Direct hydrocarbon detection experiment in Potiguar Basin

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Abstract

From March to May 2004 PETROBRAS performed an experimental geophysical survey in Potiguar basin, Brazil. For the first time, in a Brazilian sedimentary basin, the technology named "Hydrocarbon Micro-Tremor Analysis" (**HyMAS**tm from SPECTRASEIS) was used. HyMAS is an innovative passive technology for directly identifying hydrocarbons in geological structures by analyzing low frequency seismic signals. Hydrocarbon indicating information is extracted from spectral modifications of naturally occurring seismic background noise in the 0.1 – 20 Hz range.

The HyMAS technology does not demand artificial sources for data gathering, resulting in very low environmental impact. Aditionally, as it is based in low frequency signals, the HyMAS technology could bring some results in cases where surface seismic is not a valuable tool, a common case at some onshore Basins in Brazil.

Theory

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 [1]. A linear relationship between the observed signal and the total thickness of hydrocarbon layers was established by various measurements that were compared to well log data mainly in the Middle East. Earlier in 1993 other findings of low frequency seismic signals were related to oil-saturated layers by G.M. Goloshubin et al [2]. 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 modeling is based on Biot's theory [3] 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 [4] in 1986 and Ferrazzini and Aki [5] in 1987. These findings have recently been supported by up-scaled laboratory experiments [6] 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 (Figure 1). A poromechanical 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.

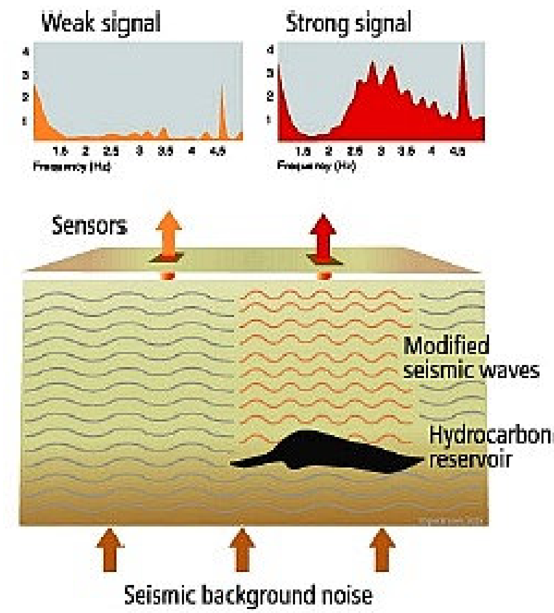

Figure 1 – Schematic of HyMAS measurements: seismic background noise interacting with hydrocarbon bearing geological structures shows spectral modifications around 3 Hz

Currently ongoing research, in collaboration with Oslo University, Zurich University and the Swiss Federal Institute of Technology (ETHZ), which combine the macroscopic wave propagation aspects of [6] as well as the microscopic poromechanical amplification mechanism, are expected to provide major steps towards the complete understanding of the occurrence of HyMAS signals. Numerical modelling and controlled studies underway at a test field in Europe should provide new insights into reservoir properties identifiable in low frequecy data. Recent successful processing of an ocean bottom dataset opens the way to marine applications.

The background noise is recorded, processed and interpreted, resulting in a final product: A contour map showing the signal amplitudes related to hydrocarbon (HISA). After an expedite quality control in the field. The data processing starts with data selection and filtering, followed by wavelet analysis, wave propagation modeling and non-linear correlation procedures, among others.

Since HyMAS technology is based on low frequencies, it should be successful for screening exploration prospects and for well location optimization in places with a poor seismic response, especially when complemented by conventional seismic data.

A very important advantage of the technology is its low environmental impact. Since there is no artificial seismic source and lightweight equipment is used, the large amount of personnel, gear and heavy equipment usually “in motion” in a regular seismic crew is not needed. Positioning of the measurement points is made with GPS and the risks for the field staff and the population, in general, are extremely low. In this sense it is possible to compare HyMAS with a gravimetric survey. HyMAS technology is therefore ideally suited for application in environmentally sensitive areas and areas with challenging access conditions.

Recording Gear

To record the low frequencies and low amplitudes required by this technology, conventional seismic reflection geophones have too little sensitivity and bandwidth. For HyMAS surveys the sensors must have the spectral response and sensitivity of instruments applied in seismology. Spectraseis selected the GÜRALP CMG-3ESP (Figure 2), a three component electro-mechanical device (vertical, N-S and E-W) coupled to a 24-bit analog to digital converter. The bandwidth of the CMG-3ESP ranges from 0.01 Hertz to 50 Hz; the unit has a self-level capacity that can overcome inclinations up to 2.5 degrees. The “field package” included a 70 Ah lead acid power source, a GPS antenna and cables. Field data is recorded in hexadecimal GCF format (Güralp Coded Format, proprietary of Güralp Systems) and stored in the sensor internal memory or on a computer connected to it.

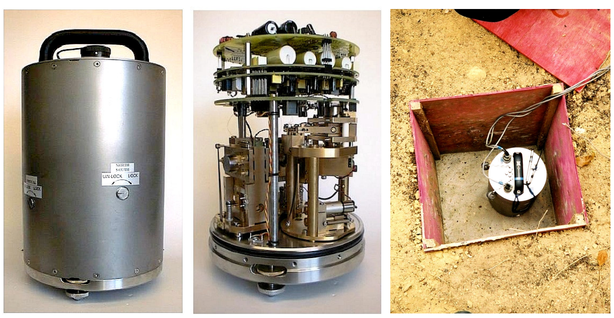

Figure 2 – The GÜRALP CGM-3ESPC seismometer in tree moments: Ready to use in the bench, with the cover out exhibiting the electro-mechanical module and the digitizer in a top mounted chassis, and in the field, leveled and connected ready for use. Dimensions are: High 292 mm including the handle, diameter 168 mm and a weight of 16 kg.

Survey Area

Survey area included some onshore Blocks and Ring Fence areas in the Potiguar basin, in the northeastern state of Rio Grande do Norte, in part of an area recently covered by a 3D seismic survey. The survey polygon has approximately 95 square kilometers, as shown in figure 3.

The Field Survey

Data were acquired in 55 days using six recording set-ups operated by a crew of 20 people. Approximately 500 measurements were taken at 266 different locations, including verification measurements for quality control. Acquisition was completed in two phases: phase one covered the whole survey area with a wide measurement grid (1000m x 1000m spacing); in phase two, a narrower grid was used (500m x 500m) in selected areas.

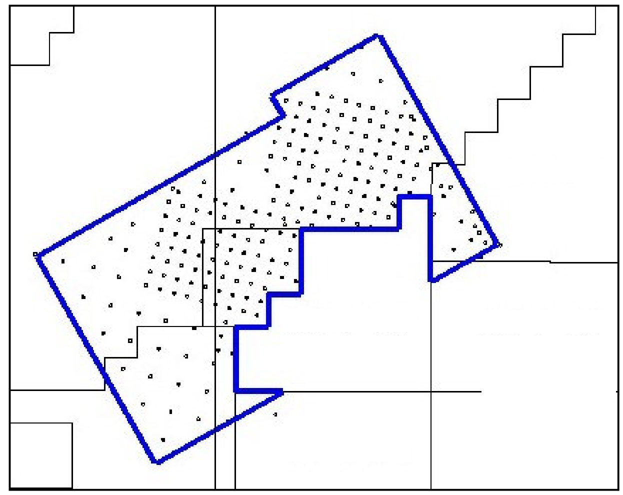

Figure 3 – Survey area and the survey points.

Preliminary analysis of phase one results was used to determine the location of the most interesting zones for 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). Actual locations could deviate up to approximately 20m from the planned regular grid coordinates to ensure good GPS coverage, firm soil conditions and the absence of nearby artificial noise sources. Where the surface was too hard to penetrate, the instruments were positioned on a plate with good ground contact or directly on solid rock.

Field Records

Data acquired in the field was transmitted from the field daily for pre-processing in order to provide immediate feedback on data quality for the field crews, determine the phase two acquisiton layout and shorten overall processing time.

A total of 376 good quality datasets were used in the final analysis, extracted from approximately 700 hours of time series recordings 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 [7]. 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 passing by, weather conditions or other artificial noise sources, the unperturbed sequences of the measurements (Figure 4) are selected for further processing (figure 5).

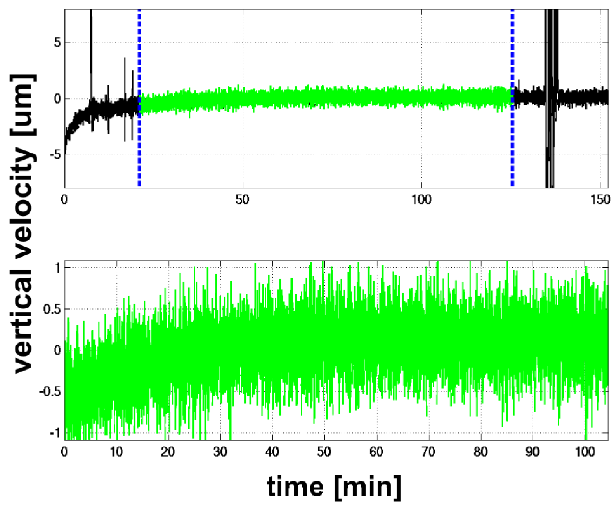

Figure 4: Time series of vertical velocity of seismic motion measured at 100 Hz sampling rate. From the original recorded time series (top) intervals which do not contain large disturbances are cut and assembled (bottom) for further processing.

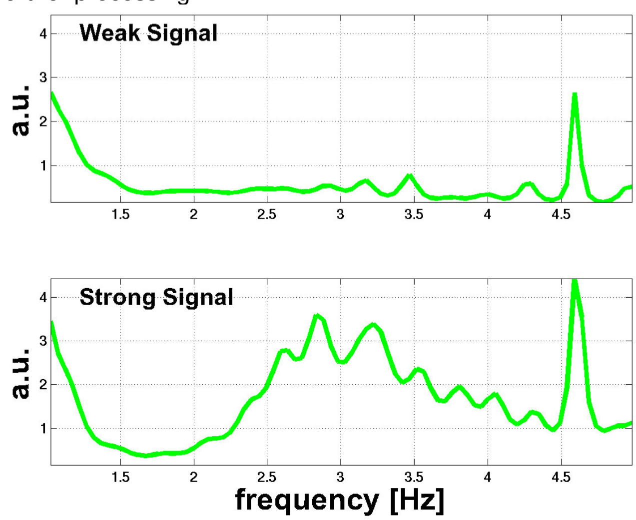

Figure 5: After suitable filtering processes both in the time and frequency domains the HyMAS value can be determined as the peak value of the frequency power density spectrum near 3 Hz. The trace on top leads to a low HyMAS value, while the trace on the bottom represents a high HyMAS value. A narrowband artificial noise source can be seen at 4.6 Hz.

Spectrograms

A time-frequency display (Figure 6) shows the presence or absence of continuous narrowband noise sources and is used to identify low noise intervals.

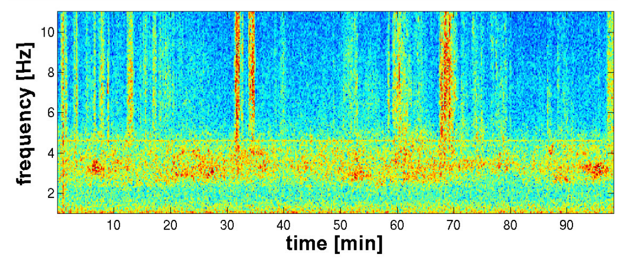

Figure 6: Time evolution of the spectrum (vertical axis) during the duration (horizontal axis) of the measurement. The color is a function of the logarithm of the spectral power density ranging from low values (blue) to high values (red). High power broad band noise is clearly visible as a vertical red line while strong narrow band signals appear as thin horizontal lines.

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 measurement locations in the survey two or more measurements were taken with an interval of several weeks in order 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 layer characteristics do not change. In order 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 [8] at a given frequency. Out of 48 pairs of measurements, 37 showed agreement within one standard deviation, 10 within two and 1 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, was also proven. Other tests were perfomed to investigate whether systematic significant deviations with regard to measurement set-up, weather conditions, surface rock material, altitude and noise conditions could be identified.

Comparison with PETROBRAS knowledge of the survey area

The aim of the pilot survey program was to demonstrate the HyMAS technology under commercial operating conditions with no prior knowledge of the survey area geology or reservoir parameters provided to Spectraseis. In other words, this was a “blind” test. After Spectraseis submitted their initial analysis and report to Petrobras, based on uncalibrated data and without correction for variations in surface geology, summary total hydrocarbon layer thickness (THLT) data from eight wells was provided for base calibration.

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 thickness derived from the well logs.

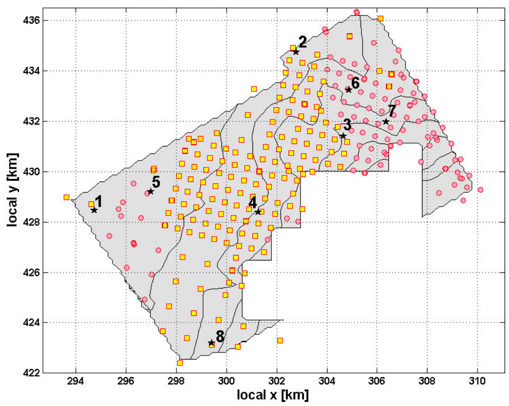

Figure 7: Locations of HyMAS measurements and wells. Squares: measurements taken in the Jandaira formation (hard limestone). Circles: measurements taken in the Barreiras formation (heterogenous sandstone). The contour lines indicate the elevation between sea level (left) and 120 m (right).

In order to verify the predictive power of the HyMAS hydrocarbon potential map, the available log information of 25 wells was used to calculate the average THLT for each zone. The result displayed in Table 1 shows an average THLT value of 41m in the high and 18m in the medium potential zone averaged over 14 and 11 wells respectively. No borehole data were 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

Hydrocarbon Potential and Relative Amplitude maps are the final products of the HyMAS technology. These maps indicate the greater possibility of hydrocarbon presence in subsurface. In this paper only an hydrocarbon potential map is shown.

A detailed representation of the measurements is shown in the *HyMAS Contour Map* (see Figure 8) as uncalibrated 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 [1] to the total hydrocarbon layer thickness. With suitable information from calibration wells, a map of absolute net hydrocarbon thickness in meters 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 identify such perturbations in interpreation, the areas of increased noise impact are displayed in a *Noise & Quality Map*. Three categories of noise impact on the measurements were identified and treated differently during analysis: i) noise that leads to a reduction of the useful length of a time series, ii) noise that increases the amplitude of the recorded signal and thereby reduces the relative strength of the HyMAS signal, iii) strong industrial noise between 10 and 40 Hz.

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

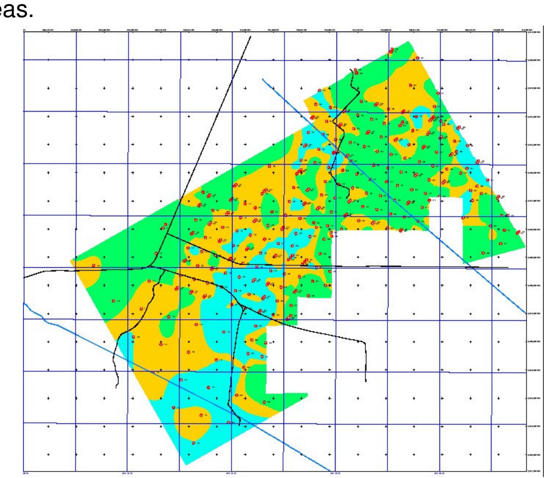

Figure 8: Uncalibrated hydrocarbon potential map before surface correction showing wells and reservoir limits as they are currently understood by PETROBRAS. Areas containing the CAM 830 and Canto do Amaro fields are identified. Producing zones within the Fazenda Canaã field in the Jandaira (hard limestone) area were partially revealed.

The amplitude maxima of the relative HyMAS signals can clearly be identified within areas of high hydrocarbon potential. Care must be taken, however, in order 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. As with all sources of geophysical data, HyMAS results are best interpreted in light of geological studies and other pre-exisitng knowledge about the survey area.

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 in order to extract useful signals of improved quality.

Conclusion

Non calibrated maps were compared with PETROBRAS knowledge, concerning the studied area. A calibrated map was generated and is still under evaluation.

It is important to highlight that the test was conceived as a “blind test” with little geological and geophysical information given “a priori” to the experiment and so to the data interpretation.

From a regional viewpoint the uncalibrated test results are valid. Canto do Amaro and an adjacent field are well emphasized on both maps; Fazenda Canaã field is an exception in that it didn’t fully show up in the maps before surface correction. This can be explained by the significant velocity change between the hard limestone in the Jandaira area and the soft, heterogeneous sandstone of the Barreiras formation.

From a local viewpoint incoherencies show up as mentioned bellow:

- SPECTRASEIS map depicts a “cool” (blue) zone on its upper corner, in fact this is a “hot” place as there we have a production area in the Canto do Amaro field.

However the results in this area are constrained by:

- Low survey resolution in this section (only five measurements points were acquired).
- Simplified surface correction performed without the benefit of a detailed geological surface map.
- Relatively high levels of artificial noise contamination in the upper right section.

Such factors should be considered in designing future surveys and when interpreting HyMAS results.

The experimental survey exhibits an absence of measurements in a central portion of the initial planned area, as we can see in figures 3 and 7. This “shadowed” area undoubtedly impaired the interpretation, not only by the data absence, *per si*, but also for the edge effect it caused.

For completeness, it should also be mentioned, that the survey area is highly complex. The geological knowledge accumulated by Petrobras over the years shows considerable uncertainties and blind spots in some locations, despite repeated 2D and 3D seismic investigations.

Facing the test results it is not possible to evaluate the HyMAS technology conclusively as a direct hydrocarbon detection tool that could attain high success rates under all geological conditions. The success rate of the new technology improves with the quality of geologic and geophysical data to be given for calibration, thus it is not a stand-alone technology but a complementary tool to be supported by other geophysical studies for a final quantitative interpretation. However HyMAS can be useful as a stand-alone tool during the early exploration phase.

In spite of the problems mentioned above, which can be minimized in future surveys, the technology demonstrated for this specific area a correlation of over 50% for the uncalibrated maps; excellent results given the harsh conditions under which the campaign was carried out and the geological complexities involved. It is expected that the method can reach higher consistency levels with the known potentials, which provides HyMAS a very high confidence value when compared with conventional seismic (indirect) methods.

HyMAS technology stands out for its ease of operation, fast turnaround time and low cost. From an operational viewpoint the method is especially attractive in environmentally sensitive areas where other geophysical methods would be forbidden. The method could provide new understandings in areas of poor quality conventional surface seismic as HyMAS technology deals with low and very low frequency signals that go beyond obstacles like thick basalt or conglomerate layers that inhibit conventional seismic.

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