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4-D seismic improves reservoir management decisions

Part 2—Conclusion to two-part article describing how new time-lapse 3-D technology provides reliable information about fluid distribution in the reservoir

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Last month's article described what 4-D Seismic (4-D) is, and its relationship with Seismic Reservoir Monitoring (SRM) and Time-Lapse Seismic (TLS). It also discussed the benefits of using 4-D as a reservoir monitoring tool and how it works.

Part 2 of this article begins with a discussion of 4-D data analysis—introduced last month—examining factors affecting the contribution of seismic data to reservoir monitoring. Also discussed are suggestions on how to start a 4-D project and comments on what improvements in relevant technology can reasonably be expected in the near future. The article comprises:

- 4-D data analysis including seismic repeatability, fluid composition change detection, seismic resolution and detectability, along with why 3-D is repeated
- How to conduct a 4-D project including factors to consider when designing a survey, and
- Future directions in data acquisition, processing and analysis, along with integrated technologies and software.

4-D DATA ANALYSIS

As 4-D is a seismic differencing technique, we need to be assured that several essential criteria can be met by modern seismic data. These criteria include expected levels of random noise, signal repeatability, navigation and survey accuracy, and resolution and detection limits.

The value of seismic data's contribution to reservoir monitoring depends on its resolution and signal-to-noise ratio. And these depend on data acquisition and processing parameters, along with the specific geological environment for a particular reservoir. Important factors include reservoir depth, as well as nature and complexity of the reservoir, overlying structures and the near surface.

Seismic repeatability. Control experiments on seismic data repeatability, under conditions when nothing is expected to have changed, show relative root-means-square (rms) differences of less than 5% in final processed seismic amplitudes between successive surveys. This corresponds to a signal-to-non-repeatable-noise ratio (SNRNR) of greater than 20.

Measured in this way, the signal is the seismic data's repeatable component and may include some systematic components, e.g., multiple reflections, that would be considered noise from a conventional reservoir description perspective. Since 4-D is concerned with differences, repeatable noise components should not be a problem. As a result, seismic data may be more appropriate for reservoir monitoring than for reservoir description.

Fluid composition change detection. Seismic monitoring is applicable to many reservoirs. For any specific reservoir, a petrophysical analysis is recommended. However, it is instructive to consider some generalizations to show types of reservoirs for which seismic monitoring might be applicable.

Percentage change in acoustic impedance (product of bulk density and acoustic velocity) for varying porosity sandstone and carbonate reservoirs under water drive or gas-driven oil recovery are shown in Figs. 5 and 6. The acoustic impedance change for both shallow (600 m) and deep (3,000 m) reservoirs is compared. A light oil that has similar acoustic properties to heavier oil with a high dissolved gas-to-oil ratio is used. Gassmann's equations were used to compute acoustic impedance changes shown.

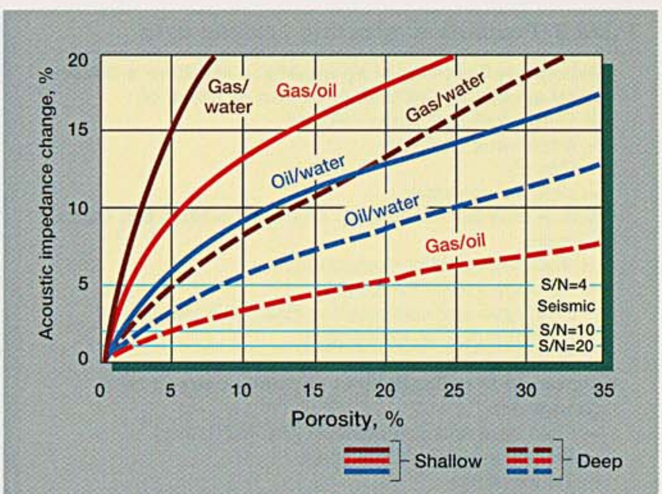

Fig. 5. Seismic monitoring potential for shallow (600 m) and deep (3,000 m) sandstone reservoirs.

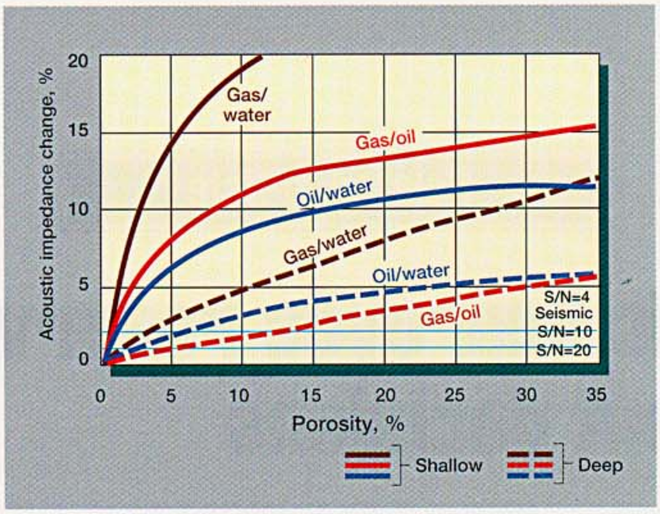

Fig. 6. Seismic monitoring potential for shallow (600 m) and deep (3,000 m) carbonate reservoirs.

Figs. 5 and 6 also show seismic detection limits for data with various SNRNRs. These detection limits are shown as horizontal lines and were derived for assumed 0.1 rms reflectivities for the reservoir zone. Shallow reservoirs are most amenable to seismic monitoring since fluid changes result in acoustic impedance changes larger than seismic detection limits shown. Shallow seismic data quality is also expected to have high signal-to-noise ratio and high resolution.

Deeper reservoir monitoring is also possible in many instances. For seismic data with an SNRNR of 10, fluid-front seismic monitoring appears to be possible for sandstone reservoirs with porosities greater than 7%. For carbonate reservoirs, seismic monitoring of gas/water and oil/water fronts requires porosities greater than 5%. Monitoring of the gas/oil front requires a porosity greater than 12% for the fluids shown; however, this could be larger for heavier oil, or less, if the oil has a large dissolved gas-to-oil ratio.

Expected changes during recovery are still more complex. As reservoirs are exploited, pore fluids undergo changes in temperature and pressure, as well as in composition. Individually, each of these changes can produce a change in seismic response, Table 2, which may be enhanced or reduced due to composition. To analyze seismic data without taking the combination of all contributory effects into account is to invite disaster, e.g., attributing the entire anomaly to compositional changes with no account of pressure changes will result in grossly incorrect estimates of saturation.

Now, the current simulation model will contain estimates of pressure and temperature regimes throughout the field. Hence, these estimates may be used to model their effect on seismic response and help separate the compositional component. Without knowledge of limits on expected reservoir conditions to guide the analysis, the 4-D seismic project results will remain ambiguous and their value will be compromised. So for many situations, seismic data has the sensitivity to track fluid movements within the reservoir.

Table 2. Properties affecting seismic data

- **Seismic reflectivity of an interface requires a difference across the interface of one or more of:**
  - — Compressional-wave velocity
  - — Shear-wave velocity
  - — Density
  - — Seismic absorption
- **Which may be caused by changes across the interface of:**
  - — Rock type and/or composition
  - — Porosity and/or fracturing
  - — Fluid type and composition (Sw, GOR, etc.)
  - — Pressure and/or stress state
  - — Temperature
- **A change in reflectivity is normally caused by a change in:**
  - — Fluid type and composition (Sw, GOR, etc.)
  - — Pressure and/or stress state
  - — Temperature

Seismic resolution and detectability. Probably the most important factors that determine 4-D method success are data resolution and detection limits. Resolution limit is the minimum separation for two features to be distinguished. Detection limit is the minimum size of a feature or contrast in property that produces a measurable response.

To detect changes in reservoir conditions, associated changes in seismic response must be greater than the data's noise level. Whereas, to resolve changes in reservoir conditions, the associated changes must occur over a distance greater than the data's resolution limit.

Simply stated, we can normally detect much smaller effects than we can resolve. Typically, current seismic data has about a 100-Hz bandwidth in the shallow section, reducing to 50 Hz at 6,500-ft depths. This corresponds to about a 7-msec vertical seismic resolution (Rayleigh resolution limit) for shallow reservoirs and 14 msec for deep reservoirs. For a 10,000-ft/sec (3,048 m/sec) velocity, resolvable layer thicknesses would be 35 ft for the shallow reservoir and 70 ft for the deep reservoir.

Sandstone reservoirs may have a lower velocity and so would show better resolution than indicated. Seismic resolution also depends on seismic data signal-to-noise ratio. Resolution improves as signal-to-noise ratio increases but is ultimately limited by the maximum frequency of the seismic data.

The goal of 4-D is not normally trying to resolve reservoir beds; rather, it is trying to detect a difference within a reservoir bed. Given typical surface seismic parameters and a conservative estimate for SNRNR of 10, this normally provides an extra factor of 5, which allows the possibility of detecting differences in beds of about 14-ft thickness at depth.

So in the 4-D situation, it may be possible to detect changes in thin beds even though it may not be possible, individually, to resolve their top and base. The problem reduces to one of attributing those changes to the correct part of the reservoir.

This interpretation can be done in terms of a known reservoir model, and is achieved by combining detailed layer information from well logs and/or current simulation models with the seismic data. Integration of these diverse information sources leads to an apparent improvement in resolution, adding spatial information in the seismic-difference data to vertical

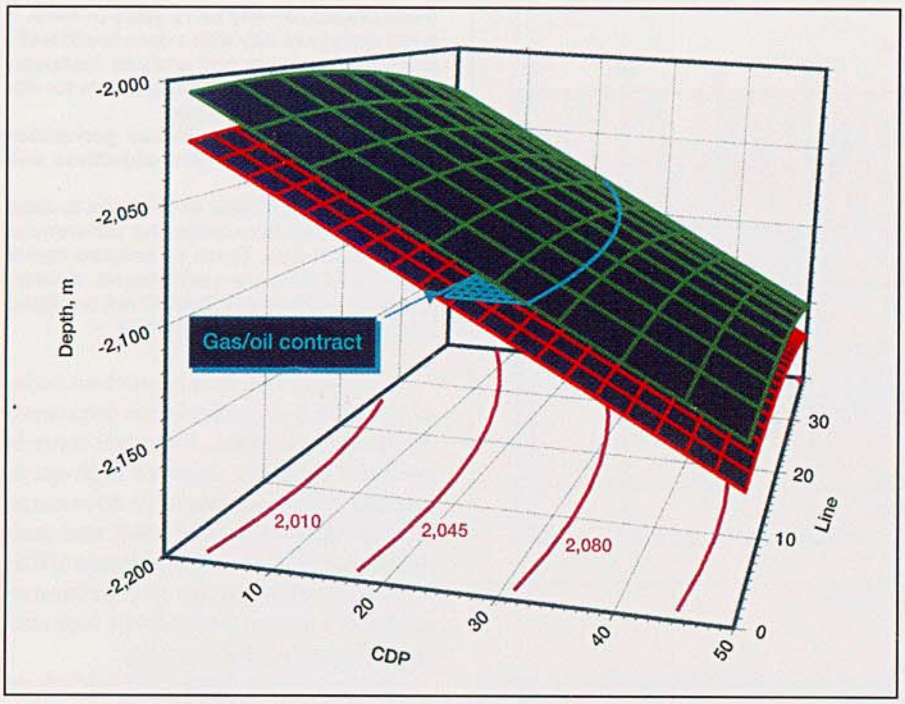

Fig. 7. Simple 3-D reservoir model.

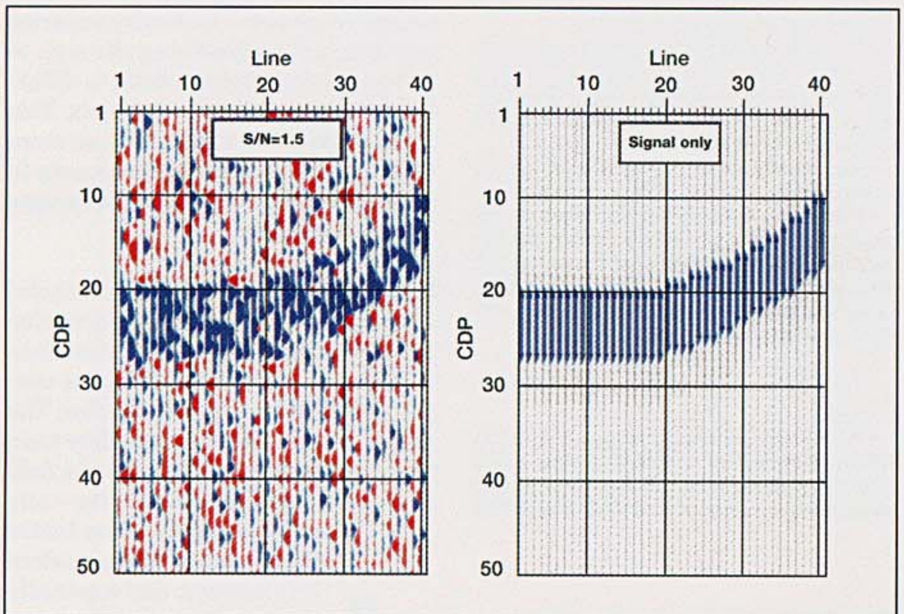

Fig. 8. Horizontal seismic section at 2,070 msec for 3-D reservoir model.

detail available from well logs and simulation models.

Why repeat 3-D? It is important to note that seismic-difference anomalies can be seen more clearly on 3-D seismic data than on 2-D data due to spatial continuity of seismic response to fluid-front movement. Also, 3-D data repeatability error is less since it allows correction of minor positioning errors that may exist between data sets, particularly for marine surveys. Consequently, 3-D data use allows seismic monitoring to be used in noisier areas than is possible for conventional 2-D seismic data.

A simple 3-D reservoir model was used to compute seismic monitoring response due to gas/oil interface movement, Fig. 7. The model shows a sand reservoir with a gas/oil contact encased in a shale. The gas/oil contact is shown at a depth of 2,080 m. Seismic response was computed for the gas/oil contact at depths of 2,070 m corresponding to seismic base survey, and 2,080 m, corresponding to a seismic monitoring survey after extraction of some oil. An average 2,000-m/sec velocity for depth-to-time conversion and a 10- to 50-Hz wavelet were assumed.

Seismic monitoring response is given by subtracting base seismic data from monitored seismic data. Band-limited random noise was added to give a signal-to-noise ratio of 1.5. A horizontal seismic section at a time of 2,070 msec clearly shows areal extent of original fluid contact location, Fig. 8, whereas fluid contact positions cannot be easily identified on a single line extracted from the same 3-D seismic volume, Fig. 9.

HOW TO CONDUCT A 4-D PROJECT

Per the previous discussions, it seems there is every reason to be optimistic about success of a 4-D project. It is, therefore, appropriate to spend some time discussing how to plan a 4-D project. While there is no one preferred solution applicable for all reservoirs, a 4-D project will typically run in three natural phases—feasibility and pilot studies, and field-wide application.

1. Feasibility study. This is by far the best way to evaluate current and future data needs. Available information is analyzed to determine expected changes in reservoir conditions and properties during production. Seismic response changes caused by these reservoir changes is estimated and compared to observed noise levels on currently available data from the area.

Recommendations for acquisition, processing, and analysis techniques are made together with an initial economic benefit analysis, Table 3. Limited data collection may be necessary to confirm estimated parameter values.

2. Pilot study. Methodology defined during feasibility study is applied to a portion of the field with good potential for success, which provides best opportunity for fine tuning project variables while limiting economic exposure. Most reported field successes fall into the "pilot study" category.

3. Field-wide application. The methodology, tuned during the pilot study, is applied to entire field with good prospects of success from both a technical and economic viewpoint.

Survey design. The 4-D technique can be applied to a variety of fields using a range of survey geometries and collection techniques. The objective in choosing a field geometry is to minimize overall cost while providing sufficient data to realize monitoring benefits. Final choice is dictated by expected fluid displacement characteristics, field terrain and relative economic risk. Data acquisition is expensive, but in the 4-D case, cannot be performed later once the moment has passed. Therefore, it is important to consider all issues carefully.

Required survey accuracy. A commonly held misconception outside the

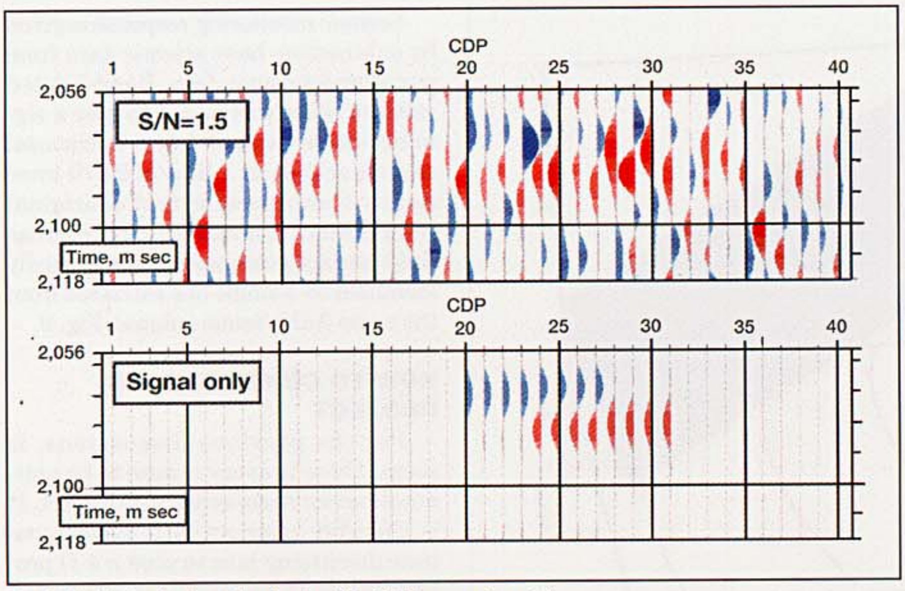

Fig. 9. Vertical seismic section for line 10 of 3-D reservoir model.

seismic community is that seismic data has a lateral resolution, limited by Fresnel zone size—typically 100s or 1,000s of meters. While it is true that absolute lateral resolution of seismic data depends on data frequency content, it can be shown that after migration—a final processing step—lateral resolution is much finer (typically 10s of meters).

Recent studies have shown that at seismic frequencies, this resolution is hardly affected by positioning errors of the size expected from today's navigational techniques. Hence, not only is conventional seismic resolution already finer than required by most simulation models, but is also probably adequate for most 4-D projects.

Full or partial field? It is sometimes argued that it is only necessary to collect data in areas of expected production problems and that fluid positions in unsurveyed areas can be implied from the model's continuity needs. This approach certainly cuts survey costs but recent field evidence shows that it may be a false economy. It puts unwarranted constraint on possible outcomes to the extent that problems in unexpected areas are completely unsurveyed and often unresolvable by modeling.

Permanently buried vs. conventional receivers. There are advantages and disadvantages for each of these options, all applicable in both land and marine environments. Factors in favor of the buried option include:

- Certainty of knowing that the position of one end of seismic raypath is exactly repeated between surveys. It is still necessary to allow for uncertainties in raypath's source-end position.
- Subsequent speed in reacquisition—since no resurveying of receiver location is required.
- Possible overall cost advantages during project life. Some buried equipment failures over the project period might make this the more-expensive option. Equipment reliability must be carefully considered and responsibility for repair divided appropriately.

For the surface option, advantages include:

- Access to best technology. A currently held misconception is need to stay with a single set of acquisition and processing parameters throughout entire 4-D project life. Since project life may be 10 years or more, it is not realistic to stay with a decade-old technology. Processing and analysis technologies are being developed to account for differences in survey vintages.
- Flexibility to modify survey geometries and parameters as project objectives and problems mature.
- Processing methods already exist to allow for small residual positioning differences between surveys. These techniques derive information from the vast amount of information in 3-D surveys that are not expected to change between survey dates.

Table 3. Feasibility study considerations

- **Expected reservoir conditions**
  - — Shape and advance of displacement fronts
  - — Reservoir layering
  - — Fluid types
  - — Production mechanism
  - — Fluid flow barriers—tar mats, sealing faults, tight porosity
  - — Local problems—coning, etc.
- **Modeling and data review**
  - — Simulate expected fluid/pressure/temperature changes
  - — Compute expected seismic changes
  - — Examine vertical and horizontal resolution required and available
  - — Estimate observed noise—random and systematic
  - — Estimate repeatability of seismic data
  - — Review special considerations—access, seasonal, etc.
  - — Estimate economic benefit
  - — Recommend appropriate parameters and course of action

In either case, it is important to be aware that it is final seismic data quality that is important. Although there is no doubt that 4-D requires high-quality data, there may be little advantage in spending excess field effort and cash to obtain pristine raw field data without first considering the immense power of current processing technology to improve data quality.

Experience on land with buried vs. conventional surface receivers has shown that raw field data quality from buried receivers is normally superior but that, after processing through to 3-D migration, there is little to differentiate between the two data sets. This trend is expected to continue as more R&D money is spent on processes to improve conventional seismic images in poor data areas.

Existing 3-D data use. Successful 4-D projects have already been carried out where significantly different data vintages acquired from different contractors have been pieced together. The data sets were used because they were the only 3-D data available for the field at the required calendar time—any adequate data being better than no data. Many modern 3-D surveys, and especially those collected with stratigraphic targets in mind, may be of adequate quality to act as the base survey for a 4-D project. In fact, it may be the only way to obtain a pre-production data set.

Another possible source is speculative data inventories from a seismic contractor. In either case, existing data value depends on specific details of the reservoir, its environment, and parameters and quality of the data.

Data collection intervals. How often should data collection be repeated? This is one of the most important results to come from a feasibility study. The criteria to use should be to collect sufficient data to answer the engineering problem. This is constrained by knowing that companies can never go back again if data is not collected at the correct time.

It is important to understand that 4-D is not a technique to apply once a disaster has happened; it is a technique to prevent the disaster. In this regard, it is similar to having regular X-rays at the dentist.

FUTURE DIRECTIONS

Application of the 4-D method is expected to become more widespread as its huge potential financial impact becomes apparent. Many 4-D projects have already been successful, but 4-D is at the proving stage where 3-D was about a decade or more ago.

Technology can be expected to improve dramatically over the next few years, spurred by economic incentive to get more hydrocarbon production from today's reserves. Among developments to be expected is a general reduction in cycle time of the entire system, to make results more useful for day-to-day field management.

Data acquisition. In data acquisition, greater use of 3-component recording and the development of reliable very-deepwater ocean-bottom cables can be expected.

Data processing. Processing of diverse data sets to a common model will become commonplace, i.e., data collected with completely different parameters and at different times will be integrated to conform to a single earth model. The current method of independently processing individual surveys will be replaced by methods in which multiple surveys, of different vintages, are processed together so as to reduce noise and emphasize true differences.

Data analysis. Already witnessed have been initial trials of combined inversion techniques, where all data vintages are combined into a common model in which only fluid parameters are allowed to vary. There will be a gradual move from qualitative to quantitative data analysis. Initially, this will take the form of explicit inclusion of uncertainties in results.

The move to quantitative results will require more advances in rock physics analysis. A key to 4-D analysis is ability to perform "fluid substitutions," i.e., to estimate seismic response of rock if its fluid content were changed. A great deal of work has been done in this field, notably by a few outstanding universities, but these studies still need to be pushed farther.

Integrated technologies/software. Even more closely integrated software packages are expected, with great emphasis placed on casual users. As computing platforms get faster, and parallel processing becomes even more familiar, simulation and seismic grid granularity will become similar, causing to the eventual disappearance of need for large amounts of upscaling and downscaling. **wo**

The author

Biography and photo of Geoff King are included in Part 1 of this article.