The 3D shear experiment over the Natih field in Oman. Reservoir geology, data acquisition and anisotropy analysis


Abstract

This paper describes a large-scale reservoir characterization experiment carried out in Oman in 1991 which comprised the acquisition, processing and interpretation of a 28.4 km² 3D multicomponent seismic experiment over the Natih field. The objective of the survey was to obtain information on the fracture network present in the Natih carbonates from shear-wave anisotropy. Shear-wave anisotropy in excess of 20% time splitting was encountered over a large part of the survey. The seismic results are confirmed by geological and well data but provide additional qualitative information on fracturing where this was not available before. Regions of stronger and weaker shear-wave anisotropy appear to be fault-bounded. The average well flow rates (which are fracture-dominated) within such blocks correlate with the average anisotropy of the blocks. The further observation that the anisotropy is largest in the fracture gas cap of the reservoir suggests that shear waves can provide a direct hydrocarbon indicator for fractured rock.

Introduction

In the northern part of the Sultanate of Oman, oil is produced chiefly from carbonate reservoirs of Cretaceous age. Major fields such as Natih were discovered in the 1960s and early 1970s and had been put on stream shortly after their discovery. Oil-bearing reservoirs occur in two carbonate formations in north Oman, the Natih and the Shuaiba. In the 1980s production geologists and reservoir engineers of Petroleum Development Oman (PDO) recognized the importance of fractures to the development of these fields and changed the field development to one of gas oil gravity drainage. Core analysis and field studies provided a semi-quantitative model for the fractured carbonate reservoirs but a hope for the future lay in recognizing and/or quantifying the degree and orientation of fracturing from 3D seismic. It was realized

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that conventional seismic data could not provide the required information on fracture frequency and orientations but that shear seismic could in principle give access to this information (Crampin 1984, 1985; Martin and Davis 1987). Since results reported by Lewis et al. (1989) indicated that areas of high fracture density could be detected by shear-wave anisotropy in a field not unlike Natih, a nine-component three-dimensional (9C3D) survey was proposed.

We describe the choice of the several candidate fields in Oman, the geology of the Natih field, the seismic data acquisition, main aspects of the data processing and the results of the survey.

Screening of candidate fields

Some 10 producing fields in northern Oman are known to have significantly fractured reservoirs. In the selection of the field for this multicomponent experiment many important issues were identified, the most important of which were:
- a knowledge of the fracture system from cores and field studies, such as tracer tests;
- structural and seismic complexity in the sequences above the reservoir;
- the quality of conventional P-wave seismic data in the area;
- the surface, i.e. where it consists of hard layers covered with only a thin layer of sand, transmission of energy is far better than, for example, in dune areas, and shear-wave statics are smaller as well;
- scope for development and/or enhanced oil recovery plans;
- physical access to the area.

The first condition was the most difficult to satisfy, but is important in order to validate the seismic results. At the time the experiment was planned, only in the Natih field was sufficient information available on the prevailing fracture system, both from cores as well as from field observations in neighbouring outcrops (further discussed below). A further attractive feature of this field was that it is indeed structurally not very complex, and that the fractures are nearly vertical. These circumstances facilitate the data processing and interpretation substantially. In addition, the presence of hard Fiqa shales directly beneath the surface was considered ideal.

Initially a pilot experiment was carried out to investigate acquisition parameters (Hake et al. 1998). On the basis of the encouraging results obtained from the pilot data, a 9C3D survey was designed.

Geology of the Natih field

General field information

The Natih field (Fig. 1) consists of a fractured carbonate antiform, measuring some 10 by 6 km, and is located within the Fahud Salt Basin, immediately west of the Maradi Fault Zone. The structure itself is a three-way dip closure, bounded to the north by a
Figure 1. Top Natih map showing TWT (in ms) and fault interpretation from the conventional 3D survey. The axes give geographical coordinates in metres. The coverage of the 3D multicomponent data is indicated by the approximate survey outline shown in black.
major reverse fault with a vertical displacement of ~ 1 km. Its two separate reservoirs are the Natih and the Shuaiba formations.

The Natih formation is a Middle Cretaceous sequence of chalky limestones, some 300 m thick. The permeability of the matrix is a very low 1–30 mD, and therefore production from the matrix is almost entirely dependent upon the fracture network. Understanding the spatial distribution and orientation of the fractures is critical for optimizing the development of the reservoir. Fracture development largely results from the regional tectonics in combination with uplift or from release of stress.

The Natih field is a NW–SE trending, relatively gentle anticline with small dips at the southern flank, where the survey was acquired. Post-Natih extensional movements first created a basin in which the Fqiqa shales, which overlie the Natih reservoir, could attain their substantial thickness. These movements are probably also responsible for the cross-axial (NE–SW, i.e. perpendicular to the main axis of the anticline) fractures.

Previously available fracture data

Earlier knowledge of fractures in the Natih field was obtained from outcrop studies, tracer tests, borehole elongation measurements, Formation Micro Scanner (FMS) logs, palaeomagnetically orientated cores and well take-off rates. Outcrop data in particular have helped in the description of fracture families, their dimensions and spacings. The outcrop data, although by necessity collected 50 km away from the field, is most valuable for calibrating the subsurface data, and complements the latter particularly with regard to fracture dimensions (Mercadier and Mäkel 1991; Mercadier and Milatz 1991). The outcrop study includes fractures of dimensions and spacings that are too large to be detected by core or FMS analysis. However, these fractures will not escape seismic detection. Two fracture groups have been identified, i.e. (a) cross-axial, NE–SW striking and (b) longitudinal, NW–SE striking. In both groups, extensional and shear fractures have been identified, so that there are four types of fracture:

1 cross-axial, NE–SW striking, extensional;
2 longitudinal, NW–SE striking, extensional;
3 cross-axial, NE–SW striking, shear;
4 longitudinal, NW–SE striking, shear.

All fractures are thought to be vertical or subvertical. In addition, small (1–10 cm) subvertical fractures have been found in the more argillaceous Natih limestone intervals, but these have no preferred direction.

Fracture spacing (the average horizontal distance between two neighbouring fractures) and fracture dimension have been observed to vary with fracture type, lithology, bed thickness and curvature, and proximity to faults. In general, fracture dimensions decrease with spacing. The largest fractures are the NE–SW extensional family, which can be traced over hundreds of metres. These are also known to extend vertically across several beds but whether they traverse the thin argillaceous intervals is not known. The outcrop study shows all fractures to be almost completely calcite
cemented, except these largest ones. This is consistent with the open fractures detected on palaeomagnetically orientated cores and FMS logs, as well as with the dominant NE-SW permeability of the Natih reservoir as established in tracer tests. Since cementation is very effective in bonding the fracture faces, this family should manifest itself in a NE-SW direction for the fast shear wave. Whereas this is the gross picture, tracer tests do not exclude the possibility of (minor) local NW-SE flow.

There are indications that the fracture frequency increases in areas with high bed curvature, where the deformation is largest. It is here, closer to the boundary fault closing off the Natih field in the north, that the NW-SE striking extensional family could be open as well and participate in the fluid-flow network. This hypothesis has been put forth to explain the high take-off rates of wells such as N-93. This area lies outside the seismic survey. Finally, the decrease in the density of the open NE-SW orientated fractures towards the west (where the deformation is less) is illustrated by low well take-off rates in that part of the field.

Seismic survey acquisition

Survey parameters and area

A compromise had to be struck between the desire to cover as large an area as possible and the perceived more stringent sampling requirements for shear-wave data. At PDO, the standard CDP bin size for 3D surveys is $25 \times 25$ m. The compromise consisted of a 50-m vibrator point interval and a 25-m geophone station interval. A further survey design parameter was determined by the requirement that maximum offsets no smaller than 800 m should be maintained throughout. The then standard zig-zag shooting pattern (Onderwaater, Wams and Potters 1996) was considered to be incompatible with the requirement for accurate orientation of the shear-wave vibrators, so a brick pattern was adopted, with parameter details as listed in Table 1.

The survey area (Fig. 2) was chosen to cover most of the western and southern flanks of the field, avoiding the installations in the centre of the field. The survey was orientated with the receiver lines east-west and was subdivided into three blocks A, B and C (see Fig. 2). The three blocks are each 72 channels (1775 m) wide. In order to acquire maximum offsets of at least 800 m, four to five shot rows were located outside the spread on each side. To facilitate the positioning of the horizontal vibrators in the N-S and E-W directions, the shot rows were orientated N-S, each containing four source points 50 m apart. The E-W interval between shot rows was 100 m. On subsequent swaths the source rows were shifted by 50 m in the so-called 'stair-step' method which gives some of the advantages of the zig-zag geometry.

The vibrators

In the following X refers to E-W and Y to N-S directions. The four horizontal vibrators were adapted by Heavyquip to allow force control using Pelton Advance II
controllers. Each swath was completed with one source component, the most efficient order being Sy (horizontal energy in the Y-direction), then P and finally Sx. With the movement of the horizontal vibrator base plates fixed at right angles with respect to the vibrator trucks, the Y-component was recorded with the horizontal vibrators travelling along extended E–W lines. For the X-component the four position N–S rows were followed, which required much more tedious manoeuvring. A tolerance of 5° was set for both the source and the horizontal receiver directions, both of which were achieved.

The three-component receiver arrays

Receiver arrays comprised 12 three-component geophones (two strings of six) laid in a half-feather 25 × 40 m pattern. In conventional operations geophones are buried. Initially it was decided not to do this for the 9C3D survey to allow a visual check on the orientation. This decision had to be revised after about one-third of the data had been acquired, as is discussed below. A colour coding system was set up to ensure proper connection of the geophones.

Operations

The survey was scheduled to last one month. Initial production rates were 400–600 vibrator positions (VPs) per day in a 24-h continuous operation compared with 350–400 VPs per day during conventional daylight operations. The orientation of the X-component source proved to be very time consuming. The same proved to be true
Figure 2. Bin multiplicity map of one data component for offsets up to 700 m as used in the anisotropy analysis.

for the P-vibrators in the orthogonal rather than zig-zag shooting geometry. The speed was improved by also directing the P-vibrators along E–W lines and by deploying the S-vibrators in two groups of two. The latter was done after some testing which demonstrated that the differences between a two- and a four-vibrator array were small enough to accept in view of the expected speed gain. This observation is at odds with that made during the pilot project (Hake et al. 1998). Daily production rose to over 1000 VPs per day.

The deployment of the three-component geophone arrays was poor at first, with the angular orientation for individual geophones sometimes almost 45° out of specification. A separate crew of geophone aligners was deployed and successfully overcame this problem. During the survey, wind caused the data to become very noisy at the northern end of block A. From then on, this was avoided by burying the geophones in blocks B and C (see Fig. 3). When the survey was concluded after 32 days, 22 million traces had been recorded on 2000 tapes and 9C3D data were obtained over an area of 28.4 km².
Figure 3. Single-trace rms amplitude averaged per receiver location (averaged over all data components).
Table 2. Processing summary for the 9C3D survey.

Make initial diagnostic and QC displays
Ident corrections
Re-bin (to 50 x 50-m grid)
Trace editing
Gain correction
Convert to Shell internal processing format
AVC, slant-stack domain linear noise removal, de-AVC
Surface-consistent amplitude equalization
Short offset velocity analysis (on 1 x 1-km grid)
Blanking, NMO and brute stack for NN, NE, EN, EE data sets
First pass of coupled residual statics on NN and EE data sets
Rotation into Fiqa eigendirections
Velocity analysis of data in Fiqa eigendirections (on 0.5 x 0.5-km grid)
Second pass residual statics
NMO stack
Rotation scan at top Natih on stacks to determine Fiqa anisotropy
Stripping to remove influence of Fiqa anisotropy
Rotation scan at top Natih to determine anisotropy over reservoir interval

Naming conventions

In order to facilitate the discussion on the various data components, we establish the nomenclature of the various wave types to avoid recurrent complications caused, for instance, by the fact that a vertical (Z) source generates shear waves as well (away from the vertical direction). Four of the remaining eight components (XX, XY, YX, YY) will be referred to as ‘shear’ or ‘horizontal’ data, and the other four (ZX, ZY, XZ, YZ) as ‘mode-converted’ data. The conventional 3D data (ZZ) is also called the ‘compressional’ data. Note that in this notation, the first letter indicates the source orientation, the second the receiver orientation. In addition, where compass directions need to be identified we also use notations EE, EN, NE and NN for the horizontal data. In addition, the polarity convention is such that N is positive, E is positive and Z (downwards) is positive.

Data processing

Preliminaries

The processing and analysis of the horizontal components (summarized in Table 2) consists of three parts:

- preprocessing up to NMO stack to prepare for anisotropy analysis;
- analysis of the Fiqa (overburden) anisotropy;
- analysis of the Natih (reservoir) anisotropy.
Although the analysis of the Fiqa anisotropy was not an objective in itself, it did exhibit some interesting features (Guest, van der Kolk and Potters 1998). It was recognized that this huge package of shales, which had, at least in part, been subjected to the same tectonic stresses as the reservoir, could have a dramatic effect on the measured reservoir anisotropy. Although the azimuthal anisotropy of the Fiqa is very small, the package is up to 900 m thick and could therefore cause significant shear-wave splitting.

Compared with conventional 3D processing, a number of constraints are imposed on the processing of the shear data. Since the four horizontal components are used as one data set in the measurements of the anisotropy parameters, much attention needs to be paid to ensuring that relative amplitudes and times between the four data sets are not impaired. Steps in the processing such as noise filtering, scaling, residual statics and NMO stack therefore need to be carefully monitored.

Polarity quality control (QC) was carried out on early linear arrivals that could be identified on most offsets. Since a horizontal source also generates vertical data for non-zero offset, it is possible to check the shot polarity by comparing the polarity of this data with that of a vertical source. For instance, a positive loop on the ZZ traces having receivers located south-west of the source should correspond to a negative loop at the corresponding time on the EZ and NZ traces (+/-/-). The corresponding event on the same receiver line but south-east of the source ought to exhibit (+/-/+). The receiver polarity check can be done in a similar fashion, but then using vertical shots and the P-wave refraction recorded by the three receiver orientations.

Although a time-consuming procedure, polarity checks (see below) were carried out for all shots and receiver lines, resulting in the rejection of only 127 shots and 37 receiver locations from the data set. A final point to be mentioned here is that the bin size was chosen to be 50 x 50 m, which is larger than usual. The reason for this is that it improves the S/N ratio and also gives better offset-azimuth uniformity in case velocity analysis needs to be performed in offset-azimuth slots. As shown by Hake et al. (1998), post-stack analysis of the shear data is effectively precluded for offsets in excess of 700 m. For this reason the range of offsets was restricted to 700 m in the processing. Except at the perimeter of the survey and where obstacles are located, the bin multiplicity is typically larger than 100.

**Noise suppression**

The amplitude was measured for all traces in a three-second gate below the P-wave first arrival. In the westernmost acquisition block (block A), many traces contaminated with high-amplitude noise, particularly in the north (see Fig. 3). This noise is mostly random, and is strong here because in this area the geophones were not buried. Prior to later removal of linear noise and amplitude scaling, traces with a high noise level were deleted after a statistical analysis; only 2.4% of the 8.5 million shear data traces were rejected.
Many shots are severely contaminated with linear noise of various velocities which often obscures reflections at the level of interest (shear arrivals around 2.5 s). In view of our special interest in the short offsets, conventional $f-k$ filtering is not an optimal approach. This is because of the swath geometry which causes the source-to-receiver distance for a shot gather in a single receiver line to vary, and this effect is particularly strong at the near-offsets. For this reason, the slant stack was used, which allows the modelling of linear events using the true shot–receiver distance.

**Amplitude scaling**

Correct determination of anisotropy requires that any processing step which induces relative changes in amplitudes of traces belonging to the same bin point should be avoided. Vice versa, any existing amplitude imbalances introduced at the acquisition stage should be correctly removed. Rotation analysis (Alford 1986), for example, is based on minimizing the energy of the components $XY$ and $YX$. If the amplitudes in the four input components are out of balance then the process can produce incorrect estimates.

Several effects would, in principle, necessitate a correction of the amplitudes. The most obvious ones are:

- changes in the source energy: a change was made in block A from a four- to a two-vibrator pattern and occasionally shots were also generated with a single vibrator;
- the fact that geophones were buried in block C and most of block B, but not in block A;
- possible differences in the coupling between NS and EW orientated sources and receivers, for example because of the prevailing surface water drainage direction.

These considerations suggest that the observed amplitude relationship between the four horizontal components could be distorted. A surface-consistent amplitude scaling approach was applied, consisting in the derivation of a set of scaling factors to correct for remaining rms amplitude differences in as much as these can be explained in a shot- and receiver-consistent manner (Li 1994). Application of the resulting scaling factors removes unwarranted shot-consistent amplitude differences between the two shot directions at the same station. Note that this procedure relies on the assumption that the rms amplitude is a correct measure of the signal energy, and it therefore takes no account of the fact that in the northern part of blocks A and B wind noise may dominate the records.

The results of this method are shown in Fig. 4, in which the rms average amplitudes for the receivers are displayed. The different character between areas with buried and non-buried geophones is clearly visible. Figure 5 shows the filtered amplitudes, which have been strongly equalized. Note that amplitude variations that could not be explained shot- or receiver-consistently are preserved. Hence, as should be expected, the structural imprint of the main reflections becomes visible. The derived scaling factors were subsequently applied to the prestack data.

Figure 4. Receiver rms average amplitudes (all horizontal data components) before shot- and receiver-consistent amplitude equalization.
Figure 5. Receiver rms average amplitudes (all horizontal data components) after shot- and receiver-consistent amplitude equalization (see Fig. 4).
Velocity analysis

The strong polar anisotropy of the Fiqa shales, caused by the strong layering of that interval and revealed in the VSPs (Hake et al. 1998), can only be taken into account completely by full prestack analysis (Thomsen 1988; Tang and Chunduru 1997), which was seen as impractical for a survey of this size. To reduce errors, stacking velocities were derived for offsets up to 700 m, in which range the effect of the Fiqa’s polar anisotropy was shown (by modelling) to be limited. The effects of shot–receiver bearing on the velocities were ignored. Determination of velocity and azimuthal anisotropy in the Fiqa was carried out iteratively in three phases (first automatic, then interactive):

1. Initial velocity analysis on NN and EE data components (i.e. the acquisition orientation) on a 1×1-km grid;
2. Velocity analysis after a first pass of residual statics determination and prestack rotation into the initial Fiqa anisotropy eigensystem (this results in the Fiqa slow and fast shear velocities), on a 0.5×0.5-km grid;
3. Final velocity analysis after prestack rotation with the initial Fiqa anisotropy direction and a second pass of residual statics, on a 0.5×0.5-km grid

Strong polar anisotropy in the Fiqa gives rise to a larger stacking velocity for shear waves polarized in the direction of the bearing (radial direction, i.e. q-S\textsubscript{waves}) than for shear waves polarized perpendicular to the bearing (transverse direction, i.e. q-S\textsubscript{h-waves}). As the bearing distribution varies with CMP, the data would first need to be rotated to the radial and transverse directions, respectively. Thus to check whether the influence of polar anisotropy was significant, this was tested on a number of CMPs. After rotation to radial and transverse directions a velocity analysis was performed and it was found that the stacking velocities of the radial and transverse data thus obtained were very similar, respectively, to those of the EE and NN data (see Figs 6a and b). This is because, close to the maximum offset, the original EE and NN data are already approximately orientated in the radial and transverse direction (note that most longer offsets are in the east–west direction).

Reflection statics

Field statics were not applied, mainly because the correction velocity for the shear waves is unknown. The mild elevation profile showed that elevation statics would not change the stack. For correct time splitting it is important in principle to create stacks of the four components with (possibly anisotropic) surface effects removed. This would involve anisotropic refraction statics which, in view of the difficulties in picking, was not possible.

For these reasons only residual (reflection) statics were computed. With the usable maximum offset of only 700 m, only the relatively short wavelength statics can be...
Figure 6. Final stacking velocities for (a) the FF(Fiqa) and (b) SS(Fiqa) data (i.e. rotated in the Fiqa polarization directions).
solved and longer wavelengths will be left in the data. Two passes of residual statics were performed:

- on the data orientated in the original frame (NN, EE), after NMO correction with the initial velocities (see previous section);
- on prestack data rotated in the Fiqa anisotropy eigendirections, after NMO correction with the stacking velocities derived in these directions.

Initially it was allowed that the statics are anisotropic (i.e. N and E shot and receiver components need not have the same statics). It turned out that the differences were fairly random and nearly everywhere quite small. The results strongly suggested that the small differences between these 'uncoupled' solutions are more likely to have been caused by instabilities in the solution than by genuine anisotropic statics. This effect was therefore ignored, to avoid the possible introduction of false time shifts that could be interpreted as anisotropy.

After a first pass of residual statics an initial anisotropy analysis of the Fiqa was made. The prestack data were then rotated into these initial eigendirections for the second pass of residual statics. As expected, this procedure improved the data quality considerably in those areas where the eigendirections deviate from the acquisition grid orientation (NS–EW). This is because away from the eigendirections the shear data consist of mixed fast and slow wave modes. The final solution showed that only in the south-east area did statics of any significance exist. These are of the order of −2 to +5 ms, with very localized outliers of −10 to +10 ms.

**Anisotropy analysis**

With pairs of perpendicular source directions and perpendicular receiver directions in the horizontal plane, data that would have been recorded by hypothetical sources and receivers in arbitrary horizontal orientations can be simulated by appropriate superpositions of the original data. These are obtained by applying horizontal rotation matrices to the 2×2 (NN, NE, EN, EE) data matrix. As long as the wave propagation directions are close to vertical, the horizontal data sets can be considered as shear data sets. Several methods for estimating shear-wave polarization from multicomponent seismic data exist (MacBeth and Crampin 1991). Anisotropy maps generated with these different approaches exhibited only small differences, so only the results of one of these (time-splitting maximization) will be shown.

**Anisotropy of the Fiqa shales**

The Fiqa shales are themselves of interest (Guest *et al.* 1998), but the influence of their anisotropy on deeper events can be removed prior to the analysis at reservoir level. The anisotropy in a time window from the surface to the top Natih reflection was determined; Figs 7a and b, respectively, show the Fiqa fast shear eigendirections and the time splitting (arrival time difference between fast and slow shear modes). Obviously the main axis of the Fiqa anisotropy system is close to north–south over a
large area, but in the lower right (SE) corner it abruptly changes to approximately NE-SW. In general, the splitting produced by the Fiqa is fairly small (0–8 ms) but in some areas it is considerable, up to 30 ms. The northernmost (top), speckled strip of data should be ignored owing to the poor data quality. The narrow red streaks are due to mispicks along faults and therefore should not be interpreted as high-anisotropy regions.

4) Anisotropy of the Natih reservoir

The splitting accumulated in the Fiqa shales can be subtracted from the stacked data set by what is effectively a multicomponent statics operation which has become popularly known as 'stripping' (MacBeth et al. 1992; Thomsen, Tsvankin and Mueller 1995). After rotating the data into the overburden (Fiqa) polarization directions, relative time delays between the components at the top reservoir reflection are removed by applying the appropriate time shifts to the traces. In this process a fixed horizon is taken for the reflection from the top of the reservoir. After a single pass of stripping, however, this interpretation may need revision. Three iterations, using a combination of maximum time splitting and minimum cross-energy criteria, were required for finding the polarization directions. Finally, an interpretation of the top Natih and top Natih-E (some 200 ms deeper) was made and the anisotropy parameters for this interval determined by time-splitting maximization. One of the best ways to display the anisotropy in detail is by final stacks rotated into the Natih eigendirections. Two such displays are shown in Figs 8a and b. These are composite displays in which the fast (red) and slow (green) data components are superimposed. Data common to both is shown in black and white. These displays clearly show the alignment of the top Natih reflection (black) on both data sets, indicating that the Fiqa anisotropy has been properly removed.

In the Natih interval itself, the difference between the fast and the slow waves manifests itself in the separation of the red and green reflections. Small time splitting is predominant at the left, i.e. at the western and southern flanks of the field. A large increase in the time splitting occurs up the structure to the north-east. Closer inspection moreover reveals that the time splitting gradually increases with increasing depth starting from the top Natih reflection, both on the in-line and on the cross-line sections. This is exactly what is expected from a fractured interval: elastic energy returning from deeper reflectors has traversed a larger interval over which the slow wave is progressively retarded relative to the fast wave.

In the 200-ms interval from top Natih to top Natih-E (these being the strongest and most reliable horizons), the anisotropy direction and time splitting were determined over the entire survey area. After dividing this by the two-way interval time for the fast wave the relative time splitting is obtained. Figures 9a, b and c show, respectively, the direction of the fast wave in the Natih reservoir, the time splitting over the top Natih to top Natih-E interval, and the percentage time splitting for the same interval.

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Figure 7. (a) Fast-mode polarization direction for the Fiaq shales, derived from the final stacked horizontal data set. (b) Shear-wave splitting over the Fiaq shales, derived from the final stacked horizontal data set. Note that splitting values up to 30 ms occur over large areas, showing the necessity of correcting for the Fiaq azimuthal anisotropy before analysing the Natih level.

Natih reservoir anisotropy and fracturing

Figure 9a shows that the anisotropy of the Natih interval is characterized by a polarization direction for the fast horizontal shear wave that is roughly NE–SW trending, as evidenced by the red colour. This observation is consistent with previous geological knowledge of the dominant open fracture direction. There are also sizeable contiguous areas where the colour tends to orange or magenta, and in which the fast-mode polarization trends more NNE–SSW and ENE–WSW, respectively. In these
cases there are no other data to check the fracture direction which this observation implies.

Figures 9b and c show that there is a very large shear-wave anisotropy present over about half the survey area. The anisotropy is very large both in absolute terms (locally exceeding 30 ms) and in relative terms (exceeding 15%). Reliable high splitting values do not as a rule coincide with mapped faults, which excludes fault-related extensional fractures as the sole cause of the anisotropy. Faults do, however, bound several domains of different shear-wave splitting whilst the splitting variations within a block are relatively small. This could imply that each of these blocks has its own fairly uniform
There are a few areas with very small time splitting near the crest of the field (i.e. tending towards the NE). One possible explanation is that the longitudinal fracture families are not completely cemented here so that locally an open NW–SE orientated fracture system exists in addition to the dominant NE–SW system. The other is that

**Figure 8.** (a) In-line (east–west) final stack line orientated into the Natih eigendirections of the fast and slow horizontal shear data. Red is the fast mode, green is the slow mode, black and white are common to both. (b) As (a), but a cross-line final stack.
the dominant NE–SW family is locally cemented. In the former case, where time splitting is reduced because of a developing orthogonal set of fractures, the leading wave transit time across the reservoir would increase and show up as a time dip for the bottom Natih reflection on the fast shear section. On shear data in isolation this could still be explained as a thickness effect. However, there is no indication of such a thickness variation. The most likely explanation for the small time splitting near the crest is therefore that the NE–SW family is locally cemented.
Figure 9. (a) Post-stripping fast-mode orientation in the interval from top Natih to top Natih-E. Note the overall NE-SW direction. The green/blue lineaments are caused by picking difficulties across faults; the erratic behaviour at the top (north) is caused by strong wind noise. (b) Post-stripping time splitting between fast and slow horizontal shear waves in the interval from top Natih to top Natih-E. Note the clear difference between the field flanks (west and south) and the crest. The narrow (pixel-width) green lineaments are caused by picking difficulties across faults; the erratic high values at the top (north) are caused by strong wind noise. (c) As (b) but with time splitting expressed as a percentage of the two-way time interval for the fast wave.

As regards production data, a comprehensive study of the correlation between individual well rates and local shear anisotropy has not yet been reported (at the time of writing, such a study was being prepared for publication (V. Hitchings, pers. comm.)). However, when averaged over a fault block, well rates in areas of large time splitting are significantly higher than those in areas of small time splitting.

Reflection amplitude differences between the fast and slow shear modes at the top Natih might be expected as a further signature of the reservoir interval's shear-wave anisotropy. It is then interesting to note that, despite the good quality of the picked top
Natih event, maps showing the ratio of slow and fast shear mode reflection amplitudes for this event did not show any convincing correlation with the reservoir's shear-wave splitting map. This apparent inconsistency has been explained in terms of a thin dolomite streak seen on the well logs at the top of the Natih interval. We suggest that the top Natih event is a reflection from the top of this very thin hard layer but that the fractures, which cause the reservoir’s shear-wave birefringence, terminate on the base of the dolomite layer such that the expected relative amplitude variations are not seen.

A final observation is a nearly structurally conforming decrease in the time splitting, which is visible in Fig. 9c as the transition from yellow to blue in a direction perpendicular to the depth contours of the Natih structure. The polarization of the waves does not change at this transition. It occurs close to the fracture gas/oil contact (not to be confused with the matrix gas/oil contact), on which there is little direct information but which has been reconstructed back to August 1991, when the survey was acquired (D. Eikmans, pers. comm.). This observation suggests that shear waves can provide a direct hydrocarbon indicator for fractured reservoirs. This is discussed and developed theoretically by Guest et al. (1998).
Conclusions

A 28 km² multicomponent 3D seismic survey has been acquired over the Natih field in Oman to obtain information on fracturing in the Natih carbonate reservoir, at a depth of ~1 km. A large intra-reservoir shear-wave anisotropy was detected over about half the survey area, both in absolute terms (locally exceeding 30 ms) and in relative terms (exceeding 15%). This should be compared with values of up to 8% reported by Lewis et al. (1989) for a smaller survey acquired over a comparable fractured carbonate field in Wyoming. It should also be pointed out that our anisotropy measurements are in agreement with the complementary VSP measurements reported by Hake et al. (1998). Reliable high splitting values in the Natih field do not as a rule coincide with mapped faults, which excludes fault-related extensional fractures as the only cause of the anisotropy. Faults do, however, bound several domains of different shear-wave splitting whilst the splitting variations within a block are relatively small. This could imply that each of these blocks has its own fairly uniform fracture pattern and intensity whilst being in a different mechanical stress state from its neighbours. These seismic anisotropy maps
improve the understanding of fracture systems even in this field with its dense well coverage. The shear anisotropy results are consistent with the gross fracture model of the Natih reservoir. NE-SW trending open extensional fractures are presumably the main cause of the observed seismic anisotropy. Because of this consistency we would expect similar surveys, conducted over reservoirs with (sub)vertical open fractures, to provide reliable information on the direction and intensity of fracturing.

The average well flow rate in areas of large time splitting is higher than in areas with low time splitting. However, there is no strong correlation between individual well rates and shear anisotropy. This can be explained because in some horizontal wells drilled within the survey area, borehole data provides evidence for localized fracture ‘swarms’ (Nelson 1985), too small to be detected seismically but large enough to increase flow rates significantly. Absence of strong seismic anisotropy does not preclude the presence of fractured zones.

As yet no attempt has been made to resolve the internal structure of the Natih anisotropy (i.e. of the four main reservoir units individually) by simultaneous inversion of the horizontal data sets. This is worth pursuing, as it would increase the understanding of fracture intensity for the separate reservoir units. Further work is necessary to quantify fracture network properties. For example, a well-known ambiguity is that a given amount of shear anisotropy can be caused by an infinite number of combinations of fracture densities and sizes. Since different combinations have different rheological properties, this problem needs to be solved, possibly by incorporating a theoretical or empirical fracture size distribution. A further problem is that flow is strongly influenced by fracture aperture, a property which is, at best, only weakly expressed in the reservoir’s mechanical properties.

Finally it should be mentioned that the acquisition costs of this survey were nearly three times those of a conventional survey. This is clearly a consideration when contemplating more widespread application of the method. However, two technical advances have been made since this survey was acquired which would significantly reduce the acquisition costs. One is the rotating actuator, the use of which can virtually eliminate the time-consuming manoeuvring of the horizontal vibrators to acquire two perpendicular directions. Furthermore, the ‘slip-sweep’ acquisition technique (Rozemond 1996), at present only tested on compressional data, could, in principle, bring further savings. Both could make 9C3D surveying a viable technique for specific applications in the next millennium.

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References

Li X.-Y. 1994. Amplitude corrections for multicomponent surface seismic data. 64th SEG meeting, Los Angeles, USA, Expanded Abstracts, 1505–1508.