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

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INTRODUCTION

Lambert *et al.* (2009) is the latest in a long series of articles that promote the assertion that anomalous spectra of microtremor recordings in the 1–10 Hz frequency range can be used to locate relatively deep hydrocarbon reservoirs. Most other articles in this series have appeared in conference proceeding volumes (Schmalholz *et al.* 2006a,b; Holzner *et al.* 2007; Lambert *et al.* 2007; Steiner, Saenger and Schmalholz 2007, 2008a; Saenger *et al.* 2007a, 2007b) or lightly reviewed journals (Holzner *et al.* 2005; Graf *et al.* 2007; Walker 2008). In addition to Lambert *et al.* (2009), five papers concerned with this theme (Dangel *et al.* 2003; Steiner, Saenger and Schmalholz 2008b; Frehner, Schmalholz and Podladchikov 2009; Holzner *et al.* 2009; Saenger *et al.* 2009) have been published in fully peer-reviewed journals. The proposed hydrocarbon-microtremor-spectra (HMS in the following) relationship is the basis for a hydrocarbon exploration service offered by a company that financially and logistically supports an industry-university consortium (IUC in the following) that includes the authors of Lambert *et al.* (2009).

We begin our commentary by summarizing critical aspects of the proposed HMS relationship and how it has been employed by IUC members, highlighting those issues relevant to the article by Lambert *et al.* (2009). We then identify a number of misleading aspects of Lambert *et al.* (2009) while demonstrating that their data contradict i) their own conclusions, ii) the proposed HMS relationship and iii) assertions made in previous IUC publications. This is followed by a short description of key information contained in recent publications concerned with the systematic analyses of microtremor data located across two hydrocarbon reservoirs in the Middle East. The results of these independent analyses are at odds with claims made by Lambert *et al.* (2009) and with the proposed HMS relationship. Finally, the proven and widely accepted explanations for microtremors, which are unrelated to the presence of relatively deep hydrocarbons, are briefly reviewed.

PROPOSED HYDROCARBON-MICROTREMOR-SPECTRA RELATIONSHIP

The HMS technique is based on the assumption that anomalously high vertical-component ground velocities of microtremor recordings in the 1–10 Hz frequency range originate from within reservoirs (Holzner *et al.* 2005; Walker 2008; Saenger *et al.* 2009). Anomalous vertical-component ground velocities and anomalous frequencies in the 1–10 Hz range are defined in IUC publications in terms of the following five spectral attributes (1–4 are from Lambert *et al.* 2009):

- Attribute 0: peak values of vertical-component power spectra;
- Attribute 1: peak values of vertical-component power spectra integrated over narrow frequency ranges;
- Attribute 2: peak values of V/H, where V and H are the amplitude spectra of vertical- and horizontal-component recordings;
- Attributes 3 and 4: frequencies at which peak values occur in V and H, respectively.

Attributes 0, 1 and 2 are described as potential or direct 'hydrocarbon indicators' (Holzner *et al.* 2005; Schmalholz *et al.* 2006a; Graf *et al.* 2007; Lambert *et al.* 2007, 2009; Saenger *et al.* 2007, 2009). Early IUC publications were based on Attribute 0 (Dangel *et al.* 2003; Holzner *et al.* 2005),

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whereas later ones were mostly based on Attributes 1 and 2. Attributes 3 and 4 were introduced by Lambert *et al.* (2009).

The key assumption of the HMS technique is that Attributes 0, 1 and 2 have significantly higher values at recording stations directly above hydrocarbon-rich sedimentary formations than elsewhere. It is well established that the ratio of H/V and its reciprocal V/H (Attribute 2) are less affected by source effects and are therefore more robust than attributes based on V or H alone (Nakamura 1989; Fäh, Kind and Giardini 2001; Bonnefoy-Claudet, Cotton and Bard 2006; Lambert *et al.* 2007). For this reason, Attribute 2, which should be >1.0 to be a hydrocarbon indicator (Walker 2008; Sanger *et al.* 2009), is emphasized in a number of recent IUC publications, including Lambert *et al.* (2009).

Two Voitsdorf hydrocarbon reservoirs in Austria were the targets of the Lambert *et al.* (2009) study. At least one of these reservoirs has also been a subject of many other IUC articles (Graf *et al.* 2007; Lambert *et al.* 2007; Steiner *et al.* 2007, 2008a,b; Saenger *et al.* 2007a; Walker 2008). Accordingly, we presume that IUC members regard the Voitsdorf site as an ideal location to test the proposed HMS relationship.

CONTRADICTIONS CONTAINED IN LAMBERT ET AL. (2009)

Important results of Lambert *et al.* (2009) were presented in their Figs 7–9 and are summarized in Tables 1(a)–1(c) of this commentary. In the following, all figure citations refer to figures presented in Lambert *et al.* (2009). Figure 7 shows single estimates and cross-line averages of Attributes 1–4 based on 30-minute microtremor recordings along 3 composite lines (Table 1a), whereas Figs 8 and 9 show information based on 5.5 hours of microtremor recording. Time variations of Attributes 1–4 along an individual line are displayed in Fig. 8 (Table 1b) and cross-line attribute averages and standard deviations are displayed in Fig. 9 (Table 1c).

Previous IUC articles that have reported the results of studies at the Voitsdorf site have only ever presented isolated spectra or a very limited number of Attribute 2 values (Graf *et al.* 2007; Lambert *et al.* 2007; Steiner *et al.* 2007, 2008a,b; Saenger *et al.* 2007b). The much more extensive data sets presented in Figs 7 and 9 show that Attributes 1 and 2 have virtually the same distribution of values inside and outside the borders of the Voitsdorf hydrocarbon reservoirs (Tables 1a and 1c), demonstrating that the proposed HMS relationship is not applicable at this site. Elevated values of the Attribute 1 average in Fig. 7 across the southern reservoir are heavily biased by two very high values out of ~10 estimates. Based on their large standard deviations, we suspect that the elevated values of the Attribute 1 average in Fig. 9 are similarly biased (Table 1c). Temporal variations of Attribute 1 are large with differences of 37% to much more than 100% (Fig. 8 and Table 1b). As expected, temporal variations of Attribute 2 are generally quite small. Attribute 2 has an average value of

Table 1 Attribute characteristics of microtremors recorded directly above the two Voitsdorf hydrocarbon reservoirs based on Figs 7–9 of Lambert *et al.* (2009). a) Shows the percentage of attributes distinguished by anomalous values inferred to represent hydrocarbon occurrences. For Attributes 1, 3 and 4 we define anomalous values to be those that are higher than the highest values outside the reservoir boundaries. Attribute 2 values are defined to be anomalous if they are >1.0 (Walker 2008; Saenger *et al.* 2009). b) Identifies the temporal variations of the respective attributes as small (robust) or large (unreliable). c) Defines whether average attribute values determined from all lines for entire nights (5.5 hours) of microtremor recording are anomalous or not

Table 1a

Percentage of anomalous attributes from Fig. 7 of Lambert *et al.* (2009)

ATTR.	S. RESERVOIR	N. RESERVOIR
1	~30 %	0%
2	~9 %	0%
3	~64 %	~8%
4	~64 %	~33%

Table 1b

Temporal variations of attributes from Fig. 8 of Lambert *et al.* (2009)

ATTR.	S. RESERVOIR	N. RESERVOIR
1	large	large
2	small	small
3	small	large
4	small	large

Table 1c

Anomalous attributes from Fig. 9 of Lambert *et al.* (2009)

ATTR.	S. RESERVOIR	N. RESERVOIR
1	yes (but biased by outliers)	no
2	no	no
3	yes	no
4	yes	no

0.8–0.9 in Figs 7 and 9, with a noticeable scarcity of values >1.0 above the two reservoirs.

We are bewildered by Lambert *et al.*'s (2009) two new Attributes 3 and 4. They are highly variable in both space and time (Figs 7–9), with small and large values inside and outside the reservoir borders. Whether peak spectral values with anomalously high frequencies are recorded inside or outside the borders depends on the chosen line. Most importantly, these attributes scarcely relate to previously published IUC concepts and assertions and the Lambert *et al.* (2009) simplistic physical explanation (Figs 10 and 11) is both implausible and inconsistent with their observations. Their 'vertically acting single body force' model predicts moderately high vertical-component and zero to imperceptibly low horizontal-component amplitudes above the hydrocarbon reservoirs (Fig. 10), which would yield extraordinarily high V/H values. These features are simply not observed in their data. Indeed, the predicted zero to low horizontal-component amplitudes would result in highly variable and unreliable estimates of Attribute 2 directly above the presumed microtremor source.

INDEPENDENT ANALYSES OF MICROTREMOR DATA RECORDED ACROSS TWO OTHER HYDROCARBON RESERVOIRS

Independent tests of the proposed HMS relationship have been conducted on spatially distributed 3-component microtremor data recorded across two hydrocarbon reservoirs and adjacent regions in the Middle East, one in Abu Dhabi (Ali *et al.* 2007; Berteussen *et al.* 2008a,b) and one in Libya (Hanssen and Bussat 2008). The Abu Dhabi data were distinguished by enhanced vertical-component microtremor energy (i.e., peaks at 2.5–2.8 Hz in the amplitude spectra) across the hydrocarbon reservoir and also across nearby locations not underlain by hydrocarbon-rich sediments. In contrast, enhanced vertical-component microtremor energy (i.e., peaks at 2–4 Hz in the amplitude spectra) in the Libyan data was only observed across the hydrocarbon reservoir and not elsewhere. Nevertheless, systematic analyses of both data sets indicated that the microtremors were predominantly surface waves little influenced by deep structures (i.e., in neither region were the elevated attribute values related to the hydrocarbon reservoirs).

ALTERNATIVE EXPLANATIONS FOR 1–10 HZ MICROTREMORS

Microseisms and microtremors have been studied for more than a century by a large number of earthquake seismologists and engineers. In a recent review, Bonnefoy-Claudet *et al.* (2006) estimated that more than 500 papers have been published on ambient noise, 175 of which are included in their reference list. There is an overwhelming consensus among earthquake seismologists and engineers that 1–10 Hz microtremors are a combination of surface and body waves mostly propagating through shallow soils/sediments. Numerous researchers have used information contained in microtremors to estimate resonant frequencies of shallow soils/sediments worldwide (e.g., independent studies in Armenia, Australia, Belgium, California, Canada, Germany, Greece, Italy, Japan, Morocco, Philippines, Romania, Spain, Switzerland, Thailand, Turkey and Venezuela). Such estimates have been employed as constraints in predictions of ground-motion amplification resulting from large earthquakes and in the preparation of seismic microzonation maps, which are essential input for planning earthquake preparedness and mitigation measures. Moreover, various investigators have estimated shallow S-wave velocities from inversions of 1–10 Hz microtremor data.

Compelling evidence for the widely accepted shallow origin of 1–10 Hz microtremors includes the following:

1 Numerous studies based on array data, particle motions and other information have determined that surface waves are dominant or at least major components of microtremors (e.g., Liu *et al.* 2000; Fäh *et al.* 2001; Louie 2001; Scherbaum, Hinzen and Ohrnberger 2003; Kind, Fah and Giardini 2005; Nunziata 2007; Draganov *et al.* 2007; Berteussen *et al.* 2008a,b; Hanssen and Bussat 2008).

2 Patterns of anomalous ground amplification observed during earthquakes are similar to predicted ground-motion amplification patterns based on microtremor data (e.g., Field and Jakob 1995 and references therein; Bindi *et al.* 2000; Nguyen *et al.* 2004; Panou *et al.* 2005).

3 Shallow S-wave velocities determined from analyses of microtremor data have been verified by other techniques (Liu *et al.* 2000; Fäh *et al.* 2001; Louie 2001; Scherbaum *et al.* 2003; Kind *et al.* 2005; Nunziata 2007).

DISCUSSION AND CONCLUSIONS

Lambert *et al.* (2009) stated that they "show how spatial attribute anomalies are extracted and used to locate the reservoirs" and that their "results indicate that passive low-frequency spectral analysis combining several spectral attributes can significantly increase the probability of locating the reservoirs". Even if one accepts the proposed HMS relationship, none of the attributes described by Lambert *et al.* (2009) can be considered to be meaningful 'hydrocarbon indicators' at the Voitsdorf site and we fail to see how the authors have shown that a combination of the attributes are more effective 'hydrocarbon indicators' than the individual attributes.

Very large variations of Attributes 1–4 along lines and between adjacent lines at similar positions relative to the reservoir borders (Fig. 7 of Lambert *et al.* (2009)) are evidence for the overwhelming influence of local shallow structures on the 1–10 Hz microtremor energy recorded at the Voitsdorf site. Such an interpretation is in accord with the conclusions of numerous microtremor studies worldwide, including those recently based on microtremor data recorded across hydrocarbon reservoirs in Abu Dhabi and Libya.

Brief reviews of previous microtremor research in several of their papers demonstrated that IUC members are well aware of the influence of shallow structures on 1–10 Hz microtremor energy. Lambert *et al.* (2006) have even computed the effects, stating: "A soft soil layer modifies the spectrum of the ambient seismic noise in the low-frequency band of hydrocarbon microtremors (1.5–4 Hz). We are able to reproduce those effects with our numerical model, which allows us to remove certain soft soil related effects from our data and thus to improve the identification of hydrocarbon related information in the microtremor spectra." Inexplicably, in none of the later IUC papers are these effects adequately discussed in the context of their own data and analyses. As outlined by Hanssen and Bussat (2008), to be able to detect any weak spectral signals that may originate from relatively deep hydrocarbon reservoirs, the substantially larger signals originating from shallow soils/sediments and even the influence of topography would need to be eliminated. This becomes especially important in the case of S-wave resonance in shallow soils because the horizontal motion is dominant.

Finally, we do not preclude the possibility of signals from deep structures contributing to microtremor wavefields. Draganov *et al.* (2007) showed 1–10 Hz filtered microtremor recordings that contain vertically travelling energy and by cross-correlating 10 hours of microtremor data heavily contaminated with random noise and surface waves they produced seismic sections that appeared to contain reflections at traveltimes as great as ~2 s. Draganov *et al.* (2007) did not claim high-resolution capabilities comparable to those of the proposed HMS technique, nor did they claim to be able to detect hydrocarbon reservoirs directly.

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