4-D reservoir monitoring, the business driver

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4-D reservoir monitoring is a cost-effective way to expand revenues throughout the development history of reservoirs through tracking and monitoring of oil, gas and water drainage patterns over time. Bypassed pay can then be targeted and remediation programs planned, increasing recovery efficiency of oil-in-place to previously unheard-of levels that are expected to approach 70% by early next century. This added efficiency comes from a fundamental "paradigm shift" in the way that oil fields are produced—"spacetime" monitoring of oil fields.

HISTORICAL IMPORTANCE OF 4-D

There is strong precedent in other disciplines for a belief that a transition from 3-D to 4-D will fundamentally change the business of oil and gas production. We need look only to the introduction of 4-D into physics at the turn of the 20th Century. Hermann Minkowski, working on the theoretical physics of the relation between space and time, termed relativity, wrote in 1908, "Henceforth, space by itself, and time by itself, are doomed to fade away into mere shadows, and only a union of the two will preserve independent reality. If space and time are merged as part of a four-dimensional whole (three dimensions of space and one of time), an absolute objective reality suddenly appears."

Einstein then seized upon this 4-D paradigm shift, spending the next 10 years defining his new General Theory of Relativity, and the rest is history. This example has relevance to oil and gas production in that the 3-D worlds of geophysicists, geologists, and reservoir engineers—previously thought of as separate disciplines—in fact always coexisted within one true reality—the 4-D spacetime continuum of the oil and gas reservoir.

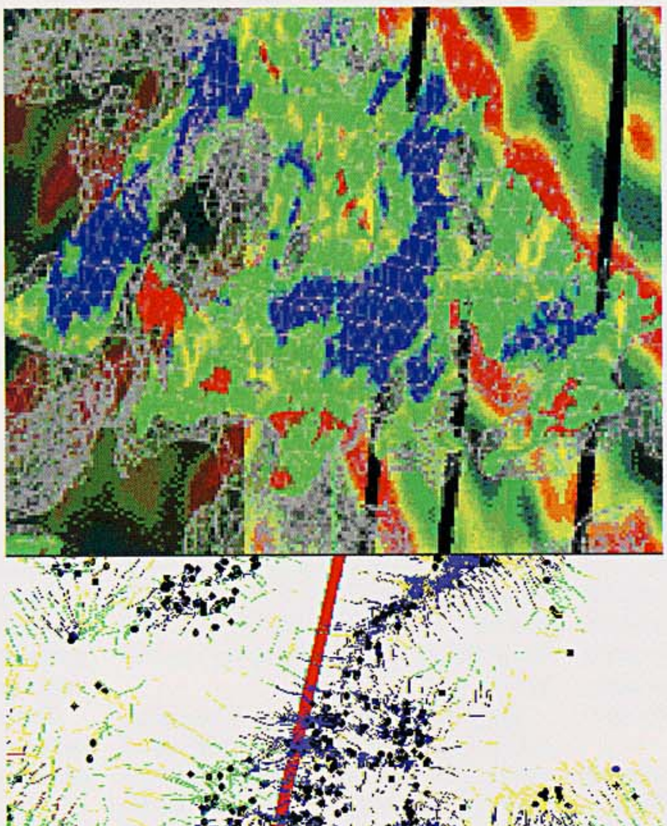


Fig.11. 4-D analysis in this reservoir indicated that water (blue) had quickly broken up-dip into producing well (top). A 4-D drainage simulation indicated that water channeling and thieving by the most up-dip well (bottom) had left considerable bypassed pay (green in top image).

THE BUSINESS DRIVER

This new 4-D view of reservoir production introduces spacetime imaging of seismic and petrophysical changes into our current 3-D world of the structure and stratigraphy of oil fields. The result is better capability for tracking and understanding the complexity of true drainage patterns of oil and gas into wells. That drainage, in the previous 3-D paradigm, was thought to be governed by relatively simple physical laws: gravitationally-driven flow of "light" liquids and gas "uphill" toward well perforations. However, 4-D is an emerging technology that is just now beginning to be understood both from a technological and a business perspective. Along the way, we will surely better understand the relation-

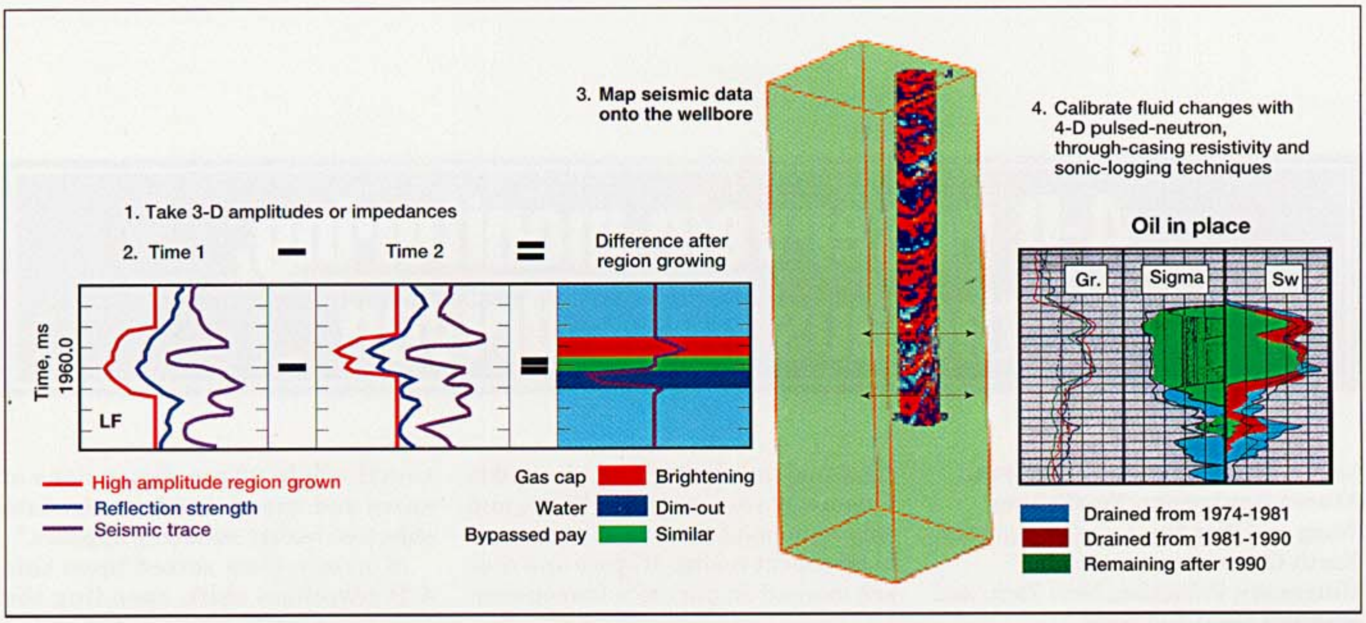


Fig. 12. The 4-D seismic differencing technique matched to cased-hole logs.

ships among, and within, fault-bounded compartments in the presence of realistic heterogeneities in permeability, pressure and connectivity, both within reservoirs and in the aquifer beyond.

The business driver of 4-D technology development is clearly production of large volumes of new oil from old fields. This increase in recovery efficiency of known fields is extremely important to the evaluation of oil companies themselves—because this added 4-D pay becomes newly booked reserves. As such, 4-D has as substantial an effect on an oil company's reserves inventory and corporate worth as do new exploration discoveries. In fact, recovery of 10% more oil from a company's known fields can increase the company's overall reserves base by several percent.

For example, Elf has discovered new deepwater reserves off West Africa that are estimated to raise its worldwide reserves booking by 8%. If application of 4-D technologies during production of these fields increases recovery efficiency by 20%, then that added oil will further increase the company's worth by an additional 2% company-wide. This scale of potential impact of 4-D technologies applies to every company's worth!

A further business driver in this transformation to 4-D production management is that cost-cutting is nearing its limits in terms of production savings. Dwindling reserves and low replacement ratios are now convincing many oil companies that increased revenues are THE management requirement for the 21st century. 4-D's "spend more to make more" technologies are custom-made for this new production environment.

SPEND MORE TO MAKE MORE

4-D produces new oil at little added cost since infrastructure and development costs have already been absorbed by each field. That means the "spend more" downside risk is substantially less than the "make more" upside potential. Think of the cost/benefit analysis of applying 4-D to any field's pending abandonment. What if 4-D could delay abandonment by several years?

Because of such obvious benefits, 4-D is expected to add a multiple of nearly 20% to a company's Return-on-Capital Employed (RoCE), when applied to a company-wide portfolio of oil and gas producing properties. That is, if your company produces a current 12% RoCE, 4-D has the potential to increase it to more than 14%.

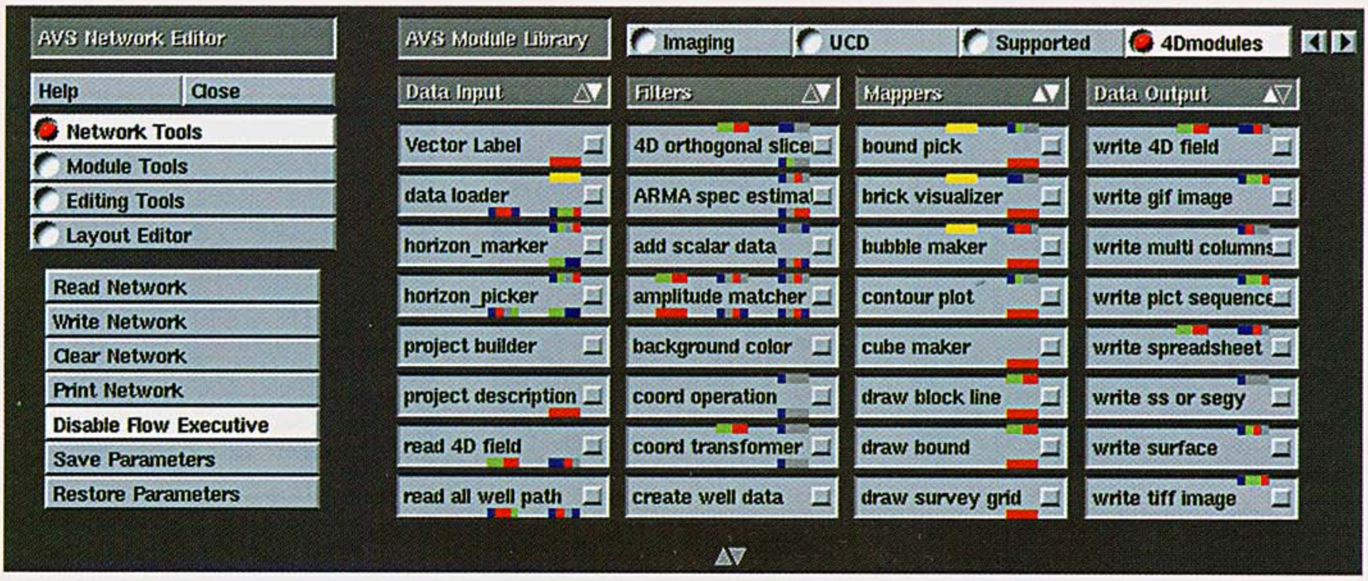
In fact, as with the introduction of 3-D, 4-D technology applications are currently being concentrated on the biggest fields now producing in the Gulf of Mexico, North Sea, Southeast Asia and West Africa. These high flowrate and high volume fields offer the initial "no-brainer" RoCE required to begin what will likely grow into an industry-wide 4-D reservoir monitoring movement, much like the acceptance of 3-D. In fact, expensive ultra-deepwater developments will require 4-D reservoir monitoring to validate reservoir simulations that are being counted on to succeed, or company share prices will suffer.

HOW AND WHERE 4-D INCREASES PRODUCTION

How do the applications of 4-D technologies result in increased production of oil and gas? In the process of delaying abandonment, 4-D produces additional drilling prospects targeted to recover bypassed pay. This optimization of new well placements, as well as its companion, intelligent scheduling of injection programs, have proved to be the biggest initial payout areas for 4-D monitoring.

Detection of production problems before they "hit" is another good example. 4-D allows mapping of water encroachment and coning. This gives the operator an opportunity to remediate before damage has occurred, Fig. 11. Tracking the efficiency of water sweep requires imaging of where water has migrated, and when. Often, an injector can produce fingering where water overruns oil production and beats it to up-dip producers. Alternatively, water may not make it to the oil front at all, going instead along the easiest migration path that sometimes is down-dip, or along-side, unswept production.

But remember, 4-D is not applicable to all fields. 4-D requires hydrocarbon fluid indicators that are observ-



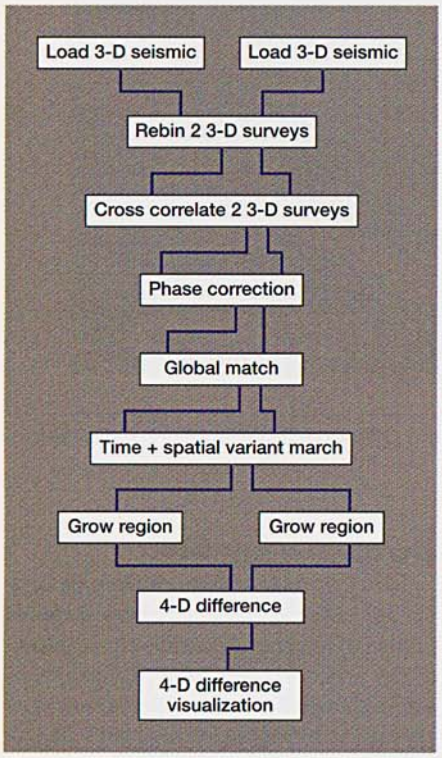


Fig. 13. 4-D software processes multiple 3-D seismic surveys to normalize power spectra. Regions are then grown about connected, high amplitude reservoirs before differencing identifies drainage changes and oil/gas/water front movement.

able in order to track drainage initially. Therefore, not all fields in the world are candidates for 4-D monitoring. Young, unconsolidated sands are the best fields to begin gaining 4-D monitoring experience, because this is where bright spots (indicating fluid or gas) were discovered in the first place. Both water and depletion drive reservoirs producing live oil should make excellent 4-D candidates in these locales. In hard-rock areas of the world—and in carbonates in general—gas, CO_2 and steam floods, as well as depletion drive reservoirs, are the most likely candidates.

4-D WORKFLOW

In a business sense, 4-D optimizes capital expenditures and increases the time-value of an operator's money. It has been said that reducing the number of dry holes does not actually add value to oil companies. However, 4-D workflow produces an interesting mutation of the "saving dry holes" mentality. Better located and better steered production wells, and injectors, will increase value because more, and better, "revenue" wells are drilled. It is, therefore, important to understand the differences between 4-D workflow and its predecessor from the 3-D interpretation world.

First and foremost, 4-D reservoir management is an engineering workflow, and as such, it must be responsive to timing constraints of modern oil field operations. It is of no use if wonderful new 4-D seismic information makes it into a field workflow three months after remediation was required. There must be, at the forefront of 4-D, a rapid analysis and response capability. And, since 4-D is the manipulation of vast volumes of geophysical, geological and engineering data, 4-D workflow is exemplified by a software system—just as 3-D workflow has come to be defined by Landmark, GeoQuest or CogniSeis software.

As a starting point, compare how seismic traces measure fluid changes over time with how cased-hole logs map the same features, Fig. 12. Seismic wavelets respond to the impedance contrast between oil and gas saturated reservoir rock at Time 1 and its water swept, and/or pressure depleted, remnant at Time 2. The "growth or shrinkage" of the acoustic region of the wavelet affected by drainage can be isolated, just as pulsed-neutron nuclear logs track variations in water saturation over time during workover logging programs. It is this calibration with wellbore data, production histories and pressure changes in wells, observed over time, that allows mapping outward from wells into full 3-D seismic volumes at Time 1 vs. Time 2.

4-D RAPID ANALYSIS SOFTWARE

In order to accomplish this differencing between new and old seismic traces acquired across reservoirs over time, 4-D rapid-analysis software workflow must have extensive tools to correct legacy 3-D seismic datasets for mismatches in amplitude, frequency and phase spectra in order to make them comparable, Fig. 13. It is here that an old dataset might be sent back to the computer center for reprocessing to better match a new survey. However, depending upon signal-to-noise ratio, filtering and spectral matching can often normalize datasets well enough to proceed with qualitative analysis of changes observed over time.

Then, tools for differencing and merging seismic changes with other spacetime data must be provided. In addition, 4-D software workflow must include tools for import and export into existing 3-D products such as

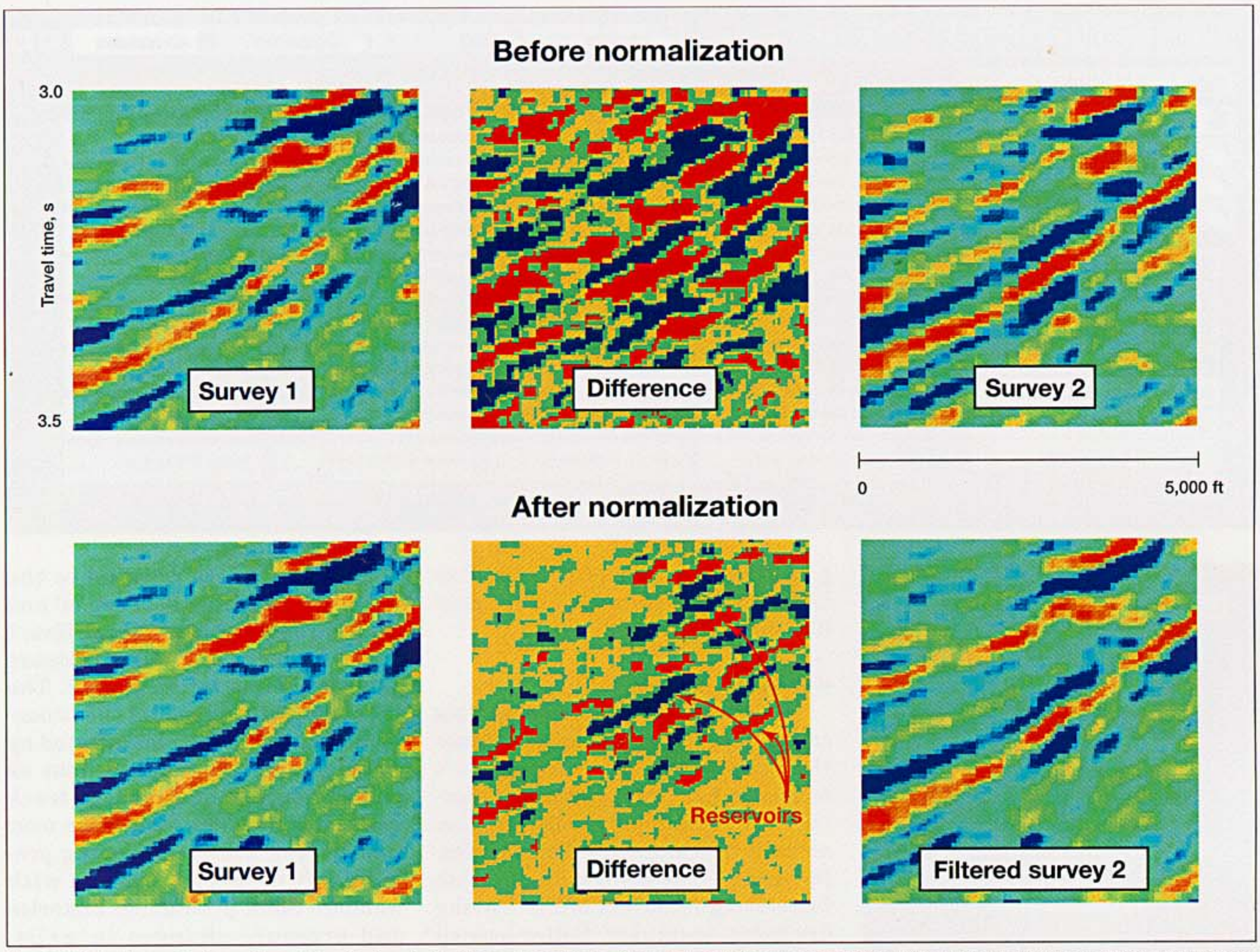


Fig. 14. Seismic amplitude sections before (top) and after (bottom) amplitude, frequency and phase normalization. Differences should be small (green) in bottom-center panel, except for reservoirs where change is shown in red (increase over time) and blue (decrease).

Landmark, GeoQuest, Tigress, Eclipse, VIP, etc. 4-D must then have tools, such as economic models and synthetic well placement options, for planning of future drilling and interrogation of various options for extending production.

The processing flow of 4-D rapid-analysis software must proceed from rebinning and reprocessing of multiple 3-D seismic datasets that are at the core of 4-D monitoring. Navigational errors and differences in bin spacing must be corrected. Procedures for amplitude, phase and frequency normalization—of separately acquired seismic datasets—are required to make them as closely matched as possible, Fig. 14.

Next, cross-correlation must be used to minimize spatial and time-varying phase changes inherent in separately acquired, and processed, seismic datasets. Phase matching across the volume yields both semblance information about the correlation between adjoining seismic traces, and often, empirical phase changes over time observed within reservoirs, Fig. 15. These normalization steps are completely different than 3-D workflow, and must be done before 4-D differences between spacetime snapshots can be computed.

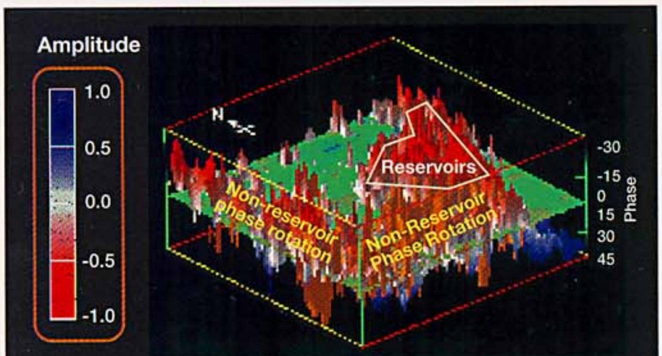


Fig. 15. Phase mis-match between two 3-D surveys shows two areas of misfit-edge effect and reservoirs.

4-D REGION GROWING

The 4-D datasets must then be converted to the seismic attribute domain before differencing can be done. However, analysis of these differences among multiple 3-D datasets requires special consideration because of the enormous size of each 3-D seismic survey. Differencing techniques, which have been perfected from far-field industries, are extremely useful for 4-D analysis of large, spacetime datasets.

Specifically, military and medical imaging technologies routinely deal with determining differences over time in large numbers of 4-D datasets. Consider repeated magnetic resonance imaging (MRI) of a brain tumor. Each week during treatment, the patient undergoes another MRI and the images are quickly differenced to deter-

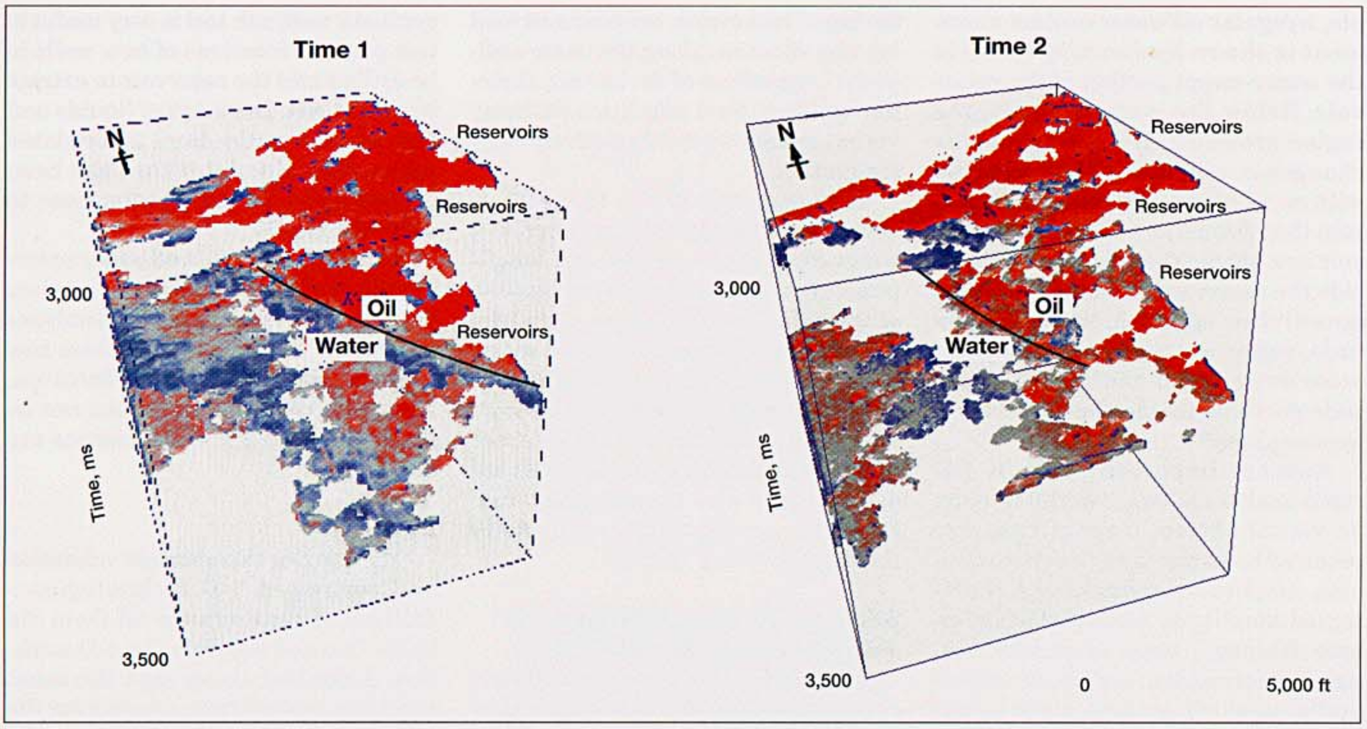


Fig. 16. High-amplitude regions within seismic cube from 3 to 3.5 sec.

mine shrinkage over time. Only the interconnected areas of change within the tumor are interrogated from Time 1 to Time 2. Techniques called "Region Growing" are used to link connectivity away from centers of the tumor.

In 4-D workflow, individual 3-D seismic datasets must also be region-grown around seed points of the highest amplitudes within each seismic dataset to obtain volumetric representations of hydrocarbon reservoirs, Fig. 16. The rest of each 3-D dataset is thrown out. Thus, a multi-Gigabyte 3-D seismic survey can be intelligently narrowed to the most important 100 Megabytes or so where the action (change-over-time) is located. In the meantime, features that are interconnected, often in complex 3-D ways, appear within each 4-D dataset.

In the example illustrated in Fig. 16, sandstone turbidite channels are visible near the top of the seismic cube in region-grown images from successive yearly interrogations of a deepwater turbidite oil field. Amplitudes within the channels increase over time because this is a depletion drive reservoir. Below that reservoir, a very active water drive reservoir shows the migration, with time, of an oil/water contact from west to east. Interference of shallower reservoirs must be taken into account in order to properly interpret drainage in deeper reservoirs that are directly beneath shallower pay.

Differencing and similarity techniques are then applied to the region-grown volumes, Fig. 17. In this exam-

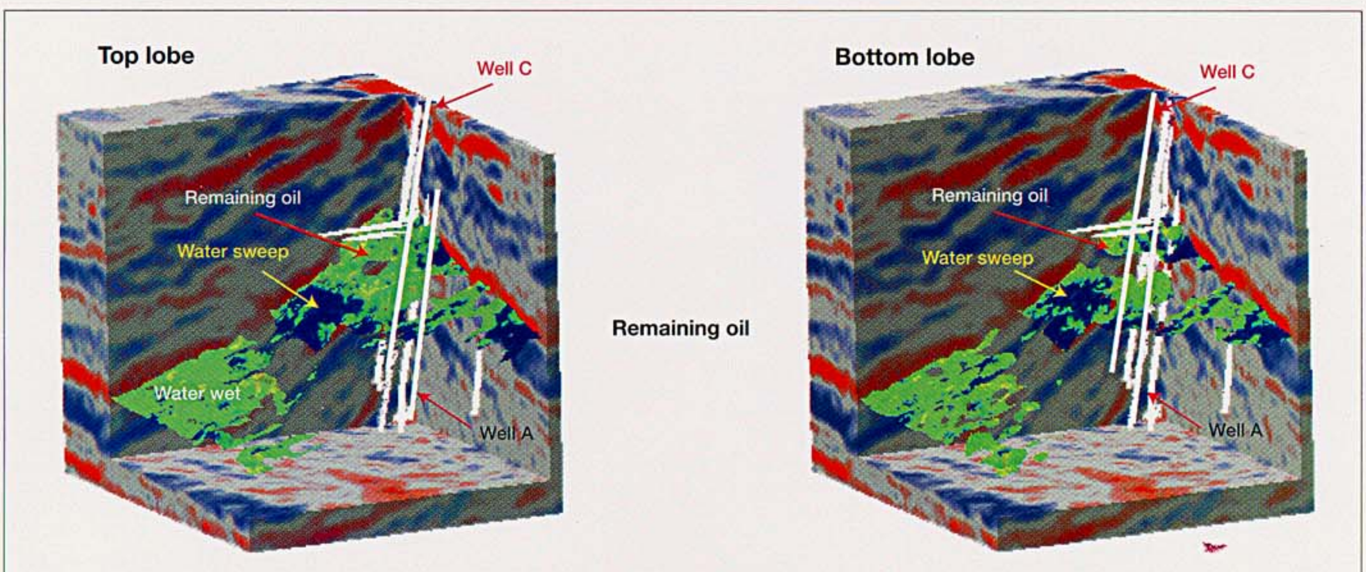


Fig. 17. Seismic impedance difference from Time 1 to Time 2 in top (left) and bottom (right) lobes of a turbidite sand in the vicinity of wells A and C. Note prediction that water (blue) sweeps much farther up-dip in bottom lobe, bypassing pay (green). A down-dip, water-wet interval is preserved to confirm that seismic changes inside the reservoir are larger than noise outside.

ple, irregular oil/water contact movement is shown by dimming (blue) in the water-swept portion of the reservoir. Below the water contact, the region grower is allowed to display changes in amplitude that occurred with no oil or gas present to make certain that differences within the reservoir are bigger than differences outside the reservoir. Areas of no change (green) show up both in this low-amplitude, water-wet region showing low noise levels, and in the highest amplitude portions inside the reservoir—bypassed pay?

Another important part of 4-D rapid-analysis software workflow must be visualization. Capabilities are required to display and recognize dimouts, amplitude brightening and sustained amplitude regions that delineate drainage, water encroachment, gas cap formation, and most importantly, areas of bypassed pay to be targeted by future drilling.

4-D software must provide as rich a set of visualization models as are required with 3-D interpretation. In addition, 4-D analysis needs added functionality, such as volumetric rendering of reservoirs, seismic and well log visualization along the same wellpaths (regardless of deviation), skeleton building, fluid migration pathway visualization and 3-D particle flow simulation.

In the example in Fig. 17, well logs show two lobes of producing sand in a water drive reservoir. Seismic amplitudes are visualized in the background of the cube for orientation purposes. 4-D seismic is then displayed along the producing horizon, which has been imported from a 3-D interpretation. Today's distributed nature of asset team management then requires that 4-D software also provide inter- and intranet connectivity and easily mountable "html" output.

SYNTHETIC WELLBORES AND 4-D DRAINAGE SIMULATIONS

The 4-D rapid-analysis workflow is not completed yet. The asset team then shifts into a planning phase to determine how to extract bypassed pay from within the reservoir undergoing analysis. 4-D software workflow must provide useful tools for planning of remediation strategies. For example, a synthetic wellpath tool is very useful to test possible locations of new wells to be drilled into the reservoir to extract bypassed pay. Drainage of liquids and gas into new perforations is simulated with a flow simulator that has been calibrated by the 4-D observations to date, see Fig. 11.

Volumes of oil, gas and water entering the synthetic wellbores must then be cataloged by a financial analyzer that predicts cash flow from these new well locations under consideration. Hundreds of well simulations can be tried before actual well locations are selected.

SUMMARY

Then begins the ultimate validation and testing of 4-D technologies—drilling to recover new oil from old fields. You can see from the 4-D workflow described above that the asset team has evolved from considering the static, fixed-structure and stratigraphy of an oil field, to a dynamic and constantly changing image of reservoirs that are actively undergoing drainage. This is the true paradigm shift that 4-D brings to the oil field. **WO**