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Advances Push Geophysics Beyond 3-D Methods

Developments in geophysics technology are extending concepts into new areas of application while introducing new ideas outside the realm of conventional seismic. Examples include wide-azimuth 3-D, passive seismic, high-frequency 4-D with permanent receivers, wireless land acquisition, surgical surveys in urban areas, electromagnetics, full-tensor gravity and magnetic gradient methods, and pattern recognition using neural networks and fuzzy logic.

By Leon Thomsen and Fred Aminzadeh

TULSA–Few disciplines are more technologically proficient than exploration geophysics. Some of the most sophisticated technologies known to man are applied as a matter of routine in the processes of finding, characterizing and developing oil and gas reservoirs.

Yet, even with the advanced state of technology in exploration geophysics, innovation continues to occur at a rapid pace across all areas of the geophysical domain–from wide-azimuth 3-D marine acquisition techniques designed to image reservoirs below complex salt bodies, to next-generation wireless land sensors engineered to capture the full 3-D waveform, to ultrafast migration algorithms that enable interactive modeling in both the time and depth domains.

Many of these geophysical technology advances are particularly suited to U.S.-based independents as they become increasingly active in challenging projects such as finding and developing unconventional resource plays, ultradeepwater fields, deep reserves below 15,000 feet, as well as implementing enhanced recovery projects in mature fields, and taking on international ventures where geological analogs to domestic basins may not exist.

Increased oil and gas commodity prices have been accompanied by corresponding increases in the costs to find and produce hydrocarbons; these costs set the scale for the associated geophysical investment. If an oil and gas company is spending $X to drill a well, then it may make sense to spend 10 percent of $X on geophysical data and analysis to ensure that well is drilled in the right place and in the right way. The geophysical investment should not necessarily be in more of the same geophysics, but should perhaps be in advanced geophysics and some of the more novel techniques that are particularly suited to the challenges before the industry today, such as the Lower Tertiary oil trend in the Gulf of Mexico and anomalously-pressured gas sands onshore.

Geophysical Applications

Geophysical technology traditionally has been used to reduce exploration risk factors associated with structural and reservoir uncertainties. This has been made possible with significant advances in 3-D imaging such as prestack depth migration, and in subsurface characterization such as amplitude variation with offset (AVO) and elastic inversion. Geophysics also has been shown to be useful for reducing seal and charge risk through use of gas chimney technology. Other applications of geophysical technology have included such areas as:

- Assisting drilling by predicting overpressures and detecting geohazards;
- Revitalizing old fields through 4-D time-lapse guidance of enhanced recovery processes;
- Estimating reserves by augmenting well bore methods with geophysical methods to quantify different risk factors away from wells;
- Sequestering carbon dioxide through discipline integration; and
- Exploiting unconventional hydrocarbon resources such as shales, tight sands and coalbed methane.

Advances in geophysics and their practical applications are both "deep" (meaning new extensions of existing ideas) and "broad" (meaning new ideas beyond conventional seismic geophysics).

Examples of deep geophysical advances include wide-azimuth seismic with a rich distribution of source/receiver azimuths; passive seismic (with no source at all); frequent time-lapse seismic with permanent receivers enabling cheaper re-shoots (done at intervals of every few weeks if necessary); cable-free land seismic using radio transmission of data to a doghouse; and "surgical," nonintrusive 3-D surveys in urban areas such as the Barnett Shale play in the Dallas-Fort Worth metroplex.

Examples of broad innovations in geophysics include both nonseismic methods (i.e., new developments in electromagnetic methods that are able to sense hydrocarbon reservoirs at depth in favorable circumstances, and full-tensor gravity gradient and magnetic gradient methods that take advantage of declassified military technology) and integration with ideas outside of geophysics (i.e., pattern recognition, and of course, ideas from geology, sequence stratigraphy, petrophysics, engineering, etc.).

Wide-Azimuth Methods

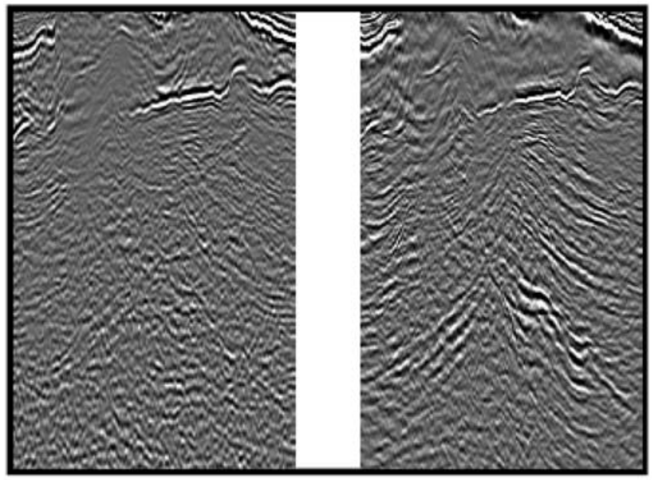
In cases where the overburden is geometrically complicated (e.g., containing an irregular salt body), the overburden acts like a complex lens, distorting the seismic wavepaths severely, disrupting illumination, and damaging the images. In such cases, it makes sense to illuminate the target from a wide variety of different azimuthal directions, so that more waves actually make it through the complicated overburden to the target and back. These surveys are expensive in absolute terms, although not in relative terms, and detailed forward modeling should precede each project. The Society of Exploration Geophysicists is organizing a joint industry project dubbed SEAM (SEG Advanced Modeling Project) to collaborate on such complex modeling projects.

In the marine context, there are a variety of ways to achieve wide-azimuth illumination. Several of these approaches were featured at SEG's annual meeting in October in New Orleans, including:

- Multiple-azimuth (MAZ) acquisition is shooting a given prospect (with conventional narrow-azimuth towed streamers and processing) multiple times from different azimuths.
- Multiboat wide-azimuth towed streamer (WATS) acquisition utilizes a conventional streamer tow augmented with additional source boats. As shown in Figure 1, this can result in a step change in image quality. The figure is from a paper presented at SEG's annual meeting in October on using WATS technology at the Mad Dog Field in the Gulf of Mexico, written by Scott Michell, Elena Shoshitaishvili, Dean Chergotis, John Sharp and John Etgen at BP. On the left it shows a cross section of a 3-D image acquired and processed using two passes (azimuths separated by 66 degrees) over the prospect. This improved the image in some places, but not here. The section on the right, acquired using the WATS technique, showed improved subsalt imaging almost everywhere.

FIGURE 1

Example Wide-Azimuth 3-D Imaging



The cross section at left is from 3-D data acquired using two passes with azimuths separated by 66 degrees, while the cross section at right was acquired from a wide-azimuth towed streamer 3-D survey.

- Autonomous ocean-bottom seismic nodes (WAN) places many ocean-bottom seismic (OBS) nodes in a coarse 2-D pattern on the seafloor, and a seismic source vessel shoots densely over this array.

On land, wide-azimuth acquisition is performed naturally, although greater attention (than is historically given) to sampling requirements may be necessary to realize the full benefits. Depending on the acquisition geometry, advanced imaging algorithms may be required to take maximum advantage of the acquisition.

Passive Seismic, 4-D Seismic

A seismic truism is, "One person's noise is another person's signal." There are several ways to use seismic noise to advantage. Suppose, for instance, that the objective is to monitor a hydrofrac process by detecting and locating the microseisms triggered by the injection, without being tied to observations from only a nearby well.

One way to do this is to lay out seismic receivers on the surface and simply turn them on, recording the microseismic events among the noise. By beam-forming the array in different directions (like shining a flashlight in different directions into a dark room), and stacking the data with a known velocity function, the microseisms can be located under favorable circumstances to reveal the regional extent of microseismicity caused by the hydrofrac operation.

Suppose that, instead, the goal is to image the reflectors inside the earth using random seismic noise. Each bit of noise, recorded by a geophone, reflects back down into the earth off a scatterer (Figure 2, from a paper presented at the 2006 SEG annual meeting by Detlef Hohl and Albena Mateeva with Shell International E&P) and back to another surface geophone (very weakly, of course). By cross correlating and stacking the recorded noise, a signal emerges. The resulting images are inferior to controlled-source images, but offer encouragement that they may lead to truly useful results in some contexts, especially where sources are very expensive.

It is well understood that repeated seismic surveys over a producing field, when properly acquired and processed, can reveal differences in hydrocarbon saturation and pore pressure caused by production during the time interval between seismic re-shoots. Such "4-D differences" can help the operator to understand the details in subsurface plumbing of a field, and can help to properly plan the next well. The problem is that the expense of such re-shoots can mean that they are acquired infrequently, and the careful processing required may consume many more months, thus limiting their value.

These problems can be avoided in offshore fields if the seismic receivers are permanently installed on the seafloor, and the 4-D re-shoots are conducted with a source boat only. The small size of the source boat means re-shoots are cheap, and the permanently installed receivers mean than survey-related artifacts are greatly reduced. These factors work together to enable the frequency of re-shoots to be reduced substantially.

For example, at the Valhall Field in the Norwegian North Sea, seven re-shoots have been conducted over 35 months, resulting in a seven-frame "movie" of subsurface changes in seismic response, according to a paper presented at the 2006 SEG annual meeting by Ruth Pettersen at the Norwegian University of Technology & Science, and Olav Barkved and Nirina Haller at BP Norway. Careful economic analysis prior to launching the program predicted that the (counterintuitive) front loading of expenses for the permanent receivers would be cost effective in the long term, and this prediction is being confirmed.

Land Seismic Systems

The jug hustler's task is considerably lightened, so to speak, if the miles of seismic cable in a 3-D survey are replaced by radio transmission. This topic, with its many ramifications, was thoroughly discussed by Robert Peebler one year ago in *The Reporter* ("Converging Technologies Drive Land Seismic Revolution," January 2006 issue), and need not be repeated here, except to report that Peebler's vision of a new era of digital, full-wave seismic land surveys using wireless micro-electro-mechanical sensors is being implemented rapidly in the field. The results of this paradigm shift in land seismic will be one of the featured topics at the 2007 SEG meeting Sept. 23-28 in San Antonio.

In congested urban areas, it is common that the acquisition design must be compromised in order to respect the rights of the inhabitants. There are a number of examples in various regions, but a paper at the SEG 2006 annual meeting (authored by Thomas Bowman with Abundant Resources, Mark Russell with Ascend Geo, and Wayne Woodside and Steve Culpepper with Trend Technology) describes how rapid acquisition of small 3-D seismic surveys in urban areas can be accomplished with modern geophysical acquisition and processing techniques using a case study from the Barnett Shale play in the Fort Worth Basin.

FIGURE 2

Passive 3-D Imaging using Random Seismic Noise

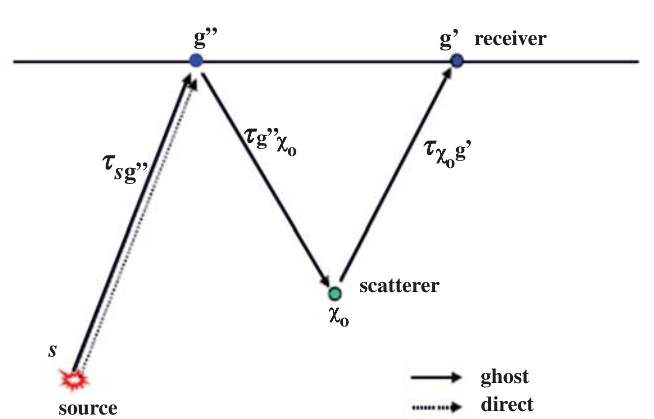
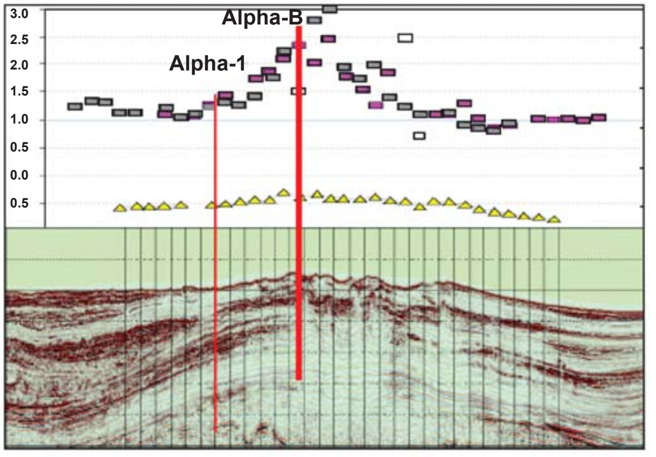


FIGURE 3

CSEM Survey Example (Deepwater Malaysia)



EM, Magnetics And Gravity

Electromagnetic (EM) methods have long been confined to the shallowest subsurface investigations. Recently, however, it has been shown that low-frequency EM waves can penetrate down to more than two kilometers sub-seafloor, revealing the presence of deep, electrically resistive formations. Under many geological conditions, the most plausible resistors are hydrocarbon reservoirs.

In practice, controlled source electromagnetic (CSEM) surveys use a deep-towed dipole antenna (radiating a continuous low-frequency square wave) and multiple autonomous sea-bottom nodes, receiving both electric (inline) and magnetic (crossline) fields deployed at ~1.0-kilometer intervals along a line on the seafloor (2-D style). The useful source/receiver offsets are sufficiently long that the water-borne arrivals are attenuated, but not so long that the perturbation of the subsurface propagation–by the target–falls below the noise.

In combination with seismic images, these data can be inverted to yield a direct hydrocarbon indicator (DHI) that has the resolution of the seismic image, and is especially useful where seismic DHI (using seismic amplitudes) is problematic.

Figure 3 is an example from a deepwater project offshore Malaysia, as presented in a paper at SEG's 2006 annual meeting (C.K. Choo, et. al., with Shell International Exploration & Production/PETRONAS management unit). The lower part of the figure shows a seismic structure with bright amplitudes on the flanks, into which an unsuccessful well (Alpha No. 1) had been drilled. The crest of the structure was not well imaged seismically. A subsequent CSEM survey over the structure showed a strong anomaly (upper part of the figure) over the crest itself, which led to a second well–the Alpha No. 2–being drilled into the seismic dim spot, discovering a substantial accumulation of full-saturation hydrocarbons.

The CSEM technique is best established in deep water where water depth is at least half the subsurface depth of the target, although several new ideas are emerging to avoid this restriction. Four technical sessions at the 2006 annual meeting explored these ideas, and related techniques in bore holes, on land, and using natural (“magnetotelluric”) sources.

If the gradient in the gravity or magnetic field is measured, instead of the field itself, the measurement can be robust against many sources of noise. The cost of this choice is that the gradient measurement has intrinsically less penetration into the subsurface. However, with modern, exquisitely sensitive instrumentation, the depth limits can be pushed down far enough so that the data investigate targets of real interest.

For example, Figure 4 is from another paper presented at the 2006 SEG annual meeting on using full-tensor superconducting quantum interference device (SQUID) magnetic airborne gradiometer systems on helicopters and fixed wing aircraft (R. Stolz, et. al., with the Institute for Physical High-Technology in Jena, Germany). It shows the vertical derivative of one horizontal component of the magnetic field, clearly revealing how one fault possesses a magnetic character quite different from the others. With the other tensor components also measured, it is straightforward to compute the various properties of the field which are independent of the (arbitrary) choice of coordinate system.

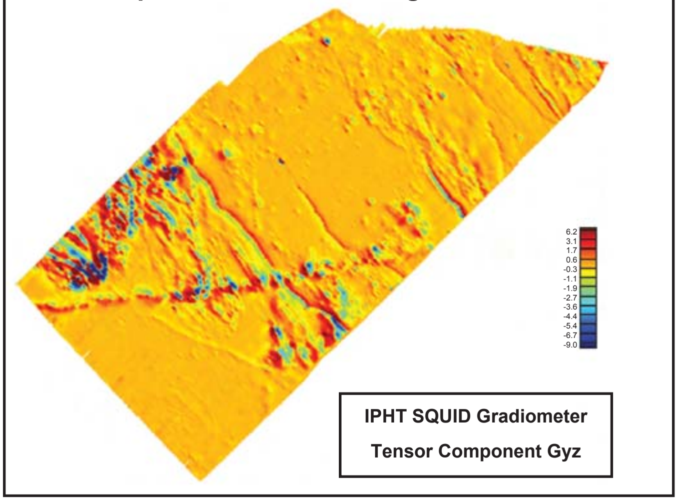
Pattern Recognition

Normally, geophysicists look for anomalies within otherwise regular patterns. In many situations, conventional statistical means are inadequate to tackle practical problems, and nontraditional methods such as neural networks, fuzzy logic, complexity theory, genetic algorithms, chaos theory, and finger printing are employed. These tools have proven useful in many complex geologic settings, such as fractured reservoirs, where simplifying assumptions such as homogenous medium and “convolutional models” are not valid.

Fuzzy logic and other nonlinear methods can describe shapes and structures with realistic geologic complexity. These techniques can push the boundaries of seismic resolution, allowing smaller-scale anomalies to be characterized. In one example of such application, a paper presented at the 2006 annual meeting detailed how a neural network was used in conjunction with fuzzy logic to high grade prospects containing hydrocarbon saturated reservoirs.

FIGURE 4

Example of Full-Tensor Magnetic Gradients



This was accomplished by using fuzzy logic to formulate general rules of thumb, derived from rock physics data and interpreter’s knowledge and experience. Integrating such linguistic rules with a neural network ranking (of the most relevant attributes for prospect risking) improves the process when compared to conventional “thresholding” methods. Figures 5A and 5B (from the paper by Fred Aminzadeh and Friso Brouwer with dGB-USA) demonstrates the results of applying this hybrid method in a North American onshore field, where the strength of each method is combined. The “fuzzy membership grade” for high gas saturation (Figure 5A) versus moderate gas saturation (Figure 5B) is shown in hot colors.

3-D Sequence Stratigraphy

New geophysical techniques and tools are also emerging to further enhance interpretation capabilities. One such example was shown at SEG’s 2006 annual meeting (Paul de Groot, Geert de Bruin and Nanne Hemstra of dGB Earth Sciences) where a 3-D “Wheeler transformation” was used to flatten horizons. In the Wheeler domain, seismic data (or derived attributes) are flattened along chrono-stratigraphic lines, while honoring truncations and nondepositional and erosional hiatuses. This allows more efficient 3-D sequence stratigraphic analysis and system tract interpretation.

FIGURE 5A

Hybrid Method to High Grade Prospects (High Gas Saturation)

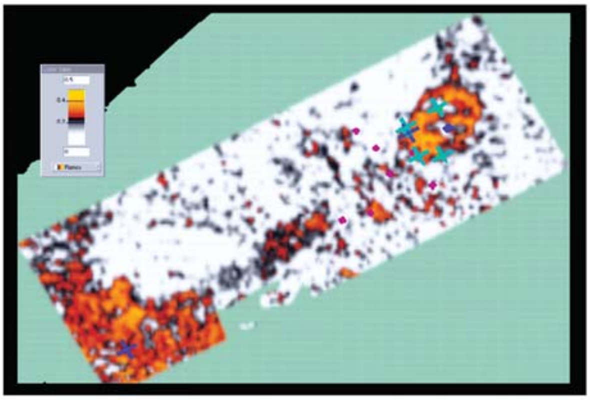


FIGURE 5B

Hybrid Method to High Grade Prospects (Moderate Gas Saturation)

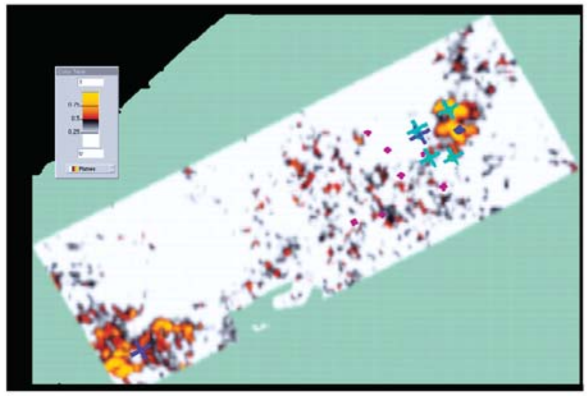


FIGURE 6

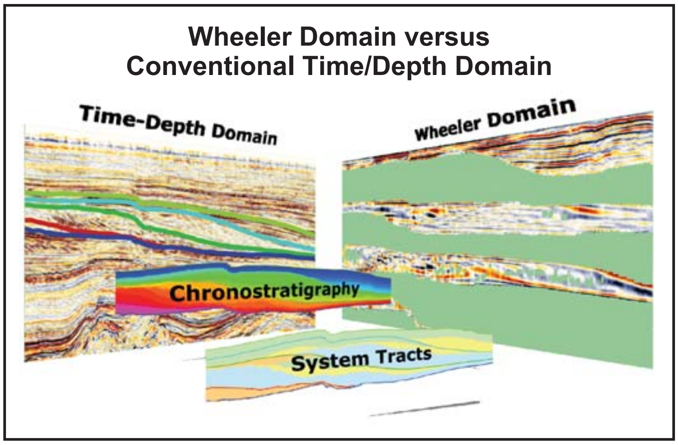
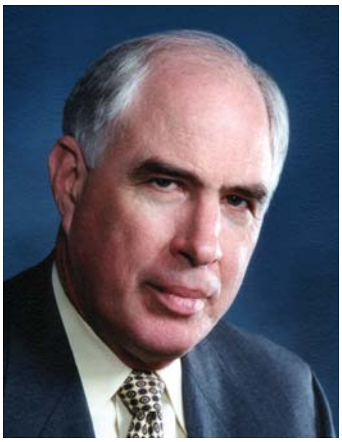


Figure 6 shows the conventional seismic data in the time (or depth) domain, next to its Wheeler transformation, recreating geologic times (flattened horizons). The interpretation in this domain is much easier. For example, a time slice in the 3-D Wheeler domain is equivalent to a horizon slice of the 3-D seismic volume. The figure also shows cross sections of chronostratigraphy and system tracts for a given stratigraphic package.

All of the geophysical technologies referenced in this article present a deep and broad array of technical options available to independents to help them understand their prospects. In deciding which of these technologies–both classical and modern–may be useful in any particular context, it is important for the operator to consider both the costs and the benefits of the technology. In this analysis, access to geophysical expertise is crucial, and SEG can help to provide it.

SEG is the largest organization of applied geophysicists in the world, but its historical roots are in the United States, where 40 percent of its members work for independents, majors, service companies, universities and agencies. A major focus of SEG activity is fostering advanced geophysical technology, helping to push these advances beyond their origins into new areas of application through publications and meetings. We urge every reader of *The Reporter* to access this information through individual or corporate membership in SEG. ❒



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Leon Thomsen is 2006-07 president of the Society of Exploration Geophysicists, and principal geophysicist in BP's exploration & production technology group in Houston. Holding a B.S. in geophysics from the California Institute of Technology and a Ph.D. from Columbia University, Thomsen held academic appointments at CNRS in Paris and California Institute of Technology, followed by tenured faculty positions at the State University of New York. In 1980, Thomsen joined Amoco's Tulsa Research Center, and then Amoco worldwide exploration in 1995. He moved to BP's exploration & production technology group after its merger with Amoco in 1999. Thomsen has led technical development through innovation in polar anisotropy, azimuthal anisotropy, azimuthal AVO, converted-waves, life-of-field-seismic, and pore-pressure prediction. He was an early recipient of an SEG academic scholarship (1960-64), and received SEG's Fessenden Award in 1994. He served as an SEG distinguished lecturer in 1997, and as an SEG/EAGE distinguished instructor in 2002. He is an honorary member of the Geophysical Society of Houston and of EAGE. He served SEG as vice president in 2003-04, and became an SEG Foundation trustee associate in 2004. He was appointed a foreign member of the Russian Academy of Natural Sciences, and received its Kapitsa Medal in 2004.

FRED AMINZADEH

Fred Aminzadeh is president-elect of the Society of Exploration Geophysicists, and president and chief executive officer of dGB-USA in Houston. Previously, he worked for 17 years at Unocal in technical and management positions. Aminzadeh has served on the U.S. National Research Council's Committee on Seismology, and is a member of Azerbaijan Oil Academy and Russian Academy of Natural Sciences. He also has served as chairman of SEG's Research Committee. He has given many industry courses, keynote speeches and technical talks on various aspects of seismic technology in more than 25 countries. He holds three patents and has authored 11 books on different aspects of the geosciences, including modeling, seismic attributes, seismic processing, AVO, gas chimneys, absorption and reservoir characterization. Aminzadeh's newest book introduces applications of advanced computing techniques such as neural networks, fuzzy logics and genetics algorithms in the oil and gas industry. He holds a Ph.D. from the University of Southern California.