PITFALLS AND IMPLEMENTATION OF DATA CONDITIONING, ATTRIBUTE ANALYSIS, AND SELF-ORGANIZING MAP TO 2D DATA: APPLICATION TO THE EXMOUTH PLATEAU, NORTH CARNARVON BASIN, AUSTRALIA

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ABSTRACT

Recent developments in attribute analysis and machine learning have significantly enhanced interpretation workflows of 3D seismic surveys. Nevertheless, even in 2018, many sedimentary basins are only covered by grids of 2D seismic lines. These 2D surveys are suitable for regional feature mapping and often identify targets in areas not covered by 3D surveys. With continuing pressure to cut costs in the hydrocarbon industry, it is crucial to extract as much information as possible from these 2D surveys. Unfortunately, much if not most modern interpretation software packages are designed to work exclusively with 3D data. To determine if we can apply 3D volumetric interpretation workflows to grids of 2D seismic lines, we apply data conditioning, attribute analysis, and a machine learning technique called self-organizing map (SOM) to the 2D data acquired over the Exmouth Plateau, North Carnarvon Basin, Australia. We find that these workflows allow us to significantly improve image quality, interpret regional geological features, identify local anomalies, and perform seismic facies analysis. However, these workflows are not without pitfalls. We need to be careful in choosing the order of filters in data conditioning workflow and be aware of reflector misties at line intersections. Vector data, such as reflector convergence, need to be extracted and then mapped component-by-component before combining the results. We are also unable to perform attribute extraction along a surface or geobody extraction for 2D data in our commercial interpretation software package. To address this issue, we devise a point-by-point attribute extraction workaround to overcome the incompatibility between 3D interpretation workflow and 2D data.
INTRODUCTION

Before attempting to interpret seismic attributes computed from 2D surveys, it is crucial to understand the differences between 2D and 3D data. Hutchinson (2016) provides a detailed discussion regarding the limitations and advantages of 2D versus 3D data in five aspects: (1) processing artifacts, (2) sharpness of discontinuities, (3) reflector dip, (4) faults, and (5) amplitude contrast. First, due to imaging of out-of-the-plane energy into the vertical plane defined by the 2D seismic line in the migration process, 2D data usually show cross-cutting and bow-tie artifacts that are otherwise properly focused in 3D data (Figure 1). This imaging limitation of 2D data also results in blurred discontinuities (Figure 2) and incorrect reflector dip (Figure 3) compared to 3D data. In general, a skilled interpreter can pick similar fault “sticks” on 2D data as with 3D data, although the fault connectivity between lines may differ (Figure 4). Because of acquisition constrains, the shallow amplitude contrast is often better on 2D data than on 3D data (Figure 5).

We also need to consider the limitations of each attribute type with respect to the number of data dimensions (Table 1). While all 3D attributes appear to be compatible with 2D data, the majority of them assume a 2.5D earth model, in which the earth looks the same in the direction perpendicular to the 2D line. In other words, there is no azimuthal information for 2D attribute calculation (e.g. we only have apparent dip and apparent reflector convergence).

A conventional 2D interpretation workflow starts with picking a horizon – a geological boundary of interest. This horizon is then interpolated to form a surface, where the two-way-travel time of this surface constitute a time-structure map of the geological boundary. The next step is to compute surface attributes, such as dip magnitude, dip azimuth, and possibly curvature of this surface to further help us interpret the structural relief of the geological boundary. Note
that these surface attributes are calculated on a surface rather than on the seismic data itself. Thus, the quality of these surface attributes highly depends on the interpreter. To overcome this dependency, Bahorich and Bridges (1992) created the Seismic Sequence Attribute Mapping (SSAM) workflow, which extracts seismic attributes computed from the 2D amplitude data and maps them as a surface. The few published SSAM workflows focused primarily on single-trace attributes (e.g. instantaneous envelope, frequency, and phase) rather than multi-trace attributes (e.g. inline dip, coherence, and GLCM attributes). Another challenge of this workflow is that 2D seismic attribute extraction is not available in many modern software packages that are designed to efficiently handle 3D data volumes.

We begin our paper with a brief review of the geologic settings of the North Carnarvon Basin. We then describe our 2D seismic interpretation workflow, including data conditioning, attribute analysis, and SOM facies classification. Next, we discuss our interpretation of regional geology and local anomalies from 2D seismic amplitude and attribute profiles. Finally, we show the pitfalls encountered during our interpretation workflow, as well as workarounds to avoid those pitfalls and to correctly display horizons and geobodies extracted from the 2D seismic attribute profiles.
GEOLOGIC SETTINGS

The North Carnarvon Basin is a major hydrocarbon reserve in Australia (Chongzhi et al., 2013) that can be divided into several sub-basins (Figure 6). Among these sub-basins, the Exmouth Plateau is the largest and contains most of the major gas fields. Thanks to these gas fields, numerous seismic surveys have been acquired over the area. The 3D surveys are relatively small (<5000 km²), concentrated around known reservoir locations. In contrast, the 2D surveys are much larger, allowing the interpretation of regional features and the identification of new area that has not been covered by 3D data.

The North Carnarvon Basin was a passive margin that underwent multiple stages of extension, subsidence, and late minor inversion, resulting in NE-SW trending faults (Tellez Rodriguez, 2015). The depositional history of the North Carnarvon Basin can be summarized by the simplified stratigraphic column shown in Table 2. The main source rocks of the Exmouth Plateau are the Locker Shale, deposited in early Triassic. The Mungaroo (middle-late Triassic) fluvio-deltaic formation and the early Cretaceous Flag sandstone of the Barrow delta are the main reservoir rocks. During the middle Cretaceous, post-rifting subsidence enabled a thick deposition of the transgressive Muderong Shale throughout the entire basin, which act as a regional seal (Chongzhi et al., 2013). During the Tertiary, the Australian Plate drifted northward to warmer tropical zones, facilitating development of carbonate sequences, including the Mandu Limestone formation (Smith, 2014).

Our project involves 55 lines forming a rectangular grid, spanning an area of ~40,000 km² in the center of the Exmouth Plateau (Figure 6). These 2D lines were acquired five to ten years before the 3D surveys, suffering from low image quality and inaccurate imaging of out-of-the-plane energy due to the limitations in acquisition and processing. Our goal is to improve
seismic interpretation of these 2D lines in order to have a better understanding of the regional geology as well as possible local hydrocarbon accumulations.
METHOD

Our interpretation workflow consists of data conditioning, seismic attribute analysis, followed by self-organizing map (SOM) classification.

**Data conditioning**

To improve seismic image quality, we implement a data conditioning workflow developed by Hutchinson et al. (2016) by applying spectral balancing and edge-preserving structure-oriented filtering (Marfurt, 2006) to the data. Figure 7 compares a shallow section of a seismic line before and after data conditioning. Thin layers are better resolved (yellow ellipse), cross-cutting migration artifacts are suppressed (cyan ellipse), while faults are sharper (red arrows), providing an improved interpretation. The same benefits can be observed in a deeper section of the same seismic line (Figure 8). In our data conditioning workflow, we need to set the analysis window’s half-width to five times the bin size of the 2D line due to the high amount of noise and cross-cutting artifacts. A detail list of data conditioning parameters is shown in Appendix A.

**Seismic attribute analysis**

In order to choose which attributes to be used in our analysis, we need to examine the attribute expressions of the seismic facies that we want to identify (Table 3). We choose conformal reflectors, anomalously strong reflectors, Mass-Transport Complexes (MTCs), and channels as four major seismic facies in our project. Based on previous works by Qi et al. (2016), Wallet (2016), and Zhao et al. (2016) on channel and MTC interpretation, we choose eight seismic attributes to analyze those seismic facies:
• seismic amplitude: for horizon picking and structural interpretation.
• energy-ratio-similarity: a high-resolution coherence attribute to identify faults, stratigraphic edges, and the discontinuity internal to MTCs.
• structural curvature: second derivative of structural dips, sensitive to anticlinal and synclinal features, for channel axis and levee identification,
• reflector convergence: measures vertical changes in the dip vector, differentiating conformal reflectors from pinch-outs, angular unconformities, and chaotic reflector orientation.
• coherent energy: the energy of a window of amplitude data, measures strong and coherent reflectors.
• Gray-Level Co-occurrence Matrix (GLCM) energy and homogeneity: texture attributes that measures the variation in lateral seismic response, sensitive to noise and chaotic features.
• peak frequency: a spectral decomposition attribute that is sensitive to layer thickness.

Details of attribute calculation parameters are shown in Appendix B.

Different seismic facies have different distinctive expressions. For example, the slump component of an MTC exhibits overall low coherence, while the related block component and conformal reflectors exhibit high coherence. Channels are usually coherent near their axes, but incoherent at their edges. Among the four facies examined in our data, incised channels express the highest curvature and reflector convergence with the highest spatial variation.

Since our data consists of 55 individual 2D seismic lines, computing attributes for one line at a time is a tedious task. In general, each line forms a separate file. In order to perform attribute calculation on all of the 2D lines at once, we merge those lines into a pseudo-3D volume, in which the length of the inline axis is the length of the longest line, and the length of the crossline axis is the total number of lines (Figure 9). Shorter lines are padded with dead
traces until they reach the length of the longest line. Then, this new pseudo-3D volume is input into our 3D attribute calculators, with the size of the crossline analysis window set to zero. After the computation, we delete the dead traces and assign each “inline” to the appropriate line in the 2D survey.

**Self-organizing maps**

One way to combine multiple attributes for facies analysis is to use self-organizing map (SOM), an automatic, unsupervised machine learning technique. This process takes $N$ attributes residing in an $N$-dimensional space and projects them onto a deformed 2D manifold. These projected data are then mapped against a 2D color table in such a way that voxels within a cluster on the 2D latent space have similar colors. A detailed description of SOM is provided by Zhao et al. (2016).

Qi et al. (2016) finds the choice of attributes to be critical to both interactive interpretation and machine learning algorithms like SOM. Examining Table 3, we note that MTCs are characterized by low coherence, low-to-moderate coherent energy, low GLCM energy, and low GLCM homogeneity. During our experiment, we find that continuous reflectors can have the same expression in reflector convergence, structural curvature, and peak frequency as MTCs if those reflectors are slightly undulating and located around the same depth as the MTCs. Therefore, reflector convergence, structural curvature, and peak frequency are not effective in differentiating MTCs from the continuous reflector background in SOM classification. We do not include the seismic amplitude in the SOM analysis either. Rather, we choose to co-render SOM result with seismic amplitude after the SOM computation. Thus, our
list of inputs for SOM classification consists of four attributes: energy-ratio-similarity, coherent energy, GLCM energy, and GLCM homogeneity.

To suppress “salt-and-pepper” effects in unsupervised classification algorithm, we follow an attribute preconditioning workflow developed by Qi et al. (2016). We first smooth the attributes along structural dip for two iterations, then apply a Kuwahara median filter to the input attributes. Detail parameters of smoothing, Kuwahara filtering, and SOM classification are provided in Appendix C. Figure 10 shows energy-ratio-similarity (a) before and (b) after preconditioning. Note the salt-and-pepper internal structure of MTCs are lost, but the boundary between chaotic and continuous facies are much better defined. Figure 11 shows the SOM result (a) with out and (b) with attribute preconditioning, in the same portion of a 2D line as that shown in Figure 10. The same salt-and-pepper effect is observed without attribute preconditioning, and thus the quality of SOM classification is significantly lower.
INTERPRETATION

Figure 12 shows a 2D seismic line with interpreted faults, key formation tops, MTCs, and channels. Major faults terminate against the top of the Muderong Shale, consistent with post-rifting subsidence during the middle Cretaceous. Figure 13 of co-rendered seismic amplitude with energy-ratio similarity attribute shows the chaotic, low-coherence nature of MTCs within the Muderong Shale. These MTCs can be tens-of-kilometers wide and are present in both the Muderong Shale and the shallower Tertiary carbonate sequences. For channels, we follow the display scheme described by Wallet (2016) to co-render seismic amplitude with structural curvatures to highlight channels’ axes and levees (Figure 14). These channels have thicknesses ranging from 20 to 100 ms (equivalent to ~ 25-125 m for a velocity of 2500 m/s) and half-widths ranging from 0.5 to 1.5 km.

We find some local anomalies in the SW and NE corner of the seismic survey. Figure 15 is a 3D perspective view showing two perpendicular seismic lines near the SW corner of the study area, with two amplitude anomalies marked by yellow arrows. These anomalies are about 2 km long, exhibiting strong negative amplitude, anticlinal shape, and a lower frequency spectrum than the surrounding reflectors. Based on such characteristics, we interpret the two anomalies as bright spots that could be potential gas-charged reservoirs. Figure 16 is another 3D perspective view showing two perpendicular seismic amplitude profiles near the NE corner of the study area, with several anomalies marked by pink arrows. These anomalies are dome-shaped features, exhibiting velocity “pull-up” effect from their tops to the deeper section. Their characteristics are consistent with carbonate mounds around the world. Since these anomalies are within the thick Muderong Shale (which is a good seal), they could be potential reservoirs as well, if they are filled with hydrocarbons.
One way to obtain information regarding the depositional environment at a specific geological time is to generate a map of reflector convergence about a horizon of interest. Reflector convergence is an attribute that shows where reflectors are converging (pinching out) rather than parallel (conformal), which can aid in seismic stratigraphic analysis. Figure 17 shows a map of co-rendered reflector convergence magnitude and azimuth extracted around the top of the Muderong Shale formation. Generally, the layers are thinning toward the NW (green and cyan color), with some exception in the middle and eastern part of the study area where they are thinning toward the NE (purple color). This geometry indicates the presence of a major landmass in the NW of the North Carnarvon Basin, as well as some local structural highs in the center and NE part of the basin during the late Cretaceous.

After combining seismic attributes using the SOM algorithm, we co-render the result with seismic amplitude as shown in Figure 18. We observe that red, light cyan, light purple, and blue colors correspond to chaotic portion of MTCs. Yellow and orange colors correspond to lower amplitude, conformal reflectors. Bright green color corresponds to moderate amplitude, continuous reflectors. Bright purple and dark violet correspond to high amplitude, continuous reflectors. To illustrate the chaotic portion of MTCs exclusively, we keep only red, light cyan, light purple, and blue colors, while setting all other colors transparent. The result is a co-rendered image of seismic amplitude and MTC “clusters” (Figure 19), with occasional imperfections in which some bow-tie artifacts associated with faults are marked (yellow ellipses). Finally, we extract these MTC clusters from a set of 2D lines in our data. The size, shape, and internal structure of a gigantic MTC sequence can be observed via 3D visualization of the extracted geobodies (Figure 20). This MTC sequence is located at the SE part of the survey, in the bottom
of the Tertiary carbonate sequences, extending more than 50 km in the dip direction and 80 km in the strike direction.
PITFALLS AND WORKAROUNDS

Applying 3D interpretation workflow to 2D seismic lines is not a straightforward process. In this section, we identify several pitfalls we encountered in our study, as well as our workarounds to circumvent the incompatibility between 2D data and modern interpretation software.

The order of filters in data conditioning

There are two main steps in our data conditioning workflow: spectral balancing and structure-oriented filtering. Because they are both nonlinear filters, the order of application makes a difference. To evaluate the differences, we apply two data conditioning workflows (Figure 21) to one of our 2D seismic lines. We find artifacts around faults when we apply structure-oriented filtering first, followed by spectral balancing (Figure 22). The other workflow does not generate such artifacts. This is because structure-oriented filter is an edge-preserving filter. For vertical faults, there is no change in the spectrum of the vertical trace. For dipping faults, however, the edge preservation introduces both high and low frequencies into the spectra of the vertical traces. These components lead to artifacts in spectral balancing. Therefore, the correct order of filters in data conditioning workflow is spectral balancing first, followed by structure-oriented filtering.

Reflector misties at line intersections

Figure 23 shows a 3D perspective view toward the intersection of two perpendicular seismic lines near the center of the study area. Migrated reflectors often do not tie at line intersections, making it difficult to pick a horizon. In the shallow part (marked by a yellow
ellipse), reflectors on the right appear to arrive later than those on the left. However, in the
deeper part (marked by an orange ellipse), the exact opposite phenomenon is observed: reflectors
on the right appear to arrive sooner than those on the left. Those misties cannot be fixed by a
simple time shift. Sattlegger and Egbers (1987) developed a workflow to properly map horizons
picked on time-migrated 2D lines. They first picked horizons on the time-migrated 2D lines as
good as possible, depth-converted the time-migrated 2D lines, performed modeling, and repeated
the process until the horizons tie at line intersections. Next, they interpolated the horizons to
form maps, and then migrate the maps using a process called “3D map migration.”
Unfortunately, their workflow requires a velocity model for depth-conversion, which is not
available to us. Our workaround is to construct two separate horizon picks for each physical
surface. First, we perform horizon picking where the lines tie. Then, we make two copies of the
common picks and continue to define two separate sets of horizon picks: one parallel to the lines
trending NW-SE, and one parallel to the lines trending NE-SW (Figure 24). Attribute extracted
along both sets of horizons can then be interpolated to form attribute maps.

**Vector attribute extraction along a surface**

Among the modern interpretation software packages we tested, none supports attribute
extraction from 2D data along a surface. Thus, we need to develop our own tool to extract
seismic attributes at the intersections between an interpolated surface and the 2D lines. For
vector attributes, such as reflector convergence, the seismic line’s direction of increasing CDP
number is important. We need to make sure all lines parallel to a trend have the same direction of
increasing CDP number. Each line trend should then have a separate set of extracted data points
(Figure 25). Next, we generate surfaces from those sets of points (Figure 26) and combine them
into a co-rendered magnitude and azimuth map (Figure 17) using the following equations:

\[
\text{convergence magnitude} = \sqrt{\text{convergence}_{NW}^2 + \text{convergence}_{NE}^2}
\]  

\[
\text{convergence azimuth} = \arctan\left(\frac{\text{convergence}_{NE}}{\text{convergence}_{NW}}\right) + \text{NW azimuth}
\]

Where

\(\text{convergence}_{NW}\) is the reflector convergence component along NW-trending lines,

\(\text{convergence}_{NE}\) is the reflector convergence component along NE-trending lines, and

\(\text{NW azimuth}\) is the azimuth of NW-trending lines.

**Geobody extraction from 2D data**

To visualize SOM clusters in 3D, we first use a geobody extraction tool that works well on 3D data. However, almost all geobody extraction engines assume 3D data inputs, thus making it impossible to extract or display geobodies from 2D data using modern interpretation software. Our next option is to use color transparency to highlight only those SOM clusters of interest on several 2D lines and then display those lines in 3D. However, we encountered a graphical shortcoming in which the line farthest from the viewpoint is sometimes not rendered correctly at some angle of view (Figure 27). This might be due to the interpretation software’s internal graphical engine: some pixels are assumed to be unnecessary and therefore not rendered on the computer screen in order to reduce memory usage. Therefore, we decided to program our own tool to extract data points of specific values from multiple 2D lines. With this tool, we are able to extract SOM clusters corresponding to MTCs and display them in 3D (Figure 20).
CONCLUSIONS

By applying data conditioning to the 2D data, we are able to improve seismic image quality. However, we need to consider the order of steps in data conditioning workflow and apply spectral balancing first, followed by structure-oriented filtering, in order to avoid unwanted artifacts. Seismic attributes, including coherence, envelope, and structural curvature, help us interpret regional geological features (such as the wide-spread Muderong Shale and the channels within the Tertiary carbonate sequences), as well as local anomalies (such as bright spots and carbonate mounds). Analysis of seismic facies, including MTCs and channels, can be accelerated using Self-Organizing-Map classification. Nevertheless, using modern interpretation software, we can neither extract attributes along a surface nor display geobodies from 2D data. Therefore, we need to develop our own point-by-point attribute extraction tools in order to correctly extract and display attribute data points from 2D lines.
ACKNOWLEDGMENTS

We thank Schlumberger for a license to the Petrel interpretation software for use in research and education. Special thanks to Geoscience Australia for providing the data used in this project. Financial support was through the industry sponsors of the OU Attribute-Assisted Seismic Processing and Interpretation (AASPI) consortium.
## APPENDIX A: DATA CONDITIONING WORKFLOW PARAMETERS

Table A-1. Spectral decomposition parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smoothing window radius (s)</td>
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</tr>
<tr>
<td>Spectral balancing factor (%)</td>
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</tr>
<tr>
<td>Bluing exponent</td>
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<tr>
<td>Line and CDP decimation</td>
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<tr>
<td>Ormsby filter f1 (Hz)</td>
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</tr>
<tr>
<td>Ormsby filter f2 (Hz)</td>
<td>10</td>
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<tr>
<td>Ormsby filter f3 (Hz)</td>
<td>90</td>
</tr>
<tr>
<td>Ormsby filter f4 (Hz)</td>
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<tr>
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<tr>
<td>Temporal taper (s)</td>
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<tr>
<td>Output f_high (Hz)</td>
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<tr>
<td>Output f_increment (Hz)</td>
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Table A-2. Structural dip computation parameters.

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<td>Algorithm</td>
<td>Semblance Search</td>
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<td>Max angle (degree)</td>
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<td>Inline window radius (m)</td>
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<tr>
<td>Crossline window radius (m)</td>
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Table A-3. Dip filtering parameters.

<table>
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<tr>
<td>Algorithm</td>
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<td>LUM percentile</td>
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<td>Vertical window radius (s)</td>
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<tr>
<td>Crossline window radius (m)</td>
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Table A-4. Similarity computation parameters.

<table>
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<td>Vertical window radius (s)</td>
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<tr>
<td>Inline window radius (m)</td>
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</tr>
<tr>
<td>Crossline window radius (m)</td>
<td>0</td>
</tr>
<tr>
<td>Spectral filtering f_low (Hz)</td>
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<tr>
<td>Spectral filtering f_high (Hz)</td>
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Table A-5. Structure-oriented filtering parameters.

<table>
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<td>Inline window radius (m)</td>
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<tr>
<td>Crossline window radius (m)</td>
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<tr>
<td>Similarity s_low</td>
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</tr>
<tr>
<td>Similarity s_high</td>
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<tr>
<td>Similarity s_center</td>
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<tr>
<td>Algorithm</td>
<td>Principle-Component</td>
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APPENDIX B: ATTRIBUTE COMPUTATION PARAMETERS

Spectral attribute (such as peak frequency) computation parameters are the same as in Table A-1.

Similarity attributes (such as energy-ratio similarity and coherent energy) computation parameters are the same as in Table A-4.
Table B-1. Curvature and reflector convergence computation parameters. The values of \((\lambda, w)\) define a long-wavelength filter in the wavelength domain.

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<tr>
<td>(\lambda_2) (m)</td>
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<tr>
<td>Weight (w_2)</td>
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<tr>
<td>Weight (w_3)</td>
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<tr>
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Table B-2. GLCM attributes (energy and homogeneity) computation parameters.

<table>
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<td>Vertical window radius (s)</td>
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<tr>
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<td>Number of gray levels</td>
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<td>Sample interpolation factor</td>
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APPENDIX C: SOM WORKFLOW PARAMETERS

Table C-1. Smoothing parameters.

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<td>Vertical window radius (s)</td>
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<tr>
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<td>Crossline window radius (m)</td>
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Table C-2. Kuwahara filtering parameters.

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<td>Vertical window radius (s)</td>
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<td>Crossline window radius (m)</td>
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Table C-3. SOM classification parameters.

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REFERENCES


Wallet, B. C., 2016, Attribute expression of channel forms in a hybrid carbonate turbidite formation: Interpretation, 4, SE75-SE86. doi: 10.1190/INT-2015-0108.1

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