Deepwater seismic facies and architectural element interpretation aided with unsupervised machine learning techniques: Taranaki basin, New Zealand

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DEEPWATER SEISMIC FACIES AND ARCHITECTURAL ELEMENT INTERPRETATION
AIDED WITH UNSUPERVISED MACHINE LEARNING TECHNIQUES: Taranaki Basin, New Zealand

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ABSTRACT

The use of unsupervised machine learning (ML) methods such as self-organizing maps (SOMs), has gained a significant foothold within the seismic interpretation community to enhance results and help identify similar patterns in the data. Workflows for each geological setting become, however, necessary. We analyzed a series of geometrical, instantaneous, spectral, and textural seismic attributes to provide multi-attribute input combinations that, with SOMs, allow for a proper interpretation of architectural elements in deepwater settings. By studying the Miocene section within the Pipeline 3D seismic dataset in southern Taranaki Basin, we show that GLCM entropy, RMS amplitude, sobel filter similarity, and frequencies seismic attributes used as inputs into the SOM enhance the interpretation of the features of interest, initially overlooked by single attributes analysis. This method had not been applied in the area yet. Results allow understanding and delineating architectural elements of deepwater systems, such as mud- and sand-filled channels, mass transport deposits (MTDs), and marine shales in the basin floor. Additionally, more minor features such as levees, overbank deposits, and sand waves are better mapped. The use of the Pukeko well helped to understand the system's evolution, which we interpret as a fan system incised by younger, more sinuous channels. Overall, the system turns more mud-prone as it becomes younger (upwards). Our study contributes to understanding the paleogeomorphology of the area, which can help optimize drilling plans, whereas our method offers three input attribute combinations for SOMs that can be applied in similar geological settings to aid in the interpretation optimization process.

Keywords: deepwater; seismic facies; architectural elements; seismic geomorphology; interpretation; seismic attributes; machine learning.
1. Introduction

The use of single and combined seismic attributes has been a common practice for predicting rock properties for the past thirty years (Hart, 2011). However, ML can help doing this in a significantly smaller amount of time than an interpreter by using several seismic attributes at the time and finding relationships between patterns which are not inherently obvious, and that can be often overlooked by an interpreter (Sacrey and Roden, 2014; Zhao et al., 2016; La Marca et al., 2019).

Most of ML applications can be expressed in terms of two categories: supervised and unsupervised learning. Supervised ML requires labels to predict classes (Pires de Lima, 2019), whereas unsupervised ML methods do not require labels, and uses input data to find patterns within the data generating clusters in most cases. In this study we use an unsupervised clustering technique called Self-Organized maps (SOMs) (Kohonen, 1982). Clustering (Hartigan, 1975) is the grouping of similar objects, where all the objects within the same cluster share a particular property in common. When ML uses seismic attributes, clusters can represent geologic information embedded in the data which sometimes cannot be interpreted by other means (Roden et al. 2015). In SOMs the clusters are represented in a 2D dimensional space.

Throughout the initial analysis of a given seismic volume, inspecting myriads of seismic attributes one by one can be tedious and time-consuming (Macrae et al., 2016) as an interpreter attempts to ascertain detailed characteristics within complex depositional environments. Therefore, there is a need to establish a repeatable seismic interpretation workflow to generate useful results in a time-efficient manner.

Although methods, such as principal component analysis (PCA) (Pearson, 1901), reduce the initial number of attributes down to a smaller subset, the results are purely statistically
based. Therefore, in this study three SOMs are computed using various attributes selected by the interpreter, which are representative of the study’s objective (better characterizing deep water channel elements) while being non-redundant. These seismic attributes include various geometrical, spectral, instantaneous, and textural attributes that are meaningful for the identification of paleo-geomorphological characteristics. Results are cross-correlated with well data (Pukeko-1) to support the proposed interpretations.

There are few studies that focused on the geomorphological investigation of the architectural elements present within the Pipeline 3D seismic dataset in the Taranaki Basin to evaluate the distribution, size, and evolution of its channel complexes (Kroeger et al., 2019; Silver et al., 2019). However, there are no studies to this date that applied ML techniques to study seismic facies or architectural elements in the location. Thus, our results are contributing to previous studies developed in the Basin and apply modern technologies for further interpreting and understand the region of interest with more detail.

This paper begins by presenting the geological setting of the study area and a description of the Pipeline-3D seismic dataset. Afterward, we explain the methodology applied, the seismic expression of each selected attribute, and the interpretation of each SOM model (SOM1, SOM2, and SOM3). The discussion of results and main findings are presented at the end.

2. Geological Setting

The study area lies in the southern Taranaki Basin, which is located offshore of north-western New Zealand (Figure 1). The basin covers an area of ~330,000 km² and is limited by the Reinga Basin to the north, and the West Coast Basin to the south. The eastern boundary
is represented by the Taranaki Fault, and the western border are the Northland Basin and New Caledonia Trough (Baur, 2012; New Zealand Petroleum and Minerals, 2014).

The Taranaki Basin is a rift basin formed in the Cretaceous and comprises a succession of around 10 km of deposits (Strogen et al., 2014; Kroeger et al., 2019) from the Cretaceous to the Neogene (King and Trasher, 1996). The evolution of the basin occurred in three stages, each one controlled by different plate boundaries kinematics (King and Trasher, 1996; Baur, 2012; Strogen et al., 2014; Bull et al., 2018; Kroeger et al., 2019) 1) an intra-continental rift transform from the Late Cretaceous to Paleocene, 2) a passive margin from the Eocene to the Early Oligocene, and 3) an active marginal basin from the Oligocene to present day.

3.1. Miocene deepwater systems

The Middle Miocene in the Taranaki Basin is characterized by the deposition of deepwater sequences controlled mainly by tectonic uplift in the hinterland. The high relief provided a south-east source of sediments carried and deposited in a north-northwest direction. (Bull et al., 2018) (Figure 1). The Miocene stratigraphic succession is comprised of intercalation of fine-grained basin floor sandstones deposited by channels and fans, in addition to silty and mudstone dominated deposits (Baur, 2012).

The fine-grained basin floor sandstones are represented by the Late Altonian to Early Lillburnian Moki Formation (18-13 Ma), deposited during lowstand and falling stage systems tracts. The silty and mudstone dominated deposits correspond to the Manganui Formation that were deposited along with the sand-waves sandstones during highstand system tracts (King and Thrasher, 1996; Kroeger et al., 2019). The resulting configuration of sandstones encased within
The Moki Formation has been documented in both well-log and seismic data (King and Browne, 2001). Nevertheless, only a few studies (Baur, 2012; Kroeger et al., 2019; Silver et al., 2020).
2019) have explored the Pipeline 3D dataset, where they focused on understanding the geomorphology and characteristics of deepwater channel complexes. These studies reported the following main findings: 1) channel complex dimensions vary from 200-600 m to ~2000-5000 m wide and ranges between 10-30 m in thickness, 2) channel sinuosity varies from low to high, and 3) the channel system becomes more mud-dominated during the Late Miocene.

3. Seismic dataset and data

3.1. Seismic data

The Pipeline 3D seismic survey acquired in 2013 by Todd Exploration covers ~515 km² of the southern Taranaki Basin (Figure 1). The data is zero phase and has SEG negative polarity. The survey has a ~25 m of vertical resolution, with a sample interval of 4 ms, and a bin size of 25 m by 12.5 m. The projection datum is NZGD2000. The PSTM volume was processed by Excel Geophysical services in 2015.

3.2. Well data and other resources

Within the Pipeline 3D, one well titled Pukeko-1 (Figure 1) was incorporated in our study to test our results. The Pukeko-1 was drilled in 2004 and reached a total depth of 4190 m (New Zealand Petroleum and Minerals, 2014). Our section of interest corresponds to the Miocene Moki and Manganui Formations, located between ~2141 m and ~2800 m (Figure 2). A gamma-ray (GR) log is available for this interval. Other data includes a report with lithology descriptions and a check-shot in the well which helped to establish a time-depth relation with the seismic dataset. All the data was provided courtesy of the New Zealand Petroleum and Minerals.
Figure 2. Stratigraphic diagram for the Taranaki Basin (modified after Roncaglia et al., 2010 in Strogen et al., 2011) focusing on the interval of study, indicating period, epoch, group, age in Ma, lithology and the corresponding tops in the Pukeko-1 well. The gamma ray (GR) log and seismic appearance of the Moki A and the Moki B reflectors are also shown.

4. Methods

The workflow applied in this study is presented in Figure 3. Main phases consist of:

4.1. 3D volume inspection and AOI definition

Preliminary inspection of the seismic volume is paramount for identifying acquisition footprint, noise, and other features that can influence the interpretation. We used amplitude and coherence volumes to perform this analysis by scanning through various inlines crosslines and time slices.
For the study we chose an AOI of ~300 km$^2$ as it comprises the channel complexes while also avoiding the structural influence of a large-scale fold present in the area. This structural feature was omitted from the SOM as it can affect the classification. Vertically, the AOI includes the Miocene Moki and Manganui Formations. We defined the AOI vertical window of 500 ms as it captures the same type of deposits that should be genetically related (facies). We recommend using a small window, that in addition to a representative AOI, allow the algorithms to process information more efficiently and further avoid miscalculations and misclassifications.

4.2. Well tie and Horizon picking/mapping

The Pukeko-1 well contains check shot data and well tops (New Zealand Overseas Petroleum Ltd., 2004), which facilitates a depth-time conversion and a well tie. This well tie allows for the recognition of the geological formations and the lithological responses present within each interval in the seismic. Once this conversion is done, we recognized the distinct formations. We picked the Moki Horizon (Figure 4) by following a clear and continuous reflector (a peak) every ten lines, in an inline-crossline sequence, to better map the reflector. After completing the interpretation, we used automatic tracking and corrected manually where necessary.

4.3. Multi-attribute analysis and attribute selection for SOM

It is paramount to have a clear goal while interpreting so that the appropriate seismic attributes are selected to best suit the purpose of the study and geological setting (Roy et al.,
This study aimed to identify different seismic facies and architectures that correspond to deepwater deposits found within the Miocene Moki Formation.

![Workflow](image)

**Figure 3.** Workflow applied for this study.

We analyzed geometrical (discontinuity) attributes because they are commonly used to define the outer shape or geomorphology of geological features (Chopra et al., 2007). In addition, we explored the use of GLCM textural attributes which aid in facies identification (Haralick et al., 1973). Spectral and instantaneous attributes, on the other side, are known for unraveling lithological content (Marfurt, 2006), and their capability of distinguishing differently sized features associated with channel complexes (Partyka et al., 1999): small architectures like
levees are usually related to high frequencies, and significant, master channels can be identified with lower frequencies. These attributes were calculated using AASPI software. Attribute volumes were extracted and flattened on the Moki Horizon to perform better interpretations of the architectural elements. Lastly, we defined the most suitable attributes by analyzing the covariance matrices in each attribute combination. We selected attribute combinations were the linear relationship between each attribute with the others resulted in $R < 0.7$, as suggested by Kim et al. (2019) to avoid using redundant attributes.

4.4. SOMs and interpretation

We used AASPI for calculating the SOMs using the attribute combinations determined. SOMs were parametrized by defining 256 clusters (prototype vectors). Then they were exported into a commercial interpretation package to visualize and interpret the results, where each SOM was flattened on the Moki Horizon. Available GR logs from the Pukeko-1 well were also incorporated into the SOM analysis and were upscaled to the resolution of the seismic data (~25 m). Details on the SOM method are found in Kohonen (1982) and La Marca (2020).
**Figure 4.** Seismic amplitude expression of architectural elements. A) In the upper left, time slice Z: 2000 ms is presented, and the vertical slice at crossline (xline) 2193 is indicated in blue color b) Vertical transect (A-A’) of the amplitude section with interpretations of some architectural elements like channels and levees. Seismic data courtesy of New Zealand Petroleum and Minerals.
5. Results

5.1. Seismic expression of the AOI

Before exploring the different seismic attributes, we evaluated the seismic amplitude character within the AOI. Figure 4 shows an amplitude time slice at -2000 ms. In crossline 2193 (A-A’), we observe the intersection of different size channels (100 m to 3000 m wide) and their variable amplitudes. Some of these channels are incised, exhibiting basal scour surfaces, and different infill patterns. These features are shown through the typically low amplitude and stacked reflector responses. Overall, the reflector configurations range from more conformable in deeper sections to more chaotic as it becomes shallower. A continuous, high amplitude reflector (trough) above the Moki Horizon is associated with sheet sands due to its high amplitude response and lateral continuity. We interpret some levees to be associated with the main channel belts. Table 1 explains the internal seismic reflection, external shape, and amplitude character of the architectural elements recognized in the dataset. Notice that although amplitude is a good preliminary tool to identify some architecture and facies, especially on vertical slices, it does not define the dimensions or aerial extent of the architectural elements. Therefore, it is necessary to integrate other attributes to create a more accurate characterization of these features.

5.2. Seismic attributes: finding the most suitable combination

Attributes that have geological significance for deepwater facies were chosen after exploring various geometrical, textural, spectral, and instantaneous seismic attributes. Table 2 presents the list of attributes selected, indicating their types, explaining its principle, and
supporting references. The common geological interpretation of each attribute is shown in each case.
<table>
<thead>
<tr>
<th>Architectural element</th>
<th>Geological scheme</th>
<th>Internal Seismic reflection configuration</th>
<th>External shape</th>
<th>Amplitude</th>
<th>Vertical slice</th>
<th>Time slice</th>
<th>Coherence</th>
<th>Curvature</th>
<th>GLCM entropy (Texture)</th>
<th>Frequency</th>
<th>Dip and reflector convergence</th>
</tr>
</thead>
<tbody>
<tr>
<td>A Mud filled abandoned channel</td>
<td></td>
<td>Subparallel reflectors, often with smaller incisions and possible lateral accretion</td>
<td>Incision of regional pattern, external pattern usually differs in amplitude, phase and frequency</td>
<td>Low to moderate, often with low S/N ratios</td>
<td>Low coherence in channel edges</td>
<td>Low to moderate</td>
<td>Most negative (due to differential compaction)</td>
<td>Low</td>
<td>Variable</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>B Sand filled channel/bars</td>
<td></td>
<td>Subparallel reflectors, often with smaller incisions and possible lateral accretion</td>
<td>Incision of regional pattern, external pattern usually differs in amplitude, phase and frequency</td>
<td>High amplitude</td>
<td>Low coherence in channel edges</td>
<td>Most positive curvature</td>
<td>Low</td>
<td>Variable</td>
<td>Frequency</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>C Levees</td>
<td></td>
<td>Subparallel reflectors, tilted</td>
<td>Wing shape, surrounding with channel complex, often stacked</td>
<td>Variable</td>
<td>Low coherence in levees edges</td>
<td>High positive curvature</td>
<td>Moderate high entropy</td>
<td>Broadband response</td>
<td>High</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D Splays/overbank</td>
<td></td>
<td>Subparallel reflectors, tilted</td>
<td>Sometimes no distinguishable between other architectures</td>
<td>Variable</td>
<td>Not easily distinguishable, similar to small levees (depends on resolution)</td>
<td>Low</td>
<td>Anomalies associated with edges</td>
<td>Moderate high entropy</td>
<td>High frequency</td>
<td>High</td>
<td></td>
</tr>
<tr>
<td>E MTD</td>
<td></td>
<td>Subparallel to chaotic</td>
<td>Rotated blocks; shingled</td>
<td>Variable (depends on A/R contrast)</td>
<td>External and internal low coherence edges</td>
<td>Anomalies (changes in block orientation)</td>
<td>High entropy, with homogeneous rotated blocks</td>
<td>Variable frequency in each block</td>
<td>Low, dip variable</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F Sheetsands/lobes</td>
<td></td>
<td>Parallel to subparallel</td>
<td>Continuous, large reflectors</td>
<td>High amplitude</td>
<td>High coherence</td>
<td>Low curvature</td>
<td>Low</td>
<td>Low frequency</td>
<td>Low</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G Marine shales</td>
<td></td>
<td>Parallel to subparallel, low amplitude</td>
<td>May lie unconformably on deeper strata</td>
<td>Low to moderate, often with low S/N ratios</td>
<td>Moderate to high</td>
<td>Low curvature</td>
<td>Moderate to high spectral response</td>
<td>Parallel to subparallel, convergent at onlap surfaces</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 1. Architectural elements in deepwater settings. Schemes from Slatt and Weimer (2004) are shown in each case. The seismic amplitude response and meaningful attributes for these deepwater architectural elements are listed here.

Secondly, the list of attributes was reduced by ensuring that these attributes are not redundant (Barnes, 2007; Kim et al., 2019). Table 3 shows the combinations used for each SOM model. The attribute combinations for SOM1 were those used by Zhao (2016), who studied deepwater seismic facies in the offshore Canterbury Basin, New Zealand. The second multi-attribute workflow explores the combination of geometrical attributes with attributes that are a useful indicator of lithology. The third combination evaluates the contribution of textural and spectral attributes. Ultimately, we aimed to test the different SOM responses by using various combinations of attribute types.

We evaluated the geologic response of the attributes when comparing among each other after flattening on the Moki Horizon. Curvedness (Figure 5d), dip magnitude (Figure 6c), and sobel filter similarity (Figure 6d) highlight the geomorphology of architectural elements within the channel belt complexes such as channels, levees, scroll bars, splays, and abandoned channels. Most positive curvature, K1, (Figure 6e) is particularly useful for defining the levees and smaller channels associated with the master channel and to further differentiate various deepwater architectural elements.

Additionally, sweetness, root mean square (RMS) amplitude, and instantaneous phase are good lithological indicators. High values of sweetness denote possible sandstone rich areas (Figure 6a), such as sandy lobes (sheets), sandy bars, and some splays. These high sweetness areas often coincide with high RMS values zones (Figure 6b).
Table 2. List of attributes selected for deepwater seismic characterization in this study. The type of attribute is indicated and explained according to the listed references (fourth column).

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Type/ measurement</th>
<th>Principle</th>
<th>References</th>
<th>Geological use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coherent energy</td>
<td>Discontinuity</td>
<td>Cross-correlation between adjacent traces (1). The coherent component of traces divided by the total energy of the traces (2)</td>
<td>1-Bahorich et al., (1995) 2-Chropra et al., (2007)</td>
<td>Channel edges and faults</td>
</tr>
<tr>
<td>Curvedness</td>
<td>Reflector</td>
<td>Measure of total deformation or intensity of folding (considers k1 and k2)</td>
<td>Roberts (2001)</td>
<td>Faults, channels and levees edges</td>
</tr>
<tr>
<td>Dip magnitude</td>
<td>Reflector</td>
<td>Semblance search estimate of vector dip</td>
<td>Barnes (2001); Marfurt (2006)</td>
<td>Apparent dip, detection of faults and other stratigraphic features</td>
</tr>
<tr>
<td>GLCM entropy</td>
<td>Texture</td>
<td>Quantifies the lateral variation in seismic amplitude. Entropy; how smoothly varying the voxel values or seismic amplitudes are within a window</td>
<td>Haralick et al., (1973)</td>
<td>Seismic fades by its textural response</td>
</tr>
<tr>
<td>Instantaneous phase</td>
<td>Phase</td>
<td>Emphasizes spatial continuity of reflections by providing a way to make coherency events more clear</td>
<td>Taner et al., (1979); Marfurt (2006)</td>
<td>Good indicator of lateral continuity, sedimentary layer patterns, sequence boundaries, onlap, oflap</td>
</tr>
<tr>
<td>Most positive curvature k1</td>
<td>Reflector</td>
<td>Measure of the maximum bending (positive or negative) of the surface at a certain point</td>
<td>Roberts (2001)</td>
<td>Feature-recognition applications. Anticlines, synclines, levees, channel</td>
</tr>
<tr>
<td>Peak spectral frequency</td>
<td>Spectral (Frequency)</td>
<td>Is the dominant frequency component during a 1-sec sampling period as determined by the fast fourier transform</td>
<td>Liu (2007)</td>
<td>Depositional, diagenetic and structural patterns, used in channel detection. Can show the vertical thickness variation</td>
</tr>
<tr>
<td>Peak spectral magnitude</td>
<td>Spectral (Frequency)</td>
<td>Computes the max. value of the absolute value of the amplitudes within a window</td>
<td>Liu (2007)</td>
<td>Strong hydrocarbon indicator. Thickness of channels</td>
</tr>
<tr>
<td>RMS (root mean square amplitude)</td>
<td>Amplitude</td>
<td>Is a measure of reflectivity within a time window. Computes the square root of the sum of squared amplitudes divided by the number of samples within the window used</td>
<td>Meek (2013)</td>
<td>Sand bodies and mud-filled channels associated with channel belts</td>
</tr>
<tr>
<td>Sobel filter (similarity)</td>
<td>Discontinuity</td>
<td>(1) Normalizes coherence (2) data to produce results between 0 and 1</td>
<td>1-Luo et al., (1996)</td>
<td>Channel edges and faults</td>
</tr>
<tr>
<td>Spectral frequency</td>
<td>Spectral (freq)</td>
<td>(1) Applies a suite of constant-bandwidth filters to the seismic data. (2) The CWT continuous wavelet transform bandpass filters the data with a filter banks that are exponentially spaced with exponentially increasing bandwidths</td>
<td>1-Partyka et al, (1999); 2-Castagna and Sun (2006)</td>
<td>Channels and minor architectural elements. Analyze stratigraphy and thickness changes</td>
</tr>
<tr>
<td>Sweetness</td>
<td>Amplitude</td>
<td>Calculated dividing the instantaneous amplitude by the square root of the instantaneous frequency</td>
<td>Radovich and Oliveros (1998)</td>
<td>Sand rich deposits, HC bearing formations, thick reservoirs</td>
</tr>
</tbody>
</table>
### Table 3. List of the input attributes for each SOM.

<table>
<thead>
<tr>
<th>SOM1</th>
<th>SOM2</th>
<th>SOM3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak frequency</td>
<td>Sweetness</td>
<td>GLCM entropy</td>
</tr>
<tr>
<td>Peak magnitude</td>
<td>Dip magnitude</td>
<td>RMS amplitude</td>
</tr>
<tr>
<td>Curvedness</td>
<td>Instantaneous phase</td>
<td>Spectral CWT 35 Hz</td>
</tr>
<tr>
<td>Coherent energy</td>
<td>(K1) Most positive curvature</td>
<td>Spectral CWT 60 Hz</td>
</tr>
<tr>
<td></td>
<td>Sobel filter</td>
<td>Sobel filter</td>
</tr>
</tbody>
</table>

Textural attributes belong to a different category of seismic attributes. In this study, GLCM entropy emphasizes changes in textures, whose interpretation is associated with different facies (Figure 7a). Therefore, this attribute is a useful input for the SOM algorithm as it will better characterize different deepwater facies. Sand prone deposits exhibit low GLCM entropy values, whereas more mud-prone and chaotic (such as MTDs) deposits are represented by higher GLCM values.

Spectral decomposition is a widely used technique for channel studies (Partyka et al., 1999). The incorporation of different frequency components with other input attributes into the SOM model can help to further differentiate facies and architectures of different thicknesses (e.g., levees and channels). The Pipeline 3D seismic dataset contains a frequency spectrum which varies from 5 Hz to almost 100 Hz. The dataset’s dominant and representative frequencies within the AOI of 13, 35, and 60 Hz, were RGB blended (Figure 7d). Smaller frequencies are useful for defining the major architectural elements, like channels, whereas higher frequencies highlight minor features, such as levees or splays.
Figure 5. Attribute combination for SOM1, proposed by Zhao (2016). a) Peak frequency, b) peak magnitude, c) coherent energy, and d) curvedness seismic attributes are presented and interpreted respectively. Interpretations are shown by their respective arrow color.
Figure 6. Attribute combination for SOM2. a) Sweetness attribute is believed to be a lithological indicator for this study. High values of sweetness (colored in red to yellow) represent possible sandy deposits. b) Instantaneous phase helps to add contrast and provides further insight into the lithological distributions. This attribute separates the different possible lithologies into various colors. c) Dip magnitude delineates the outer shape of the channel and improves the definition of larger features within the system. High values of dip are shown in black. d) Sobel filter similarity (coherence) seismic attribute helps to define the geometry of the channel. High values of coherence depict the channel edges (shown in black) and provide a detailed delineation of the architecture of channel elements such as scroll bars.
Figure 7. Attribute combination for SOM3: a) GLCM entropy, b) RMS amplitude, c) sobel filter similarity, d) spectral CWT decomposition (13 Hz, 35 Hz, and 60 Hz) is presented.
Figure 8 shows a schematic representation of the location of various deepwater elements from proximal to distal areas. Table 1 presents the seismic expression of the various deepwater architectural elements recognized in this study in addition to their responses within the meaningful seismic attributes. Note that the elements in Table 1 appear in Figure 8 with letters to show their relative position in the system.

Figure 8. Schematic illustration of the main architectural elements in deepwater systems. Modified after Posamentier et al. (2003). Notice some features have letters that are related to the content described in Table 1.

5.3. Testing non-linear relationships between attributes

Kim (2019) states that while relevant attributes preserve a relationship with the output classes, redundant attributes have a higher correlation between them. This is the reason for evaluating the linear relationship between attributes to better optimize our SOM models.
Table 4 presents a correlation matrix for each SOM model. The main diagonal presents values of one (1) since it is comparing the same seismic attribute with itself. For each attribute combination explored, attributes that had a correlation smaller than 0.7 were considered as input to be used in the various SOM models as this value indicated that there is a weak linear relationship amongst the list of attributes selected.

Table 4. Correlation matrixes from SOM1, SOM2, and SOM3. Main diagonals indicate the value of 1 because it compares each attribute with itself. When comparing every other attribute, the correlation is less than \( R = 0.7 \), which, according to Kim et al. (2019), represents the non-linear relationship between the attributes. From this, every attribute used as an input for each SOM is unique and representative of the dataset.

5.4. **SOMs - Interpretations per workflow**

We evaluated the results of each of the SOM results by flattening their volumes on the Moki Horizon so that features of interest are comparable between the different SOM models. We applied principles of seismic geomorphology to interpret the different architectural elements present within the AOI. The results of each combination of attributes (SOM1, SOM2 and SOM3) are presented as follows:
5.4.1. Combination 1- (SOM1)

SOM1 uses a combination of attributes that are beneficial for deepwater facies characterization after studies from Zhao et al. (2016). SOM1 was calculated by combining peak frequency, peak magnitude, coherent energy, and curvedness seismic attributes (shown in Figure 9). The yellow and orange colors (or classes) represent more sand-prone deposits, which include point bars and sheet sands (fan-lobe) as well as some sediment waves as defined recently by Kroeger et al. (2019). These sediment waves are perpendicular to the paleo-flow direction, which follows a southeast-northwest trend, and can be sometimes overlooked or misinterpreted as noise when only looking at a single attribute. The purple and blue colors possibly indicate more shaley elements such as mud-filled channels, and marine shales commonly found in the basin floor.

5.4.2. Combination 2- (SOM2)

SOM2 was derived from using a combination of sweetness, instantaneous phase, dip magnitude, sobel filter similarity, and most positive curvature (K1) seismic attributes. Figure 10 highlights different colors than the ones that were prominent in SOM1. It is essential to mention that the colors assigned to output classes in the SOMs are randomly chosen after each iteration. As a result, the same architectural elements can be represented in different colors. This means that yellow color in each of the SOMs does not always correlate to sandy scroll bar facies. However, what is more important is that the classes are positioned in similar zones over the same AOI. This can be seen in SOM2, where the orange to greenish colors represents sandstone prone elements, like scroll bars, lobes, and some overbanks and are in the same location as the yellow and orange colors from SOM1. However, the fuchsia and purple colors represent silty
levees and smaller channels positioned around the main channel (Figure 10). The purple and
light blue colors represent mudstone deposits like mud-filled channels (both small and large
scale) and basin floor marine shales. In SOM2, geomorphological features are better
differentiated than they were in SOM1. Upon looking at a vertical slice (Figure 12), the
identification of architecture shapes suggests a strong influence from the geometrical attributes
used in the classification.

5.4.3. Combination 3- (SOM3)

Finally, SOM3 (Figure 11) conveys the best representation of the different architectural
elements when compared to the other SOMs. In this case, we used the seismic attributes GLCM
entropy, RMS, sobel filter similarity, and spectral frequencies as inputs into the SOM. These
results show that the orange colors isolate sandstone-prone features like bars, splay, and fans
(sheets). The greenish to yellowish colors are interpreted to represent silty deposits where
sediment waves deposits are identified. The blue and purple classes help to identify the mud-
filled turbiditic channels (Figure 11 and 12) and basin floor marine shales. The purple color
especially helps to delineate the external geometry/geomorphology of features like levees. The
SOM3 results suggest that the combination of spectral and textural attributes further refine the
classes identified in the previous SOMs while also helping to resolve channels thicknesses that
are slightly below seismic resolution.

Figure 12 presents the SOM results in a vertical slice. When comparing SOM1, SOM2,
and SOM3, in general, sand-prone facies (channels and fans) are located relatively in the same
position (in time/vertically). The mud-prone facies, recognized as the basin floor marine shales,
are positioned in similar areas in the three SOMs cases. SOM3 appears to present more details
and classes than the other two SOM results. Therefore, it suggests that the incorporation of
textural and spectral attributes generates a more robust classification of the deepwater facies.

**Figure 9.** SOM1 flattened on the Moki Horizon. The yellow and orange classes represent sandier to
siltstone prone deposits that include point bars, sheet sands (fan), and some splays recognized in the
outer zone of the cut banks. Also, some sediment waves, perpendicular to the paleo-flow, as proposed
recently by Kroeger et al. (2019), are depicted by this class. The latter can be overlooked or
misinterpreted as noise if just evaluating individual attributes. The purple and blue colors possibly indicate more shaley deposits, this is, mud-filled channels and marine shales.

Figure 10. SOM2 flattened on the Moki Horizon. The results of the classes are similar to the ones presented in SOM1 but with different colors and smaller elements detected, which is shown by the thin channels (fuchsia color).
Figure 11. SOM3 flattened on the Moki Horizon. In this case, sandy bars, splays, and fans (sheets) are clearly represented by the orange color/class, while blue and purple classes correspond to mudstone prone deposits (mud-filled channels and marine shales). Single attributes did not allow for the recognition of these features.
Figure 12. a) Crossline 2239 in seismic amplitude within the interval of study b) results of SOM1, c) results of SOM2, d) results of SOM3. Notice how each SOM represents similar seismic facies in different colors, and SOM3 appears to provide a more detailed classification. The upscaled Pukeko-1 GR log is shown in the section.
5.5. *Testing results, time evolution, and architectural elements*

After generating the SOMs and interpreting the deepwater system at the time of the deposition of the Moki Formation, we evaluated the SOM results. Figure 13 shows a series of time slices that intersect the Pukeko-1 well, tied to the seismic volume. In the vertical slice, we defined sample areas to evaluate the output classes from the SOM3 model. For example, in the time slice taken at -1916 ms, the well has a high GR, serrated signature, which is characteristic of marine shales. These characteristics are shown by the blue and purple colors in SOM3. However, in the time slice taken at -1968 ms, there is a low GR value, which is characteristic of sandstones and possesses a signature that is representative of channels (blocky to finning upward log pattern).

This GR log feature is shown by the orange color in the SOM. In the other time slices that are more mixed to silty, the class is represented by green-yellowish color in SOM3. The well log profiles matching the SOM results (Figure 13) allowed us to corroborate our analyses and be able to make geological interpretations on the evolution of the system. These findings can be further used to determine volumetric estimations of these reservoirs or seismic facies of interest. In this instance, the seismic data shows how the geomorphology of the channel complexes change upwards, from straight-linear (most likely channelized gullies) to a higher sinuosity, meandering character (channel-levee complexes). The channel widths also vary from ~200 m to 5 km for these channel complexes. This suggests that there were changes in the energy, slope, and trigger factors (Catuneanu, 2009) within the Miocene deepwater system, having individual older channels followed by younger channel complexes.

After looking at vertical and time slices, it seemed that the sandy-prone facies were predominant in the lower time slices, and the system becomes more mud-rich up section. We
interpret the system in our section of interest to be a channelized turbidite fan system where the channels became progressively more carved and migrated laterally due to avulsion. Additionally, the deposits that were reworked by bottom currents, as suggested by Kroeger et al. (2019), were recognized in the horizon slices with the aid of the SOM results. Single attributes did not allow for the recognition of these features.

**Figure 13.** Evaluation of the interpreted facies and architectural elements by using the gamma-ray (GR) log from the Pukeko-1 well and upscaling it to the seismic resolution (~25 m). We show four time slices where the SOM3 results can be evaluated. These slices highlight the evolution of the architectural elements. A vertical amplitude slice (B-B’) is shown perpendicular to the paleo flow direction alongside the SOM results that aid in the interpretation. This is interpreted as a fan system that was carved or
incised by younger channels, and the system turns more mud prone as it becomes younger (upwards) as represented by the cartoons on the right.

6. Discussion

We generated spectral, geometric, textural, and instantaneous attributes as only a PSTM seismic volume is available for this. However, these seismic attributes help define the geomorphological properties of deepwater architectural elements while also providing an understand of their possible lithologies as presented in the SOM results. Chopra and Marfurt (2014) highlighted the importance of using different types of attributes to capture both structural and stratigraphic features present within the dataset. The incorporation of multiple attribute types as input for SOM studies to enhance seismic interpretation has become a common practice, as observed by Sacrey et al. (2014) and by Roden and Sacrey (2016). These studies are the first step in a promising direction for efficient and robust seismic characterization.

The selection of the attributes considered the findings presented in Barnes (2007) and Kim (2019). When selecting the appropriate attribute combinations, we discarded the GLCM homogeneity attribute as it shared a redundant classification with the GLCM entropy attribute.

We corroborated that the sweetness and RMS amplitude seismic attributes are good lithological indicators. The higher the values of these two attributes, the more sand-prone the facies are, as can be seen in Figures 6a and 7b. On the other hand, seismic attributes, such as coherence and dip magnitude, highlight the geomorphology of the architectural elements within the channel belt complex. This can be seen in the various channels, levees, scroll bars, splays/overbank, and abandoned channel features present in Figure 6c. Most positive curvature (k1) excels in identifying the positive relief created by levees when compared to the other attributes (Figure 6e).
Although each seismic attribute provides individual hints about the facies and the geomorphology of the deepwater elements, this study demonstrates that SOMs create a more efficient workflow for classifying and highlighting channel elements within the AOI. Features such as splays and levees are quickly identified in the SOMs (shown by arrows in Figures 9-13), whereas they were not confidently imaged by individual attributes (shown in Figures 5-7). Sandy wave deposits that were recently suggested by Kroeger et al. (2019) in the Pipeline 3D seismic survey were confirmed after SOM analysis, similarly to the levees, making the local paleogeomorphology interpretation more robust.

The seismic facies or groups are represented by different colors in each of the SOM models, as the colors are assigned randomly in each iteration. The orange and greenish zones in SOM1 correspond to coarser-grain facies (sandstones and siltstones). The orange color represents the sand- and silty-rich zones in SOM2, and these are yellowish-greenish in the SOM3. Additionally, SOM2 and SOM3 better highlight the levees and channels edges, shown by the purple color. This may be associated with the incorporation of geometrical attributes within the SOM models.

Figures 12 and 13 lead to a better understanding of the deepwater system within the AOI. First, the sandier and siltier facies (represented by warmer colors) have a facies distribution typical of channels and sheet-sands (basin floor lobes). Secondly, the mud-prone facies, such as the mud-filled channels (zones within the channel complexes), and marine shales (basin floor hemipelagic-predominant background) are represented by the blue or purple colors in the SOM1, SOM2, and SOM3. Finally, from the SOM3 interpretations of the associated seismic facies and architectures, the system goes from a more sand-rich basin floor fan system in the older sediments and evolves into individual channels (that carved the fan system).
system becomes more mud-prone in the younger deposits (upper section). These changes are interpreted to attend to a compensational style (sandstones being deposited where space was available), which occurs as consequence of the interaction of accommodation space and sediment supply (Slatt, 2004). This evolution was analyzed by using the Pukeko-1 well and is represented in Figure 13.

Because the seismic resolution tends to decrease with depth (Hart, 2011) and depositional systems vary vertically (Slatt and Weimer, 2004), this study focused on the Moki Formation (500 ms interval in TWT) to characterize this Miocene deepwater system. Future work would evaluate the different SOM results for different vertical ranges and windows of operation.

After understanding the configuration of this deepwater system, the potential location of the best quality hydrocarbon reservoirs can be determined. These optimal reservoirs are defined as sandstone-prone elements like sheet sands and scroll bars, as presented by Slatt and Weimer (2004). The recognition of these architectural elements can optimize drilling designs, make production plans more efficient, and can significantly reduce operational costs. However, since the SOMs lack an error uncertainty measure for the output clusters, the interpreter should apply their knowledge and experience by using seismic geomorphology and “in context” interpretation to analyze the SOM results if well log data is not available. A comparative analysis between the SOM results with other data types and analogs is strongly encouraged.

We found that SOM3 performed better than SOM1 and SOM2 when differentiating between facies. From these results, we suggest using at least one textural attribute (e.g., GLCM entropy) that can highlight continuity, one instantaneous or amplitude attribute, like sweetness or RMS amplitude, that denotes amplitude and provides hints about the lithological
composition. We also recommend using one or more spectral attributes that highlight frequency
e.g., iso-frequencies, peak spectral magnitude) and thickness changes. Finally, we recommend
including one geometrical attribute like coherence or curvature. You could even use a
ger"eometrical attribute to highlight channel edges by co-rendering with the SOM results. The
incorporation of these different attributes may vary depending on the data available and the
objective of the study. For example, Zhao (2016) was able to identify channels, point bars,
crevasse splay and slope fans elements in the Canterbury Basin, New Zealand by applying
SOM1, but in our location (located at the northwest) we recognized the presence of sand waves
deposits and levees associated with channels. When using SOM3 combination that contains
frequency attributes we can better recognize these subtle elements.

ML algorithms can serve as a tool for assisting seismic interpreters by identifying
relationships within the data that humans may not be able to recognize easily, saving the
interpreter’s time. However, the interpreter is vital for either training the algorithms or for
interpreting the results within a geological context, which is something that these algorithms
cannot yet accomplish.

7. Conclusion

• In this paper, we tested a wide range of geometrical, spectral, instantaneous, and textural
attributes, and we later incorporated the chosen combinations into different SOM models to
enhance deepwater architectural elements and facies interpretations testing them in the Moki
Formation within the Pipeline 3D dataset, in the Taranaki Basin.

• Based on our results, for SOMs to be optimal, we suggest using a combination of
meaningful (in line with the study objective) and non-redundant seismic attributes as input. We
suggest using geometrical attributes that define the geomorphology of the architectural elements (e.g., dip magnitude for channel edges), RMS or sweetness attributes for accentuating sand-prone facies and architectures (e.g., sand-filled channels, or sheet sands), and textural attributes such as GLCM entropy to differentiate facies (e.g., MTDs from mud-filled channels). We highly recommend using spectral attributes and curvature, which were beneficial for discriminating elements like levees (positive curvature, high spectral frequency) from major dimension architectures like channels (low spectral frequency).

- If seismic attributes (input) are tested to be meaningful before the application of any clustering algorithm, we may get a more robust classification. By providing "in-context" interpretation by the expert geoscientist, they can extract additional details regarding architectural elements and the implications that these could pose on the potential reservoirs.

- Whereas each seismic attribute provides hints about facies and geomorphology, we demonstrate that the application of SOMs allows for a more efficient workflow in deepwater element discrimination and classification (e.g., splays, levees, and minor features). In the case of Moki Formation in the study area, SOMs results cross-correlated with the Pukeko well allowed for the interpretation of the paleo-geomorphologic evolution of the system, interpreted as a series of sand-rich lobes that have been incised by mud-rich, 200m-5Km wide, sinuous channels.

- The identification and isolation of groups (architectural elements) are useful to further generate two-dimensional and three-dimensional maps. This allows the geoscientist to not only describe and define the facies but also quantify hydrocarbon accumulations within them. Our workflow may enable others to maximize the potential of their datasets if geological settings are analog.
Data Availability

Datasets related to this article can be found at https://data.nzpam.govt.nz/GOLD/system/mainframe.asp, an open-source online data repository hosted at New Zealand and Petroleum Minerals.

Acknowledgments

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**Figure 1.** Map of western offshore New Zealand highlighting the Taranaki Basin and the study area. The seismic dataset (Pipeline 3D) location is shown in yellow and the Pukeko-1 well with a fuchsia point. The paleo-trend of deposition (southeast-northwest) and principal faults trend (southwest-northeast) are indicated as reported in Kroeger et al., (2019). Notice that the study location is close to the distal fans area near Miocene time, when the Moki Formation was deposited. The paleo-shelf break limit by that period is indicated using a blue dashed line after Strogen (2011).

**Figure 2.** Stratigraphic diagram for the Taranaki Basin (modified after Roncaglia et al., 2010 in Strogen et al., 2011) focusing on the interval of study, indicating period, epoch, group, age in Ma, lithology and the corresponding tops in the Pukeko-1 well. The gamma ray (GR) log and seismic appearance of the Moki A and the Moki B reflectors are also shown.

**Figure 3.** Workflow applied for this study.

**Figure 4.** Seismic amplitude expression of architectural elements. A) In the upper left, time slice Z: 2000 ms is presented, and the vertical slice at crossline (xline) 2193 is indicated in blue color b) Vertical transect (A-A’) of the amplitude section with interpretations of some architectural elements like channels and levees. Seismic data courtesy of New Zealand Petroleum and Minerals.

**Figure 5.** Attribute combination for SOM1, proposed by Zhao (2016). a) Peak frequency, b) peak magnitude, c) coherent energy, and d) curvedness seismic attributes are presented and interpreted respectively. Interpretations are shown by their respective arrow color.

**Figure 6.** Attribute combination for SOM2. a) Sweetness attribute is believed to be a lithological indicator for this study. High values of sweetness (colored in red to yellow) represent possible sandy deposits. b) Instantaneous phase helps to add contrast and provides further insight into the lithological distributions. This attribute separates the different possible lithologies into various colors. c) Dip magnitude delineates the outer shape of the channel and improves the definition of larger features within the system. High values of dip are shown in black. d) Sobel filter similarity (coherence) seismic attribute helps to define the geometry of the
channel. High values of coherence depict the channel edges (shown in black) and provide a
detailed delineation of the architecture of channel elements such as scroll bars.

**Figure 7.** Attribute combination for SOM3: a) GLCM entropy, b) RMS amplitude, c) sobel
filter similarity, d) spectral CWT decomposition (13 Hz, 35 Hz, and 60 Hz) is presented.

**Figure 8.** Schematic illustration of the main architectural elements in deepwater systems.
Modified after Posamentier et al. (2003). Notice some features have letters that are related to the
content described in Table 1.

**Figure 9.** SOM1 flattened on the Moki Horizon. The yellow and orange classes represent
sandier to siltstone prone deposits that include point bars, sheet sands (fan), and some splays
recognized in the outer zone of the cut banks. Also, some sediment waves, perpendicular to the
paleo-flow, as proposed recently by Kroeger et al. (2019), are depicted by this class. The latter
can be overlooked or misinterpreted as noise if just evaluating individual attributes. The purple
and blue colors possibly indicate more shaley deposits, this is, mud-filled channels and marine
shales.

**Figure 10.** SOM2 flattened on the Moki Horizon. The results of the classes are similar to the
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shown by the thin channels (fuchsia color).

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are shown in each case. The seismic amplitude response and meaningful attributes for these
deepwater architectural elements are listed here. |
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Table 3. List of the input attributes for each SOM.

Table 4. Correlation matrices from SOM1, SOM2, and SOM3. Main diagonals indicate the value of 1 because it compares each attribute with itself. When comparing every other attribute, the correlation is less than $R = 0.7$, which, according to Kim et al. (2019), represents the nonlinear relationship between the attributes. From this, every attribute used as an input for each SOM is unique and representative of the dataset.
<table>
<thead>
<tr>
<th></th>
<th>Architectural element</th>
<th>Geological scheme</th>
<th>Internal Seismic reflection configuration</th>
<th>External shape</th>
<th>Amplitude</th>
<th>Vertical slice</th>
<th>Time slice</th>
<th>Coherence</th>
<th>Curvature</th>
<th>GLCM entropy (Texture)</th>
<th>Spectra (frequency)</th>
<th>Dip and Reflector convergence</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Mud filled abandoned channel</td>
<td>Subparallel reflectors, often with smaller incisions and possible lateral accretion</td>
<td>Incision of regional pattern, external pattern usually differs in amplitude, phase and frequency</td>
<td>Low to moderate. Often with low, s/n ratios</td>
<td>Low coherence in channel edges</td>
<td>Most negative (due to dif. Compaction)</td>
<td>Low to moderate</td>
<td>variable</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Sand filled channel /bars</td>
<td>Subparallel reflectors, often with smaller incisions and possible lateral accretion</td>
<td>Incision of regional pattern, external pattern usually differs in amplitude, phase and frequency</td>
<td>High amplitude</td>
<td>Low coherence in channel edges</td>
<td>Most positive curvature</td>
<td>Low</td>
<td>Variable frequency</td>
<td>High</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>C</td>
<td>Levees</td>
<td>Subparallel reflectors, tilted</td>
<td>Wing shape. Surrounding with channel complex. Often stacked</td>
<td>Variable</td>
<td>Low coherence in levees edges</td>
<td>High positive curvature</td>
<td>Moderate high entropy</td>
<td>Broadband response</td>
<td>High</td>
<td></td>
<td></td>
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<tr>
<td>D</td>
<td>Splays / overbank</td>
<td>Subparallel reflectors, tilted</td>
<td>Sometimes no distinguishable between other arch. elements</td>
<td>Variable</td>
<td>Not easily distinguishable, similar to small levees (depends on resolution)</td>
<td>Low</td>
<td>Anomalies associated with edges</td>
<td>Moderate high entropy</td>
<td>High frequency</td>
<td>High</td>
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<tr>
<td>E</td>
<td>MTD</td>
<td>Subparallel to chaotic</td>
<td>Rotated blocks, shingled</td>
<td>Variable (depends on A1 contrast). Generally low</td>
<td>External and internal low coherence edges</td>
<td>High entropy, with homogenous rotated blocks</td>
<td>Variable in each block</td>
<td>Low, dip variable</td>
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<tr>
<td>F</td>
<td>Sheetsands / lobes</td>
<td>Parallel to subparallel</td>
<td>Continuous, large reflectors</td>
<td>High amplitude</td>
<td>High coherence</td>
<td>Low curvature</td>
<td>Low</td>
<td>Low frequency</td>
<td>Low</td>
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<tr>
<td>G</td>
<td>Marine shales</td>
<td>Parallel to subparallel, Low amplitude</td>
<td>May lie unconformably on deeper strata</td>
<td>Low to moderate. Often with low s/n ratios</td>
<td>Moderate to high</td>
<td>Low curvature</td>
<td>Low</td>
<td>Moderate to high spectral response</td>
<td>Parallel to subparallel, convergent at onlap surfaces</td>
<td></td>
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<tr>
<td>Attribute</td>
<td>Type/ measurement</td>
<td>Principle</td>
<td>References</td>
<td>Geological use</td>
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</table>
| Coherent energy    | Discontinuity     | Cross-correlation between adjacent traces (1). The coherent component of traces divided by total energy of the traces (2) | 1- Bahorich et al., (1995)  
2- Chiropra et al., (2007) | Channel edges and faults                                                   |
| Curvedness         | Reflector configuration | Measure of total deformation or intensity of folding (considers k1 and k2) | Roberts (2001)                                                           | Faults, folds, channels and levees edges            |
| Dp magnitude       | Reflector configuration | Semblance search estimate of vector dip                                   | Barnes (2001); Marfurt (2006)                                            | Apparent dip, detection of faults and other stratigraphic features |
| GLCM entropy       | Texture           | Quantifies the lateral variation in seismic amplitude. Entropy: how smoothly varying the voxel values or seismic amplitudes are within a window | Haralick et al., (1973)                                                   | Seismic facies by its textural response             |
| Instantaneous phase | Phase             | Emphasizes spatial continuity of reflections by providing a way to make coherency events more clear | Taner et al., (1979); Marfurt (2006)                                      | Good indicator of lateral continuity, sedimentary layer patterns, sequence boundaries, onlap, offlap |
| Most positive curvature k1 | Reflector configuration | Measure of the maximum bending (positive or negative) of the surface at a certain point | Roberts (2001)                                                           | Feature-recognition applications. Anticlines, synclines, levees, channel |
| Peak spectral frequency | Spectral (Frequency) | Is the dominant frequency component during a 1-sec sampling period as determined by the fast fourier transform | Liu (2007)                                                               | Depositional, diagenetic and structural patterns, used in channel detection. Can show the vertical thickness variation |
| Peak spectral magnitude | Spectral (Frequency) | Computes the max. value of the absolute value of the amplitudes within a window | Liu (2007)                                                               | Strong hydrocarbon indicator. Thickness of channels |
| RMS (root mean square amplitude) | Amplitude | Is a measure of reflectivity within a time window. Computes the square root of the sum of squared amplitudes divided by the number of samples within the window used | Meek (2013)                                                               | Sand bodies and mud-filled channels associated with channel belts |
| Sobel filter (similarity) | Discontinuity | (1) Normalizes coherence (2) data to produce results between 0 and 1 | 1- Luo et al., (1996)  
<p>| Spectral frequency | Spectral (freq)   | (1) Applies a suite of constant-bandwidth filters to the seismic data. (2) The CWT continuous wavelet transform bandpass filters the data with a filter banks that often are exponentially spaced with exponentially increasing bandwidths. | 1- Partyka et al., (1999); 2- Castagna and Sun (2006) | Channels and minor architectural elements. Analyze stratigraphy and thickness changes |
| Sweetness          | Amplitude         | Calculated dividing the instantaneous amplitude by the square root of the instantaneous frequency | Radovich and Oliveros (1998)                                             | Sand rich deposits, HC bearing formations, thick reservoirs |</p>
<table>
<thead>
<tr>
<th>SOM1</th>
<th>SOM2</th>
<th>SOM3</th>
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<tr>
<td>Peak frequency</td>
<td>Sweetness</td>
<td>GLCM entropy</td>
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<tr>
<td>Peak magnitude</td>
<td>Dip magnitude</td>
<td>RMS amplitude</td>
</tr>
<tr>
<td>Curvedness</td>
<td>Instantaneous phase</td>
<td>Spectral CWT 35 Hz</td>
</tr>
<tr>
<td>Coherent energy</td>
<td>(K1) Most positive curvature</td>
<td>Spectral CWT 60 Hz</td>
</tr>
<tr>
<td></td>
<td>Sobel filter</td>
<td>Sobel filter</td>
</tr>
</tbody>
</table>
A) SOM1

<table>
<thead>
<tr>
<th>Attribute Name</th>
<th>Coherent energy</th>
<th>Peak Magnitude</th>
<th>Peak frequency</th>
<th>Curvedness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coherent energy</td>
<td>1.00</td>
<td>0.70</td>
<td>-0.01</td>
<td>-0.01</td>
</tr>
<tr>
<td>Peak Magnitude</td>
<td>0.70</td>
<td>1.00</td>
<td>0.32</td>
<td>-0.01</td>
</tr>
<tr>
<td>Peak frequency</td>
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<td>0.32</td>
<td>1.00</td>
<td>-0.01</td>
</tr>
<tr>
<td>Curvedness</td>
<td>-0.01</td>
<td>-0.01</td>
<td>-0.01</td>
<td>1.00</td>
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</tbody>
</table>

B) SOM2

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<thead>
<tr>
<th>Attribute Name</th>
<th>Sweetness</th>
<th>Dip magnitude</th>
<th>Instantaneous phase</th>
<th>Sobel filter similarity</th>
<th>K1: most positive curvature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweetness</td>
<td>1.00</td>
<td>-0.12</td>
<td>-0.01</td>
<td>0.32</td>
<td>-0.01</td>
</tr>
<tr>
<td>Dip magnitude</td>
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<td>1.00</td>
<td>0.00</td>
<td>-0.16</td>
<td>0.01</td>
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<td>Instantaneous phase</td>
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<td>0.00</td>
<td>1.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>Sobel filter similarity</td>
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<td>-0.16</td>
<td>0.00</td>
<td>1.00</td>
<td>-0.03</td>
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<tr>
<td>K1: most positive curvature</td>
<td>-0.01</td>
<td>0.01</td>
<td>0.00</td>
<td>-0.03</td>
<td>1.00</td>
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</table>

B) SOM3

<table>
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<tr>
<th>Attribute Name</th>
<th>RMS</th>
<th>Sobel filter similarity</th>
<th>GLCM entropy</th>
<th>CWT spectral 35</th>
<th>CWT spectral 60</th>
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<tr>
<td>RMS</td>
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<td>0.41</td>
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<td>GLCM entropy</td>
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<td>1.00</td>
<td>-0.38</td>
<td>-0.22</td>
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<tr>
<td>CWT spectral 35</td>
<td>0.7</td>
<td>0.27</td>
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<td>1.00</td>
<td>0.46</td>
</tr>
<tr>
<td>CWT spectral 60</td>
<td>0.59</td>
<td>0.18</td>
<td>-0.22</td>
<td>0.46</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Highlights

- Interpreter selection of attributes and statistical relations allows for an optimal seismic attribute selection to use as unsupervised machine learning input.
- Incorporation of textural and iso-frequency seismic attributes enhanced SOMs results for deepwater seismic facies.
- SOMs allow the interpretation of information from more than three seismic attributes at once, highlighting subtle elements like bottom current deposits, that are not easily recognized in single attributes.
- Integration of well log data corroborated the neuron cluster interpretations that depict architectural elements positioned in the basin floor.
- In the Pipeline 3D seismic dataset, the Moki Formation was interpreted to be deposited by sand-rich channels whose sinuosity increased in younger stages, when the system became more mud-rich.
- The system is interpreted as a channelized turbidite fan system that was carved by channels of 200m-5Km wide. Migration of channels was interpreted due to avulsion.
Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: