Exploring for Stratigraphic Traps

Discovery of new resources in mature provinces and deep offshore demands new technology to find the most elusive of petroleum reservoirs, stratigraphic traps, which may well hold the vast majority of the new millennium’s yet-to-be-discovered hydrocarbons.

There was a time when exploration consisted simply of following surface signs such as seeps, creek beds and salt domes, and drilling where the party boss poked his stick; but those days are gone. Petroleum seismology has revolutionized the search for hydrocarbons and brought about a period of remarkable discoveries. Seismic exploration has expanded dramatically with the tandem advent of 3D seismic technology and powerful computer capabilities. Exploration has been a race at sea and on land for ever greater efficiency. The current limits of contemporary technology were apparently reached last year, however. In marine seismic acquisition, eight streamers formed 750-meter [2460-ft] wide swaths and 10,000-meter [32,800-ft] offsets, and in land seismic acquisition, very large-channel capacity, 24-bit recording systems and three-component sensors were employed.

Computing power has also grown exponentially, with massively parallel computers such as the CM-5 (576 nodes and over 32,800-ft) cutting processing time to a tenth of what it was just ten years ago. Sophisticated software systems are now integrating the process flow so seamlessly that engineering, petrophysical, geological and geophysical data can be merged at the explorationist’s workstation to facilitate interpretation.

Despite these tremendous technological strides, easy discoveries have become a thing of the past. All of the world’s more obvious reservoirs have been found, and most have been tapped and put into production. Those in accessible areas that have been the easiest to identify, the hydrocarbons trapped in structural faults and anticlines that manifest themselves so readily in 2D and 3D seismic data, are almost all in production, as are the stratigraphically entrapped reservoirs that revealed themselves as bright spots in otherwise lackluster seismic data.

Today, fully 40% of the oil found in mature hydrocarbon provinces is being found in stratigraphic traps. In fact, most of the remaining oil and gas in these areas probably lie in such traps, making future exploration deliberate searches for these elusive geological units. Worldwide, except for those principally structural accumulations in Russia and the Persian Gulf, some 60% of known giant oil and gas fields (500 million bbl [79 million m³] oil and 3.5 Tcf [4.7 billion m³] of gas) are stratigraphic. These include Venezuela’s Bolivar Coastal with 30 billion bbl [4.9 billion m³], the 6 billion-bbl [1 billion-m³] East Texas field, and Mexico’s Poza Rica field, with 2 billion bbl [0.3 billion m³]. Furthermore, as exploration presses farther into the world’s deepwater provinces, the prospect is frequently a stratigraphic trap, too—the Shell Mars field, with 700 million bbl [111 million m³], for example, and Ram-Powell with 250 million bbl [38 million m³].
Regardless of the method of exploration, today’s undiscovered stratigraphic traps are difficult to find and are frequently encountered purely by accident while drilling stepout wells to further delineate a field. That notwithstanding, with ever greater success, the technological advances in the geosciences that helped reveal so many of yesterday’s hydrocarbons are now being put to the task of identifying these less discernible reserves. These lie in isolated depositional units beneath seismic data’s hills and valleys, the pinchouts, unconformities, reefs and barrier bars collectively known as stratigraphic traps (above).

**Structural Versus Stratigraphic Traps**

Hydrocarbons migrate upward from their source through porous subterranean strata until their route is blocked by a layer of impermeable rock, and they accumulate beneath the sealing body, structure or trap. Geologists divide these traps into two types, structural and stratigraphic. Structural traps are formed by tectonic forces after the sedimentary rocks have been deposited. They generally fall into two categories: anticlines, where the rock has been folded or bent upward, and faults, where movement along a joint or fracture has driven an impermeable layer above a permeable layer.

Stratigraphic traps, on the other hand, are most often formed at the time the sediments are deposited. They fall into three categories: pinchouts, most common in stream environments where a channel through a flood plain has been filled with permeable sand that was then surrounded by less permeable clays or silts when the channel moved; unconformities, where a permeable reservoir rock has been truncated and covered by an impermeable layer following a nondepositional period or a time of erosion; and carbonate reefs, fossilized coral constructions and associated deposits that arose from ancient ocean shelves and were overlain by layers of both permeable and impermeable rock (see “Types of Stratigraphic Traps,” page 51).

Pinchout and unconformity traps are often found in sand-shale beds in basins that have experienced considerable tectonic activity, where there are unconformities and overlaps as well as marine, coastal and fluvial facies. Reefs, however, are frequently found either on stable shelves beside troughs containing fine clastic sediment or in evaporite basins. Since reef traps exhibit an anticlinal structural expression, their delineation with traditional seismic methods is ordinarily accomplished with relative success, unlike pinchouts and unconformities, whose physical subtleties have evaded explorationists until recently. For this reason, we are focusing mainly on nonreef stratigraphic traps. We examine why they have been so difficult to identify, and then describe the seismic acquisition and processing techniques that have been developed to bring these features to light.

**Why Are They Difficult to Find?**

Stratigraphic traps were first identified in Pennsylvania in 1880, but exploring for them remained a mystery until the mid-1930s, when seismology began to be applied in the petroleum industry. Explorationists find structural traps far easier to identify than stratigraphic traps in both 2D and 3D seismic data. For background on early exploration for stratigraphic traps: Halbouty MT: “The Time is Now for All Explorationists to Purposefully Search for the Subtle Trap,” and other contributions to AAPG Memoir 32: The Deliberate Search for the Subtle Trap. Tulsa, Oklahoma, USA: American Association of Petroleum Geologists (1982): 1-10.
because structural traps are seen as highly dipping reflections and discontinuities in otherwise smooth reflections. Thus for years, acquisition and processing techniques have been tailored to accentuate these features, allowing interpreters to concentrate their efforts on faults, anticlines and reef formations rather than their more subtle stratigraphic counterparts. Other methods, such as detecting bright spots (reflections with anomalously high amplitudes), are used with some success on both structural and stratigraphic traps. Certainly, many bright spots do illuminate stratigraphic traps, which make these traps so easily identified with today’s techniques that experts say few await discovery (right). But, until recently, the search for the more elusive unconformities and pinchouts has been thwarted by limitations in seismic data, namely low resolution, noise and a multitude of technological barriers—the need to expand bandwidths, attenuate multiples (false reflections), reduce differences of scale between seismic data and well logs, bring core and log measurements into harmony, and improve synthetic seismograms.

Stratigraphic traps are generally visually subseismic, so thin or so conformable to their surrounding geometry that their subtleties are nearly invisible in traditional seismic data. The detail that can indicate a stratigraphic trap in seismic data may well be just a small part of a single seismic trace, perhaps only a small bump on an otherwise smooth wiggle or a change of curvature or slightly different wave shape that wasn’t present earlier.

Detecting these subtleties requires data of the highest possible quality. For these purposes, high quality means large bandwidth or a wide range of frequencies to resolve small features, and low noise. Yet some stratigraphic traps generate the very noise in the seismic data that makes them hard to see. For example, some stratigraphic traps are associated with unconformity surfaces or surfaces of major velocity contrast. Reflections off these surfaces can reverberate or reflect multiple times, giving rise to the type of seismic noise called multiples. The presence of these multiples in data can conceal the trap and make it difficult to define its exact depth. Frequently, however, there is no strong reflection associated with a stratigraphic trap. Instead, the trap is associated with a gradual change in lithology instead of an abrupt contrast. In these cases, a more typical seismic signature would be small changes in the character of a reflection from one trace to another (right).
Types of Stratigraphic Traps

Stratigraphic traps were first recognized in 1880 by Carll, but not so named until 1936 by Levorsen, who defined them simply as traps “in which a variation in the stratigraphy is the chief confining element in the reservoir which traps the oil.” He noted that, “the dominant trap-forming element is a wedging or pinching-out of the sand or porous reservoir rock, a lateral gradation from sand to shale or limestone; an uplift, truncation, and overlap, or similar variation in the stratigraphic sequence,” to differentiate them further from structural traps. Structural traps, conversely, are usually formed by tectonic forces after sedimentary rocks are deposited and include anticlines or folds and faults (right).

Stratigraphic traps include pinchouts, in which a lens of permeable sand is surrounded by less permeable silts and clays. These form in both land and submarine stream environments. Here sand is deposited in the stream channel and in coastal settings when beach sediments are covered by impermeable clays that are laid down if sea level rises. Unconformities represent a gap in the geological record due to erosion, nondeposition, or both (right). The reservoir seal may be created by alteration of the exposed portion of the reservoir rock itself, or by deposition of a later impermeable layer. Reefs, either mound or shelf-margin carbonate units, form by growth of coral and deposition of calcite precipitated from seawater.


Diagram:
- Types of Traps. Structural traps are generally classified as either anticlines or folds, or faults. Stratigraphic traps are generally categorized as pinchouts, unconformities and reefs.
- The development of an unconformity. An unconformity is typically created through a process of deposition, uplift and tilting, erosion and redeposition.
Synthetics for a survey design in the Gulf of Mexico. A synthetic seismogram shows the correlation between log and seismic data and can indicate how well a stratigraphic target will be mapped. Here the most important tracks are tracks 3 and 4, representing the synthetic and the seismic data (repeated for clarity). The impedance log in track 2 is created from the velocity log in track 1 and the density log in track 8. Track 6 indicates the semblance, or accuracy, of the match between the synthetic and seismic data, with green representing high semblance. Track 5 is the recorded seismic line and includes the well trajectory (vertical red line)—which missed both red bright spots. SP and porosity logs are shown in tracks 7 and 8, respectively.

Fortunately, many reservoirs formed by stratigraphic traps also have a structural component that makes them easier to discover. They are found to have stratigraphic elements many years later, when cumulative production volumes surpass original estimates. In the North Sea, Gulf of Mexico and Campos basin of Brazil, giant stratigraphic traps are only recently coming to light after decades of exploitation of smaller predominately structural traps, suggesting a bright future in exploration for stratigraphic traps in nominally mature provinces.

Because they are so hard to see, exploration for stratigraphic traps requires knowing where to look. It is fundamental to understand the structural setting and important, even if difficult, to recognize the depositional setting of a prospect to know where to anticipate the occurrence of stratigraphic traps. The application of seismic stratigraphy to existing seismic data and well logs aids in this understanding by providing needed information on the direction of sedimentary flow, whether the sea level was rising or falling, and other depositional conditions.

Designing for Discovery
Explorers don’t select a drill site based on intuition and the whim of the party boss anymore. Nor are today’s seismic shoots simple exercises in geometry; considerable geological and geophysical input goes into the planning of a modern survey.

To reduce the risk of an expensive dry hole, as much a priori knowledge of the location as possible is factored into the development of a stratigraphic model from which to design a new, comprehensive 3D seismic acquisition program. This preliminary model indicates not only the target depth for the survey, but when a stratigraphic trap is the target, provides an approximation of how large the trap is, so that the final survey can render the desired subsurface coverage. All known geological layers are included in the model, as are their velocities and densities. With ray tracing or, in the case of a targeted stratigraphic trap, applying the full-wave equation, a seismic survey can be simulated to optimize the measurements and fine-tune the survey design.

The technology for both onshore and offshore exploration for stratigraphic traps has been in existence for 20 years, beginning with sequence or seismic stratigraphy, then 3D acquisition and its higher resolution of the details in seismic data. Offshore, however, advances in technology have recently been changing the way acquisition is being performed in deep water and mature provinces. There, to alleviate the two most troublesome problems associated with exploring for stratigraphic traps, low-resolution data and related multiples, the survey is conducted in one of two ways. Towed multistreamer surface acquisition with long streamers (from 3 to 12 streamers, 5000 m [16,400 ft] to 10,000 m long) can yield wider bandwidths for higher resolution and obtain offsets long enough to attenuate multiples (next page, top). And, more recently, four-component (4C) ocean-bottom cable (OBC) acquisition has become feasible, which not only achieves greater resolution in the resultant seismic data, but provides more reliable information on the lithology and porosity of the target than can be obtained by towed streamers.

Shear Enlightenment
Although the resolution and signal quality achieved by towed acquisition have improved the ability to image stratigraphic traps, 3D seismic exploration is even further enhanced by employing the new technology of four-component seabed systems. Geco-Prakla took the concept of a seabed system with external hydrophones and geophones, originated by Statoil as SUMIC, and developed its new seabed system as an entirely self-contained cable with internal hydrophones and geophones, the Nessie 4C MultiWave Array system (next page, far right). The four components comprise three orthogonally mounted geophones and one hydrophone mounted within the ocean-bottom cables that are laid in direct contact with the seafloor.

This form of deployment allows measurement of rock properties that towed or vertical hydrophones cannot measure, since hydrophones record only compressional (P) waves. The vast majority of surveys, including those recorded on land, rely entirely upon P waves to obtain a seismic image, but appropriately deployed geophones, onshore
or offshore, also record shear (S) waves, which react differently to the properties of the rock they penetrate (see “Full-Wave Spectrum: P and S Waves,” next page).

Because stratigraphic traps are not necessarily associated with structural events and are not domal in shape, they are often invisible in P-wave data, but are equally as often readily identified in combination P and S data. This is because shear waves have complementary information to that of the P waves, which allows more complete characterization of the elastic properties of the rock and fluid and allows identification of the subtle changes in lithology that come with stratigraphic traps.

Because shear waves do not travel through water, the cable must be in direct contact with the seabed to accomplish the 4C shoot, a deployment that requires precise positioning of the cables as they are laid from the back of the acquisition vessels. Once a seismic traverse has been shot, the cable is either dragged or taken in and redeployed in a new location; additional lines of seismic data are acquired until the entire area has been covered.

The information obtained in a four-component survey complements that from P waves in eight ways. First, because S waves are relatively unaffected by pore fluids, including gas, they can be used to obtain structural and stratigraphic information in areas where the presence of such fluids precludes coherent images from P waves only. Targets below gas chimneys and gas clouds are notoriously difficult to image with P waves, and S waves have been highly successful in this application.


Second, S waves yield independent information about rock properties, allowing more complete prediction of both fluid type and rock lithology. When only P waves are recorded in a seismic section, it is frequently difficult to discern whether a detected direct hydrocarbon indicator event is due to the presence of hydrocarbons or is simply due to lithologic changes. Shear-wave data lessen this difficulty considerably when acquired simultaneously with P-wave data. In areas where P-wave data produce amplitude anomalies and the S-wave data do not, the presence of hydrocarbons is likely. If the anomaly is observed in both S-wave and P-wave data, it is most likely either a diagenetic or lithological phenomenon. The ratio of P-wave to S-wave velocities, Vp/Vs, is often used to predict lithology, and the P-wave amplitude to the S-wave amplitude ratio may turn out to help predict fluid-saturation differences.

Third, in deepwater acquisitions, the triple-sensor nature of the geophone data provides a unique opportunity for demultiplexing. Shear waves contribute another velocity function to use in distinguishing between multiples. Since shear waves produce multiples themselves that are similar to those produced by P waves, this helps the interpreter sort the principal reflections from the multiples to image more accurately.

Fourth, by acquiring both P and S waves, explorationists expect to illuminate shadow zones beneath high-velocity salt structures. Because the raypaths bend at a boundary of two different velocities, and salt bodies often have irregular boundaries, shadow zones, areas with no reflections, are created. By using both P and S waves, some of the shadow zones of one are illuminated by the other. Therefore, better structural and stratigraphic images can be achieved beneath salt.

Fifth, variations in seismic velocities, both P-wave and S-wave, may help identify different lithologies. The use of interval traveltime ratios, T1/Tp—related to but easier to measure than interval Vp/Vs—over a relatively small time window in the seismic data, may indicate lateral or vertical changes in lithology and pore fluid type. Further, the use of these ratios, in conjunction with seismic facies interpreted from reflection patterns, provides a relatively powerful way to begin inferring lithologic information at a scale more detailed than most seismic velocity models.

Conventional seismic surveys use compressional or pressure (P) waves to penetrate the earth and sea and reflect back data on the strata and structures these energy waves encounter. When these waves become disturbances propagating through the body of a medium, they either remain compressional waves (P waves) or are converted into shear waves (S waves).

Compressional waves occur when a liquid, solid or gas is sharply compressed. The compression sets off small particle vibrations in the same direction that the compressional waves are traveling. Shear waves, on the other hand, are waves of shearing action and occur only in solids. In shear waves, the small rock particle motion is perpendicular to the direction of wave propagation. They may be generated by a seismic source in contact with a rock formation or by the non-normal incidence of P waves on rock. The generation of S waves from a reflected P wave is called mode conversion. It is slight for small incident angles and becomes more pronounced as the offset increases.1

The velocity at which these waves travel is controlled by the mechanical properties of the rock, its density and elastic dynamic constants. In fluid-saturated rocks, these properties depend on the amount and type of fluid present, the composition of the rock grains and the degree of intergranular cementation, formation pressure and temperature. Soft, loosely consolidated rocks are generally less rigid and more compressible than hard, tightly consolidated rocks. As a result, P and S waves travel slower in soft rock than in hard. Extremely unconsolidated rocks support only weak shearwave propagation.

P waves and S waves propagate through rock and reflect differently at interfaces (next page, top). A P wave reflecting as a P wave, called a P-P reflection, is symmetric about the point of reflection at the common midpoint (CMP) halfway between the source and receiver. A P-S reflection is asymmetric at the point of reflection, called the common conversion point (CCP), which is different from the CMP. The difference in reflection points must be taken into account through processing.

The combination of P- and S-wave data rather than P-wave alone can yield previously unavailable information about fluids in the pore spaces and improve the potential for identifying the prospect lithology. Because gas in a formation causes the compressional velocity to slow but has little effect on shear waves, the combination of compressional and shear measurements helps in identifying gas-related amplitude anomalies. In addition, S-wave data are also able, in some cases, to image structures that P waves cannot adequately portray, such as reservoirs with gas clouds in porous rocks above the reservoir (next page, bottom).2

Until recently, P and S waves could be acquired simultaneously only onshore, but with the advent of ocean-bottom cable (OBC), both can be obtained. Although the marine seismic source continues to generate only P waves, once those waves have reflected off deep strata, they may be converted and propagate upward as S waves. The new 4C seabed cable system is in contact with the ocean floor and can record both waveforms.

P and S waves. When P waves (red) reflect as P waves, they do so symmetrically about a common midpoint (CMP). When P waves convert upon reflection to an S wave (black), they do so asymmetrically, about a common conversion point (CCP).

Value of shear waves. Shear waves are useful for imaging beneath gas clouds, as they travel through this low-velocity zone relatively undisturbed. The lateral displacement of the CCP due to P-S reflection must be taken into account in processing.

Imaging through gas with shear waves. The lower panel shows an image created by migrating P-P CMP-stacked seismic data. The center of the image is weak and disrupted by a gas cloud obscuring the crest of the structure. The top panel shows migrated P-P CCP-stacked data. The reflectors are clearly imaged all the way across the panel.
Sixth, experience with a few situations in the North Sea has shown that some reservoirs have low P-wave reflectivity while having relatively high P-to-S mode-conversion capabilities. Therefore, these reservoirs, which can not be seen at all on P-wave data, become visible using the mode-converted shear waves. An extension of this idea leads to the conclusion also that by acquiring both P and S waves, seismic information and log and core data can be correlated more convincingly, and perhaps explains why correlation has been difficult in some areas.

Seventh, a stationary acquisition system like the Nessie 4C MultiWave Array permits true 3D acquisition, meaning complete offset and azimuth distributions within the data. Towed 3D surveys, while providing coverage of a 3D volume, do so with a series of essentially 2D traverses, as the source is in line with the receiver cable. By acquiring P and S waves propagating in all azimuths, velocity anisotropy (the variation of a property with direction) of P and S waves may be determined. Velocity anisotropy can be especially pronounced in S waves, and depending on the type and amount, can be used to help

\[ \text{Methodology Used by Geoscientists.} \]

\[ \text{Depositional and termination patterns. Types of depositional and termination patterns sought in seismic data indicative of stratigraphic traps, including discontinuities.} \]

\[ \text{After Visher, reference 9, main text.} \]
discriminate rock types, detect source rocks and identify principal fracture directions. For example, shales are often highly anisotropic, displaying transverse isotropy wherein the vertical velocity is different from the horizontal velocity. Sometimes this can be observed in 4C seismic data, and could indicate a shale, suggesting the existence of what is a common sealing formation for many stratigraphic traps. Velocity anisotropy is also an important consideration when processing surface seismic data for stratigraphic interpretation, as small errors in velocity can impact the resolution of the final seismic image.

An eighth benefit of acquisition with the Nessie 4C MultiWave Array is it allows for the calibration of AVO (amplitude variation with offset) analysis derived from streamer survey data. An AVO effect occurs when the reflection coefficient at an interface changes as a function of distance between source and receiver. When P-wave energy strikes a particular interface, some of it will be transmitted as P waves and some will be reflected as P waves, while some of the energy will reflect as S waves and be transmitted as S waves. Some lithology-fluid combinations generate dramatic AVO effects, and the observed AVO signatures, or anomalies, can be diagnostic of hydrocarbons. But these effects are not seen in conventionally processed seismic data, because the processing step of stacking averages amplitudes from traces at different offsets.

If an AVO effect is suspected, the seismic data can be processed to preserve and highlight rather than average amplitude variations. The data can also be visualized in 3D cubes in the same way stacked data are visualized. But in this case there would be multiple cubes: one for near-offset data, one for medium offsets and one for far offsets. A multitude of 3D cubes can be produced, limited only by how much offset information is captured in the analysis. Geco-Prakla scientists have created as many as 23 different offset ranges for a survey.

Once an AVO anomaly has been detected, it needs to be interpreted to identify the rocks and fluids that created it. This is done by generating models and comparing observed AVO effects to the modeled ones. Most models contain information from P waves alone, and the shear-wave velocities required for the model are extrapolated from distant well logs or inferred from empirical transforms relating P to S velocities. Shear-wave velocities extracted from Nessie 4C MultiWave Array data provide crucial input for construction of the models and allow for more reliable interpretation of lithology and fluids in the trap.

Processing
Geco-Prakla researchers have developed the SCT Seismic Classifier Toolbox software system for seismic stratigraphic mapping or inversion specifically for the identification of stratigraphic traps. The SCT methodology is based on work done by Peter Vail when he was at Exxon. An extension of the Vail technique, which was developed using 2D seismic data, the process begins by identifying depositional environments and their sequence boundaries in the 3D seismic data volumes and, within the sequence boundaries, identifying certain stratigraphic and geometric patterns that should be sought. Using advanced image processing algorithms that allow the geometry of interbed reflections between the sequence boundaries to be enhanced, primitives—computer templates—were developed to map these patterns automatically.

The goal is to determine the lithologic composition of the stratigraphic objects. The objects are defined by their boundaries, which may be subtle and difficult to delineate. Boundaries are sometimes identified implicitly by the way some of the seismic reflectors terminate against them. This is especially the case with submarine fan systems and their associated channels. For this reason, the Geco-Prakla SCT method includes reflection termination recognition systems (below).


The patterns produced by SCT processing of the 3D volume are then passed through classification, a type of generic inversion process wherein the desired stratigraphic pattern defines a set of attributes that are sought in the data. This produces either a catalog of patterns that the interpreter can use, or these patterns can go directly into the actual 3D volume following pattern enhancement.

At this point, the system is trained by the interpreter, who can simply point at a particular pattern and instruct the SCT system to recognize comparable patterns in the seismic dataset. The toolbox runs all of the seismic volume through the enhancement step and classifies based on the patterns that have been presented as the training data, either from the catalog or the identified patterns in the dataset. This produces a class volume, or voxel set, in the cube. Each voxel will have one value for each of the classes or stratigraphic patterns that were defined for the SCT process or it will have a value that indicates there is doubt in the pattern that has been identified.

At the end of the session, a set of voxel volumes is produced from the kinematic, or geometric, part of the seismic data, indicating the density of the bedding between the sequence boundaries and how the bedding terminates within the retaining system. At this point, the dynamic information is added, such as the reflection strengths of the various geometric patterns that were identified. These help discriminate between the types of lithology that may be lying between each of the stratigraphic objects.

Even if the 3D seismic data being processed through the set are solely acoustic or P-wave information from conventional towed streamers, there is some dynamic information that can be used to identify stratigraphic traps, including the same set of primitives. In addition, AVO methods can provide a fair understanding of lithologies. This is an implicit way of getting shear-wave information without the added cost of multicomponent acquisition.

Available well logs are now added to the process. To put the well and seismic data on the same scale, the log is used to construct a synthetic seismogram by convolving reflection coefficients from the sonic and density log with a band-limited seismic wavelet. This process achieves the same low resolution as that of the selected wavelet.

In a case study for Statoil in the Danish sector of the North Sea, for example, the Norwegian state oil company had a 2D line and two wells in which Geco-Prakla was able to identify two stratigraphic sequences with the SCT Seismic Classifier Toolbox system and map them in 3D. One of the wells showed hydrocarbons in the sands of a submarine channel system. The SCT approach, using fluid indicators from the ratio of P- to S-wave velocities, \(V_p/V_s\), measured in both the wells and inferred from the seismic data, made it possible to determine the reservoir's fluid distribution.

To discriminate between hydrocarbon-bearing lithology and non-hydrocarbon-bearing lithology, it is essential to calibrate the lithological effect of the \(V_p/V_s\) ratio versus its fluid effect. If perturbations are present, they can be associated with fluid rather than lithology. The Danish example was a 2D traverse, not a 3D multicomponent OBC dataset, which would have allowed further identification of each layer of the stratigraphy with its full elastic field observations. Nevertheless, it was processed through a new set of software tools Geco-Prakla calls model-based processing, which assured consistency between the 3D geometric model of the dataset and its P-wave velocity models, and confirmed the identification of hydrocarbons in the stratigraphic trap in zones not tapped by the wells.
Visualization and Attribute Analysis

Looking for stratigraphic traps in seismic reflection data, the geophysicist searches for subtle variations within formations rather than the obvious structures. This requires analyzing the seismic attributes, or characteristics, of the seismic traces. Key attributes of the seismic data reveal whether the trap is structural or stratigraphic and provide additional characteristics that are helpful in determining the precise nature of the lithology.

In mapping sand channels, for example, the termination attribute is analyzed to determine the shape of the channel, where a reflector terminates against a particular channel. If there are channel complexes and high amplitudes are present, they will also be visible in the seismic data’s texture and can be verified. The texture of the seismic traces, another attribute, the rough or smooth appearance of the data, serves as an excellent indicator of lithology. When the sediments are deposited under high-energy conditions, as are sands, the seismic data look chaotic; if quiet sedimentation, such as clays, then the data appear smooth (right).

Of the many different seismic attributes, the majority of which have arguable value in exploration, amplitude, the maximum departure of a wave from the average value, is the most important indicator of stratigraphic traps. This is because amplitudes can light up stratigraphic traps as bright spots, in which the amplitudes are dramatically greater or less than those of the adjacent layers. Even more important is when there is an updip drop in amplitude, because it can indicate a potential reservoir unit. In addition, when a stratigraphic interval thins with two beds coming together as happens in a pinchout, wavelets from these two beds merge causing reinforcement, or brightening of amplitude, and the location of that brightening is where the trap lies.

A great deal of information about the rock properties of the formation is available from amplitude. If true amplitudes are obtained, reflection coefficients derived from the data can be employed to compute acoustical impedance. This, in turn, can be related to density, velocity and porosity. Amplitude is also a major factor in estimating the net pay of the stratigraphic field, because amplitude changes with the amount of hydrocarbons present.

One useful attribute in identifying stratigraphic traps in 3D seismic data is amplitude versus azimuth, an aspect of anisotropy that combines both travel time and amplitude information and can indicate appropriate hydrocarbon reservoirs by whether the unit has closure and whether its amplitude is dim in the updip direction. Another use, in mapping fracture zones, from which primary production often comes, is that it indicates areas of weakened amplitude, which is caused by a poor coupling of S waves across fractures. Azimuthal coverage is typically 360° in a 4C survey, thus assuring the acquisition of this key attribute.

Accurate velocity measurement is also essential to correctly interpreting structures as stratigraphic traps, and particularly in gauging variations in the recorded velocities. Incorrect analysis can result from following the wrong reflecting wavelet. If the medium is 4C 3D seismic data, the measurement of shear information is much more reliable, permitting the use of the anisotropic effect and identification of both the P-wave layer velocity and the S-wave layer velocity, and adding to the discrimination power with respect to different lithologies, pore fluids and abnormal pressure regimes.

Although amplitude and velocity are integral to an accurate interpretation of 3D seismic data, different attributes are important in different aspects of the interpretation process. To determine which are more important, discrimination analysis is undertaken by compressing the seismic data into a set of attributes that might be relevant for the particular problem that has been identified, in this case the discovery of stratigraphic traps. From these attributes, a set of attribute transformations is selected.10

In what is called attribute space in the model, points are defined for each position with several attribute values. These can be thought of as clusters. Separations between the clusters permit discrimination, because they show that there is no overlap between the two classes of attributes. If, for example, there are only two attributes, the attribute space is two-dimensional and appears as a crossplot, with each of the axes in that crossplot now an attribute parameter. If there are two separate clusters in that crossplot, then

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Stratigraphic features frequently are better imaged by Coherence Cube processing, a recently perfected methodology that may be applied either after or during the processing of 3D seismic data and utilized during the interpretation to further reveal the stratigraphic trap (below right). A non-traditional procedure, Coherence Cube processing, which was developed in the geophysical labs at Amoco and licensed exclusively to Houston-based Coherence Technology Company, processes 3D seismic data not for imaging reflections, but for imaging discontinuities by analyzing waveform similarity (below). Traces that are similar to each other are mapped with high-coherence coefficients, and when similarities end, discontinuities may be inferred. As a consequence, when visualized in a 3D volume or cube, coherence coefficients enhance the detection and understanding of stratigraphic features (as well as faults) that are often not visible in traditionally processed data.

Stratigraphic features are frequently difficult to see in seismic data due to the low level or chaotic nature of the seismic reflections they provide. Coherence Cube processing brings stratigraphic features into focus as it computes the variations in the waveform regardless of the amplitude of the

High-Coherence Event

Low-Coherence Event

Multiple images of a subtle channel processed for coherence. What appears to be a barely perceptible, low-amplitude body in the black and white section of stacked data is revealed by Coherence processing (right) to be a subtle submarine channel, with its trend and areal extent (red arrow) clearly visible. (Images courtesy of Coherence Technology Co.)

Integration of conventional seismic line with Coherence Cube (Created by Coherence Technology Co. using GeoViz software from GeoQuest). Zones of low coherence (black) are interpreted as discontinuities.
discrimination between those two cases with that particular attribute set has been successful. If, however, the two clusters are overlapping, then there is no discrimination.

Geco-Prakla has patented a set of new attributes that allow the reconstruction of all the information that exists in a given layer—for example, between the top and base of the reservoir. And it can be done in an orthogonal sense; for each new attribute that is added to the classification system, additional information is obtained, limited only by computer running time.

Once the attributes have been selected that the geoscientist feels are key to a valid interpretation, a number of identification methodologies may be applied, including horizon slicing (above). Coherence Cube processing reveals the stratigraphic trap further (see “Coherence Technology,” previous page).1

Now, and in the years to come, the petroleum industry is relying on discovery of new resources in two areas: mature provinces and the deepwater offshore frontier. Both demand new technology to find the elusive hydrocarbons that lie beneath the earth and sea. Since stratigraphic traps may well hold the vast majority of the new millennium’s yet-to-be-discovered hydrocarbons, particularly when reefs are considered among them, “The time is now for all explorationists to purposefully search for the subtle trap,” in the words of Michel T. Halbouty. New acquisition technology now illuminates these stratigraphic traps as never before, and remarkable advances in processing and interpretation software and methodology reveal their attributes for analysis, visualization and verification. Difficult to find, yes, but as the giant stratigraphic traps around the world testify, well worth the search.

—DG
