Conceptual model of hydrocarbon reservoir related microtremors

Erik H. Saenger, ETH Zurich and Spectraseis, Marc-André Lambert and Stefan M. Schmalholz, ETH Zurich*

Summary

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, frequently show similar spectral anomalies. A preliminary model is presented to explain the potential source mechanism of microtremors generating the spectral anomalies. 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 in general agreement with this conceptual model.

Introduction

A number of surveys over different oil and gas fields throughout the world have reported the presence of spectral anomalies in the passive seismic wavefield, i.e., microtremors, with a high degree of correlation to the location of hydrocarbon reservoirs (e.g. van Mastrigt and Al-Dulaijan, 2008, Saenger et al. 2009a, Goertz et al. 2009 and references therein). If these microtremors originate from the reservoirs, they can be used as a reservoir indicator for optimizing well placement during exploration, appraisal, and development. In contrast to conventional seismic technologies, the investigation of hydrocarbon reservoir-related microtremors is generally passive and does not require artificial seismic excitation sources.

The ever-present seismic background noise of the earth (e.g., Peterson, 1993) most likely acts as the driving force for hydrocarbon-indicating (i.e. indicating a partial saturation) signals. Some possible underlying rock-physics mechanisms that generate spectral anomalies are discussed in Graf et al. (2007) and are considered further in this paper. The main observation (e.g., van Mastrigt and Al-Dulaijan, 2008) is usually an energy anomaly in the low-frequency band of passive seismic data between approximately 1 and 6 Hz. When measured at the surface, spectral energy is elevated above a hydrocarbon reservoir, compared with spectral energy measured at positions away from a reservoir. It is important, theoretically, that the generating mechanism and the observed anomaly may be present in a much wider-frequency range. However, between 1 and 6 Hz there is a typical noise trough in the background spectrum (e.g. Peterson, 1993), which might be the only frequency window where hydrocarbon-related effects are visible.

In addition to the energy anomaly, Lambert et al. (2009) describe another independent spectral attribute. They propose that the spectral ratio between horizontal and vertical components can show an anomaly in the presence of hydrocarbon reservoirs. Because of the well-known presence of surface waves, locating the source of these anomalies is of primary importance. By using a time-reverse wave-propagation method, Steiner et al (2008) suggest to locate the corresponding source of the anomaly in depth.

The analysis of low-frequency microtremors for detecting hydrocarbon reservoirs is an emerging technology with ongoing research especially focusing on data-analysis techniques. Ambiguous results and possible pitfalls also are reported (e.g. Berteussen et al., 2008; Hanssen and Bussat, 2008). Analyzing microtremors around reservoirs with considerable noise (e.g., production noise) requires careful data analysis because (a) anomalies caused by noise can be misinterpreted as caused by the reservoir or (b) such a high noise environment can overwhelm the signal. The question of whether spectral anomalies in the passive surface wavefield are correlated to all, many, or only a few hydrocarbon reservoirs can only be answered if more and detailed results of passive seismic surveys are reported and published.

The exact nature of the physical mechanisms of microtremors observed above hydrocarbon reservoirs 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.

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. In addition, 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 reported. 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.

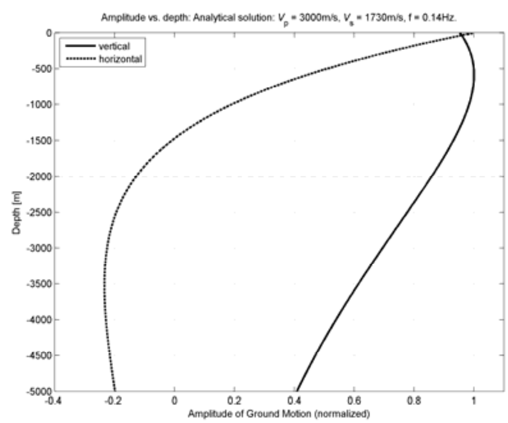

Figure 1: Amplitude vs. Depth for a Rayleigh wave of 0.14 Hz propagating through a homogeneous half-space. *P*− and *S*−wave velocities are set to 3000 m/s and 1730 m/s, respectively.

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 (i.e. ocean microseism) have sufficient amplitude at normal hydrocarbon reservoirs depths to perturb these 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. Interestingly, also a geological storage of CO_2 is a partially saturated rock system and we expect similar effects as for hydrocarbon reservoirs. Anomalies for relatively low frequencies in active seismic data are reported for a CO_2 storage site in Kazemeini (2009).

Another possibility would be a higher intensity of low-frequency fracturing 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 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 theoretically 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 resonance 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 (Figure 2 and Saenger et al. 2009b).

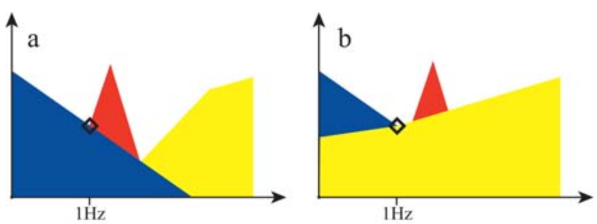

Figure 2: Alternative models (Saenger et al 2009b) for the dominant energy source triggering a hydrocarbon reservoir related signal (red area). a) The flank of the ocean peak (blue) as source. b) The flank of local noise (yellow) as source. The black diamonds highlight the first minimum of the PSD plot.

The preliminary rock physical model

We summarize our theoretical review in a preliminary interpretative model about the origin of hydrocarbon reservoir related 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 3 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 (not valid for very shallow reservoirs). Therefore we also expect this preferred direction for a resonant amplification effect of hydrocarbons in the pore space. It is not known whether and to what degree 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 reservoirs. Also observed 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 3.

Conclusions

We propose a preliminary rock physical model to explain the possible origin of hydrocarbon reservoir related tremors. This model can be verified or falsified with passive seismic data measured around hydrocarbon reservoirs. 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. The reservoir is surrounded by rocks that are saturated with only a single fluid for which multiphase effects are not present. The observed microtremor attributes above reservoirs are consistent with the preliminary model.

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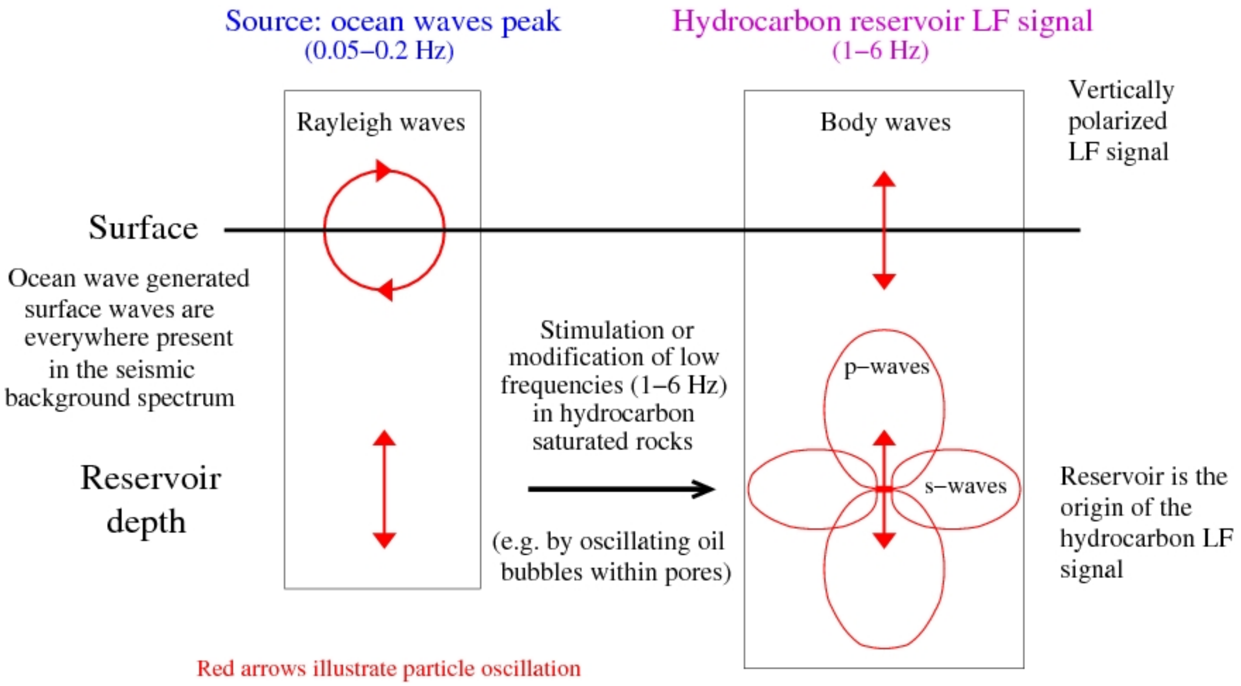

Figure 3: A preliminary model which explains the origin of hydrocarbon reservoir related tremors and which is consistent with observed spectral attributes. One important observation is that the vertical polarization of the ocean wave generated Rayleigh waves at reservoir depth is also present in the low frequency (LF) hydrocarbon reservoir related microtremor signal.