Related Article

4-D seismic improves reservoir management decisions

Part 1—Introduction to two-part article that describes how new time-lapse 3-D technology provides reliable information about fluid distribution in the reservoir

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Advances in seismic technology now make it possible to obtain reliable information about fluid distribution in reservoirs, areally and with respect to depth. This information can help provide better decisions and simulate various options to optimize production, improve oil recovery and reduce costs. Integral to these advances are 4-D or time-lapse 3-D seismic surveys.

During the last decade, many successful seismic reservoir monitoring case studies covering diverse geologic and reservoir conditions have been disclosed. This two-part article explores the major issues and considers the various stages needed to get a successful 4-D project underway. Topics introduced in Part 1 are:

- What is 4-D
- Its benefits and uses
- How it works, and
- An introduction to data analysis—what is expected of 4-D.

INTRODUCTION

Since the mid-1980s, 3-D seismic technology use has progressed from providing accurate structural pictures, to defining stratigraphic description. Now, when integrated with well log, core and other petrophysical and production data, it can be used for reservoir characterization. Just as 3-D seismic has improved understanding of hydrocarbon storage, seismically enhanced 4-D reservoir monitoring offers the potential of improved understanding of hydrocarbon recovery.

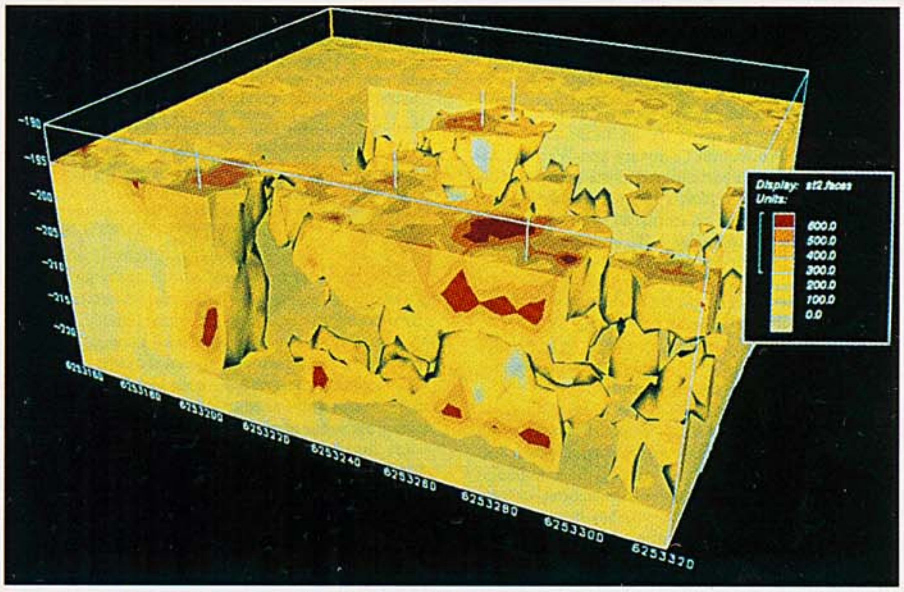

Fig. 1. 3-D volume display of velocity difference between base survey and monitor survey number 2. Units are in meters per second.

Recovery improvements. Seismic information, in combination with more traditional reservoir monitoring and management technologies, can help reservoir engineers adapt field development to suit complexities of each reservoir. The end result is increased reserves produced at a lower cost. Recent oil company estimates have valued potential net profit improvements of up to \$2.5 billion, depending on field size and the stage at which 4-D is initiated.

Characteristics and limitations. Successful 4-D results disclosed to date have been from a wide range of environments and conditions—onshore and offshore, both carbonates and clastics. Results cover a range of recovery mechanisms—steam and fire floods, miscible solvent floods, CO_2 injection, conventional waterfloods, gas injection and gas storage, Figs. 1–2. In all these diverse situations, projects have had one important thing in common—they have all been essentially qualitative.

Comparisons of spatial predictions from reservoir simulation with observed seismic anomalies, and visual comparison of modeled seismic response with seismic trace data have been used to allow manual updates of reservoir models; thus introducing more detail and accuracy. Even this limited analysis has proven valuable, resulting in better fluid flow predictions and hence, improvement in future reservoir performance.

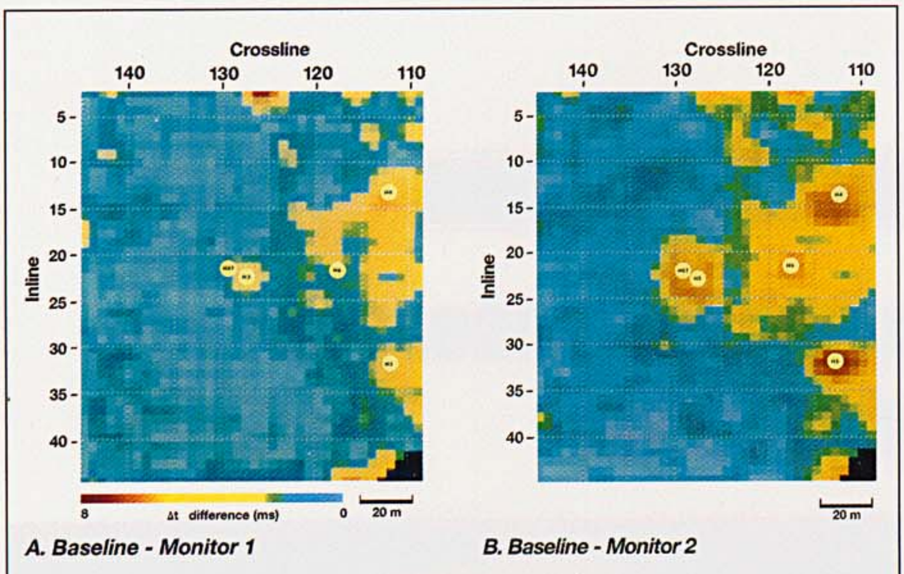

Fig. 2. Push down maps illustrating areal distribution of heated tar sands. A. Baseline—Monitor 1, B. Baseline—Monitor 2

Table 1. 4-D nomenclature: synonyms or hierarchy?

- **Seismic Reservoir Monitoring (SRM)**
  - Use of seismic data to monitor behavior within a reservoir
  - Component of a comprehensive monitoring campaign
- **Time-Lapse Seismic (TLS)**
  - Use of repeated seismic surveys
  - Subset of seismic reservoir monitoring
- **4-D Seismic (4-D)**
  - Use of repeated 3-D seismic surveys
  - Subset of time-lapse seismic

WHAT IS 4-D?

Even though seismic reservoir monitoring is a relatively new technique, there is already a set of confusing terminology that needs to be clarified. As shown in Table 1, the terms Seismic Reservoir Monitoring (SRM), Time Lapse Seismic (TLS), and 4-D Seismic (4-D) should form an ordered hierarchy. Sometimes industry uses these three terms as synonyms and sometimes as a hierarchy.

Awareness of this possible confusion provides the ability to identify what is being referred to, and the actual semantics should not be a problem. In a later section, it will be shown that there are distinct advantages from taking the repeat 3-D approach. The term 4-D will be used throughout this article as shorthand for the entire range of this seismic monitoring technique.

4-D and its benefits. 4-D uses a series of repeated 3-D seismic surveys over a field; the fourth dimension is "calendar time"—the interval between surveys. Differences between successive seismic surveys indicate changes in producing reservoirs, such as fluid movement, or pressure and/or temperature changes.

Analysis of these differences allows fluid-front surfaces to be tracked within reservoirs as a function of time. Tracking reservoir fluid position during production provides advanced warning of production behavior changes that may be used to prolong well life and/or change production schedules to enhance ultimate recovery.

Conventionally, wells provide most data available during production. 4-D can provide similar data and provide it throughout the interwell space. Great economic benefits can be expected by identifying unswept pools using 4-D.

Reservoir monitoring with seismic. Inclusion of seismic information in a reservoir monitoring campaign has many advantages. Most important, only seismic data can provide necessary information in the interwell regions, where no conventional reservoir monitoring tool can reach. Integration of this extra data into engineers' models provides extra constraints on the situation, which results in more accurate and detailed reservoir models, Fig. 3.

Seismically monitored field simulations differ from other simulations because they must account for spatially distributed saturation information. This introduces an additional type of data (seismic) into an accepted reservoir engineering procedure—reservoir monitoring. It must be made clear that seismic data is complementary to normal monitoring methods. Potentially it provides valuable extra information, but it is the timely integration of all data types into a consistent reservoir model that results in added value.

Integration to make 4-D work. Successful implementation of a 4-D project relies on integration of several technologies and organizations. Project success requires that a change in fluid conditions (saturations, pressures, temperatures) within a reservoir will change the reservoir's seismic response. Response changes may be small when compared to other factors, hence, good quality seismic data acquisition and processing are necessary. Moreover, acquisition and processing parameters must be chosen to enhance fluid indicators.

If taken alone, seismic response to changing fluid conditions is ambigu-

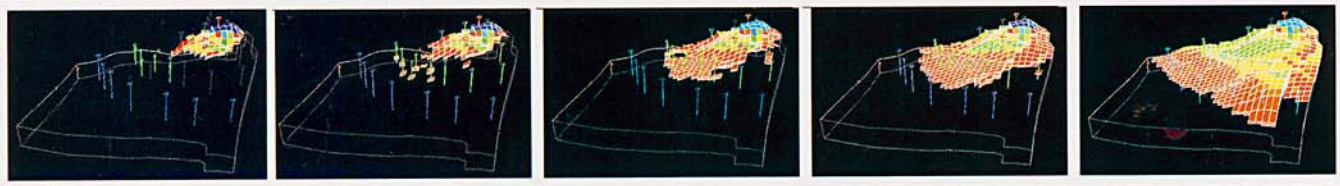

Fig. 3. Different stages of gas cap expansion due to primary depletion. Such monitoring makes it easier to identify areas where gas overrunning may lead to difficulties in managing the reservoir.

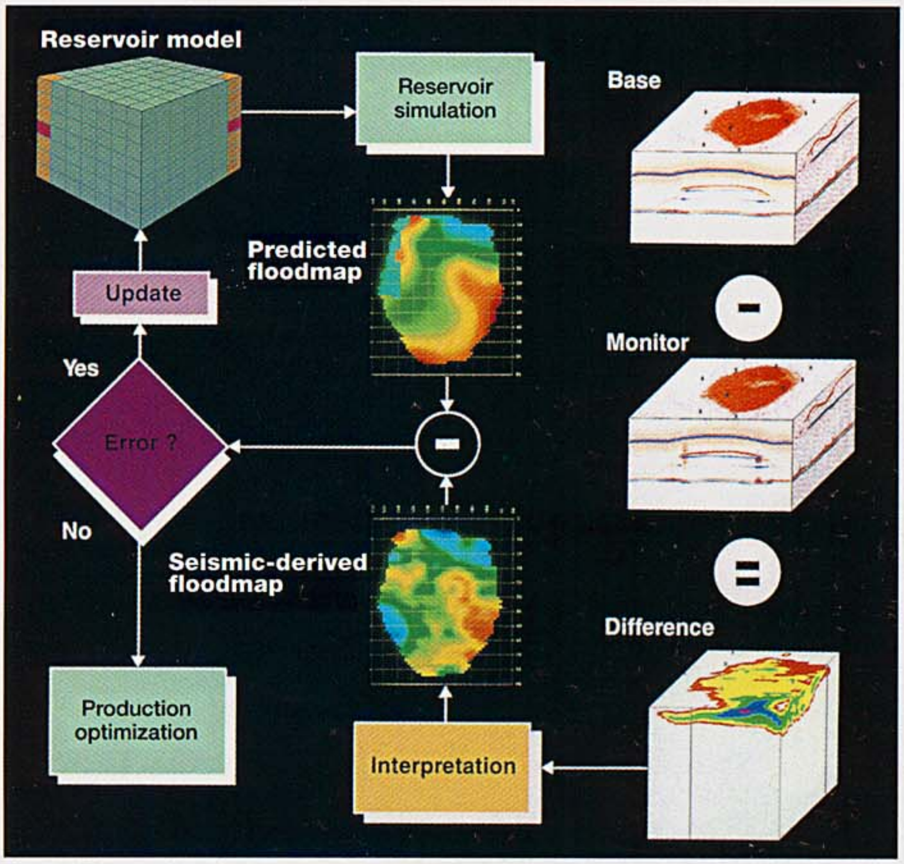

Fig. 4. 4-D reservoir monitoring process shows need for feedback loops and hence need for organizational and software integration.

ous. In many cases, these fluid effects can be resolved, provided an initial reservoir description has been completed and reservoir simulation is available. Hence, the initial simulation model is necessary so the second and subsequent seismic may be interpreted in terms of fluid changes. The entire process can be viewed as a continuous feedback loop, Fig. 4.

It is imperative that seismic, geologic and engineering software tools are all compatible and that common models may be used by all geoscientists involved. Need for these interdisciplinary decisions and analyses forces the project team to be truly integrated. This may be the first time that the nature of data analysis has dictated team integration.

4-D DATA ANALYSIS

As 4-D is a seismic differencing technique, it should be realized that several essential criteria need to 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.

In next month's article the author will examine how these factors affect the contribution of seismic data to reservoir monitoring, suggest how to start a 4-D project, and comment on what improvements in relevant technology can reasonably be expected in the near future. *WO*

The author

Geoffrey King *conducts reservoir description research at Western Geophysical in Bedford, England. His current interests are data integration, interactive seismic interpretation technology and seismic reservoir monitoring. Author of several papers on geophysical signal processing and reservoir description, King holds a BS degree in physics from Bristol University and a PhD in geophysics from the Royal School of Mines, London.*