5028 A Low Frequency Passive Seismic Survey in Libya

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Introduction

A growing number of passive seismic surveys at different oil and gas field locations throughout the world have established that hydrocarbon (HC) reservoirs modify the spectral content of the ambient noise field measured at the surface (e.g. Lambert et al. 2008, van Mastrigt and Al-Dulaijan, 2008 and references therein). The main observation (Dangel et al. 2003, Saenger et al. 2007) is a positive energy anomaly in data spectra between 1-6 Hz for measurements above a reservoir that is absent over wet formations. Such a hydrocarbon reservoir indicator is a useful de-risking tool which is complementary to structural imaging using active seismic methods. Passive data can be acquired in frontier areas to focus active seismic data collection, corroborate trap and accumulation over positive structures and for optimization of drilling locations.

Steiner et al. (2008) showed that the reservoir zone is the origin of the energy anomaly observed in the frequency domain. The method extrapolates time-reversed surface data into the subsurface with a fully elastic propagator and saves the maximum particle velocity at every location in the model domain as an imaging condition. Sources are thereby re-focused in the subsurface. The co-location of the energy source and the reservoir shows that the reservoir acts as a secondary source of seismic energy by modifying the background wave field. The rock-physics describing potential mechanisms for the modification are discussed in Walker (2008).

Many individual energy sources contribute to the full spectrum of the ambient seismic noise field in the earth, which is modified by interaction with a reservoir. The Low Noise Model developed by the U.S. Geological Survey (Peterson 1993) identifies a strong energy component due to ocean waves interacting with the coast line at ~0.14 Hz, and a seismically quieter window, usually between ~0.5-10 Hz, before local (largely anthropogenic) energy dominates the background wave field at higher frequencies. Energy anomalies associated with reservoirs observed within the relatively quiet window can be caused by a modification of the components of the background wave field from either side of the low energy window.

Figure 1 shows schematically the hydrocarbon energy anomaly (red) visible in the relatively quiet frequency window between the ocean wave energy (blue) and local energy (yellow). The power spectral density (PSD) plot of the measured noise field is the envelope of all constituents. The frequency of the background minimum is indicated conceptually and does vary over time. The hydrocarbon signal is a total energy anomaly defined by the area under the curve in a region of the PSD plot. The amplitude of the first minimum of the PSD curve is indicated by diamonds and can be used as a measure of the level of total energy in the ambient noise field in the frequency band of interest.

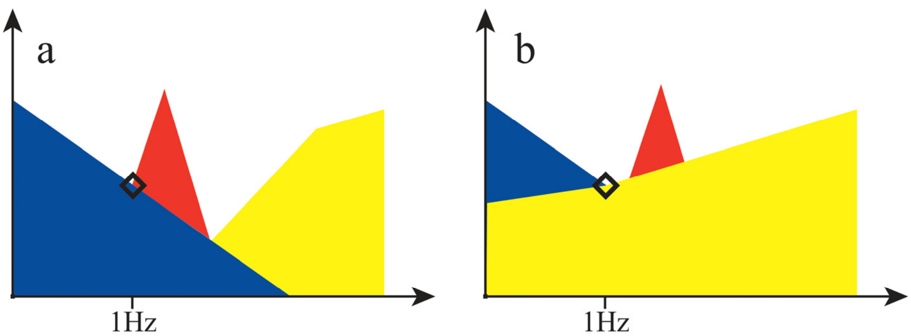

Figure 1: *Alternative models for the dominant energy source triggering HC signals (red area).* ***a)*** *The flank of the ocean peak (blue) as source.* ***b)*** *The flank of local noise (yellow) as source. The black diamonds highlight the first minimum of the PSD plot.*

Data from surveys collected at many locations on the globe have very similar characteristics, which leads us to assume a common source stimulating the HC signal (red area of Figure 1a): the relatively constant ocean wave energy. Active stimulation of HC microtremor is presented in Kouznetsov et al. (2005) with vibrator sources and Nguyen et al. (2008) with an earthquake source. While both presentations show that energy other than the global ocean wave energy can additionally stimulate the HC microtremor signal, they also warrant the search for naturally occurring energy sources from higher frequency bands.
Figure 1b presents the case where the HC signal is a modification of the higher frequency background energy (yellow). The energy at higher frequencies can usually be correlated with time of day: total energy is less at night than during the day, due to human activity during the daytime. However, if the energy in yellow sources the HC anomaly, we would expect the red area to track the diurnal changes of the ambient noise field rather than diminish as the envelope of the yellow area increases. A passive seismic data set recently collected in Southern Libya has several unique features that indicate the latter model for HC anomaly sourcing.

Survey

In 2006 a relatively large passive seismic survey was conducted in the Murzuq basin in Southern Libya near the Algerian and Niger borders. The survey was centered over a producing field and recorded data at more than 200 locations in areal grid patterns and long (~30 km) lines. The desert terrain in this location has an unconsolidated surface sand layer of unknown thickness. However, if there are no significant lateral variations in the near subsurface, low-frequency measurements of HC microtremor anomalies are tested to be relatively independent of well-known soft-soil layer effects. Very low shear wave velocities of the unconsolidated sand will generate strong scattering and wave conversion effects.
The known reservoir within the survey is situated approximately 800m below the surface. At this depth, the elliptical Rayleigh waves (RW) from the ocean wave energy that passes through the reservoir still contain substantial horizontal and vertical particle motion. For deeper reservoirs (around 2500m) RW particle motion at 0.2 Hz is almost totally vertical. This preferred direction is usually also visible in the hydrocarbon microtremor signal (Saenger et al. 2007), which further substantiates the assumption that the ocean wave energy is the common source for observed HC anomalies. However, the shallow depth of this reservoir means no preferred orientation of particle motion should be expected for either source mechanism presented in Figure 1.
The survey was designed as a proof of concept test over a known reservoir. In addition to the noise associated with flowing fluids and pumps, there was drilling and work-over activity during the day. As such, it is impossible to eliminate, with absolute certainty, production noise as the primary source of the energy anomaly expected over the accumulation. By the same argument, it is possible that production processes provide additional energy that is modified by the hydrocarbons resulting in frequency-domain anomalies. Continuous production centered within the area of acquisition generates an obvious signature in the passive records. Figure 2 shows integrated amplitude maps accumulating energy from 20-40 Hz during day and night intervals. The total energy during the day is greater than at night, but both maps show similar patterns for energy associated with production activities that operate continuously.

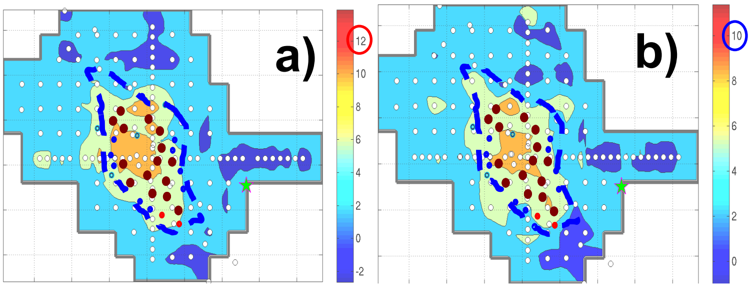

Figure 2: *20-40 Hz energy maps with structural closure and well locations overlay. White dots are station locations. Note color scale differences.* **a)** *Day data.* **b)** *Night data. The star is the location of the crew camp.*

Figure 3 shows a 2 hour spectrogram from a station in the center of the survey. The lower plot is the 1-5 Hz section of the upper. Continuous (time) monochromatic signals are indicative of machinery noise. To obtain a clean, stable signal related to HC presence, we remove time intervals with transients (e.g. vehicle noise) containing energy extending into the frequency range of the HC anomaly (blue oval). Thus, the interval in the red oval would be removed, while the bulk of the time indicated by the black arrow could be used to calculate a PSD response for this station. This is an important preprocessing step and is the first interpretative step in the workflow. Most contamination problems can be resolved due to separation of signal from noise in space, both frequency and time, and by the acquisition of at least 24 hours of data at every station.

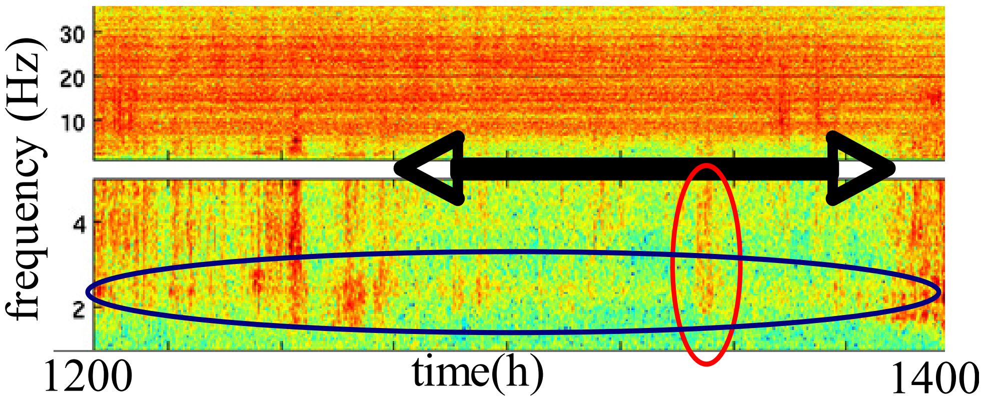

Figure 3: *Spectrogram for a typical point located in the high noise area of this survey. Black arrow shows good interval, red oval bad transient, blue oval HC signal.*

While some of the gross features within the data are readily interpretable with respect to the reservoir location, there are many features that still require further study. The data show a very large difference in the total energy recorded during the day vs. at night. The day interval shows steadily increasing total energy that tracks the heating of the desert by the Sun.

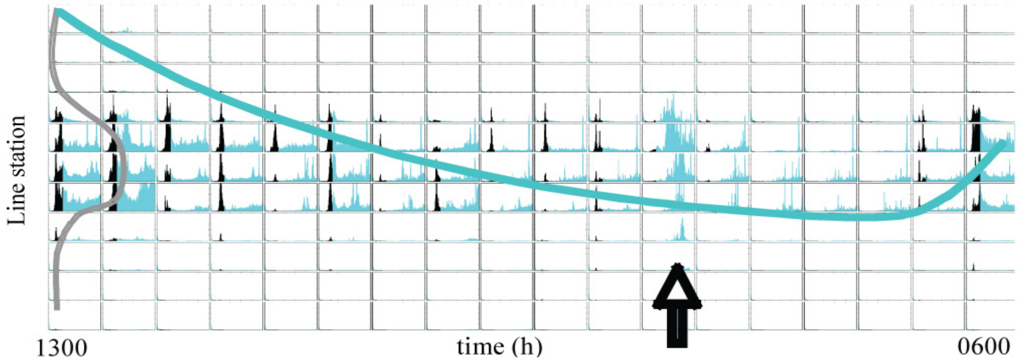

Figure 4: *Time evolution of hydrocarbon signal along a 30 km line crossing reservoir. Individual spectra are calculated from 1 hour of data. 1-3 Hz is highlighted in black. The gray line overlay indicates trend of HC signal along in-line. The blue line overlay indicates trend of decreasing energy during the night.*

Data were also collected along three ~30 km NW-SE (the long axis of the elliptical reservoir) lines that are approximately three times longer than the diagonal extent of the maps in Figure 2. Figure 4 shows the spatial and temporal variation of the data along one such line. The vertical axis progresses to the SE from the top. Each individual box is a PSD plot [0.5-15 Hz] using one hour of data. The vertical axis within each plot is a logarithmic scale, so the changes seen in the records are order of magnitude or more in scale. The first column uses data during the hour 13:00-14:00 and 18 hours of data are shown (13:00-06:00). One hour of data is insufficient to assure stable, high quality results but is used here to highlight the large change in the total energy in the records.

The hydrocarbon signal for this survey area is located between ~1-3 Hz. This energy is highlighted in black on the figure. The gray line overlay shows the trend of the hydrocarbon signal along the survey line. The evolution of the total energy recorded through a daily cycle is indicated by the blue line overlay. The raw data used to generate this plot has not been edited to remove transient signals. The black arrow at 24:00 highlights the influence of a strong event on the calculation of PSD. The intriguing aspect of this presentation of the data is that the hydrocarbon signal decreases steadily over the late hours of the day and is nearly absent during the night interval, when the overall level of energy in the recording is very weak.

Figure 5 shows data from two of the stations within Figure 4. The solid lines are data from a station over the center of the reservoir; the dashed lines are from the very end of the line, some 15 km away. In both cases, the version with greater total energy is calculated with data from 12:00-16:00, while the less energetic lines are from 00:00-04:00.

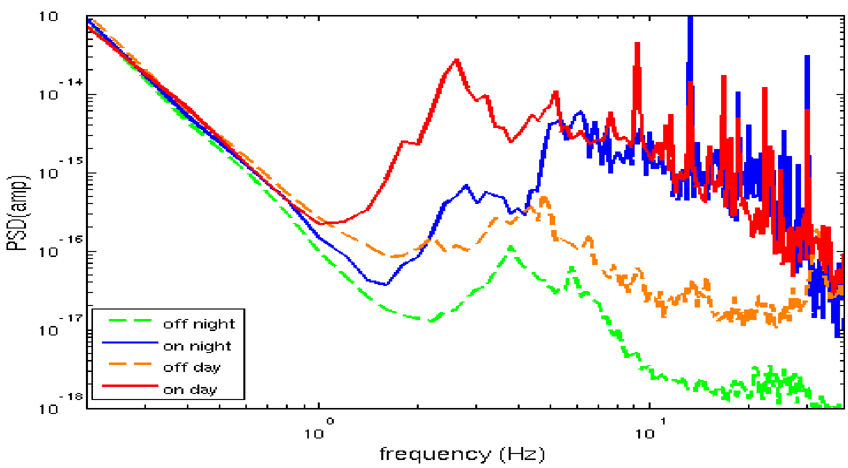

Figure 5 *PSD plot for station over reservoir (solid lines) and 15 km away (dashed). High amplitude versions use data from 12:00-16:00. Low energy lines use data from 00:00-04:00. HC anomaly is between 2-4 Hz on solid lines.*

The end station, 15 km distant from production, contains no production noise. The smooth bowl-shape of the dashed lines between 1-4 Hz is typical of the low noise model (Peterson 1993). The energy hump in the dashed lines from 2.3-10 Hz is interpreted to be a characteristic of the local noise field, unrelated to hydrocarbons. Absent the understanding that this data was acquired away from the reservoir, this feature could well have been interpreted as a potential hydrocarbon signal.

Human activity cannot explain the overall increase in the energy budget across the entire length of the line. Production related noise in the solid lines is very stable and isolated above 6 Hz (also Figure 2). Wind and temperature effects associated with the sand, the so-called singing dunes (Douaday et al., 2006), both contribute to the energy budget of the desert to a large extent. Importantly, this isolated desert location suffers no anthropogenic noise away from the main facilities in the area. Even at measurement stations tens of kilometers away from any human activity, recordings during daylight hours contain about an order of magnitude more energy than at night as shown by both pairs of curves in Figure 5.

The solid lines show a positive energy anomaly between 2-4 Hz that has no counterpart on the dashed lines. The distinct separation of this feature from the production noise beginning at 5 Hz is obvious on the data from the night, though it blends into the background energy during the day sufficiently well that it would be missed without the night data as reference. The peak amplitude of the feature is approximately 30 times larger during the day interval.

The solid red line in Figure 6 shows the evolution of HC signal from the sensor in the previous figure over a daily cycle. The value is schematically shown as the area in red in Figure 1. The black dashed line is amplitude of the first minimum shown as the diamond in Figure 1. This value is a convenient measure of the total energy in the low frequency part of the background wave field. The blue dashed line is the temperature of the sensor. Since the seismometers are buried during acquisition, there are magnitude and phase differences between instrument and outside temperatures. However, because the solid lines above 6 Hz in Figure 5 overlay so well, we conclude that there is no temperature effect on the instrument itself.

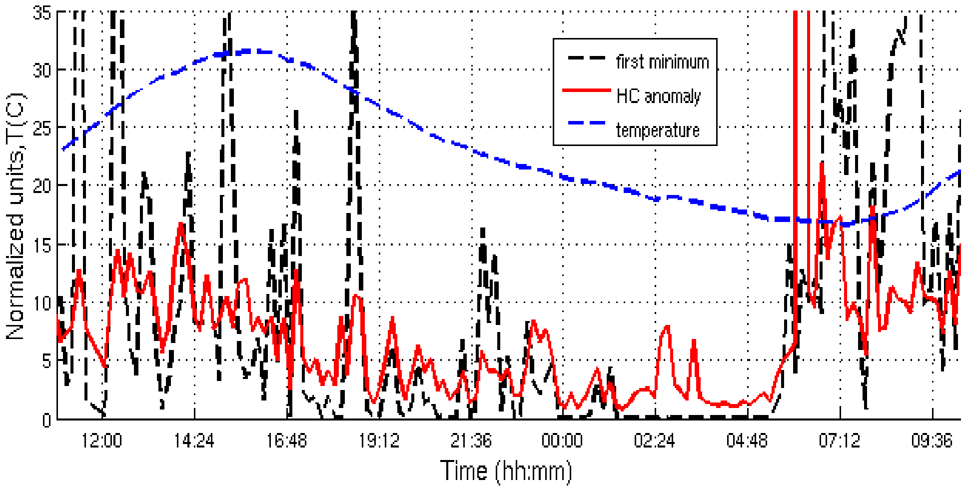

Figure 6 *Daily variation of energy budget and sensor temperature. Vertical axis is degrees C for blue temperature line, and normalized amplitude for first minimum and HC anomaly strength. Figure 1 includes the concepts to calculate both of the latter curves.*

The red and black lines have been normalized to show the character of the curves. The measure of the anomaly is an integrated area as compared to the amplitude measure used to quantify the total energy in the ambient wave field. Instead of the increased local energy during the day masking the HC signal, the magnitude of the HC anomaly changes in lock step even at very fine scales. The gross diurnal trend of the overall energy matches well the temperature data, although some allowance needs be made for the effects of burying the sensor.

Discussion and conclusion

The low frequency passive data acquired in this survey are complex. Local characteristics of the ambient wave field could be mistaken for hydrocarbon (HC) signal as seen in the broad peak around 4-6 Hz of Figure 5. Therefore, it was important to acquire sufficient data off the reservoir to characterize the local ambient wave field. In prospective areas, this can also be inferred from structural depth information. It is very important to remove the effects of human noise from the calculation of PSD plots to avoid misinterpretation of of the data. This is usually possible due to the spatial, temporal, and frequency separation of the HC signal from noise contaminates.
The magnitude of the ocean wave energy is very stable over periods of weeks. Figure 5 shows the stability of the ocean wave energy as well as the fact that the increased energy level during the day is coming from the high frequency direction. Figures 5 and 6 show the HC signal amplified by diurnal changes in the energy budget of the ambient wave field. The increase of energy from the local noise side of the seismic quiet window and coupled with the concomitant increase in the HC anomaly leads us to conclude that we are observing the sourcing model presented in Figure 1b in this data set. The night data still show a HC anomaly, which we attribute to the ocean wave energy (model Figure 1a).
The interpretation of such microtremor signals can be ambiguous since both the hydrocarbons and production noise are co-located. Supporting evidence that the low frequency anomaly identified here is in fact associated with hydrocarbons and not simply an artifact of production noise include: 1) the low frequency anomaly is distinct from the ambient noise frequency pattern, 2) there is no persistent correlation over time between the signal level of the higher frequencies and the lower frequency anomaly, and 3) the HC anomaly is amplified rather than masked by production noise.

Acknowledgements

We thank the licence holders Repsol-YPF, National Oil Corporation, OMV, Total and StatoilHydro for permission to publish the data presented in this study. We also acknowledge Dr. Rob Habiger, Sabrina Meztger, Dr. Tamara Mueller, Nima Riahi and Dr. Barbara Schechinger from Spectraseis for their contributions and work with this data set.

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