Geophysical Prospecting EAGE EUROPEAN ASSOCIATION OF GEOSCIENTISTS & ENGINEERS
Geophysical Prospecting doi: 10.1111/j.1365-2478.2009.00827.x

Reply to comment on 'Low-frequency microtremor anomalies at an oil and gas field in Voitsdorf, Austria' by Marc-André Lambert, Stefan M. Schmalholz, Erik H. Saenger and Brian Steiner, *Geophysical Prospecting* 57, 393–411

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Received July 2009, revision accepted July 2009

INTRODUCTION

We welcome the opportunity to respond to Professors Green and Greenhalgh's analysis of our work in this journal. In addressing their observations we hope to contribute towards a better understanding of our work in general.

Green and Greenhalgh (2009) commented not only on Lambert *et al.* (2009) but also on peer-reviewed papers, conference proceedings and magazine articles authored by at least one of us, thereby combining formative early work with more advanced results in their critique. Additionally, they commented on publications that none of us has co-authored (e.g., Dangel *et al.* 2003; Walker 2008), addressing questions to a scientific community beyond our research group. This reply necessarily focuses only on the work that at least one of us has co-authored.

Green and Greenhalgh (2009) asserted that our conclusion that "the results indicate that passive low-frequency spectral analysis can increase the probability of locating reservoirs significantly" is unfounded. We identify three main arguments in their commentary: i) that our attributes are not applicable to reservoir detection, ii) that the results of our numerical study do not fit the data and iii) that our attributes are in fact sensitive to shallow structures and we inadequately consider these potential shallow effects in our work. We first respond to these three main points and then to additional criticism, which is included as discussion within their commentary. Finally, we describe the objectives of our research to put it in the correct perspective and to address Green and Greenhalgh's (2009) assertion that the results of Lambert *et al.* (2009) contradict our earlier work.

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RESPONSE TO SPECIFIC COMMENTS

Attributes 1 and 2

Green and Greenhalgh (2009) expressed the view that our Attributes 1 and 2 do not indicate the two reservoir locations. Based on our qualitative analysis of the correlation between these spectral attributes and reservoir locations, we agree with them. In Lambert *et al.* (2009) we explicitly stated: "Attributes 1 and 2 are not sensitive for the northern reservoir", "For Attribute 1, temporal variations are rather large and, therefore, the observed anomalies are less significant" and "Attribute 2 behaves very stable in time ... the profiles do not show clear lateral anomalies". We clearly stated that the profiles of Attributes 1 and 2 are not useful for detecting the two reservoirs at this site. We do not see the supposed contradiction in Lambert *et al.* (2009) because we did not claim that all attributes must show anomalies above both reservoirs in order to increase the probability of detecting reservoirs.

Attributes 3 and 4

Attributes 3 and 4 are based on more stable frequency values rather than on amplitude values, which can vary substantially in experiments utilizing an uncontrolled source. Green and Greenhalgh (2009) wrote that "Lambert *et al.'s* (2009) simplistic physical exploration is both implausible and inconsistent with (our) observations". Our numerical study was in fact a feasibility (or plausibility) study intended to show that seismic signals emitted by a subsurface source in a homogeneous, linear elastic medium with no dispersion can generate spectral patterns along the model's free surface that are similar to the peak-frequency shift pattern identified from the field data for Attributes 3 and 4. Green and Greenhalgh (2009) contrasted our numerical feasibility study for Attributes 3 and 4 with field data of Attribute 2 (V/H values). The objective of our numerical study, using a simplistic parameter space, was to demonstrate a concept; the aim was not to explain the natural wave propagation processes at the Voitsdorf site, nor to reproduce the distribution of all other attributes recorded in the survey. Hence, there is no contradiction with the patterns observed for Attribute 2 in the field data.

To extend the analysis with more realistic complexity, we offer two new numerical simulations and the resulting V/H profiles (Fig. 1). The top panel shows the modelled distribution of the peak-frequency attribute due to a single, vertically-acting line source at 2000 m depth. The middle panel is the result from multiple, vertically-acting line sources. The multiple sources are randomly distributed in time and space within a source area in the subsurface to generate a tremor-like signal. The results show that for both source models, there is a considerable peak-frequency shift pattern indicating the location of the subsurface source area (Fig. 1a,b). Importantly, the corresponding V/H profiles in Fig. 1(c) are very different. The singular anomaly due to a single source is not only removed for the case of multiple sources (Fig. 1c, dashed line) but the result does not correspond with the surface projection of the source area (grey area in Fig. 1c). These results show that our physical justification for the attribute patterns is not inconsistent with observation because the spatial patterns of different attributes can be independent. Therefore, there is no contradiction arising from 'not observed' 'extraordinarily high V/H values'.

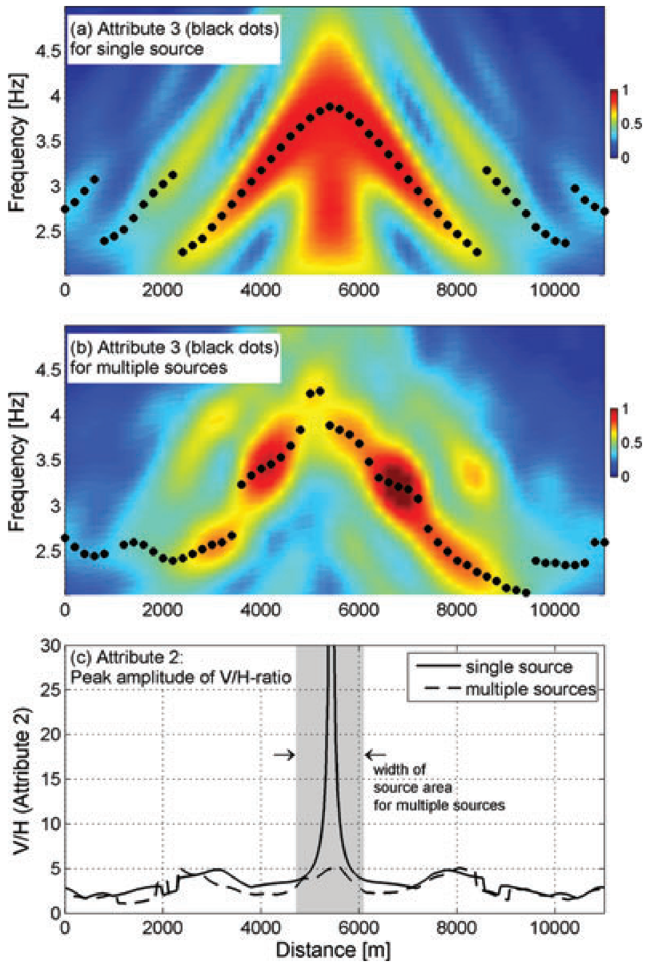

Figure 1 Results of numerical simulations with two different seismic sources. Details of the model set-up are described in Lambert *et al.* (2009). a) Normalized spatial spectrogram of the vertical component of the synthetic wavefield at the free surface for a single source. Black dots show the shift of the peak-frequencies (Attribute 3) indicating the source location. b) Same as (a) but for multiple sources (tremor-like signal). c) Profiles of V/H values (Attribute 2) along the model's free surface for the two simulations. Only the single source model exhibits extraordinarily high V/H values (Attribute 2) although for both simulations the patterns of Attribute 3 around the source location are similar (a and b).

The influence of shallow structures

Green and Greenhalgh (2009) stated that the "very large variations of Attributes 1–4 along lines and between adjacent lines" in our figure 7 "are evidence for the overwhelming influence of local shallow structures". As described in the paper, Fig. 7 of Lambert *et al.* (2009) illustrated intermediate processing steps for stacking in space. It showed six profiles for each attribute where each profile has been recorded for 30 minutes by synchronized stations. Each of the six profiles had been recorded on a different day. Therefore, the disputed figure 7 does not show a representative spatial variation of the attributes, because results of adjacent lines are up to 6 days apart and each profile represents only 30 minutes of data. A representative spatial variation was displayed in Fig. 8 of Lambert *et al.* (2009). Figure 8 showed variations of the four attributes for 11 profiles, each measured for 30 minutes during a continuous time period of 5.5 hours together with the corresponding time average. We are unable to see how the observed spatial variations of the four attributes in these Figs 7 and 8 of Lambert *et al.* (2009) are "evidence for the overwhelming influence of local shallow structures". These variations could be due to shallow structures but our numerical feasibility study showed that these variations could equally well originate from deeper sources (Figs 10 and 11 of Lambert *et al.* (2009) and Fig. 1 in this reply).

The possible influence of shallow structures was not emphasized in Lambert *et al.* (2009). As we have discussed in other publications (e.g., Lambert *et al.* 2006; Saenger *et al.* 2009), we are aware that such effects can strongly affect the data. In the Voitsdorf case study, the limited data on near surface geology available to us makes it difficult to conclude conclusively on the effects of shallow structures. It is well established that the ratio of H/V is less affected by source effects and, therefore, is suitable to analyse shallow structures. We analysed its reciprocal (V/H) in the frequency range of 1–6 Hz and did not find evidence for an 'overwhelming influence' of shallow structures along the survey lines. Values of V/H were mainly between 0.6–1.2. We chose not to discuss possible shallow structure effects in detail in this paper because we do not present a quantitative correlation analysis among the four attribute patterns and the reservoir locations; instead we focus on the spatial and temporal variation of the attributes.

The Voitsdorf site

Green and Greenhalgh (2009) speculated that we "regard the Voitsdorf site as an ideal location to test the proposed HMS relationship" (the term HMS has been introduced by them for hydrocarbon-microtremor-spectra). On the contrary, the Voitsdorf site in the Alpine Foreland Basin is far from ideal. The site features high anthropogenic noise and complex geology that made our analysis more difficult. Nevertheless, there are good reasons why we chose to study data at this location:

- We have permission from the field operator to publish the data.
- The site offers relatively easy operating access, allowing us to repeat measurements quickly, safely and cost-effectively.
- Good geophysical data (e.g., reservoir model, P-wave velocity model) are available.
- The site is suitable for developing and testing new methods for data filtering, noise cleaning and stacking (e.g., Nguyen *et al.* 2009).

For an example of a site more ideally suited to testing the basic hypothesis that low-frequency wavefields can be modified by reservoirs in the subsurface we would refer to van Mastrigt and Al-Dulaijan (2008), who studied a proven non-producing gas reservoir in an exceptionally quiet location, less conveniently situated deep within Saudi Arabia's Rub' al Khali desert.

Selection of applicable literature

Microtremor analysis focusing on reservoir effects is an emerging field. There is currently limited discussion of the topic in the refereed literature. We have sought to address this by submitting our own work for scrutiny and publication by peer-reviewed journals such as this one. Green and Greenhalgh (2009) emphasized two experimental descriptions (Ali *et al.* 2007; Berteussen *et al.* 2008a,b; Hanssen and Bussat 2008), which did not conclude that the analysed microtremor energy is related to known reservoirs. It would be suspicious if a nascent technique was especially easy to apply, universally applicable, or not subject to complexity or failure. We cannot think of an accepted exploration method about which this could be said. However, not mentioned in Green and Greenhalgh's (2009) comment are a number of other studies (not co-authored by us) reporting correlation between the presence of reservoirs and observed low-frequency seismic signals (e.g., Kouznetsov *et al.* 2005; Turuntaev, Burchik and Turuntaev 2006; Birialtsev *et al.* 2006; Zhukov *et al.* 2007). Moreover, van Mastrigt and Al-Dulaijan (2008) showed correlations between anomalies in passive seismic data and a proven non-producing subsurface reservoir in a remote and unusually quiet location. The results of this study cannot easily be reconciled with the arguments advanced by Green and Greenhalgh (2009) and the articles they cite. In our view, all studies should be considered. While it is correct to be sceptical, one should remain open-minded in the far-from-resolved field of oil and gas exploration.

The nature of 1–10 Hz microtremors

Green and Greenhalgh (2009) argued that there is "compelling evidence for the widely accepted shallow origin of 1–10 Hz microtremors". We do not disagree that there are many 1–10 Hz microtremors of shallow origin. However, there are also studies showing a dominantly deep origin of microtremors. For example, Zhang, Gerstoft and Shearer (2009) showed that the ambient wavefield between 0.6–2 Hz is dominated by continuous P-wave energy at two sites in California. These P-waves propagate through the Earth and arrive at the stations from beneath the array. We also note that at specific geological locations, such as volcanoes, microtremors can include tremor signals originating from depth (e.g., Chouet 1996).

Importantly, Green and Greenhalgh (2009) also wrote that they "do not preclude the possibility of signals from deep structures contributing to microtremor wavefields". They refer to Draganov *et al.* (2007) who extracted two-way traveltimes of reflections – also a seismic attribute (Chopra and Marfurt 2005) – as great as ~2 s from passive seismic data. Draganov *et al.* (2007) worked with data in a frequency range from 1–80 Hz and stated that "useful information was concentrated between 2 and 10 Hz". If it is possible to extract attributes such as two-way traveltimes from passive seismic data, then it should, in principle, also be possible to extract other attributes from passive seismic data, such as attributes related to fluid and rock properties of reservoirs.

We emphasize that we did not 'claim high-resolution capabilities', as implied by Green and Greenhalgh (2009) in their final paragraph referencing Draganov *et al.* (2007). In contrast, Lambert *et al.* (2009) stated that "...the maximum lateral resolution for the reservoir would be expected to be in the same order of magnitude as the wavelength of the measured signals, i.e., several hundreds of metres".

Our research organization and earlier work

We have consistently sought to present and discuss our research, results and interpretations at relevant international conferences, such as EAGE and SEG. To do this, we must submit extended abstracts, often six months or more in advance of the presentation. These abstracts present data, results, hypotheses and interpretations at the time they were written. Our research is active and ongoing and the volume and quality of data available to us has increased with time. Accordingly, we have modified some of our earlier hypotheses and interpretations as our understanding has evolved. This normal process of scientific discovery has inevitably led to modified statements, which we do not consider to be contradictions of earlier 'assertions', as suggested by Green and Greenhalgh (2009) and we have made no effort to obscure the progression of our research.

Green and Greenhalgh (2009) described our research collaboration with industry as an "industry-university consortium (IUC)". In fact, our research in this field is supported by both industry partners and the Swiss Confederation's innovation promotion agency (CTI, see http://www.bbt.admin.ch/kti/). The salaries of PhD students and Post-Doctoral researchers are paid and guaranteed by the CTI.

CONTEXT FOR THE STUDY AND AIMS OF OUR RESEARCH

Several independent studies (e.g., Dangel *et al.* 2003; Zhukov *et al.* 2007; van Mastrigt and Al-Dulaijan 2008) have reported an apparent correlation between characteristic patterns, or anomalies, in the spectra of low-frequency passive seismic ground motion recordings and the location of hydrocarbon reservoirs. Our research addresses the question how and to what extent the analysis of passive ground motion can increase the probability of detecting hydrocarbon reservoirs or, more generally, can provide useful information about the subsurface. We refer to the method of analysing passive ground motion in the context of reservoir detection as low-frequency microtremor analysis. Low-frequency microtremor analysis is an emerging methodology both under development and evaluation. As of now, there is no established theoretical and physical model that fully explains the relationship between the recorded data, the ambient seismic wavefield and the physical processes related to the reservoir. So far, only basic and heuristic models have been suggested (e.g., Saenger *et al.* 2009). Low-frequency microtremor analysis therefore is currently a statistical method based primarily on empirical observations. One goal of our work is eventually to apply statistical classification and pattern recognition methods (e.g., Avseth, Mukerji and Mavko 2005) to passive seismic attributes. Such methods are already applied in active seismics.

To apply and evaluate such methods in the context of low-frequency microtremor analysis requires:

1 Data preprocessing (e.g., filtering, cleaning, stacking etc.).
2 Defining, extracting and evaluating attributes for passive data.
3 Models providing some physical justification and a better understanding of attributes and their spatial and temporal variation.
4 Performing statistical classification and/or pattern recognition (e.g., neural networks) to the passive seismic attributes.
5 A large number of case studies to test whether low-frequency microtremor analysis can increase the probability of detecting reservoirs for few, many or most case studies.

The work reported in Lambert *et al.* (2009) focused on points 1) to 3) with the main aim being to introduce and define, for the first time in a peer-reviewed journal, the calculation of four new passive seismic attributes. The attributes presented in the paper are similar to conventional seismic attributes, which are a quantitative measure of a seismic characteristic of interest (e.g., Chopra and Marfurt 2005). Attributes can be classified into general and specific categories (Liner *et al.* 2004). General attributes have a well-defined basis in physics or geology and are universally applicable. In contrast, specific attributes have a less well-defined basis in physics and may be well correlated to a target feature (e.g., a hydrocarbon reservoir) for a given case study. These correlations often do not carry over to different areas (Chopra and Marfurt 2005). The attributes presented in Lambert *et al.* (2009) are specific. The same attributes can therefore show different patterns across different reservoirs (at different sites) without being in contradiction. Often multiple specific attributes are combined to enhance the contrast between features of interest and their surroundings (e.g., Avseth *et al.* 2005). Lambert *et al.* (2009) therefore also introduced multiple attributes. Not all of these attributes need to, or should be expected to, exhibit anomalous patterns across the same reservoir.

CONCLUSIONS AND OUTLOOK

Green and Greenhalgh's (2009) claim that results, models and conclusions presented in Lambert *et al.* (2009) are inconsistent is not justified by their analysis, which reflects an apparent misunderstanding of the reported study and its context. We stand by our conclusion, which stated that "the results indicate that passive low frequency spectral analysis can increase the probability of locating reservoirs significantly". We reiterate the following findings from our study that support this conclusion: i) Attributes 3 and 4 show statistically a stronger variation in space than in time (useful to quantify spatial variations in the passive ground motion) and ii) Attributes 3 and 4 qualitatively indicate a relationship with the reservoir location. We recognize that our conclusion incorporates a subjective assessment with which Professors Green and Greenhalgh are entitled to disagree. However, the analysis presented by Green and Greenhalgh (2009) in their Table 1 is inappropriate, because the question of whether attribute values are anomalous or not should be answered in terms of probability rather than 'yes' or 'no'. Our study suggested that a future statistical classification using the attributes we describe would be a promising approach to improving the probability of detecting reservoirs. This view is now supported by a statistical classification, using a Bayesian methodology, of similar attributes to compute hydrocarbon probability maps at a different location (Riahi *et al.* 2009). More conclusive evidence that passive seismic attributes are useful to increase the probability of detecting reservoirs can only be provided by additional studies performing statistical predictions and subsequent verification/falsification by drilling.

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