Preliminary Model of Hydrocarbon Reservoir Related Microtremors and Recent Application in the Potiguar Basin

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Abstract

Passive seismic low-frequency (between about 1 Hz and 6 Hz) data has been acquired at several locations around the world. Spectra calculated from this data, acquired over fields with known hydrocarbon accumulations, show common spectral anomalies. A preliminary model is presented which can explain the source mechanism of those microtremors. Poroelastic effects due to wave induced fluid flow and oscillations of different fluid phases are significant processes in the low-frequency range which can modify the earth's omnipresent seismic background spectrum. These processes only occur in partially saturated rocks. We assume that hydrocarbon reservoirs are partially saturated whereas the surrounding rocks are fully saturated. Real data observations are consistent with this conceptual model.

This paper also discusses a recent application of the technology in the Potiguar Basin, onshore Brasil. Although this project included acquisition, processing and some interpretation, only the main points of the project are highlighted, as follows: out of the five project areas, one area shows the highest potential, two medium and two low/no potential. Both PSD-IZ and V/H attributes are calculated for all areas, but given the high environmental and anthropogenic noise conditions in most areas, the V/H attribute proves to be the most reliable one, which correlates well with operator field knowledge of hydrocarbon locations. Also, a mini-survey conducted over the previous 2004 Mossoro I project location shows good repeatability of results in an area which has not been produced and utilizing new tools that do not require surface correction. Finally, we learned that 24hour measurements, longer synchronized lines and greater aperture are essential for this area, adding them into our requirement base for new projects in similar locations.

Introduction

The exact nature of the physical mechanisms of microtremors observed above hydrocarbon reservoirs (e.g. van Mastrigt and Al-Dulaijan, 2008; Lambert et al. 2009; Saenger et al. 2009a) is not fully understood. Since this is an on-going research field we expect a continuous refinement of the rock physics model presented in this paper. However, it is based on well-documented observations and well-known rock-physical wave propagation theories. Although there could be other mechanisms contributing to the low-frequency observations we assume that the rock-physical effects discussed below at least contribute to the observed signal characteristics. An important method for improving the theoretical understanding of this phenomenon is reported by Steiner et al. (2008). They suggested to utilize time reverse modeling to investigate whether the low-frequency anomaly originates from the hydrocarbon reservoir itself. This time-reverse algorithm images the locus of an energy source rather than imaging reflectors, as done by interferometry. This localization study complements a study by Lambert et al. (2009) on the observations of low frequency domain anomalies in the wavefield at the surface. We split our consideration into three parts: sources, mechanism and observations. As we do not use any active source, we have to consider the seismic background wave field. Second, we review possible rock-physical mechanisms within a hydrocarbon deposit which are able to modify the spectra in the low-frequency range above it. Third, we compare observed hydrocarbon reservoir related spectral attributes to the theoretical description of the source and mechanism questions.

Seismic background spectrum

The strength of ambient Earth noise was considered in detail by Peterson (1993). He developed a low-noise model which predicts the worldwide minimum energy for seismic background noise for a large frequency band. This spectrum has two important features with respect to microtremors. First, there is a relatively quiet interval between 1-6 Hz (i.e. a minimum). This is the frequency window where hydrocarbon reservoir related microtremors have been observed. Presumably, similar reservoir related rock-physical effects are also present in other frequency bands, but much more difficult to discriminate. Secondly, there is a dominant peak around 0.14 Hz. The origin of this peak is ocean waves interacting with the coast structure. This produces oceanic microseism which can be observed at all locations around the world. It is reported that the corresponding surface waves propagate through whole continents and can, for example, be used for determining seismic velocities down to a depth of 20 km. Interestingly, Rayleigh waves with frequencies around 0.14 Hz oscillate at reservoir depth (deeper than 500 m) mainly in vertical direction. This is illustrated in Figure 1.

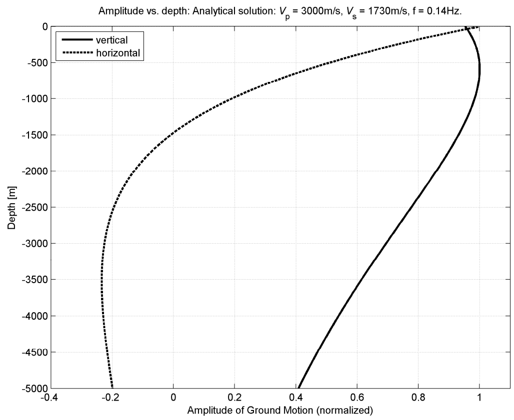

Figure 1: Amplitude vs. Depth for a Rayleigh wave of 0.14 Hz propagating through a homogeneous half-space. P− and S−wave velocities are set to 3000 m/s and 1730 m/s, respectively.

This preferred particle oscillation direction is also observed for the microtremors above a reservoir which show V/H values above 1 and a strong vertical polarization (e.g. Saenger et al. 2009a). Note that these waves have sufficient amplitude at normal hydrocarbon reservoirs depths to perturb the reservoir.

Rock-physical low-frequency mechanism

From a theoretical point of view it is very hard to explain specific low-frequency effects of a hydrocarbon reservoir with elastic properties only. We therefore consider poroelastic effects which can cause high attenuation uniquely associated with reservoirs and consequently increase the complex impedance contrast between the reservoir and the surrounding rocks. In that case the reservoir acts as a scatterer and we refer to the related effects as resonant scattering. We also consider micro-scale fluid oscillations caused by the surface tension between two pore fluids and refer to such oscillation effects as resonant amplification. Importantly, the mechanisms causing resonant scattering and resonant amplification can only occur in multi-phase, or partially-saturated rocks.

We assume that the hydrocarbon reservoir is partially saturated (e.g., with gas and water) whereas the surrounding rocks are fully saturated with water. The low-frequency resonant scattering and amplification effects therefore only occur within the reservoir and may modify the background seismic wave field in a way characteristic of the reservoir. These characteristic modifications can be observed in the spectral attributes above hydrocarbon reservoirs.

Another possibility would be a higher intensity of low-frequency fracture and/or fluid migration processes within the reservoir compared to outside the reservoir. Further possible non-linear mechanisms are discussed in Zhukov et al. (2007). However, a detailed review of those ideas is beyond the scope of this paper.

Resonant Scattering

Seismic low-frequency effects of hydrocarbon reservoirs have been known for many years (Chapman et al. 2006 and references therein). Chapman et al. (2006) state that 'abnormally high reservoir attenuation is the observed ground truth'. A high seismic attenuation of reservoirs in the frequency range between 1 and 6 Hz may be caused by wave-induced flow in partially saturated rocks. Following this argument, the reservoir itself acts as a strong scatterer of seismic waves because of high complex impedance in contrast to the surrounding rocks which have small or no attenuation (Quintal et al., 2009). Therefore, a reservoir may become visible at the surface by typical scattering phenomena like, for example, single scattered body waves or standing waves. However, standing shear waves would not generate anomalously high V/H values and the dominant frequency of the microtremor will be depth dependent, neither of which is generally observed in field data.

Resonant Amplification

Oil bubbles can be shown theoretically to oscillate in pore spaces (e.g. Beresnev, 2006; Holzner et al., 2007). The main restoring force of the bubbles in those considerations is the surface tension at the oil-water contact. From a theoretical point of view, all systems with a wetting and a non-wetting fluid exhibit a typical resonant frequency. Therefore this resonant amplification effect can also be present for reservoirs with partial gas saturation. Such oscillations can theoretically occur on many scales, for example on the pore scale, the typical fracture scale or the reservoir scale (for example around the oil-gas contact). It has been shown that the resonance frequencies can be in the frequency band between 1 and 6 Hz (Holzner et al., 2007). Seismic background waves reaching the reservoir can induce a resonant amplification of those frequencies. Frehner et al. (2009) show that those oscillations at the pore scale can be visible in the seismic spectra, measured at the surface above a reservoir. This has important consequences:

- These types of systems will emit energy after excitation (i.e. there is no perfect time correlation with the triggering source). This is consistent with considerations using an active seismic vibrator source (Turuntaev et al., 2006). Earthquakes can also be used to test whether hydrocarbon related spectral anomalies can be stimulated by seismic waves (Nguyen et al., 2008).
- Those systems will act as secondary sources and as such it should be possible to locate them. A localization method was suggested by Steiner et al. (2008).
- Preferred direction of the triggering waves will be inherited in the radiation pattern of the emitted wave field (i.e. V/H values above 1).
- Production noise at the surface may also stimulate the reservoir (Saenger et al. 2009b).

The preliminary rock physical model

We summarize our theoretical review in a preliminary interpretative model about the origin of hydrocarbon tremors. Although it may be necessary to modify this model in the future, it is consistent with theoretical investigations described above as well as with the experimental observations (i.e. the identified seismic attributes) of the surveys discussed in this paper. Figure 2 illustrates and summarizes the main points: Ocean waves generate low-frequency high amplitude Rayleigh-waves around 0.14 Hz which are observable worldwide. The strength of those waves varies in time and therefore they contain also energy around between 1 Hz and 6 Hz. As discussed, they oscillate at reservoir depth mainly in the vertical direction. Therefore we also expect this preferred direction for a resonant amplification effect of hydrocarbons in the pore space. It is not known whether and the degree to which non-linear effects are important in this process and this is part of ongoing research. The resulting radiation pattern of this secondary source will mainly emit *P*-waves in vertical and *S*-waves in horizontal directions. Additionally, any kind of body waves hitting the reservoir also contribute to the excitation of resonance effects. This is consistent with the observed microtremor attributes (e.g. Saenger et al. 2009a). An energy anomaly has been reported between 1 and 6 Hz above h Also oserved is a peak above 1 in the spectral V/H-ratio (e.g. Saenger et al. 2009a) and both are consistent with *P*-waves originating from the reservoir. The seismic attributes of the polarization analysis above hydrocarbons, i.e., a constant high dip of the particle velocity, a relatively high rectilinearity, a strongly varying azimuth, and a non-vanishing largest eigenvalue (Saenger et al. 2009a) are also in agreement with the model shown in Figure 2.

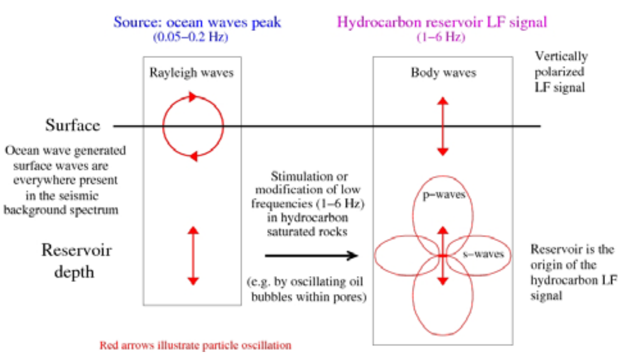

Figure 2: A preliminary model which explains the origin of hydrocarbon tremors and which is consistent with observed spectral attributes. One important observation is that the vertical polarization of the ocean wave generated Rayleigh waves at reservoir depth is also present in the low frequency (LF) hydrocarbon reservoir related microtremor signal.

The Potiguar Basin Project

A survey encompassing five different areas was carried out between August and November of 2007 (figure 3). Each area had a particular objective: Area **MOS-2A** (field extension, from the Mossoro I project), Areas **MOS-2B** and **MOS-2C** (exploration, seismically blind areas), Area **MOS-2D** (new exploration, block with deep gas potential), and area **MOS-2E** (new oil exploration block). In addition, we also surveyed a previously studied location during the Mossoro I project in 2004 (Macedo et al. 2005), to determine whether the newly acquired data matched the results presented in the previous survey (location had not been produced since the original survey).

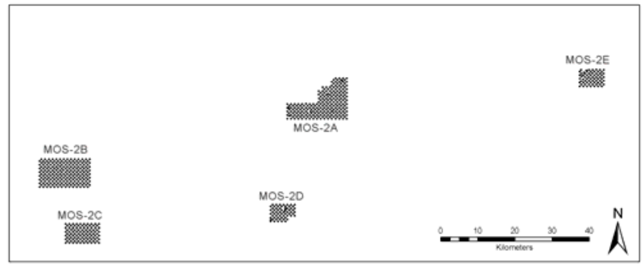

Figure 3: survey locations in relation to each other

A total of 1026 stations, including 40 stations for re-measurements of the 2004 project, were recorded utilizing 22 highly portable broadband seismometers, as shown in Figure 4. Each of the 18 movable stations measured between 8-10 hrs each (day time only), while the remaining reference stations measured continuously throughout the survey time, in each particular area.

Figure 4: 3-component, high sensitivity broadband seismometers.

Data Processing and Analysis

The processing of the data started in the field, with the Field Office Data engineer reviewing the recorded signal to ensure data quality before transmitting to the Processing Center in Zurich. The time signal was inspected to determine data quality, noise level, and 3-component recording, amongst other parameters. Properly recorded stations were then uploaded to the database via internet connections and defective stations were set to be re-recorded the following day.

After the data arrived in Zurich, the data was processed both in the time and frequency domain, removing transient noise and other perturbations. Standard processing also included total energy map plotting (noise mapping, by calculating the mean energy for each station), Earthquake analysis, performed by accessing the USGS database for information and comparing to our recorded signal, and noise pattern analysis (to determine fingerprints of artificial sources).

Once a clean stream of data was available, much of the analysis was done in the frequency domain. Power Spectral Density (PSD) is calculated using Yule-Walker Auto-Regression estimator method, with 40-second time windows on average, displayed in spectrograms. Synchrograms, or spectrograms of synchronized data, are displayed on a common timeline to better understand events and features of the signals. Spectral Distribution of Amplitudes (SDA) is calculated to show variations of the spectra, highlighting the most repeatable amplitudes. And Polarization analysis, an area under development previously discussed, is also carried out to further characterize any anomalies and other energy.

Survey Results

As expected, the results for each area varied depending on the local conditions and hydrocarbon content. Noise, a major problem during the analysis, was present in all areas, but particularly in Areas 2D and 2E, located near urban settings and/or industrial activities.

It should be mentioned that the two main attributes are independent, do not always coincide and each has its own advantages and disadvantages, which are taken into consideration at the time of interpretation of the results. Since we are looking for an energy anomaly, the PSD-IZ is often considered a primary attribute, but its weakness is that the area under the spectral curve calculated by this attribute can be contaminated by noise, leading to a biased attribute, and this appeared to be the case for this project. The V/H spectral ratio is less sensitive to general noise since the spectral ratio can effectively cancel noise that affects both components more or less equally, but its weakness is that is can be affected by local geology, especially in the near surface. Depending on the project, either or both attributes can provide good result and final interpretation is done with the customer utilizing the local knowledge and other data, if available, to determine the best suited result. For this project, there is evidence that the V/H spectral ratio maps provided good correlation with existing hydrocarbon locations, especially in Areas 2A and 2B, and are better suited than the PSD-IZ maps (due to the high noise levels in all areas).

A summary of the results follows: ***Area MOS-2A*** was the best prospective area with well-distributed LF anomalies and clear trends (Figure 5); additional geophysical data confirms this prospectivity. ***Area MOS-2B*** had smaller energy anomalies than Area I, with anomalies mostly clustered in the western portion of the block but still potentially interesting (per Petrobras knowledge). ***Area MOS-2C*** had moderate, intermittent LF anomalies, especially in the SE (under study for prospectivity). ***Area MOS-2D*** showed no clear LF trend, and contained perturbing noise in all frequencies. This area showed the lowest potential of the sub-set of surveys. ***Area MOS-2E*** also had no clear LF anomaly trend (low signal/noise ratio) and was highly contaminated due to wind and industrial activities, as well as being affected by surface geology (complex subsurface geology, water saturated/flooded ground).

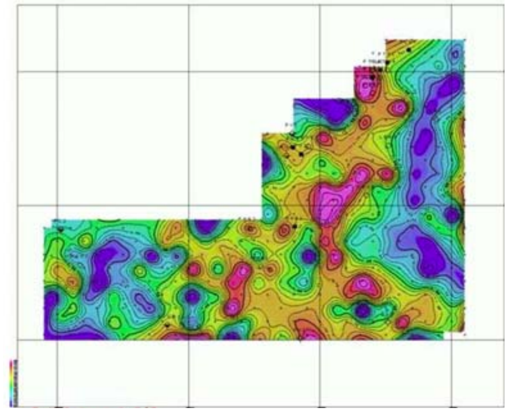

Figure 5: Area MOS-2A V/H anomaly map.

The comparison of the 2004 project results with the newly available attributes (2008) show good agreement, with the additional benefit that the new attributes have reduced sensitivity to noise and do not need calibration for surface effects (as done in the previous project). Both the old 3-Hz peak amplitude and the newly-acquired PSD-IZ (Saenger et al. 2009a) match, showing good prospectivity for the area, with the additional V/H ratio attribute also showing favorable results. It is clear, therefore, that even though there is a 3-year gap between projects, both surveys present similar results in an area that has not yet been drilled.

Areas of future improvements were identified and include mandatory 24-hour measurements (rather than day-only), more synchronized stations (30 or more), and greater aperture for better special coverage.

In summary, we observe a good correlation between field knowledge and the survey results for Areas I and II, and are studying the results of Area III. Independently from this study and before the results were presented, the Areas IV and V were classified as low prospectivity, which is in-line with the LF survey results. And finally, two surveys that lapse 3 years showed similar results, providing good repeatability and increased confidence in the presence of hydrocarbons in the area.

Conclusions

We propose a preliminary rock physical model in an attempt to explain the origin of hydrocarbon reservoir related tremors. Poroelastic effects due to wave induced fluid flow and oscillations of different fluid phases are considerable effects in the low frequency range which can modify the omnipresent seismic background wavefield. Both can contribute independently to the specific signal characteristics observed in the described survey and both are based on the assumption that the reservoir is a partially saturated multiphase system surrounded by rocks off the reservoirs that are mainly saturated with only a single fluid for which multiphase effects are not present. Our observed microtremor attributes above reservoirs are consistent with the preliminary model.

The practical experience in the Potiguar Basin described in this document showed good correlation between the field knowledge, achieved from standard geophysical methods, and the survey results. Things learned from this project included the need for 24 hour recording times and greater acquisition apertures, both of which will contribute to better results in future surveys.

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