Pitfalls of tremor-like signals for hydrocarbon exploration in producing oil fields in Potiguar Basin, northeast Brazil

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The Earth's ambient noise has been used over the past four decades for sedimentary basin studies, but only in the past ten years have geophysicists begun to apply ambient seismic noise, a technique known as passive seismic, to hydrocarbon exploration.

This method uses a simple empirical observation of an increase of the spectral energy of an anomaly, the so-called hydrocarbon microtremor which has frequencies between 2 and 4 Hz. This method is potentially very attractive for hydrocarbon exploration because it does not require artificial sources or large staff, is low cost, and can be used in sensitive biomes where conventional seismic faces environmental problems.

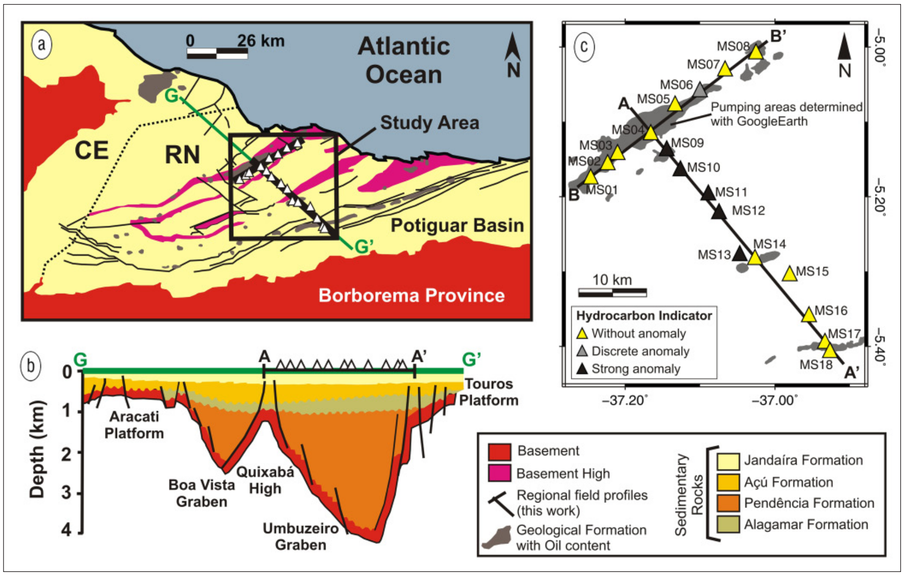

Figure 1. (a) Geological map of the study area, showing the passive seismic lines (black thick lines), seismographic stations (triangles), and geological profile GG' shown in (b) with main layers and basement highs. (c) Study area, including oil production areas (gray), stations (triangles), and hydrocarbon microtremor results.

In this article, we show the main results of a regional passive seismic experiment in the Potiguar Basin (Figure 1), northeast Brazil, from two profiles crossing the sedimentary basin where the thickness varies from 1 to 4 km. The profiles cross the Canto do Amaro, Serraria and Estreito oil fields, and some recorded hydrocarbon microtremors seem to be composed of transient events, possibly triggered by cultural sources (Hanssen and Bussat, 2008). Another unexpected observation is that seismograph stations near pumping areas, and consequently over known reservoirs, did not show the spectral anomalies expected in areas with hydrocarbon reservoirs. This same observation was made at a single measurement point by Dangel et al. (2003) and, if correct, implies that the spectral pattern used in passive seismic is not applicable to producing areas. On the other hand, some positive results recorded in producing areas (Kaya et al., 2007) may be caused by a different horizon than the one under production. These observations have important implications for development of new hydrocarbon microtremor models, and will be discussed in detail.

Additionally, records of three stations away from known oil fields show a strong spectral anomaly near 2.7 Hz, perhaps indicating a new region with high oil potential or alternatively that the resolution of passive seismic is lower than claimed in other studies (Graf et al., 2007).

Acquisition and processing

The experiment was carried out between 11 and 22 May 2009 in Potiguar Basin with some points over and near producing onshore oil fields. The acquisition geometry and consisted of two perpendicular passive seismic lines (Figure 1a), 48 km in the SE direction (profile AA′) and 33 km in the NE direction (profile BB′).

The ambient seismic wavefield was recorded using three-component Guralp CMG-6TD seismometers with flat velocity response from 0.03 to 100 Hz, a sensitivity of 1600 V/m/s, at a rate of 100 samples per second. All recordings were made continuously for 2–6 hours. Overall 20 recordings were obtained at 18 points, including remeasurements on different days for very noisy sites.

We experimented in the lab to find the best way to install the seismometers and concluded that the most practical way without quality reduction was burying the sensor directly into the firm ground at a depth of 60 cm with plastic protection and covering it with 30–40 cm of soil to reduce the effect of temperature fluctuations and noise caused by direct contact with the wind. All sensors were oriented to the magnetic north (N22°W).

Data were processed with SAC software (Goldstein et al., 1999) and maps and plots were drawn with GMT (Wessel and Smith, 1991). We first removed the initial and final part of the record (noise caused by field staff). We then removed the linear trend caused by temperature fluctuations. We split the noise wavefield signal into windows of 327.68 s, with 50% overlap, and finally estimated the spectra with a simple fast Fourier transform. Several spectral estimation methods were tested, including maximum entropy (used by Dangel et al.), power spectral density (used by Saenger et al., 2009), and maximum likelihood. We concluded that, although these methods are robust, they smooth the spectra too much and hide some features like strong anomalies in narrow frequency bands, higher harmonics of 1.167 Hz (caused by pumping), and the main narrow peak at 4.5 Hz possibly related to a pumping system or other machinery.

Another benefit of passive seismic is that the thickness of the sedimentary basin can be estimated with the horizontal-to-vertical spectral ratio (HVSR) method, known as the Nakamura technique (Parolai et al., 2002). These data are still being processed.

Regional geology

The Potiguar marginal basin, in the Borborema Province, developed from the rupture of the African and South American plates and is controlled by pre-existing basement shear zones. This basin covers an onshore area of 22,000 km^2 in the states of Rio Grande do Norte (RN) and Ceará (CE).

The basement of Potiguar Basin is divided into three basic units (Figure 1c): (1) grabens filled with sedimentary sequences of the Lower Cretaceous; (2) basement highs, mainly Quixabá, Serra do Carmo, and Macau highs, represented by elongated basement crests consisting of gneiss and migmatite blocks uplifted by normal faults; and (3) basement platforms (shallow basement) bounding the central grabens to the east and west, called Touros and Aracati platforms (Bertani et al., 1990).

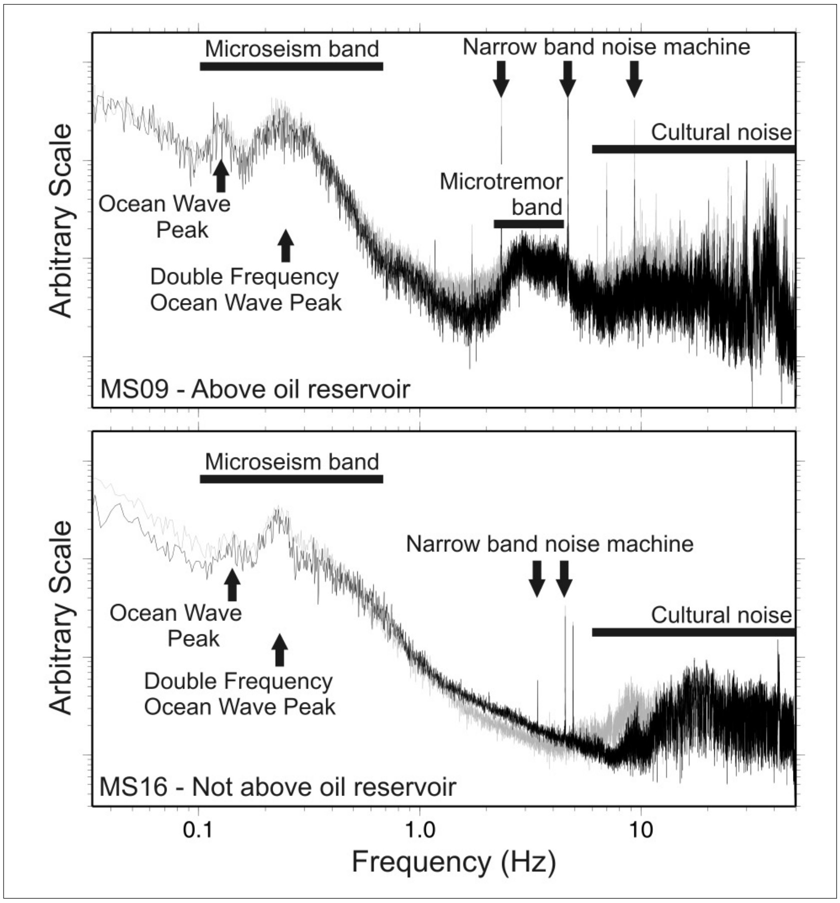

Figure 2. *Examples of typical spectra of ambient seismic vibrations recorded in (a) a region with an oil reservoir (station MS09) and (b) without an oil reservoir (MS16). Note the bands for microseism (double-frequency microseisms), microtremors, and cultural noise.*

Potiguar Basin has 77 gas and oil fields in development and production, with accumulated production of 686 million barrels of oil, and reserves of 371 million barrels; 4000 oil wells produce 88,000 b/d, 10% of Brazilian production (Barbosa et al., 2008). The main reservoirs are Cretaceous-age, mainly from fluvial-to-deltaic sandstones of the Açu Formation, which have porosity of 19–30%, permeability of 200–500 mD, and represent 80% of the production of this region. The remaining production areas are sandstones of Alagamar Formation (5%) and turbidites of Pendência Formation (15%), a lower quality reservoir with good porosity (12–24%) but low permeability (50–75 mD).

Figure 1 shows the regional geology and profiles of the passive seismic experiment. Profile AA′ sampled a region with basement depth between 1.5 and 4.0 km. Profile AA′ has points in four oil fields: (1) Canto do Amaro, near the NW extreme of the profile (station MS04); (2) Serraria in the middle (MS14); (3) Estreito, near the SE extreme (MS17); and (4) another small oil field (MS09). Almost all stations of profile BB′ are on the Canto do Amaro oil field. The two profiles were measured with regional geometry to study the characteristics of the hydrocarbon microtremors and the basement depth with the HVSR method.

Canto do Amaro is a major oil field with 85 km^2 in the Mossoro high divided into 32 production zones in Açu Formation at a depth of 500–900 m and its oil has API gravity of 28–45.

Results

The data can be divided into three distinct frequency bands (Figure 2): microseism (0.1–0.4 Hz), microtremor (2–3 Hz), and high-frequency cultural noise (> 5 Hz). The occasional effects of the pumping systems or other machines appear in the spectra as narrow peaks. Figure 2 shows that in the frequency range of 0.1–0.4 Hz, the noise spectrum is dominated by a strong and easily recognizable peak at around 0.2 Hz called the double-frequency microseismic peak. It is believed that these microseisms occur as a result of a nonlinear interaction between two opposing ocean swells. Until recently, it was believed that the vibrations of these microseisms were the main source of the energy causing the hydrocarbon microtremors through a poorly understood nonlinear process (Holzner et al., 2009). More recently (Ali et al., 2010; Hanssen and Bussat), it became clear that the hydrocarbon microtremors are triggered by cultural noise, mainly because the microtremors

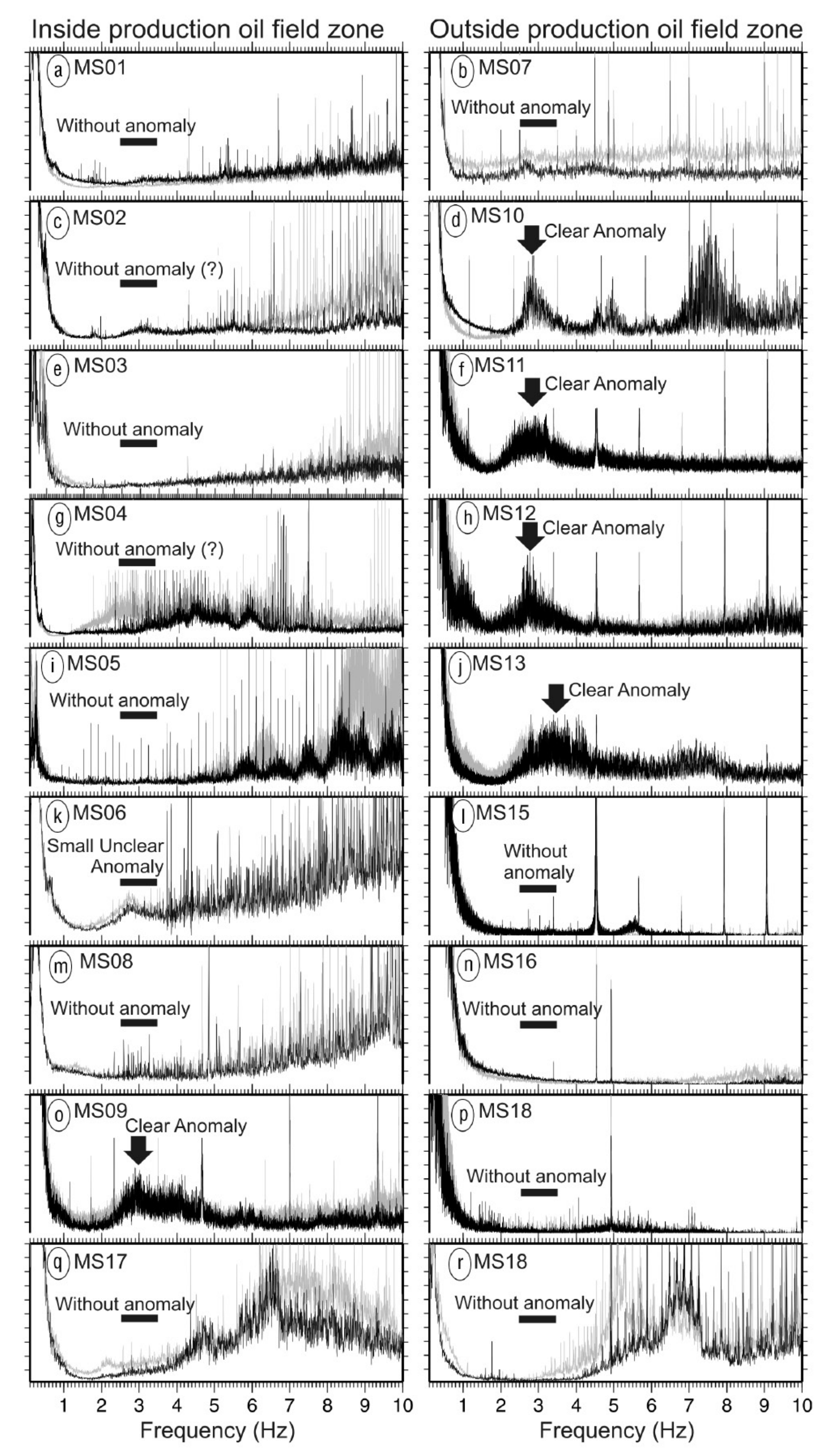

Figure 3. *Microtremor measurements at each station. (left) Spectra of stations inside producing areas. (right) Spectra from outside producing areas, but not necessarily outside unknown reservoirs.*

rarely occur at night. In this, work we use the microtremor band to identify the presence of hydrocarbon microtremors possibly associated with oil reservoirs.

The main results are shown in Figure 1c. The stations on profile BB′ on the largest oil field (Canto do Amaro) do not indicate the expected spectral anomaly near 2.7 Hz. On the other hand, the first station group of profile AA′ (MS09-MS12) has a strong spectral anomaly near 2.7 Hz, but only station MS09 can be related to a small oil field near Canto do Amaro. Some stations on oil fields near the border of the pumping area have a weak spectral anomaly. Figure 3 presents the spectrum of ambient seismic noise at each station.

Many studies about hydrocarbon microtremors describe the spectral anomalies generated by these events as quasi-continuous in time. However, as shown in Figure 4, it is clear that the high energy around 2.7 Hz is caused by short transient events. The same conclusion is given by Hanssen and Bussat, who confirmed that remote stations far from a reservoir had a signal of 3.0 Hz detectable at any time, and that stations placed over producing reservoir had a strong transient signal of 3 Hz only during day time and almost no peak at night when cultural noise was limited.

Discussion and summary

Regional maps indicate a concentration of major producing oil fields on profile BB′ where no spectral microtremor anomaly near 2.7 Hz was observed. On the other hand, on profile AA′, most points with a spectral microtremor anomaly are not associated with any oil fields. The lack of spectral anomalies on producing oil

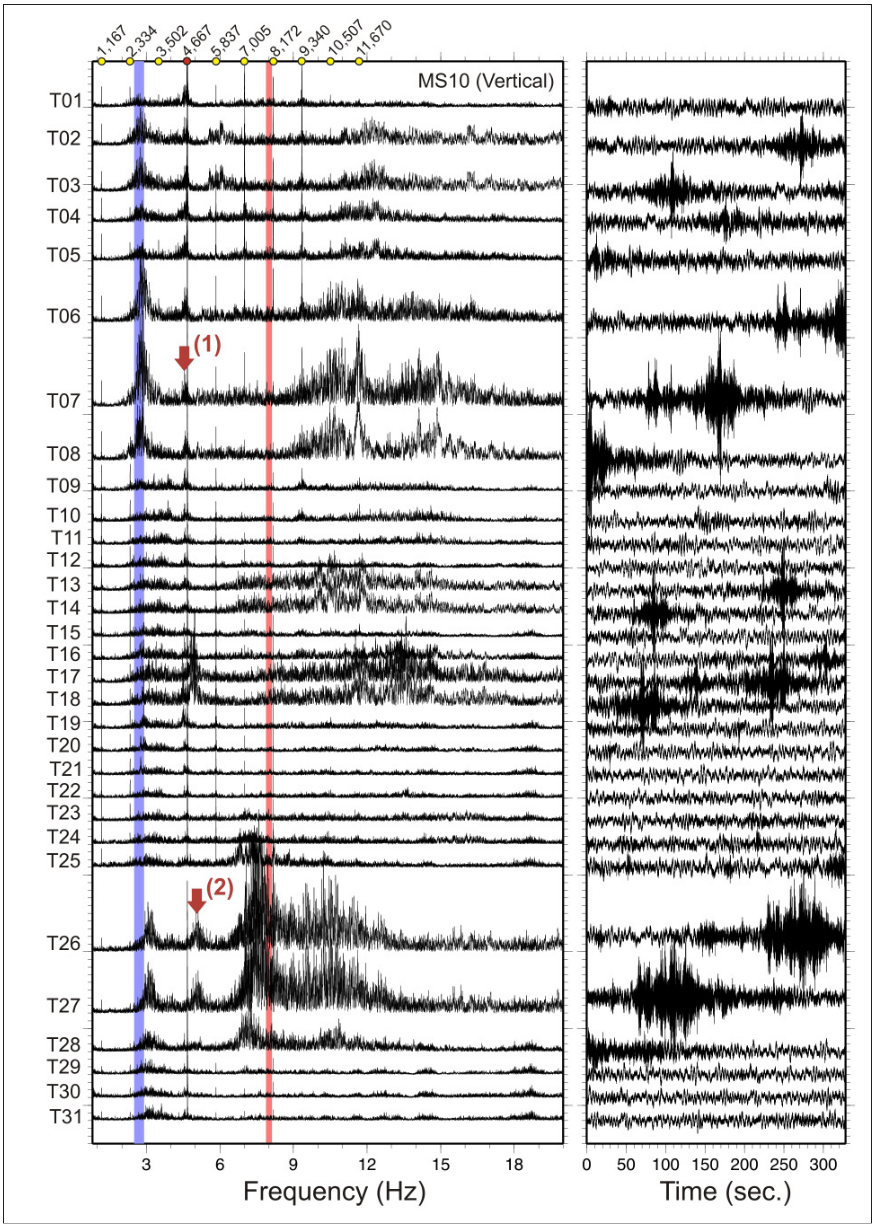

Figure 4. *The continuous seismogram of station MS10 was divided into five-minute windows (left) with 50% overlap (right). The left column presents the spectra of each window. The blue line indicates 2.7 Hz and the red line the maximum frequency used in most passive seismic work. Arrows (1) and (2) indicate a secondary peak, possibly associated with a major hydrocarbon microtremor.*

fields may indicate one of two things: (1) oil pumping changes the physical mechanism responsible for the hydrocarbon microtremor or (2) because the hydrocarbon microtremors are transient (Figure 4), records of 2–4 hours are not long enough to record completely this type of phenomenon. Dangel et al. show a negative microtremor result near an open oil well and positive results at the same place three months after this well was capped, supporting the first idea. On the other hand, Kaya et al. show positive results for a mature producing oil field in the Caspian region, but the spectral anomalies observed may be related to new reservoirs deeper than the exploited reservoir. This agrees with the local geology which contains at least nine oil-bearing Jurassic and Triassic horizons.

Regarding the length of records for this type of study, we will only be able to determine the correct minimum recording time when we understand the physical phenomenon that generates the hydrocarbon microtremors. Until then, research has to be planned with acquisition time of at least one day, and preferably one or two weeks, as done by Ali et al.

The microtremor anomaly observed at three stations away from known oil fields may indicate new areas of high oil potential or be related to possible low spatial resolution of the method. However, this differs from most studies that indicate resolution between 150 m (Graf et al.) and 1000 m (Hanssen and Bussat).

Hanssen and Bussat observed very strong signal, associated with hydrocarbon microtremors, with variable length that occurred intermittently during the day but not at night. Ali et al. observed the same pattern in a passive seismic experiment near an oil field in Abu Dhabi. Additionally, the microseism signal increased by a factor of 10 during Cyclone Gonu in the Gulf of Oman; at the same time no increase of microtremor amplitudes was observed, indicating that the hydrocarbon microtremor is not generated by microseisms as previously proposed by many, but is triggered by anthropogenic noise. Hanssen and Bussat and Ali et al. determined the velocity of the hydrocarbon microtremor was between 300 m/s and 1150 m/s, compatible with surface-wave velocities in shallow layers. These considerations are important for development of a realistic model for the generation of hydrocarbon microtremors.

We view the hydrocarbon microtremor as an ultra micro-earthquake, which has particular characteristics, and possibly variable magnitude. Note that it is possible to observe in spectrum T26 (Figure 4) a main peak near 3.0 Hz, a secondary peak near 5.0 Hz, and increasing spectral energy between 7 and 13 Hz. This observation is related only to station MS10, and can be energy of different seismic phases developed only by major microtremors, or new information related to the geometry of an unknown reservoir. Another possibility is that the possible magnitude of a hydrocarbon microtremor shows only the stress drop, and not the total stress.

In the future, we will need long passive seismic experiments recorded with seismometer arrays to determine a frequency-magnitude relationship that can be related to reservoir structure, properties, and fluid type. Passive seismic has potential for oil exploration, but right now it is a secondary tool to support conventional seismic and potential fields methods. TLE

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