A 9C-2D Land Seismic Experiment for Lithology Estimation of a Permian Clastic Reservoir

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ABSTRACT

In 1997, a nine-component shear wave experiment, the first of its kind in the country, was carried out in central Saudi Arabia over the Umm Jurf and Usaylah fields. The seismic source consisted of conventional and shear-wave vibrators. The objective of the experiment was to test the feasibility of using multicomponent seismic data for lithology estimation and differentiation between sand, silt and shale in the clastic Permian Unayzah Formation. The estimates of average ratios of compressional to shear-wave velocities for the target interval are encouraging as they identified lithologic variations within the Unayzah that are in agreement with the available well logs. Specifically, the seismic ratios correlate satisfactorily with sand/(silt+shale) ratios measured in key wells.

INTRODUCTION

The past 15 years have seen several successful examples of the application of multicomponent seismic technology in hydrocarbon exploration (for example, Tatham and McCormack, 1991; Nieuwland et al., 1994). Many of the reported successes have been accomplished in the marine environment (for example, Berg et al., 1994; Granli et al., 1995), where statics and surface wave noise are a less serious problem than on land. Nevertheless, research into land multicomponent methods continues with many encouraging results (Potters et al., 1999).

Whereas marine multicomponent surveys rely on converted waves due to the impossibility of shear-wave propagation in water, on land it is possible to utilize shear vibrators and obtain full nine-component recordings. Despite their high acquisition costs, such multicomponent surveys provide a wealth of information and the opportunity to capture more completely the seismic wavefield.

In this paper we present results from a pilot nine-component (9C) 2-D seismic experiment over the Unayzah clastic reservoir in central Saudi Arabia (Figure 1). The objective of the experiment was to test the feasibility of using multicomponent seismic data for detecting sand versus silt+shale within the Unayzah reservoir. The seismic program consisted of three 2-D lines that totaled 36 km and were recorded using both conventional and shears vibrators. Several deep wells penetrated the target intervals. Full suites of logs, including dipole shear in several wells, provided adequate well control for the study. In addition to the surface seismic data, five 9C shallow (200 m) vertical seismic profiles were acquired in order to calibrate the compressional (P) and shear (S)-wave statics in the near surface.

GEOLOGY

The Unayzah reservoir is at a depth of about 1,900 m in the study area. The reservoir is sealed above by the basal shales of the carbonate Upper Permian Khuff Formation and below by the Lower Silurian Qusaiba Shale on which it rests at the pre-unayzah unconformity. The lower Unayzah Formation is a complex succession of clastic continental sedimentary rocks consisting of braid-plain and eolian sands and floodplain silt. Figure 2 shows schematically the depositional model of the Formation in the study area. The lower part of the Unayzah consists mainly of debris-flow gravel and coarse clastics that fill erosional channels into the Qusaiba Shale (Wender et al., 1998). The Unayzah fines upward into braided-stream longitudinal bars, channel-fill sandstone, and floodplain siltstone.
Figure 1: Location map for the Central Arabia 9C-2D Shear Experiment.
Figure 2: Depositional model of the Unayzah Formation (after Evans et al., 1997) demonstrating the high degree of lateral lithological variation to be expected in the Formation.

WELL LOG DATA

Figure 3 is a composite of logs that include dipole shear, at well (Usaylah-1). The well is a key stratigraphic discovery well that tested 35 ft of oil in an eolian dune facies in the upper part of the Unayzah reservoir. The upper, middle and lower sands in the target Unayzah (especially the upper producing interval), are clearly delineated by low values on the Poisson’s ratio curve that correlate with low values on the gamma ray log. In contrast, shaly and silty-sand intervals give rise to higher Poisson’s ratio and gamma ray values. Figure 4 shows sand/(silt+shale) ratios in well U-1. They clearly define the position of the clean sand intervals. For example, the producing eolian sands in the upper Unayzah have considerably larger sand ratios than the non-producing fluvial sands immediately below at a depth of about 6,250 ft, whereas the porosity log does not distinguish between the two intervals. A cross-plot of sand/shale and the ratio of compressional to shear-wave velocities ($V_P/V_S$) (Figure 5), convincingly demonstrates a decreasing $V_P/V_S$ trend with an increasing sand/shale ratio. No such trend is present in a cross-plot that used $V_P$ instead of $V_P/V_S$. This implies that it was possible to calibrate $V_P/V_S$ ratios estimated from seismic multicomponent data in terms of sand-to-shale ratios and create a more powerful reservoir quality index than from porosity alone. Similar observations were made in other wells in the study area and provided much of the impetus for pursuing a seismic multicomponent study of the Unayzah Formation.

ACQUISITION

In order to optimize the design of the source array, field tests were conducted using both conventional and shear vibrators that recorded into a downhole 3-component receiver at a depth of 195 m. The source array consisted of four vibrators and four sweeps in an orthogonal pattern. The move-up used in the production surface data was 5 m, as dictated by the results of the downhole test.
| Depth (feet) | Depth (feet) | Density (g/cc) | VP (ft/s) | VS (ft/s) | Poisson's ratio | Gamma ray (API) | Porosity | Time (ms) |
|-------------|-------------|----------------|----------|----------|----------------|----------------|----------|-----------|
| 5,842       | 5,926       | 5,926          | 6,019    | 6,106    | 6,175          | 6,238          | 6,360    | 6,481     | 6,544     |
| 6,293       | 6,360       | 6,423          | 6,481    | 6,544    | 6,610          | 6,675          | 6,748    | 6,821     | 6,894     |
| 6,926       | 6,999       | 7,062          | 7,126    | 7,190    | 7,253          | 7,316          | 7,379    | 7,443     | 7,516     |

Figure 3: Composite logs for well Usaylah-1 (U-1). Clean sand intervals in the Unayzah Formation are delineated by low values of Poisson's ratio that correlate with low values on the gamma ray log.

Figure 4: Lithology and porosity logs of well Usaylah-1 showing that the sand/(silt+shale) ratio is a better indicator of lithology than porosity alone.
An important issue was the selection of the optimal size of the source array. It was found that the quality of signals obtained from a typical 30 m x 30 m shear-source array was inferior to the signal from a 15 m x 15 m array (Figures 6a, b). The poor signal quality from the larger array can be attributed to the detrimental effect of large intra-array shear-wave statics.

The 3C receiver arrays used for the acquisition of the surface data were deployed in an orthogonal pattern of 12.5 m in the inline direction and 2.5 m in the cross-line. They consisted of two parallel strings of six 3C receivers connected in series. Group and source spacing were 15 m. The acquisition geometry is shown as Figure 7. The spread was off-end with 480 channels at 160 channels per component. The nominal fold was 80. Alternatively, a split-spread design could have been used and may have been advantageous for the analysis of forward and reverse traveltime branches in refraction studies. However, limitations in the number of available 3C geophones would have dictated a coarser group interval of 30 m.

The data were acquired using two sets of vibrators. These were conventional Litton LRS-362 (60,000 lb peak force) for the P-wave, and Mertz M-185 (30,600 lb peak force) for the S-wave. The P-wave sweep was 60–80 hertz (Hz) and the S-wave 6–50 Hz. Both were upsweeps and the sweep length was 22 seconds in both cases. The P vibrators were driven to 75 percent of peak force and the S vibrators to 50 percent to ensure that distortion remained minimal. The receiver elements had a 10 Hz response.
Strong, low-frequency (5–20 Hz), source-generated noise in all nine components posed a major challenge for the processing of the data. Among many techniques and test trials, frequency-wave length (F-K) filtering proved effective in attenuating the coherent surface wave noise. However, it was decided to use F-K only for conditioning the data prior to residual statics and velocity analysis, and to exclude it from the stack processing flow to avoid smearing of the data and loss of the high-frequency content. Surface-consistent deconvolution that was part of the stack flow also proved effective in attenuating some of the coherent noise.

Figure 7: Schematic illustration of the acquisition geometry. Sign convention for the SH and SV components is shown. The spread was off-end.
In general, the quality of the P-P and SH-SH stacks is good. The SH-SH is better than the SV-SV and, rather surprisingly, better than the P-SV, which in turn is better than SV-SV. These four stacks are shown as Figures 8a to 8d for Line 1. The P-SV (and P-SH) velocities were extremely difficult to pick because of the poor signal-to-noise ratio of the data. Consequently, the P-S velocity field was synthesized from the available P-P and SH-SH velocity fields. This new velocity field was then perturbed by fixed percentage increments of 2.5 percent and the optimal velocity was picked from the best stack response. Higher order normal moveout was applied to the common conversion point (CCP) gathers to account for the non-hyperbolic nature of the moveout. The binning of the CCP gathers was achieved by means of a time-variant approach with space and time variant $V_T/V_S$. Finally, P-S dip moveout with a constant $V_T/V_S$ was carried out.

Rotation of the horizontal components resulted in no preferred axis of orientation and indicated that little or no azimuthal anisotropy existed in the data. Similar conclusions regarding azimuthal anisotropy in the near surface were drawn from the analysis and rotation of the 9C uphole data. The upholes consistently indicated a three-layer model for the near surface with a fast transition into a high-velocity limestone layer occurring at an average depth of 70 m. The average $V_T/V_S$ ratio of the near surface (top two layers) was about 2.8. The $V_T/V_S$ of the limestone layer was 2.0 with $V_T$ consistent at 4,000 meters/second. Refracted arrivals from the high-speed limestone layer for both the P-P and SH-SH data were systematically picked and analyzed, and near-surface models for P and S were constructed that correlated satisfactorily with information obtained from the uphole data.

![Figure 8a: Stack section, Line 1: P-P.](image)
Figure 8b: Stack section, Line 1: SH-SH.

Figure 8c: Stack section, Line 1: P-SV.
Figures 9a and 9b show migrated stack sections of the P-P and SH-SH components, respectively, for Line 1. Interpreted picks for the tops of the Khuff and Unayzah formations and of the pre-Unayzah Unconformity (PUU) are also shown. The validity of all picks was verified by tying the seismic data with P and S synthetics at the available wells. PP and SS isochrons and interval-time $\Delta t_P/\Delta t_S$ ratios computed from the horizon picks allowed us to compute average $V_P/V_S$ ratios for the Khuff and Unayzah intervals (Figures 10a and 10b). The two $V_P/V_S$ profiles have different trends and values that reflect the differences in lithology and depositional history between the two intervals. The $V_P/V_S$ ratios for the carbonate Khuff interval (Figure 10a) are in a narrow range from 1.8 to 1.98 that indicates a carbonate lithology. The higher values in the eastern part of the profile indicate limestone that is purer than elsewhere and coincident with the location of a known paleohigh. Away from the paleohigh, greater amounts of dolomite are to be expected with consequently somewhat lower $V_P/V_S$ ratios. This is indeed the case near well Umm Jurf-4.

Sand and silt percentages measured from the available logs are superimposed on the $V_P/V_S$ profile in Figure 10b. The $V_P/V_S$ ratios for the target clastic Unayzah interval vary widely from 1.5 to 2.8 and indicate lithologies that range from clean sand to silt and shale. The lowest seismic $V_P/V_S$ ratios correspond to higher percentages of sand in the Unayzah interval whereas higher ratios relate to higher amounts of silt. The lowest $V_P/V_S$ value of about 1.6 in the center of the profile corresponds to...
Figure 9: Migrated stack sections on Line 1 with interpreted picks for major horizons (PUU = pre-Unayzah Unconformity): (a) P-P; (b) SH-SH. Note that in (b) the time scale is half that in (a) in order to facilitate visual comparison between the two sections.
Figure 10: Profiles of average $V_p/V_s$ ratios for Line 1, computed from $\Delta t_s/\Delta t_P$ interval-time ratios for (a) the carbonate Khuff interval above the Unayzah and (b) the clastic Unayzah interval. Note in (b) the strong correlation between the seismic $V_p/V_s$ ratios and log-measured silt and sand percentages in wells Umm Jurf-8, Umm Jurf-1 and Umm Jurf-15.

Higher $V_p/V_s$ suggests cleaner limestone lithology; coincides with area of known paleo-high in the Khuff.
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a thick section of wadi-fill sand. The structural expression of the wadi is evident in the seismic stack sections. The high values of about 2.7 in the western part of the profile indicate silt and shale whereas intermediate values of about 2.0 in the east indicate a mixture of sand and shale. These lithologies interpreted from the seismic $V_P/V_S$ ratios were confirmed by the gamma ray log. Figure 11 is a stratigraphic cross-section for Line 1 based on well log information with the gamma ray logs superimposed. Notice the truncation of the upper Unayzah sands against the pre-Khuff Unconformity west of well Umm Jurf-1 and the correlation of high gamma ray values with silt.

CONCLUSIONS

A pilot 9C-2D experiment consisting of three seismic lines totaling 36 km in length was conducted in central Saudi Arabia with the objective of delineating lithological variations within the Unayzah reservoir. The complementary 9C-downhole surveys in five shallow wells on the seismic profile helped in the design of field arrays and provided calibration points for P- and S-wave statics. The analysis of the horizontal components of the surface and downhole data showed no significant amounts of azimuthal anisotropy. Special attention was paid during data processing to statics estimation by means of systematic picking of P-P and SH-SH refracted arrivals. Average $V_P/V_S$ ratios were estimated from $\Delta t_S/\Delta t_P$ isochron ratios that were obtained from the P-P and SH-SH stack sections for both the clastic Unayzah and the overlying carbonate Khuff intervals.

Low $V_P/V_S$ ratios of about 1.6 in the Unayzah indicate the predominance of clean sands whereas higher ratios of about 2.4 relate to silty sand and shale. This interpretation has been validated at several control points using well log data, including dipole shear, that show a strong correlation between low $V_P/V_S$ ratios and high sand-to-silt and shale ratios. $V_P/V_S$ values estimated for the overlying...
Khuff interval have a different pattern and fall into a narrower range of from 1.8 to 1.98 corresponding to a carbonate lithology. Values near the upper end of this range in the vicinity of a known paleohigh, indicate pure limestone surrounded by dolomitic limestone.

In conclusion, variations in average $V_P/V_S$ ratios that are estimated from PP and SS isochrons for the carbonate Khuff and clastic Unayzah correctly delineate lithological changes within them. Future work on this project will focus on the analysis of the converted wave data and on the estimation of interval $V_P/V_S$ ratios from joint P and S post-stack amplitude inversions.

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