frac{V_p}{V_s} \) ratio in the Upper Barnett Shale formation, which corresponds to the layer identified in Figure 7b, and the high \( \frac{V_p}{V_s} \) ratio correlates with the blueish color facies. Such details are not presented in Figure 7a, where the VMD constraint is not used. It is common for shale reservoir to have layering sub-structures, but without the sedimentary circle constraint, the original SOM will miss this thin layer, which is important for unconventional plays characterization.

### Conclusions and Future Work

In this study, we explored the feasibility of constraining the SOM facies analysis using sedimentary cycle information. The constrained SOM facies map provides more details, and shows layers that are more likely being overlooked on unconstrained SOM facies map. The sedimentary cycle is estimated by decomposing seismic amplitude signal into a finite number of modes using VMD. However, the geological meaning of such modes is not well understood, and these modes need to be carefully calibrated with well logs. Furthermore, different layers with the same VMD gradient are not distinguishable, and each seismic trace is decomposed individually. Therefore, a spatial/temporal constraint may further improve the SOM performance.

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Figure 6. Vertical sections along line AA' (location shown in Figure 5) through SOM facies maps generated (a) without VMD constraint and (b) with VMD constraint. Note the layers are better separated in (b) at the Marble Falls Limestone and Upper Barnett Limestone formations. Also the facies map in (b) presents more contrast in color which leads to an improved definition of different layers. The blue curves are Gamma Ray logs at well A.

Figure 7. Vertical sections along line BB' (location shown in Figure 5) through SOM facies maps generated (a) without VMD constraint and (b) with VMD constraint. Note the formation highlighted by the black ovals is clearly presented in (b) but vague in (a). Trace $X_1$ and $X_1'$ are discussed in Figure 8.

Figure 8. Trace display of the SOM facies at traces $X_1$ and $X_1'$. Note the layer at $t = 1.255$ s is defined more clearly when a VMD constraint is introduced in the SOM.

Figure 9. Vertical section along line BB' (location shown in Figure 5) through $V_p/V_s$ ratio. The black oval highlight a layer with high $V_p/V_s$ ratio within the Upper Barnett Shale. This layer corresponds to the layer in blueish color identified in Figure 7b, which is also marked with a black oval. In contrast, this layer is not well defined in Figure 7a, in which the VMD constraint is not used.
EDITED REFERENCES
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REFERENCES
Li, F., T. Zhao, Y. Zhang, and K. J. Marfurt, 2016, VMD based sedimentary cycle division for unconventional facies analysis: Presented at the Unconventional Resources Technology Conference 2016, accepted.