Challenges Direct Future Of Geophysics

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SUGAR LAND, TX.–Geophysical technology has come a long way over the last four decades. These advances, particularly in three-dimensional seismic, have been credited for drastically improving exploration risk and reducing finding cost. Most recently, geophysics (with the advent of time-lapse or 4-D seismic), in conjunction with geostatistics, has begun playing a role in reservoir management and production optimization. As the new millennium begins, it is becoming more apparent that geophysical technologies will make an even larger impact on the bottom line for oil and gas companies in the years ahead.

With these great opportunities, however, also come even greater challenges in addressing practical problems in the modern oil and gas field–problems that are continually increasing in complexity. To rise to these challenges, the capabilities of geophysics–properly integrated with petrophysical, geological, and reservoir and computing technologies–will have to be stretched to new boundaries. This will require going beyond the conventional methods with their intrinsic resolution and accuracy limitations. Maintaining the flow of innovations will require demonstrating their economic value in a commodity-based industry where reducing cost has appeared to be the only reliable way to increase profit margins over the last few years.

Key Practical Problems *Pushing the geophysical limits*

The need for even greater advances in geophysical technology is necessitated by a number of practical problems. What are the most challenging problems with the largest potential financial impacts in the exploration, drilling and production industry? Table 1 identifies 10 of the most challenging problems that

"The capabilities of geophysics–properly integrated with petrophysical, geological, and reservoir and computing technologies–will have to be stretched to new boundaries . . . Although incremental improvements will take place in various steps of geophysical processing, analysis and interpretation, the real breakthroughs will come from unconventional measurement tools, alternative processing methods, true integration of disciplines, and quantitative interpretation ideas based on non-traditional mathematical and statistical methods."

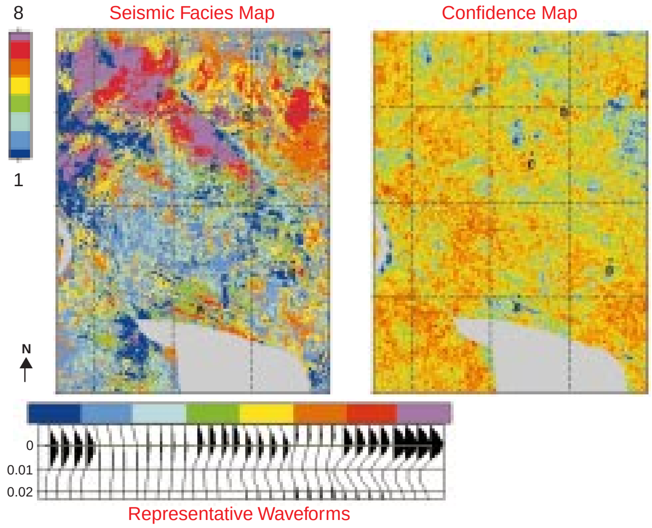
TABLE 1

Major Geophysical Challenges

1. Accurate positioning and hydrocarbon detection of subsalt and salt flank plays.
2. Characterization of thinly-laminated sand/shale sequences.
3. Deep exploration and accurate depth imaging.
4. Distinguishing "fizz-water" and non-hydrocarbon gas from commercial gas.
5. Distribution of faults, magnitude of throw & type (sealing versus non-sealing).
6. Environmental remediation using geophysical techniques.
7. Exploration in difficult data areas (gas chimney, mud volcano, karst, etc.).
8. Fluid and permeability prediction, detection and monitoring.
9. Fractures: Type, orientation, frequency and connectivity.
10. Predicting and evaluating over-pressured reservoir zones.

FIGURE 1

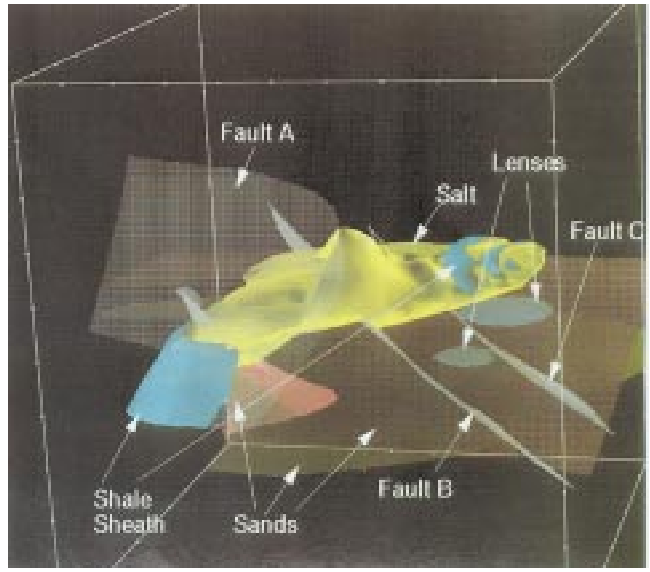
Example of Using Neural Networks in Quantitative Interpretation



Note: Courtesy of dGB

FIGURE 2

Salt Model Used to Simulate the SEG/EAGE Model



geophysical technology can help solve. These problems have been selected based on how much financial gain could be realized if they were successfully solved, and the degree to which geophysics and related technologies can contribute to these solutions. The challenge is to not only push the limits of today's geoscience technologies, but also to adapt new technologies from outside the oil and gas industry to make technological breakthroughs possible.

These are indeed real-life oil field problems, and all provide the necessary economic incentives for more intensive research and development. All 10 of these problems fall into two major categories where geophysical technology has proven useful: structural problems in nature, or reservoir property-related issues. The key questions are related to discovering new methods to create accurate images of complicated geologic structures in depth, and predicting reservoir properties such as fluid type, porosity and lithology from the character and attributes of seismic and other geophysical data.

The tools to solve structure and reservoir-type problems have evolved over the years somewhat in parallel. One of the main issues in recent years has been the ongoing attempt to narrow the apparent differentiation in the those methodologies. Thanks to the advances in computer hardware and software, it is no longer necessary to make simplistic assumptions about structure to solve the reservoir property prediction problem. True amplitude migration, preserved amplitude processing, and elastic wave imaging and anisotropic migration are some of the tools that enable geoscientists to accomplish this.

Likewise, there is no need to make restrictive assumptions such as homogenous medium, layered models or constant attenuation to address imaging problems. Vector exploration, wavelet transformation, prestack depth migration and random medium theory are some of the tools that will be used to solve imaging problems. In short, the division between imaging and res-

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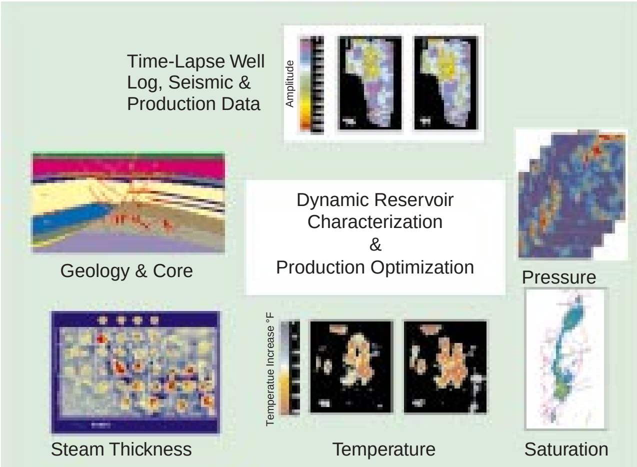
MIKE BAHORICH, vice president of E&P technology at Apache Corporation and first vice president of the Society of Exploration Geophysicists: "The concepts behind many of tomorrow's helpful innovations are known today, but will become widespread as costs come down. Multicomponent seismic utilizes converted shear waves in addition to compressional waves and enables geoscientists to view reservoirs obscured by gas clouds because shear wave velocities vary less and generate less scattering than compressional waves. Shear wave information can also help distinguish hydrocarbon bright spots from strong reflections caused by lithologic changes. Advances in computing will enable more widespread use of 3-D prestack depth migration and 3-D seismic visualization. Seismic acquisition will become more sophisticated with the advent of digital geophones and recording systems that route information around cable breaks much like a computer network."

WILLIAM BARKHOUSE, strategic directions coordinator for Exxon-Mobil and president of the Society of Exploration Geophysicists: "Truly one of the exciting things about geophysics will be its impact with new full quantitative description of various reservoir rock properties and fluid contents. Furthermore, the primarily measurement-based geophysical methodologies of the past will move toward more predictive and model-based simulation capitalizing on the available computer power. The combination and convergence of these two new technology trends will lead to a better description of subsurface structure, rock and fluid properties. A significant business impact is the further reduction in finding and producing costs."

DR. RICHARD D. CHIMBLO, director, GTRI, Houston Advanced Research Center: "New technology will change the way we work, and the way we work will direct the development of new technology. This may sound a bit like the 'chicken and egg,' but as new technology improves accuracy and reduces cycle time, the technology user will find new activities to undertake to make his or her analysis even more accurate and comprehensive. Once these new activities or processes are identified to the technology designer and developer, a new wave of technology will be

FIGURE 3

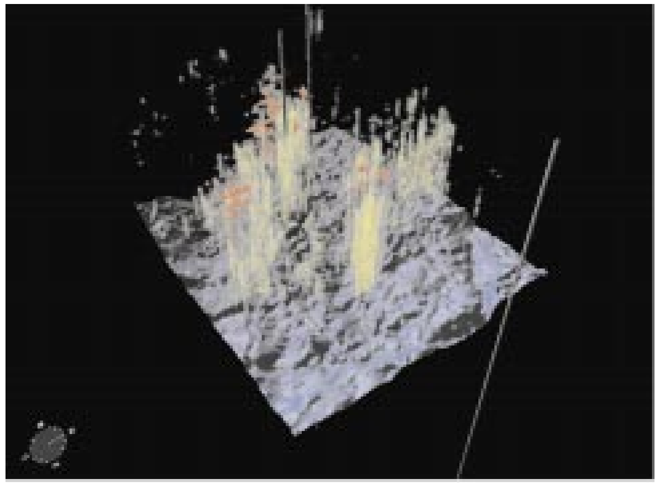
Dynamic Reservoir Characterization (with Data and Discipline Integration)



Note: Courtesy of 4th Wave Imaging Inc., dGB-USA and FACT Inc.

FIGURE 4

Gas Chimney Visualization with Interpreted Surfaces



Note: courtesy of dGB and Statoil

ervoir characterization approaches, which has largely been necessitated by limitations imposed by computer resources and their related costs, will be eliminated.

Major Geophysical Trends *Future breakthroughs*

What are major geoscience technology trends for the first decade of the new millennium and beyond? What are the next probable technology "breakthroughs" following the advances in seismic stratigraphy and 3-D seismic in the 1970s, '80s and '90s? As the industry's problems become too complex to rely only on one discipline, is it moving any closer to true cross-disciplinary integration? Can new geophysical tools help operators reduce risk and manage uncertainty more effectively?

Table 2 highlights 10 areas where expectations are high for technological advances in geophysical applications. Innovations in these areas are expected to provide answers to many of the challenges listed in Table 1, and bring the industry closer to real solutions.

The first area is broader use of traditional and unconventional

TABLE 2

New Technology Trends in Geophysics

1. Broader use of traditional and unconventional statistical methods.
2. Depth imaging and modeling.
3. Dynamic reservoir characterization.
4. Linking seismic patterns and attributes to physical rock properties.
5. New seismic acquisition methods.
6. Non-linear processing for multiples & near-surface heterogeneities.
7. Data processing and analysis in the compressed domain/"data mining."
8. Seismic and logging while drilling and real-time imaging.
9. True integration of data, knowledge and disciplines.
10. Visualization techniques/immersive technology.

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introduced to further improve productivity and results. Perhaps more time should be spent analyzing and documenting the processes of how we work and what we do in order to optimize these activities based on pre-determined criteria (metrics, objectives, etc). In the future, all E&P companies–large and small–will be equalized by the ownership of affordable technology. The true differentiation will be based on the best use of technology and its application to the most efficient processes."

DR. RAYMOND LEVEY, director, the Energy & Geoscience Institute at the University of Utah, and member of the American Association of Petroleum Geologists' Research Committee: "The value of research for the industry is increasing, dependent on the utilization of robust data sets. In the new business climate of asset management, corporations are divesting technologies after a company has invested millions of dollars in R&D. The corporate world is clearly focused on 'better to buy than to build.' An effective strategy for research organizations is to capture these outsourced technologies, whether in reservoir characterization or exploration for further development and application. For example, EGI inherited Amoco's worldwide biostratigraphic composite standards for 120 basins around the world, which was developed with a 40-year investment of more than $100 million. These technologies, once only available to a single company, are now available to more than 30 member companies, thereby totally flattening the playing field and allowing a wider use of technologies."

DR. DON PAUL, executive vice president of Chevron Corporation for technology & environmental affairs**:** "Seismic processing and interpretation technology continue to ride the curve of exponential growth in computational capability and connectivity. Virtually all work is done via the Web, with interactive, on-demand access to applications, compute engines, and data becoming common. The Web becomes the key enabler by reducing costs, providing worldwide access to expertise and technology, and by supporting adaptation to local exploration and reservoir manage-statistical methods. As oil and gas companies attempt to explore and produce from more complex reservoirs, the conventional deterministic approaches are no longer adequate. Statistical methods will be in higher demand in at least three respects:

• Integrating information from various sources with varying degrees of uncertainty;

• Establishing relationships between measurements and reservoir properties; and

• Assigning risk factors or error bars to predictions.

Today's deterministic processing and interpretation ideas will give way to stochastic methods, even if the industry has to rewrite the book on geophysics. That is, using wave equations with random coefficients to describe subsurface velocities and densities in statistical terms, thereby enabling a better description of wave propagation in the subsurface–particularly when a substantial amount of heterogeneity is present. More generalized applications of geostatistical techniques will emerge, making it possible to introduce risk and uncertainty at the early stages of the seismic data processing and interpretation loop.

Furthermore, where conventional statistical means are deemed inadequate to tackle practical problems, non-traditional methods such as neural networks and fuzzy logic will be employed. Figure 1 demonstrates the use of neural networks in generating facies maps through effective segmentation of seismic patterns. It also shows the confidence level in the accurate segmentation.

The second area is depth imaging and modeling, where recreating subsurface structure in depth using geophysical measurements made in time continues to be of significant importance. The current state of the art for depth conversion is still far from ideal. New methods of 3-D prestack depth migration with anisotropy effects and elastic waves are being developed. Accurate velocity models using a combination of surface and cross-well tomography, and aided by three-component measurements are also being investigated.

Given the need to tackle imaging and reservoir property problems in tandem, processing methods with preserved amplitude and other attribute information are gaining in popularity. Three-dimensional modeling is expected to play a bigger role in designing seismic surveys and validating depth imaging and reservoir characterization. To accomplish that, the elastic version of 3-D models will have to be simulated. For example, the acoustic model of Figure 2 that was used to generate the SEG/EAEG 3-D salt model, will have to be revised to include more realistic subsurface properties–including elastic, anisotropy and attenuation parameters.

Dynamic Characterization *New role for seismic methods*

Accurate reservoir description is crucial for optimally developing, managing and producing a reservoir. Dynamic reservoir characterization using time-lapse seismic, well log and production data is one of the significant areas of emerging new technology. The potential of this technology lies in the ability to merge geophysical, geological and reservoir engineering data in a natural way to significantly enhance the understanding of a producing reservoir.

Therefore, seismic methods will move from being primarily an exploration tool to a reservoir delineation and monitoring tool. This allows the operator to manage and produce a reservoir more effectively, increasing its economic life cycle while reducing production costs. To fully realize the benefits of this technology, the industry first has to develop cost-effective and high-quality repeat seismic, production, well log and petrophysical data–including necessary tools such as permanent sensors. Better understanding the underlining physical properties of the reservoir, combined with recognizing the intrinsic power and limitations of different data types for predicting, is a major requirement.

To achieve the desired accuracy and ensure that all of the information available at any given time is incorporated in the reservoir model in an efficient manner, new data mining model updating methods need to be employed. Figure 3 shows different elements of dynamic reservoir characterization. As new data become available, they are integrated with the prevailing information (including the current reservoir model) and necessary updates are made to the model.

Pre- and poststack seismic attributes have proven useful for direct hydrocarbon detection. The new generation of attributes will attempt to link seismic patterns to the underlining characteristics of the rock and reservoir properties. Higher-order spectral analysis techniques, time frequency analysis and wavelets, in conjunction with different prestack attributes and those derived from three-component data, will make it easier to draw conclusions about the properties of a reservoir from the charac-

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ment requirements. More sophisticated human-machine data interfaces will develop well beyond the capabilities of today's visualization centers. Advanced measurement systems and device-to-device interactions create a new flood of data about reservoirs, wells and operating facilities. Seismic imaging technology continues to improve interpretation reliability in complex imaging environments, such as subsalt plays, as interactive 3-D depth imaging and velocity modeling becomes standard. Multi-component and time-lapse measurements grow in use for the reservoir management business, driving down unit costs, expanding application and stimulating advances in imaging and interpretation technologies. Next-generation earth modeling technology incorporates quantitative representations of geological processes and stratigraphic variability at the reservoir scale. The shared earth model becomes the centerpiece for end-to-end technology integration from seismic imaging through reservoir and well performance simulation. As cycle time and costs for reservoir modeling and prediction fall, integration and feedback with real-time operational data become practical."

Dr. KURT M. STRACK, president of KMS Technologies and former chief scientist of Western Atlas: "The past decade has seen the emphasis being the integration into a unified model. This was driven mainly from the bore hole and reservoir. The advances in visualization have moved the driver seat to the seismic data set. That means that the next decade will be guided by integrating all reservoir data directly at the seismic data set level. On one side, the reservoir model, which matches the shared earth model on the other. Solutions for the major challenges already exists, but are not commonly available or not yet part of common practice. This makes training/education, with the goal of better utilizing new technologies, a key objective. Parallel to multi-component sensors for the surface, a large number of variations of bore hole seismic, cross-well seismic and electromagnetics, and downhole sensors–in particular permanent ones–will become more common. The permanent reservoir monitoring applicater and attributes of seismic data.

Figure 4, interpreted by Roar Heggland of Statoil, is an example of using a combination of different attributes and neural networks to help determine a gas chimney and the corresponding gas migration (a feature article by the author and his colleagues on detecting gas chimneys using Statoil/dGB's patented method, including case histories from the Gulf of Mexico, will appear in the February 2000 issue of *The American Oil & Gas Reporter*).

Acquisition And Processing *Next-generation technologies*

The fifth area for future technological advancement is seismic acquisition methods. In the future, advances in data processing and interpretation will have to be combined with new acquisition tools with higher data resolution and more sensitivity to reservoir properties. The cost effectiveness of new acquisition tools should keep pace with their resolution. Ocean-bottom seismic (OBS) surveys with four-component (4-C) recording will be more widely used as their cost and reliability improves. Deepwater exploration will be one of the main beneficiaries of this technology.

The use of time-lapse surveys with OBS and their land counterparts will also increase as their calibration and repeatability are improved, enabling operators to monitor the dynamics of a reservoir. Vertical cables, nine-component data acquisition (with three-component sources and receivers), gradiometers, multi-beam bathymetry, cross-well seismic, cross-well electromagnetic, and bore hole gravity and nuclear magnetic resonance (NMR) tools will also be widely used to address the problems in Table 1.

The sixth area for future technological development is nonlinear signal processing. Although seismic signal processing has advanced tremendously over the last four decades, the fundamental assumption of a "convolution model" is violated in many practical settings. Among these are highly heterogeneous environments, very absorptive media (such as unconsolidated sand and young sediments), fractured reservoirs, mud volcano, karst and gas chimney. In the environments, the industry must turn to non-linear processing and interpretation methods.

Neural networks, fractals, fuzzy logic, genetic algorithms, chaos theory and complexity theory are among the possible frameworks around which the next generation of seismic signal processing and analysis tools will be developed. These tools can create stable and robust behavior in very complex, high-dimensional systems with a high degree of freedom.

The highly heterogeneous earth model that geophysics attempts to quantify is an ideal place for applying these concepts. The subsurface lives in a high-dimensional space (the properties can be considered as the additional space components), but its actual response to external stimuli initiates an internal coarse-grain and self-organization that results in a low-dimensional structured behavior. Fuzzy logic and other non-linear methods can describe shapes and structures generated by chaos. These techniques will push the boundaries of seismic resolution, allowing smaller-scale anomalies to be characterized.

Data compression methods have been introduced in light of the tremendous growth of data volumes in the 1990s. This data explosion will be further intensified as operators explore for deeper targets, use much larger offsets with lower sampling rates, and acquire time-lapse and multi-component data. As a result, data compression will be of increasing significance to data transportation and storage.

Yet, the biggest impact of advances in data compression techniques will be realized when geoscientists have the ability to fully process and analyze data in the compressed domain. This is another focus area for future technological development, and will make it possible to carry out computer-intensive processing of large volumes of data in a fraction of the time, resulting in tremendous cost reductions.

The eighth area for future technological development is seismic while drilling (SWD), whereby seismic data are generated using drill bit and production noise. As SWD advancements continue, it is expected to become more widely applied. SWD data, combined with data logged while drilling and producing, will provide useful information to carry out real-time reservoir characterization and imaging. This will further the benefits of horizontal and oscillatory drilling, reducing costs and increasing effectiveness.

New Form Of Integration *More than a buzzword*

The true integration of data, knowledge and disciplines is a key area for the future. The integration of data, knowledge and disciplines has to take place at different levels. Multidisciplinary approaches that involve integrating data and intelligence of dif-

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tions will also cause a growth of local small consultancies serving the assets teams. At the same time, the distance between equipment manufacturers and final users will become smaller in an effort to enhance the value chain and reduce cost."

DR. LEON THOMSEN of BP Amoco and chairman of the SEG Research Committee: "BP Amoco thinks that the remarkable advances in exploration effectiveness of the last decade are the result of several factors. Among these, the chief technological factor was the maturation of 3-D exploration, with associated improvements of imaging technology. These factors have doubled the finding rate per dollar spent in exploration; It is clear that the industry, and the geophysical profession, have a lot here to be proud of. However, there have been only marginal improvements in the effectiveness of the exploitation of hydrocarbons already found. It is here that we feel that the greatest future advances will be made, and we intend to be industry leaders in this arena. We will focus our seismic effort particularly on high-resolution imaging of lithology and fluids, and on production-induced changes in the reservoir. These seismic advances will be fully harvested through tight integration of geophysics, geology and reservoir engineering. Furthermore, we anticipate that intelligent wells (i.e. bore hole sensors linked to downhole flow control), coupled with frequently repeated 4-D seismic surveillance (perhaps using permanently-installed seabed 4-C recorders) are likely to revolutionize reservoir management. These advances will be particularly important for the successful exploitation of the large deepwater discoveries, because mistakes and interventions are so costly in that deepwater environment."

DR. RON WARD of Burlington Resources' technical services group and the general chairman of SEG's 1998 annual convention: "Seismic technology will impact both the exploration for hydrocarbons and the management of hydrocarbon recovery from reservoirs, with its role increasing more rapidly in optimizing hydrocarbon recovery from newly-discovered reservoirs. Among the seismic technologies having the greatest impact are ferent types, scales, uncertainties and resolutions for reducing risk will be more of a necessity than a corporate buzzword. The walls built around classical disciplines such as reservoir engineering, geology, geophysics and geochemistry are becoming more permeable. The data base, data fusion and data mining methodologies will have to cut across various disciplines.

Consequently, today's "integration," which is based on the integration of results, will give way to a new form of integration: the integration of disciplines and knowledge. Ideally, these new integration techniques will be equipped to handle data fusion problems with data sets involving wide ranges of uncertainties and scales. Achieving the true integration objectives will require professionals with working cross-disciplinary knowledge, and perhaps many more generalists than are now available. Figure 4 demonstrates true integration in the process of generating and updating a reservoir model.

The final area for future technology development is advanced visualization techniques, which will help monitor the impact of data and information integration at various steps of the process. Advanced visualization tools and immersive 3-D visualization technology allow more effective data representation, integration of different types of data, and increased productivity of multidisciplinary teams. Figure 1 shows how different data (seismic velocities and the geologic model) can be displayed effectively.

Furthermore, to make the whole operation more efficient, intelligent links between different disciplines need to be established to allow the proper flow of information, data and decision making between various components. Integrating the different disciplines could be one major oil and gas application for artificial intelligence and neural networks.

Although incremental improvements will take place in various steps of geophysical processing, analysis and interpretation, the real breakthroughs will come from unconventional measurement tools, alternative processing methods, true integration of disciplines, and quantitative interpretation ideas based on nontraditional mathematical and statistical methods.

Many of these geophysical breakthroughs will undoubtedly adopt, complement or build on technologies developed in other disciplines–both within the oil and gas industry and outside of it. Information technology, computing, statistics and physics are only a few of the disciplines from which the industry can benefit, and hopefully, to which it can contribute.

As true integration becomes more of a reality, a balance will need to be established between general geophysical practitioners and geophysical specialists. Since the complexity of the industry's problems will continue to grow, a reasonable link between the physics, or the ground truth, and the data (statistics) and geophysical models will be a necessity. Hybrid methods that combine physical- and statistical-based methods will play a key role in accomplishing this task. ❒

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wave-equation 3-D prestack depth migration, utilization of four-component P and converted wave data, and illumination modeling of seismic acquisition both before and after surveys are acquired. In the area of reservoir characterization and management, offset-dependent inversion techniques will find increased use. Permanent surface and bore hole geophone arrays will provide continuous differential seismic data to manage EOR operations."

AGOSTINO MACCAGNI, vice president of exploration, Agip Petroleum: "The progress made by geophysics is impressive, but there remains a lot of space for further improvements. Depth imaging of complex geological structures is far from accurate, and a beneficial contribution to reduce the errors of the present methodologies could come from a deep integration with other geophysical measurements (i.e. gravity, electric and magnetic fields) and with geological modeling. Measuring the uncertainty of the description of the earth model is another topic in which research could play a big role, and it is a very important issue because of the connection with risk evaluation and the managerial decision process. The integration of discipline and knowledge also needs a change (with respect to) people's attitudes. The industry has to train a new breed of geoscientists able to work together and understand the particular problems related to each phase of the cycle–from exploration to development to production."

LUC SCHLUMBERGER, executive vice president of technology, CGG Americas: "Seismic data are the only ones that cover all of the reservoir volume; the only ones available to characterize the reservoir between wells. We are only beginning to relate seismic parameters to petrophysical properties such as porosity, shaliness, fracturation intensity and main direction. Soon, it will be possible to quantitatively interpret the results of repetitive seismic surveys in order to act on the way the reservoir is produced. Ultimately, sensors of all kinds–permanently installed at various depths in all wells–will detect any changes in pressure, saturation and the composition of fluids in the proximity of the wells, and will deliver early the information necessary to take corrective measures. This will result in lower production costs, higher production rates and higher recovery."