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Frequency–amplitude range of hydrocarbon microtremors and a discussion on their source

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Abstract
Recently, some studies have suggested using ambient noise as a tool for hydrocarbon reservoir investigation. This new passive seismic technique, named HyMas, is based on the positive energy anomaly in data spectra between 1 to 6 Hz for microtremor measurements over reservoirs, which are called hydrocarbon microtremors. Despite the acceptable results obtained by the HyMas technique, there are many unknowns, especially concerning the source and generation mechanism of hydrocarbon microtremors and the relations between reservoir characteristics and the attributes of hydrocarbon microtremors. In this study we tried to find the relations between reservoir characteristics, including fluid content and depth, for 12 sites around the world with hydrocarbon microtremor attributes, including peak amplitude and frequency. Based on the power spectral density curves of these 12 reservoirs, a frequency–amplitude range is also proposed as a criterion for separating hydrocarbon microtremors from local noise not related to reservoirs. Finally, the source of the hydrocarbon microtremors is discussed and tidal displacement is suggested as a probable agent for the generation of these anomalies.

Keywords: hydrocarbon, reservoir, microtremors, ambient noise, passive geophysics

(Some figures may appear in colour only in the online journal)

1. Introduction

Numerous continuous seismic signals exist which are usually rather weak and which were often considered as useless background noise only. However, this noise can carry useful information that is contained in its characteristics, such as the frequency spectrum, statistical properties and non-linear behaviour. Moreover, it may contain a spectral signature characteristic of the media or environment that it has passed through (Dangel *et al* 2003).

Ambient noises below 1 Hz are largely generated by oceanic and large-scale meteorological events (microseism) (Longuet-Higgins 1950, Peterson 1993, Webb 2007) and frequencies above 1 Hz are dominated by cultural sources in urban settings and by wind-generated noise in remote sites (high-frequency noise) (Peterson 1993, Withers *et al* 1996, Young *et al* 1996, Wilson *et al* 2002, McNamara and Buland 2004, Marzorati and Bindi 2006, Bonnefoy-Claudet *et al* 2006). Usually, there is a rather seismically quieter window which dominates the background wave field at frequencies between 0.5 to 10 HZ (Peterson 1993).

Background noise (microtremor) recordings have been used as an inexpensive and convenient tool for estimating the resonant frequency and shear-wave velocities of relatively shallow sediments (Nakamura 1989, Field and Jacob 1995, Field *et al* 1995, Fäh *et al* 1997, 2001, Bard 1999, Bindi *et al* 2000, Liu *et al* 2000, Louie 2001, Parolai *et al* 2001, Ohori *et al* 2002, Hartzell *et al* 2003, Scherbaum *et al* 2003, Talhaoui

Table 1. Hydrocarbon reservoirs that the highamplitude anomaly in microtremors observed.

Row	Country	Location	References
1	Jordan	Dead sea rift valley	Dangel *et al* 2003
2	Northern Italy	Milan	Dangel *et al* 2003
3	Central Ukraine	Unknown	Dangel *et al* 2003
4	UAE	Unknown	Dangel *et al* 2003
5	UAE	Empty Quarter	Dangel *et al* 2003
6	Morocco	Unknown	Dangel *et al* 2003
7	Central Italy	Unknown	Dangel *et al* 2003
8	Ukraine	Unknown	Dangel *et al* 2003
9	Southern Switzerland	Unknown	Dangel *et al* 2003
10	Northern Switzerland	Unknown	Dangel *et al* 2003
11	Ukraine	Unknown	Dangel *et al* 2003
12	UAE(Dubai)	Unknown	Dangel *et al* 2003
13	UAE(Dubai)	Unknown	Dangel *et al* 2003
14	USA	Eastern Texas	Dangel *et al* 2003
15	USA	Central Texas	Dangel *et al* 2003
16	Austria	Voitsdorf	Lambert *et al* 2009a, 2009b
17	Mexico	Burgos Basin	Saenger *et al* 2007a, 2007b
18	Brazil	Potiguar	Veras *et al* 2005, Holzner *et al* 2005a, 2006a
19	Southern Libya	Murzuq basin	Saenger *et al* 2009c
20	Kuwait	Unknown	Bloch and Akrawi 2006
21	Jordan	Unknown	Bloch and Akrawi 2006

et al 2004, Tuladhar *et al* 2004, Chavez-Garcia and Luzon 2005, Kind *et al* 2005, Bard *et al* 2005, Bonnefoy-Claudet *et al* 2006, Tada *et al* 2006, Nunziata 2007, Chavez-Garcia and Rodriguez 2007, Dutta *et al* 2007, Haghshenas *et al* 2008, Guillier *et al* 2008, Wathelet *et al* 2008, Stephenson *et al* 2009, Gerivani *et al* 2011, Shabani *et al* 2011).

Using the information carried by ambient noise has been developing very quickly and new gathering techniques and new fields of study have been presented. For example, 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, 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).

More recently, microtremor measurements have been proposed as a tool in the study and detection of hydrocarbon reservoirs. High spectral amplitude anomalies of microtremor signals in the 1–6 Hz frequency range, with a peak around 3 Hz, have been reported over a number of hydrocarbon reservoirs and named 'hydrocarbon microtremors' (HMs) (Singer *et al* 2002, Dangel *et al* 2003, Holzner *et al*, 2005a, 2005b, 2006a, 2006b, 2006c, 2007a, 2007b, Frehner *et al* 2006, 2007, Rached 2006, 2009, Lambert *et al* 2007, 2009a, 2009b, Steiner *et al* 2007, 2008a, Graf *et al* 2007, Kaya *et al* 2007, Saenger *et al* 2007b, van Mastrigt and Al-Dulaijan 2008, Nguyen *et al* 2008, 2009, Goertz *et al* 2009, Saenger *et al* 2009a, 2009b, 2009c). Table 1 shows a list of reservoirs where the existence of this type of anomaly has been reported.

In all of these studies, the researchers showed a correlation between microtremor characteristics and the presence or absence of hydrocarbons. Dangel *et al* (2003) studied microtremors over 15 sites worldwide and concluded that there is a decreasing tendency in the peak of spectral amplitude of microtremors toward the border of the reservoirs and that the peaks vanish in sites outside the reservoir area. They also reported a strong correlation of the tremor power with the thickness of the hydrocarbon-bearing layers (pay zone thickness) determined by well-logging techniques. Holzner *et al* (2005c), Bloch and Akrawi (2006) reported a similar correlation.

Steiner *et al* (2008b) applied time reverse modelling to determine the location and depth of hydrocarbon reservoirs; however, Green and Greenhalgh (2009) believe that time reverse modelling is controlled *a priori* by the input velocity model more than microtremors.

Holzner *et al* (2006d) tested the reproducibility of hydrocarbon microtremors in 48 stations which were surveyed at two different times and showed a confidence level better than 95%.

Furthermore, in a microtremor survey in Mexico, several hydrocarbon reservoir-related microtremor attributes were calculated, and the maps prepared based on these attributes, were compared with known gas intervals. The results reveal a good agreement between the distribution of these attributes and the location of the gas reservoir. The wells drilled after the survey, confirmed high hydrocarbon potential in the exploration area (Saenger *et al* 2009b). Based on the results of surveys in the UAE, Kuwait and Jordan, performed by Bloch and Akrawi (2006), several new exploration areas were identified and additional hydrocarbon pools were found as the extension of existing under-developed fields and avoided a lot of dry holes. More than 13 wells were drilled and most of them confirmed hydrocarbon potential, presented on passive seismic-direct hydrocarbon indication maps.

Despite these successful experiences, there are some case studies that reject or throw doubt upon the applicability of the microtremor technique in hydrocarbon detection (Berteussen *et al* 2008a, 2008b, Ali *et al* 2007, 2009a, 2009b, 2009d, 2009e, 2010, Hanssen and Bussat 2008).

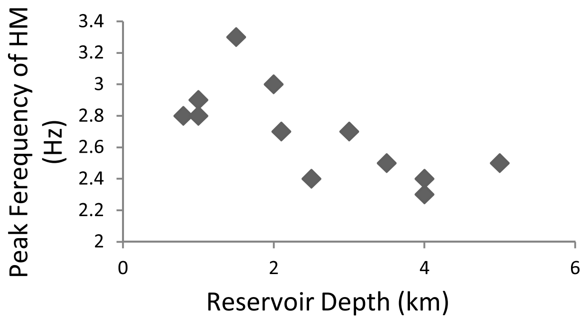

Figure 1. Correlation between peak frequency of HMs and depth of reservoirs in 12 sites around the world.

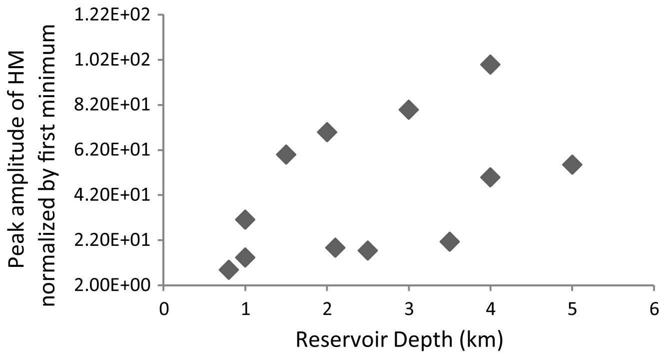

Figure 2. Correlation between normalized peak amplitude of HMs with depth of reservoirs at12 sites.

In this paper, we first reanalyze the data from 12 sites around the world, studied and presented by Dangel *et al* 2003. This showed that there is no correlation between the depth and fluid content of reservoirs and HM signals but our analysis did reveal a correlation between a reservoir's characteristics and HM's characteristics (peak frequencies and normalized amplitude). Secondly, we normalized all 12 power spectral densities (PSDs) of HM signals as they could be comparable to each other and suggested the frequency–amplitude zone as a tool for distinguishing hydrocarbon reservoir-related microtremors from other none related noises. Thirdly, we discuss the source of hydrocarbon microtremors and introduce 'tidal force' as a likely agent in the generation of HMs, and which changes over a 24 h period.

2. Comparison of reservoir characteristics and hydrocarbon microtremors

2.1. Effect of reservoir depth on hydrocarbon microtremors

In a microtremor measurement, manipulated worldwide by Dangel *et al* (2003), they noted that despite highly variable reservoir conditions (depth, type of fluid content, reservoir rock type and overlying geology), all of the observed hydrocarbon tremor spectral peaks lay within a remarkably narrow frequency range, about 1.5 to 4 Hz. By reprocessing these data, we found that the peak frequencies of HMs change in this narrow frequency range, depending on the depth of the reservoir. Figure 1 shows the correlation between the peak frequency of HMs and the depth of the reservoir. As shown, the peak frequencies of HMs decrease as the depth of the reservoir increases. A reasonable justification for this observation is the attenuation of the high-frequency content of HM signals in the propagation path from the reservoir to the Earth's surface. Studying the power spectral density curves of HMs precisely shows that those composed of some smaller curves, overlie each other. Whereas amplitudes with higher frequencies are attenuated more than amplitudes with lower frequencies, and the amplitudes of small curves in the higher frequency range decrease faster than lower ones, the peak amplitude migrates to lower frequencies. It must be noted that not only depth, but also other parameters of the reservoir probably affect the peak frequency of HMs and must be studied. For example, Holzner *et al* (2009), by numerical modelling partially saturated pores, showed that the peak frequency of HMs decrease with pore size and fluid viscosity.

Another characteristic of HMs that we tried to correlate with reservoir depth was peak amplitude. Due to the high variation of microtremor amplitude and energy, a normalization of the HM amplitude, by the level of total energy in the ambient noise wave field, is necessary before an assessment of this correlation. Saenger *et al* (2009c) suggested the amplitude of the 'first minimum' of a PSD curve can be used as a measure of the level of the total energy in the ambient noise wave field in the frequency band of interest. A first minimum is defined as the lowest part of a PSD curve between microseisms and hydrocarbon microtremors. So, we normalized the peak amplitudes of HMs with their first minimum and tried to correlate this with the depth of reservoirs in 12 sites (figure 2). Although it is expected that amplitude decreases as depth increases because of attenuation, as can be seen, normalized amplitude increases for deeper reservoirs.

Because of the over-burden pressure of rocks over reservoirs, the fluid pressure of reservoirs increases as depth increases and this augmentation of pressure may be the reason for the higher amplitude of HMs with depth increase. Dangel *et al* (2003) measured microtremors over a gas reservoir, near to a well at two different times: once during the production activity of the gas field and again after disruption of production for three months. The first time, HM signals were very weak, but, the second time, high-amplitude HM signals were observed (figure 3). The augmentation and reduction of pressure due to production and closure of the productive wells in the hydrocarbon industry is a well known phenomenon (Dake 2001) that can be explained by the variation of HM amplitude.

Dangel *et al* (2003) proposed that fluid saturation, incremented with depth, is responsible for the increment of the HM amplitude, because they observed a good correlation between the thicknesses of the total net pay zone. Based on the results obtained in our study, it seems that the role of pressure is more important than fluid saturation. Of course it is clear that pressure can also affect fluid saturation.

As depth and consequently overburden pressure increase, the size of pores and the porosity of reservoir rock also decrease. A numerical study of Holzner *et al* (2009) suggests amplitudes increase in materials with higher porosities and smaller pores. If we accept the accuracy of this modelling, it

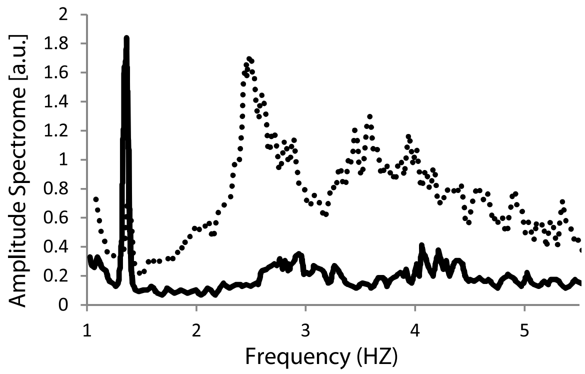

Figure 3. Solid line: spectral amplitude of HMs measured during gas producing (low pressure period of reservoir) near to a well over a gas reservoir in Switzerland. Dashed line: spectral amplitude for the measurement performed three months after the closure of the well (high pressure of reservoir) (Dangel *et al* 2003).

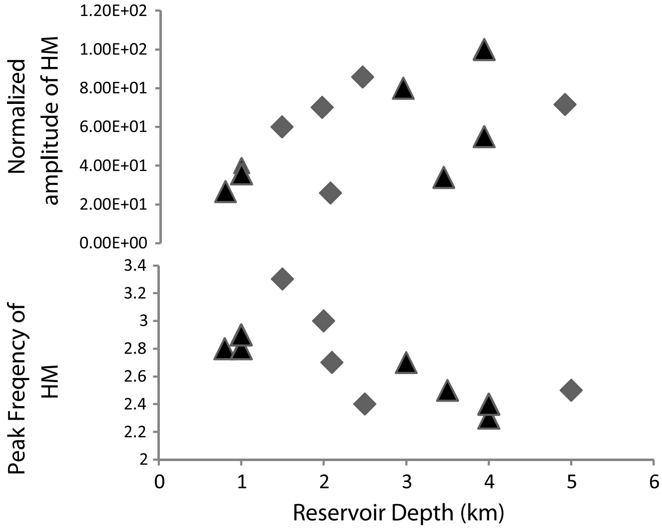

Figure 4. Variation of peak frequency and normalized amplitude of HMs with depth, regrouped based on the type of reservoir. Triangles show gas reservoirs and grey points show oil reservoirs.

can be concluded that the positive effect of the decrement of pores sizes is more than the negative effect of the decrement of rock porosity.

2.2. Effect of reservoir fluid content on hydrocarbon microtremors

As mentioned, many parameters can affect the generation and propagation of HM signals to the Earth's surface. The characteristics of preliminary energy, shape and size of the reservoir (like the thickness of the pay zone), reservoir rock type, depth of the reservoir, characteristics of the fluid content (saturation per cent, type of fluid oil or gas or viscosity), pore pressure, attenuation and resonance scattering are the main parameters. In order to evaluate the effect of fluid type on the HM characteristics, we redraw the variation curves of HM frequency and amplitude against depth in figure 4 by highlighting the type of fluid content.

As shown, the gas reservoirs are at two different depths: around 1 km and between 3 to 4 km. At each depth, the

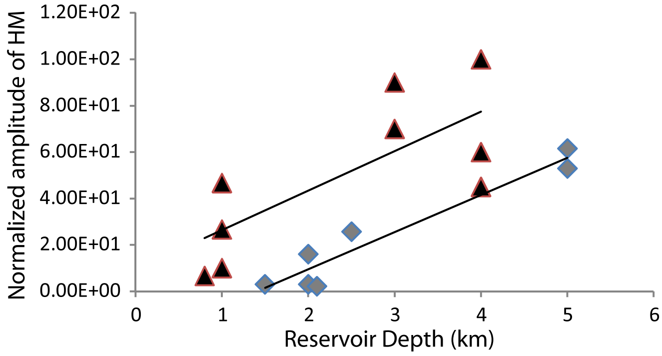

Figure 5. Correlation between normalized amplitude of small curves of HMs in the frequency range 2 to 2.3 HZ with the depth of reservoirs. Triangles show gas reservoirs and grey points show oil reservoirs.

frequency and amplitude of HMs are relatively similar to each other. This may show that the fluid content of a reservoir probably can influence the characteristics of the observed HM signals but more research is required to discover the quality of this influence.

Here we picked all the peak frequencies and amplitudes (even very small peaks) in all 12 PSD curves. We categorized amplitudes based on their frequency range, and tried to correlate the normalized amplitude with the depth of the reservoir. None of them, except in the frequency range of 2 to 2.3 HZ, showed any correlation. For the frequency range of 2 to 2.3 HZ, oil and gas reservoirs were separated and the results presented in figure 5. As is shown, the amplitude of HMs over oil and gas reservoirs correlated with depth in different ways. This can be interpreted as the influence of the fluid content of reservoirs on the HM signals. Another conclusion from this correlation could be that not only the peak amplitude of HMs with a frequency greater than 2.3 HZ are related to reservoirs, but also that signals with smaller curves in the frequency range 2 to 2.3 HZ are probably related to reservoirs.

3. Amplitude–frequency range of hydrocarbon microtremors

In past years, studies have been conducted on HM but none of them resulted in introducing the amplitude and frequency range. We think that knowing the range of these parameters is helpful for a better understanding of this phenomenon. Here, we assessed the PSD curves of HMs in the 12 sites mentioned above. Despite a narrow band of frequencies, the amplitudes of HM signals change in a very broad range (10^{-17} to 10^{-10}). Due to this variability in amplitude, a comparison between the different sites is very difficult or impossible, therefore we normalized the HM amplitudes using the first minimum which we discussed above. Figure 8 shows all the normalized PSD curves for 12 sites around the world, together. As can be seen, all normalized curves swing in a band between the black lines. In one of the curves, in the frequency range of 2.7 to 3.8 HZ, amplitudes anomalously decrease under the black lines, which could be because of local site deamplification.

Concerning the sources and mechanisms of hydrocarbon microtremors, some studies have suggested that these HMs

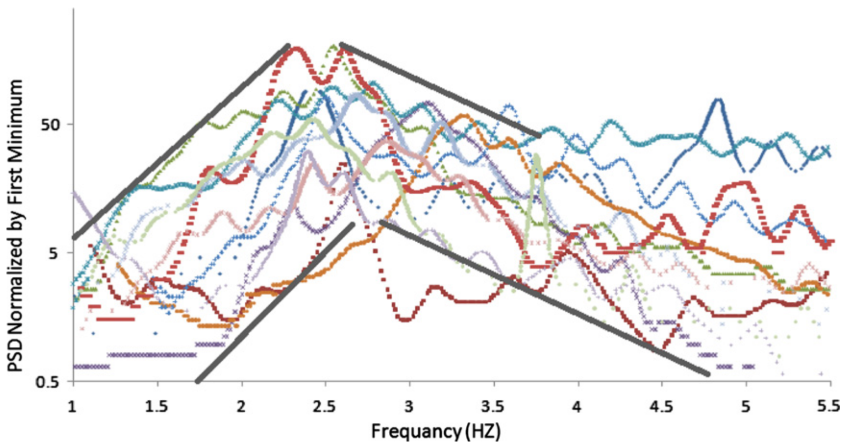

Figure 6. Frequency–amplitude range of hydrocarbon microtremors. Amplitudes were normalized by first minimum.

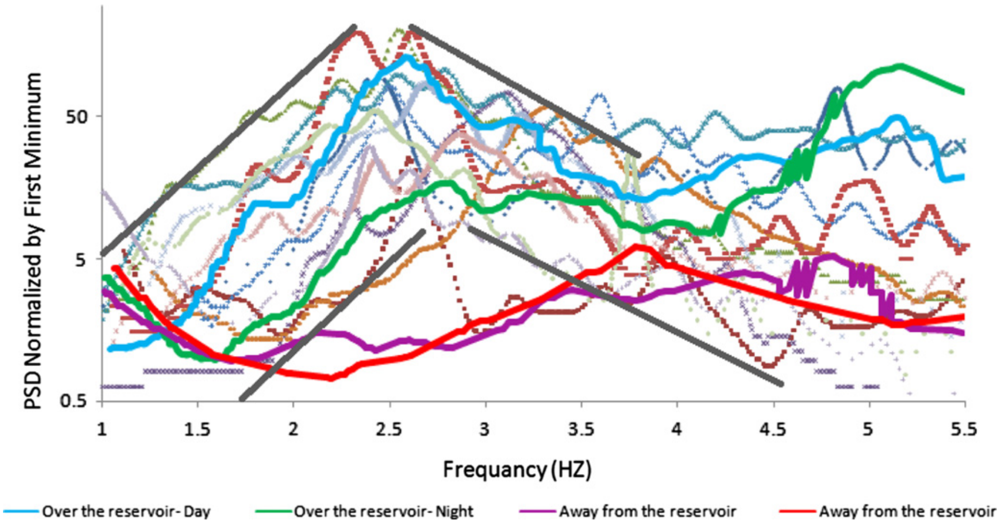

Figure 7. Testing the frequency–amplitude criterion by power spectral density of a reservoir in Libya.

are produced from resonant scattering and amplification of the microseism within porous multi-phase (or partially-saturated) reservoir rocks (Holzner *et al* 2005c, 2009, Schmalholz *et al* 2006, Graf *et al* 2007, Saenger *et al* 2007a, 2009a, 2009b, Walker 2008, Frehner *et al* 2009), but other studies claim that these HM signals are not related to hydrocarbon reservoirs, rather, they are caused by surface waves travelling through shallow sediments (Berteussen *et al* 2008a, 2008b, Hanssen and Bussat 2008, Ali *et al* 2009c) (see the detailed discussion in the below). Saenger *et al* (2009c) believe that energy anomalies associated with reservoirs observed within a relatively quiet window can be caused by a modification of the components of the background wave-field from either side of a low energy window (high-frequency noise and microseism). Since many HM signals are reported over hydrocarbon reservoirs and signals in the adjacent areas have not been observed, (table 1), that some studies reported high-amplitude anomalies in the same frequency range not over the reservoirs and that these studies show these anomalies were probably caused by cultural noise (Ali *et al* 2009c) or anthropogenic noises (Hanssen and Bussat 2008), it seems that this new idea is more reasonable. Therefore, a hydrocarbon reservoir detection survey using this passive method to distinguish real HM signals coming from reservoirs from other noise must be tried. To do this, the frequency–amplitude range of HMs presented in figure 6 can be used.

Here, in order to test the suggested criterion for distinguishing real HMs presented in figure 8, we used the HM curves presented by Saenger *et al* (2009c). In 2006, they conducted a relatively large passive seismic survey in the Murzuq basin in Southern Libya, near the Algerian and Niger borders. They presented two PSD curves at the centre of the reservoir: one during the day and the other at night, and two PSD curves 15 km away from the reservoir centre, one during the day and one at night. In this paper, we overlay the HM curves of the Murzuq basin on the frequency–amplitude range and the result is presented in figure 7. As can be seen, two curves measured over the reservoir follow the trend suggested as the frequency–amplitude range, while the two curves obtained for the area away from reservoir show a different behaviour.

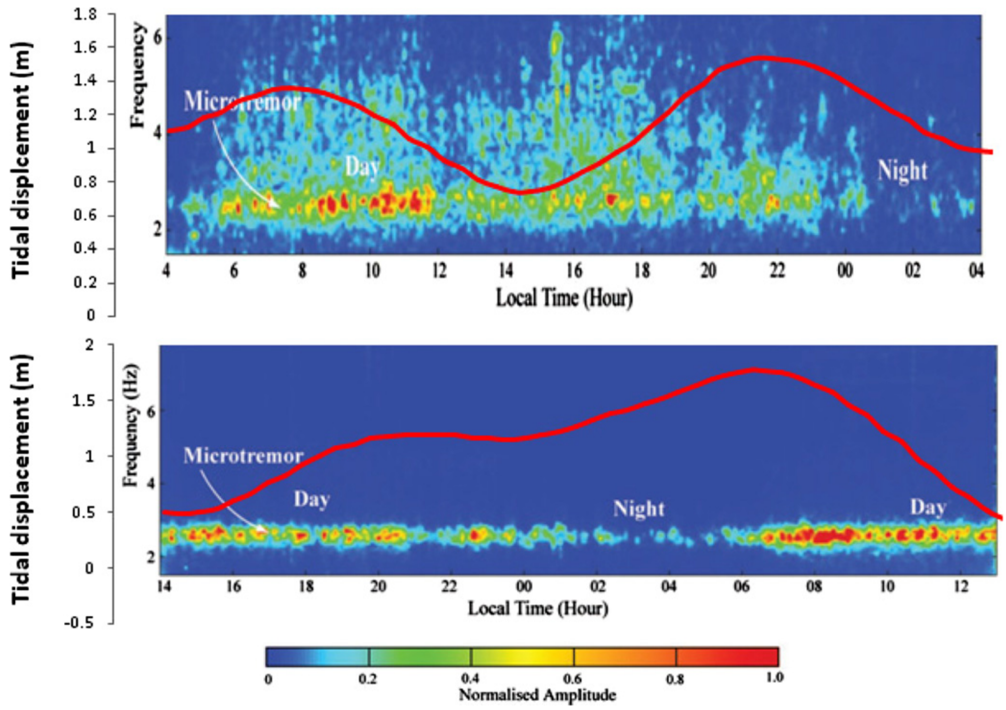

Figure 8. Tidal displacement overlaid on a time frequency display or data recorded from the vertical component of the seismometer: (top) over the reservoir on 26 May 2007 and (bottom) close to a dry exploration well, around 100 km away from the reservoir, on 20 January 2009. Time–frequency plots taken from Ali *et al* (2009c) and tidal displacement data taken from the website of the National Cartography Centre of Iran (http://www.iranhydrography.org) for the Abu Musa station.

4. A discussion on sources of hydrocarbon microtremors

Over the years, using ambient noise in the frequency range 1 to 6 Hz, known as hydrocarbon microtremors, has been discussed as a cheap, passive geophysical method to study hydrocarbon reservoirs. Some studies have presented observations to demonstrate the relation between microtremors and reservoirs and argue the usefulness and accuracy of this method for determining reservoir location and estimating its characteristics. On the other hand, other studies have presented some observations and case studies which show there is no relation between microtremors and reservoirs.

As mentioned in the sections above, there is no comprehensive and unique idea about the existence of hydrocarbon microtremors and their generation mechanisms, which can scientifically explain all the observations. Regarding previous studies, five possibilities can be suggested for HM anomalies.

(a) HM is a kind of cultural or meteorological noise (high-frequency noise) and not related to reservoirs.
(b) Reservoirs produce HMs by mechanisms like fluid flow and the induced seismicity of reservoirs.
(c) HMs are generated by the interaction of microseisms with hydrocarbon reservoirs.
(d) Microseism and high-frequency noise both can interact with a reservoir to produce HMs.
(e) Both shallow high-frequency noise and deep microseism can create an anomaly in the frequency band of HMs caused by two different mechanisms. The first is not related to the reservoir and the second is.

The first possibility (a) does not seem to be correct, because there are a many observations that confirm the existence of HMs over the reservoir area (sometimes in very quiet areas far from urbanization facilities) and, simultaneously, the absence of these tremors for the neighbouring area (Dangel *et al* 2003, Saenger *et al* 2009b, 2009c) (table 1). There are even a few successful wells drilled based on these observations (Saenger *et al* 2007b, Bloch and Akrawi (2006).

Dangel *et al* (2003) ignored fluid induced seismicity because the signals generated by this mechanism are short cracking events. They believed slow fluid flow is a possible phenomenon in hydrocarbon reservoirs (even non-producing ones). The agent for this slow fluid flow can be gravity, pressure differences due to natural factors or due to non-steady production. However, as in (a), they also ignored this mechanism. Regarding the very small frequency range for observed spectral peaks for all reservoirs surveyed up to that time, they believed that the source mechanism for the HM must be independent of the pore geometry of the reservoir rocks or the geometry of fractures in the reservoir. Holzner *et al* (2009) using numerical modelling, showed that HM amplitudes and frequencies depend on the size and shape of pores. In this study, we show the dependence of the frequencies of peaks on reservoir depth and this means reservoir characteristics determine the observation frequencies: if so then it is necessary for fluid flow mechanisms for producing HM signals to be reconsidered. Kouznetsov *et al* (2005) and Turuntaev *et al* (2006) reported that hydrocarbon microtremors can be stimulated by seismic vibration sources at the surface, but Ali *et al* (2009c) and Hanssen and Bussat (2008) reported high-amplitude noise in the frequency range of hydrocarbon microtremors, caused by surface local high-frequency noise but not related to reservoirs. Then each of the possibilities (c), (d) and (e) alone cannot describe all the observations.

In addition to high-frequency noise, vibrations in the surface and microseism, Nguyen *et al* (2008) showed that earthquakes can affect HMs in hydrocarbon reservoirs. In contrast to this study, Ali *et al* (2009c) showed that earthquakes did not affect HM amplitudes in their study area.

As a conclusion, it seems that background microseisms are the main source of HMs but other sources of vibration like earthquakes, high-frequency surface waves, scattered from nearby surface heterogeneities and converted to body waves, can also interact with the reservoirs and generate HM signals. A reservoir's ability to generate the maximum amplitude of HMs is limited by its characteristics and because of this, for example, in case studies like Ali *et al* (2009c), the earthquake did not increase HM amplitudes. Furthermore, local noise can also mask and contaminate HM signals.

Observations show a variation in the amplitude of HM during the day and night. Surface high-frequency noise and even microseisms change over a 24 h period and could be an acceptable reason; but other possibilities like 'tide' can increase the influence of microseisms (and other waves) on reservoirs and then amplitudes of HMs change over a 24 h period. Tidal deformations of the Earth affect a wide range of geophysical and geodetic measurements (Baker 1984, Lambeck 1988). For example, tidal forces can cause an expansion and contraction of the Earth's crust and reservoirs, and consequently cause changes in reservoir pressure.

Tidal displacement of sea level can be used as an index of Earth crust displacement but the station recording the displacement measurement must be near to microtremor stations and the measurement taken at exactly the same time because tidal forces change throughout the day, month and year and are different even at the same latitudes and longitudes. In this study, we overlaid the tidal displacement of the sea level in the Persian Gulf, at exactly the time of the microtremor measurement and near to their stations, on a time-frequency display of HMs, carried out by Ali *et al* (2009c) in the UAE. As shown in figure 8, tidal displacement, relatively, has a correlation with HM amplitudes which were recorded over a known reservoir (upper picture), whereas the amplitudes of microtremors recorded 100 km away from a reservoir near to a dry well, do not show any correlation with tidal displacement (lower picture). In the upper picture, the amplitude of HMs and tidal displacement decreased from 1200 to 1500 h and after midnight. This correlation shows the effect of tidal displacement on HM signals generated by hydrocarbon reservoirs.

5. Conclusion

In this study, the correlation of reservoir depth and HM characteristics, including normalized peak amplitude and peak frequency, based on the data of 12 hydrocarbon sites around the world (studied by Dangel *et al* 2003), were assessed and showed that the peak frequency of HMs decreases and normalized peak amplitudes increase in deeper reservoirs. The reservoir pressure seems to be the main agent that affects the characteristics of HM signals.

The trend of HM parameter variation seems to be different for both oil and gas reservoirs but the assessment of the effect of the fluid content needs more measurement and evidence.

Also, it was shown that not only peak amplitudes of HMs with a frequency greater than 2.3 HZ are related to reservoirs, but also signals with lower amplitudes in the frequency range 2 to 2.3 HZ.

It seems that microseisms are the main source of hydrocarbon microtremors but any other seismic source, such as earthquakes and surface high-frequency noise, that cause excitation of reservoirs can also generate HM signals.

It seems that, in addition to the inner characteristics of a reservoir, other external agents, such as the tide, can affect a reservoir and then increase or decrease the amplitude and frequency of hydrocarbon microtremors.

Furthermore, surface high-frequency noise can have a peak frequency near and similar to hydrocarbon microtremors and this must be separated from HMs. To do this separation, in addition to spatial, temporal and frequency processing of the signal, a frequency–amplitude criterion is suggested which can be improved by adding new results that will be obtained as microtremor investigations over hydrocarbon reservoirs increase.

References

Ali M Y, Berteussen K A, Small J, Anjana B T and Barkat B 2009a Recent passive experiments in Abu Dhabi *EAGE Passive Seismic Workshop—Exploration and Monitoring Applications (Limassol, Cyprus)* p A36 (Expanded abstracts)

Ali M Y, Berteussen K A, Small J, Anjana B T, Barkat B and Pahlevi O 2009b Recent low frequency passive seismic experiments in Abu Dhabi *71st EAGE Meeting (Amsterdam, The Netherlands)* p S037 (Expanded abstracts)

Ali M Y, Berteussen K A, Small J and Barkat B 2007 A low frequency passive seismic experiment over a carbonate reservoir in Abu Dhabi *First Break* **25** 71–3

Ali M Y, Berteussen K A, Small J and Barkat B 2009c Low-frequency passive seismic experiments in Abu Dhabi, United Arab Emirates: implications for hydrocarbon detection *Geophys. Prospect.* **58** 875–99

Ali M Y, Berteussen K A, Small J and Barkat B 2010 A study of ambient noise over an onshore oil field in Abu Dhabi, United Arab Emirates *Bull. Seismol. Soc. Am.* **100** 392–401

Ali M Y, Berteussen K A, Small J, Barkat B and Pahlevi O 2009d Results from a low frequency passive seismic experiment over an oilfield in Abu Dhabi *First Break* **27** 91–7

Ali M Y, Berteussen K A, Small J and Pahlevi O 2009e Microseism and microtremor analyses over an oilfield in Abu Dhabi—implications for cyclone and hydrocarbon detection *71st EAGE Meeting (Amsterdam, The Netherlands)* p SO34 (Expanded abstracts)

Baker T F 1984 Tidal deformations of the Earth *Sci. Pry.* **69** 197–233

Bard P-Y 1999 Microtremormeasurements: a tool for site effect estimation? *The Effects of Surface Geology on Seismic Motion* ed K Irikura, K Kudo, H Okada and T Sasatani (Rotterdam: Balkema) pp 1251–79

Bard P-Y *et al* 2005 Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations measurements, processing and interpretation Deliverable D23.12 of the

SESAME project http://www.SESAME-FP5.obs.ujf-grenoble.fr
Berteussen K A, Ali M Y, Small J, Anjana B T and Barkat B 2008a Analysis of low frequency passive seismic data from an experiment over a carbonate reservoir in Abu Dhabi *Proc. Abu Dhabi Int. Petroleum Exhibition and Conf. (Abu Dhabi, United Arab Emirates)* SPE-117925-MS
Berteussen K A, Ali M Y, Small J and Barkat B 2008b A low frequency, passive seismic experiment over a carbonate reservoir in Abu Dhabi—wavefront and particle motion study *70th EAGE Meeting (Rome, Italy)* p B046 (Expanded abstracts)
Bindi D, Parolai S, Spallarossa D and Catteneo M 2000 Site effects by H/V ratio: comparison of two different procedures *J. Earthq. Eng.* **4** 97–113
Bloch G and Akrawi K 2006 Application of passive seismic (IPDS) surveys in Arabian Peninsula *EAGE Passive Seismic Workshop—Exploration and Monitoring Applications (Dubai, United Arab Emirates)* p A28 (Expanded abstracts)
Bonnefoy-Claudet S, Cotton F and Bard P 2006 The nature of noise wavefield and its applications for site effects studies: a literature review *Earth-Sci. Rev.* **79** 205–27
Chavez-Garcia F J and Luzon F 2005 On the correlation of seismic microtremors *J. Geophys. Res. Solid Earth* **110** B08302
Chavez-Garcia F J and Rodriguez M 2007 The correlation of microtremors: empirical limits and relations between results in frequency and time domains *Geophys. J. Int.* **171** 657–64
Curtis A, Gerstoft P, Sato H, Snieder R and Wapenaar K 2006 Seismic interferometry—turning noise into signal *Leading Edge* **25** 1082–92
Dake L P 2001 *The Practice of Reservoir Engineering* (Amsterdam: Elsevier)
Dangel S, Schaepman M E, Stoll E P, Carniel R, Barzandji O, Rode E D and Singer J M 2003 Phenomenology of tremor-like signals observed over hydrocarbon reservoirs *J. Volcanol. Geotherm. Res.* **128** 135–58
Dutta U, Satoh T, Kawase H, Sato T, Biswas N, Martirosyan A and Dravinski M 2007 S-wave velocity structure of sediments in Anchorage, Alaska, estimated with array measurements of microtremors *Bull. Seismol. Soc. Am.* **97** 234–55
Fäh D, Rüttener E, Noack T and Kruspan P 1997 Microzonation of the city of Basel *J. Seismol.* **1** 87–102
Field E H, Clement A C, Jacob S M, Aharonian V, Hough S E, Friberg P A, Babaian T O, Karapetian S S, Hovanessian S M and Abramian H A 1995 Earthquake site-response study in Giumri (formerly Leninakan), Armenia, using ambient noise observations *Bull. Seismol. Soc. Am.* **85** 349–53
Field E H and Jacob K H 1995 A comparison and test of various site-response estimation techniques, including three that are not reference-site dependent *Bull. Seismol. Soc. Am.* **85** 1127–43
Frehner M, Schmalholz S M, Holzner R and Podladchikov Y Y 2006 Interpretation of hydrocarbon microtremors as pore fluid oscillations driven by ambient seismic noise *EAGE Passive Seismic Workshop—Exploration and Monitoring Applications, Dubai, United Arab Emirates* Expanded Abstracts A05
Frehner M, Schmalholz S M and Podladchikov Y 2009 Spectral modification of seismic waves propagating through solids exhibiting a resonance frequency: a 1-D coupled wave propagation oscillation model *Geophys. J. Int.* **176** 589–600
Frehner M, Schmalholz S M, Podladchikov Y, Eth Z and Oslo U 2007 Interaction of seismic background noise with oscillating pore fluids causes spectral modifications of passive seismic measurements at low frequencies *77th SEG Meeting, San Antonio, TX, USA* pp 1307–11
Gerivani H, Haghshenas E, Safaeian R and Shafiee A 2011 Regional site effect zonation of Qeshm Island (Iran) *Proc. 6th Int. Conf. of Seismology and Earthquake Engineering (Tehran, Iran, 16–18 May)* pp 52–60
Goertz A V, Schechinger B, Koerbe M and Krajewski P 2009 A low-frequency passive seismic survey in an urban setting in Germany *71st EAGE Meeting (Amsterdam, The Netherlands)* p S039 (Expanded abstracts)
Gouédard P *et al* 2008 Cross-correlation of random fields: mathematical approach and applications *Geophys. Prospect.* **56** 375–93
Graf R, Schmalholz S M, Podladchikov Y Y and Saenger E H 2007 Passive low frequency spectral analysis: exploring a new field in geophysics *World Oil* **228** 47–52
Green A and Greenhalgh S 2009 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 *First Break* **27** 5–11
Guillier B *et al* 2008 Influence of instruments on the H/V spectral ratios of ambient vibrations *Bull. Earthq. Eng.* **6** 33–74
Haghshenas E, Bard P-Y and Theodulidis N 2008 Empirical evaluation of microtremor H/V spectral ratio *Bull. Earthq. Eng.* **6** 75–108
Halliday D, Curtis A and Kragh E 2008 Seismic surface waves in a suburban environment: active and passive interferometric methods *Leading Edge* **27** 210–8
Hanssen P and Bussat S 2008 Pitfalls in the analysis of low frequency passive seismic data *First Break* **26** 111–9
Hartzell S, Carver D, Williams R A, Harmsen S and Zerva A 2003 Site response, shallow shear-wave velocity and wave propagation at the San Jose, California, dense seismic array *Bull. Seismol. Soc. Am.* **93** 443–64
Holzner R, Eschle P, Dangel S, Frehner M, Narayanan C and Lakehal D 2009 Hydrocarbon microtremors interpreted as nonlinear oscillations driven by oceanic background waves *Commun. Nonlinear Sci. Numer. Simul.* **14** 160–73
Holzner R, Eschle P, Dangel S and Narayanan C 2007a Hydrocarbon related microtremors—verification of an analytical oscillator model by the Navier–Stokes equations *69th EAGE Meeting (London, UK)* p P212 (Expanded abstracts)
Holzner R, Eschle P, Frehner M, Schmalholz S and Podlachikov Y 2006a Hydrocarbon microtremors interpreted as oscillations driven by oceanic background waves *68th EAGE Meeting (Vienna, Austria)* p D036 (Expanded abstracts)
Holzner R, Eschle P, Frehner M, Schmalholz S and Podladchikov Y 2006b Interpretation of hydrocarbon microtremors as nonlinear oscillations driven by oceanic background waves *76th SEG Meeting (New Orleans, LA, USA)* pp 2294–8
Holzner R, Eschle P, Meier P F and Dangel S 2007b Linear model for low-frequency pore liquid oscillations observed in hydrocarbon microtremor analysis (HyMAS) *GeoArabia* **12** 169
Holzner R, Eschle P, Zurcher H, Graf R, Dangel S and Meier P F 2005a Identification of hydrocarbon reservoirs by microtremor analysis (HyMAS)—successful and reproducible *Proc. 2nd SEG/EGS/EPEX/EPA Int. Petroleum Conf. (Cairo, Egypt)* p 36
Holzner R, Eschle P, Zurcher H, Graf R, Dangel S and Meier P F 2005b Case study of successful identification of hydrocarbon reservoirs by microtremor analysis (HyMAS) *Proc. AAPG Int. Conf. (Paris, France)*
Holzner R, Eschle P, Zurcher H, Lambert M, Graf R, Dangel S and Meier P F 2005c Applying microtremor analysis to identify hydrocarbon reservoirs *First Break* **23** 41–6
Holzner R, Esehle P, Dewarrat R, Lambert M and Graf R 2006c Marine application of hydrocarbon microtremor analysis (Hy-MAS) *76th SEG Meeting (New Orleans, LA, USA)* pp 2290–3
Holzner R, Lambert M, Graf R, Dangel S and Meier P F 2006d Reproducibility test for the identification of hydrocarbon reservoirs by HyMAS *EAGE Meeting (Dubai, United Arab Emirates, 10–13 Dec. 2006)*
Kaya S, Rode E D and Kier D 2007 Integrated application of passive seismic technology for trapped oil detection in mature

fields and hydrocarbon discoveries in adjacent compartments *Proc.10th Int. Congr. of the Brazilian Geophysical Society*

Kind F, Fäh D and Giardini D 2005 Array measurements of S-wave velocities from ambient vibrations *Geophys. J. Int.* **160** 114–26

Kouznetsov O L, Chirkin I A, Dryagin V V, Aroutunov S L and Meltchouk B Y 2005 Induced seismoacoustic emission Basis for new technologies of fluid identification *67th Ann. Int. Meeting European Association Geoscience Engineering* p G048 (Expanded abstracts)

Lambeck K 1988 Geophysical Geodesy (Oxford: Oxford University Press) ISBN 0-19-854438-3

Lambert M-A, Schmalholz S M, Saenger E H and Steiner B 2009a Low-frequency microtremor anomalies at an oil and gas field in Voitsdorf, Austria *Geophys. Prospect.* **57** 393–411

Lambert M A, Schmalholz S M, Saenger E H and Steiner B 2009b Passive seismic study at an oil and gas field in Voitsdorf, Austria *EAGE Passive Seismic Workshop—Exploration and Monitoring Applications (Limassol, Cyprus)* p A34 (Expanded abstracts)

Lambert M, Schmalholz S M, Saenger E H and Podladchikov Y Y 2007 Low-frequency anomalies in spectral ratios of single-station microtremor measurements: observations across an oil and gas field in Austria *77th SEG Meeting (San Antonio, TX, USA)* pp 1352–6 (Expanded abstracts)

Larose E, Margerin L, Derode A, Tiggelen B V, Campillo M, Shapiro N M, Paul A, Stehly L and Tanter M 2006 Correlation of random wavefields: an interdisciplinary review *Geophysics* **71** SI11–21

Lin F, Ritzwoller M H, Townend J, Bannister S and Savage M 2007 Ambient noise Rayleigh wave tomography of New Zealand *Geophys. J. Int.* **170** 649–66

Liu H-P *et al* 2000 Comparison of phase velocities from array measurements of Rayleigh waves associated with microtremor and results calculated from borehole shear-wave velocity profiles *Bull. Seismol. Soc. Am.* **90** 666–78

Longuet-Higgins M S 1950 A theory of the origin of microseisms *Phil. Trans. R. Soc.* A **243** 1–35

Louie J L 2001 Faster, better: shear-wave velocity to 100 meters depth from refraction microtremor arrays *Bull. Seismol. Soc. Am.* **91** 347–64

Marzorati S and Bindi D 2006 Ambient noise levels in north central Italy *Geochem. Geophys. Geosyst.* **7** Q09010

McNamara D E and Buland R P 2004 Ambient noise levels in the continental United States *Bull. Seismol. Soc. Am.* **94** 1517–27

Nakamura Y 1989 A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface *Q. Rep. Railw. Tech. Res. Inst.* **30** 25–30

Nguyen T T, Lambert M, Saenger E H, Artman B and Schmalholz S M 2009 Reduction of noise effects on low frequency passive seismic data *71st EAGE Meeting (Amsterdam, The Netherlands)* p S038 (Expanded abstracts)

Nguyen T T, Saenger E H, Schmalholz S M and Artman B 2008 Earthquake triggered modifications of microtremor signals above and nearby a hydrocarbon reservoir in Voitsdorf, Austria *70th EAGE Meeting (Rome, Italy)* p P025 (Expanded abstracts)

Nunziata C 2007 A physically sound way of using noise measurements in seismic microzonation, applied to the urban area of Napoli *Eng. Geol.* **93** 17–30

Ohori M, Nobata A and Wakamatsu K 2002 A Comparison of ESAC and FK methods of estimating phase velocity using arbitrarily shaped microtremor arrays *Bull. Seismol. Soc. Am.* **92** 2323–32

Parolai S, Bormann P and Milkereit C 2001 Assessment of the natural frequency of the sedimentary cover in the Cologne area (Germany) using noise measurements *J. Earthq. Eng.* **5** 541–64

Peterson J 1993 *Ambient Earth Noise: A Survey of the Global Seismographic Network* (US Geological Survey) pp 93–322

Rached G R 2006 Surface passive seismic in Kuwait *EAGE Passive Seismic Workshop—Exploration and Monitoring Applications (Dubai, United Arab Emirates)* p A27 (Expanded abstracts)

Rached G R 2009 The challenge for surface passive seismic measurements in Kuwait *EAGE Passive Seismic Workshop—Exploration and Monitoring Applications (Limassol, Cyprus)* p A33 (Expanded abstracts)

Sabra K G, Gerstoft P, Roux P and Kuperman W A 2005 Surface wave tomography from microseisms in southern California *Geophys. Res. Lett.* **32** L14311

Saenger E H, Lambert M A, Nguyen T T and Schmalholz S M 2009a Preliminary model of hydrocarbon reservoir related microtremors *71st EAGE Meeting (Amsterdam, The Netherlands)* p S035 (Expanded abstracts)

Saenger E H *et al* 2009b A passive seismic survey over a gas field: analysis of low-frequency anomalies *Geophysics* **74** O29–40

Saenger E H *et al* 2007a Scientific strategy to explain observed spectral anomalies over hydrocarbon reservoirs generated by microtremors *69th EAGE Meeting (London, UK)* p A033 (Expanded abstracts)

Saenger E H, Torres A and Artman B 2009c A low-frequency passive seismic survey in Libya *EAGE Detective Stories Behind Prospect Generation Workshop—Challenges and The Way Forward (Muscat, Oman)* p 5028 (Expanded abstracts)

Saenger E H, Torres A, Rentsch S, Lambert M, Schmalholz S M and Mendez H E 2007b A hydrocarbon microtremor survey over a gas field: identification of seismic attributes *77th SEG Meeting, (San Antonio, TX, USA)*

Scherbaum F, Hinzen K G and Ohrnberger M 2003 Determination of shallow shear wave velocity profiles in the Cologne, Germany area using ambient vibrations *Geophys. J. Int.* **152** 597–612

Schmalholz S M, Podladchikov Y Y, Holzner R and Saenger E H 2006 Scientific strategy to explain observed spectral anomalies over hydrocarbon reservoirs generated by microtremors *EAGE Passive Seismic Workshop—Exploration and Monitoring Applications (Dubai, United Arab Emirates)* p A06 (Expanded abstracts)

Shabani E, Ekandari-Ghadi M and Mirzaei N 2011 The SPAC method for a finite M-station circular array using horizontally polarized ambient noise *Bull. Seism. Soc. Am.* **101** 544–7

Shapiro N M and Campillo M 2004 Emergence of broadband Rayleigh waves from correlations of the ambient seismic noise *Geophys. Res. Lett.* **31** L07614

Shapiro N M, Campillo M, Stehly L and Ritzwoller M H 2005 High-resolution surface wave tomography from ambient seismic noise *Science* **307** 1615–8

Singer J M, Barzandji O, Leu W, Rode E D, Akrawi K, Linthorst S and Dangel S 2002 Spectroscopic identification of tremor phenomena over hydrocarbon reservoirs *64th EAGE Meeting (Florence, Italy)* p H-46 (Expanded abstracts)

Steiner B, Saenger E H and Schmalholz S M 2007 Time-reverse modeling of microtremors: a potential method for hydrocarbon reservoir localization *77th SEG Meeting (San Antonio, TX, USA)* pp 2115–9 (Expanded abstracts)

Steiner B, Saenger E H and Schmalholz S M 2008a Case studies on 2D- and 3D-time reverse modeling of low-frequency microtremors—application to reservoir localization *70th EAGE Meeting (Rome, Italy)* p B045 (Expanded abstracts)

Steiner B, Saenger E H and Schmalholz S M 2008b Time reverse modeling of low-frequency microtremors: application to hydrocarbon reservoir localization *Geophys. Res. Lett.* **35** L03307

Stephenson W J, Hartzell S, Frankel A D, Asten M, Carver D L and Kim W Y 2009 Site characterization for urban seismic hazards in lower Manhattan, New York City, from microtremor array analysis *Geophys. Res. Lett.* **36** L03301

Tada T, Cho I and Shinozaki Y 2006 A two-radius circular array method; inferring phase velocities of Love waves using microtremor records *Geophys. Res. Lett.* **33** L10303

Talhaoui A, Iben Brahim A, Aberkan M H, Kasmi M and El Mouraouah A 2004 Seismic microzonation and site effects at al Hoceima city, Morocco *J. Earthq. Eng.* **8** 585–96

Tuladhar R, Yamazaki F, Warnitchai P and Saita J 2004 Seismic microzonation of the greater Bangkok area using microtremor observations *Earthq. Eng. Struct. Dyn.* **33** 211–25

Turuntaev S B, Burchik V N and Turuntaev D S 2006 Microseismic background study for gas field exploration *EAGE Conf. (Saint Petersburg, Russia)* p P245

van Mastrigt P and Al-Dulaijan A 2008 Seismic spectroscopy using amplified 3C geophones *70th Ann. Int. Meeting European Association Geoscience Engineering* p B047 (Expanded abstracts)

Veras I M, Chaves R D, de Oliveira A S, Holzner R and Graf R 2005 Direct hydrocarbon detection experiment in Potiguar basin *Proc. 9th Int. Cong. of the Brazilian Geophysical Society (Salvador, Brazil, 11–14 Sep.)*

Walker D 2008 Recent developments in low frequency spectral analysis of passive seismic data *First Break* **26** 69–77

Wapenaar K, Draganov D and Robertsson J 2006 Seismic interferometry supplement *Geophysics* **71** SI1–229

Wathelet M, Jongmans D, Ohrnberger M and Bonnefoy-Claudet S 2008 Array performances for ambient vibrations on a shallow structure and consequences over versus inversion *J. Seismol.* **12** 1–19

Webb S C 2007 The Earth's 'hum' is driven by ocean waves over the continental shelves *Nature* **445** 754–6

Wilson D *et al* 2002 Broadband seismic background noise at temporary seismic stations observed on a regional scale in the southwestern United States *Bull. Seismol. Soc. Am.* **92** 3335–42

Withers M M, Aster R C, Young C J and Chael E P 1996 High frequency analysis of seismic background noise as a function of wind speed and shallow depth *Bull. Seismol. Soc. Am.* **86** 1507–15

Yao H, van der Hilst R D and de Hoop M V 2006 Surface-wave array tomography in SE Tibet from ambient seismic noise and two station analysis: I. Phase velocity maps *Geophys. J. Int.* **166** 732–44

Young C J, Chael E P, Withers M M and Aster R C 1996 A comparison of the high-frequency (>1 Hz) surface and subsurface noise environment at three sites in the United States *Bull. Seismol. Soc. Am.* **86** 1516–28