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Low-Frequency Seismic Gives Geophysicists A New Look At Reservoir Information

By Brice Bouffard

ZURICH, SWITZERLAND–The past few years have seen an explosion of global geophysical activity. In the quest to image hydrocarbon reserves more precisely, operators have looked for means by which they can further enhance conventional seismic and electromagnetic exploration techniques, and improve the value of the data generated.

The increasingly complex and remote reservoirs, often characterized by poor seismic responses with acoustic and electrical signals obscured, have exacerbated the need to improve the value of conventional seismic data and adopt techniques that complement them.

One such technology is low-frequency (LF) passive seismic technology, which is helping to improve the value of conventional seismic data by overlaying structural interpretations with reservoir information. Where geographic and/or political obstacles stand in the way, LF passive seismic has the potential to operate in areas off limits to traditional exploration, paving the way for new resource plays.

This article will look at the development of LF passive seismic, what it has achieved to date in conjunction with conventional seismic, the future impact it will have on oil and gas exploration, and some of the challenges in further commercializing the technology.

One future development we will look at is how LF passive seismic is localizing hydrocarbon microtremors through the technique of time reverse modeling.

LF Passive Seismic

LF passive seismic is a technology first discussed in Russian seismic literature in the 1990s. It has come to prominence since 2003 because of the work of the University of Zurich's Dr. Stefan Dangel and the research work of Spectraseis, which was established out of Zurich University.

In his article, Dangel highlights a strong and consistent empirical relationship between low-frequency spectral anomalies in seismic background wave fields and geologic characteristics of a collection of reservoirs, mainly in the Middle East. Dangel's research focused on one feature in particular: curious amplitude peaks clustered around 3 Hz in surface velocity data measured above hydrocarbon reservoirs.

As a result, LF passive seismic analyzes the spectral attributes of naturally occurring, low-frequency (<10Hz) seismic wave fields. This is achieved by collecting the data through portable broadband sensors capable of recording rich seismic data as low as 0.001 Hz, and without the traditional seismic requirements of conventional geophones and artificial energy sources.

The resulting data are processed to remove unwanted signals and spectral analysis, and attribute calculations then are performed to generate profiles and maps indicating likely hydrocarbon-bearing zones within the survey area.

Since Dangel's research, a number of research programs have been developed to move LF passive seismic forward. Research partners of Spectraseis, for example, include the Swiss Federal Institute of Technology, the Swiss Commission for Technology and Innovation, the University of Oslo, the University of Berlin, Johns Hopkins University, and the Australian National University.

PEMEX Example

There are many examples of the effectiveness of LF passive seismic and its correlation with hydrocarbons.

Low-frequency passive seismic technology is helping to improve the value of conventional seismic data by overlaying structural interpretations with reservoir information, and is giving surveying crews the ability to acquire data off limits to traditional exploration. Shown here, a seismic crew deploys equipment to conduct a passive low-frequency spectral analysis survey in Austria.

In August 2006, Spectraseis conducted a survey in the Burgos Basin in northwestern Mexico for Petróleos Mexicanos, Mexico's state-owned petroleum company. The results found a high correlation of the hydrocarbon microtremor signal with the known location of the gas reservoir.

Using ultrasensitive portable three-component broadband seismometers (frequency range: 0.03 to 50 Hz), more than 700 measurements of the omnipresent seismic wave field at the surface were acquired over an area of 200 square kilometers. A sensor grid layout was used with node spacing ranging from 750 to 1,000 meters. Several reference stations were installed for the duration of the survey.

The raw data included strong perturbations (noises and artifacts) and discontinuities (data gaps). In order to obtain a clean signal in the time domain, all time intervals were cut out with obvious strong artificial signals. This is an important step in the workflow because it is the first interpretative, nonautomatic routine in the data processing.

The collected data were used to produce a certain number of maps based on seismic attributes related to the low-frequency energy anomalies in the expected bandwidth of the hydrocarbon signature (usually between 1 Hz and 6 Hz).

All attribute maps showed consistent patterns. In the proven hydrocarbon-bearing area, an energy anomaly was observed clearly. In order to characterize this anomaly in more detail, several seismic attributes were extracted, correlative with the known field boundaries. These attributes were significantly different in data acquired away from the reservoir.

The Mexican pilot demonstrated that low-frequency anomalies are related to the presence of hydrocarbons, and can be used as complementary information to structural imaging methods to reduce drilling risk and assist well positioning.

North America Pilots

Two further pilots are taking place in North America. Both are in environmentally sensitive areas where operations must be aligned with the strong safety and environmental requirements of working with a large multinational oil and gas company. Each pilot covers an area of 100 square kilometers.

In order to maximize data quality and consistency, quality control and organization of the field data are performed at the base camp after downloading from the field stations and before transmission for processing and analysis, where a proprietary data acquisition system has been set up to provide real-time control and supervision.

The processing team performs rapid processing and analysis of the data and provides feedback to the operations crew in terms of measurement quality and other characteristics. At the same time, the analysis team works on understanding the recorded signal and determines a potential re-measurement sequence, so that crews can perform additional measurements before leaving the field, if necessary.

After the entire survey has been acquired, the entire data set will be processed and analyzed to generate the deliverable product to the operator.

In response to the growth in ever-more remote deepwater fields, LF passive seismic is going offshore as well. In April 2007, a 14-day pilot survey was carried out over a proven oil field in the North Sea. The survey 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. The possibility of applying LF techniques in high-stakes marine settings to address challenges such as imaging below salt is a tantalizing prospect.

Shell And SRAK

It is not just Spectraseis and partners such as PEMEX and Petrobras that are putting their resources behind LF passive seismic; many other operators are doing the same. For example, Shell has published several articles on the results of its development work–in particular in relation to South Rub Al-Khali Company (SRAK), Shell's joint venture with Total and Saudi Aramco to explore for gas in a 210,000 square-kilometer area of Saudi Arabia known as the Empty Quarter.

At SRAK, amplified high-sensitivity geophones were used to assess whether low frequency, passive seismic could be used as a direct hydrocarbon indicator.

According to a paper abstract on the subject, observations included "a good correlation with a known subsurface hydrocarbon accumulation using this technique," and "a rather striking anomaly over the field outline."

The abstract concludes, "SRAK has firm plans to take full advantage of this emerging technology by integrating LF recording on a survey-wide scale on its potential future seismic campaign."

As LF passive seismic further develops as a hydrocarbon indicator technology, it has the ability to provide strong support to conventional seismic techniques. Hydrocarbon reserves can be imaged more precisely, well positions optimized, and drilling decisions made with greater confidence.

Passive seismic data can be integrated with other complementary sources of geologic and geophysical data, such as 2-D/3-D active seismic, bore hole and production data. The information also can be used to upgrade the operator's understanding of the subsurface and improve decision making, productivity and profitability.

What was previously dismissed as seismic "noise" will play a crucial future role alongside conventional seismic techniques in helping oil and gas companies more efficiently find and produce hydrocarbon reserves.

Future Challenges

So far we have tracked what has been achieved with low frequency passive seismic to date, but what of the future? What are the key challenges the technology faces as it continues its route into the commercial domain? The commercialization of low frequency spectral analysis faces a critical but exciting few years as the technical boundaries are better defined and operations are industrialized.

Increased survey capacity, synchronized acquisition, sophisticated modeling, data analysis, signal processing, and software tools will be crucial in transforming raw, low-frequency data into the valuable attribute profiles, maps, and 3-D volumes the industry demands.

One new development and a sophisticated attribute analysis technique, which has the ability to localize the source of hydrocarbon microtremors and spectral anomalies, is time reverse modeling. TRM is the outcome of research into sophisticated attribute analysis techniques, which are more reliable than simple single-component, single-attribute analysis methods.

TRM images hydrocarbon deposits at depth by utilizing passive measurements of the surface particle velocity to actively locate the origin of low frequency (<10 Hz) spectral anomalies associated with hydrocarbon reservoirs.

Two-D and 3-D images derived from TRM of LF passive seismic survey data–a form of reverse time migration of continuous seismic energy–requires only the addition of a sufficiently accurate velocity model to provide valuable new information for exploration and field development decisions. In general, most other prior methods are not applicable because they require identifying single event phases or first arrivals that are not present in low-frequency data.

Properly parameterized for low-frequency hydrocarbon data, TRM localizes LF passive seismic reservoir signals to their originating subsurface locations using continuous, synchronous recordings acquired over the reservoir area with an array of sensitive broadband receivers. No single event or first arrival time identification is necessary. TRM results then can be integrated with other geologic and geophysical data to improve operator understanding of the subsurface.

Austria Example

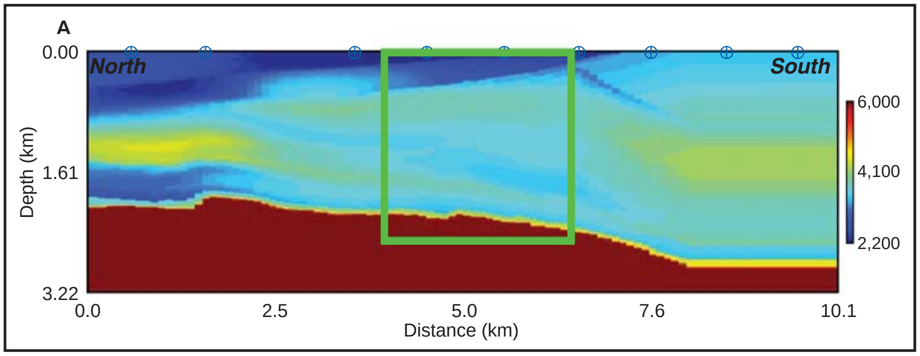
In 2007, we applied TRM to low frequency passive seismic survey data acquired over oil reservoirs operated by Rohöl-Aufsuchungs Aktiengesellschaft (RAG) near Voitsdorf in upper Austria to generate new

Recoverable ocean-bottom sensors can be deployed offshore to acquire marine passive seismic data. A pilot program conducted in the Gulf of Mexico demonstrated that low-frequency anomalies in the seismic data are related to the presence of hydrocarbons.

The Future

FIGURE 1

Austrian Seismic Data Velocity Model



images of reservoir locations.

TRM was applied successfully to two data sets, acquired 16 months apart above known oil reservoirs, to image the hydrocarbon-bearing zones using spectral anomalies observed in the vicinity of the reservoirs. The data were acquired using sensitive broadband receivers deployed at the surface for periods of 24 hours

The results indicate that low-frequency signal anomalies originate from the reservoir locations, and demonstrate that subsurface reservoir locations can be imaged using this method.

The velocity model and results of TRM applied to these data are shown in Figures 1 and 2. The velocity model, illustrated in Figure 1, is adapted to TRM for P and S waves using stacking velocities from a 3-D seismic survey over the area.

Figure 2 illustrates the results from TRM for two separate time windows of three minutes each (called "B" and "C") of synchronous data from nine receivers spanning the survey area. The known locations of the two single-layer reservoirs, seated on basement rock, are identified by the ellipses, and correspond to areas of high particle velocities output from TRM.

Synthetic studies of TRM indicate that characteristics of source radiation significantly influence source localization accuracy. Sources that emit mainly S waves in the vertical direction yield the most accurate source localization.

The results show that TRM accurately localized the area of the source at the reservoir. A good qualitative agreement was found between the positions of known hydrocarbon reservoirs in both the synthetic model and from the two separate surveys recorded 16 months apart. The Austrian experience successfully demonstrates TRM's ability to reveal the origin of continuous low frequency signals originating at hydrocarbon reservoirs–crucial information for future development planning and a significant breakthrough in the commercialization of LF passive seismic.

TRM also allows for further research to be extended into whether reservoirs emit oscillatory seismic energy. TRM allows for the direct imaging of subsurface reservoir positions for this purpose.

New Plays, New Challenges

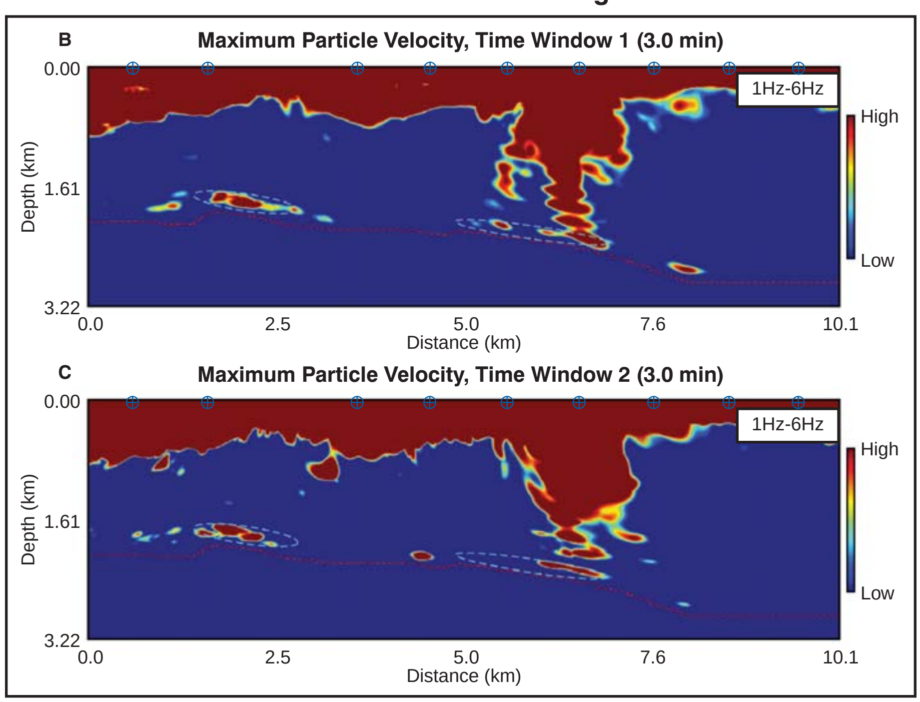
TRM is an example of how potential new resource plays can be generated through LF passive seismic where there may be geographical, environmental or political obstacles.

While the case study in Austria was in a relatively accessible area, LF passive seismic's light equipment and limited resource requirements can be particularly valuable in more remote areas–areas often characterized by poor or complex geophysical responses to acoustic and electrical sources

Acquiring traditional seismic data requires artificial energy sources such as explosives or vibrators, and extensive amounts of resources and time

FIGURE 2

Time Reverse Modeling



with the deployment of vast, cable-based systems. LF passive seismic surveys, on the other hand, require no artificial energy sources, can generate data from some of the world's most remote locations, and surveys can take place in days and weeks.

By finding new resource plays, LF passive seismic can play a crucial role in delivering data on hydrocarbon deposits, which can in turn, be further defined and developed with conventional evaluation technologies and techniques.

There are, of course, many other challenges LF passive seismic faces in helping operators generate maximum returns from the data. For example, the need to clarify any ambiguity in separating hydrocarbon related signals from acoustic signals that correlate with production dynamics–fluid flow or reservoir relaxation dynamics, for example.

Recent surveys, however, have provided the opportunity to address this question through enhanced processing techniques.

Data from synchronized recordings over an active producing field in Africa offer clear evidence of a low-frequency anomaly, distinct from the higher frequency noise that is associated with the field production activity. The field is in a remote location, where virtually all anthropogenic noise can be sourced to production-related activity.

While a low frequency anomaly observed around 2 Hz is coincident with considerable broadband noise from the field and related activities, there were a number of factors which pointed to the low-frequency anomaly being associated with the reservoir.

These factors included the low-frequency anomaly being distinct and often spectrally isolated from the general broadband noise, no persistent correlation over time between the signal level in the higher frequencies typically associated with anthropogenic noise and the signal level of the low frequency anomaly, and energy in the low-frequency band increasing more than the higher frequency noise band over the reservoir.

A North American survey encompassing both producing and exploration areas backed this. It showed low frequency based high hydrocarbon potential indicators in the exploration area–subsequently confirmed by drilling–which were similar to those indicators observed over the producing reservoir.

Enhanced Signal Processing

Signal processing research to better interpret the data is vital to the evolution of LF passive seismic. To this end, everything from normal-mode analysis, to poroelastic theory, attenuation, inversion and numerical modeling are being developed. The goal is that operators can interactively integrate low frequency data with their earth models to offer more complete views of the reservoir. LF passive seismic is on its way to being considered an integrated element of the entire reservoir characterization workflow.

This article has scratched but the surface of what is a fascinating and fast moving technology.

There is much research, for example, being done to identify the underlying physical mechanisms behind the observed phenomenon. Resonant amplification model, resonant scattering model, and the mechanisms for emitting seismic energy from a reservoir such as the oscillatory movement of fluids, all are research targets.

What is clear, however, is that LF passive seismic is maturing rapidly and is becoming an important complement to conventional seismic, and provides opportunities to generate more resource plays. Its most recent developments, such as time reverse modeling and enhanced signal processing techniques, are generating highly commercially valuable information for exploration and field development decisions. If LF passive seismic can develop as quickly in the next five years as it has in the past five, then we are in for an exciting ride. ❒

BRICE BOUFFARD

Brice Bouffard joined Spectraseis as vice president of sales and marketing in October 2007. Bouffard's brief is to oversee the delivery of Spectraseis services to its fast-growing customer base of E&P companies, and to increase market penetration in the fast-emerging field of low frequency passive seismic surveys. He has 12 years experience in a range of sales, marketing and operations management roles for Schlumberger worldwide, most recently as sales and marketing manager of Schlumberger Oilfield Services in continental Europe. Brice received an M.S. in geophysics from Institut Français du Pétrole and a B.S. in naval architecture and oceanography from the Ecole Nationale Supérieure des Techniques Avancées.