Low-frequency Seismic Noise:
The Music of oil?

Passive low-frequency seismic is an area of active research and development, and is rapidly being taken up as a new direct hydrocarbon indicator (DHI) technique for exploration. The interest in the method is high, in particular since Spectraseis AG, the leading provider of low-frequency geophysical solutions to the oil and gas industry won the World Oil Award for Best Exploration Technology in October 2007. However, despite the empirical evidence supporting the technique, the underlying physical mechanism has not yet been fully identified.

Martin Landrø is professor in Applied Geophysics at the Norwegian University of Science and Technology (NTNU), Department of Petroleum Engineering and Applied Geophysics, Trondheim, Norway.

Lasse Amundsen is adjunct professor at the Norwegian University of Science and Technology (NTNU) and at the University of Houston, Texas.

Technologists like technology that succeeds greatly, often as a result of megabucks of research and development. Conversely, technologists are somewhat suspicious of technology that comes easily and seems too simple. They think: how could the big brains in the industry overlook this simple idea? Or did they look into it and reject it?

In this issue of GEO ExPro the authors present a technology that is partly in the latter category. Even though a significant amount of research on low-frequency seismic has been conducted over the past five years, it is a technology that needs better understanding to fully judge its potential and validity.

Low frequency ambient seismic waves are ubiquitous in the earth's crust. Recording this "voice" of nature by employing arrays of geophones on the ground actually may give information about the near-surface geology. Japanese seismologists over the last 25 years have developed the use of background noise into a mature science for engineering-scale studies.

But does passive seismic listening hold potential for oil and gas prospecting? Do hydrocarbon reservoirs produce a unique low-frequency signature or a kind of "music" that can be measured to provide valuable information about their locations and characteristics?

Brief history

According to www.anchar.ru a group of Russian scientists, today part of the geophysical service company ANCHAR, performed studies over fields in East Siberia and North Caucasus in the early 1990's, and demonstrated that the spectral power of background noise above the hydrocarbon reservoir in the frequency range 1-10 Hz is higher than it is outside the hydrocarbon reservoir.

Could this empirical observation point to a possible universal hydrocarbon indicator?

In the west, the company ADNR Technology (recently launched as GeoDynamics) was formed in the mid-1990's to work on the use of passive low-frequency noise to detect hydrocarbons.

Passive low-frequency seismic for exploration received new and high attention when *Dangel and co-workers* in 2003 reported amplitude peaks clustered around 3 Hz in seismic data measured above hydrocarbon-bearing reservoirs in the Middle East. The key observation was that the seismic background noise seemed to be modified in the low frequency range above hydrocarbon filled structures relative to the background noise measured above water filled structures.

Based on the results of Dangel, Spectraseis AG was founded in 2003 to acquire low-frequency seismic data and to develop industrial applications as research progressed. Funding from the Swiss government and investment in 2005 by Hydro Technology Ventures helped the company to develop commercial acquisition systems and data processing software. In November 2007 Warburg Pincus, a global private equity firm, acquired a significant minority stake in Spectraseis, providing new equity to finance the company's growth plans. StatoilHydro Venture Capital now owns a stake in the company together with Spectraseis' management team.

An early technology blind test of the Spectraseis technology took place for Petrobras in 2004. The survey covered a producing oil field in the Potiguar basin in northeastern Brazil. According to Spectraseis (see Graf et al. 2007), "the test clearly identified two, and partly revealed the third, producing zone within the block". The figure, which is adapted from Graf et al., shows the published amplitude frequency spectra of the seismic background noise within (red curve) and outside (black curve) the boundaries of the reservoir. The low-frequency signal anomalies in the 2-4 Hz band is what we here call the "music" or "voice" of oil. The amplitude peak at around 0.2 Hz is the background noise, probably generated by ocean waves.

Passive seismic techniques using low-frequency ambient waves were a major topic at the 2006 EAGE workshop on passive seismic methods and applications held in Dubai. A crowd of 120 professional participants representing almost all major E&P companies confirmed a large industry interest in this technology.

What causes the spectral anomalies?

The source of the anomalous 2-4 Hz signal remains unclear at the moment. The precise physical mechanisms at play are still the subject of active research. Several potential causes have been suggested.

Two candidates have been proposed by Spectraseis. The first is a resonant amplification occurring at the pore scale within the reservoir, whereby seismic energy is trapped in a multiphase fluid system and then emitted with detectable energy levels. Secondly, at the macro scale, resonant scattering due to complex impedance contrasts between hydrocarbon-bearing rocks and the surrounding media alter the ambient seismic wavefield to become detectable at low frequency.

Interestingly there are some ideas suggesting that this signal can be enhanced by natural phenomena such as earthquakes or using active sources, such as vibroseis.

Market acceptance

Although the theory is not fully understood yet, it is possible to evaluate the technology by studying field examples and comparing results from various environments world wide.

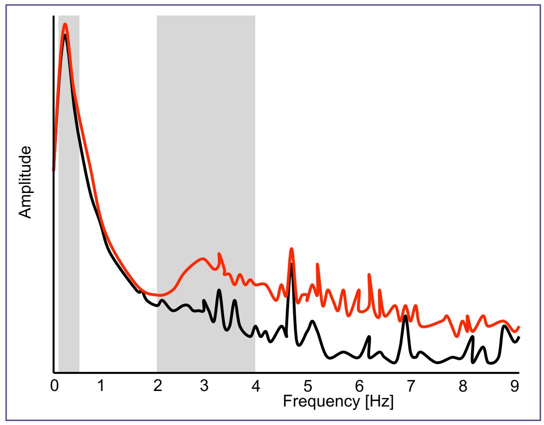
To obtain market acceptance, it is important that case studies are published, not only by vendors, but also by the major oil and gas companies. Successful published case studies will whet the 'show-me' companies' appetite, and back up the technology. Spectraseis states that the following companies have published independently or together with them: EniRepSA, Shell/SRAK, Petrobras, Pemex and RAG. Publications from other vendors are limited.

Examples

Onshore gas reservoir survey: In 2006 Spectraseis completed a 200 km² survey over a gas field in the Burgos Basin in Mexico for Pemex. Saenger et al. (2007) report a high correlation between the low-frequency spectral anomaly and the known location of the gas reservoir. The reader is referred to the Saenger paper for more detailed results and figures.

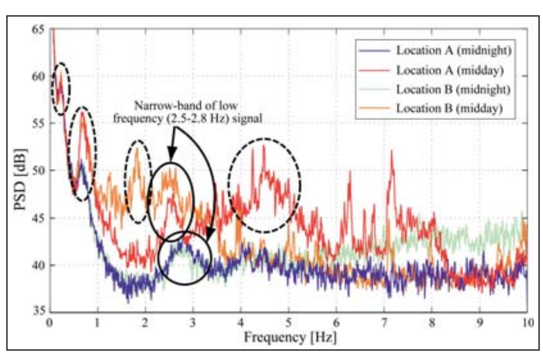
Marine survey: In April 2007, Spectraseis completed the first offshore test of its technology. The 14-day pilot survey, over the non-producing Astero field north of the Troll field in 350 m water depth in the Norwegian sector of the North Sea, demonstrated the feasibility of deploying and recovering broadband ocean bottom receivers to record passive low-frequency data at more than 130 locations on the seabed. No results have been published from this survey so far. The program was a collaborative effort among field operator Hydro and Spectraseis, with Scripps Institution of Oceanography and Bergen Oilfield Services providing technical and operational services.

Saudi Arabian Rub al-Khali: Dr Pieter Van Mastrigt of SRAK, a joint venture between Shell, Total and Saudi

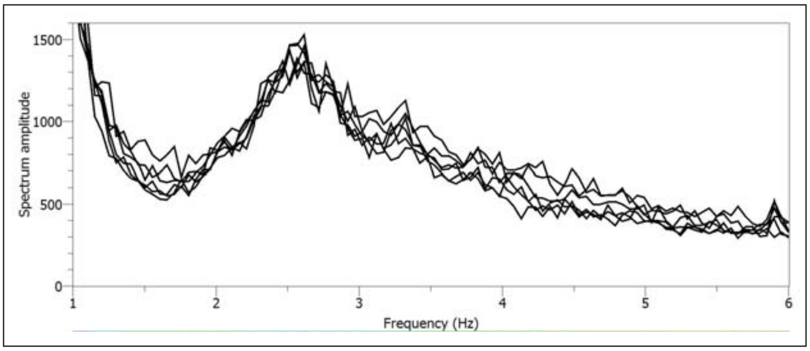


Amplitude spectra characteristic of measurements of seismic background noise within (red curve) and outside (black curve) the boundaries of a known oil reservoir in the Potiguar Basin, Brazil. The curves are hand-drawn after Graf et al (2007). The right bar highlights the frequency band where hydrocarbon anomalies are usually found. The left grey bar highlights were the noise from ocean waves is found.

Deployment of ultrasensitive three-component seismometers with frequency response of 0.03 Hz to 50 Hz in the Abu Dhabi low-frequency, passive seismic experiment (Ali et al 2007).



Comparison of frequency spectra of passive z-component recordings over location A (above oil reservoir) and B (outside reservoir) for midday and midnight acquisition. A narrow band of low frequency (2.5-2.8 Hz) signals is observed. The spectrum is higher during night compared with that observed at midday. The solid ellipses indicate the narrow low frequency band. The dashed ellipses indicate other anomalous signals that are observed (Ali et al 2007).



Amplitude spectra from several locations along the passive seismic profile in Abu Dhabi showing minor changes between reservoir and no-reservoir locations (Ali et al 2007).

Aramco targeting deep gas prospects, has reported on low-frequency seismic data using amplified 3C geophones at a recent OGEP meeting. Calibration over a known gas accumulation showed a rather striking anomaly over the field-outline. Noise spectra differences observed between sand dunes and the intra-dune areas, as well as significant day/night differences were overcome in the processing of the data. SRAK plans to continue integrating low-frequency recordings with future seismic campaigns.

Time Reverse Model for reservoir localisation applied to data from Austria: Dr Brian Steiner at ETH Zurich has recently reported on a successful depth localisation of two reservoirs in Austria using survey data from Spectraseis. Spectraseis Time Reverse Modeling processing method localizes the 'microtremors' to their originating subsurface locations at the hydrocarbon reservoir. According to Spectraseis this work suggests that the 'resonant amplification model' may play a significant role in explaining the physics underlying the phenomenon of spectral anomalies.

Onshore carbonate reservoir test Dr Mohammed Ali from the Petroleum Insitute in Abu Dhabi, together with his colleagues, has analyzed low-frequency data acquired directly over a carbonate oil-reservoir and compared these to measurements outside the reservoir. The results show no significant difference in low-frequency behavior between the two sites. However, they do observe significant changes between midday and midnight measurements, and this effect is not fully understood yet. Furthermore, based on utilising two-dimensional seismic array data, preliminary investigations indicate that the wave mode in question is some type of surface wave. More work is in progress, and new experiments are planned to gain more insight into low-frequency exploration.

Conclusion

The questions now are which applications will prove most useful and how quickly the rest of the industry will embrace them. We encourage oil and gas companies to report more results. The key challenge is to identify the underlying physical mechanisms of the observed low-frequency spectral anomalies.

Acknowledgements

We are grateful to Dr M. Ali for providing figures and illustrations, and giving us insight into their results. The material in this article is based upon published material. The reader is referred to the articles listed below to find figures related to the case studies cited above.

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Seismic background noise

The earth's surface is always in motion at seismic frequencies. These vibrations of the surface are called microseisms, microtremors, or simply seismic background noise. Although the vibrations are very small in amplitude, and far below human sensing, they may represent a useful source of signal that can be used to analyse the response of the ground to earthquake movement. Microtremor surveying basically is a passive seismic method that is relevant for engineering geophysics in densely populated areas where there is a difficulty in using conventional seismic techniques.

The nature of microtremors has been vigorously debated. Recent literature debated whether microtremors are dominated by S-wave resonances or by Rayleigh wave propagation. However, it is accepted that microtremors are caused by both daily human activities as well as natural phenomena. Examples of human activities are motor cars and movement of machinery in factories, which typically produce microtremors with signal components higher than 1 Hz in frequency. Natural phenomena are ocean waves, variations in atmospheric pressure, and wind. The corresponding microtremors are dominated by signal frequency components lower that 1 Hz. The most energetic part of this background noise is frequencies around 0.2 Hz, and is most likely related to seismic surface waves generated by ocean waves.

Reference: Okada H 2003: The microtremor survey method: Society of Exploration Geophysicists.