Attribute expression of channel forms in a hybrid carbonate turbidite formation

Bradley C. Wallet

ABSTRACT

Much of the world’s conventional oil and gas production comes from turbidite systems. Interpreting them in three dimensions using commercially available software generally requires seismic attributes. Hybrid carbonate turbidite systems are an interesting phenomenon that is not fully understood. I have examined the attribute expression of channel forms in a hybrid carbonate turbidite system from off the coast of Western Australia. I have determined several characteristic responses to attributes that improve the ability to identify and delineate the channel forms. Finally, I have evaluated and developed a workflow that is effective at modeling and extracting the channel forms in three dimensions, leading to a product that can be used in further understanding of how carbonate turbidite systems develop.

Introduction

Deepwater marine depositional systems are one of the most important reservoirs and have given rise to most of the recent conventional discoveries. Turbidite systems constitute an important class of hydrocarbon reservoirs in deepwater settings (Slatt, 2014), and considerable work has been published on the characterization of deepwater turbidite reservoirs.

Because of their resemblance to common earth features, such as rivers, canyons, and gullies and their strong laterally 2D (though often stacked) nature, deepwater turbidites have inspired significant study using seismic geomorphology. Posamentier (2006) completes a detailed analysis of a marine depositional system, looking at architectural elements at shallow depths as well as regions of exploration interest. In his work, he analyzes vertical, time, and horizon slices of amplitudes to illustrate channels and other elements. Additionally, he shows the value of using seismic attributes such as dip and curvature.

Braccini and Adeyemi (2011) focus upon the use of seismic attributes to map a deepwater turbidite in offshore Nigeria. They use spectral components, near- and far-offset limited stack amplitudes, and coherence to visualize channels and mass-transport complexes. They show a number of vertical slices of the seismic data, demonstrating the 3D nature of these elements, but they only apply the attributes in map views to visualize the lateral extent of these features.

Although classic deepwater turbidites have been the subject of considerable study (Deptuck, 2003; Posamentier, 2006; Braccini and Adeyemi, 2011), significantly less work has been done in the area of hybrid carbonate turbidite reservoirs (Weimer and Slatt, 2006). Carbonates can make an excellent environment for the development of a turbidite system. This is due to their grain-rich facies that can be transported by turbidity flows (Harris and Wright, 1998). Producing reservoirs of this type include the Hasa field in Abu Dhabi, the Fateh field in Dubai, and the Poza Rica field in Mexico.

Another example of a hybrid carbonate turbidite is the Mandu Formation, off the northwest coast of Australia. Figure 1 shows a vertical slice through seismic data acquired in this region taken parallel to the paleoshoreface. Evidence of channel forms is clearly seen in this vertical slice in the form of many lens shaped structures, and even a novice interpreter could interpret many though not all of these forms. Figure 2 shows the same slice with a partial interpretation overlaid on the seismic.

Figure 3 shows a vertical slice perpendicular to the paleoshoreface. The most evident feature visible in this image is a series of clinoforms. An experienced interpreter can relate the internal structure of these to global eustatic changes in sea level (Figure 4). These clinoforms constitute the Mandu Formation, an Oligocene aged prograding carbonate shelf (Heath and Apthorpe, 1984). This image gives little information useful for mapping the architectural elements of the turbidite system.

In this paper, I evaluate the attribute expression of a series of channel forms in the prograding carbonate Mandu Formation with the goal of visualizing the channel-form geometry in 3D, as well as in conventional
methods. Then, I describe a workflow based for extracting channel forms in 3D using curvature.

Geologic and geophysical background
Regional geology

The study area is located on the Rankin Platform of the Carnarvon Basin off the coast of Western Australia (Figure 5). A major low-stand event occurred during Early Oligocene time. This resulted in a progradational wedge of carbonate slope that resulted in the Mandu Formation. This progradation continued until it was terminated by a eustatic sea-level rise approximately 15 MYA (Richardson, 2000).

During the period of deposition from the Oligocene to the middle Miocene, there were several high-stand, low-stand, and transgressive intervals, although the overall pattern was a lower frequency sea-level rise (Figure 6). During the Oligocene to the middle Miocene, there developed a series of channel forms or canyons (for a detailed look at the geology of the Mandu Formation, see Tellez Rodriguez, 2015).

There is some uncertainty as to the mechanism by which these form. It is believed that during low-stand events, clastic systems tend to shed the majority of their material into the basin (Vail et al., 1977; Figure 7). However, it is unknown if this is the case in carbonate environments, and this topic has been the subject of considerable controversy (Bernet et al., 2000). Therefore, improved mapping of these canyons might add to the understanding of the nature of carbonates in general.

There exist a number of modern analogs for the Mandu Formation. One such analog is the Little Bahama Bank (Mullins et al., 1984). In this case, foreslope reefs in this zone exhibit a channel-form architecture that is present in my study area (Figure 8).

Another modern analog can be found in the Florida Keys, Florida, USA. This system is a carbonate structure that is currently experiencing subaerial exposure. Viewing this structure in aerial imagery (Figure 9) demonstrates channel forms that are very similar in their size and geometry to those presented in my data set.

Data description

The Rosie 3D survey used in this study was provided by Geoscience Australia (Cathro et al. 2003; Figure 10).

**Figure 1.** A vertical slice through the seismic data volume taken parallel to the paleoshoreface. Evidence of channel forms is clearly seen in this image in the form of many lens shaped structures.

**Figure 2.** A partial interpretation overlaid on the vertical slice. The green arrows denote the channel forms in the prograding carbonates.

**Figure 3.** A vertical slice through the seismic data volume taken perpendicular to the paleoshoreface. An experienced interpreter can glean considerable information regarding global eustatic sea levels from this view, but it does not clearly map the channel forms and other architectural elements of the turbidite system.

**Figure 4.** A vertical slice through the seismic data volume taken perpendicular to the paleoshoreface with an interpretation overlain. The blue lines indicate the tops of high-stand events. The green lines indicate the tops of transgressive events. The red lines indicate the tops of low-stand events.
It was acquired between November 1996 and February 1997 by Geco-Prakla, with a line orientation of northeast–southwest (49.5°) with a dual-source/four-streamer configuration. The cable separation was 150 m and the source separation was 75 m, resulting in an initial subsurface CDP line spacing of 18.75 m. Each streamer had 304 channels, resulting in a nominal fold of 50.

Processing was completed by Western Geophysical from December 1996 through July 1997 with a resulting sample increment of 4 ms. The data are of good quality and broad bandwidth for the time of acquisition and processing. Dominant frequency through the Mandu Formation is approximately 35 Hz (Figure 11) (more details about the acquisition and processing of this data set can be found in Richardson, 2000).

Seismic expression of channel forms

Historically, interpretation has reflected the 2D origins of seismic analysis with interpreters using vertical slices through seismic data to interpret geologic features, such as faults and horizons. By interpreting these features on successive slices, an interpreter is thus able to construct 3D interpretations using an adapted 2D approach.

Geologic modeling or geomodeling is the science of using geologic and geophysical data to construct computerized models of the subsurface. Typically, this is thought of as being done in 3D. Although successive 2D interpretations can construct 3D models of some geologic features, it is more efficient to use a direct 3D approach.

To establish a background for 3D geomodeling of the channel forms, I examined the expression of channel forms in my seismic data using a number of seismic attributes. The focus was upon visualizing these channel forms using seismic geomorphological methods combined with seismic attributes. Recently, there has been a trend in published work to focus upon the attribute expression of specific geologic features. These works examine a suite of attributes, and show examples of how these features are illu-

Figure 5. Location of the Carnarvon Basin along the coast and offshore of Western Australia. ©Commonwealth of Australia (Geoscience Australia). Used with permission.

Figure 6. Relative sea-level curve for the Rankin Platform from the Oligocene to the present.
minated with various attributes. The goal of this work is to illustrate how specific attributes are tied geologically and geophysically to the feature of interest.

This approach is in contrast to an all too common approach to seismic attributes of calculating a large number of attributes with little regard for their underlying geologic or geophysical tie to the interpretation task at hand. Commercial packages typically have 50+ attributes, many of which are poorly understood by interpreters. The problem is compounded when the interpreter then relies upon partially understood data analysis techniques, such as neural networks or latent space modeling (Wallet et al., 2009) to automatically process these attributes without careful examination.

Figure 7. Bypass margins are believed to form turbidity flows during low-stand events. (a) Transgressive-stand event, (b) high-stand event, (c) low-stand event, and (d) drowning unconformity.

Figure 8. One modern analog for the Mandu Formation can be found on the Little Bahama Bank. Bypass margin slopes in this zone exhibit a similar channel-form architecture.

Figure 9. A modern analog for the Mandu Formation that is currently experiencing subaerial exposure is the Florida Keys, Florida, USA. Similar channel-form architecture is readily visible in aerial images (Courtesy of Google Earth™).

Figure 10. The location of the Rosie 3D survey that is used in this study.

Figure 11. Frequency spectrum of the Rosie 3D data set through the Mandu Formation.
In contrast, interpreters who are experienced in the use of seismic attributes typically use a very small number of attributes they understand well, and that they have found useful in the past. However, the ability to do this properly involves understanding and experience as to what attributes work within a given geologic and data quality setting. Furthermore, we are happiest when we can link the response of a chosen attribute to some geologic and/or geophysical feature of our data, and thus explain our results in a meaningful manner. With this in mind, I will test a number of attributes, focusing upon their expression of channel forms in the hybrid carbonate turbidite system.

**Single attribute analysis**

I begin my analysis by examining individual attributes to better understand the seismic attribute expression of the channel forms. Close examination of Figure 1 suggests three distinct sets of channel forms. Approximate locations of these sets of channel forms are designated in Figure 12.

Because seismic geomorphology involves using visualization techniques to illuminate features at a given geologic time, a common workflow is to pick horizon slices and flatten the data rather than work with time slices. However, as seen in Figure 2, more than half the lateral extent of the Mandu Formation is channel forms. In this environment, picking a consistent surface for flattening proved impossible. Best practice in this case typically involves picking a strong continuous reflector above or below the channelized region and generating phantom horizon slices (Brown, 2011). Figure 13 shows a horizon I interpreted for this purpose.

Figure 14 shows the results of flattening using the horizon shown in Figure 13. This appears to have flattened the data well in the lowest portion of the Mandu Formation. However, given the strong progradational nature of the formation, the flattening horizon has little bearing upon the internal geometry of the Mandu Formation. Hence, further up in the system, the flattening has little result, and horizon slices will tend to cut across geologic ages, which should be recognized as a limitation of this flattening workflow.

Figure 15 shows a magnified view of the vertical slice of amplitude data centered about a representative channel form. Several details concerning the channel form...
suggest attributes that may be useful. Specifically, the shown channel form is associated with discontinuities, converging reflectors, and an overall concave shape.

Figure 16 shows a horizon slice taken 52 ms above the flattening surface. Many meandering channel forms are visible in this horizon, which appear to have been deposited upon a relatively flat topography. My interpretation is that these systems formed in a depositional environment before the carbonate reef prograded into the region of this data set.

Figures 17 and 18 show horizon slices taken 152 and 352 ms above the flattening horizon, respectively. The channel forms in these horizons cut sharply through the carbonate, and they appear to result from erosion rather than deposition.

The variance attribute detects boundaries and edges by calculating the second central moment (statistical variance) for a windowed region in a seismic data set (Marfurt et al., 1998). In the presence of a boundary, the window contains observations from either side of the boundary, thus resulting in a higher variance value. Variance would thus help in interpreting channel forms by highlighting their edges. Figure 19 shows the variance attribute for a vertical line. In this image, the channel forms are visible. However, the edges and form of the channel forms are not clear, and the overall impression is “blurry.”
Figure 20 shows a magnified view of the variance attribute corendered with the seismic amplitude over a channel form. Although variance detected some of the boundaries, it missed others, and it did not provide for a closed boundary.

Figures 21, 22, and 23 show the variance attribute for 52, 152, and 352 ms above the flattening (green) horizon shown in Figure 13. Unlike in the vertical slice (Figure 19), the edges are clear and crisp. This contrast suggests that although variance may be useful in understanding and interpreting channel forms, it is not suitable for 3D geomodeling of them as it does not achieve closure (fully defining the boundaries in 3D).

The next attributes I will consider is the principal curvature attribute: most-negative principal ($k_2$) curvature (Mai et al., 2008). Because channels are frequently described as “lens-shaped” or valley cross-sectional structures in seismic data, it seems reasonable that channel forms would have a curvature response, and hence principal curvature should be useful in their interpretation. Highly negative values of $k_2$ would tend to be associated with structural valleys. Generally, this is the expected shape of seismically thick channel forms.
Figures 24 and 25 shows the $k_2$ curvature corendered with seismic amplitude for the vertical slice. In this figure, the highly negative values of $k_2$ (dark blue) are clearly associated with the channel forms. However, these regions do not appear to span the full width of the channels but rather accentuate the channel-form axes.

Figures 26, 27, and 28 show the $k_2$ curvature attribute for 52, 152, and 352 ms above the flattening (green) horizon shown in Figure 13. In Figures 26–28, the highly negative regions appear to completely map the channels. Furthermore, unlike variance, they appear to correspond to the channel forms axes rather than the

**Figure 24.** The $k_2$ principal curvature for a vertical. Highly negative values appear to follow the centers of the channel forms, but they do not appear to fully cover the lateral crosswise extent.

**Figure 25.** Most-negative curvature magnified in upon a channel form. Highly negative values of $k_2$ characterize the vertical extend of the channel form, they do not reach the full-lateral extent as shown by the green arrows.

**Figure 26.** The $k_2$ principal curvature for 52 ms above the flattening horizon. Highly negative values appear to map out the channel forms.

**Figure 27.** The $k_2$ principal curvature for 152 ms above the flattening horizon. Highly negative values appear to map out the channel forms.

**Figure 28.** The $k_2$ principal curvature for 352 ms above the flattening horizon. Highly negative values appear to map out the channel forms.
channel-form boundaries. This makes them suitable for geobody extraction methods based upon value thresholding. However, I note that Figure 24 suggested that such an approach might not lead to the modeling of the full-crosswise extent of the channel forms.

Because k2 curvature appears to map the center of the channel forms, I turn my attention to what might be used to “fill in the gaps.” Examination of Figure 15 leads to the observation that although the middle of the channel forms have a trough-like appearance, the edges “roll-off” into angular unconformities. Reflector convergence (Marfurt and Rich, 2010) is an attribute sensitive to such unconformities. It works by calculating the magnitude to which reflectors converge together, as well as the direction of any such convergence.

Figure 29 shows the reflector convergence azimuth and magnitude for the vertical line. The sides of the channel forms appear visible as adjoining regions of values separated by 180°. In general, the values of these regions are mostly in east/west sets perpendicular to the channel-form axes. Contrasting values appear on the flanks of the channel forms. These values on the flanks are caused by the erosional nature of the channel forms’ cross-cutting layers.

Figure 30 shows a magnified portion of the vertical line. Contrasting azimuths are seen on the edges of the channel forms and the flanks. Figure 31 shows how such a configuration will tend to occur in an incised channel-form architecture.

Geobody extraction

Given these observations on the response of the k2 curvature attribute to the channel forms, I can now use a thresholding approach to modeling and extracting the channel forms in 3D (Myer et al., 2001). Geobody extraction is a process by which attribute values in one or more 3D volumes are used to create objects in 3D. These objects could correspond to salt diapers, channels, or other geologically meaningful features. Figure 32 summarizes typical workflow used for geobody extraction (Moore, 2001).

The first step in the geobody extraction workflow is the selection of attribute(s). In the previous section, I looked at a number of attributes and I concluded that k2 curvature was the best candidate.

The next step in the geobody extraction workflow is to select attribute parameters. Although k2 curvature was a good candidate for geobody extraction, highly negative values did not extend fully across the lateral extent of the channel forms. I took measurements of a number of channel forms, and determined that 600 m was a typical lateral width for the channel forms. I then constructed a spatial operator with a half wavelength of 600 m to use in the curvature calculation process. This operator is shown in Figure 33.

Using the spatial operator shown in Figure 34, I calculated k2 curvature for the extent of the Mandu Formation (Figure 34). In this case, the highly negative values did a much better job extending across the full lateral extent of the channel forms.
Using the calculated k2 curvature shown in Figure 34, I then established a threshold to be used in the geobody extraction process (Figure 35).

Figure 36 shows the values that fell below the selected threshold. These results appear to well define the channel forms and were thus used to continue the geobody extraction workflow.

The final step of the geobody workflow involves postprocessing of the thresholded values. This step includes region growing to define objects and a postprocessing step to reject objects that are too small in size. The results of this extraction process are shown in Figure 37. The extracted channel forms appear to be geologically feasible, and correlate closely to the channel forms seen by animating through a suite of east–west vertical slices through the seismic amplitude data. This seems to confirm the viability of the use of k2 curvature for 3D geomodeling.

Figure 38 shows a representative intersection of the extracted geobodies with the seismic amplitude for the vertical line (Figure 14) used in the validation process. The geobodies in this slice have modeled every channel

Figure 32. A typical geobody extraction workflow.

Figure 33. A spatial operator with a half-wavelength of 600 m.

Figure 34. The k2 curvature calculated using a spatial operator designed for 600 m wide features calculated for the extent of the Mandu Formation. Highly negative values of k2 do a much better job of extending across the full-lateral extent of the channel forms. Note that several of the “interfluvials” or regions between the channel forms have a dome shape, which gives rise to a positive value (red) for k2.

Figure 35. In the thresholding process, highly negative values of k2 curvature are assumed to correspond with the channel forms.

Figure 36. Values of k2 curvature below the selected threshold are candidates for inclusion in the geobody being extracted.
form that is present in the data. However, there were some additional small valley features that were extracted below the larger channel forms that should not have been. Furthermore, as expected, the modeled geobodies do not cover the full crosswise extent of the channel forms. The overall results are quite promising, although further parameter tuning is necessary.

**Conclusions**

In this chapter, I have examined the seismic attribute expression of channel forms in a hybrid carbonate turbidite formation using a 3D data set from the Carnarvon Basin, Australia. This formation is highly channelized, and mapping these channels through traditional seismic geomorphological methods is complicated by the difficulty in picking appropriate flattening horizons. Therefore, I have designed and implemented a more modern workflow based on seismic attributes.

I have shown how these channel forms are expressed by a number of seismic attributes including variance, principal curvature, and reflector convergence. These were picked due to articulable characteristics of the morphology of channels and channel-like structures. I also used multiattribute visualization to demonstrate the interaction and synergy of multiple attributes.

In my analysis, I found that $k_2$ curvature was very effective in mapping the trough-like nature of the channel forms. The utility of $k_2$ was enhanced by the fact that the channel forms were seismically thick relative to velocity differences. I then used this relationship to build 3D models of the channel forms. I showed that this approach provided promising results in that it appears to map all of the channel forms. However, it did have a weakness in that it captured a small number of unwanted features. Furthermore, although it mapped the channel forms, it did not provide complete coverage of their crosswise extent.

I have laid the groundwork for future work. Specifically, further tests could be used to reject falsely mapped regions. Additionally, I would suggest using the extracted channel-form models as a starting point for heuristic analysis that would expand the models until the full extent was captured.

Carbonate turbidite systems are not as widely understood as the more traditional clastic turbidites, and there exist questions concerning how they are formed. Specifically, it is unknown during what timing of the system evolution they are formed. Accurate and complete modeling of these channel forms should help to further study their nature, contributing to our understanding of carbonate turbidite systems.

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A biography and photograph of the author are not available.