Stratigraphic Analysis in Carbonate Zones: An Investigation Using 3D Seismic Analysis Techniques on an Offshore UAE Field

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Abstract

Carbonate reservoirs in the Arabian Gulf are complex integrated systems which are often hard to interpret. The identification of pinch-outs and build-ups is further complicated by poor data quality. We present the results of applying 3D seismic analysis techniques to create attribute and geobody volumes which provide insight into the stratigraphy at the reservoir level of a producing field, offshore UAE.

This investigation focuses on the middle Cretaceous Mishrif reef build-ups which form major reservoirs and were controlled by localized salt diapirism and associated bathymetric variations. A good understanding of the geomorphological evolution as well as the structural and stratigraphic properties of these formations is crucial in defining reservoir properties.

The work flow applied to the data was split into two sections: data conditioning and stratigraphic analysis. The post stack depth-migrated seismic data were dominated by steeply dipping coherent noise. Application of structurally oriented edge preserving filters as well as spectral enhancement successfully attenuated the noise and provided a high resolution input dataset for the remaining work flows. Identification of a prograding rudist reef with associated clinoform features as well as pinch-outs formed from the truncation of the reef by the Mishrif erosional surface was achieved by use of a bed-form attribute which identified individual reflectivity events by isolating constant phase events. A

combination of the bed-form attribute with the instantaneous frequency was used to create an attribute for the analysis and extraction of stratigraphic clinoforms, pinchouts formed from truncations, and onlapping and downlapping events. Extraction of potential pinchout features as geobodies enabled their lateral extent and shape to be easily visualized and analyzed throughout the area.

Introduction

The stratigraphy in the Arabian Gulf region has been studied and described at length (*e.g.*, Van Bellen *et al.* 1959; James and Wynd 1965; Dunnington 1967; Murris 1980; Koop and Stoneley 1982. These studies have been largely motivated by interests in hydrocarbon exploration. The Middle East region has for decades been a major oil and gas producer and held 56.6% of proven world reserves at end of 2009 (BP statistical review, 2010). Some of the largest offshore oil and gas fields lie within this area. This article focuses on the Cretaceous interval within an area offshore UAE shown in Figure 1, which is host to a large number of the reservoirs in this region.

The Cretaceous stratigraphy is divided into three main cycles separated by regional unconformities (Harris *et al.*, 1984; Alsharhan and Nairn, 1990) (Fig. 2). The divisions include the Lower Cretaceous Thamama Group which are comprised of the Berriasian to middle-late Aptian age rocks, the middle Cretaceous Wasia Group formed during the late Aptian-latest Cenomanian or earliest Turonian and the Upper Cretaceous Aruma Group, which has beds of Coniacian-Maastrichtian age. Further subdivisions of these three cycles have been done but are not represented in all areas.

The Lower Cretaceous Thamama Group was deposited over a time period of about 30 million years during a period of extensive flooding of the Arabian Peninsula. The middle Cretaceous Wasia group was deposited over a span of 20 million years, while the Upper Cretaceous Aruma Group was deposited over a period of 25 million years following a period of emergence and erosion during the Turonian, which may have lasted as long as 5 million years in the northern United Arab Emirates (Harris *et al.*, 1984; Alsharhan and Nairn, 1990). The sedimentary succession was influenced by sea-level fluctuations and tectonics: during the initial period of sea-level rise, shallow marine carbonates accumulated (Alsharhan and Nairn, 1993). These Arabian platform carbonates demonstrate two models: a mixed carbonate-siliciclastic ramp that developed during regression and relative low sea level and a differentiated carbonate shelf that formed during transgression and relative highstands of sea level (Ahr, 1973; Bay, 1977; Murris, 1980; Read, 1985; Alsharhan and Nairn, 1993).

Of particular interest to this study is the presence of prograding rudist reefs-bioherms which are concentrated within three formations: the Aptian Shuaiba, the

Cenomanian Mishrif, and the Maastrichtian Simsima formations. These rudist-bioherms contain significant hydrocarbon reservoirs (Alsharhan and Nairn, 1993).

The middle Cretaceous Mishrif formation hosts major reservoirs in offshore United Arab Emirates. Some of these reservoirs contain different growth stages of the prograding rudist reefs and varying porosity and permeability characteristics which in some cases have been greatly enhanced by leaching due to subaerial exposure to meteoric waters. The leaching resulting from relatively minor sea level fall has produced moldic porosity in these rudist reefs. The basinal source rocks formed during the early part of the next succeeding transgressive cycle have sealed the reservoirs (Alsharhan and Nairn, 1993).

The quality of these middle Cretaceous prograding rudist reservoirs makes them primary targets for oil exploration in the region, necessitating comprehensive stratigraphic analysis. This case study presents a work flow that has been successfully applied to extract prograding rudist features that pinch out below the Mishrif horizon from seismic data. The work flow has been applied in two stages (Fig. 3): a data conditioning stage which involved the application of noise-attenuation filters along with a spectral enhancement technique to boost the quality and vertical resolution of the target; and a stratigraphic analysis stage aimed at visualizing and extracting the rudist features as 3D geobodies.

Data Conditioning

The ability to use poststack depth-migrated 3D seismic data to extract subtle prograding carbonate features, such as the rudist reefs in this study, depends on the ability to image them with good vertical resolution and without the effect of noise. The data conditioning work flow used here has been applied in 2 stages;

Stage1: Application of structurally oriented noise cancellation filters.

Stage 2: Application of spectral enhancement.

The dataset used for the study is dominated by steeply dipping coherent noise which has to be attenuated to reduce the presence of artifacts in the subsequent volumes and improve the seismic quality. Figure 4 shows the work flow used to condition the data.

Noise cancellation

The noise cancellation workflow involved the application of adaptive, structurally oriented FMH filters (finite impulse response median hybrid filters) that removed coherent noise in the data while at the same time preserving subtle details like edges, corners, and sharp dips in the structure. The structural orientation of the FMH filter was achieved by means of dip and azimuth volumes that were preconditioned to guide the filter across and not along any noise that was to be attenuated. Noise cancellation of the data improved the signal to noise ratio and allowed for more accurate tracking of events due to the improved continuity of reflectors. Faults and fractures also were preserved in the noise-cancelled volume (Fig. 5).

Spectral enhancement

The spectral enhancement process increases the mean frequency and bandwidth of the data while simultaneously removing noise. This enables the vertical resolution and spatial localization of the imaged seismic events to be optimized, resulting in differentiation of previously unresolved events. Localization accuracy of subtle stratigraphic terminations and pinch outs, such as the prograding rudist reefs in question, is of paramount importance for interpretation and well planning, as the terminations and events can be mapped to their actual positions and extents.

Spectral enhancement has been applied to improve the vertical resolution within the prograding features at the Mishrif level. In order to ascertain the frequencies that require enhancement, the frequency spectrum at the level of the Mishrif has been calculated on the noise cancelled data. The data were then split into discrete frequency bands using a selection of Gabor filters of varying central frequencies. Since the data is in depth domain, the frequency units are expressed in cycles per kft as opposed to Hz which is commonly used for data in time domain. Appropriate scale factors for each of the frequency responses were calculated and applied to increase the relative contribution from the higher frequency bands. A graph showing the frequency distribution of the resultant spectrally enhanced volume is shown in Figure 6.

The bandwidth was increased slightly while maintaining the peak frequency at the same level. Other levels of spectral enhancement were investigated, extending the high frequency contribution further and also enhancing the lower frequencies to create a flatter “white” spectrum. However other levels of enhancement either over-enhanced the features of interest or masked them behind the lower frequency response. The optimal level of enhancement was chosen by analysis of both the frequency spectrum and the resultant data volume. The spectral enhanced data shows an increase in vertical resolution within the prograding features directly beneath the Mishrif horizon (Fig. 6).

Stratigraphic Analysis

The stratigraphic analysis for this study was aimed at creating volumes that would provide detailed and comprehensive information about the pinchouts below the Mishrif surface, as well as to gain an insight into their geometry and connectivity.

To meet these objectives, a suite of volumes were generated employing the use of frequency decomposition and RGB blending, a customized bed-form work flow, and a geobody extraction technique. The spectrally enhanced volume was used as the input volume to all the work flows.

Frequency decomposition and RGB blending

Frequency decomposition and red-green-blue (RGB) blending are employed primarily as a screening tool to help analyze in a quick fashion the frequency responses associated with the rudist reef and clinoform features. Frequency decomposition generates a series of volumes that show the magnitude response at a range of discrete frequencies. This has been shown to be more effective for analyzing data than the full frequency magnitude response and can provide information about stratigraphic facies boundaries, structural and stratigraphic geometries, stratigraphic heterogeneity and bed thickness (Henderson *et al.*, 2007).

The RGB blending tool was used to combine the three magnitude volumes so that they could be viewed simultaneously, so as to reveal the geological interplay between the responses at the three frequencies. Comparisons between maps generated using standard attribute techniques and maps generated using the RGB blending technique have highlighted the value of the RGB technique for the extraction of geological information directly from seismic data (Henderson *et al.*, 2007). Similar analysis performed 90 ft below the Mishrif horizon revealed a number of frequency response changes which potentially relate to the presence of the rudist reefs. A dominance of the low and high frequency magnitude responses, which in this case were the 4 and 8 cycles/kft, were observed in places and are interpreted as the prograding clinoform features associated with the rudist reefs (Fig. 7). A quick analysis of the geometry and lateral extents of these features was possible with the use of the RGB blend volume.

Bed-form attribute

The bed-form attribute provided a volume in which the trace has been simplified to highlight only the central position of each reflector. Each event was assigned either a positive value (peak) or a negative value (trough); all other areas were set to zero. By adding in the negative component from the instantaneous frequency attribute as a third value, the location of doublets also was mapped, as these interference events result in a negative response in the instantaneous frequency estimate. This enabled the lateral extension of reflection events beyond the distinct peaks and troughs and into areas where events are not fully resolved (Fig. 8). The bed-form attribute aided the stratigraphic interpretation of the interval as the Mishrif surface could be tracked and associated prograding features and clinoforms analyzed with ease.

Bed-form frequency combined volume

The bed-form frequency combined attribute was derived by embedding the bed-form attribute into the instantaneous frequency volume and assigning all the bed-form locations a value of zero. This produced a volume that gave both reflector structure and frequency information. This volume also enabled the frequency content of pinch out areas, toplaps on the Mishrif and the prograding clinoforms to be seen easily as the eye is drawn towards the red of the higher frequencies (Fig. 9).

Pinchout attribute

The pinchout attribute provided a template for the extraction of high instantaneous frequency geobodies that correspond to potential pinch outs in the data. This was computed by running a structurally oriented smoothing filter on the bed-form frequency volume. This resulted in the concentration of high frequency zones, making them better connected and more continuous (Fig. 10A). This attribute helped in highlighting the potential pinchout features below the Mishrif as well as other high frequency zones corresponding to downlaps and onlaps. In order to focus the delineation of the pinchout features specifically below the Mishrif surface, the pinchout attribute was cropped between the Mishrif surface to 250 ft below as seen in Figures 10 B-D.

Pinchout geobodies

The pinchout attribute volume was used as the input to a geobody extraction technique, in which a segmentation threshold was selected and all data below the threshold level were ignored and given a background (zero) value, while data above the threshold level were labeled as geobodies. Connectivity analysis was performed on the geobodies so that each discrete area was given its own value (color). This technique made it possible to extract varying sizes and shapes of the geobodies depending on the thresholds applied. The threshold range that was selected was targeted at extracting the pinch outs in full, using the shapes visually identified from the bed-form attribute. Figure 11A and B shows the geobody volume displayed in 3D render mode. The pinch out geobodies provided a good understanding of the lateral extents and connectivity of the pinch out zones directly below the Mishrif surface.

Generating skins about geobodies

By extracting the outer skin (what we denote to be a "skinin") of the pinchout geobody and embedding this into the spectrally enhanced reflectivity data, a good visual correlation of the pinchout geobody within the data has been gained. This volume helped increase the understanding of the exact outline and extents of the pinchout zones within the reflectivity data as shown in Figure 12.

Conclusions

Middle Cretaceous reservoirs of the Gulf of Arabia contain prograding rudist reefs which have enhanced porosities due to leaching and are prime exploration targets. These prograding reef features form clinoforms; where they toplap with the Mishrif sealing surface, they form pinchouts in places necessitating a comprehensive stratigraphic analysis. A seismic imaging technique has been successfully applied on an offshore UAE field targeted at extracting stratigraphic information about the morphology and extents of these features including their 3D geometry.

The poststack data were subjected to necessary data conditioning techniques that improved the signal to noise ratio of the data and increased the vertical resolution, enabling the extents of potential pinch out features to be better imaged. Stratigraphic imaging techniques, such as frequency decomposition and RGB blending, were utilized to provide a quick analysis of the prograding clinoforms and rudist reef pinch outs. The application of the bed-form work flow created the bed-form and bed-form frequency attributes which highlighted the prograding clinoforms, onlaps, and pinch outs, thereby providing templates for 3D geobody extraction. The pinchouts that potentially correspond to the carbonate reservoirs were subsequently extracted and analyzed in 3D and in combination with the reflectivity data. These results effectively guided the interpretation of these complex carbonate features and also served as high quality input for seismic modeling of the field.

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Figure 1. Study area offshore UAE.

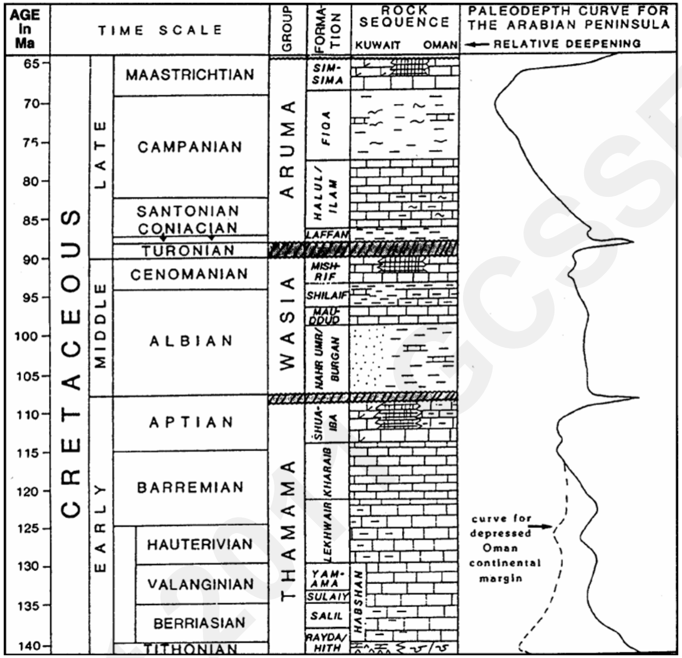

Figure 2. Cretaceous stratigraphy and sea level fluctuations in the Arabian Gulf. Reef buildup is shown by cross-hatchures. (From Harris *et al.*, 1984; Alsharhan and Nairn, 1990.)

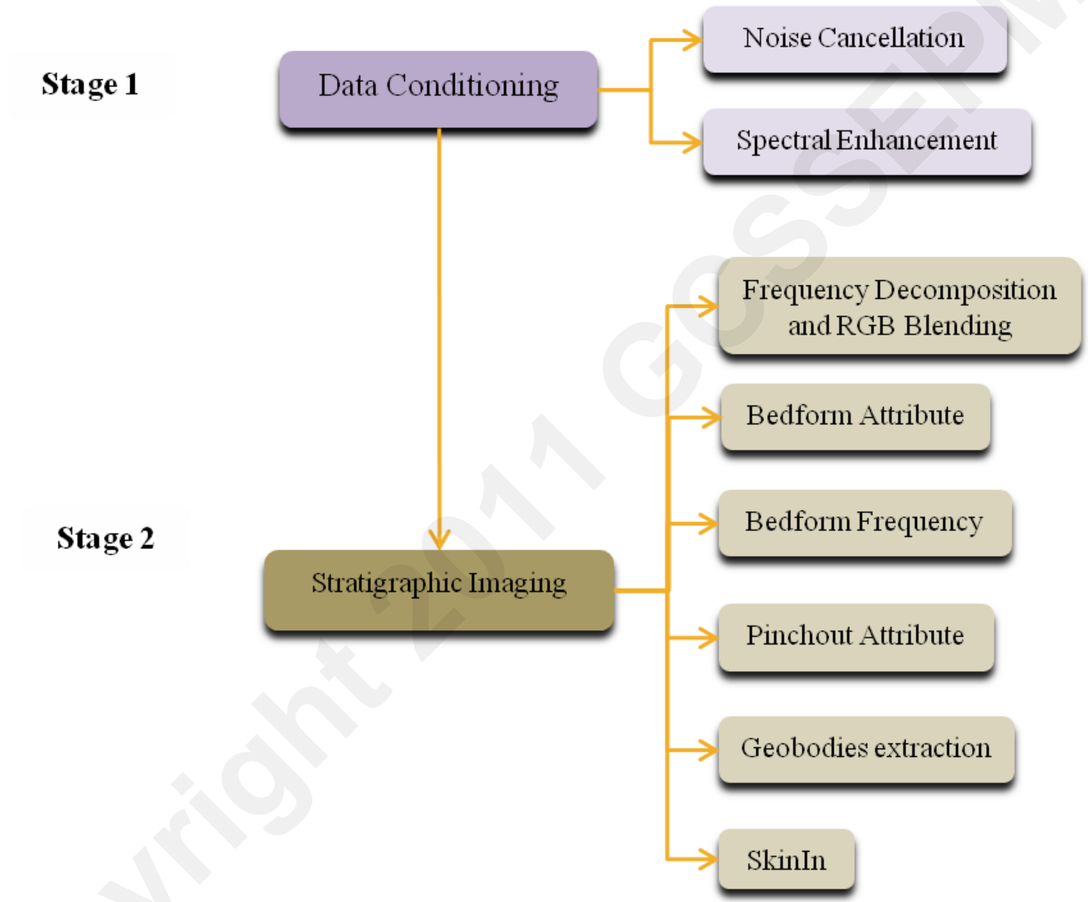

Figure 3. Work-flow chart.

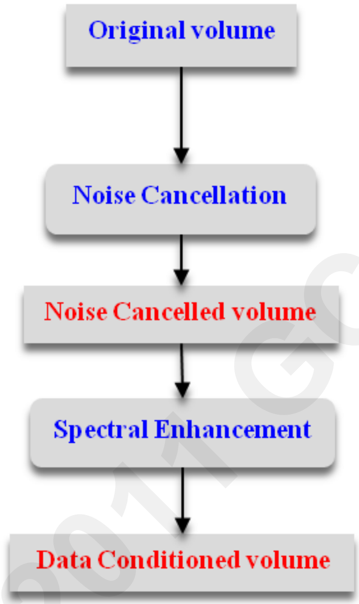

Figure 4. Data conditioning work-flow sequence.

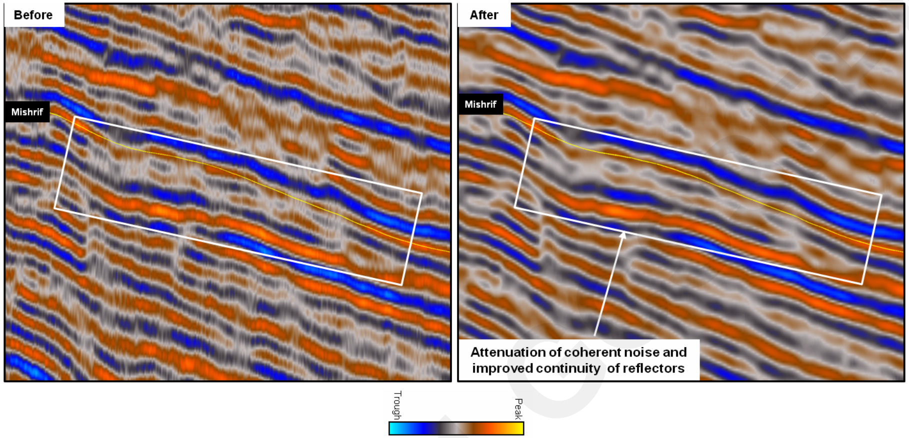

Figure 5. Original input data on the left and the noise-cancelled data on the right showing improvement in reflector continuity and removal of coherent noise after application of noise cancellation filters.

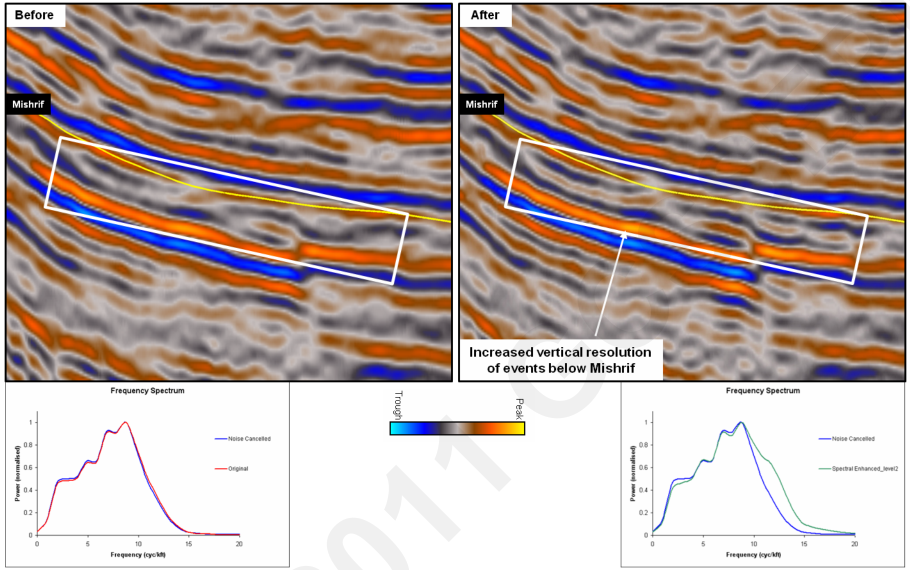

Figure 6. Noise-cancelled input data on the left and the spectral enhanced data on the right showing the marked improvement in vertical resolution of the events below the Mishrif surface. The graph shown below each image corresponds to the spectrum of the data calculated at the Mishrif surface before and after spectral enhancement.

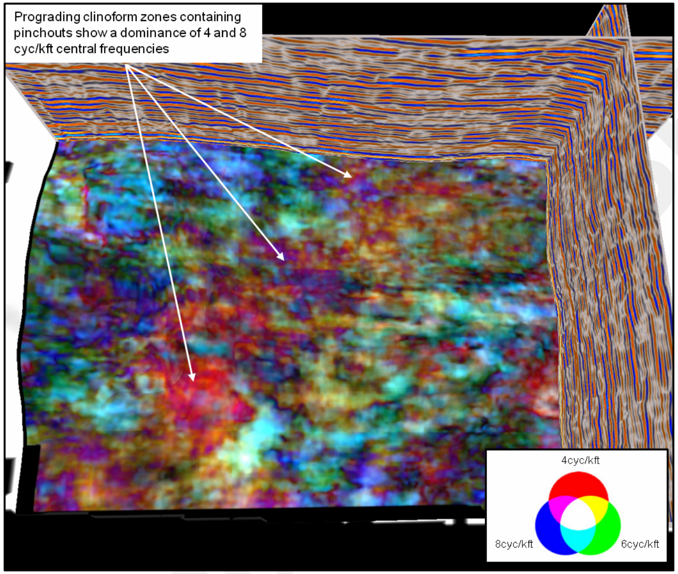

Figure 7. RGB blend shown at 90 ft below the Mishrif surface.

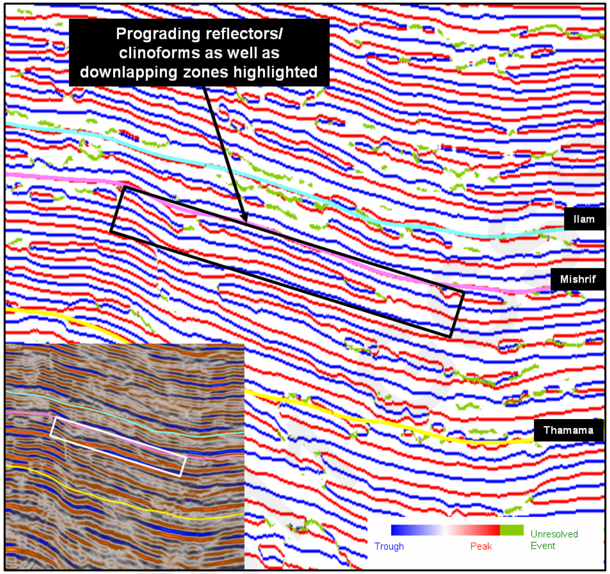

Figure 8. Bed-form attribute shown with the data-conditioned volume inset.

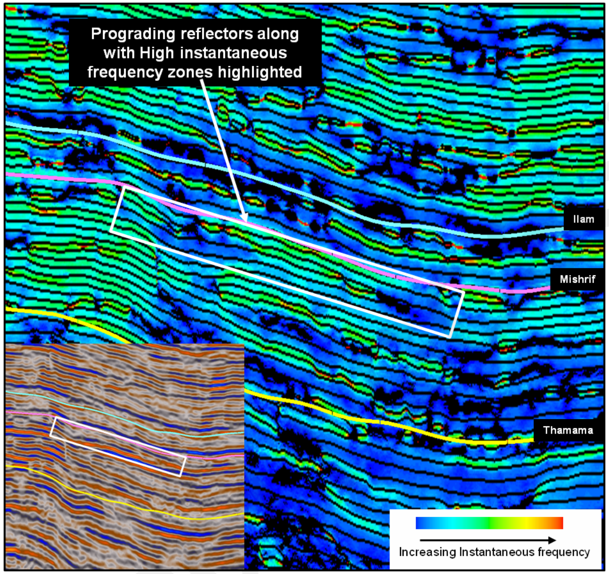

Figure 9. Bed-form frequency volume shown with the data-conditioned volume as inset.

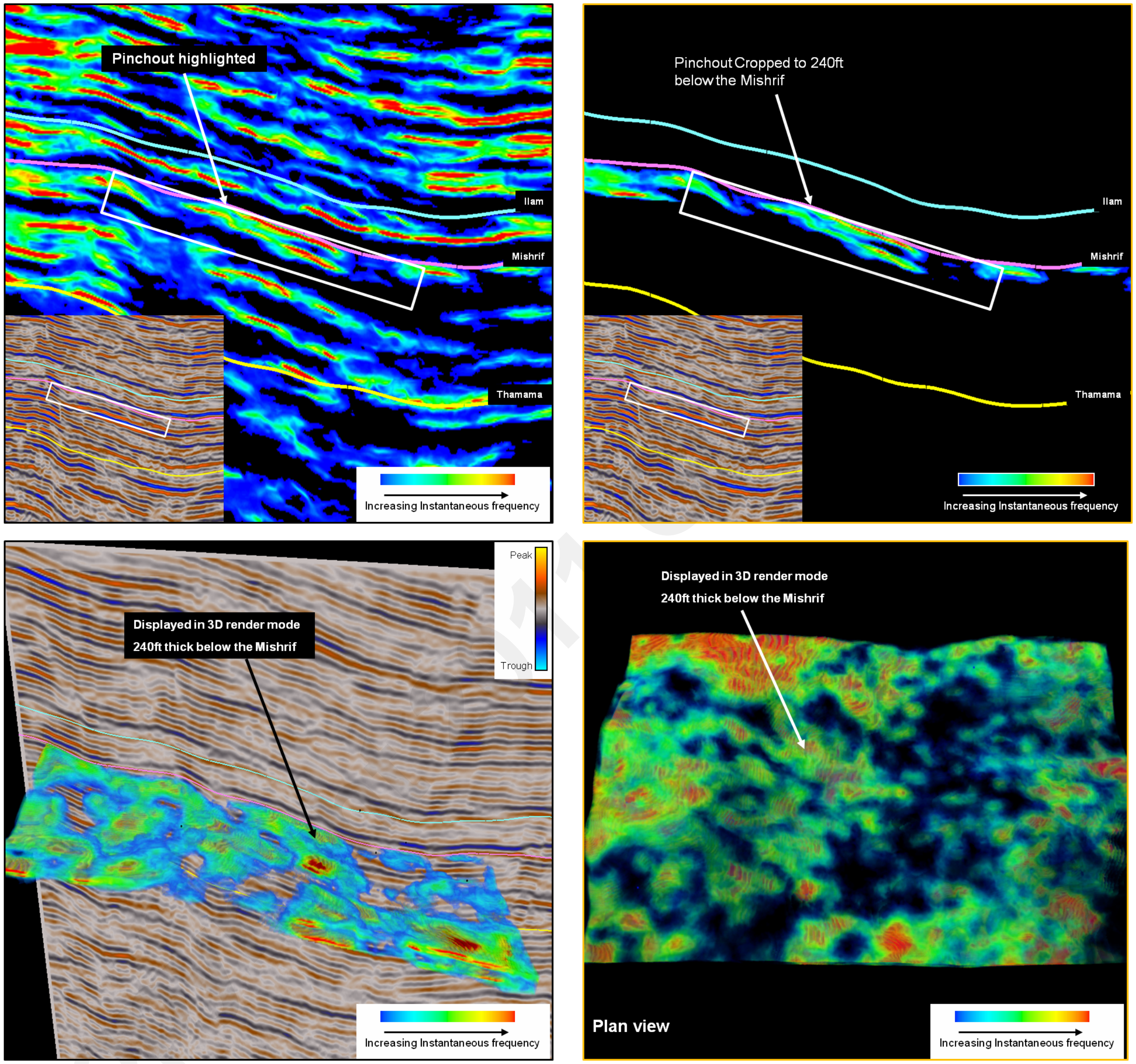

Figure 10. The pinchout attribute with the data conditioned volume as insets. (A, upper left) Shown over a cross section. (B, upper right) Cropped to a depth of 250 ft below the Mishrif. (C, lower left) Displayed in 3D render mode along a cross section. (D, lower right) Shown in 3D render-mode in plan view.

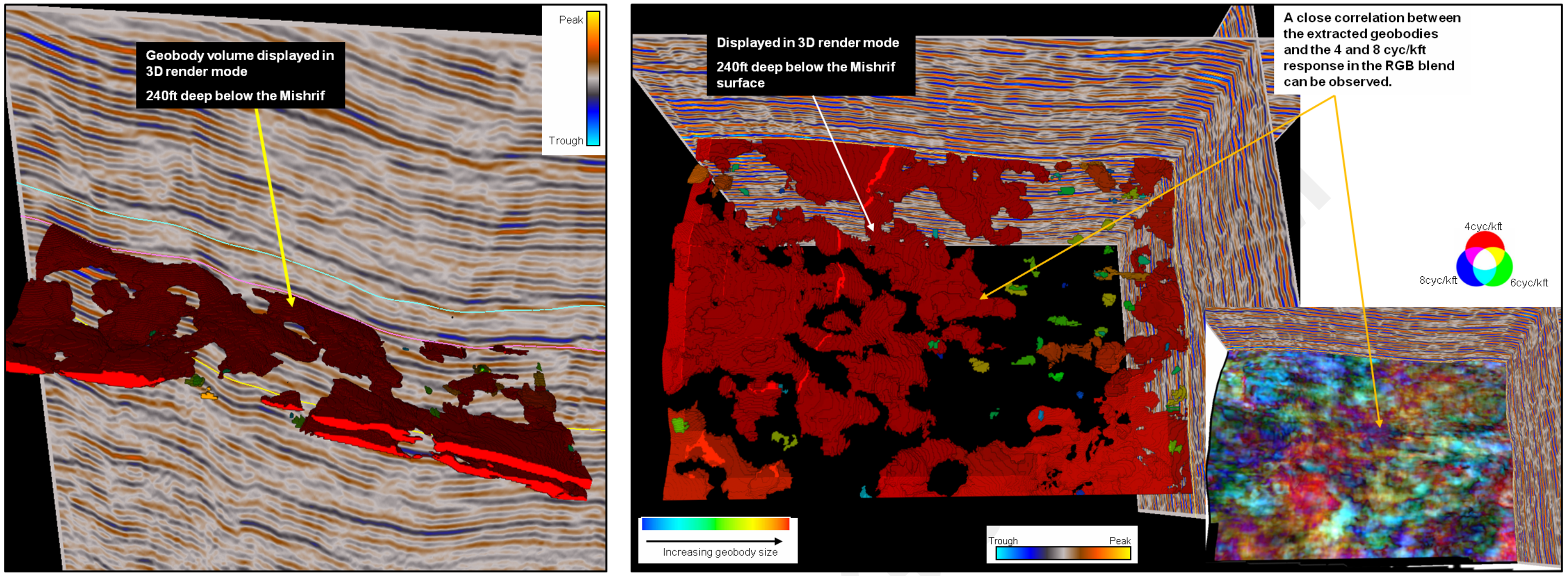

Figure 11. Pinch out geobody volume: (A, left) shown on a cross section in 3D render-mode. (B, right) shown in plan view with the RGB blend as inset. Notice the close correlation between the reddish and bluish zones dominated by the 4 and 8 cyc/kft responses that were earlier identified as potential rudist features.

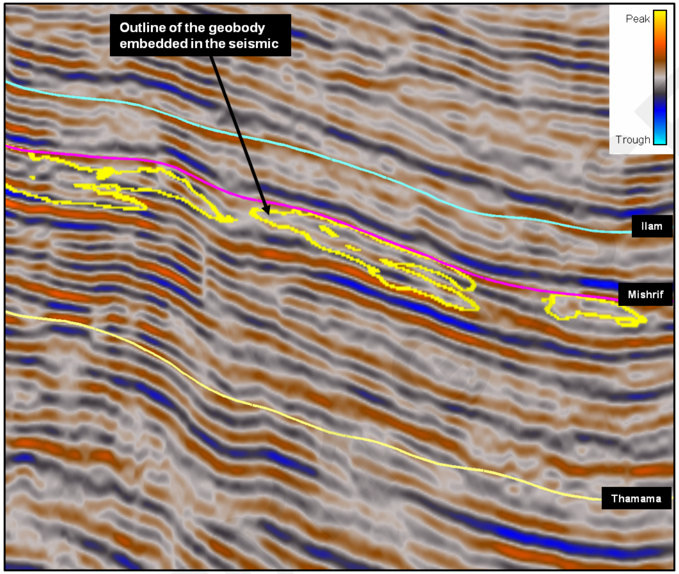

Figure 12. Geobody "skinin" volume shown in cross-section. The yellow lines mark the outline of the pinchout geobody.