TECHNOLOGY Locations: Worldwide, onshore and offshore

3-D Seismic

SUMMARY

Advances in 3-dimensional (3-D) seismic technology over the past 25 years have enabled oil and gas producers to evaluate prospects more effectively, drill fewer exploratory wells, and develop fields more efficiently. The result is decreased environmental impact and increased profit. To establish a visual orientation of the subsurface without drilling, energy waves directed downward through the earth's strata are reflected off the rock layers and sent back to the surface. The resulting data undergo complex processing and interpretation and provide explorationists with a 3-D visual characterization of the subsurface's geological features. This allows detailed assessment of the opportunities and risks of developing a reservoir, an increasingly important capability as the search for resources pushes into new exploration frontiers, such as deepwater and subsalt formations.

BLUEPRINT ON TECHNOLOGY

Two decades of successively better geologic interpretation demonstrate tangible results and environmental benefits

From 2-D to 3-D technology

Until the 1960s, developers had to rely on inaccurate, low-resolution analog data in planning their exploration investments. In the 1970s, improved 2-D seismic techniques enabled explorers to characterize subsurface opportunities with greater effectiveness. Now, with 3-D seismic, they can establish more accurate 3-D characterization of geologic structures. Reservoir characterization is key across all stages of a hydrocarbon field's life. Seismic information, critical during the exploration and appraisal phase, is now used for development until the field is abandoned. In the last 20 years, the discovery cost has decreased from $20 per barrel with 2-D seismic to just under $5 per barrel with 3-D seismic. Better geologic representations, coupled with advanced drilling and production technologies, also lead to increased recovery efficiencies.

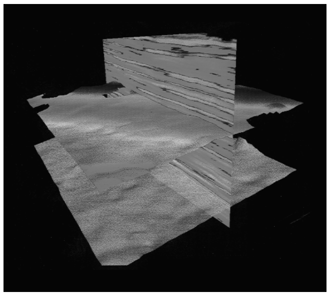
Several major improvements in 3-D surveying occurred during the 1990s, in seismic data acquisition, processing, computer hardware, and interpretation and display. Particularly remarkable have been the hardware improvements. Within the last five years, recording systems have increased capacity from 48 to 2,000 channels, as many as 32 seismic data lines can be recorded in a single pass, and satellite navigation systems have evolved to pinpoint accurate positioning of sources and receivers. At the same time, technological improvements have reduced computing time and lowered costs. 3-D stack-time migration can now be performed in a few hours on massively parallel processors, and between 1980 and 1990, costs dropped from $8 million to $1 million for a 50-square-mile survey using 3-D post-time depth migration. By 2000, costs for an equivalent survey are expected to be near $90,000.

ECONOMIC BENEFITS

- Helps explorers to better identify oil and gas prospects
- More effective well placement improves development of resources
- Fewer dry holes ultimately reduces drilling and exploration costs
- Can substantially improve project economics by reducing overall drilling costs
- Exploration time relative to successful production is cut

ENVIRONMENTAL BENEFITS

- More accurate exploratory well-siting reduces the number of dry holes and improves overall productivity per well drilled
- Less drilling waste is generated
- Better understanding of flow mechanics produces less water relative to oil and gas
- Overall impacts of exploration and production are reduced because fewer wells are required to develop the same amount of reserves



3-D seismic has now gained widespread acceptance. Whereas by 1980 only 100 3-D seismic surveys had been done, by the mid-1990s an estimated 200–300 3-D seismic surveys were being conducted annually. Offshore growth has been tremendous: in 1989, only 5 percent of the wells drilled in the Gulf of Mexico were based on 3-D seismic data; by 1996, nearly 80 percent used 3-D seismic. Onshore, 75 percent of all surveys were conducted with 3-D seismic by 1993.

Answering environmental and safety challenges

Today, producers are working to assess and minimize the impact of 3-D seismic equipment and crews on sensitive environments. Explosives used to generate sound waves recorded by a seismograph can now be replaced where necessary by vibrating technology that sends an acoustic signal. Offshore seismic surveying now relies on the use of compressed air guns to ensure protection of marine life. Depending on the kind of information needed, the geology expected, the nature of the field, and the costs, 3-D seismic exploration can be customized to protect the specific terrain. For example, in mountainous terrains, standard seismic techniques (2-D) required densely gridded surveys for accurate geologic descriptions. 3-D acquisition techniques allow for more widely spaced, less invasive surveys while providing better quality data.

Advancements in 3-D data processing also allow for survey acquisition in areas congested with urban or industrial noise sources.

CASE STUDIES

Success in the Field

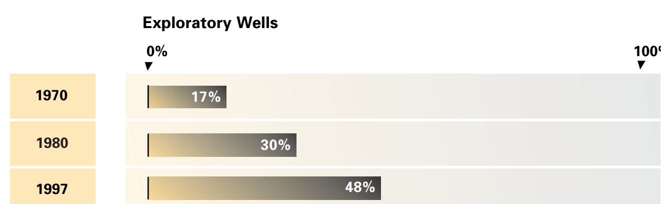
3-D seismic highly effective for portfolio management at Amoco

Amoco Corporation established an exploration drilling success rate of 48 percent for its 3-D seismic exploration activities between 1990 and 1995. By contrast, its exploration success rate for wells drilled without the benefit of 3-D seismic was only 13 percent. To evaluate the effectiveness of using 3-D, data were collected on 159 seismic surveys and a control group of 15 other prospects. 3-D proved extremely valuable at defining geometries, particularly in the North Sea and Gulf of Mexico. Where conventional surveying turned up eight prospects, 3-D narrowed these down to two. In addition, while all eight had been given an economic success probability of between 22 and 53 percent, 3-D seismic correctly predicted that the two selected had a potential success rate of 60 percent.

METRICS

Exploration success in the United States

Advances in 3-D seismic and drilling and completion technology dramatically increased drilling successes.



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TECHNOLOGY Locations: Worldwide, onshore and offshore

4-D Visualization

SUMMARY

Three-dimensional (3-D) seismic technology has revolutionized oil and gas exploration and served as a springboard to visualization technology. Now emerging visualization and 4-D time-lapse monitoring technologies are improving interpretation of the data 3-D seismic imaging provides. Invaluable in locating bypassed reserves in existing formations and discovering new resources, seismic reservoir characterization can now incorporate perceptual cues such as projection, lighting and shading, depth, motion, and transparency. This technology enables a more consistent, detailed picture of a complex formation. 4-D monitoring goes one step further, providing a dynamic picture of hydrocarbon flows and other reservoir changes over time, information valuable for both exploration and reservoir management of existing resources.

BLUEPRINT ON TECHNOLOGY

Evolving seismic technologies improve accuracy and interpretation, allowing operations to be tailored to protect the environment

Adding a fourth dimension—time

PETROLEUM ENGINEERS, geologists, and planners have a far better understanding of the geologic structures of potential hydrocarbon-bearing formations now that reservoir images are projected in three dimensions. Four are better still, largely due to DOE-supported research. A reservoir's fluid viscosity, saturation changes, temperature, and fluid movements can be analyzed by time-lapse monitoring in three dimensions. The time-lapse picture is built out of data re-recorded at intervals, compared and plotted by computer onto a 3-D model. Engineers can view changes occurring over time and link these to static and dynamic reservoir properties and production techniques. They can then follow the consequences of their reservoir management programs and make predictions as to the results of future activities. 4-D monitoring is an offshoot of the computer processing techniques developed for 3-D seismic interpretation.

With improved visualization techniques, petroleum engineers, geologists, and geophysicists are integrating many types and ages of data (well logs and production information, reservoir temperatures and pressures, fluid saturations, 2-D and 3-D seismic data) into time-lapse imagery and reservoir performance modeling. As this time-dependent tool is c orrelated with physical data acquisition, more accurate characterization of subsurface reservoirs will be possible, pushing maximum recovery efficiencies.

Geologists and planners are better able to understand the structure of promising formations. As computing science advances, further gains will be made. Already, audio technology is being added, both for controlling images and presenting complex geological data so that scientists can share data in real time from remote locations.

ECONOMIC BENEFITS

- Improved recovery due to precise placement of injector wells and infill drilling
- More efficient operations due to better identification of drainage patterns
- Lowered operating costs because of improved program timing and fewer dry holes
- Increased identification and ultimate recovery of as yet untapped resources

ENVIRONMENTAL BENEFITS

- Reduced drilling due to more successful siting of wells, with greater recovery from existing wells
- Less drilling waste through improved reservoir management
- Lower produced water volumes through better well placement relative to the oil/water interface in the formation
- Increased ability to tailor operations to protect sensitive environments

CASE STUDIES

Success in the Field

4-D seismic in Indonesia

The Duri field in central Sumatra was the first 4-D project of its kind. Today over 60 time-lapse projects follow its lead. Producing 300,000 barrels of oil per day, the PT Caltex Pacific Indonesia project is the largest steamflood in the world. In 1992, Caltex began 4-D recording in a series of eight surveys to determine whether time-lapse could successfully monitor a steamflood. The goal: to improve oil recovery and cut energy use. The data generated helped direct the injection process and identify both swept and unswept zones. Due to the project's success, Caltex started baseline surveys in six new areas, and other companies are also initiating use of time-lapse monitoring.

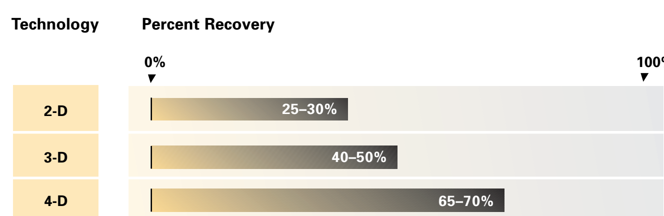
Immersed in 3-D visualization at ARCO

The ultimate formation viewing experience is to be immersed in a walk-in virtual reality cube that replicates geophysical features. In ARCO's Immersive Visualization Environment, images from projectors and mirrors outside the cube are projected onto three 10-foot walls of seamless screens. An electromagnetic tracking system orients the viewer's perspective, and stereoscopic goggles use alternate left- and right-eye images and infrared timing devices to create 3-D effects.

ARCO's exploration teams have used the facility to study data from the North Sea, Alaska's North Slope, and a project near the Philippines, using its superior visualization capabilities to produce solutions to drilling problems. In the North Sea's Pickerill field, for example, drilling plans for a multilateral hole were complicated by pressure changes among the reservoir's different compartments and drilling hazards above the reservoir. Adjustments to the original drilling plan were dictated by judgments made in the Visualization Environment, avoiding potential problems.

METRICS

Estimated recovery for oil-in-place at BP Amoco/Shell's Foenhaven field in offshore U.K.



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TECHNOLOGY Locations: Worldwide (especially deepwater)

Remote Sensing

SUMMARY

Used in conjunction with other exploratory techniques, such as 3-D seismic imaging, remote sensing systems detect and map concentrations of hydrocarbons with greater accuracy than other technologies alone, and with less environmental impact. Technologies such as satellite imagery, aeromagnetic surveys, and gravimetry are now being applied by the largest exploration companies to attempt to detect the vertical or near-vertical migration of oil and gas to the earth's surface and help identify promising geologic structures. These systems measure gases, solids, and liquids, using their physical properties to attenuate or reflect beams of electromagnetic energy. Resulting geophysical data are processed into easily understood images and maps, and form an integral part of current onshore and offshore programs throughout the world.

BLUEPRINT ON TECHNOLOGY

Remote exploration helps pinpoint hydrocarbon resources, pollution sources, and sensitive environments

Enhanced satellite imaging systems

OPTICAL SATELLITE imagery has been the predominant source of data for identifying and mapping onshore geology since the early 1970s, when the first Landsat Earth Observation satellite was launched. Today, satellite imagery, onshore and offshore, is also provided by radar satellites very sensitive to the earth's surface contours. For example, various types of satellites can see through 70 feet of clear water and up to 20 feet beneath the surface. Early optical satellites depended on visible or near-infrared light to collect energy reflected from the earth's surface. By contrast, radar satellites emit energy at microwave frequencies, enabling them to acquire imagery under nearly any atmospheric condition. Sophisticated digital image processing systems can now convert and sort raw satellite data into thematic maps that point to the location of productive formations, even detecting oil and gas seepages that indicate migration pathways from undrilled traps. Similarly, remote sensing techniques can also identify hydrocarbon spills and leaks in remote areas, such as along pipelines.

Current multispectral satellites such as the Landsat Thematic Mapper create images by gathering up to seven bands of light spectra in prism-like fashion. In 2000, when the U.S. Navy plans to launch its Navy EarthMap Observer satellite, an exciting new satellite technology called hyperspectral analysis, accessing upwards of 200 bands of light, will further increase imaging accuracy.

Improved aeromagnetic surveys

Initially developed for military applications, aeromagnetic surveying has evolved into a productive exploration technology that can recognize the magnetic signature of potential hydrocarbon-bearing basins from altitudes over 10,000 feet. Using a

ECONOMIC BENEFITS

- Increased exploratory success rates
- Dramatically reduced exploratory costs
- Access to geological data otherwise unobtainable
- Increased recovery of resources from frontier basins
- Identification of hydrocarbon "seeps" as distinguished from oil spills or pollution

ENVIRONMENTAL BENEFITS

- Accurate identification of fragile ecosystems, enabling care when drilling
- Increased ability to address environmental needs
- Fewer dry holes and nonproductive exploratory wells are drilled
- Improved characterization of earth's natural systems
- Identification of spills and leaks in remote areas

magnetometer mounted on a magnetically cleaned aircraft, explorers are successfully mapping sedimentary anomalies critical to oil and gas exploration, detecting salt/sediment contact, mineralized shear zones, and intrasedimentary markers.

Recent improvements in magnetometer design, digital signal processing techniques, and electronic navigation technologies, in combination with faster sampling of the magnetic field and the use of more detailed survey grids, allow mapping of subtle magnetic signatures. These advances improve the interpretation and visualization of geological data.

Measuring gravity to gauge resources

Gravimetry measurement is now derived from both satellite and airborne observations. Gravity anomalies can be measured and mapped to give geoscientists an idea of the size and depth of the geological structures that caused them.

Satellite gravity imaging uses radar to measure undulations in the sea surface that reflect density variations in the earth's upper crust. This technology enables mapping of areas of mass deficit, where sedimentary deposition is likely to have occurred. Identification of such areas gives explorers a better idea of where hydrocarbons may be located.

Putting it all together

Exploration companies like BP Exploration, Exxon, Mobil, Texaco, Unocal, and RTX are tailoring their remote sensing programs to combine technologies as needed. Recent advances in radar imaging and sophisticated image-processing packages, combined with satellite-derived gravity and bathymetry data, for example, present new opportunities to use remote sensing for deepwater exploration. Remote sensing is now considered critical to such operations. It is also extraordinarily cost-effective.

CASE STUDIES

Success in the Field

Satellites help explore in the Caspian Sea

After water-level changes along the shallow coast of the Republic of Kazakhstan made their bathymetric maps obsolete, Oryx Energy and its exploration partner, Exxon, turned to remote sensing to gauge depths. Water depth fluctuations caused by wind can make movement of seismic and drilling equipment challenging. With satellite image processing technology, the team created new bathymetric maps (e.g., the 12,200 square km Mertvyi Kultuk block, some 30 km south of the giant Tengiz field) and used these maps to position a successful new drilling program in one of the world's most productive oil exploration areas.

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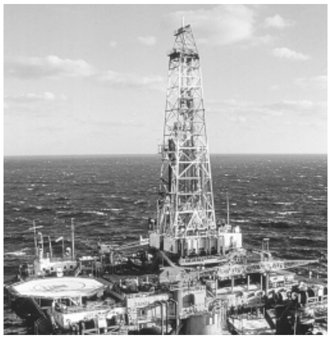


TECHNOLOGY Locations: Gulf of Mexico, West Africa, and other salt formations

Subsalt Imaging

SUMMARY

Now that most easily accessible domestic resources have been discovered, oil and gas explorers are investigating the promising but more inaccessible resources beneath saltsheet formations in the Gulf of Mexico. Large, irregular saltsheets may cover 60 percent of the slope beneath the Outer Continental Shelf in the Gulf and are found throughout the world. Advances in 3-D imaging technologies are crucial to providing reliable images of what lies below the thick layers. A 3-D prestack depth migration method of seismic data processing and an advanced marine magnetotellurics technique are now making it possible to image the structure and thickness of subsalt sediments. Together, these technologies provide sufficient information to help locate new oil or gas deposits, estimated at 15 billion barrels of oil equivalent in the Gulf of Mexico alone.

BLUEPRINT ON TECHNOLOGY

Interpretation of formations hidden under layers of salt allows more accurate siting of new reserves

Getting under the salt

DEVELOPING IMAGES of subsalt structures poses a critical challenge to exploration. Seismic imaging is based on the transmission of sound waves and analysis of the energy that is bounced back. But large amounts of energy are lost when sound waves pass through salt; thus, an extremely strong seismic source is required. Often seismic data are incomplete, preventing explorers from obtaining accurate readings of a structure's shape and thickness. Traditional imaging methods cannot deliver accurate readings when seismic sources are blocked by salt squeezed into sheets between sediment layers from an underlying salt base. The oil and gas sandwiched between the salt layers can only be imaged by a combination of advanced seismic source technology, complex mathematical modeling simulations, and improved data processing and imaging techniques. DOE's public/private Natural Gas and Oil Technology Partnership has helped develop several such technologies, among them improvements to the speed and reliability of 3-D prestack depth migration, which creates a coherent image by processing as many as 25 million records.

Using electromagnetic resistance

As a part of this DOE partnership, the National Laboratories and industry are currently investigating the feasibility of marine magnetotellurics, which is ideal for subsalt exploration since it is based on electrical resistance. Because salt's resistivity is 10 times greater than that of surrounding sediments, the contrast between salt and sediment resistance to low-frequency electromagnetic radiation from the earth's ionosphere makes it easier to map the extent and thickness of salt structures.

Stealth imaging breakthrough

The latest technology used to enhance seismic data is 3-D full tensor gradient (FTG) imaging, originally developed by the U.S. Navy during the Cold War for stealth submarines. A 3-D gradiometer survey takes real-time measurements of very small changes in the earth's gravity field, each relaying information directly related to mass and geometry of subsurface

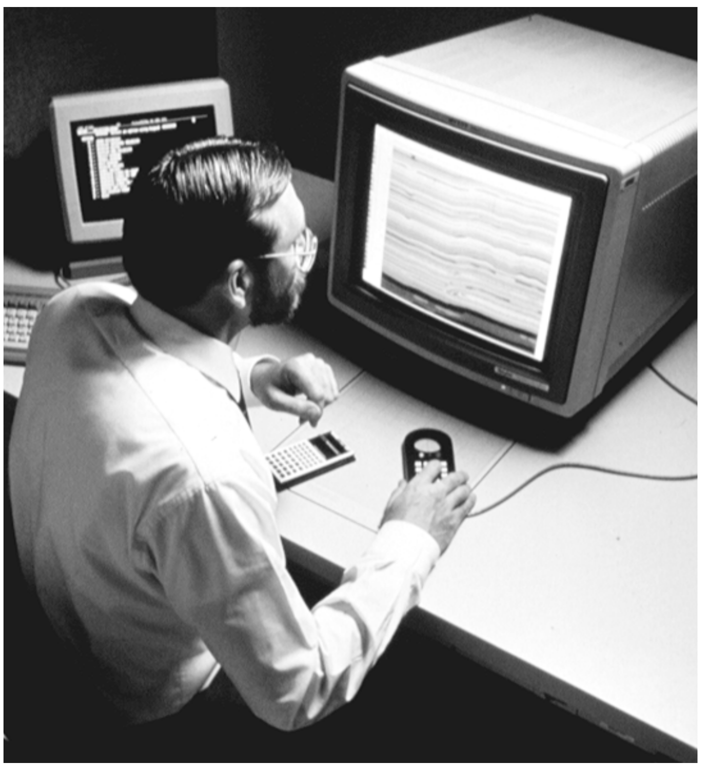
ECONOMIC BENEFITS

- More efficient exploration to pinpoint new oil and gas, reducing the financial risks
- Cost-effective exploration: an average 30-image seismic survey costs $500,000, while an MT survey covering the same area costs about $50,000

ENVIRONMENTAL BENEFITS

- Increased resource recovery due to better reservoir characterization
- Better, more careful siting of new drilling operations
- Reduced drilling wastes as fewer wells are drilled

geological bodies. FTG provides the depth and shape of almost any geological structure, independent of seismic velocities, allowing geoscientists to develop more complete images of complex salt formations. Two field tests have demonstrated a significantly improved view of the Gulf's subsalt geology, and FTG promises to be an affordable tool with which to enhance existing 3-D seismic imaging technology in salt formations around the world.



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CASE STUDIES

Success in the Field

Beneath the Mahogany field salt

Drilling beneath the salt formations of the Gulf of Mexico, an exploration play spanning 36,000 square miles south of the Louisiana coast, began in the 1980s. A decade of unsuccessful exploration followed, and it took advanced subsalt technologies to break through the visual block. Nine subsalt discoveries were drilled in the play from 1990 to 1996, representing a phenomenal success rate of 35 percent. The centrally located Mahogany field (the Gulf's first commercial subsalt play) was discovered in 1993, and four wells were completed by 1997, now flowing at a daily rate of 15,000 barrels of oil and 35 million cubic feet of gas. Mahogany field's total reserves are estimated at 100 million barrels of oil-equivalent, and total recovery from this and the Gulf's other subsalt discoveries is estimated to be 650 million energy equivalent barrels, resources that would have remained inaccessible without advanced subsalt imaging technology. A new discovery, the Tanzanite field, is estimated to hold reserves of 140 million barrels of oil-equivalent. Due to the size of this discovery, subsalt exploration in the Gulf is likely to remain active. Future subsalt technology advances may be the key to discovering other large untapped fields. As technology progresses, so will resource recovery.

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