Microtremor spectra: a proven means for estimating resonant frequencies and S-wave velocities of shallow soils/sediments, but a questionable tool for locating hydrocarbon reservoirs

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Abstract

Over the past five years, established techniques for estimating the resonant frequencies and S-wave velocities of shallow soil/sediment layers using microtremor spectra in the 1–10 Hz frequency range have been implicitly challenged by members of an industry-university consortium who claim that these same spectra can be used to map the detailed locations, depths, and thicknesses of hydrocarbon-rich sediments. But recently published spectral attributes based on 1–10 Hz microtremor recordings and associated analyses suggest that any microtremor signals originating from relatively deep hydrocarbon reservoirs are likely to be overwhelmed by surface-waves and other seismic energy travelling through the near-surface soil/sediment layers.

Introduction

For many years, earthquake seismologists and engineers worldwide have been using the spectra of microtremor recordings in the 1–10 Hz frequency range as an inexpensive and convenient means for estimating resonant frequencies and shear-wave velocities of shallow soils/sediments (e.g., Nakamura, 1989; Field and Jacob, 1995; Field et al., 1995; Fäh et al., 1997, 2001; Bindi et al., 2000; Liu et al., 2000; Louie, 2001; Parolai et al., 2001; Scherbaum et al., 2003; Talhaoui et al., 2004; Tuladhar et al., 2004; Kind et al., 2005; Bonnefoy-Claudet et al., 2006; Nunziata, 2007). This conventional microtremor spectra (CMS) approach requires shallow soils/sediments to be the overriding influence on microtremor characteristics.

Recently, applications of interferometric (cross-correlation) techniques have allowed seismic sections to be created from microtremor recordings (Wapenaar et al., 2006; Curtis et al., 2006). These seismic sections, which have the same appearance as conventional source and receiver gathers generated by active seismic sources, are generally dominated by surface waves that sample the top few hundred metres of the Earth (Shapiro and Campillo, 2004; Sabra et al., 2005; Shapiro et al., 2005; Larose et al., 2006; Yao et al., 2006; Lin et al., 2007; Halliday et al., 2008; Gouédard et al., 2008). The CMS and interferometric surface-wave approaches to studying microtremor data are complementary.

Nearly parallel to, but quite distinct from developments and applications of the interferometric approach, an industry-university consortium has been promoting simple spectral attributes of microtremor recordings in the 1–10 Hz frequency range as tools for locating and estimating the thicknesses of relatively deep hydrocarbon reserves (Schmalholz et al., 2006a, 2006b; Graf et al., 2007; Holzner et al., 2005, 2007; Lambert et al., 2007, 2009; Steiner et al., 2007, 2008a, 2008b; Saenger et al., 2007a, 2007b 2009; Walker, 2008; Frehner et al., 2009; Holzner et al., 2009). The proposed hydrocarbon microtremor spectra (HMS) approach requires oscillating fluids in deep sedimentary units to be the overriding influence on microtremor characteristics (Holzner et al., 2005; Walker, 2008; Saenger et al., 2009).

Clearly, the physical bases for the CMS and HMS approaches to analysing the same narrow frequency band of microtremor signals are mutually exclusive: simple spectral analyses of 1–10 Hz microtremor signals are unlikely to provide resonant frequencies and shear wave velocities of shallow soils/sediments and simultaneously yield accurate estimates of geographic coordinates, depths, and thicknesses of deep hydrocarbon reservoirs. In the following, we outline the proposed sources and uses of 1–10 Hz microtremors, with emphasis on their spectral characteristics. We begin by providing short descriptions of the CMS and HMS approaches. Subsequently, we review the mounting evidence against the latter approach, with emphasis on new information provided in HMS publications and the results of recent systematic analyses of microtremor data recorded across hydrocarbon reservoirs.

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Two approaches to 1–10 Hz microtremor research

CMS approach

Earthquake seismologists and engineers have studied ambient seismic noise (microseisms and microtremors) for more than a century, with some of the world's top seismologists contributing to the early studies (e.g., Gutenberg, 1918, 1958; Aki, 1957, 1965; Toksöz, 1964). The results of a major European-wide investigation of ambient seismic noise, including a number of useful reviews, are provided on the 'Site Effects Assessment Using Ambient Excitations' web page (SESAME, 2004). Although there is a general 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, the general conditions under which microtremors are dominated by surface waves (Rayleigh waves having larger vertical motion) versus resonant S-waves (having larger horizontal motion) remain poorly understood (Bonnefoy-Claudet et al., 2006). Nevertheless, diverse investigations based on seismic array data, particle motions, and other information have demonstrated a dominant or strong component of surface-wave energy in microtremor recordings (Arai et al., 1996; Liu et al., 2000; Fäh et al., 2001, 2008; Louie, 2001; Scherbaum et al., 2003; Köhler et al., 2004; Malischewski and Scherbaum, 2004; Kind et al., 2005; Dutta et al., 2007; Nunziata, 2007; Ali et al., 2007; Berteussen et al, 2008a, 2008b; Hanssen and Bussat, 2008).

The vast majority of investigations concerned with 1–10 Hz microtremors have involved estimating resonant frequencies of shallow soil/sediment layers. The following selection of references highlights the global nature of these investigations: Armenia (Field et al., 1995), Australia (Gaull et al., 1995), Belgium (Nguyen et al., 2004), California (Field and Jacob, 1995), Canada (Molnar et al., 2007), Germany (Parolai et al., 2001, 2004), Greece (Panou et al., 2005), Italy (Bindi et al., 2000, Nunziata, 2007), Japan (Satoh et al., 2001a), Morocco (Talhaoui et al., 2004), Philippines (Abeki et al., 1996), Romania (Zaharia et al., 2008), Spain (Alfaro et al., 2001; Al Yuncha et al., 2004), Switzerland (Fäh et al., 1997), Thailand (Tuladhar et al., 2004), Turkey (Ansal et al., 2001) and Venezuela (Abeki et al., 1998). Resonant frequency estimates have been used to predict ground motion amplifications that would result from large earthquakes and to prepare seismic microzonation maps, which are essential input for planning earthquake preparedness and mitigation measures. Moreover, patterns of ground motion amplification observed during earthquakes are very similar to the microtremor-based predictions (Ohta et al., 1978; Lermo and Chavez-Garcia, 1994; Field and Jakob, 1995; Arai et al., 1996; Duval et al., 1998; Rodriguez and Midorikawa, 2003; Nguyen et al., 2004; Parolai, 2004; Panou et al., 2005).

Modelling or inversions of 1–10 Hz microtremor data have supplied shallow S-wave velocity versus depth models, many of which have been verified by other techniques (Fäh et al., 2001; Liu et al., 2000; Louie, 2001; Scherbaum et al., 2003; Kind et al., 2005; Nunziata, 2007). By extending the input to include substantially lower frequencies (i.e. microseisms with frequencies as low as 0.01–0.2 Hz), lower resolution S-wave velocity information has been determined to depths as great ~2 km (Yamanaka et al., 1994; Ibs-von Seht and Wohlenberg, 1999; Satoh et al., 2001b, 2001c; Hinzen et al., 2004; Dutta et al., 2007).

HMS approach

The HMS approach to analyzing 1–10 Hz microtremors is extremely simple: anomalously high vertical-component microtremor ground velocities are said to be recorded above hydrocarbon-rich sediments but not above water-saturated ones (Dangel et al., 2003; Schmalholz et al., 2006a, 2006b; Graf et al., 2007; Holzner et al., 2005, 2007; Lambert et al., 2007, 2009; Steiner et al., 2007, 2008a, 2008b; Saenger et al., 2007a, 2007b, 2009; Walker, 2008; Frehner et al., 2009; Holzner et al., 2009). High vertical-component velocities are variously defined by elevated values of the following spectral attributes:

- V_{ps} — vertical-component power spectra;
- V_{int} — vertical-component power spectra integrated over narrow frequency ranges; and
- V/H — the ratio of vertical-component (V) to horizontal-component (H) amplitude spectra, particularly V/H values greater than 1.

Elevated attribute values have been 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., 2007a, 2009). Because ratios are less influenced by source effects than V or H alone (Nakamura, 1989; Fäh et al., 2001; Bonnefoy-Claudet et al., 2006), V/H has been emphasized in recent HMS papers (Graf et al., 2007; Lambert et al., 2006, 2007, 2009; Saenger et al., 2007a, 2007b, 2009; Walker, 2008).

The generation of anomalously high vertical-component ground velocities within hydrocarbon reservoirs is a prerequisite of the HMS approach (Holzner et al., 2005; Walker, 2008; Saenger et al., 2009). Several physical mechanisms for creating the necessary anomalous conditions within reservoirs have been proposed (Schmalholz et al., 2006a, 2006b; Graf et al., 2007; Holzner, 2007, 2009; Saenger et al., 2007a, 2009; Walker, 2008), with the common driving force assumed to be the ever-present 0.1–0.2 Hz microseismic waves generated by meteorological phenomena and interactions of ocean waves with continental margins (Bonnefoy-Claudet et al., 2006; Berger et al., 2004). None of the theories has been proved and they remain speculative at best.

Dangel et al. (2003) have displayed single examples of V_{ps} inside and outside the boundaries of 12 known or assumed hydrocarbon reservoirs in Europe, North Africa, the Middle East, and the Ukraine. In all cases, V_{ps} values inside the hydrocarbon boundaries were much larger than values outside, with an order-of-magnitude difference in some examples. A number of HMS publications have presented examples of microtremor spectra and/or associated spectral attributes from hydrocarbon fields in Brazil, Mexico, and Austria (Graf et al., 2007; Holzner et al., 2005; Lambert et al., 2007, 2009; Steiner et al., 2007, 2008a, 2008b; Saenger et al., 2007a, 2007b, 2009; Walker, 2008). V_{ps} and V_{int} were used to construct hydrocarbon potential maps for regions in Brazil and Mexico (Holzner et al., 2005; Saenger et al., 2007a, 2009; Walker et al., 2008), and Graf et al. (2007) state that microtremor spectral attributes were the basis for a successful oil-play prediction in Austria.

Spectra and/or spectral attributes of microtremor data acquired across oil and gas fields at Voitsdorf in Austria have been presented in a number of HMS articles (Graf et al., 2007; Lambert et al., 2007, 2009; Steiner et al., 2007, 2008a, 2008b; Saenger et al., 2007a; Walker, 2008). Furthermore, by time-reverse finite-difference modelling selected microtremor data from this site, Steiner et al. (2007, 2008a, 2008b) appear to have determined the locations, depths, and thicknesses of two hydrocarbon reservoirs with remarkable accuracy. Our first criticisms of the proposed HMS relationship are based on published microtremor spectral attributes from the Voitsdorf site.

Observations that contradict the proposed HMS relationship

Data from the Voitsdorf site

Most HMS articles that refer to the Voitsdorf site show only isolated amplitude spectra or a limited number of V/H values (Graf et al., 2007; Steiner et al., 2007, 2008a, 2008b; Saenger et al., 2007b; Walker, 2008). Lambert et al. (2007, 2009) present many more microtremor spectral attributes that allow the applicability of the HMS technique at this site to be assessed. In the following, we describe a selection of their spectral attributes based on 30–60 minutes of 1–6 Hz bandpass filtered microtremor data (Figures 1 and 2).

Figure 1 (information extracted from Lambert et al., 2007) displays V/H values determined from 21 microtremor recordings, of which nine are located directly above a hydrocarbon reservoir and 12 are situated outside the reservoir boundaries (Figure 1). These recordings were made along three nearly parallel ~2 km long profiles separated by distances of only ~ 250 m. There are no elevated V/H values anywhere along the east profile and only four of the other six recordings above the reservoir have values significantly higher than those in adjacent regions. We conclude that less than 50% of the V/H values directly above this reservoir can reasonably be classified as diagnostic of hydrocarbon-rich sediments according to the V/H criteria.

Figure 2 (information extracted from Lambert et al., 2009) displays much larger V_{int} and V/H datasets determined from ~60 microtremor recordings, of which ~20 are located directly above two hydrocarbon reservoirs and ~40 are situated outside the reservoir boundaries. Again, these recordings were made along three nearly parallel profiles, but this time the profiles were ~12 km long and ~500 m apart. It is notable that only three of the ~20 V_{int} values directly above the hydrocarbon reservoirs can be considered to be elevated and that there are no significant differences between V/H values inside or outside the boundaries of the two reservoirs; the peak in the V_{int} average curve (bold line) above the left reservoir is caused by two outliers from a total of 10 observations and there is only a single V/H value >1 inside the reservoirs' boundaries, but six V/H values >1 outside the boundaries. Lambert et al. (2009) demonstrate that V_{int} values vary substantially (i.e. 37 % to > 100 %) during 5.5 hours of recording, but V/H values are relatively stable (mostly <15% variation) over the same period. Nevertheless, our description of the spectral attributes based on the 30-minute microtremor recordings is generally valid for the

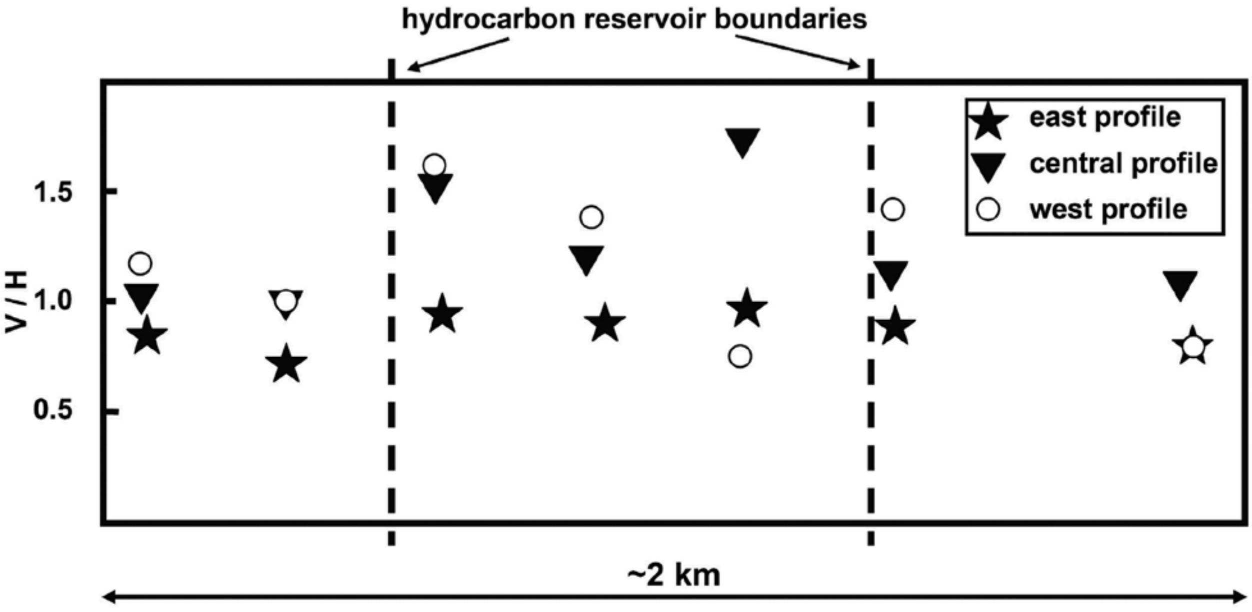

Figure 1 *Peak V/H values (V and H are the amplitude spectra of vertical- and horizontal-component recordings) for three closely spaced (~250 m apart) microtremor profiles that cross a Voitsdorf hydrocarbon reservoir. Redrawn from Lambert et al. (2007).*

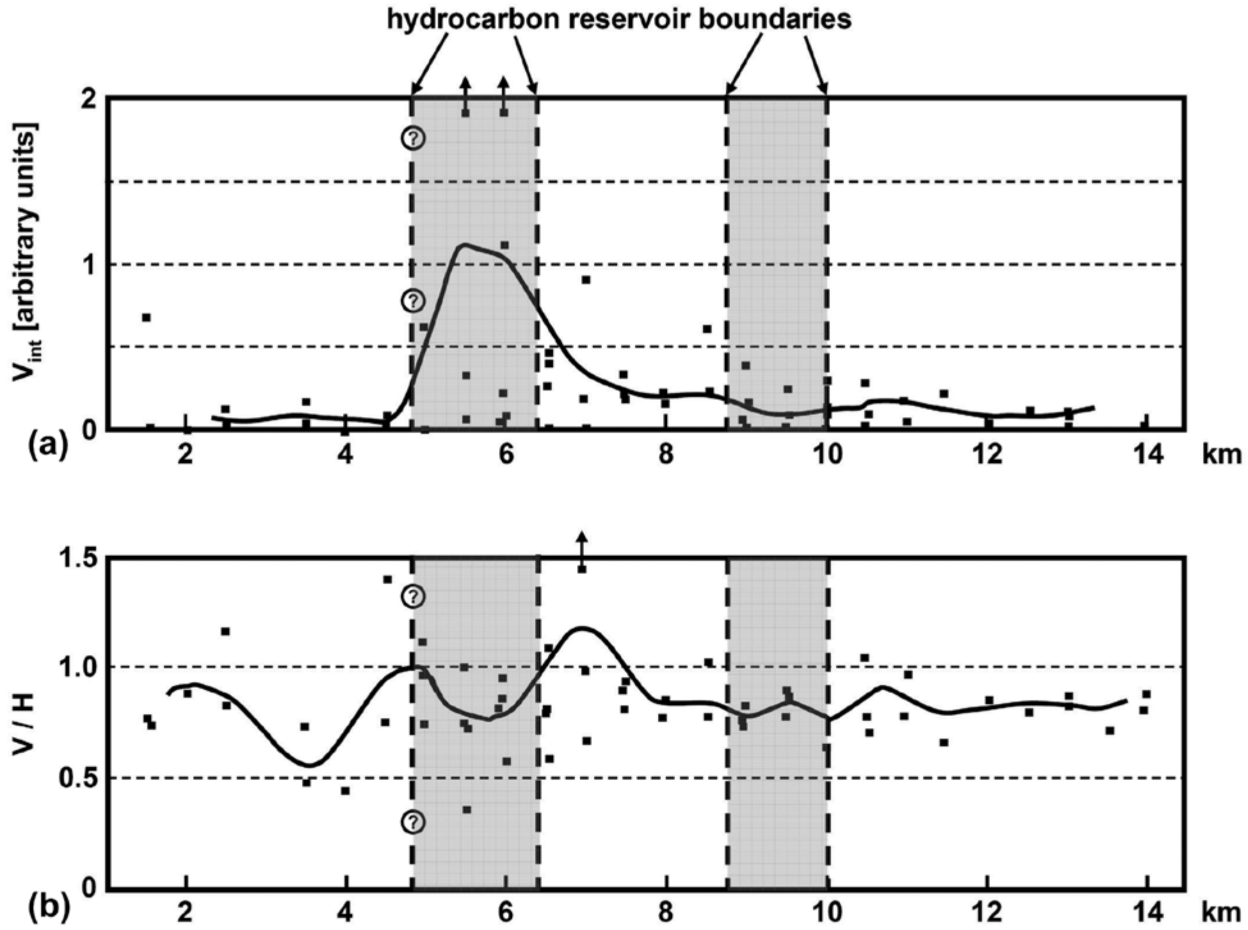

Figure 2 For three closely spaced (~500 m apart) microtremor profiles that cross two Voitsdorf hydrocarbon reservoirs, the two figures show: (a) V_{int} (values of vertical-component power spectra integrated over 1–5 Hz); (b) peak V/H values (V and H are the amplitude spectra of vertical- and horizontal-component recordings). Question marks indicate that the left boundary of the left reservoir is poorly defined. Lines are weighted averages of the point estimates. Note that the profiles shown in this figure are much longer than those displayed in Figure 1. Redrawn from Lambert et al. (2009).

averaged spectral attributes based on the 5.5-hour recording period (compare Figures 7 and 9 in Lambert et al., 2009).

We judge that the V_{int} and V/H values displayed in Figures 1 and 2 are a poor basis for hydrocarbon exploration using the HMS criteria.

Independent studies of microtremor data recorded across hydrocarbon reservoirs

At least two groups have tested the proposed HMS relationship in the Middle East. Ali et al. (2007) and Berteussen et al. (2008a, 2008b) have presented the initial results of a microtremor study in Abu Dhabi designed to determine the apparent velocities, azimuths, and particle motions of seismic waves responsible for microtremors across a known hydrocarbon reservoir. They analysed three-component microtremor data recorded on two linked cross arrays of 9 × 9 broadband seismographs, with one array located above oil-rich sediments and the other located above presumed water-saturated sediments. Enhanced vertical-component microtremor energy (i.e. peaks at 2.5–2.8 Hz in the amplitude spectra) was not only observed across the hydrocarbon reservoir but also at locations outside the reservoir boundaries. Based on their analysis of the broad-band array data, they estimated that the microtremor energy at both arrays originated from the nearby Arabian Gulf coastal region and that surface waves with dominant velocities of ~900 m s^{-1} were the likely principal wave types (i.e. they present no evidence for substantial body-wave energy travelling vertically from the hydrocarbon reservoir).

Hanssen and Bussat (2008) describe the most thorough analysis to date of microtremor data recorded across a hydrocarbon reservoir. Their dataset, comprising an areal distribution of 264 recordings, was acquired across a hydrocarbon reservoir and adjacent region in Libya. Unlike the Abu Dhabi study area, spectral peaks (2–4 Hz in the amplitude spectra) are observed in vertical-component microtremor recordings directly above the Libyan hydrocarbon reservoir but not at other locations. According to the proposed HMS relationship, these 2–4 Hz spectral peaks are direct hydrocarbon indicators. However, the careful analysis by Hanssen and Bussat (2008) precludes that interpretation. They prove that microtremors distinguished by 2–4 Hz spectral peaks do not originate from the underlying reservoir, but instead are surface waves little influenced by structures deeper than ~100 m.

The key findings of Hanssen and Bussat (2008) can be summarized as follows:

1. Episodes of substantially enhanced amplitudes of the 2–4 Hz microtremor spectra do not correlate with changes in the level of the ubiquitous 0.1–0.2 Hz microseismic energy, thus precluding the latter from being the forcing agent for the former.
2. Elevated amplitudes of the 2–4 Hz microtremor spectra above the hydrocarbon reservoir correlate with higher frequency microtremor energy clearly generated by anthropogenic sources (e.g., traffic and production noise).
3. Enhanced 2–4 Hz microtremor energy originates as discrete bursts of surface-wave energy that has well-defined 250–300 m s^{-1} moveouts in both the time-distance and frequency-distance domains.
4. The enhanced surface-wave energy is likely caused by the interaction of anthropogenic noise with near-surface soils/sediments.
5. Analysis of data collected during quiet times minimally affected by anthropogenic disturbances show a strong correlation between the distribution of enhanced 2–3 Hz microtremor energy and the topography of the sand dunes.

Points 3 and 5 are not compatible with the proposed HMS relationship, and points 1, 2 and 4 eliminate the proposed driving force for the various HMS explanations.

Discussion and conclusions

A large number of studies worldwide have provided compelling evidence in favour of the CMS approach: analyses of array data¸ particle motion plots, and other information have proven surface waves to be the dominant or major component of microtremor wavefields; many microtremor-based predications of ground-motion amplification patterns during earthquakes have been confirmed; and microtremor-based estimates of shallow S-wave velocities have been verified by other methods. There is no doubt that shallow soils/sediments have an overwhelming or very substantial influence on the vast majority of microtremor recordings.

In contrast, the evidence in support of the HMS approach is meagre and diminishing. The principal arguments for a predominantly deep origin of 1–10 Hz microtremors are the elevated V_{ps}, V_{int} and V/H values above hydrocarbon reservoirs and the non-elevated values outside reservoir borders reported in HMS publications. However, such correlations are proving to be exceptions. Non-elevated values of these spectral attributes are also observed above hydrocarbon reservoirs and elevated values have been recorded across neighbouring regions well outside the reservoir boundaries. Moreover, elevated values of V/H (i.e. >1) in 1–10 Hz microtremor spectra have been observed at many locations very far from potential hydrocarbon-rich sediments, including Anchorage in the USA (Dutta et al., 2007), Bangkok in Thailand (Tuladhar et al., 2004), Kreuzlingen and Basel in Switzerland (Fäh et al., 2001, 2008), Barcelona in Spain (Alfaro et al., 2001), Bucharest in Romania (Zaharia et al.; 2008), the Fraser River Delta in Canada (Molnar et al., 2007), and the Sendai Basin in Japan (Satoh et al., 2001a).

Although HMS publications refer to various 1–10 Hz microtremor studies of their own and others, there are currently only three cases for which there is sufficient published information (e.g., spectra, spectral attributes, and/or spectral analyses) to allow an objective assessment of the proposed HMS relationship to be made: the Austrian data reported by Lambert et al. (2007, 2009); the Abu Dhabi data and analyses presented by Ali et al. (2007) and Berteussen et al. (2008a, 2008b); and the Libyan data and analyses described by Hanssen and Bussat (2008). A fourth case study recently published by Saenger et al. (2009) contains spectra, spectral attributes, and analyses of microtremor data recorded across a gas field in Mexico, but as for most previous HMS publications, the data for only two isolated microtremor recording sites are presented. Furthermore, the distribution of their V_{int} values are quite different from the distribution of their V/H values and neither V_{int} nor V/H are convincingly correlated with the quantity of gas detected in holes drilled after the microtremor study. In all three cases which allow an objective assessment of the proposed HMS relationship to be made, it is shown to be inappropriate and none of the spectral attributes can be interpreted in terms of hydrocarbon indicators. At the Voitsdorf site in Austria, values of V_{int} and V/H above the hydrocarbon reservoirs are not significantly different from values outside the reservoir boundaries. Elevated vertical-component spectral amplitudes are observed both above the hydrocarbon reservoir and outside the reservoir boundaries at the Abu Dhabi site, with surface waves being the likely source of the elevated amplitudes. Although elevated vertical-component spectral amplitudes are only observed above the hydrocarbon reservoir at the Libyan site, surface waves are again the source of the elevated amplitudes. The careful analysis by Hanssen and Bussat (2008) also indicates that the elevated spectral amplitudes at this site are not powered by microseisms, the assumed driving force for all HMS explanations of the proposed HMS relationship. Furthermore, they demonstrate a strong correlation between the distribution of enhanced 2–3 Hz microtremor energy and the sand-dune-dominated topography, an observation that is incompatible with the proposed HMS relationship.

Considering the paucity of hydrocarbon indicators in the data of Lambert et al. (2007, 2009), it is not clear how these or similar data were used to identify the geographic location and thickness of a new hydrocarbon reservoir at the Voitsdorf site (Graf et al., 2007); other data and considerations must have been employed in the exploration strategy. Moreover, the growing evidence against the proposed HMS relationship raises serious doubts about the general value of hydrocarbon potential maps (Holzner et al., 2005; Saenger et al., 2007b, 2009; Walker, 2008).

Finally, we do not preclude the possibility of signals from deep structures contributing to the microtremor wavefield. But to detect any weak spectral signals originating from deep in the sedimentary section, the substantially larger shallow soil/sediment signals and the influence of topography need to be eliminated. Applications of interferometric (cross-correlation) techniques to very long microtremor time series have yielded seismic sections that not only contain high amplitude surface waves, but also transmitted P- and S-phases (Roux et al., 2005; Gouédard et al., 2008; Miyazawa et al., 2008) and even reflected P-phases (Draganov et al., 2007; Gouédard et al., 2008). For example, Draganov et al. (2007) show 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 produce seismic sections that appear to contain reflections at traveltimes as great as ~2 s. These authors recognize the dominance of random noise and surface waves in their microtremor data. Accordingly, they design methods to minimize their effects on the final processed sections. Draganov et al. (2007) do not claim high-resolution capabilities comparable to those of the proposed HMS technique, nor do they claim to be able to directly detect hydrocarbon reservoirs.

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