Impact of 3-D Seismic Surveys on Development of the Minagish Oolite Reservoirs, Minagish and Umm Gudair Fields, Kuwait

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ABSTRACT

The Kuwait Oil Company acquired 2-D and 3-D seismic data from 1996 to 1998 in a program that is believed to be one of the largest undertaken in the region. The 2-D surveys were used to define possible prospective areas, whereas the 3-D surveys have helped to increase the productivity of the existing oil fields. The 3-D surveys acquired over the Minagish and Umm Gudair fields in onshore West Kuwait were two of the first to be completed. The data is of excellent quality with high signal-to-noise ratios and stable phase and amplitude characteristics. The rapid 3-D interpretation was made possible by using state-of-the-art interpretation and visualization software, and has already had a considerable impact on the perception of the subsurface geology of the mainly Cretaceous reservoirs. In both fields, fault patterns were reliably defined for the first time and accurate depth maps resulted from careful attention to the near-surface static corrections, depth conversions and interpretations made from the superior 3-D imaging. These factors have enabled the accurate placement of wells. Acoustic impedance data is being used to define reservoir and aquifer porosity distribution. The impact of the 3-D surveys has enabled optimum development decisions to be made, thus helping to maximize Kuwait’s valuable oil resources.

INTRODUCTION

The Minagish and Umm Gudair oil fields are located in onshore West Kuwait (Figure 1). The Umm Gudair field straddles the border between Kuwait and the Kuwait-Saudi Arabia Partitioned Neutral Zone. Both fields have been producing for more than 30 years. The main production is from the Minagish Oolite reservoir of the Lower Cretaceous (Neocomian) Minagish Formation that is approximately equivalent to the Sulaiy Formation found elsewhere in the Gulf region. Secondary reservoirs are in Upper Cretaceous and Jurassic strata.

The Minagish Oolite is at a depth of about 2,440 m in the Umm Gudair field and at about 2,740 m in Minagish. The Oolite reservoir in both fields is approximately 122 m thick and consists of a series of interbedded grainstones, packstones and wackestones, as well as the true oolitic intervals that give the reservoir its name. The Oolite was deposited in a carbonate ramp setting (Al-Salem et al., 1998; Al-Eidan et al., 2000). The reservoir is of excellent quality with porosities ranging from 10 to 25 percent and permeabilities in the range of 1 mD to more than 1,000 mD. A tarmat occurs at the base of the oil column in the Minagish field (Al-Ajmi et al., 2001). Both fields were affected by phases of Jurassic, Cretaceous and late Tertiary structural development (Carmen, 1996), the main element of which was Late Cretaceous faulting.

Field development has been dominated by the drilling of crestal producer wells. Production rates are low. In the future, production rates will be much higher as more flank producer and injector wells are drilled and larger facilities are brought online. The use of 3-D seismic will be critical in defining optimum locations for these wells on the relatively undefined flanks. It will also provide details of depths, faults and the reservoir-quality envelope needed for the definition of reservoir simulation models.

The Kuwait Oil Company (KOC) had acquired between 1978 and 1987 more than 8,000 km of 2-D onshore seismic data (Mohammed and Al-Anzi, 1997). However, the coverage of the Minagish and Umm Gudair fields was very irregular with variable line spacing from 1 to 3 km and the data were sufficient to reveal only generalized structural and stratigraphic information. The 2-D image and
survey resolution proved to be inadequate for defining the often complex structure and stratigraphy of the Minagish and Umm Gudair fields. New 2-D and 3-D surveys were therefore acquired during 1996 to 1998 to ensure optimum subsurface imaging that would meet the challenges of the current development plans. This study examines the ways in which the 3-D seismic surveys have affected the development of the Minagish Oolite reservoirs.

**ACQUISITION PARAMETERS AND DATA QUALITY**

**3-D Survey Design and Parameters**

In order to ensure that all the Kuwait onshore 3-D surveys met the imaging objectives required for field development, two 3-D pilot surveys were made over the Burgan and Sabiriyah fields (Figure 1) (Mohammed and Al-Anzi, 1997). Vibroseis was used for source waveform generation. The effect of reduced effort was simulated by data decimation during processing. Based on these trials, optimum parameters were chosen for the Minagish (228 sq km) and Umm Gudair (478 sq km) 3-D surveys (Table 1).

**Table 1**

| Acquisition Parameters for the Minagish and Umm Gudair 3-D Surveys |
|---------------------------------------------------------------|
| • Conventional brick pattern of sources and receivers       |
| • 6 sweeps of 8 seconds length (12 seconds in locally noisy areas) |
| • 4 vibrators were used for each VP salvo                    |
| • Sweep frequency range 8–64Hz                               |
| • Source lines spaced 300 m apart                            |
| • 8 simultaneous receiver lines with 200 m spacing (E–W orientation) |
| • 144 live channels per line (1,152 total)                   |
| • Offset range 35 m to 3,658 m                               |
| • Bin size 25 m x 25 m                                       |
| • Nominal 48 fold                                            |

**Figure 1: Location of Minagish and Umm Gudair fields, Kuwait.**
Processing

The generalized processing sequence used for the Minagish and Umm Gudair 3-D surveys is shown in Table 2. Processing focused on deconvolution before stack, horizon-consistent velocity analysis, dip moveout (DMO) and spectral whitening. A novel approach to processing involved fixing the weathering and replacement velocities during the processing and applying a post-stack adjustment to correct to the final static model based on the upholes. This allowed processing to continue in parallel with uphole drilling and analysis. Its success relied on the fact that short-wavelength statics for stack purposes can be removed using a combination of refraction and residual statics. Furthermore, since the same preliminary fixed velocities have been used in the processing of all 3-D and 2-D surveys in Kuwait, the initial versions of the data could be tied countrywide. The final statics will be applied post-stack to all the processed seismic data once a full onshore statics model has been produced. Meanwhile, early but local uphole-based static models are applied at the interpretation stage to ensure correct depth prediction.

Table 2
Generalized Processing Sequence used in the Minagish and Umm Gudair 3-D Surveys

|   |   |
|---|---|
| 1. | Reformatted data |
| 2. | Minimum phase conversion (required for input to deconvolution) |
| 3. | Spherical divergence |
| 4. | Airwave filter |
| 5. | FK filter |
| 6. | Deconvolution before stack |
| 7. | Spectral whitening (only on Minagish) |
| 8. | Trace equalization |
| 9. | Refraction statics to floating datum |
| 10. | Residual statics (surface consistent) |
| 11. | Velocity analysis after Dip Moveout; grid spacing 1,000 x 1,000 m; horizon consistent picking |
| 12. | Normal Moveout correction |
| 13. | Dip Moveout correction |
| 14. | 48-fold stack |
| 15. | DAS (deconvolution after stack) |
| 16. | 3-D migration |
| 17. | Spectral whitening (only on Minagish, but produced as a second version at Umm Gudair) |
| 18. | FY then FX deconvolution (reduces random noise) |
| 19. | Datum static shift |
| 20. | Bandpass filtering |
| 21. | Trace scaling |

Uphole Static Correction Model

Refraction and residual statics were used in processing to maximize stack quality, but the seismic data itself had not been correctly shifted to be consistent with all uphole control. The main challenge regarding statics is to define the medium- to long-wavelength statics for depth-conversion purposes, and these are not defined by either refraction or residual statics. This element of the statics has historically been a problem in the West Kuwait area due to the relatively high ground elevations of about 180 m (600 ft) above datum, and the variable near-surface geology.

The long-wavelength, near-surface velocity variations were dealt with by implementing an aggressive uphole drilling program of 26 deep upholes to the Top Rus refractor (about 335 m below surface) in both fields. Ten shallow upholes to the Top Dammam (about 122 m below surface) were also drilled in Minagish to further define the shallow-velocity field. The upholes were concentrated on the undrilled flanks as the depth structure of the reservoirs was relatively well constrained over the area of the main fields. The deeper upholes provided both velocity information and Rus Formation depth values with which to constrain the field structure in areas outside the control of production wells.

It has been found that the best medium- to long-wavelength statics model can be developed only by the integration of uphole and production well data, and by progressively refining the model. The analysis of reflection and refraction time topography of the Rus seismic interpretation has proved...
important in constructing accurate Rus Formation depth maps that were used as the datum for downward depth conversions. This approach assumed that the Rus surface is smooth and that most short-wavelength features rightly belong in the variable near-surface layers.

Data Quality

Figures 2 and 3 illustrate the quality of the 3-D seismic data from both fields. The data is of high quality being relatively noise free and having good penetration. Small-scale structural and stratigraphic details can be seen even in a cross-sectional view of the data, although multiple contamination, near-surface coverage gaps and the acquisition footprint are evident on close inspection. The Umm Gudair E–W inline (Figure 2) shows the two-limbed structure with virtually no faulting whereas the Minagish N–S cross-line (Figure 3) shows that a major E-trending fault cuts the Minagish structure. On both lines, the Minagish Oolite section is a relatively low-amplitude interval about 250 milliseconds beneath the very strong Shu’aiba reflection.

Figure 4 compares the quality of the 1979 2-D data with that of the new 3-D. The most striking difference is an improvement in the temporal resolution. This is the result of the 3-D survey having a sweep frequency range of 8 to 64 Hz whereas the older 2-D had limited frequency sweeps of from 10 to 40 Hz. The lateral resolution is also much better on the 3-D due to the higher bandwidth and the 3-D imaging. Some features that are now recognized as local velocity and imaging effects on the 3-D data due to erosion of the Shu’aiba (see discussion below), were previously interpreted as faults on the 2-D images.

Figure 2: 3-D inline from the Umm Gudair field showing the west and east limbs of the structure and the relatively unfaulted deeper strata. Small-scale faulting is present in the shallow section (0.6–0.8 sec), and small erosional features affect the Shu’aiba. The shallow section (0–0.5 sec) that includes the important Rus reflector, is affected by the acquisition footprint.
Figure 3: 3-D crossline from the Minagish field showing major E–W fault (arrowed). Note that the apparent throw of the fault becomes less with increasing depth between the Shu’aita and Minagish Oolite reflections. The effect of the fault is diminished significantly at the Gotnia level (1.8 sec).

Figure 4: Comparison of recent 3-D seismic imaging with the older 2-D data (Umm Gudair field). The major difference is the low resolution of the 2-D data due to the limitations of the Vibroseis sweep (10–40 Hz). The 3-D lateral resolution is also superior because of the increased bandwidth and 3-D coverage/migration. Erroneously interpreted faults on the 2-D data are recognized from the 3-D data as imaging effects beneath the eroded Shu’aita.
Figures 5 and 6 are dip maps of the Top Shu’aiba formation for both the Minagish and Umm Gudair fields. These show the details available from the 3-D seismic data that had been unrecognized or misinterpreted on the earlier 2-D surveys. The Top Shu’aiba surface is shown by the 3-D seismic data to be faulted and to have impressive karstic effects, such as sinkholes and channels or valleys, and extensive eroded areas that may represent collapsed cave systems. However, these features are poorly understood geologically as no wells penetrate them. The Shu’aiba Formation is not an oil reservoir in Kuwait but the 3-D results will have an impact on the siting of water-disposal wells into it. Velocity contrasts caused by the erosional topography on this surface and the compaction-collapse of overlying rocks present some imaging problems at the Minagish Oolite level about 250 milliseconds below the Shu’aiba, and this is discussed later.

DEPTH AND FAULT MAPPING

Interpretation Methodology

The 3-D seismic data was interpreted using integrated UNIX workstation software. The phase of the seismic data was established by deterministic wavelet extraction techniques and horizon identification using synthetic seismograms on the workstation. Autotracking techniques were used to obtain basic interpretation of time surfaces, but much painstaking manual interpretation was necessary in order to minimize the effects of multiple interference and overburden velocities. The apparent velocity approach to multilayer depth conversion was used to convert the time surfaces to depth.

Minagish Field

The benefits of 3-D imaging are now thoroughly documented in the Gulf region (Al-Husseini and Chimblo, 1995; Onderwaater et al., 1996), most notably through improved fault and surface definition. These benefits are clearly seen in the interpretation of the Minagish and Umm Gudair 3-D survey results.
Figure 7 compares the Top Minagish Oolite depth maps before and after 3-D seismic. The interpretation prior to 3-D seismic was based mainly on well control and the sparse 2-D seismic coverage (Carmen, 1996). Numerous fault cuts had been identified in the wells and connected together in a dominantly radial pattern. Nearly all of the fault cuts seen in the wells occurred in the Upper Cretaceous above the Minagish Oolite level, but the structural model employed extrapolated the faults downwards into the Minagish Oolite. The resultant depth maps were commonly found to be inaccurate when new wells were drilled, and the complex segmented nature of the field led to the perception of separate fluid compartments.

Interpretation of the 3-D seismic data shows that the Minagish Oolite level is much less faulted than expected, although a significant E-trending fault system partially cuts the field with throws of from 15 to 60 m. Possible smaller faults (throws of 10–15 m) have been identified from dip maps but, because of the high quality of the reservoir, they are probably not large enough to significantly impede fluid flow. The recognition that the Minagish Oolite is less faulted than had been previously thought, together with more accurate depth mapping and imaging, and additional uphole control on the flanks of the field, has resulted in a significant redistribution of reserves. The reservoir flow model has been considerably simplified by the reduction in the number of faults. The accurate placement of flank injector wells is now possible due to the improved reservoir depth prediction and the proper identification of possible compartments.

Figure 8 is a 3-D visualization of the two-way time surface of the Top Minagish Oolite showing the dominant E-trending central fault system and the relatively smooth surface over the rest of the field. The higher time surface of the Ahmadi horizon that is close to the secondary Wara/Burgan reservoir shows a higher degree of faulting than at the level of the Minagish Oolite. Most of the faults cutting the Ahmadi die out with depth and do not reach the Minagish Oolite. This is consistent with a compressional origin of the structures (Carmen, 1996). The complex
Faulting and structure at the Ahmadi level will have a significant impact on the development of the Wara/Burgan reservoir. An initial feasibility study by Foster and Lau (2000) established the potential for 3-D seismic reservoir characterization of the Wara Sand.

**Umm Gudair Field**

Figure 9 compares Top Minagish Oolite depth maps before and after the 3-D survey of the Umm Gudair field. The earlier mapping was based on a loose grid of predominantly 2-D lines shot in 1979 and shows localized minor faulting (Carmen, 1996). The mapping based on the results of the 3-D survey indicates that there is no significant faulting of the Minagish Oolite. The depth structure has also changed, particularly around some of the flank areas; for example, on the northern closure of the eastern limb of the field. Figure 10 shows the depth changes more clearly by comparing an arbitrary contour line both before and after the 3-D, although the area of greatest change had poor 2-D seismic coverage. The change in field shape has had a significant impact on the flank development and appraisal well program.

**PREDICTING RESERVOIR PROPERTIES**

In addition to the impact of improved structural definition, the 3-D surveys can add further value through detailed reservoir mapping and the prediction of reservoir properties. However, before quantitative reservoir characterization is possible, the quality of the seismic data has to be investigated.
by analyzing VSP and synthetic ties to the seismic data. Figure 11 shows a typical seismic-to-synthetic match and illustrates the generally good quality of the data. Local mismatches between the seismic data and synthetic seismograms or VSPs are mainly due to poor log quality that affects the accuracy of the synthetic seismograms, or by multiple contamination of the seismic. Extracted wavelets indicate that the 3-D surveys are very close to zero phase (Figure 12) (S. Smith, unpublished KOC report, 1997). Multiple contamination of the Minagish Oolite reservoir level varies considerably from one area to another but is quite significant in the Umm Gudair field. This is revealed by synthetic seismograms and VSP ties (T. Redshaw and S. Smith, unpublished KOC report, 1998).

The main tool used to characterize the reservoirs in both fields was absolute acoustic impedance inverted from seismic. The main benefits of this approach are the ability to visualize reservoir layering and the direct prediction of rock properties. Acoustic impedance data sets were prepared using the sparse constrained spike inversion method, with the below-seismic bandwidth frequencies reconstructed from high bandpass-filtered and interpolated well log data (T. Redshaw and S. Smith, unpublished KOC reports, 1998).

Figure 13 is an example of an acoustic impedance cross-section through the Minagish field. This highlights the Minagish Oolite interval as a low acoustic-impedance zone due to its porosity development. Analysis of petrophysical data shows an excellent correlation between log acoustic impedance and log porosity (Figure 14). A large difference exists in acoustic impedance between the minimum and maximum expected porosity values. Consequently, it should be possible to map porosity from acoustic impedance values alone if the seismic data is of good quality.

The scatter in the acoustic impedance and porosity cross plot is assumed to be due to a combination of reservoir facies, variable log quality and the effects of varying oil properties and water saturations. The fluid saturation effect has been investigated for 4-D seismic planning purposes by analyses...
of logs (A.J. Hill, unpublished KOC report, 1998) and the acoustic measurement of core plug samples (Z. Wang and M. Cates, unpublished KOC report, 1998). These confirm that increasing water saturation increases acoustic impedance. Some sample values based on the acoustic core measurements and fluid substitution are shown on Figure 14. For the most accurate porosity prediction, the fluid effects should be removed, for example by using different acoustic impedance to porosity trends in the oil-leg and water-leg.

Figure 15 is an example of acoustic impedance data at the Minagish Oolite level illustrating reservoir layering that has a good qualitative correlation with the sonic log at the well tie. This line also illustrates an increase in acoustic impedance downward and laterally into the aquifer across a sub-horizontal zone approximately coincident with the base of the hydrocarbon column. Because of the excellent empirical relationship between acoustic impedance and porosity values obtained from logs, it is possible to convert the acoustic impedance data from seismic into approximate porosity values in the Minagish Oolite reservoir.

Figure 10: Comparison of 8,500 ft depth contour based on 2-D and 3-D data. The field outline has significantly changed, particularly in an area of poor 2-D coverage.

Figure 11: Typical seismic-to-synthetic match and sonic log from Minagish field. The match is generally good and local mismatches are likely to be due to poor log quality (e.g. at 1.65 to 1.7 sec).
Figure 16 is a 3-D visualization of the ‘sculpted’ porosity volume (that is, with overburden and underlying data removed to show only the reservoir interval) of the Minagish Oolite reservoir in the Minagish field (D. Foster and D. Roberts, unpublished KOC report, 1998). This shows that there is an overall crest to flank and aquifer reduction in porosity, a trend confirmed by porosity data from well logs. A very low porosity trend across the northeast flank of the field (deep blue on Figure 16) was confirmed by well data and may represent a facies-related change associated with a northward pinch-out of the Minagish Oolite. A noticeable reduction in apparent porosity coincides approximately with the downdip extent of hydrocarbons (shown on Figure 16). It is probably due to a combination of genuine porosity reduction in the aquifer through diagenesis and the increased acoustic impedance of 100 percent water-saturation in the aquifer. This causes apparent lower porosity values unless corrected. Prediction accuracy is locally affected by areas of poor data quality that generally show as patches of lower apparent porosity. These areas of poor-quality data will be discussed in detail below.

The results of porosity mapping from the acoustic impedance are being evaluated but, so far, they have been used to try to avoid areas of poor porosity when siting flank injector wells. In the future, the predictions will be refined for use in siting infill drill holes and defining the nature and distribution of the aquifer.

**Limitations of Original Seismic Processing**

Despite the high quality of the basic seismic data and the processing, some limitations in the original data have been identified when used in the quantitative prediction of rock properties. These limitations are the subject of current and planned reprocessing efforts aimed at maximizing the value of the 3-D seismic data for reservoir characterization.
Much of the surface and interbed multiple energy is removed in the basic processing sequence, mainly through the power of the stack process that discriminates against many low-velocity events presumed to be multiples. However, residual multiple reflections still contaminate the section, particularly in areas (such as the Minagish Oolite zone) where the amplitude signal is low. They are most obvious to the interpreter where they have discordant dips with primary events, but modeling studies have shown them to be ubiquitous by comparing the response in VSPs and synthetics to the actual seismic.

Multiples at the level of the Minagish Oolite are common in the Umm Gudair field and on the southwest flank of the Minagish field. Their effect, when they cut reservoir reflections, is to introduce unreal two-way-time perturbations and distort the true amplitude levels by both destructive and constructive interference. The eroded and karstified surface of the Shu’aiba carbonate (Figures 5 and 6) causes low-velocity anomalies because of the extreme velocity contrast between the Shu’aiba Formation (4,880–5,490 m/sec) and the overlying Burgan formation (3,050–3,350 m/sec). The relatively low-velocity fill of the karst depressions causes a significant time sag below them, and the very rapid lateral velocity changes prevent accurate stacking of events in a simple stack beneath the Shu’aiba due to the distorted move out.

Figure 17 is a seismic section from the Umm Gudair field that shows multiples and overburden shadows at or near the Minagish Oolite level. It illustrates the serious effect of the Shu’aiba erosional features on the timing, character, and amplitude of the underlying seismic data. Beneath these
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Figure 14: Relationship cross-plot between acoustic impedance (AI) and porosity from log data, Minagish Oolite, Mingish field. Correlation between AI and porosity is excellent, the scatter being due to a combination of fluid effects and variable log quality. Sample acoustic core measurements indicate the sensitivity of AI between the aquifer and oil-leg. Saturation estimates are from acoustic core measurements and Gassman fluid substitution.

Figure 15: Example of acoustic impedance (AI) section from the Minagish field, showing reservoir layering and the increase in AI below the oil column.
features, the Minagish Oolite zone suffers a time sag and reduction in amplitude due to mis-stacking. These features give rise to the lower apparent porosity anomalies at the Minagish Oolite level, illustrated on Figure 16.

The effect of both multiples and overburden shadow features on porosity prediction can be further assessed by comparing the acoustic impedance from the seismic with an acoustic impedance forward model derived only from wells—the wells-only model being multiple free. Figure 18 is a difference map between porosities predicted from the seismically derived acoustic impedance and the well model. This shows both noise effects and real porosity changes not present in the well model. The effect of the Shu’aiba erosional features and shallow faults can be seen by the striking correlation between the large-difference areas and the corresponding overburden features. The effect of multiples is subtler, but can be seen as NNW-trending red anomalies along the southwest flank of the field. The modeling shows that the seismically derived porosities are generally underestimated over the local poor-data areas because the overburden shadows and multiples tend to reduce the reservoir reflection amplitudes. This causes higher apparent acoustic impedance and thus a lower apparent porosity.

Figure 16: 3-D visualization of sculpted porosity volume of the Minagish Oolite reservoir, Minagish field (cut at 16.5 msec below top reservoir). The apparent porosity decreases below the hydrocarbon column, the decrease in porosity along the NE flank of the field is associated with northward pinching-out of the Minagish Oolite, and there are areas of poor data. The high apparent porosity at the crest of the field is partly due to the enhancement of seismic response by the crestal secondary gas cap.
Figure 17: Example of a seismic line from the Umm Gudair field to show some limitations in the original processing. The main problem at the Minagish Oolite level is due to the widespread presence of interbed multiples. Imaging limitations beneath the eroded Shu’aiba are also a serious local problem.
CONCLUSIONS AND FUTURE PLANS

The new 3-D surveys of the Minagish and Umm Gudair fields have had a major impact on the perception of the subsurface complexity and definition of the Minagish Oolite reservoirs, which were the priority of early interpretation efforts. The most striking change is the simplification of the overall fault pattern in the Minagish field. The perception of faulting complexity at the Umm Gudair field has also been reduced.
The immediate impact of this simplification is to define reservoir models more accurately for production performance prediction. The new fault patterns together with improved depth mapping have allowed optimum placement of producer and injector wells to maximize recovery. Flank-well risk has also been considerably reduced. Furthermore, because the cost of each 3-D survey is approximately equivalent to one or two development wells, it is estimated that the 3-D surveys will rapidly pay for themselves by preventing the drilling of poorly sited wells.

Interpretation is also being directed to the other stacked reservoirs in the Umm Gudair and Minagish fields. The Umm Gudair 3-D data was reprocessed and achieved its primary objective of multiple attenuation at the Minagish Oolite level. The initial interpretation results from a 4-D pilot survey over a Minagish Oolite injector well in the Minagish field are encouraging. Test reprocessing of Minagish 3-D data that focuses on improving imaging at the Wara/Burgan and Minagish Oolite reservoir levels is in progress. Methods to remotely detect fractures in the non-conventional Jurassic reservoirs of the Najmah/Sargelu formations are also being investigated. These include a multi-azimuth walk-away walk-around VSP survey that is promising for fracture characterization from both compressional and shear-wave data (Abdul Malek et al., 2000).

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