Passive Seismic Study at an Oil and Gas Field in Voitsdorf, Austria

M.-A. Lambert* (ETH Zurich), S.M. Schmalholz (ETH Zurich), E.H. Saenger (ETH Zurich and Spectraseis) & B. Steiner (ETH Zurich)

SUMMARY

We present the results of a passive seismic survey over two separate reservoirs of an explored oil and gas field near Voitsdorf, Austria. Four different spectral attributes of the ambient seismic wave field are used to identify spatial correlations between anomalies in the surface wave field and the presence of hydrocarbons in the subsurface. The attributes quantify characteristic features of the wave field’s Fourier spectra in the low-frequency range (< 10Hz). The data indicate the position of the southern reservoir. The northern reservoir is less clearly identified. Nevertheless, using several attributes significantly increases the reliability of hydrocarbon reservoir detection compared to using only one attribute. Time-reverse modeling applied to the same data-set shows that the observed attribute anomalies at the surface may be caused by low-frequency seismic energy that is emitted from the reservoir areas. Preliminary results of a time-lapse experiment (comparison of data acquired in April 2007 and in April 2008, respectively) reveals a good reproducibility for two of the four attributes. A first comparison between time reverse modeling applied to the 2007 and the 2008 data-set consistently indicates the presence of seismic sources in the area of the two reservoirs.
Introduction

Low-frequency (< 10 Hz) spectral anomalies observed in the ambient seismic wave field at the Earth’s surface have recently been used as hydrocarbon (HC) indicators (Dangel et al. 2003; Graf et al. 2007, and references therein). The main observation is an energy anomaly in the low frequency band of passive seismic data approximately between 1 and 6 Hz. At the surface, above the reservoir, spectral energy is elevated compared to positions off the reservoir. Most of these empirical observations are based on the vertical component of ground motion only. However, Saenger et al. (2007) and Lambert et al. (2008) have introduced vertical-to-horizontal spectral ratios (V/H-ratios) for the same purpose. Spectral ratios are especially useful because they are more stable than single component, or absolute, spectra (Bard 1999, and references therein). Motivated by these observations, a passive seismic survey has been carried out over an explored oil and gas field near Voitsdorf, Austria. We use this field as a test site to investigate correlations between anomalies of four different spectral attributes and the HC reservoir locations. We compare the results of a survey done in April 2007 with preliminary results of a survey done in April 2008 in order to test the results for consistency and reproducibility.

Survey

The passive seismic survey presented in this study was performed in April 2007 on the Voitsdorf oil and gas field in Upper Austria. The survey was designed to cover two spatially separated reservoirs. Figure 1 shows the locations where the ambient seismic wave field has been measured with thirteen portable, three-component broadband seismometers. The small red dots refer to the 40 stations of a dense sensor array, deployed one year later in April 2008. A more detailed description of the 2007 survey can be found in Lambert et al. (2008).

Spectral Attributes

We use spectral attributes of the ambient wave field to identify possible spatial correlations between anomalies in the wave field at the surface and the presence of subsurface reservoirs (Saenger et al. 2007, Lambert et al. 2008). The original observation which was characterized as increased average peak strength above the reservoir (Dangel et al. 2003) is not considered as an optimal attribute, mainly because of its sensitivity to unwanted noise influence. We
therefore look for attributes that provide more stable values. Furthermore, we think that analyzing multiple attributes provides a more consistent picture compared to only one attribute. Figure 2 illustrates the four attributes that are mapped in this study. The anomaly in the power spectral density of the vertical component of the wave field (PSD-IZ attribute), panel (a), is defined as the integral from the frequency value of an individual energy minimum ($f_{\text{min}}$) up to a fixed frequency, here 5 Hz. Using an individual minimum for each measurement has a normalization effect by taking noise variations into account. The peak amplitude of the V/H-ratio (PAVH attribute), panel (b), is extracted by scanning the V/H spectrum for the dominant peak in the frequency range between 1 and 6 Hz. Spectral ratios are useful because they are known to be more stable in time and less affected by source characteristics compared to absolute spectra. Finally, the peak frequency of the vertical and horizontal Fourier spectra of the wave field (PFV and PFH attribute), panels (c) and (d), are defined as the frequency values, in Hz, of the maximum amplitude in the 1-to-6-Hz range. These two attributes are based on frequency values and are therefore less dependent on absolute amplitudes.

The frequency intervals considered to determine the four attribute values are empirically defined to be above the oceanic microseismic peak (~0.2 Hz) and below strong anthropogenic noise. Therefore they must be reassessed for other survey areas.

To account for temporal variations of the attribute values and to enhance the consistency of the results we explore several stacking methodologies. In a first step, the data of the six profiles were stacked in the cross-line direction. This projection is reasonable since all measurement lines lie parallel to each other, perpendicular to the reservoirs’ extension and close together compared to their length. In a second step, the cross-line stacks derived from consecutive time sections of the continuous raw record were stacked in time domain. Figure 3a-d show the resulting stacked profiles for each attribute based on 11 consecutive time windows of 30 minutes (resulting in 5.5 hours of data at each station). The dashed lines indicate the plus-minus one standard deviation range from the time average. Only nighttime measurements have been used (time window from midnight to 5:30 am) because of strong artificial noise contamination during daytime. We want to emphasize that we use the full time domain record and do not remove any signal parts. Grey areas show the location of the reservoirs from interpretations of active seismic and well log data. The southern boundary of the southern reservoir has yet to be precisely defined and is therefore indicated with a grey fading boundary towards the South.
Figure 3. Stacked profiles (solid lines) of the attributes (a) PSD-IZ, (b) PAVH, (c) PFV and (d) PFH. Dashed lines are the plus-minus one std.-deviations. Grey areas indicate the reservoir locations. Panel (e) displays a depth section from time-reverse modeling applied to the same 2007 data-set (modified after Steiner et al. 2008). High values are interpreted as source areas of low-frequency seismic waves and coincide with the reservoir locations (dashed ellipses). Note that the horizontal axis corresponds to the distances given in panels (a-d).
The profiles show several significant anomalies. In most cases the temporal variation (given by the standard deviation) is smaller compared to the spatial variation (given by the width of the anomaly). This property shows that the attributes are suitable to quantify lateral variations of the microtremor wave field. Most of the anomalies are spatially coincident. For example, the largest and most significant anomalies of PSD-IZ, PFV and PFH are located at a distance of about 5500m along the measurement lines (Figs. 3a, 3c and 3d). This coincides with the location of the southern reservoir. The two broad anomalies of the PFV and PFH attribute (Figs. 3c and 3d) have maxima around 9500 m, which coincides with the northern reservoir. The PSD-IZ and PAVH attributes are not sensitive for the northern reservoir. The standard deviations show that the PSD-IZ attribute is less stable in time than are the other three attributes. We think the temporal variability of the PSD-IZ attribute may also be boosted by artificial noise (such as from a nearby highway) which is rather strong in this area of the survey. As mentioned earlier, there was no elimination of artificial noise performed and the full dataset was used to calculate the spectral attributes. Considering the variability of the PSD-IZ attribute, it is interesting to observe that the PAVH attribute is relatively stable even though the vertical spectrum is also used to determine this value. This shows that the signals on the vertical and horizontal components apparently evolve similarly and therefore temporal variations are cancelled in the ratio between the components.

Lambert et al. (2008) present a numerical study of seismic wave propagation to better characterize how the shape of the PFV- and PFH-profiles depends on the nature of a subsurface seismic source. Their results show that such a source needs to have a preferred directionality (emitting P- and S-waves) in order to create anomalies at the surface similar to those shown in Figure 3c and 3d. Furthermore, they suggest that the PFV- and PFH-attribute may be used as a potential depth-indicator for hydrocarbon reservoirs.

A relevant question is whether the measured attribute anomalies shown in Figure 3a-d are caused by natural mechanisms in the reservoirs or by anthropogenic noise at the surface. Steiner et al. (2008) have applied time reverse modeling on the Voitsdorf data-set to locate focusing of seismic energy at low frequencies. They found a significant focusing at the reservoir locations in depth. Fig. 3e shows one of their results which support the assumption that there is low-frequency seismic emission originating from the reservoir areas.

**Time-lapse analysis**

Data acquired in April 2008, i.e. one year after the survey presented above, is considered to evaluate the reproducibility of the results. The data-set consists of a synchronized line-array of 40 seismometers with an in-line spacing of 250 m (small red dots in Fig. 1). This line spatially coincides with line 1 and 4 of the 2007 data-set (green stars and blue triangles in Fig. 1). The same processing steps have been applied and the same amount of data has been used (i.e. stack of 11 consecutive time windows of 30 minutes from midnight to 5:30 am) to allow a direct comparison between the two sets of data. Figures 4a-d show the results for the 4 attributes. The blue profiles correspond to the 2008 data-set, whereas the magenta and cyan profiles are derived from line 1 and 4 of the 2007 data-set, respectively. The error-bars indicate the standard deviation at each station and were computed from the individual values of the 11 time windows. The profiles are well reproduced for the PSD-IZ and PAVH attribute. Differences may be explained by the change of survey parameters, such as anthropogenic noise, equipment and reservoir status. The profiles of the PFV and PFH attributes are not as well reproduced. Compared to the results of the 2007 data-set (Figures 3c-d), the preliminary results of the 2008 survey (presented here for only one measurement line) also show less distinct anomalies that would correspond to the reservoir locations (Figures 4c-d). The smaller seismometer spacing causes rougher profiles for the 2008 survey. Nevertheless, some patterns are similar in both data-sets (e.g., the peak above the southern reservoir, low values between the two reservoir locations). Strong narrow-band noise (as for example produced by industrial machinery) is a critical issue when computing the PFV and PFH attributes and may be the explanation for the limited reproducibility. Several filtering methodologies to reduce
such effects (e.g. f-k dip filtering) and also spatial stacking are part of ongoing research and may improve the S/N-ratio for the PFV and PFH profiles.

Figure 4e displays a section from time reverse modeling applied to the 2008 data-set (using data from 39 synchronized seismometers) and shows that the results from the 2007 data-set are reproducible (compare with Figure 3e).

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**Figure 4.** Comparison of results from data acquired in April 2007 (magenta and cyan profiles) with results from data acquired in April 2008 (blue profiles). Panels (a), (b), (c) and (d) correspond to the PSD-Iz, PAVH, PFV and PFH attribute, respectively. Grey areas indicate the reservoir locations. Panel (e) displays a depth section from time reverse modeling applied to the 2008 data-set. Note that the horizontal axis corresponds to the distances given in panels (a-d).
Conclusions
Analysis of field data from a passive seismic survey over two hydrocarbon reservoirs in Voitsdorf, Austria, resulted in a distinct mapping of the southern reservoir and a less clear mapping of the northern reservoir. The localization analysis is based on a combined interpretation of four spectral attributes. Because of the considerable temporal variation of the signals, new processing methods were developed and applied, which significantly improve the consistency of the results by temporal and spatial stack. The time-lapse analysis (1 year time span between acquisitions) shows a generally good reproducibility of the data. Filtering methodologies to enhance the robustness of the attribute values (especially for PFV and PFH) are part of ongoing work. Time reverse modeling applied to both, the 2007 and 2008 dataset, consistently indicates the presence of seismic sources in the area of the two reservoirs. Results indicate that passive low-frequency spectral analysis and time reverse modeling can increase the probability of locating reservoirs.

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References


