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Increasing Bandwidth for Reservoir Characterization with Single-sensor Seismic Data

A case study from Libya's challenging Lehib field

From November 2006 to March 2007, Sirte Oil Company successfully conducted the first application of the WesternGeco Q-Land single-sensor seismic system in Libya. The goal was to see if single-sensor acquisition and processing of 3D seismic data could enhance the seismic data resolution and help construct a more accurate reservoir model of Libya's challenging Lehib field.

Compared to conventional acquisition methods, the Lehib survey showed an improved signal-to-noise (S/N) ratio and broader bandwidth over the target zone. One key to its success was the ability to integrate acquisition geometry, source design, processing, and interpretation.

The Challenge

The survey covered about 400 sq km in Concession 6, some 130 km south of Marsa Brega, over a variety of challenging desert terrain (*Figure 1*). To the north and east, the land is dominated by a hard limestone plateau that drops over steep 150-m escarpments to a sandier area below. To the south are low dunes and an extensive area of harsh flatlands that are inaccessible by vehicles. The established oil and gas infrastructure within the producing field presented further challenges to the acquisition team.

The Basin

The Sirte Basin consists of sedimentary infill with a series of raised horsts (long, elongated blocks between two faults) and grabens (horsts displaced relative to the blocks on either side). The first commercial discovery in the Sirte Basin was in April 1958, and recoverable reserves are now estimated to be about 40 billion barrels of oil.

The Lehib field is a faulted anticline that trends west-northwest to east-southeast over a block-faulted horst on the western margin of the Zelten platform. Lehib was discovered in 1965 and produces oil, gas, and condensate. Most of the producing zone varies from a sandy limestone to a calcareous sandstone, and there is additional production from the underlying sandstone formation.

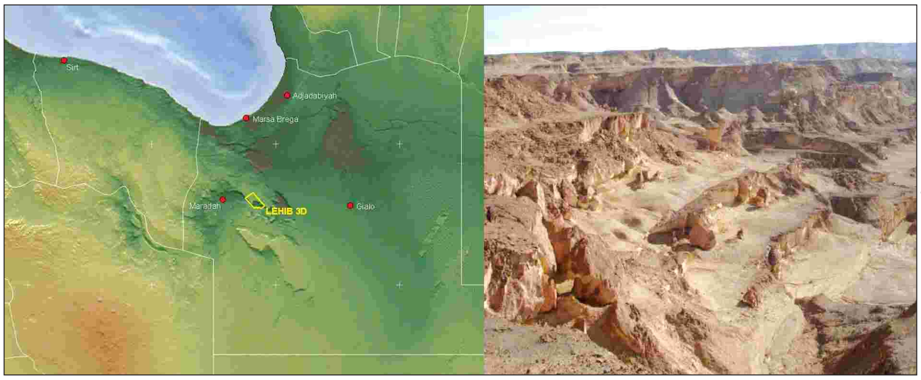

Figure 1: Location and topography of Lehib survey area.

All graphics are courtesy of Schlumberger

The primary objectives of the new seismic survey were to outline the extent and thickness of the Waha reservoir at the main Lehib structure, to identify fluid contacts, and to determine any potential reserves away from this structure. A secondary objective was to determine the fracture density and fracture/fault orientation at the Gargaf level.

The Waha formation lies at a depth of about 2.5 km and produces from zones up to 110 m thick, thinning to zero thickness. It has previously been mapped using the overlying Kalash marker formation.

Survey Design

The survey design team reviewed well log models and previous seismic data, and conducted field tests to determine the parameters for acquisition and processing. The key geophysical requirement for the survey was to achieve maximum frequencies of 70 Hz or better.

By testing the single-sensor acquisition geometry, the design team evaluated both the signal and the coherent, source-generated noise characteristics of the survey area. In pre-survey tests they also measured the velocity, frequency, and wavelength of each noise mode, and tested different digital group forming (DGF) schemes to reduce the level of coherent noise while leaving the underlying signal intact.

Seismic data in this area typically shows recoverable frequencies up to 40-50 Hz. Conventional acquisition methods combine and average signals received by adjacent receivers, but the Q-Land system records individual digital single-sensor traces. Both signal and noise are recorded with adequate spatial sampling and accuracy such that superior noise removal can be performed, and signal fidelity preserved. With Q-Land, we expected to increase the maximum recoverable bandwidth by up to 20 Hz.

Survey Parameters

The Lehib survey was acquired using a live spread of 22,272 single sensors, with an inline sensor spacing of 10 m. Each receiver line used four sub-lines of sensors spaced 10 m apart. DGF was applied to groups of 16 geophones (on a 4x4 grid) to deliver 40-m intervals for subsequent processing.

The single-sensor system records data with geophone accelerometers (GACs) that provide signals with broader bandwidth and less low-frequency distortion than the velocity geophones typically used for surface seismic data acquisition. Combined with an effective broad-bandwidth source, GACs offer higher resolution imaging and more reliable seismic inversion than alternative sensors.

Two vibrators, each with a peak force of 60,000 pounds per foot, provided the seismic source. The vibrators were spaced 15 m apart and each delivered a 5 to 80 Hz signal. The WesternGeco proprietary Maximum Displacement sweep (MD Sweep) was used to complement the high-fidelity recording system and enhance the low-frequency content The MD Sweep enables vibrators to output the required ground-force power spectral density (PSD) without spending more time than necessary level at the beginning of the sweep in a way that is optimized for the vibrator and permits the transmission of the maximum energy from the vibrator to the ground.

The ability to record single-sensor data was a key advantage in Lehib's rolling dunes and steep escarpments. With conventional systems, the outputs of all the sensors in an array are combined before being recorded for subsequent processing. Each sensor array in the Lehib survey extended over a 40x40 m area. The elevation differences of the sensors within the array can be considerable in such surface conditions, creating a significant difference in the time of the signals reaching individual sensors. Most acquisition methods simply do not correct for these variations between sensors within each group. This can lower the data fidelity by altering the combined signal arrival-time and decreasing the signal strength and bandwidth. Using single-sensor data allows correction of these intra-array perturbations before group forming.

Effective Noise Attenuation

Because Lehib is a producing field, parts of the survey area had high levels of ambient noise. Some traces recorded high-amplitude spikes – particularly those from geophones close to the vibrators. Acquisition using single-sensors enabled an attenuation process to remove such unusually high amplitudes.

Following digital group forming, a certain amount of coherent noise remained. In any seismic survey, coherent noise is the unwanted data that is consistent from one trace to the next, such as ground roll or multiple reflections of the original source output. To reduce coherent noise, we applied a combination of cross-spread filters to model the noise, followed by adaptive subtraction to remove it.

To address incoherent random noise, such as the sound of heavy equipment moving about on the surface, an additional pass of common-offset filters was run to further improve the signal-to-noise ratio.

Reservoir Characterization

Schlumberger Reservoir Seismic Services carried out a full reservoir characterization study of the single-sensor seismic data. Seismic data were integrated with the borehole data to further understand the rock and fluid properties. This included building a static reservoir model that was populated with the spatial distribution of facies type,

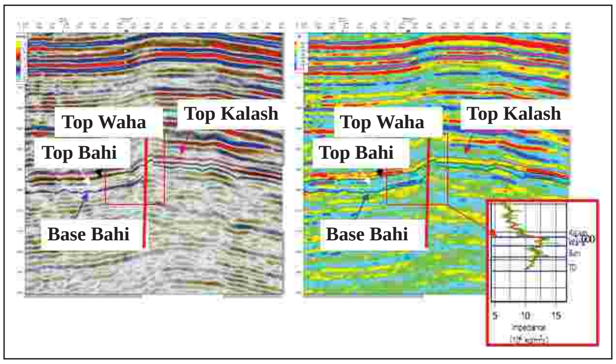

Figure 2: The well/seismic tie indicates that Kalash is an increase in impedance, and therefore, a trough on the seismic data. Waha and Bahi are decreases in impedance, and hence, peaks on the seismic data.

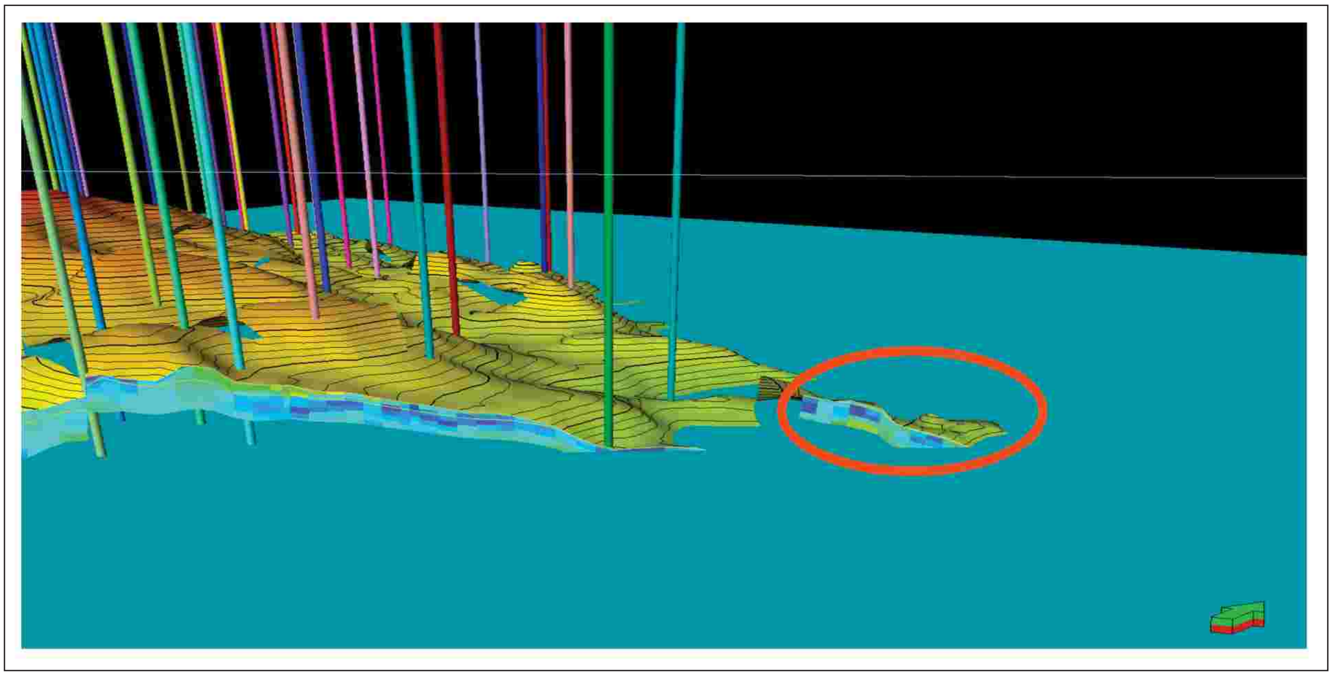

Figure 3: Base Kalash depth surface with depth slice (blue) depicting depth when the structure was isolated from the main Lehib field. A slice is displayed through the lead and Well UU12. Acoustic impedance (AI) is resampled into the cross section.

effective porosity, matrix permeability, and hydrocarbon saturation in each reservoir layer. Simultaneous AVO inversion to impedance volumes and a detailed petro-acoustic well calibration aided interpretation and constrained interpolation of reservoir properties in the interwell space. The static reservoir model was used to generate a list of prospects and leads, ranked according to their hydrocarbon potential and reserve estimation.

Interpretation and Inversion

Both the seismic amplitude data and the simultaneous inversion results were interpreted with well logs and marker information, correlated and tied to the seismic data. In the reservoir interval, the inversion data were particularly important in distinguishing between top Waha and top Bahi. The inversion results provided good resolution and ability to map the Waha and Bahi formations. *Figure 2* (*previous page*) shows the relative absolute impedance compared to the seismic data.

Model Building and Property Mapping

A geological model was built using picked faults and 3D interpretation. The model was gridded and layered to provide fine detail. The grid system allowed the sampling of seismic attributes such as acoustic impedance and the petrophysical properties from the well in a common framework. Lithology, porosity, and fluids were predicted from within the frame. Facies changes within the Waha formation were geostatistically mapped, incorporating information from completion logs. Petrophysical rock properties were also geostatistically mapped using derived petrophysical logs and inverted rock properties.

Reserve Estimates and Drilling Locations

Using the new interpretation from the single-sensor data and the geological model, the remaining reserves increased by approximately 8%. Moreover, by using the new geological model and the current and original oil/water contact (OWC) information, several new leads with potential drilling locations were identified within the main Lehib structure. *Figure 3* illustrates one lead;

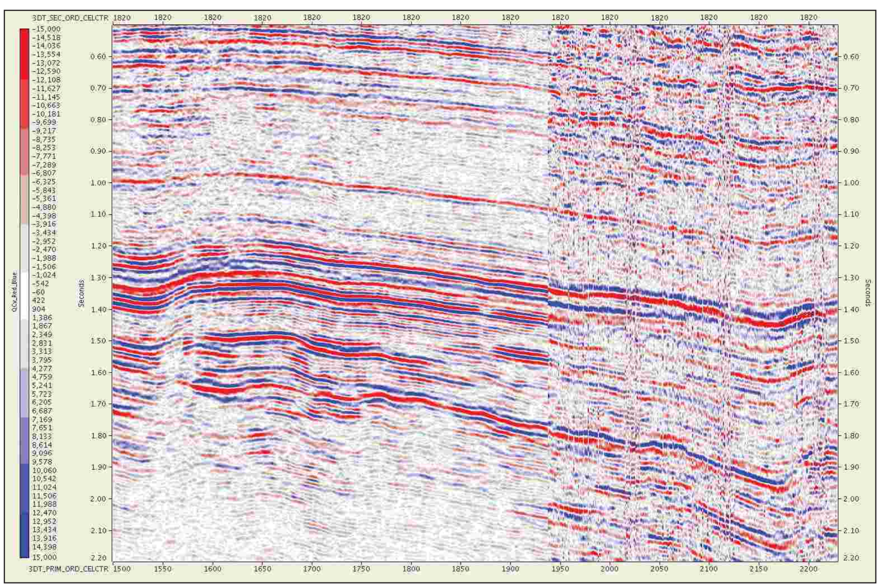

Figure 4: The Arshad South conventional seismic section (right) is compared to the extended section of the newly acquired Lehib data (left).

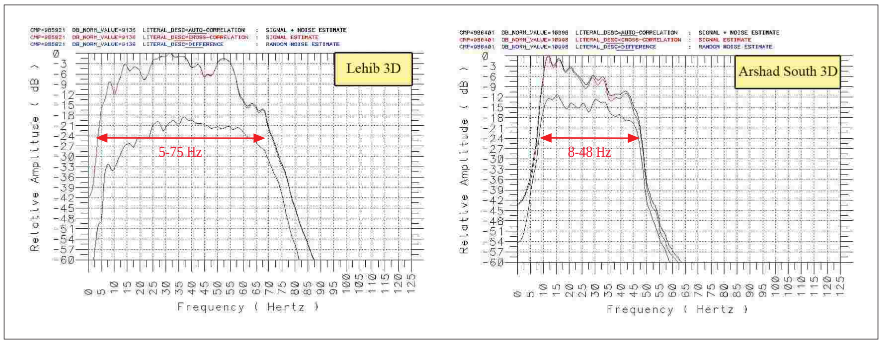

Figure 5. Amplitude spectra over 1000 -2000 ms TWT for the Lehib Q-Land and Arshad South conventional 3D surveys.

a fault-bounded stratigraphic high on the eastern flank of the main Lehib field.

Survey Results

The Lehib survey, using single-sensor data, achieved an increase in both the signal-to-noise ratio and bandwidth over the target zone. Maximum frequencies of 70 Hz or better were achieved as indicated in *figure 5*. Compared to conventional surveys, the enhanced resolution and frequency in the single-sensor data added confidence to our interpretation, a better match with the existing well data, and ultimately, a more accurate reservoir model.

The additional lower frequencies reduced dependence on the low-frequency background geological model in the simultaneous AVO inversion, effectively allowing the seismic data to control more of the derived reservoir rock properties.

When the results were compared with a conventional 3D survey from the adjacent Arshad South field, the Lehib survey achieved an increase of 20 Hz in bandwidth and 12 dB of additional separation between signal and noise.

This study demonstrates how single-sensor technology properly sampled the 3D seismic wavefield in the Lehib area, and effectively removed noise and corrected deviations in the collected data. This resulted in increased bandwidth and signal fidelity in the prestack data, which significantly improved final data quality in an area where conventional seismic techniques had traditionally not shown enough detail to effectively manage the reservoir.

The reservoir characterization workflow has lead to a revision of the reserve estimates and identification of two leads on the main Lehib structure, five compartmentalized leads around the Lehib field, and three leads in other parts of the study area.