Multi-attributes and Seismic Interpretation of Offshore Exploratory Block in Bahrain—A Case Study*

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Abstract

An exploration well, M-1, was drilled targeting a low-relief, four-way dip closure mapped at Jurassic and Cretaceous levels. M-1 well logs show an oil-water contact in the Jurassic Arab zone; it was confirmed by an oil gradient from reservoir pressure points. A quick post-drilling analysis of the seismic data showsthat the well M-1 was drilled downdip of the low-relief structure. This compelled a challenging reinterpretation and mapping of the seismic vintage over such low-relief structures with abundant velocity variations. A different approach was used with improved velocity models and depth conversion to overcome these challenges and better understand the subsurface structures. Seismic attribute analysis was carried out to locate and define subtle stratigraphic and structural features, and to delineate potential reservoir as well as non-reservoir lithofacies within the mapped reservoir units. Attributes calculated from seismic amplitude data are used in conjunction with horizontal time slices and vertical sections to identify and allocate potential hydrocarbon pay zones. In addition, it was observed that the M structure is located in a merging zone between two seismic vintages, and thus an effort was made to remap the prospect by attempting to minimize the effect of merging. Generated maps suggest that the well was drilled at the edge of a more robust M structure which extends at deeper Permian levels. The study concludes that there is a significant upside exploration potential in this area.

Introduction

Structural Setting

The study area is located in offshore Bahrain which lies in the western Gulf sub-basin within the Central Arabian Province. This sub-basin is limited by the NE-trending Qatar Arch to the east and the major Ghawar/Damman highs to the west. The Qatar Arch is a broad anticlinorium that may have been active as early as Infra-Cambrian time. Highs in the region like the neighboring Awali and Dukhan structures are thought to be controlled by some combination of basement faulting and diapiric activity associated with a deeply buried (>18,000 feet) Infra-Cambrian salt layer. The tectonic setting along with the major structural features of the Arabian Plate is shown in Figure 1.

Sequence Stratigraphy and Petroleum Systems

The depositional sequence is identical for both offshore and onshore Bahrain and can be summarized as follows:

- Early to Middle Paleozoic continental through shallow marine clastic deposition
- Post-Hercynian / Permian carbonate deposition
- \Jurassic shallow-water carbonate deposition
- Cretaceous shallow-water carbonate deposition with intermittent clastic input
- Early Tertiary shallow carbonate deposition associated with margin of Zagros foredeep basin
- Late Tertiary non-deposition to marginal marine deposits associated with compressive foreland setting.

Two major petroleum systems are active within this region of the gulf. Together they account for most of the oil and gas accumulations in the area. The younger system is the focus of most of the drilling campaigns in this area and is sourced by Jurassic marine carbonates of the Hanifa-Tuwaiq Mountain zone. All of the major producing oil fields in the region are a product of this petroleum system. The older system consists of the sequence of the Khuff Formation along with older gas and condensate reservoirs; which are sourced by the marine shales of the Silurian Qusaiba (Qalibah) Formation. A possible third system is associated with organic-rich Cretaceous strata that may be mature in northern areas of Bahrain. Figure 2 summarizes the general petroleum system in this area.

Current Study

M-1 well was drilled to target a low-relief structure at Jurassic and Cretaceous sections. This prospect was earlier mapped as a four-way dip closure, called M- structure. A quick post-drilling analysis of the seismic data shows that the well M-1 was drilled downdip of the low-relief structure. This emphasized the need to reinterpret the seismic data over the M-structure and surrounding areas with improved velocity models and depth conversion. This study also reflects how the integrity of M structure is affected by merging of two vintages of seismic data. Detailed subsurface structural maps were generated at selected levels by integrating 3D seismic, geological and petrophysical data. Seismic attribute analysis has been carried-out to locate and define subtle stratigraphic and structural features.

Results of M-1 Well

Resistivity logs over the Arab zones show an oil-bearing interval which was confirmed by an oil gradient from reservoir pressure points. In addition, elevated total gas readings were measured across lower Hanifa Formation. Logs and reservoir pressures over this section indicated low to moderate porosities and high hydrocarbon saturations. Post-drilling mapping show that the well was drilled downdip from the crest of the structure. These results are summarized in Figure 3.

Seismic Interpretation

In preparation for seismic interpretation, synthetic seismograms were generated to tie the seismic sections to the well. Vertical Seismic Profiles (VSPs) and velocity surveys provide the best available velocity control at the location of M-1 well. The output synthetics are attuned to create a 'best-fit' to the seismic trace, thus allowing the correlation of well tops to the vertical seismic section. Figure 4 shows the results of the seismic-well tie of M-1 well. After the log editing and well correlation, synthetics for all other wells in the area were generated using a commercially available software package. Well logs were reloaded, edited, marked, correlated and tied to seismic.

Several seismic horizons at different stratigraphic levels were picked including: Arab, Hanifa, Tuwaiq Mountain, Fadhili and Khuff formations. For best mapping results, the most continuous reflector closely correlating to a well-top pick was chosen at each level; this may be a trough, peak, or zero crossing. Seismic multiples at target levels, basic tuning thicknesses and presence of acquisition footprints were taken into account while making the interpretation. Horizon picking was made more effective by using selective 3D seed-picking in some levels where the signal quality was found to be of acceptable level. In other levels the impedance contrast was not good due to remnant noise in the seismic data; every 10th Inline was picked and gridded to create a good time surface for attribute generation. Time surfaces were created and smoothing corrections and gridding artifact removals were applied. All calibrated time surfaces were generated using convergent gridding algorithm. The resulting surfaces were consistent with the well markers.

Velocity Modeling and Depth Conversion

A 3D time model was built using the defined geometry and available interpreted surfaces. Dummy surface at the top (SRD) and the bottom (below Khuff) were added to extend the model boundaries. Zones were defined by the seismic surfaces and optimum representative layers were added between the zones.

The average velocity data from wells and surface seismic were up-scaled to the model. During the up-scaling, all values that fall within a cell were averaged and represented by single value for that grid cell. After the up-scaling, velocity gridding was done using the moving average method. A correlation was made between the average seismic velocities and average well velocities to deduce a time varying scaling factor. A scaled average seismic velocity was calculated using the time-varying scaling factor. Variogram analysis is also done to find out the major and minor directional changes in average velocity. A residual correction was also applied to compensate for time difference between seismic interpretation and well tops.

The workflow implemented for this study, shown in Figure 5, was adopted after analyzing other methods of depth conversion and comparing the results. The result of each stage of this process is displayed in Figure 6.

Attribute analysis

This analysis focuses on identifying attributes that reveal anomalous features with respect to the typical seismic character of an interval. As the area was dominated by a platform environment during deposition of all intervals of interest; the assumption of a flat sequence boundary surface was a reasonable approximation. Seismic data was conditioned to enhance subtle features and terminations to identify alignments which are critical to establish fault orientations in the area that are consistent with regional tectonic framework. Therefore, Variance Attribute was found to be the most reliable when compared to Chaos and dip deviation attributes. The Variance attribute was used to establish fault planes validated by vertical seismic sections. Moreover, Surface attributes, such as RMS amplitude, relative acoustic impedance, sweetness maps along with frequency attributes, were generated to identify the reservoir character at the Arab and Khuff levels. Most of attribute analysis results show an anomaly feature consistent with the M structure geometry. This anomaly can be attributed to either better reservoir properties or facies change. The RMS amplitude maps and sweetness maps prepared on Arab zone are shown in Figures 7a and 7b, respectively.

Discussion and Conclusion

The study resulted in identifying a number of potentially prospective areas to support the ongoing exploration efforts. Reinterpretation results show that M-1 well did not penetrate a structural closure at the shallow Cretaceous levels. However, it penetrated the edge of the structure at the Arab sequence and Fadhili Formation (Figure 8a). The oil gradient from reservoir pressure points and the high water saturation levels observed in logs confirm that the well was drilled on the flank of the structure and has possibly penetrated the fluid transition zone.

The oil shows observed in zones of Fadhili Formation suggest that a source older than Hanifa-Tuwaiq Mountain might be acting in this area. This provides an opportunity for investigating the deeper Jurassic sections which have not been penetrated by the well. Furthermore, the four-way, shallow-relief structure was interpreted to extend to the deeper Khuff horizons (Figure 8b). These results suggest that there is a good exploration potential in the deeper sections of this area.

An alternative interpretation based on knowledge of the seismic data acquisition and processing history suggests that the M-1 structure is affected by seismic data merging. The available seismic volume consists of two distinct vintages (one set of streamer seismic data and another set of OBC seismic data) merged together. A small area between the vintages overlaps; however; the shooting lines were in perpendicular directions. These differences in acquisition design caused a different reflection response in both vintages – making mapping the structure even more challenging. At the merging zone of both vintages, a structural low feature is observed, which is anomalous to the regional trend (Figure 9). Isochron maps of Arab zone (Figure 10) support the interpretation that a structural high existed at the time of deposition of the Jurassic sediments. Typically, such thickness maps are not affected by geometrical factors, such as merging, since they reflect the relative difference in arrival times/ depth boundaries.

All analysis has been made in the time domain since such low-relief structure, like M-1, can be easily distorted with minimal changes in velocity during the depth conversion, especially when building an accurate velocity model is very challenging in a stacked carbonate system with many pit falls.

The various attribute analyses conducted during the study show that similar attribute anomalies are observed on either side of the low trend (possibly caused by the merging zone) suggesting that the same distinct facies is possibly continuous across the merging zone. Moreover, from a geological perspective, considering the depositional environments, tectonic setting and expected geometries, such as abrupt change in geometry, is highly unlikely.

Consequently, the structure can possibly be a much bigger low-relief structure partially masked by a non-real low trend with the well drilled right at the edge. Considering such interpretation, along with the results of M-1, suggests a much more prospective robust structure and larger potential reserves.

Reference Cited

Pollastro, M.R., 2003, Total petroleum system of the Paleozoic and Jurassic, Greater Ghawar Uplift and adjoining provinces of central Saudi Arabia and northern Arabian Persian Gulf: U.S. Geological Survey Bulletin 2002-H; 100p.

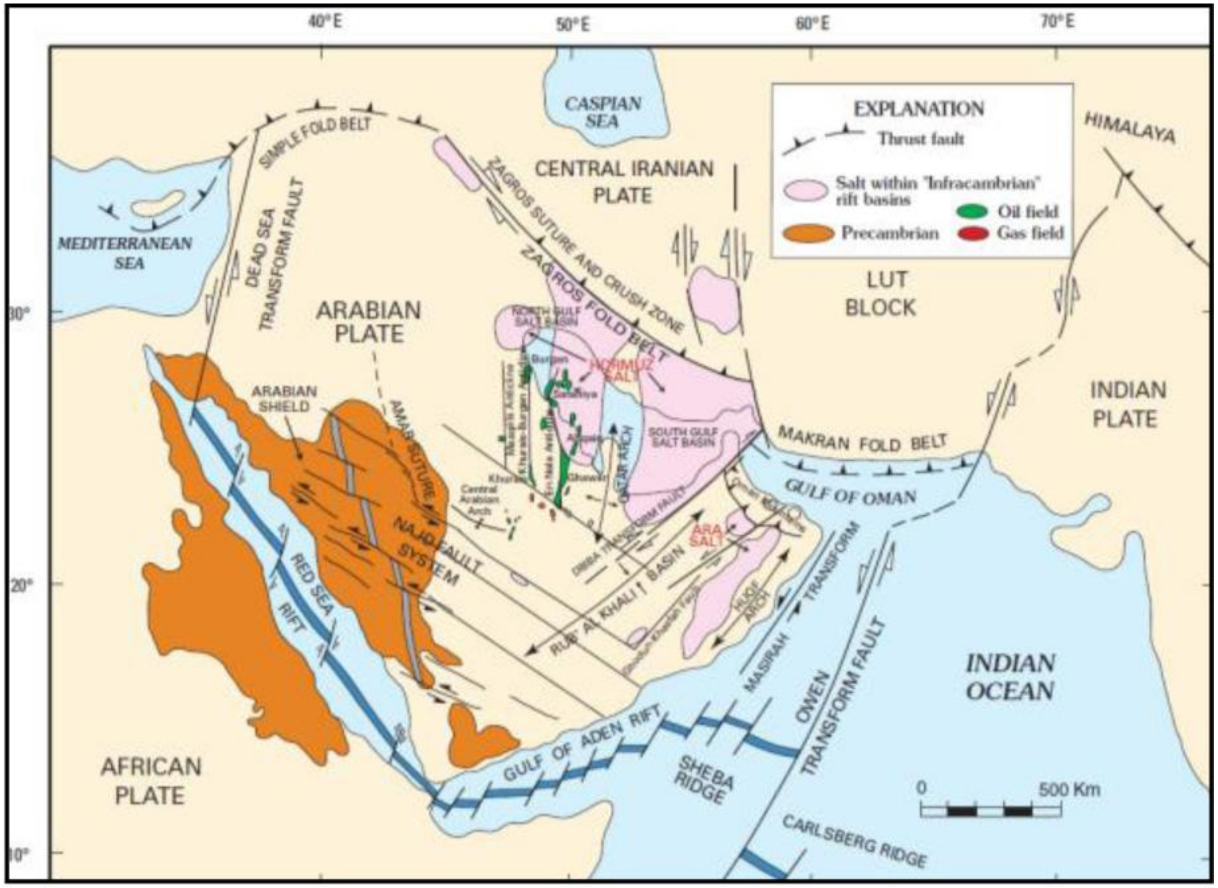


Figure 1. General tectonic and structural features of the Arabian Plate (Pollastro, 2003).

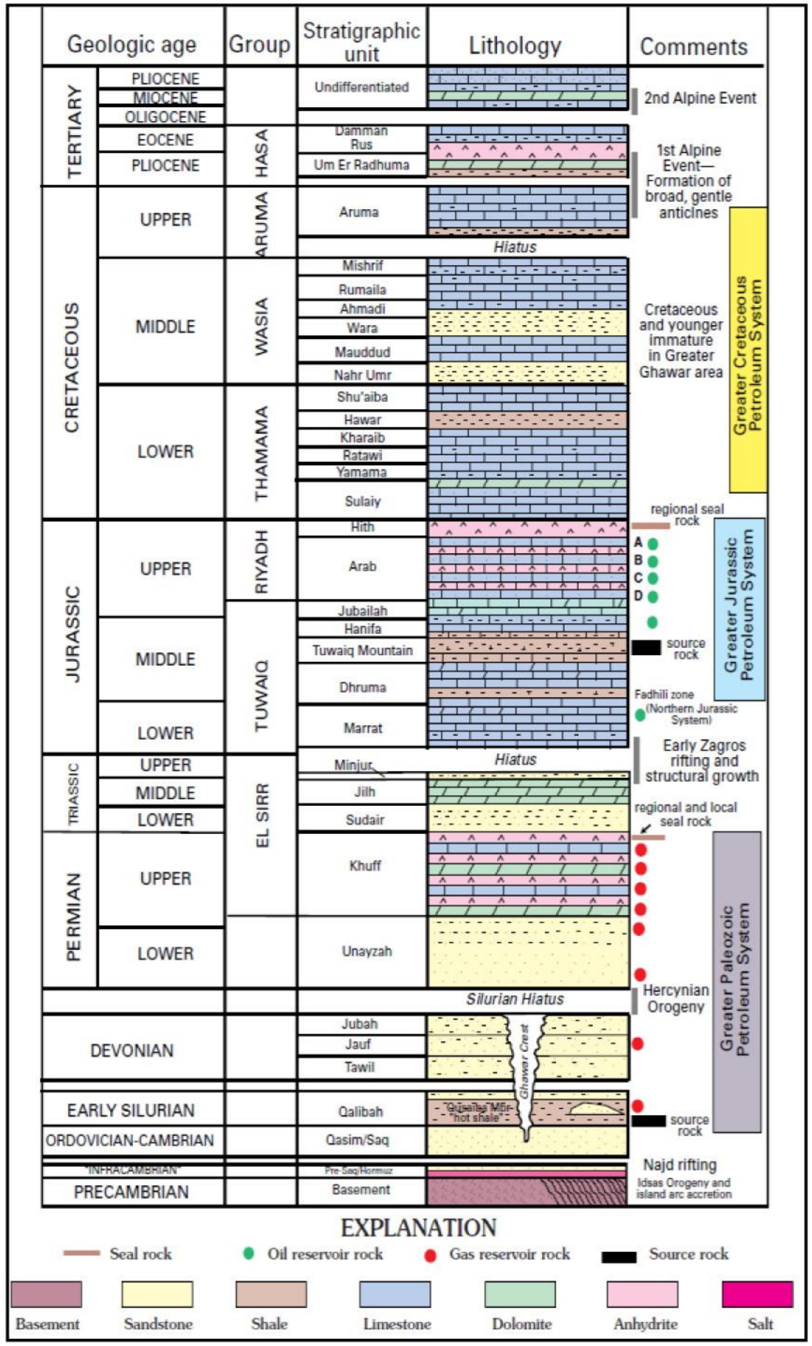


Figure 2. The major petroleum systems in Bahrain.

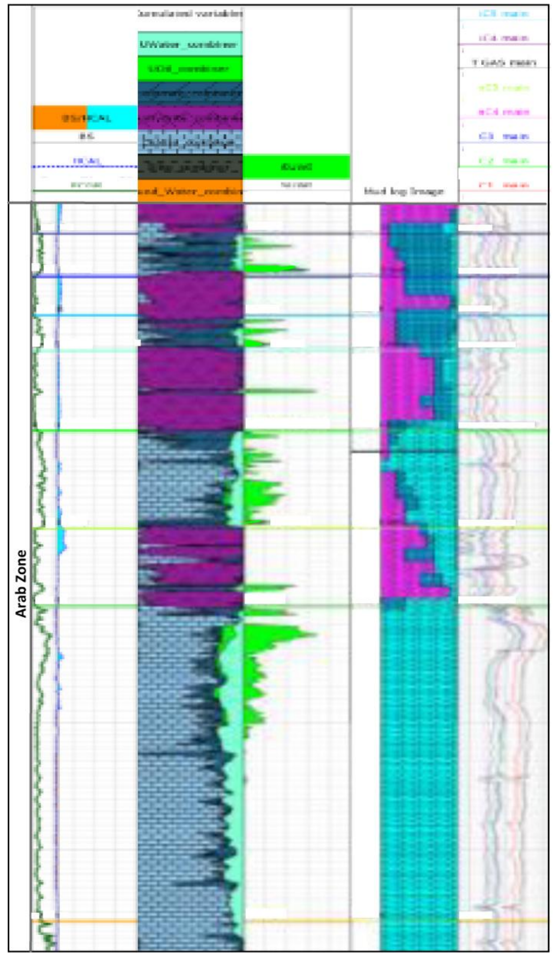


Figure 3. Petrophysical analysis of M-1 well.

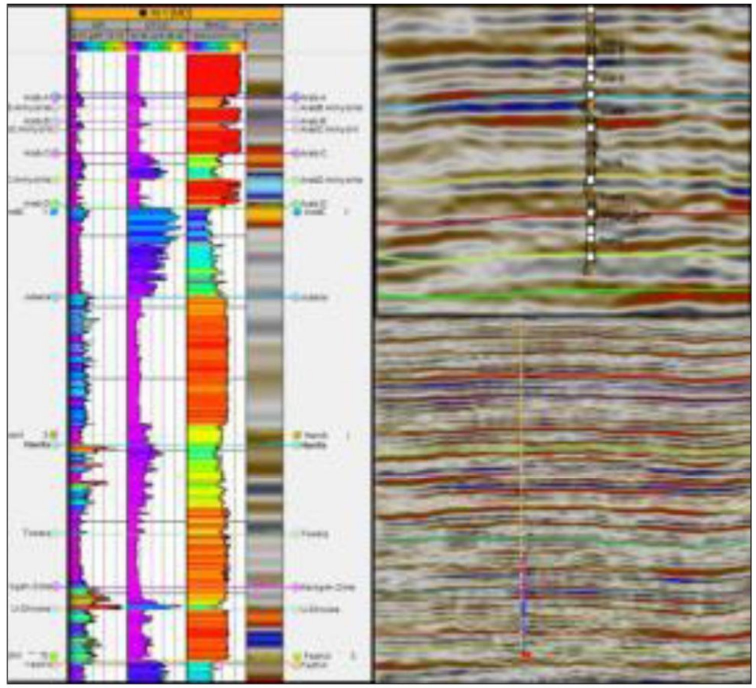


Figure 4. .The results of M-1 well and the well to seismic tie.

Figure 5. Adopted workflow for depth conversion.

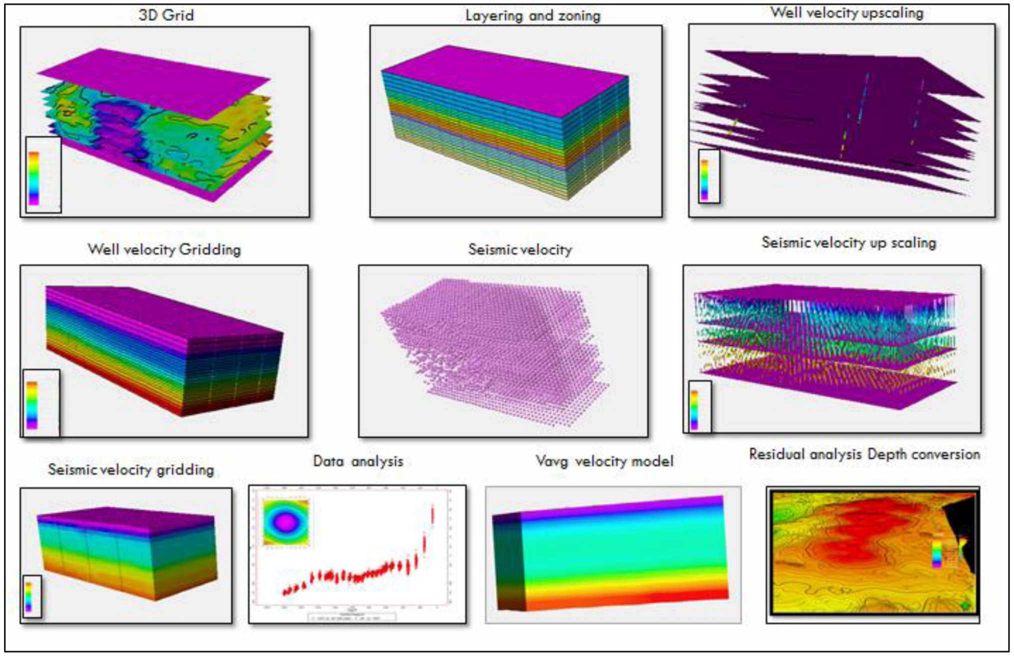
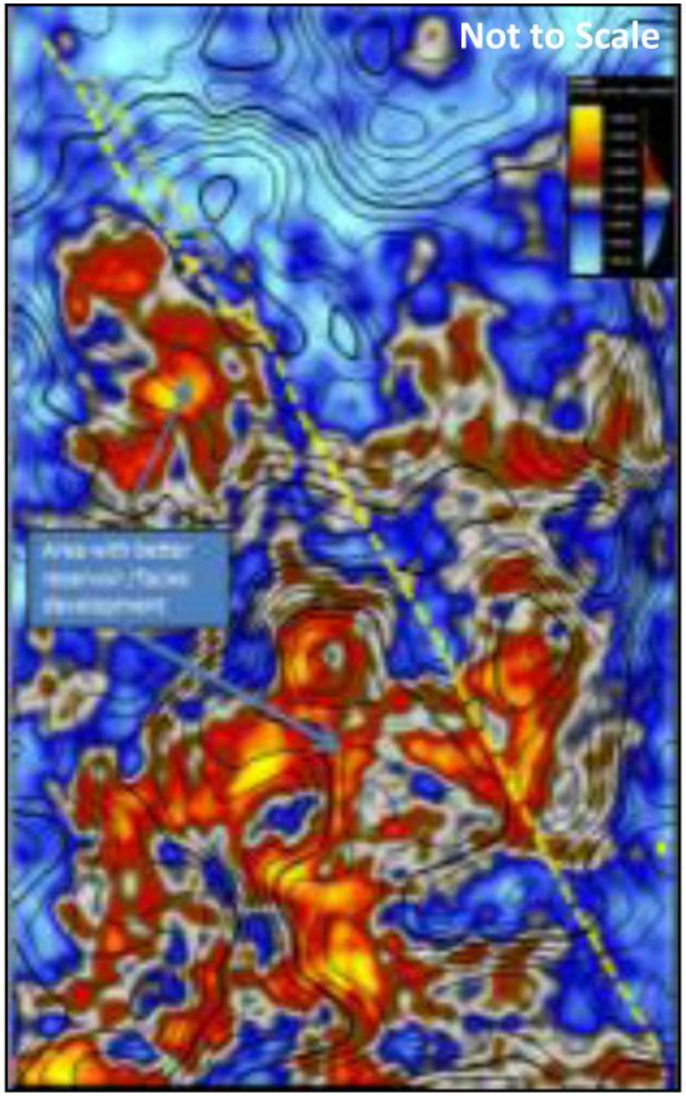


Figure 6. Results of each stage of the Velocity Model building workflow.



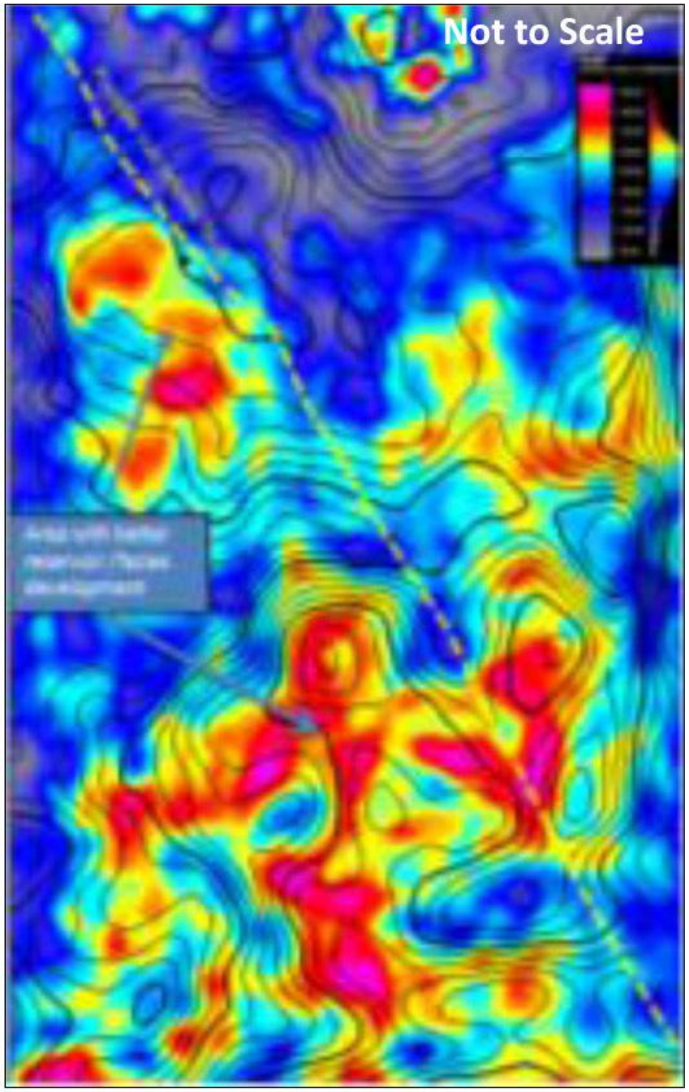
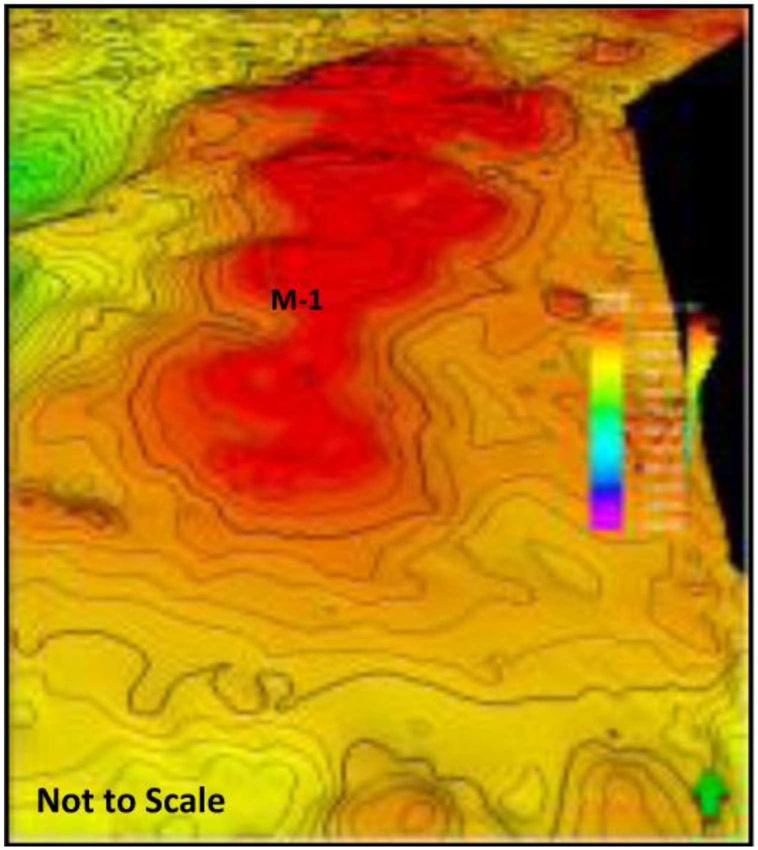


Figure 7a. RMS amplitude extracted along the top of Arab zone.	Figure 7b. Sweetness attribute extracted along the top of Arab zone.



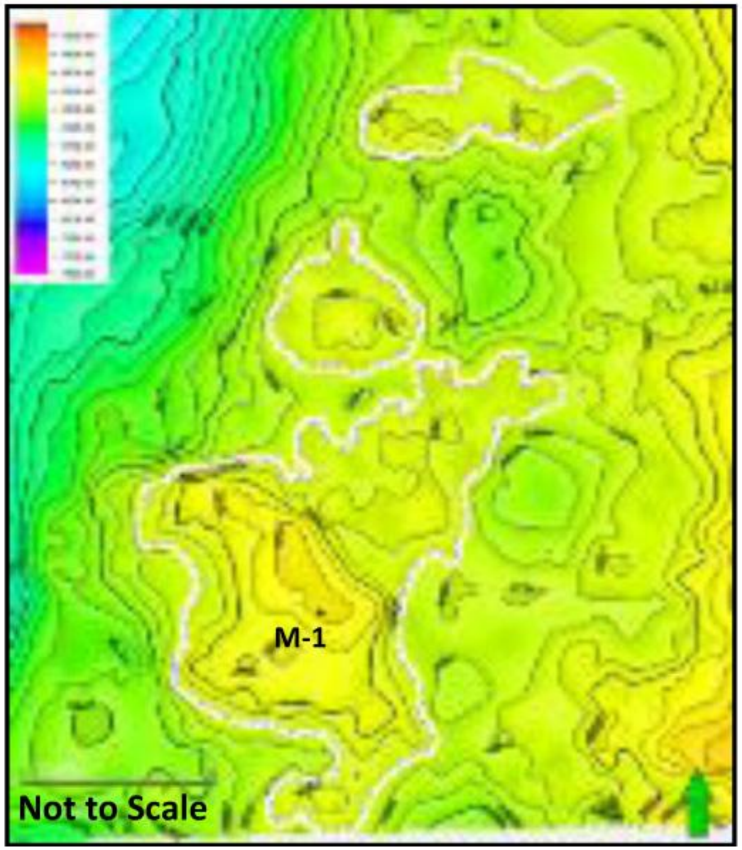


Figure 8a. Depth map of Fadhili showing a robust low-relief structure with M-1 drilled on the edge of the structure.	Figure 8b. Depth map showing the structure at Permian level which was not penetrated by M-1 well.

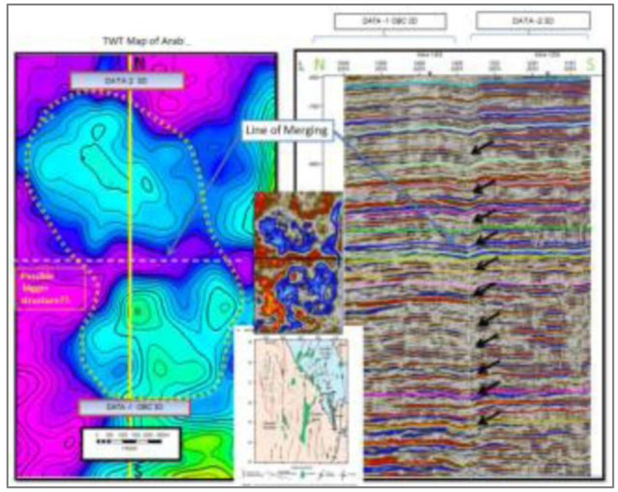


Figure 9. Time maps of Arab Zone showing the effect of the seismic merging of the integrity of the structure.

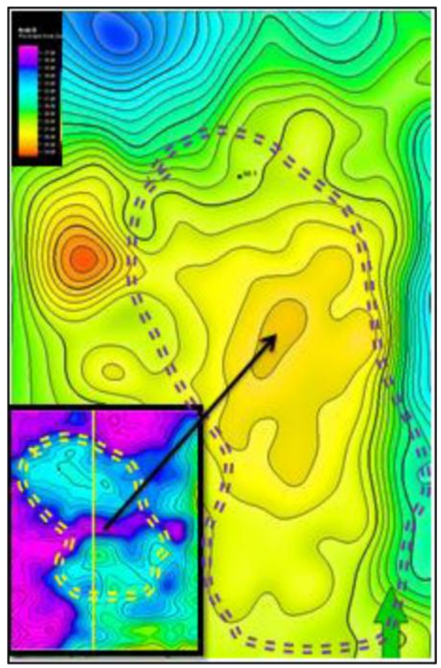


Figure 10. Isochron map of Arab zone shows thinning at M-1 structure.