Depth Imaging Sub-salt Structures: A Case Study in the Midyan Peninsula (Red Sea)

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ABSTRACT

In the Midyan Peninsula (onshore northern Red Sea, Saudi Arabia), the current prospective oil and gas exploration targets are sub-salt structures. In this region, conventional time-migrated seismic sections are distorted due to the presence of salt diapirs, faults, and related lateral velocity variations. As demonstrated in other sub-salt prospects (North Sea, Gulf of Suez, and Gulf of Mexico), pre-stack depth migration can remove these distortions and accurately focus the structural image. Depth migration, however, requires a model which includes both lateral and vertical velocity variations to compensate for ray bending. Building such a velocity model is an iterative process which involves integration of various time/depth processing and interpretation skills. A 2-D seismic line, crossing various extensional structures in the dip direction, is used to illustrate these depth-imaging techniques. At the location of the sub-salt prospect, the depth image is improved and the lateral position of the main fault is shifted by 345 meters. The resulting structural model has refined the target definition and well position. This imaging approach is compared with the different steps of the seismic processing/interpretation flow.

INTRODUCTION

In most of Saudi Arabia the strata are gently dipping at less than a few degrees and conventional time processing produces well-focused seismic images. The seismic imaging problems in such low dip areas are related to the interference of noise and multiples with the primary reflections, and to the distortion of these reflections by near-surface heterogeneities. In the northern Red Sea area (Figures 1 and 2), however, the sub-surface structures are complex due to Miocene rifting and salt diapirism (Mitchell et al., 1992). In such conditions, strong lateral velocity variations, related to lithology contrasts between steeply-dipping layers, bend the seismic rays and distort the sub-surface image.

Sub-salt structures are prospective oil and gas targets in the Midyan Peninsula (Figure 1) in northwestern Saudi Arabia. Such targets require the more sophisticated approach of depth migration to seismic imaging rather than conventional time-migration. Time migration assumes regularly curved rays from the surface (i.e. ray propagation through a fine layered horizontal medium), because it uses a unique Root Mean Square Velocity (VRMS(t)) value down to each reflection point. In contrast, depth migration takes into account a more realistic ray path including refraction across dipping velocity contrasts according to Snell’s Law (Figure 3). The difference between time and depth migrations increases therefore in proportion to the dip and the velocity contrast across geological horizons. Although depth migration is a computer intensive approach, particularly when it is performed in 3-D or in the pre-stack domain, or both, it can produce a better image due to correct lateral positioning, provided that the velocity model is accurate.

Migration in the depth domain has been available since the early 1980s, but the lack of computer power and procedures to build an accurate velocity model prevented this method from being implemented in production. The model includes the depth of the main velocity contrasts and the interval velocity variations between them. Therefore, preliminary knowledge of the sub-surface is required to produce a seismic image. To solve this problem, sophisticated techniques have been developed since the beginning of the 1990s which require:

1. easy integration of the different seismic domains (pre- and post-stack, time and depth, and corresponding Stacking Velocity (VSTACK) and Interval Velocity (VINT));
2. powerful workstations to perform iterative depth migrations and velocity analyses; and
3. experienced geoscientists to process and interpret seismic data.
Figure 1: The Midyan Peninsula is located at the junction of the Red Sea, Gulf of Suez, and Gulf of Aqaba. The Red Sea and Gulf of Suez are rift basins initiated during Late Oligocene to Early Miocene extension, whereas the Gulf of Aqaba strike-slip movement started only in the Miocene. Oil and gas fields are found in sedimentary grabens between the uplifted basement highs.

Figure 2: Isobaths (in meters below MSL) of the top reservoir (H₄) in the vicinity of the Midyan oil and gas fields. Also shown are the location of the seismic line (Figure 7), onshore exploration wells, and deep extensional faults (Johnson et al., 1995). The part of the seismic line that crosses the “New Prospect” is shown in Figures 8 to 10.
These methodologies are now mature, and software and computer resources are available to implement such an interpretive processing approach within a reasonable time-schedule (Schultz and LeNoble, 1996; Bloor et al., 1997; Fagin, 1998; Jones et al., 1998).

In this paper, we compare the structure of the Midyan Peninsula with some classic sub-salt plays. After a brief review of the sub-surface geology, we demonstrate the improvement of sub-salt imaging achieved in the depth domain. A 2-D seismic section (see Figure 3) which crosses extensional faulted structures around the Midyan field is used in the building of a velocity model.

**SUB-SALT IMAGING**

Imaging salt structures has long been one of the main challenges faced by geophysicists (Bloor et al., 1998; Marschall, 1998). Salt diapirs are major targets for petroleum exploration, as they trap hydrocarbons above, along the side, and below the salt body (Figure 4). Above a diapir, anticlinal structures, radial faults or collapse structures provide many possibilities to trap hydrocarbons. Alongside a diapir, dipping layers are well-known targets when truncated by a salt body. Below the salt, which acts as a layer of discontinuity, a totally different structural style may occur, that generates new traps with the salt acting as a top seal. In many salt basins, current exploration efforts are focused on new sub-salt trends (Ward et al., 1994). Some classic sub-salt plays, such as Gulf of Mexico, Gulf of Suez, and North Sea, are reviewed so as to understand better the complexity of the Midyan Peninsula.

**Salt Imaging in the Gulf of Mexico**

In the Gulf of Mexico, pioneering exploration concentrated on structures above the diapirs, as these are the shallowest and the easiest to image. Drilling pinch-outs against the steep flank of a diapir proved to be more challenging because the salt wall needs to be located correctly. If the well is placed too far down-dip the hydrocarbons are missed, and if it is too close to the flank, the salt is encountered.

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**Figure 3:** Time migration assumes propagation of regularly curved rays from the surface, which corresponds to the use of a unique $V_{RMS}(t)$ value down to each Common Mid Point (CMP). If a velocity variation occurs along a dipping interface (brown dashed line), the Common Mid Point is mis-positioned with respect to the location of the actual Reflection Point (RP) defined by the image ray. Depth migration takes into account the refraction along this lateral velocity variation (between $V'_{INT}$ and $V''_{INT}$) and the Common Reflection Point (CRP) is correctly positioned (vertical ray) with respect to the location of the Mid Point (MP).
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(Figure 4). For a CMP beside the flank of a diapir, rays at near offsets propagate in the low velocity sediments, while the far offsets cross the high velocity salt body. The Dix’s hyperbolic moveout assumption is no longer valid and the stack is not a zero-offset section. Thus, pre-stack migration is required to image and correctly position the steep flanks. However, seismic imaging will be successful only if the acquisition is properly designed. Due to structural complexity, it is necessary to use larger offsets (of up to 6 or 8 kilometers (km)) to reach a correct illumination of the whole salt mass. Also the propagation of the rays is not confined in a 2-D plane containing source and receivers, which makes the use of 3-D seismic and 3-D migration mandatory to focus energy and to avoid interferences with out-of-plane reflections.

In today’s production processing of the very large 3-D non-exclusive surveys acquired in the Gulf of Mexico, steep flank imaging is implemented in the time domain by steep-dip, 3-D pre-stack migration which requires only a smooth $V_{\text{RMS}}$ velocity model. For the specific conditions in the Gulf of Mexico (velocity gradient in sediments, extensive salt sheets), particular ray paths named “turning waves” are also used (Hale et al., 1991), making it possible to image the vertical flanks of diapirs and the base of overhanging salt masses.

Figure 4: Diapirs are major features for petroleum exploration, as they generate traps above, alongside, and below the salt body. During early exploration, structures above the diapirs are the easiest to image and discover. During later exploration, pinch-outs on the flanks of the diapirs are explored. These require accurate positioning of the well. Sub-salt exploration is a recent phenomenon in the late exploration of mature basins. It requires careful imaging before the drilling of deep wells.
Interest in sub-salt imaging in the Gulf of Mexico was fostered by the wells "Mickey"-1 by Exxon in 1990 and "Mahogany"-1 by Phillips in 1993 which first demonstrated the existence of sedimentary layers with significant sandstone reservoirs below the salt (Montgomery and Moore, 1997). Since 60% of the outer continental shelf and upper slope in the northern Gulf of Mexico is covered by allochthonous salt, a major new exploration frontier was opened, with the benefit of existing production infrastructures. At the same time, pre-stack depth migration (2-D and 3-D) and the corresponding model building tools became available for the industry. These proved to be essential for targeting this new trend (Ratcliff and Weber, 1997). By the end of 1998, 46 sub-salt prospects had been drilled (DeLuca, 1999). Most of these were targeted using depth-migrated seismic data.

In practice sub-salt imaging in the Gulf of Mexico is relatively simple, since the velocity of the salt (constant) and of the clastic sediments (a linear function, \( V = V_0 + k \times Z \), where \( Z \) is depth) are well known. The model building task involves the definition of the complex shape of the allochthonous salt body (Ratcliff et al., 1994) within a relatively undeformed post-rift Neogene sedimentary pile (Figure 5). New approaches in the Gulf of Mexico include the use of Shear Waves, converted at the salt interface (PSS Waves), to image the sub-salt geometry from three-component geophones lying on the sea floor (Kendall et al., 1998).

**Sub-salt Imaging in the Gulf of Suez and the North Sea**

More challenging are sub-salt prospects in the Gulf of Suez, where the combination of strong internal multiples with complex pre- and syn-rift structures beneath the salt, makes it difficult to build an accurate velocity model (Western and Ball, 1992). In this area, 3-D depth migration and multiple attenuation are necessary for interpreting structures and targeting wells, and they are now standard processing steps (Dolson et al., 1997).

An increasing degree of complexity is encountered in the North Sea, as the salt deposit is older (Zechstein Series of Late Permian age, Figure 5). Target layers along the steep salt flanks were affected by both pre-rift and syn-rift deformations, while the sub-salt gas reservoirs were faulted during the Hercynian Orogeny. Strong velocity gradients, like the one in the Cretaceous Chalk, combined with the interaction between faulting and diapirism make it very difficult to minimize the errors in the velocity model above the sub-salt prospects (Négron et al., 1997). The main challenge is therefore to define the correct lateral and vertical position of sub-salt structures to target a well.

From a tectonic point of view, the structural style of the Midyan Peninsula is similar to the North Sea where salt diapirs are also associated with extensional faulting. However, movements were much younger and occurred in the late Miocene to Quaternary (Figure 5). Sub-salt structures also correspond to faulted basement blocks with a completely different configuration from the overburden, with the salt acting as a décollement level.

**GEOLOGICAL SETTING OF THE MIDYAN PENINSULA**

The Midyan Peninsula formed during two tectonic phases: (1) Late Oligocene-early Miocene Red Sea rifting; and (2) Miocene-Recent strike-slip movement along the Aqaba-Levant Transform Fault. This evolution differs from the Gulf of Suez, where rifting ceased in the middle Miocene as indicated by the salt (South Gharib Formation) which seals the faults and marks the onset of regional (thermal) subsidence. At that time, the opening of the Red Sea started to be accommodated to the north by the Aqaba-Levant Transform Fault which acted as a new boundary between the Arabian and Levant Plates (Bayer et al., 1988).

The Midyan Peninsula is strongly affected by the sinistral strike-slip motion on the Aqaba-Levant Fault, which induced compressional features along the Gulf of Aqaba coast (Bayer et al., 1987), whereas the central and southern parts of the Peninsula (the triangular-shaped Ifal basin) were mainly affected by extensional pull-apart tectonics. As a result, the basement is highly faulted and its total offset between the Hajar Range to the north (up to 2,580 m elevation at Jabal Al-Lawz) and the South Midyan trough (as much as 3,500 m deep from seismic data (Figure 2)) may reach 6,000 m. The Ifal basin is filled with thick coarse- to fine-grained clastics, and older carbonates and evaporites.
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Figure 5: Sub-salt plays corresponding to four mature basins are represented with respect to the chronology of the depositions in an extensional basin (pre-, syn- and post-rift formations). Although the stratigraphy of the Gulf of Suez and of the Midyan Peninsula are similar, their tectonic settings are different. The North Sea has some similarities with Midyan. The Gulf of Mexico is completely different due to allochthonous salt sheets.
Petroleum Geology

Nine exploration wells have tested prospects in the Midyan region (six of them are located in Figure 2). In 1969, three offshore wells evaluated structures and encountered commercial quantities of gas with condensate (Ahmed, 1972). Burqan-1 bottomed in granite at 2,900 m after having encountered four gas-bearing lower Miocene sandstones. Burqan-2 tested 600 barrels of condensate per day (bcpd) and some gas. Yuba-1 was drilled on a different structure and did not find any hydrocarbons (Figure 1). In 1992, Saudi Aramco renewed exploration onshore on the Midyan Peninsula. As reported in the August 1993 issue of World Oil, three wells tested commercial quantities of condensate and wet gas (1,300 bcpd and 45 million cubic feet per day respectively at Midyan-1), and sweet crude (2,300 bpd of 39°API oil at Midyan-3) at a depth of about 2,300 m. Finally, by the end of 1997, three more wells were drilled to the southwest of Midyan field and tested new structures with variable results.

In the Midyan region, the source rock was identified as the lower Miocene clastic formation (Burqan Formation; see Figure 6) which is deeply buried and mature in the South Midyan Trough (Figure 2), between the Midyan and the Burqan fields (Alsharhan and Salah, 1997). The oil expulsion occurred from late Miocene to Quaternary times (Cole et al., 1995), after deposition of the evaporites, which act as a major seal. Onshore, the reservoir corresponds to carbonates at the top of the Jabal Kibrit formation (lower Miocene) or at the base of the Kial formation (middle Miocene).

Stratigraphy

Due to the tectonic rejuvenation and to the lack of vegetation, outcrops in the Midyan Peninsula are of excellent quality for studying the lithostratigraphy of the Neogene formations (Hughes et al., this issue). Fossils recovered from the exploration wells also provided new biostratigraphic constraints for all surface and sub-surface stratigraphic studies in the Ifal basin (Hughes and Filatoff, 1995). Using Vertical Seismic Profiles (VSP) and synthetic seismograms, the formation boundaries were identified and picked on the time-migrated seismic sections (Figure 7), and the following stratigraphic and velocity units were described in the Ifal basin (Figure 6):

1. Post-salt Series consists of upper Miocene to Quaternary clastics (Ghawwas and Lisan formations) for which velocity increases with depth, due to the compaction ($V = 2,000 \text{ m/s} + 0.5 \times Z$). These tilted layers appear to be truncated by an erosional surface, buried under a level referred as a seismic Weathering Zone, $WZ (V = 1,400 \text{ m/s})$.
2. Middle Miocene Evaporites are predominantly salt (Mansiyah formation, $V = 4,300 \text{ m/s}$) interbeded with shale and anhydrite layers. The strong reflections at the base of the salt body (Figure 7) are related to these anhydrites (Kial formation, $V = 5,700 \text{ m/s}$).
3. Sub-salt Series consists of lower Miocene carbonates (Jabal Kibrit formation, $V = 4,700 \text{ m/s}$) and clastics (Burqan formation, $V = 3,900 \text{ m/s}$) which are highly-faulted, and the crystalline basement rocks (velocity up to 5,300 m/s). These rapid lateral and vertical lithologic variations make it difficult to correlate rock units and predict reservoir development. In particular, the velocity contrast at the top of the basement is very variable, due to its heterogeneity and weathering. This complicates the tracking of the seismic reflection from the base of the sub-salt sediments and the estimation of their thickness. This sub-salt section includes the main potential reservoirs and source rocks.

Structure

Even with the dense network of 2-D seismic sections available (spaced up to one kilometer apart), sub-surface structures may be difficult to map. Numerous out-of-plane events and velocity contrasts generated by faults and diapirs obscure and distort the seismic image. However, the selected 2-D line at the center of the Ifal basin is located away from the main basement faults and clearly displays representative extensional features (Figure 7). It is characterized by a good signal-to-noise ratio due to adequate acquisition parameters (split-spread, 120 fold coverage, 12.5 m between Common Mid Point (CMP) and 3,000 m maximum offset) and a gradual increase of velocity with depth.
Above the undulating reflection from the top of the salt (violet marker H3 in Figure 7), the clastic formations are highly deformed. On the right-hand side of Figure 7, these dip towards the northeast, in conformity with the northern flank of the diapir. Such a structure is identical to raft tectonics (Fox, 1998), and it could be due to gravity sliding towards the trough located above the Midyan field. This trough corresponds to the hanging-wall of a growth fault. It is filled with clastic rocks 2,000 m thick in a large roll-over anticline caused by differential subsidence. At least along this seismic line, all the Neogene deformations can be related to extension, which is in accordance with their syn-rift nature. Close to the surface, the truncation of strata by a sub-horizontal reflection (yellow marker H1) is interpreted as the base of the low-velocity seismic weathering zone. As the dipping Plio-Quaternary layers outcrop above this apparent unconformity, as evidenced by satellite images (Gardner et al., 1996), this yellow marker (Figure 7) is probably more of a diagenetic boundary than a stratigraphic one and may represent the water table.

Below the salt, strong seismic reflections mark the base (blue marker H4 in Figure 7) and the top of the anhydrite. This horizon is faulted and displays prominent pull-ups below the diapirs. Time deformations are principally due to the high velocity of the salt and anhydrite, compared with lower velocities in the clastics. Before identification of such paleo-highs as new prospects, it is necessary to compensate for lateral velocity variations by changing the vertical scale of the section from time to depth. Assuming the velocity model is known, this can be done by vertical time-to-depth conversion. This 1-D stretching, however, will not properly focus the seismic energy and accurately position the sub-salt reflections. Acting like an optical lens, diapirs bend the seismic rays and induce deviations. The only way to remove this effect is to define the velocity variations by building a velocity model and performing depth migration, which compensates for these ray-bending propagation effects.

**MIDYAN VELOCITY MODEL BUILDING**

Building a velocity model is a highly interpretive procedure and requires flexibility as it is data driven (Kessler et al., 1995; Kim et al., 1996; Bloor et al., 1997; Fagin, 1988; Jones et al., 1998). The velocity distribution in the sub-surface is summarized by layers separated by the main velocity contrasts (Figure 6). In each of these layers, a vertically constant interval velocity, or gradually increasing...
Figure 7: Post-stack time-migrated section (see position on Figure 2) used to pick horizons and to calibrate the seismic at the well location. This image is distorted due to lateral velocity variations, specially below the salt diapirs where the high amplitude reflections (anhydrite) are pulled up. The New Prospect frame displays the location of the section represented in Figures 8 to 10. $H_1$ to $H_5$ are reference horizons and FDP is the smooth surface elevation used as a datum (0.0 seconds two-way time).
instantaneous velocity (e.g. $V = V_0 + k x Z$), is used. First, an initial model is built by defining successively the velocity and the depth of each layer within an iterative top-down approach (Figures 8 and 9). The model is then refined by a global tomographic update (Figure 9) which provides the final velocity section used to perform the optimal pre-stack depth migration (Figure 10).

**Model Parameters**

The initial velocity model construction involves the identification of observable velocity contrasts from a well and their correlation with the main reflectors. Five interfaces (Figures 6 and 7) were selected corresponding to the base of the Weathering Zone (H1), the Top Miocene Unconformity within the clastics (H2), the top of the Salt (H3), the base of the Anhydrite (H4), and possibly the top of the Basement (H5). The high-velocity contrast between the salt and the top anhydrite, together with the contrast between the carbonates and the clastics in the sub-salt sequence, were not chosen because the anhydrite and carbonates are layers less than 100 m thick with a negligible ray-path distortion.

**Top-down Approach for Building the Initial Model**

The interval velocity and the depth of each layer were iteratively determined, beginning from a smooth topography (Floating Datum Plane) down to the target horizon (Figure 9). To define interval velocities, a horizon-based Coherency Inversion is used (Paradigm, 1998). In this approach, CMP ray-tracing is performed using different interval velocities ($V_{INT}$) in the layer above the selected interface. Amplitudes of the corresponding pre-stack reflections are summed along the various Normal Move Out (NMO) curves. On the semblance display, picking the maximum of coherence provides the value of $V_{INT}$

**Facing Page - Figure 9:** Different stages in building the initial depth-velocity model using a top-down approach from the weathering zone (WZ) to the basement. The corresponding procedure utilizes 12 different steps. The initial model resulting from this top-down approach using Coherency Inversion is compared with the final model derived by a global tomographic inversion. The variation in depth of the horizons increases from top salt to top basement, while the lateral variations in interval velocities become smoother from the initial to the final model.
INITIAL MODEL: Top-down Approach with Coherency Inversion

FINAL MODEL: Global Approach with Tomographic Inversion
Figure 10: Improvement of the depth image (from top down) is related to: (1) the use of pre-stack migration instead of post-stack (top and middle sections using the same initial model but different migrations); and (2) the accuracy of the velocity model (middle and bottom sections computed with the same migration but different models). The flatness and the fracturing of the anhydrite layers at the base of the salt are better restored on the image below, together with the picture of the fault plane delineating a tilted basement block.
For horizons below the salt, this technique becomes less accurate, since the ray-tracing is sensitive to all errors accumulated from the surface. Other sources of uncertainty are related to unresolved statics (Turki Al-Ruwaili, personal communication, 1998) and to possible out-of-plane reflections, which could affect the value or the quality of the coherence on the semblance display (Figure 11). For the deeper levels, these ray-tracing techniques must be replaced by pre-stack depth migration and depth gather analysis to update the velocity model.

Global Approach for Tuning the Final Model

To define the deeper part of the velocity model or to update the initial model, it is necessary to perform the analysis in the pre-stack depth domain which requires powerful workstations. First, travel time trajectories between shots and receivers are computed from ray-tracing through the velocity model. Using the first arrival time table, Kirchhoff pre-stack depth migration is performed to produce Common Reflection Point (CRP) depth gathers from preprocessed CMP time gathers. The flatness of the reflections in each CRP depth gather is then used to control the quality of the velocity model (Figure 12). At a fixed reference offset, a residual depth delay correction is defined for each horizon and at each CRP (Paradigm, 1998). These delays are the input for the tomographic inversion which globally updates the velocity and the depth for all horizons, while preserving the consistency with their zero-offset time ($T_o$).

In this example, two iterations of tomographic inversion were applied, each one requiring previous calculation of the CRP gathers (i.e. pre-stack depth migration). From the final model, a third pre-stack depth migration was performed to check the flatness of the reflections (i.e. a zero-delay value, Figure 12) and thus the accuracy of the velocity model. The final depth image (Figure 13) was then produced by muting and stacking these CRP gathers.

MIDYAN DEPTH MIGRATION

The comparison of the depth images produced at each step of the procedure offers another way to control the modifications of the velocity model. This requires a close collaboration with the interpreter.
Figure 12: The depth gathers (left track) are stacked to produce the final pre-stack depth-migrated section (right track). At the same time, the depth gathers provide a control of the accuracy of the velocity model. If velocity is correct, the reflections of the depth gathers are flat. If not, it is possible to compute a depth delay (middle track) to be input in the tomographic inversion to update the velocity model.
to define criteria for the evaluation of the improvement of the seismic image. In this example, there were favorable factors to make the assessment of the structural image relatively easy. The prospect is located below a large diapir which induces ray-bending (Figure 8). Modifications in the velocity distribution of the overburden strongly influence the image below the salt. At the target level, the focusing of the seismic energy along the fault plane, the continuity of the reflection at the top of the tilted block (H5), together with the flatness of the anhydrite (H4), are objective criteria to assess the improvement of the model (Figure 10).

The fastest way to produce a depth image from a velocity model and seismic data is to perform post-stack depth migration. This approach however has two major drawbacks:

1. it assumes that the stack is representative of the zero-offset reflectivity, which is never the case when lateral velocity variations occur due to a non-hyperbolic NMO (Marschall, 1998); and
2. it does not produce CRP depth gathers to quality control the accuracy of the model.

In this example, the comparison of the post-stack with the pre-stack depth images, computed from the same initial velocity model, shows clear differences which demonstrate the superiority of the pre-stack approach (Figure 10). The lack of the Dip Move Out (DMO) before stack probably enhanced the difference between these two migrated sections.

After picking the depth delays from the CRP’s along each horizon (i.e. the vertical shift to apply at a given reference offset to flatten the corresponding reflection), the velocity model was updated by global tomographic inversion. On the resulting final pre-stack depth image (Figure 10), the structures become clearer. The flatness of the reflections in the CRP’s (Figure 12) confirms the accuracy of the final velocity model. Nevertheless, this does not mean that the procedure applied is the only possible one, or that our final velocity model is the optimal. With a completely different methodology based on the Common Focus Point (CFP) technology and different parameters for the velocity model, Kelamis et al. (1998) obtained a very promising pre-stack depth migration of the same seismic line (outside the prospect location) and the corresponding flat CRP gathers.

In order to evaluate the overall improvement related to the depth imaging project, it is necessary to compare the final depth image with the conventional time migration. This requires the conversion of one of these two sections to the same domain as the other (both in time or depth). We chose to convert the time migration to the depth domain by using the vertical stretching provided by the final velocity model (Figure 13). The comparison demonstrates the clear advantage of depth imaging, which is not only a method to remove distortions due to velocity variations, but is also a technique to better focus the seismic energy by repositioning the reflections at their correct lateral position (i.e. the one provided by the image ray, Figure 3). Nevertheless, depth imaging is not a “magic box” to solve conventional processing problems. The best signal preservation and noise attenuation should be applied prior any depth imaging project as these issues, particularly multiples, will be detrimental when performing pre-stack depth migration.

On the final depth section (Figure 13), the fault plane is clearly imaged and the lateral displacement of its top by 345 m establishes the value of the depth imaging. This result is consistent with the one from a previous pre-stack depth migration across the coastal Al-Wajh basin (southeast of the Midyan Peninsula), from which the apex of the faulted structure, below a steep piercing diapir, shifted laterally by 1.2 km (Tsingas et al., 1994).

CONCLUSIONS

The Midyan area is representative of most sedimentary basins where structural complexity increases with depth (Figure 14). Here it is necessary to use a sophisticated processing route to image deep targets, particularly those located below the salt or in areas of complex faulting. In such circumstances, the efficiency of pre-stack depth migration, which relies on a velocity model to focus and image the reflectivity of complex structures, has been demonstrated. Focusing is improved because pre-stack...
Figure 13: A comparison of the position of the fault plane between the depth converted time-migration (above) and the final depth-migration (below) shows a lateral shift of 345 m. Assuming a well targeted at the top of the faulted block, it would have been mis-positioned with the time migration. Notice the much clearer structural image on the depth migration.
reflections from CRP depth gathers are flat (Figure 12), even if the ray-paths cross strong velocity contrasts along dipping interfaces. Due to a correct compensation of the propagation effects, these pre-stack events are also accurately positioned and their stack (i.e. the depth-migrated section) provides a correct image of the structure.

If we consider the processing and the interpretation of seismic data as a whole, different steps have to be completed and different velocity models have to be defined before one can accurately model the sub-surface (Figure 14). The focusing step corresponds to the processing done to get a zero-offset section (stack) when the seismic energy is concentrated by removing the effect of the offset. During the imaging step, the effect of the propagation is compensated by migration. Assuming there is no lateral velocity variations, this migration can be performed in the time domain. If the structure is gentle, as in most parts of Saudi Arabia, the corresponding time-migrated section correctly depicts the reflectivity of the sub-surface, assuming that all noise and near-surface effects have been removed. If dipping velocity contrasts bend the rays, as in the Red Sea area, a depth-migration is required to compensate for this distortion and to move the reflections to their proper lateral position. This depth imaging requires a highly interpretive velocity-model building phase, but it provides a better structural image, as demonstrated by our example.

Even if the result is in depth, we have to be aware that this depth does not represent the true vertical position of the reflections. This is related to the fact that the velocities used for focusing or imaging the seismic section are different from the true propagation velocities (such as sonic logs or check-shots). This is due to the heterogeneity and to the anisotropy of the sedimentary layers (Al-Chalabi, 1994; Al-Khalifa, 1997). If the seismic image is to fit the well markers and predict the correct depth in the interwell gap, a calibration of the velocity model should be done at the well locations and interpolated in between by using deterministic (e.g. cross-plots) or geostatistical (e.g. co-kriging) approaches. This depthing step is carried out by simple vertical stretching of each seismic trace (or each horizon) in accordance with the new calibrated velocity model. A geological depth model can then be derived which is consistent with well and seismic data. Obviously, integration of seismic data into a geological model requires strong interaction between processing and interpretation.
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