Why 4-D?

The Information Technology revolution has changed the way we do business

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The concept of using multiple seismic datasets to image changes over time in oil and gas reservoirs, which we term 4-D, is not new. 4-D experiments date to the 1970s. To understand why 4-D will finally mature in the next several years into a new production paradigm for operators and service companies requires an understanding of both the methodology of 4-D and the market it plays into. Understanding these keys also gives insight into the shape of this new market. In this article we discuss our perceptions of these keys to understanding "Why 4-D now?"

INTRODUCTION

4-D is not one, but a whole suite of technologies being developed for a new approach to reservoir monitoring, Fig. 7. 4-D makes use of seismic monitoring, and integrates it with more traditional methods of reservoir engineering such as borehole measurement and cased hole logging. This new approach is "information rich" and can, for the first time, use and integrate, via coupled models (primarily seismic and reservoir), all the information coming in from an oil or gas field during production. The key to understanding "why 4-D now" is to understand why the industry is ready to adopt—and even insist upon—this integration.

4-D is not cost-cutting. This new 4-D reservoir management approach, with repeated acquisition of 3-D seismic surveys linked to large scale computing consisting of seismic inversion, Monte-Carlo reservoir characterization, seismic modeling and reservoir simulation, is more expensive than the industry norm currently requires for production planning. The oil patch and seismic service industries have previously conducted their production business in ways unique to the oil industry. However, that is changing as the Information Technology (IT) revolution and an end to the "Cold War" percolate down to profoundly change day-to-day business.

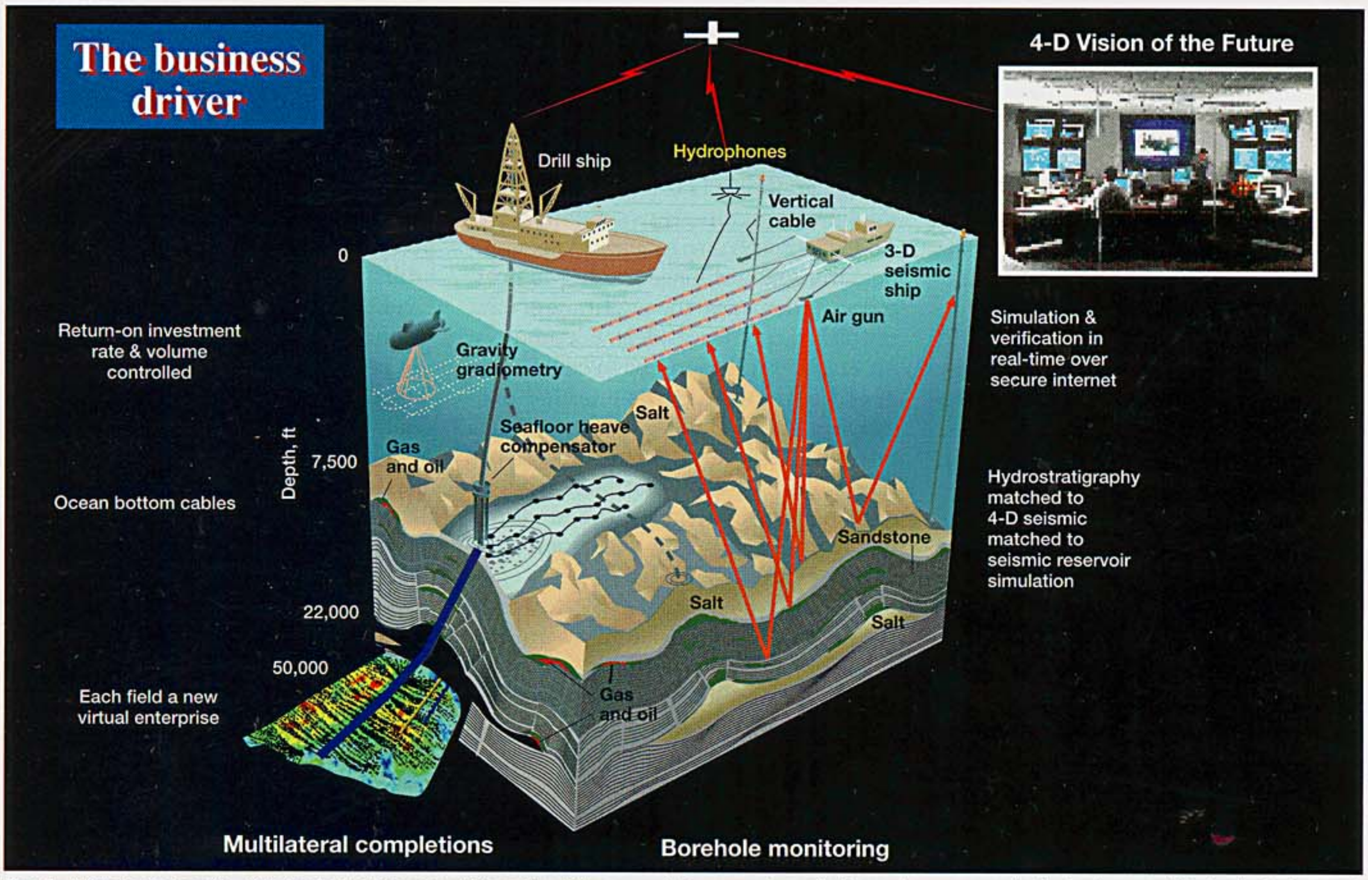

Fig. 7. 4-D is part of a suite of technologies for a new, information-rich approach to reservoir monitoring and management. The business and technological aspects of the oilfield of the future will force a virtual enterprise, with equity and risk sharing and a distributed information infrastructure supporting each other—much like today's large airframe manufacturing infrastructure.

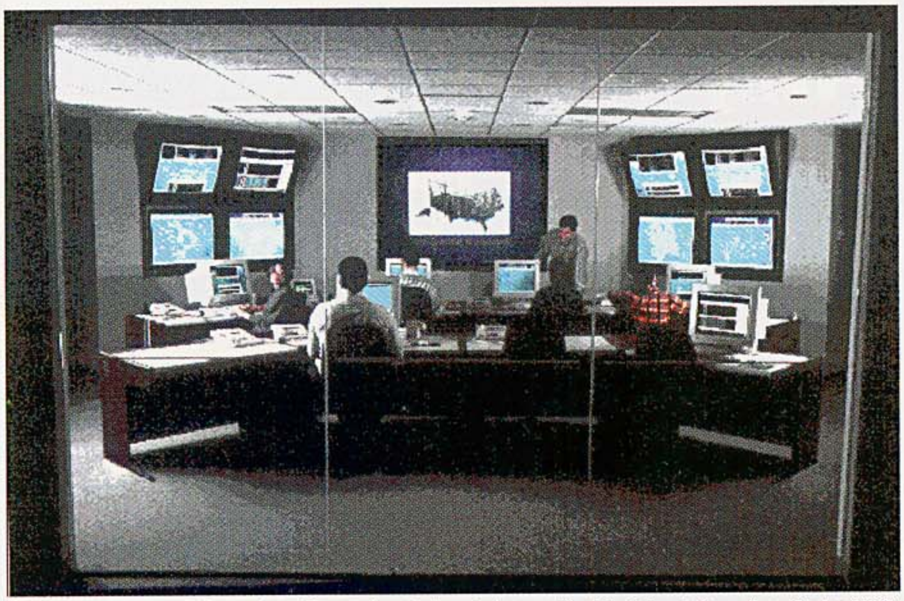

Fig. 8. Future fields will be produced from networked control rooms like this Network Operations Center (NOC), at BBN, Inc. in Boston, from which the Internet is managed.

This article will outline the characteristics of this new IT approach and why the industry is undergoing a paradigm shift that will embrace 4-D seismic and other information-rich reservoir monitoring technologies as a cost-effective way to get new oil out of old fields. A subtitle to this article could be "How to increase revenues and profits through the added expense of 4-D reservoir monitoring." The discussion below is organized into the impact of 4-D on three major aspects of oil and gas production: 1) scale, 2) economics, and 3) methodology.

SCALE

Understanding a reservoir is a large, multi-scale earth problem. Diversity of scales requires "heavy-iron" computation and massive data warehousing and database mining capability only recently available to the oil industry. Four separate oil field technologists—reservoir engineers, geologists, geophysicists and petrophysicists are joining forces to interpret 4-D.

Large and multi-scale problem. Analyses and computational products in oil and gas exploitation/reservoir production cover several interacting scales of interest. These include the spectrum from large-scale sedimentary basin models to small-scale, high-resolution models and analysis that can match well log resolution. In fact, reservoir characterization is said to occur at four scales: 1) microscopic (mm to cm), 2) mesoscopic (cm to meters), 3) macroscopic (10s to 100s of meters) and, 4) megascopic (kms and above).

Grand challenge in scope. Computational requirements for simulation and analysis of various scales to the resolution, extent and accuracy required for more efficient and better control of producing fields is truly a "grand challenge" computing problem. This challenge is defined in the High Performance Computing & Communications "Blue Book" of the U.S. Office of Science and Technology Policy. The internet address is: http://www.hpcc.gov/blue96/section.2.6.1.html#OILRESERVOIR.

One major reason for the success of 4-D reservoir monitoring now is that computer capability is finally available to implement an integrative architecture. An IT approach also requires data warehousing and database mining to host, collect and retrieve the multitude of data needed by coupled models. Fortunately, an exponential increase in computing speed and storage has enabled progression from 2-D to 3-D; and now 4-D is possible. The next decade will see a flourishing of computational models for oil and gas production as the computational gates swing ever wider, and at an exponential pace at that.

On a broader scale, exploitation of the next frontier of oil and gas production, the ultradeep waters (3-km water depths and greater), is a grand challenge economic, engineering and logistics problem.These problems can be aided by a properly functional, inter-operational, information infrastructure. The exploitation of the ultradeep is at such a scale of effort that no single oil and gas company can go at it alone—collaboration in an information-rich partnership is mandatory to spread risk and corral enough resources to make the task cost-effective. This is a collaboration beyond the usual beehive of specialty data products that service companies are providing in the producing oil fields of today.

Distributed by nature. The geophysicists who analyze and visualize 4-D seismic data use different computational tools than petrophysicists who process well logs, or reservoir engineers who make the production decisions and geologists who process reservoir characterization. This division of computational tools and expertise is mirrored by the scale of the problem addressed by each, as well as by the methodology used to analyze that scale. These specialty areas often sit in different organizations or companies, yet they need to inter-operate.

The new, cross-functional computing infrastructure that is emerging from entertainment, military and other far-field disciplines can serve to better integrate these scales and their attendant methodologies. Further, this inter-operation has to become more "seamless" for the "grand challenge" oil production problems of the future, such as the exciting prospects of the ultradeep Gulf of Mexico and the North Sea.

ECONOMICS

Seismic surveys are the industry's "treasure maps." 4-D increases the dimension of these maps by adding time to length, width and depth. Changes in value recovery make 4-D attractive now. Production rates, in addition to volumes, are now critical. Ever increasing capital investments in harder to exploit fields is increasing potential risk.

4-D increases efficiency and reduces risk, thus making "spend more to make more" a viable management decision. Corporate downsizing has forced "knowledge bases" to be computer-based, and the architecture for this knowledge base is still emerging.

Another major dimension involved in the question of "Why 4-D now?" is how changes in the industry are rewriting the economic equation for production decisions in a way that makes 4-D reservoir monitoring attractive, if not required. The key issue is that successfully producing fields generate enormous future revenue streams, but require enormous up-front capital expenditures to realize maximum income, especially in ultradeep water. Companies now need not only get predicted amounts of oil and gas out of the ground (volumes), but get them quickly as well (rates).

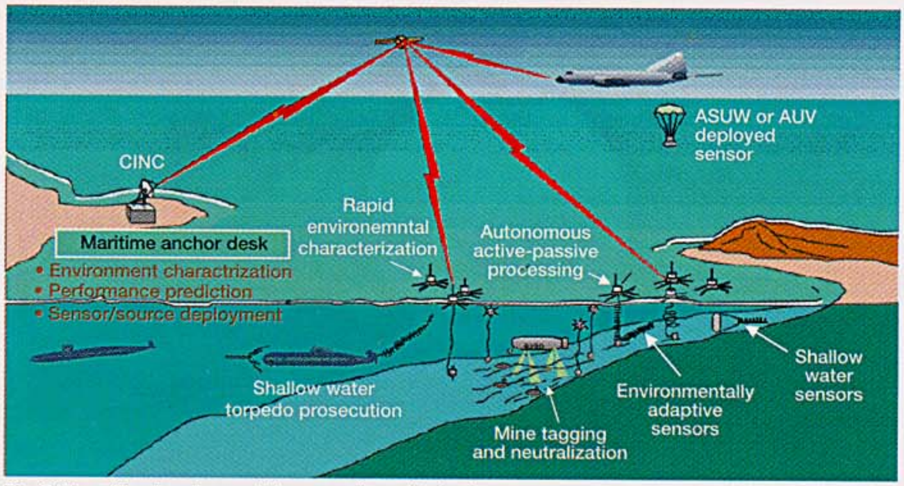

Fig. 9. The military has done real-time acoustic monitoring for many years. This illustrates anti-submarine warfare.

Treasure maps. Datasets that make up 3-D seismic surveys each have an established, $ multi-million value. They represent "sunk" costs that can be audited for cost sharing purposes. One can view these seismic datasets as treasure maps of large value that tell the owners of the maps where to "dig" for treasure. These datasets are highly protected by their owners; and therefore, there are architectural implications of this fact in the design of an inter-operating information infrastructure within the production environment.

For example, the industry has been reluctant to adopt the Internet information superhighway because of security worries. The necessary coupling between components of the production loop will drive the industry to increase use of the Internet, as secure high-bandwidth transport becomes more and more available. Already we see major service companies acquiring and partnering with major communication providers to provide secure, remote access from the field to databases and models.

Value recovery. 4-D enhances the value of 3-D seismic surveys because they can be combined with other time-varying data such as production histories and cased hole logs—either at the service company or at the oil company—to provide added information of extreme value, i.e., change within the reservoir. Service companies "mine" the potential 4-D value of their speculative survey databanks, and then search out operators who produce from those locations, thus increasing the value of their databanks.

The software industry also provides products for oil and gas production that add significant value to the treasure maps in their current 3-D configurations. In the new 4-D paradigm, they must adapt their products to incorporate changes observed over time in reservoirs. During the 1990s, industry has witnessed a vertical integration by acquisition or partnering of capabilities that now extends from software to drill bit to produced barrel. The information-rich, 4-D reservoir management of the future will require addition of horizontal integration among software and hardware packages. Plug-and-play is the norm in entertainment, medical and military software industries, and it will become so as well in the oil industry.

Ever-increasing capital investments. The large capital investments required in the future will forge new economic mechanisms to manage financial risk. Increased risk will drive reservoir monitoring. Deviations between a reservoir simulator's predictions of rates and volumes must be verified, and if necessary, modified, virtually instantly, if economic models that predict profits are to be consistently converted into true performance. 4-D reduces risk, and thus makes "spend more to make more" a viable management decision in this production climate. It is no longer enough to cut costs alone—revenues must be maximized. 4-D's success is now being driven in large part by the need to control risks in fields in the deep and ultra-deep waters of the Gulf of Mexico and North Sea.

Corporate downsizing. Advanced technologies from industries unrelated to oil and gas are needed to successfully produce in grand challenge areas like 4-D reservoir monitoring. The oil industry outsources this advanced technology research and development not only to service companies (who in turn, have vertically integrated in response to this demand), but also to universities, national labs and former military R&D companies.

Another development is the growing use of technology consortia as a way of conducting pre-competitive R&D. This outsourcing produces a computational architecture that is ever more distributed. This is another shaping factor in how the industry is structuring itself for the 4-D reservoir monitoring age.

Finally, the value of 3-D seismic imaging has been proven to the industry in just the last few years, even though 3-D has been around for 20 years. Industry experience gained in proving the value of 3-D over 2-D will accelerate the proof of value of 4-D, and thus, its acceptance period should be far shorter.

METHODOLOGY

As discussed in this section, 4-D reservoir monitoring is an ill-posed "inverse" problem. Iterative improvement in the reservoir model is conducted throughout the life of a field. Rapid analysis capability is required for quick answers to short-term field problems. Inversion and modeling are then required for more detailed, quantitative answers to longer-term drainage problems.

The most influential force that affects the computer processing methodology behind 4-D reservoir monitoring is that it is, in fact, an ill-posed inverse problem. Inverse problems solve for earth models that give the most likely answer to all observations, i.e., geophysical, geological, petrophysical and engineering. Moreover, 4-D reservoir monitoring is an inverse problem in four dimensions: length, width, depth and time. The quest is to build a model of what is happening "down there" at relevant spatial and time scales of interest so that observations of changes in seismic, well-logs, pressure and fluid mixes can be understood and optimized.

Future control of production, guided by such models, is like a multi-arm Shiva with information gathering and control arms working at different time and spatial scales. Today's technology has not allowed the smaller time and spatial scales of current modeling practices to be done in an information-rich way. The challenge is to match moni-

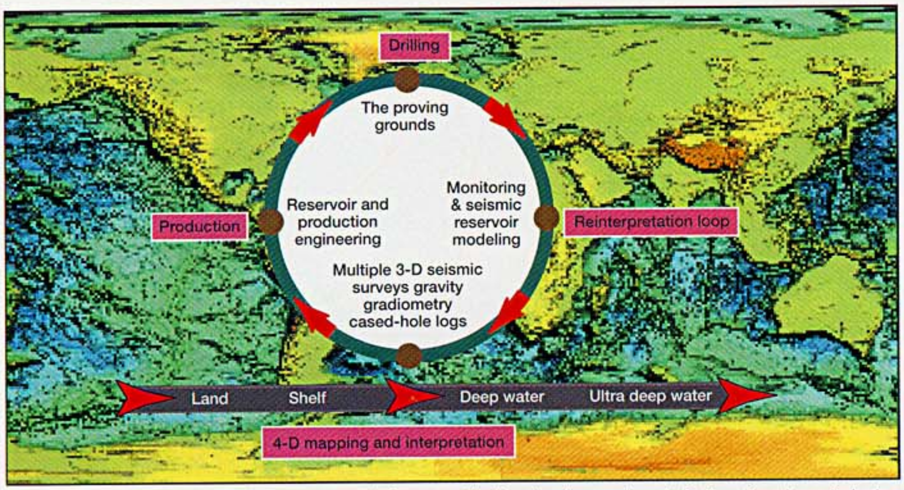

Fig. 10. Drilling has been the ultimate proof-of-concept in the development cycle in the oil and gas industry. This development "wheel" rolls along successively more challenging trends in the Gulf of Mexico—the newest of which is the ultradeep trend where drilling will be one of the proving grounds for 4-D seismic.

toring of actual field recordings such as surface acoustic sensors and downhole instruments, with modeling of expected performance of the field. This would consist of coupled reservoir characterization and fluid and seismic simulation models. The long term goal is to couple seismic scale of observations to reservoir scale of production.

Iterative process, rapid analysis. The process of selecting a model that best fits the data is an iterative, optimization process, and this multiplies the computing demands. These demands are exacerbated by the constantly increased fidelity for the forward model, which has to be evaluated many times. Fortunately, more sophisticated and accurate modeling, like elastic finite element modeling instead of raytracing, for example, can lead to increasingly faster convergence.

4-D reservoir monitoring must provide tools to gain an initial, rapid understanding of changes in a reservoir from legacy seismic and logging data. This allows an initial idea of changes in a reservoir to drive evaluations of the worth of expensive acquisitions of seismic and borehole monitoring infrastructure that are then required to monitor into the future.

This two-fronted approach allows some breathing room as the full economic model comes on-line and is iterated with the field under actual production conditions. Matching development of a 4-D reservoir model with the actual production cycle of the field allows the next step—planning of future re-acquisitions of 3-D seismic and other monitoring datasets—to proceed within a realistic financial model.

Quality control. Distributed modeling, analysis, visualization, database mining and networking will become the norm. 4-D reservoir monitoring will make use of the "network as the computer." The oil industry will use 4-D to achieve quality control of oil and gas production.To control, one has to model. The challenge is to provide the information-rich infrastructure so that proper models can be built that allow accurate simulation of field performance, constantly updated with new information coming in from the field, Figs. 7 & 8.

We want to be able to track and model oil-water-gas contact boundary movements and estimate rates and capacities of reservoirs. With this information, better real-time control of a field can be realized. Detailed information from drainage patterns can be coupled with directional drilling and multi-lateral completions to target and produce bypassed pay, thus increasing ultimate recovery percentages of oil-in-place.

Increasingly, the oil patch has seen the introduction of Cold War military technologies, such as vertical cables of Texaco and gravity gradiometry of Bell Geospace (http://www.bellgeo.com). The military has done real-time acoustic monitoring, integrated with command and control, for many years, Fig. 9. The technologies behind rapid deployability, real-time acquisition, assimilation, and control of acoustic detection networks will find their way into the command and control infrastructure of the 4-D oil field of the future.

Engaging technology. 4-D reservoir monitoring engages many emerging technologies. At last, new seismic, drilling and completion technologies are emerging that can realize the value enhancement of 4-D far beyond its computational base, for example:

- 4-D/3-component shear wave seismic
- 4-D amplitude vs. offset (AVO)
- Multi-lateral directional drilling
- Cased hole logging—resistivity and sonic as well as nuclear, and
- 4-D gravity gradiometry.

In the midst of all this computing, the fact remains that drilling is the ultimate proof-of-concept and discovery mechanism in oil and gas exploration. Guidance to, and feedback from drilling is indeed a product of, and a valuable resource to, seismic modeling and analysis. 4-D will be accepted only after wells based on this technology are drilled, Fig. 10.

Vision of the future 4-D oilfield. To conclude, we foresee a 4-D enterprise within the oilfield of the future like that of today's airframe manufacturing enterprise. A new major airframe is so costly, with such high risks, that building one has become a computational enterprise with many partners sharing risk and equity.

No longer are planes designed in wind-tunnels. Now, hundreds of design scenarios are tested on a computer before a final design is passed, almost as a formality, through a wind-tunnel. We are just emerging from the "wind-tunnel" days of oil production. No longer will a new well be drilled just to see what happens to a particular production problem. In the oilfield of the future, distributed modeling, analysis, visualization, database and networking will become the norm so that hundreds of drilling scenarios will be tried before the optimal location is settled upon, Fig. 7.

Multiple datasets will be collaboratively visualized from remote locations scattered all over the globe, and acted upon within immersive, 3-D environments like caves, with gloves and other tools to probe the volume. Data from the field will be collected in semi-real-time, over packet-switched satellite links by sensor networks placed in all important producing fields. Periodic seismic re-acquisitions will be delivered via satellite and quality controlled remotely. 4-D model components will be distributed across equity partner networks using high-speed, international information infrastructures—all steered at remote visualization and collaboration consoles. **wo**