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Time-lapse seismic reservoir monitoring

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SUMMARY

Time-lapse seismic reservoir monitoring has advanced rapidly over the past decade. There are currently about 75 active projects worldwide, and more than 100 cumulative projects in the past decade or so. The present total annual expenditures on 4-D seismic projects are on the order of $50–100 million US. This currently represents a much smaller market than 3-D seismic, but the use of 4-D seismic has grown exponentially over the past decade and is expected to continue to do so.

The major opportunity provided by 4-D seismic data is its ability to image fluid flow in the volumetric region not sampled by wells. Fluid flow is thus directly imaged by 4-D seismic data, rather than solely predicted by flow simulation. In contrast to 3-D seismic, which is an exploration and development tool, 4-D seismic is quickly becoming a vital engineering reservoir management tool. Time-lapse seismic images can identify bypassed oil to be targeted for infill drilling, and add major reserves to production to extend a field's economic life. 4-D seismic can monitor the progress of costly injected fluid fronts (water, gas, steam, CO_2, etc.) that can save hundreds of millions of dollars in optimizing injection programs. 4-D seismic can map reservoir compartmentalization and the fluid-flow properties of faults (sealing versus leaking), which can be extremely useful for optimal design of production facilities and well paths in complex reservoir flow systems.

Rock physics measurements made in the mid 1980s at Stanford University predicted that thermal enhanced oil recovery (EOR) processes, especially steam injection, should be visible in repeated surface seismic surveys. The first field tests of the concept were conducted in the mid-late 1980s and early 1990s in Canada, the US, and Indonesia at several steam injection sites and one fireflood site. These early projects showed conclusively that large anomalies related to steam and heated gas were indeed strikingly visible in time-lapse seismic data. This was followed by projects to monitor isothermal gas-fluid movement, particularly by early work in the North Sea and Paris basin. These gas monitoring experiments were also successful, but it became clearer that the interaction of the reservoir rock, fluid, and gas components could enhance or degrade the time-lapse seismic signal depending on specific reservoir conditions. The past five years has seen an increased focus on monitoring of oil-water systems. Here, the 4-D seismic technique works well in unconsolidated high-porosity sands with high gas-to-oil ratio (GOR) oil and salty brine, works moderately well in somewhat consolidated porous rocks with live oil, and is technically challenging in applications involving dead oil or stiff rocks like carbonates or cemented sandstones, independent of the rock's fluid content.

It is now recognized that successful monitoring of fluid flow depends on critical reservoir rock and fluid properties, pressure and temperature values, and high-fidelity seismic acquisition, processing, and interpretation. Much work has been done on feasibility risk analysis, and on modeling time-lapse seismic data from 3-D heterogeneous reservoir models, rock physics data, and flow simulation results. Acquisition and processing service companies continue to enhance repeatability and accuracy of their field hardware and processing algorithms. Multicube quantitative interpretation and inversion techniques for time-lapse seismic data are evolving, especially in ways that integrate 4-D seismic data with other reservoir data types such as well logs, pressure, temperature and saturation data, core measurements, flow simulations, and production data. Current research and the road ahead involves ocean-bottom and borehole seismic, permanent sensor installations, real-time reservoir monitoring instrumentation, shear waves, nonseismic techniques (such as electromagnetics, gravity and radar), inversion for fluid-flow properties with uncertainty analysis, reservoir data integration, seismic history matching and reservoir model updating.

INTRODUCTION

Time-lapse seismic reservoir monitoring is the process of acquiring and analyzing multiple seismic surveys, repeated at the same site over calendar time, in order to image fluid-flow effects in a producing reservoir. If each survey is "3-D seismic," then the resulting set of time-lapse data is often termed "4-D seismic," where the extra fourth dimension is calendar time. In addition to 4-D seismic, there are other viable methods of time-lapse seismic monitoring including repeated 2-D surface seismic, surface-to-borehole VSP, and borehole-to-borehole crosswell seismic geometries. There are interesting new developments in nonseismic monitoring techniques, including

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time-lapse electromagnetic surveys, gravity data, and satellite and ground-penetrating radar data. The primary focus of this article will be on the 4-D seismic technique.

The goal of seismic reservoir monitoring is to image fluid flow in a reservoir during production. This is possible because, as fluid saturations and pressures in the reservoir change, the seismic reflection properties change accordingly. The geology is assumed to be time-invariant during production. This may not always be the case as demonstrated by dramatic reservoir subsidence, compaction, and porosity loss in some California and North Sea reservoirs, for example. Whereas the geology is assumed to be constant, fluid-flow variables such as saturation, pressure, and temperature are highly time variant during production. A single 3-D seismic data set images reflectors that contain combined information about both the static geology and the dynamic fluid-flow properties, but the coupled rock and fluid contributions are difficult to separate. In two or more time-lapse 4-D seismic data sets, difference images can be constructed in which, to first order, the geology part subtracts out since it is time invariant, to produce images of the time-variant fluid-flow changes. This is the basic concept of time-lapse seismic reservoir monitoring.

ROCK PHYSICS AND 4-D SEISMIC FIELD DATA STUDIES

The idea of repeating seismic surveys to monitor changes in a producing reservoir is an old one (Sam Allen, personal communication, 1996). However, the first quantitative data came from rock physics measurements at Stanford University in the mid 1980s. These laboratory measurements on heavy-oil saturated core samples showed large decreases in seismic rock velocity when the viscous oil was heated (Nur et al., 1984; Wang and Nur, 1986, 1990; Nur, 1989). If this thermal effect is further enhanced by the presence of free gas, as in steam injection, dramatic velocity decreases of up to 40% were measured. Although highly controversial at the time, even to the point that the Stanford rock physics research group lost some skeptical sponsors (Amos Nur, personal communication, 1991), these rock physics predictions have now been validated by many 4-D seismic field data projects at steam injection sites worldwide. Notable successful field tests of monitoring steam injection were conducted by Pullin et al. (1987), Eastwood et al. (1994), Lumley (1995a, b), and Jenkins et al. (1997). Greaves and Fulp (1987) received a Best Paper in GEOPHYSICS award for their careful experiment design and analysis of a 4-D seismic project to monitor a fireflood EOR process. The presence of free gas in a reservoir without an associated temperature change can also significantly decrease the rock's seismic impedance, as shown by the early lab measurements of Domenico (1976). This leads to the possibility of monitoring gas-fluid contact movement and injected gases such as methane, air, and CO_2. Notable gas monitoring projects include a North Sea gas cap expansion project by Johnstad et al. (1995), a Paris basin gas storage project by Meunier and Huguet (1998), and a west Texas CO_2 injection project by Harris et al. (1996).

Monitoring oil-water systems is a more difficult technical objective because the seismic impedance contrast between oil- and water-saturated rock is often much smaller than the free gas or heated oil effect (Wang et al., 1991). The most successful oil-water monitoring candidates involve high-GOR oil and salty brine in soft unconsolidated high-porosity sands (e.g., Anderson et al., 1997; Sonneland et al., 1997; Ebrom et al., 1998; Hirsche and Harmony, 1998; Lumley et al., 1999). Medium risk candidates involve oil and water in average-porosity consolidated rocks (e.g., Moore, 1997; He et al., 1998; Johnston et al., 1998). The most difficult candidates involve dead oil and water, or stiff or low-porosity rocks such as carbonates or cemented sandstone, independent of the pore-fluid content (Johnstad et al., 1995; Hirsche et al., 1997; Wang et al., 1998; Walls et al., 1998; Talley et al., 1998). Lumley and Behrens (1998) discuss the practical issues relevant to successful monitoring of oil-water and other reservoir fluid-flow systems.

FEASIBILITY, ACQUISITION, AND PROCESSING

The more elusive time-lapse fluid signal for oil-water systems has placed an increased design emphasis to extract the best signal-to-noise ratios possible from 4-D seismic data by performing prior feasibility and modeling studies, implementing special acquisition techniques, and designing custom time-lapse data processing algorithms and workflows.

For high-risk projects, it is advisable to perform a rigorous feasibility study before acquiring 4-D seismic data. Lumley et al. (1997) received the Best Paper award at the 1996 SEG meeting for developing a quick spreadsheet analysis technique to assess the risk of 4-D seismic projects. Further feasibility analysis requires log analysis, rock physics measurements, and seismic modeling from flow simulations. Moore (1997) modeled various degrees of waterflood in a North Sea reservoir as 1-D amplitude-variation-with-offset (AVO) gathers from well logs. Rock physics measurements can be conducted on core samples representing expected reservoir saturation, pressure, and temperature conditions to predict changes in seismic velocity and density (e.g., Wang, 1997; Hirsche et al., 1997). Lumley et al. (1994) modeled 2-D seismic data from flow simulations to assess the feasibility of monitoring horizontal-well oil production from a thin oil zone in the North Sea Troll reservoir. Lumley and Behrens (1998) performed 3-D seismic modeling with heterogeneous earth models, history-matched flow simulations, and rock physics core measurement data.

Advances in seismic acquisition repeatability have led to enhancements in 4-D seismic signal-to-noise ratios. Repeatability studies have shown that small changes in tides, water table, ambient noise conditions, near-surface properties, source and receiver positioning, etc. can have significant deleterious effects on 4-D seismic data (Moldoveanu et al., 1996; Beasley et al., 1997; Ebrom et al., 1997; Rennie et al., 1997; El-Emam et al., 1998; Porter-Hirsche and Hirsche, 1998). Some of these acquisition effects can be reduced by minimized streamer cable feather, improved design of ocean-bottom and land positioning methods, and installation of permanently emplaced receiver arrays. Some acquisition effects, like water table variation, may not be addressed by improved acquisition design, and instead may need to be addressed in the time-lapse data processing stages.

Processing of multiple 3-D seismic cubes recorded at the same site has brought an awareness that our 3-D processing methods may not be as accurate as we once thought. Contrary to our algorithm theories, model-based and surface-consistent processing techniques that should give repeatable results on multiple 3-D seismic cubes often do not. On the other hand, image events that are not comprehended in an original 3-D survey, and so categorized as "noise," are found to be highly repeatable in subsequent surveys, and therefore must be real signal, not noise, to our surprise. The goal of 4-D seismic data processing is to obtain excellent 3-D seismic images for each data set, and simultaneously optimize time-lapse repeatability in regions of no subsurface change. Lumley (1995a) processed six 3-D prestack time-lapse data sets in this manner by developing custom 4-D processing algorithms and optimizing processing parameters to obtain high-quality 3-D images while minimizing nonreservoir 4-D image differences. Others have developed similar custom processing tools, which have generally come to be known as "cross equalization" in the industry. The main purpose of 4-D seismic cross-equalization tools is to coregister repeat survey data and equalize spectral bandwidth and phase, amplitude gain variations, differential statics, and event positioning to optimize 4-D seismic difference anomalies. Examples of 4-D seismic cross equalization are given by Ross et al. (1996), Altan (1997), Eastwood et al. (1998), Harris and Henry (1998), and Rickett and Lumley (1998).

INTERPRETATION AND ANALYSIS

Once optimal 4-D seismic difference anomalies have been obtained from processing, full time-lapse interpretation and analysis can begin. This usually starts with a calibration step in order to tie time-lapse changes in the seismic data to time-lapse changes in other reservoir data types—well logs, core measurements, pressure or temperature data, production history, etc. (Ecker et al., 1999). This calibration step, which usually involves modeling seismic data from well data, builds confidence that the 4-D seismic changes are real and not an artifact of nonrepeatable acquisition and processing methods. Once calibrated, 4-D seismic data can be interpreted in terms of "what do the time-lapse seismic anomalies mean?" The multicube interpretation is qualitative at this stage in the sense that anomalies are often inferred to be changes in oil, water, or gas saturation (Anderson et al., 1997; Sonneland et al., 1997; He et al., 1998). However, the interpretation can be complicated by changes in other dynamic properties, like gas saturation, pressure, or temperature (Lumley, 1995a, b; Jenkins et al., 1997), and geologic properties like porosity or rock compressibility may change unexpectedly due to compaction (Walls et al., 1998) or fracturing (Johnston et al., 1998).

To reduce the interpretation ambiguity, it is preferable to make a quantitative interpretation by inverting the 4-D seismic data to produce maps of the changes in the dynamic properties directly. This is an active industry research topic. Lumley (1995a, b) and Jenkins et al. (1997) estimated temperature and steam saturation maps from the Duri steam-injection pilot. Sonneland et al. (1997) used an attribute clustering technique to make maps of oil, water, and gas saturation from the Gullfaks project. Lumley et al. (1999) estimated oil, water, and gas saturation maps by seismic modeling transforms at the Meren field, offshore Nigeria. Tura and Lumley (1998, 1999a, b) and Landro (1999) present methods to simultaneously estimate fluid saturation and pressure changes using time-lapse AVO inversion. An important part of estimating dynamic properties is uncertainty analysis. Ecker et al. (1999) estimated steam thickness and temperature maps with uncertainty values in order to generate minimum or maximum property value maps, but much more research remains to be done.

After interpretation and analysis, a reservoir management recommendation should be made. More than at any time in the past, seismic technology has the potential to influence engineering decisions by using 4-D seismic data to monitor reservoir fluid flow. Thus, an important final step in the work flow is to make recommendations based on the 4-D seismic analysis. At the Duri steam injection project, 4-D seismic analysis plays an ongoing role in reservoir management by prioritizing well workovers, and adjusting production and injector well configurations to optimize oil recovery and the placement of injected steam (Waite and Sigit, 1997). Horizontal wells have been drilled on 4-D seismic results to target bypassed oil or avoid revealed water-swept zones (e.g., Anderson et al., 1997; Sonneland et al., 1997). More published case studies are needed to quantify the economic benefit of 4-D seismic technology, but common sense indicates the financial leverage of this technology is clear.

THE ROAD AHEAD

4-D seismic technology is advancing exponentially. The road ahead involves closely coupling 4-D seismic data into the reservoir modeling and management loop (Lumley and Behrens, 1998). The first step is a "seismic history match." This term is a modification of the petroleum engineering practice of a production history match, in which a reservoir model is found such that, after flow simulation, the predicted flow at wells matches the measured amount of fluids produced in the wells. Similarly, in a seismic history match, a reservoir model is found such that, after both flow simulation and seismic modeling, the synthetic seismic data additionally match the recorded field seismic data. If the predicted seismic data does not match the actual field data, the residual seismic error can be used to update the reservoir model to improve the data fit. This can be done in a manual workflow or with an automatic update algorithm (such as the method of conjugate gradients). Either way, reservoir model updating is a time-consuming iterative process that is very much an active research problem. Published examples of seismic history matching and reservoir model updating include Huang et al. (1998), and Lumley and Behrens (1998).

A final thought on the road ahead is the trend towards the fully instrumented oilfield. This concept involves wiring up an oil reservoir with every imaginable monitoring sensor in boreholes and on the earth's surface. The monitoring data would be available in near-real time so that the asset team could make a reservoir management decision and track its impact with continuous monitoring feedback. Many of the instruments for such permanent sensor applications will use fiber optics to overcome the long-term reliability concerns of electronic systems. Seismic monitoring information may not need to be as continuous and real time as borehole pressure and temperature sensors since the 3-D reservoir volume at seismic resolution does not change as fast. Soon, low-cost multicomponent P- and S-wave seismic sensors will be available to emplace in both boreholes and along the earth's surface to provide on-demand 3-D snapshots of the reservoir's condition. These seismic surveys, while probably not continuous or real time, will undoubtedly be demanded at short notice with minimum delay from the time of acquisition to the delivery of final images. These challenging cycle time and geometry requirements will drive the development of a new wave of seismic acquisition hardware; processing, inversion, interpretation, and analysis software; and multidimensional visualization capabilities for future real-time time-lapse seismic monitoring.

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