PRELIMINARY MODEL OF HYDROCARBON RESERVOIR RELATED MICROTREMORS

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 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.

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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 investigate time reverse modeling whether the low-frequency anomaly originate 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 complement the observations about frequency domain anomalies in the wavefield at the surface by Lambert et al. (2009). We split our consideration into three parts: Sources, mechanism and observations. First, we look at possible sources. 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 identified 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.

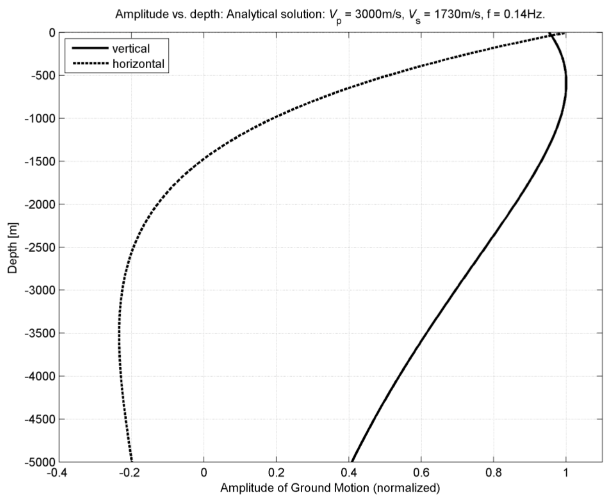

Figure 1*: Amplitude vs. Depth for a Rayleigh wave of 0.14 Hz propagating through a homogeneous half-space. P− and S−wave velocities are set to 3000 m/s and 1730 m/s, respectively.*

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 hydrocarbon reservoirs are always perturbed by the seismic background waves.

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 characteristic way. 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 a 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 V/H values above 1 and the dominant frequency of the microtremor will be depth dependent and relatively low.

Resonant Amplification

Oil bubbles can 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 (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. Whether and the degree to which non-linear effects are important, in this process, 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). One observes an energy anomaly between 1 and 6 Hz above hydrocarbons (e.g. van Mastrigt and Al-Dulaijan, 2008). A peak above 1 in the spectral V/H-ratio (e.g. Saenger et al. 2009a) will also be an expected characteristic for *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.

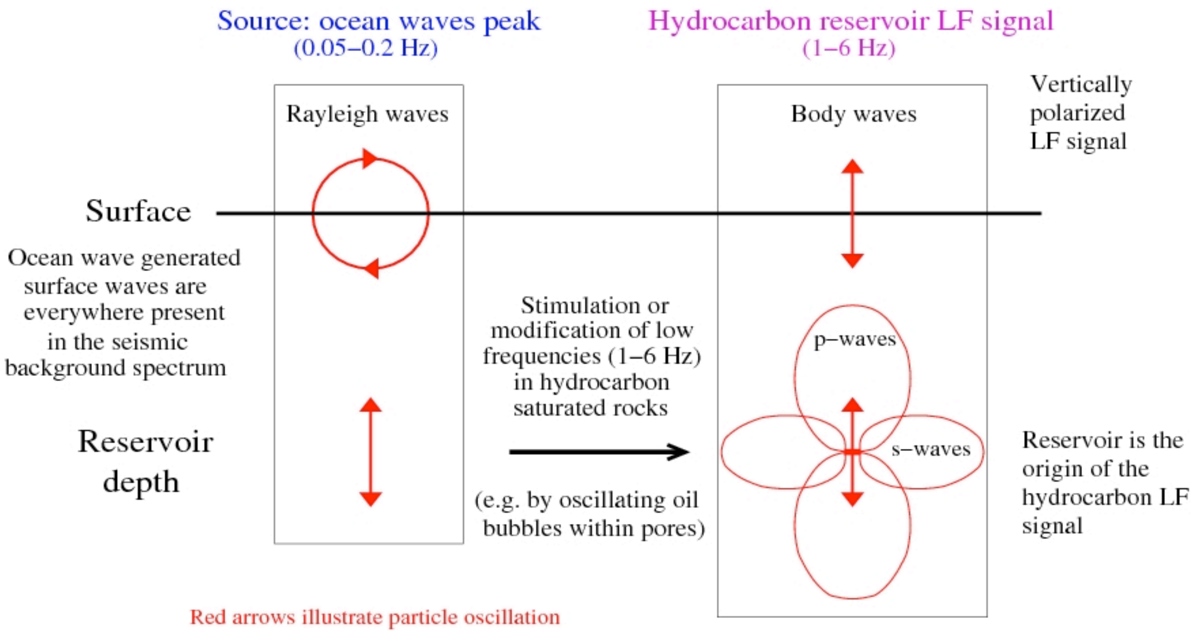

Figure 2*: A preliminary model which explains the origin of hydrocarbon tremors and which is consistent with observed spectral attributes. One important observation is that the vertical polarization of the ocean wave generated Rayleigh waves at reservoir depth is also present in the low frequency (LF)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

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 spectrum. Both can contribute independently to the specific signal characteristic and both are based on the assumption that the reservoir is a partially saturated multiphase system. We assume that the surrounding rocks off the resevoirs are mainly saturated with only a single fluid and multiphase effects are not present. Our observed microtremor attributes above reservoirs are consistent with the preliminary model.

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