Applying microtremor analysis to identify hydrocarbon reservoirs

R. Holzner, P. Eschle, H. Zürcher, and M. Lambert of Spectraseis[1], R. Graf of Proseis[2], and S. Dangel and P. F. Meier of University of Zurich[3] **describe an innovative passive technology for identifying the presence of geological structures containing hydrocarbon by analyzing low frequency seismic signals. They illustrate the method with results from a pilot study in Brazil.**

A new tool to identify and delineate hydrocarbon-bearing geological structures by analyzing low frequency seismic signals has been developed by Spectraseis. It provides a direct hydrocarbon indicator for the optimization of borehole placement during exploration, appraisal and production. Hydrocarbon Microtremor Analysis (HyMAS) exploits the selective absorption and hydrocarbon-induced amplification of low frequency seismic background noise. In contrast to conventional 2D and 3D seismic technologies, HyMAS is entirely passive and does not require artificial seismic excitation sources. Instead, the ever-present seismic background noise of the earth acts as the driving force for the generation of hydrocarbon indicating signals. The seismic background noise spectrum is modified in a different way when interacting with geological structures containing hydrocarbon filled pores compared with interaction with similar structures not containing hydrocarbons (Figure 1).

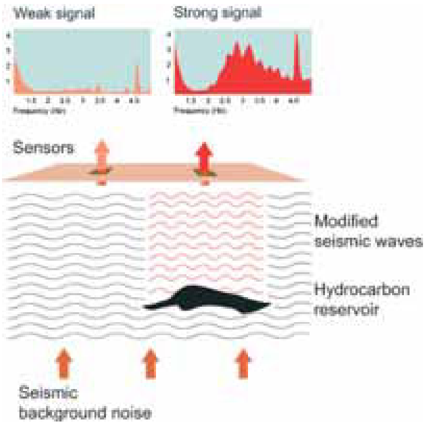

Figure 1 *Schematic of HyMAS measurements: seismic background noise interacting with hydrocarbon bearing geological structures shows spectral modifications around 3 Hz. The traces on top indicate typical spectral power densities of the vertical velocity component (HyMAS signal) measured beside (left) and on top (right) of hydrocarbon reservoirs. These traces are shown in more detail in Figure 4.*

The first consistent report on low frequency seismic measurements and analysis to investigate the hydrocarbon content of geological formations was given in 2001 by S. Dangel et al. A linear relationship between the observed signal and the total thickness of hydrocarbon layers was established by various measurements that were compared with well log data mainly in the Middle East. Earlier on, in 1993, other findings of low frequency seismic signals were related to oil-saturated layers by G.M. Goloshubin et al. They analyzed experimental cross-hole seismic data from a field in West Siberia and found very low frequency (10 Hz), very low velocity (300 m/s) and high amplitude 'slow wave' signals inside oil-saturated layers. Their explanation and modelling is based on Biot's theory (Biot, M.A., 1956) but includes a two-phase medium consisting of a solid body with fluid filled cracks, a model which was successfully applied for the analysis of volcanic tremors by Chouet in 1986 and Ferrazzini and Aki in 1987. These findings have recently been supported by up-scaled laboratory experiments (Korneev, V.A., Goloshubin, G.M., Daley, T.M., and Silin, D.B. and can explain low frequency response from thin hydrocarbon containing layers measured during reflection-seismic surveys.

A possible mechanism causing HyMAS signals can be understood within the framework of a simple linear oscillator model. A poro-mechanical amplification mechanism driven by the ever present seismic background noise resonantly enhances low frequency seismic signals due to the interaction of liquid hydrocarbons, water, and pore-rock material. The resulting oscillations are transmitted from the reservoir to the surface almost without attenuation or scattering losses due to the low frequency. Current investigations which combine the macroscopic wave propagation aspects of Korneev et al., as well as the microscopic poro-mechanical amplification mechanism, are expected to provide major steps towards the complete understanding of the occurrence of HyMAS signals.

HyMAS technology combines several processes and procedures which are described in more detail below and are illustrated with results from a recent commercial pilot pro-

---

[1] *Spectraseis, Giessereistrasse 5, CH-8005 Zurich, Switzerland.* [2] *Proseis, Siewerdtstr. 7, CH-8050 Zurich, Switzerland.*
[3] *University of Zurich, Winterthurerstr. 190, CH-8057 Zurich, Switzerland.*

gramme in Brazil. Data acquisition, processing, and interpretation for a 120 km^2 wide area were completed within five months. Results were initially displayed as contour maps of the uncalibrated HyMAS signal strength. The signals were subsequently compared with the integrated thickness of the hydrocarbon containing layers identified by log data of eight wells, establishing a provisional calibration for a hydrocarbon layer thickness map. The preliminary results of this survey are promising and an ongoing more detailed calibration involving log data of additional wells will allow the HyMAS results to be used to position new wells at locations indicating the highest probability of producible reservoirs.

Data acquisition

Data was acquired over an area of 120 km^2 using high sensitivity broadband seismometers (0.03-50 Hz with $5 \cdot 10^{-10}$ m/s resolution) operated by a crew of 20 people during 55 days. Approximately 500 measurements were taken at 266 different locations, including verification measurements for quality control. Acquisition was completed in two phases: in phase one the whole survey area was covered by measurements on a wide grid with 1000 x 1000 m spacing; in phase two a narrower 500 x 500 m grid was used. Preliminary analysis after the first phase outlined the most interesting zones which were investigated by the higher resolution measurements in phase two.

At most locations the instruments were positioned in 60 cm deep holes with a thin concrete base, plywood encasing, and cover (Figure 2). Locations were chosen within a radius of a few tens of metres from the planned regular grid coordinates for good GPS coverage, firm soil conditions, and the absence of nearby artificial noise sources. Where the surface was too hard to penetrate, the sensors were placed on a plate with good ground contact.

Figure 2 *Preparation of a sensor before a measurement*

Data processing and analysis

Data acquired in the field was pre-processed to provide immediate feedback on data quality for the field crews and to transform the files of raw data into the structured datasets needed for processing by Spectraseis proprietary software tools. Although the data processing itself is highly automated, the signal quality of each measurement is repeatedly monitored visually by experienced interpreters throughout the entire signal analysis process as an important means of quality control.

A total of 376 good quality datasets were used in the final analysis, extracted from approximately 700 hours of time series recorded at a 100 Hz sampling rate. These datasets were further reduced to a single HyMAS value for each measurement location, and displayed in contour maps together with information about signal quality and percentile ranking.

Depending on the quality of the measurements, various combinations of signal-enhancing techniques involving operations in both time and frequency domains are applied in order to improve the signal to noise ratio and to extract the maximum possible information. Note that the measured HyMAS signal strength is expected to show fluctuations with variations of the seismic background noise intensity (Aki, K. and Richards, P.G., 1980). For the analysis, HyMAS signals were averaged over the duration of undisturbed measurement sequences.

Time series

The data recorded from an individual sensor is displayed as a time series. Large amplitude perturbations as well as discontinuities of the data stream during the recording process can be identified and together with information from measurement reports on external perturbations such as vehicles

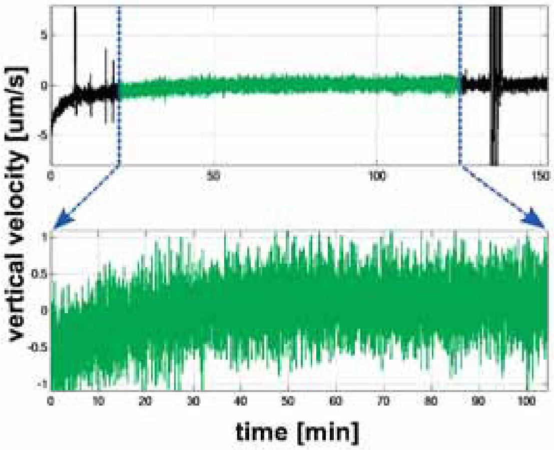

Figure 3 *Time series of vertical velocity of seismic motion measured at 100 Hz sampling rate. From the original recorded time series (top) intervals which do not contain large disturbances are cut and assembled (bottom) for further processing. The decision on which intervals are used is based on several previous analysis steps.*

passing by, weather conditions, or other artificial noise sources, the unperturbed sequences of the measurements (Figure 3) are selected for further processing.

Frequency spectrum power density

The frequency spectrum is best suited to determine the amplitudes of HyMAS signals, as shown in Figure 4.

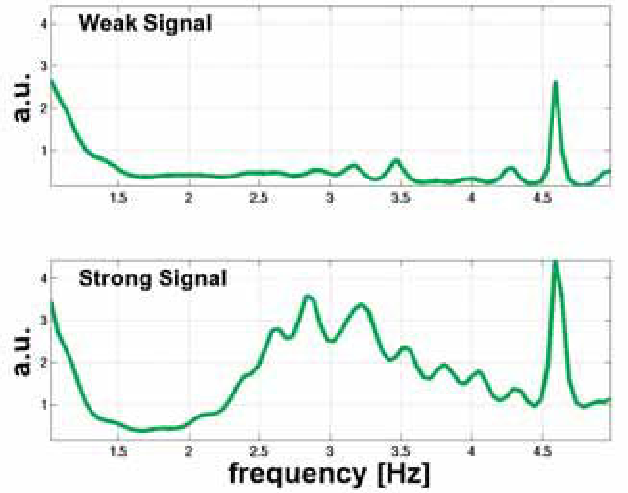

Figure 4 *After suitable filtering processes both in the time and frequency domains, the HyMAS value can be determined as the peak value of the frequency power density spectrum near 3 Hz. The trace on top leads to a low HyMAS value, while the trace on the bottom represents a high HyMAS value. At 4.6 Hz a narrowband artificial noise source can be identified.*

Correlation length spectrum

This is an alternative method to the *frequency spectrum power density* based on evaluating the temporal coherence properties of the signals under investigation. It is best suited to distinguish between HyMAS signals and coherent low amplitude artificial noise sources.

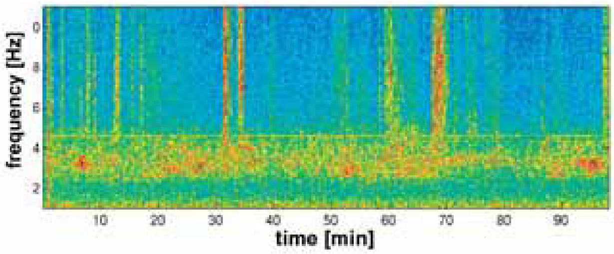

Figure 5 *Time evolution of the spectrum (vertical axis) during the duration (horizontal axis) of the measurement. The colour is a function of the logarithm of the spectral power density ranging from low values (blue) to high values (red). High power broad band noise is clearly visible as a vertical red line while strong narrow band signals appear as thin horizontal lines.*

Spectrograms

A time-frequency display (Figure 5) shows the presence or absence of continuous narrowband noise sources and is used to identify low noise intervals.

Signal quality definitions

Throughout the signal analysis process, the signal quality of each measurement is repeatedly determined and classified distinguishing four levels based on specific signal properties. Depending on the quality level, suitable signal analysis methods are applied to improve the signal quality to a higher level.

Dynamic (time evolution) spectrum analysis

The frequency spectrum is calculated for a narrow time window which is moved in appropriate time increments over the total length of the measurement to analyze the dynamic behaviour of the signal and to identify periods of stable behaviour where other analysis processes can be applied most efficiently. Using the same procedure simultaneously on different frequency segments allows for the identification of correlations between effects which exhibit amplitude changes in different parts of the spectrum.

Visual inspection

The visual inspection of results is of major importance for the control of automated procedures. It also allows for the determination of values by eye where automated curve fitting procedures are not successful. The signal quality levels are usually assigned during such inspections.

Consistency considerations

Reproducibility investigations, statistical artifact analysis, and other quality control procedures are used to monitor the signal processing steps to assure the reliability of the results.

Data display and interpretation

A detailed analysis of the measured HyMAS signals and several signal quality features are summarized in the 'HyMAS Hydrocarbon Potential Map' (Figure 6, left) which supports decisions on well placement for prospecting, appraisal, and production of hydrocarbon reservoirs. The map shows the area which contains the one third of all measurements where the strongest HyMAS signals, and therefore the highest potential for hydrocarbon containing formations, were detected (green area) and, in contrast the area which contains the third of all measurements where the lowest HyMAS signals were recorded (blue area).

A more detailed representation of the measurements is shown in the 'HyMAS Contour Map' (Figure 6 centre) as non-calibrated relative amplitudes of the HyMAS signals (spectral power density around 3 Hz) normalized to a range from 0 to 100. The distribution is expected to be proportional (S. Dangel et al., 2003) to the total hydrocarbon layer thickness. With suitable information from calibration wells, a map of absolute net hydrocarbon thickness in metres can be generated.

External noise induced by traffic, production installations, or other industrial facilities as well as urban activity has an impact on the quality of the high sensitivity seismic measurements. In order to investigate such perturbations, the areas of increased noise impact (orange areas in Figure 6, right) and quiet areas (green areas) are displayed in the 'Noise & Quality Map'. Three categories of noise impact on the measurements have been identified: 1) noise that leads to a reduction of the useful length of a time series; 2) noise that increases the amplitude of the recorded signal and thereby reduces the relative strength of the HyMAS signal; and 3) strong industrial noise between 10 and 40 Hz.

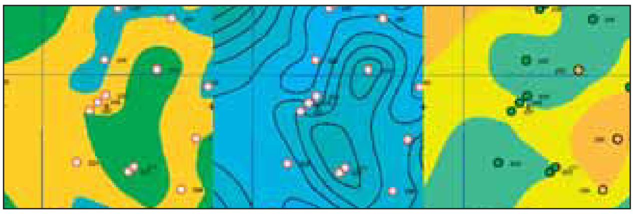

Figure 6 *'Hydrocarbon Potential Map' (left), 'Hydrocarbon Contour Map' (centre) and 'Noise & Quality Map' (right). The circles, labelled by identification numbers, indicate measurement locations on a selected area of 2 km x 2 km including multiple measurements (e.g. 225, 226, 227) taken at the position of the lower left circle. The green filled circles in the 'Noise & Quality Map' indicate highest quality measurements.*

The HyMAS Hydrocarbon Potential Map, the HyMAS Contour Map, and the Noise & Quality Map display specific information which can be used in combination to identify high potential hydrocarbon areas.

The amplitude maxima of the relative HyMAS signals can clearly be identified within areas of high hydrocarbon potential. Care must be taken, however, not to overestimate HyMAS peak values until they are calibrated with suitable well log data, as several circumstances can contribute to such high values: a reservoir located close to the surface, several stacked reservoirs at different depths, shallow gas occurrences, or effects of particular near-surface geological structures which are known to locally amplify or channel seismic signals due to a steep density and velocity gradient.

On the other hand, there is no such ambiguity for areas with low HyMAS signals of good quality and the prediction of low hydrocarbon potential is more conclusive. While most of the recordings were of high quality, there were some localized regions of lower signal quality due to extensive seismic emissions from producing wells. In these areas, advanced signal processing methods were required to extract useful signals of improved quality.

Integrating data for calibration

Once the HyMAS data has been processed, the result is compared with other existing geophysical information from the survey area. For the recent survey in Brazil (see section below), log data was available for eight wells distributed over the entire area. The comparison as well as our statistical tests suggested a linear relationship between hydrocarbon layer thickness and measured HyMAS values which varies with the surface geological formation. The well log data was therefore used for an adequate calibration of both formations (Figure 8). As a result, a calibrated map of expected hydrocarbon layer thicknesses of the entire area was compiled.

Quality control

Quality control routines are an integral part of the field measurements and the subsequent data processing steps. The routines assure high quality and completeness of data, correct measurement locations, adequate consideration of strong external noise sources, secure data storage, reproducibility, and the absence of systematic instrument errors.

Reproducibility

At over 60 locations in the Brazil survey, two or more measurements were taken within an interval of several weeks to verify reproducibility. Although a HyMAS signal might fluctuate on a short time basis due to environmental noise or subsurface micro seismic transients, it is expected to exhibit a constant average value over the duration of a measurement (0.5-2 hours) as well as over the period of time in which the hydrocarbon content does not change. To demonstrate this important property, measurements taken during the first phase were partly repeated during the second phase two to six weeks later. A pair of measurements passes the reproducibility test if its individual measurements show the same HyMAS values within the statistically added uncertainty. The uncertainty of a measurement is represented by the standard deviation of the Fourier power density spectrum of the processed data according to the Welch method (Welch, P.D., 1967) at a given frequency. Out of 48 pairs of measurements, 37 showed agreement within one standard deviation, 10 within two and one larger than two standard deviations of their respective statistical measurement errors. This represents an excellent confidence level of better than 95%. Since more than 25% of all measurements were involved, this test is representative for all measurements.

Statistical tests

One of the most fundamental statistical properties, the assumption that the distribution of measured values is the same within expected statistical fluctuations for all instruments, could be proven. Further tests involved the investigation of systematically significant deviations with regard to measurement set-up (in-ground or on a plate at the surface), weather conditions, surface rock material, altitude, and noise conditions.

Environmental compatibility and safety

Conventional 2D and 3D seismic surveys can have detrimental impact on the environment due to the use of vibrators and other heavy machinery for drilling shot holes, transporting material, or clearing vegetation and soil for access lines. The application of HyMAS during the exploration phase usually leads to the identification of selected areas of high hydrocarbon potential which can limit subsequent 2D or 3D seismic surveys and the related environmental damage to a smaller area.

HyMAS surveys have virtually no environmental impact and are therefore well suited for sensitive environments. Access can be by 4WD, helicopter, or foot, and equipment can be hand-carried over long distances between measurement points allowing low impact initial investigations of otherwise forbidden areas with regard to wild life or plant protection. Minor surface penetrations at measurement locations used for sensor placement are easily remediated to return the environment to its natural state.

Considering today's possibilities of directional drilling, HyMAS is the ideal tool to detect reserves beneath protected areas which can be exploited by drilling rigs positioned several km outside the protected area. The absence of explosives or heavy vehicles also significantly reduces the risk of crew injuries compared with conventional seismic campaigns. There have been no lost-time incidents during HyMAS surveys.

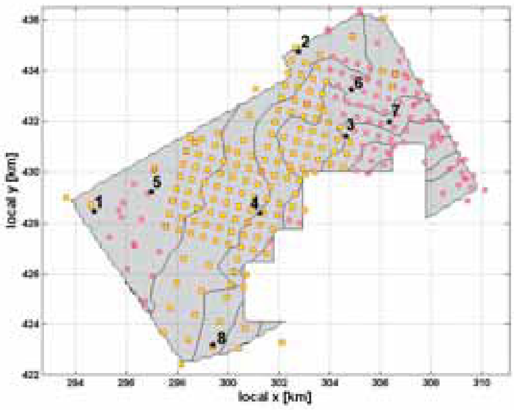

Figure 7 *Locations of HyMAS measurements and wells. Squares: measurements taken in the Jandaira formation. Circles: measurements taken in the Barreiras formation. The contour lines indicate the elevation between sea level (left) and 120 m (right).*

Results from Brazil case study

A recent pilot programme for Petróleo Brasileiro (Petrobras) in Brazil successfully demonstrated HyMAS technology under commercial operating conditions. The measured dataset was compared with log data of eight previously drilled wells. For demonstration reasons (blind test) this well log data was not provided until after the completion of the data analysis. The main result of this comparison is the provisional calibration indicating a linear relationship between the measured HyMAS signal strength and the total hydrocarbon layer thicknes derived from the well logs (see Figure 8). This is consistent with the results of earlier surveys in the Middle East and elsewhere (Dangel, S. et al., 2003). As shown in Figure 8 a different slope of the provisional calibration line applies for the measurements taken in the Barreiras (alluvial sediments) and the Jandaira (hard limestone) surface geological formations (Figure 7), which can be explained by the large difference in the acoustic impedance. Figure 7 shows the locations where measurements were taken. The eight locations where well log data was provided are marked by black stars labelled 1-8. From typical well log data the structures containing hydrocarbon were identified with a resolution of 0.2 m. The total hydrocarbon layer thickness (THLT) is the sum over all the identified sections. Figure 8 shows the THLT versus the measured HyMAS val-

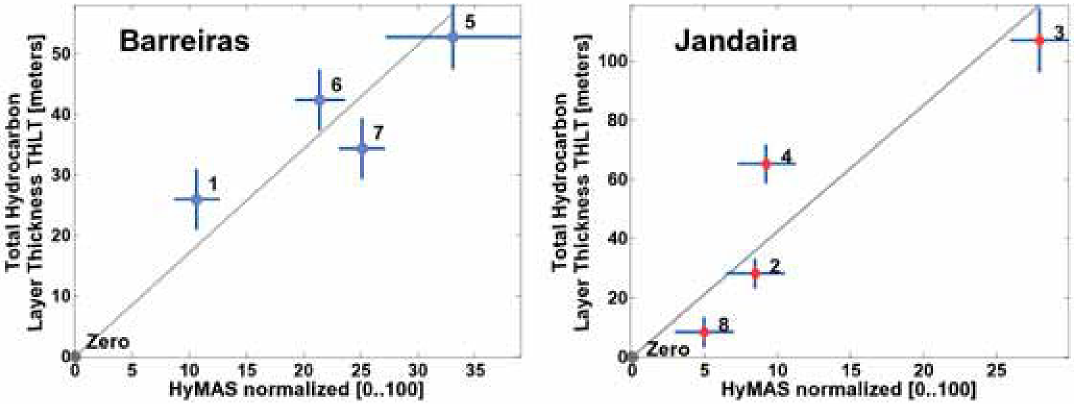

Figure 8 *Calibration between measured HyMAS values and total hydrocarbon layer thickness (THLT). Two different linear regression lines correspond to two different sets of measurements taken in the Barreiras (left) with a slope of 3.9 ± 1.9 or in the Jandaira (right) with a slope of 1.3 ± 0.4. Error bars in the y-direction (THLT) correspond to a 10% variation in the estimated water filling factor used for the determination of the hydrocarbon containing layers. Error bars in the x-direction (HyMAS value) correspond to signal fluctuations during the measurements. Numbering of the wells corresponds to Figure 7.*

ues and the least square fit linear regression lines for the measurements taken in the Barreiras and Jandaira formations close to the eight wells.

In order to verify the predictive power of the HyMAS Hydrocarbon potential map, the available log information of 25 wells (Figure 9) was used to calculate the average total THLT for each zone. The result displayed in Table 1 shows an average THLT value of 41 m in the high and 18 m in the medium potential zone averaged over 14 and 11 wells respectively. No borehole data was available for the low potential zone. The large variation of the THLT values for each zone reflects the fractured nature of the reservoir structure where adjacent wells can show vastly different THLT values.

Potential	Mean THLT [m]	Variation of THLT [m]	Number of Wells
High	41	47	14
Medium	18	11	11
Low	0	0	0

Table 1 *Mean values and variations of the encountered total hydrocarbon layer thickness (THLT)*

For this comparison, the HyMAS signals measured in different surface geological formations were corrected according to the calibrations shown in Figure 8, and only the highest quality data points with regard to external noise were used to define the potential zone boundaries.

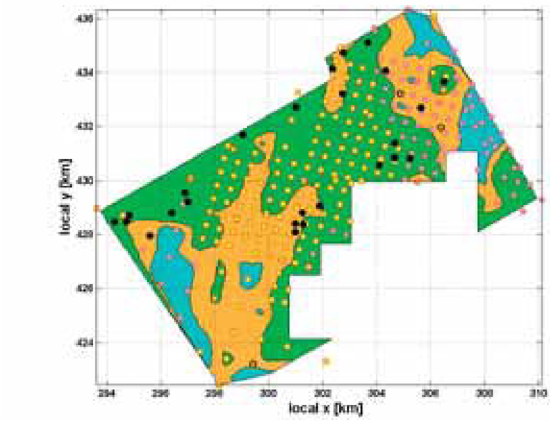

Figure 9 *Corrected and calibrated HyMAS Hydrocarbon Potential Map with the full black circles indicating producing oil wells; open black circle indicates non- producing oil wells. Yellow filled red squares = Jandaira; pink filled red circles = Barreiras. Green area = high hydrocarbon potential; yellow area = medium hydrocarbon potential; and blue area = low hydrocarbon potential.*

Fields of application and benefits

The benefits of HyMAS technology to an operator are manifold. In general HyMAS provides a direct hydrocarbon indicator for the optimization of borehole placement during exploration, appraisal, and production. Applied during the early stages of exploration campaigns, the areas where more expensive 2D and 3D seismic should be applied can be drastically reduced and significant cost and time savings can be achieved.

HyMAS is the ideal complement to 2D and 3D seismic since it provides the crucial information on the hydrocarbon content of geological structures which usually cannot be provided otherwise. While reflection seismic often shows poor results for unconsolidated sand formations or hard top layers, HyMAS is likely to be successful due to the analysis of information contained in the low seismic frequency range. Also the short turnaround time makes HyMAS the technology of choice for many applications.

Conclusions

The HyMAS survey in Brazil has demonstrated that the analysis of low frequency seismic signals yields consistent accurate information on the hydrocarbon potential of an area. Applied at an early stage, HyMAS can minimize expensive reflection seismic surveys and reduce the risk of drilling dry exploration wells. Combined with 2D or 3D seismic data, HyMAS allows optimal well placement for appraisal and production.

Acknowledgements

The authors thank Petróleo Brasileiro (Petrobras) for its collaboration and, in particular, Jurandyr Schmidt, for his support for survey organization and Wagner Preda and Wander N. de Amorim for their help during the final analysis work.

References

Aki, K. and Richards, P.G. [1980] *Quantitative Seismology, Theory and Methods.* Freeman.

Biot, M.A. [1956] Theory of propagation of elastic waves in a fluid-saturated porous solid - 1. Low-frequency range. *J. Acoust. Soc. Am.,* **28**, 168-178.

Chouet, B. [1986] Dynamics of a fluid-driven crack in three dimensions by the finite- difference method. *J. Geophysics.Res.* **91** 13967-92.

Dangel, S. et al. [2003] Phenomenology of tremor-like signals observed over hydrocarbon reservoirs. *Journal of Volcanology and Geothermal Research,* **128**, 135-158

Ferrazzini, V. and Aki, K. [1986] Slow wave trapped in a fluid-filled infinite crack: Implication for volcanic tremor. *J.Geophysics.Res.* **92**, 9215-23

Goloshubin, G.M. et al. [1993] Slow Wave Phenomenon at Seismic Frequencies. *63th Annual International SEG Meeting*, Washington DC, SL4.6,.809-811.

Korneev, V.A., Goloshubin, G.M., Daley, T.M., and. Silin, D.B [2004] Seismic low-frequency effects in monitoring fluid-saturated reservoirs. *Geophysics,* **69**, 522-532..

P.D. Welch, P.D. [1967] The Use of Fast Fourier Transform for the Estimation of Power Spectra: A Method Based on Time Averaging Over Short, Modified Periodograms. *IEEE Trans. Audio Electroacoust.* Vol. AU-15, 70-73.