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Scientific Strategy to Explain Observed spectral Anomalies over Hydrocarbon Reservoirs Generated by Microtremors

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SUMMARY

Worldwide one has observed narrow-band, low-frequency (1.5-4 Hz) tremor signals on the surface over hydrocarbon reservoirs (oil, gas and water multiphase fluid systems in porous media). These ‘hydrocarbon tremors’ possess remarkably similar spectral and signal structure characteristics, pointing to a common source mechanism, even though the depth (some hundreds to several thousands of meters), specific fluid content (oil, gas, gas condensate of different compositions and combinations) and reservoir rock type (such as sandstone, carbonates, etc.) for each of those sites are quite different. However, the physical mechanisms underlying these observations are presently not fully understood. Therefore we propose a scientific strategy for a better understanding of those phenomena. Using well-known rock physical relationships we have identified on macro-, meso- and microscale different mechanism which can induce anomalies in the low-frequency band. Using different numerical approaches we are able to compare these mechanisms with observations in the field.

Introduction

During several surveys at different oil and gas field locations throughout the world (so far more than twenty), the presence of 'hydrocarbon tremors' was observed and a high degree of correlation to the location and geometry of hydrocarbon reservoirs could be established (Dangel et al., 2003; Holzner et al., 2005; Graf et al., 2007 and references therein). These tremors provide a direct hydrocarbon indicator for the optimization of borehole placement during exploration, appraisal and production. In addition, there is a strong correlation between the tremor power and the total hydrocarbon-bearing layer thickness (THLT) determined by borehole logs. The ever-present seismic background noise of the earth (e.g., Berger et al., 2004) acts as the driving force for the generation of hydrocarbon indicating signals. In contrast to conventional 2D and 3D seismic technologies, the investigation of 'hydrocarbon tremors' is entirely passive and does not require artificial seismic excitation sources. The modification of the seismic background noise spectrum is different for interactions with geological structures containing hydrocarbon filled pores compared to interactions with similar structures not containing hydrocarbons (Figure 1). Therefore, the hydrocarbon microtremor analysis is in line with an increasing number of methods which investigate ambient noise signals to get information of the subsurface structure (e.g.; Bard, 1999).

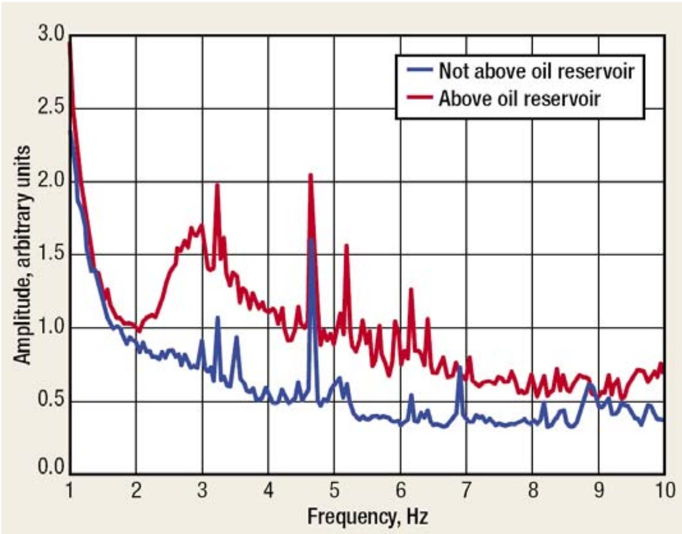

Figure 1

Data from a survey in Brazil showing consistent anomalies in the Fourier spectra of surface velocities, measured within and outside the boundaries of a known oil reservoir. The highest difference is mostly observed in the range between 1.5Hz and 4Hz.

As reported above, the characteristic spectral anomalies caused by hydrocarbon bearing structures have been consistently measured during several field studies but the physical mechanisms causing these anomalies are not yet fully understood. In this paper we discuss different possible physical mechanisms on macro-, meso- and microscale, which can generate low-frequency spectral anomalies of a broadband incoming background signal (i.e. ambient seismic noise). The qualitative and quantitative influence of those mechanisms is investigated by numerical modeling tools and compared to a large variety of available field measurements.

Numerical tools

One main methodology to study the influence of possible low-frequency mechanisms is numerical modeling of wave propagation in porous rocks. We use the velocity-stress and displacement-stress formulations of the governing equations and solve these equations numerically using an explicit finite difference method on a standard or rotated staggered grid (e.g., Virieux, 1986; Saenger et al., 2000). We solve equations describing an elastic medium, a poroelastic medium (Biot, 1962) and a poroelastic medium with partial saturation (Carcione et al., 2004). Numerical simulations are performed for 1D, 2D and 3D. A particular aim is to study under what conditions simpler 1D and 2D models provide similar characteristic spectral anomalies than full 3D models. In a later stage the numerical models will be implemented into a new hydrocarbon detection method. The idea is to fit observed spectral anomalies with numerically produced spectral anomalies by optimizing/minimizing the misfit between real and synthetic spectra. The continuously improved physical understanding will be used to design suitable update mechanisms that vary the material properties and the geometry of the reservoir to provide probabilities for the location, thickness and type (oil or gas) of the reservoirs.

Rock physical mechanisms in the sub-10Hz domain

Possible low-frequency mechanisms are (i) standing wave resonance (macroscale), (ii) selective attenuation (mesoscale) and (iii) resonant amplification (microscale). They are illustrated in Figure 2. Even if one or more of these mechanisms are not responsible for the characteristic hydrocarbon tremor signals, we need to quantify these effects anyway to clean the measured data from spectral anomalies which have not been generated by the hydrocarbon bearing geological structures.

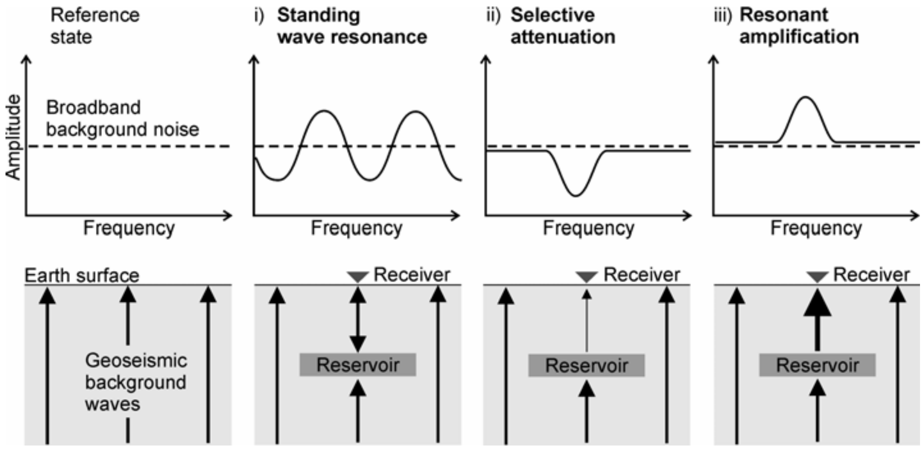

Figure 2 *Three possible mechanisms that generate characteristic modifications of the geoseismic background spectrum. The Reference state exhibits no heterogeneities in the subsurface and an incoming broadband ambient noise. i) Characteristic maxima in the spectrum are generated due to reflections between the reservoir and the surface and within the reservoir caused by smaller impedance within the reservoir. ii) Characteristic peaks in the microtremor spectra are generated due to selective, i.e. frequency dependent, attenuation within the reservoir. iii) Characteristic peaks are generated due to a resonant amplification of certain frequencies within the reservoir.*

(i) Standing wave resonance

When waves propagate from one medium into another medium with different material properties, then a part of the wave is reflected. The characteristic two-way travel time or resonance frequency between the Earth surface and the bottom of the surface layer or the reservoir generates characteristic spectral anomalies. Importantly, the effective impedance contrast can be enhanced significanly by high attenuation in the low-frequency range in reservoir rocks (Korneev et al., 2004, Chapman et al., 2006). We study spectral anomalies generated by standing wave resonance for elastic and poroelastic media. For poroelastic media, we compare results obtained with the Biot model and the models of the theory of porous media (TPM, e.g., Ehlers and Kubik, 1994). The motivation to study wave propagation also with the TPM equations is that the TPM is a priori a nonlinear approach in contrast to Biot's theory, which is purely linear. Another focus is to study the effects of several reservoirs which are located at different depths and to develop a methodology which allows for estimating the number of reservoirs in depth.

(ii) Selective attenuation

There exist several models to describe the attenuation of seismic waves due to wave-induced flow (e.g., Pride et al., 2004). These models describe wave attenuation on different spatial and temporal scales. A model which describes presumably the dominant mechanism in the low frequency range between 1 and 10 Hz is the so called patchy saturation model (White et al., 1975; Gurevich and Lopatnikov, 1995; Johnson, 2001). We study patchy saturation effects within the reservoir to determine under what conditions a selective, frequency dependent attenuation could generate spectral anomalies similar to the observed hydrocarbon microtremor signal. The results for wave attenuation on the reservoir scale will be approximated by an effective viscoelastic model to simulate wave propagation on the upper crustal scale (top 10 kilometers). In particular, we study the differences between gas and oil pore fill and the consequences on the frequency dependence of the reflection coefficient.

(iii) Resonant amplification
Resonant amplification effects of the ambient seismic noise are promising candidates for explaining the hydrocarbon microtremor signal. These effects will behave like a driven source and they are supported by the following observations (Dangel et al.; 2003):

- The relative narrow frequency range of the signal (1.5-4Hz).
- The mean absolute power of the hydrocarbon tremor depends on the level of the environmental noise.
- The power of the signal seems to be proportional to the total hydrocarbon-bearing layer thickness of the reservoir.
- Three component recordings show a trough instead of a peak in the H/V-ratio.
- Preliminary tests using a directional sensitive sensor setup showed that the signals causing the anomaly originate from the reservoir direction.

Direct numerical simulations using Navier-Stokes equations show that pores which are partially saturated with oil and gas exhibit a resonance frequency. This resonance mechanism can be approximated by a damped oscillator model. Depending on the geometry of the pores, the oscillator models are either linear or nonlinear (Holzner et al., 2006). We couple the oscillator model to a one-dimensional wave propagation equation. We study under what conditions the resonance of the oil filled pores is activated and under what conditions the resonance frequency can be measured at the surface. In particular, we investigate the coupling between the porous reservoir material and the ambient rock material and the subsequent propagation of the resonant waves to the Earth surface. With a finite-difference time reversal approach (Figure 3) we are currently improving the possibility to localize the origin of the low-frequency anomaly.

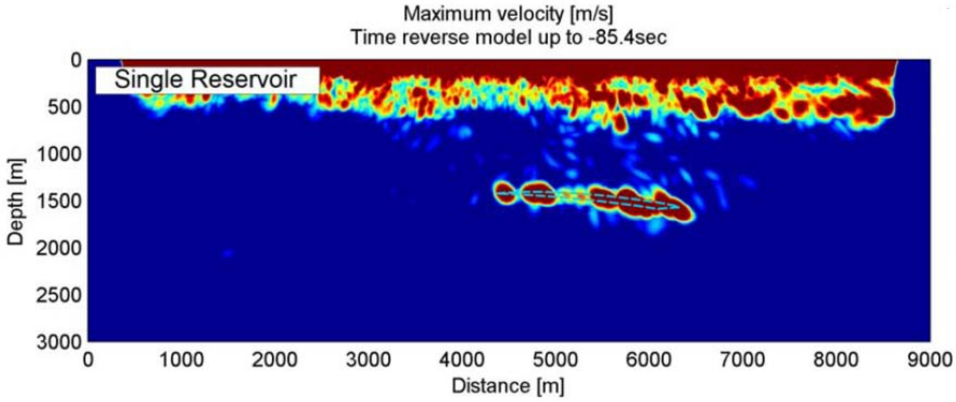

Figure 3 *Distribution of maximum velocities in reverse modeling simulations. Shown is the result of a numerical feasibility study with the focus on microtremor localization.*

Discussion and Conclusions

The mechanism causing the observed hydrocarbon tremors is still an open rock physical question. Therefore, our theoretical and numerical findings will be compared with measured data from known oil fields and available geological and geophysical information (Figure 4), such as rock type, well logs and other relevant reservoir parameters, will be implemented in our multiscale research strategy in order to test the validity of the models. In particular, the wave types which generate the spectral anomalies and which represent the source are

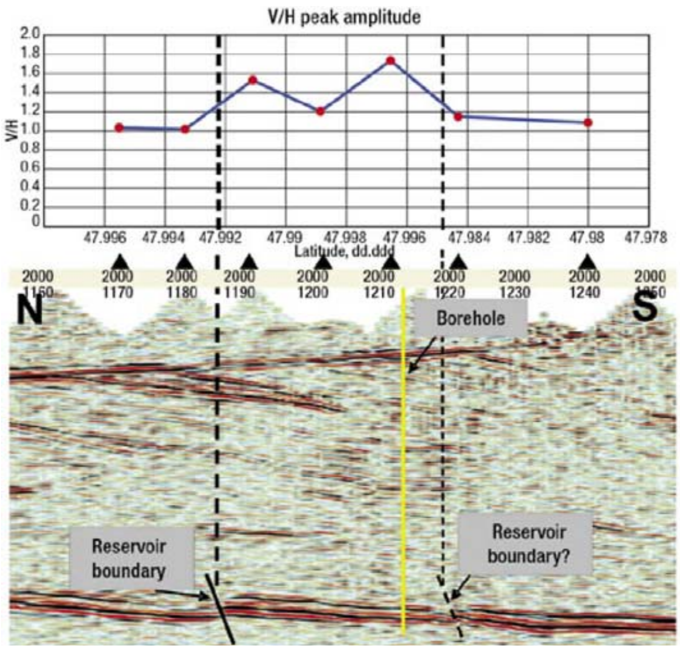

Figure 4

The maximal value of the V/H ratio within the 1- to 6-Hz range for each sensor is shown over the southern part of a fully explored reservoir in Voitsdorf, Austria. This alternative to the standard H/V technique is an additional, proprietary attribute for microtremor hydrocarbon detection.

analyzed by investigating the ratios of spectra of the horizontal and vertical velocities and by comparing measurements at different locations to measurements done at well known reference locations. Another focus of our research is filtering and removing of noise caused by anthropogenic and industrial activities.

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