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Advanced Seismic Data Interpretation for Carbonate Targets Based on Optimized Processing Techniques

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ABSTRACT

Seismic data from the shelf area of the Cretaceous Shu'aiba Formation in Abu Dhabi is used to investigate stratigraphic and structural seismic anomalies. The data consists of a 2-D grid of seismic lines, acquired in the late 1980s and 1993. The data was reprocessed in several phases. The first phase consists of standard time domain processing upto final Dip Move Out stack and migration. In the second phase, a macro-velocity model for post-stack depth migration is generated and tested by the interpreters. The third phase is the interpretation of the pre-stack depth migration stack. Due to the structural irregularity of the Shu'aiba Formation, the pre-stack depth migrated data is considered the most reliable for Amplitude Versus Offset analysis. Further steps are L-1 deconvolution followed by Born Inversion. These last steps are required before the lithology can be modeled with high-resolution. The final lithological model is verified by applying forward modeling. The lithological model forms the basis for reservoir and geostatistical evaluations which account for heterogeneities.

INTRODUCTION

The Lower Cretaceous (Aptian) Shu'aiba Formation, Thamama Group, is one of the most prolific hydrocarbon reservoirs in Abu Dhabi (Figure 1). Today low-relief structural and stratigraphic traps in the Shu'aiba represent important exploration targets. This study shows how developments in seismic exploration techniques, such as pre-stack depth migration and high-resolution lithological inversion, can image these exploration targets.

Geology and Stratigraphy

The Shu'aiba Formation was deposited in a vast, shallow-water shelf covering the eastern Arabian Peninsula (Figure 2). Three facies belts are recognized within the intrashelf basin: (1) shallow water shelf carbonates; (2) a carbonate "build-up" belt rimming the intra-shelf basin centered in Abu Dhabi; and (3) basinal deposits in the intra-shelf basin areas. The shelf margin build-ups (mainly reefs) form the most prominent hydrocarbon reservoirs (Frost et al., 1983). The shallow water shelf carbonates also form a potential reservoir due to increased porosity from subareal exposure and weathering by meteoric waters during the sea level lowstand.

The Shu'aiba Formation is conformably underlain by the dense Hawar limestones of the Kharaib Formation and disconformably overlain by the shales of the Nahr Umr Formation (Figure 1). Based on seismic sequence analysis, log correlation and lithofacies examinations,

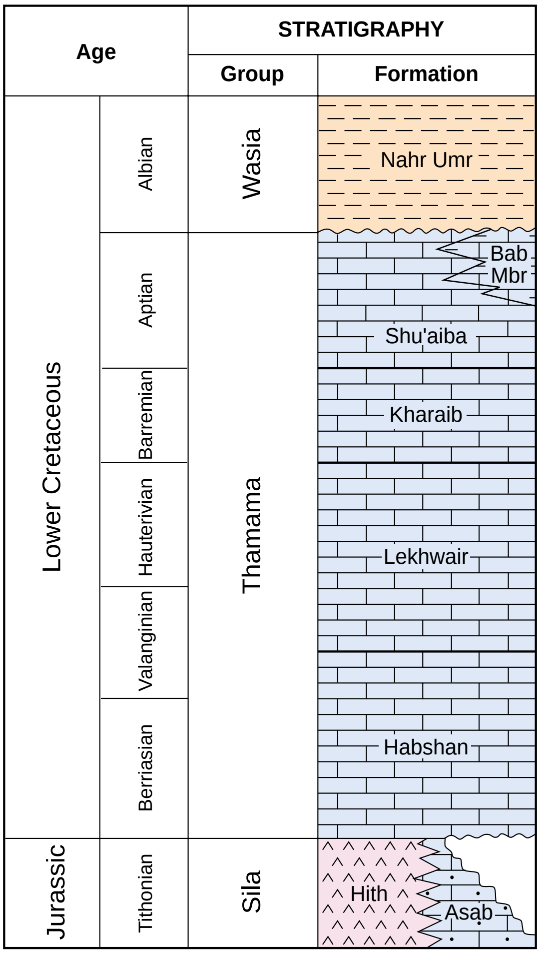


Figure 1: Stratigraphy of the Lower Cretaceous in Onshore Abu Dhabi (Abou-Choucha and Ennadi, 1990).

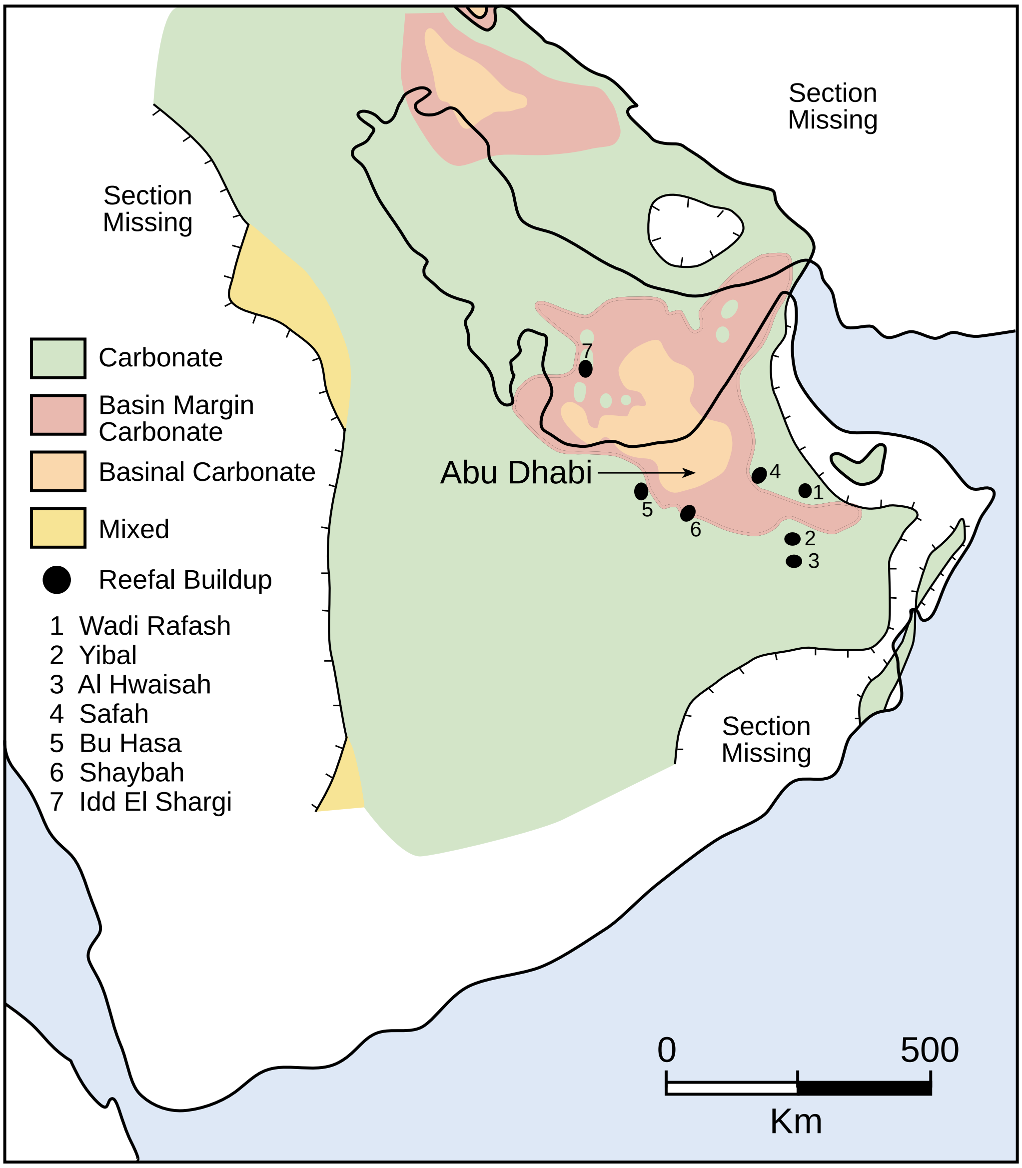


Figure 2: Depositional facies of the Shu'aiba Formation, Eastern Arabian Peninsula.

Abou-Choucha and Ennadi (1990) divided the Shu'aiba into three stratigraphic sequences (Figure 3):

112 Ma Highstand Sequence

This sequence was deposited during a highstand which ended at approximately 112 Ma. The sequence comprises all of the Shu'aiba rock units which form prograding wedges of upward shoaling carbonates with good porosity. The sequence thins rapidly basinward and mainly contains non-porous carbonates (Figure 3). This sequence is the subject of this investigation.

112 Ma Lowstand Sequence

The second sequence includes the Lower Bab Member which consists of calcareous shales and fine-grained limestones. It was deposited in the lowstand period after the 112 Ma lowstand. It is restricted to basinal areas.

108 Ma Restricted Highstand Sequence

The third sequence includes the Upper Bab Member which forms a wedge of basin restricted carbonates (Figure 3). This sequence is again basin restricted.

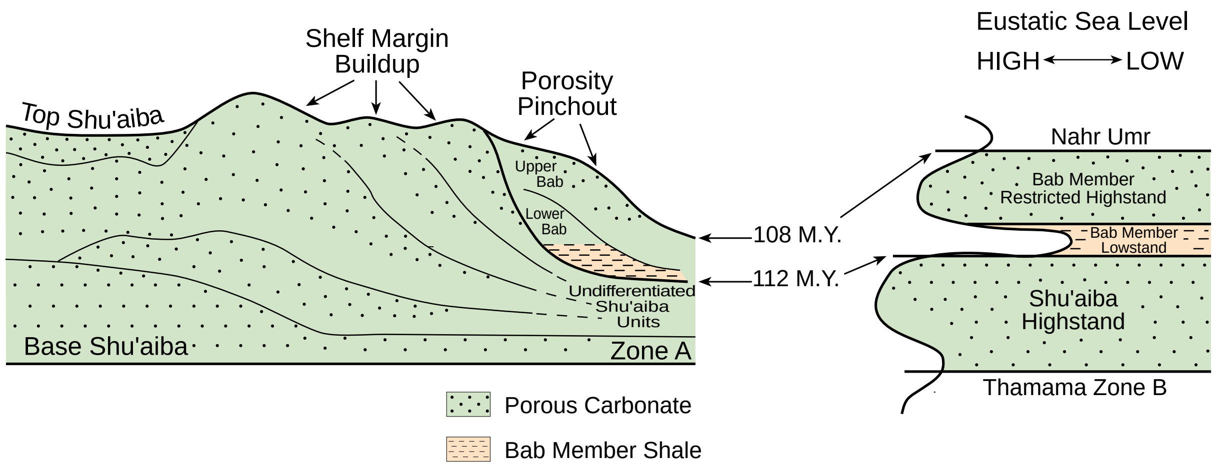


Figure 3: Sequence stratigraphy of the Shu'aiba Formation in Onshore Abu Dhabi. Stratigraphic plays are (1) Shelf Margin Buildups consisting of thick porous reef trends with stratigraphic relief equivalent to less porous carbonates, both shelfward and basinward; and (2) porosity pinchouts in the Shu'aiba Bab Member, basinward and/or shelfward (Abou-Choucha and Ennadi, 1990).

PLAY CONCEPTS

There are two main stratigraphic play concepts related to the Shu'aiba Formation (Figure 3; Abou-Choucha and Ennadi, 1990).

(1) The primary play concept is Shu'aiba prograding highstand multiple reef trends (Shelf Margin Buildups in Figure 3). These trends have stratigraphic relief and contain porous, shallow-water carbonates. Adjacent carbonates, both shelfward and basinward, are less porous. In the strike direction of the trend, structural development is required to provide closure.

(2) The secondary play concept is associated with the basinward and shelfward pinchout of porosity within the upper Bab Member (Figure 3). Again structural development is required to provide closure along the strike trend.

PROCESSING TECHNIQUE

Database

The data presented was initially believed to represent the Shu'aiba shelfal area with shallow water carbonates. Seismic data however indicated an anomalous thickening of the Shu'aiba interval. The internal reflection pattern is different from the typical parallel type and appears mounded and progradational. A grid of several seismic lines acquired in the late 1980s and additional data from 1993 were used for a detailed investigation of the anomaly. The newer seismic data have 160-fold coverage and a 2 ms sample-rate.

Phase A: Time Domain Processing

All the available data were processed in a state-of-the-art manner including Dip Moveout Out (DMO). The final result was the time migration which was zero-phased using sonic and density logs of three wells in the area (Figures 4 and 5). The processing was closely coordinated with the interpreters to insure adequate stratigraphic insight (e.g. optimum lateral and vertical resolution). Following the final time migration, L-1-Decon (12-70 Hz, Figure 6) and Born Inversion (Figure 7) were applied to support the stratigraphic interpretation for two seismic lines.

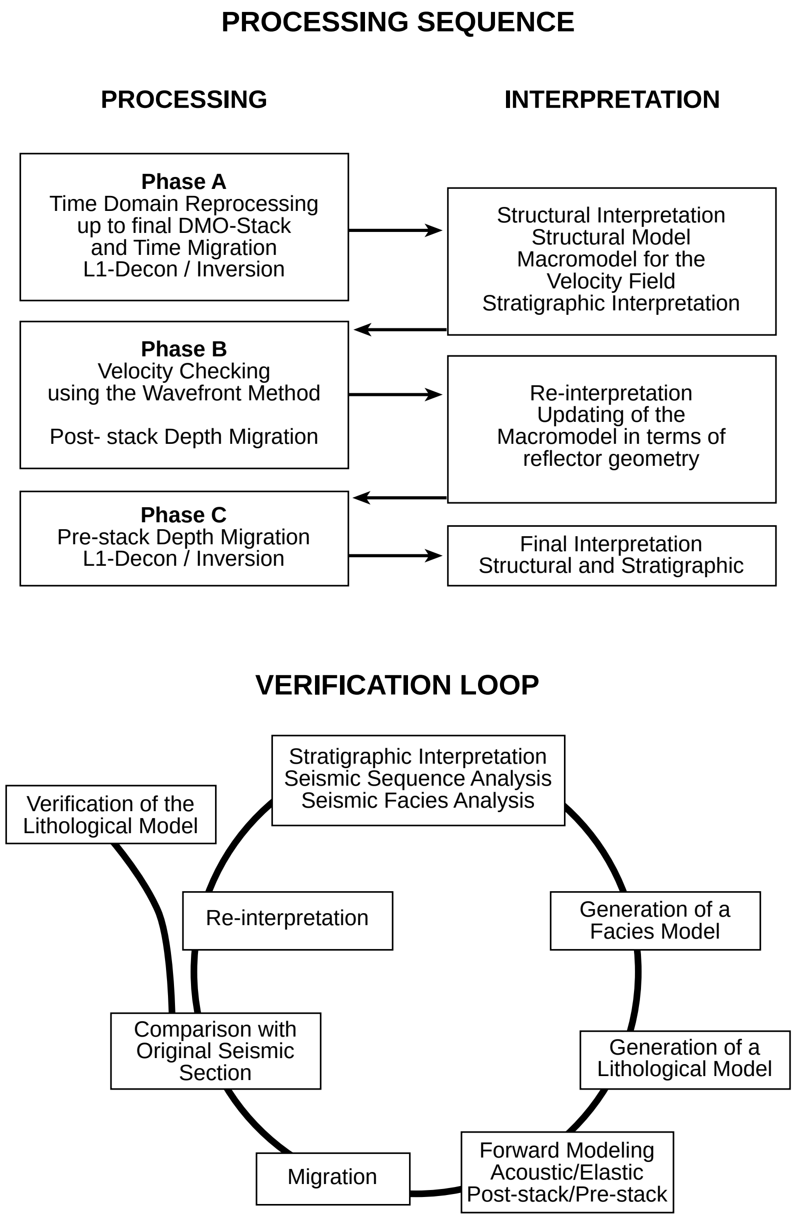


Figure 4: Project Flowchart.

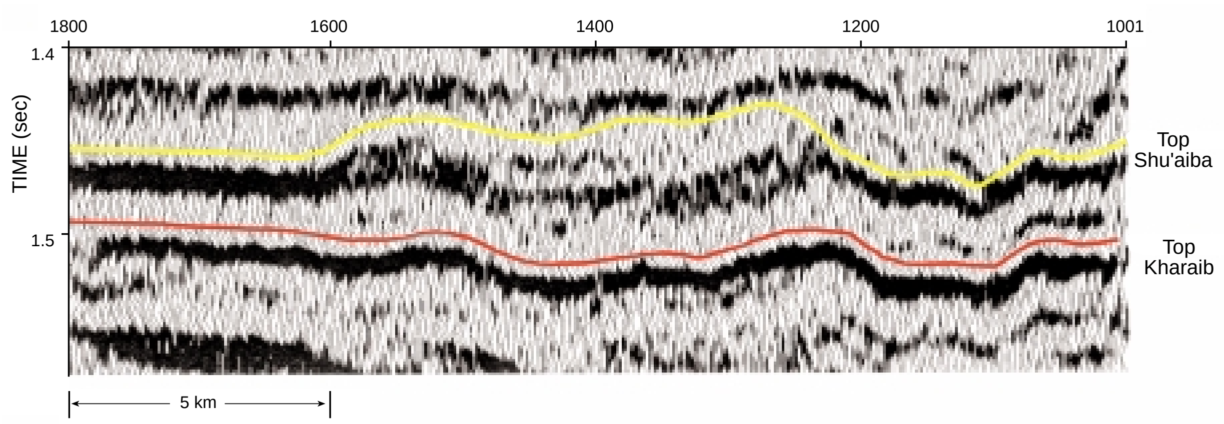


Figure 5: Phase A: Time domain processing, time migration and structural interpretation of Top and Base Shu'aiba.

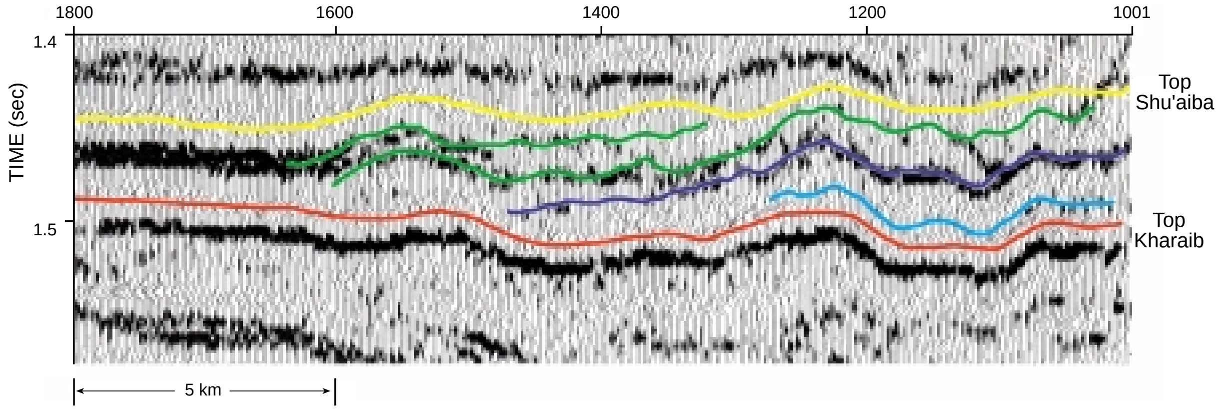


Figure 6: Phase A: Time domain processing, time migration - L-1-Decon and structural interpretation of Top and Base Shu'aiba with Shu'aiba progradational cycles.

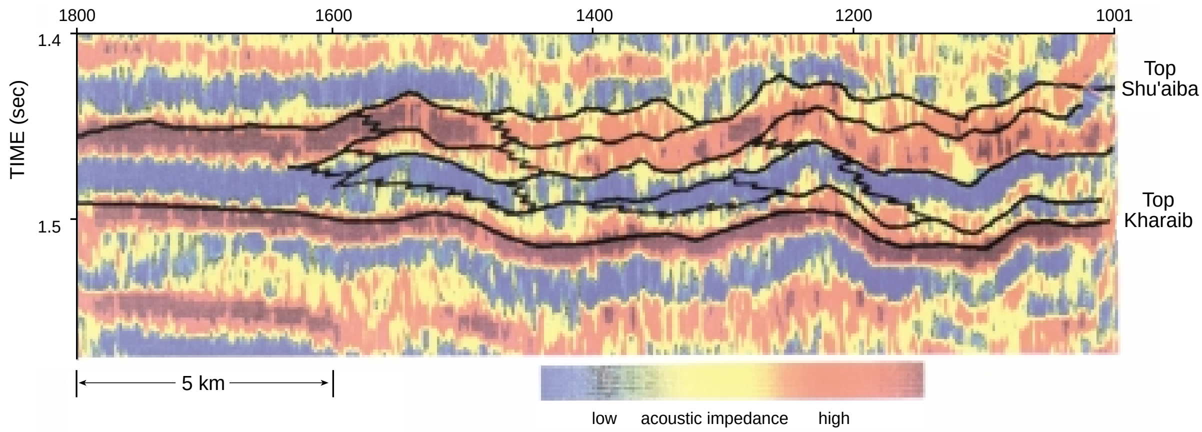


Figure 7: Phase A: Time domain processing, time migration - Inversion and structural interpretation of Top and Base Shu'aiba with Shu'aiba progradational cycles.

The procedures described in the following discussion were applied to only one seismic line. The final time migration was structurally interpreted in order to establish a macro model for the velocity field. Overall eleven markers were picked and a first estimate of the velocity field was established. In general, the initial field can be either interval- or average-velocity-fields or based on velocity laws (linear, Faust). In the present example interval velocities were used based on well data.

Phase B: Post-stack Depth Domain Processing

In this phase the velocity field was checked and updated using the wavefront method (Marschall, 1991). This procedure uses pre-stack travel-times from constant offset sections to verify and correct the velocity field. The travel-times are depth migrated by event-based raytracing. At least two offsets with corresponding travel-times per CMP (Common Midpoint) are required. Due to the relatively uniform lithology and simple geological settings, the checking and updating procedure was restricted to three major interfaces; namely: Top Simsima, Top Kharaib and Top Upper Araej.

The resulting velocity field is correct for these interfaces. The intermediate markers within the three intervals are updated using the correction factor as identified for the checked interfaces. The refraction from the intermediate interfaces, however, is still taken into account. The final model is therefore consistent with measured offsets and travel-times. For example, suppose a velocity field $v(z)=v_0+kz$ is used as the initial velocity field for an interval. Then after the update, the final data-consistent velocity field is again $v(x,y,z) = v_0(x,y)+kz$.

The final macro model is then used for post-stack depth migration. The interpreters again review the final reflector geometry for all interfaces within the model.

Phase C: Pre-stack Depth Domain Processing

The final macro model is the input for pre-stack depth migration. Image gathers are generated and displayed for final quality control. In addition, the advantages of pre-stack depth migration over standard time migration with respect to a selected target window are now examined.

The depth section was converted into time by applying the given velocity field so that it could be tied to the remaining seismic grid. This allows the final processing steps involving L-1-Decon (12-70 Hz, Figure 8) followed by Born Inversion (Figure 9).

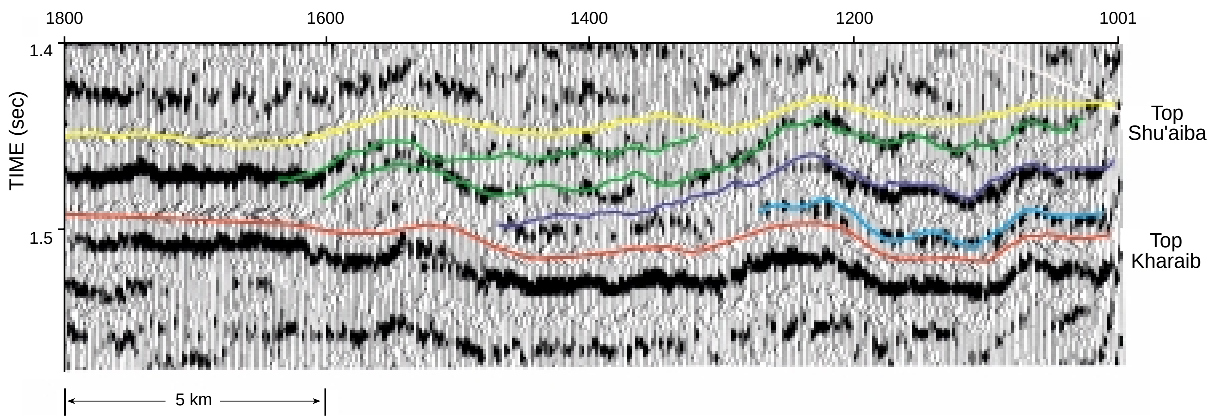


Figure 8: Phase C: Pre-stack depth domain processing, time converted pre-stack depth migration - L-1-Decon and structural interpretation of Top and Base Shu'aiba with Shu'aiba progradational cycles.

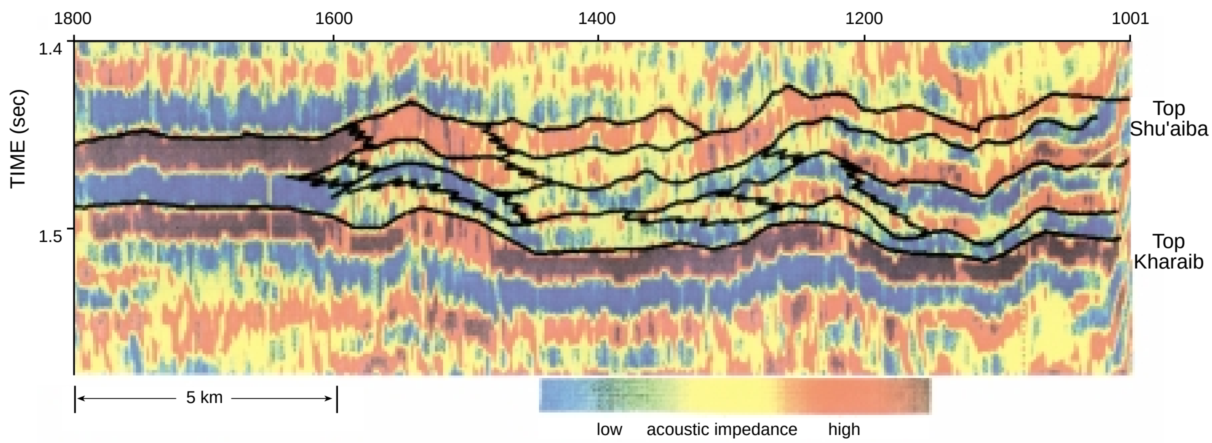


Figure 9: Phase C: Pre-stack depth domain processing, time converted pre-stack depth migration - Inversion and structural interpretation of Top and Base Shu'aiba with Shu'aiba progradational cycles.

STRUCTURAL INTERPRETATION

The structural interpretation was based on time migrated seismic data (phase A - processing, Figure 4) and subsequent post-stack depth migration. The interpretation had to be locally modified on the pre-stack depth migrated seismic line due to the irregular Shu'aiba surface. The image of the Shu'aiba reflection was improved in terms of lateral and vertical resolution (Figures 5 and 8). As the structural closures are generally very low relief, these modifications have a major impact on their shape and size.

The time-migrated data was depth-converted (image-ray migration) with the updated velocity field determined by the checking procedure in Phase B (i.e. the control points from velocity checking were gridded and used for generation of interval velocity maps). In the case of low relief structures the exact velocity field plays an essential role in defining the exact size and relief of the structure. It also affects the imaging of the target zone below an irregular interface.

STRATIGRAPHIC INTERPRETATION

The stratigraphic interpretation consists of five steps: (1) seismic sequence analysis; (2) seismic facies analysis; (3) generation of seismic facies maps; (4) generation of a combined facies / geological model; and (5) generation of a lithological model which is verified with forward modeling.

The stratigraphic interpretation identified four progradational cycles within the target interval (Figure 10). This result was supported by two additional seismic lines which were processed with high resolution L-1-Deconvolution, followed by inversion.

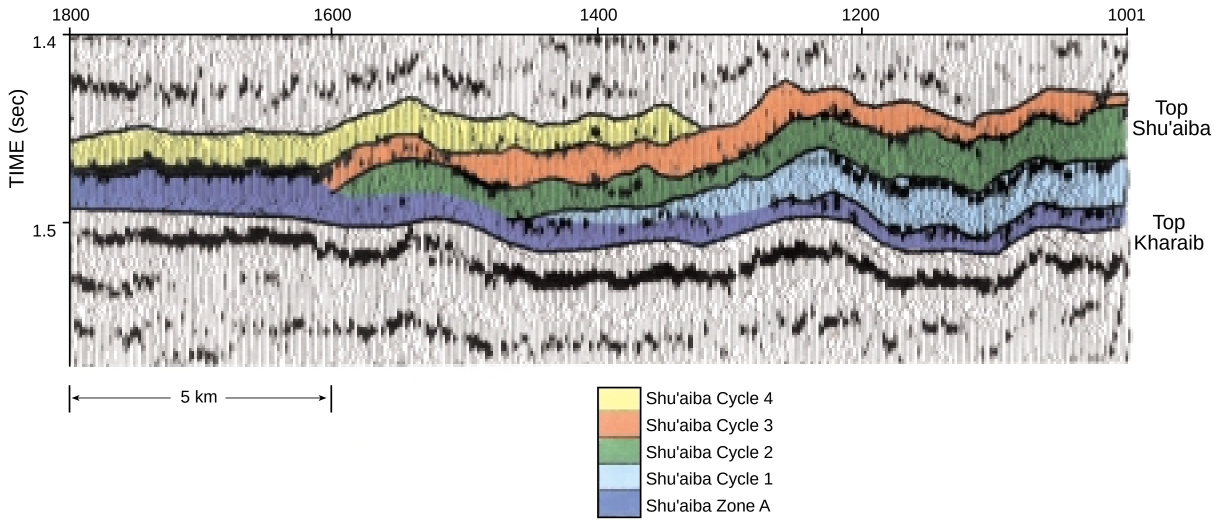


Figure 10: Phase C: Time converted pre-stack depth migration with Shu'aiba cycles.

Within these cycles a lateral variation of the reflection strength and configuration (Figure 11) was recognized as four seismic facies belts. These are: (1) conformable and parallel layering of reflections; (2) mounded reflection pattern; (3) transition from mounded into parallel reflection pattern; and (4) parallel reflection pattern. These seismic facies belts were interpreted as corresponding to: (1) low energy shallow water carbonate facies of shelfal / lagoonal environment; (2) higher energy shoal deposits; (3) slope deposits; and (4) low energy deeper water deposits.

The facies belts show northward progradation. Regional geologic considerations indicate that the area is located in a low energy shelfal environment. Therefore the series are interpreted either as older shelf margin settings or as an isolated high energy shoal area.

The resulting model was cross-checked with the time converted pre-stack depth migration (Figure 8) and subsequent inversion (Figure 9). The improved vertical and lateral resolution support this model. At the end of the stratigraphic interpretation an additional quality control-step is the forward modeling of the resulting lithomodel.

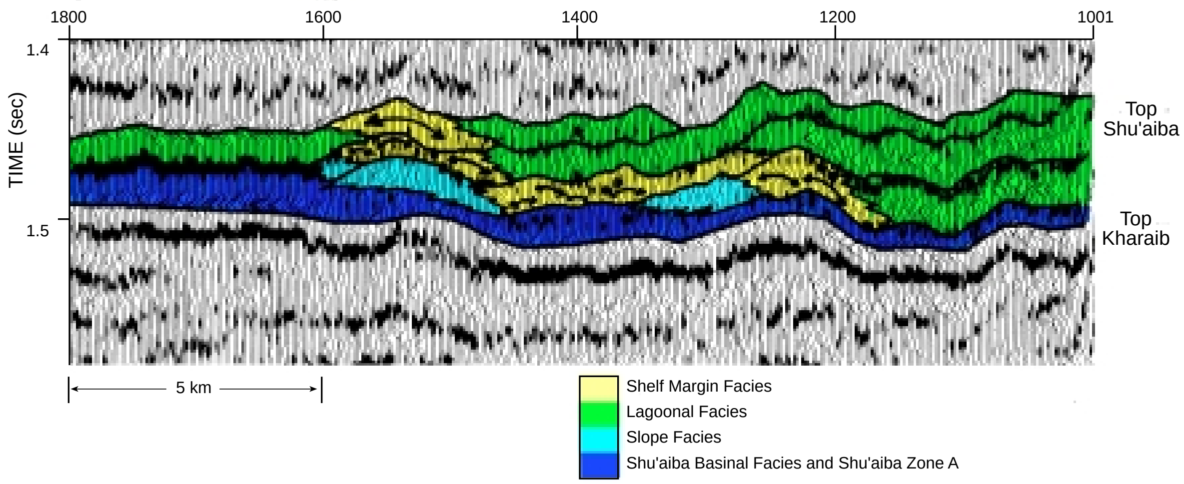


Figure 11: Phase C: Time converted pre-stack depth migration with seismic facies analysis of the Shu'aiba cycles.

VERIFICATION LOOP

In the verification loop, the seismic response of the lithological model is compared to the original seismic data. This comparison identifies discrepancies which are used to update the model until an optimum fit is obtained. This process is limited by the bandwidth of the seismic data.

In general the steps are: (1) generation of a lithological/impedance model; (2) forward modeling, using acoustic or elastic in either pre-stack or post-stack modes; (3) migration, time or depth, depending on actual application; (4) comparison with original seismic section (similarly to repeated 3-D seismic or 4-D seismic); and (5) re-interpretation or validation of the model.

Essential inputs for forward modeling are velocity and density values (i.e. impedances) for various litho-units derived from core and log data. Cross-plots allow for correlation of velocity and porosity for different litho-units (Figure 12). The porosities were derived from neutron measurements. These cause a shift of litho-unit 7 (shale) to high porosities due to high neutron readings in shaly intervals which should be tight.

Based on the bandwidth of the data 9 litho-units were identified (Figure 13).

Table 1
Litho-Units for Forward Modeling (Fischer et al., 1994)

Lithounit	Lithology	Paleo-Environment	Velocity [m/s]	Density (avg.)[g/cm^3]	Porosity (avg.)[%]
1	bioclastic packstone/grainstone	reef	4,233	2.300	20
2	pelloidal packstone/grainstone	reef debris	3,907	2.275	23.5
3	packstone	upper/middle slope	3,763	2.425	25.5
4	packstone/wackestone	middle/lower slope	4,323	2.300	19
5	mudstone	lower slope-basin/lagoon	5,166	2.650	5.5
6	grainstone/packstone/ wackestone/mudstone	mixture	3,615	2.450	
6A	grainstone/packstone/ wackestone/mudstone	mixture, upper ramp	3,615	2.450	21.5
6B	mudstone/wackestone packstone/grainstone	mixture, lower ramp	4,997	2.475	9
7	shale	basin/transgressive systems tract	3,175	2.500	

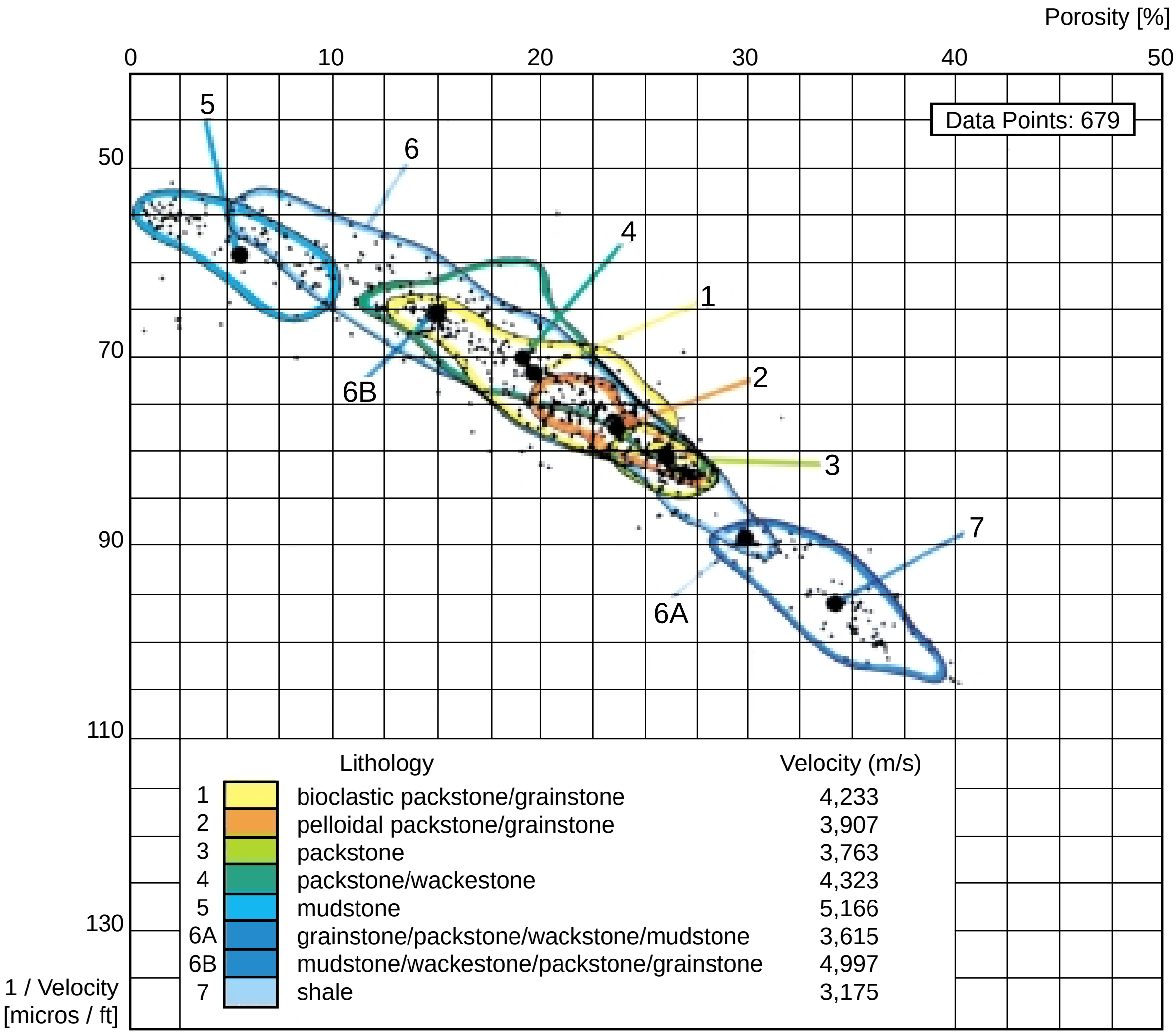
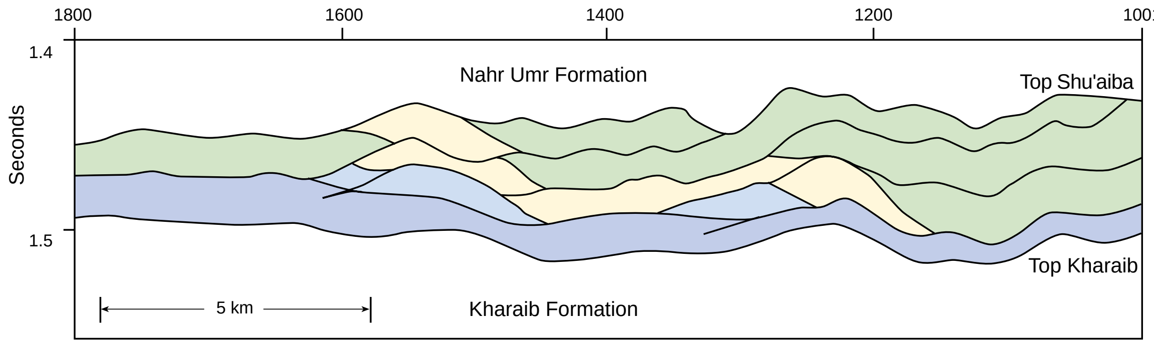
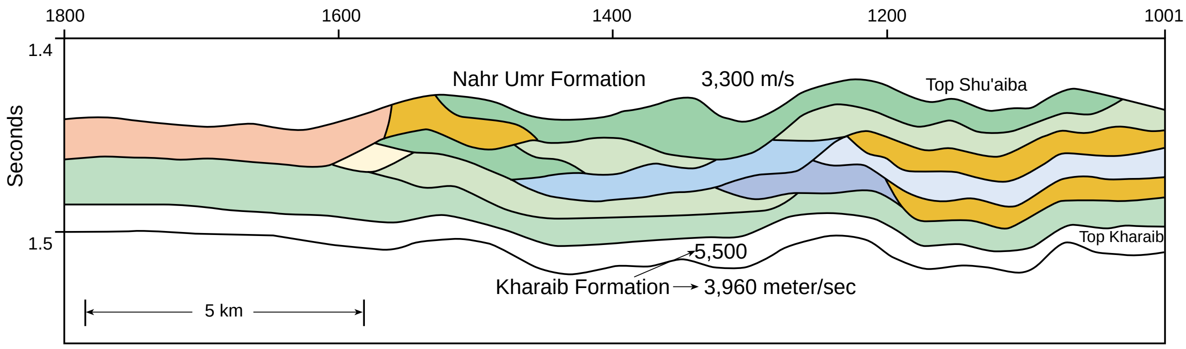


Figure 12: Cross-plot acoustic slowness versus porosity for the Shu'aiba Formation.



Lithology	Depositional Environment	Velocity Range (meter/sec)	Porosity Range (%)
packstone	Lagoon, cycle 4	5,000	9
packstone/wackestone	Lagoon, cycles 1-3	4,300 4,100 4,000 3,900	18 21 22 24
bioclastic packstone/grainstone, pelloidal packstone/grainstone	Shelfmargin/Shoal	4,300 4,100 3,800 3,700	18 21 26 27
packstone/wackestone packstone	Slope	4,200 4,000	19 22
grainstone/packstone/ wackestone/mudstone	Basin / Zone A	4,170	low

Figure 13: Facies model for the Shu'aiba Formation.



Lithology	Depositional Environment	Velocity Range (meter/sec)	Porosity Range (%)
packstone/wackestone	Lagoon, cycle 4	5,000	9
packstone/wackestone	Lagoon, cycles 1-3	4,300	18
		4,100	21
		4,000	22
		3,900	24
bioclastic packstone/grainstone, pelloidal packstone/grainstone	Shelfmargin/Shoal	4,300	18
		4,100	21
		3,800	26
		3,700	27
packstone/wackestone packstone	Slope	4,200	19
		4,000	22
grainstone/packstone/ wackestone/mudstone	Basin / Zone A	4,170	low

Figure 14: Lithological/Velocity model for the Shu'aiba Formation.

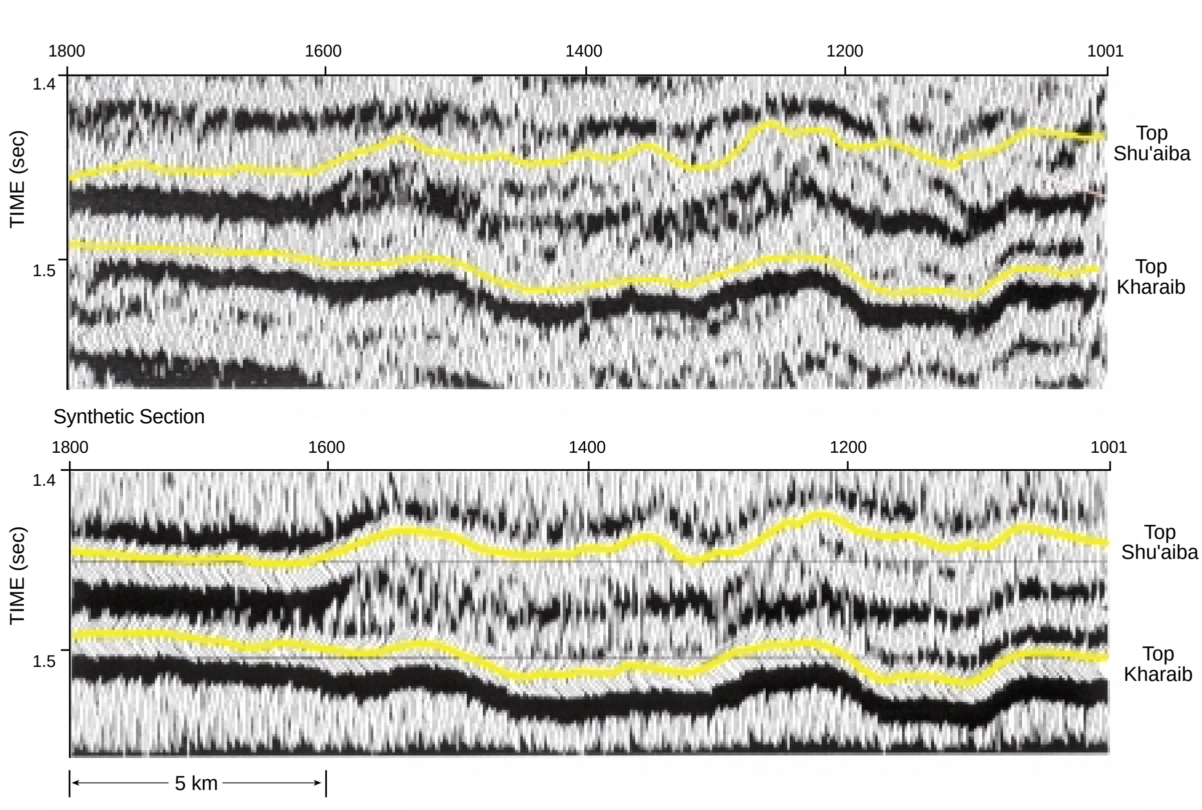


Figure 15: Comparison of original seismic section (upper section) and result of normal incidence forward modeling (lower section).

Based on the facies model (Figure 13) of the four progradational Shu'aiba cycles a lithological model (Figure 14) was derived and forward modeled. The first quality control-step was a normal incidence forward modeling (Huygen-Fresnel method in ISPoo3, Sattlegger GmbH) of the whole section for the target level (Figure 15). This resulted in an overall good match with the original seismic data. In the next step, a part of the section was modeled using a 4 by 4 meter grid of the model with the "acoustic/post-stack exploding reflector" method. Again a good match with the original data was achieved validating the model.

For 3-D data the final product would be impedance maps of the reservoir. In this case the 3-D acquisition geometry should be designed for the specific target (Marschall, 1996).

CONCLUDING REMARKS

The close cooperation between processors and interpreters resulted in a general improvement of the results which decreased the exploration risk. In particular the accurate definition of the velocity field increased the confidence in delineating the extent and shape of low relief structures in the depth domain.

Pre-stack depth migration optimized the image of the Shu'aiba reflection. It also improved the reflection's continuity, as well as the vertical and lateral resolution of its internal reflections. This results in improved confidence in the structural and stratigraphic interpretation and the extent and shape of low relief structures. Ultimately, 3-D seismic data would yield the most detailed impedance map of the target horizon.

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